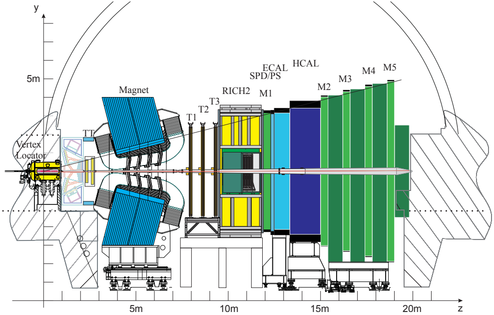
# Tracking, Vertexing and data handling strategy for the LHCb upgrade

Paul Seyfert
on behalf of the LHCb collaboration

CERN

VERTEX 2017

# scope I




LHCb-DP-2014-002

- Fully equipped forward detector at the LHC
- Approaching 400 papers
- exceeding our own expectations:
  - online calibration and alignment
    j.nima.2016.06.050
  - 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 | ~0.003 |
| | $2\beta_s(B_s^0 \to J/\psi\, f_0(980))$ | 0.17 | 0.045 | 0.014 | ~0.01 |
| Higgs penguins | $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ | $1.5 \times 10^{-9}$ | $0.5 \times 10^{-9}$ | $0.15 \times 10^{-9}$ | $0.3 \times 10^{-9}$ |
| Gluonic penguins | $2\beta_s^{\text{eff}}(B_s^0 \to \phi\phi)$ | – | 0.17 | 0.03 | 0.02 |
| Unitarity triangle angles | $\gamma(B \to D^{(*)}K^{(*)})$ | ~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 |

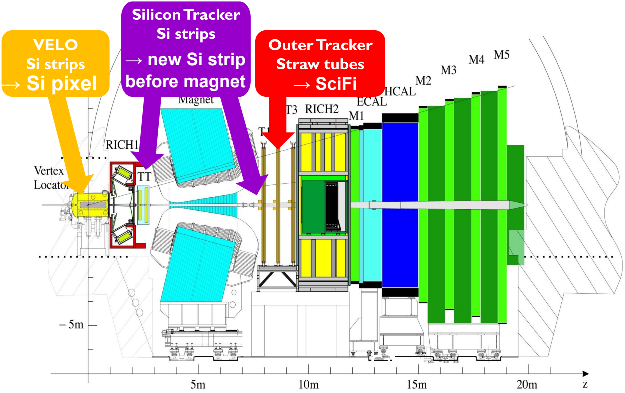
Eur. Phys. Journal C (2013) 73:2373

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

$\rightarrow$ Significantly more statistics needed

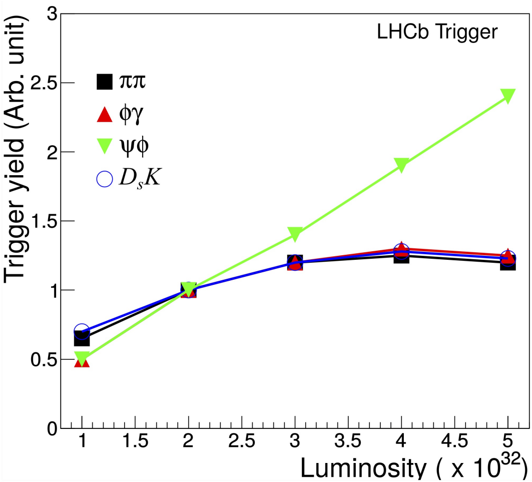
$\Rightarrow$ Go to higher luminosity

# 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

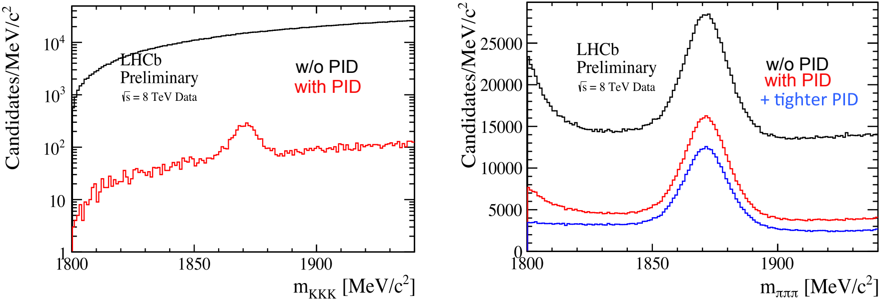
$\rightarrow$ events passing hardware trigger

