Trigger and reconstruction for the LHCb upgrade

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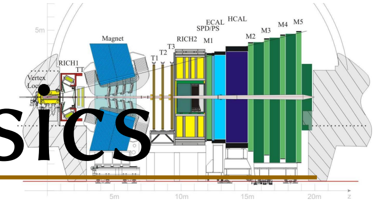
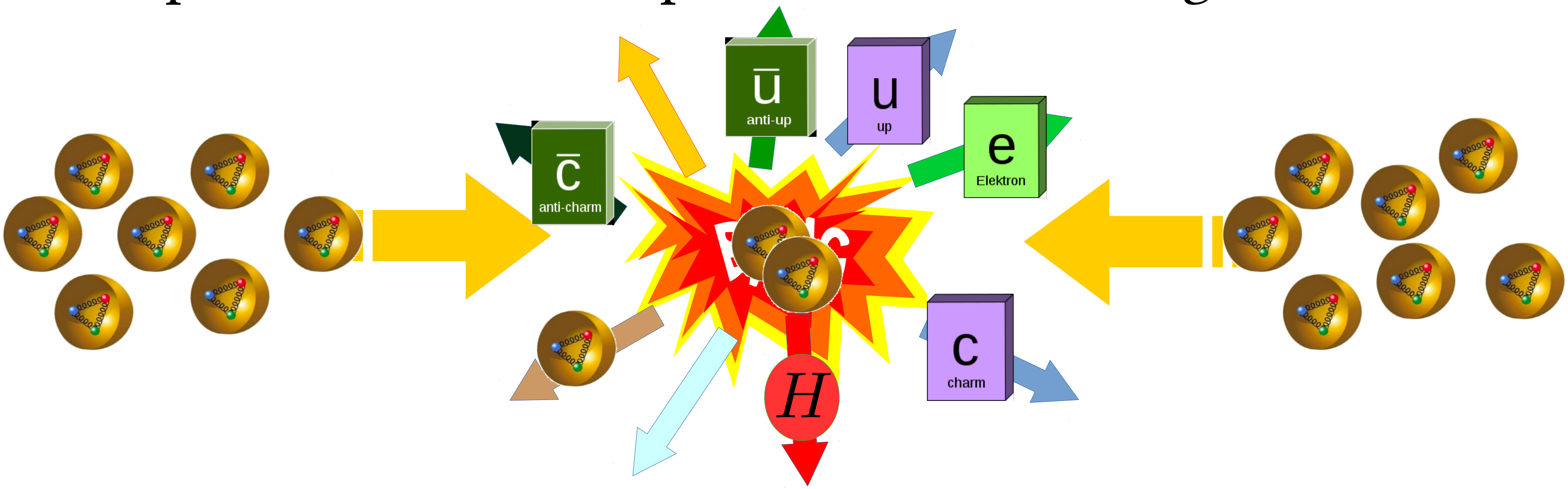
FSP Meeting, Siegen

7/10/2017

LHC, opportunity for flavour physics

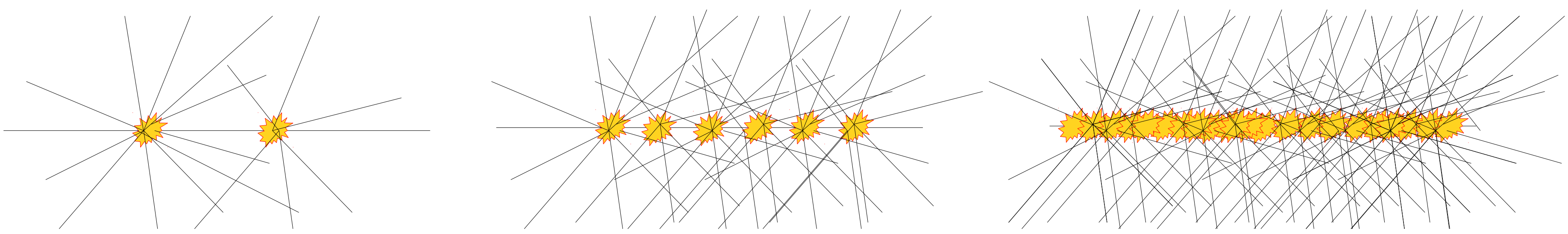


- LHC provides 30 MHz of proton bunch crossings

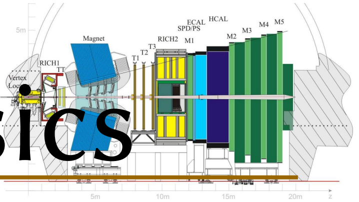


- LHCb, per crossing 1.1 collisions, times 5 for the Upgrade, …

Current Upgrade Phase 2 Upgrade



LHC, opportunity for flavour physics



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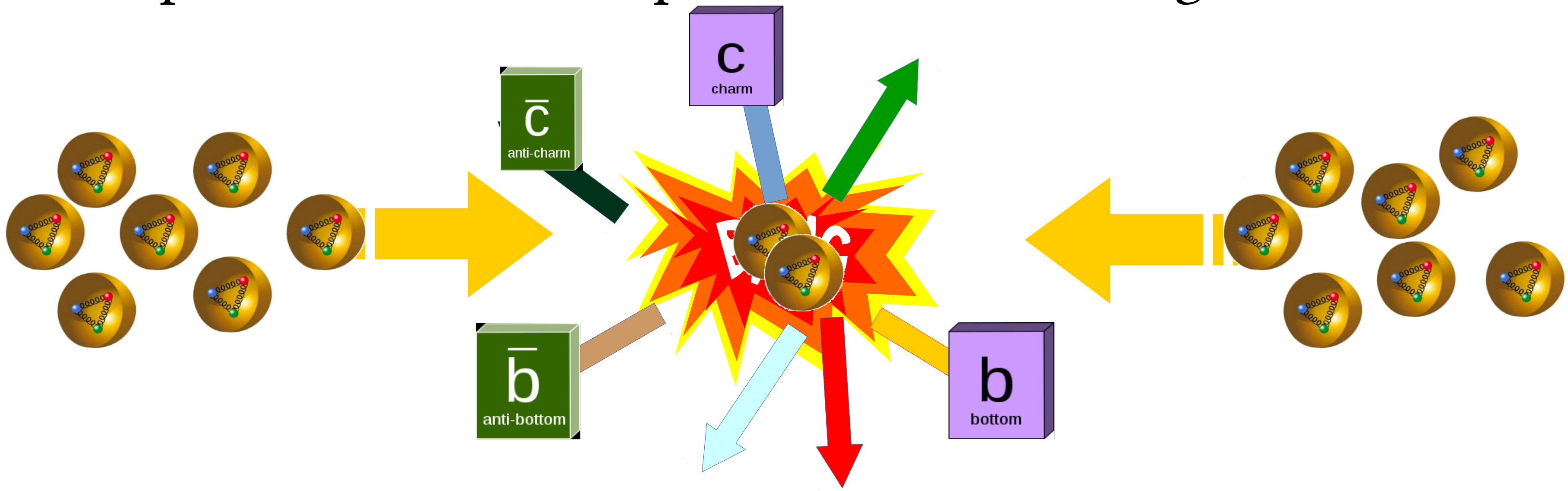
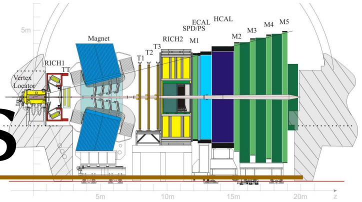


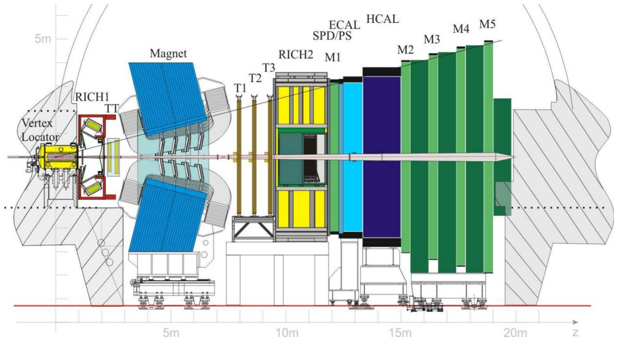
- Large beauty and charm production:

~45 kHz $b\bar{b}$ pairs and ~1 MHz $c\bar{c}$ pairs now, times 5 for the Upgrade, …

Most events are interesting.

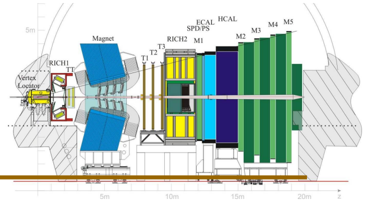
LHC, challenge for flavour physics





- Detection of collisions and the originating particles (I rely on Chris here)
- Huge data rate, O(TB/s), limited storage capacity
  ⟶ Reject “non-interesting” events, keep the interesting
- Limited computing power
  ⟶ Need to be fast in event analysis

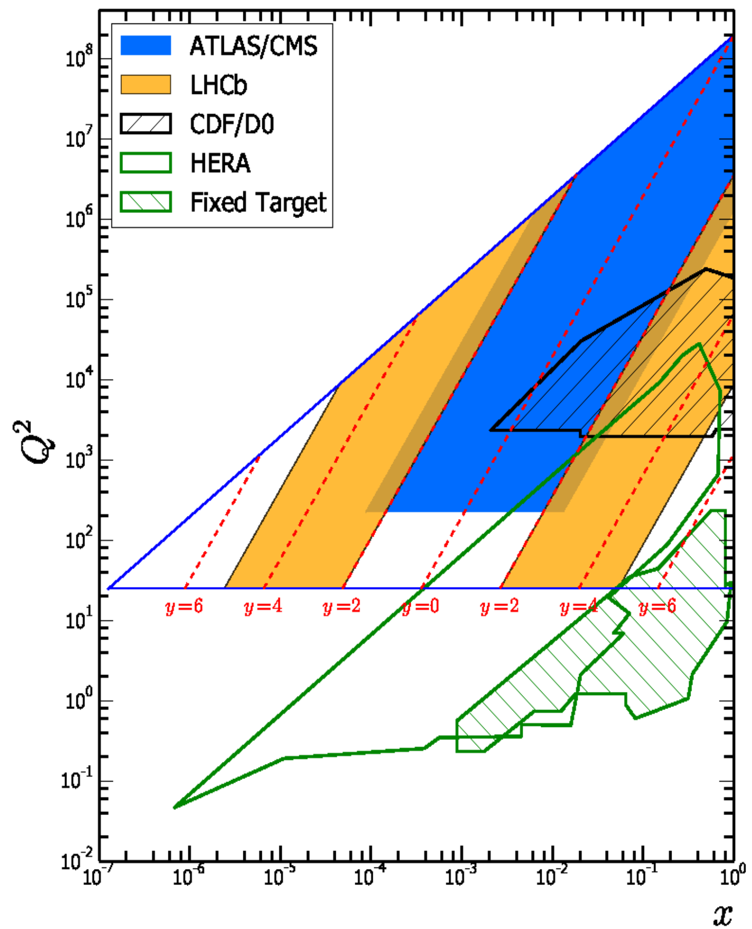
LHCb physics goals



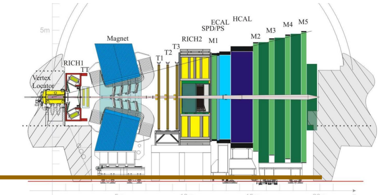
LHCb – General purpose detector in forward direction

