The LHCb trigger and its upgrade

PANIC 2014, Hamburg

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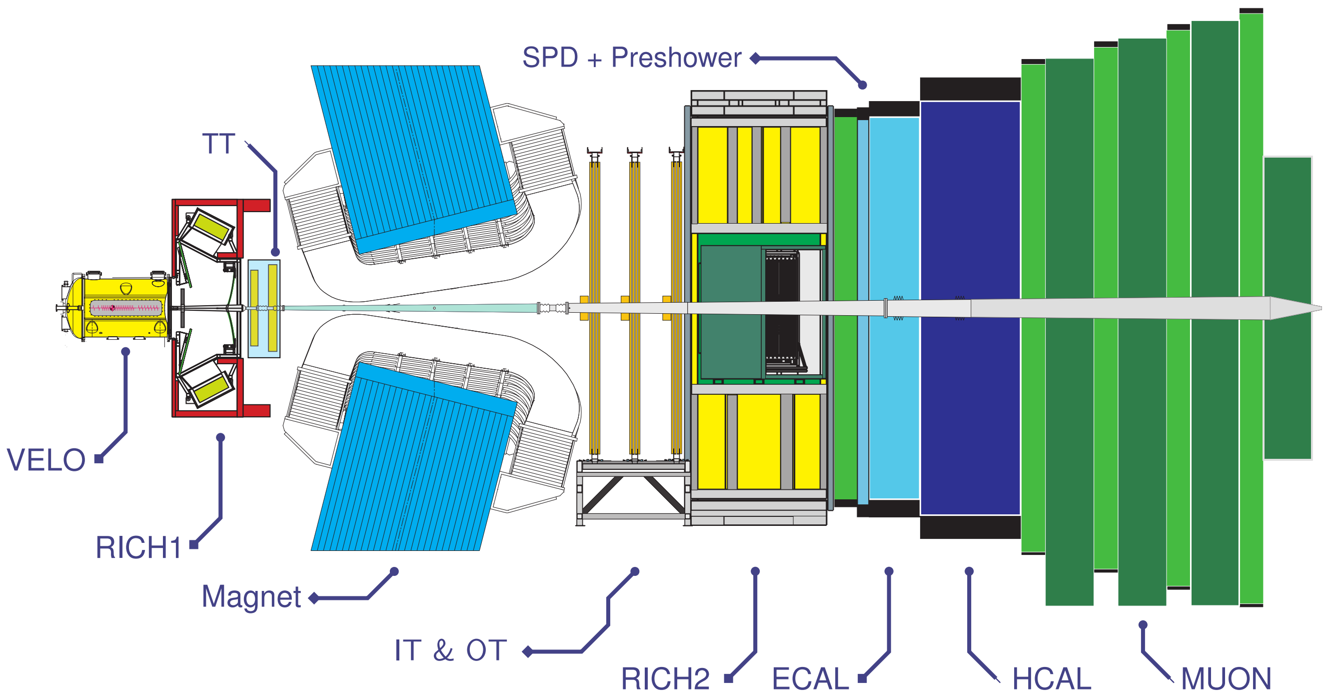
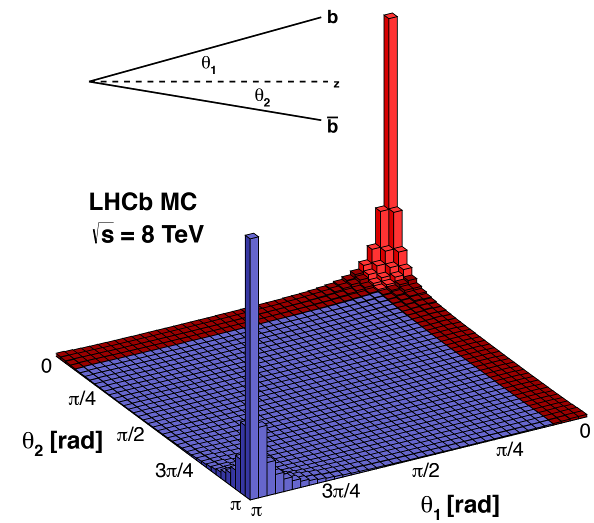
on behalf of the LHCb Collaboration

LHCb detector

single arm forward spectrometer designed for precision measurements of b- and c-hadrons (CP violation, rare decays, heavy flavour production)

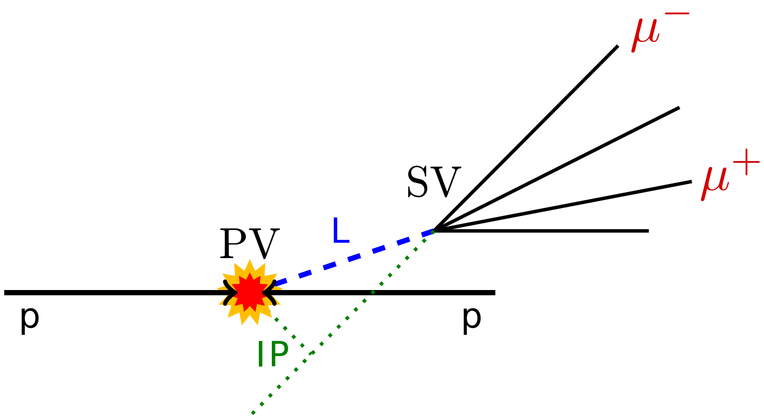
- acceptance coverage $2 < \eta < 5$





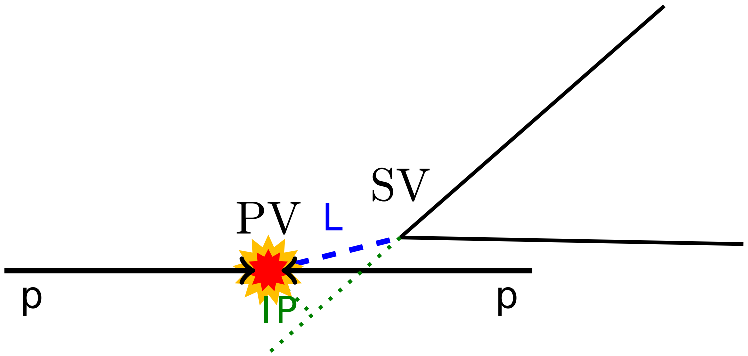
- VELO: excellent decay time resolution ~ 45 fs –> good separation of B vertices
- Tracking System: good momentum ($\Delta p / p = 0.4 – 0.6$ %) and mass resolution
- Particle Identification: good K - π separation (~ 95 % efficient for ~ 5 % mis-id)
  and muon identification (~ 97 % efficient for 1-3 % mis-id)

Beauty hadrons



- B$^{\pm}$ mass ~ 5.28 GeV
- daughter p_T O(1 GeV)
- Flight distance ~ 1 cm (τ ~ 1.5 ps)
- Common signature: detached μμ

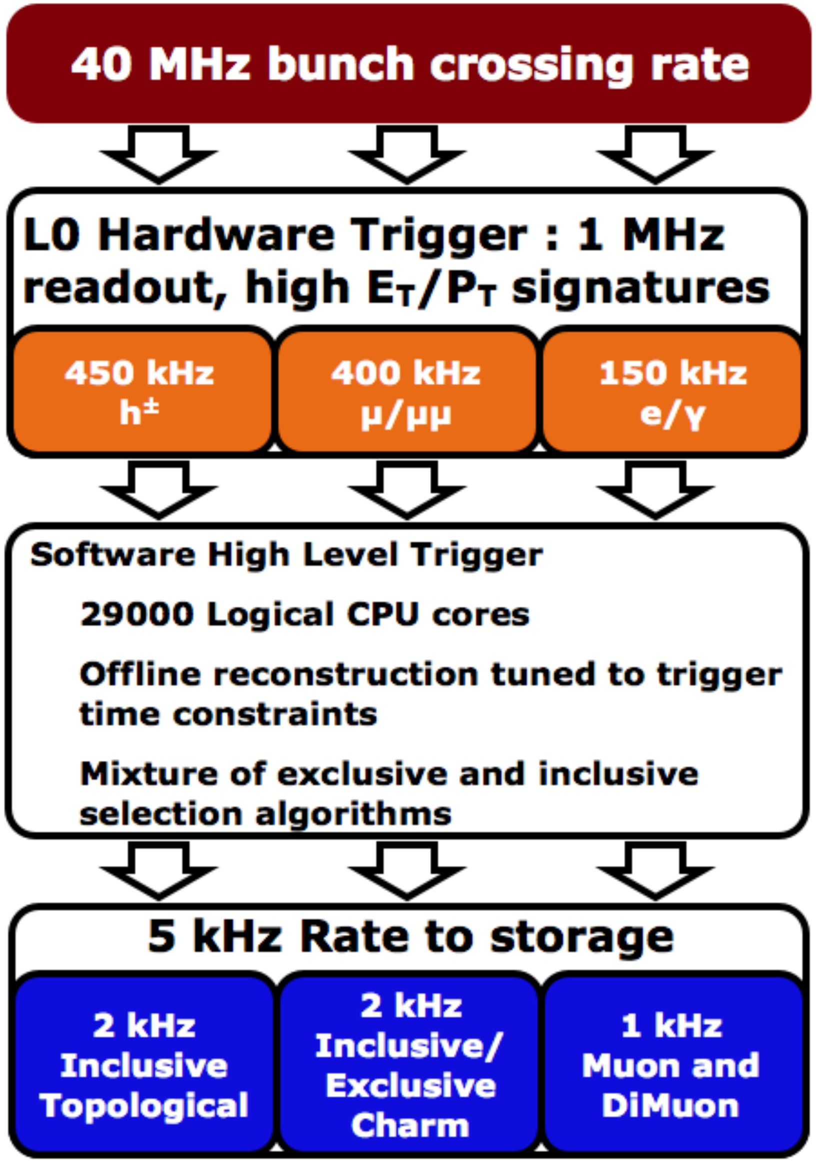
Charm hadrons



- D^{0} mass ~ 1.86 GeV
- sizeable daughter p_T
- flight distance ~ 4 mm (τ ~ 0.4 ps)
- Can be produced in B-decays

–> triggering on displaced vertices with high p_T tracks

LHCb trigger in Run1



Two level trigger:

L0 hardware trigger –> reduces rate to 1 MHz
(maximum rate imposed by front-end electronics)

HLT software trigger –> reduces rate to ~ 5 kHz
C++ based program running in Event Filter Farm

