Tracking, Vertexing and data handling strategy for the LHCb upgrade

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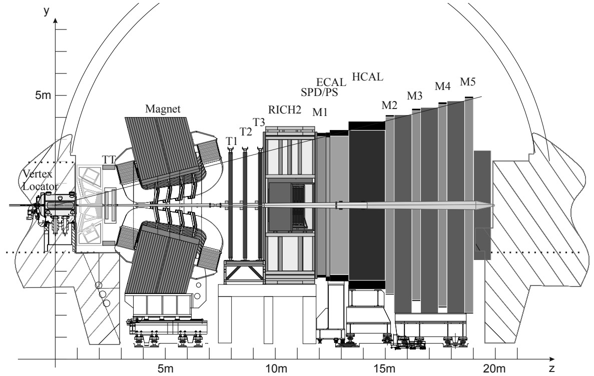
on behalf of the LHCb collaboration

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

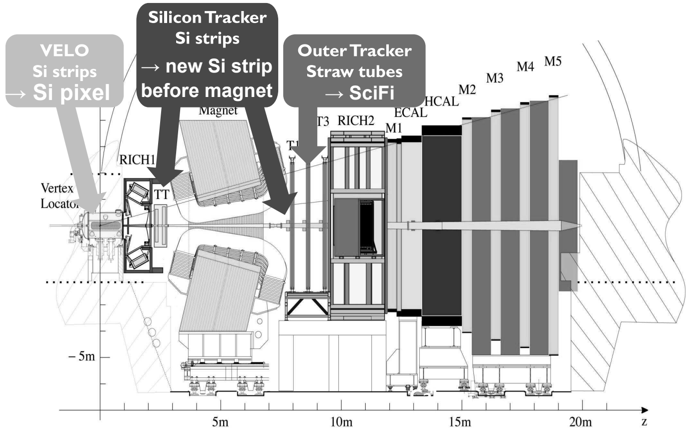
`Eur. Phys. Journal C (2013) 73:2373`

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

$\rightarrow$ Significantly more statistics needed

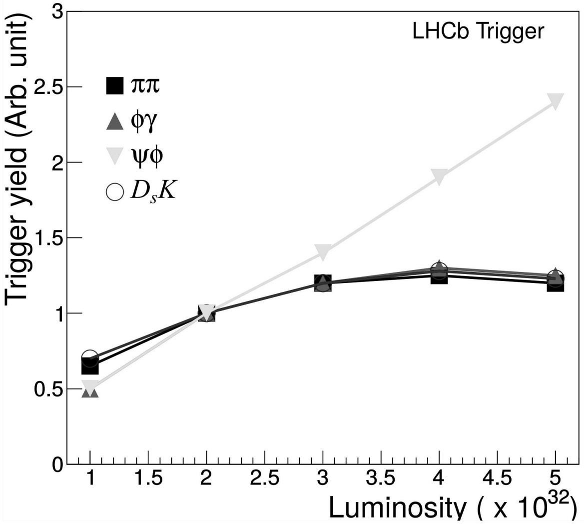
$\Rightarrow$ Go to higher luminosity

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

