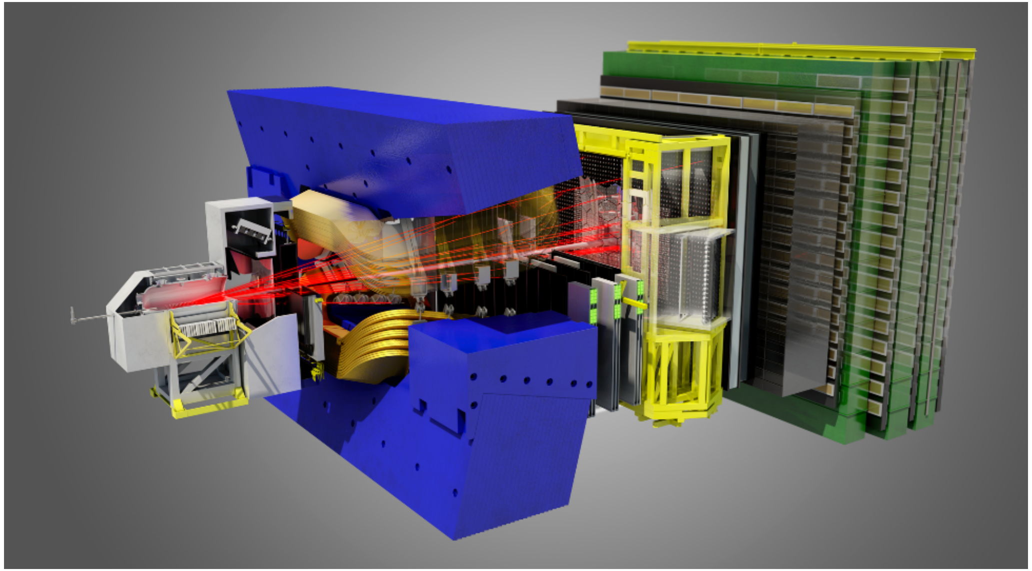
Running a flavour experiment at the LHC

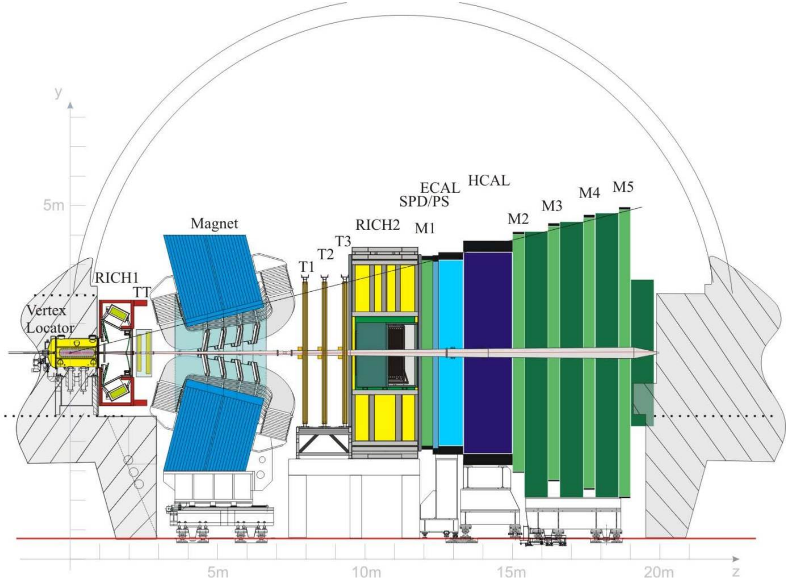
Patrick Robbe, LAL Orsay, 7 Nov 2018

Introduction

- How to maximise data taking of a flavour physics experiment
  - Example of LHCb at the LHC
- The LHCb experiment is finishing operation before its first upgrade:
  - Almost 10 fb^{-1} were collected since 2011
  - Pushing the limits of the detector in order to maximize the data taking efficiency

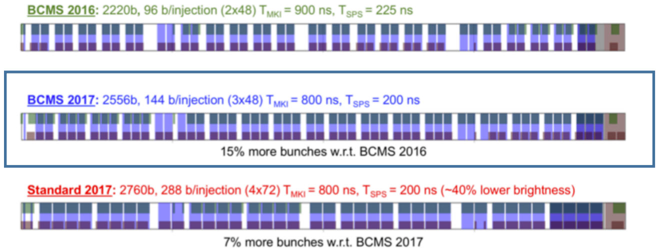
Detector

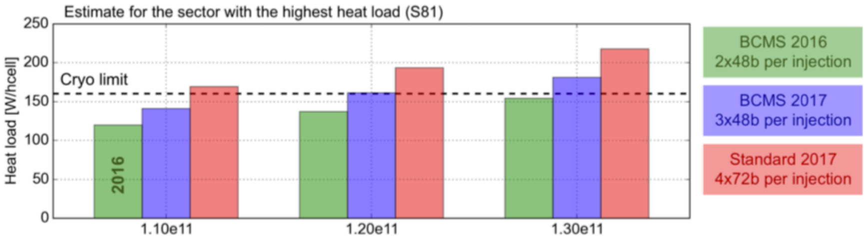



y
5m
Vertex Locator
RICH1
TT
Magnet
T1
T2
T3
RICH2
M1
SPD/PS
ECAL
HCAL
M2
M3
M4
M5
5m
10m
15m
20m
z

Constraints

- How to push up statistics of recorded events:
  - LHC:
    - Increase luminosity per bunch
    - Increase number of bunches (ultimately the only possibility for LHCb)
      - The design maximum number of bunches in the LHC is **2808**. Because the LHCb interaction point is displaced with respect to the center of the cavern, less bunches collide in LHCb, about 90%
      - This maximum was never reached:
        - During Run I, the spacing between bunches was 50ns: maximum of 1400 bunches
        - During Run II,
          - In 2016, vaccuum leak in the SPS
          - In 2017, frozen air in one LHC magnet
          - In 2018, ultimately limited by cryogenics



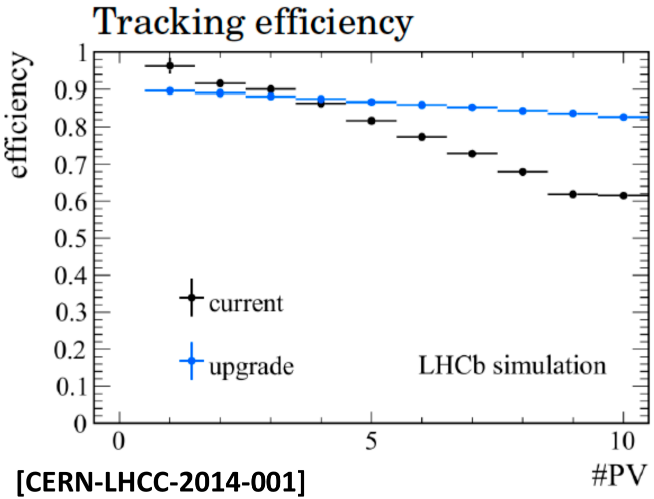


Constraints

- The LHCb detector is built to run with low multiplicities, the performances of the detector degrade with high multiplicity.

- The multiplicity is proportional to μ = average number of <u>interaction</u> per crossing. This is controlled by the instantaneous luminosity per bunch.

- Since the performance of the detector depends on multiplicity, keep the average multiplicity constant over time to have uniform datasets.