1st stage (HLT1):
partial event reconstruction + inclusive selections

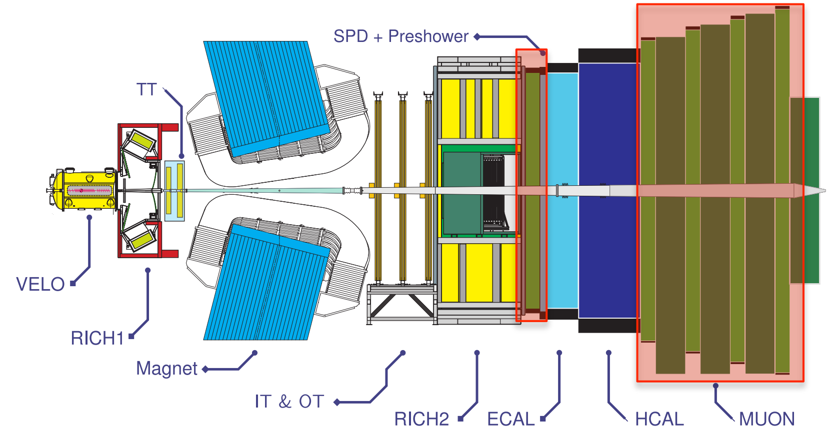
2nd stage (HLT2):
full event reconstruction + several inclusive and exclusive selections

L0 Muon trigger

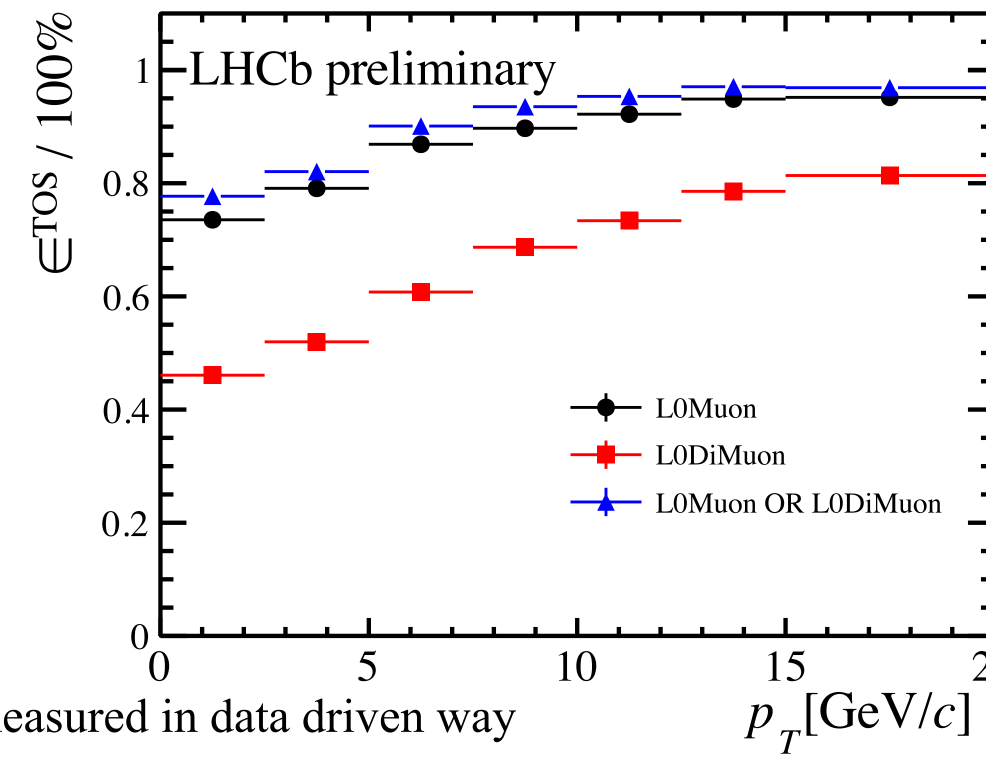
- Reconstructs muon track segments

Search for straight lines of hits in five muon chambers pointing towards interaction point

–> momentum resolution of ~ 20 %



B –> J/Ψ K$^+$



Triggers:

- single muon p_T > 1.76 GeV
- di-muon p_T1 x p_T2 > (1.6 GeV)^2

- Total muon rate ~ 400 kHz

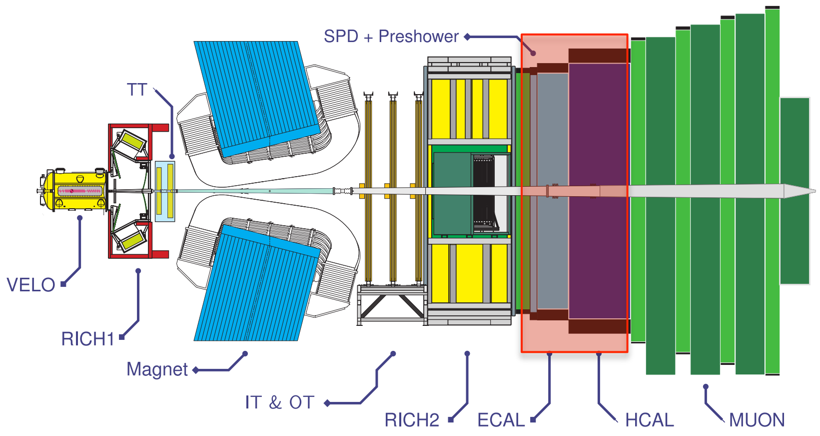
- integrated efficiency ~ 90 %

efficiencies after offline selection / measured in data driven way

L0 calorimeter trigger

- Requires calorimeter clusters with minimum transverse energy:

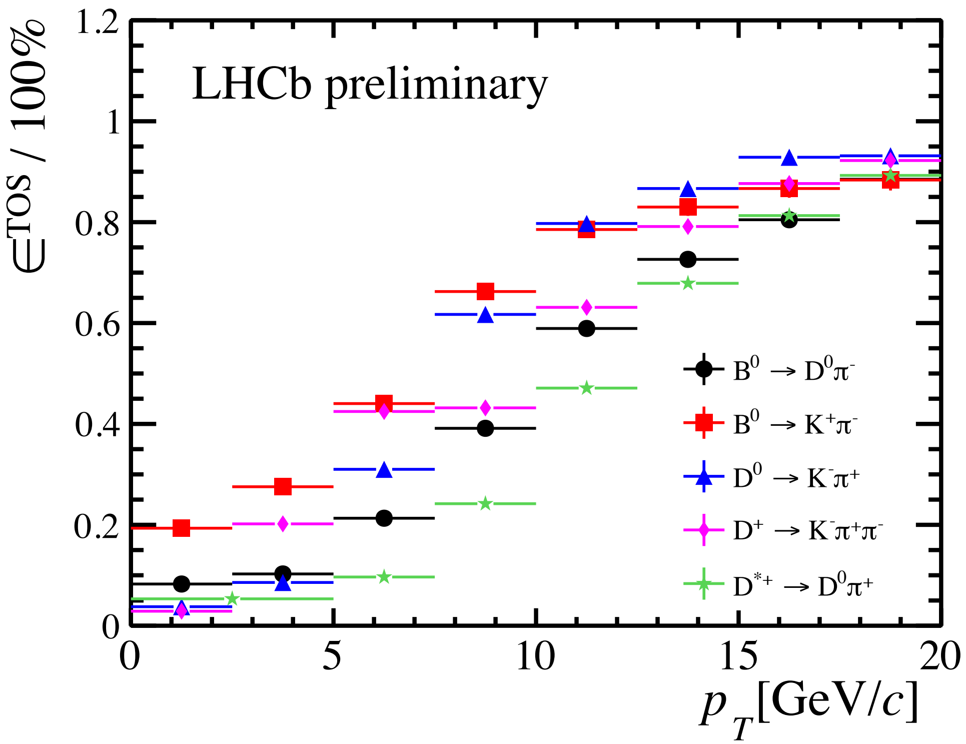
$$E_T = \sum_i E_i \sin\theta_i$$



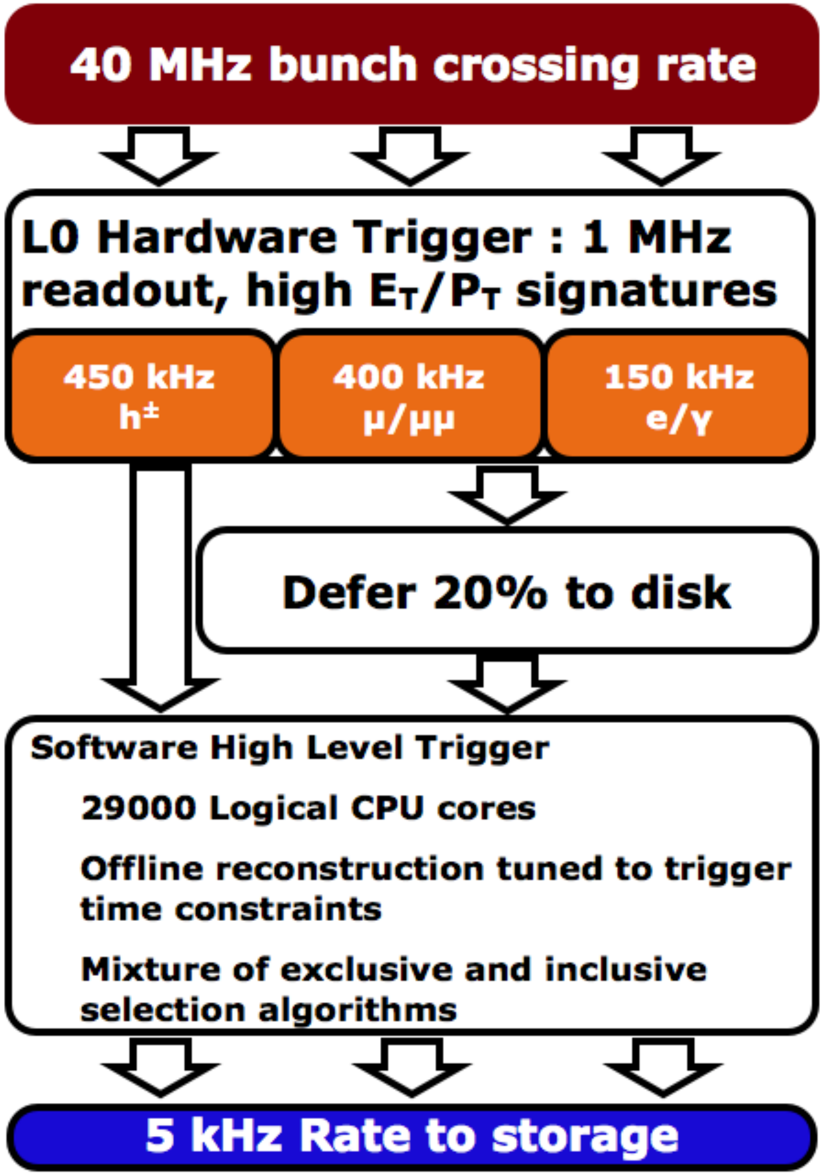
Hadron trigger:
- ECAL + HCAL clusters
- $E_T > 3.7$ GeV
- Rate: ~ 450 kHz

Electron / Photon trigger:
- PS + ECAL
  (SPD discriminates between e / γ)
- $E_T > 3.0$ GeV
- Rate: ~ 150 kHz

(~ 80 % efficient for radiative B –> X γ decays)