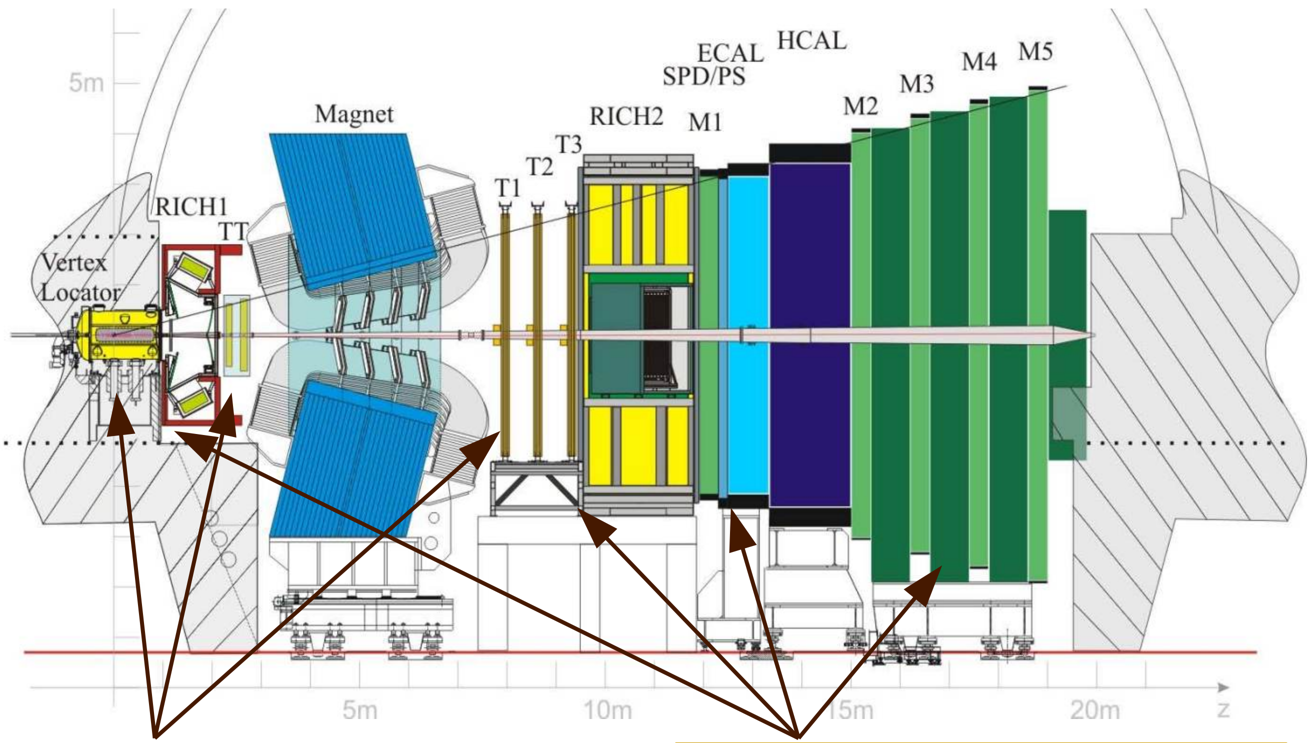
- Focus here on Heavy Flavour physics
- But LHCb trigger enables and has to enable a wide range of phyics
- Unique rapidity coverage at hadron collider
- Rich program of:
  - Electroweak physics
  - Production and spectroscopy
  - Heavy Ion and fixed target physics
  - Strange physics

LHC 14 TeV Kinematics



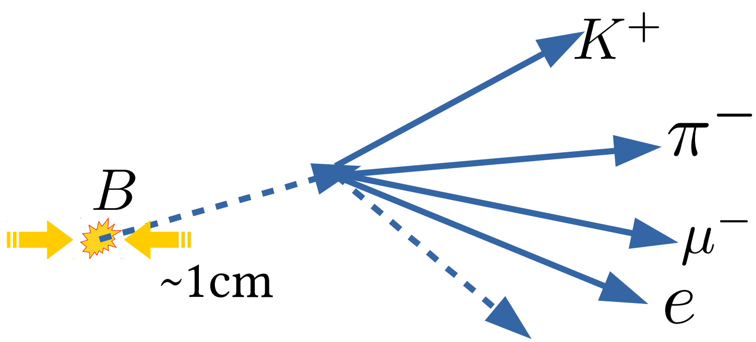
The LHCb experiment

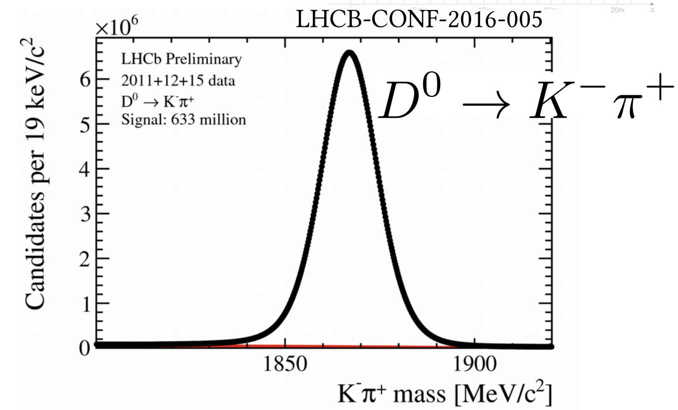


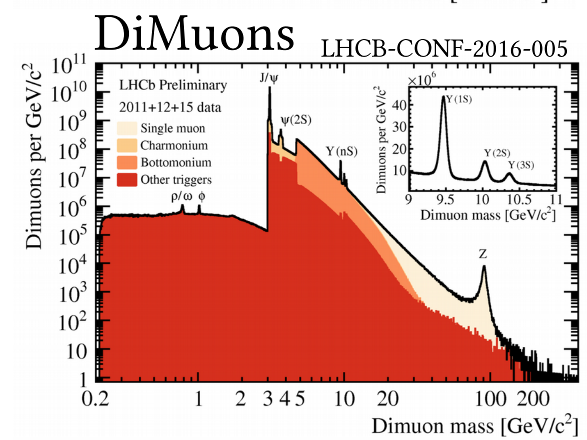


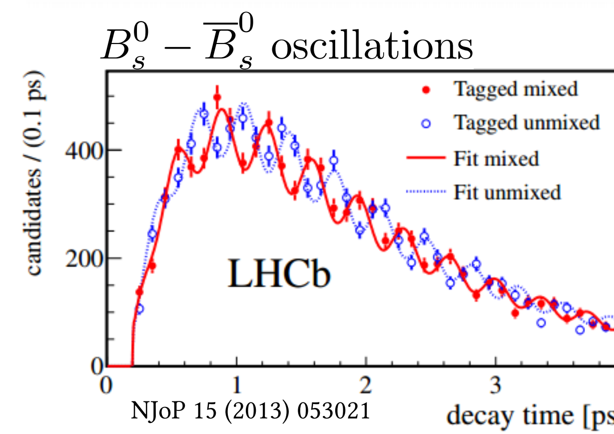
Vertex and track finding

Particle identification

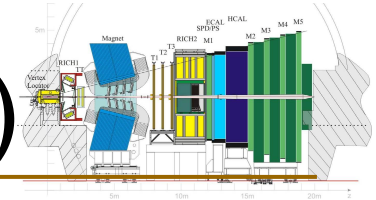


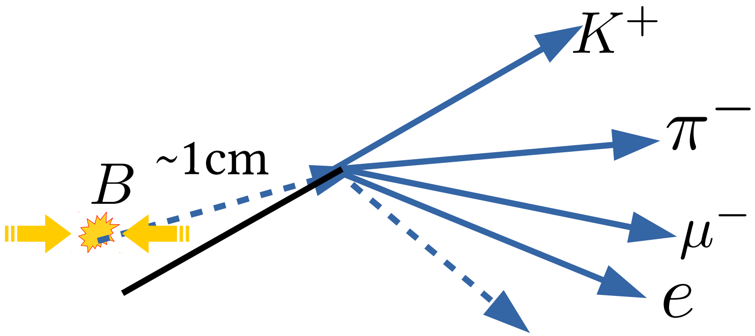






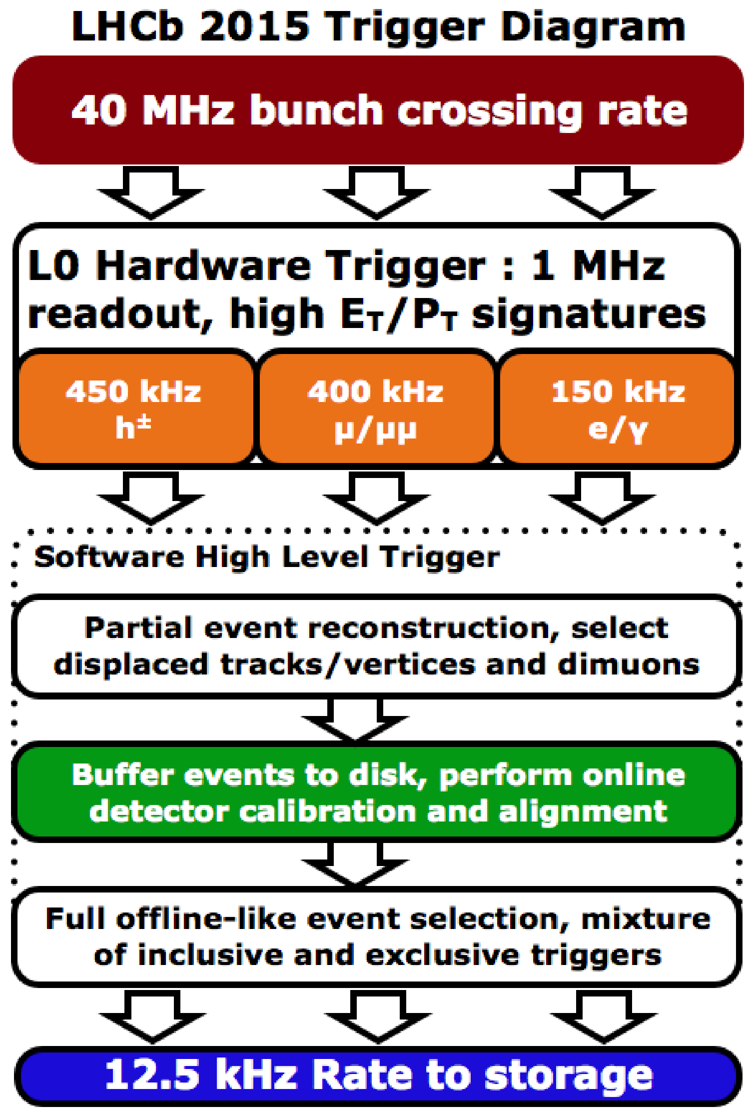
Event selection and analysis (now)





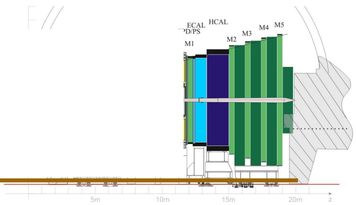
Heavy flavour decays:

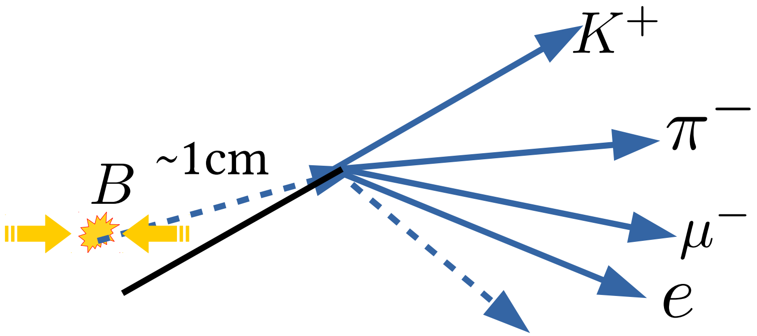
- High transverse energy or momentum
- Particles with high impact parameter
- Identify particle species to reconstruct decay



(will explain individual boxes)

L0 Hardware trigger (now)

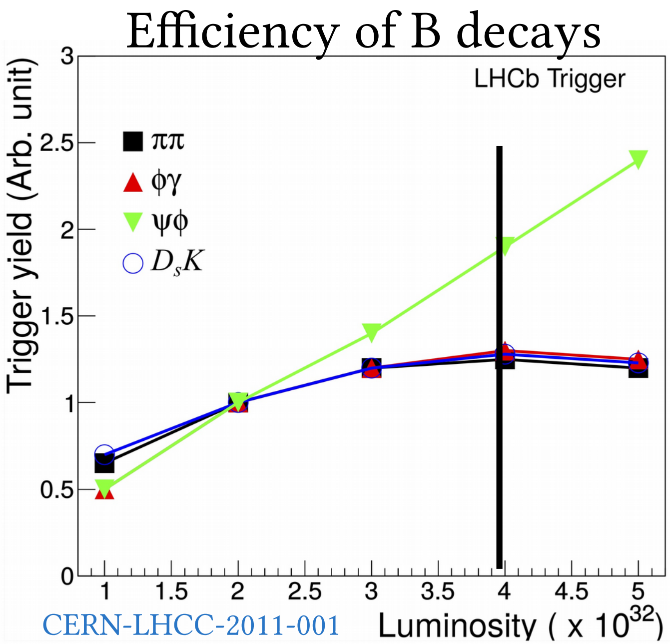




Heavy flavour decays:

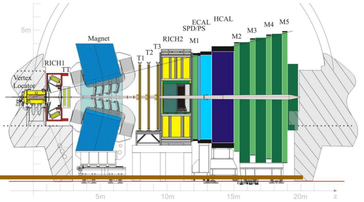
- High transverse energy or momentum
- ~~Particles with high impact parameter~~
- ~~Identify particle species to reconstruct decay~~
- "Easier" when muon in decay

