LHCb Trigger in Run I and Prospects for Run II

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CERN PH-LBD

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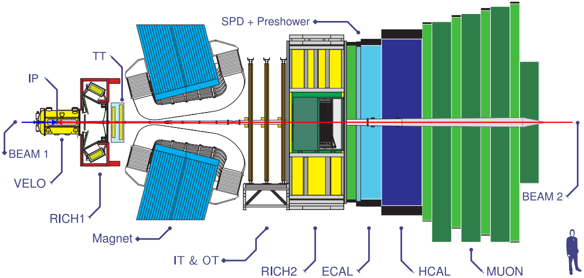
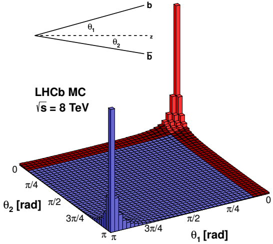
The LHCb Experiment

Precision Beauty and Charm Physics

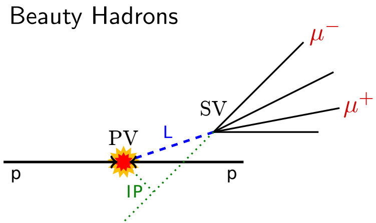
- *LHCb* is a single-arm ($2 < \eta < 5$) spectrometer at the LHC
  - *CP* violation measurements, rare decays, heavy flavor production
  - Exploits the correlated production of $b\bar{b}$ pairs in the LHC environment

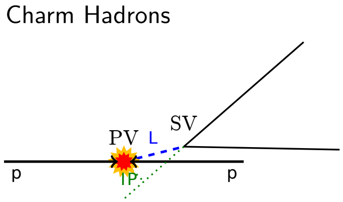




- Time-dependent analyses require good time resolution: ~ 40 fs (VELO)
- Flavor tagging, final state discrimination needs excellent particle ID: (RICH)
- Rare decays and extremely small asymmetries require pure data samples with high (and controlled) signal efficiency: (Trigger)

- Beauty and charm hadron typical decay topologies:



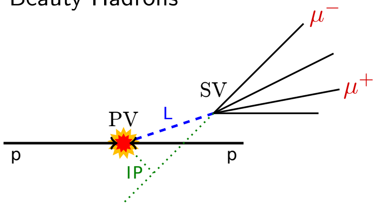


- $\mathrm{B}^{\pm}$ mass $\sim$5.28 GeV, daughter p_{T} O(1 GeV)
- $\tau\sim$1.6 ps, Flight distance $\sim$1 cm
- Important signature: Detached muons from $\mathrm{B}\to \mathrm{J}/\psi X$, $\mathrm{J}/\psi\to\mu\mu$

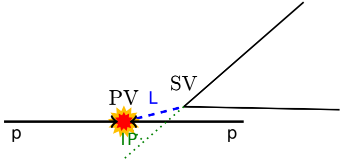
- D^0 mass $\sim$1.86 GeV, appreciable daughter p_{T}
- $\tau\sim$0.4 ps, Flight distance $\sim$4 mm
- Also produced as 'secondary' charm from B decays.

- Beauty and charm hadron typical decay topologies:

Beauty Hadrons



Charm Hadrons



- $B^{\pm}$ mass $\sim$5.28 GeV, daughter p_T O(1 GeV)
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- D^0 mass $\sim$1.86 GeV, appreciable daughter p_T
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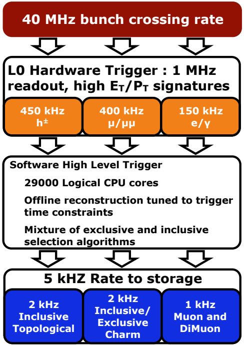
Trigger Strategy:

- Inclusive triggering on displaced vertices with high-p_T tracks and muons
- Exclusive triggering for (almost) anything else

2011-2012 Trigger Architecture
and Running Conditions



The present Trigger consists of three stages:

- Level 0 (L0) near-detector hardware, readout decision in 4 μs
- Higher Level Trigger (HLT) 1&2: flexible software triggers running on dedicated Event Filter Farm (EFF), 29 000 cores
- Documented in ↪ [JINST 8 (2013) P04022] and ↪ [arXiv:1310.8544]

