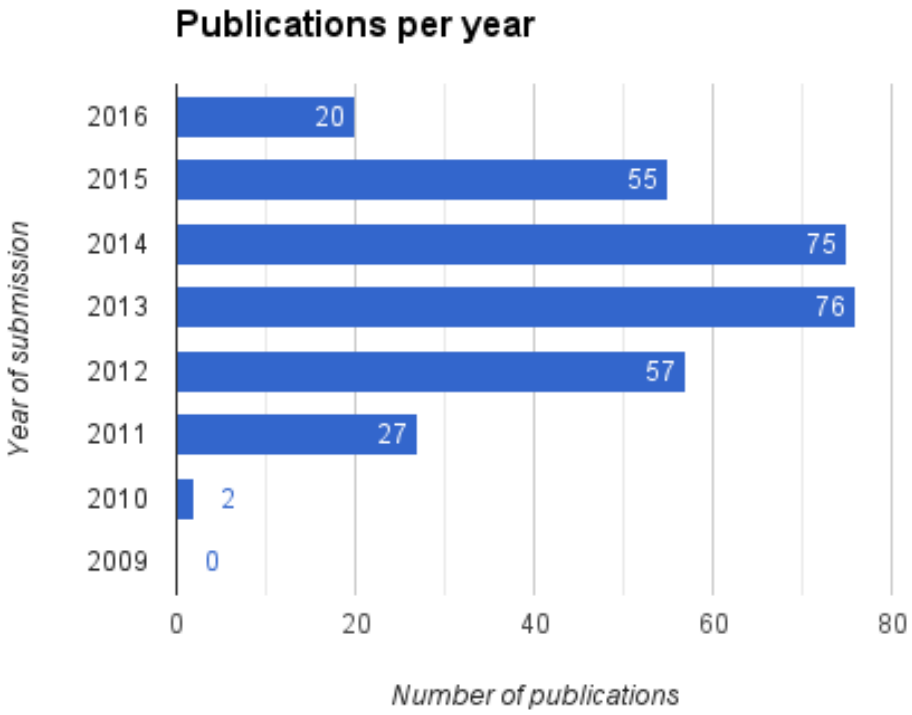
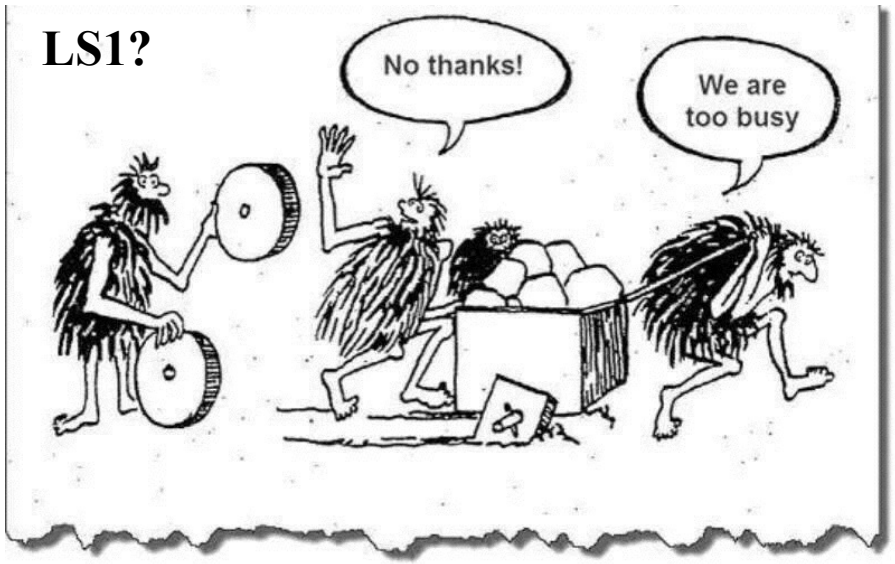
Beauty 2016

LHCb Run 2 trigger performance

Barbara Sciascia (INFN)
on behalf of LHCb Collaboration

Setting the stage





Recent past (Run 1, 2010 - 2012)

Very successful running and triggering

312 publications so far [22 April 2016]

21 conference-report and 14 detectors papers

Still a lot to do with Run 1 data

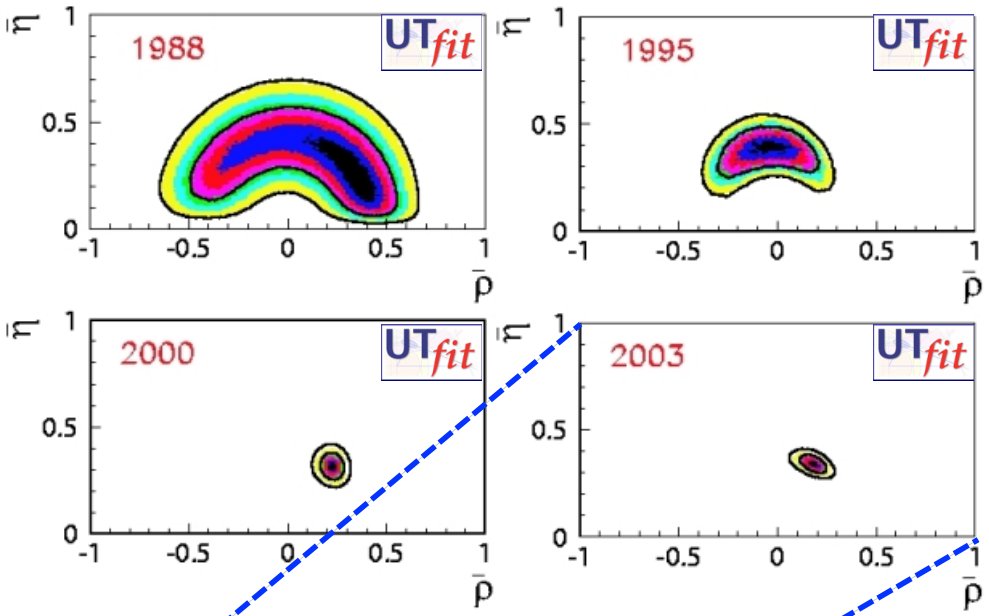
Present (Run 2, 2015 - 2018)

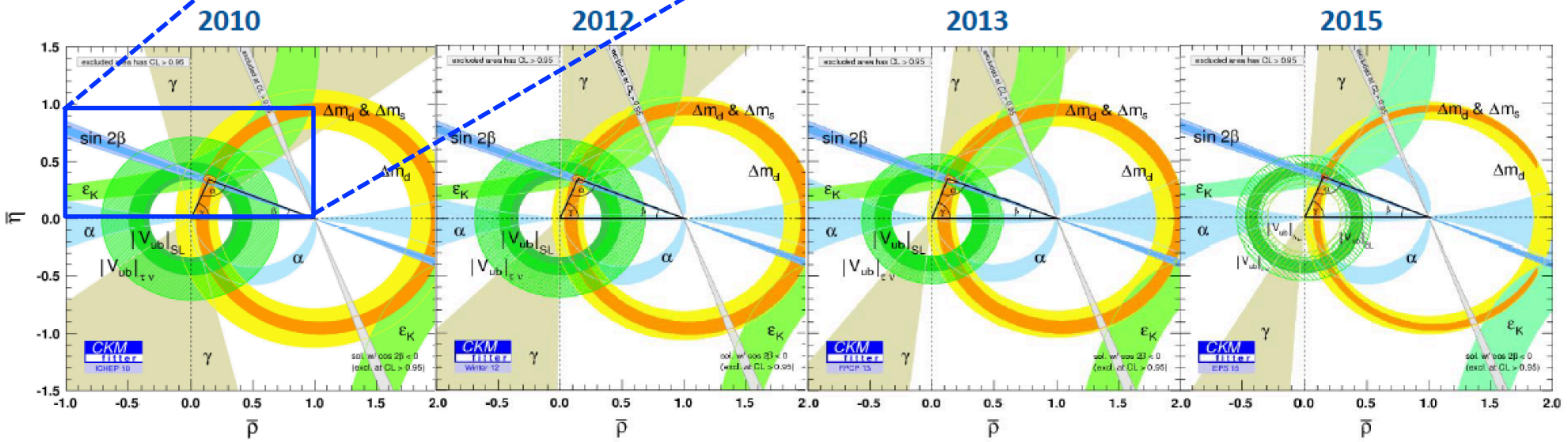
- Increased beam energy 7/8TeV→13TeV
- Similar luminosity as in Run 1
- Identical LHCb detector
- Completely revised trigger

Future, called upgrade (Run 3, 2020++)

- see G. Simi [Thu] and F. Teubert [Fri] talks

More and more (and better) data!



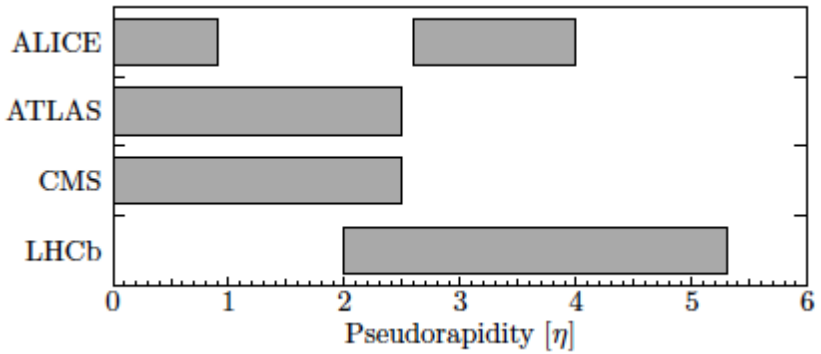


For LHCb, more data is more important than higher energy:

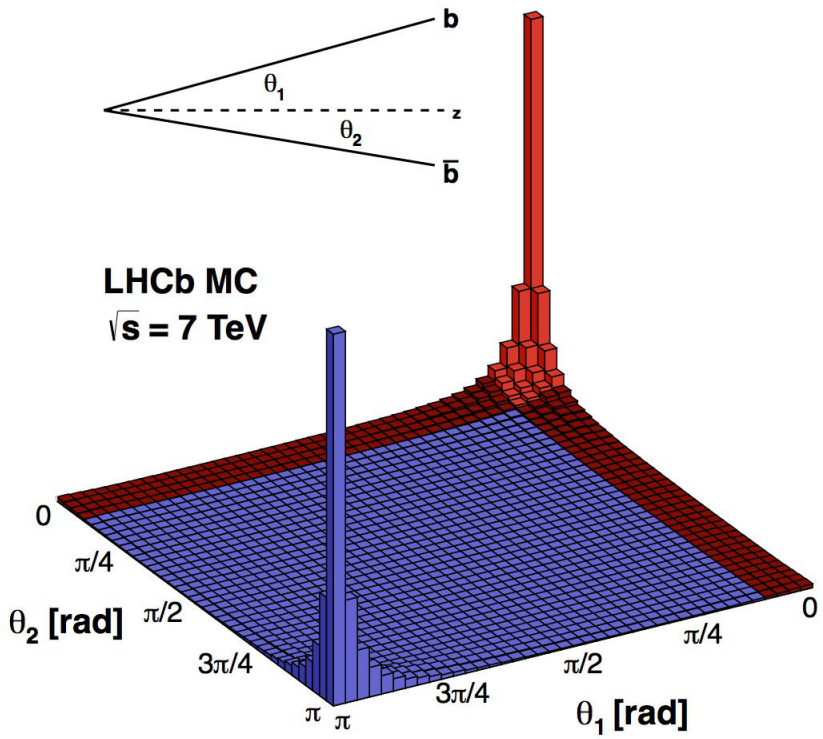
- Direct searches: at new energy, new particles could appear above threshold

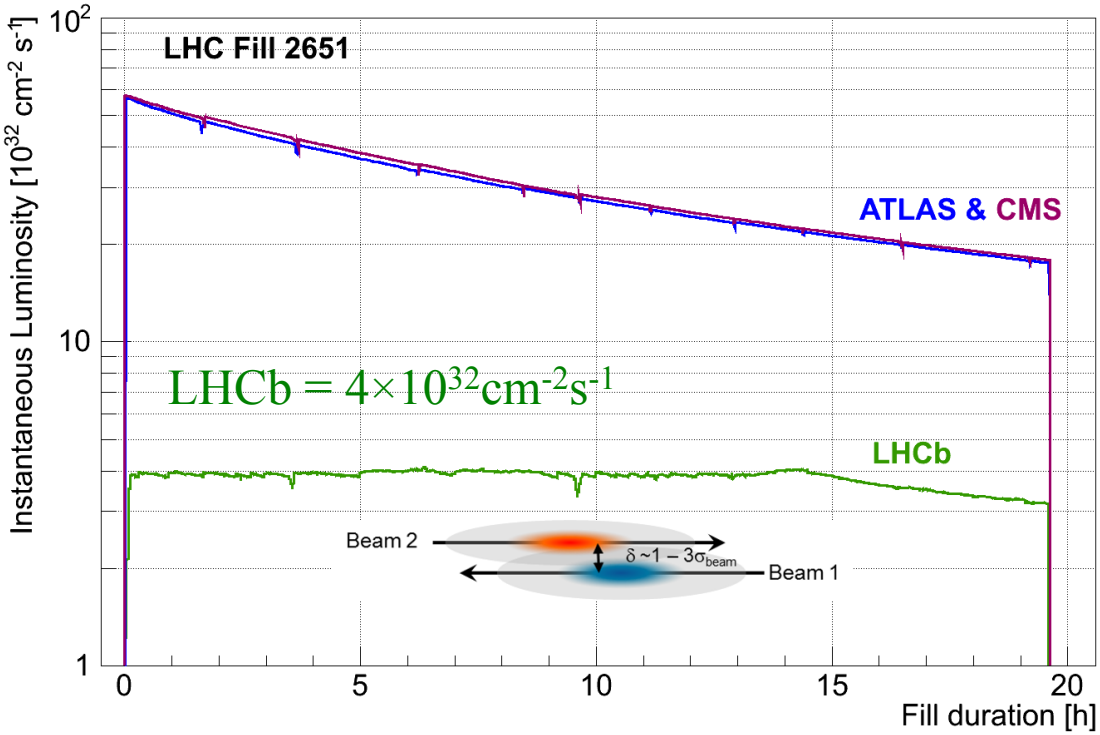
- **Precision measurements: gain in increased production rates**

Data taking



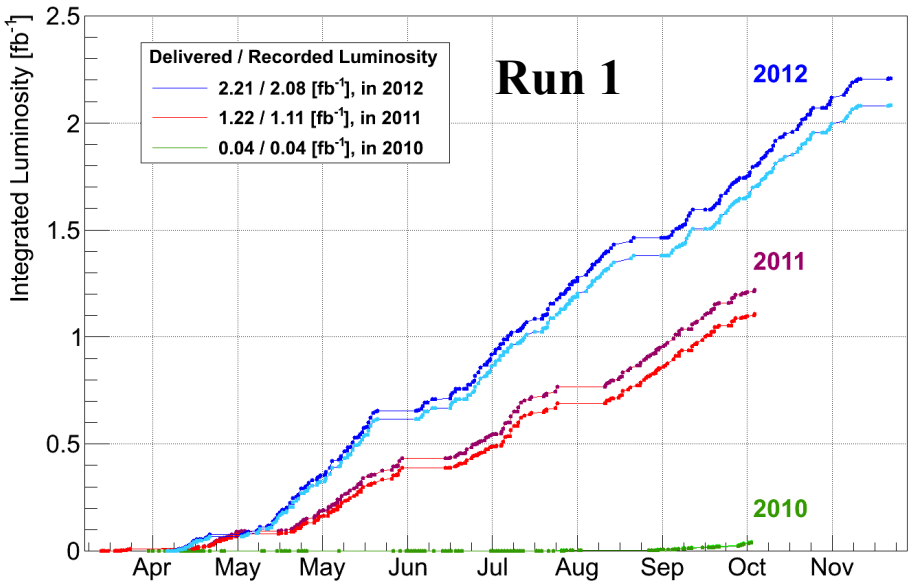
Luminosity leveling:
stable running and trigger conditions for LHCb
even with LHC running at high luminosity

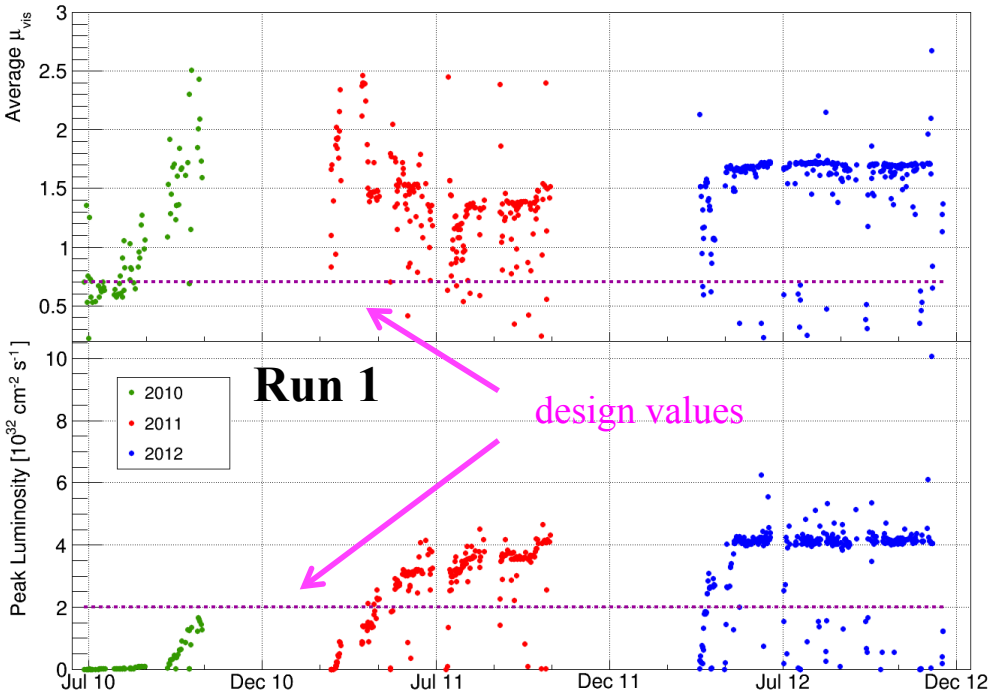


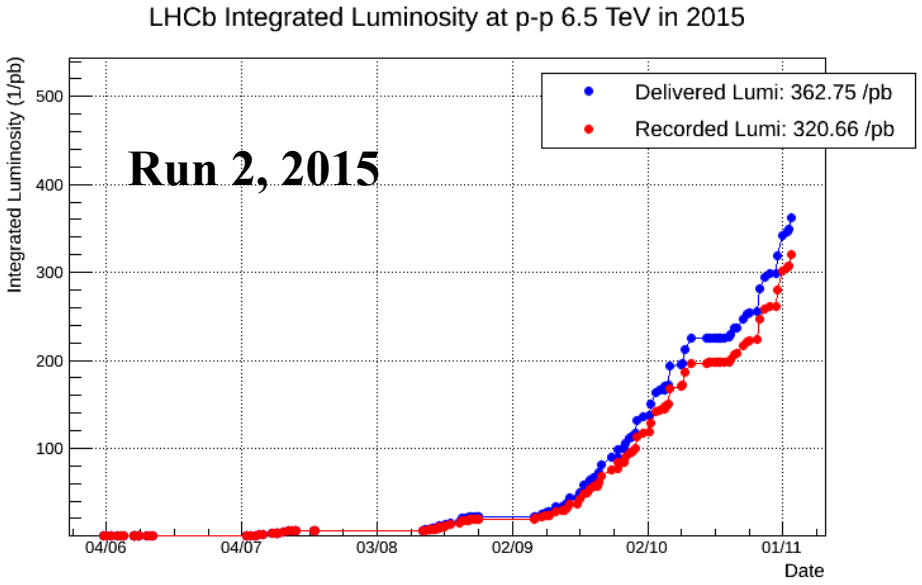


Extremely large σ(bb) and σ(cc) in LHC hadron collisions.

