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

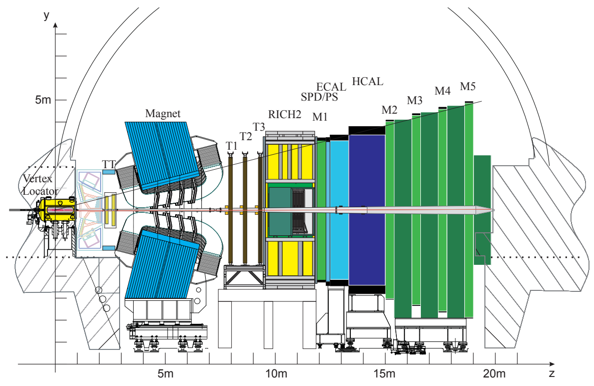
Paul Seyfert
on behalf of the LHCb collaboration

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 | ∼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 | $2\beta_s^{\rm eff}(B_s^0 \to \phi\phi)$ | – | 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

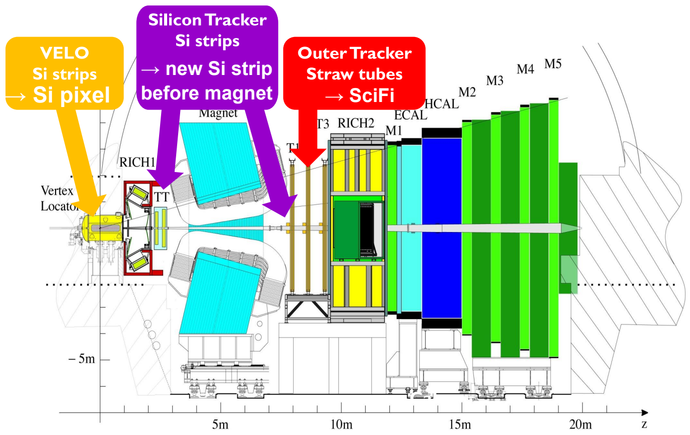
- By 2018 important analyses will still be statistically limited
- Theoretical uncertainty smaller than experimental