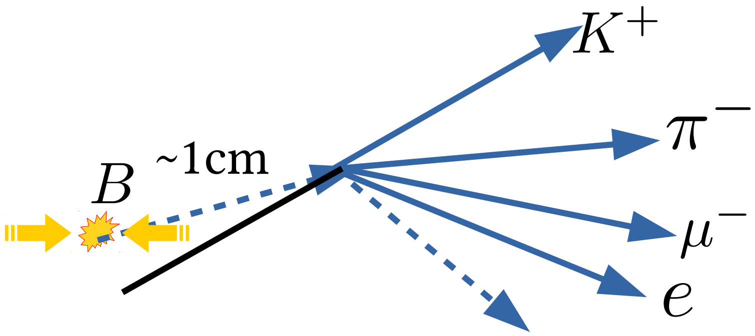
- Only calorimetry and muons
- ~1 MHz read-out limit



Limits efficiency at higher luminosities

L0 Hardware trigger (Upgrade)





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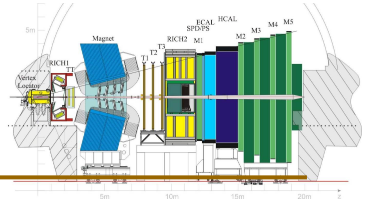
Trigger-less readout



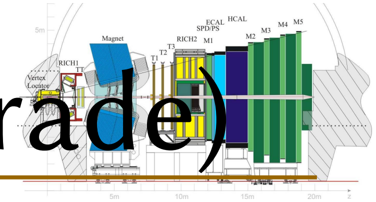
Opportunity:

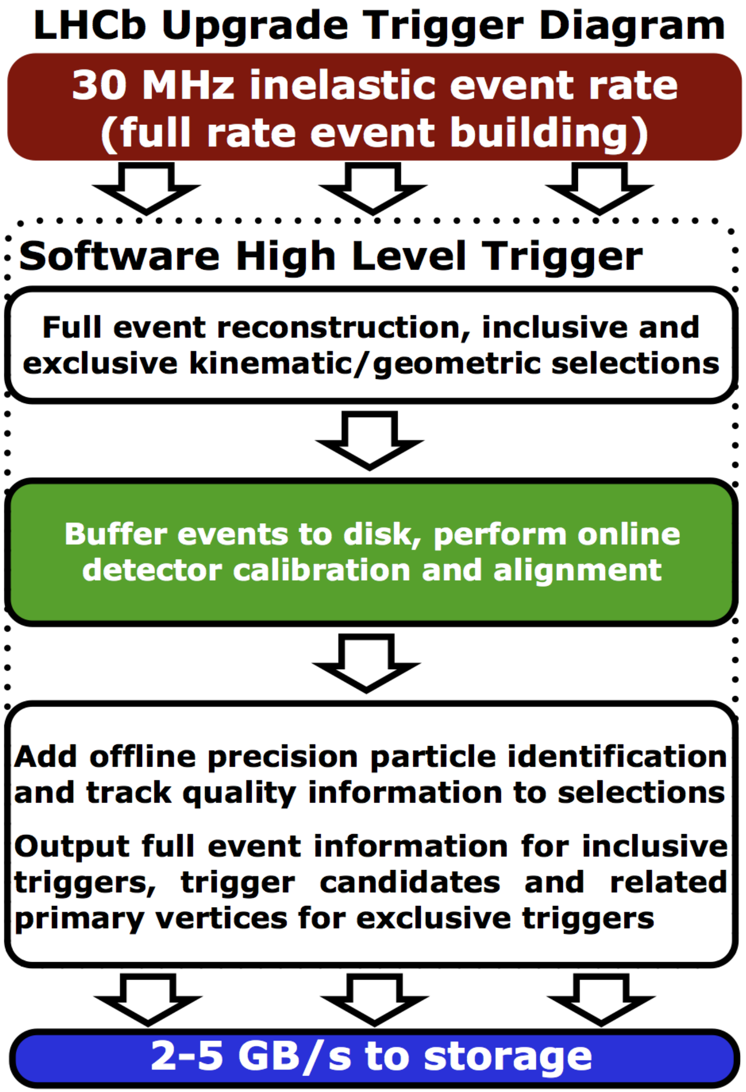
- Removes efficiency bottleneck of hardware trigger
- Flexible and adaptable software trigger running on non-custom hardware
  - New physics ideas can easily be added
  - LHCb trigger continuously expanded and improved during Run 1 and Run 2 (examples later, some Upgrade concepts already deployed)
  - People without much previous knowledge can quickly contribute

Challenge:

- Software trigger has to process 30*5 more collisions in real-time

Event selection and analysis (Upgrade)

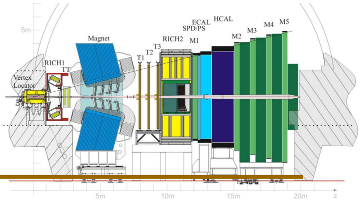


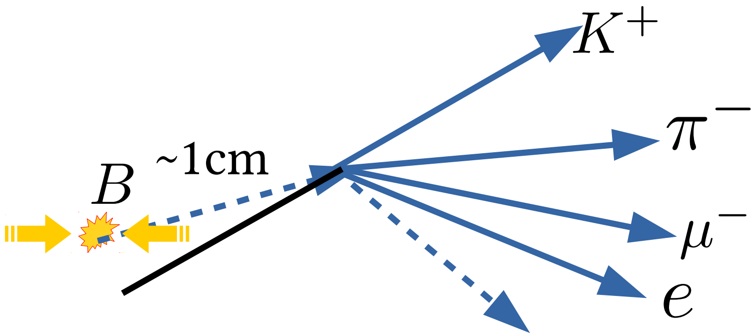


Requirements:

- First trigger stage (Hlt1):
  - Process events at 30 MHz
  - Select interesting decays with high efficiency
  - Discard as much background as possible
- Second trigger stage (Hlt2):
  - Process Hlt1 output
  - Time per event orders of magnitude larger than in Hlt1 (Run 2 factor 20)
  - Do not fill buffer

First trigger stage





Heavy flavour decays:

- High transverse (energy or) momentum
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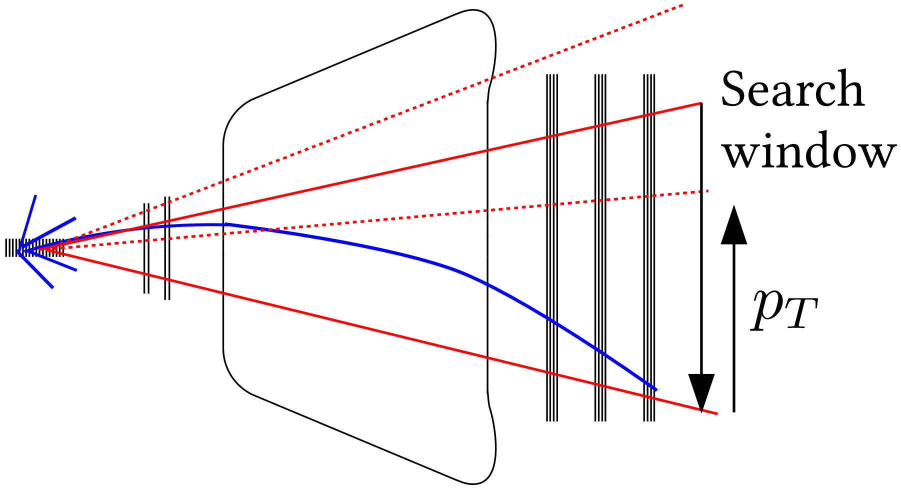
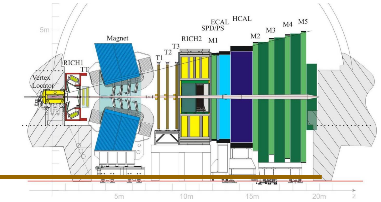
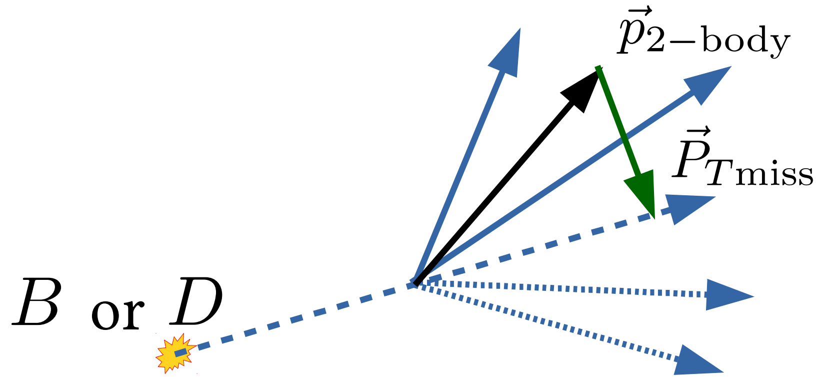
- ~~Identify particle species to reconstruct decay~~
- “Easier” when muon in decay



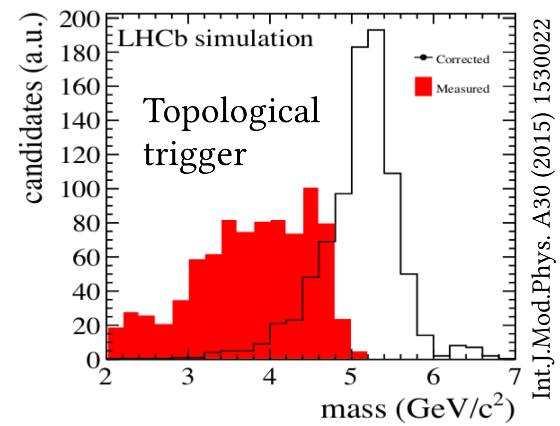
- Essential event reconstruction to be fast
  - Primary vertices
  - High pt tracks
  - Muon ID
- Combine information to 1- and 2-track signatures

Hlt1 inclusive trigger lines



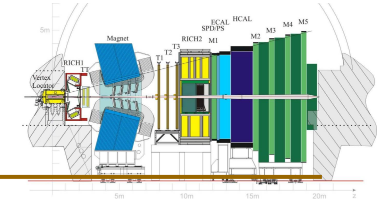


- Inclusive charm and beauty triggers:
  - Developed for Run 2
  - Based on 1- and 2-track signatures
  - Track quality and displacement cuts (2-track lower pt per track)
  - Multivariate selections using momentum, impact parameter and corrected mass (2-body)
- Tuned for Upgrade conditions (next slide)



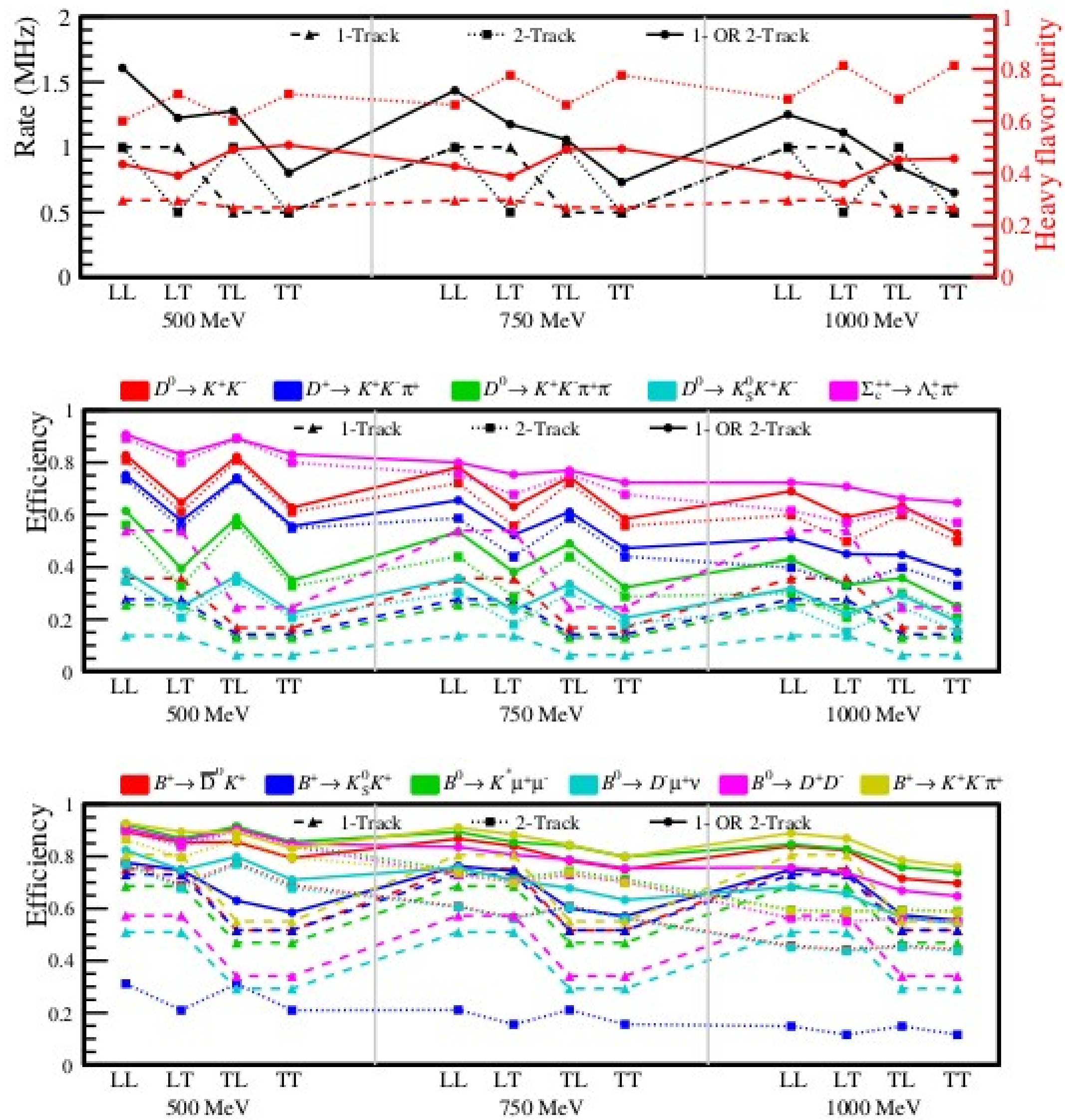
	Run 2 rate
1-Track	76 kHz
2-Track	30 kHz
1- or 2- Track	89 kHz
Hlt1	120 kHz

