Operation and Performance of the LHCb experiment

Conference on Discovery of Physics at the LHC, South Africa, 5-10 December 2010

F. Alessio, CERN, Switzerland

on behalf of the LHCb collaboration

Outline

1. Introduction to LHCb, readout system and LHCb trigger architecture
2. LHCb operational aspects, 2010 running conditions and trigger strategy
3. LHCb global performance
4. Plans for 2011/2012
5. Conclusions

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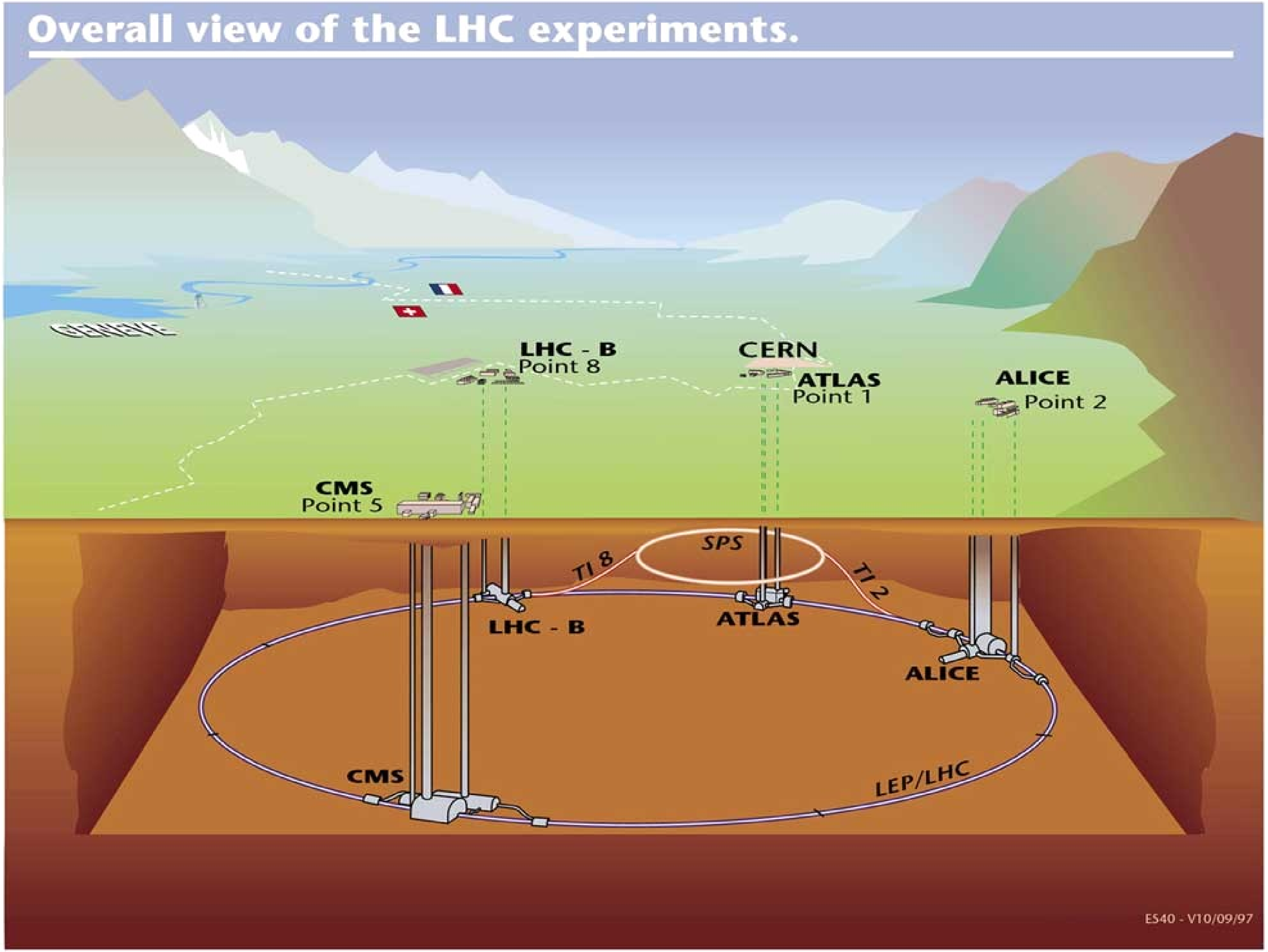
First LHC collisions at 3.5 TeV

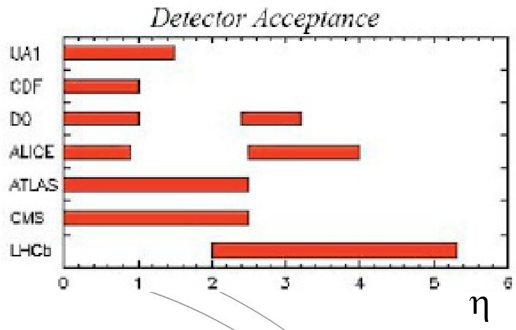
30 March 2010 – around 1pm

The LHCb experiment at CERN

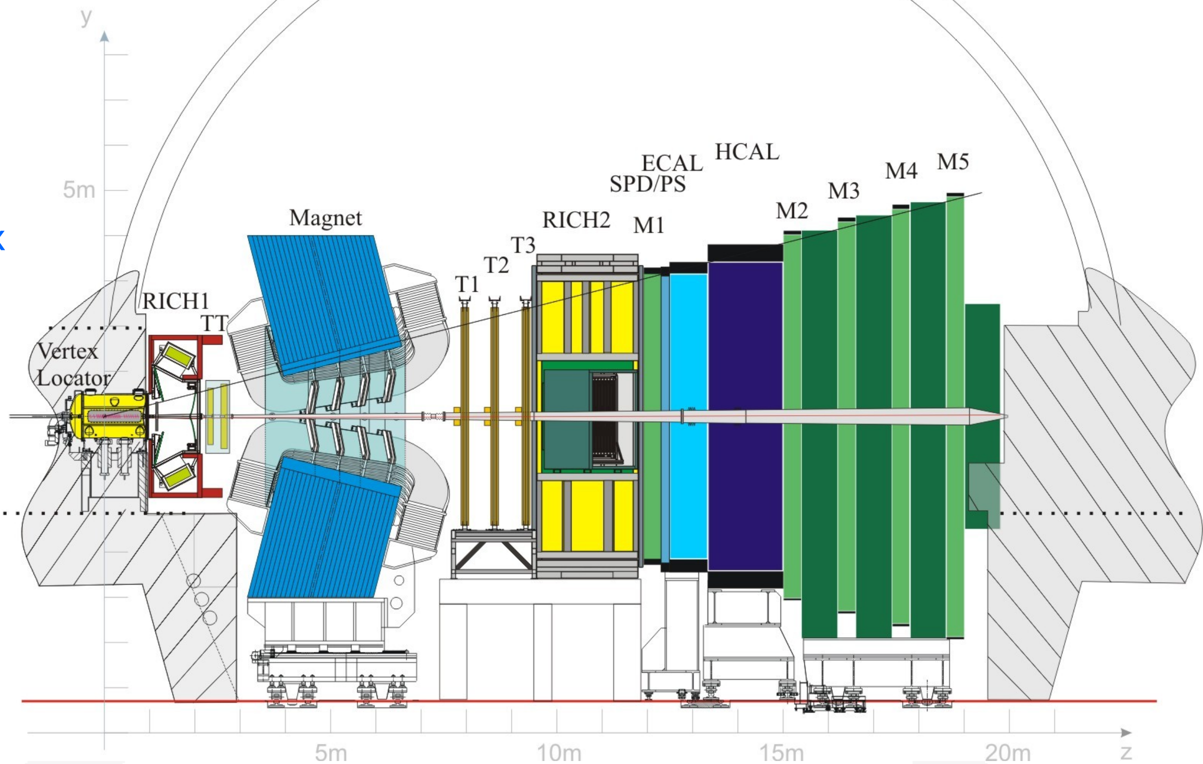


The LHCb experiment

Physics scope:
✓ Precision study of CP violation and look for New Physics
✓ Study of rare b and c decays
✓ Complementary to General Purpose Detectors (ATLAS/CMS)
→ In certain sense as a forward GPD



LHCb has:
- ✓ Efficient trigger for many B decays topologies
- ✓ Efficient particle identification
- ✓ Precision vertexing, movable Vertex Locator
- ✓ Good tracking and mass resolution
- ✓ Angular coverage 10÷250 mrad (V) and 10÷300 mrad (H)



See *LHCb Status, First Physics and Discovery Potential*, O. Steinkamp

LHCb nominal running conditions

$$L = \sum_{i=1}^{N_{bb}} \frac{f_{rev} * N_i^1 * N_i^2 * S}{4\pi * \varepsilon * \beta^*}$$

Number of colliding bunches per beam
2622

Bunch revolution frequency:
11.245 kHz

Colliding bunches populations:
~1.15*10^11 ppb

Geometrical factor
e.g. LHCb Crossing angle
-673 μrad

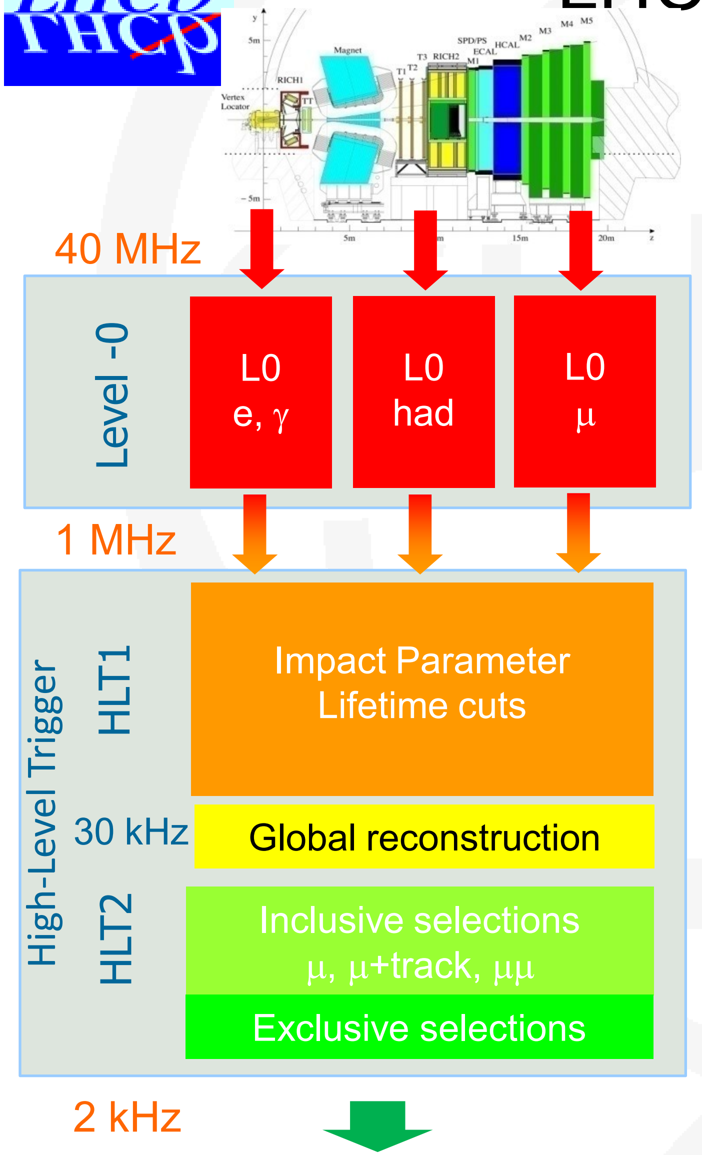
Instantaneous Luminosity
average $2*10^{32}cm^{-2}/s$

Bunch transverse emittance
$\varepsilon_N = \varepsilon * \gamma$ = 3.75 μm normalized emittance
for beam energy E = 7 TeV

"beta star" = 30m
after beam squeezing

- → 1 vertex / bb interaction (Pileup average)
- → 0.4 visible pp interactions per bunch crossing in LHCb acceptance (Mu average)
- → Foresee to collect 2 fb^{-1}/year (Integrated Luminosity)

LHCb trigger architecture



→ Level-0 Hardware Trigger 40 MHz → 1 MHz

- ✓ Search for high-p_T , μ, e, γ, hadron candidates

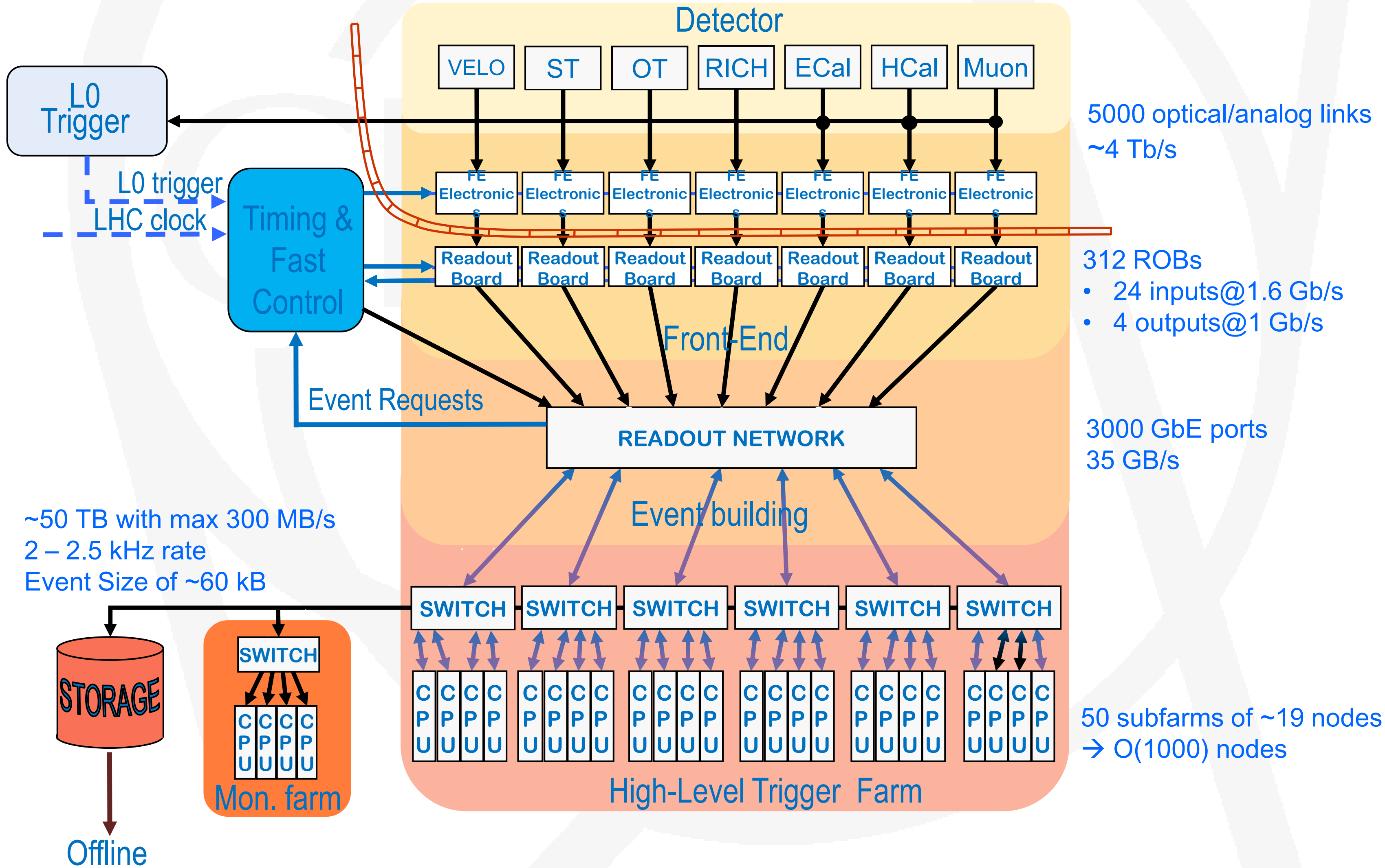
→ High Level Software Trigger Farm

- ✓ HLT1: Add impact parameter and lifetime cuts
- ✓ HLT2: Global event reconstruction + selections
- ✓ Processing time available O(20 ms)
- ✓ Physics output rate 2 kHz – 2.5 kHz

