LHCb Luminosity Monitoring and Control

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Outline
- LHCb physics strategy
- LHCb key requirements
- Luminosity control motivations
- Luminosity monitoring and control implementation
- Performance
- Conclusion

Complementary paper:
“Online Luminosity Optimization at the LHC”, F. Follin, R. Alemany, R. Jacobsson, THPPC123
Focus on measuring *indirect* effects of New Physics in CP violation and Rare decays using FCNC processes mediated by loop (box and penguin) diagrams

- Strongly suppressed processes allow distinguishing NP sources
- Virtual effects allow probing energies much higher than the $E_{\text{cms}}$ of the LHC

Complementary to the direct searches by Atlas and CMS

While initial aim of LHCb was b-physics, has also demonstrated that it can do

- Charm physics (oscillations, CP violation)
- QCD physics (PDFs via Z/W production, Central Exclusive Production,...)

In beyond design conditions, LHCb has earned the title of « General Purpose Forward Detector »
Key Requirements for Flavour Physics at LHC

- Collect high statistics of a large variety of B and D final states in an environment with very large background
  - >100,000 $b\bar{b}$ pairs per second at LHCb interaction point and $c\bar{c}$ production 20x more
  - Fast and efficient trigger for both hadronic and leptonic final states
  - Requires reconstruction of decay chains

- Resolve fast oscillations, background reduction and flavour tagging
  - Very good vertex resolution
  - Determination of track parameters
  - Charge determination and momentum resolution
  - Mass resolution
  - $K/\pi$ separation in a wide momentum range
  - $\gamma/\pi^0$ reconstruction, electron identification
  - Muon identification

Difficult task in conditions of large event pileup
Key Requirements for Flavour Physics at LHC

- **Requirements from precision physics programme**
  - Accurate knowledge about the integrated luminosity
  - Systematics errors must be negligible compared to statistical errors to reach sensitivity below the predictions of SM.

- **Systematic effects from changing running configuration and conditions**
  - Attenuated by the initial design specification for nominal running conditions of LHCb
    - Maximize the probability of a single interaction per bunch crossing, minimizing pileup
    - Average number of interactions per bunch crossing $\mu \sim 0.4$
    - Valid up to June 2010…
  - In June 2010, LHC changed commissioning strategy:
    - Commissioning many bunches with low intensity ➔ Commissioning bunch intensity
    - LHCb pileup reached $\sim 3$ due to chosen over-focussing!
  - Detector and reconstruction performs well with event pileup
  - Forced a healthy change of strategy in LHCb at all levels

- **Compensatory measure: Luminosity/pileup control**
  - Experiment with luminosity control with separated beams for the first time July 18, 2010
    - By phone…!
Direct tool to maximize LHCb physics yield

- Allows optimizing the efficiency of luminosity integration
  - Running constantly at the optimal pileup for physics
- Stable luminosity (pileup) through fills (no decay!) / over months
  - Same trigger settings
  - Predictable detector performance and ageing

Optimum luminosity is also a function of dynamic readout system parameters
- Full event readout rate (<1.1 MHz)
- Average number of interactions per crossing (<2.7)
- Max readout network through-put (<70 GB/s)
- High-Level Trigger CPU time/event at 1 MHz, ~30ms in 2011 and ~40ms in 2012
- Physics trigger overall dead-time (≤5%)
- High Level Trigger output rate to storage (≤5 kHz)
- Detector stability, still exploring

Translate into equivalent luminosity limits which may depend on experimental conditions (e.g. background) and system status

Target luminosity determined real-time with slow time constants of O(seconds)
Many ways by which luminosity control may be performed

\[ L = \frac{n_{bb} \times N^2 \times f_{rev}}{A} \times R(\beta, \theta, \sigma_z, \phi_p, \delta_s, \delta_c, \Delta t) \]

Simplest consist of semi-continuous adjustment of transversal offset of colliding beams

\[ \delta \sim 1 - 3 \text{ beam sigma} \]
Luminosity controller based on a state machine which is driven LHC Beam Modes

- Implementation based on Siemens WinCC OA (former ETM PVSS)

F. Follin, R. Alemany-Fernandez, R. Jacobsson, THPPC123
Luminosity Control Protocol

The luminosity adjustment is performed by an iterative procedure:

