Tracking, Vertexing and data handling strategy for the LHCb upgrade

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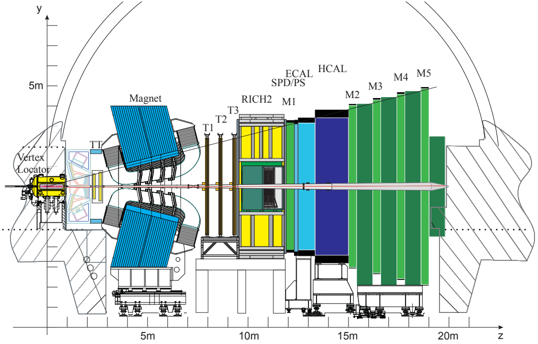
on behalf of the LHCb collaboration

CERN

VERTEX 2017

scope I



- Fully equipped forward detector at the LHC
- Approaching 400 papers
- exceeding our own expectations:
  - online calibration and alignment
  - exceeding design pile-up

scope II

Type	Observable	Current precision	LHCb 2018 (8 fb^{-1})	**Upgrade** (50 fb^{-1})	Theory uncertainty
B_s^0 mixing	$2\beta_s(B_s^0 \to J/\psi\phi)$	0.10	0.025	0.008	$\sim$0.003
	$2\beta_s(B_s^0 \to J/\psi f_0(980))$	0.17	0.045	0.014	$\sim$0.01
Higgs penguins	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9}	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
Gluonic penguins	$2\beta_s^{\rm eff}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	$\sim$10–12°	4°	0.9°	negligible
	$\gamma(B_s^0 \to D_s K)$	–	11°	2.0°	negligible
	$\beta(B^0 \to J/\psi K_S^0)$	0.8°	0.6°	0.2°	negligible

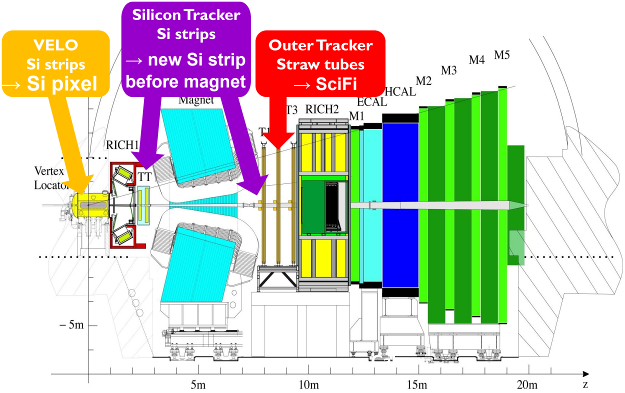
Eur. Phys. Journal C (2013) 73:2373

- By 2018 important analyses will still be statistically limited
- Theoretical uncertainty smaller than experimental

$\rightarrow$ Significantly more statistics needed

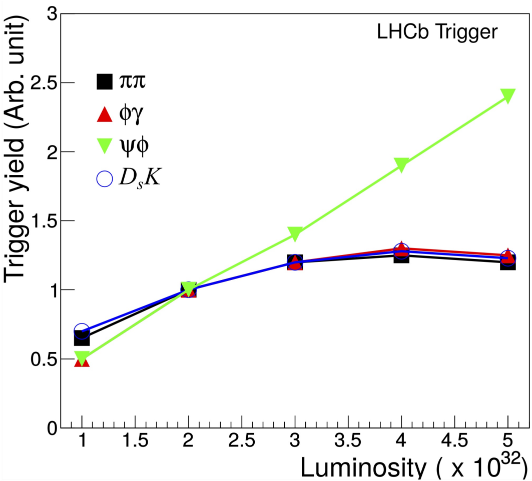
$\Rightarrow$ Go to higher luminosity

Upgrade of the tracking system



- Vertex pixel detector
  see talk by Edgar Lemos Cid
- silicon strip detector
  see talk by Marco Petruzzo
- scintilating fiber tracker