→ HLT needs operational flexibility

- ✓ Trigger Configuration Key (TCK) to distribute the configuration to 1000 nodes simultaneously when optimizing parameters during LHC fill
- ✓ Allowed for easy luminosity following also in extreme conditions during 2010

LHCb readout system



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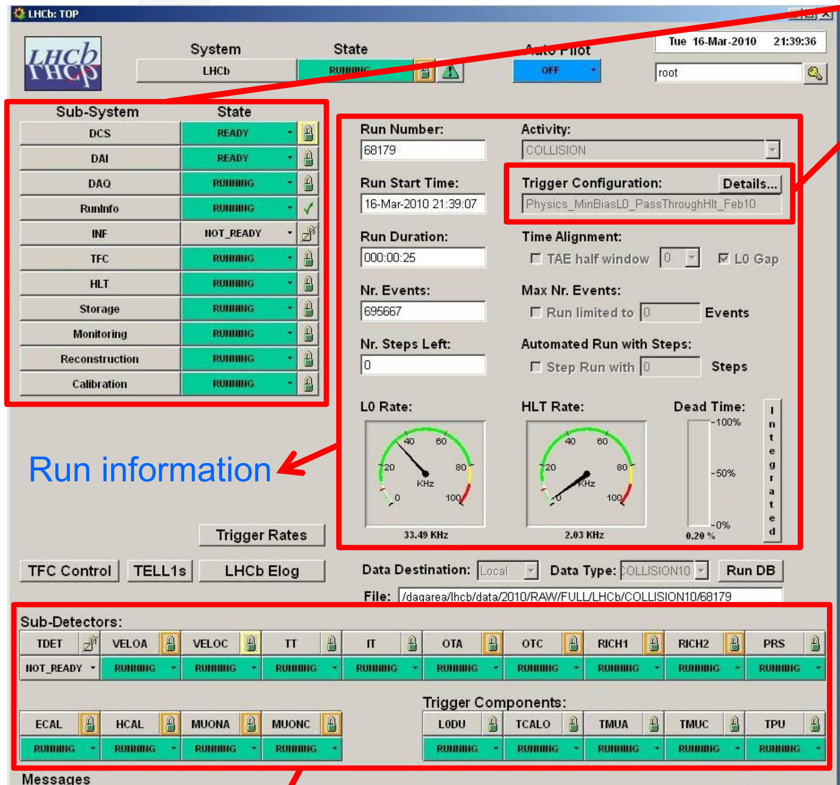
Routine operations at LHCb

24/7 Shift Leader + Data Manager in LHCb Control Room + sub-system piquets on call

Centralized Control System

All LHCb controlled with two graphical user interface panels – PVSS-II

→ High level of automation → Shift Leader supervises and acts if needed



Control of every DAQ sub-system

Trigger Configuration

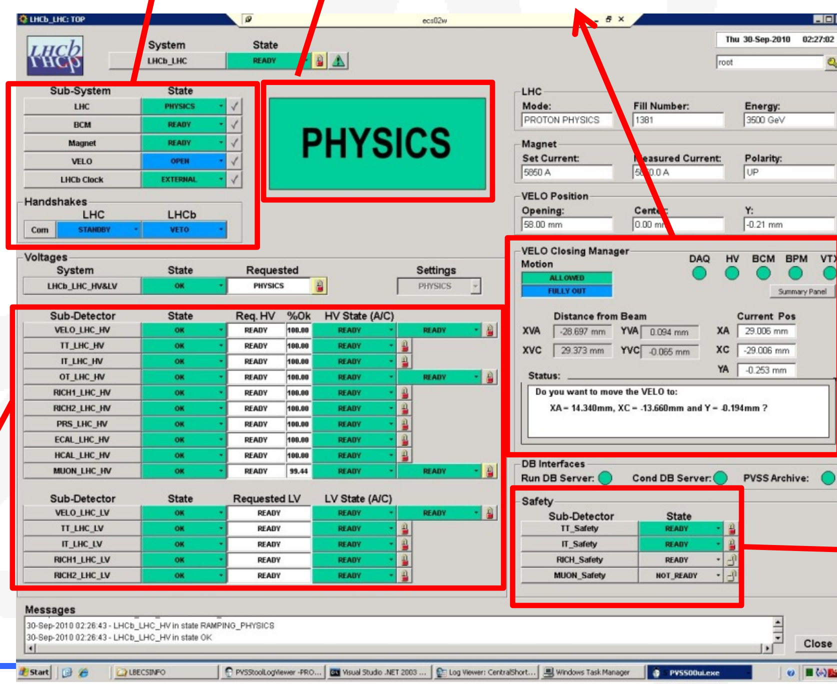
LHCb main state

Run information

LHC communications

VELO motion: only in PHYSICS!

Safety systems



Access and control to every control system of each sub-detector

All HV/LV channels

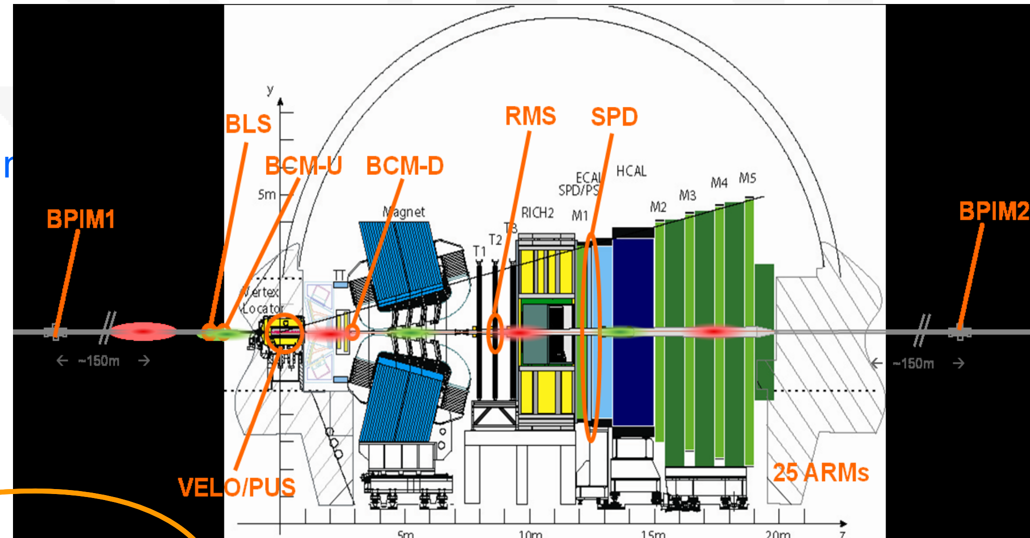
Experimental Conditions Monitoring

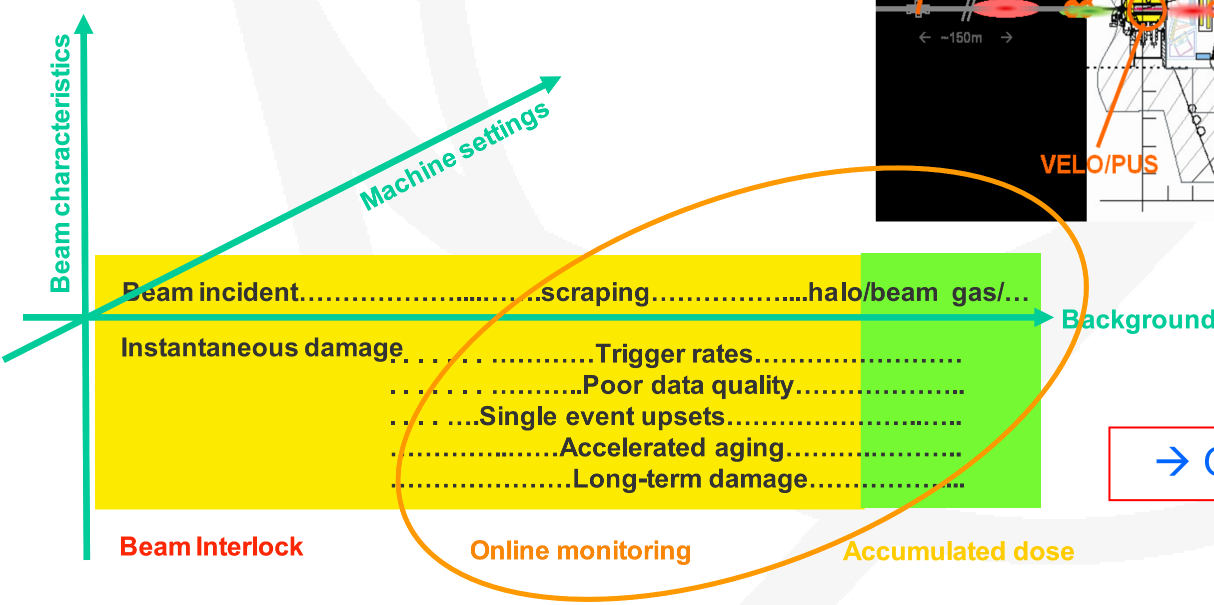
Helped machine commissioning and increase LHCb efficiency

Complete study framework which involves:

- ✓ Background monitoring
- ✓ Beam monitoring

- → Careful implementation to be prepared in case of bad background
- → No bad background seen so far!





→ Optimize Luminosity / Background

Running in 2010 – extreme conditions

Operational objective: explore LHCb physics potential in extreme running conditions which are very different from nominal conditions!

→ Tune detector, trigger and readout performance

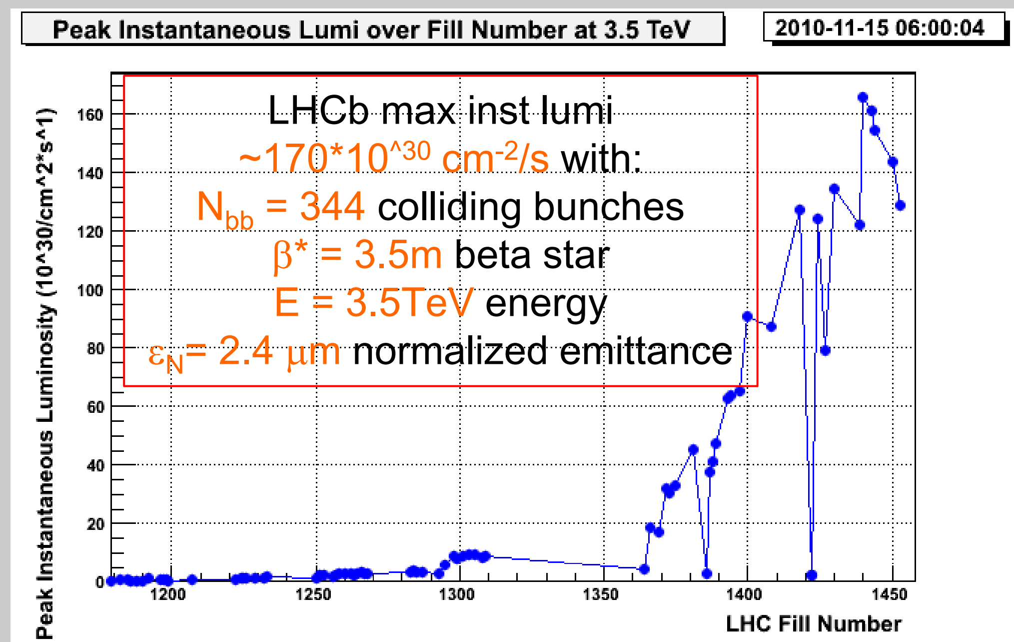
Reached ~80% of designed LHCb instantaneous luminosity with 8 times less colliding bunches!

- → More interactions per crossing
- → Bigger event size
- → More vertices per collision

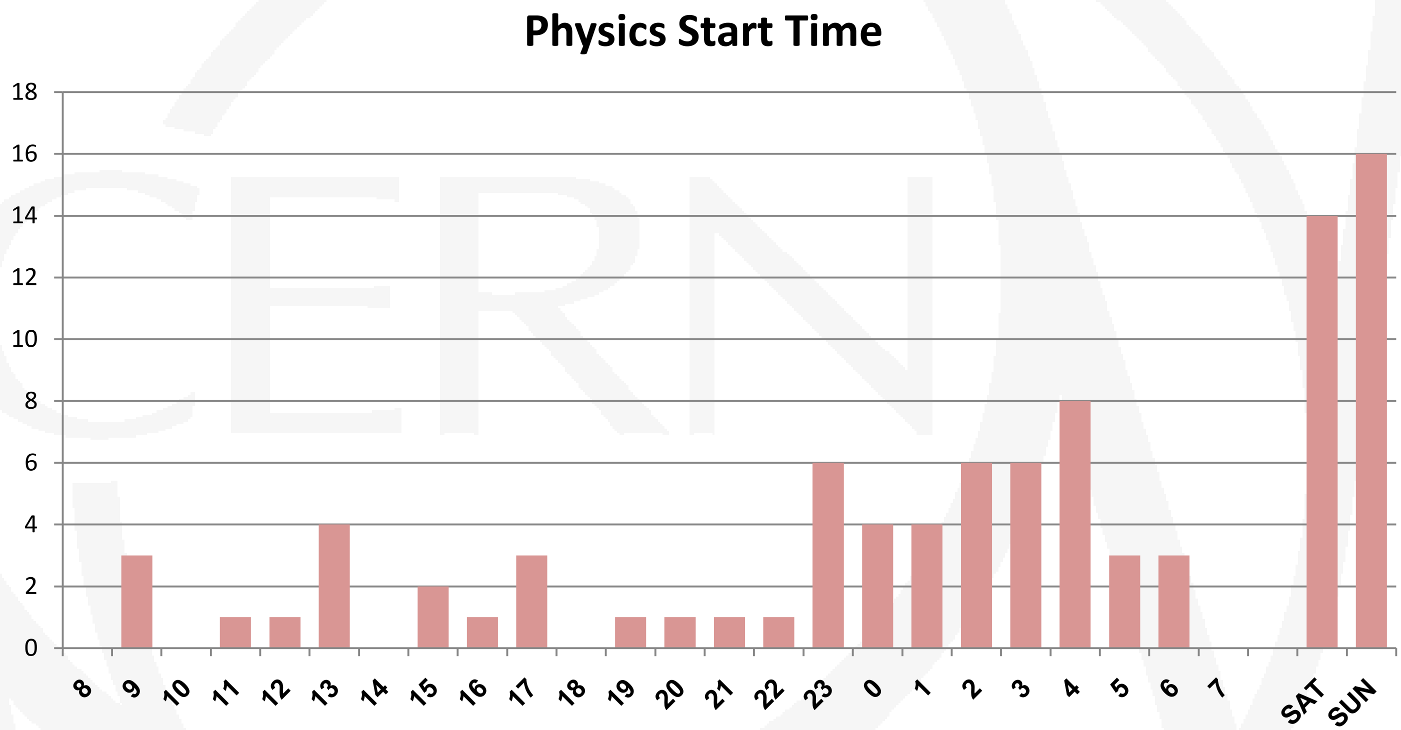
↓

Mostly focused on LHC machine commissioning, LHCb had to face with preparations without knowledge about the ultimate parameters