$\rightarrow$ saturating bandwidth

$\rightarrow$ tighten thresholds

$\rightarrow$ loss in efficiency

$\Rightarrow$ no increase in statistics for analyses (depending on the decay channel)




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

$\Rightarrow$ 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 |
|---|---|---|
| $h^\pm$ | $\mu/\mu\mu$ | $e/\gamma$ |

**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

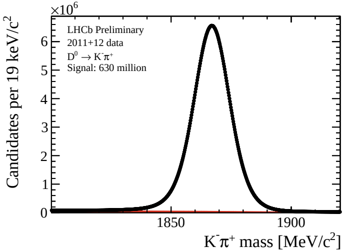
Output full event information for inclusive triggers, trigger candidates and related primary vertices for exclusive triggers

**2-5 GB/s to storage**

# Luxury problem: MHz signals


**Triggers today**

**Real-time data analysis tomorrow** [5]




LHCb-CONF-2016-005

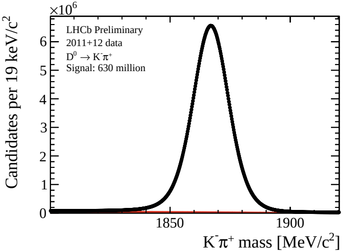
- Selecting and storing full events could work for rare signal
- When dealing with "millions" of good signal events, rejecting background isn't enough to stay within processing bandwidths

# Luxury problem: MHz signals


**Triggers today**

**Real-time data analysis tomorrow**

5

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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)

# Luxury problem: MHz signals


**Triggers today**

**Real-time data analysis tomorrow**

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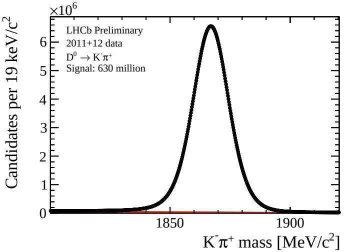


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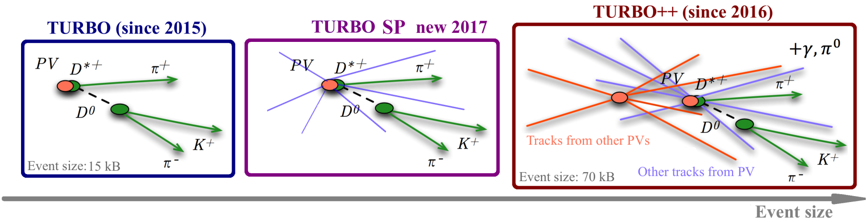
## The TURBO approach

- once a decay is reconstructed (mass, decay time, Dalitz plot) cannot afford to store all raw data offline
- once a decay is reconstructed in the trigger cannot afford to re-reconstruct all data offline
- **Finite budget for offline computing resources**

# 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

- In a perfect world we could store and process all selected events
- wide Physics program requires compromise
- limit *sensitivity* loss in a fair share

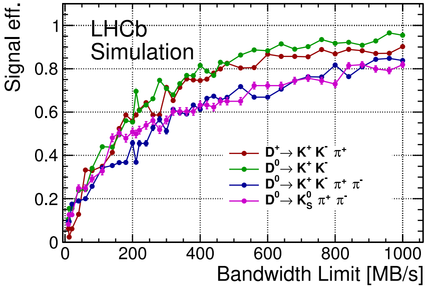
- Genetic algorithm approach
  - Minimise the $\chi^2$ by varying the MVA response for each decay
    - $\omega_i$ channel weight ( = 1.0 here)
    - $\varepsilon_i$ channel efficiency
    - $\varepsilon_i^{\max}$ maximum channel efficiency when given the full output BW

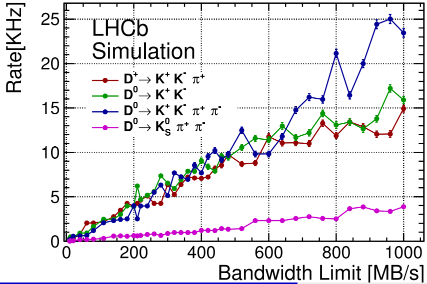
$$\chi^2 = \sum_i^{\text{channels}} \omega_i \times \left(1 - \frac{\varepsilon_i}{\varepsilon_i^{\max}}\right)^2$$