2011:

- $\mathcal{L} \sim 2 \cdot 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- 50 ns bunch spacing; $\left\langle \frac{\#\text{visible collisions}}{\text{bunch crossing}} \right\rangle \mu = 1.4$

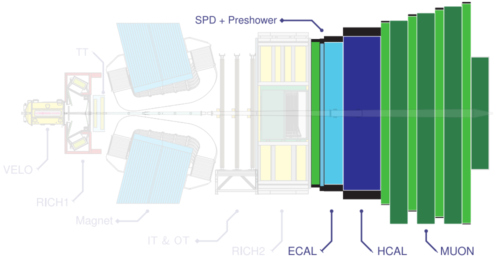
2012:

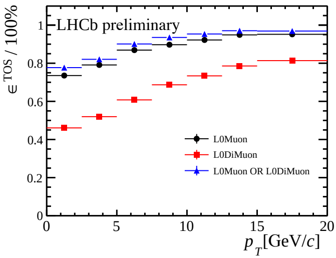
- $\mathcal{L} = 4 \cdot 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- 50 ns bunch spacing; $\mu = 1.6$

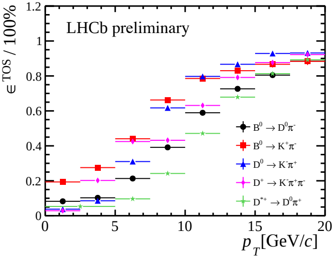
L0 Trigger

L0 hardware trigger in Run I: high p_T and E_T signatures

- L0 muon:
  - $\Delta p/p \sim 20\%$
  - Single- and Di-muon p_T thresholds
  - 90% efficient for most dimuon channels
- L0 calo: High E_T hadrons, $e^{\pm}$, γ
  - 50% efficient on hadronic B decays
  - 80% efficient for radiative $B \rightarrow X\gamma$ decays



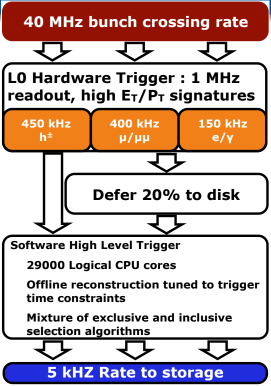




Efficiencies wrt offline-selected signal

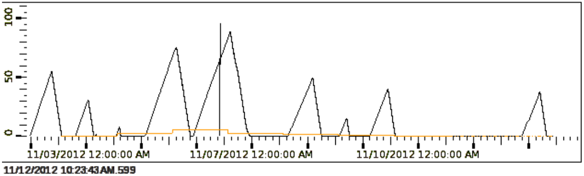
Deferred Trigger

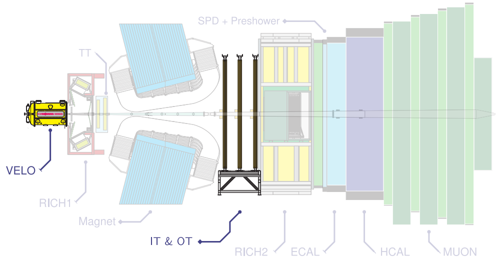
Maximizing Usage of Computing Resources

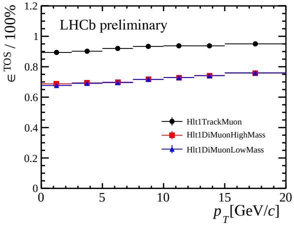


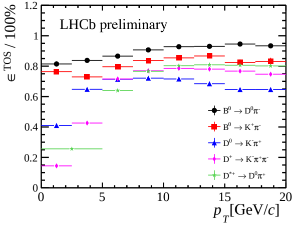
- Farm nodes idle between fills, large disks (1PB total) not used by HLT software
- Buffer 20% of L0 events on EFF disks, process in inter-fill time
- Effective 25% Extra CPU allowed us to lower tracking thresholds from $p_T = 500 \rightarrow 300\text{MeV}$
- Increased efficiency for charm signatures
- Peak disk usage, 88% after $>$ 16h fill