Deferred triggering

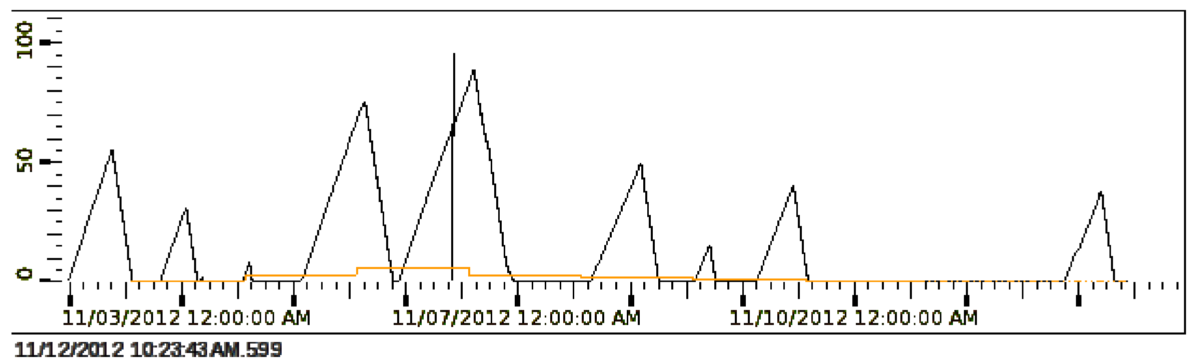


LHC delivers stable beams only for 30 % of the time
-> Event Filter Farm is unused for the rest

deferred triggering:

- 20 % of the L0 triggered events are temporarily saved
- analyzed later during inter-fill gaps

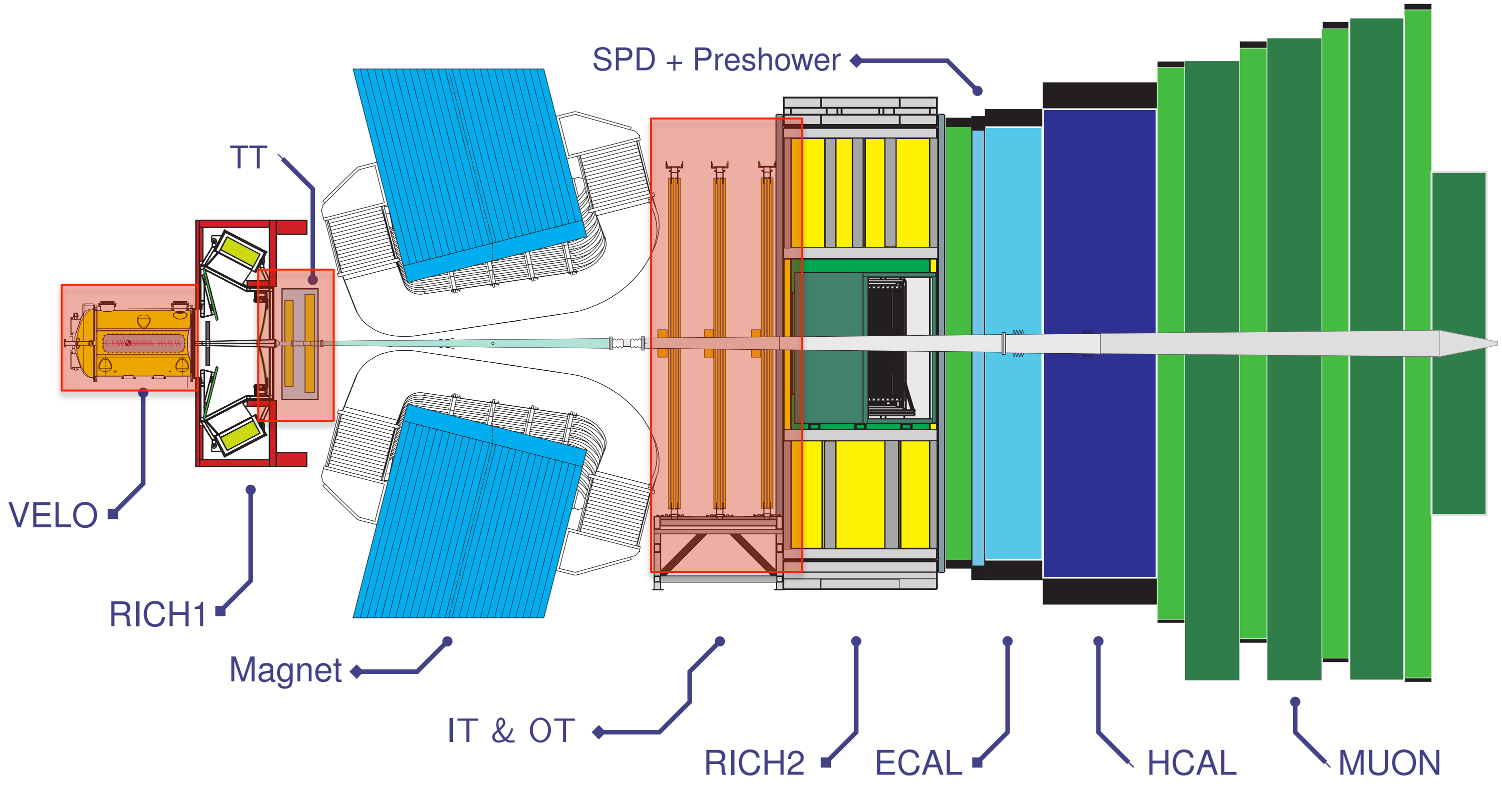
Disk usage in % as function of time



gain of CPU time used to improve reconstruction:

decrease minimum p_T from 500 to 300 MeV
special reconstruction for long-lived particles

Tracking in HLT1

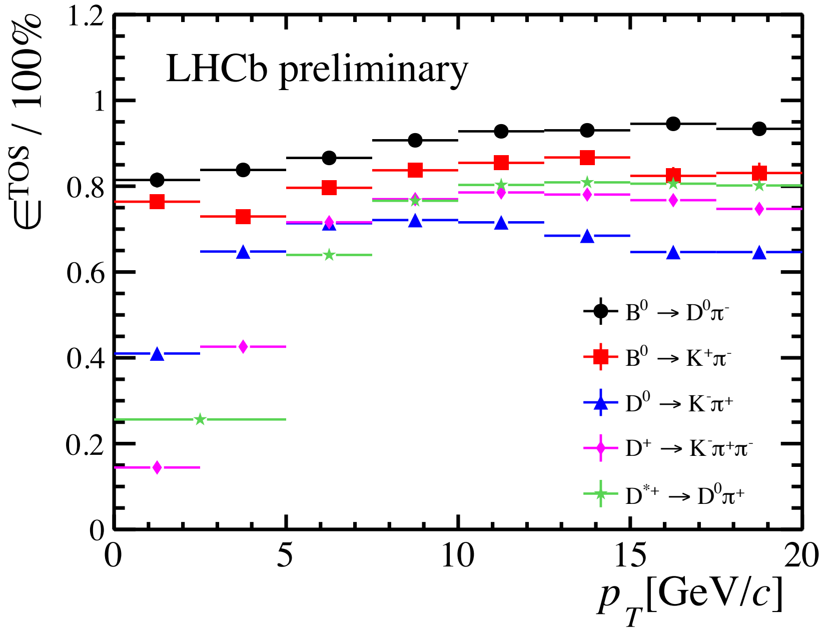


- Reconstruction of track segments in the vertex detector
- Select tracks with high IP or matched with hits in muon chambers
- Extrapolation to main tracking stations using same tracking algorithm than offline

HLT1 inclusive triggers

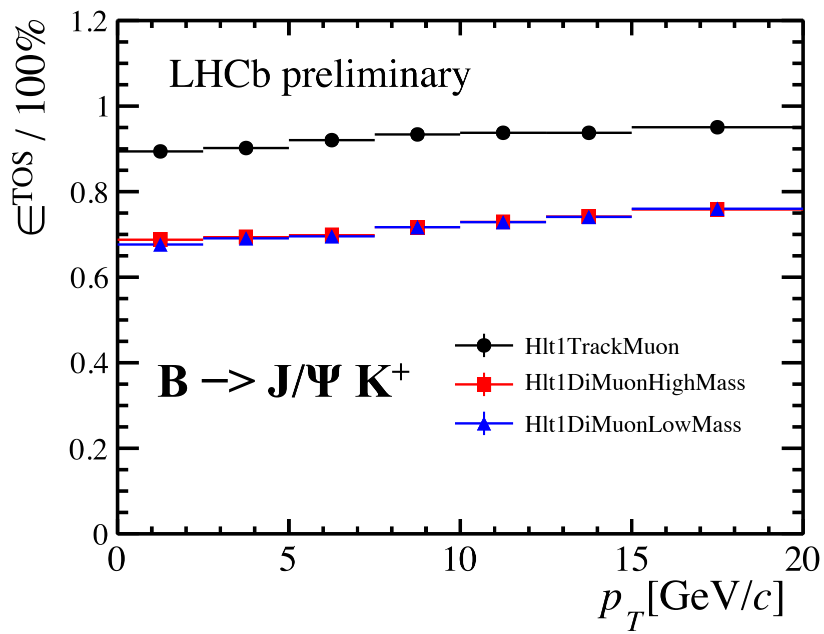
Inclusive beauty and charm trigger:

- single track with requirements on p_T and IP
- dominant trigger for most channels without leptons
- output rate of ~ 58 kHz



Inclusive muon triggers:

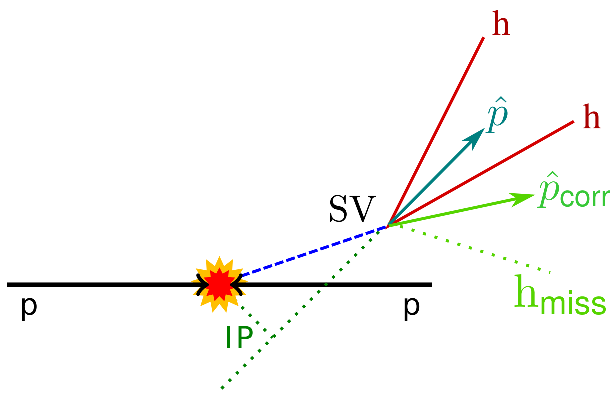
- single + dimuon triggers
- requirements on p_T, IP and di-muon mass
- output rate of ~ 14 kHz



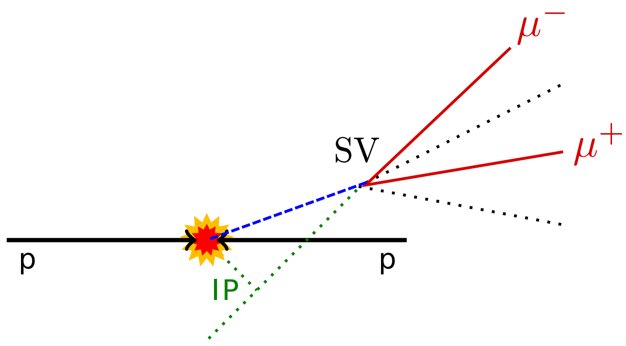
- Full event reconstruction for all tracks with $p_T > 300$ MeV
- Composition of inclusive + exclusive selections

