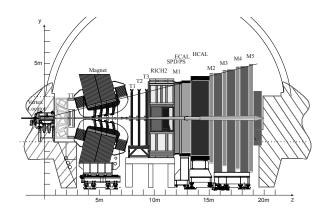
## Tracking, Vertexing and data handling strategy for the LHCb upgrade

Paul Seyfert on behalf of the LHCb collaboration

CERN

VERTEX 2017



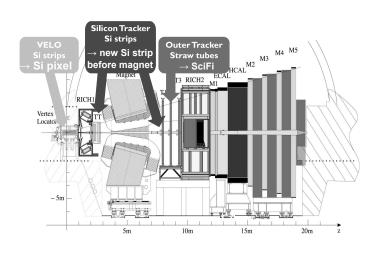
- Fully equipped forward detector at the LHC
- Approaching 400 papers
- exceeding our own expectations:
  - online calibration and alignment
  - exceeding design pile-up

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scope II	Upgrade of the tracking system								

Туре	Observable	Current precision	LHCb 2018 (8 fb <sup>-1</sup> )	$\begin{array}{c} \textbf{Upgrade} \\ (50 \text{ fb}^{-1}) \end{array}$	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	$\mathcal{B}(B_s^0 \to \mu^+ \mu^-)$	$1.5 \times 10^{-9}$	$0.5\times10^{-9}$	$0.15\times10^{-9}$	$0.3\times10^{-9}$
Gluonic penguins	$2\beta_s^{ m eff}(B_s^0  o \phi\phi)$	_	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
	$\beta(B^0 \to J/\psi K_{\rm S}^0)$	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



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

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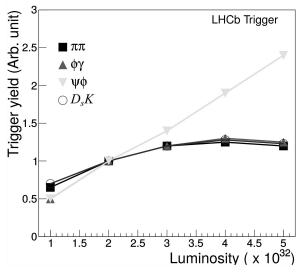
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M)

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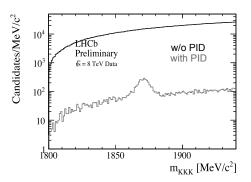
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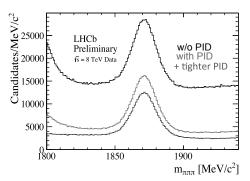
## removal of hardware trigger II



#### what doesn't work

- increased luminosity
- $\rightarrow$  events passing hardware trigger
- saturating bandwidth
- tighten thresholds
- loss in efficiency
- ⇒ 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
- ⇒ even selection in software

Paul Seyfert (CERN) LHCb upgrade Paul Seyfert (CERN) LHCb upgrade 8th September 2017 5 / 18 8th September 2017 Luxury problem: MHz signals LHCb 2015 Trigger Diagram LHCb Upgrade Trigger Diagram 30 MHz inelastic event rate 40 MHz bunch crossing rate (full rate event building) Candidates per 19 keV/ $c^2$ LO Hardware Trigger: 1 MHz Software High Level Trigger  $D^0 \rightarrow K^-\pi^+$ readout, high E<sub>T</sub>/P<sub>T</sub> signatures Full event reconstruction, inclusive and exclusive kinematic/geometric selections 400 kHz 150 kHz 450 kHz  $\mu/\mu\mu$ e/y **Triggers** Buffer events to disk, perform online Real-time data : Software High Level Trigger detector calibration and alignment analysis tomorrow today Partial event reconstruction, select displaced tracks/vertices and dimuons Buffer events to disk, perform online Add offline precision particle identification and track quality information to selections detector calibration and alignment Output full event information for inclusive triggers, trigger candidates and related Full offline-like event selection, mixture primary vertices for exclusive triggers of inclusive and exclusive triggers

- LHCb Preliminary 2011+12 data Signal: 630 million 1850  $K^-\pi^+$  mass [MeV/c<sup>2</sup>]
- 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

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12.5 kHz (0.6 GB/s) to storage

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2-5 GB/s to storage

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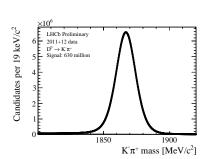
## Luxury problem: MHz signals







Real-time data analysis tomorrow



### 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)

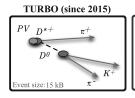
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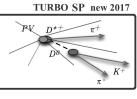
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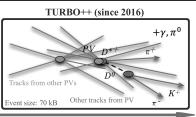
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#### store what you need







