Real time triggering and reconstruction at LHCb, its upgrade and the future

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Outline

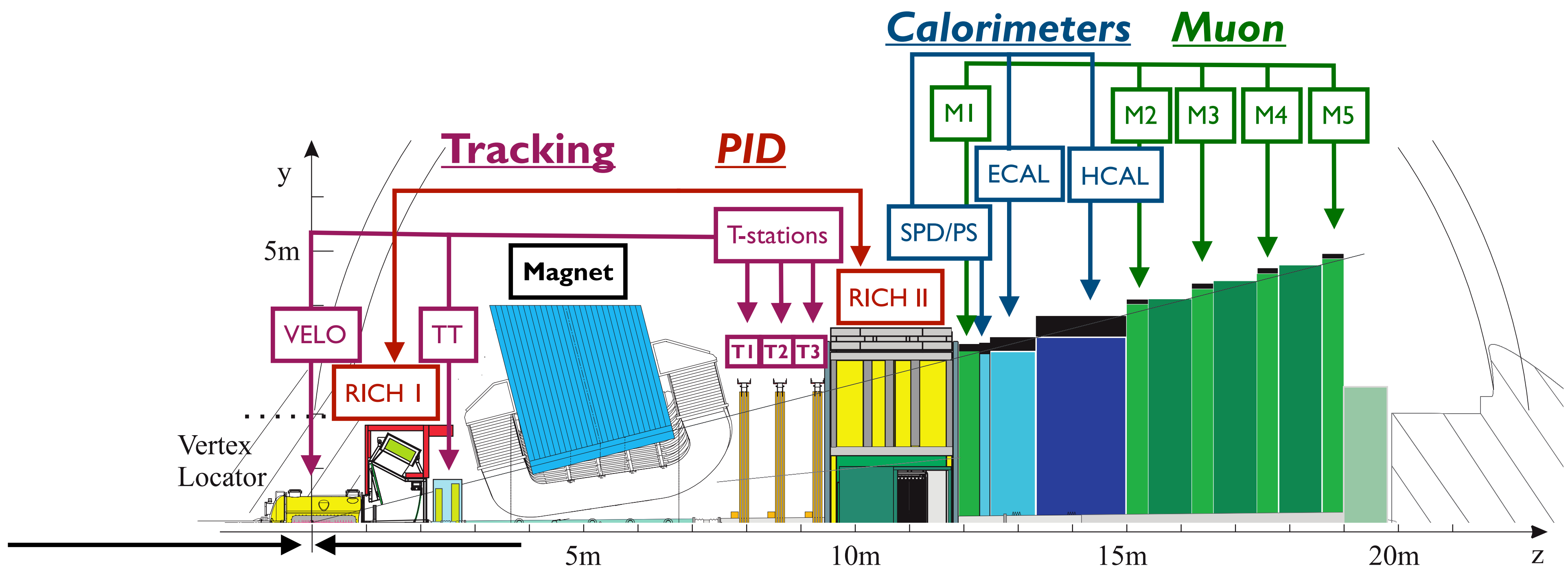
Introduction LHCb

The LHCb trigger evolution during years

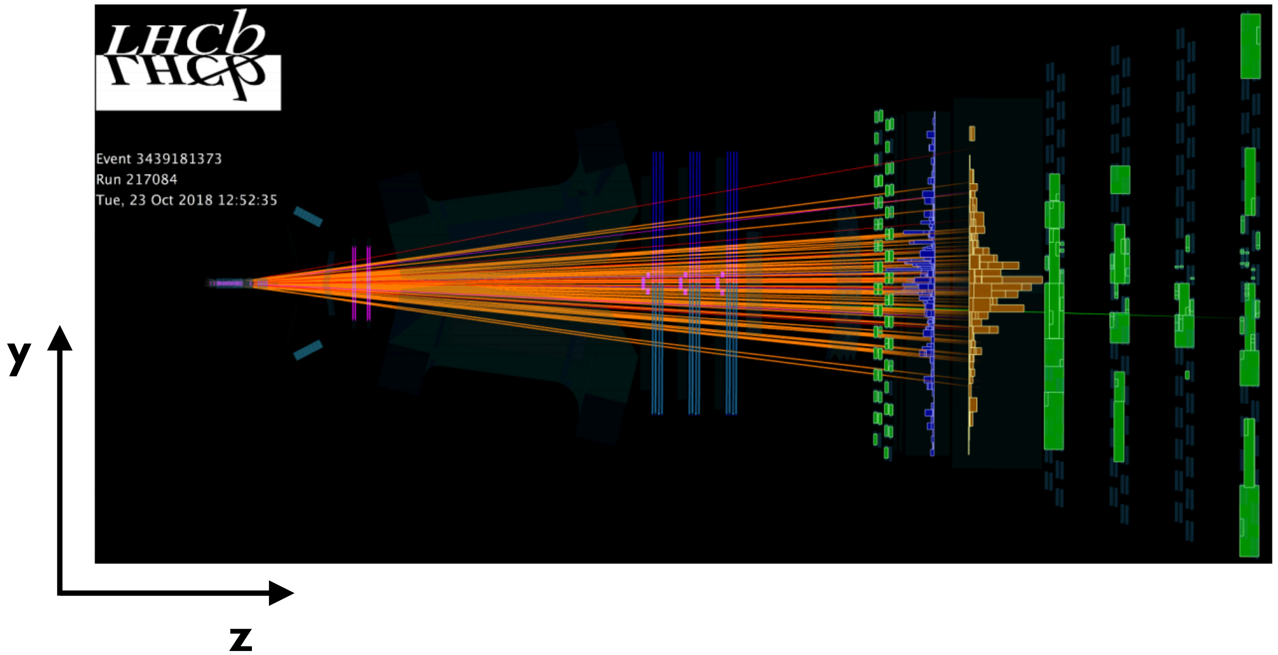
The LHCb trigger in Run III

Plans for the HL-LHC

The LHCb detector



2018 event : PU = 1-2



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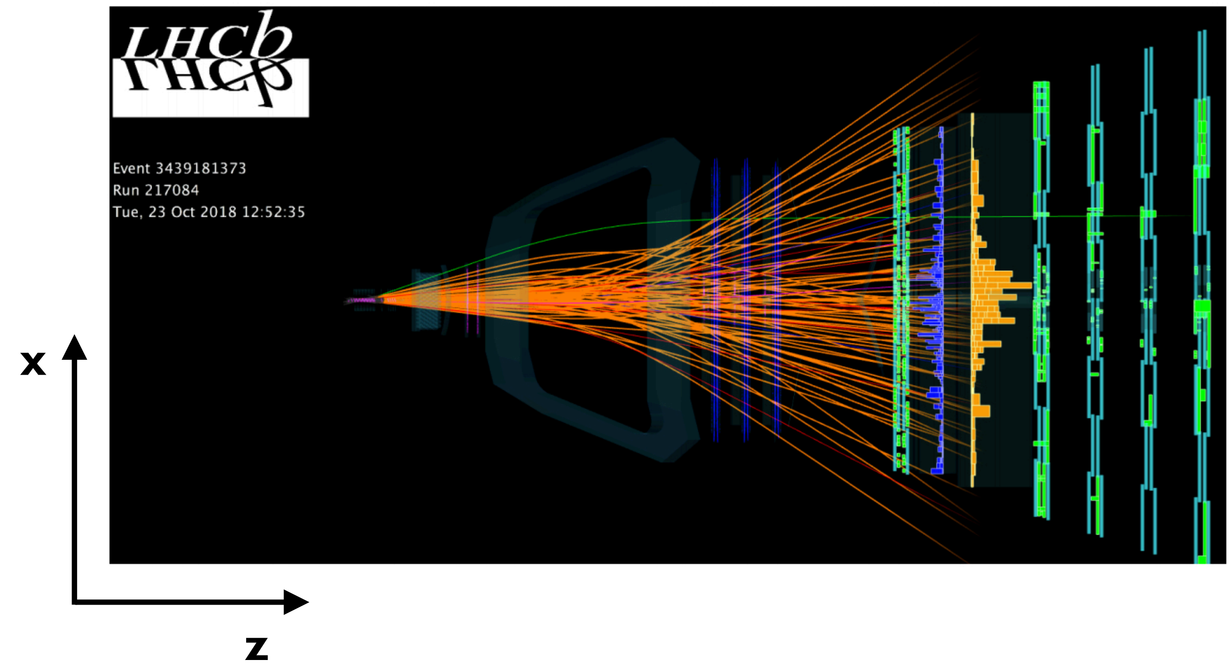
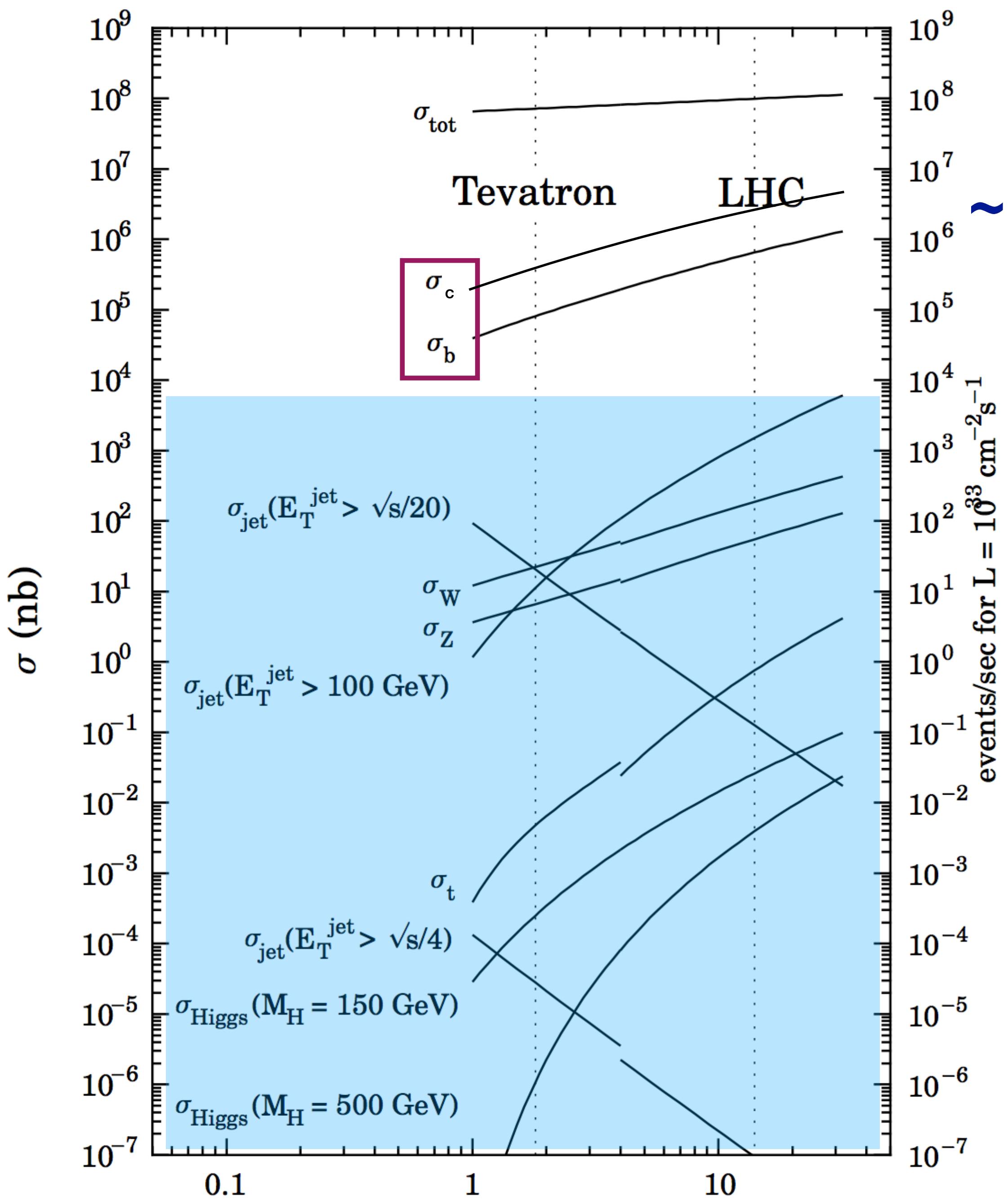


The LHCb detector

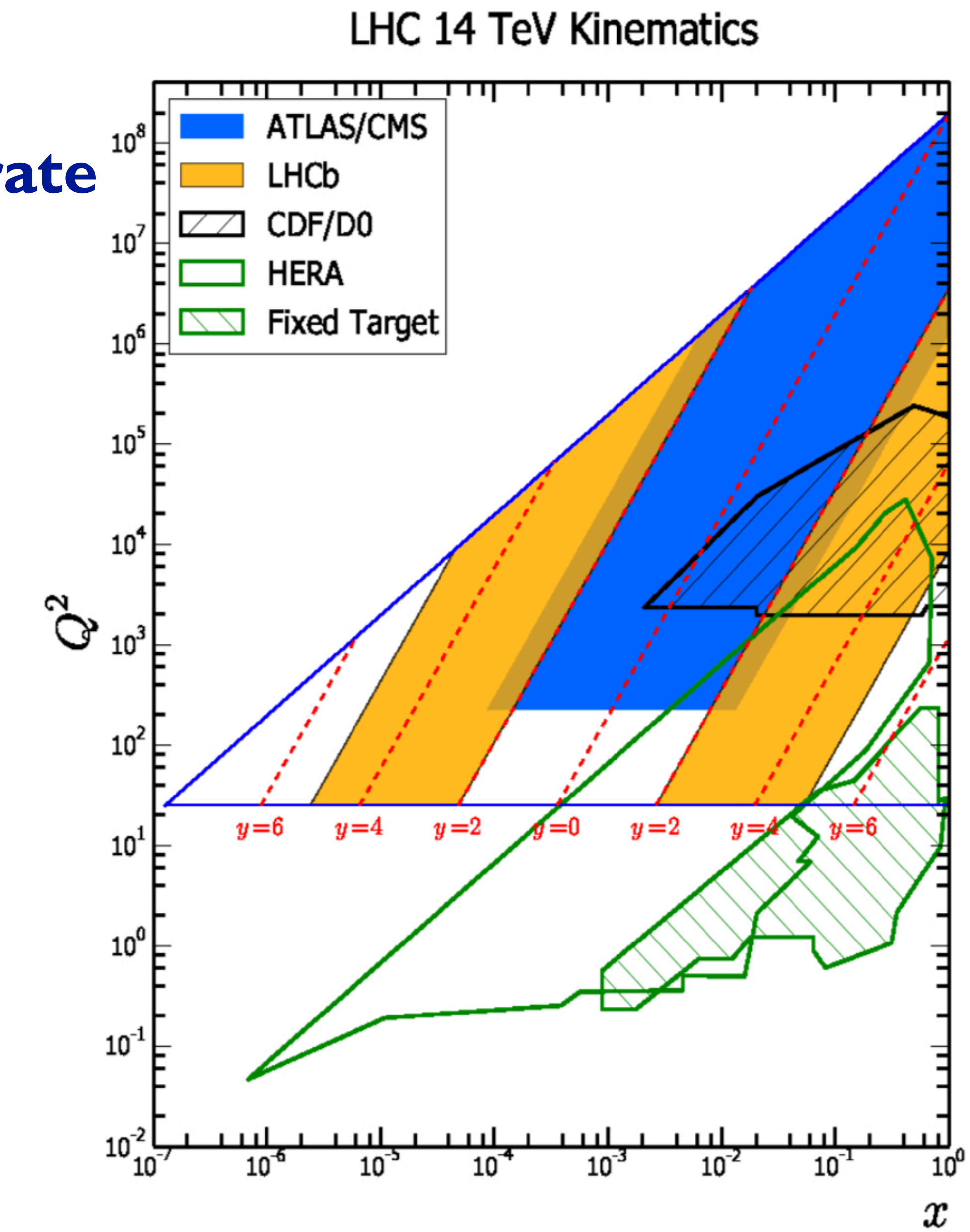
A dedicated flavour physics experiment



~MHz signal rate

100 kHz

Unique η acceptance, complementary to Atlas/CMS

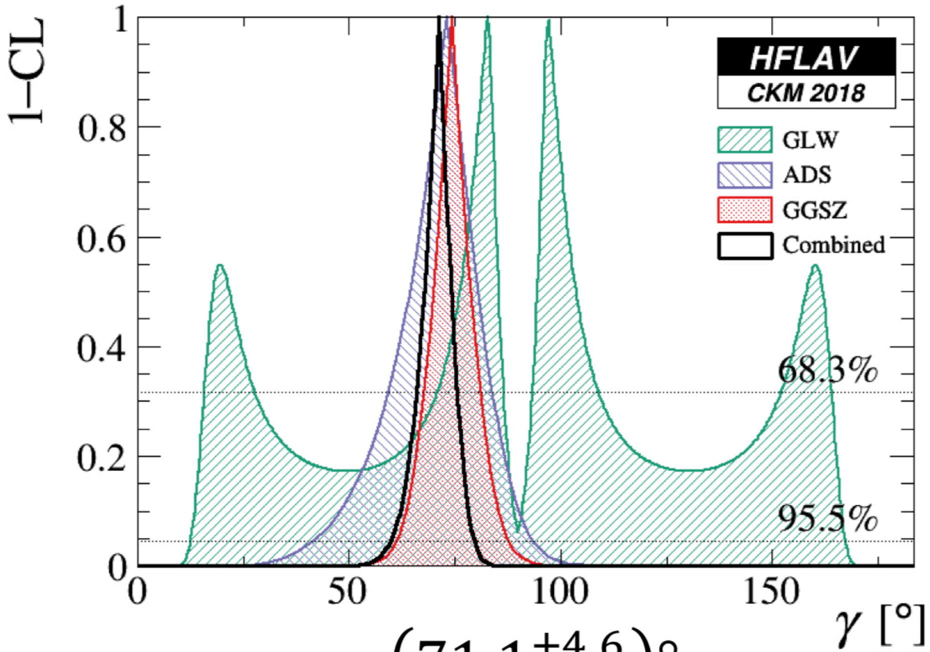


ATLAS/CMS efficient trigger using a O(100kHz) read-out with ~straightforward E_T requirements. Trigger at hardware level is crucial. Also higher PU but looking to very rare events.

LHCb signal rate @LHC with PU=1, 45 kHz bb and 1 MHz cc bar. Can be efficient with 1 MHz read-out

Few highlights from LHCb Run I and Run II

Constrain the CKM angles

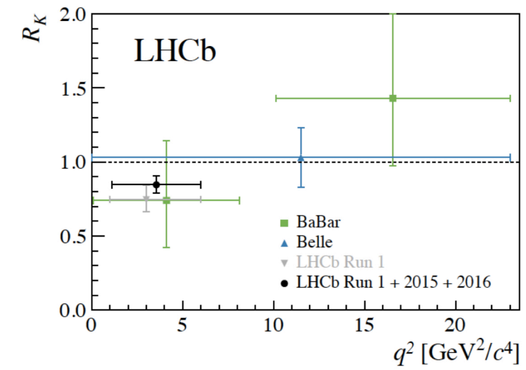


$\gamma = (71.1^{+4.6}_{-5.3})^\circ$

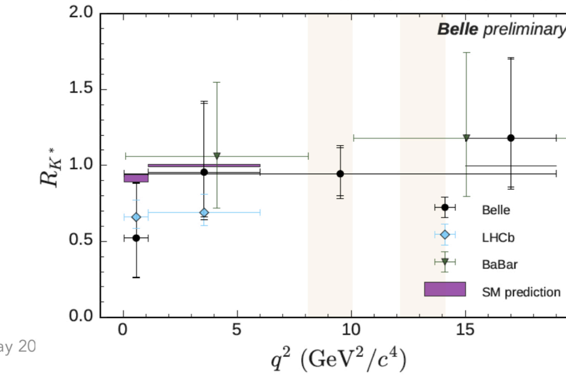
Hints of NP in FCNC transitions?