Several inclusive and exclusive selections:

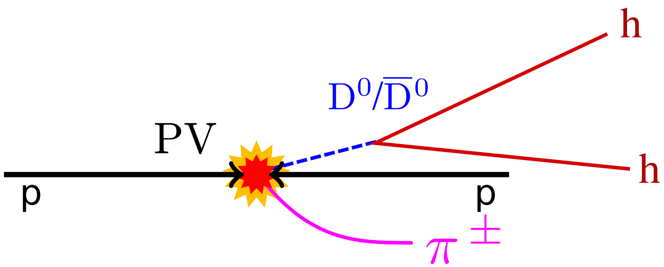
Generic beauty trigger (Topological trigger)



Inclusive dimuon triggers

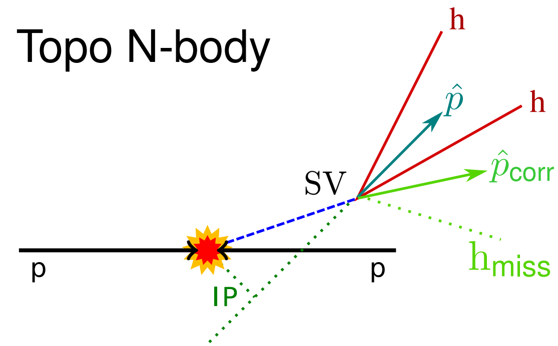


Inclusive and exclusive charm triggers



HLT2 Topological lines

Inclusive trigger for b-decays to 2, 3 or 4 charged tracks

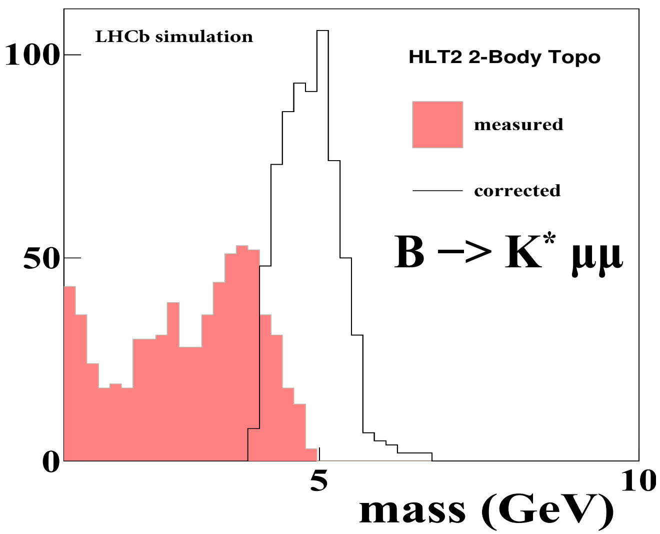


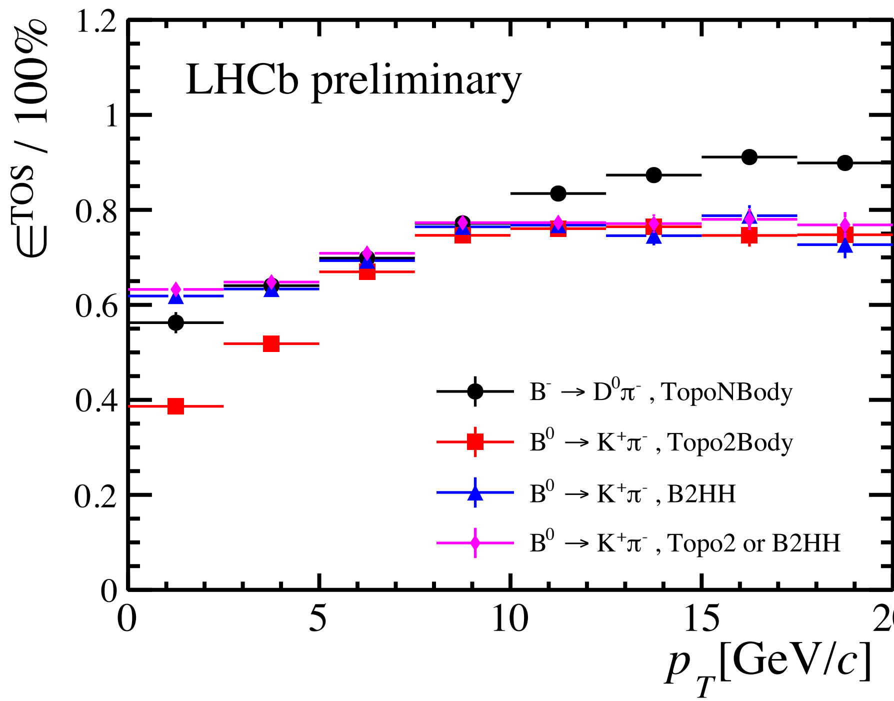
- fast and robust implementation using BDT
- corrected mass is important input variable

$$m_{corr} = \sqrt{m^2 + |p_T^{miss}|^2} + p_T^{miss}$$

allows also to select partially reconstructed decays

output rate is ~ 2 kHz

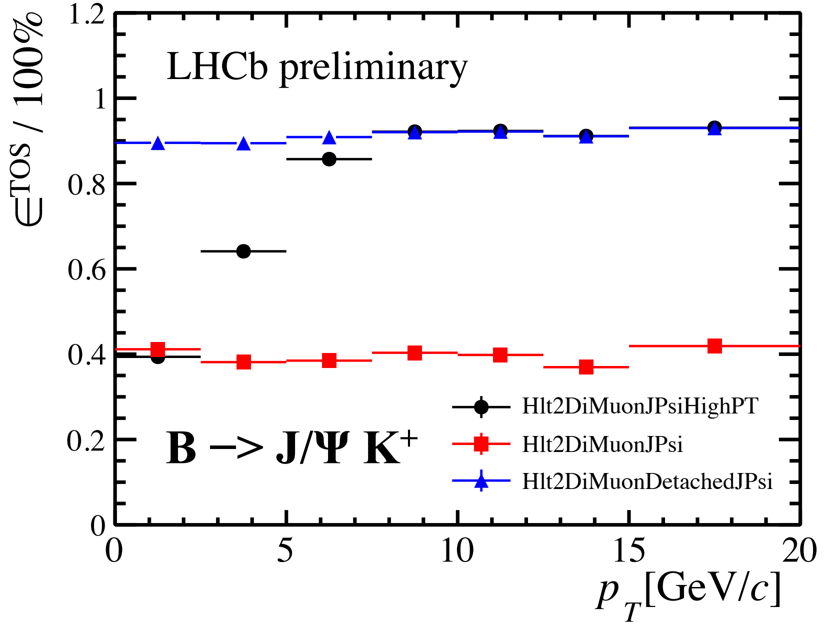




HLT2 Inclusive + exclusive trigger lines

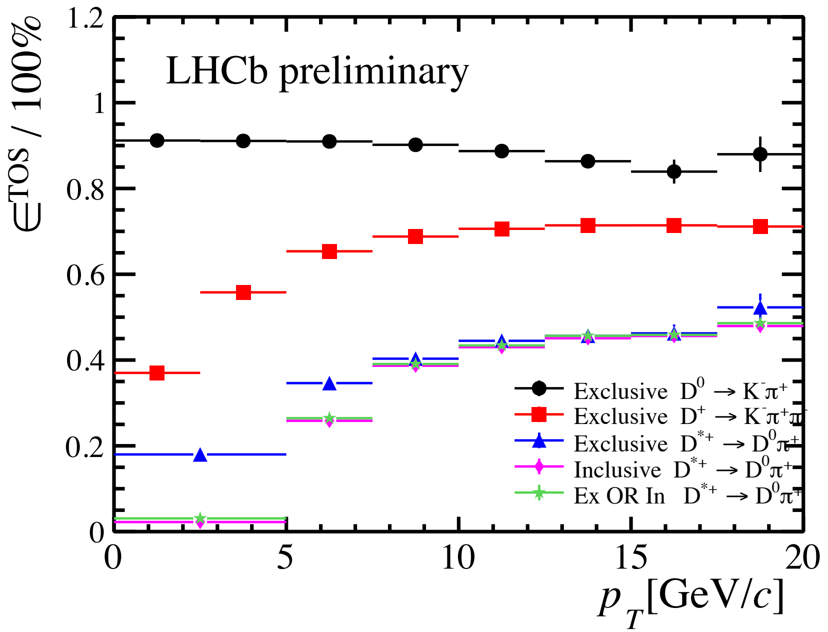
Inclusive dimuon triggers:

- Prompt and detached dimuon lines
- muon ID identical to offline
- total output rate ~ 1kHz



Exclusive charm triggers:

- based on tight cuts on invariant mass
- Total charm output rate ~ 2 kHz
- only D* –> D^0 π selected inlcusively



Conditions for Run 2

Running at $\sqrt{s}$ = 13 TeV:

–> 15 % increase of σ_{inel}

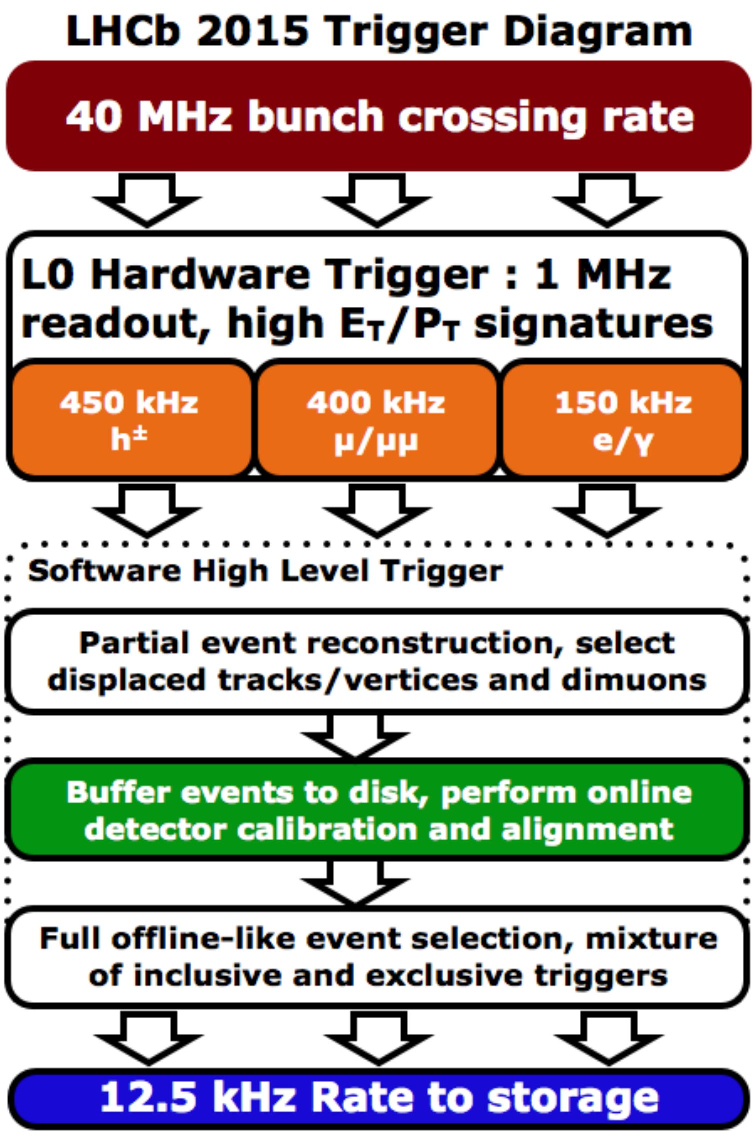
–> 20 % increase of multiplicity per collision