Hlt1 trigger selection (Upgrade)



- Studied for different track pt thresholds
- MVA parameters adjusted to target rate:
  - L(oose) = 0.5 MHz, T(ight) = 1 kHz per line
- Result:
  - 1-Track line, high rate, low purity and efficiency (needed for some topologies)
  - 2-Track line, much better efficiency and purity

⟶ Need secondary vertexing capabilities in Hlt1



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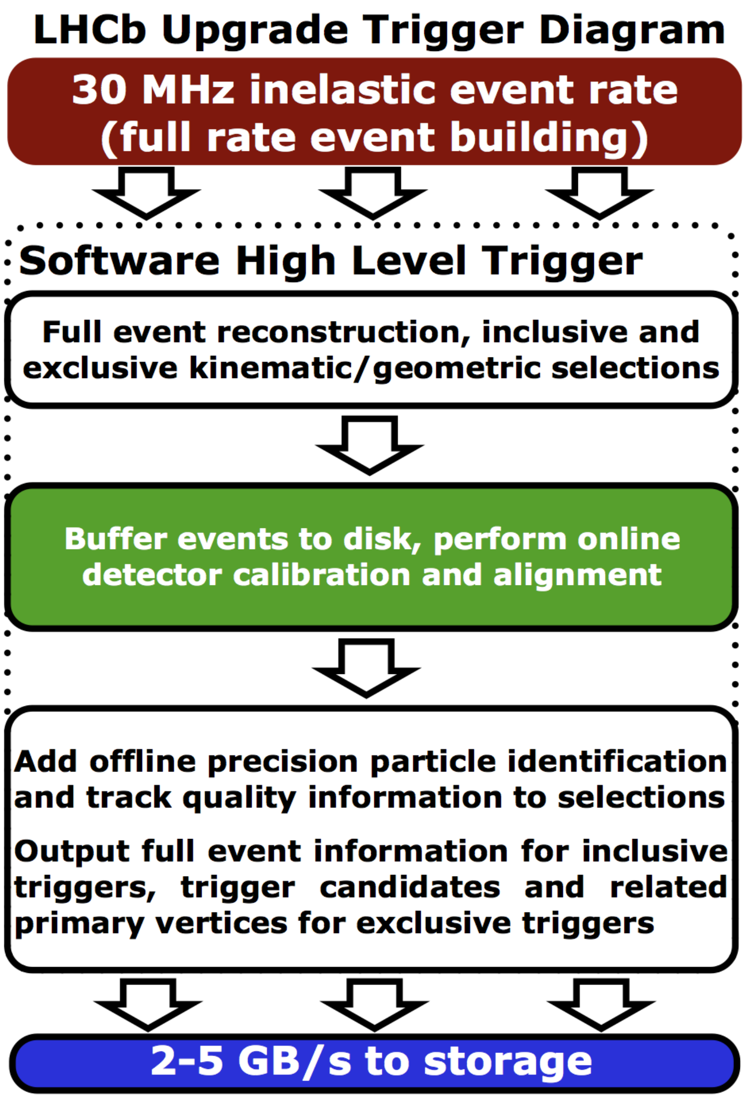
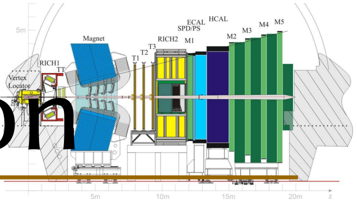
Event selection and analysis (Upgrade)



Buffer:

- Store events for immediate alignment and calibration
- Allows to use computing farm in and out fill

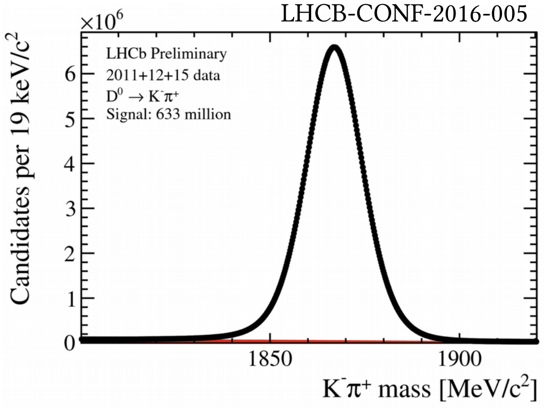
Real-time alignment and calibration



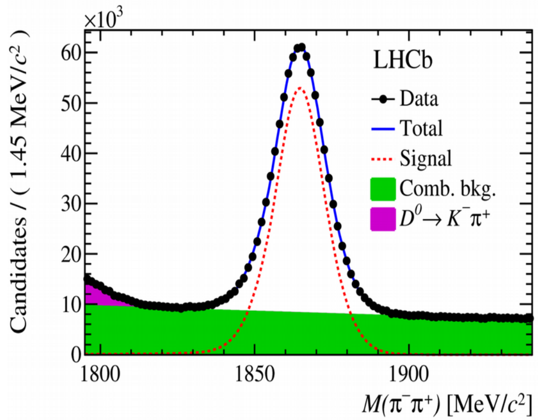
- Need optimal tracking system alignment for Hlt1 selections
  - E.g. the Velo is moved in and out for every fill
- Optimal particle identification in Hlt2
  - E.g. calibration of RICH depends on pressure

- Align and calibrate all subdetectors while taking data
- Process second trigger stage only after full alignment and calibration

$D^0 \rightarrow K^-\pi^+$



$D^0 \rightarrow \pi^-\pi^+$



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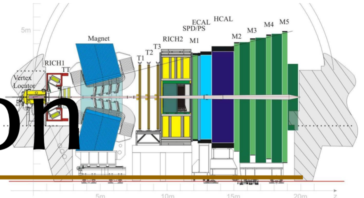
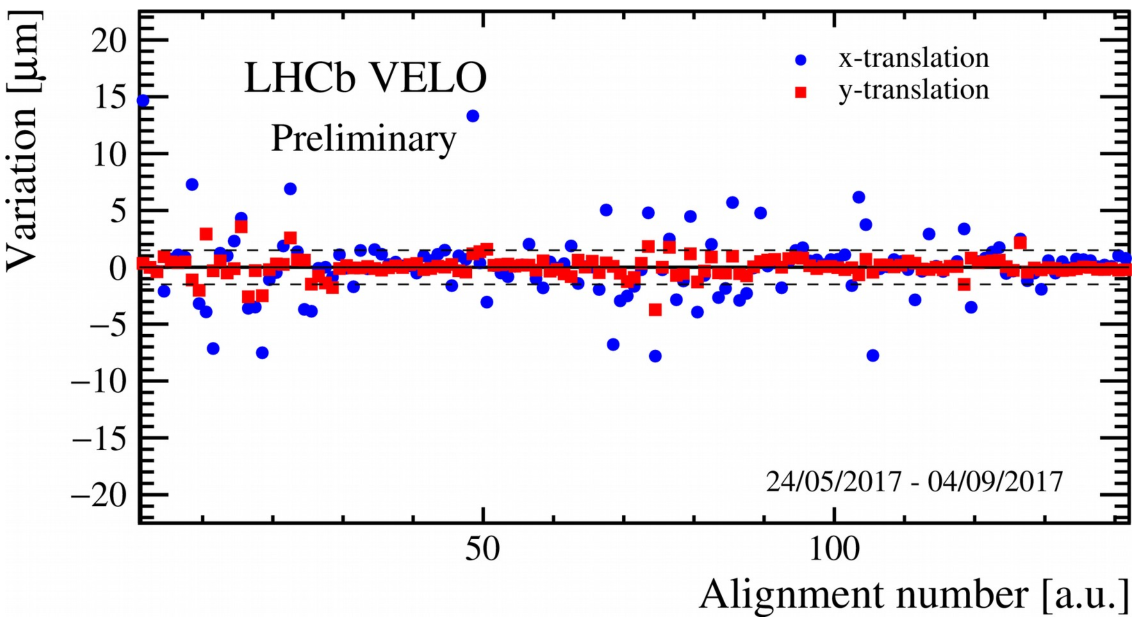
Real-time alignment and calibration

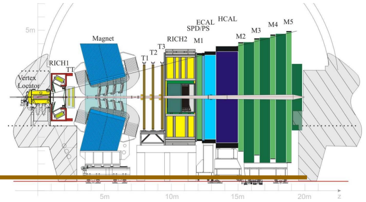


- System very successfully implemented in Run 2
- Tracking system aligned and calibrated within minutes after start of fill
  - Update of alignment parameters automatically triggered if necessary

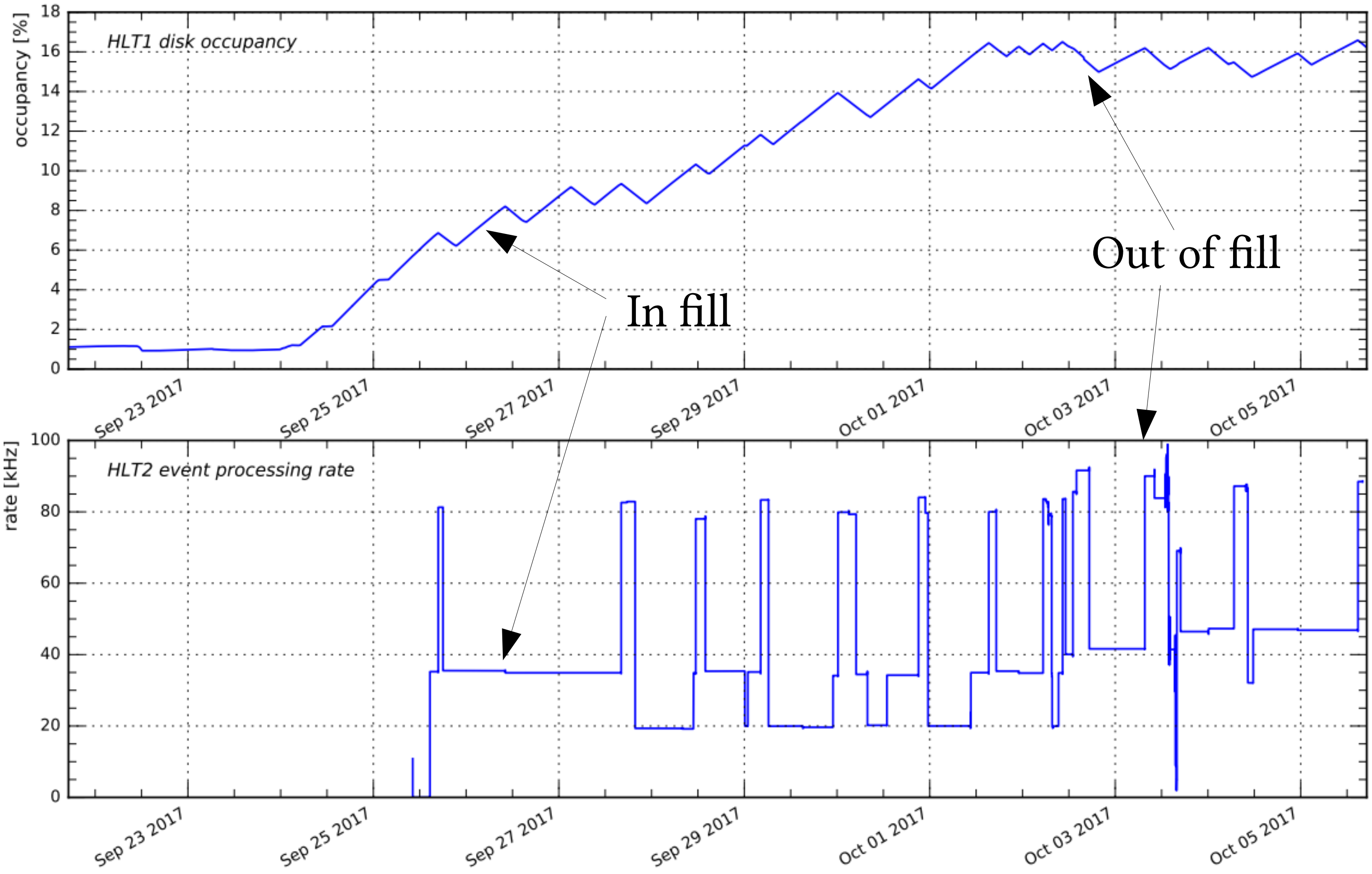


- Particle identification systems calibrated and aligned within hours
  - HLT2 waits before analysing HLT1 output