removal of hardware trigger I



what doesn't work

- increased luminosity

→ events passing hardware trigger

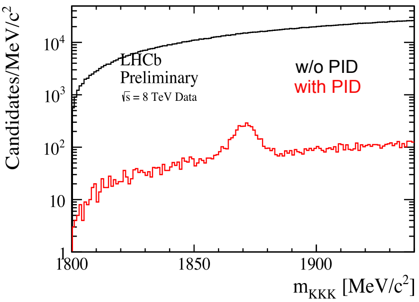
→ saturating bandwidth

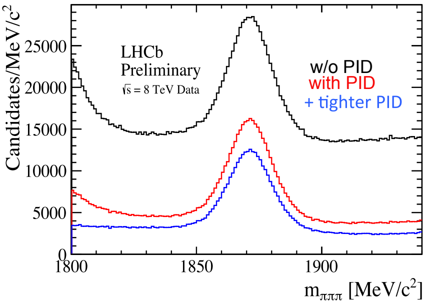
→ tighten thresholds

→ loss in efficiency

⇒ no increase in statistics for analyses (depending on the decay channel)

removal of hardware trigger II





- backgrounds from real physics events
- cannot distinguish signal from background w/o RICH PID

⇒ even selection in software

LHCb 2015 Trigger Diagram

40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures

450 kHz	400 kHz	150 kHz
$h^{\pm}$	$\mu/\mu\mu$	e/γ

Software High Level Trigger

Partial event reconstruction, select displaced tracks/vertices and dimuons

Buffer events to disk, perform online detector calibration and alignment

Full offline-like event selection, mixture of inclusive and exclusive triggers

12.5 kHz (0.6 GB/s) to storage

$\Rightarrow$

LHCb Upgrade Trigger Diagram

30 MHz inelastic event rate (full rate event building)

Software High Level Trigger

Full event reconstruction, inclusive and exclusive kinematic/geometric selections

Buffer events to disk, perform online detector calibration and alignment

Add offline precision particle identification and track quality information to selections

Output full event information for inclusive triggers, trigger candidates and related primary vertices for exclusive triggers

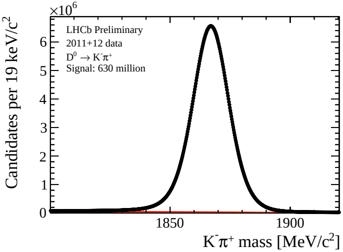
2-5 GB/s to storage

Luxury problem: MHz signals

Triggers today

Real-time data analysis tomorrow

5

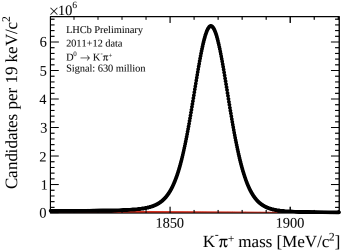


- Selecting and storing full events could work for rare signal
- When dealing with "millions" of good signal events, rejecting background isn't enough to stay within processing bandwidths

Luxury problem: MHz signals

Triggers today

Real-time data analysis tomorrow



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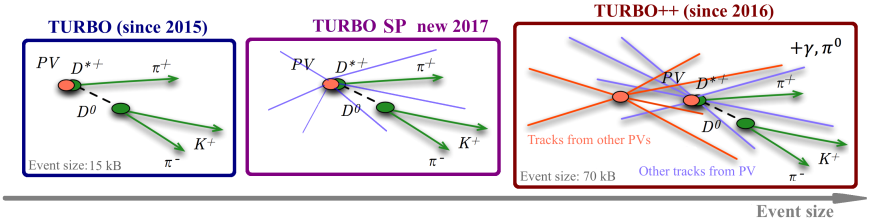
The TURBO approach