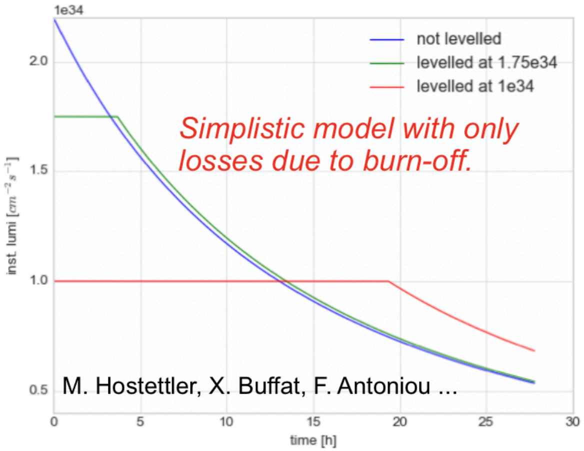


[CERN-LHCC-2014-001]

<u>Number of interactions</u>

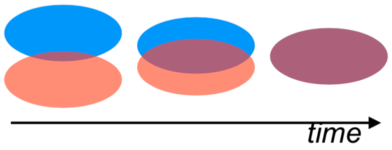
Luminosity levelling

- This is done by luminosity levelling: beams are displaced with respect to each other continously to keep the instantaneous luminosity per bunch constant.
- An <u>interaction</u> in LHCb is defined as a collision visible in the calorimeter.
- The average number is measured by the calorimeter from the rate of non-empty beam crossings with 0 interaction and sent as feedback to the LHC so that it maintains a constant lumi.
- In Run I (2012), μ was kept to 1.7. Because of the change in center-of-mass energy (8 TeV to 13 TeV), to keep a constant multiplicity, μ in Run II (2015-2018) was 1.1



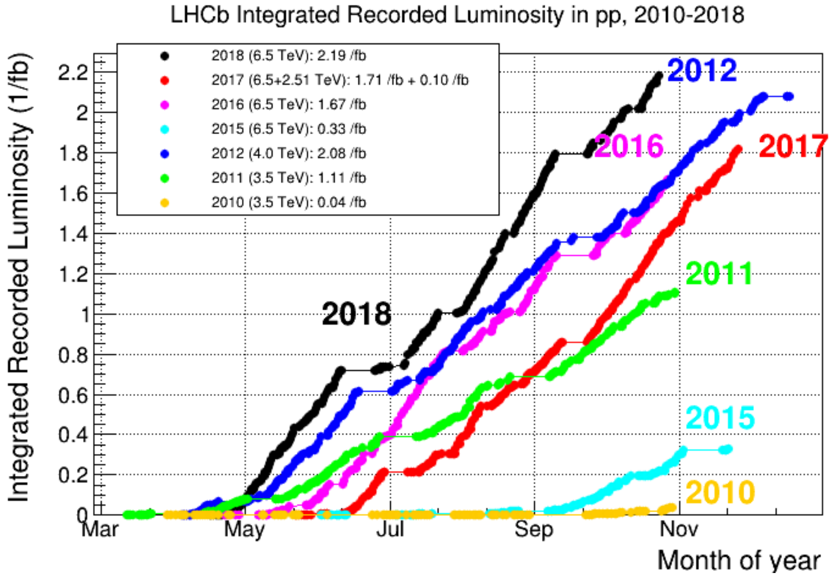
Simplistic model with only losses due to burn-off.

M. Hostettler, X. Buffat, F. Antoniou ...



Luminosity

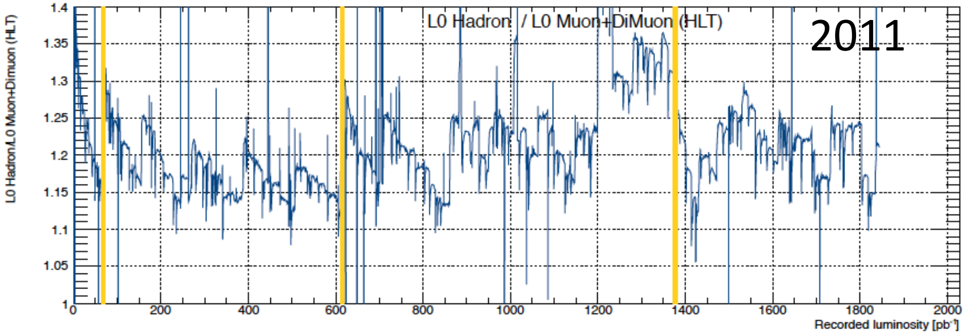
Year	Max # bunches	Energy	μ	Lumi
2011	1320	7 TeV	1.4	$3.5\mathrm{x}10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
2012	1262	8 TeV	1.7	$4.0\mathrm{x}10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
2015	2036	13 TeV	1.1	$3.5\mathrm{x}10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
2016	2036	13 TeV	1.1	$3.5\mathrm{x}10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
2017 (before summer)	2332	13 TeV	1.1	$4.4\mathrm{x}10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
2017 (after summer)	1749	13 TeV	1.1	$3.3\mathrm{x}10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
2018	2332	13 TeV	1.1	$4.4\mathrm{x}10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

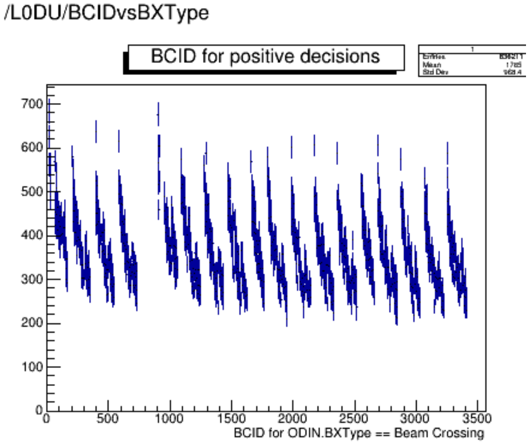


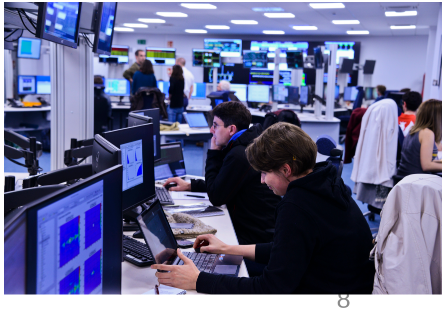
NB: the heavy-flavour cross-section is ~twice at 13 TeV compared to 8 TeV

Luminosity levelling

- Because of radiation, the calorimeter response changes as a function of time: ageing. It is thought that the optical fibers collecting the scintillation light of the HCAL for example loose transparency. This is compensated by calibrating with a LED system to maintain response constant.
- This system does not exist for the ECAL (well it exists but it ages also), and is replaced by the monitoring of occupancy.
- The High Voltage of the calorimeter photo-multipliers are adjusted every day, but sometimes it is not enough and can vary during long fills.
- Also the value of μ can vary a lot bunch by bunch

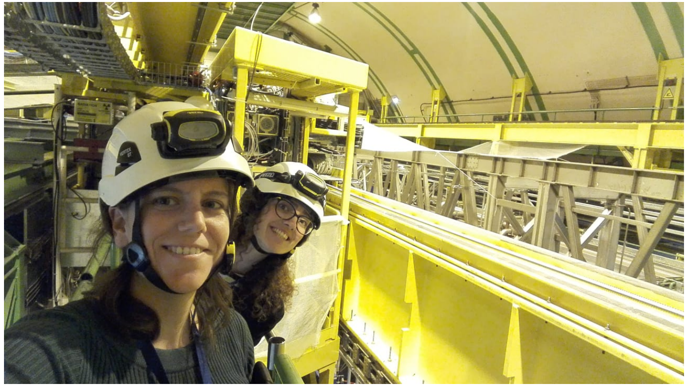


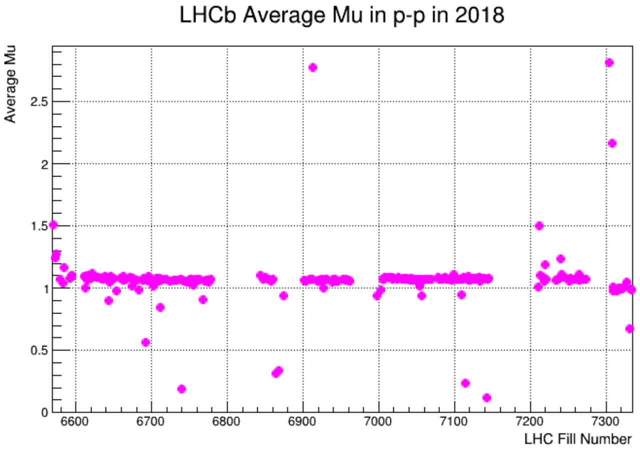




Luminosity levelling

- Worked perfectly during 7 years, based on calorimeter measurement, except during the very last week of running... (two weeks ago) !
- One cooling turbine of the calorimeter electronics failed and had to be replaced during an emergency access, and after that the calorimeter measurement changed….