Disk usage in % of 1 PB storage used as function of time







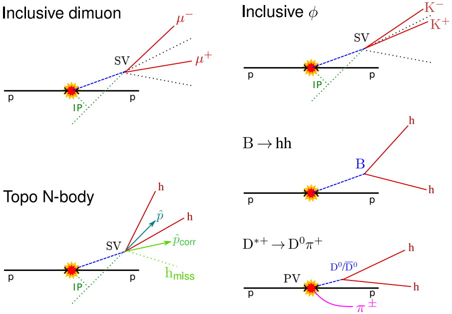


- HLT1 Adds tracking and PV information:
- VErtex LOcator (VELO) tracking + PV reconstruction
- Tracks matched to L0muon hits or with large displacement from PV are selected for forward tracking into the Inner & Outer trackers (IT&OT)

HLT2

Take full offline track reconstruction $\rightarrow$ simplified version

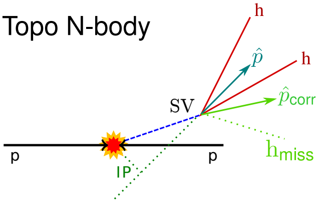
- Close to offline performance with time/event reduced 2s $\rightarrow$ 200 ms
  - omit low-p_t tracks, simplified track error estimates
  - limited PID and calorimetry
- Allows for a range of selection criteria of varying complexity
- Combination of Inclusive and Exclusive lines, eg:



- Extremely flexible software environment: Supports MVA-based selections
- Composition of trigger lines and individual prescales can be adjusted to suit running conditions

Topological $N-$body lines

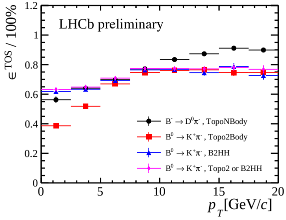
Inclusive trigger on 2,3,4-body detached vertices $\hookrightarrow$ [LHCb-PUB-2011-016]



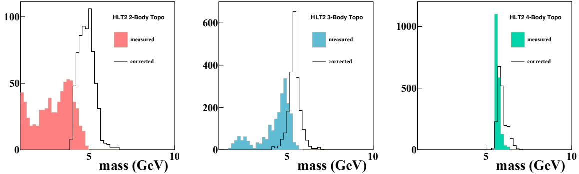
- Primary trigger for B decays to charged tracks
- Uses modified BDT algorithm
  $\hookrightarrow$ [JINST 8 (2013) P02013]
- BDT inputs: p_{T}, $IP\chi^2$, Flight distance χ^2, mass and m_{corr}, corrected mass:

$$m_{corr} = \sqrt{m^2 + |p_{\mathrm{T}miss}|^2} + |p_{\mathrm{T}miss}|$$

- $p_{\mathrm{T}miss}$: missing momentum transverse to flight direction



2,3,4-body trigger on 4-body final state



- Very efficient on fully hadronic B decays

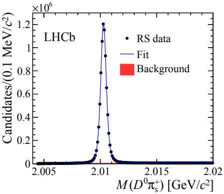
Run I Trigger performance

Trigger efficiencies for selected channels

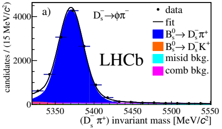
	Hadronic		Dimuon	Radiative
Mode	$D \to hhh$	$B \to hh$	$B^+ \to J/\psi K^+$	$B^0 \to K^*\gamma$
ϵ(L0) [%]	27	62	93	85
ϵ(HLT | L0) [%]	42	85	92	67
ϵ(HLT $\times$ L0) [%]	11	52	84	57

- Extremely pure samples after offline selection:

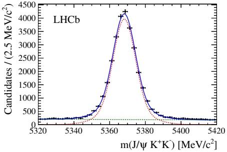
$D^* \to D^0\pi \hookrightarrow$ [1211.1230]



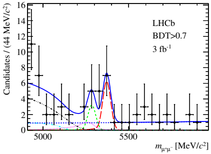
$B_s^0 \to D_s\pi \hookrightarrow$ [1304.4741]



$B_s^0 \to J/\psi\phi \hookrightarrow$ [1304.2600v3]

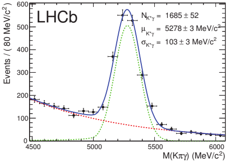


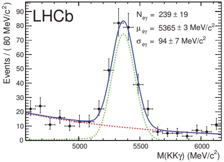
$B_s^0 \to \mu\mu \hookrightarrow$ [1211.2674]