- → expert availability 24/7
- → adaptability readout system
- → flexibility trigger
- → upgrades "on the fly"



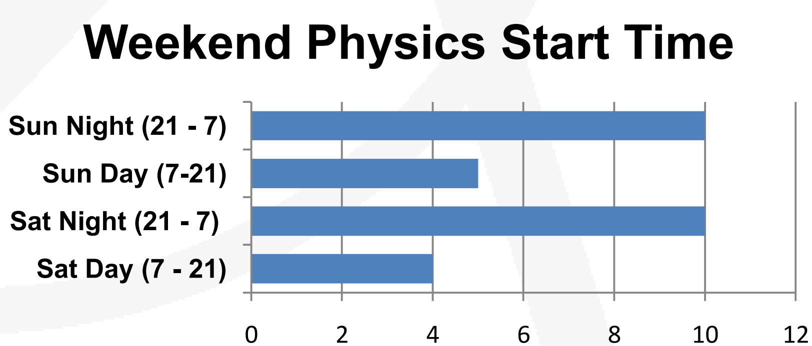
Running in 2010 – availability



89 physics fills, total of 28 days of STABLE BEAMS

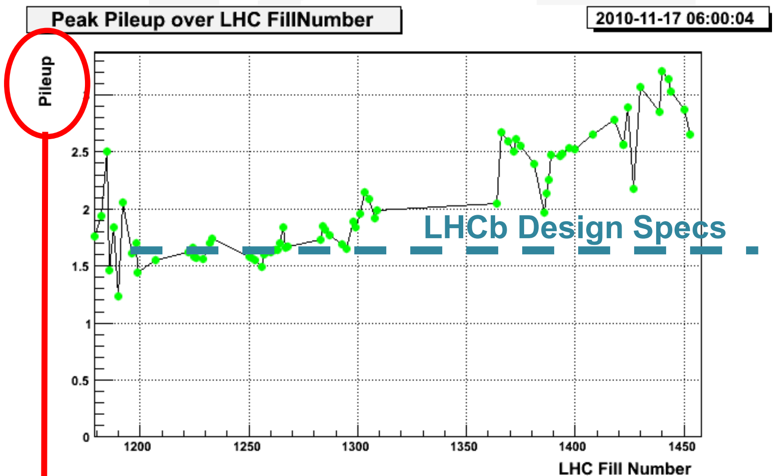
→ Massive workload!

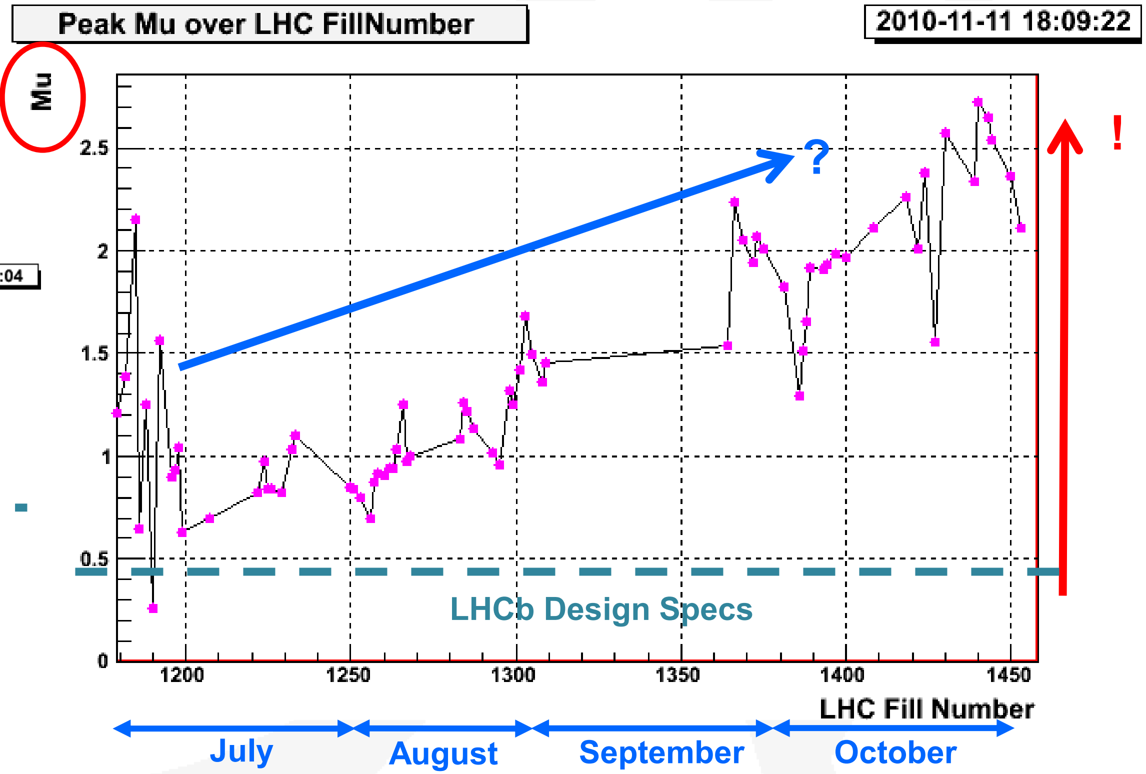
→ Very limited day time to commission properly trigger and tune detector for each luminosity step



Running in 2010 – flexibility

"average number of visible pp interactions per bunch crossing in LHCb acceptance"





"# of Primary Vertices at L0"

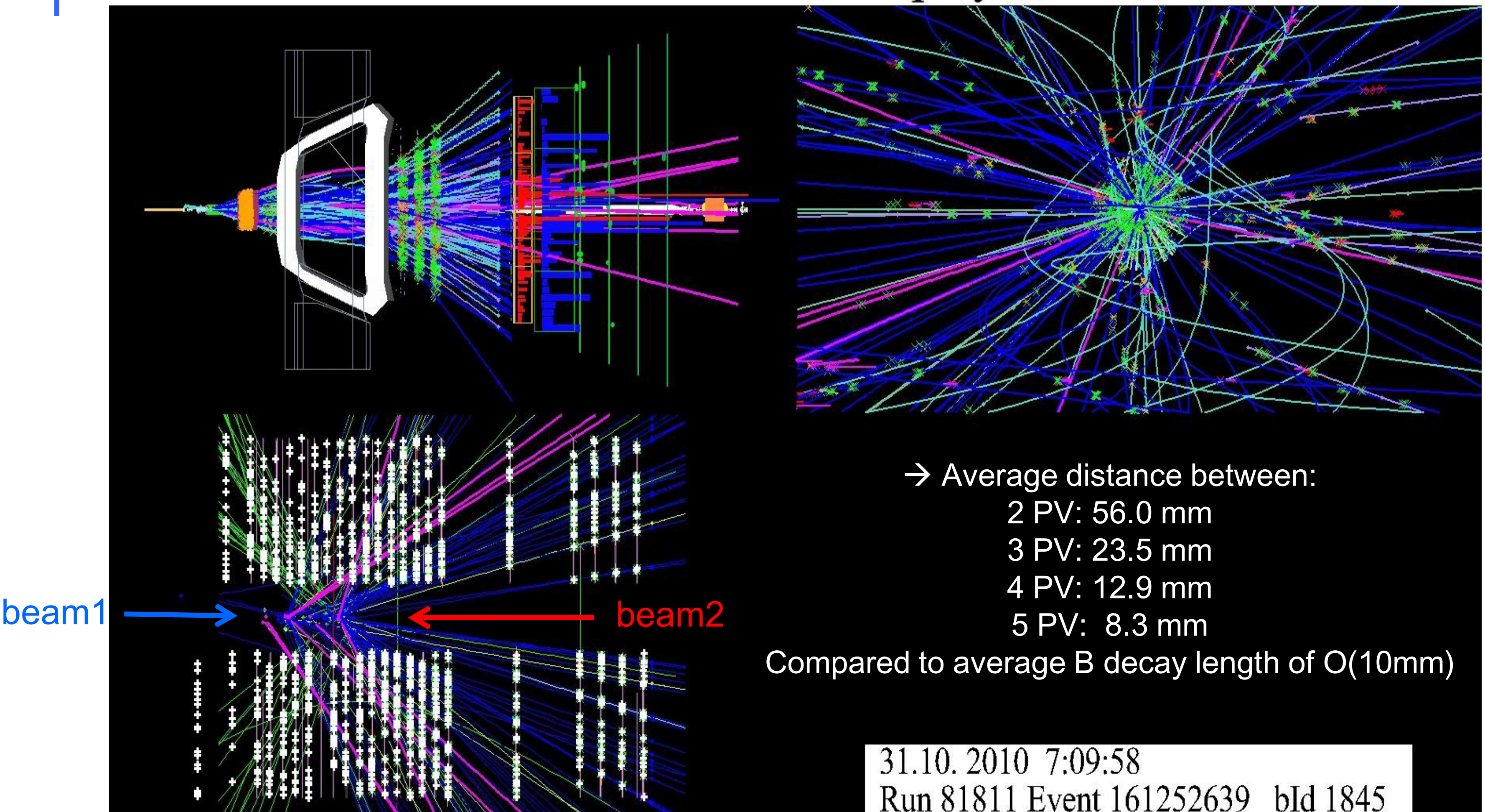
$$\text{pileup} = \frac{\text{Mu}}{1 - e^{-\text{Mu}}}$$

Operational consequences of high-Mu (~2.5):

- ✓ Increases readout rate per bunch crossing → bandwidth limitation
- ✓ Increases event size → bandwidth limitation
- ✓ Number of tracks and event complexity → processing time increase
- ✓ High particle flux →Trigger strategy → Global Event Cuts

Running in 2010 with high-Mu

LHCb Event Display



Example of an event with high-Pileup in LHCb

LHCb 2010 trigger strategy - I

→ Explore LHCb physics potential in extreme (for LHCb) running conditions

Early running conditions

Few colliding bunches
=
Low L0 rate
=
Less CPU consumption

↓

Choice to let event complexity increase, following Mu by machine
=
Increase # events/crossing (Mu)
=
Increase # vertexes at L0 (Pileup)
=
Increase Luminosity

Early running strategy

Keep loose trigger
Commission Reconstruction and put it in operations

↓

Read out every crossing
Simply search for 1 VELO track (MB)

↓

When reached the output bandwidth rate limit on MinimumBias events applied (1kHz then 100Hz)

LHCb 2010 trigger strategy - II

→ LHC machine kept increasing number of colliding bunches AND Mu …

Late running conditions

Many colliding bunches
=
Higher L0 rate
=
More CPU consumption

↓

Still follow Mu from machine, but cut harder!
=
Increase Mu
=
Increase Pileup
=
Increase Luminosity
=
Reduce number of very large events

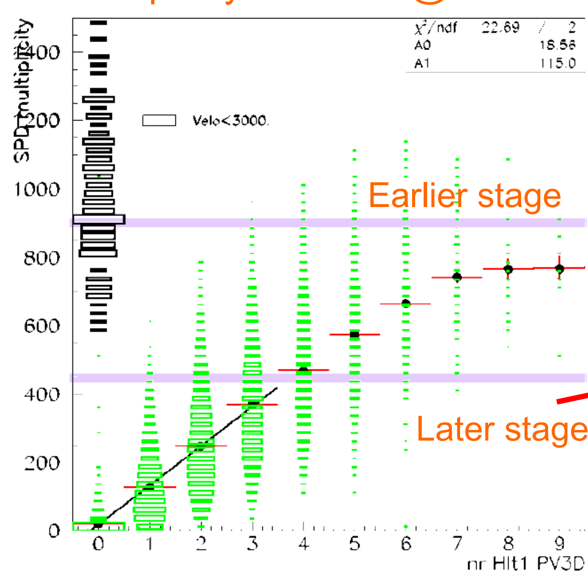
Late running strategy

Global Event Cut (GEC) → Trigger Configuration Keys (TCK)

→ High priority to μ triggers ($B_s \rightarrow \mu\mu$)

→ Check PVs are distinguishable at high-Mu

multiplicity vs # PVs @ HLT1



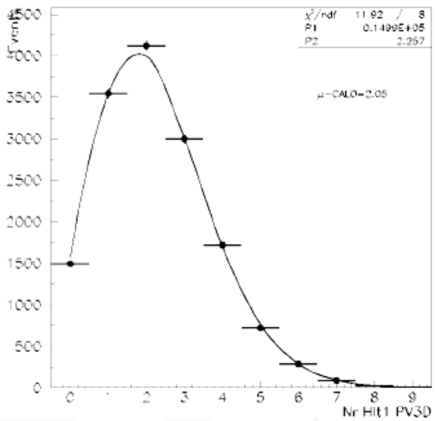
→ # PVs ∝ SPD multiplicity

Cutting at mult < 900
=
reduce number of very large events, but still explore all the physics potential

Cutting at mult < 450
=
reduce number of large events, but still keep some events with large #PVs, but lower multiplicity