Disk Buffer (Now)



- Asynchronous processing of Hlt2 allows to optimally use farm resources



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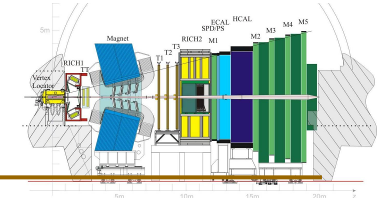
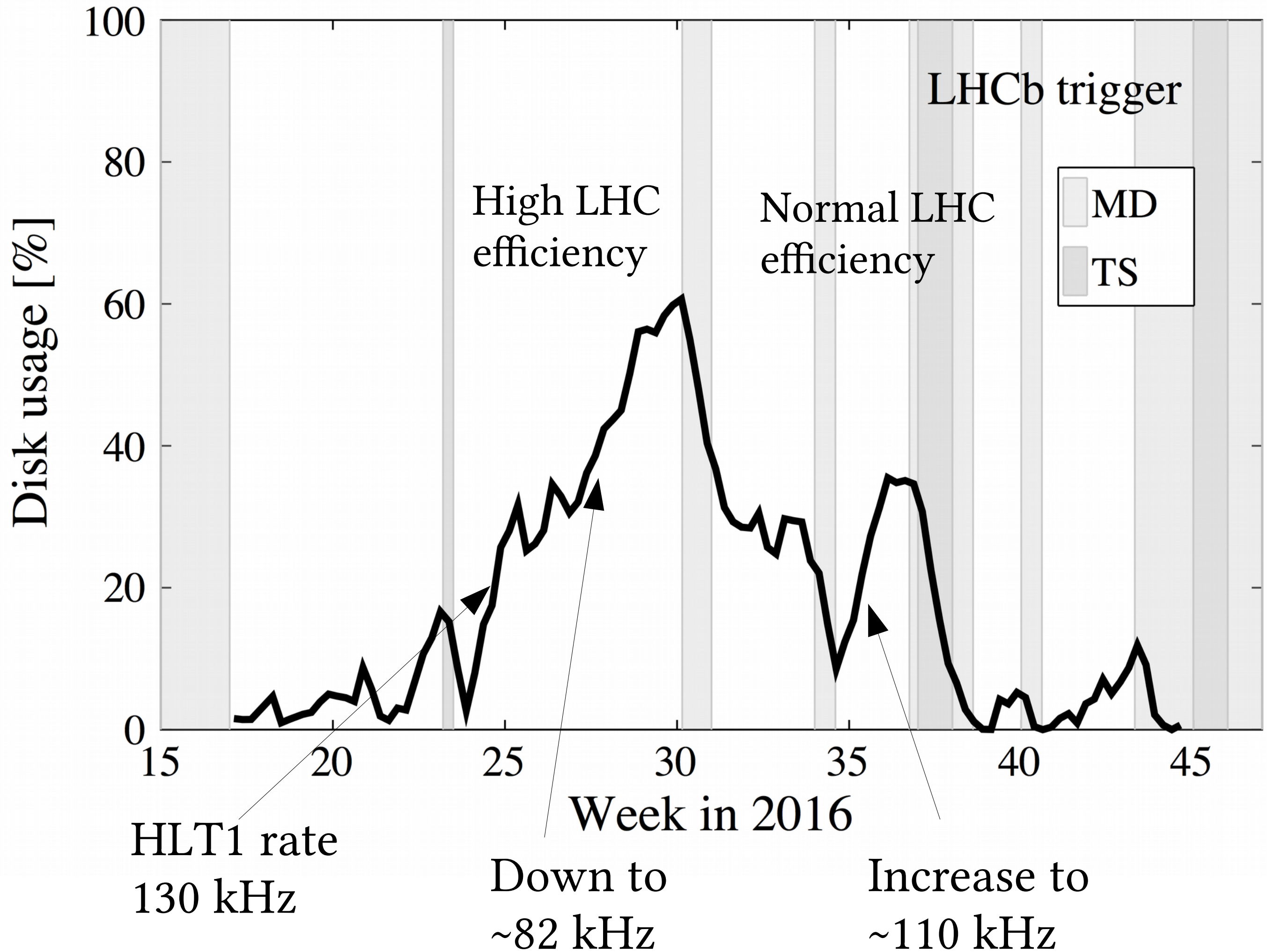
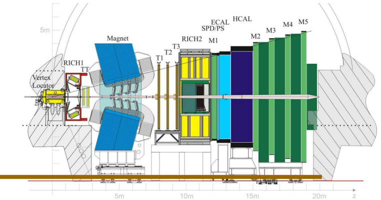


- Asynchronous processing of Hlt2 allows to optimally use farm resources to maximise physics output.



Disk Buffer in Upgrade?

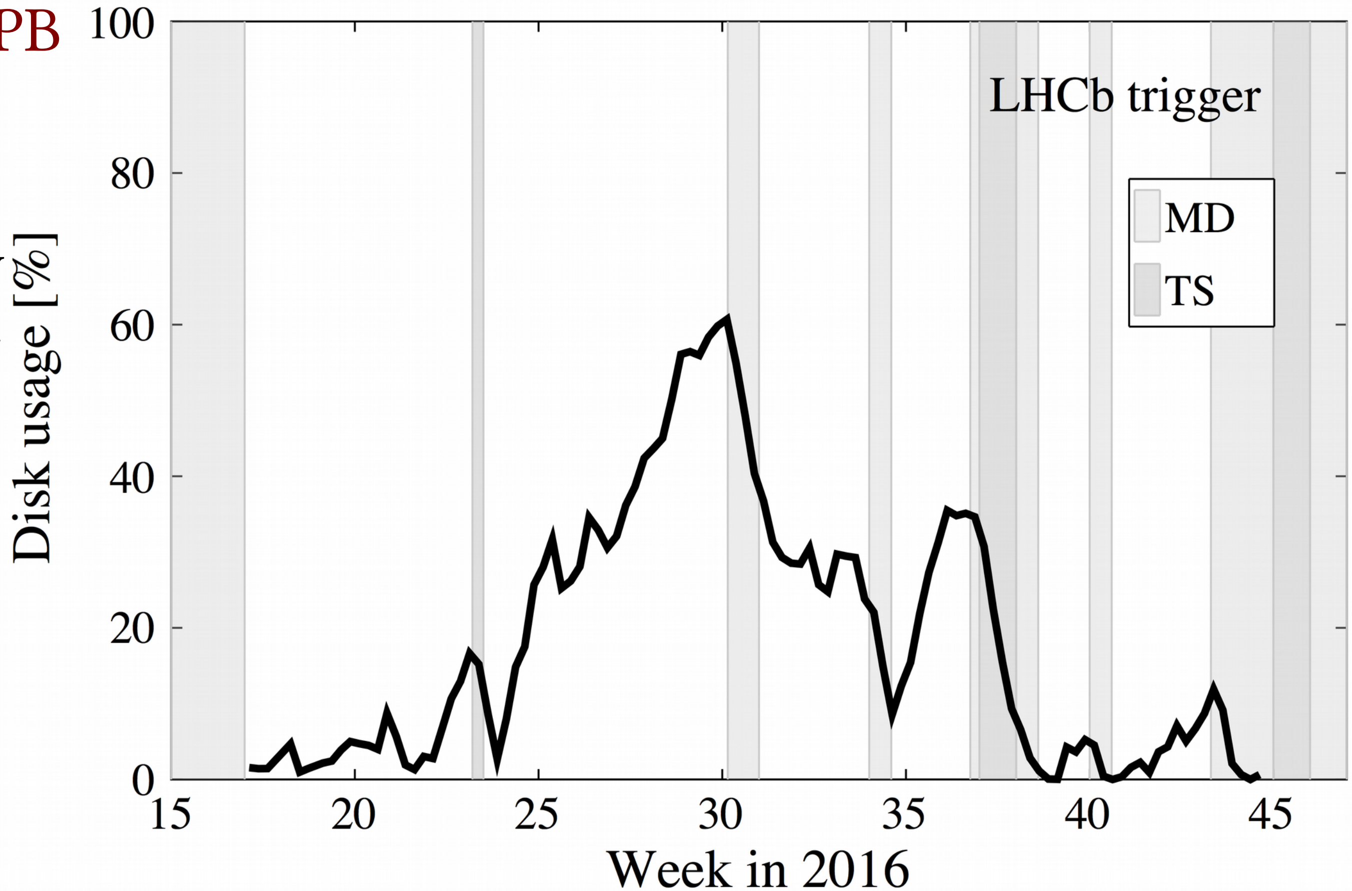


- Asynchronous processing of Hlt2 allows to optimally use farm resources to maximise physics output.

Now 10 PB

Filled in 1 day at 1 MHz Hlt1 output.

Increase by orders of magnitude???



Now takes weeks to empty if full.

Months to process?

Disk Buffer in Upgrade?

