Tracking, Vertexing and data handling strategy for the LHCb upgrade

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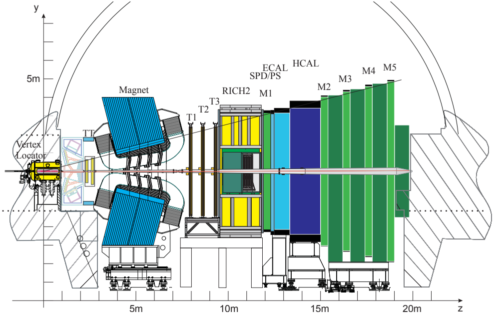
on behalf of the LHCb collaboration

CERN

VERTEX 2017

scope I



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	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9}	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
Gluonic penguins	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\phi)$	–	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

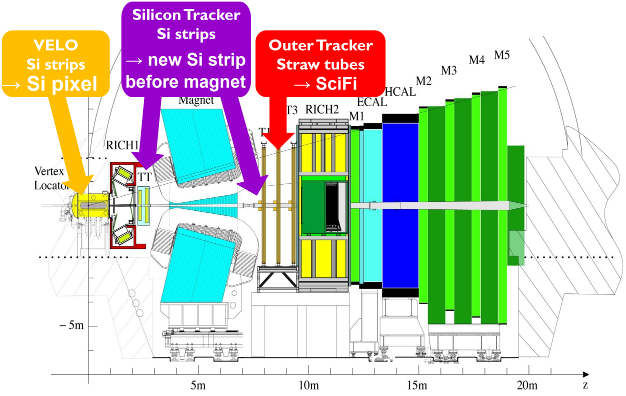
Eur. Phys. Journal C (2013) 73:2373

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

$\rightarrow$ Significantly more statistics needed

$\Rightarrow$ Go to higher luminosity
($\mathcal{L} = 2 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1} \Rightarrow \nu \sim 7.6$)
LHCb-PUB-2014-027

Upgrade of the tracking system



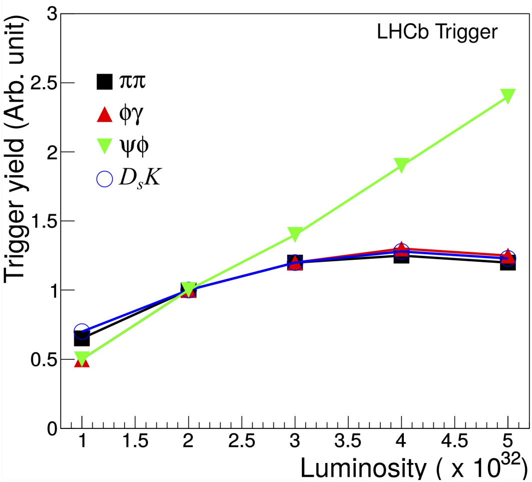
- Vertex pixel detector
  see talk by Edgar Lemos Cid
- silicon strip detector
  see talk by Marco Petruzzo
- scintilating fiber tracker

σ_z (vertex)
$<$ 90 µm (more than 20 tracks) $<$ 50 µm (more than 50 tracks)

σ_t (decay)
$<$ 45 fs

σ_p/p
$< 0.5\,\%$

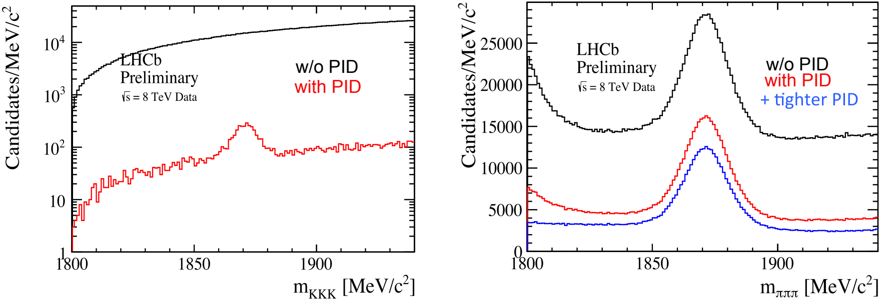
removal of hardware trigger I



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)