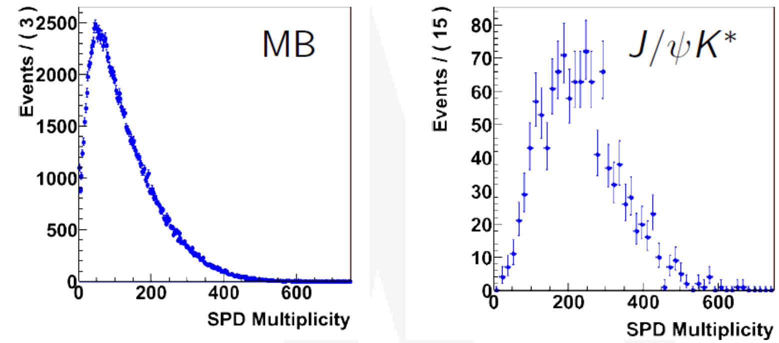
LHCb trigger strategy – Considerations

1. Distribution of # PVs at HLT1 at Mu ~2



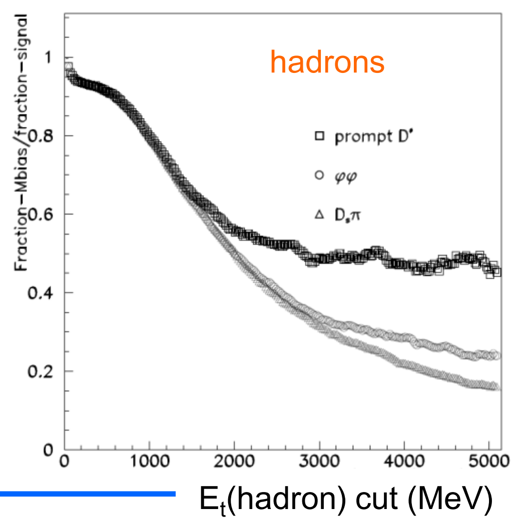
Most of the events are with 1 to 4 PVs

2. multiplicity distribution for a MinimumBias event and a particular resonance



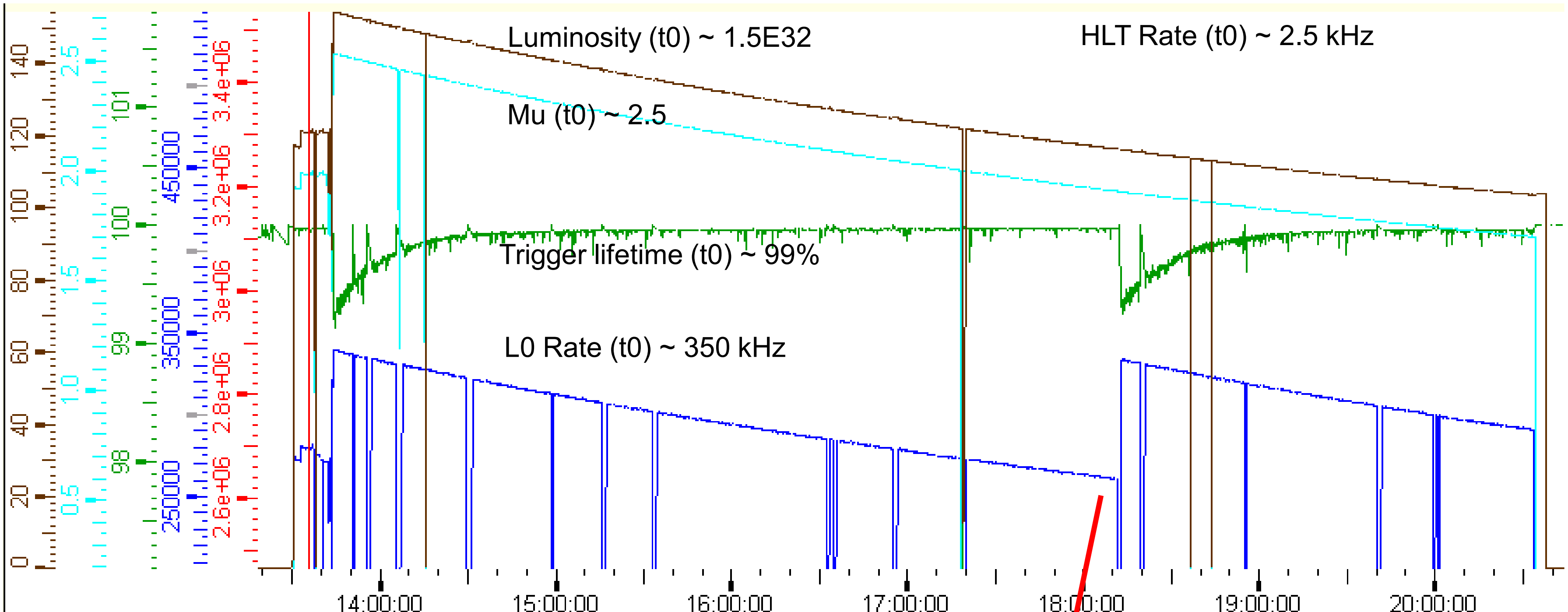
A generic event will sum the multiplicity of a MB event and the one from the signal → eventually, cutting at 450 at high-Mu means wasting luminosity

3. Ratios of fraction of MB and fraction of signal yields



For some signals, cutting at higher energy doesn't enrich the sample
→ doesn't change the ratio of fraction of MB and fraction of signal events which is selected

An "operational" trigger



Legend:
Blue: L0 Trigger Rate
Green: Trigger lifetime
Light Blue: Mu
Brown: Luminosity

When a "lower" value of Mu is reached throughout a fill:

1. new Trigger Configuration Key is applied
2. new run is started

→ Same behavior with two different configuration at two different running conditions

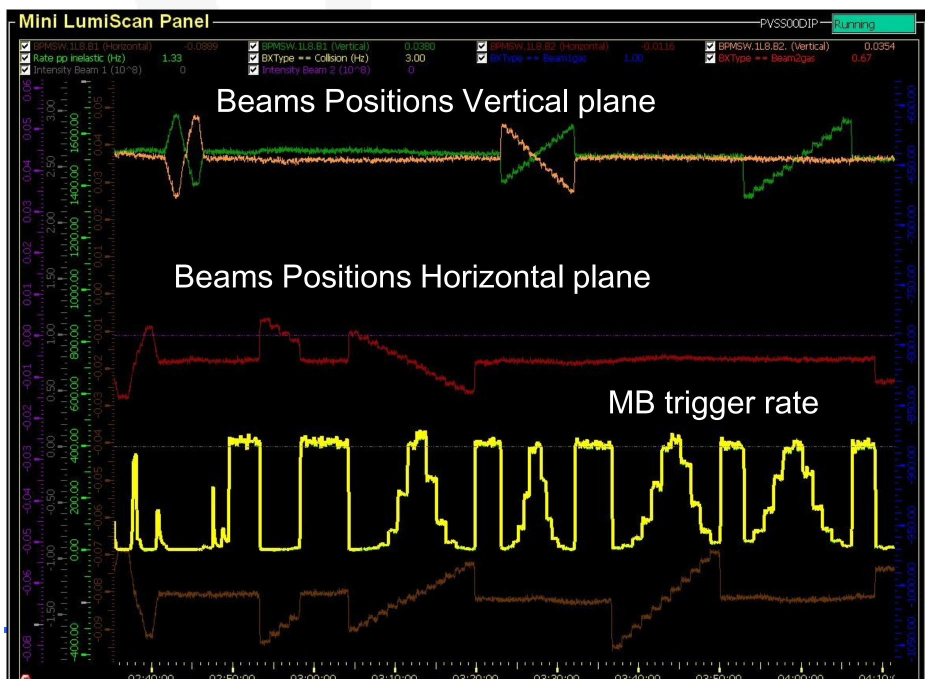
Luminosity measurement

Two methods to **directly** determine Luminosity

$$TriggerRate = Luminosity * CrossSection$$

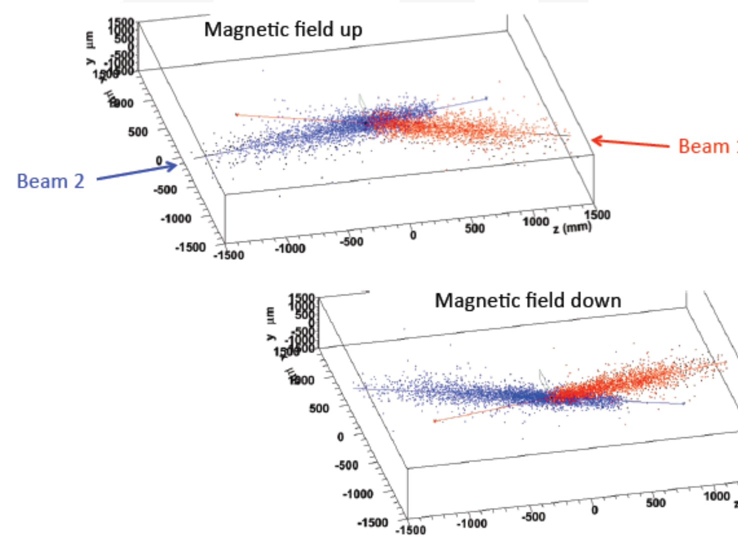
Van der Meer method
- based on beam separation scans
- moves beams in horizontal and vertical plane

Completely automatized with LHC machine
→ uses MinimumBias trigger



Beam gas imaging method
- based on beam-gas vertex reconstruction

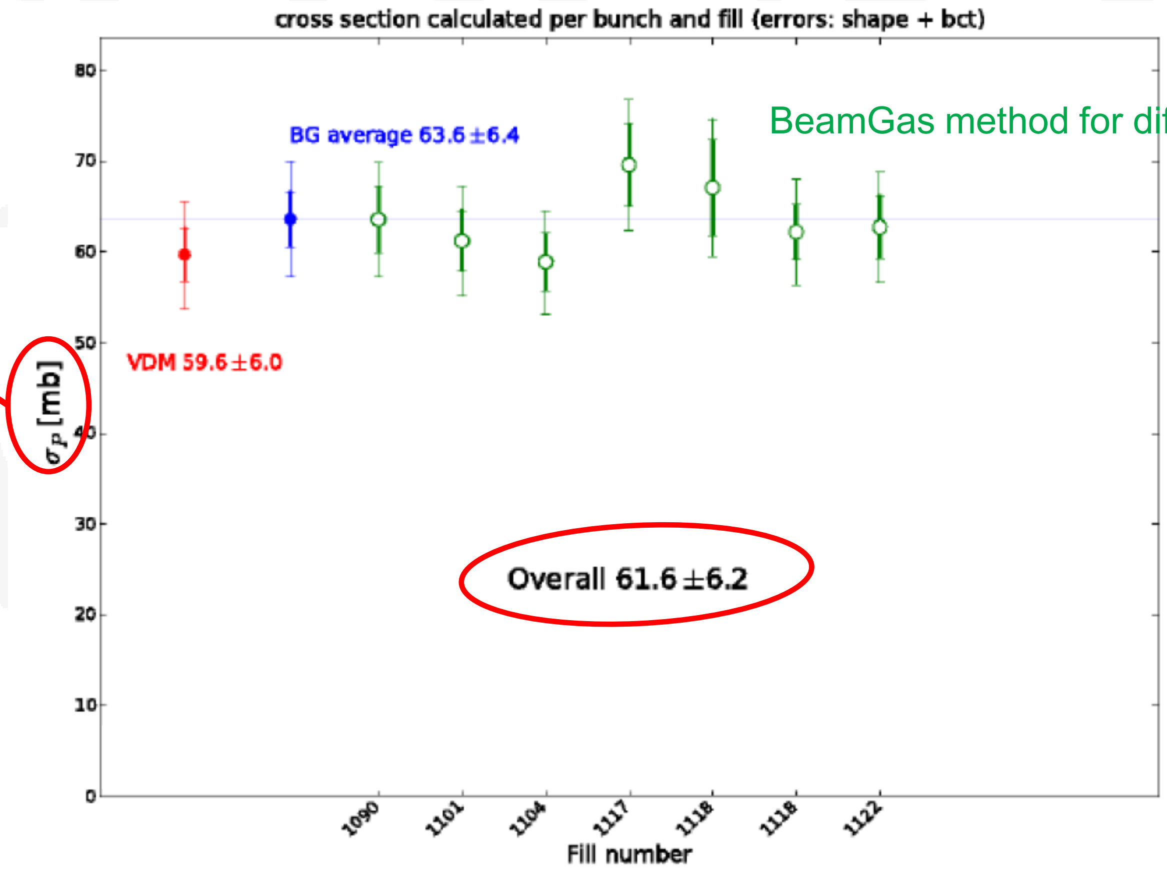
LHCb “Beam gas trigger”:
- LHCb Luminous region
- beam 1 spot and beam 2 spot
- effective crossing angles and beam angles
- debunching effects



Luminosity measurement

First result from both method combined gave CrossSection = 61.6 mb ± 6.2
→ More studies are ongoing from more recent scans

CrossSection of event with two or more VELO tracks



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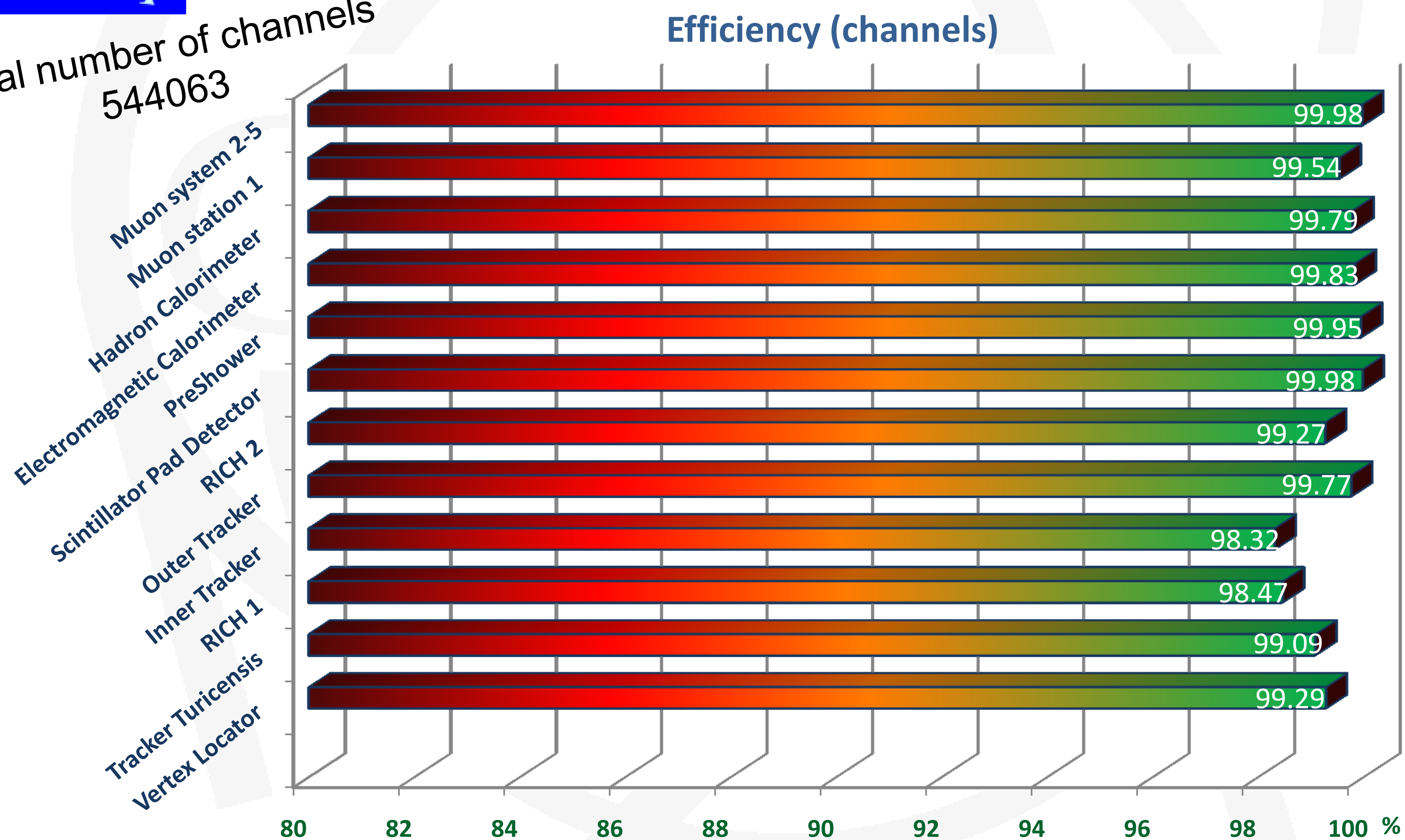
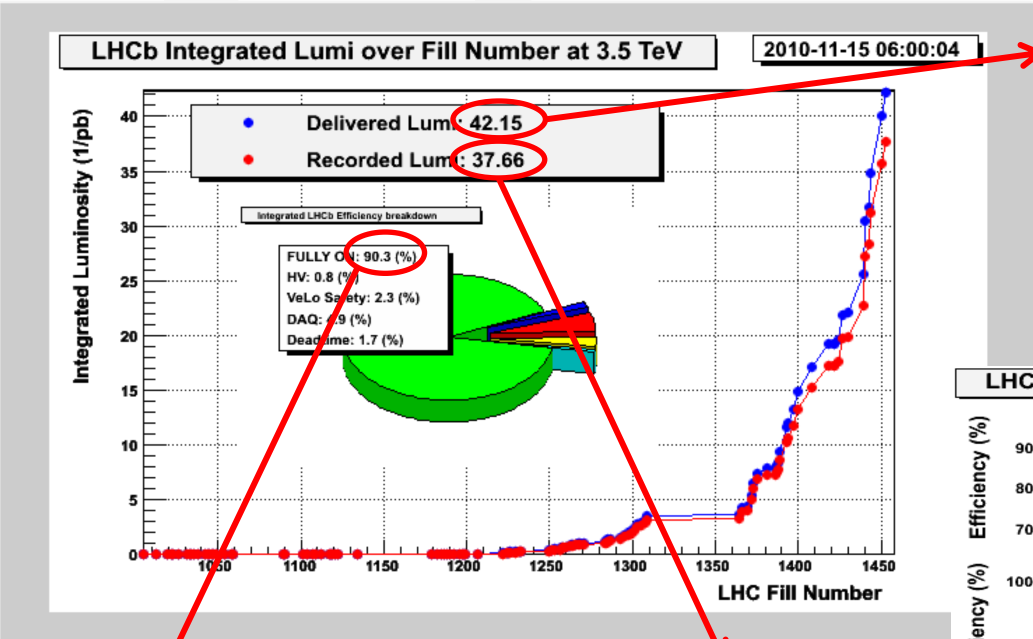
Detector Status Overview in 2010