–> 60 % increase of σ_{bb}

With bunch spacing of 25 ns (2200 bunches) and target luminosity of **$4x10^{32}$ $cm^{-2}s^{-1}$**

–> 1.1 visible collisions per bunch crossing (compared to 1.7 at 8 TeV)

–> slightly simper events than in 2012 but more beauty and charm



More signal means trigger needs to be more selective:

–> make trigger more compatible to offline selection

Requirements:

- alignment and detector calibration already in HLT
- offline like RICH PID

–> event buffering is moved after HLT1 and used to run calibration

–> full offline-like selection in HLT2

Additional resources:

CPU in Event Filter Farm will be doubled

buffer storage: 1 PB –> 4 PB

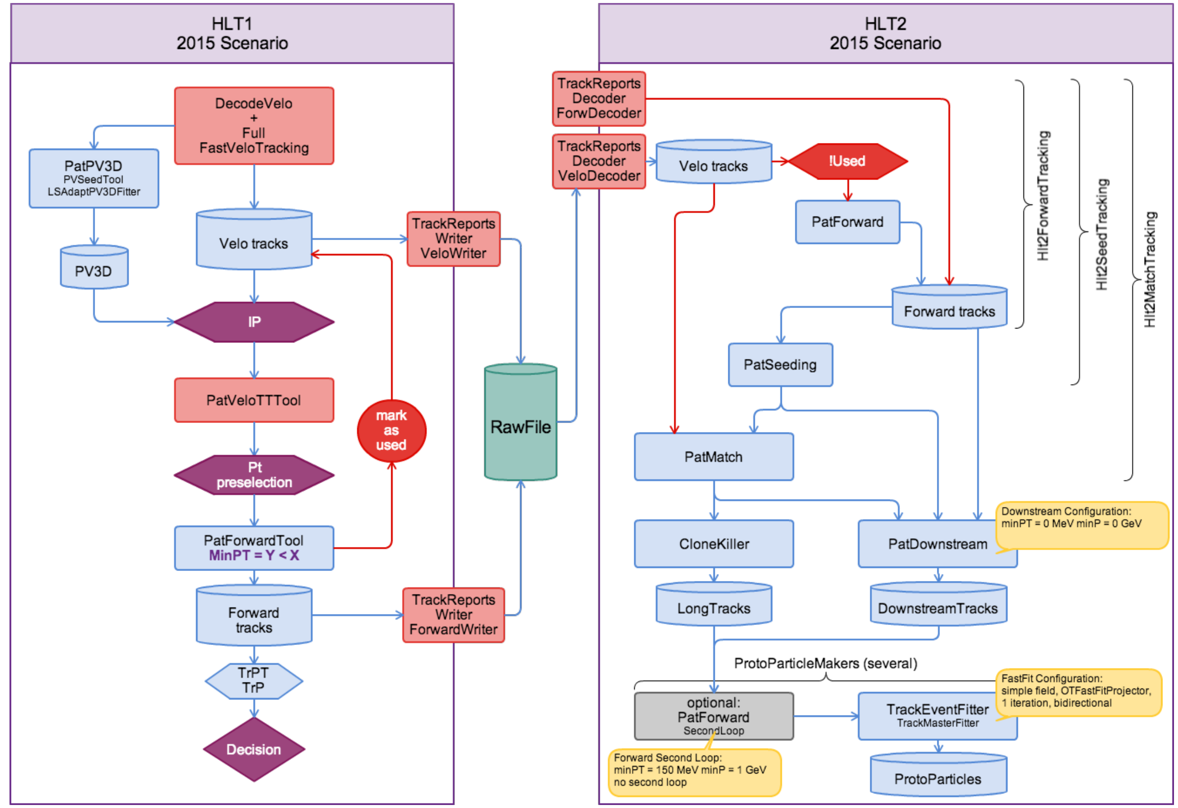
Developments for Run2

Tracking:

- full VELO tracking in HLT1
  all tracks with $p_T > 500$ MeV
  extrapolated to tracking stations

- tracks from HLT1 reused in HLT2

- updated alignment constants and
  offline-like tracking in HLT2



TurboStream:

- Signal rates start to become more and more challenging (especially for charm)

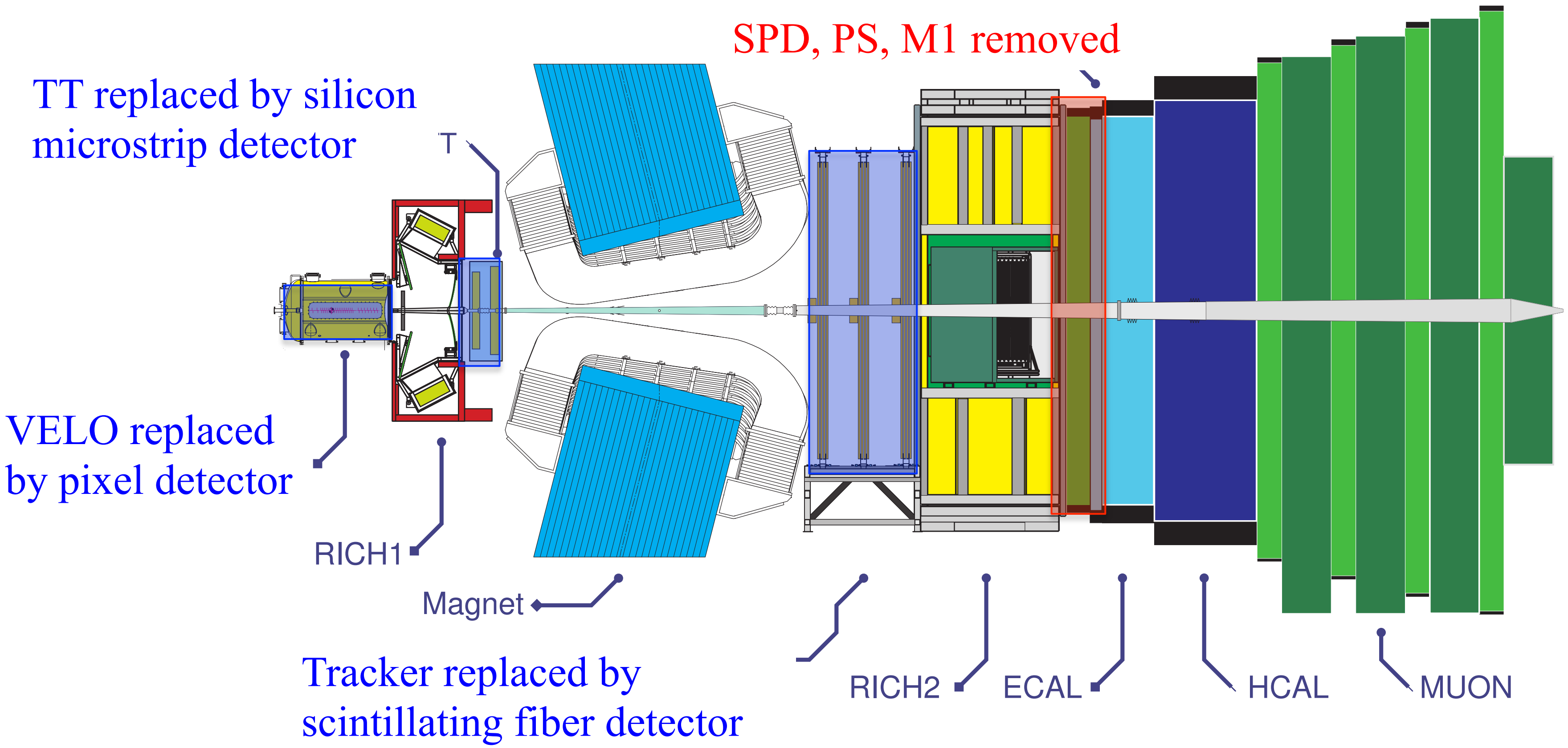
- Idea: Only particles found by trigger are used to perform analysis
  (smaller event size allows higher output rate)

–> these things become even more crucial for the upgrade

LHCb Upgrade

- Instantaneous luminosity: **L = 2 x 10^{33} cm^{-2} s^{-1}**
- Average number of interaction per bunch crossing **ν = 7.6**
- **30 MHz** inelastic collision rate
- Planed to collect a total sample of **50 fb^{-1}**

LHCB-TDR-013
LHCB-TDR-014
LHCB-TDR-015



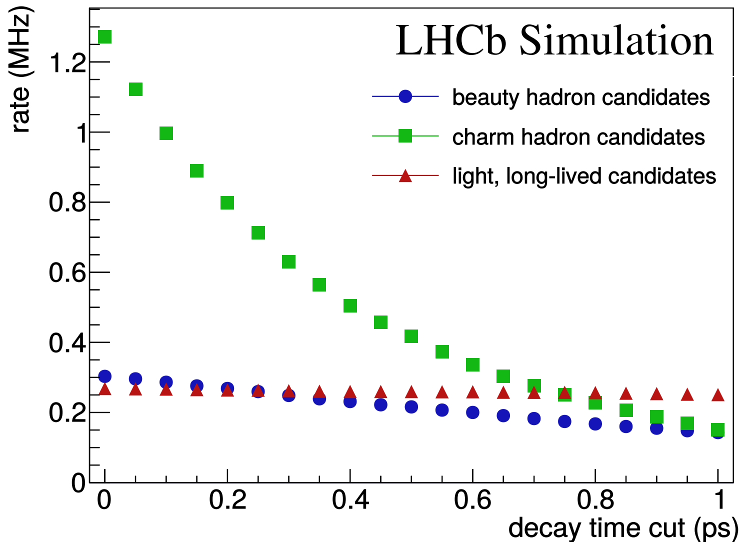
+ new photo detectors for RICH

Upgrade event anatomy

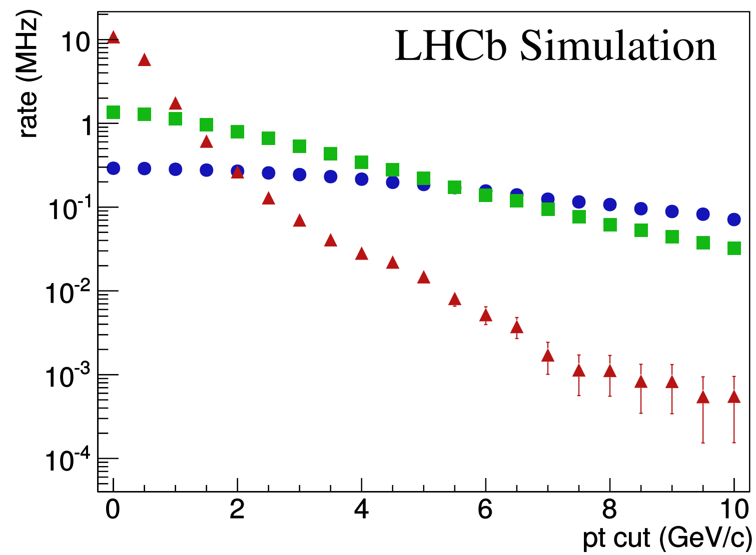
LHCb-PUB-2014-027

For upgrade conditions in LHCb acceptance:
6x higher b-hadron rate, 5x higher charm rate, 4x higher rate of light, long-lived particles