Data taking



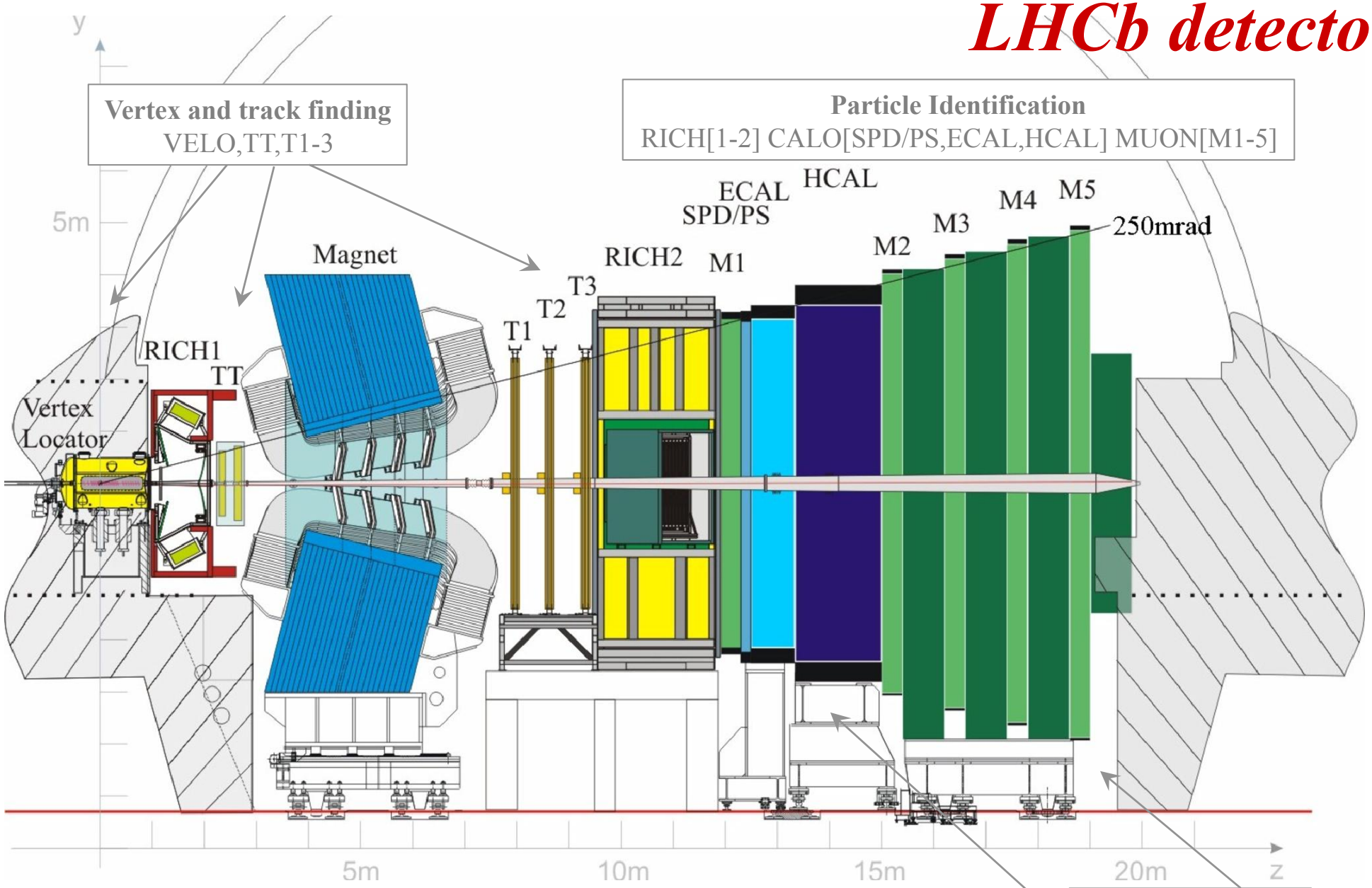




Conditions for Run 2:

- $\sigma(bb) \sim 45$ kHz and $\sigma(cc) \sim 1$MHz cc
  [at 13TeV, in acceptance]
  [HF cross section ~2× with respect to Run 1]
- Bunch spacing 25ns (smaller pileup)
- LHCb: ~same luminosity

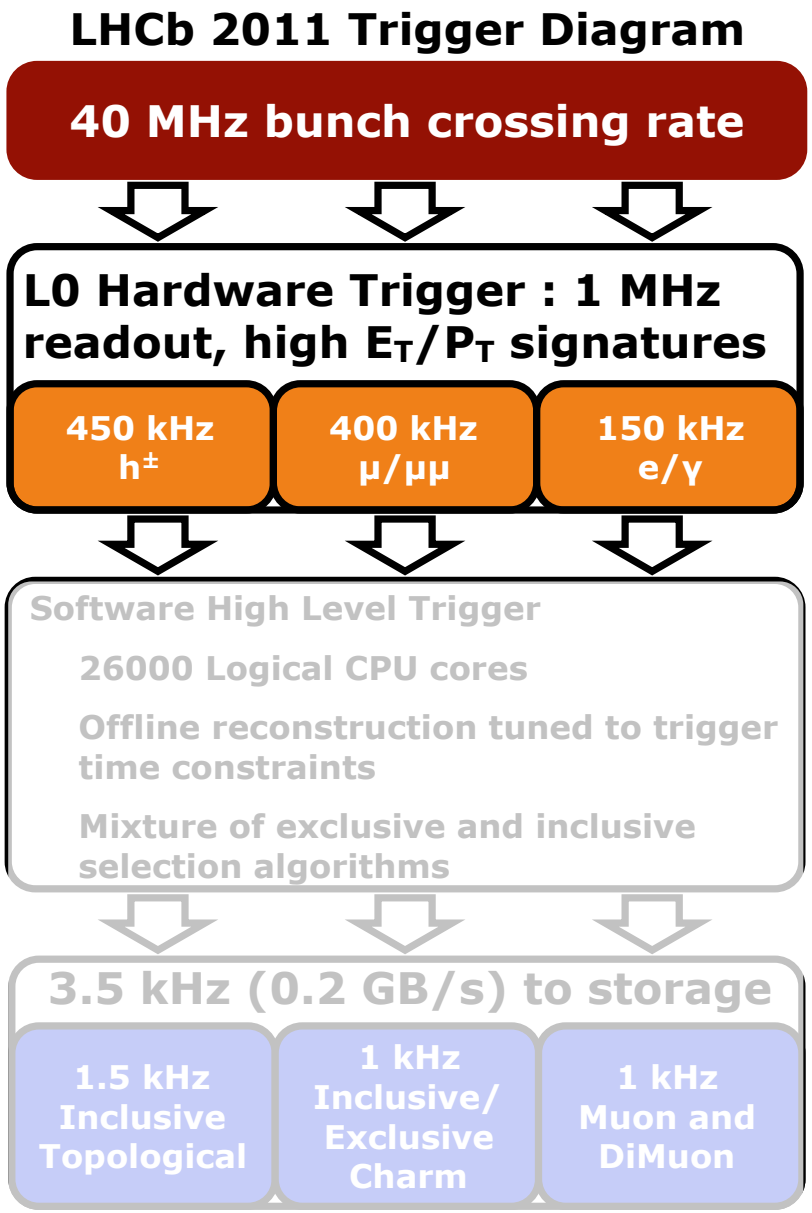
LHCb detector



[LHCb, A. Alves et al., The LHCb Detector at the LHC, JINST 3 (2008) S08005]

[LHCb Detector Performance Int.J.Mod.Phys. A30 (2015) 1530022]

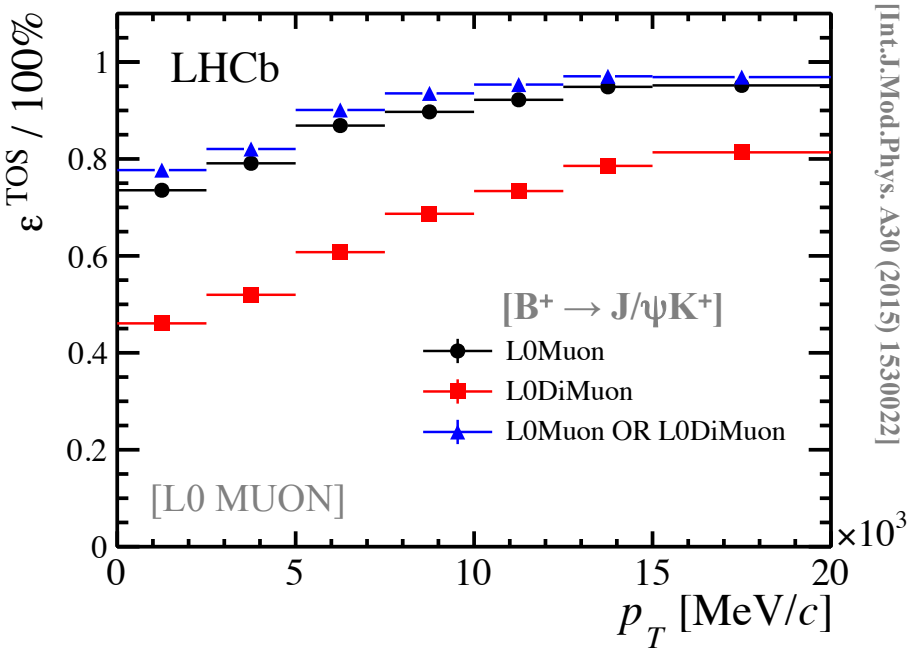
Trigger system in Run1



Hardware trigger (L0)

Reduce bunch crossing-rate to ~1 MHz
[fixed latency of 4 μs]
[LHCb detector read out at 1 MHz]

Muon trigger [2012 thresholds]:
- Single Muon: $p_T > 1.76$ GeV
- Di Muon: $(p_{T1} \times p_{T2}) > 1.6$ GeV^2



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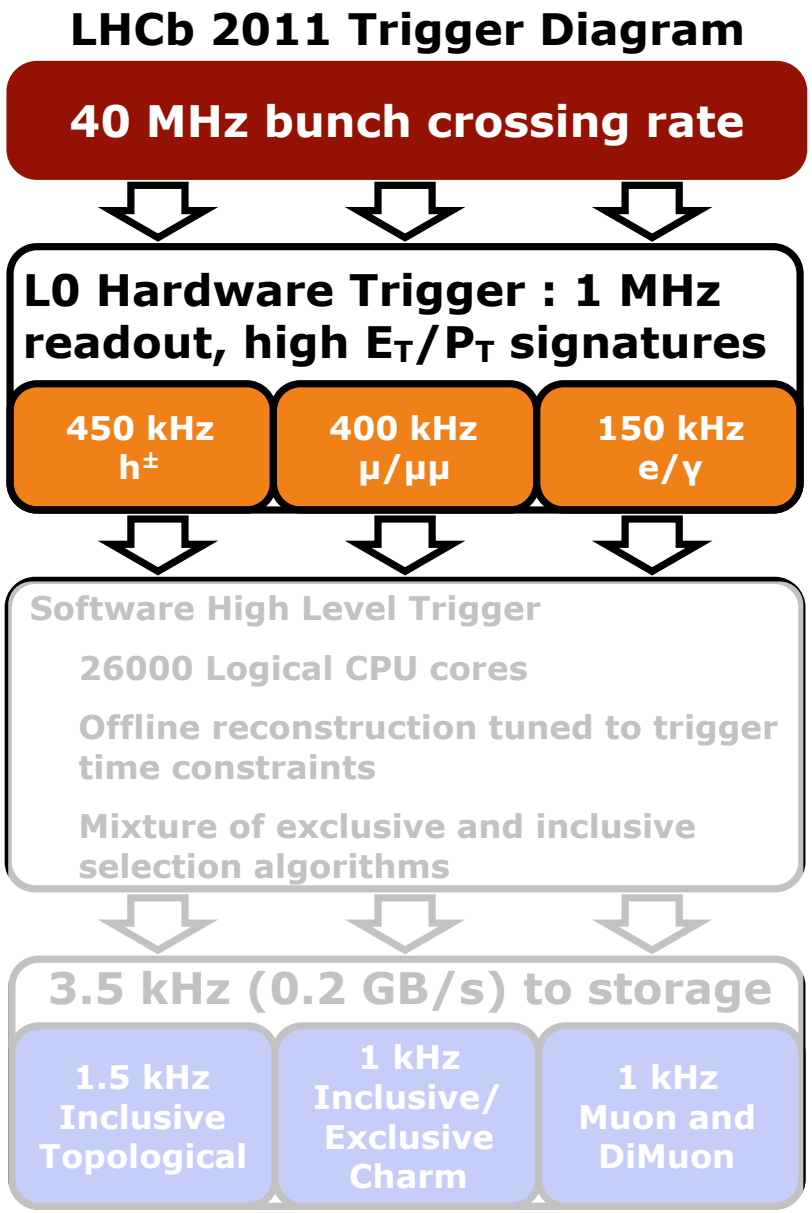
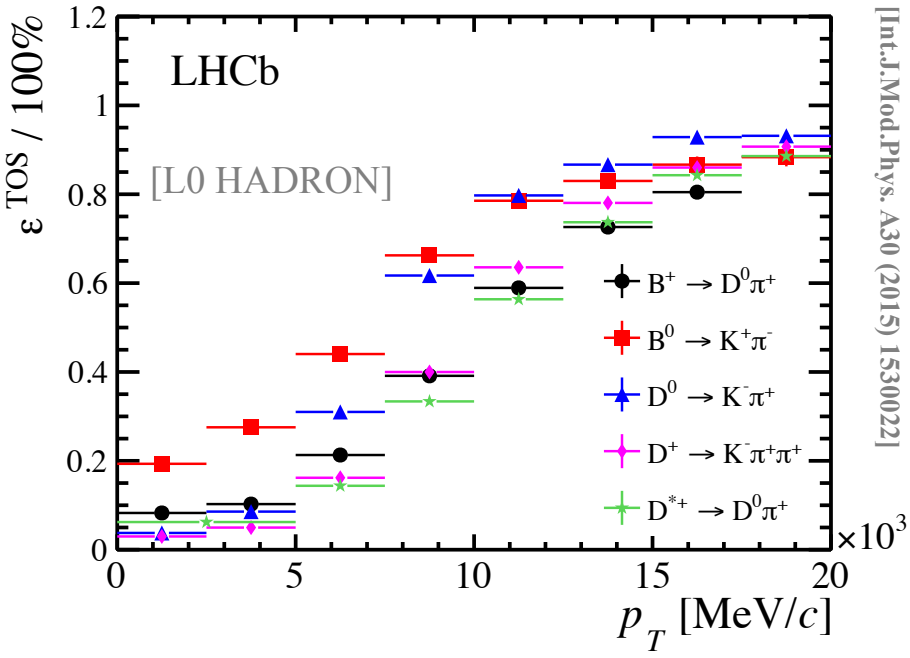


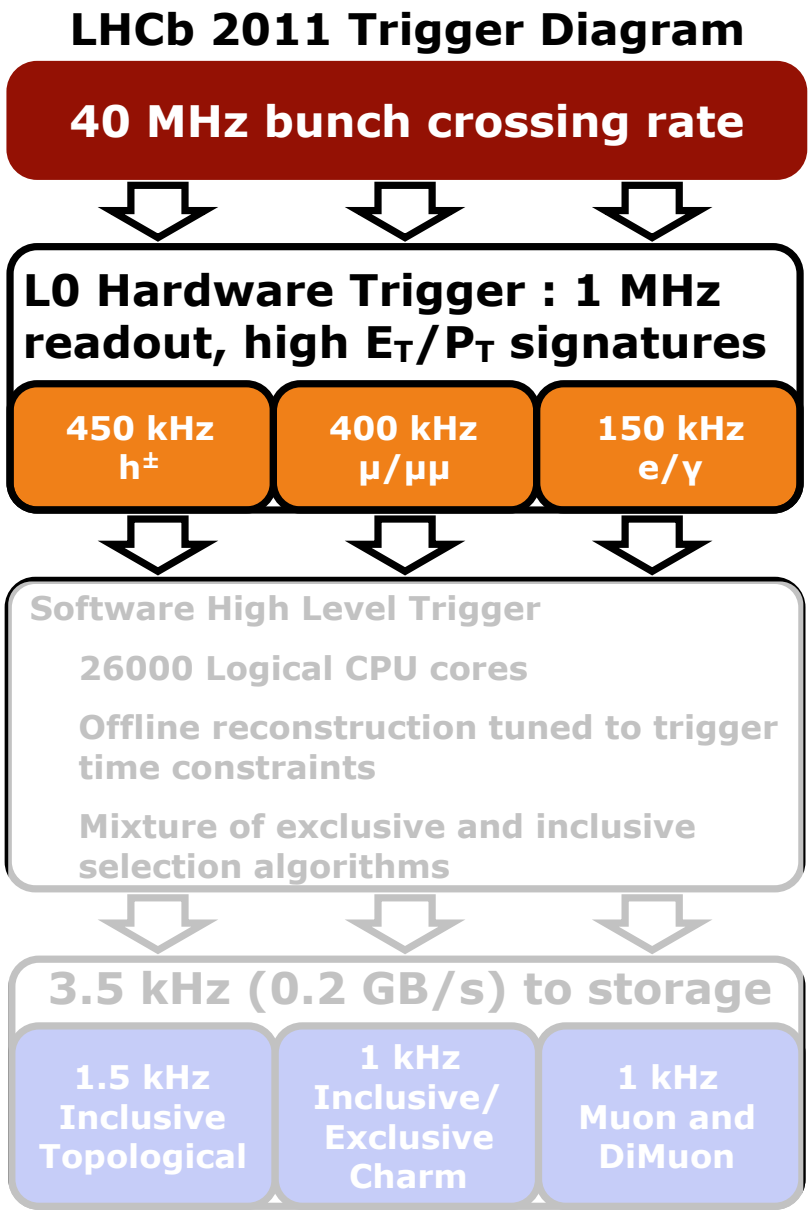
Hardware trigger (L0)