→ Significantly more statistics needed

⇒ Go to higher luminosity

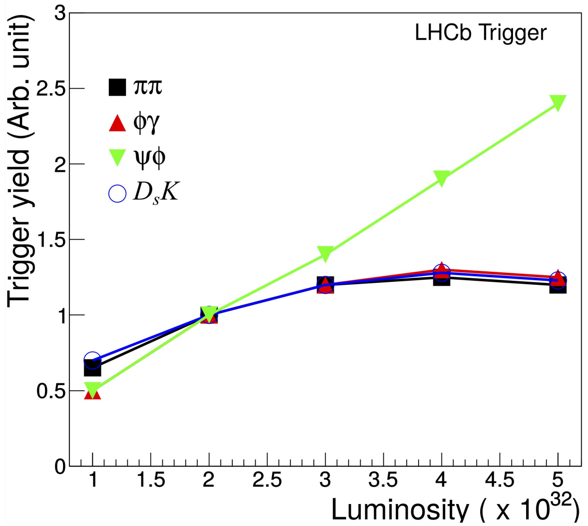


## Upgrade of the tracking system




- 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

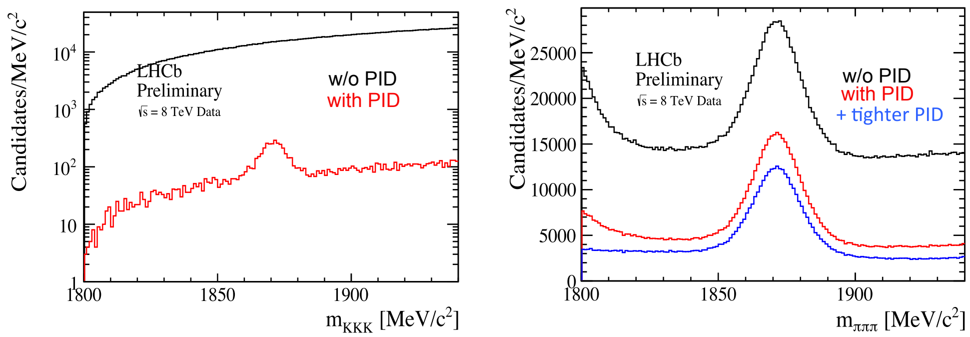



**what doesn't work**

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

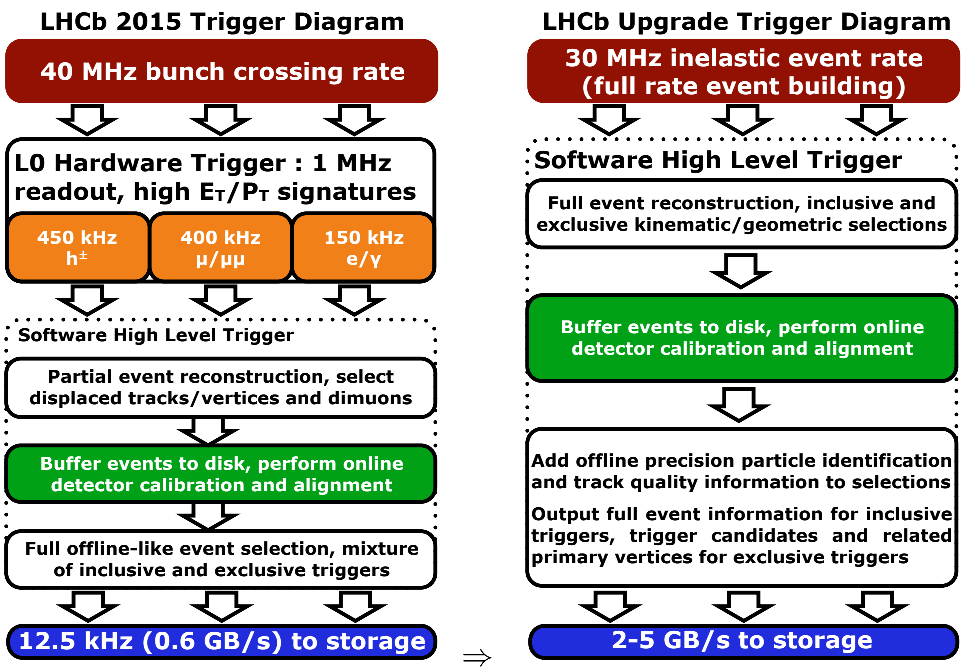


## removal of hardware trigger II




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



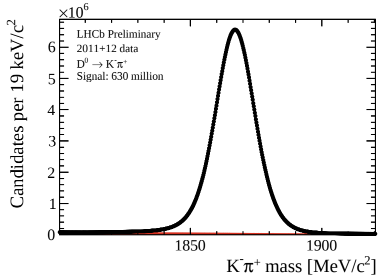





## Luxury problem: MHz signals


**Triggers today**

**Real-time data analysis tomorrow**

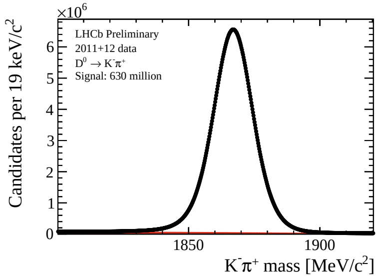



- Selecting and storing full events could work for rare signal
- When dealing with "millions" of good signal events, rejecting background isn't enough to stay within processing bandwidths

# Luxury problem: MHz signals


**Triggers today**

**Real-time data analysis tomorrow**



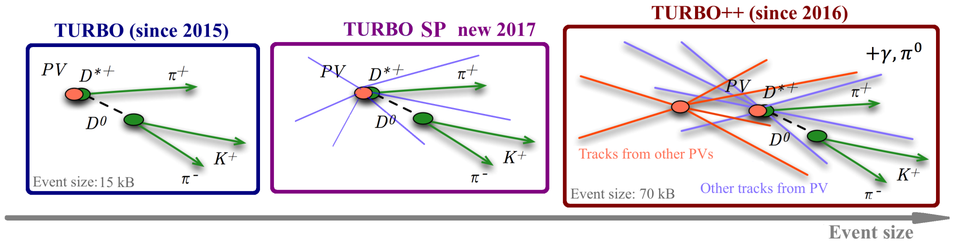

5

## 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 $\chi^2$ 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

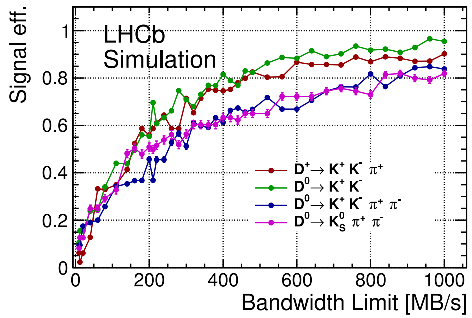
$$\chi^2 = \sum_i^{\text{channels}} \omega_i \times \left(1 - \frac{\varepsilon_i}{\varepsilon_i^{\max}}\right)^2$$

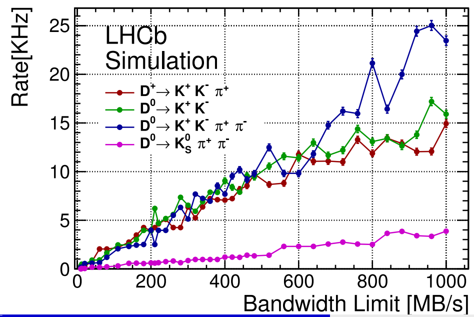
- if sum of all channels exceeds total bandwidth
  → assume random dropping of events