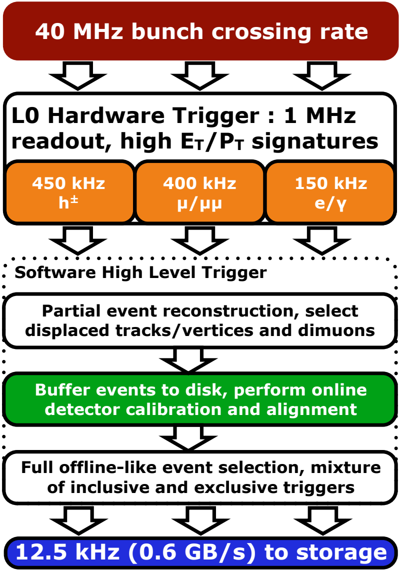
removal of hardware trigger II



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

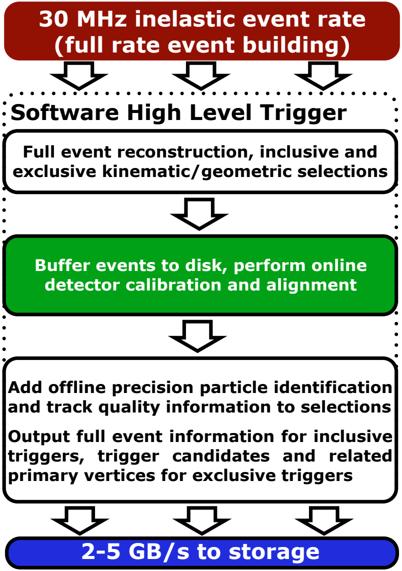
$\Rightarrow$ even selection in software

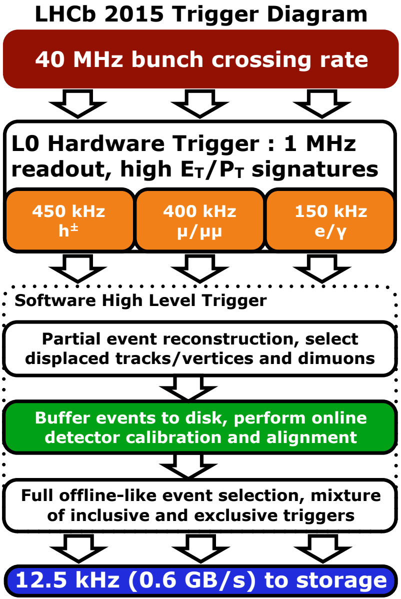
LHCb 2015 Trigger Diagram



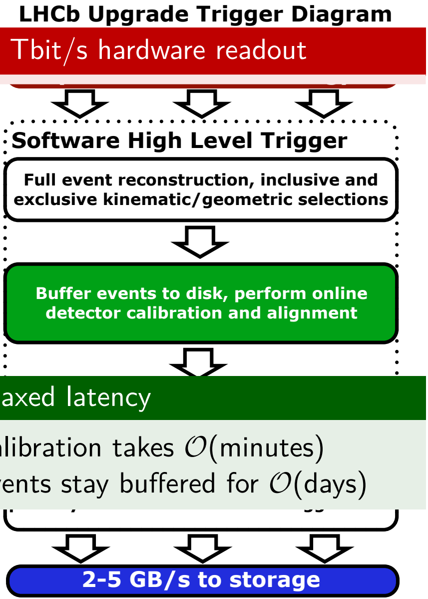
$\Rightarrow$

LHCb Upgrade Trigger Diagram





$\Rightarrow$



40 Tbit/s hardware readout

relaxed latency

Calibration takes $\mathcal{O}$(minutes)

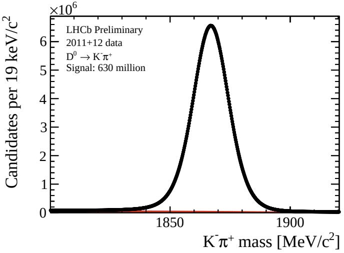
Events stay buffered for $\mathcal{O}$(days)