Event size

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

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## 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

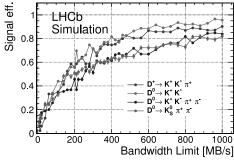
#### Genetic algorithm approach

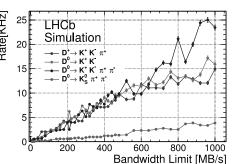
- Minimise the  $\chi^2$  by varying the MVA response for each decay
  - $w_i$  channel weight ( = 1.0 here)
  - $oldsymbol{arepsilon}_i$  channel efficiency
  - $\varepsilon_i^{ ext{max}}$  maximum channel efficiency when given the full output BW



- if sum of all channels exceeds total bandwidth
  - $\rightarrow$  assume random dropping of events

### Bandwidth division II





going from maximal bandwidth to restricted bandwidth

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

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

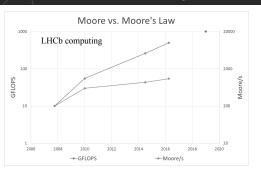
# Moore vs. Moore's Law LHCb computing

- 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
  - $\rightarrow$  7/8 of the silicon unused!

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

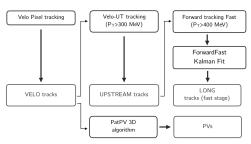


- theoretical computing power of CPUs increases (per second, per Watt, per CHF)
- observed computed trigger decisions does not follow that increase

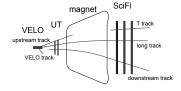
#### reasons from a CPU's point of view II/II

- 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

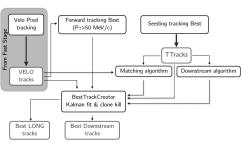
#### Paul Seyfert (CERN) LHCb upgrade 12 / 18 Paul Seyfert (CERN) 12 / 18 8th September 2017 LHCb upgrade 8th September 2017 tracking sequence tracking sequence



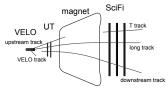
full sequence 6.0 ms/evt VELO tracking 2.0 ms/evt VELO-UT tracking 0.5 ms/evt forward tracking 2.3 ms/evt PV finding 1.1 ms/evt (present HLT1: 35 ms)



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



(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**

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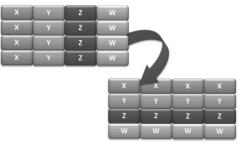
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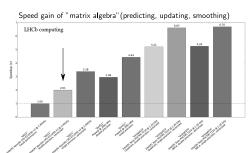
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## Kalman filter track fit

- 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)

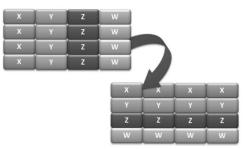




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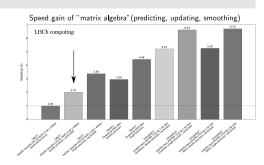
grain of salt

- 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



parametrised Kalman fit

 $\mathcal{O}(20)$  parameters



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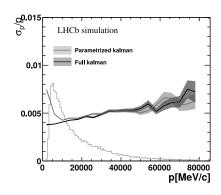
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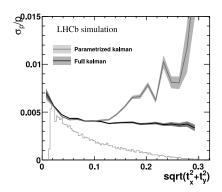
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## parametrised Kalman fit

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





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■ avoid first-principles math for every track
 → parametrisations can be equally accurate reduce complicated B field propagation and material lookup to



#### work in progress

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

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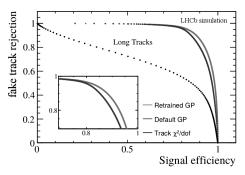
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fake track identification

#### fake track identification

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

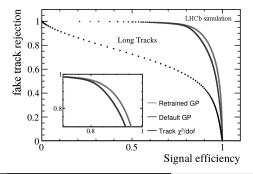
#### upgrade fake rejection:



#### impact on run II

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

- fake tracks a big contribution to computing budget in run I
- lacktriangle 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

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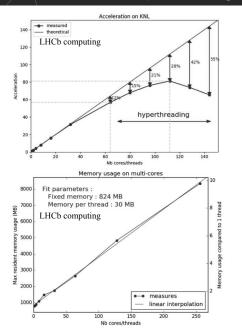
Conclusion

LHCb upgrade

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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

- 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

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