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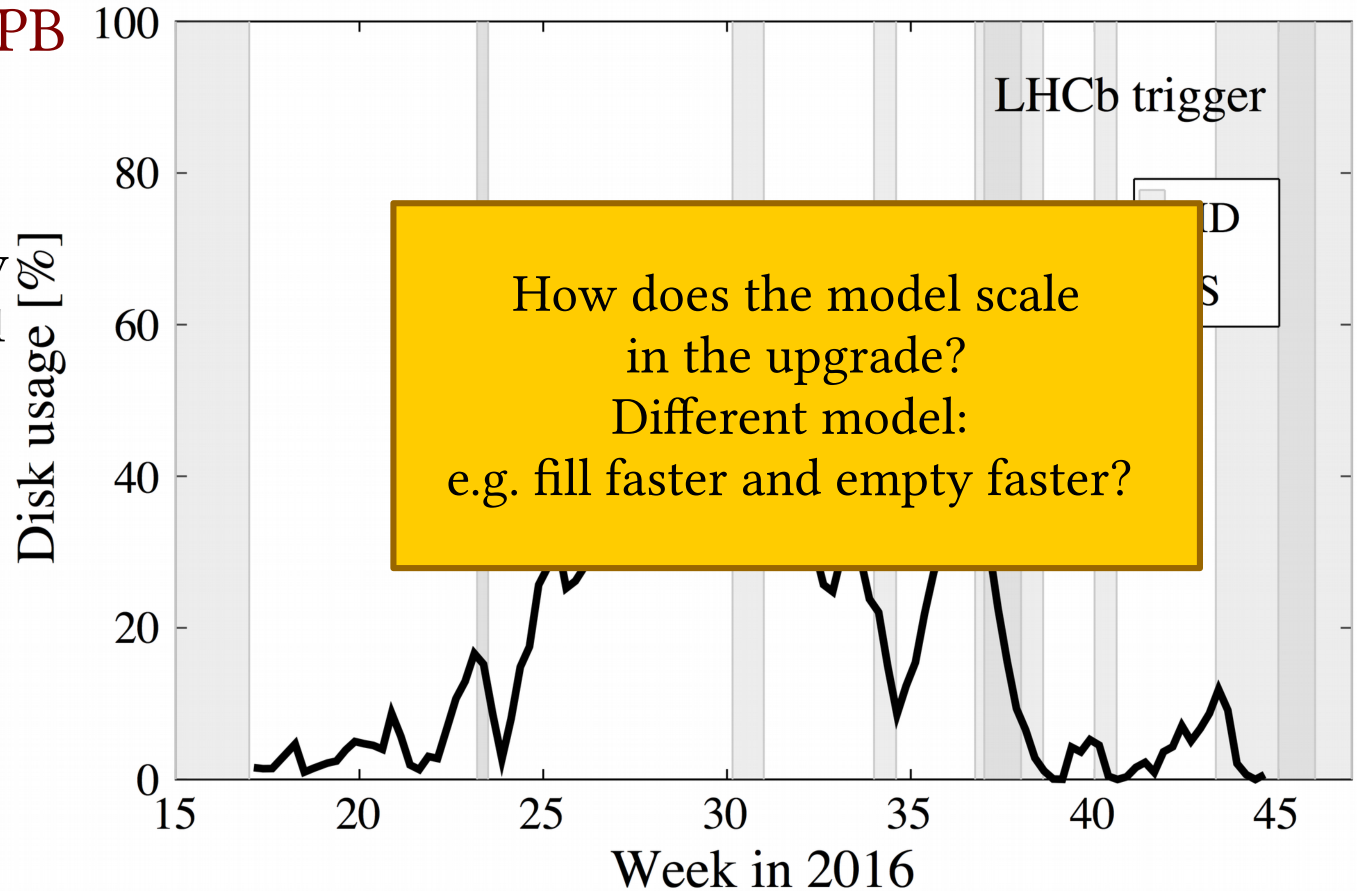
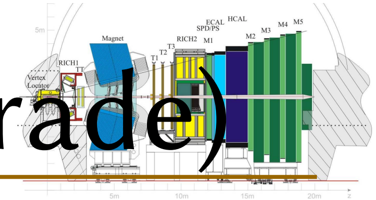
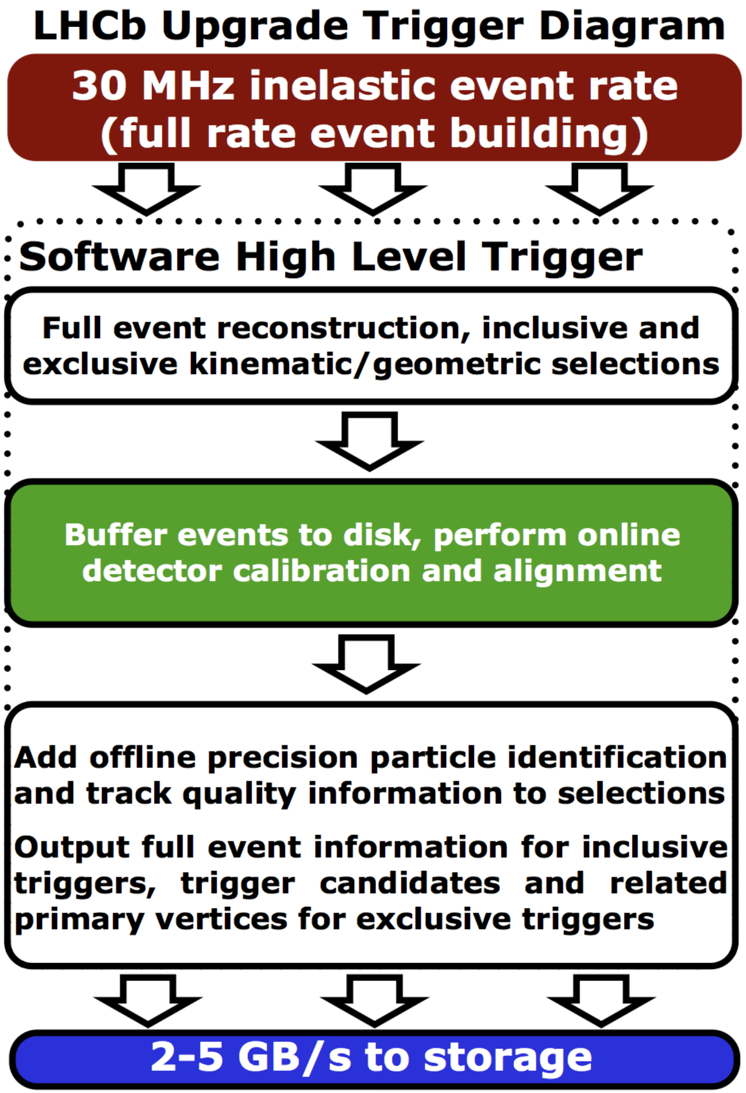


Now takes weeks to empty if full. → Months to process?

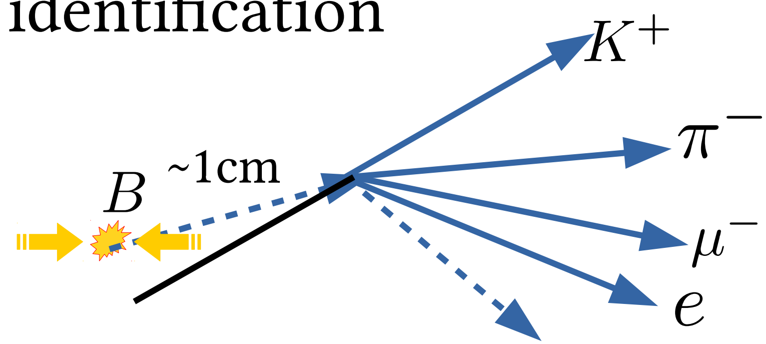
Event selection and analysis (Upgrade)





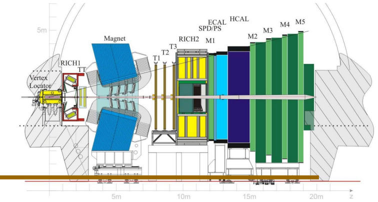
Hlt2:

- Reconstruct full event including particle identification



- Reduce bandwidth written to storage
  - Pure and efficient event selection
  - Reduce event information

Output bandwidth



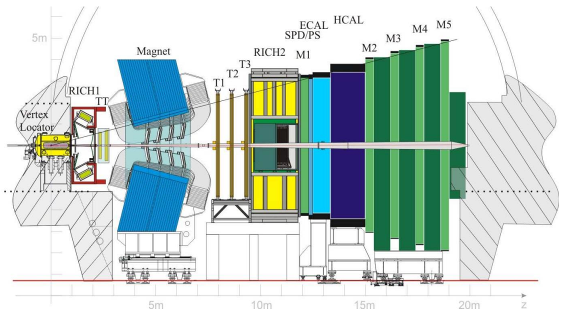
- Limit to tape storage 2 – 5 GB/s
- Upgrade events size 100 kB
- Assume 10 (5) % efficiency of full selection chain

  ⟶ Beauty bandwidth = 100 kB * 200 kHz * 0.1 = 2 GB/s,
  Charm bandwidth = 100 kB * 5 MHz * 0.05 = 25 GB/s

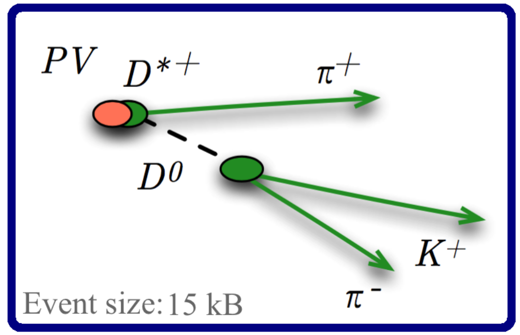
  ⟶ No way to write out full information of all signal events, beauty and charm

Turbo stream

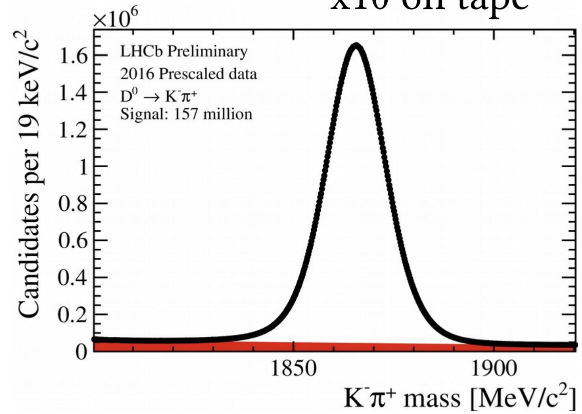
arXiv:1604.05596



TURBO (since 2015)

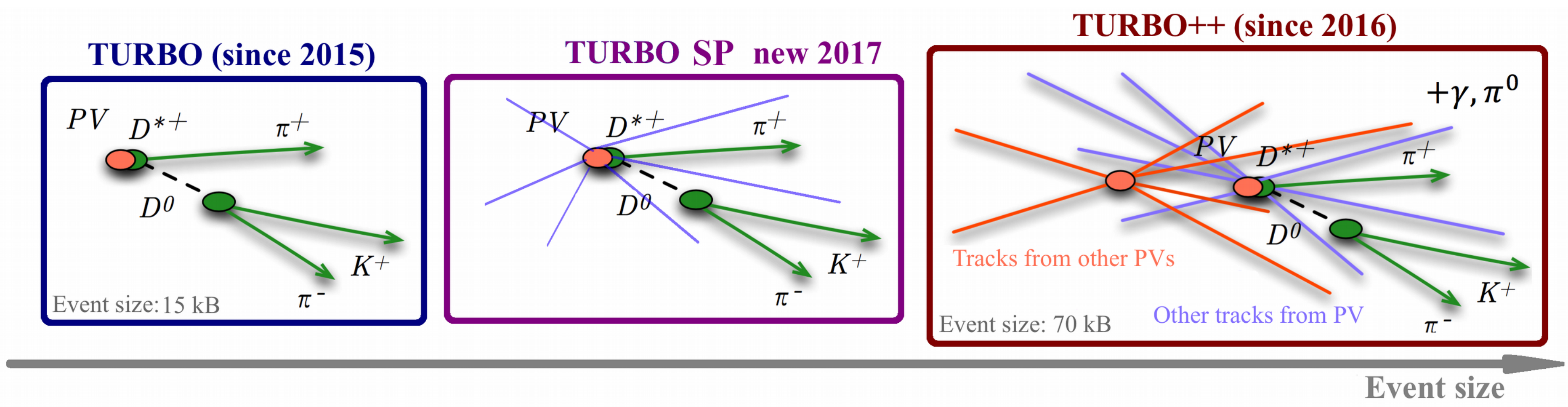


x10 on tape



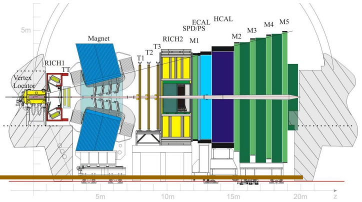
- Save objects reconstructed in trigger, discard raw detector information
  - Order of magnitude reduction in event size
- Analyses done on trigger output
  - Requires best detector calibration, and precise and efficient reconstruction in trigger
- Most published LHCb Run 2 analyses done with Turbo stream
  - Run 2 online reconstruction equals Run 2 offline reconstruction
  - Charm yields factors higher in Run 2 compared to Run 1

Turbo stream options



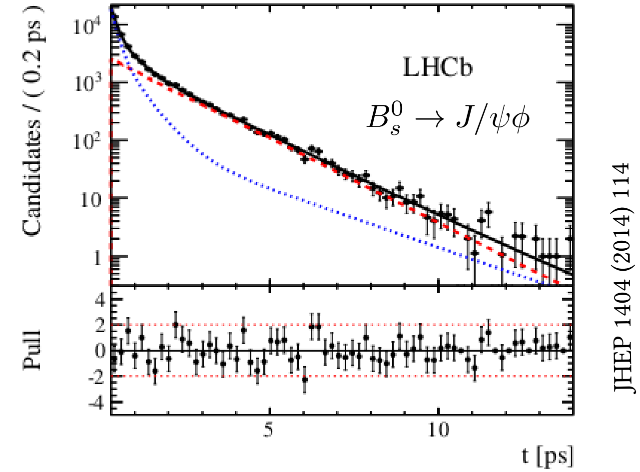
- Turbo concept evolved over last years to give flexibility to analysts
  - Choose what you want to persist with a given bandwidth
  - Trade off between number of events and information per event
- Turbo: E.g. ideal for high rate charm (25 GB/s $\longrightarrow$ 2.5 GB/s), beauty
- Turbo SP: E.g. save B-hadron candidate and opposite B for flavour tagging, spectroscopy, jets, dark photons, ...
- Turbo++: E.g. rare decays with small trigger rate, to later optimize selection and event classification