Luxury problem: MHz signals

Triggers today

Real-time data analysis tomorrow

5



LHCb-CONF-2016-005

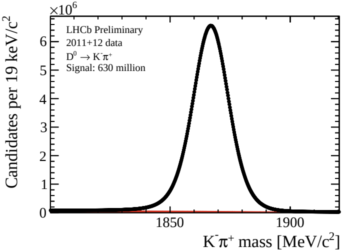
- Selecting and storing full events could work for rare signal
- When dealing with "millions" of good signal events, rejecting background isn't enough to stay within processing bandwidths

Luxury problem: MHz signals

Triggers today

Real-time data analysis tomorrow

5



LHCb-CONF-2016-005

The TURBO approach

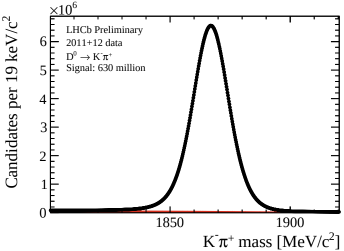
- once a decay is reconstructed (mass, decay time, Dalitz plot) no need to access raw data for analysts
- once a decay is reconstructed in the trigger no need to re-reconstruct offline
- (unaffordable to study raw data for millions of events anyway)

Luxury problem: MHz signals

Triggers today

Real-time data analysis tomorrow

5

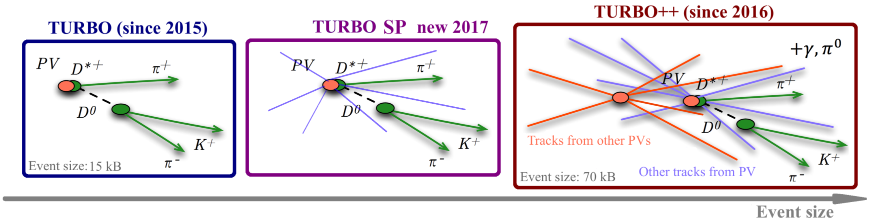


LHCb-CONF-2016-005

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
  $\rightarrow$ we will face offline storage limits
- wide Physics program requires compromise
- limit *sensitivity* loss in a fair share

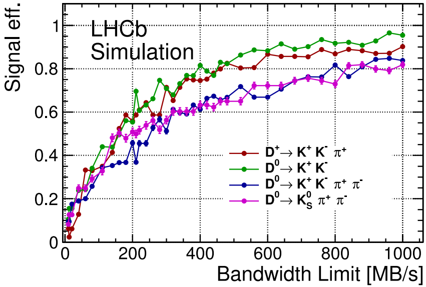
- Genetic algorithm approach
  - Minimise the χ^2 by varying the MVA response for each decay
    - ω_i channel weight (= 1.0 here)
    - ε_i channel efficiency
    - $\varepsilon_i^{\max}$ maximum channel efficiency when given the full output BW

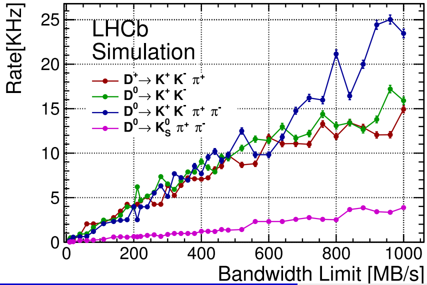
$$\chi^2 = \sum_i^{\text{channels}} \omega_i \times \left(1 - \frac{\varepsilon_i}{\varepsilon_i^{\max}}\right)^2$$

- if sum of all channels exceeds total bandwidth
  $\rightarrow$ 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

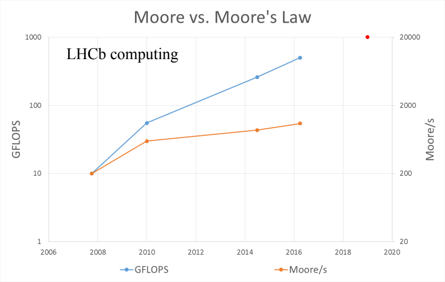




going from maximal bandwidth to restricted bandwidth

- 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”