R_K , R_{K^*} , R_ϕ , R_{pK} …

arXiv 1903.09252

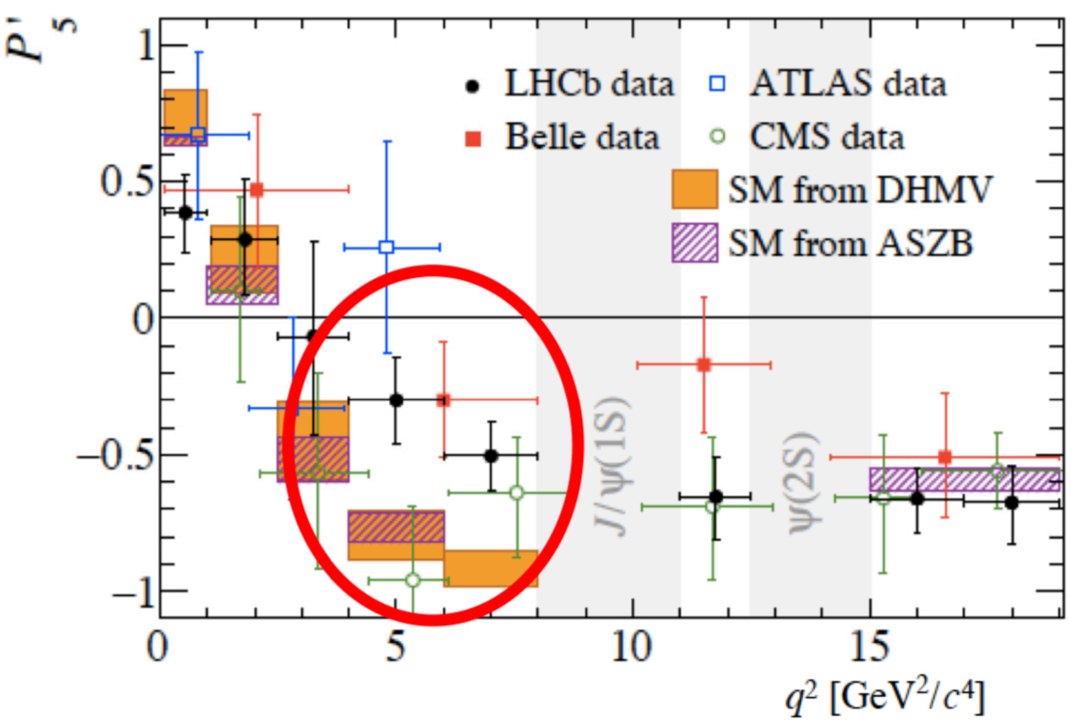


Belle M. Prim Moriond 2019

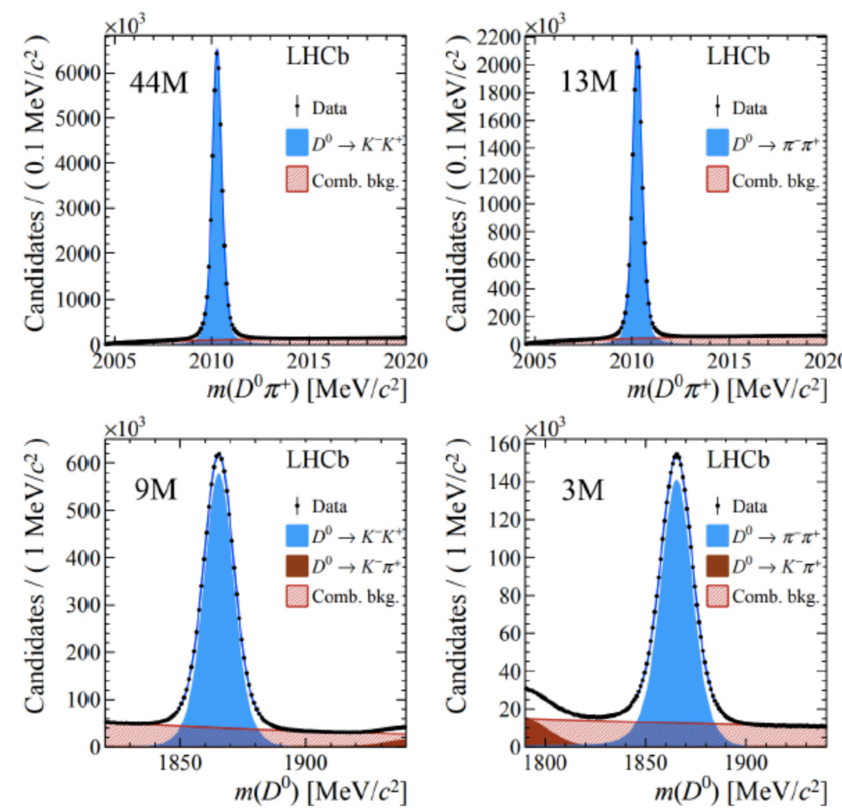


ESPP Granada May 20

Angular distributions in FCNC decays



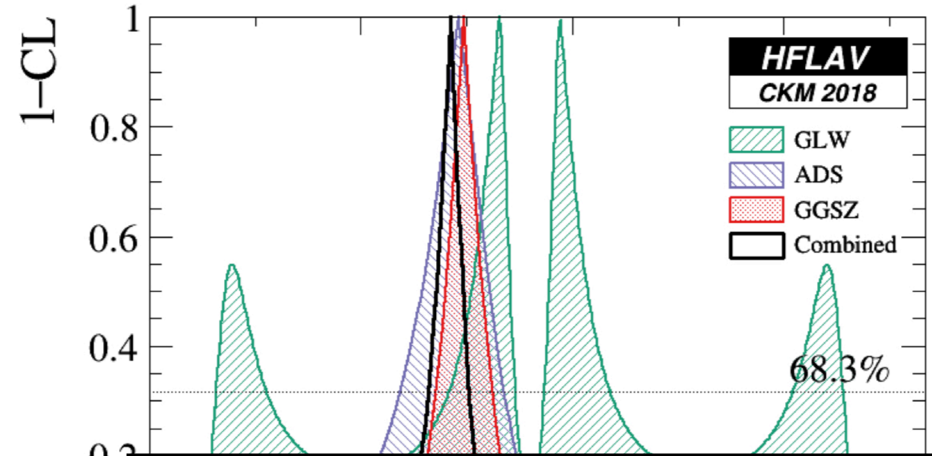
Discovery of CP violation in charm sector



+++ Pentaquark, $B_{s/d} \to \mu\mu$ (B.F. $10^{-9\,/-10}$)

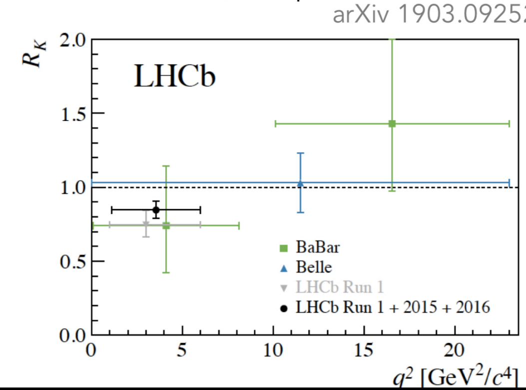
Few highlights from LHCb Run I and Run II

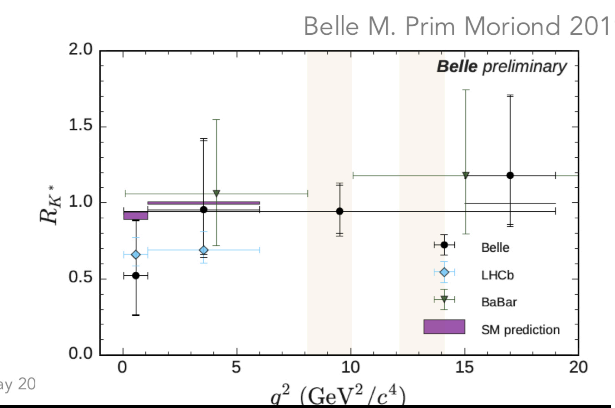
Constraint the CKM angles



Hints of NP in FCNC transitions?

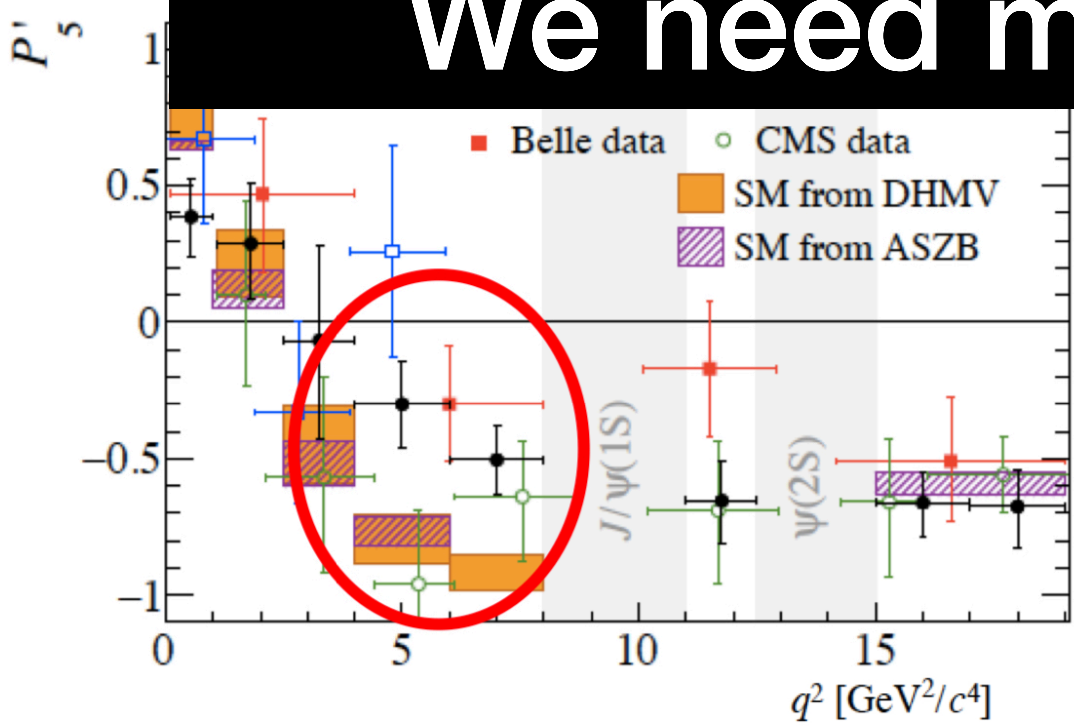
R_K , R_{K*} , R_ϕ , R_{pK} …



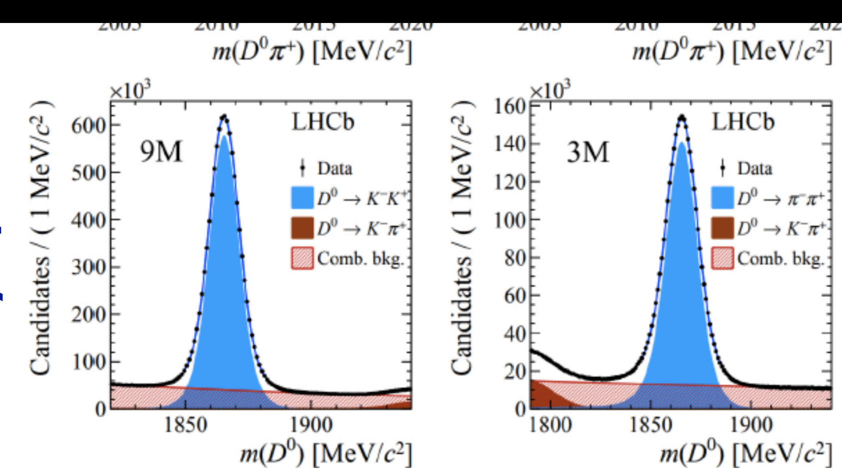


No New Physics discovered so far.
Higher and higher precision needed.
We need more and more data.

A



Discovery of CP viola



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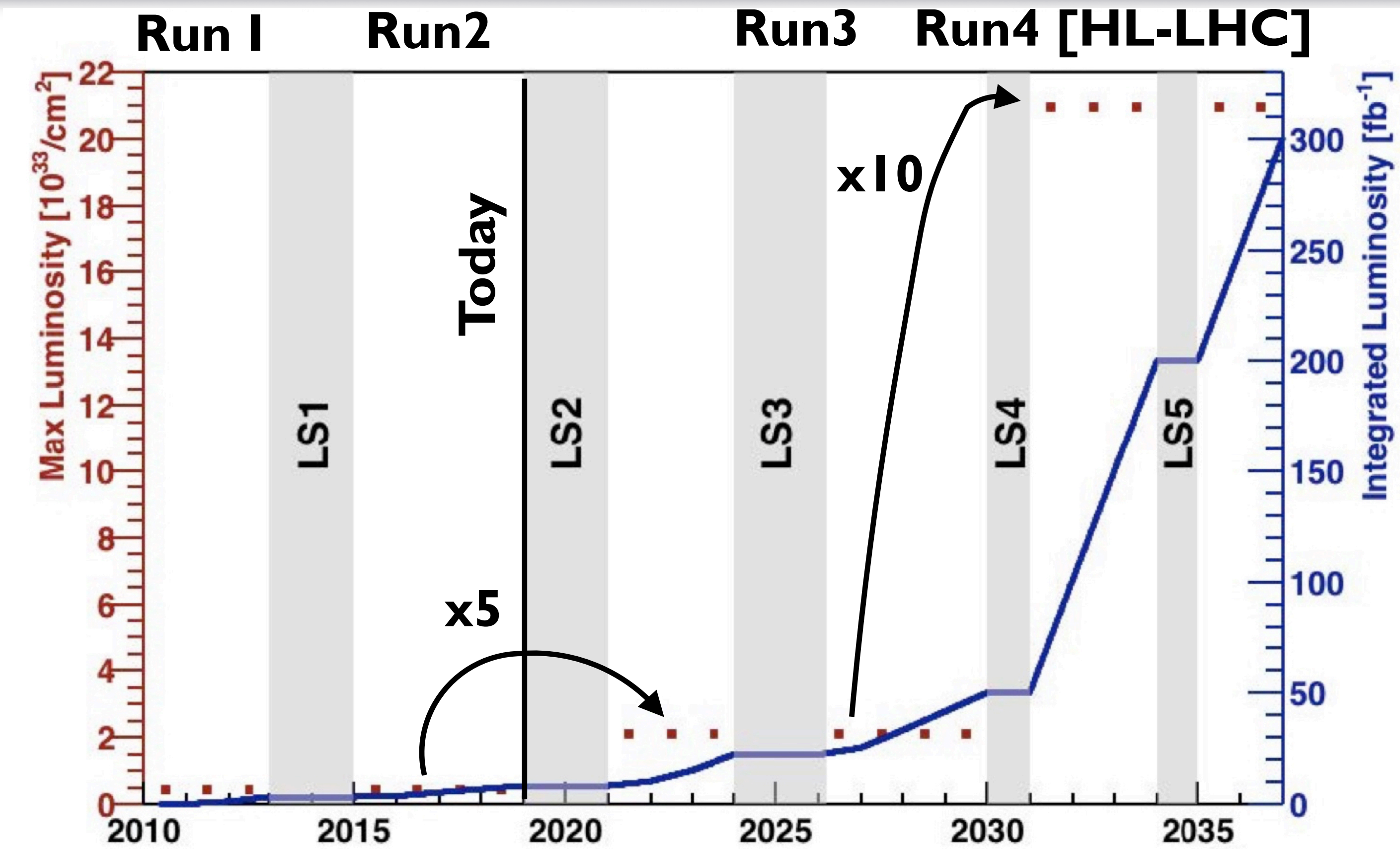
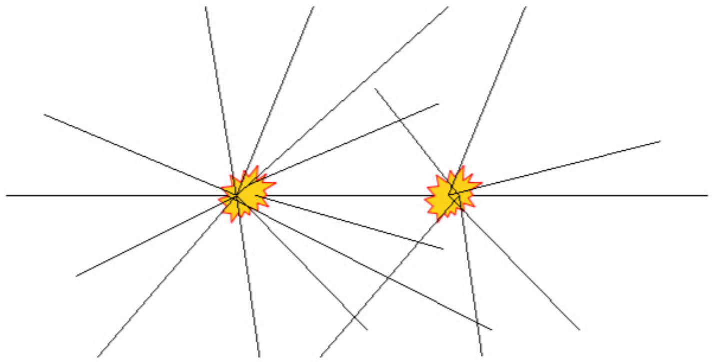
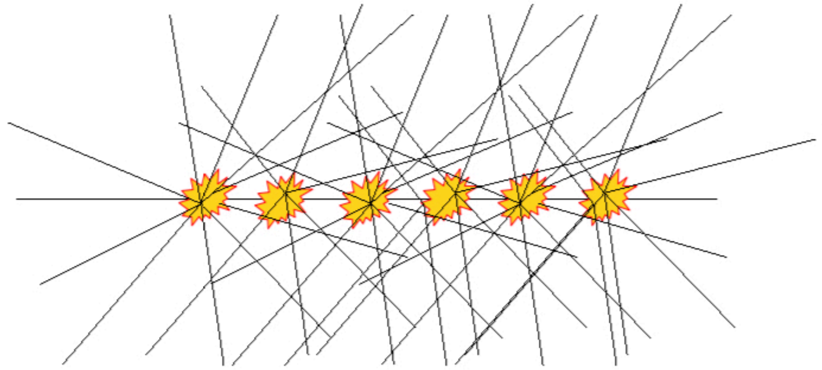


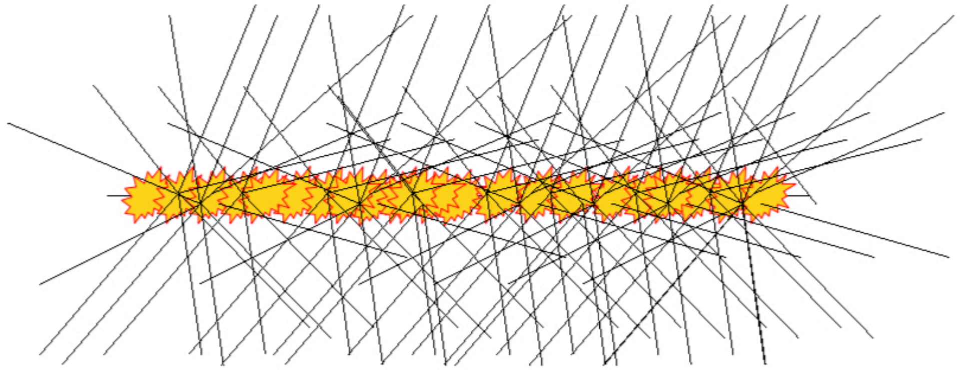
Current



Upgrade



Phase 2 Upgrade



RUN1 & RUN2 2011-2018

RUN3 2021-2030

HL-LHC 2030++

The LHCb detector

☞**Large cross section of *b* and *c* quark production** in pp collision.

1 event (Run 1 / Run II) ~ 50 kB

The success of LHCb in Run 1/2 relied on few ingredients

☞**Excellent tracking :** σ_{IP} ~ 20 μm (p_T > 2 GeV/c), $\varepsilon_{tracking}$ > 96 %, Δp/p ~ 0.5-1%.

☞**Excellent particle identification (PID)**: ε_K-ID ~95% , ε_μ-ID ~97%

☞**Excellent decay time resolution**: $\sigma_{\tau\text{-decay}}$ ~ 45 *fs* for *b* hadrons

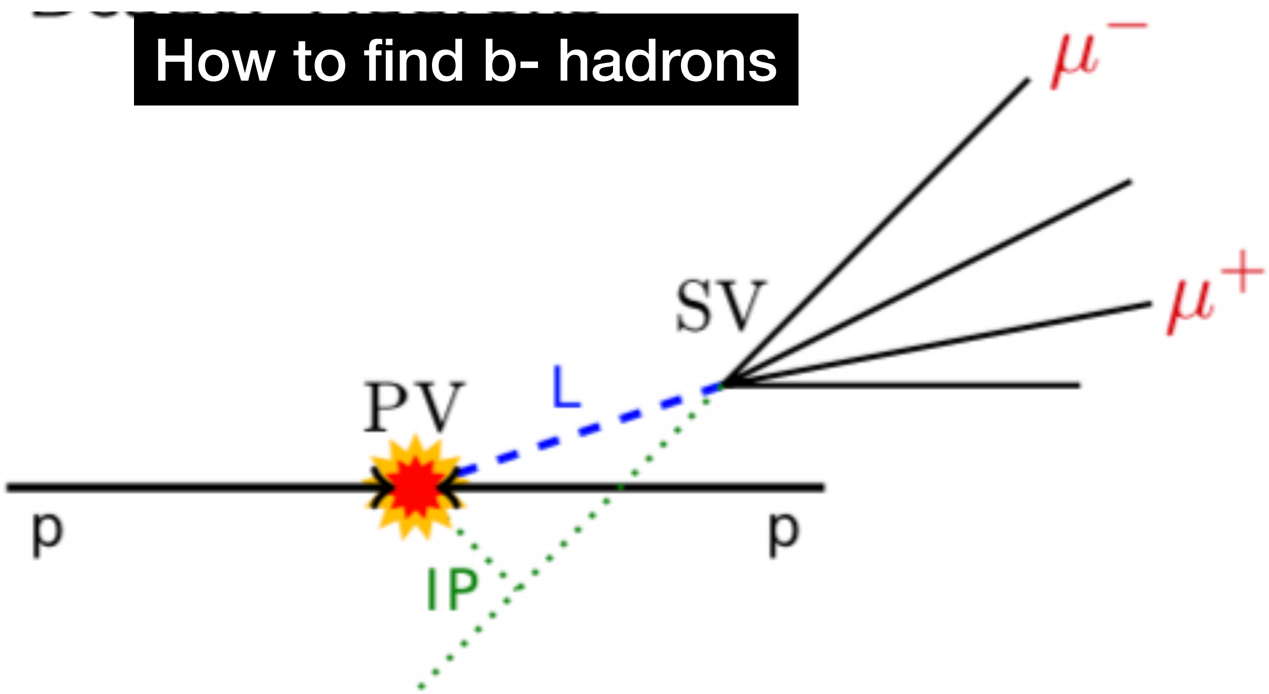
An incredible versatile detector able to efficiently select and record very rare processes and very frequent ones.

(true for all experiments but…)

<u>The trigger in LHCb plays a critical role</u>

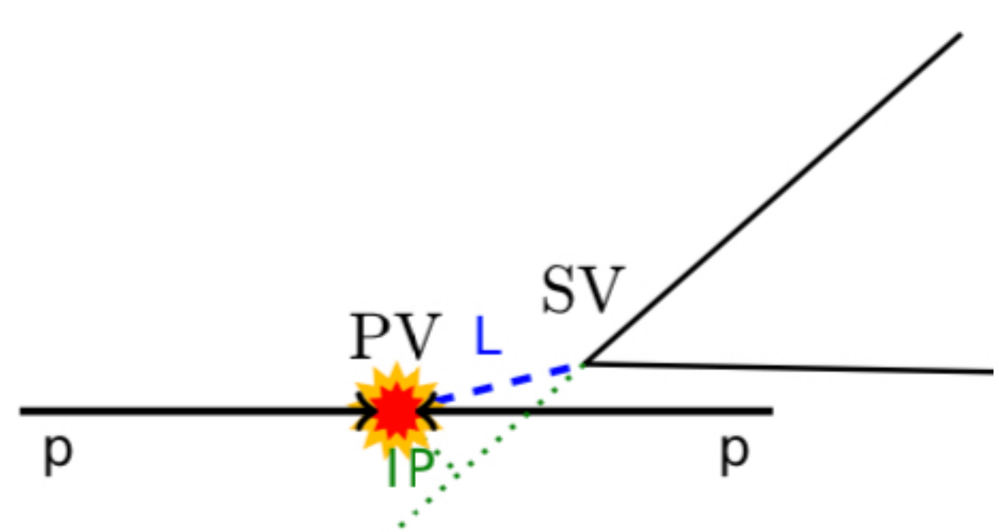
The b/c hardons signatures

How to find b- hadrons



- ☞ m ~ 5.28 GeV, daughters p_T O(1GeV)
- ☞ τ ~1.16 ps , FD ~ 1 cm
- ☞ Detached muons from B→J/ΨX
- ☞ Or highly displaced tracks with high p_T

How to find c- hadrons



- ☞ m ~ 1.86 GeV, daughters p_T O(1 GeV)
- ☞ τ ~0.4 ps , FD ~ 0.4 cm
- ☞ Also as 'secondary' from B decays

Key ingredient for efficient triggering and event topology identification

- ☞ Primary vertex finding , High P_T tracks reconstruction, Optimal MuonID
- ☞ Cabibbo Suppressed and Cabibbo Favoured decays ID (requires precise PID)
- ☞ Inclusive triggering using MVAs on 1&2 track signatures

Challenges in flavour physics

☞ **Detection of collisions and the originating particles.**

☞ **Event reconstruction within available budget**

☞ **Huge rate of signal of interest. O(TB/s) and a limited storage capability [few GB/s]**

- How to maximise and keep as flexible as possible the physics outcome of the experiment?