Reduce bunch crossing-rate to ~1 MHz
[fixed latency of 4 μs]
[LHCb detector read out at 1 MHz]

Calorimeter trigger [2012 thresholds]:
- Hadrons: $E_T > 3.7$ GeV
- Photons and electrons: $E_T > 3$ GeV



Trigger system in Run1



Hardware trigger (L0)

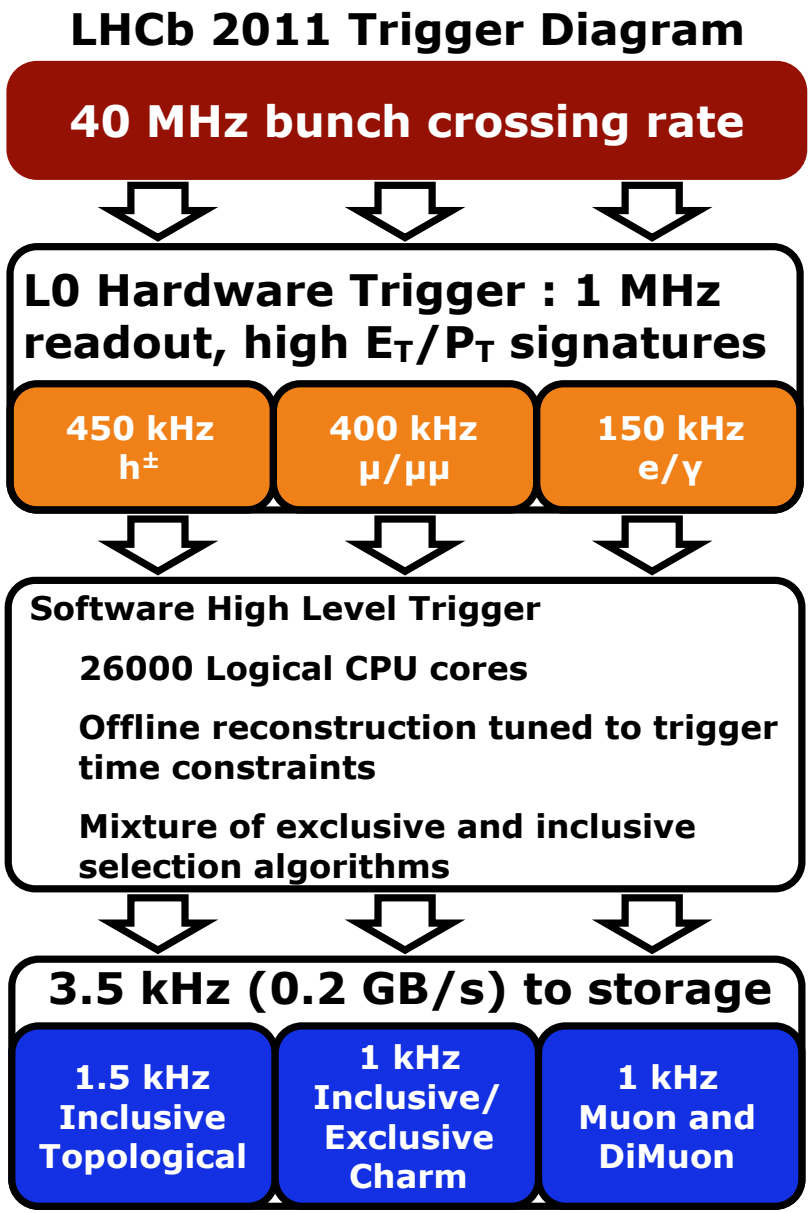
Reduce bunch crossing-rate to ~1 MHz
[fixed latency of 4 μs]
[LHCb detector read out at 1 MHz]

Also:
- Low multiplicity triggers
- Filters out very complex events

Run 1, Run 2, and beyond:
- **same in Run 2 as in Run 1**
- removal planned for Run 3
  [LHCb detector readout at 40 MHz]
- requires redesigned DAQ and trigger
- **recovers L0 hadron efficiency at low p_T**

[LHCb Trigger and Online Upgrade Technical Design Report, LHCb-TDR-016]

Trigger system in Run1



Software trigger (HLT)
- Runs on HLT farm
- Split in two stages: HLT1 and HLT2

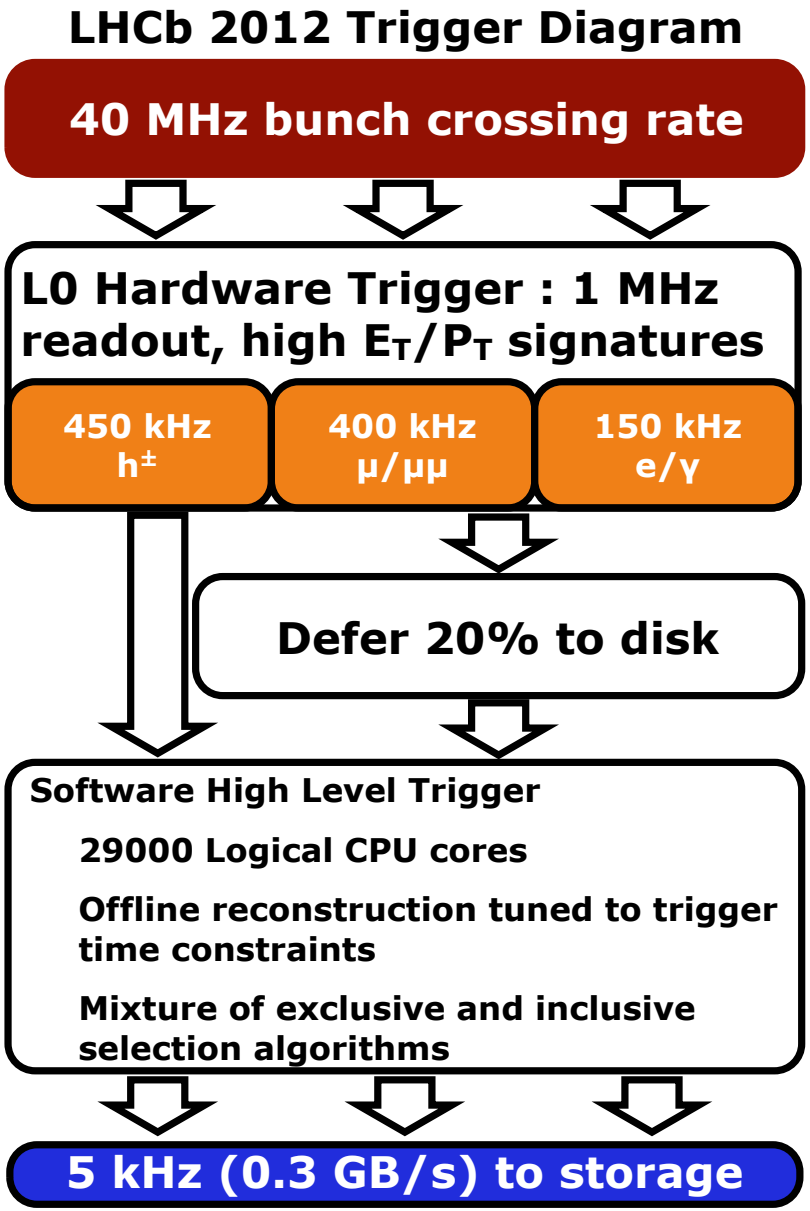
HLT1 performs a partial event reconstruction and an inclusive selection of signal candidates

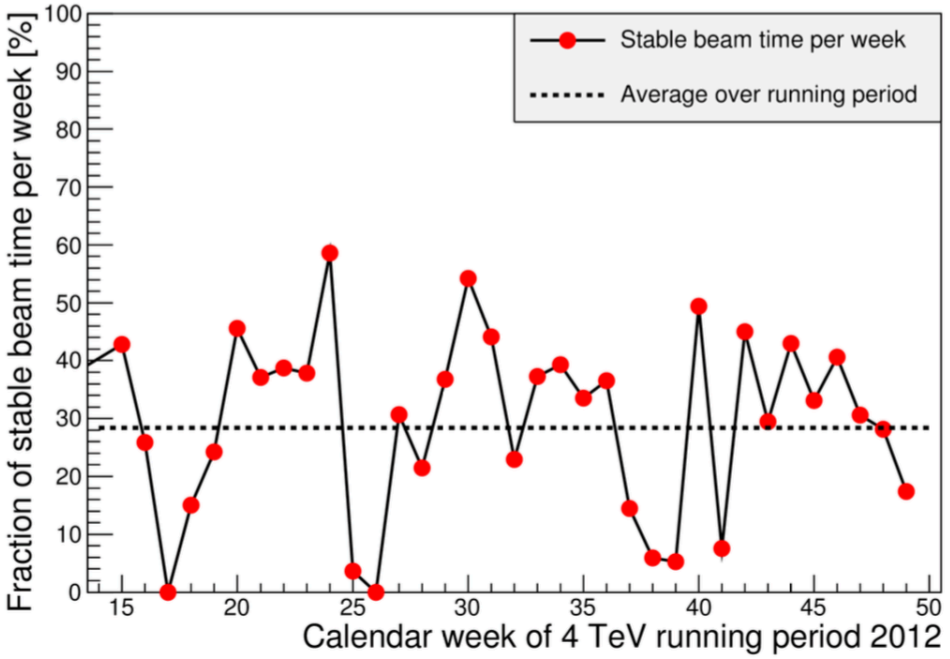
HLT2 [~40 kHz rate]
- **full simplified** event reconstruction, with **preliminary alignment and calibration** of the detector and only **marginal use of RICH PID information**
- a set of inclusive and exclusive selections

Output rate 3.5 kHz (2011)
[saved for later offline analysis]

Total time budget: O(35 ms)/event

Trigger system in Run1

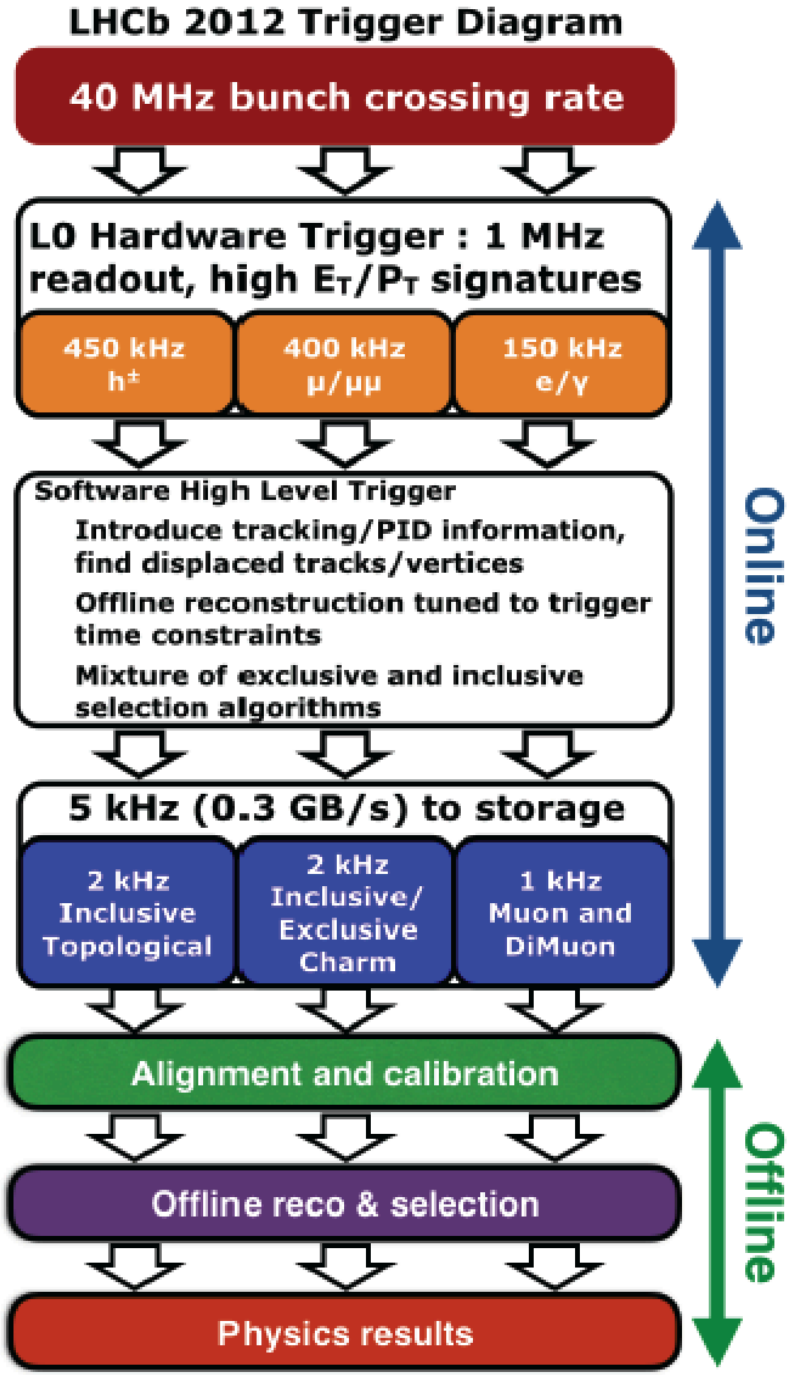




Same hardware trigger (L0)
- **20% of L0 events buffered** to allow processing out of fill

Software trigger (HLT)
- **HLT2** [~80 kHz rate]
- **Output rate 5 kHz (2012)**

Trigger system in Run1

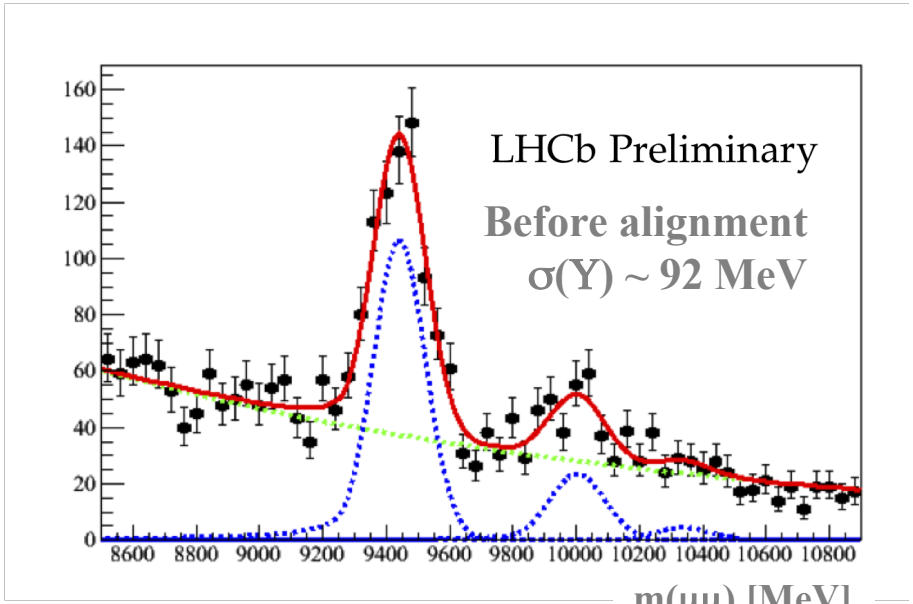


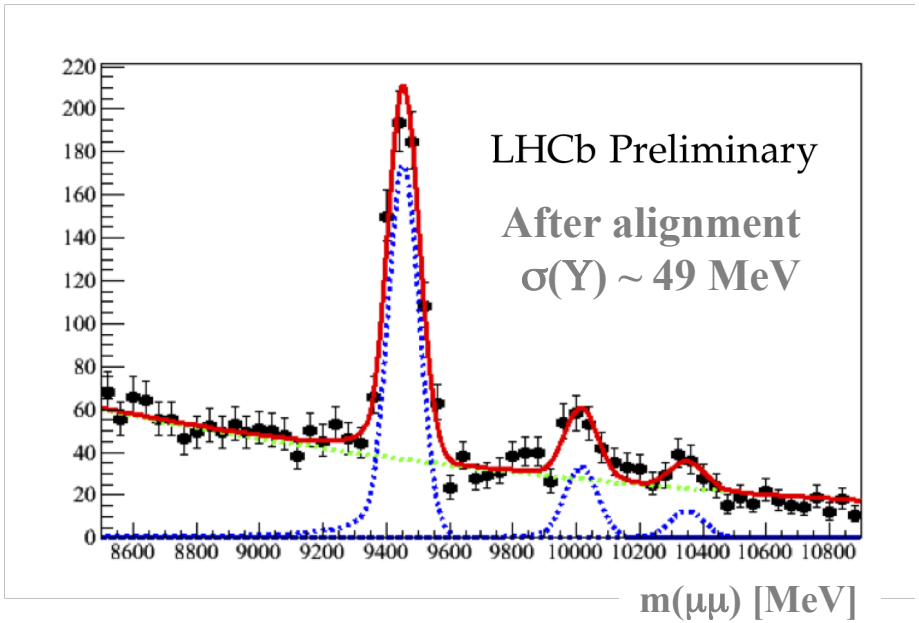
Online: compromise between performance and stringent timing requirements

Differences:
pattern recognition, detector alignment and calibration, candidate selection

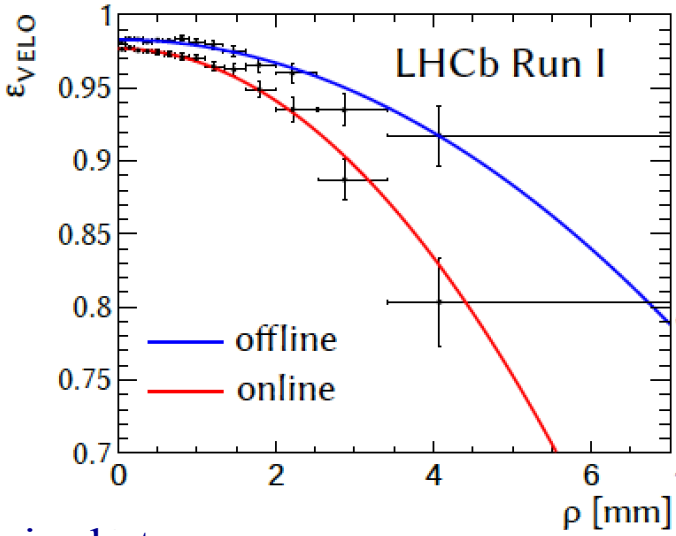
Offline: best available performance without stringent timing requirements