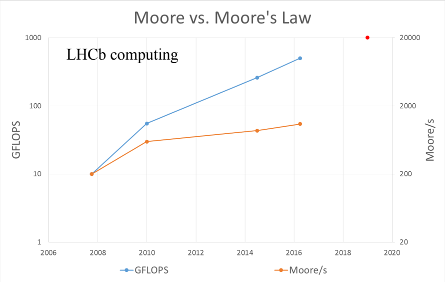


- theoretical computing power of CPUs increases (per second, per Watt, per CHF)
- observed computed trigger decisions does not follow that increase

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

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

“Moore doesn’t obey Moore’s law”



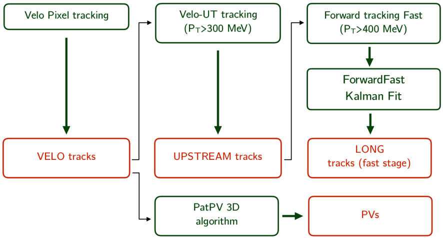
- theoretical computing power of CPUs increases (per second, per Watt, per CHF)
- observed computed trigger decisions does not follow that increase

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

tracking sequence

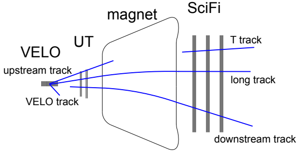
LHCb-PUB-2017-005



fast sequence 6.0 ms/evt @ 30 MHz

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

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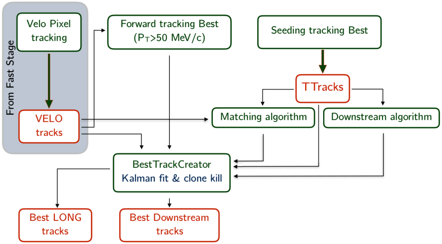
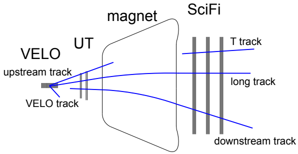


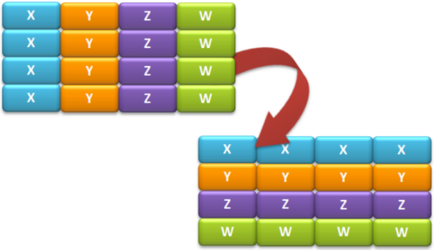
full sequence aim
$\sim 20\times$ slower
$1/30$ rate ($1\ MHz$)
Kalman fit large contributor
(present HLT2: $650\ ms$)



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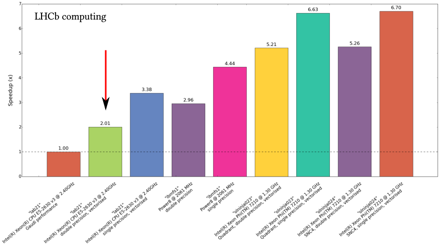
Speed gain of "matrix algebra" (predicting, updating, smoothing)

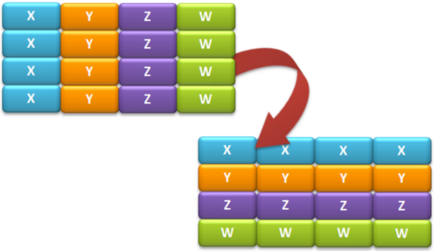


Kalman filter track fit

grain of salt

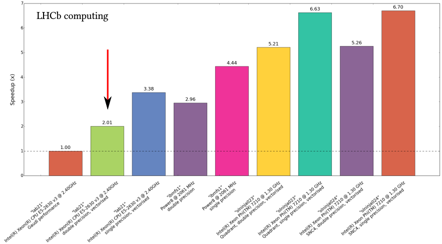
- only speeds up the matrix algebra
- material lookup remains
- now requires back-and-forth conversion of memory layout

⇒ to be consequent need to adapt underlying event model



LHCb-TALK-2016-372

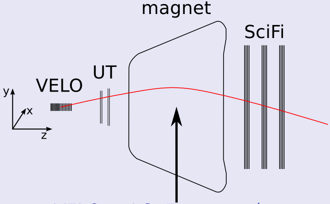
Speed gain of "matrix algebra" (predicting, updating, smoothing)