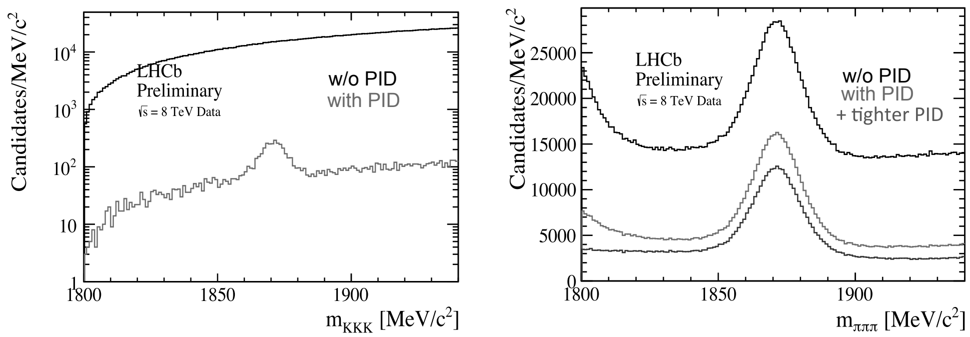
removal of hardware trigger I



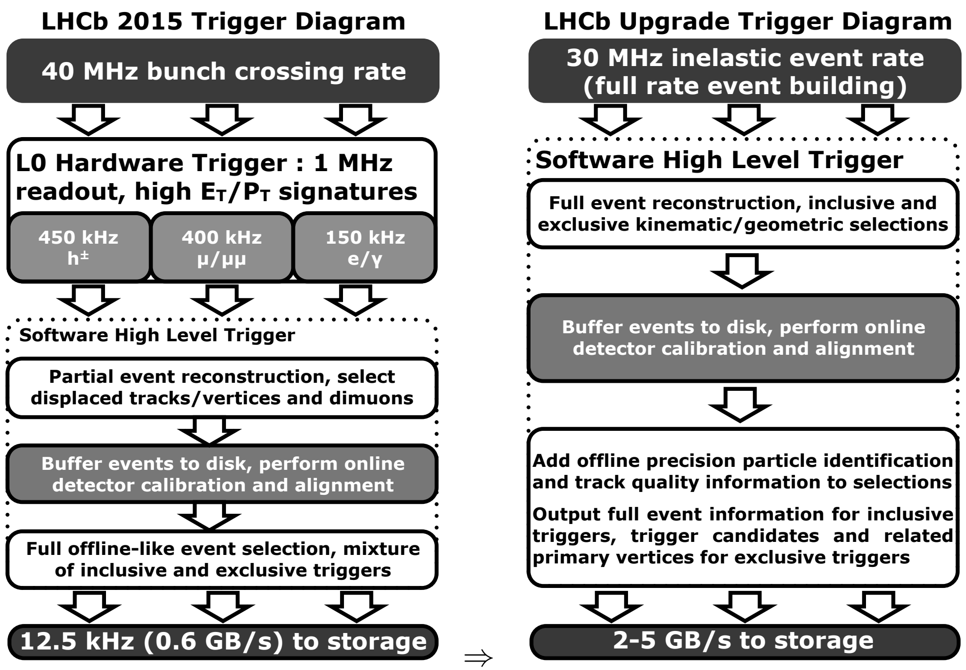
what doesn't work

- increased luminosity
- → events passing hardware trigger
- → saturating bandwidth
- → tighten thresholds
- → loss in efficiency
- ⇒ no increase in statistics for analyses (depending on the decay channel)

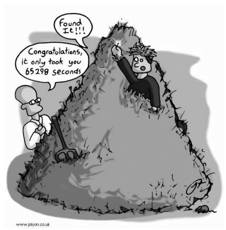
removal of hardware trigger II



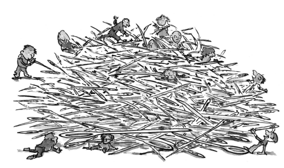
- backgrounds from real physics events
- cannot distinguish signal from background w/o RICH PID
- ⇒ even selection in software