☞ **You want to reject non-interesting events , keeping the interesting ones only.**

- What if all events can be of interest [Run III and LHC]?

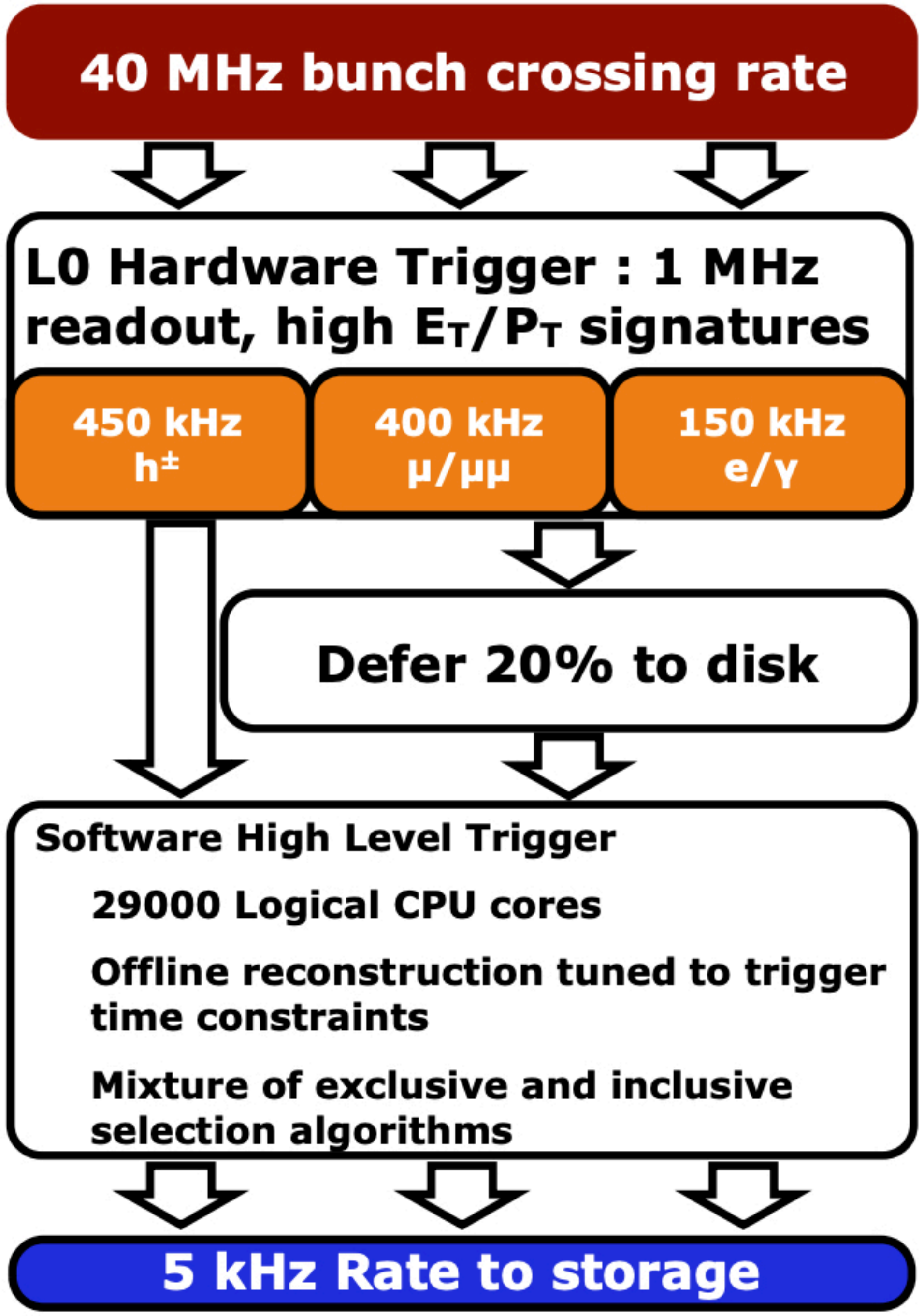
☞ **Limited computing power:** event reconstruction and analysis have to be fast!

Maximise the physics outcome requires a sophisticated trigger

The LHCb trigger evolution/revolution during years

The LHCb trigger: 2011-2012

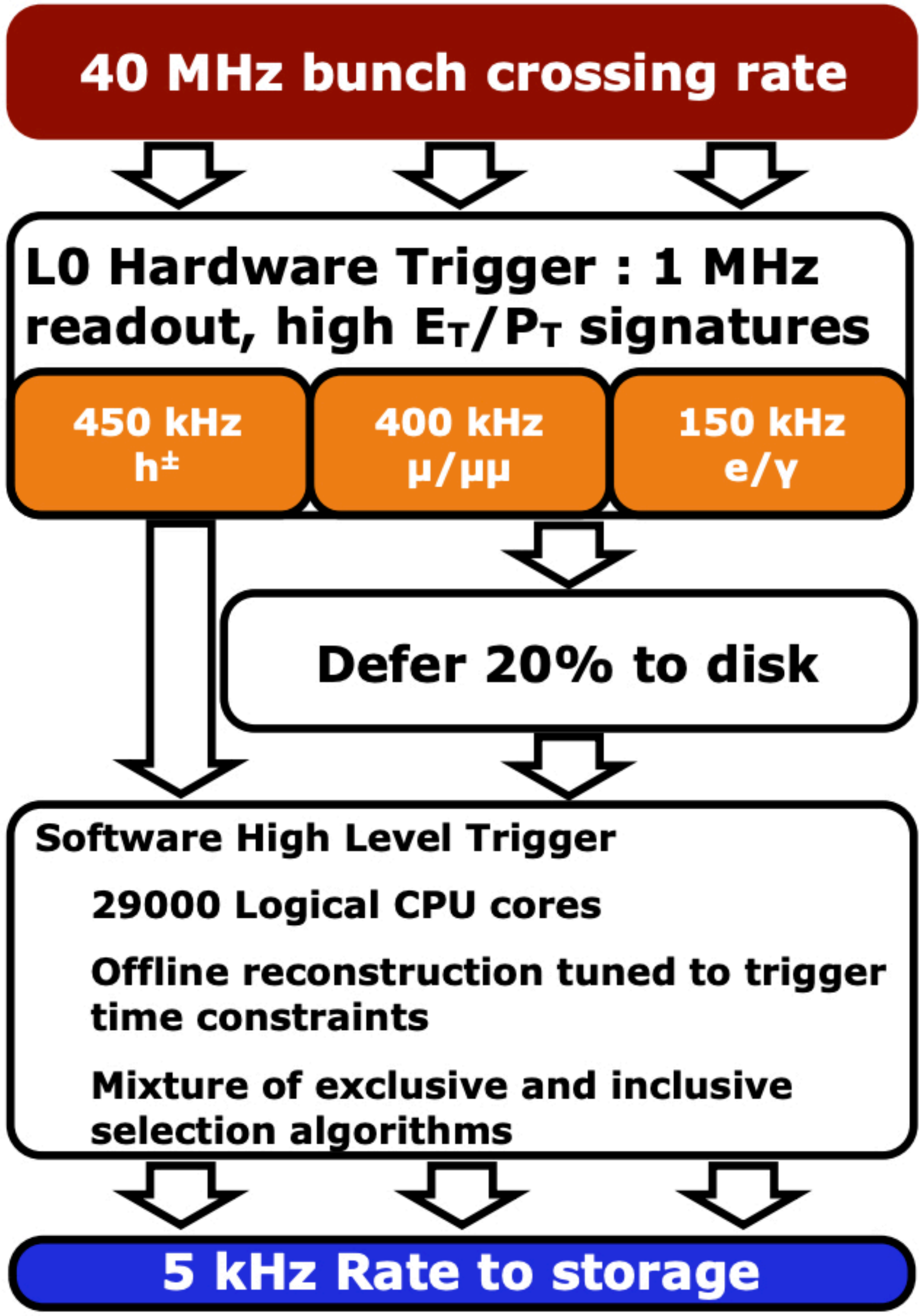
Operates at PU 1 [~45kHz of bb expected for 40 MHz bunch crossing rate at LHC]



- **Hardware stage based trigger (output 1 MHz)**
  - Selection of events based on multiplicity
  - Calorimeters E_T
  - Muon(s) p_T tresholds.
- **Software trigger running on HLT farm**
  - **2 stages** : HLT1 and HLT2.
  - **HLT1**: partial reconstruction reducing rate for full event reconstruction **(HLT2)**
  - **Buffer 20% of L0 selected events to disk for later processing during beam downtime**
  - Final output rate of 5 kHz storing ~65kB/event

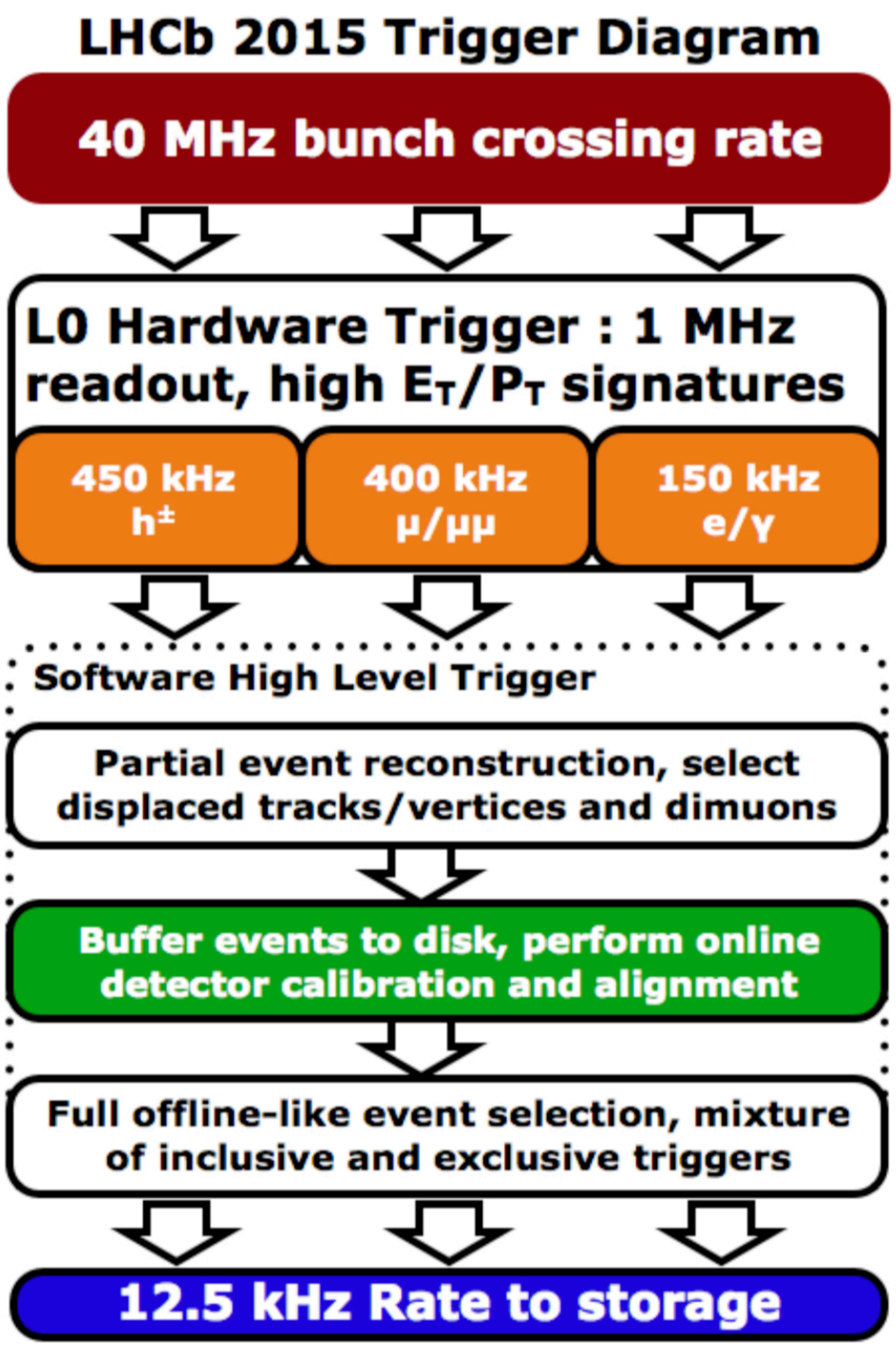
The LHCb trigger: deferring to disk

Operates at PU 1 [~45kHz of bb expected for 40 MHz bunch crossing rate at LHC]

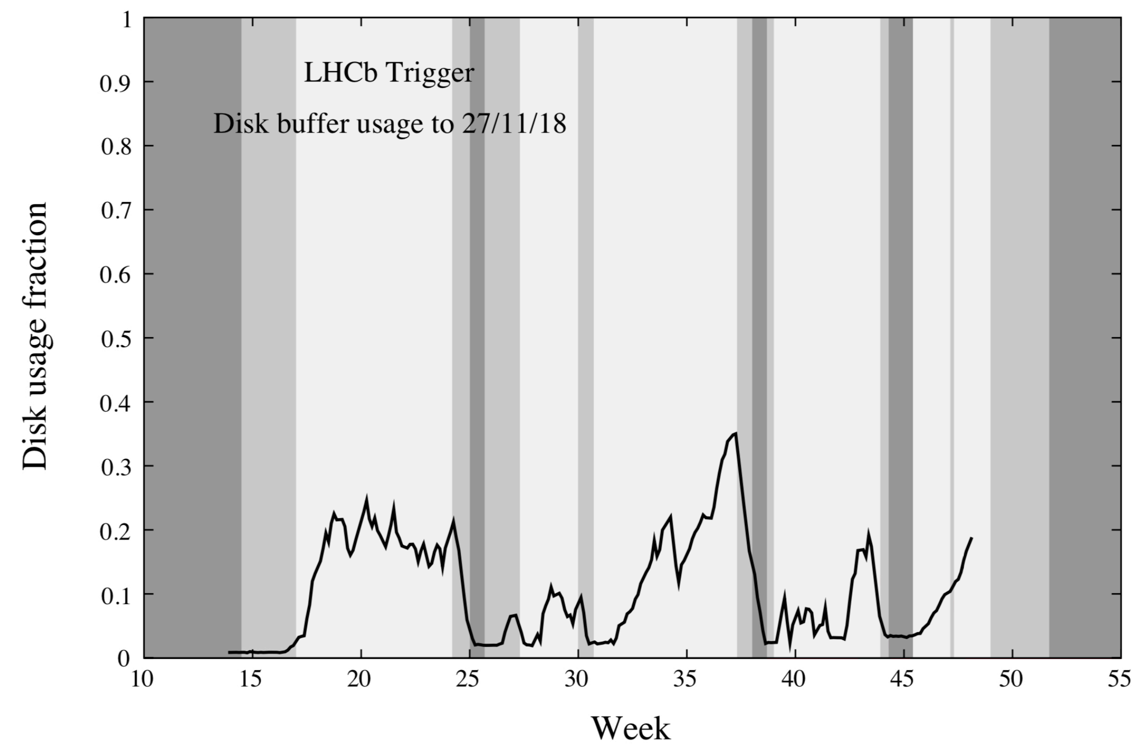


- ☞ **Deferred trigger concept (from 2012)**
  - ☞ **Stable beams only 30-50% of the time.**
  - ☞ **Disks costs much less than CPU.**
  - ☞ **Buffer events allow for out of fill processing allowing an effective 3x more powerful farm.**
  - ☞ **Implemented begin 2012**

The LHCb trigger: deferring to disk evolution in Run2

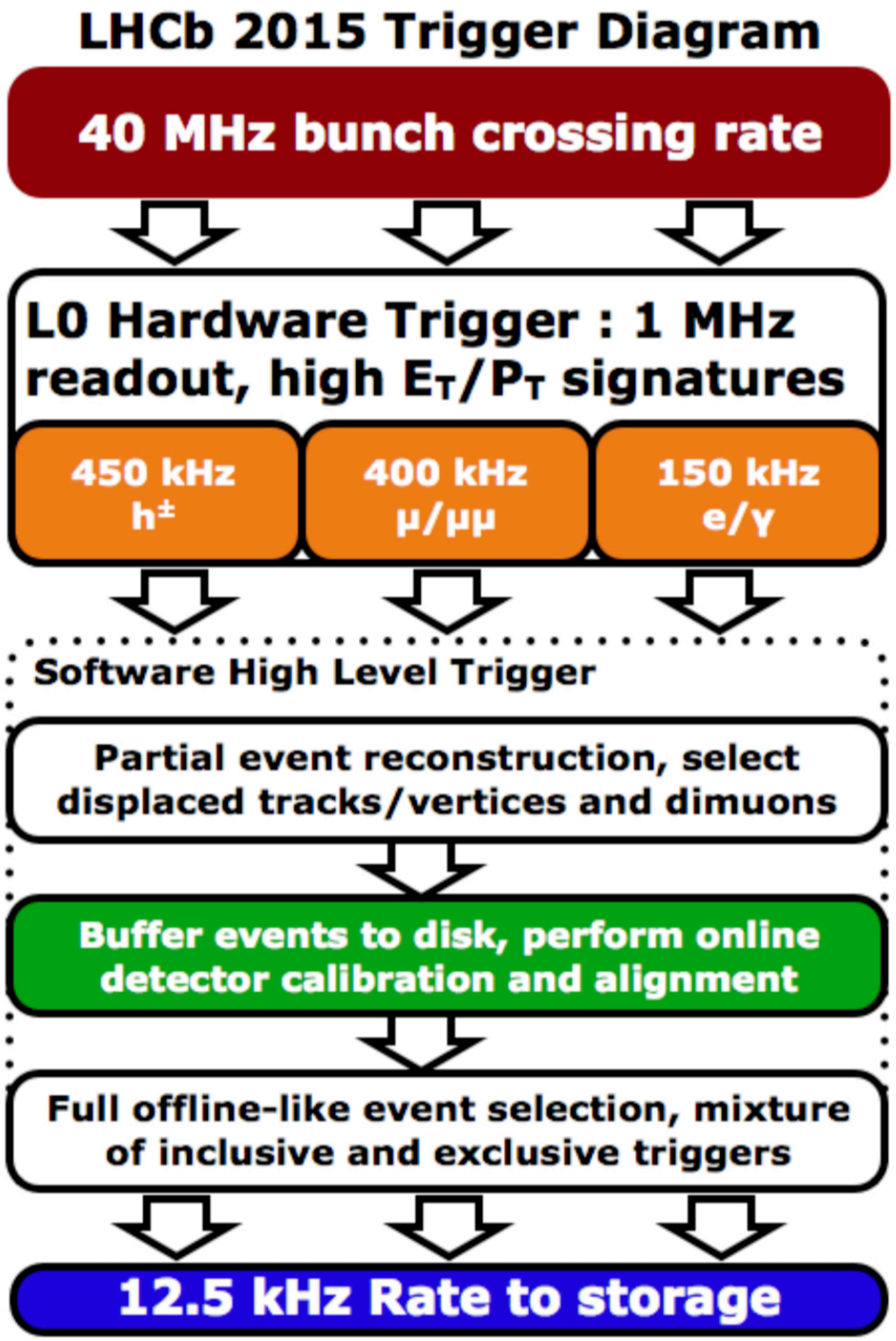


- ☞ HLT1 accepted events written to disk in-fill at 100 kHz (2 weeks contingency).
- ☞ **Perform real-time alignment and calibration of the whole detector with the buffered data from HLT1 reconstruction.**
- ☞ **Offline-like reconstruction available on-line in HLT2.**