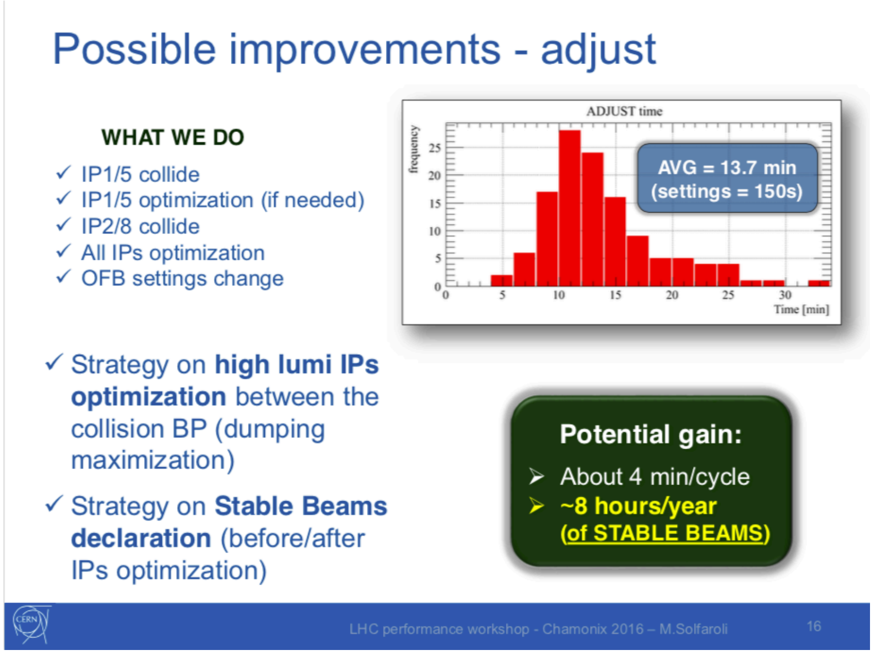


Calibration

- Since conditions can vary even if all is done to keep them stable
- And Monte Carlo simulation cannot cover all possible conditions.
- Need to calibrate using data.
- Most of them are automatic, some other manual: MUON detector is moved by hand at the beginning of every year to keep it well aligned.

Interplay with the LHC

- The number of colliding bunches in LHCb is not the only handle from the LHC side to increase the statistics. The time in collisions (stable beam) and the LHC running efficiency plays an important role.
- Every minute counts



Possible improvements - adjust

WHAT WE DO

- ✓ IP1/5 collide
- ✓ IP1/5 optimization (if needed)
- ✓ IP2/8 collide
- ✓ All IPs optimization
- ✓ OFB settings change

- ✓ Strategy on **high lumi IPs optimization** between the collision BP (dumping maximization)
- ✓ Strategy on **Stable Beams declaration** (before/after IPs optimization)

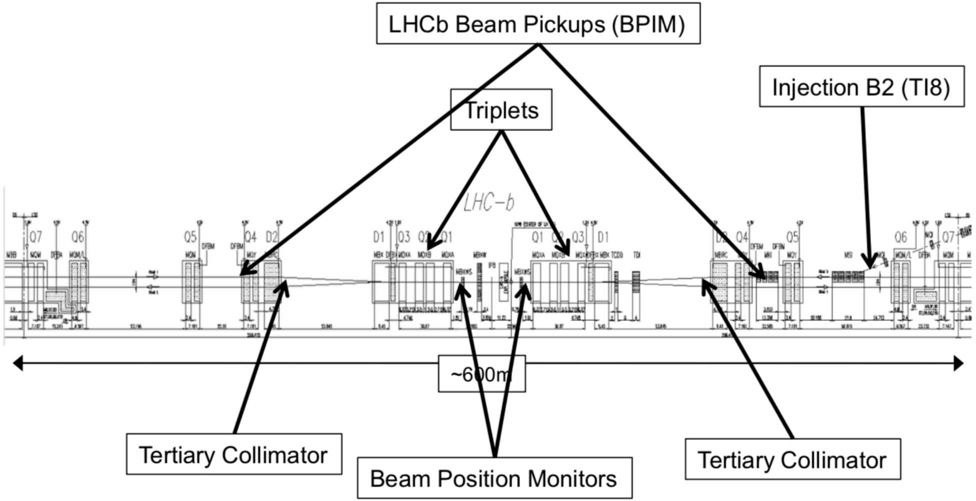
Potential gain:

- ➢ About 4 min/cycle
- ➢ **~8 hours/year**
  (of STABLE BEAMS)

LHC performance workshop - Chamonix 2016 – M.Solfaroli 16

Interplay with the LHC

- The position of the interaction moves because of the LHC magnets
- PV = Primary Vertex (position of the interaction)



LHCb Beam Pickups (BPIM)

Triplets

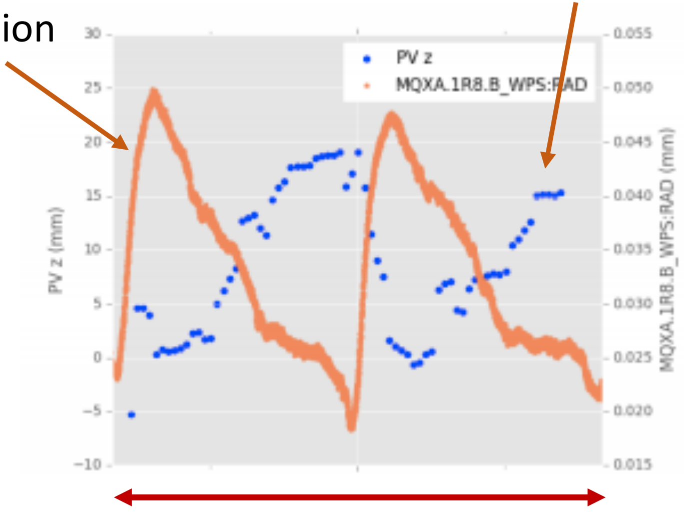
Injection B2 (TI8)

~600m

Tertiary Collimator

Beam Position Monitors

Tertiary Collimator



LHCb PV z position (mm)

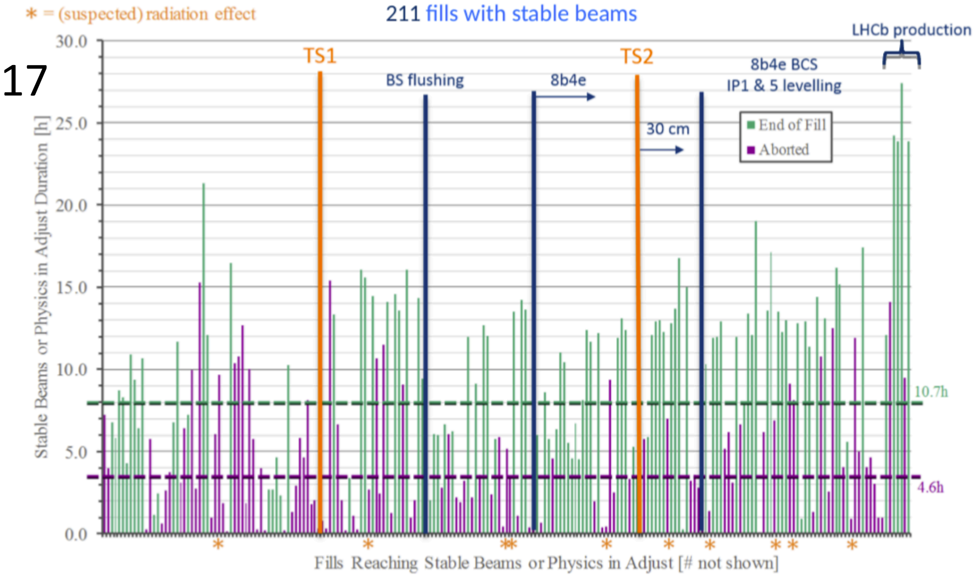
IR8 triplet position

16 hours

Interplay with other experiments

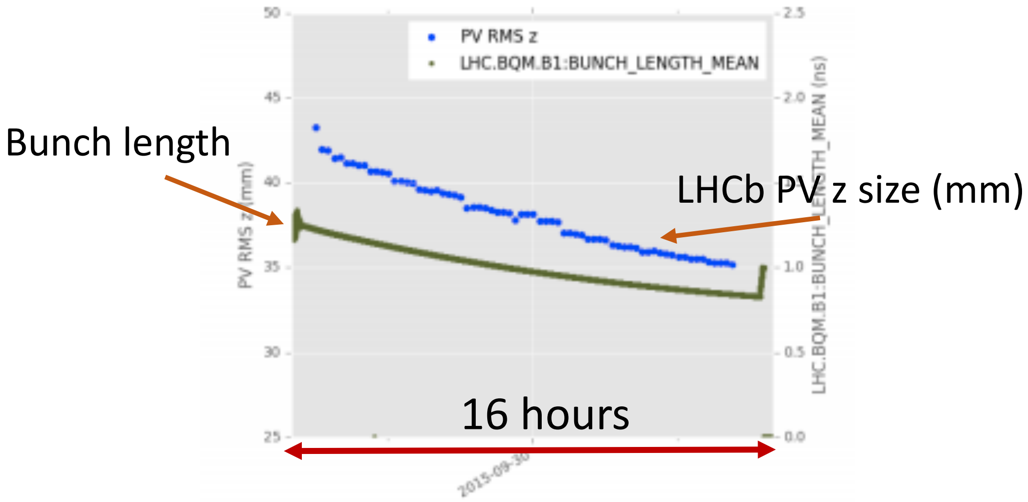
- ATLAS and CMS loose luminosity when the duration of the fill is too long (because of luminosity decay), optimal around 12h of stable beams.
- This is in conflict with LHCb where long fills are preferable