Trigger system in Run1





[JHEP 04 (2014) 114]

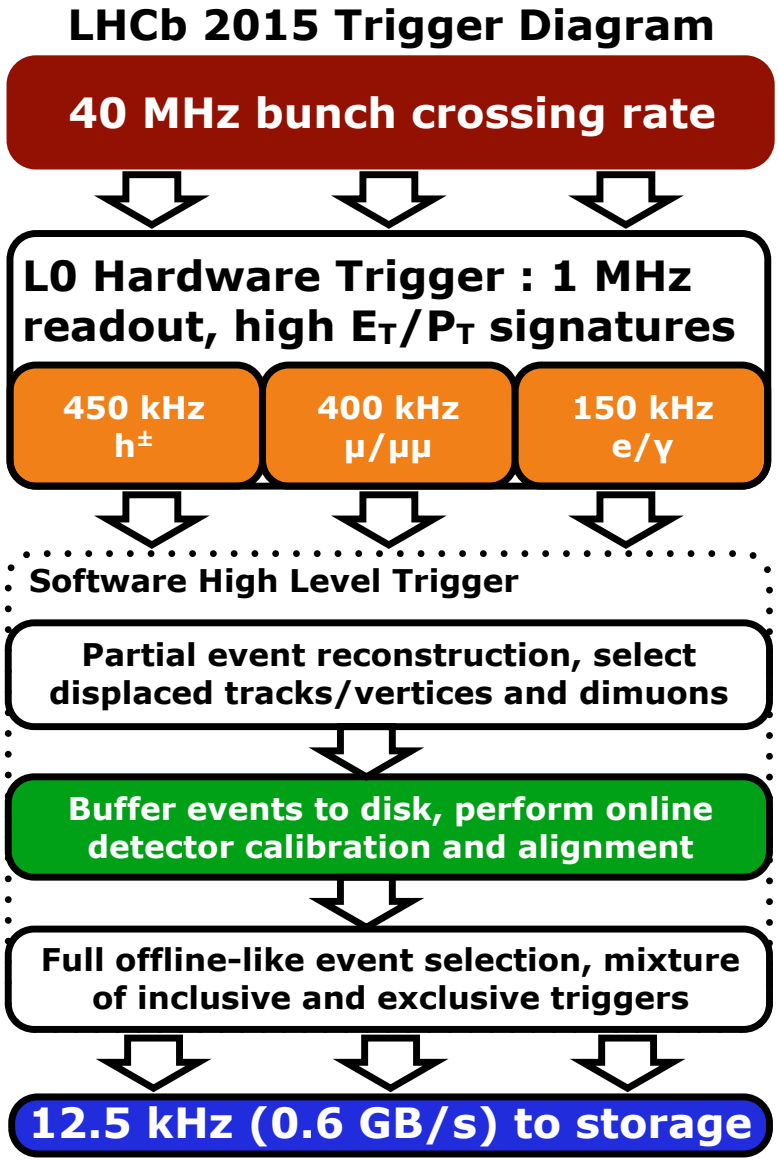


Online: compromise between performance and stringent timing requirements.

Differences:
pattern recognition, detector alignment and calibration, candidate selection.

Offline: best available performance without stringent timing requirements.

Trigger system in Run2



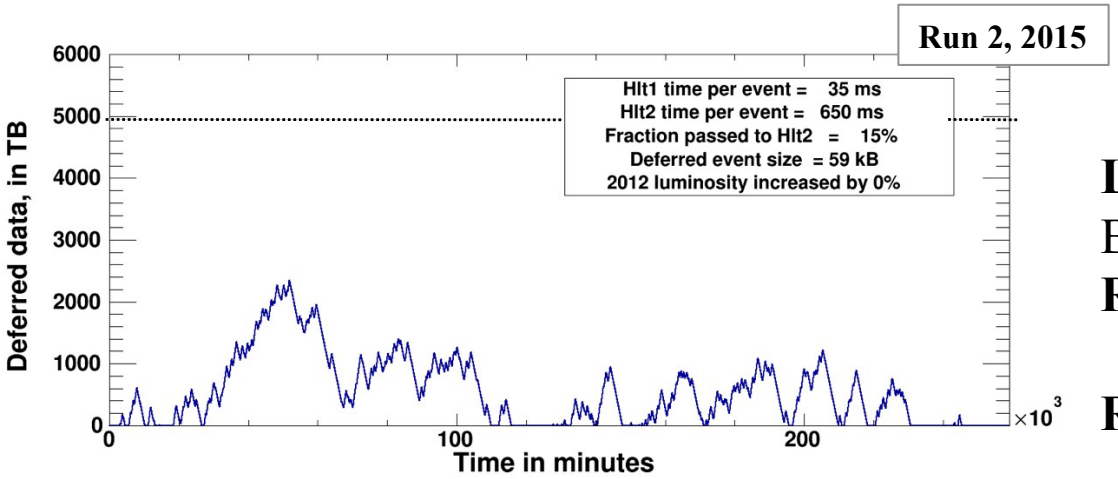
Disadvantages of Run 1 model:
- Takes time: alignment and calibration applied after data taking, **reconstruction run twice**
- Costs money: uses a lot of computing resources
- Costs physics: loss of imperfectly reconstructed data in trigger

For Run 2:
- **Aim at online same reconstruction as offline**
- **Need "online" calibrations and alignments**

Same hardware trigger (L0)
[optimized (typically higher) thresholds]

Software trigger (HLT):
- HLT splits in two applications: HLT1 and HLT2
- **Events buffered after HLT1**
- Alignment and calibration run on dedicated HLT1 samples

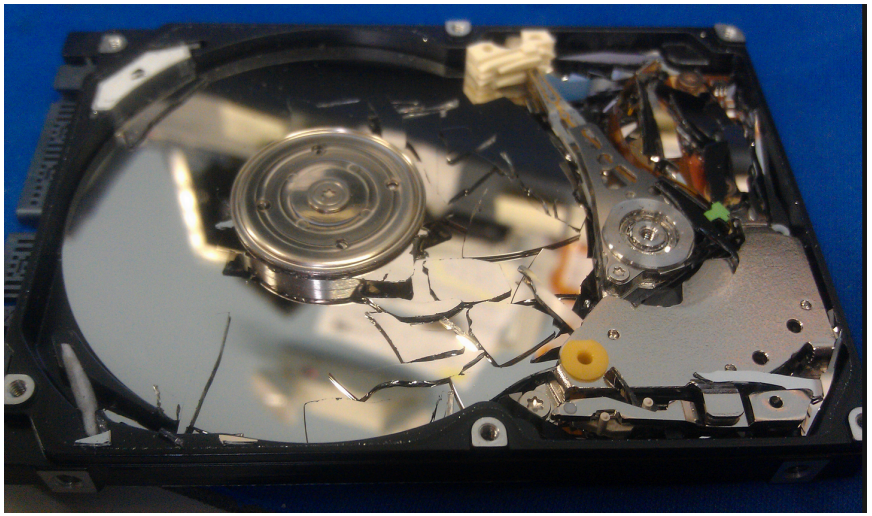
Resources



LHC stable beams 30% of the time.
Buffer events for out of fill processing
Run 1: Defer 20% of L0 accepted evts.
[25% more effective CPU power]
Run 2: Defer all HLT1 accepted evts.

5 PiB [Run 2, 2015]: space for 160 hours of data with 150 kHz of 60 kiB events out of HLT1

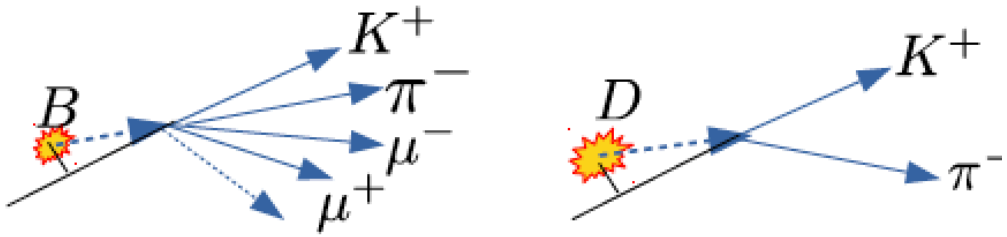
From 2012 experience: ~1 disk per day is replaced due to unrecoverable errors.
- un-mirroring the disks doubles our buffer with the risk of per mil loss of data
- keeping them mirrored means, e.g.
reduction in charm of ~15% OR
reduced online-offline compatibility



Total farm disk space is 10PiB [Run 2, 2016; in 2015 mirrored to 5PiB for redundancy]

Event Filter Farm doubled in Run 2 (now~50k logical cores)
Larger real-time (HLT1) reduction allows more efficient use of buffers

HLT1 in Run 2



More resources, improved code: tracking down to p_T=500 MeV

Inclusive charm and beauty trigger:
- Single and two tracks MVA selections (~100 kHz)

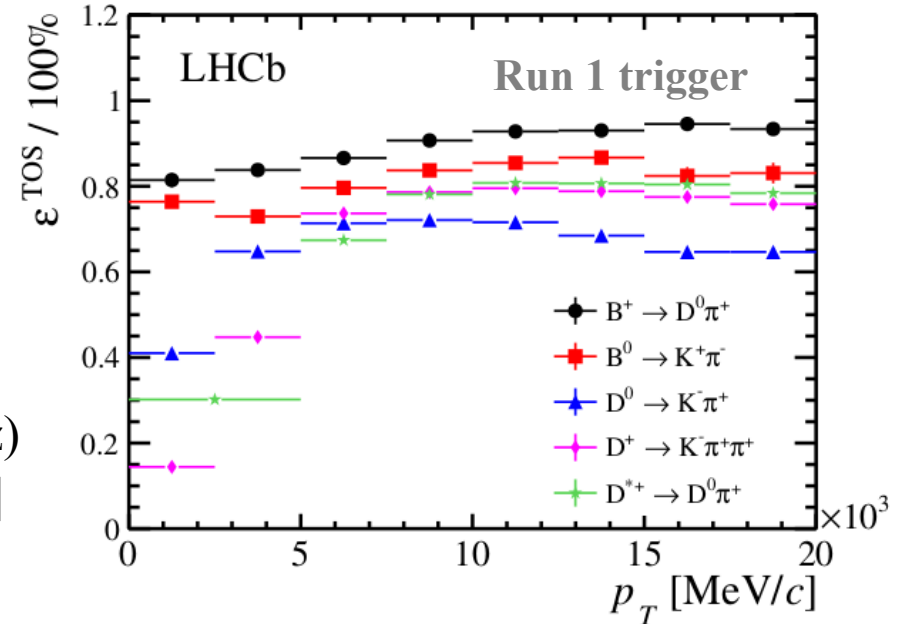
[e.g. efficient 2-body charm triggers, 2× wrt Run 1]

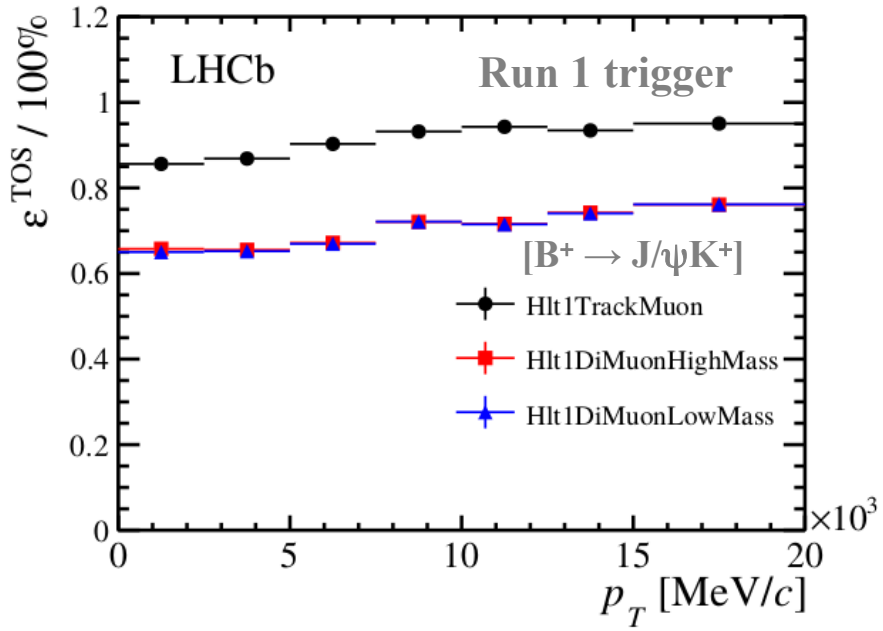
Inclusive muon trigger:
- Single and dimuon selections
- Additional low p_T track reconstruction (~40 kHz)

Exclusive trigger, e.g.:
- Lifetime unbiased beauty and charm selections

[no selection criteria on quantities correlated with the signal particle's decay-time]
- Selections for alignment

Low multiplicity trigger for central exclusive production [CEP] analyses

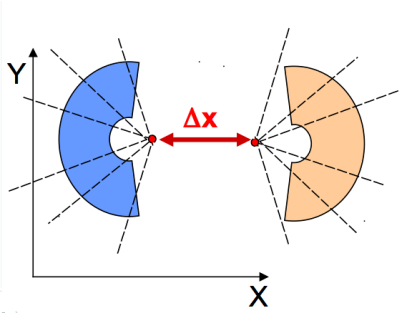


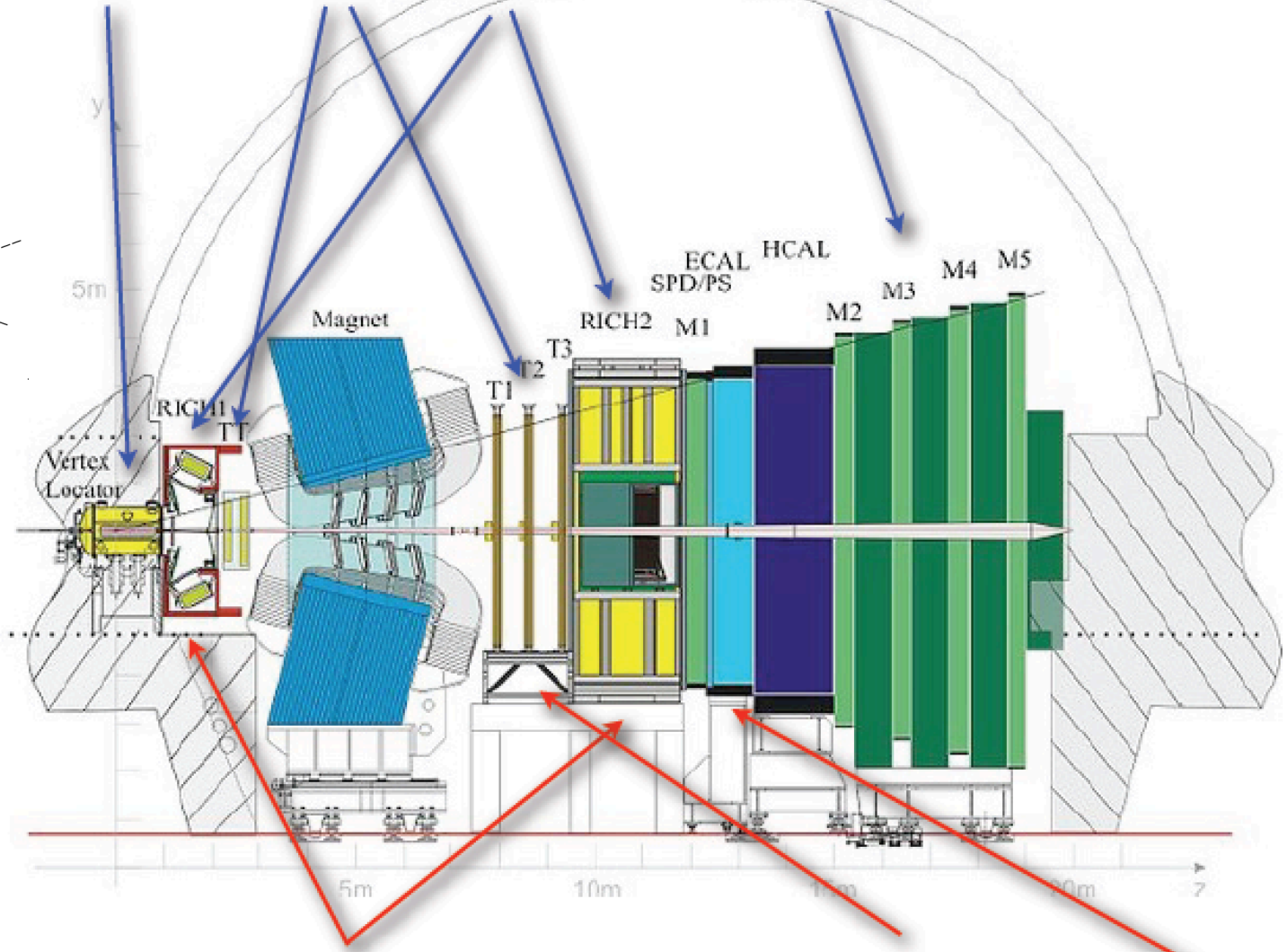


[Int.J.Mod.Phys. A30 (2015) 1530022]

Alignment and calibration

- Alignments: VELO, Trackers, RICH mirrors, Muon





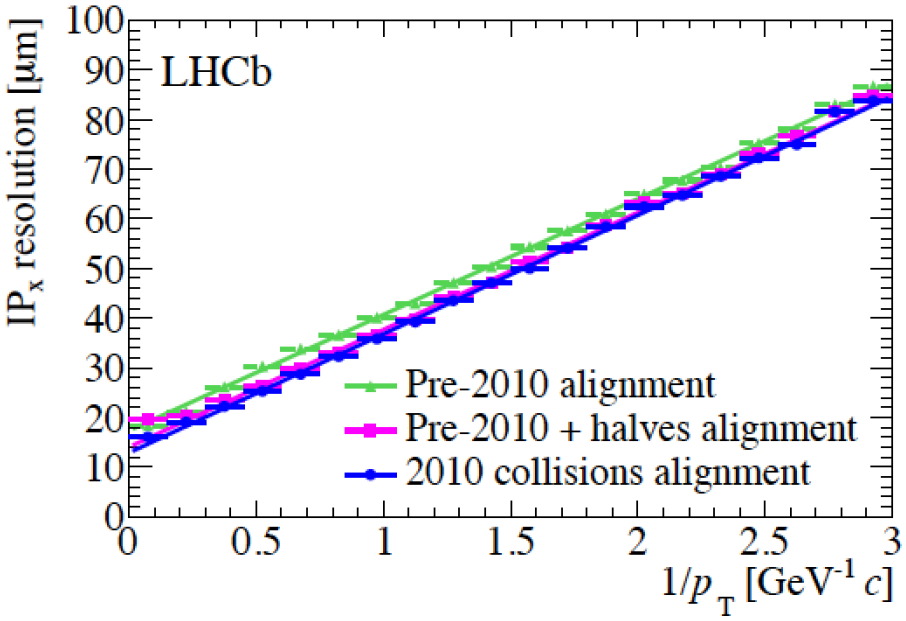
- Calibrations: RICH refractive index and HPDs, OT time, Calorimeters

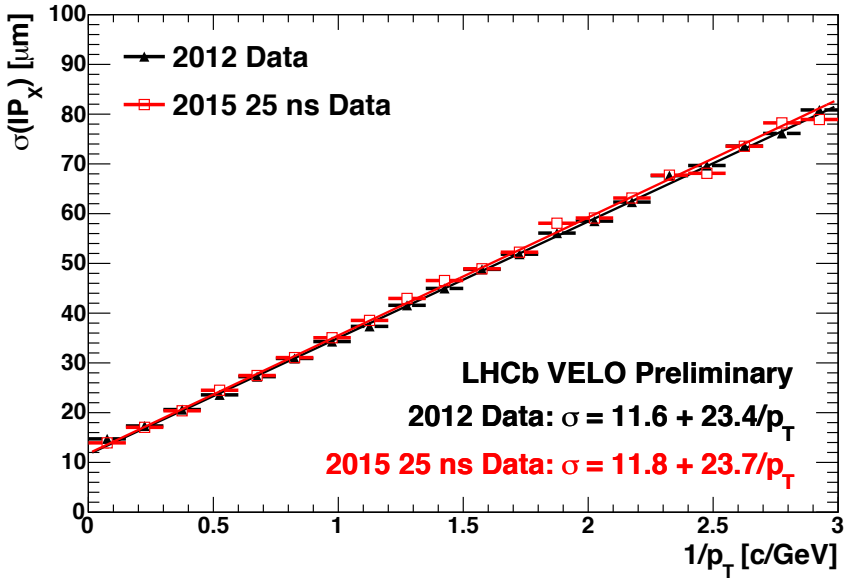
Alignment

Alignments Run on the HLT-farm at the beginning of every fill

[Automatic update of constants]

- **VELO alignment**: Alignment of both halves for translations and rotations in x, y and z
- **Tracker alignment**: Alignment of TT, IT and OT for translations in x, rotations and translations in z.