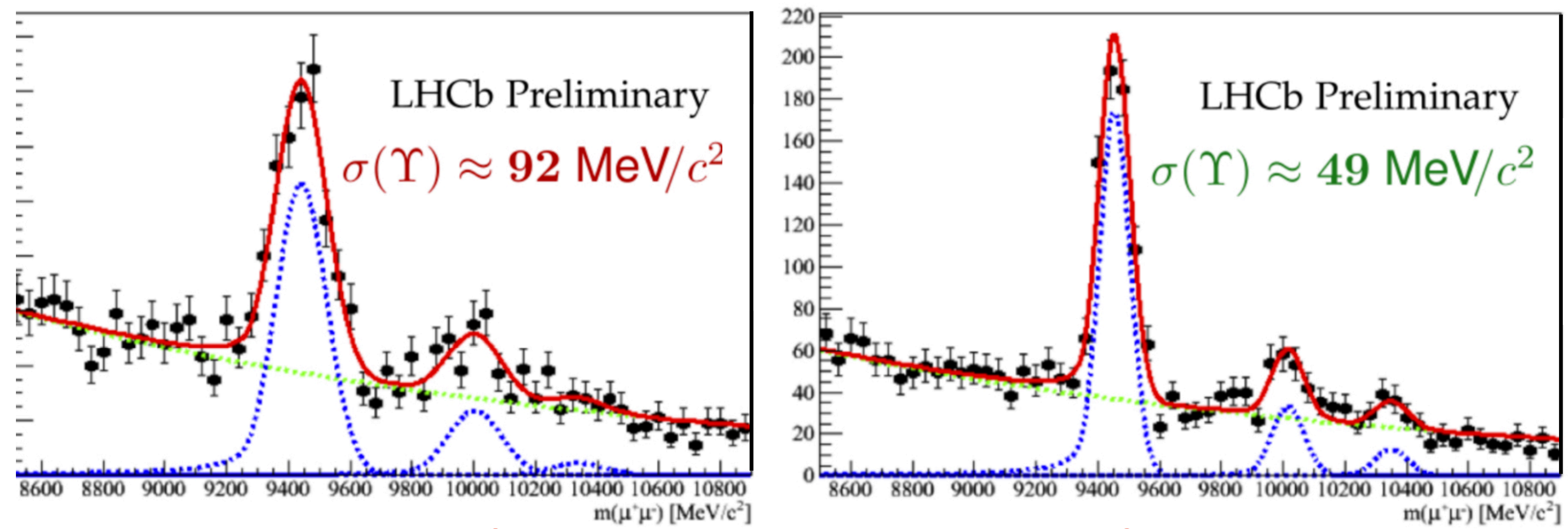


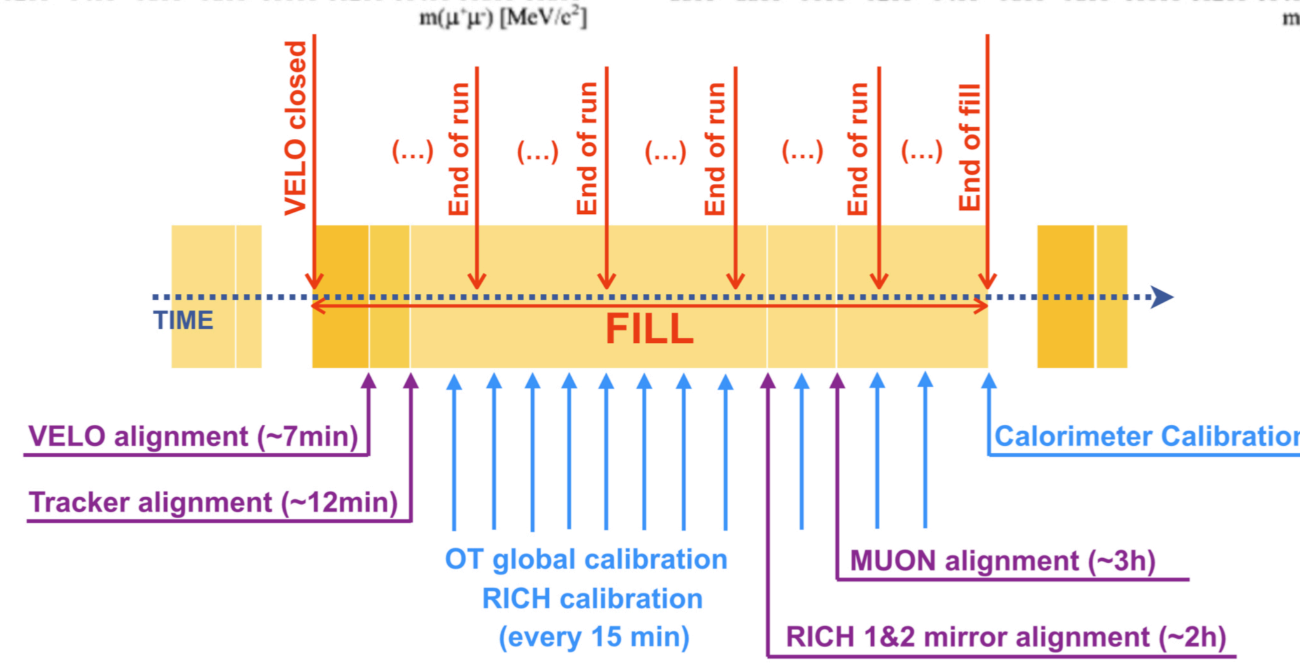
From 5 PB to 10 PB available in Run II , more powerful CPUs optimisation of Reconstruction

The LHCb trigger: Real time alignment and calibration



A fully aligned and calibrated detector in real-time (few hours)



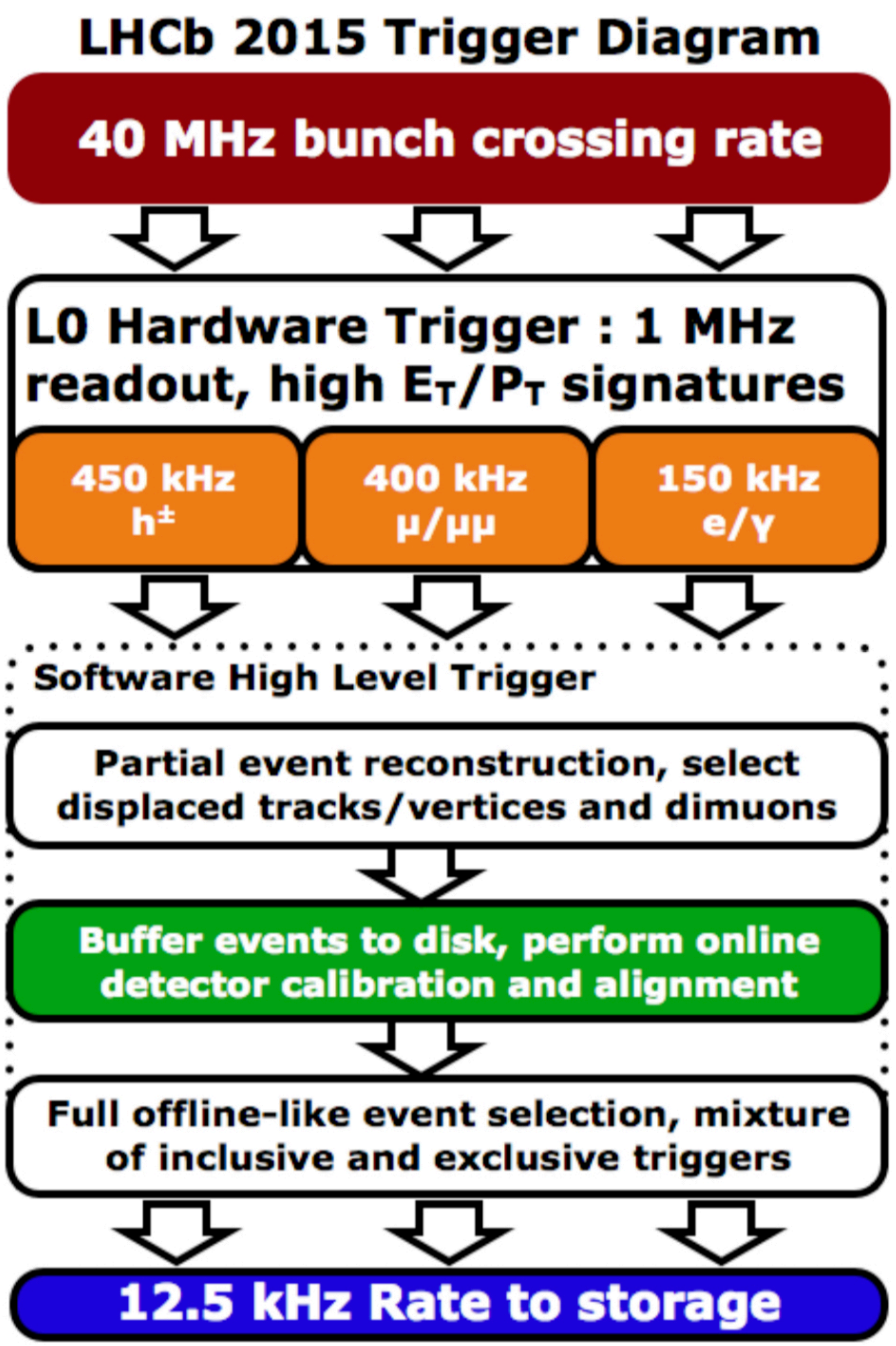


((~7min),(~12min),(~3h),(~2h)) - time needed for both data accumulation and running the task

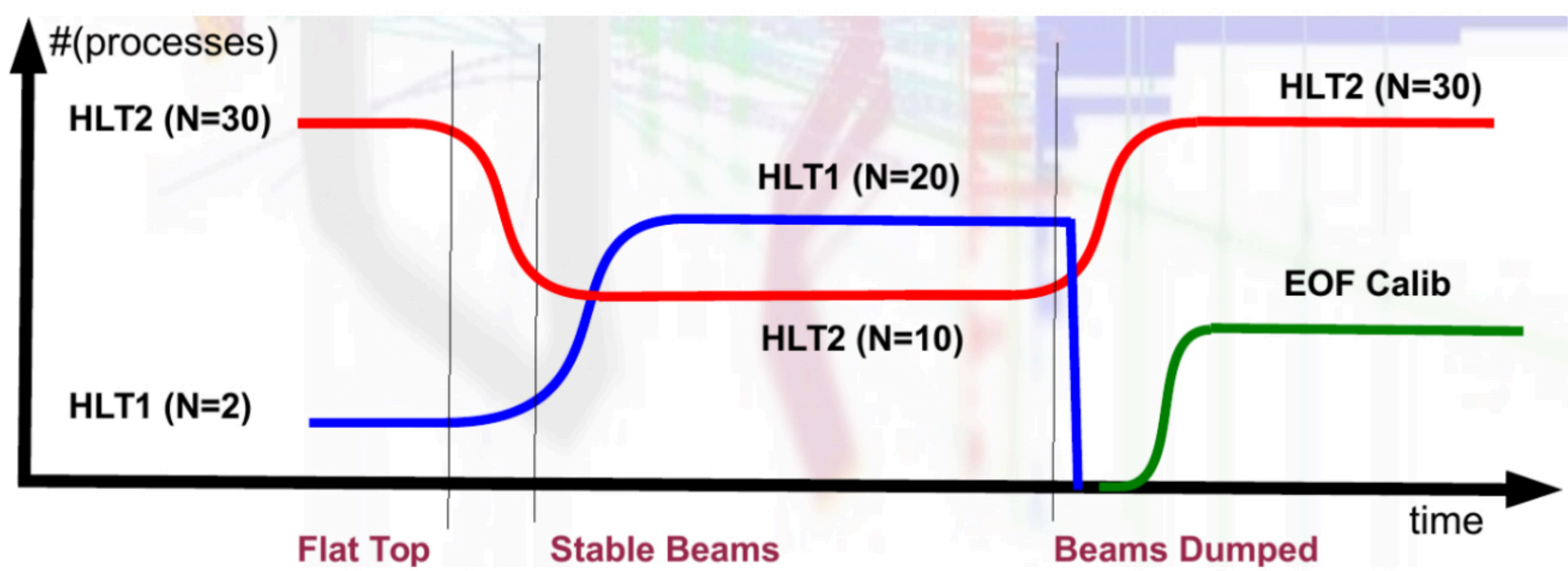
Updated alignment constants used in HLT2 full event reconstruction

The offline-quality PID information and optimal performance achieved within the trigger system

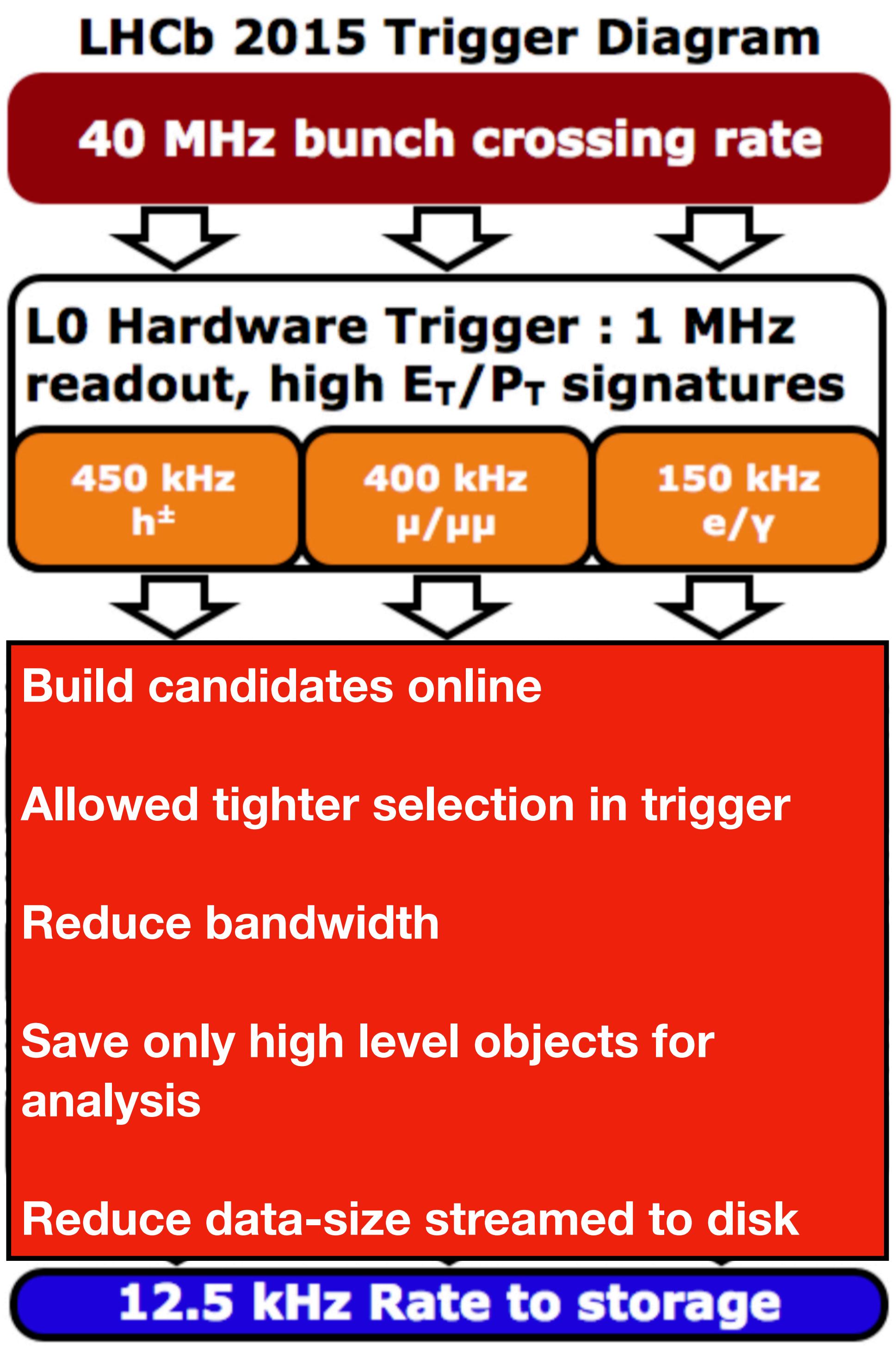
The LHCb trigger: Real time alignment and calibration



- Asynchronous processing of HLT2 allows to optimally use farm resources.

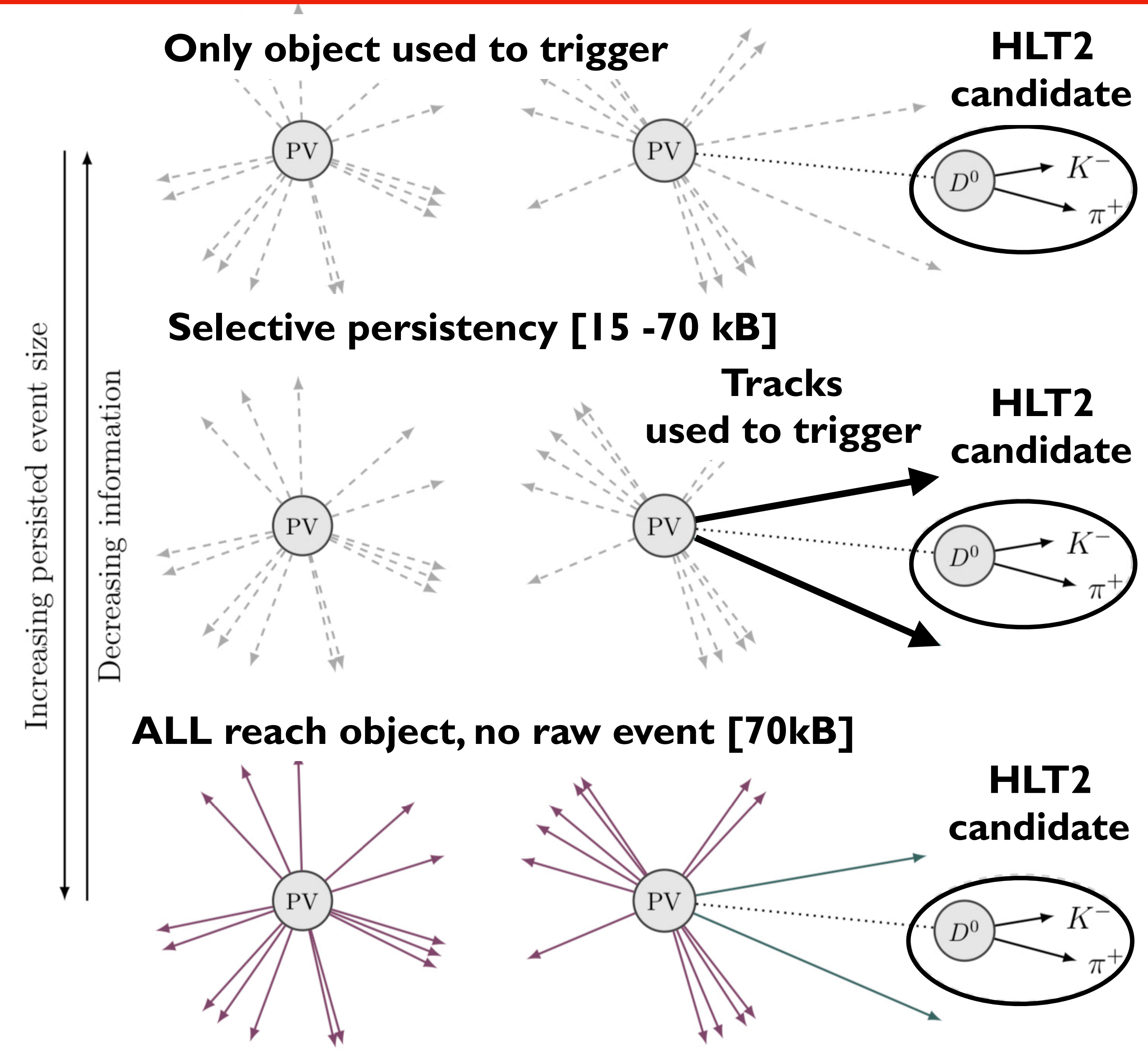


The LHCb trigger: bandwidth optimization



☞ **Real-time candidate reconstruction and building possible with no loss on precision at trigger stage.**

Selective persistency of TURBO reconstructed candidates

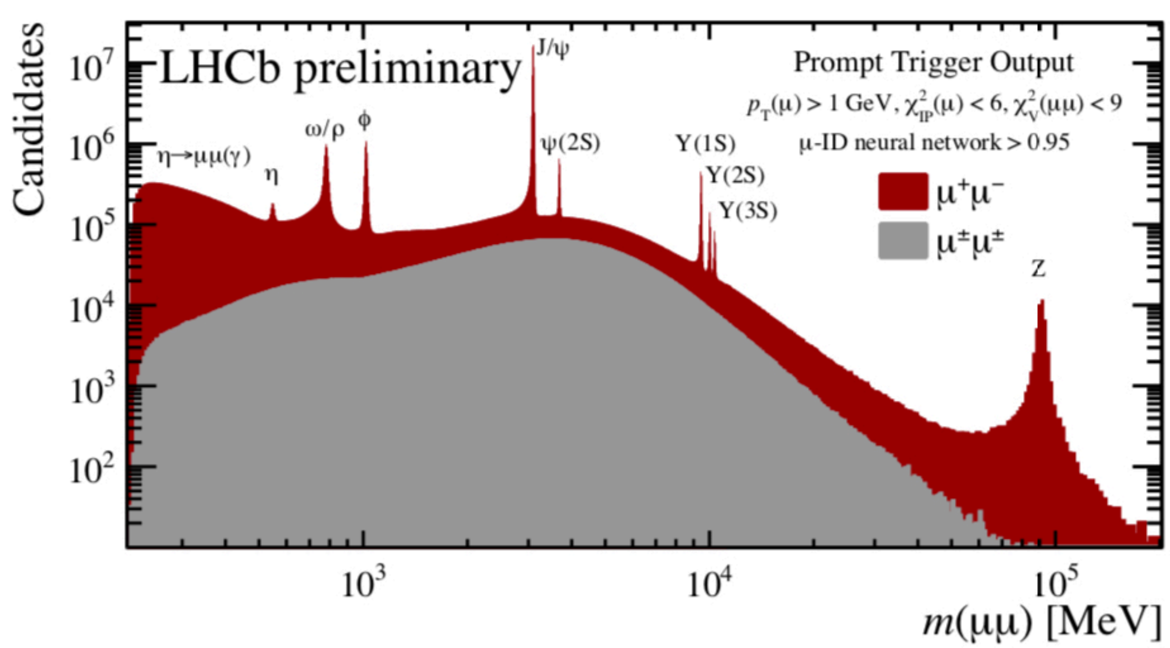


TURBO lines in Run 2

- Run 2 composed one 528 trigger lines and 50% are Turbo
- 25% of the rate is Turbo but it counts for only 10% of the bandwidth
- Many analysis would not be possible without Turbo