Total number of channels
544063



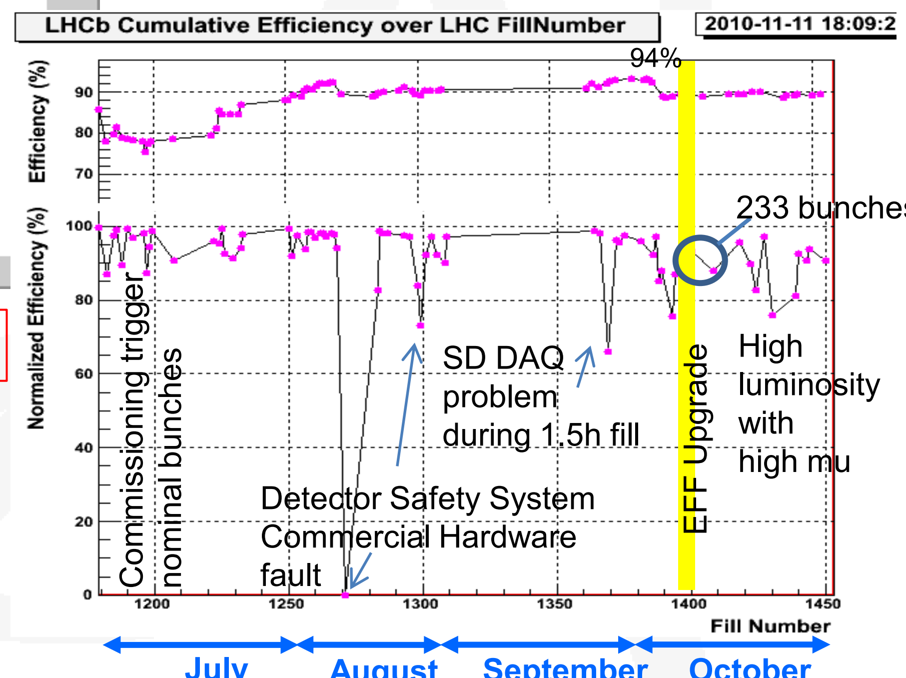
Detector hardware behaved extremely well through 2010, few problems which never had impact on LHCb operations.

LHCb global operational performances



Luminosity difference with ATLAS/CMS:
- Known geometrical factor due to crossing angle + magnetic field: Up to 9% reduction with Magnet Field "DOWN"
→ > 50% of annual lumi in this condition
- Other effects are under study (Normalization factor, β^* / waist effect, longitudinal scan)

37.7 pb^{-1} recorded



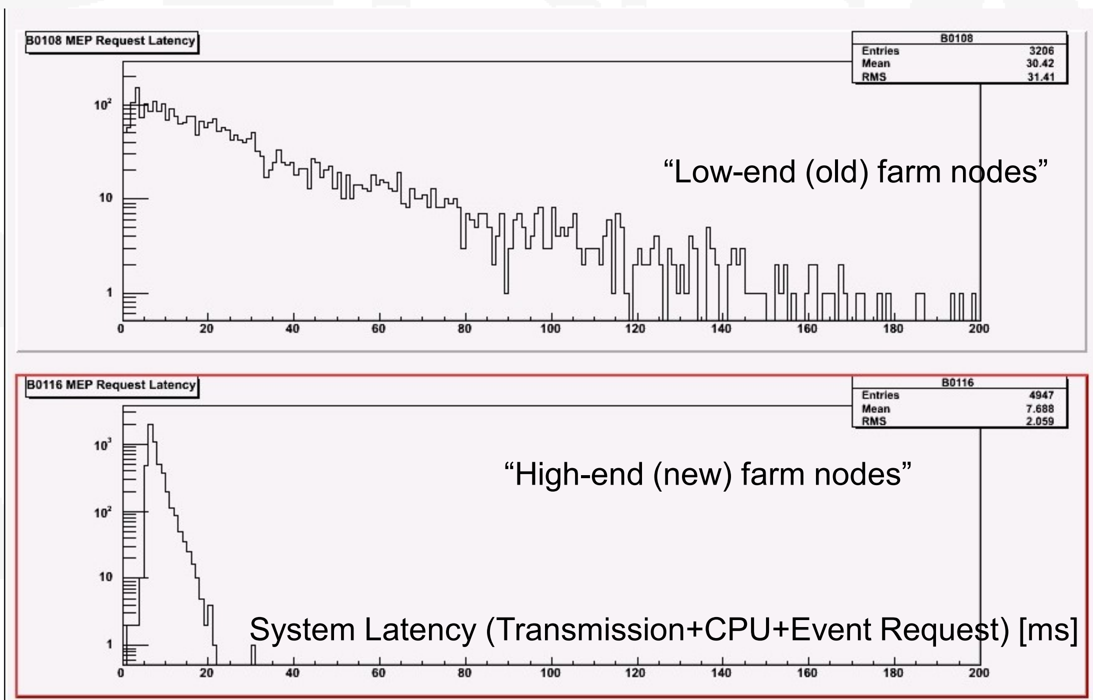
90% efficiency:
- detector HV > 99.5% fully ON
- all detectors included
- VELO fully closed
- trigger and DAQ deadtime included!

Upgrade of EFF "on the fly"

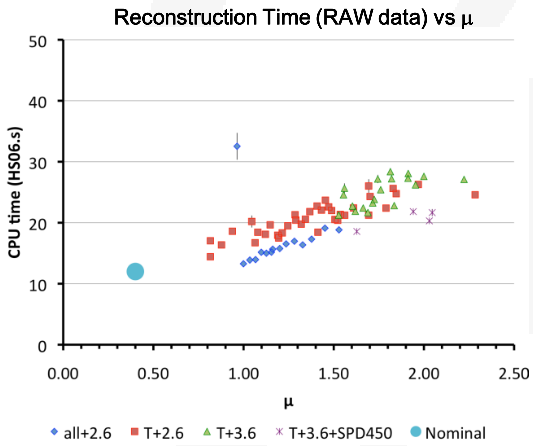
Added 400 nodes in less than 3 days in order to double the FARM capacity

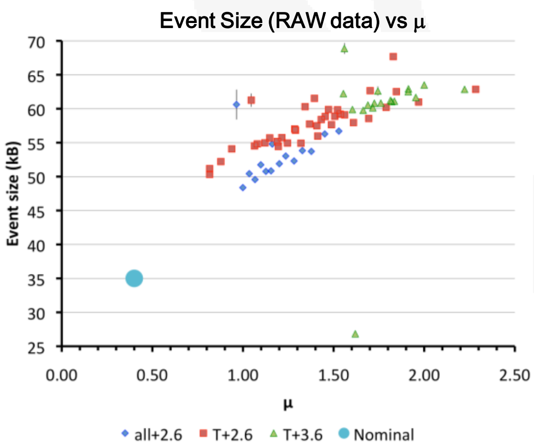
- ✓ configuration time down to 6 minutes for 1000 nodes
- ✓ mixture of farm nodes → optimization of events readout and system latency
- ✓ event processing time ~15 ms for fast nodes, ~30 ms for slow nodes
- ✓ reached event size of ~70kB at high-Mu (nominal is 35kB!)

Foreseen another upgrade by 400 nodes in the winter shutdown

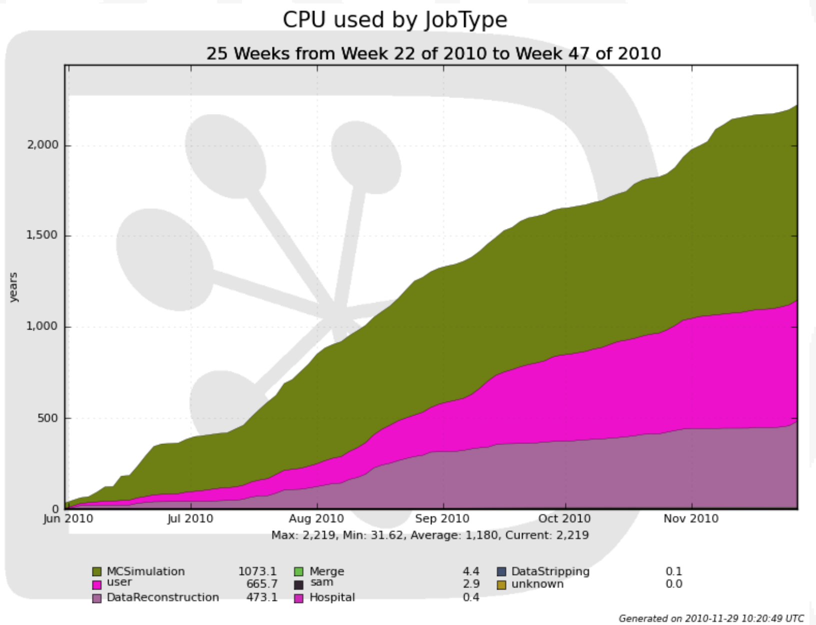


Offline computing and reprocessing



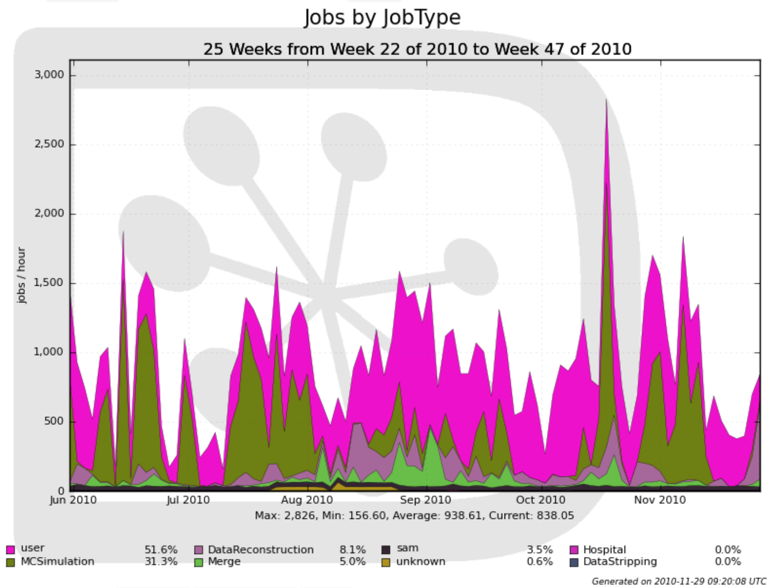


- All LHCb data is being reprocessed on the Grid (20k jobs/day)
- Both event size and CPU time rise with Mu
- Compatible with expectations at nominal Mu (~0.4)
  - → Need to adapt continuously to changing running conditions

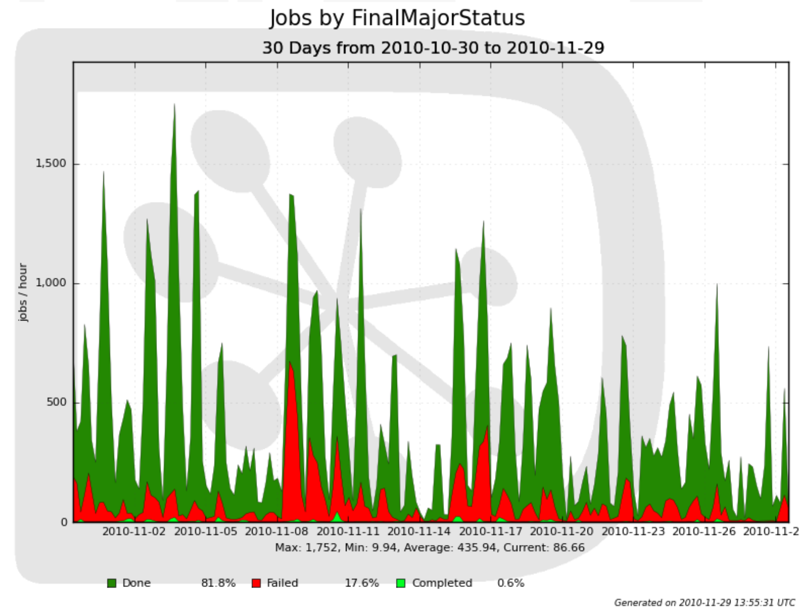


- More than 2000 CPU years in 6 months
  - → Equally share between MonteCarlo and Analysis+Reconstruction
- About ~400 TB of physics RAW data collected
- Distributed immediately to Tier1s

Offline computing and reprocessing



- Overall **82% success rate**
- Main cause of failures **(18%): job exceeding CPU time limit or user mistakes**



- 115 sites used
  - 21 countries

- Analysis: 52%
- Simulation: 32%
- Reconstruction: 8%

- Currently using Tier1s for Analysis
  → Soon use large Tier2s for Analysis (and Reconstruction) as well!