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

example parametrised extrapolation through the magnet



Between VELO and SciFi stations (strong mag. field)

$$\Delta p_x = p\left(\frac{t_{x,T}}{\sqrt{1+t_{x,T}^2+t_{y,T}^2}} - \frac{t_{x,V}}{\sqrt{1+t_{x,V}^2+t_{y,V}^2}}\right) = q\int |d\mathbf{l}\times\mathbf{B}|$$

$$x_T = x_V + (z_{mag} - z_V)t_{x,V} + (z_T - z_{mag})t_{x,T}$$

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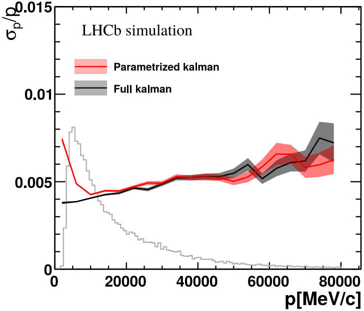
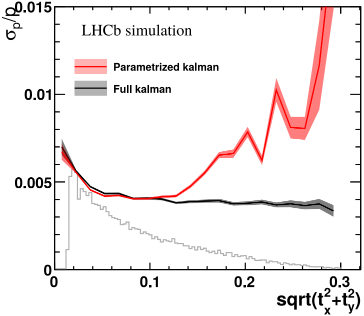
parametrised Kalman fit

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





parametrised Kalman fit

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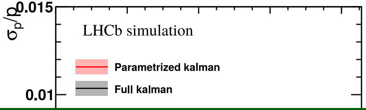
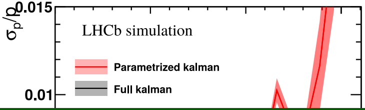




work in progress

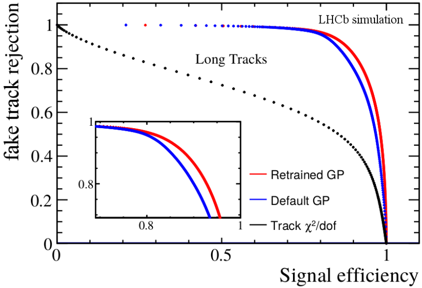
- resolution close to reference
- potentially use full fit for tracks with large $\sqrt{t_x^2 + t_y^2}$
- find alternative parametrisations

⇒ 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 χ^2 alone

upgrade fake rejection:



impact on run II

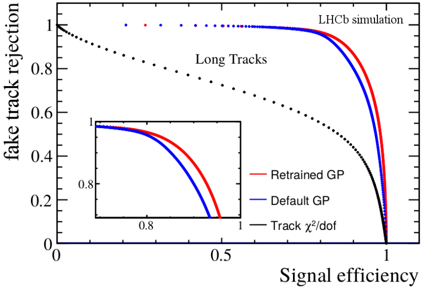
- RICH PID $-\mathcal{O}(20\,\%)$ CPU
- combinatorics $-\mathcal{O}(60\,\%)$ CPU
- trigger $-\mathcal{O}(30\,\%)$ rate

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:



impact on run II

- RICH PID $-\mathcal{O}(20\,\%)$ CPU
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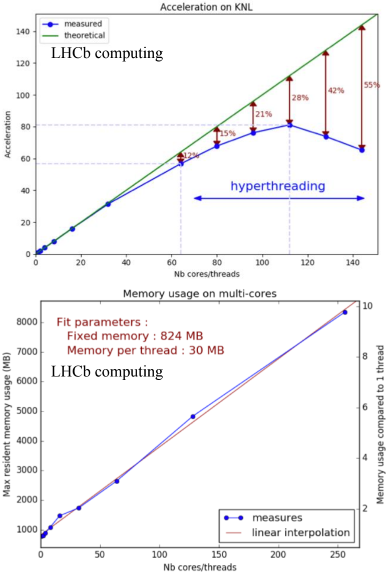
multi threaded processing framework