Rates as a function of decay time cut for part. reco. candidates



Rates as a function of pT cut for part. reco. candidates



Output rate (for $p_T > 2.0$ GeV , $\tau > 0.2$ ps) in GBs^{-1}:

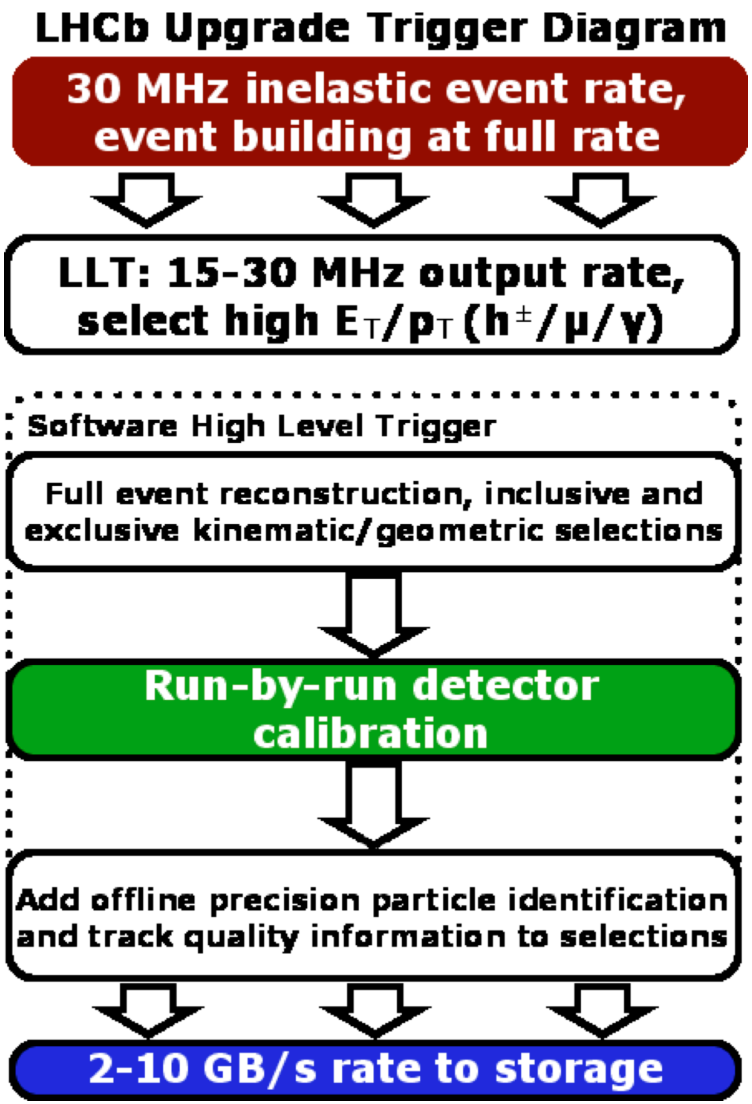
	b-hadrons	c-hadrons	long-lived hadrons
RUN1	0.9	3.3	1.1
Upgrade	**27**	**80**	**26**

(100 kB event size)

New Challenge: discriminate between different similar signals
–> trigger must be very flexible and as close as possible to offline selection

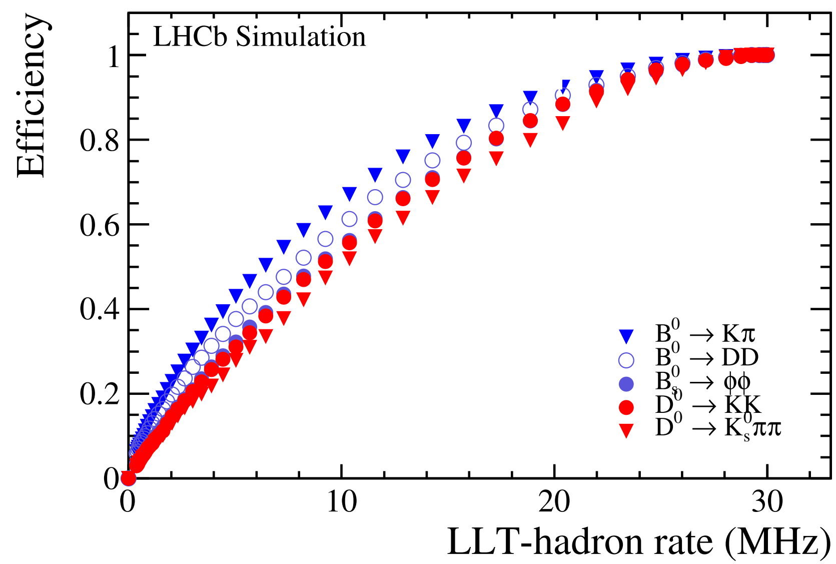
Upgrade trigger

Readout at full 30 MHz collision rate + fully software based trigger:



Software based Low Level Trigger (LLT) replaces L0:

- uses limited information from calorimeters and muon stations
- can reduce the input rate to HLT by factor 2
- chosen as backup in face of changing beam condition

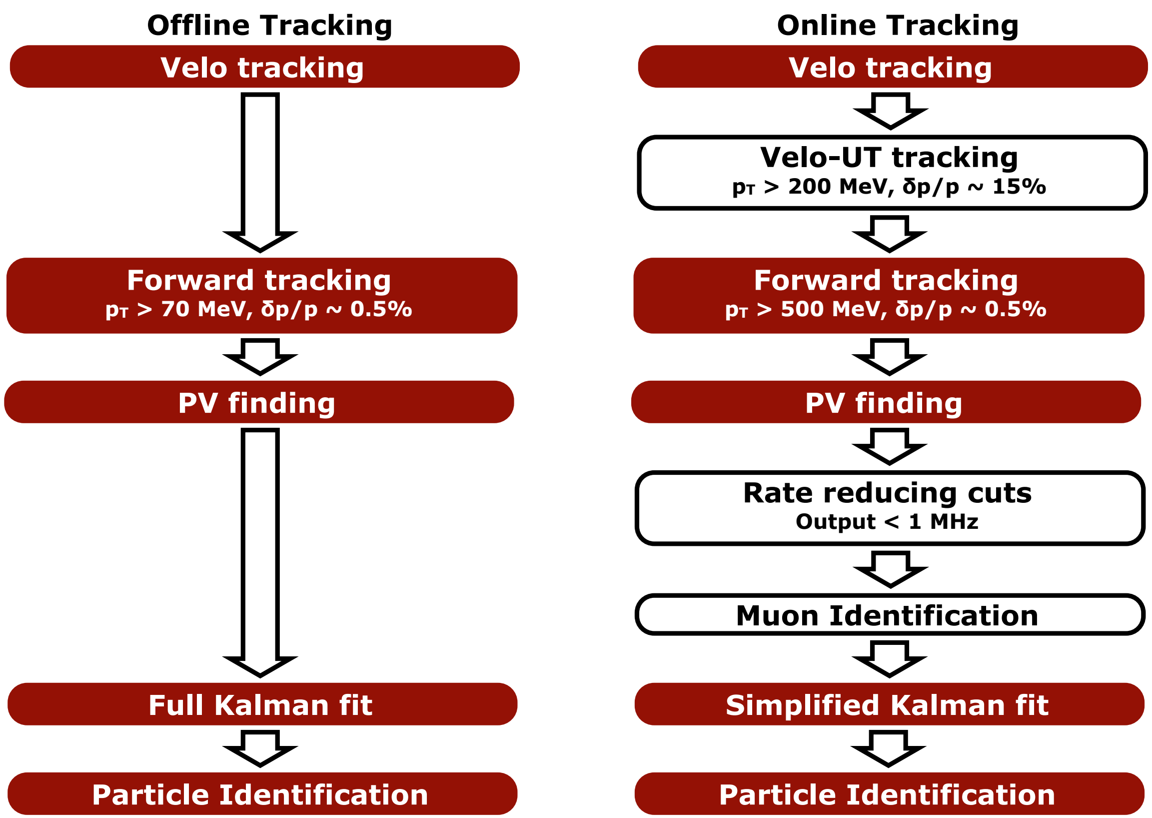


Event Filter farm equipped with O(1000) nodes
Total output rate: 20 – 100 kHz

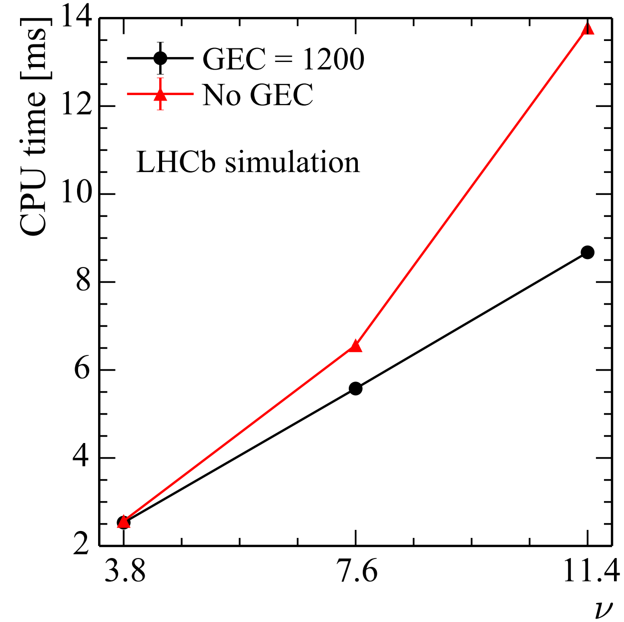
Upgrade tracking

LHCb-PUB-2014-028

Challenge: tracking similar to offline but fitting in the online time budget (13 ms)



Timing studied for three possible scenarios:



(global event cuts (GEC) reject high multiplicity events)