$B_d^0 \to K^*\gamma, B_s^0 \to \phi\gamma$

$\hookrightarrow$ [1202.6267]





Run II Scenario

- $\sqrt{s} = 13\,\text{TeV}$ expectations:
  - $\sim 15\%$ increase of $\sigma_{\text{inel}}(LHCb) \sim 70mb$
  - $\sim 20\%$ increase in multiplicity (per collision)
  - $\sim 60\%$ increase of $\sigma_b(LHCb)$
- Bunch spacing 25ns, 2250 bunches (2012: 50ns, 1260 bunches, $\mu = 1.7$)
- Target Luminosity (levelled): $\mathcal{L} = 4 \cdot 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- $\Rightarrow \mu = 1.1$ (event multiplicity equivalent to $\mu = 1.3$ @ 8 TeV)
- Events are “simpler” than 2012 thanks to 25ns spacing, but contain more beauty and charm
- $\rightarrow$ Trigger will push larger fraction of events to later stages
- $\leftarrow$ Make early stages more selective

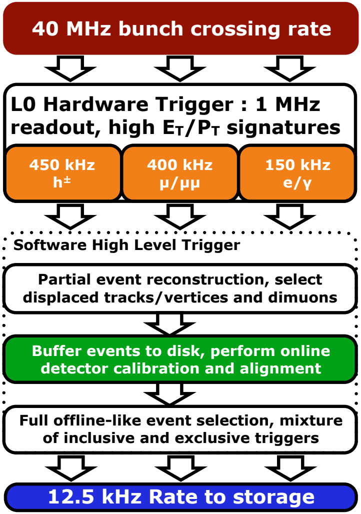
Resources

- Instantaneously available CPU power in Event Filter Farm doubled
- Additional buffer storage: 1 PB $\rightarrow$ 4 PB

Post-LS1 Trigger

Evolution of HLT Architecture

LHCb 2015 Trigger Diagram



- **Goal: make trigger more compatible with offline analysis environment**
- Requires HLT to perform detector alignment and calibration
  - Move buffering to after HLT1
  - Average week 2012: 49h beam buffering → factor 2 effective CPU
  - Run calibrations during buffering
- Allows us to use selections similar to offline:
- eg: full RICH PID ↪ [EPJC 73 2431], currently used in a limited capacity
- Major advantage: Suppress background to charm channels.
  Identify Cabibbo-favoured vs. suppressed modes in the trigger

Go Small and Fast – TurboStream

Analysis on Online Reconstructed Particles

With Run II we start to enter a regime where signal rates become a challenge for computing

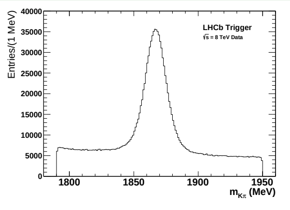
- Example: Cabibbo favoured Charm decays (Spectroscopy!)
- Prompt Charm analyses rely on exclusive triggers
  - Exclusive charm rate 2012: 2.5 kHz
  - Expect a factor ~ 2 for 2015
  - For exclusively triggered modes offline cannot add new particles

Perform analysis on online reconstructed particles

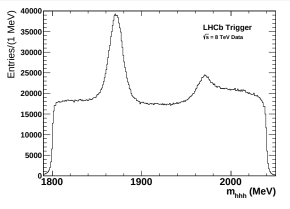
- Only save the particles found by the trigger $\rightarrow$ TurboStream
- very small event size allows larger rate to be pushed to offline at same bandwidth
- No offline reconstruction
- Completely rely on quality of online tracking/PID
- Proof of concept in Run II; Essential tool for Run III and beyond

2012: Online, exclusive D-samples (No PID!)