[Monitor only]

- **RICH mirror alignment**: Alignment of all individual mirrors for rotations around x and y
- **Muon alignment**: Alignment of both halves of each station for translations in x and y

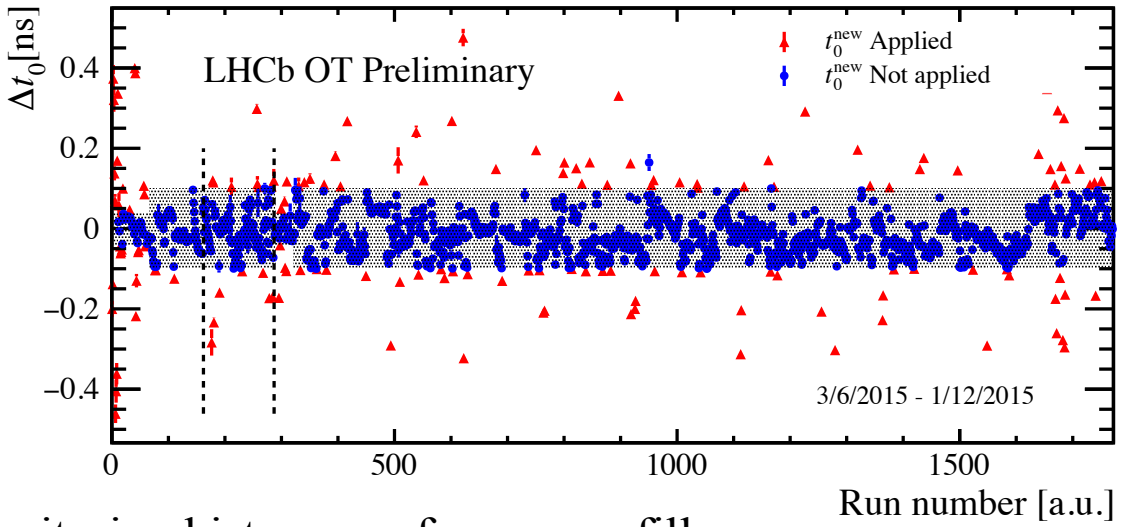
[**Stable L0 conditions**]

Calibration

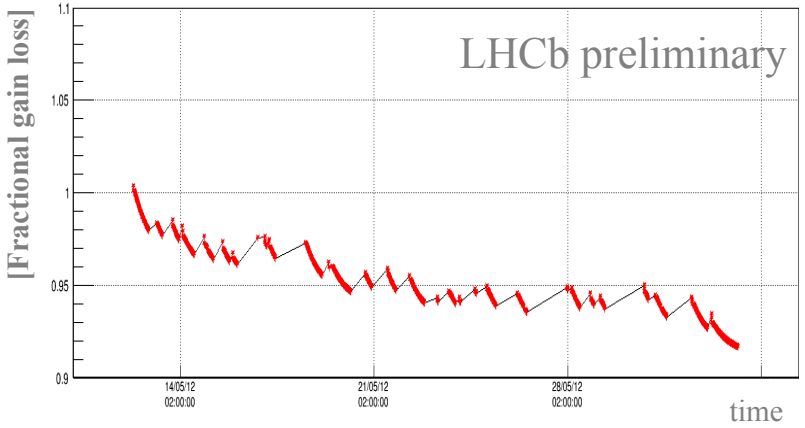
Calibrations run on the monitoring histograms for ~every run;

- **OT calibration**: global time alignment of the OT wrt LHC clock

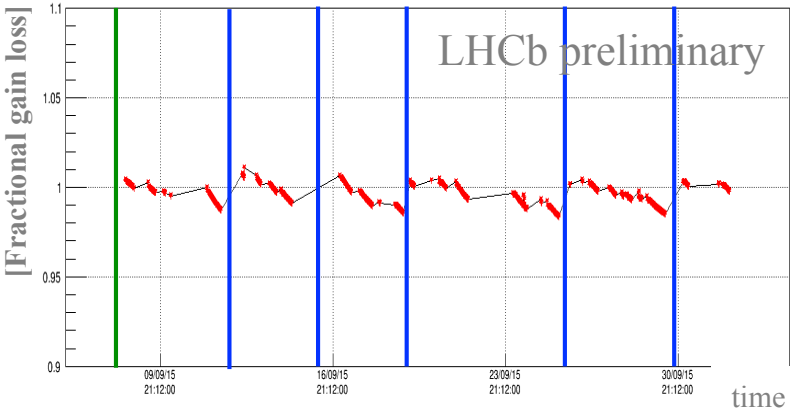
- **RICH**: refractive index calibration and HPD image calibration



- **Calorimeter** calibrations run on monitoring histograms for ~every fill **[stable L0 conditions]**



2012: no corrections applied



2015: (green line) π^0 based calibration
2015: (blue lines) LED based corrections

HLT2 in Run 2

Full event reconstruction:

- Start from HLT1 vertices and tracks
- Reconstruct all tracks

[In Run 1 p_T>300 MeV, no redundancy]

- Neutral particles, RICH, Muon and Calo PID
- Full particle identification for long tracks

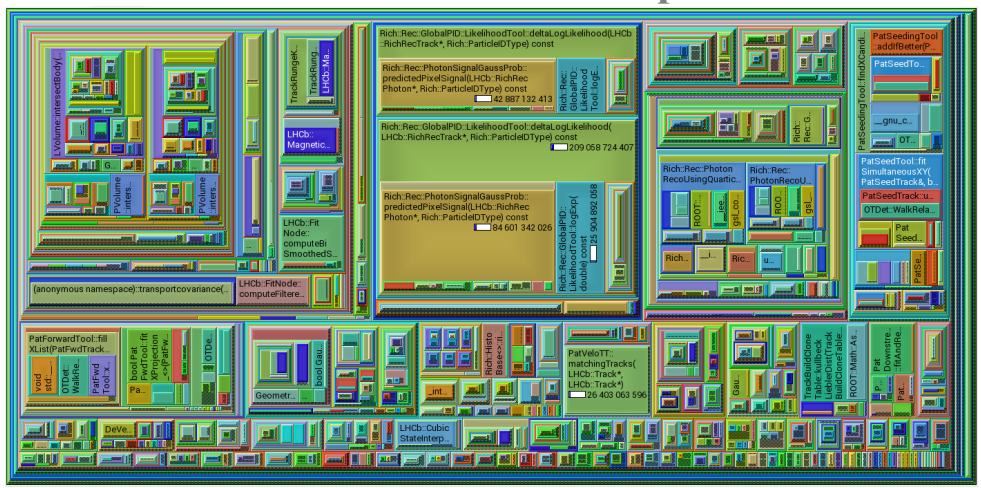
[new in Run 2]

Same strategy as offline

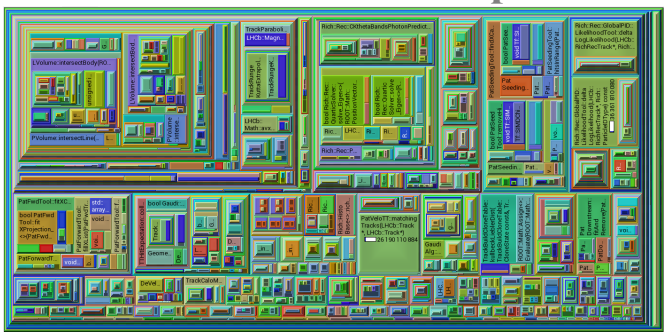
30% speedup achieved

Reconstruction	Run II	Run I
HLT1 rate	~150 kHz	~ 80 kHz
HLT1 time	~ 35 ms	~ 20 ms
Track finding	~200 ms	
Track fit	~100 ms	
Calorimeter reco	~ 50 ms	
RICH PID	~180 ms	
Muon ID	~200 ms	
Total HLT2	~650 ms	~150 ms
HLT2 rate	~ 12.5 kHz	~ 5 kHz

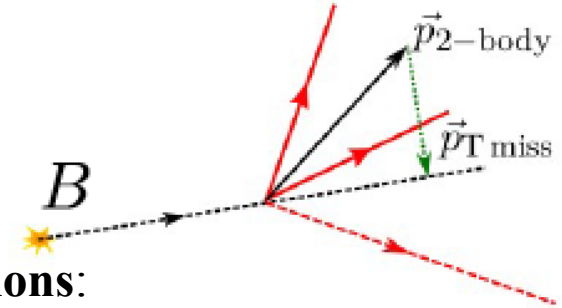
2012 CPU Heat Map



2015 CPU Heat Map

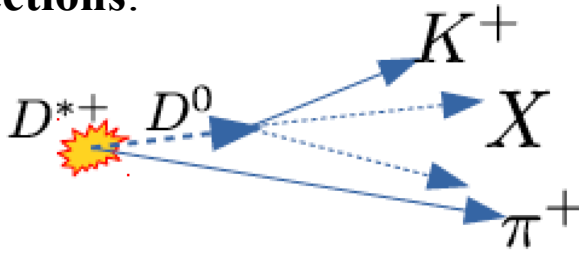


HLT2 in Run 2



Inclusive beauty selections:
- MVA based 2, 3, and 4 body detached vertices
- Dimuon selections

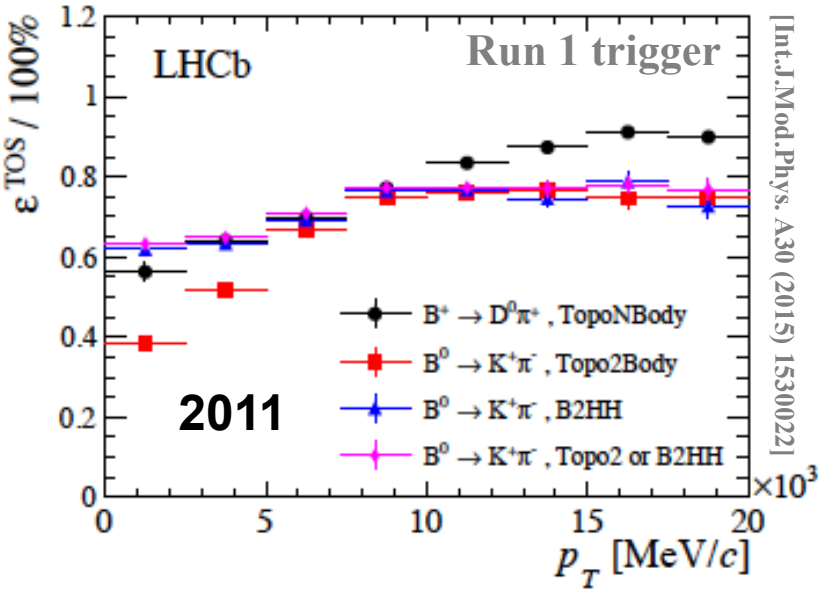
Exclusive beauty selections:
E.g. B→ φφ, B→ γγ

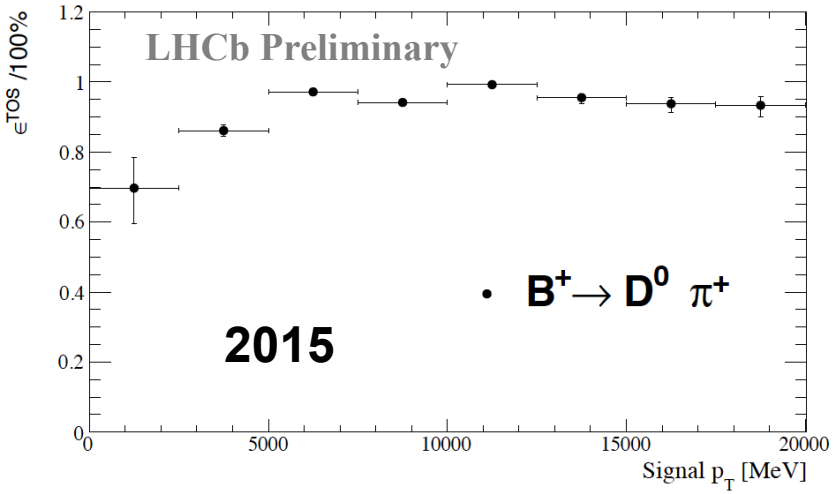


Charm selections:
- Inclusive selection of $D^* \rightarrow (D^0 \rightarrow X)\pi^+$
- Charmed baryons
- Final states with K_S
- 2,3,4,5-body final states

Electroweak bosons

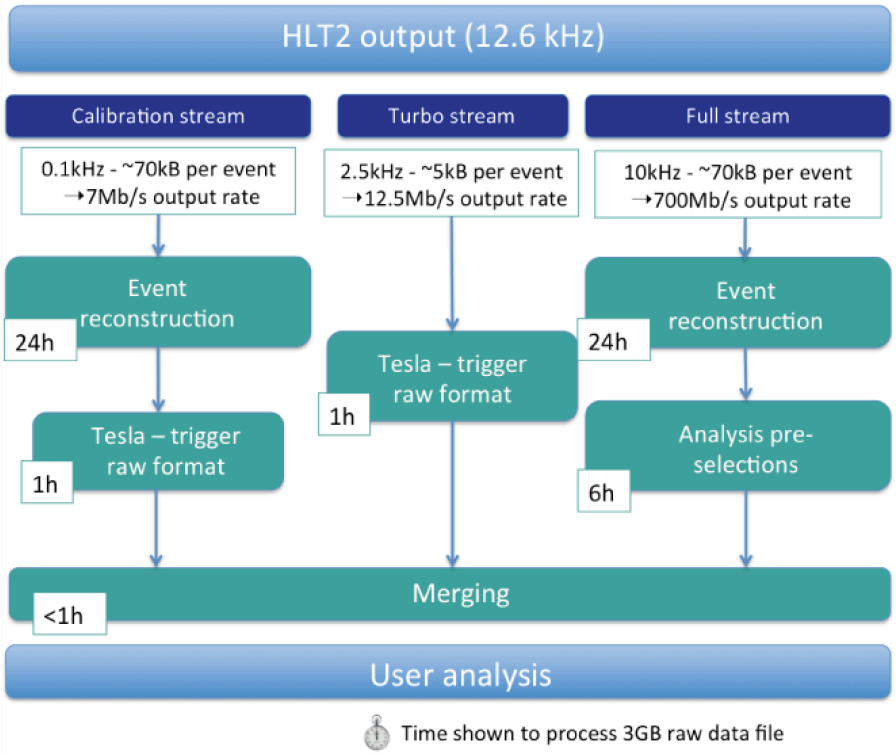
Nearly 400 selections in total





[e.g. **HLT2 efficiency for inclusive b trigger: $B^+ \rightarrow D^0\pi^+$ increased from ~75% to >90%**]

"Turbo publications"



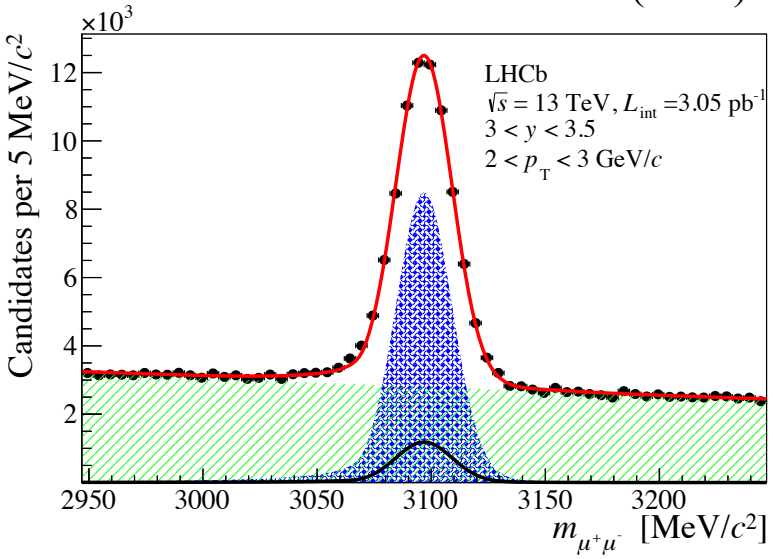
Online has offline quality: use it for physics!