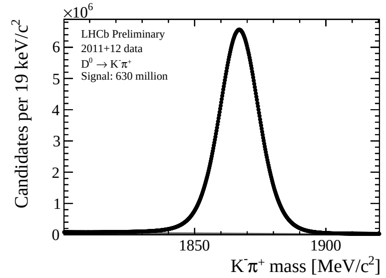
Luxury problem: MHz signals



Triggers today

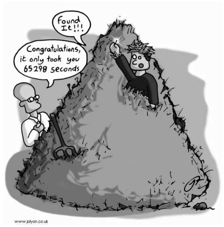


Real-time data analysis tomorrow



- 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

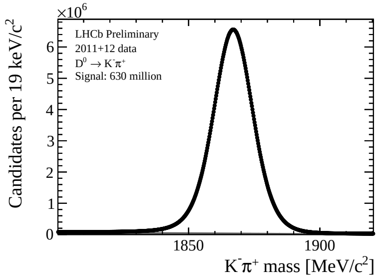
Luxury problem: MHz signals



Triggers today

Real-time data analysis tomorrow

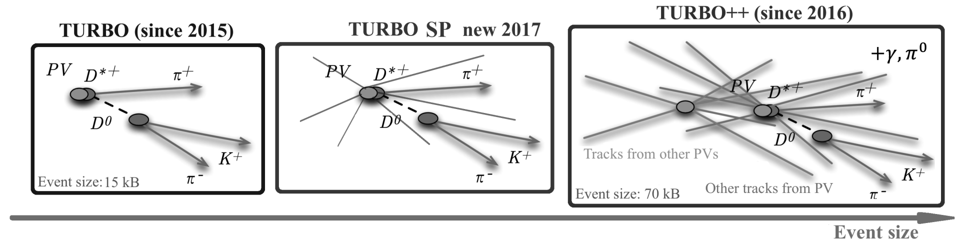
5



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 $\to$ assume random dropping of events

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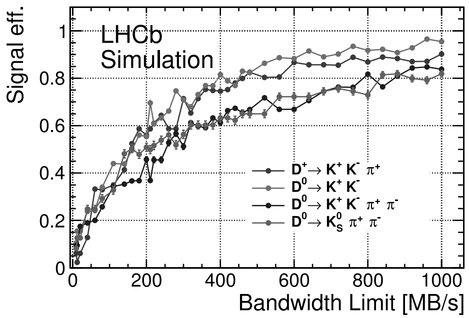
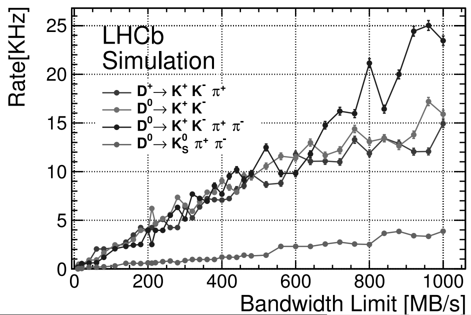
Bandwidth division II

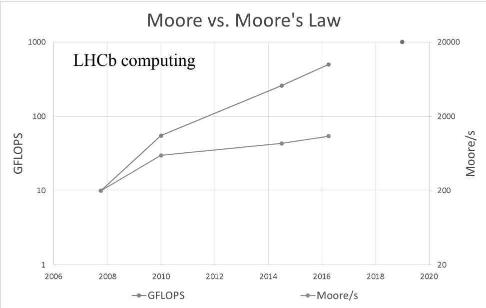




going from maximal bandwidth to restricted bandwidth

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

“Moore doesn’t obey Moore’s law”

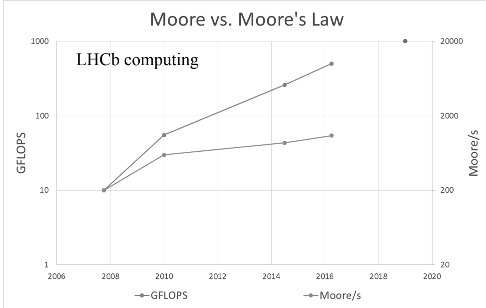


- theoretical computing power of CPUs increases (per second, per Watt, per CHF)
- observed computed trigger decisions does not follow that increase

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

- modern vector units process 2, 4, or 8 inputs at a time
  ⇝ our software often didn’t use these
  → 7/8 of the silicon unused!