LHCb-PUB-2017-006



# Bandwidth division II

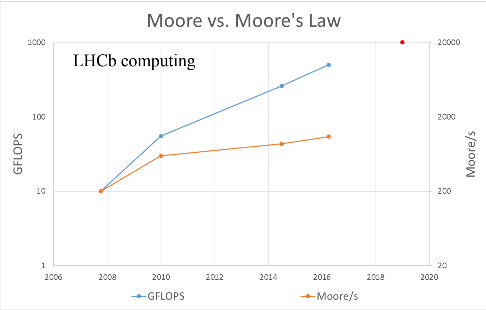



going from maximal bandwidth to restricted bandwidth

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

# “Moore doesn’t obey Moore’s law”



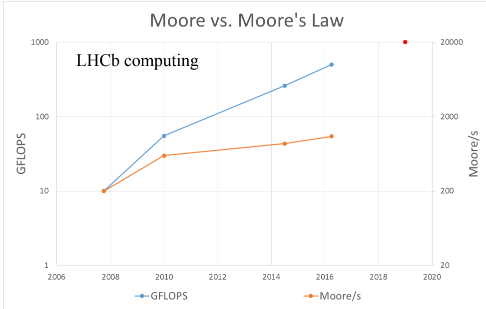

- theoretical computing power of CPUs increases (per second, per Watt, per CHF)
- observed computed trigger decisions does not follow that increase

**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”



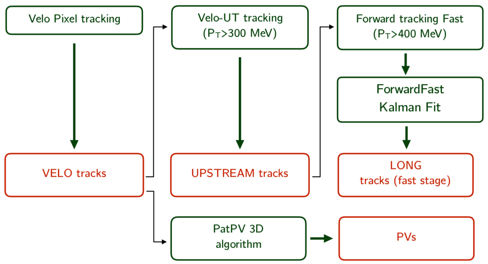

- theoretical computing power of CPUs increases (per second, per Watt, per CHF)
- observed computed trigger decisions does not follow that increase

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

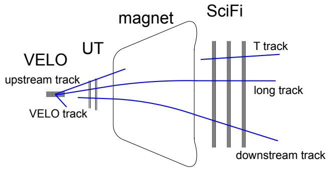
- software not parallelised (just start multiple processes on a multicore machine)
  $\rightsquigarrow$ processes compete for memory
  $\rightsquigarrow$ even multiple instances of the same data (detector geometry)
  $\rightarrow$ CPU waits for data instead of computing



# tracking sequence



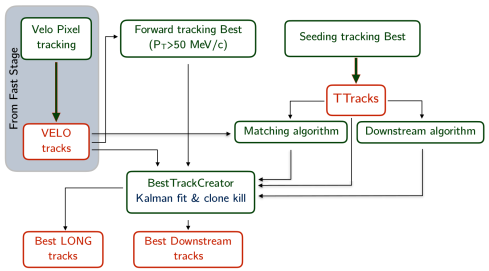

full sequence 6.0 $ms/evt$
VELO tracking 2.0 $ms/evt$
VELO-UT tracking 0.5 $ms/evt$
forward tracking 2.3 $ms/evt$
PV finding 1.1 $ms/evt$
(present HLT1: 35 $ms$)



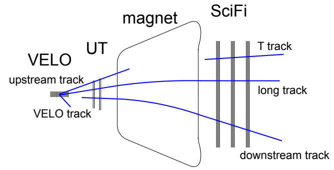

- similar to current software trigger
- single track and two track selections for displaced objects (“easy” combinatorics, limited reconstruction)



# tracking sequence



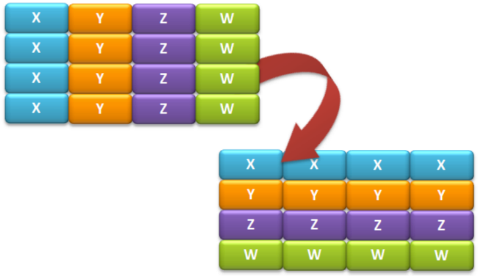

(present HLT2: 650 $ms$)

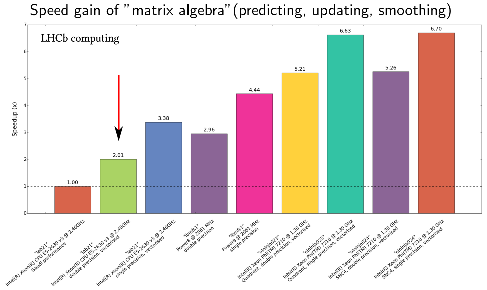



- similar to current software trigger
- single track and two track selections for displaced objects (“easy” combinatorics, limited reconstruction)
- reconstruct remaining tracks in the “full stage”
- also reconstruct decay products of strange decays outside the VELO