- 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
- Need to face tight constraints from offline storage and processing as well as online processing power
  - $\rightarrow$ reconstruction right out of the trigger
  - $\rightarrow$ "per analysis" storage
- Fast tracking *without performance loss* crucial for LHCb upgrade
- Needs reconstruction software close to computer hardware to optimally use it

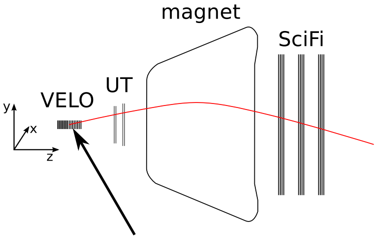
BACKUP

these slides online

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

parametrisations I

Inside the VELO (weak mag. field)



Straight line prediction for y

First order correction in q/p for x (effect is small)
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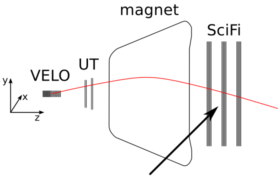
Inside the SciFi stations (medium mag. field)

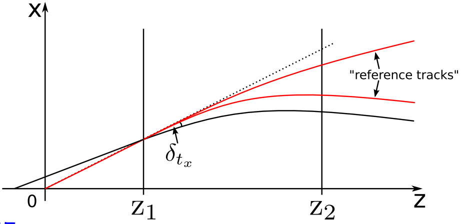


Empirical parametrization depending on q/p and y for prediction

$t'_x = t_x + par_1 \frac{q}{p} + par_2 \left(\frac{q}{p}\right)^3 + par_3 y^2 \frac{q}{p} \left|\frac{q}{p}\right|$

parametrisations II

- Use primary (x,y=0 at z=0) tracks as "reference":
  - For them the extrapolation is a expansion in $\frac{q}{p}$ (4th order)
  - Using coefficients that are tabulated as a function of x, y
- Perform a expansion in the deviation from these tracks (δ_{t_x} and δ_{t_y}) for the correction of the coefficients of the $\frac{q}{p}$ expansion



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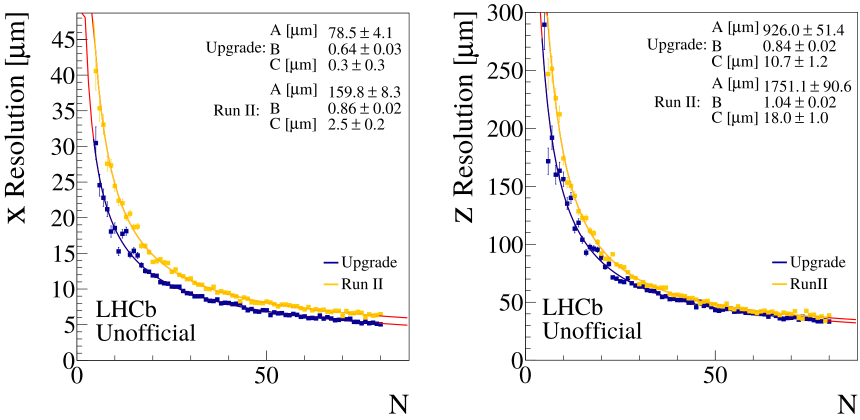
Vertex resolution



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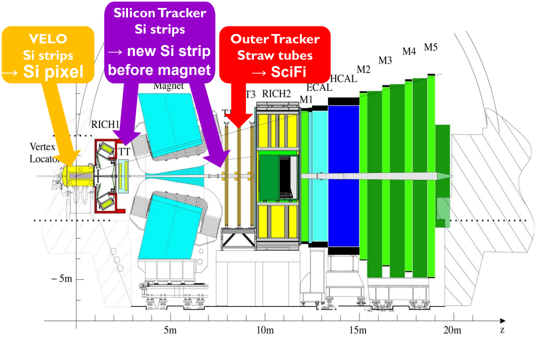
Upgrade of the tracking system



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

σ_t (decay)

< 45 fs

$$\left(\mathcal{D} \sim \exp(-\underbrace{\Delta m^2}_{1/56\text{ fs}} \sigma_t^2/2) \right)$$

for time dependent B_s analyses