“Moore doesn’t obey Moore’s law”

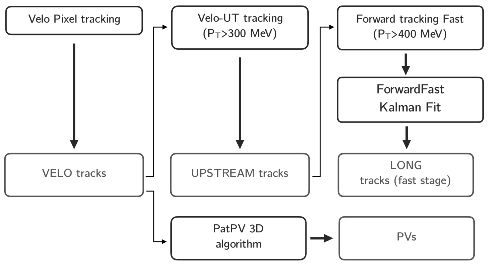


- theoretical computing power of CPUs increases (per second, per Watt, per CHF)
- observed computed trigger decisions does not follow that increase

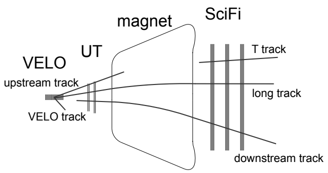
reasons from a CPU’s point of view II/II

- 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

tracking sequence

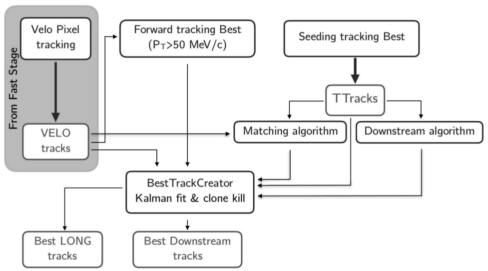


full sequence 6.0 ms/evt
VELO tracking 2.0 ms/evt
VELO-UT tracking 0.5 ms/evt
forward tracking 2.3 ms/evt
PV finding 1.1 ms/evt
(present HLT1: 35 ms)

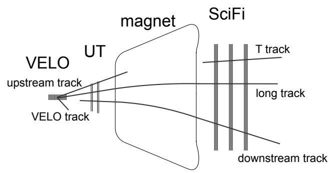


- similar to current software trigger
- single track and two track selections for displaced objects (“easy” combinatorics, limited reconstruction)

tracking sequence



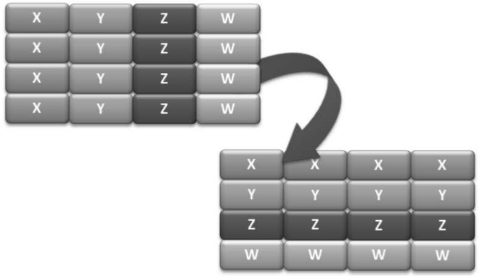
(present HLT2: 650 ms)

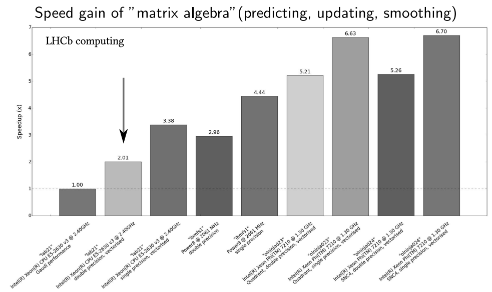


- similar to current software trigger
- single track and two track selections for displaced objects (“easy” combinatorics, limited reconstruction)
- reconstruct remaining tracks in the “full stage”
- also reconstruct decay products of strange decays outside the VELO

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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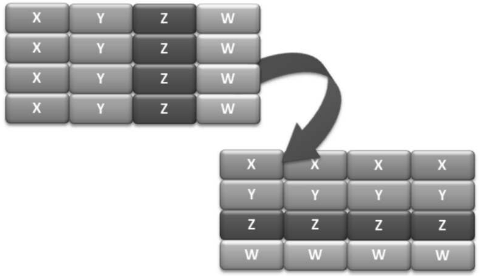
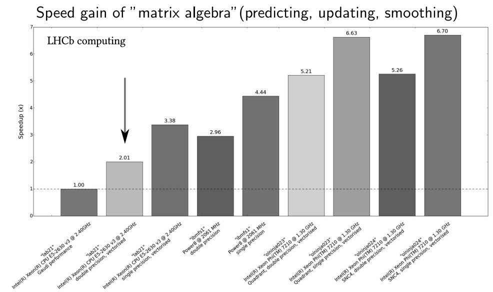
Kalman filter track fit