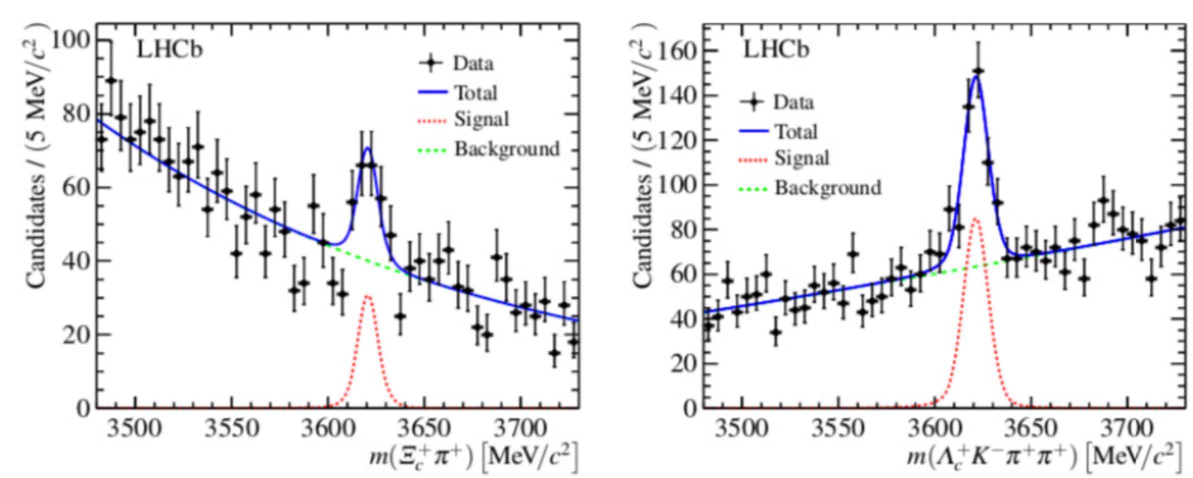
CERN-EP-2017-248
LHCb-PAPER-2017-038
October 5, 2017

Search for dark photons produced in 13 TeV pp collisions

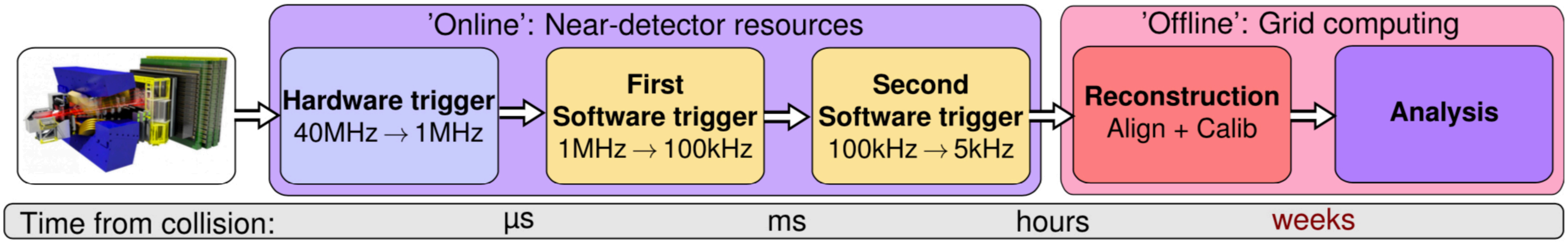


CERN-EP-2018-172
LHCb-PAPER-2018-026
October 18, 2018

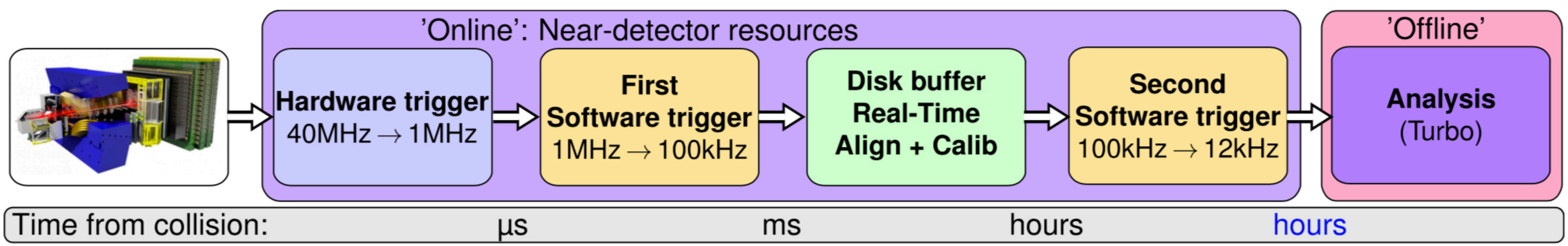
First observation of the doubly charmed baryon decay $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$



2011



End of Run 2



All this serves as proof of concept and preparation of the Run III data taking.

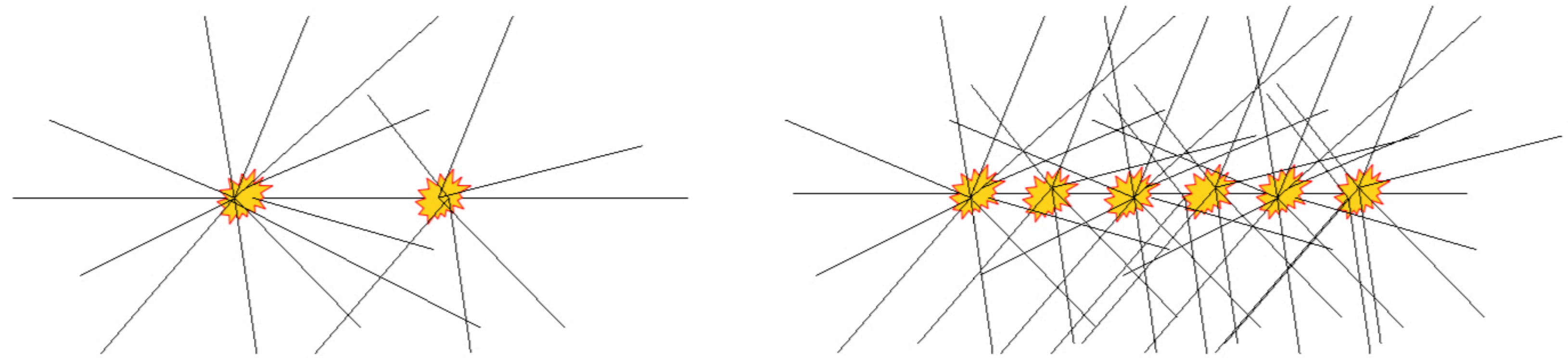
First issue when facing Run III condition

Run I and II

$\mathcal{L}_{inst} = 4 \times 10^{32} cm^{-2} s^{-1}$

☞**PU = 1.1-1.8**

☞**3 (Run I) + 5 (Run II) fb^{-1}**



Run III target

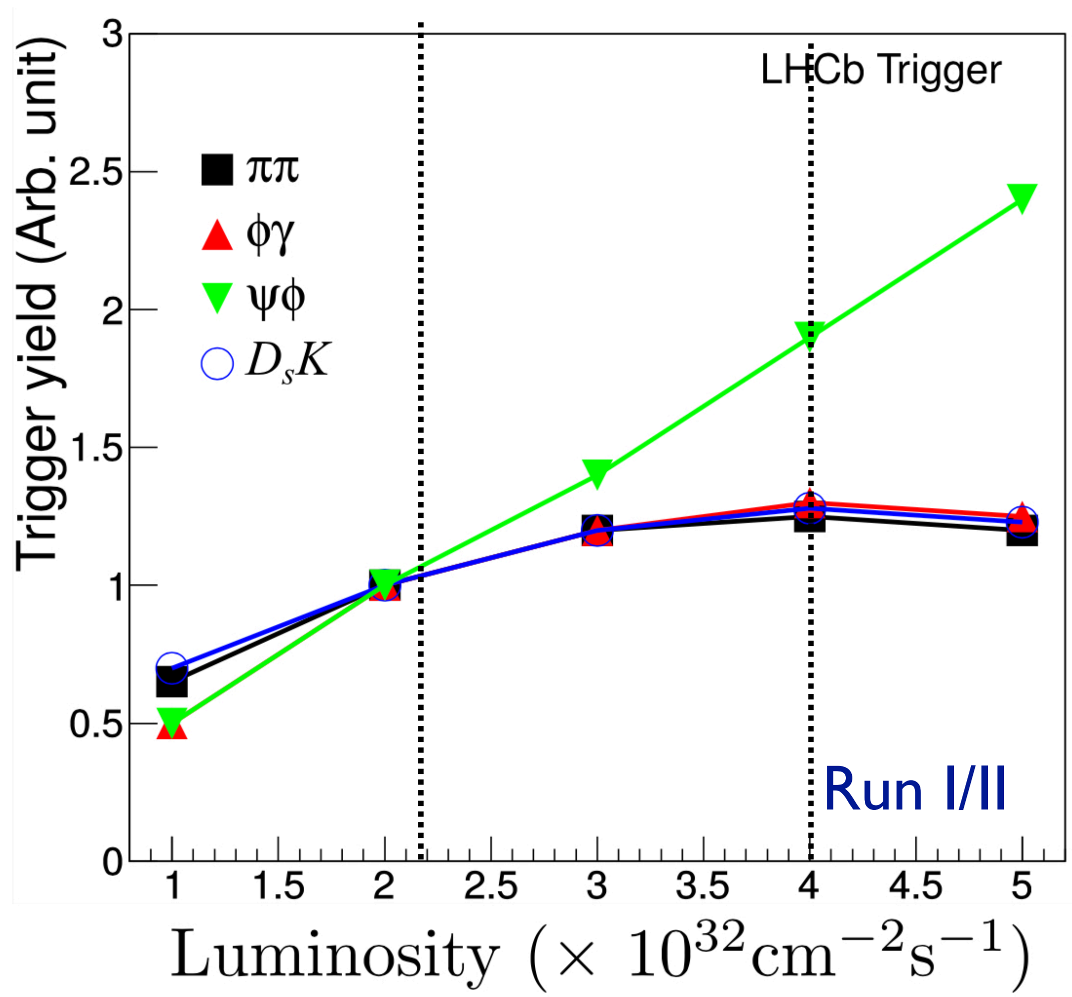
$\mathcal{L}_{inst} = 20 \times 10^{32} cm^{-2} s^{-1}$

☞**PU = 7.6** ☞**50 fb^{-1} in 10 years**

Solution :

- ☞ Get rid of L0 hardware trigger
- ☞ A full 30 MHz software trigger adopted
- ☞ All detector read-out at collision rate.
- ☞ Upgrade of DAQ system
- ☞ Upgrade detectors to cope for higher occupancy

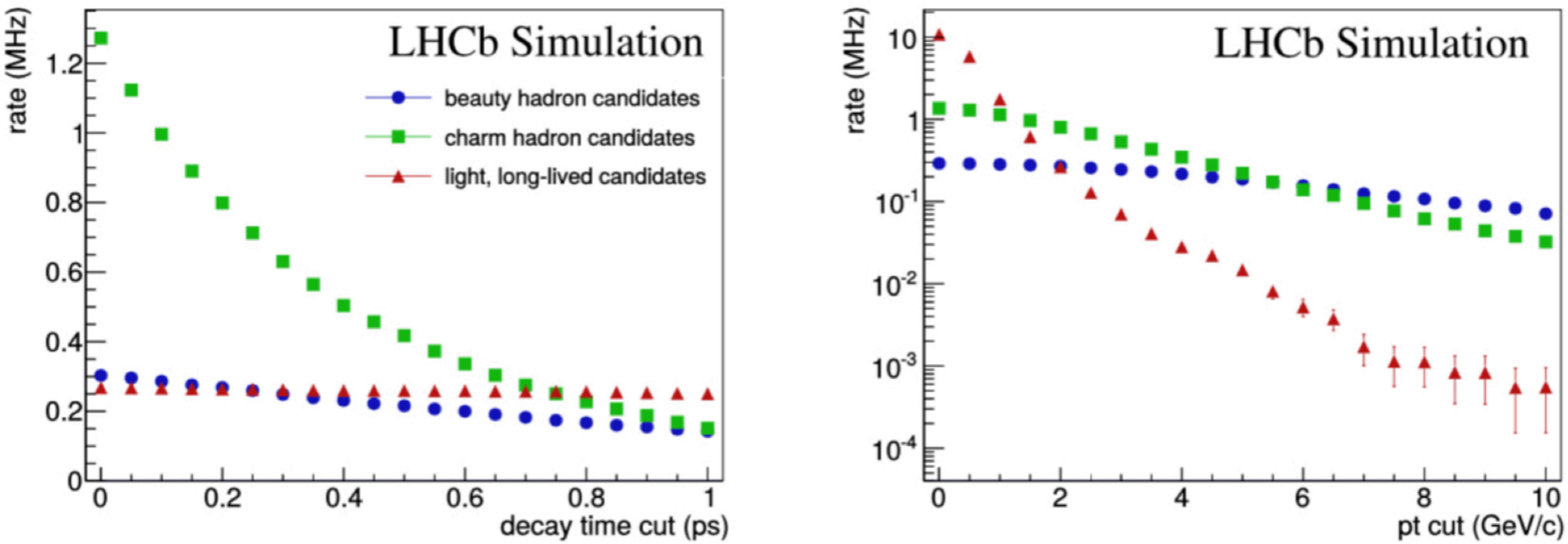
Issue 1 : 1 MHz read-out limit



Scaling of trigger yields with current LHCb

Issue 2 : too many interesting signal to save

Rate of signal for 2-track combinations [after HLT1]



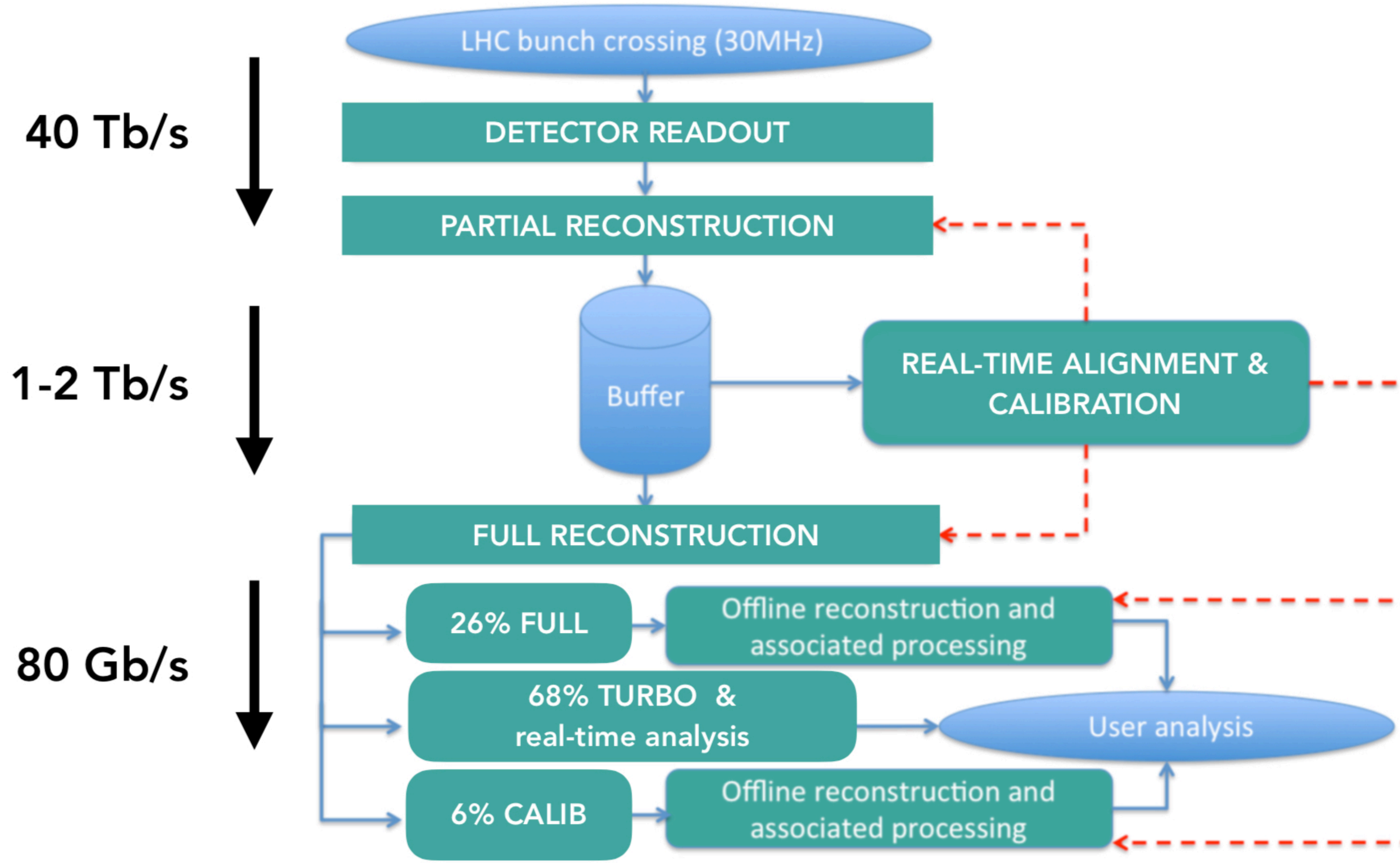
	b-hadrons	c-hadrons	light, long-lived hadrons
Output rate	270 kHz	800 kHz	264 kHz

~ 1 MHz to disk [100 GB/s] of interesting signals with a 30 MHz full event reconstruction at the higher luminosity

Not affordable data tape rate and loss of power for inclusive triggers

Real Time Analysis, fully reconstruct the decay of interest in the online trigger

The big plan for Run III [2021]



The path towards Run III

- ☞ Full construction and installation of new detectors for the upgrade [during LS2] is on-going now

Partial event reconstruction (HLT1) must be able to run at 30 MHz and provide enough information to reduce the event rate [0.5, 1 MHz]

- ☞ **Displaced physics can be efficiently selected using high-P_T displaced tracks from collision**

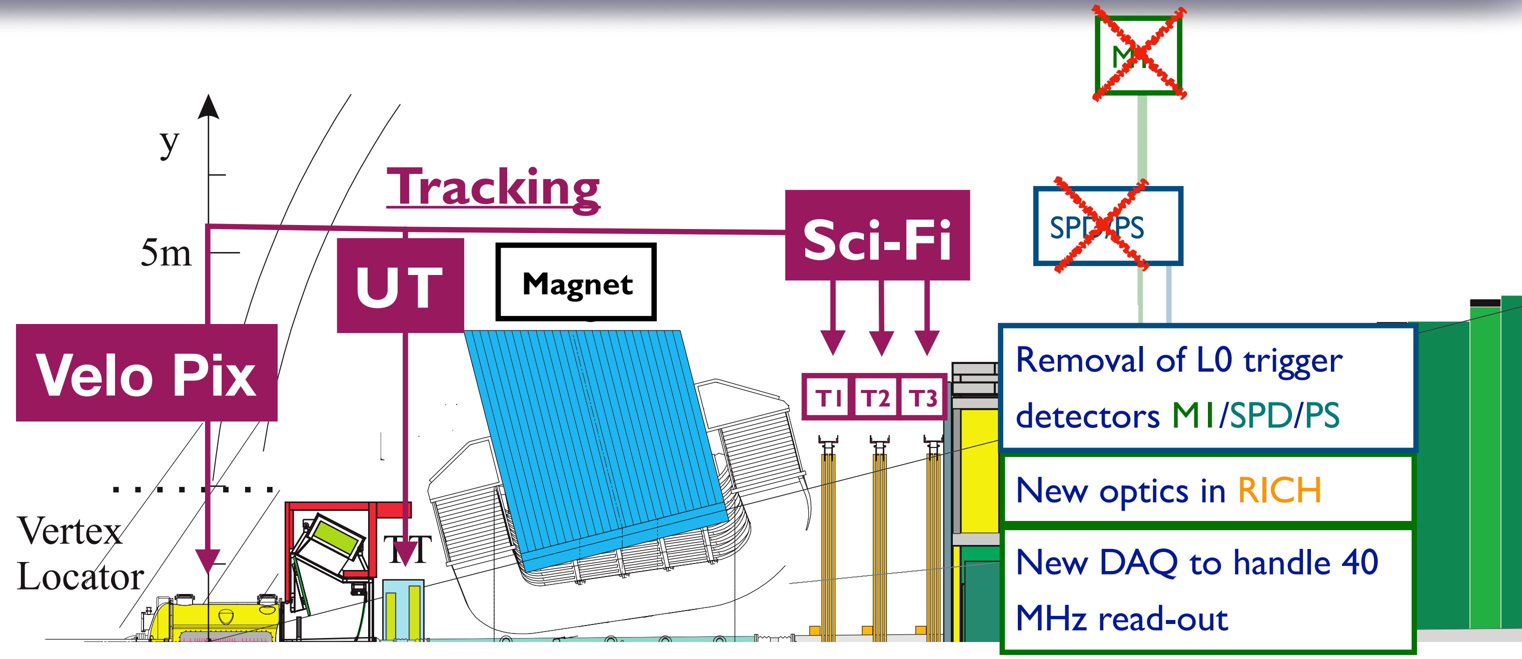
- ☞ **Full "Run 3 physics" also requires lower P_T and prompt tracks**

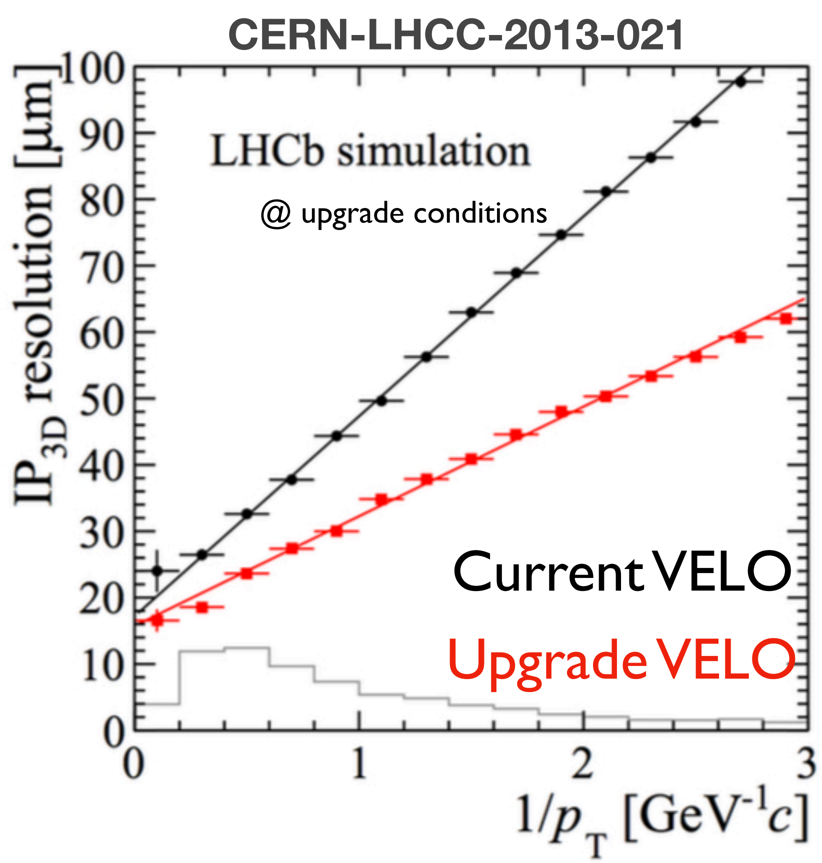
- ☞ **Still working on a reliable estimate of the cost of the full reconstruction which includes also the 500+ selections required for the real time analysis program. Numbers expected by end of this year**