- once a decay is reconstructed (mass, decay time, Dalitz plot) no need to access raw data for analysts
- once a decay is reconstructed in the trigger no need to re-reconstruct offline
- (unaffordable to study raw data for millions of events anyway)

store what you need



10.1016/j.cpc.2016.07.022

per trigger line storage definition

- only decay and nothing else
- decay and selected reconstructed objects
- all *reconstructed* objects (no raw data)
- full raw event

TURBO triggers must be a default for many analyses

Bandwidth division I

- There's always an efficiency vs. event rate tradeoff
- assume: every analysis could max out the full data bandwidth to maximise their *efficiency*
- compromises need to be made
- ideally with little *sensitivity* loss

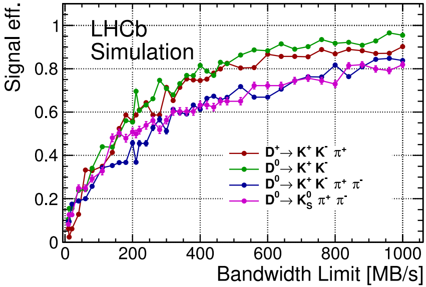
- Genetic algorithm approach
  - Minimise the χ^2 by varying the MVA response for each decay
    - ω_i channel weight (= 1.0 here)
    - ε_i channel efficiency
    - $\varepsilon_i^{\max}$ maximum channel efficiency when given the full output BW

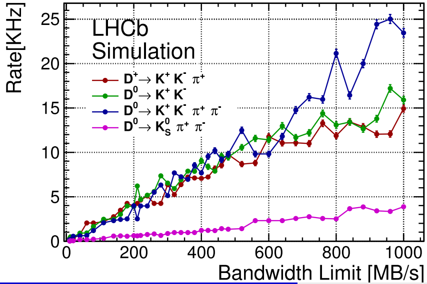
$$\chi^2 = \sum_i^{\text{channels}} \omega_i \times \left(1 - \frac{\varepsilon_i}{\varepsilon_i^{\max}}\right)^2$$

- if sum of all channels exceeds total bandwidth
  → assume random dropping of events

LHCb-PUB-2017-006

Bandwidth division II

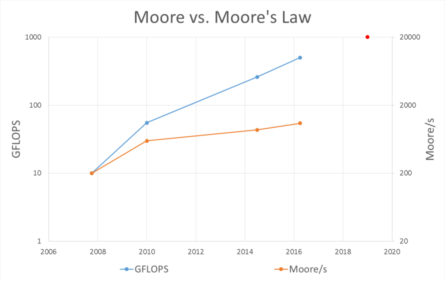




going from maximal bandwidth to restricted bandwidth

- only small efficiency decrease
- "90 % of the data holds 95 % of the statistical power"

“Moore doesn't obey Moore's law”

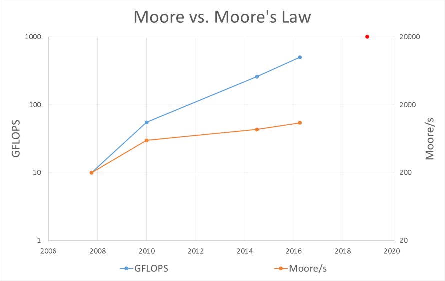


- theoretical computing power of CPUs increases (per second, per Watt, per CHF)
- observed computed trigger decisions does not follow that increase

reasons from a CPU's point of view I/II

- modern vector units process 2, 4, or 8 inputs at a time
  $\rightsquigarrow$ our software often didn't use these
  $\rightarrow$ 7/8 of the silicon unused!