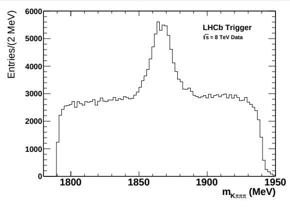
$D^0 \to K\pi$



$D_{(s)} \to hhh$



$D^0 \to K\pi\pi\pi$



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HLT Tracking Evolution

towards offline-like track reconstruction in the trigger

- Software trigger already uses the same code as the offline reconstruction

- In 2012 (38ms / event average over HLT1&2):
  - HLT1: strict requirements on VELO tracks, continue displaced, high $p_T > 1200\,\text{MeV}$ and muon tracks into forward spectrometer
  - HLT2: redo complete tracking on full event
    simplified geometry, only 1 Kalman-filter iteration

- For 2015 ($\sim 4\times$ effective CPU from new farm + buffering):
  - Use full VELO reconstruction in HLT1
  - Forward-track all tracks above threshold $p_t > 500\,\text{MeV}$ – remove displacement criterion
  - Improved forward pattern recognition (early p and p_T estimates from fringe field tracking in front of the magnet)
  - Save completed HLT1 tracks and reuse them in HLT2
  - Split HLT allows updated alignment constants in HLT2 fill-by-fill
  - Use offline-like tracking in HLT2: Kalman filter iterations, material map

The largely software-based architecture of the LHCb trigger has already paid off in Run I

- 3-stage approach with full event reconstruction in HLT2 allows application of advanced, MVA-based selections
- Achieves excellent efficiency for Dimuon, Radiative and Hadronic B and D decays
- Introduction of trigger deferral in 2012 allowed optimal usage of resources

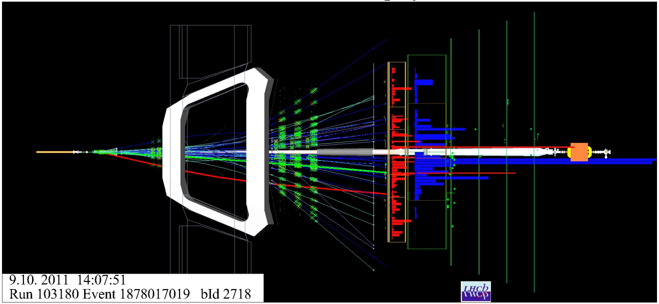
For Run II this flexibility will be used to make the trigger reconstruction more offline-like

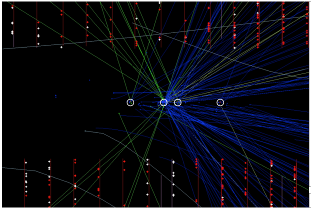
- Buffering between HLT1 and HLT2 allows online computation of calibrations (alignment and PID)
- Use Rich-PID in HLT2 to distinguish between cabibbo-favoured and suppressed decays
- Retuning tracking sequence to remove simplifications

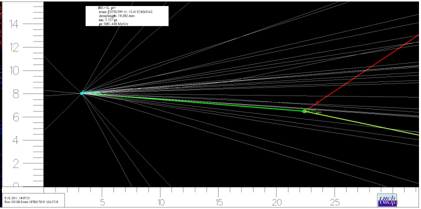
Backup

A typical LHCb event

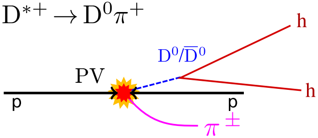
LHCb Event Display

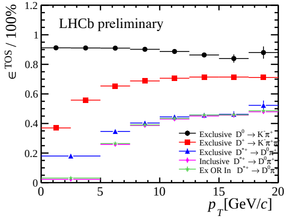






$D^{*+} \to D^0\pi^+$





- Charm is an important part of the LHCb physics programme:
  - Observation of D^0-$\overline{D}^0$ oscillations: $\hookrightarrow$ [PRL 110 (2013) 101802]
  - Measurement of D^0-$\overline{D}^0$ mixing parameters: $\hookrightarrow$ [PRL 111 (2013) 251801]
- 600 kHz of $c\bar{c}$ in 2012: Easy to swamp the output bandwidth unless exclusive selections are used
  - Exception: $D^* \to D^0\pi$ inclusive trigger uses $M(D^*) - M(D^0)$ to reduce the rate
  - D^0 exclusively reconstructed in $K\,K$, $\pi\,\pi$, $K\,\pi$, $\pi\,K$ final states, any in mass window are kept
- Cabbibo favored $D^0 \to K^-\pi^+$ is $\sim$300 times more abundant than Doubly cabbibo suppressed $D^0 \to K^+\pi^-$