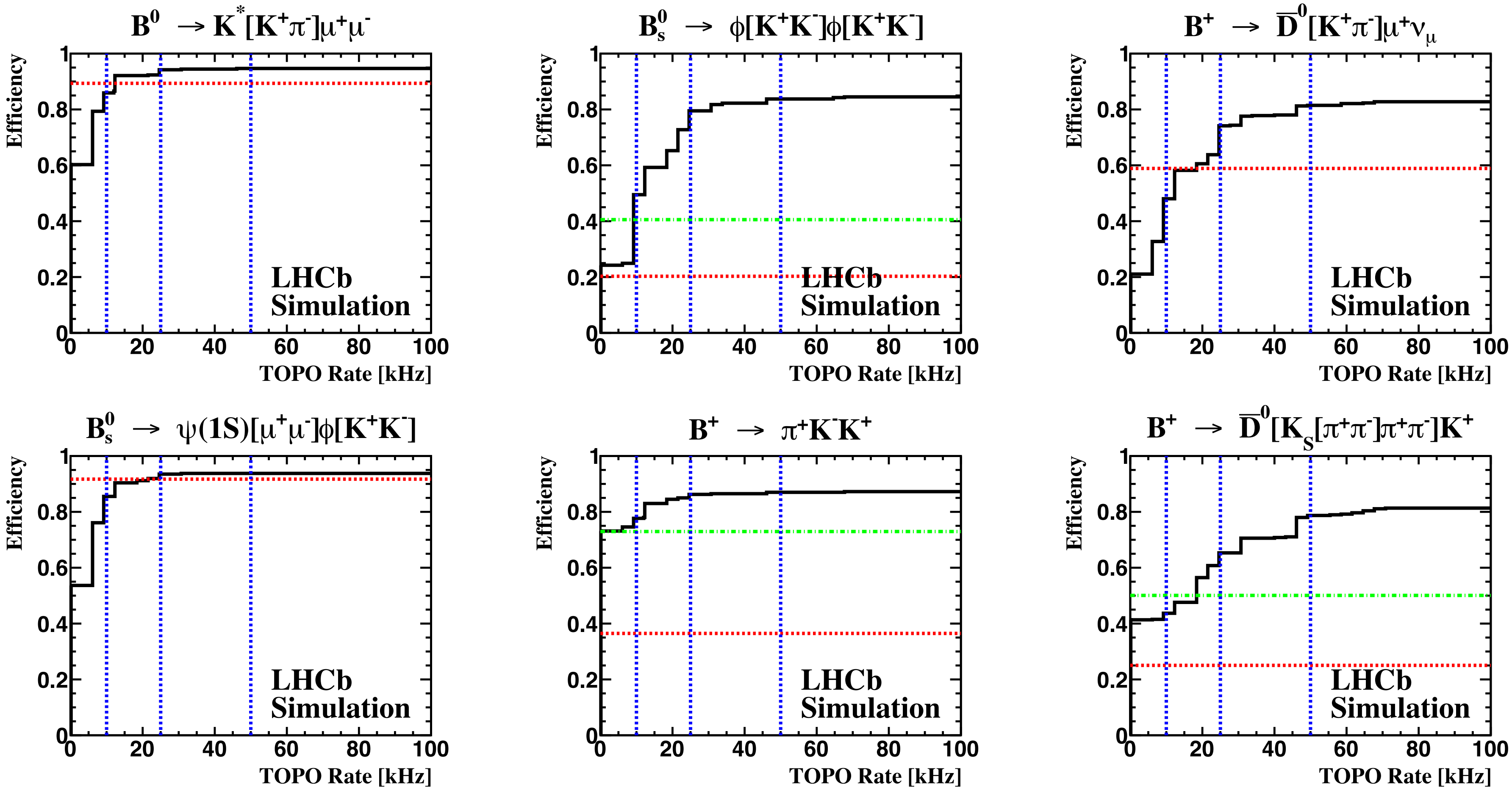
Performance of tracking in upgrade trigger:

- track finding eff. relative to offline for B, $p_T > 0.5$: 98.7 %
- total tracking time: 6.6 ms (5.4 ms with GEC)

First time possible to fully reconstruct events at 30 MHz rate at hadron collider

Topological trigger for the Upgrade

- Uses same strategy as Run1 topo trigger (inclusive for b-hadrons to 2, 3, 4 charged tracks)
- Based on BDT with corrected mass as input variable
- Performance depends on output rate dedicated to topo trigger (three scenarios highlighted)



Lifetime unbiased triggers

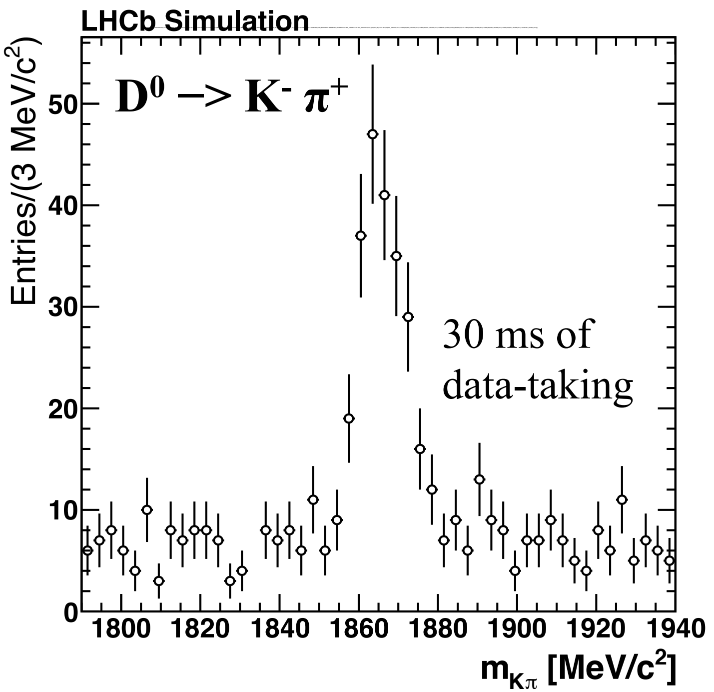
- availability of all high p_T tracks in event gives possibility to select fully hadronic decays without requirements that bias the lifetime
  (for the first time at hadron colliders at full input rate)

- Removes the need to control decay time acceptance effects –> lowers systematics

Challenge:
control time to make possible track combinations and output rate

- Efficiencies for B^0 –> hh: 60 %
  for D^0 –> hh: 10 %

- Timing for B^0 –> hh, D^0 –> hh decays ~ 0.16 ms



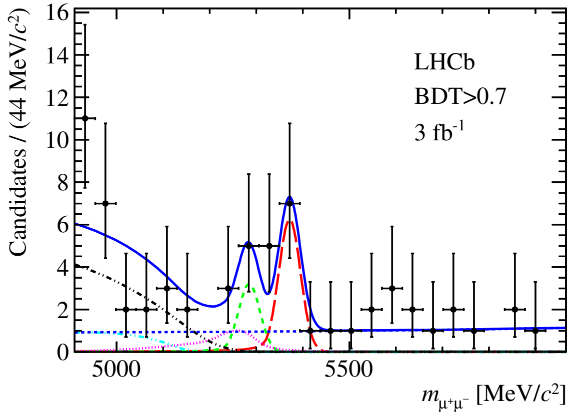
Summary and Outlook

LHCb trigger performed excellent in 2011 and 2012

A wide range of physics channels covered:

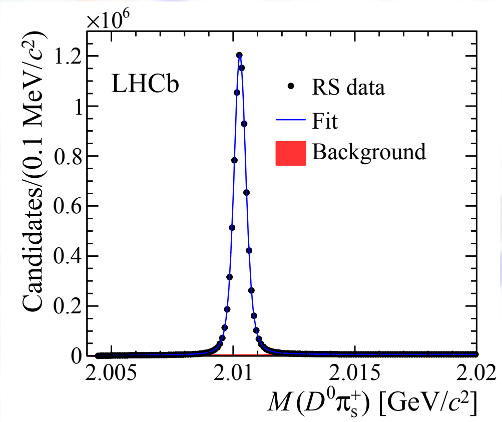
high efficiency for rare channels

arXiv:1211.2674



high purity for huge charm samples

arXiv:1211.1230



For Run2:

Online alignment and calibration –> allows usage of RICH particle ID in trigger

new concept of TurboStream

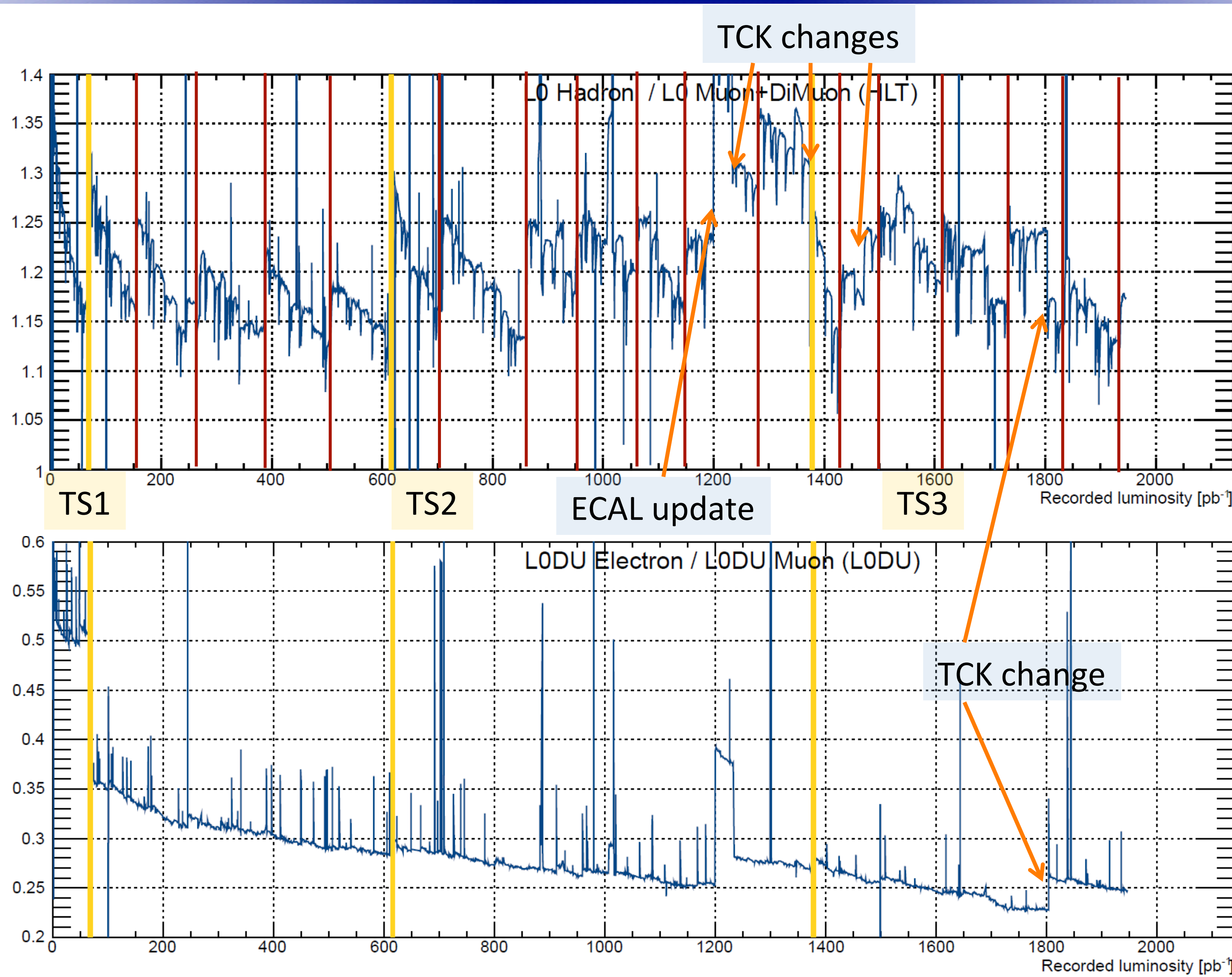
For the upgrade:

full software triggering, reconstruction of all events at 30 MHz

–> significant gains in signal efficiency + allows lifetime unbiased hadronic triggers