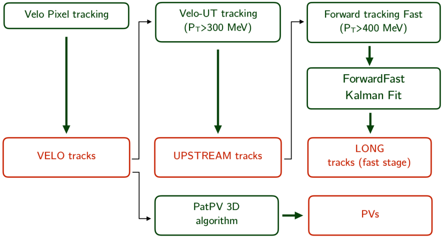
“Moore doesn’t obey Moore’s law”



- theoretical computing power of CPUs increases (per second, per Watt, per CHF)
- observed computed trigger decisions does not follow that increase

reasons from a CPU’s point of view II/II

- software not parallelised (just start multiple processes on a multicore machine)
  - ⇝ processes compete for memory
  - ⇝ even multiple instances of the same data (detector geometry)
  - → CPU waits for data instead of computing



full sequence 6.0 ms/evt

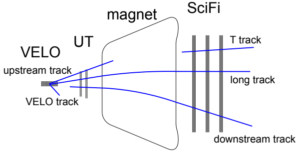
VELO tracking 2.0 ms/evt

VELO-UT tracking 0.5 ms/evt

forward tracking 2.3 ms/evt

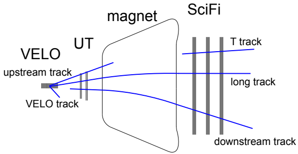
PV finding 1.1 ms/evt

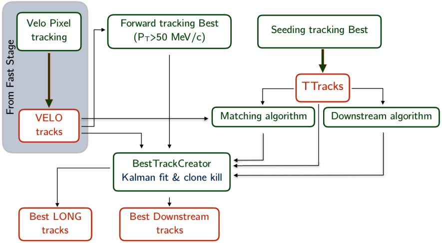
(present HLT1: 35 ms)



- similar to current software trigger
- single track and two track selections for displaced objects ("easy" combinatorics, limited reconstruction)

tracking sequence



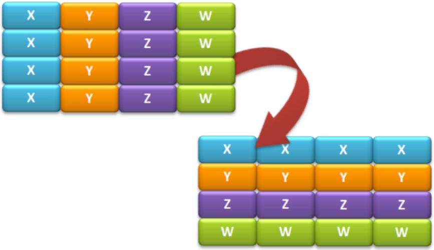


(present HLT2: 650 ms)

- similar to current software trigger
- single track and two track selections for displaced objects ("easy" combinatorics, limited reconstruction)
- reconstruct remaining tracks in the "full stage"
- also reconstruct decay products of strange decays outside the VELO

Kalman filter track fit

- track fit one of the big CPU time consumers
- written for sequential adding of hits
- but different tracks can be fitted independent of each other (thread parallelisable)
- matrix operations are always the same (vectorisable)



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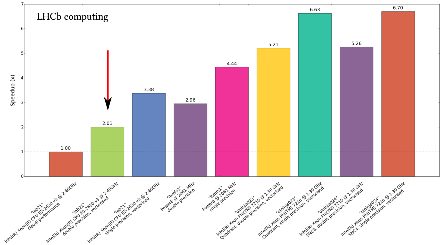
Speed gain of "matrix algebra" (predicting, updating, smoothing)

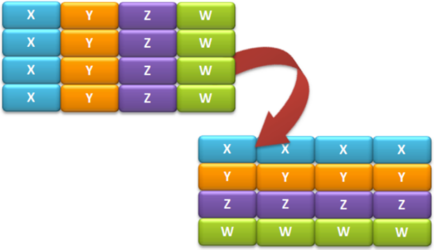


Kalman filter track fit

grain of salt

- only speeds up the matrix algebra
- material lookup remains
- now requires back-and-forth conversion of memory layout

⇒ to be consequent need to adapt underlying event model



LHCb–TALK–2016–372

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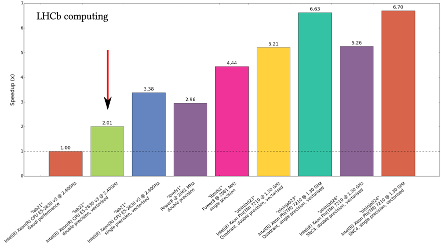
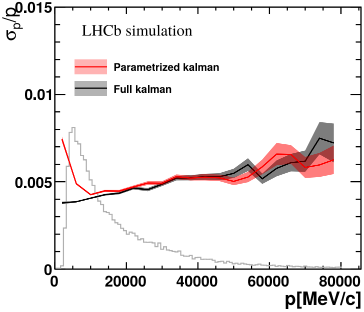
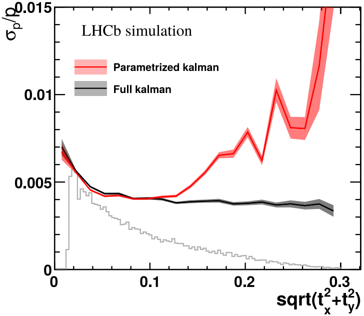