- if sum of all channels exceeds total bandwidth
  $\rightarrow$ assume random dropping of events
- weight to reduce impact of calibration channels
  (different order of magnitude in branching fraction)

LHCb-PUB-2017-006

# Bandwidth division II

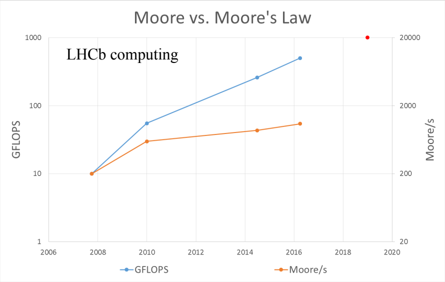



going from maximal bandwidth to restricted bandwidth

- only small efficiency decrease
- "90 % of the data holds 95 % of the statistical power"
- different persistency tested, too:
  $D^0 \to K_S \pi\pi$ as Turbo++
  $\Rightarrow$ more restricted total rate

# "Moore doesn't obey Moore's law"

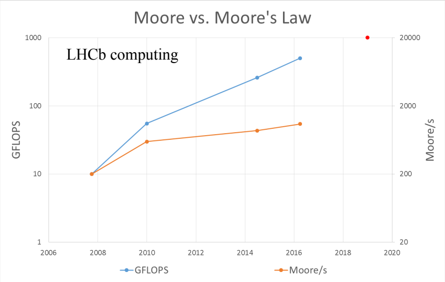



- theoretical computing power of CPUs increases (per second, per Watt, per CHF)
- observed computed trigger decisions does not follow that increase

## 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)
  $\rightsquigarrow$ processes compete for memory
  $\rightsquigarrow$ even multiple instances of the same data (detector geometry)
  $\rightarrow$ CPU waits for data instead of computing

# tracking sequence

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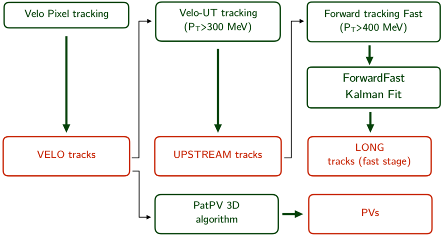



full sequence 6.0 $ms/evt$

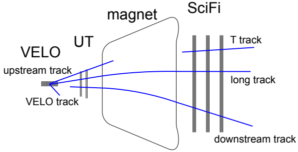
VELO tracking 2.0 $ms/evt$

VELO-UT tracking 0.5 $ms/evt$

forward tracking 2.3 $ms/evt$

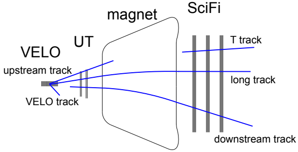
PV finding 1.1 $ms/evt$

(present HLT1: 35 $ms$)

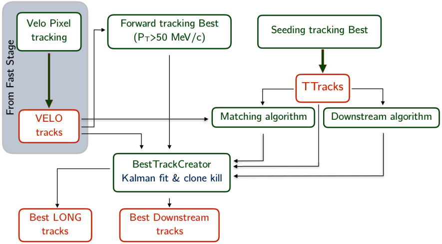



- similar to current software trigger
- single track and two track selections for displaced objects ("easy" combinatorics, limited reconstruction)

# tracking sequence




[LHCb-PUB-2017-005](LHCb-PUB-2017-005)

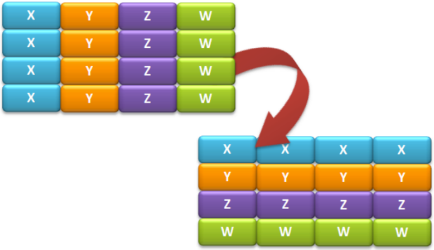



(present HLT2: 650 $ms$)

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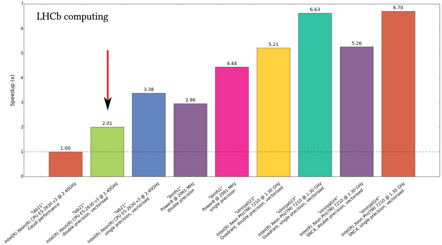
Speed gain of "matrix algebra" (predicting, updating, smoothing)