## 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)




LHCb-TALK-2016-372

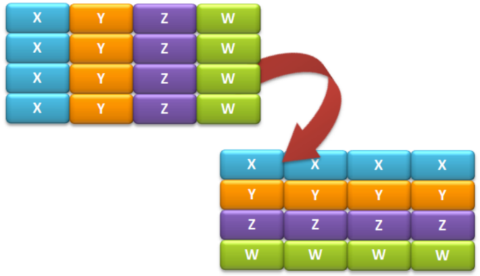


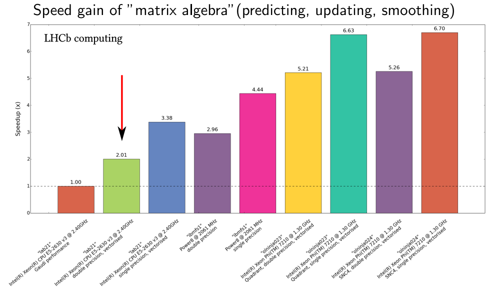
## Kalman filter track fit

**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



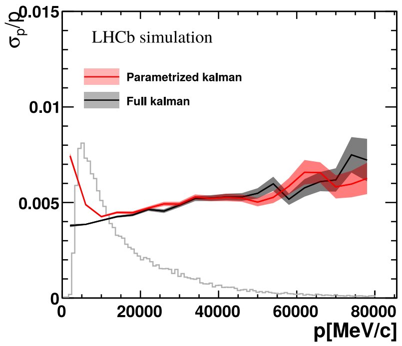



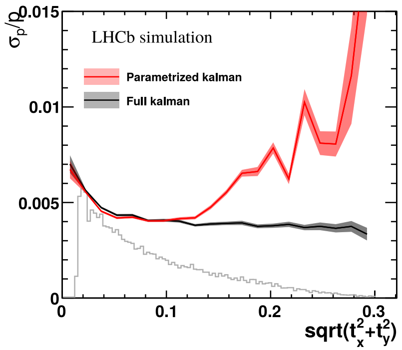

LHCb-TALK-2016-372



## 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

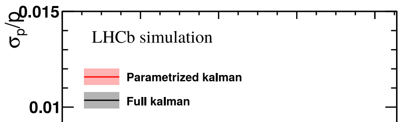


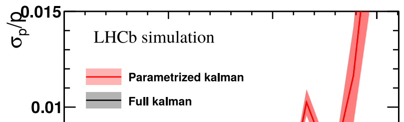






## parametrised Kalman fit

- 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



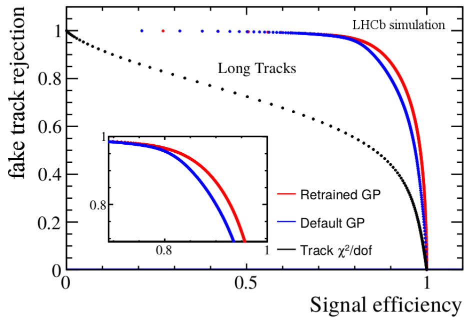

**work in progress**

- 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 $\chi^2$ alone

upgrade fake rejection:




**impact on run II**

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

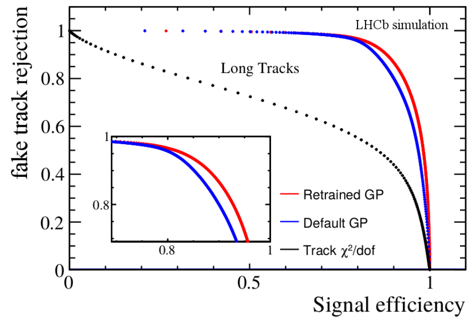


# fake track identification

- 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:

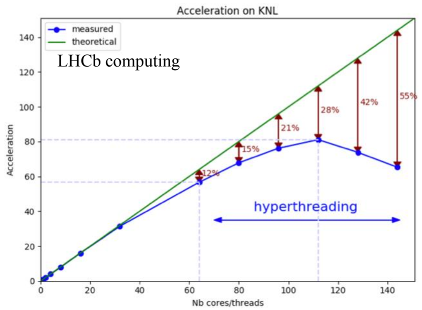


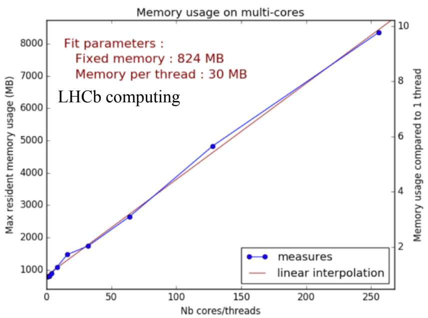

**impact on run II**

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



# 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