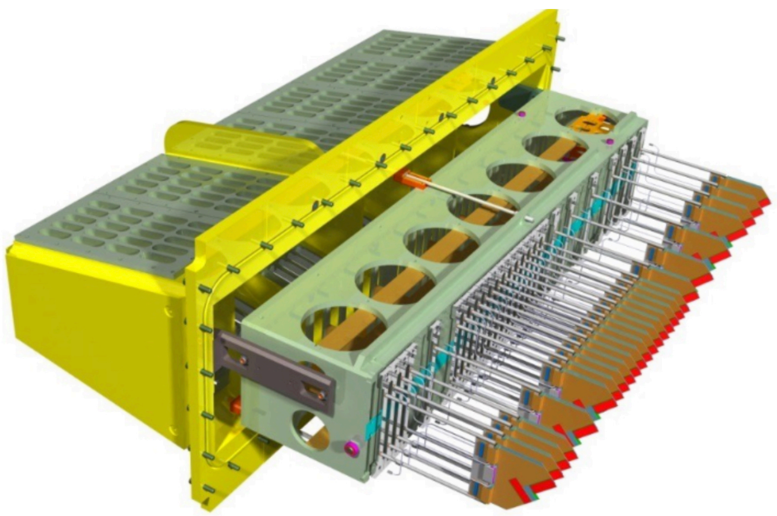
The upgrade of the LHCb detectors for tracking

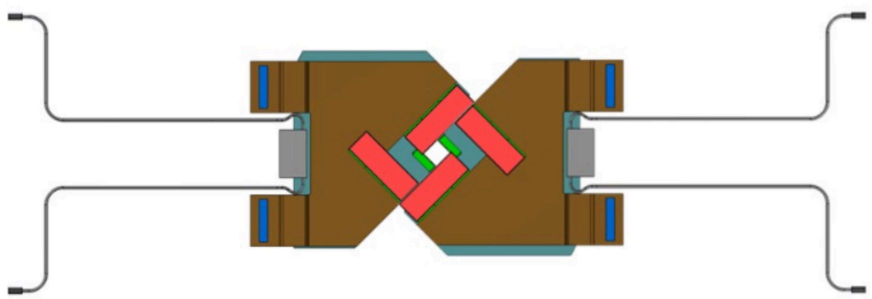
Velo Pix

- **2-D pixel sensor** @-20°C: direct **x-y** measurement.
- **Fast tracking on raw data.**
- **5.1 mm distance** from interaction point (8.2 mm current VELO)









26 modules

Simplify reconstruction via a direct 3D measurement.

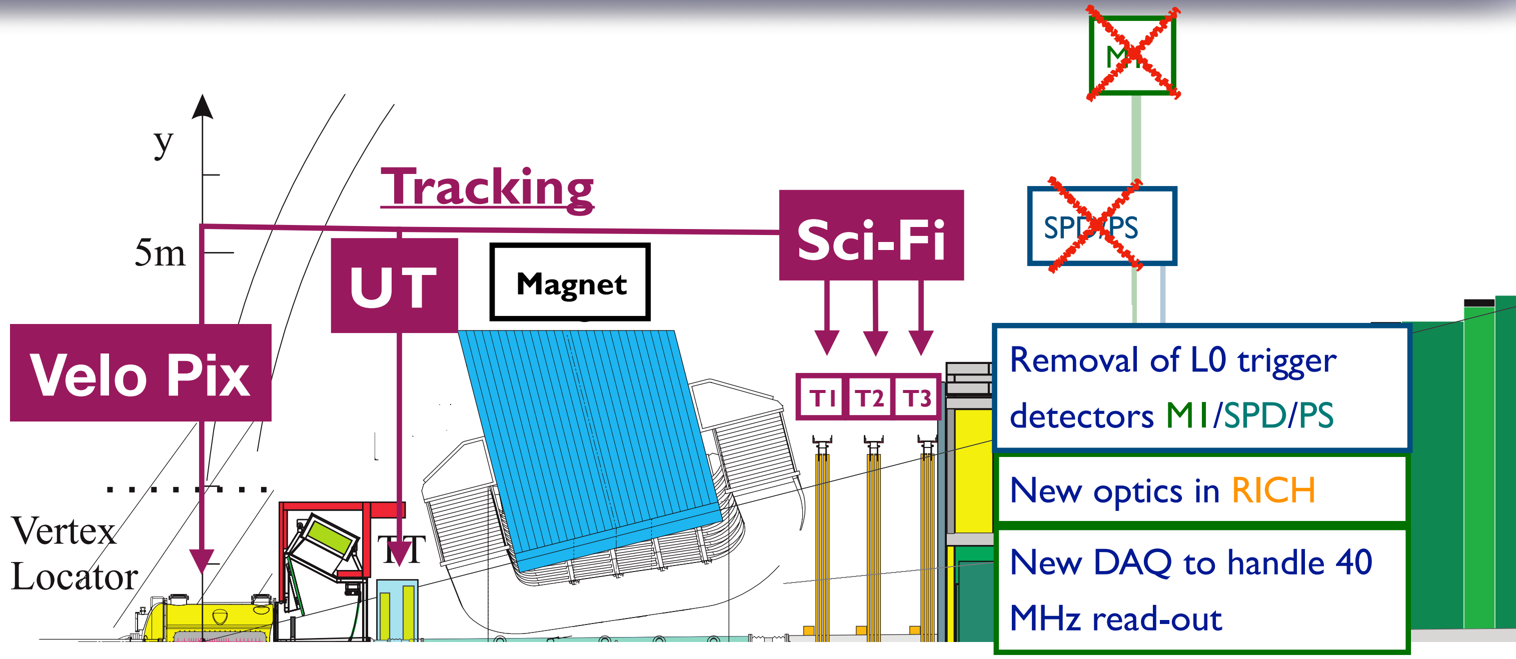
3D line finding algorithm.

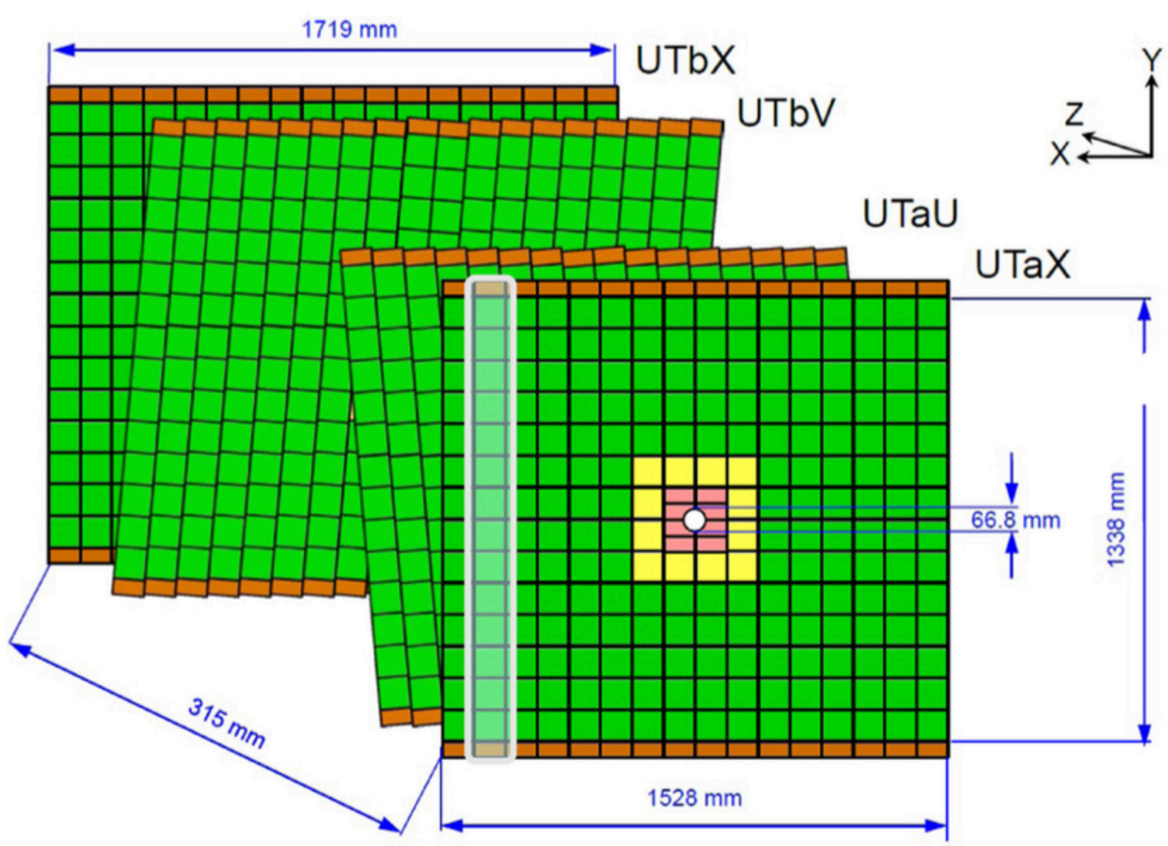
Vectorisation of the algorithm on-going

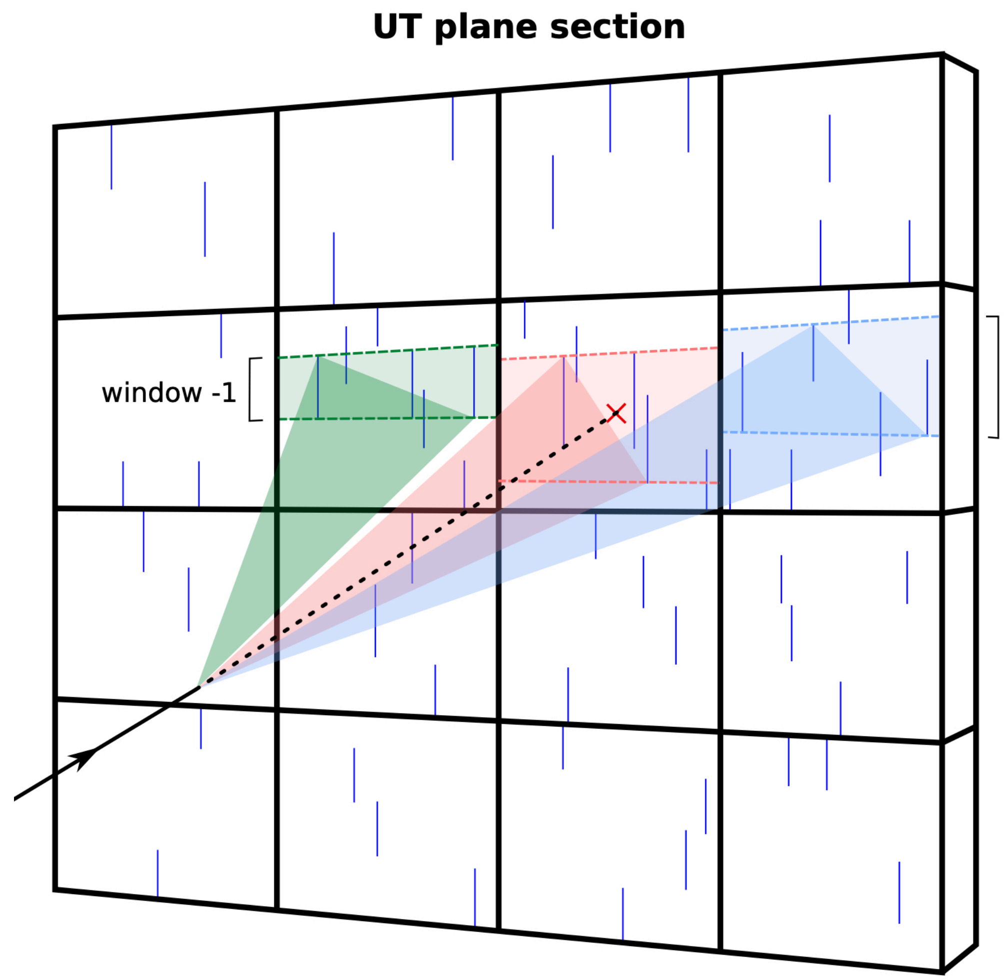
Upstream tracker (UT)

- **Larger acceptance** in central region
- **Reduced thickness**
- **Improved $\sigma_{x\text{-}z} \sim 50\ \mu m$**
- **Fast VELO tracks validation**

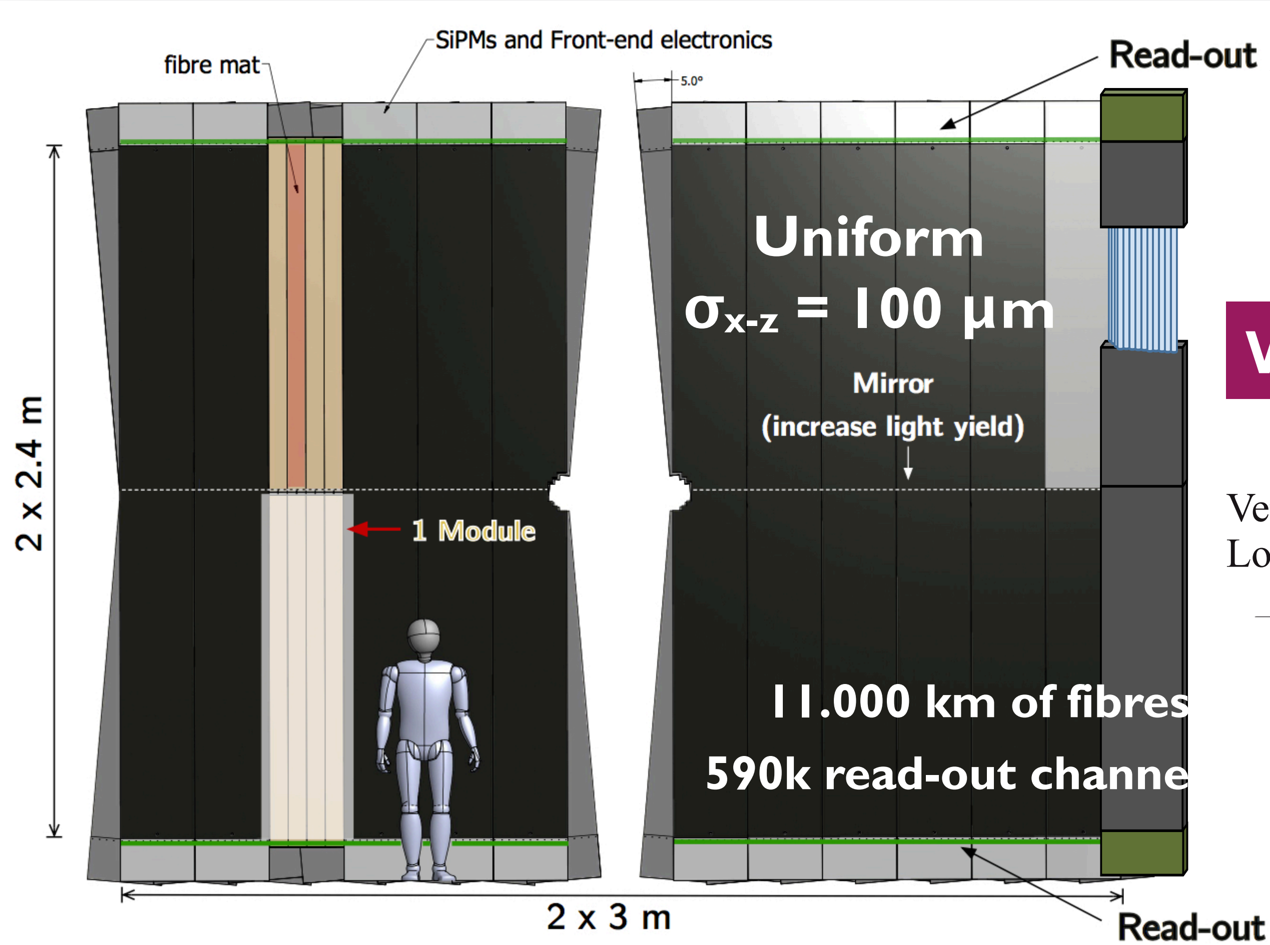
- **Velo-UT tracking: $\Delta p/p \sim 15\text{-}30\%$**
  allows to reduce search window in forward tracking.

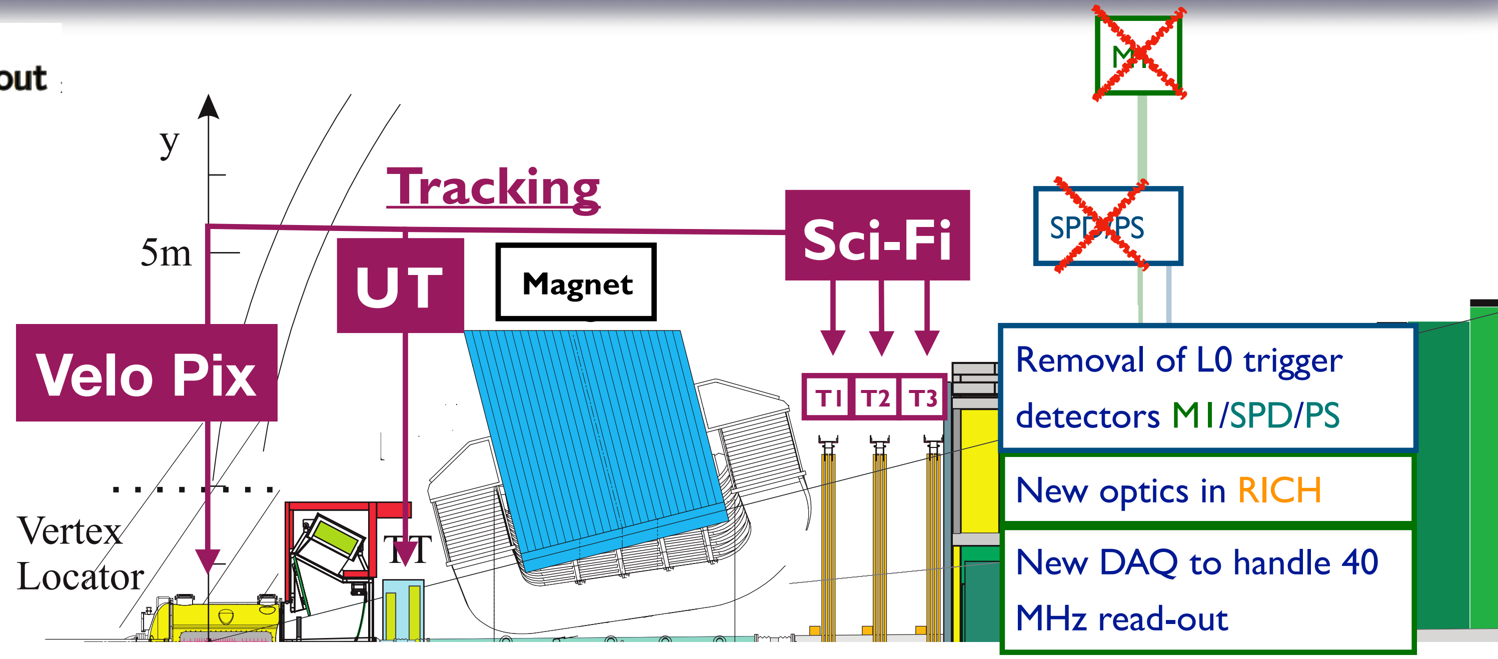






LHCb detector upgrade : Sci-Fi

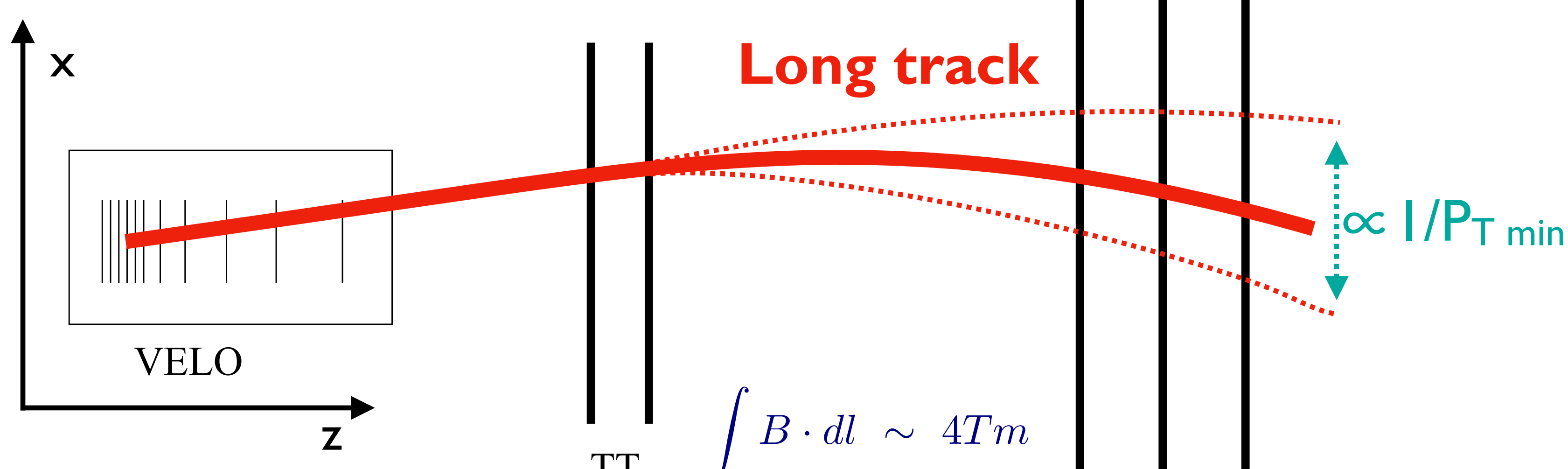




- 3 stations x 4 planes (*x*/*u*/*v*/*x*) of 6 stacked 2.4 m long scintillating fibres.