2017



Interplay with other experiments

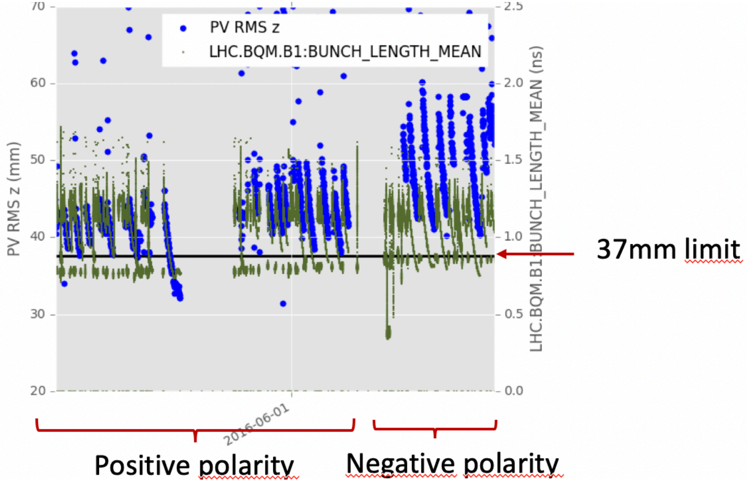
- Bunch length decreases over time because of proton synchrotron radiation



Bunch length

LHCb PV z size (mm)

16 hours



37mm limit

Positive polarity

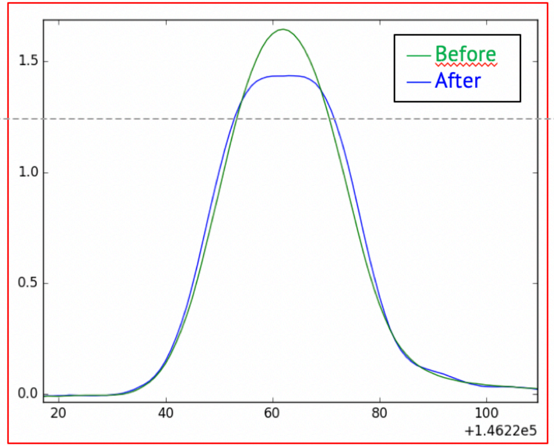
Negative polarity

- When the interaction region is too small, more difficult to find the PV associated to the particles of interest
- When the length is below 37mm, the fraction of mis-associated PV increases by 10%
- Asked the LHC to keep this length above 37mm

Bunch flattening in long fills

Vertex reconstruction is not accurate enough for LHCb for bunch lengths < 0.9 ns (for one polarity)

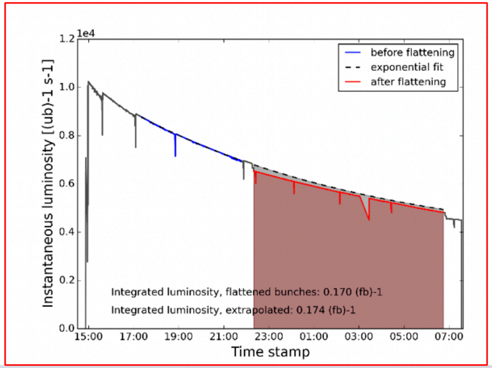
- Bunch flattening used operationally to regulate the bunch length [5]

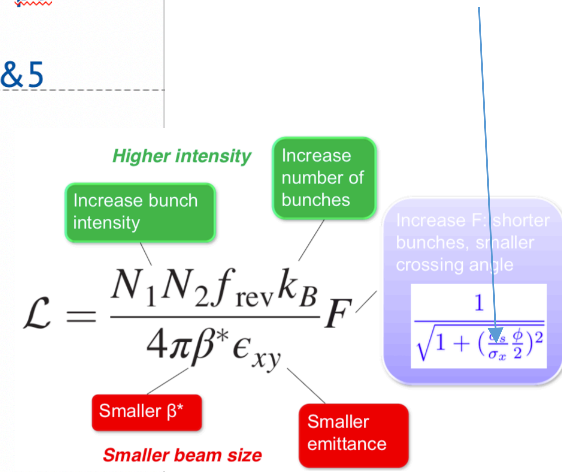


Bunch flattening in Stable beams 17th June 2016 (B2)

- Increases bunch length by 150-200 ps
- Reduces heat load (~5 %)
- Luminosity loss ~2.5-4.5 % in IPs 1&5
- Loss-free mechanism

ATLAS Luminosity, 6th August 2016





Higher intensity

Increase bunch intensity

Increase number of bunches

Increase F: shorter bunches, smaller crossing angle

$$F = \frac{1}{\sqrt{1+(\frac{\sigma_s}{\sigma_x}\frac{\phi}{2})^2}}$$

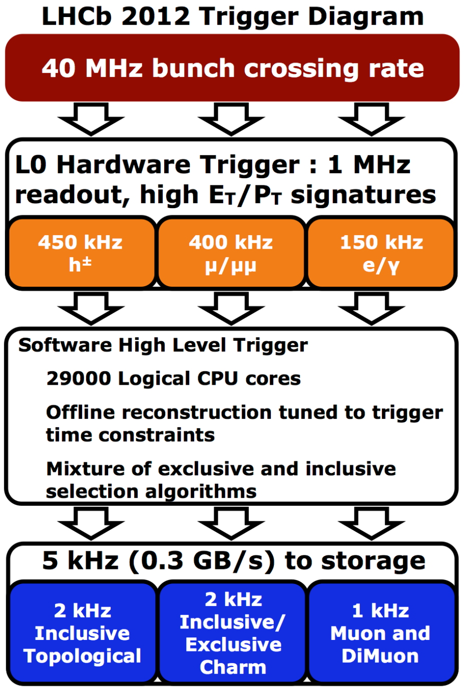
$$\mathcal{L} = \frac{N_1 N_2 f_{\mathrm{rev}} k_B}{4\pi\beta^* \epsilon_{xy}} F$$

Smaller β*

Smaller emittance

Smaller beam size

Trigger and reconstruction



LHCb 2012 Trigger Diagram

40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures

450 kHz $h^\pm$	400 kHz μ/μμ	150 kHz e/γ

Software High Level Trigger

29000 Logical CPU cores

Offline reconstruction tuned to trigger time constraints

Mixture of exclusive and inclusive selection algorithms

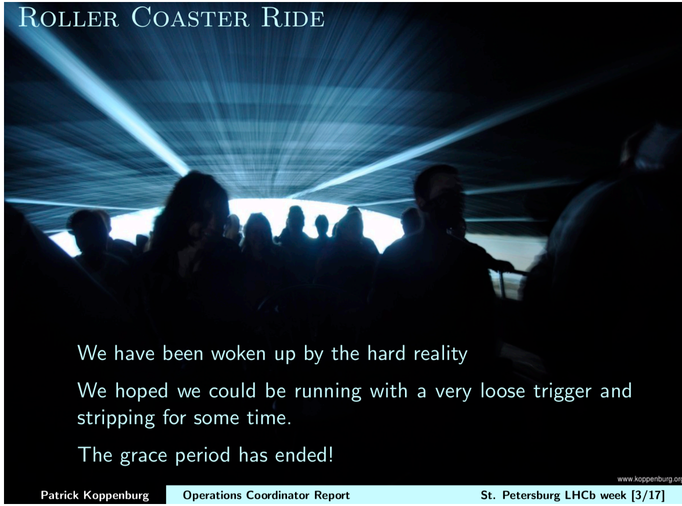
5 kHz (0.3 GB/s) to storage

2 kHz Inclusive Topological	2 kHz Inclusive/ Exclusive Charm	1 kHz Muon and DiMuon

- Detector readout is limited by construction to 1 MHz
- Collision rate reduced by a hardware trigger based on calorimeter and muon informations
- Because it is done in electronics, not very precise, but main goal is to optimize as much as possible the input bandwidth not to loose what is gained from beam operation
- Other bottleneck is the rate to storage system

Trigger and reconstruction

- Situation is better because the output rate is controlled by the software trigger, closer to physics analysis
- It can however be dangerous: each CPU should process one event within ~30ms but some events can take very long, timing increases exponentially with multiplicity:
    - The number of interaction distribution is a Poisson distribution, some events can have many interactions
    - Beam gas ?
- Software trigger tasks get stuck one after the other and the entire acquisition chain is blocked within few minutes:
    - “St Petersburg Crisis” in 2010
    - Apply cuts on event multiplicity in the software trigger
- In order not to waste input bandwidth, apply also multiplicity cuts at hardware trigger
- On SPD hit multiplicity: 450 for calo triggers, 900 for muon triggers



ROLLER COASTER RIDE

We have been woken up by the hard reality

We hoped we could be running with a very loose trigger and stripping for some time.