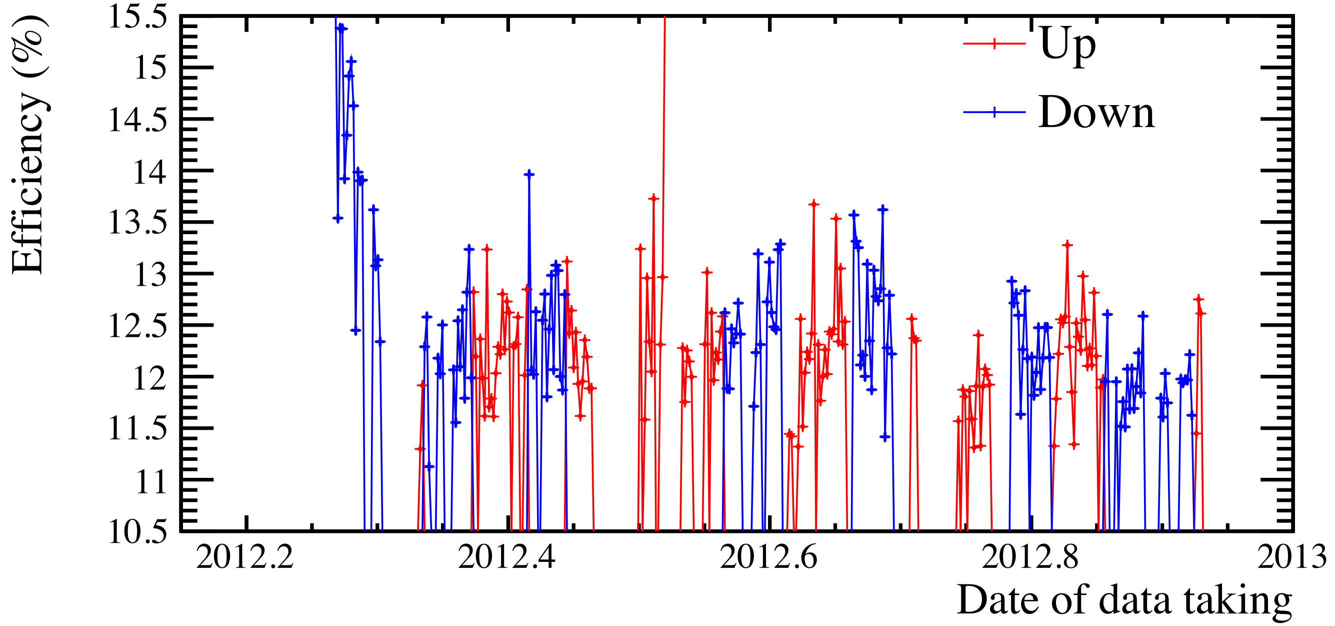
Backup

L0Hadron / L0Electron rate



L0Hadron efficiency

Variation of L0Hadron efficiency for $D^0 \to K\pi$ as a function of data taking time:



Upgrade event

Candidates per event and efficiencies after the upgrade:

Category	In 4π	ϵ(VELO)	ϵ(VELO) $\times$ ϵ(LHCb)
b-hadrons	0.1572 ± 0.0004	$34.9 \pm 0.1\%$	$11.9 \pm 0.1\%$
c-hadrons	1.422 ± 0.001	$24.73 \pm 0.04\%$	$15.12 \pm 0.03\%$
light, long-lived hadrons	33.291 ± 0.006	$7.022 \pm 0.004\%$	$6.257 \pm 0.004\%$

Yields after partial offline reconstruction:

	b-hadrons	c-hadrons	light, long-lived hadrons
Reconstructed yield	0.0317 ± 0.0006	0.118 ± 0.001	0.406 ± 0.002
$\epsilon(p_T > 2\text{GeV/c})$	$85.6 \pm 0.6\%$	$51.8 \pm 0.5\%$	$2.34 \pm 0.08\%$
$\epsilon(\tau > 0.2\text{ ps})$	$88.1 \pm 0.6\%$	$63.1 \pm 0.5\%$	$99.46 \pm 0.03\%$
$\epsilon(p_T) \times \epsilon(\tau)$	$75.9 \pm 0.8\%$	$32.6 \pm 0.4\%$	$2.30 \pm 0.08\%$
$\epsilon(p_T) \times \epsilon(\tau) \times \epsilon(\text{LHCb})$	$27.9 \pm 0.3\%$	$22.6 \pm 0.3\%$	$2.17 \pm 0.07\%$
Output rate	270 kHz	800 kHz	264 kHz

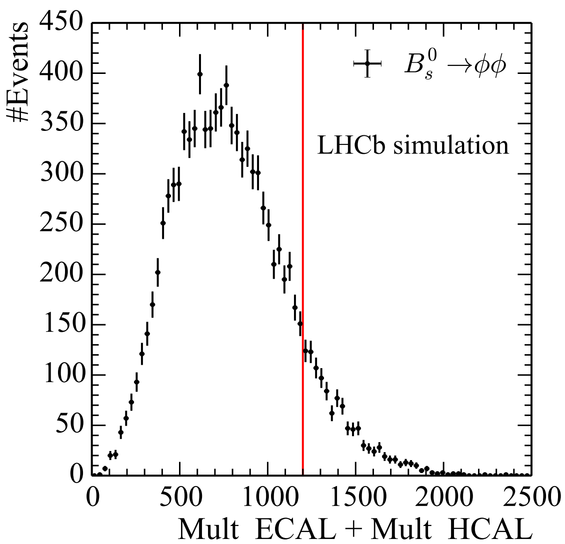
Upgrade selections

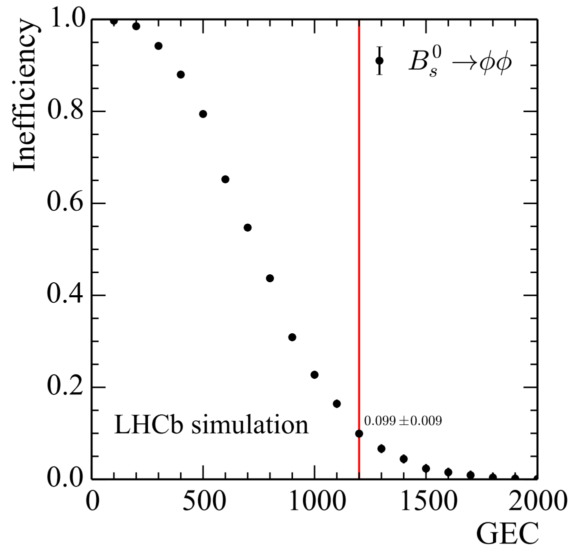
Unbiased hadronic triggers:

	$B^0 \to h^+h^-$	$D^0 \to h^+h^-$	$B_s^0 \to \phi\phi$
track p_T	$> 1000\,\mathrm{MeV}/c$	$> 500\,\mathrm{MeV}/c$	$> 500\,\mathrm{MeV}/c$
$M - M(\mathrm{TRUE})$	$\pm 250\,\mathrm{MeV}/c^2$	$\pm 75\,\mathrm{MeV}/c^2$	$\pm 250\,\mathrm{MeV}/c^2$
τ	> 0.3 ps	> 0.2 ps	> 0.3 ps
$\sum \lvert p_\mathrm{T} \rvert$	$> 4.5\,\mathrm{GeV}/c$	$> 2.5\,\mathrm{GeV}/c$	$> 4.5\,\mathrm{GeV}/c$
DIRA	$< 3.6^\circ$	$< 3.6^\circ$	$< 3.6^\circ$
parent IP	< 0.1 mm	< 0.1 mm	< 0.1 mm
Max DOCA	< 0.1 mm	< 0.1 mm	< 0.1 mm

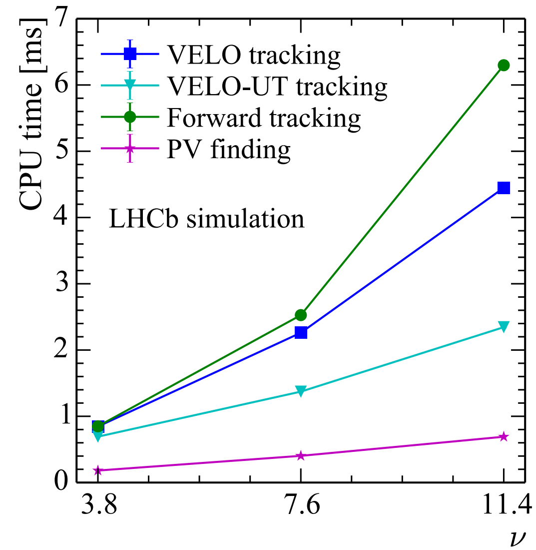
Upgrade tracking

Effect of global event cut (GEC):

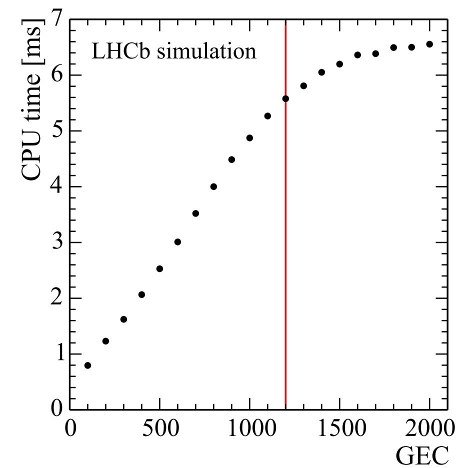




Timing of tracking sequence:



Time spent in trigger reconstruction as a function of GEC:



Track finding efficiency:

	$\nu = 7.6$ [%]		
	no GEC	GEC=1200	relative
Ghost rate	10.9	5.9	-
long	42.7	42.9	50.4
long, from B	72.5	72.8	80.3
long, $p_T > 0.5\,\text{GeV}/c$	86.9	87.4	97.2
long, from B, $p_T > 0.5\,\text{GeV}/c$	92.3	92.5	98.7