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Plans for detector operations in 2011

From the detector point of view:

- → Upgrade of Event Filter Farm to reach O(1500) nodes
- → bandwidth limitation: 70kB event size @ 1 MHz
- → load balancing and additional links will be needed
- → up to Mu = ~2.5, detector operations seems feasible and possible
- → LHCb designed to run for 10 years at 2-5*10^{32} cm^{-2}/s (operational stability)

From the trigger point of view:

- → Cutting on the SPD at high-Mu is not necessarily beneficial
- → evaluate the use of Global Event Cuts
- → CPU time/event will have to improve in order to do more in the same amount of time
- → Some physics channels don't gain significantly at Mu > ~2.5

↓

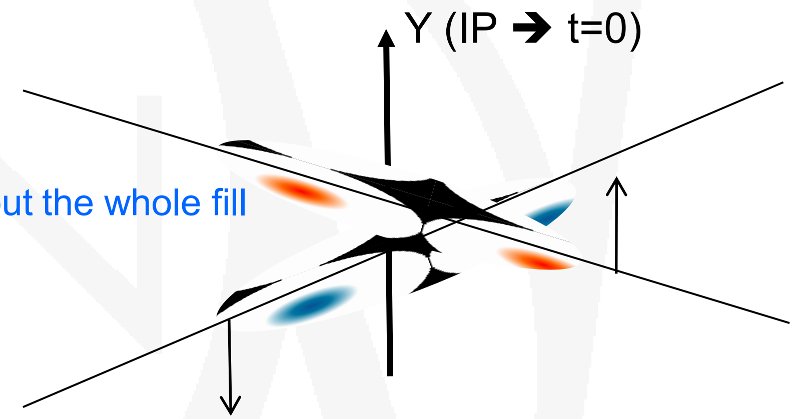
LHCb future running strategy:

- → maximum instantaneous luminosity of 2-5*10^{32} cm^{-2}/s
- → maximum Mu of 2.5
- → follow increase of number of bunches by LHC:
  - ✓ for 50ns bunch scheme up to ~1400 colliding bunches
  - ✓ ε_N = 2.4um, N_i = 1.6*10^{11} ppb

LHCb future running strategy

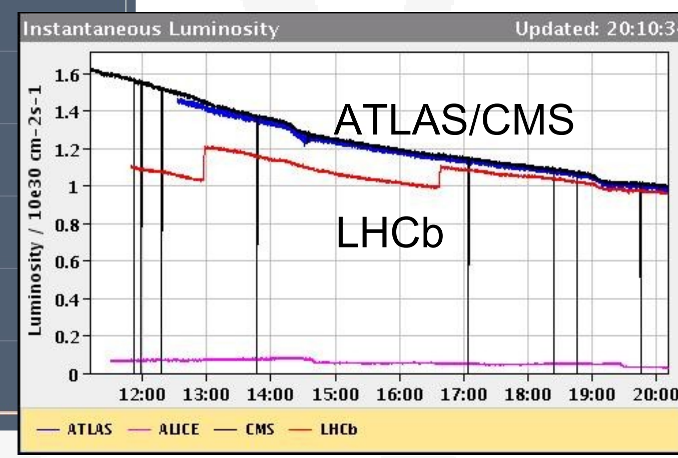
Luminosity leveling:

→ "simply" displacing beams
→ allow selecting favorite value of Mu
→ allow keeping the value of Mu constant throughout the whole fill



Many feasibility tests performed with the machine

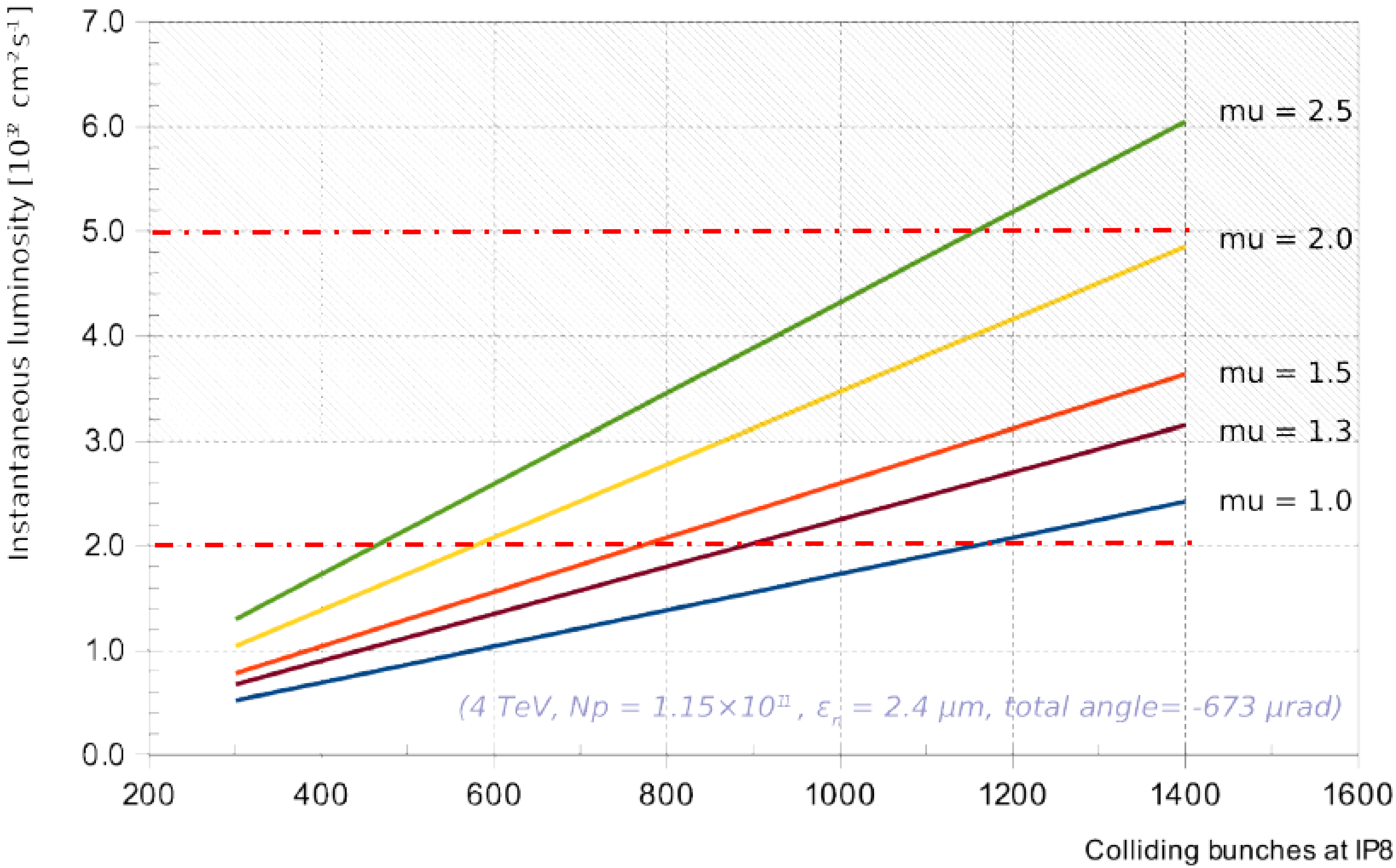
→ Up to now no sign of problems
→ Should not affect other 3 experiments



→ keep increasing number of bunches, gradually decreasing number of interaction per crossing

LHCb future running strategy

→ Three phase space strategy: number of bunches, instantaneous luminosity, Mu



Conclusions

LHCb spent an incredibly exciting year collecting about $37pb^{-1}$ of recorded data with an efficiency above 90%.

→ The challenges of a first year of running of a brand new experiment, in extreme conditions have been overcome without showstoppers and being able to follow the luminosity growth together with the GPDs

→ The main aim remained however to exploit and explore the physics potential of the detector at extreme operational conditions

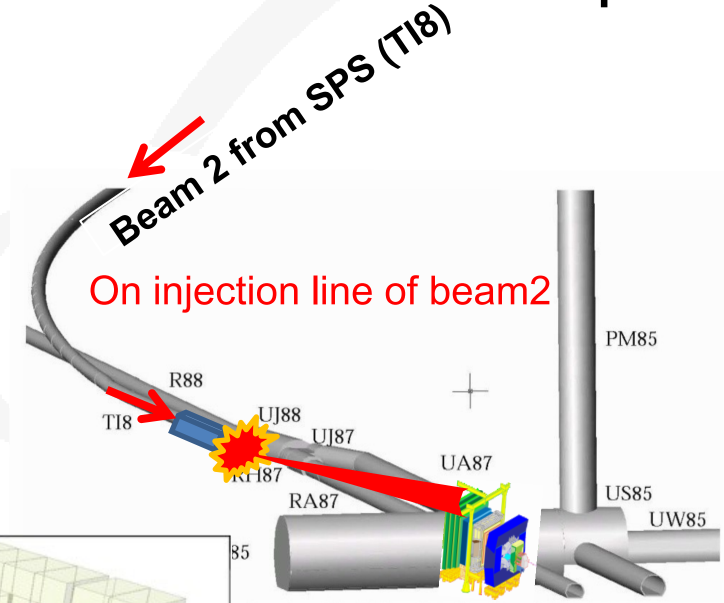
→ The trigger strategy changed over time to accommodate the changes in running conditions and to try to expand our physics potential so that we could define LHCb as a forward GPD

→ The detector performances are excellent and the physics potential in the field of B physics is world class

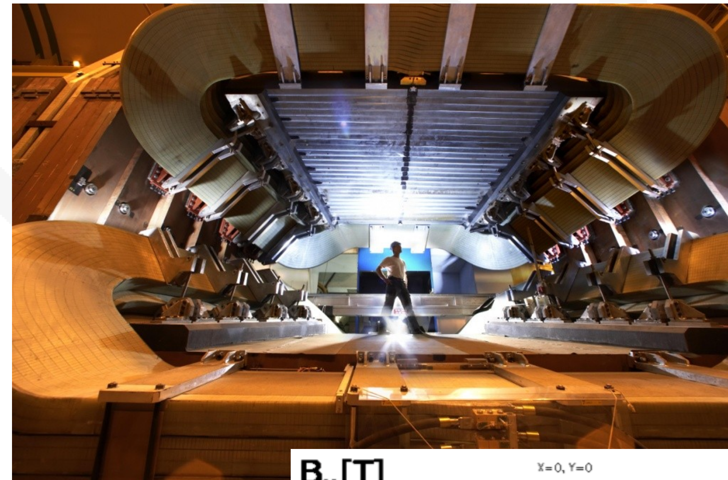
→ Many months of success were lived and many years of success are ahead of us

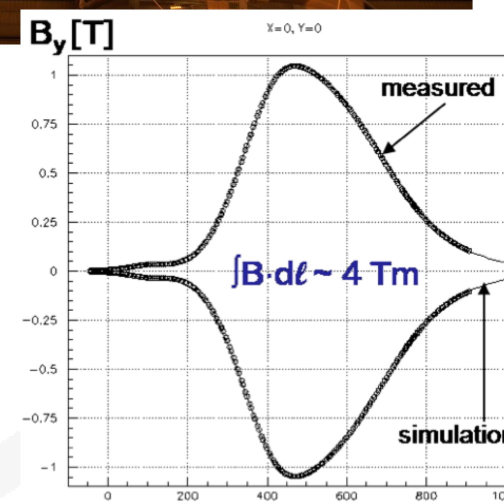
Backups

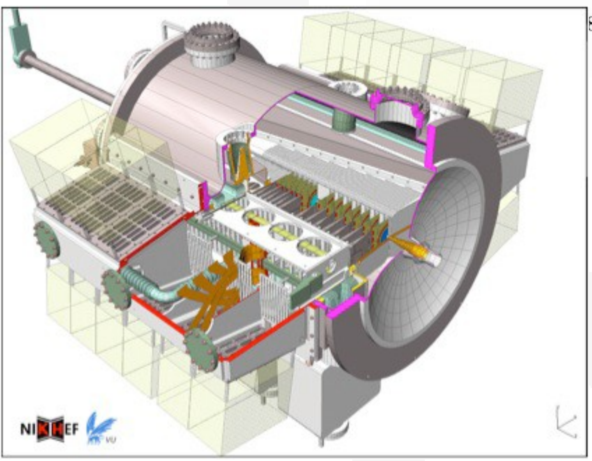
LHCb particularities



Magnet spectrometer





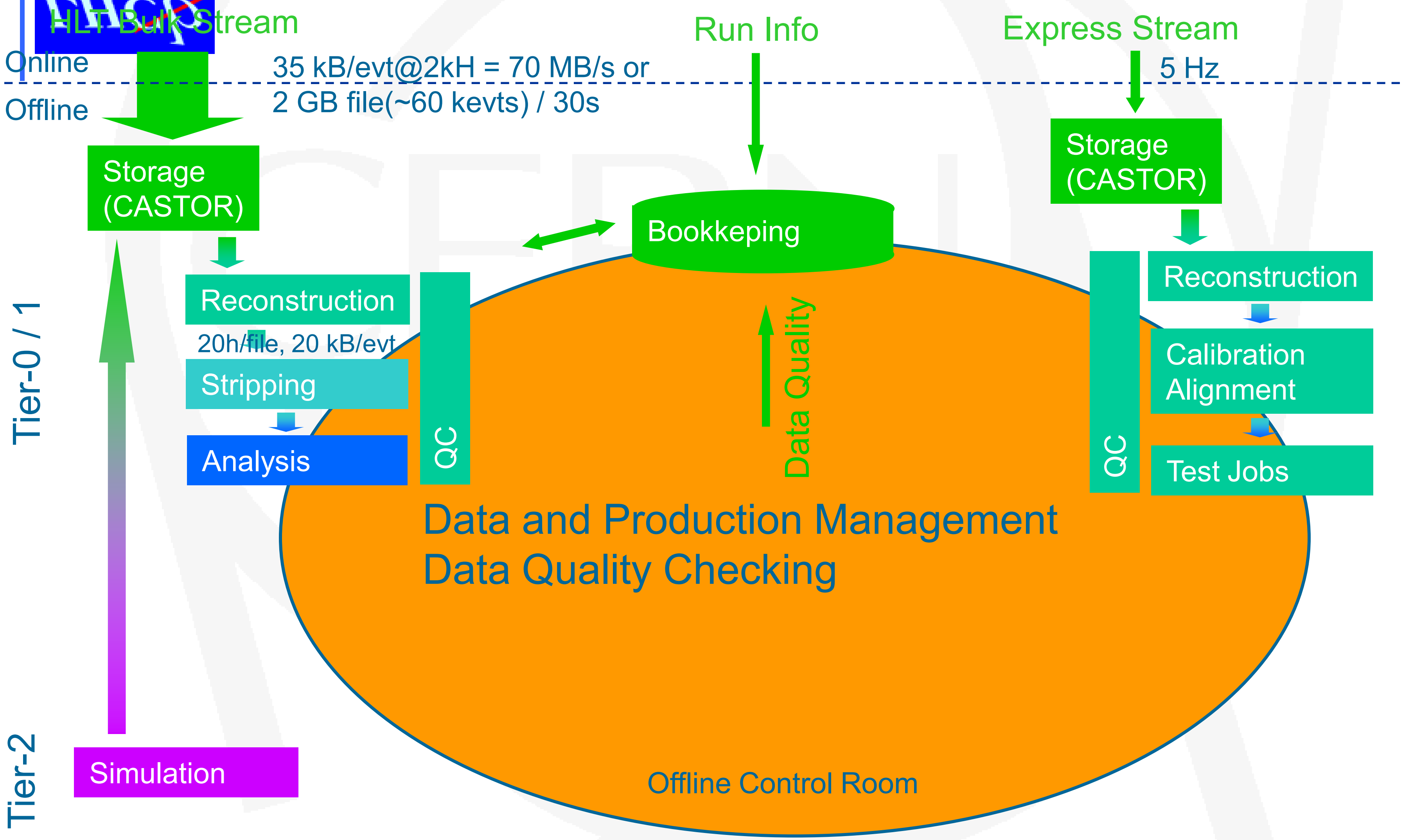


Movable Vertex Locator

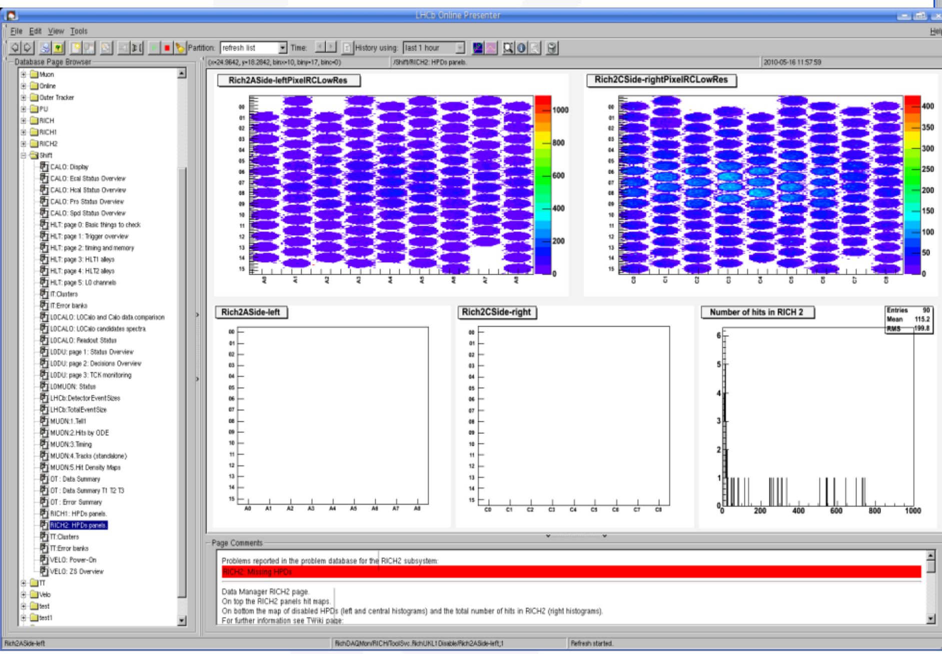
Displaced interaction point (~11.5m)
Complex background
Luminosity reduction due to magnet field
Safety (and defense)