grain of salt

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

$\Rightarrow$ to be consequent need to adapt underlying event model





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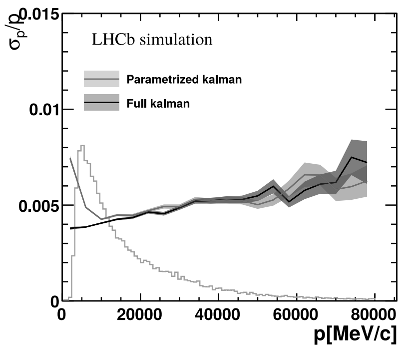
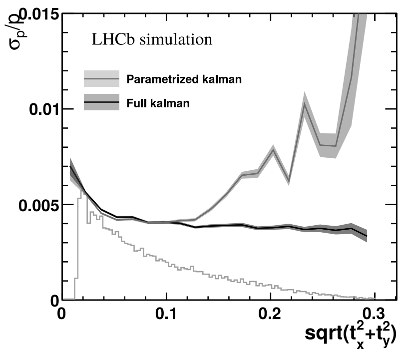
parametrised Kalman fit

- 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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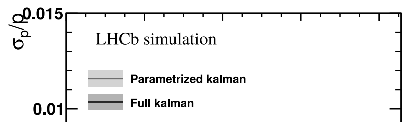
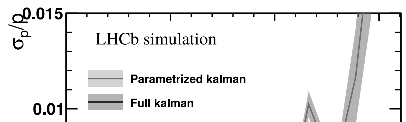




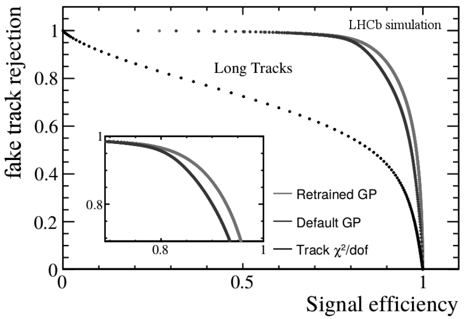
work in progress

- 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

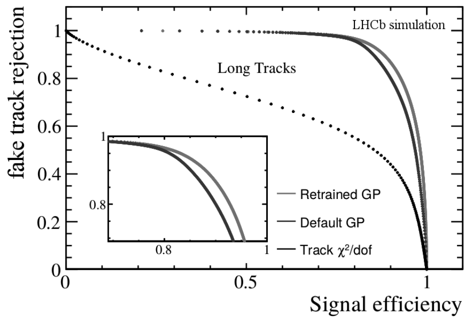
fake track identification

- 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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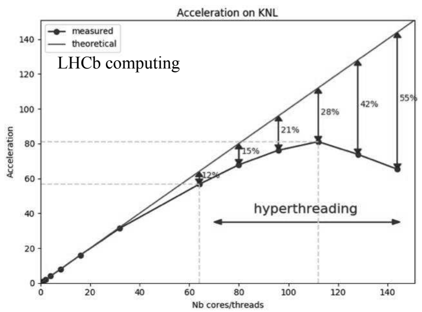
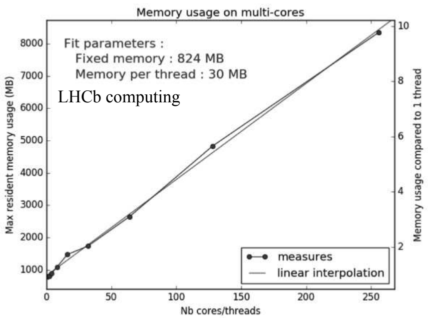
multi threaded processing framework





- 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