Turbo Stream + Tesla Application:

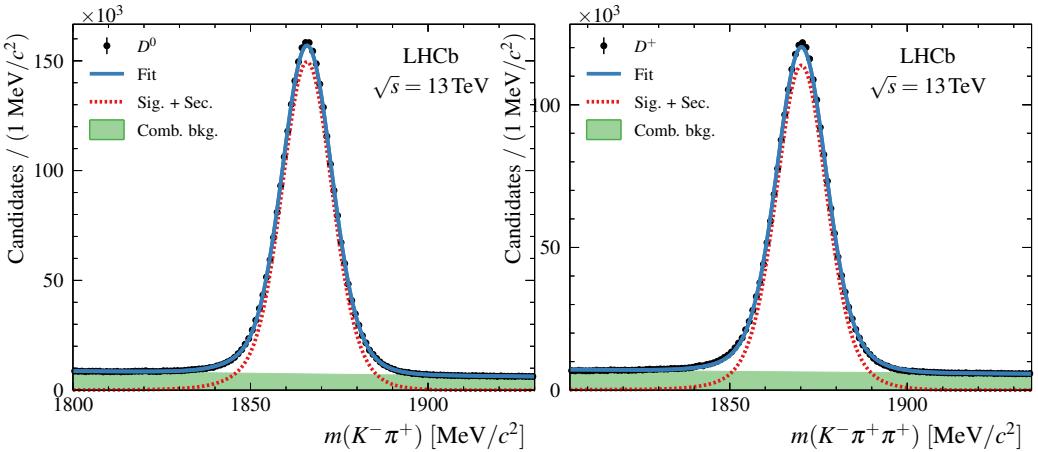
- store full information of trigger candidates
- remove most of detector raw data
- save more than 90% space
- ideal for very high signal yield [millions]
- very quick turn around [24 h]

- [**2016**] Persistency of the reconstruction information for the full event, higher level variables available for a few selections

Measurement of differential J/ψ cross-section:
[LHCB-PAPER-2015-037 / JHEP10 (2015) 172]



Measurement of differential charm cross-section
[LHCb-PAPER-2015-041 / JHEP 03 (2016) 159]



Summary

- LHCb is the first HEP experiment implementing a fully automatic tracking system alignment, PID calibration and track reconstruction in the online system

- Full offline-quality reconstruction available online

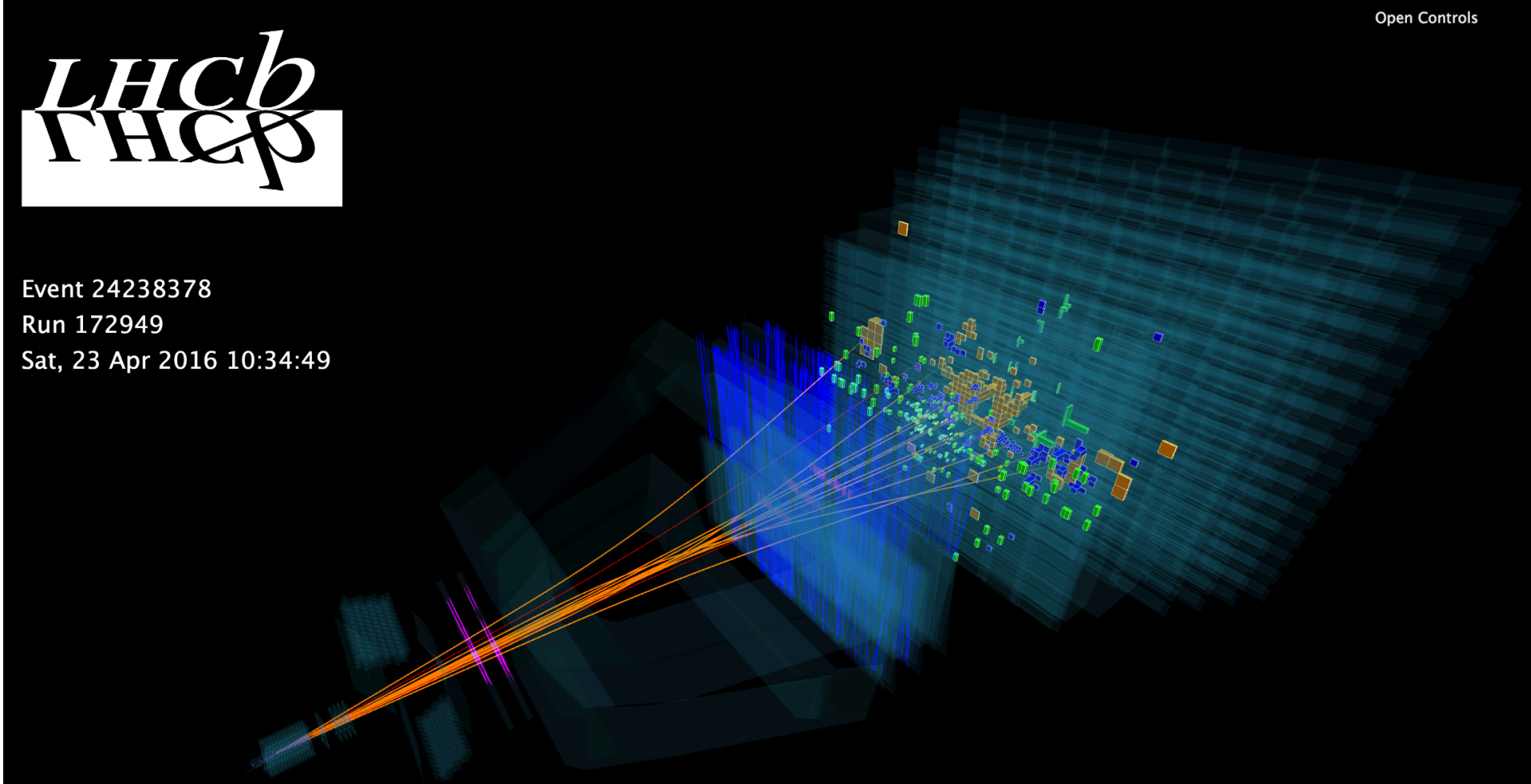
- Achieved thanks to the huge effort in tracking improvements and development of the new automatic procedure during LS1
[HLT reorganized to allow buffering after HLT1; additional HLT farm purchased: effectively 2 times larger, 1800 servers, 27000 physical cores, 10 PiB disk space; software optimized to fit reconstruction in time budget]

- New tool (Turbo + Tesla) for direct analysis: saves space and allow to achieve physics results few days after data taking
A working model for future experiments

"All I'm saying is now is the time to develop the technology to deflect an asteroid."

Much better trigger in Run 2 than in Run 1

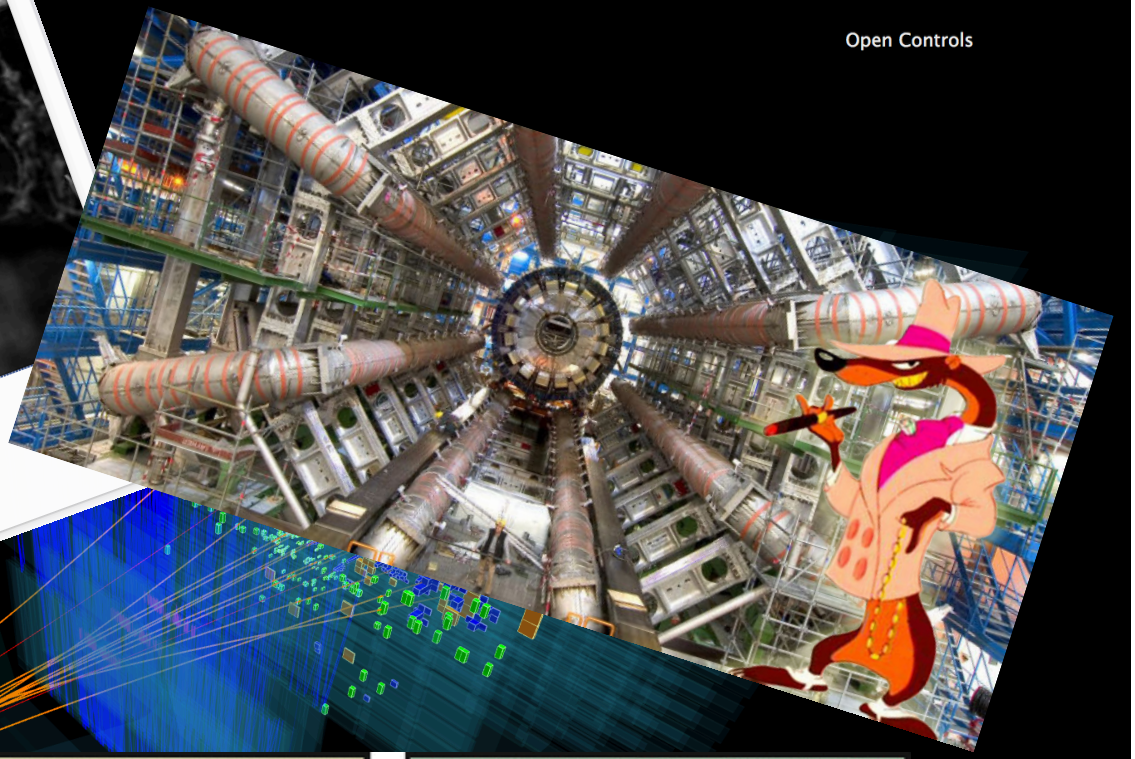
Back on track!



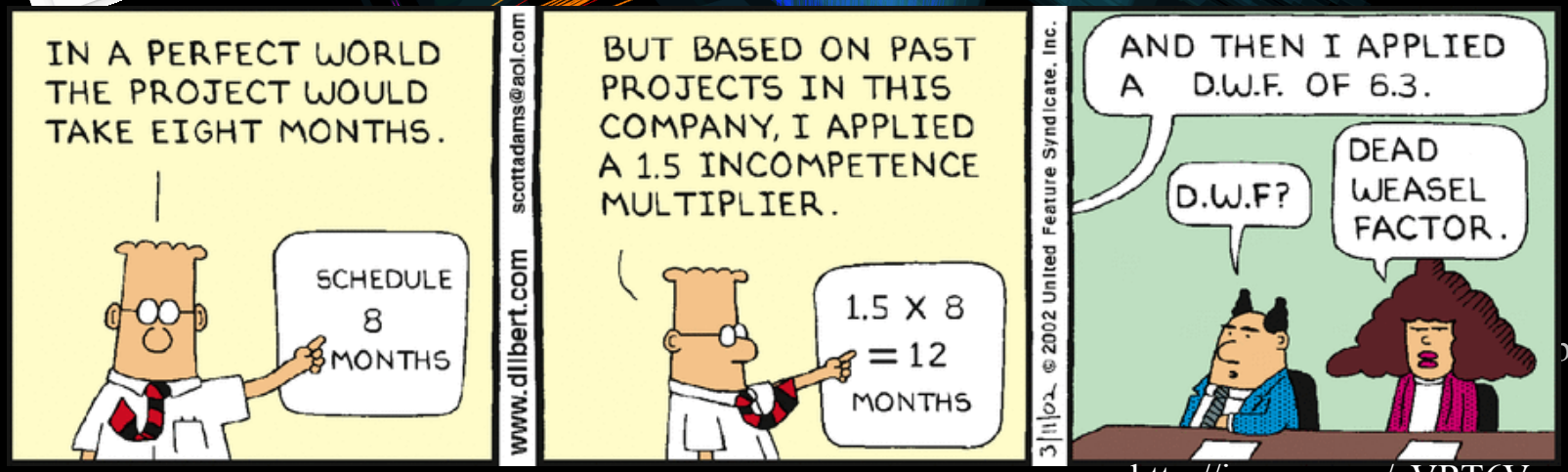
[Run 2 year 2 physics commissioning with stables beams]

(Nearly…) Back on track!

http://kdungs.github.io/WeaselDefense/



Eve
Run
Sat, 2

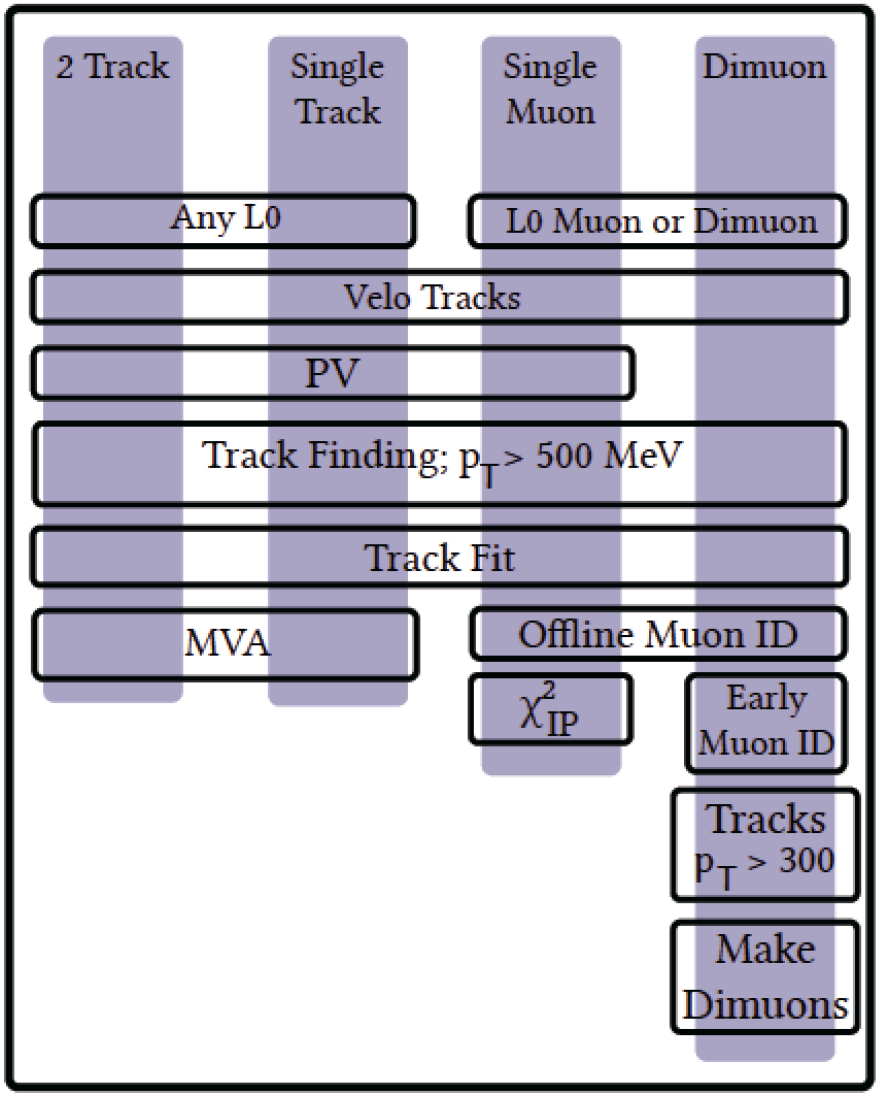


ples beams]

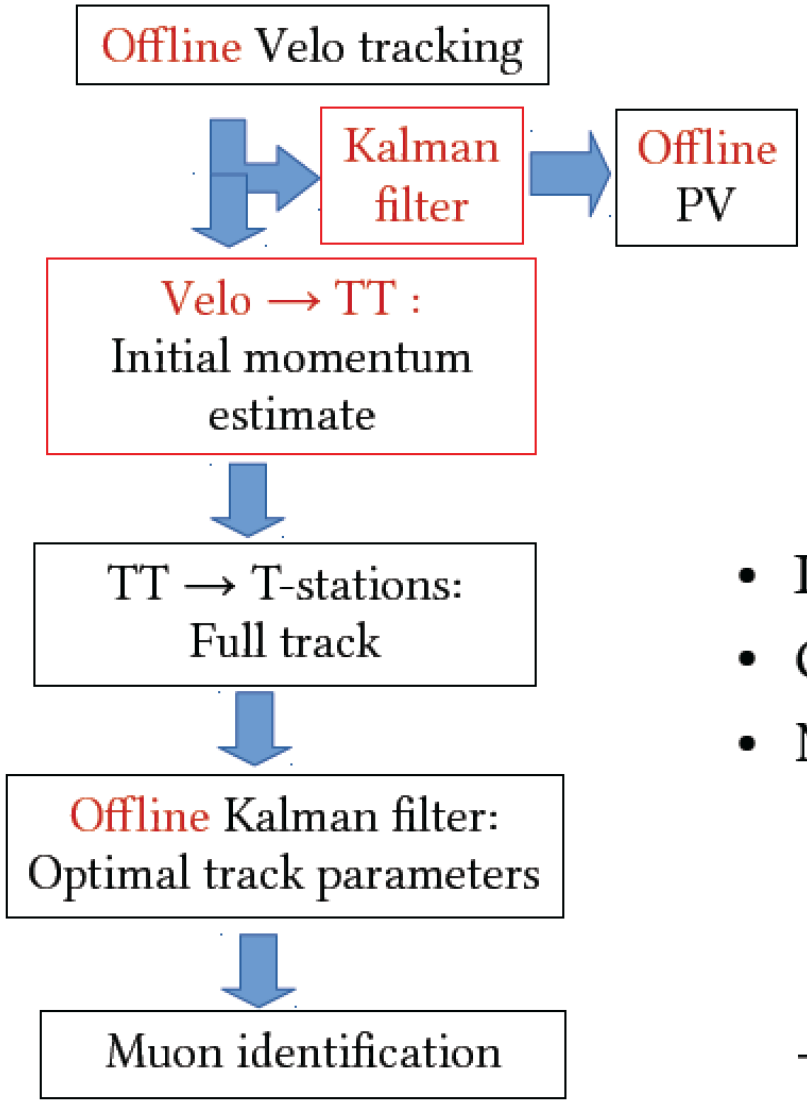
http://imgur.com/eVRT6Vu

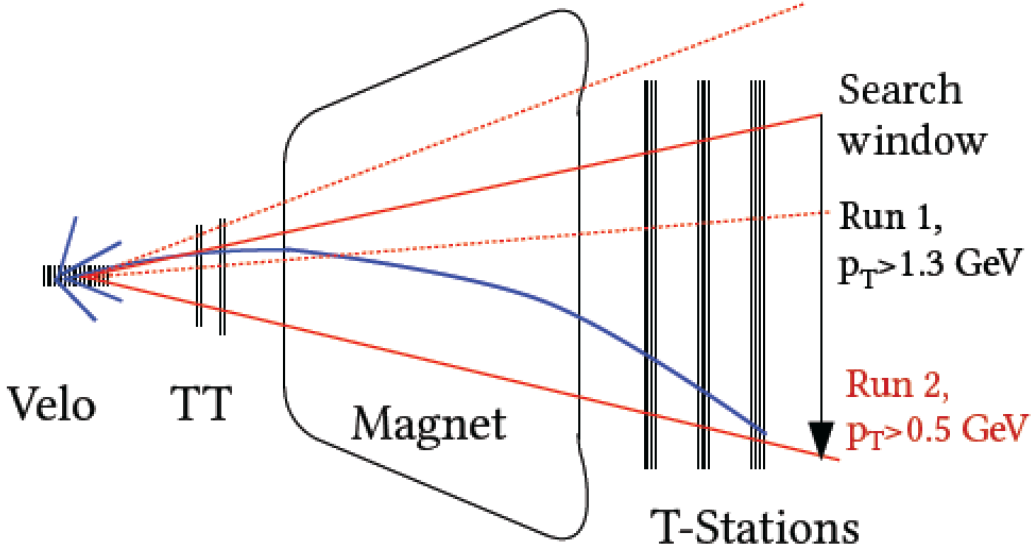
HLT1 event reconstruction

- Inclusive selections:
  - Single and two track MVA selections
  - $\sim$ 100 kHz
- Inclusive muon selections
  - Single and dimuon selections
  - Additional low p_T track reconstruction
  - $\sim$ 40 kHz
- Exclusive selections
  - Lifetime unbiased beauty and charm selections
  - Selections for alignment
- Low multiplicity trigger for central exclusive production analyses