- Scintillating fibers diameter: 250 µm

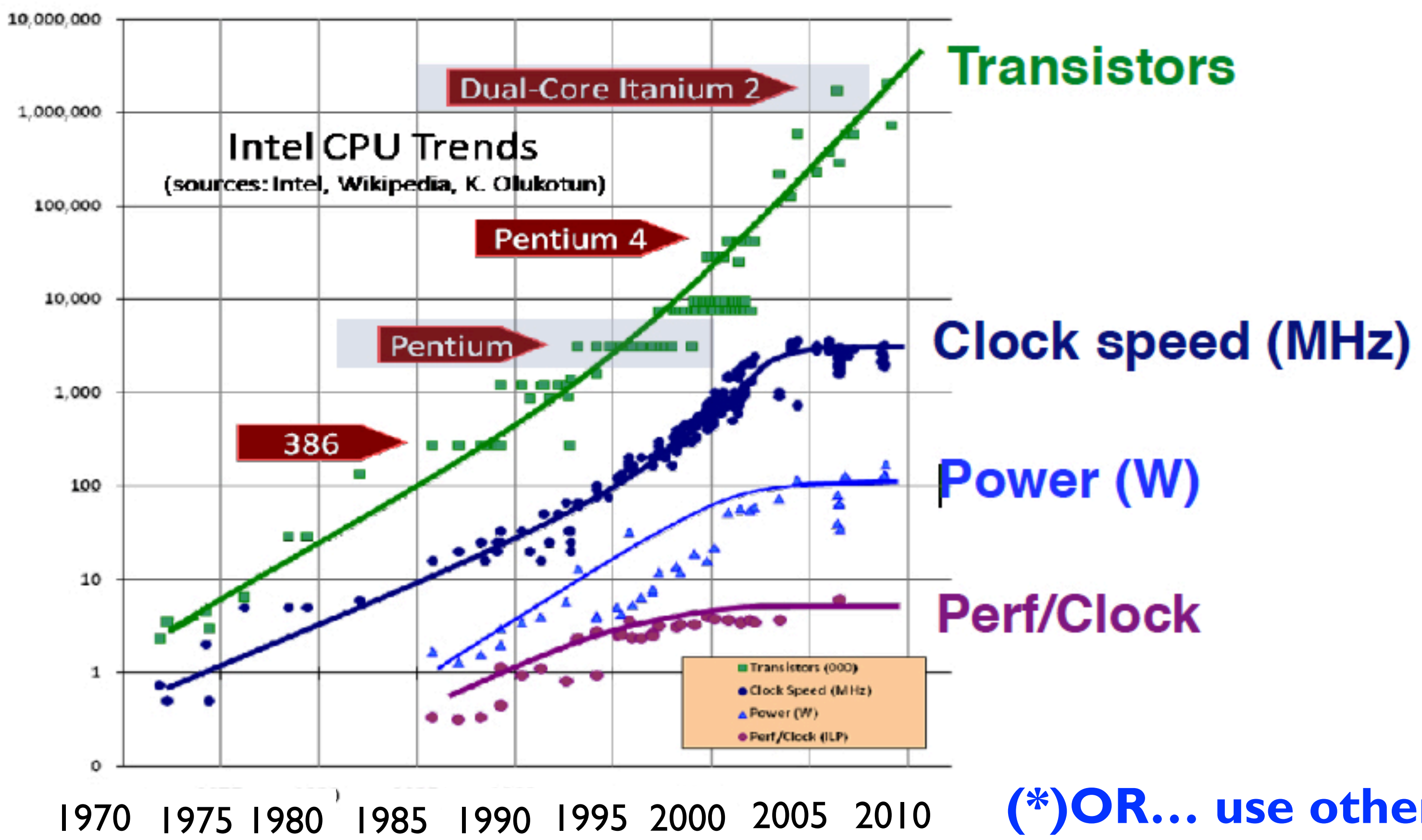
- Read-out by Silicon-Photon multipliers (250 µm channel pitch)



Forward tracking
(Velo-UT as input)

The LHCb software framework revolution

HLT1 will be executed in real-time at 30 MHz and it is composed from a small set of crucial algorithms



Clock speed gains of CPU has stop to improve since 20 years

No resource wasting and scalable HEP software

For x86 architecture

More and more CPUs/area

More and more memory for registers

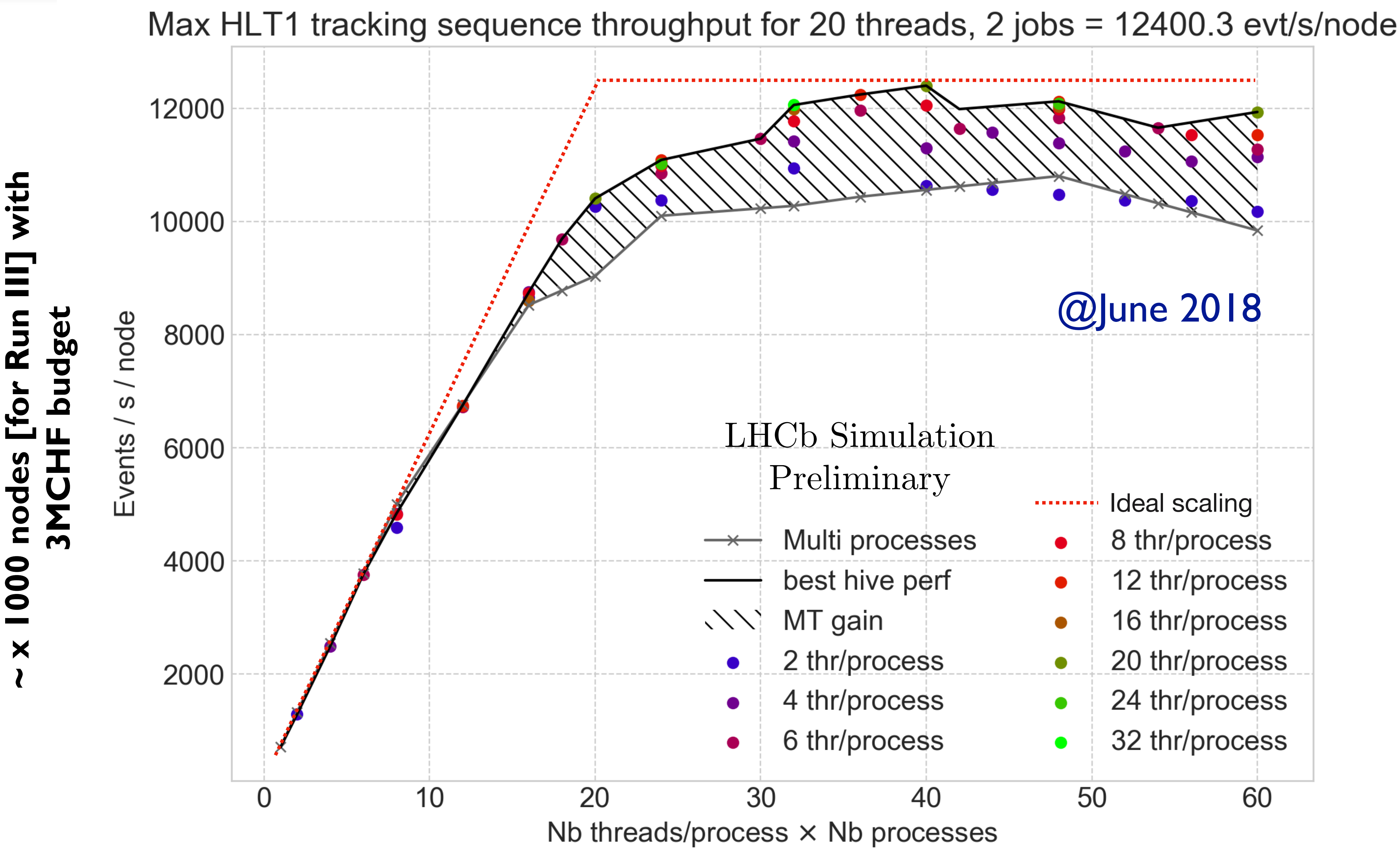
Gain(s) comes with a better usage of memory, vectorization, reduce cache misses, always keep 100% busy all CPUs

(*)OR… use other architectures (like GPUs) and/or "problem" oriented architectures

The real-time reconstruction trigger system for the LHCb upgrade

To enable multi-threading, LHCb has introduced a new multi threaded framework to perform event reconstruction at collision rate.

High-throughput software for the LHCb upgrade

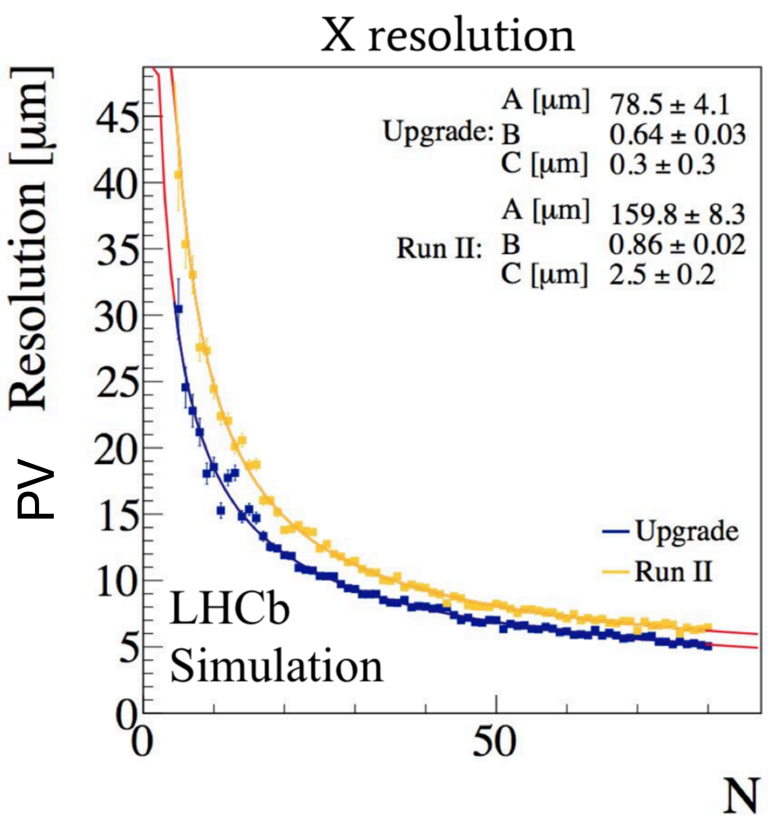


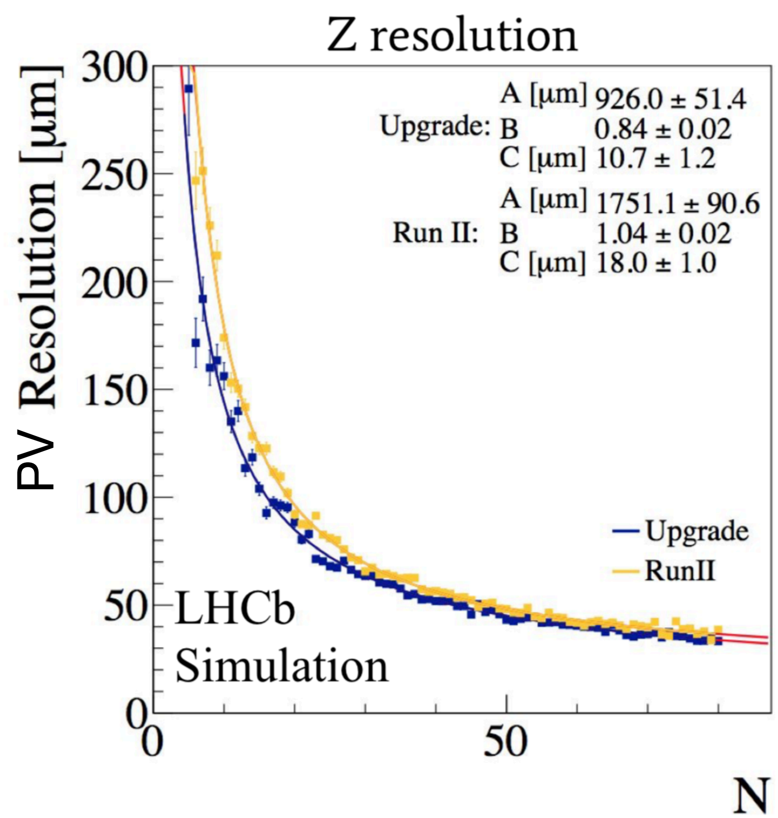
The multi-thread framework brings a 20% extra speed-up in the reconstruction sequence.

Since 2018 : algorithms have been deeply reworked to allow faster and faster reconstruction

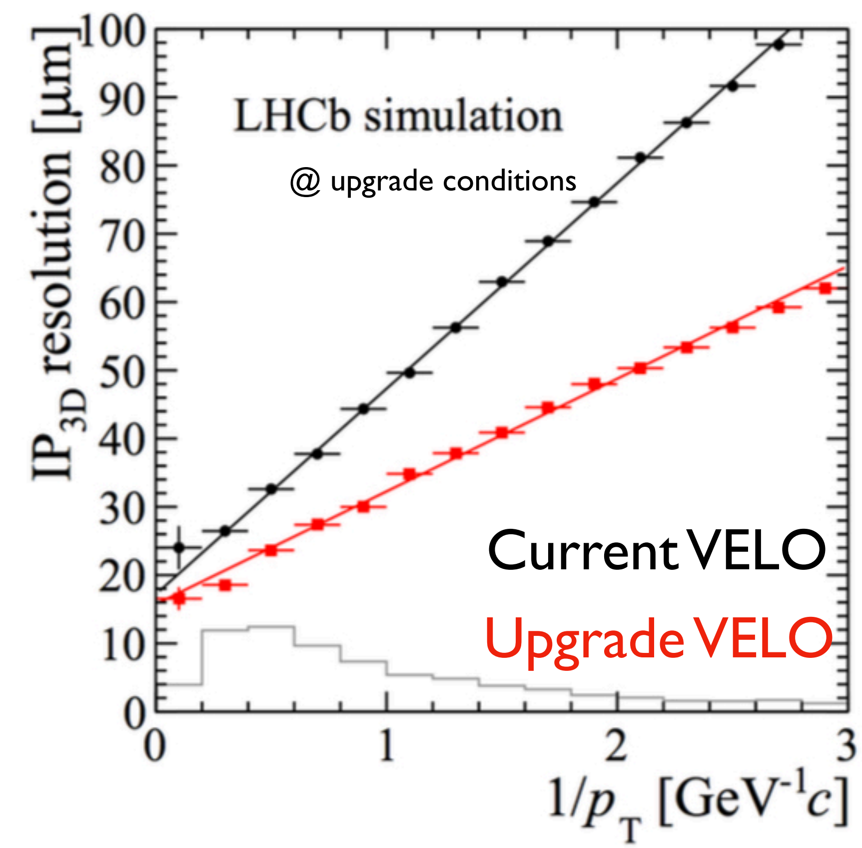
Partial reconstruction sequence : physics handles

[LHCb-PUB-2017-005]



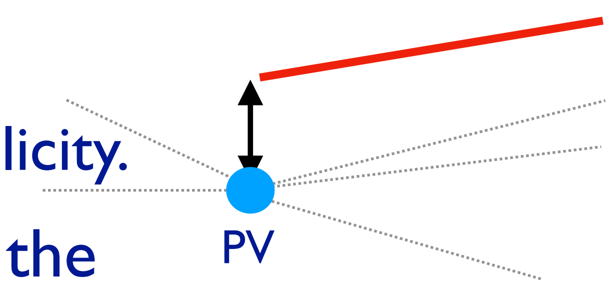


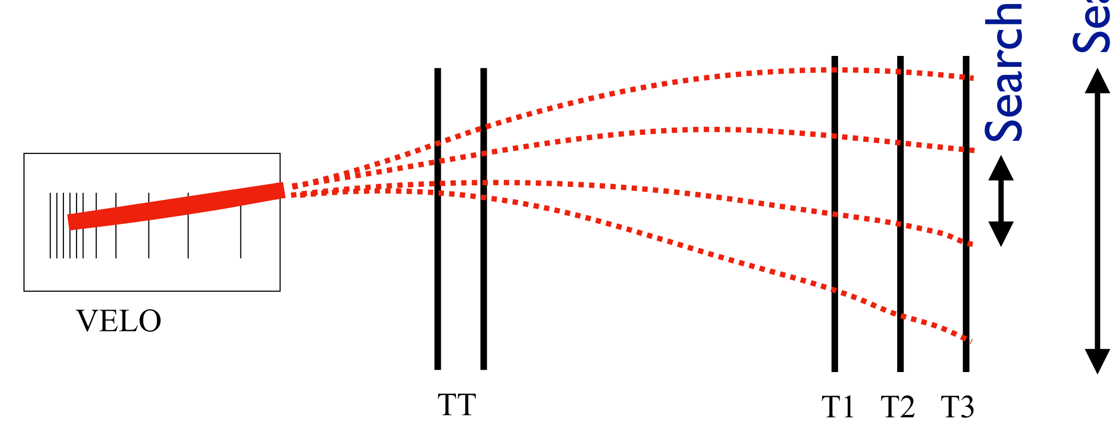
CERN-LHCC-2013-021



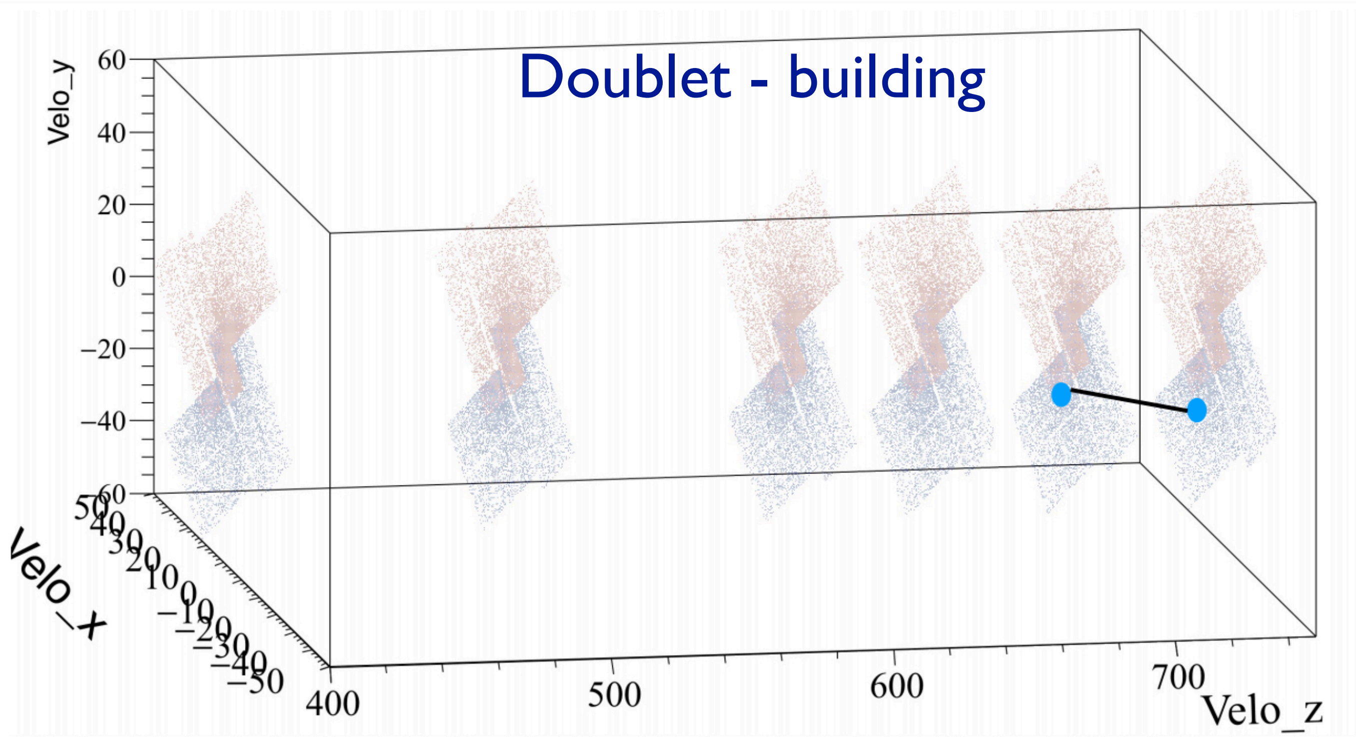
At the upgrade conditions

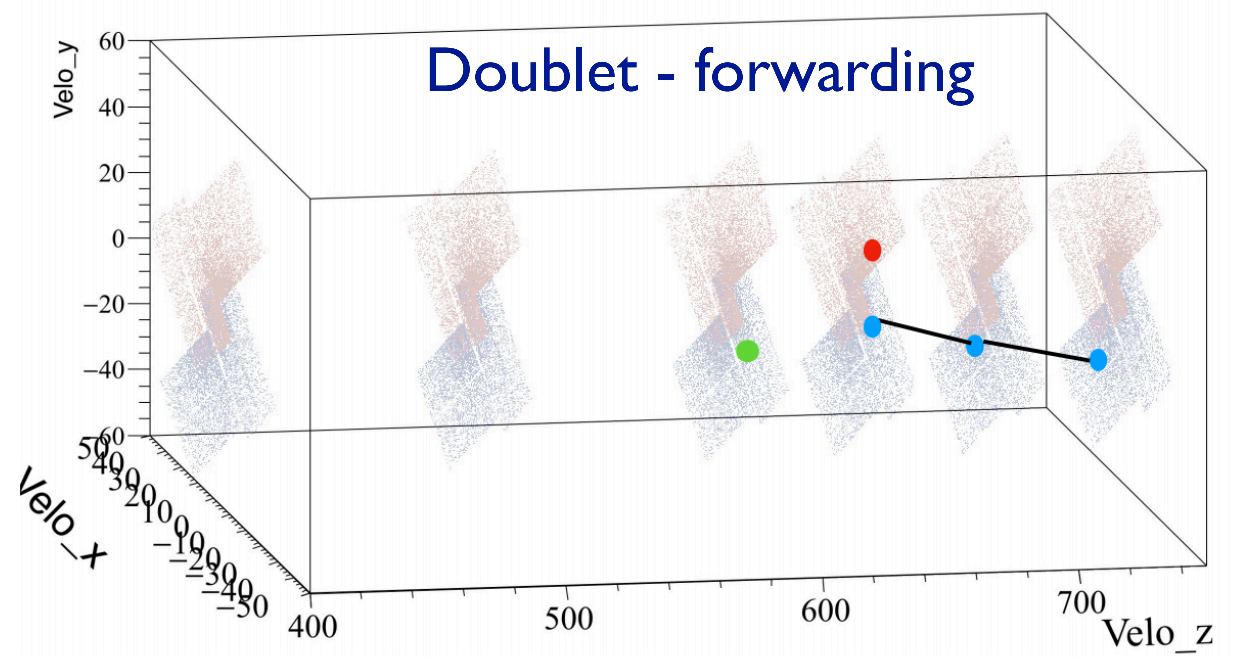
- ☞ 3-4 times more PVs and 2-3 times higher Track multiplicity.
- ☞ Tuning of reconstruction sequence has impact on the physics capabilities of the detector.
- ☞ To speed-up the partial reconstruction: select only displaced tracks and/or tight the p_T thresholds to reduce the search windows in UT and Sci-Fi.