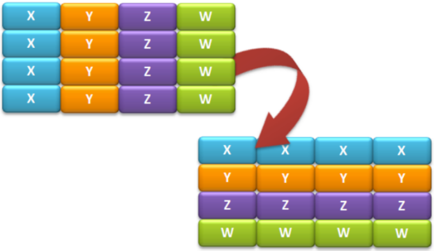


# Kalman filter track fit

## 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

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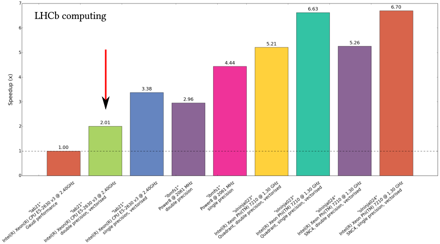


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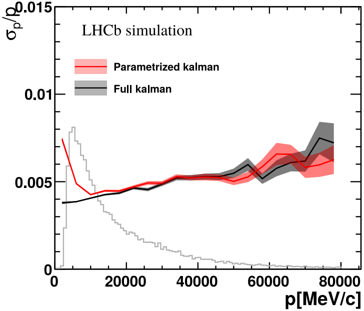
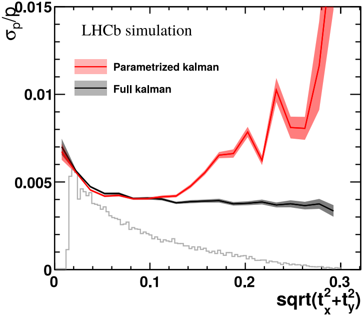
# parametrised Kalman fit

- 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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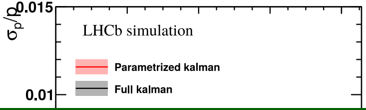
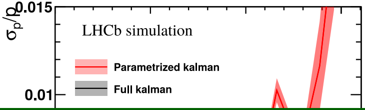



## work in progress

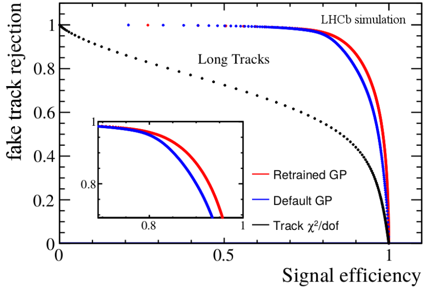
- resolution close to reference
- potentially use full fit for tracks with large $\sqrt{t_x^2 + t_y^2}$
- find alternative parametrisations

$\Rightarrow$ fast track fit must not deteriorate resolution

# 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 $\chi^2$ alone

upgrade fake rejection:




**impact on run II**

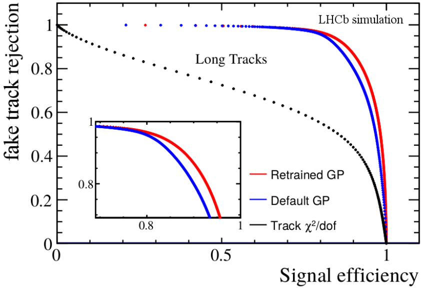
- RICH PID $-\mathcal{O}(20\,\%)$ CPU
- combinatorics $-\mathcal{O}(60\,\%)$ CPU
- trigger $-\mathcal{O}(30\,\%)$ rate

# 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 $\chi^2$ 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:




**impact on run II**

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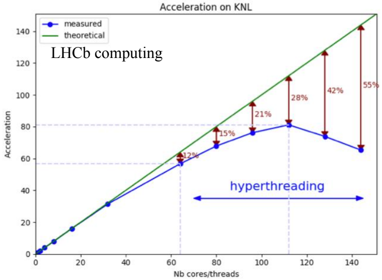
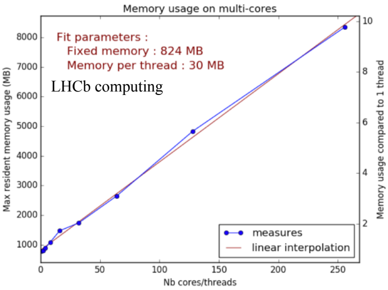
# multi threaded processing framework




- 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

# BACKUP

# these slides online

https://gitlab.cern.ch/pseyfert/Vertex2017