parametrised Kalman fit

- avoid first-principles math for every track
  $\rightsquigarrow$ parametrisations can be equally accurate
  reduce complicated B field propagation and material lookup to $\mathcal{O}(20)$ parameters





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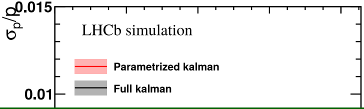
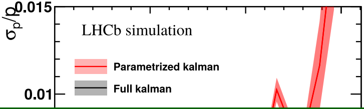




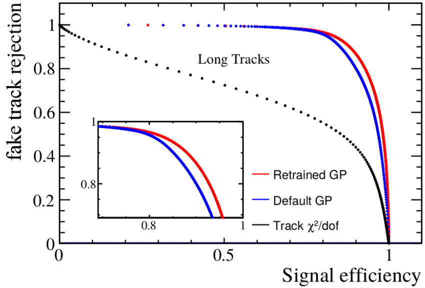
work in progress

- resolution close to reference
- potentially use full fit for tracks with large $\sqrt{t_x^2 + t_y^2}$
- find alternative parametrisations

fake track identification

- fake tracks a big contribution to computing budget in run I
- identification of fakes w/ neural network after track fit more powerful than track fit χ^2 alone

upgrade fake rejection:



impact on run II

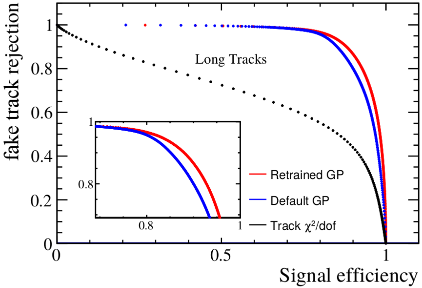
- RICH PID $-\mathcal{O}(20\,\%)$ CPU
- combinatorics $-\mathcal{O}(60\,\%)$ CPU
- trigger $-\mathcal{O}(30\,\%)$ rate

fake track identification

- fake tracks a big contribution to computing budget in run I
- identification of fakes w/ neural network after track fit more powerful than track fit χ^2 alone
- As more and more ML goes into earlier stages of the track reconstruction, there are less fakes to remove after the track fit

$\rightarrow$ looking forward for this to become less important

upgrade fake rejection:



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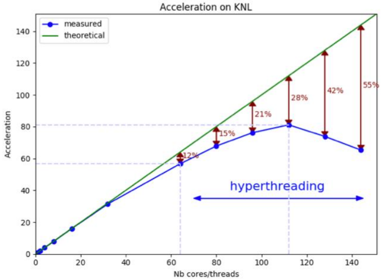
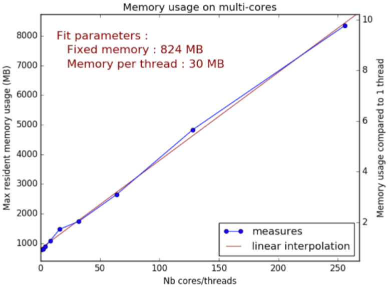
multi threaded processing framework





- introduce harder framework constrains (functional programming)
- observe near optimal speedup when increasing number of threads
- observe little memory increase when increasing number of threads

Conclusion

- LHCb physics program relies on software trigger at 30 MHz
- Fast tracking *without performance loss* crucial for LHCb upgrade
- Needs reconstruction software close to computer hardware to optimally use