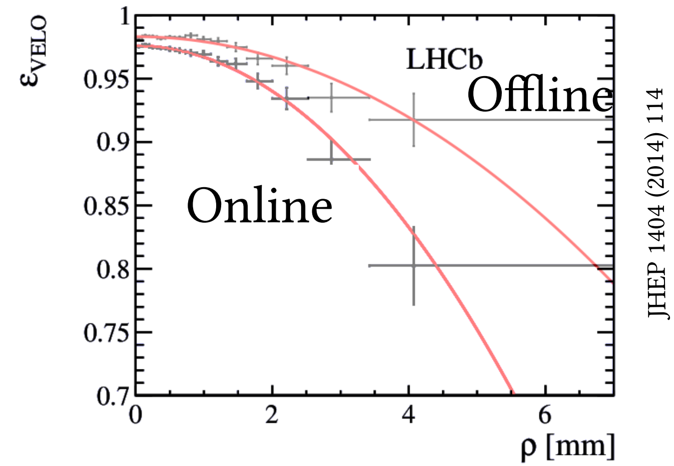
Online = Offline (Best quality)

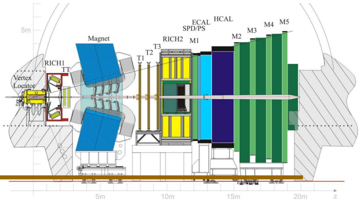


- High precision measurements require understanding of efficiencies
  - Efficiencies determined via combination of simulation and data-driven methods
- Any big inefficiency leads to systematic uncertainties in analysis
  - Best to have fewer inefficiencies $\longrightarrow$ Online = Offline
  - And high efficiency reconstruction from the start
- Also: Better use of resources
  - No offline processing needed
  - More resources for analysis and simulation

Example:
Lifetime measurement





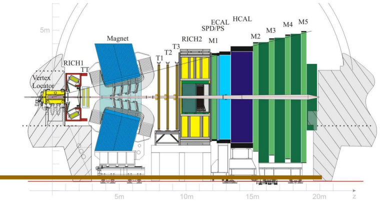


Conclusion

- Everything is awesome…

- … wait

Coming back to challenges



30 MHz

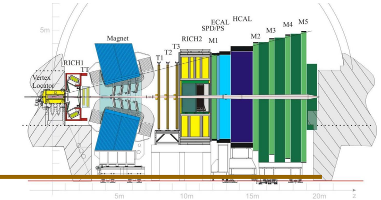
- Farm budget for 1000 computing nodes
- Benchmark on today's CPUs and extrapolate to 2021

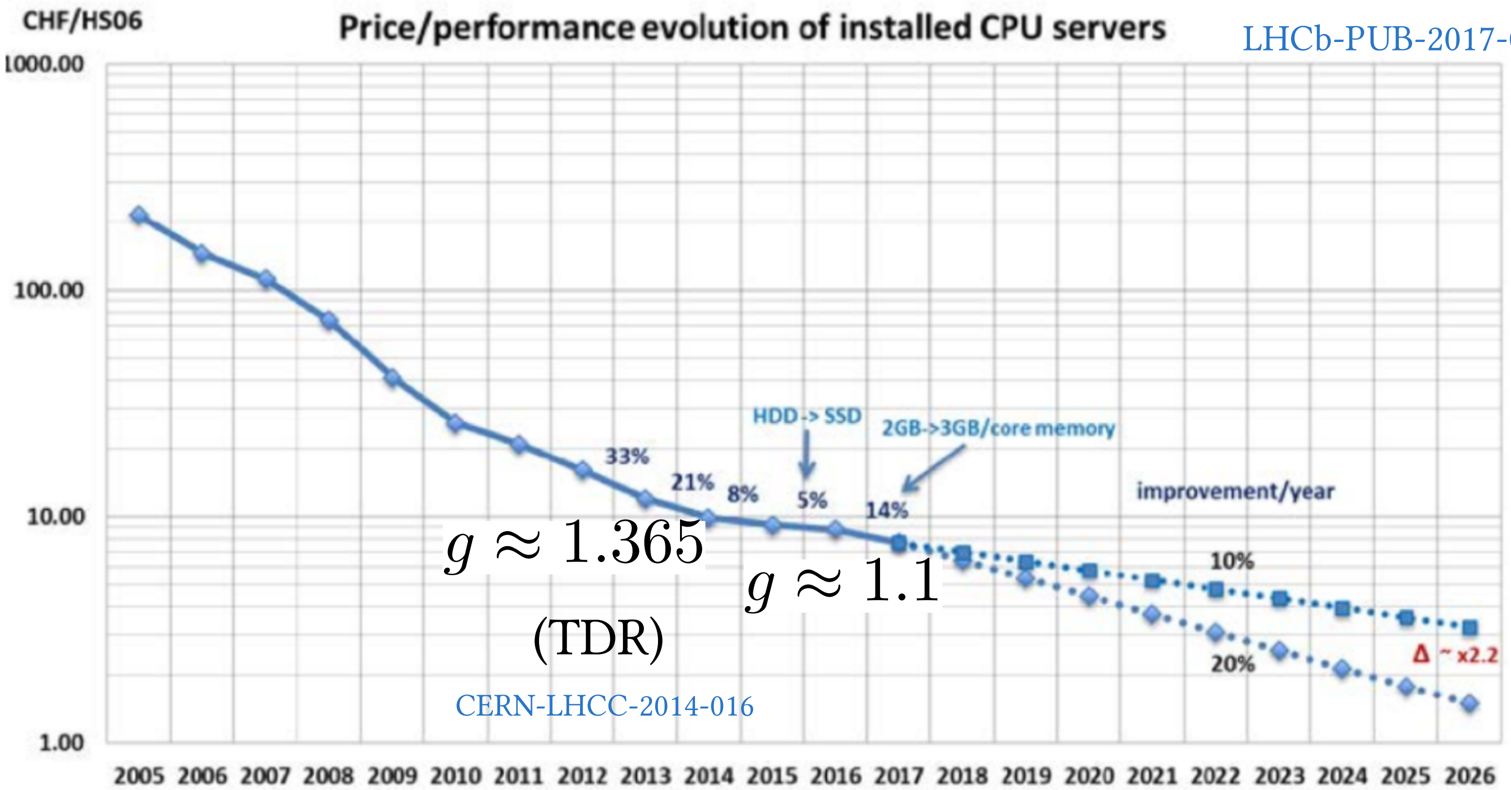
$$T = N \times t \times g^{\Delta y}$$

- Farm throughput T, Number of nodes N, node throughput t, growth factor per year g, years until data taking Δy
- Goal:

$$T > 30\,\mathrm{MHz}$$

Farm throughput estimates





LHCb-PUB-2017-005

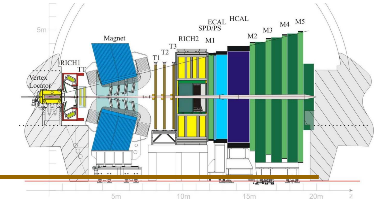
$g \approx 1.365$ (TDR)

$g \approx 1.1$

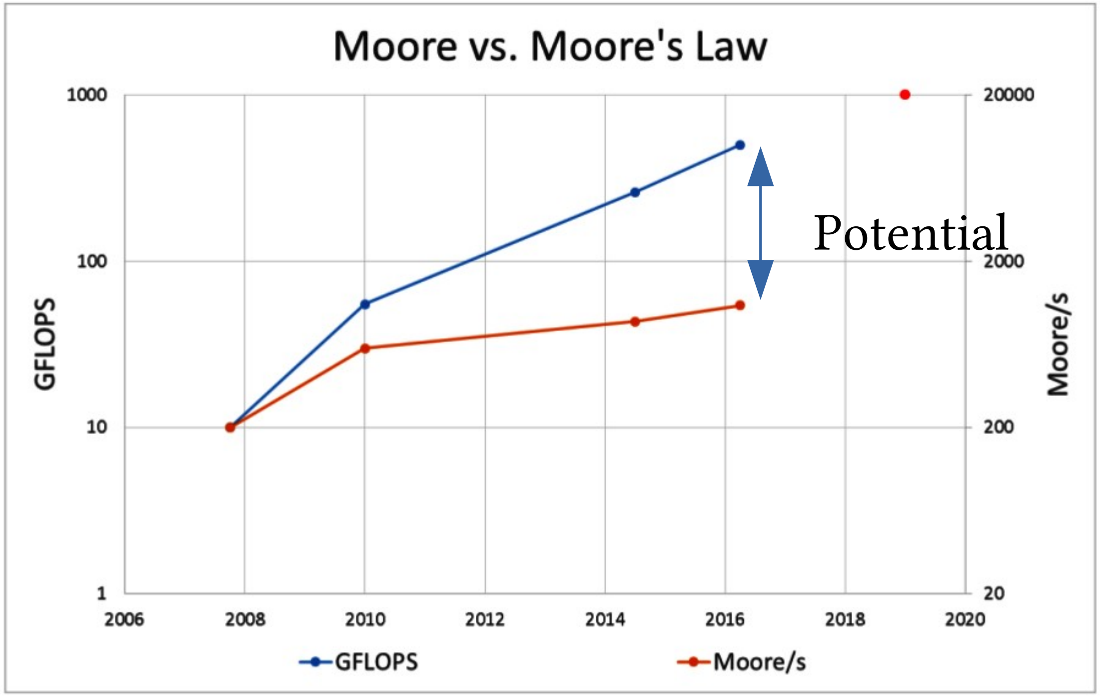
CERN-LHCC-2014-016

Reconstruction	T in 2012	T in 2017
PVs + high pt tracks	33 MHz	5 MHz
+ Kalman filter	14 MHz	2.4 MHz

Changing CPUs



LHCb-PUB-2017-005

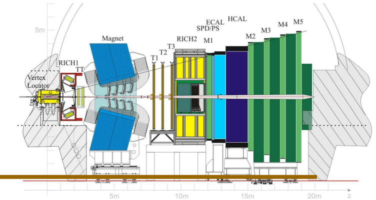


Moore name of LHCb trigger application.

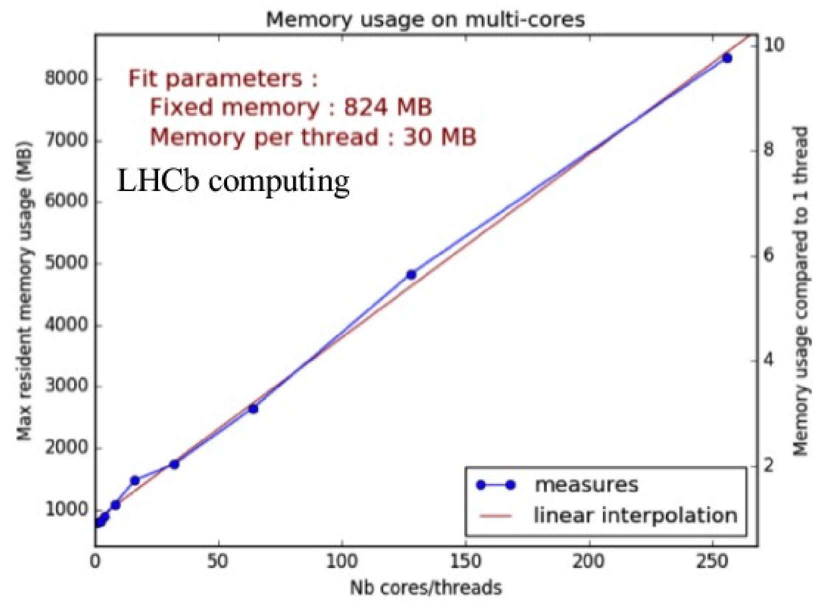
- Clock frequency increase slowed down since a decade
- Made up by more cores per processor (multi-threading) and more instructions per cycle (vectorisation)

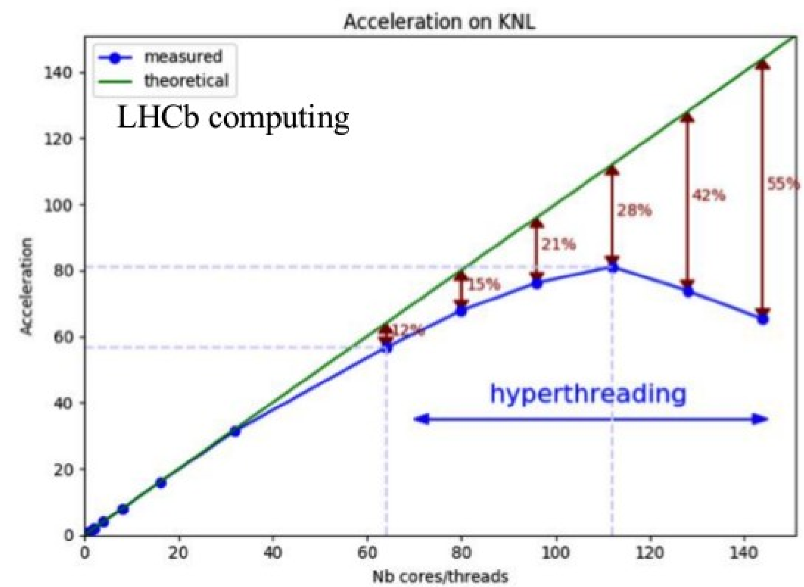
  ⟶ Both need optimised software

Multi-threaded framework

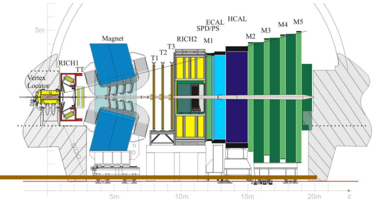


- Currently, run many independent instances of same application.
- First prototype with new software framework running one instance with multiple threads
  - Significant work was needed
  - Tested on special hardware with many more cores than usual CPUs
  - Small increase in memory per thread
  - Nearly optimal scaling with number of cores
- How much does it gain us compared to old framework?