- **LHCb Luminosity Controller** publishes:
  - **Current Luminosity**: Measured luminosity
  - **Luminosity Status**: Depends on source of luminosity, reliable or not
  - **Target luminosity**: Dynamically computed by LHCb leveling controller
  - **Leveling Request**: Dynamical signal requesting leveling to target
    - Request will only ON if the LHCb data acquisition is running, even if it is far away from target
    - If request if OFF, target is not (should not be) considered
    - When luminosity is not reliable, request is OFF whatever target luminosity is
  - **Step size [percentage of beam sigma]**: Depends on separation

- **LHC Luminosity Leveling Application** publishes:
  - **XPlaneOptimizationDone**: Set when the crossing plane optimization has been done
    - *LHCb Luminosity Controller will only start requesting luminosity ramp when this is received*
  - **Enable**: ON if luminosity leveling application is running
  - **Active**: Leveling to target is in progress
  - **StepSize**: Beam movement used in the last leveling step in mm
Luminosity monitoring and control are implemented in the LHCb Readout Control hardware and the LHC/LHCb communication control system.
ODIN = Single FPGA-based readout master with two redundant "copies" for fail-over

- Two different methods for offline and online determination of luminosity
LHCb Luminosity Control Procedure

- ADJUST - idle
  1. LHC luminosity control OFF, LHCb luminosity control OFF
  2. Collapse separation bump to constant offset (e.g. \( \sim 2-3\sigma \)) \( \rightarrow \) \( L \sim 1.5 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1} \) in vertical
  3. Optimize in horizontal (crossing plane) keeping vertical separation constant

- STABLE BEAMS - ramp
  1. LHCb Vertex Locator (VELO) detector closing to its final data taking position with initial luminosity
  2. Luminosity increase to target over a few minutes

- Coast - levelling
  - Continuous publication of instantaneous luminosity and target luminosity
  - Luminosity leveling requested when current luminosity and target different by > \( \pm 3\% \)
Luminosity Monitor

- Procedure require no actions from the people on shift.
95% of integrated luminosity in 2011–2012 recorded within 3% of desired luminosity
Running conditions 2010 - 2012

#Colliding bunch pairs

Visible crossing rate

\(<\text{Pileup}>\)

Inst. luminosity

[MHz] [10^30 cm^{-2}s^{-1}]

Sept 2010 Apr 2011 Apr 2012

LHCb Design

Exploratory
Luminosity control has been part of routine operation in LHCb 2011 – 2012

- It has also been used in a similar way for the ALICE experiment
- Great experience in developing a close feedback system between experiment and accelerator
- Allowed LHCb to venture well beyond the design specs and operating detector at twice the luminosity, collecting up 3x more luminosity in Run 1
- Operating LHCb constantly in the optimal conditions
- Important reduction in the systematics effects
- Stability of the detector performance and trigger configuration

Luminosity control will continue to be a vital tool for LHCb in the future, both in Run 2 and after the LHCb upgrade

Important experience to pave the way for luminosity control in the future by all experiments

- Method of luminosity control may be different but procedure well established
- Exploiting LHC at maximum benefits from handling procedures with mechanical routine

Acknowledgement:

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- The LHC operators for their particular attention to the LHCb interaction point!
RESERVE SLIDES
Luminosity determination

- Two different methods for offline and online determination of luminosity
  - Both implemented in ODIN hardware
    - **Offline:**
      - Random sampling of beam-beam crossings with observables proportional to luminosity
      - Random sampling of beam1 alone, beam2 alone, and empty crossings for background subtraction.
        - Luminosity trigger implemented in ODIN based on an advanced pseudo-random generator producing two 32-bit random numbers at 40 MHz
        - Events carry special flags that allow offline analysis of any data set
    - **Online:**
      - Counting of minimum bias trigger condition with maximum acceptance on beam-beam crossings
        - Transverse energy criteria, together with muon minimum bias and noPV condition as stability check
        - Conditions counted on beam1 alone and beam2 alone for background correction
        - Instantaneous luminosity determined from Poisson statistics ($P_0 = e^{-\mu}$)
          \[
          \mu = -\ln \frac{1 - \rho_{trg}}{f_{rev} * n_{bb}} \quad \quad L = \frac{\mu * f_{rev} * n_{bb}}{\sigma_{mbias} * \varepsilon_{det}}
          \]
      - LHC filling scheme loaded real-time into ODIN sequencer during filling of LHC
      - Online integrated luminosity well within 1% of best value from offline