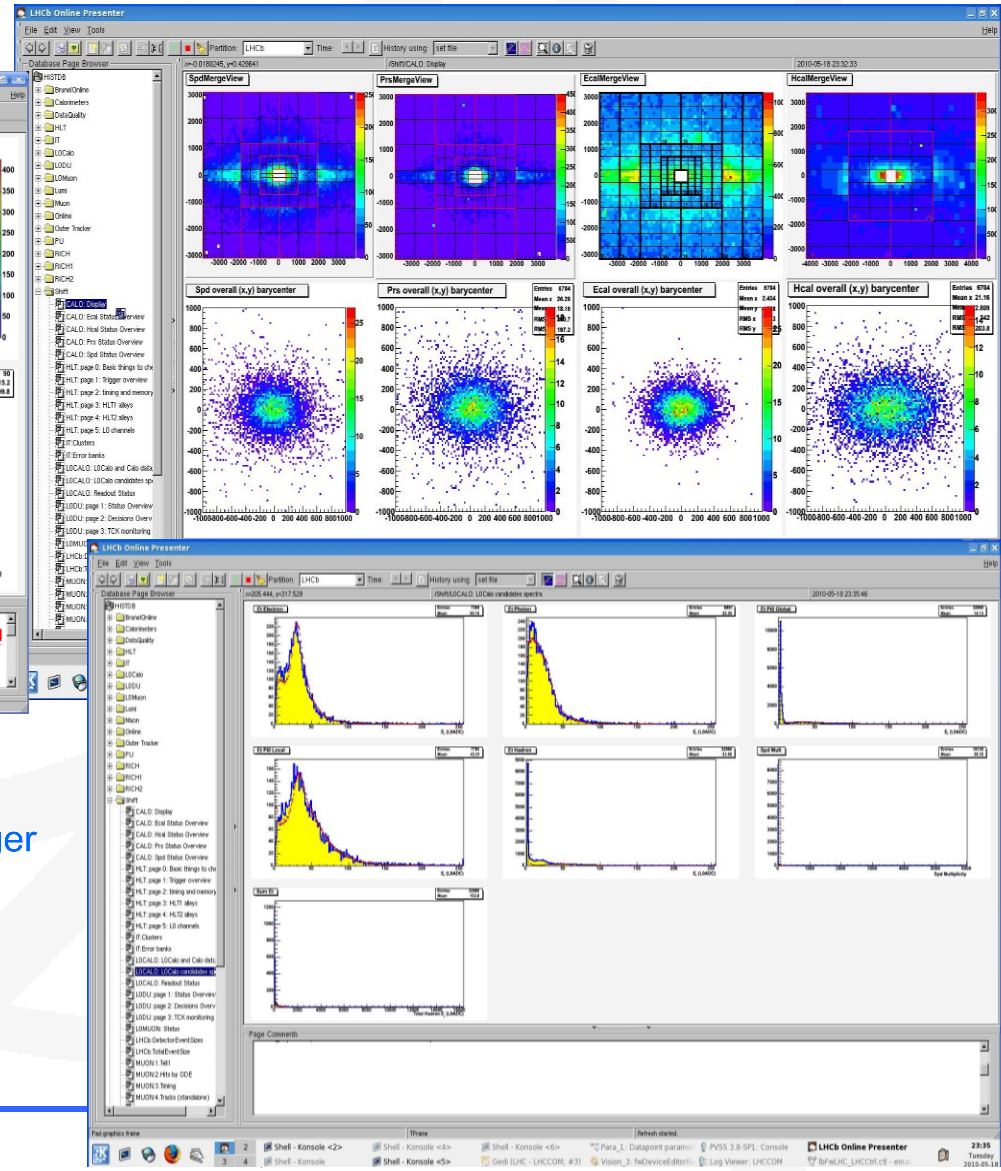
Centralized readout system
Centralized global operations
2 stage trigger

LHCb Data and Process flow



Data Quality





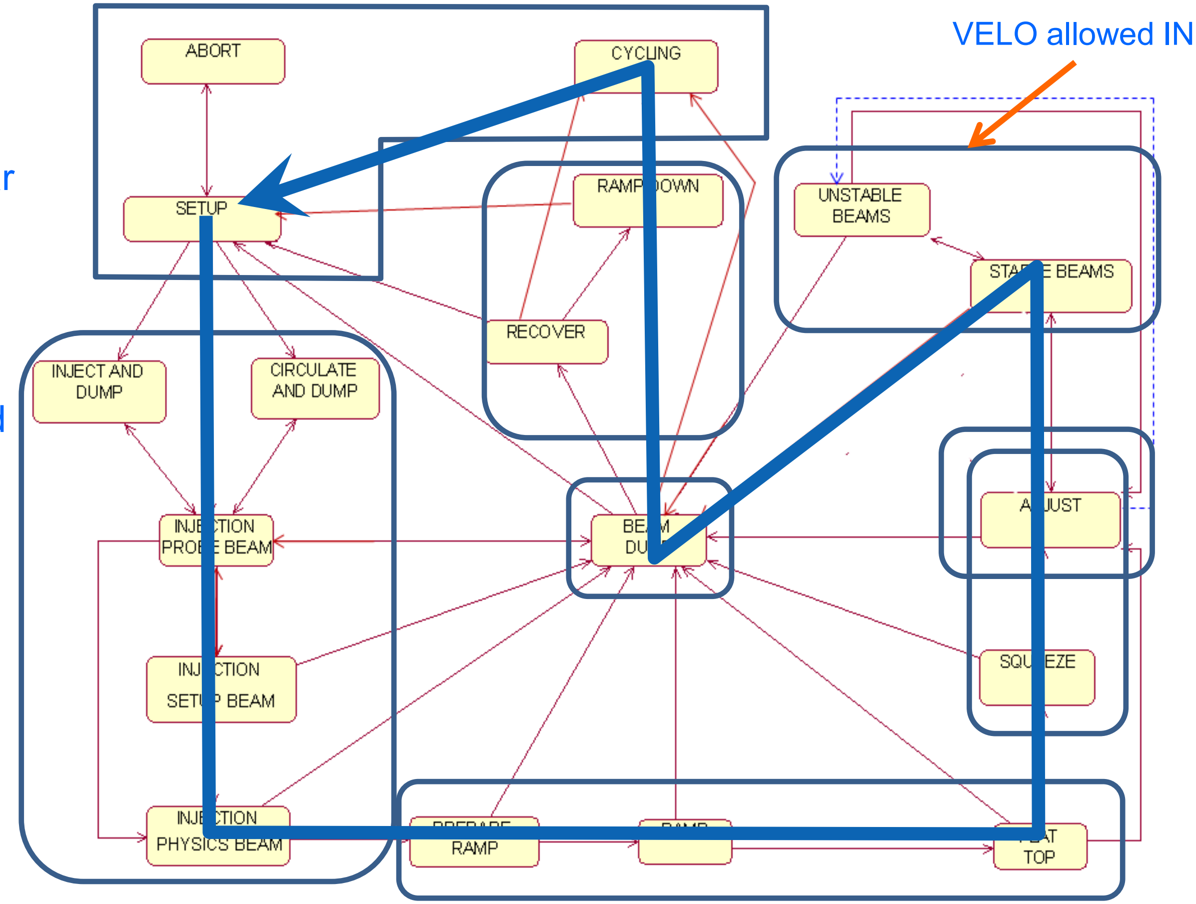
LHCb Online Presenter:

- → Online Data Quality performed by Data Manager
- → Full data taking with ROOT interface
- → Alarms associated
- → Interfaced with Databases
- → Spot problem "live" and correct them!

Centalized Control System

Automation as function of LHC mode

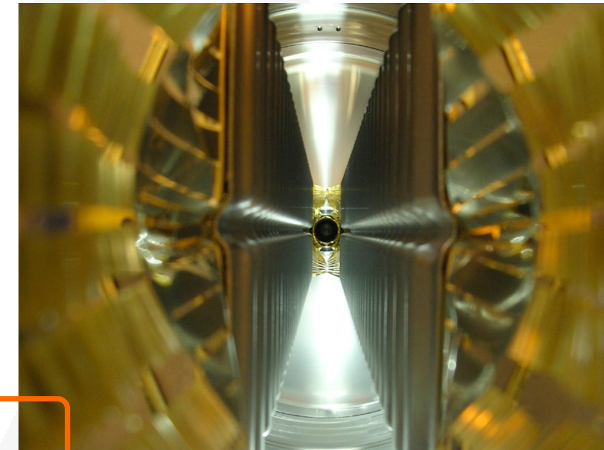
- → Reduced 19 LHC states into 8 LHCb states by regrouping similar states
- → HV & LV of each sub-detector and data taking is controlled via LHCb state machine
- → New LHCb State is proposed and simply acknowledged by shifter (cross check)
- → Movable devices only allowed to move during the collision phase
  - ✓ Next slide
- → Reliability and completeness to ensure to be in the right state at the right moment



VELO Safety and Motion

VELO allowed to move towards the beam only when Safe Stable Beam flag is declared

→ only during collisions, closest strip at ~7mm.

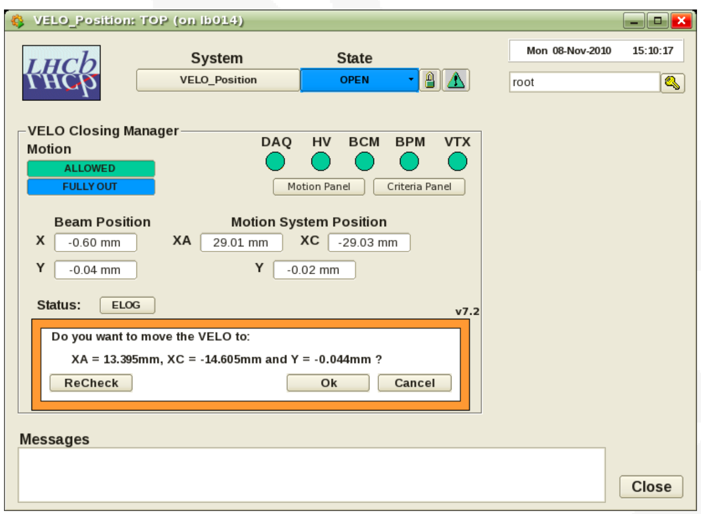


STABLE BEAMS declared

Online monitoring of beam vertices and beam movements gives ok to move in (wait for ~400 vertices)

Step 2 is repeated 3 times for 3 different positions (± 29mm, ± 10mm, 0)

VELO closed! → Full LHCb datataking



Procedure is semi-automated, shifter only acknolewdges the motion and cross-check the information via Interface panel

→ Hard limit due to motion system: 3 min.

→ Fastest closing procedure: ~4.5 min.

→ Safety procedure accounts for only ~2.3% of entire LHCb inefficiency. Foreseen to decrease even more as procedure become more automated!

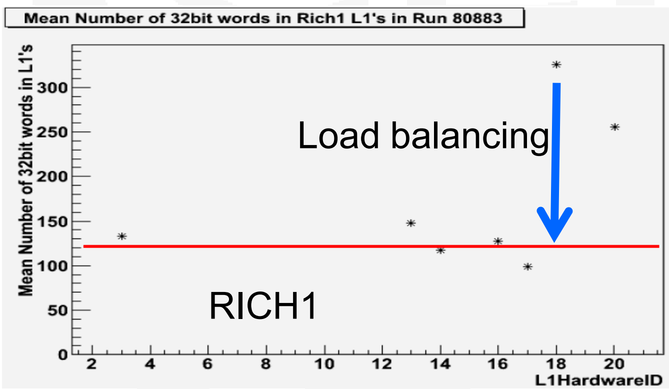
L0 bandwidth

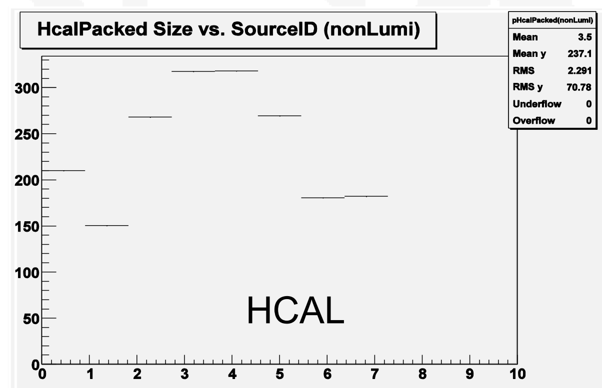
L0 bandwidth calculation comes from output of Readout Boards:

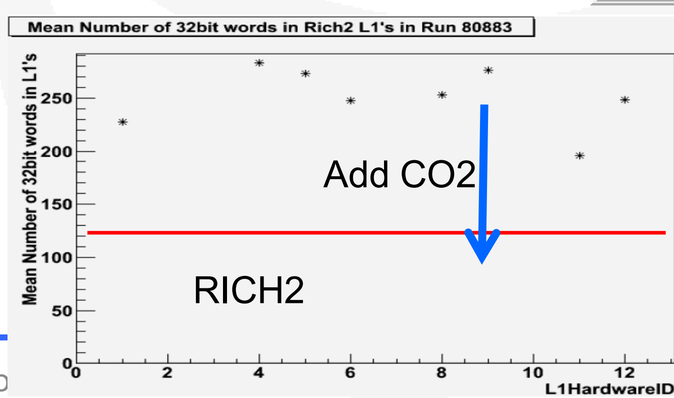
→ 450 Bytes at 1 MHz = 450MB/s x 312 ROBs = ~140GB/s = ~1.1 Tb/s