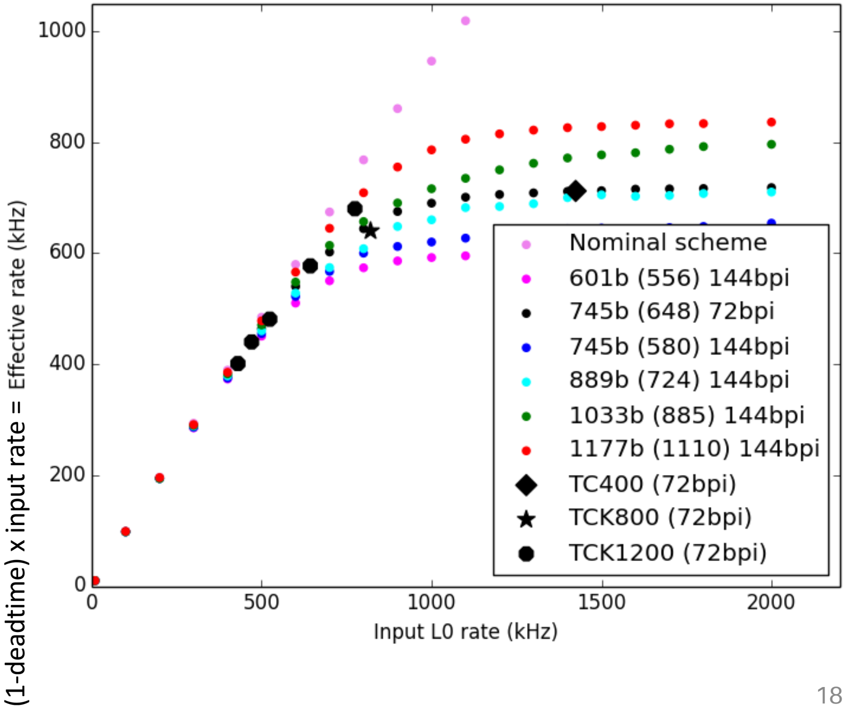
The grace period has ended!

www.koppenburg.or

Patrick Koppenburg | Operations Coordinator Report | St. Petersburg LHCb week [3/17]

Hardware trigger optimization

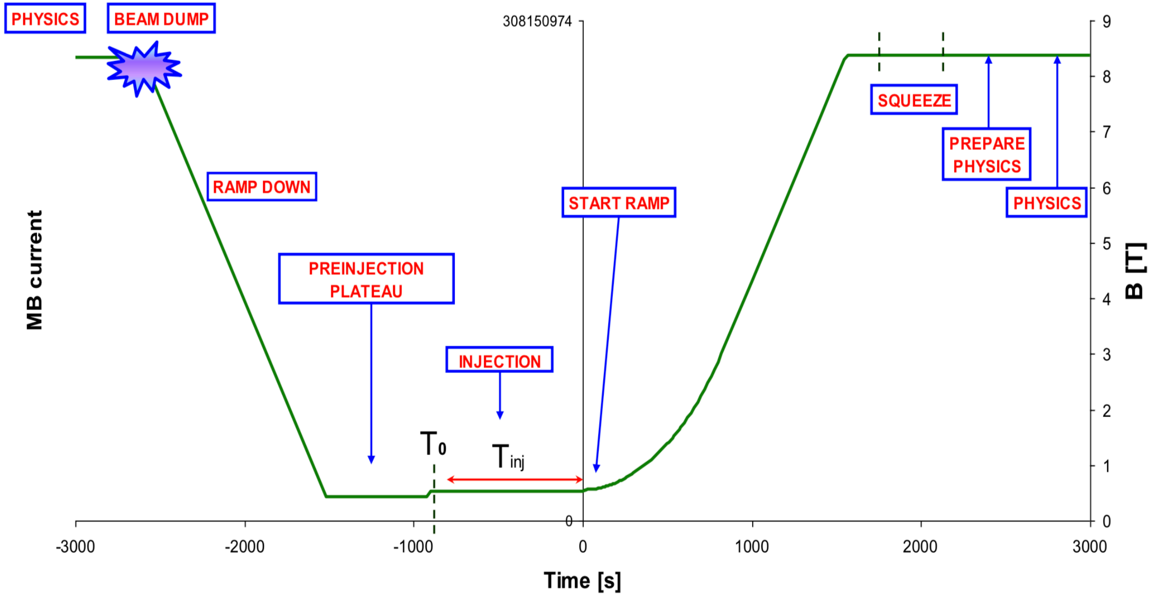
- Features of readout electronics
  - Cannot read out two consecutive bunch crossings (25ns),
  - Buffer limited in the Front-End electronics,…
  - When these limits are reached, the events are rejected: deadtime
- Deadtime depends then on hardware trigger rate and can be predicted precisely.
- What is important to maximize is the final number of “interesting B events”
- Decide the hardware trigger cut on optimal value: we found out it is better to run with non-zero deadtime (up to 10%) with looser cuts

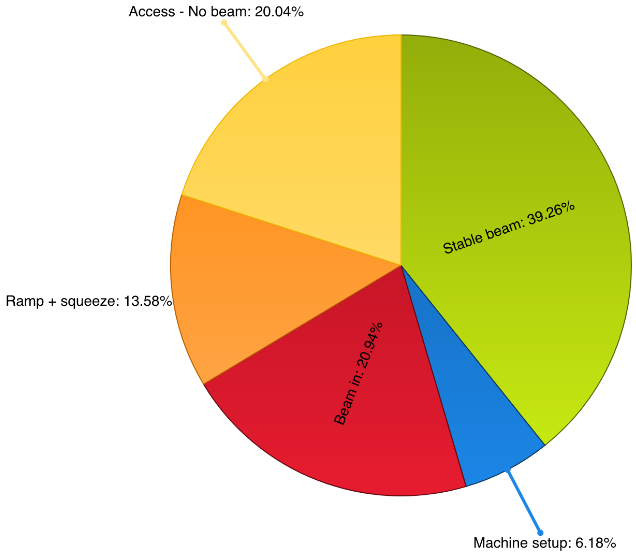


Hardware trigger optimization

- The ultimate bottelneck for the hardware trigger is due to the size of the events: when the events are too big, there is not enough bandwidth to send them to the software trigger.
- The detector reaching this limit first is the Outer Tracker, because it sends information about several consecutive bunch crossings.
- It can be reduced requiring events where the previous crossing had low multiplicity:
  - Introduce a new cut in the trigger level which is the multiplicity of the previous crossing
- Ultimate trigger rate of LHCb: 970 kHz with 8% deadtime (with one magnet polarity, with the other the maximum rate was 950 kHz)