HLT1 event reconstruction

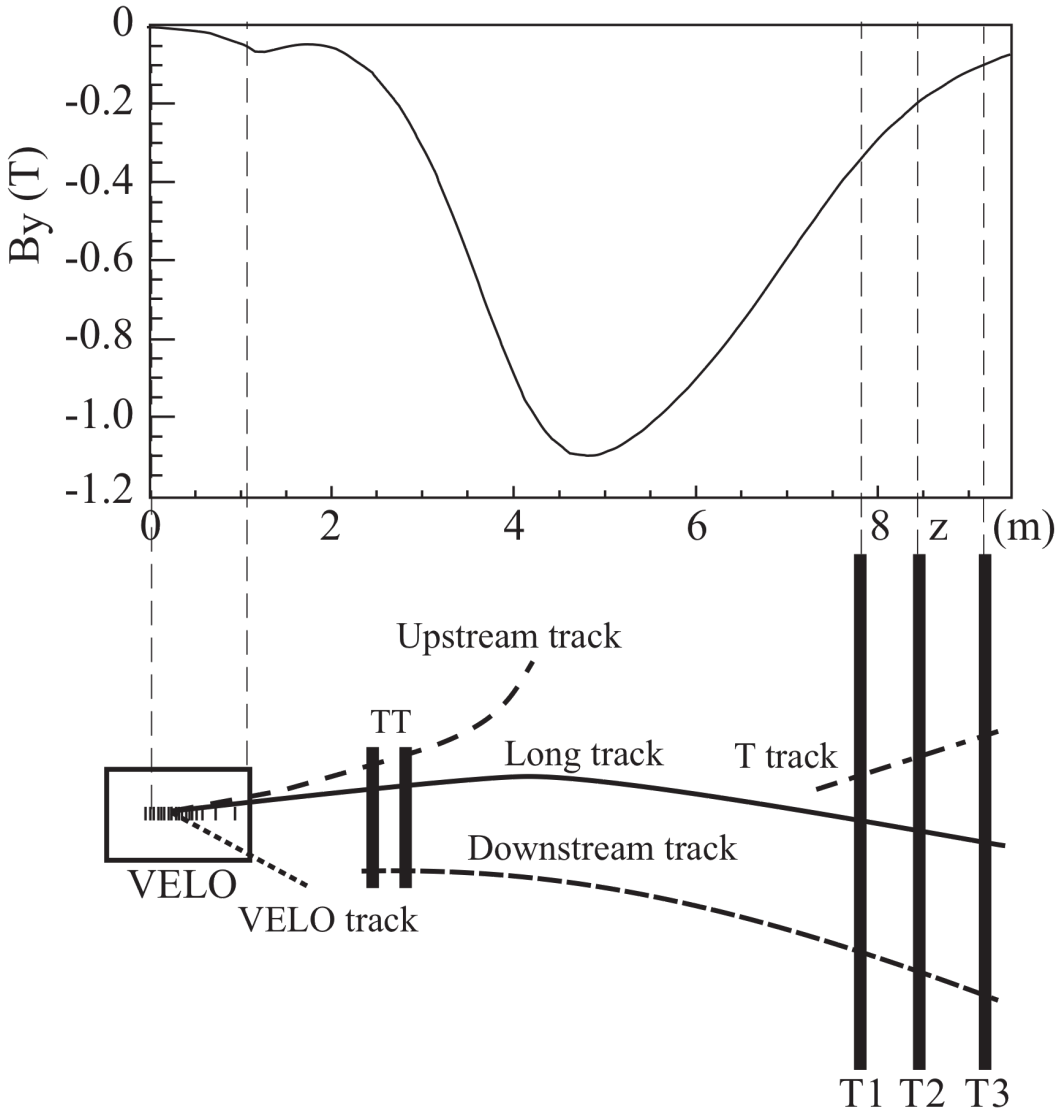




- Improved sequence (Velo → TT)
- Code optimization
- New offline:
  - PV fit only with Velo tracks
  - Kalman filter with fast geometry description
  - No performance degradation

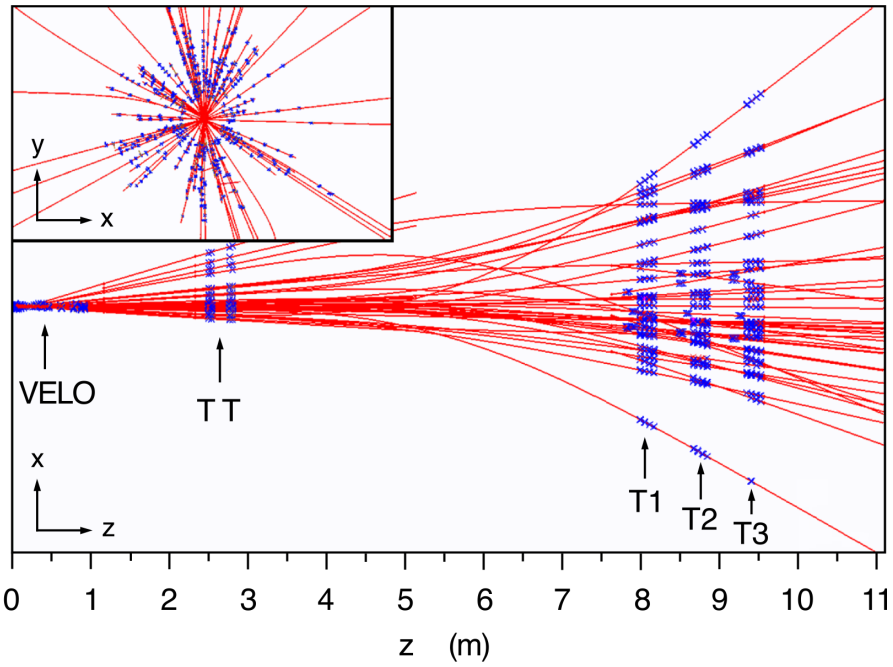
→ Consistent PV and track parameters

Track reconstruction



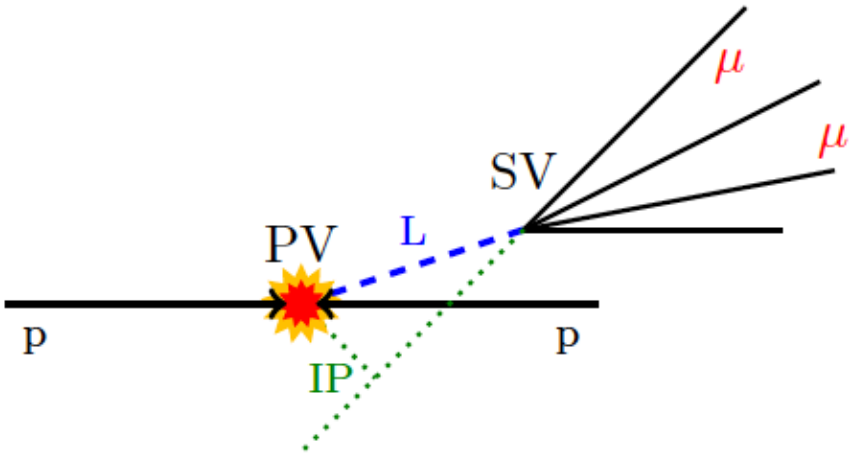
Dipole magnet implies an intrinsic charge asymmetry (left-right differences in the detector).

Direction of magnetic field changed regularly and data sets combined.



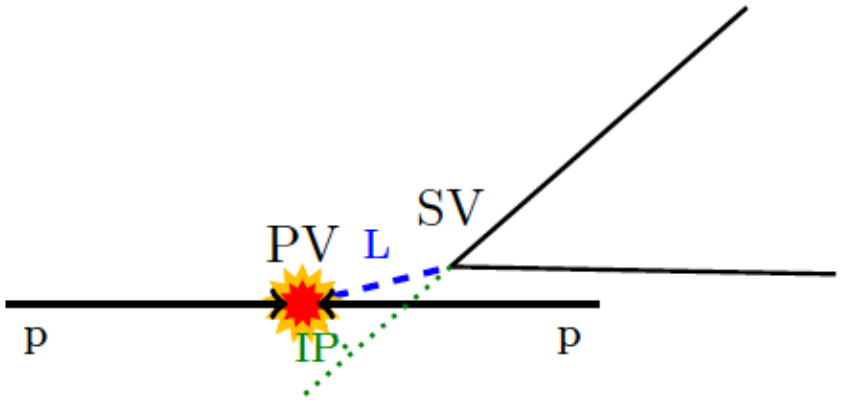
Heavy flavour signatures

B hadrons



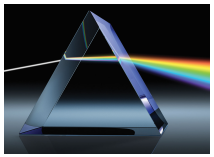
- mass $m(B^+) = 5.28\,\mathrm{GeV}$
  daughter p_T $\mathcal{O}(1\,\mathrm{GeV})$
- lifetime $\tau(B^+) \sim 1.6\,\mathrm{ps}$
  flight distance $\sim 1\,\mathrm{cm}$
- common signature: detached $\mu\mu$
  $B \to J/\psi X$ with $J/\psi \to \mu\mu$

charmed hadrons



- mass $m(D^0) = 1.86\,\mathrm{GeV}$
  sizeable daughter p_T
- lifetime $\tau(D^0) \sim 0.4\,\mathrm{ps}$
  flight distance $\sim 4\,\mathrm{mm}$
- can be produced in B decays

At 13TeV σ(bb) ~ 45 kHz and σ(cc) ~1MHz cc in LHCb acceptance



Particle IDentification

Data driven performance

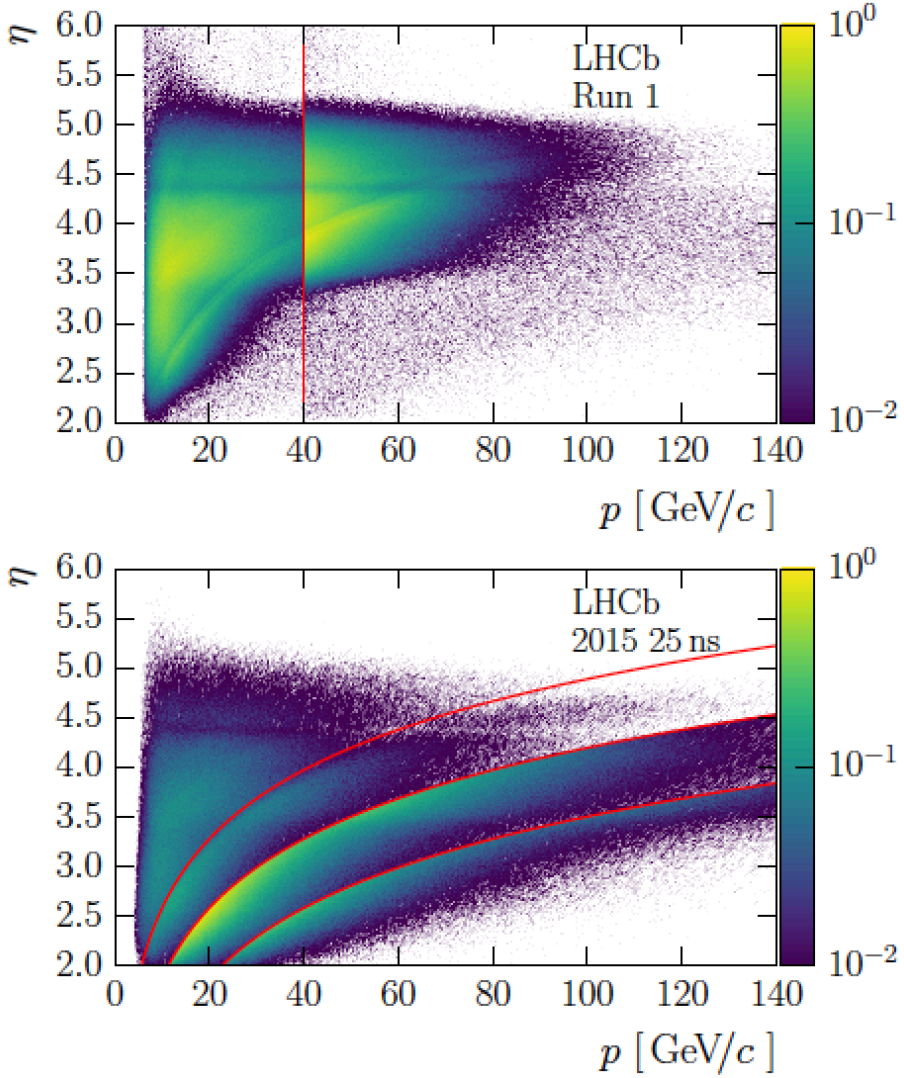
PID samples [Run 1 and Run 2]:
- low-multiplicity modes with large BRs
- without using PID variables (e.g. $D^0 \to K\pi$)
- tag-and-probe method (e.g. $J/\psi \to \mu\mu$)

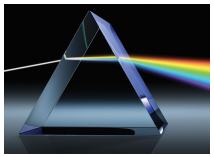
Species	Soft	Hard
$e^\pm$	—	$J/\psi \to e^+e^-$
$\mu^\pm$	$D_s^+ \to \mu^+\mu^-\pi^+$	$J/\psi \to \mu^+\mu^-$
$\pi^\pm$	$K_S^0 \to \pi^+\pi^-$	$D^* \to D^0\pi^+$, $D^0 \to K^-\pi^+$
$K^\pm$	$D_s^+ \to K^+K^-\pi^+$	$D^* \to D^0\pi^+$, $D^0 \to K^-\pi^+$
$p^\pm$	$\Lambda^0 \to p\pi^-$	$\Lambda^0 \to p\pi^-$, $\Lambda_c^+ \to pK^-\pi^+$

Selected directly in the trigger [Run 2]:
- larger statistics
- easier trigger-decorrelation

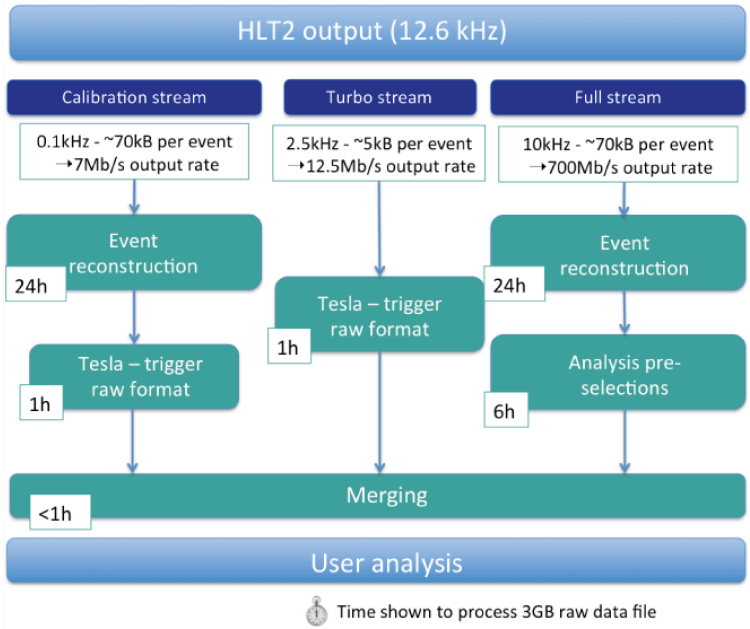
[Muon and CALO are used in L0 and HLT1]

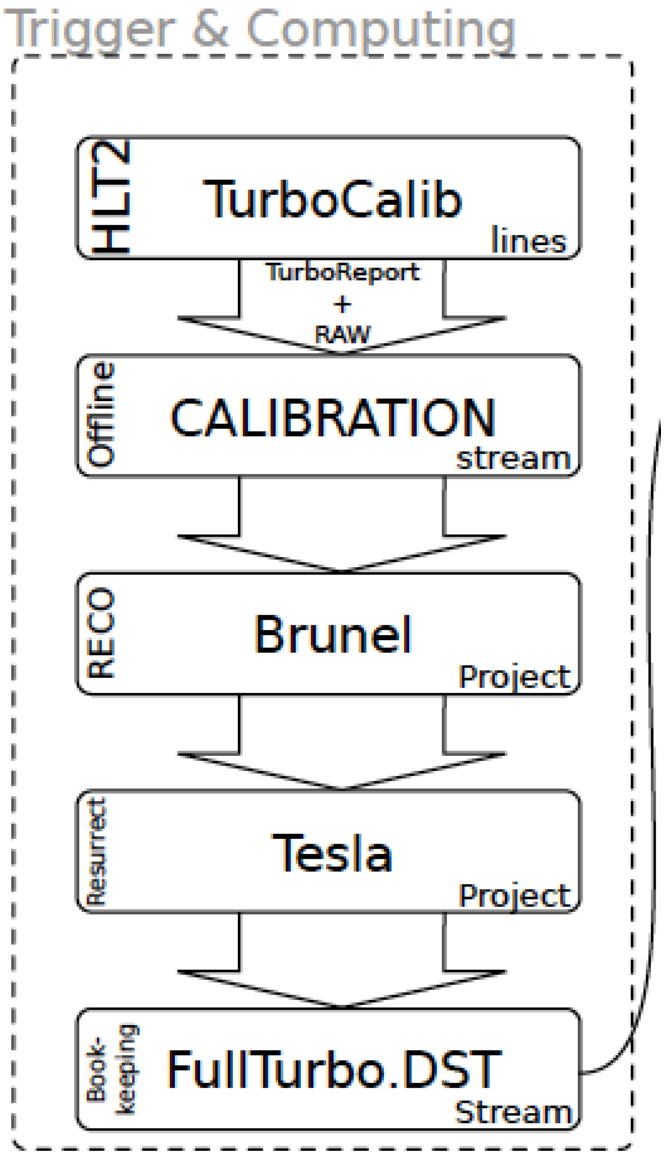
[Proton samples]