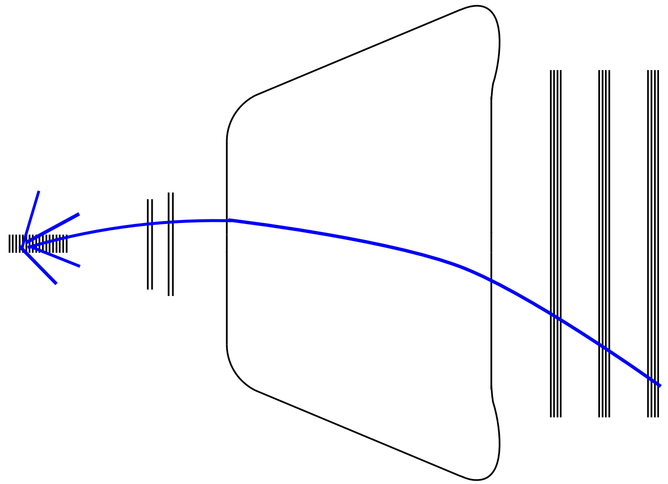




Being smarter and avoiding work

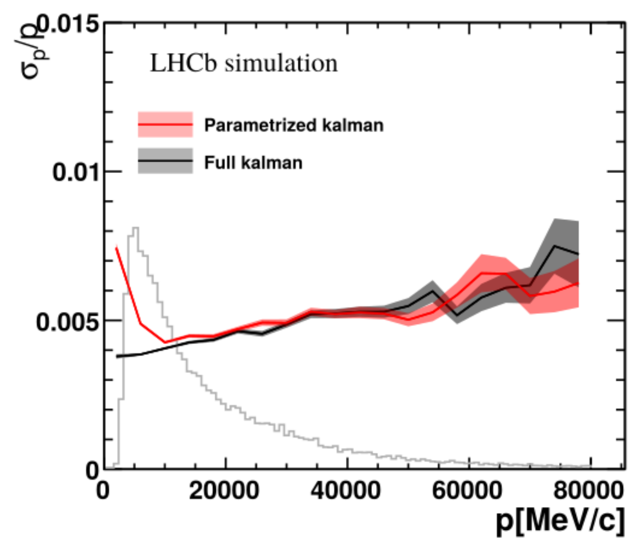


(one of many examples)

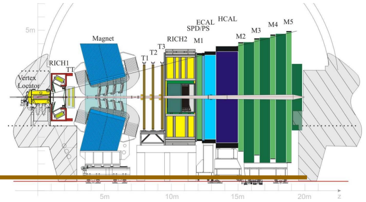


- Track fit (Kalman filter) time consuming
  - Material lookup
  - B-Field propagation
- From Run 1 to Run 2 replaced detailed material map with a simplified map

- One step further "Parameterized Kalman"
  - Parameterize material look-up and B-field propagation with analytic functions
  - Very fast and already good performance



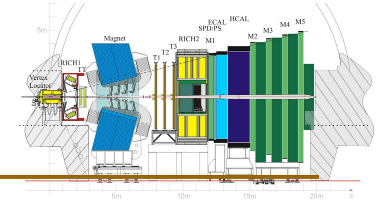
Conclusion



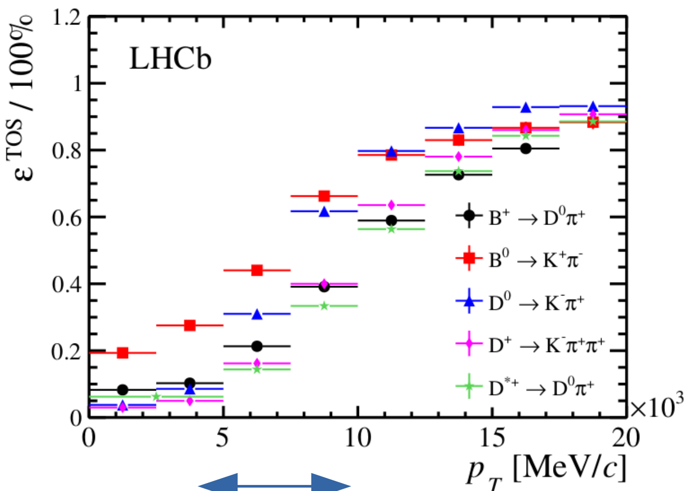
- Full software trigger is a unique opportunity to fully exploit increased luminosity
- Several concepts for Upgrade already up and running
  - Real-time alignment and calibration
  - Real-time event analysis (Turbo stream)
- Challenging and exciting to
  - Solve a big computing problem in the next years
  - Provide high quality for precision measurements

- Backup

Efficiency comparison (backup)

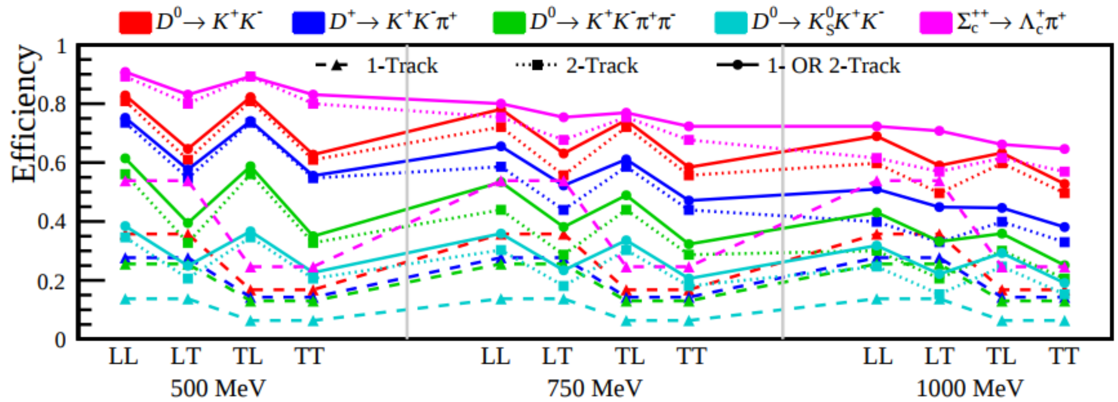


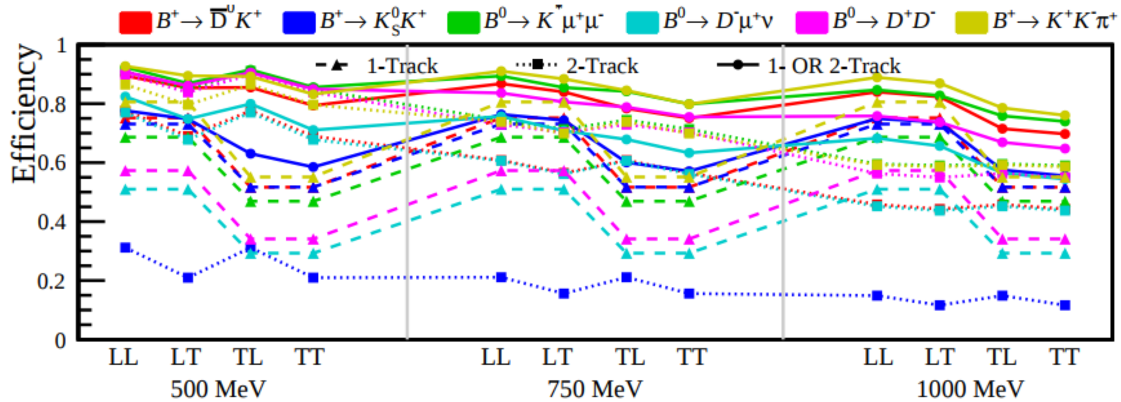
Run 1 L0 efficiency



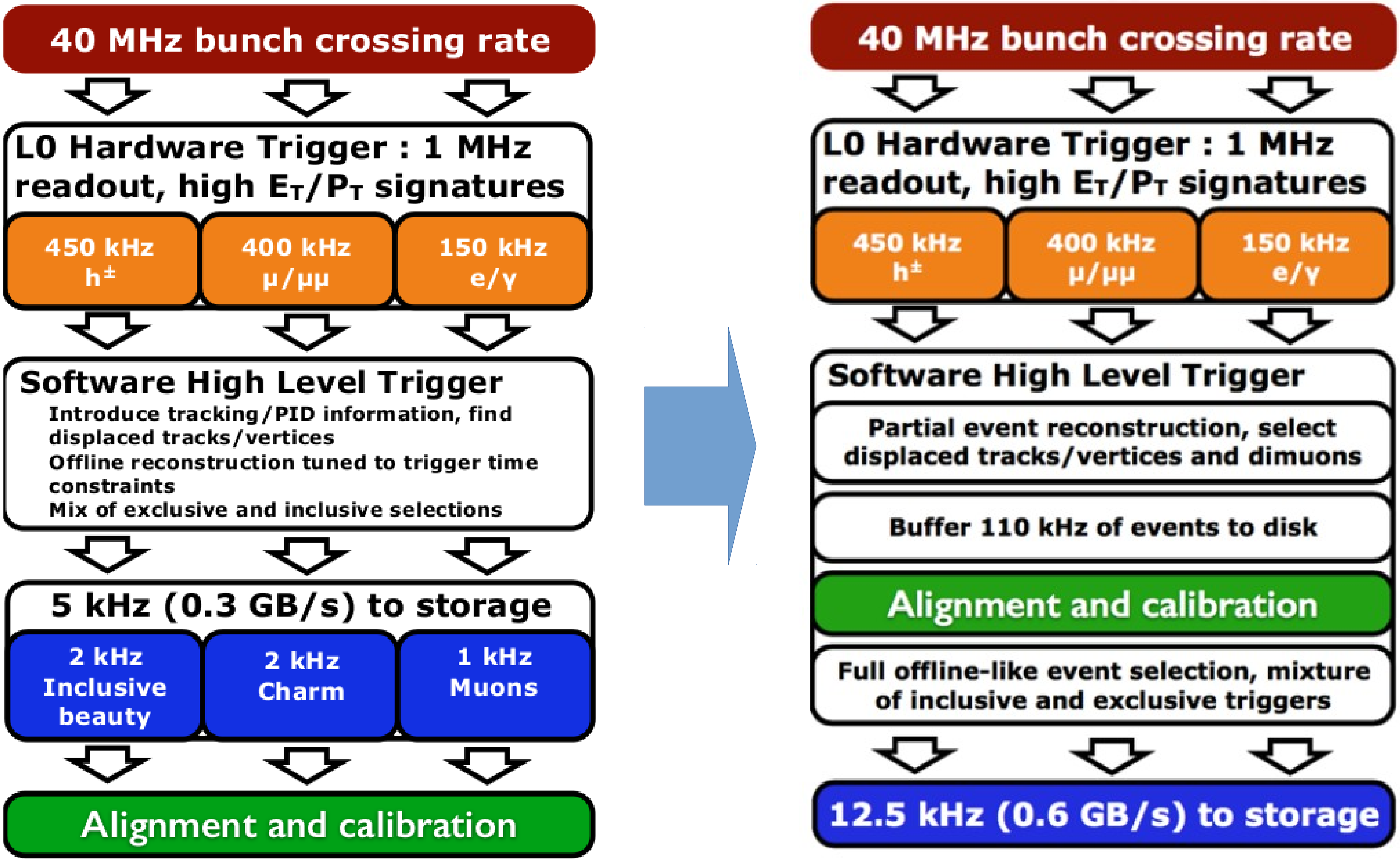
Average pt

Hlt1 efficiency estimates for Upgrade





Trigger from Run1 to Run2



Run 2 summary

- Run2 **software** trigger really nice
  - Coherent reconstruction from Hlt1 to offline (alignments, calibrations, algorithms)
  - Hlt1 very efficient, learned how to adjust purity in times of high LHC efficiency
  - Hlt2 runs previous offline reconstruction upfront
  - Turbo provides great flexibility to trade event size vs. event rate