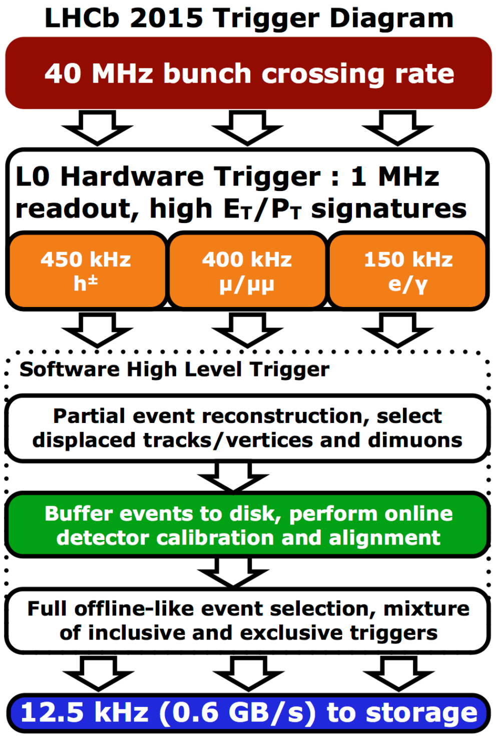
LHC sequence





- Instead of running the software trigger during stable beams, run it also when there is no collision. This will allow to increase the effective output rate and remove this limitation

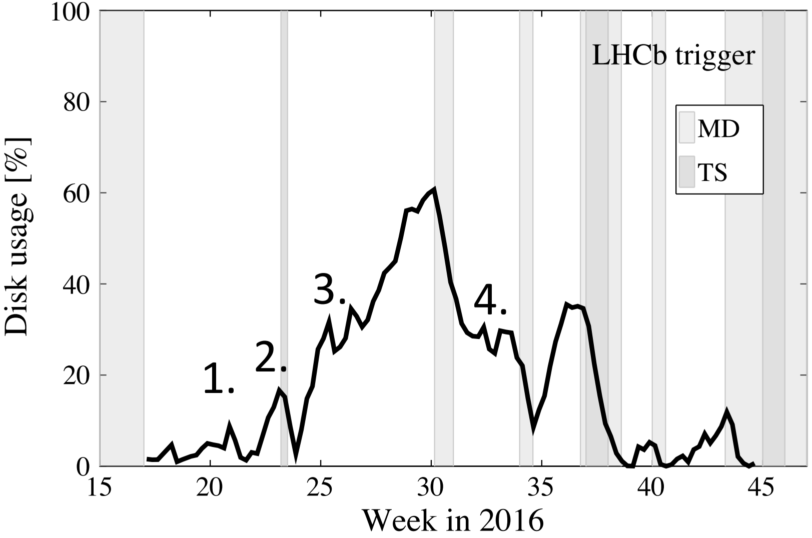
Run II Trigger Scheme



- After the hardware trigger, a loose software selection is applied, and events are written to disks attached to the CPU (access is much faster than central storage).
- Second part of software trigger is ran continously (at full speed when there is no collision, and at reduced speed when there are collisions)
- Take advantage of the delay between the two software stages to perform calibration and alignment:
  - More and better quality data

Run II Trigger Scheme

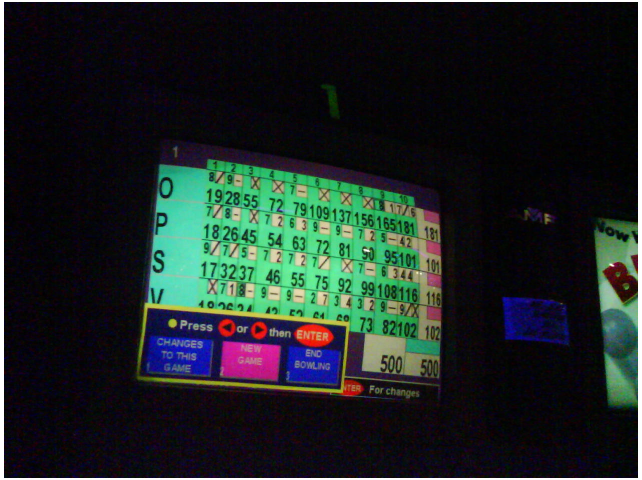
- Another constrain is then the size of the buffer disks: 5 PB. Should not be filled otherwise data taking is impossible.
- Filling speed must be predicted but depends on many factors:
  - Main one is the time the LHC spends in collisions, which is unpredictable



1. Write to disk buffer at 130 kHz out of the 1st software trigger stage
2. LHC performing better than expecting: reduce rate to 115 kHz
3. Reduce to 85 kHz
4. Relax to 105 kHz

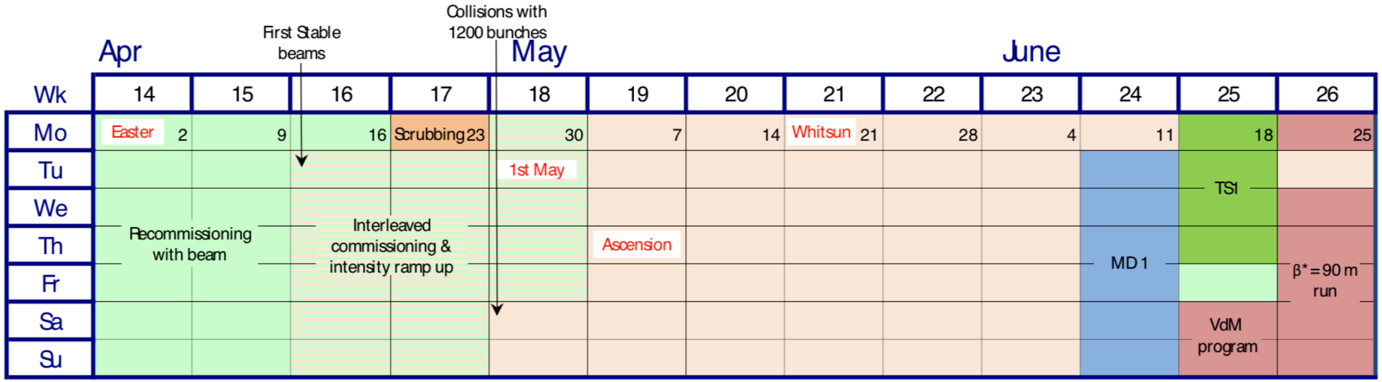
Trigger…

- Playing with the trigger was really the way to optimize data taking once the environmental conditions were fixed
- Olivier Deschamps prepared 175 hardware trigger configurations during the lifetime of the experiment
- Mainly small variations around common main features to keep analysis easy:
  - Cannot rely on simulation to describe all possible configurations
  - Need of calibration or unbiased trigger lines to determine efficiencies



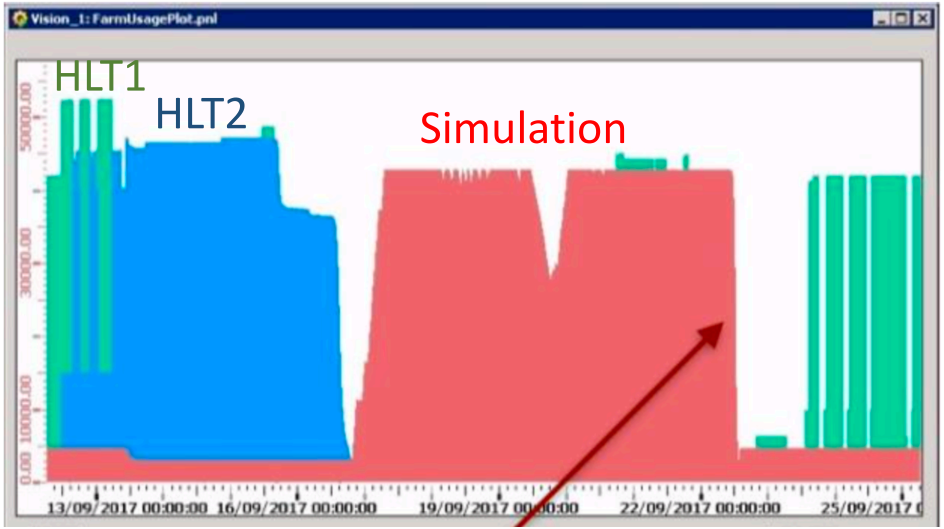
Simulation

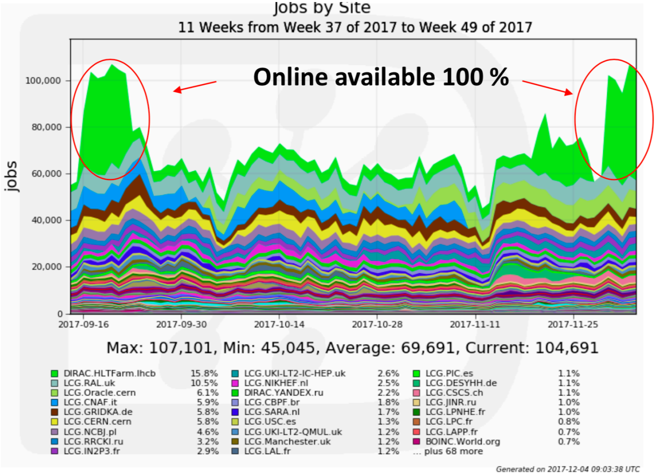
- Large need of simulation: usually simulate each type of event for every data taking year and magnet polarity.