PID



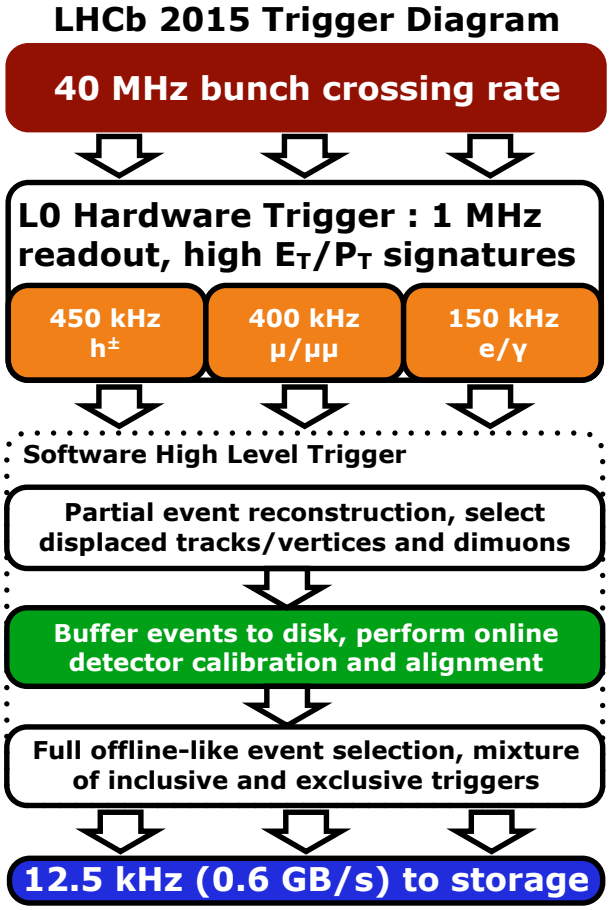


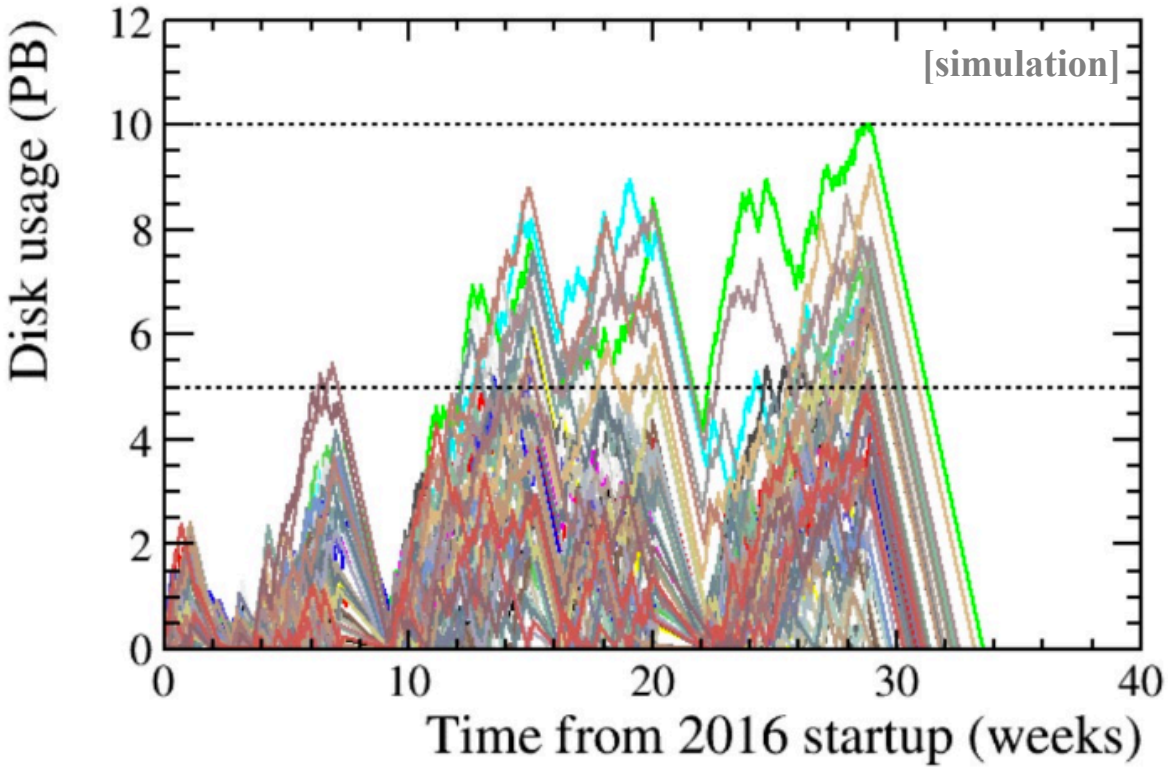
PID samples are used in data-driven techniques to measure the PID performance

PID information built in the trigger with offline-quality; keep the chance of further improvements (e.g. high-CPU-load)

Dedicated Stream:
- online/trigger information plus full raw event (can be reconstructed).
- key tool for the quality validation of "online data analyses" (TURBO stream / Tesla)

Making the most of the farm



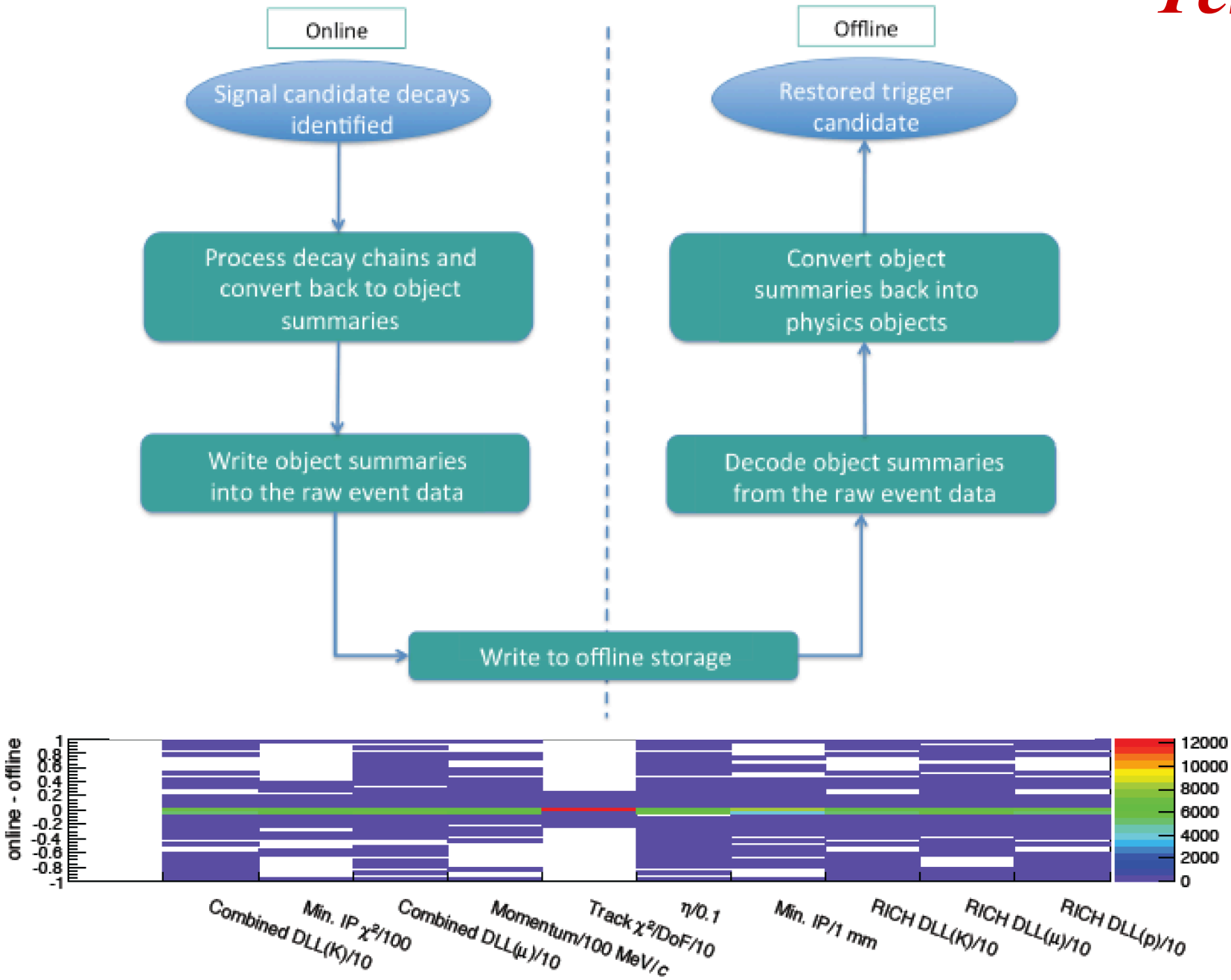


Interplay between LHC schedule and farm behaviour is hard to predict: study it with toys.
- 2012 running period machine availability used as input. Technical stops follow 2016 calendar
- assuming HLT2 throughput of 60 kHz
- percent level probability of reaching 10 PiB

Toys will be regularly re-run through the year as LHC schedule and farm performance is better understood.

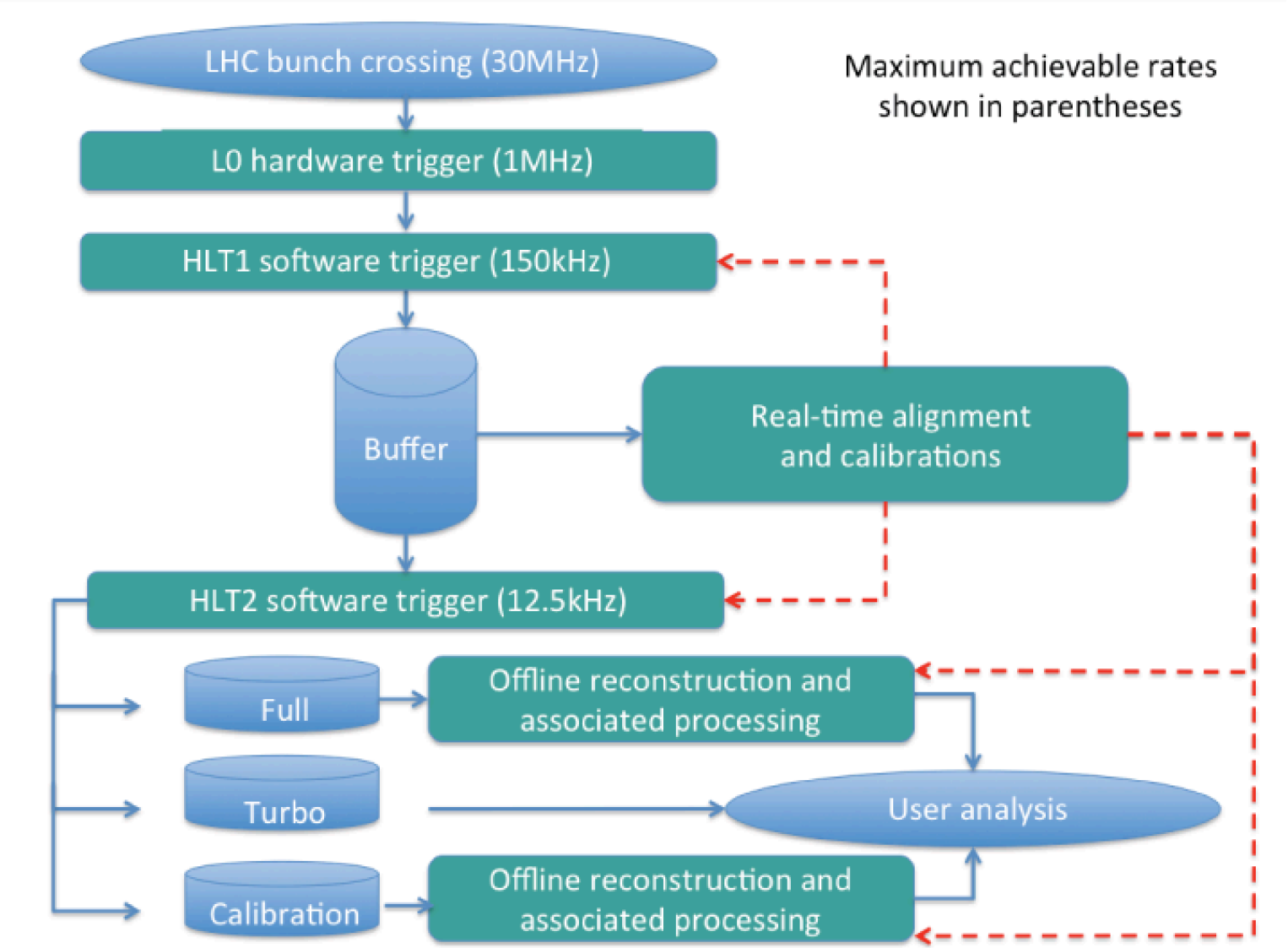
[Tesla : an application for real-time data analysis in High Energy Physics, 1604.05596v1]

Tesla



[Tesla : an application for real-time data analysis in High Energy Physics, 1604.05596v1]

Tesla



Trigger in Run 2

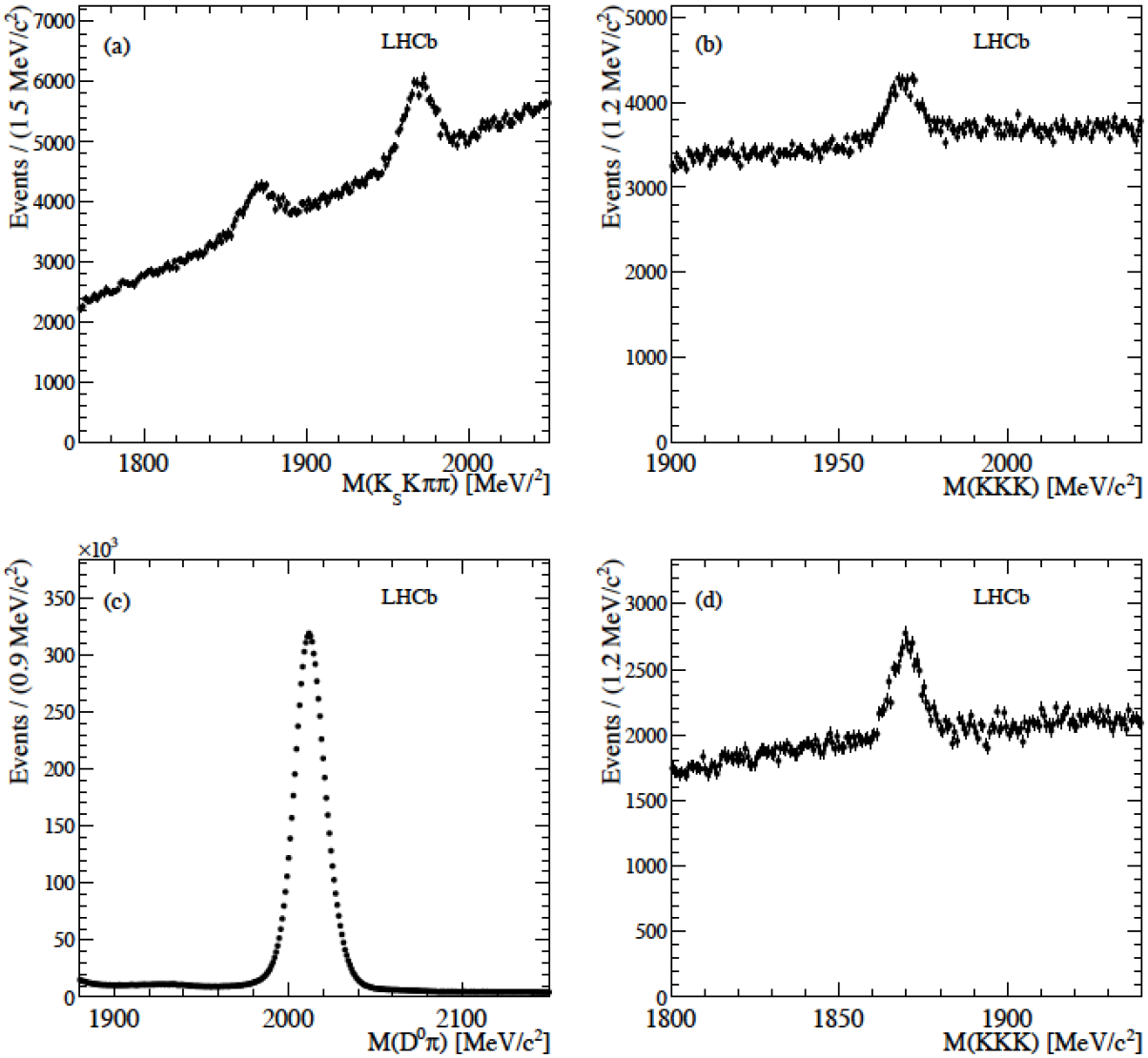
[Tesla : an application for real-time data analysis in High Energy Physics, 1604.05596v1]

Physics out of the trigger with Turbo Stream:

- Raw info discarded, candidates directly available few hours after being recorded

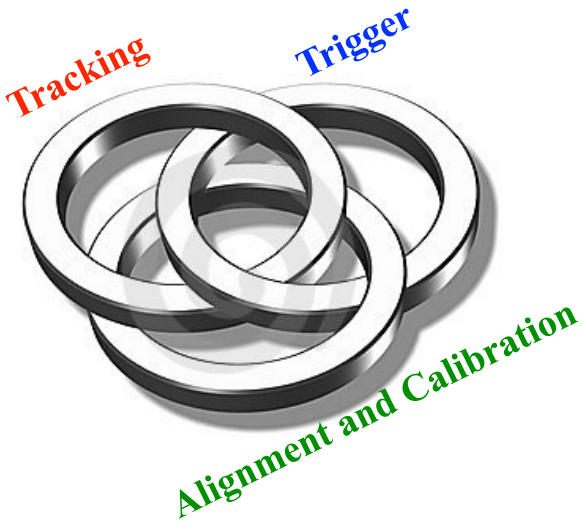
- More decays can be collected and therefore more precise measurements performed than would have been possible under the Run-I computing model.

- [2016] Persistency of the reconstruction information for the full event, higher level variables available for a few lines.



Alignment and calibration

The idea: do physics directly on HLT output



Challenges:
- do the full reconstruction in few ms achieving offline performance quality;
- alignment and calibration of the detector "on real time";
- efficient trigger selection of signal candidates.

Strategy:
- speed-up/improve reconstruction;
- HLT split: HLT1 output stored on disk;
- Enough time to perform alignment and calibration tasks between HLT1 and HLT2.

- Automatic evaluation at regular intervals (beginning of the run or fill depending on the task)
- **Dedicated data sample** collected with a specific trigger selection line for each task
- Compute the new alignment or calibration constants in a few minutes
- Update the constants only if needed

The same new constants will be used both by the trigger and the offline reconstruction