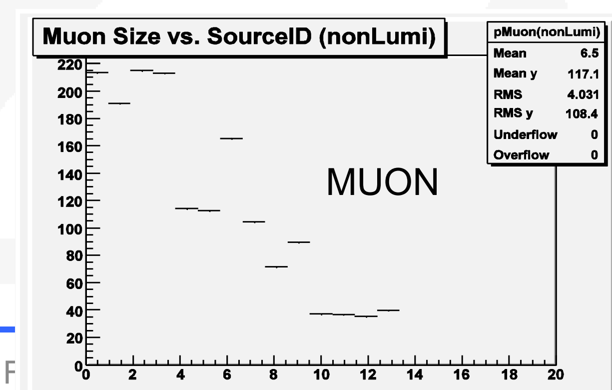
→ High-mu events have higher size and rate → Occupancies in detectors play a role

- → load-balancing of channels in Readout Boards
- → add number of Readout Boards
- → add CO_2 in RICH2 to decrease event size by quenching scintillation light





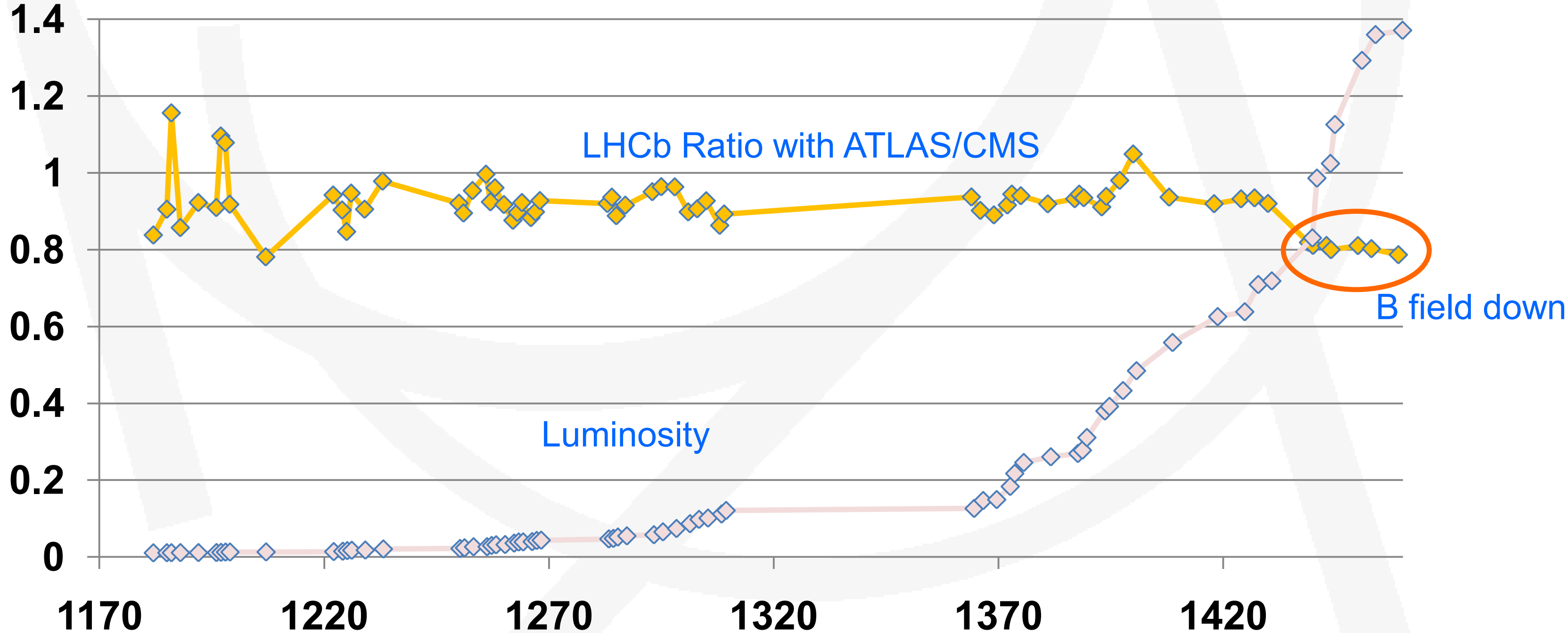




Luminosity discrepancy

Systematic luminosity difference IP1/5 and IP8 – Not understood

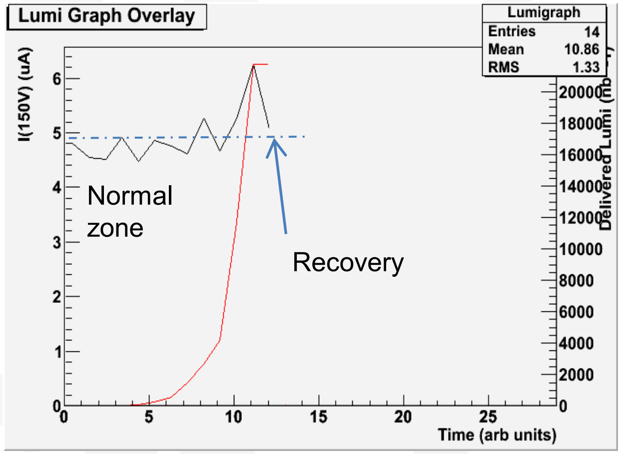
1. Geometrical factor
   - July – August: LHCb 2x270 μrad ➔ 8-9% as compared to Atlas/CMS with 0μrad
   - B up+α_{ext}: LHCb 2 x (270 – 100) μrad ➔ 3% as compared to Atlas/CMS with 200 μrad
   - B down+α_{ext} : LHCb 2 x (270 + 100) μrad ➔ 9% as compared to Atlas/CMS with 200 μrad
2. Normalization – work starting up to normalize via Alice
3. β* / Waist effect? ➔ Observations of strange geometrical effects during scans



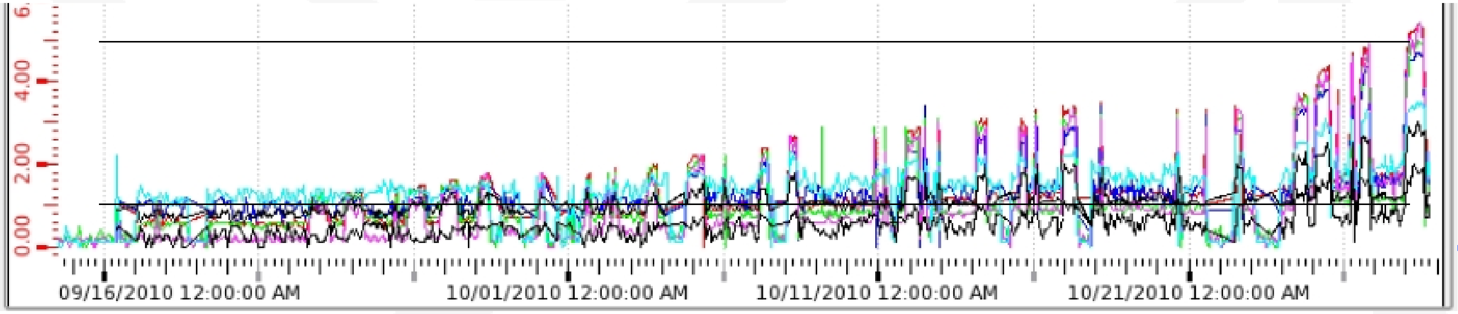
Ageing

No abnormal ageing observed in situ in any detector

LHCb detector built for 10 years @ $2x10^{32}$ cm-2s-1
→ Lumi per bunch of $7.6x10^{28}$ cm-2 s-1
→ How about >>$2x10^{32}$ cm-2s-1 with 1400 bunches??
→ $5x10^{29}$ cm-2s-1/bunch

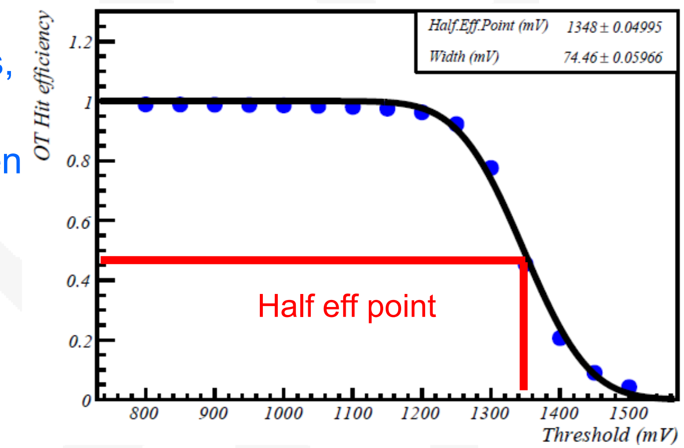


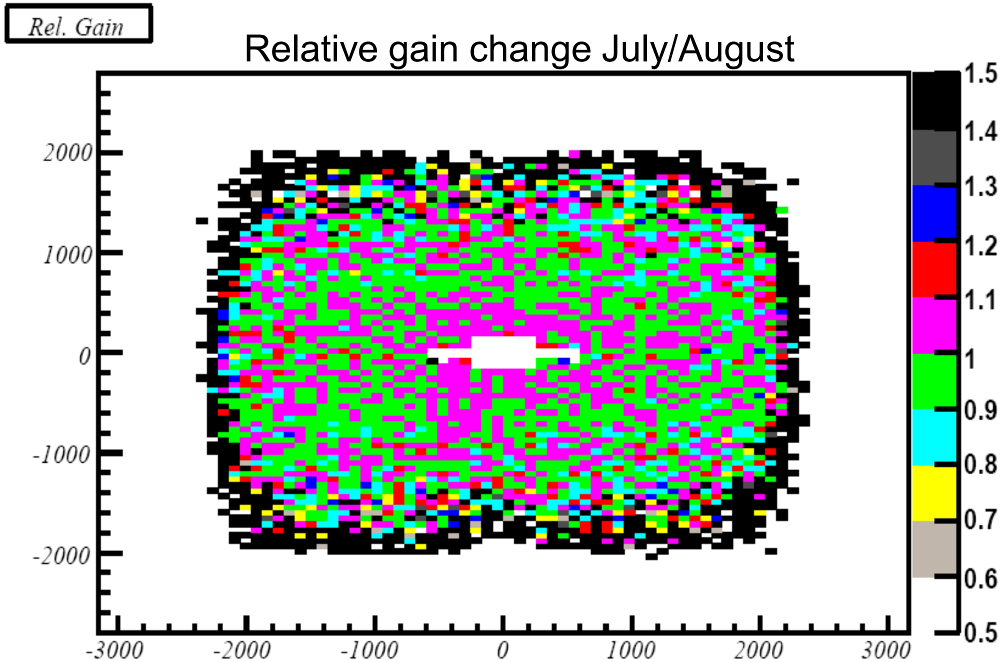
- VELO
  - No surprises
  - No sign of bulk damage, some effects compatible with surface damage
  - Worst sensor shows factor of three increase in current consumption
    - Some sensors actually reduced current consumption
- ST
  - No surprises
  - Type inversion in TT expected next year → cooling
  - Observed increase of about 4.5 mA in central region of IT completely in agreement with model at 40 pb-1 eq. to 2E5s @ nominal luminosity



Ageing

- Outer Tracker
  - Ageing measured and modeled in vitro – potentially serious, model has to be confirmed
  - Two threshold scans performed during the year (half-efficien point)
    - August after 1 pb^{-1}
    - October after 25 pb^{-1} ➔ Analysis ongoing

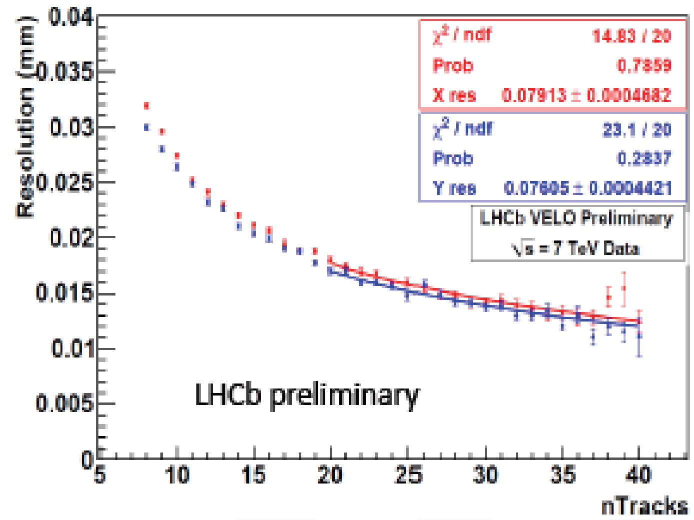


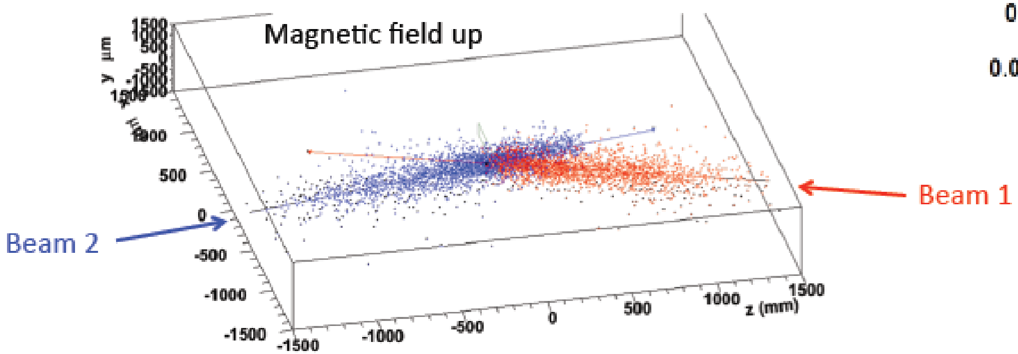


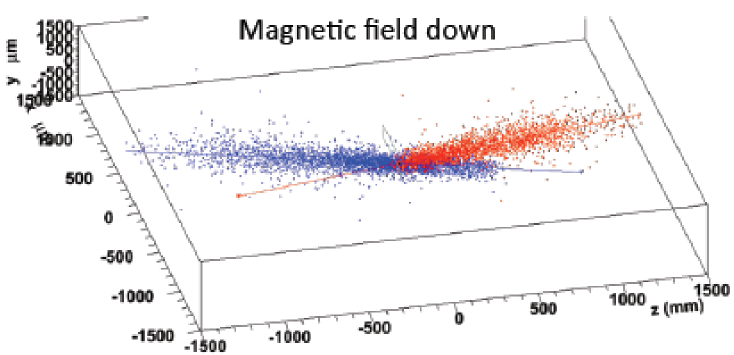
Ageing model needs validation

Primary Vertex Resolution

Primary vertex resolutions:
- ✓ σ_x and σ_y = ~15um
- ✓ σ_z = ~76 um







Special Beam gas trigger in LHCb used to determine:
- LHCb Luminous region
- beam 1 spot and beam 2 spot
- effective crossing angles and beam angles
- debunching
- absolute luminosity measurement (LHCb cross-section)

HV trips

Excellent situation, detector hardware behaves properly!

MUON HV trips:
→ Muon trips correlated with chambers which were less conditioned after production
→ Fraction of it due to backsplashes in the upper region of the detector for beam2
→ No real effect because of high redundancy
→ Conditioning in situ

Silicon Tracker HV trips:
→ Occurring at rapid luminosity change (when beams are brought into collisions

Outer Tracker HV trips:
→ Very few

No HV trip affected efficiency considerably
→ Accounts for less than 1% of the inefficiencies