- Simulation events are mainly produced on the grid.
- Use also the time with no beam to simulate events on the trigger computing farm.

Simulation

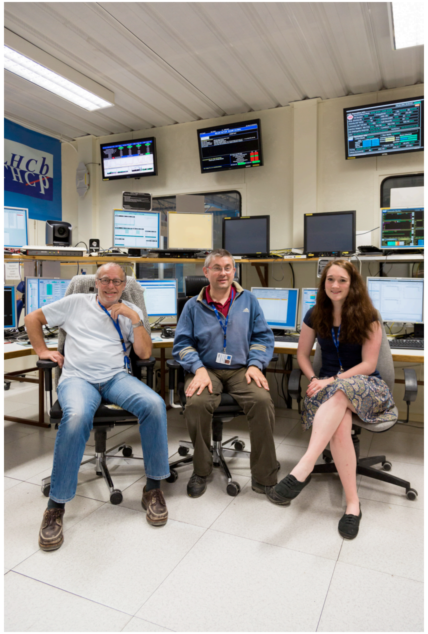




- Example here: profit from a 2 day unforeseen stop of the LHC to produce simulation events and stop production when beams come back
- There is also a small continous simulation production running
- It is not a gadget: when trigger farm is fully available, it doubles the computing capacities for simulation (compared to the grid alone)

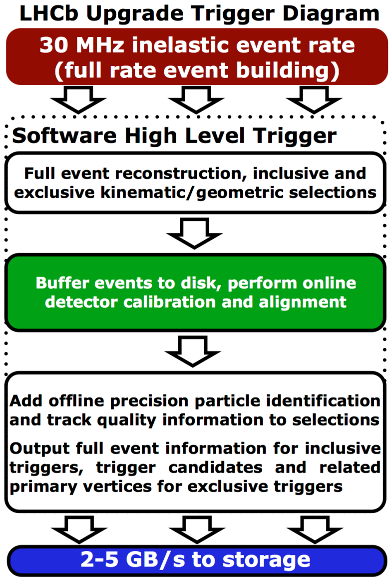
Shifts

- The last parameter in the optimisation of the data taking is the operation efficiency. It is 97.6% over the LHCb lifetime.
- Large level of automatisation: two persons on shift:
  - Shift Leader
  - Data Manager: essential role, in a flavour physics experiment, data where one detector is not working properly has to be discarded
- And 12 piquets (detector expert on site for 1 week)



Upgrade

- Now that we reached the optimal operation working point, it is time to replace the detector to do better.
- To increase statistics, the only way now is to increase the instantaneous luminosity per bunch, and reach in total 2x10^{33} cm^{-2}s^{-1} (μ=5.5). But the gain in statistics would be lost because of the imprecision of the hardware trigger -> remove hardware trigger



LHCb Upgrade Trigger Diagram

30 MHz inelastic event rate (full rate event building)

Software High Level Trigger

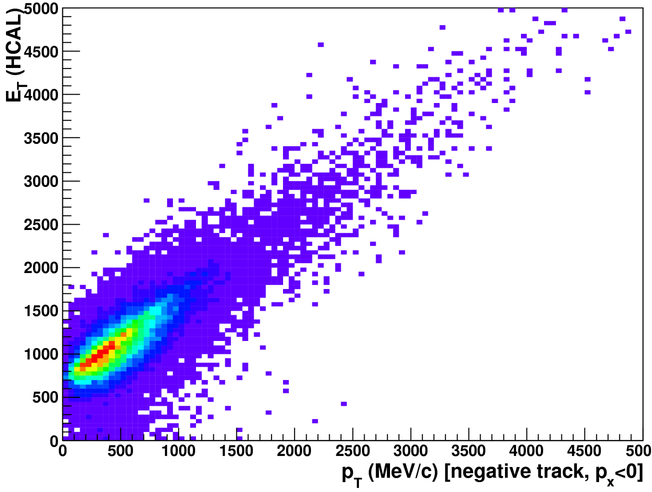
Full event reconstruction, inclusive and exclusive kinematic/geometric selections

Buffer events to disk, perform online detector calibration and alignment

Add offline precision particle identification and track quality information to selections

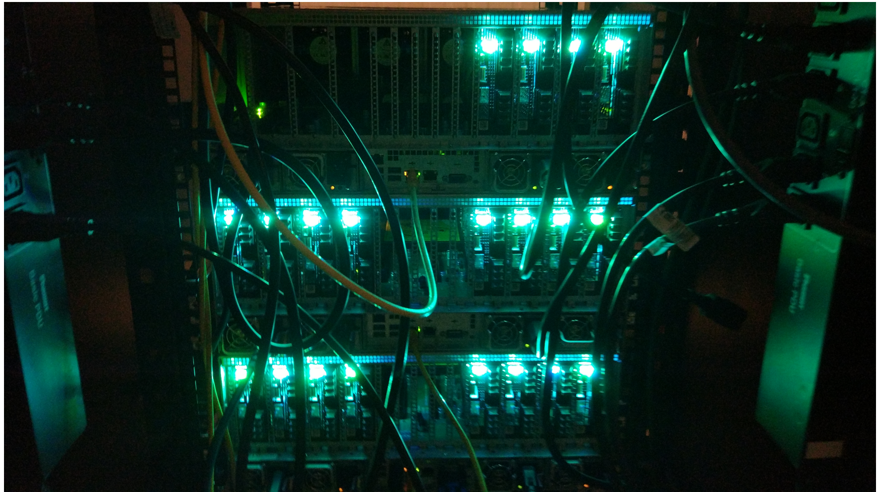
Output full event information for inclusive triggers, trigger candidates and related primary vertices for exclusive triggers

2-5 GB/s to storage

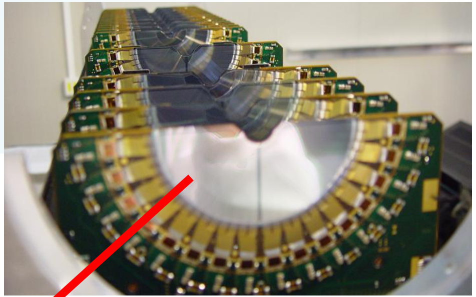


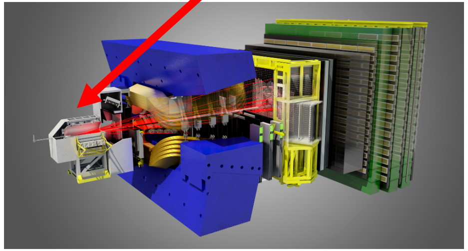
Upgrade

- But this implies building new tracking detectors to cope with higher multiplicities
- And designing new readout Front-End and backends.
- PCIe40 boards made (at CPPM) to fulfill this new backend role: first pre-serie batch of 20 boards under test at CERN. 500 in total will be produced.

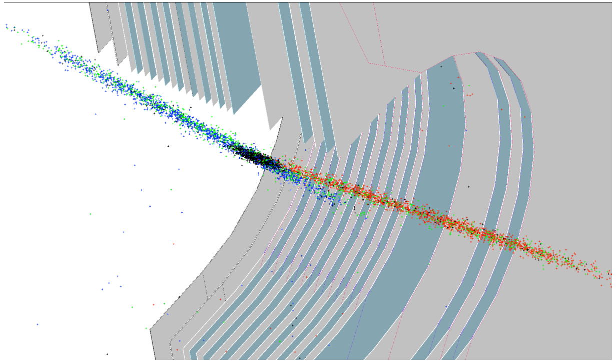


LHCb fixed target – SMOG

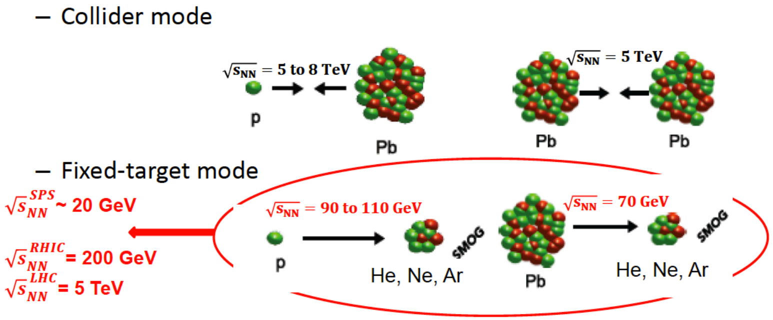




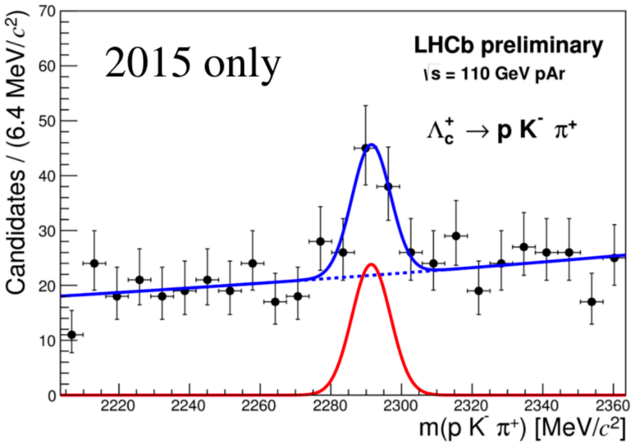
- Gas can be injected in the interaction region of LHCb, in the VELO vaccuum (*ie* the LHC vaccuum).
- Initially this was designed to measure the luminosity of LHCb, by measuring the beam images with beam-gas vertices: used during LHC van der Meer scan sessions: 1.2% precision on integrated luminosity.
- Other use cases emerged:
  - Measure LHC ghost charge (proportion of particles outside the colliding buckets) for the ALICE, ATLAS and CMS luminosity.
  - Fixed target physics interesting at the LHC [S. Brodsky, F. Fleuret, C. Hadjidakis, J.P. Lansberg, Phys. Rep. 522 (2013) 239].



LHCb fixed target operation

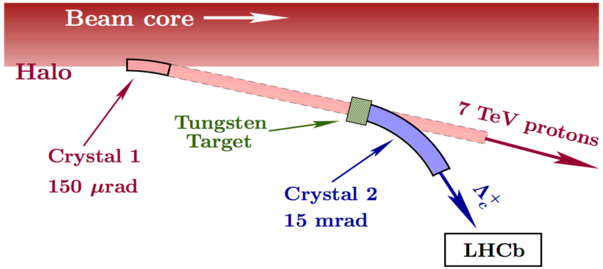


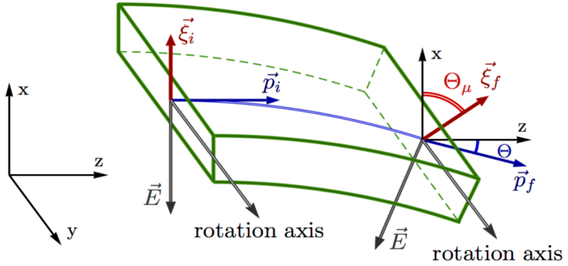
LHCb rapidity 2.5 < yLHCb < 4.5 $\Rightarrow \begin{cases} \text{7 TeV beam:} & -2.3 < y^*_{LHCb} < -0.3 \\ \text{2.75 TeV beam:} & -1.8 < y^*_{LHCb} < 0.2 \end{cases}$



- During Run II, the possibility to operate in parallel LHCb in fixed target mode and in collision mode was established.
- This proves more generally that fixed target experiments can be run without interfering with the normal LHC running. This opens possibilities for dedicated experiments, ideally with larger statistics than what is possible now. For example, measurement of charm or τ MDM.

Charm g-2 setup





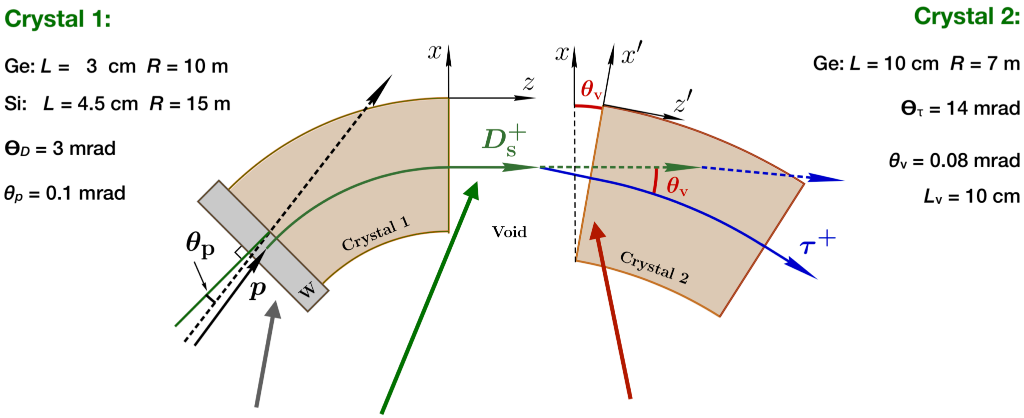
$$\Theta_\mu \approx \gamma\left(\frac{g}{2}-1\right)\Theta \qquad \Theta = \frac{L_{\text{crys}}}{R}$$

$$\vec{\xi}_i = \xi\,(\;1\;,0\,,\;0\;)$$
$$\vec{\xi}_f = \xi\,(\cos\Theta_\mu,\,0\,,\,\sin\Theta_\mu)$$

Detailed in LHCb-INT-2017-011, EPJC 77 (2017) 181, JHEP 2017(8):120 (2017) and EPJC 77 (2017) 828.

- Measure charm MDM from Λ_c and Ξ_c MDM
- A small fraction of the beam is extracted by a first crystal and sent on a fixed solid target to produce Λ_c
- MDM is obtained from the precession of the spin in a second crystal: compare Λ_c polarization after and before the crystal, from a Dalitz plot analysis of the $\Lambda_c \rightarrow pK\pi$
- 10% precision on g-2 could be achieved with 30 days of dedicated data taking at LHCb

τ g-2 setup



Crystal 1:

Ge: $L = 3$ cm $R = 10$ m

Si: $L = 4.5$ cm $R = 15$ m

$\Theta_D = 3$ mrad

$\theta_p = 0.1$ mrad

Crystal 2:

Ge: $L = 10$ cm $R = 7$ m

$\Theta_\tau = 14$ mrad

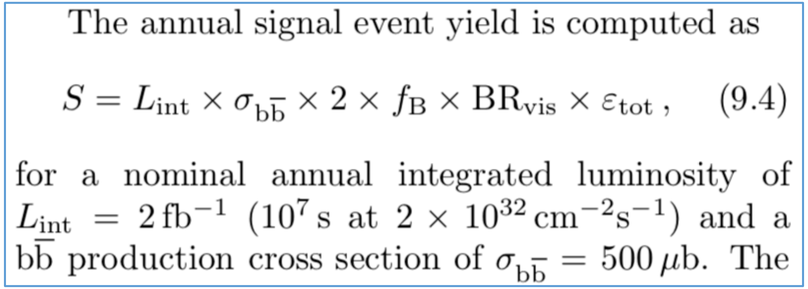
$\theta_v = 0.08$ mrad

$L_v = 10$ cm

- τ produced polarized in $D_s \rightarrow \tau\, \nu_\tau$ decays and reconstructed in the 3 pion mode (with constraint on D_s momentum imposed by first crystal to be able to measure τ polarization)
- LHCb can be used as a detector to establish proof of principle, but large statistics are required with a dedicated experiment
- Details in arXiv:1810.06699

Conclusions

- LHCb TDR stated:



The annual signal event yield is computed as

$$S = L_{\mathrm{int}} \times \sigma_{\mathrm{b\overline{b}}} \times 2 \times f_{\mathrm{B}} \times \mathrm{BR}_{\mathrm{vis}} \times \varepsilon_{\mathrm{tot}} \,, \qquad (9.4)$$

for a nominal annual integrated luminosity of $L_{\mathrm{int}} = 2\,\mathrm{fb}^{-1}$ ($10^7\,\mathrm{s}$ at $2 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$) and a $\mathrm{b\overline{b}}$ production cross section of $\sigma_{\mathrm{b\overline{b}}} = 500\,\mu\mathrm{b}$. The

- A lot of creativity and innovations were needed to achieve the goals set, which will benefit to the LHCb upgrades and other experiments
- A large part of the success is due to the LHC which also surpassed all predictions.
- This is not by chance:


2016