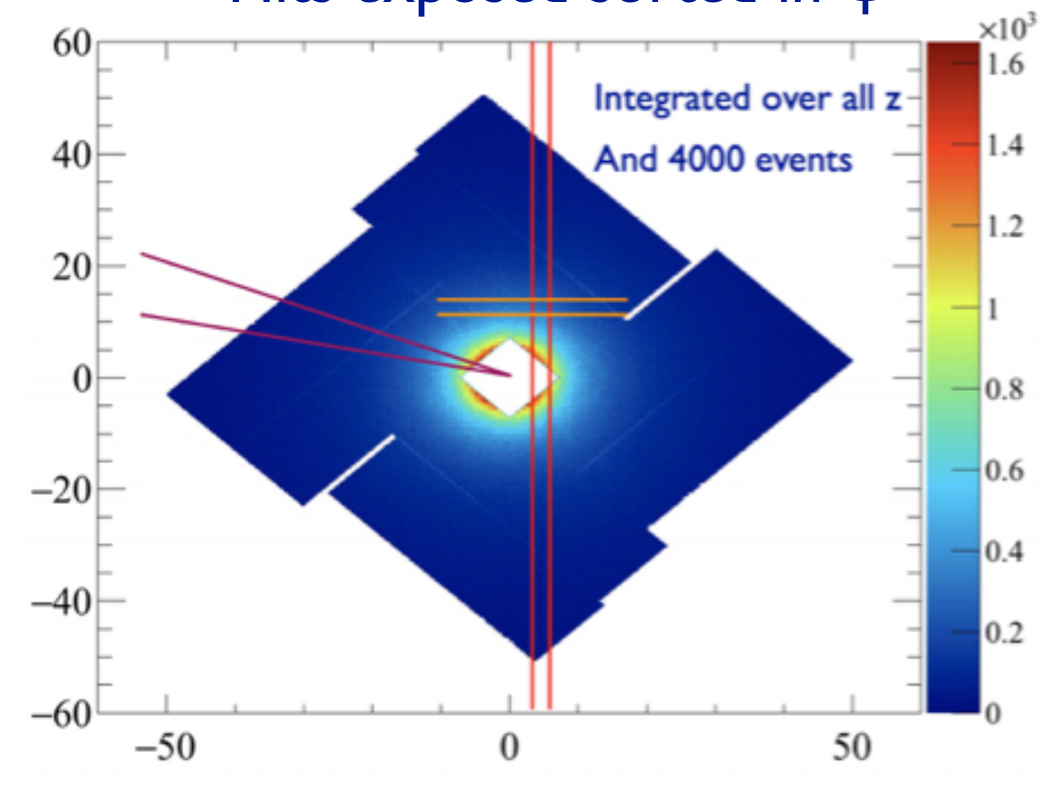


Velo Tracking for the upgrade in a nutshell

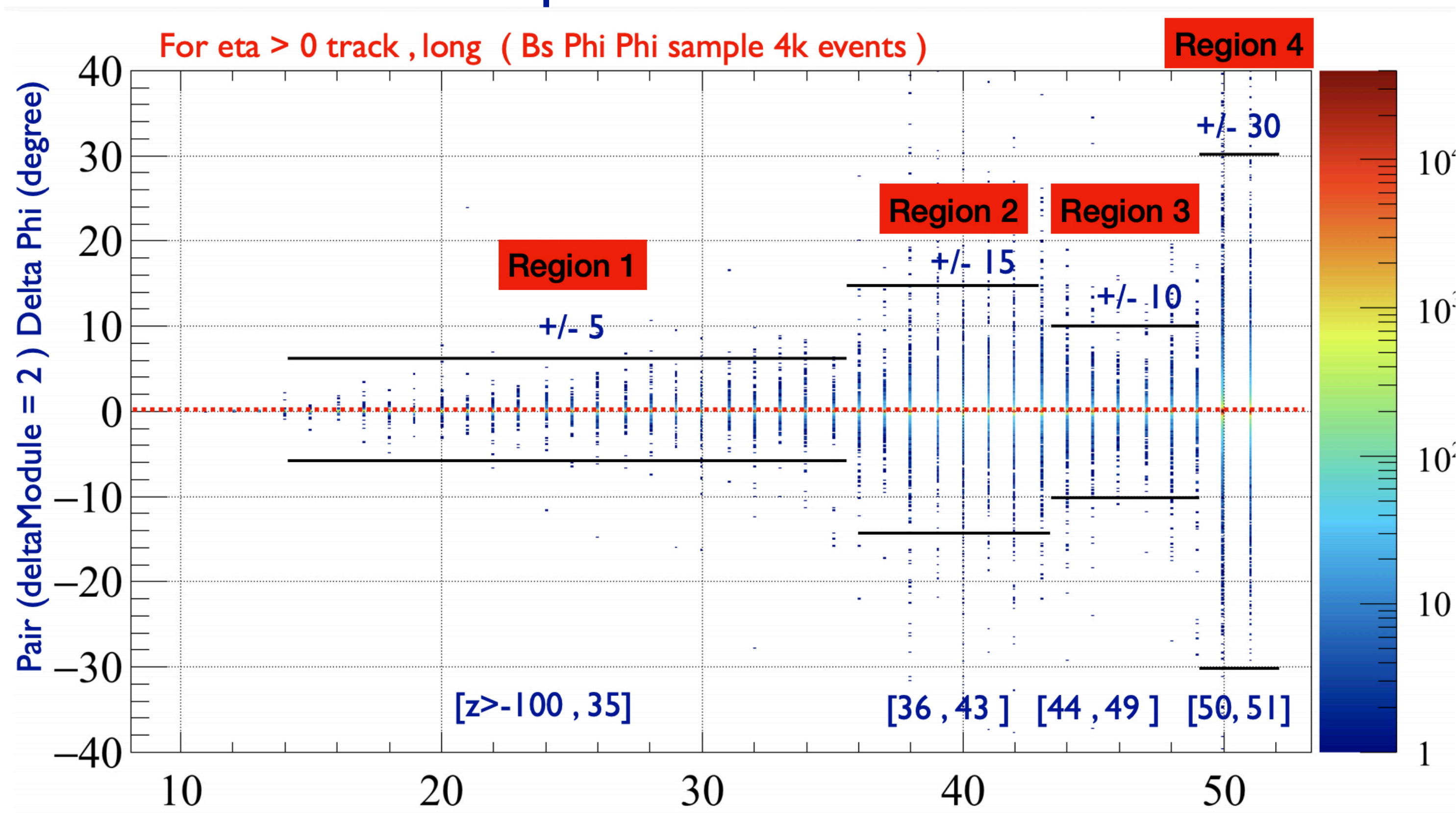




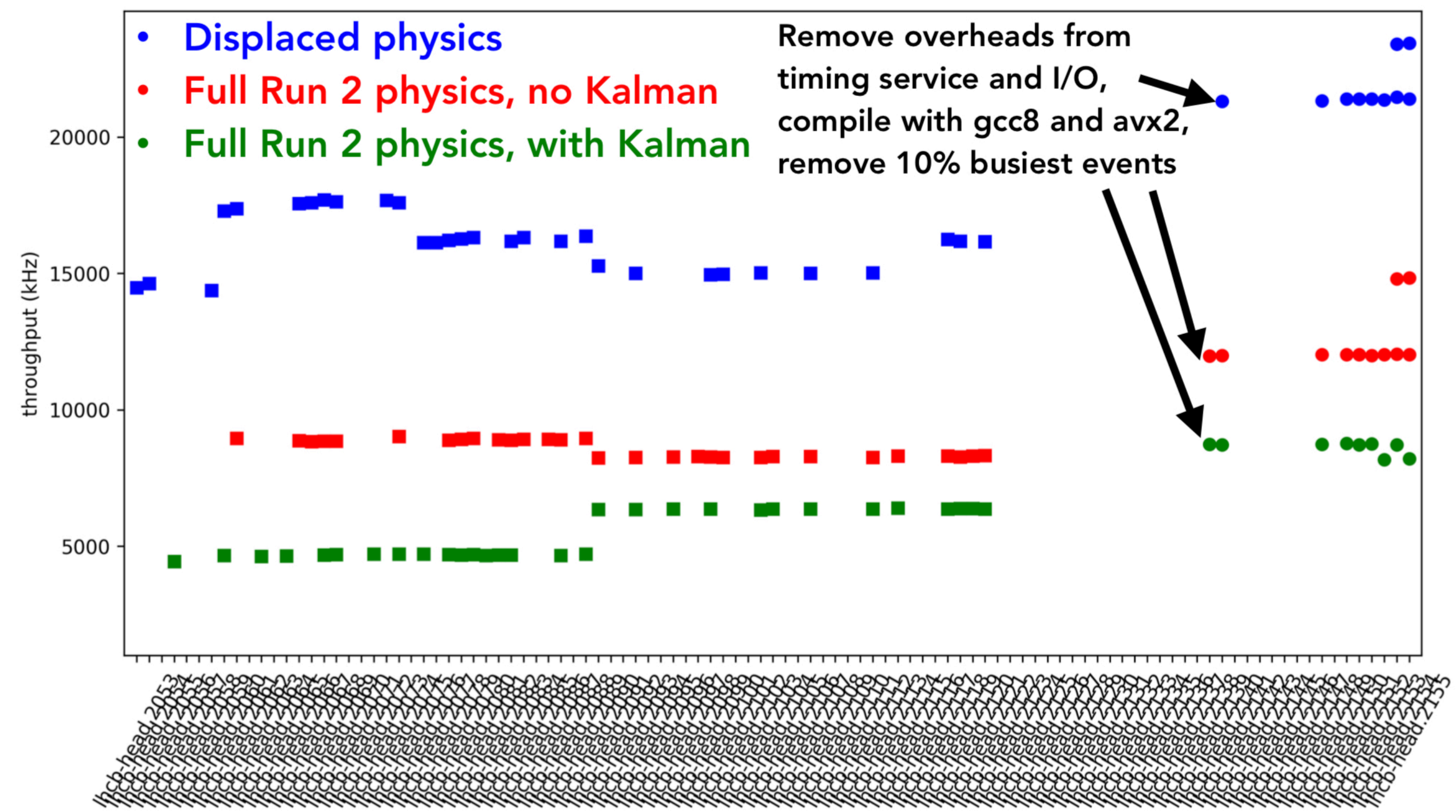
Hits exposed sorted in ϕ

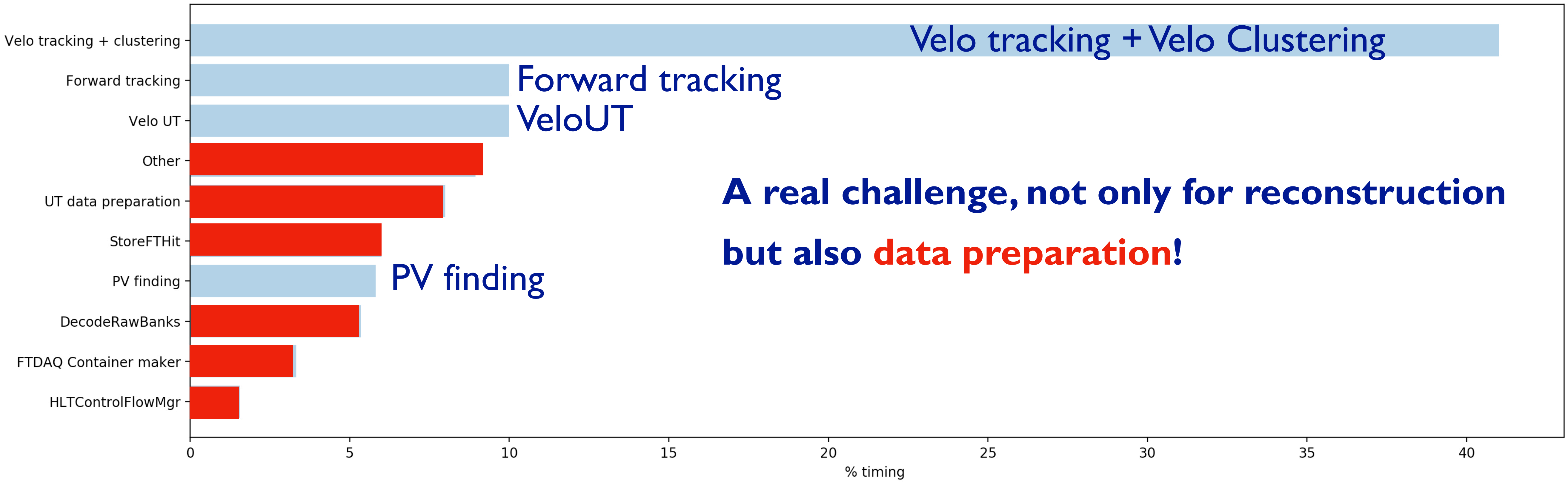


Adaptative search windows



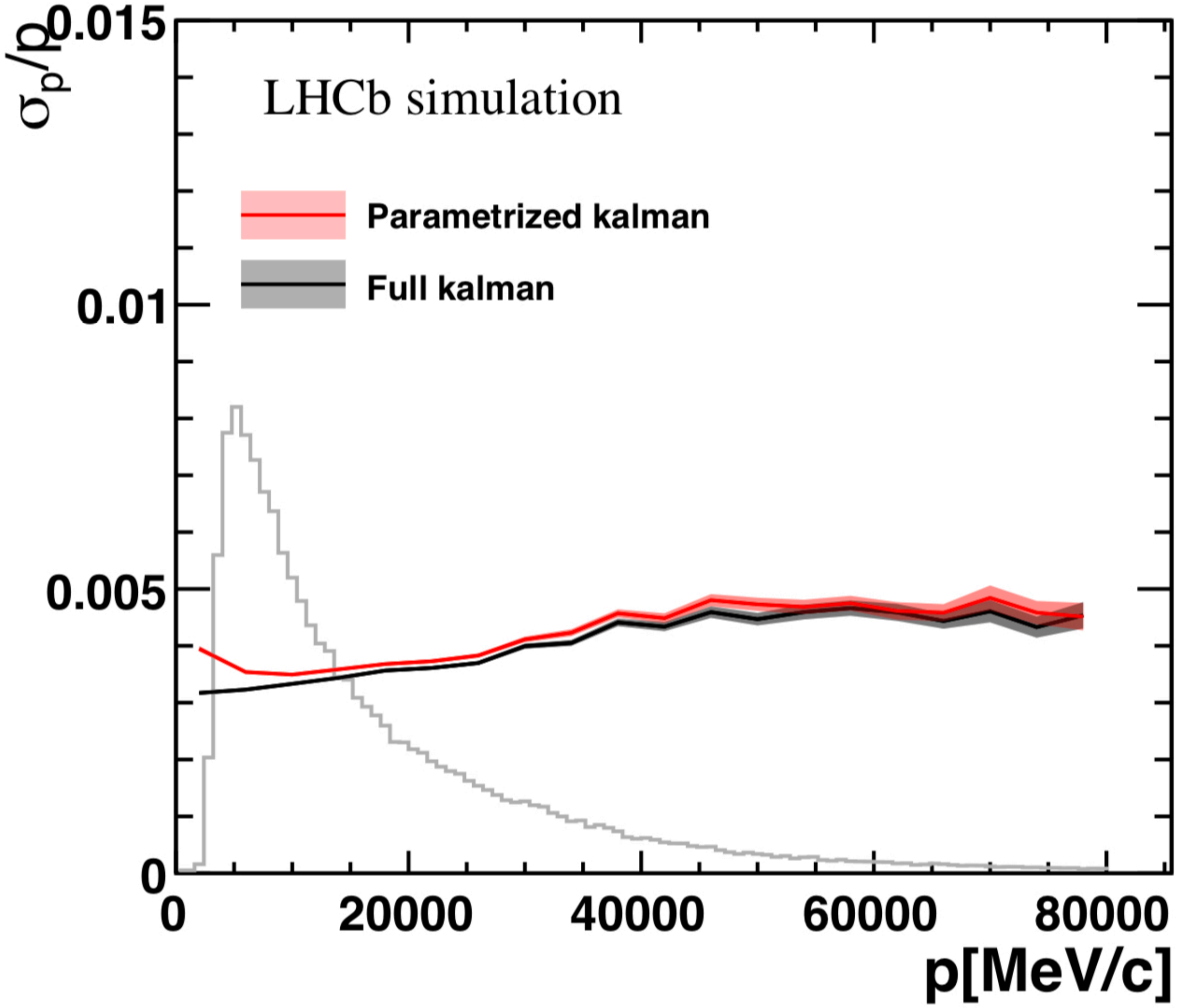
Keep monitoring of performance developments to be on track for Run III start of data taking





A real challenge, not only for reconstruction but also data preparation!

Track fit : Parameterized Kalman



- **Much faster than the default Kalman Filter** using simple parameterization to propagate through magnetic field and material effects. Polynomials used to parameterise the jump from Upstream to Downstream magnet region.
- Moderate loss in precision for HLT1 purposes.

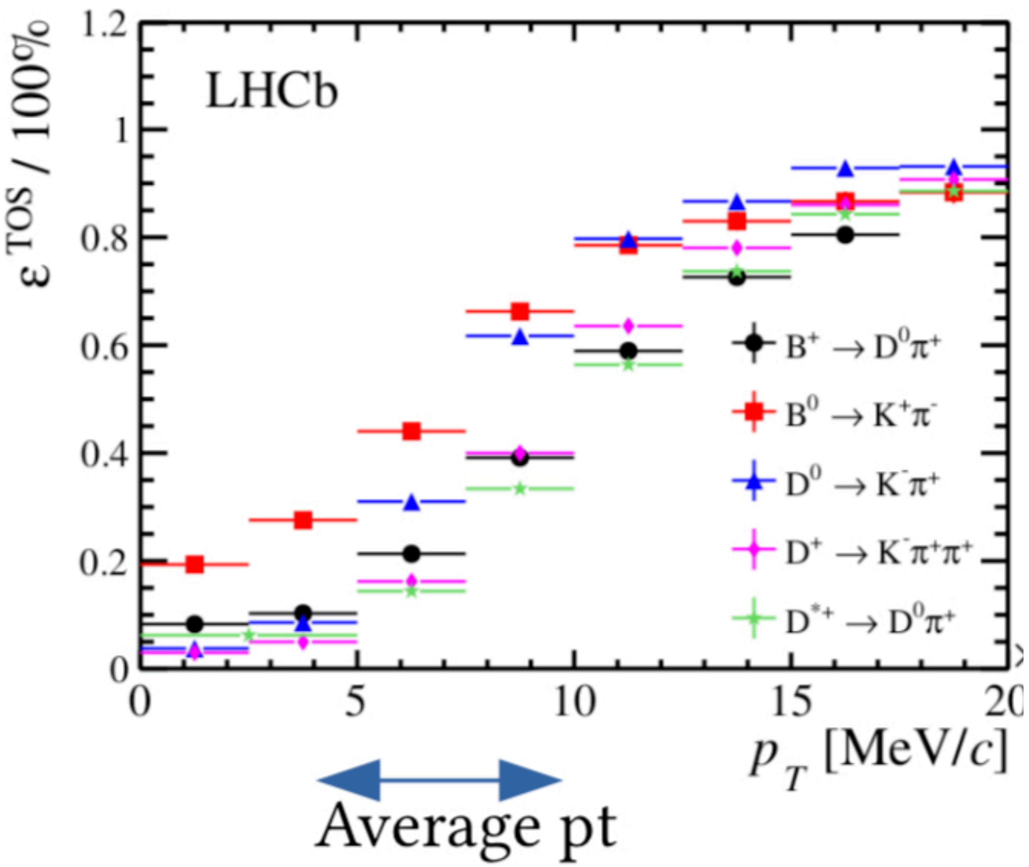
LHCb signal rate has changed the definition of trigger

- ☞ Rejection of background → categorisation of signal.
- ☞ Reduce rate → reduce bandwidth

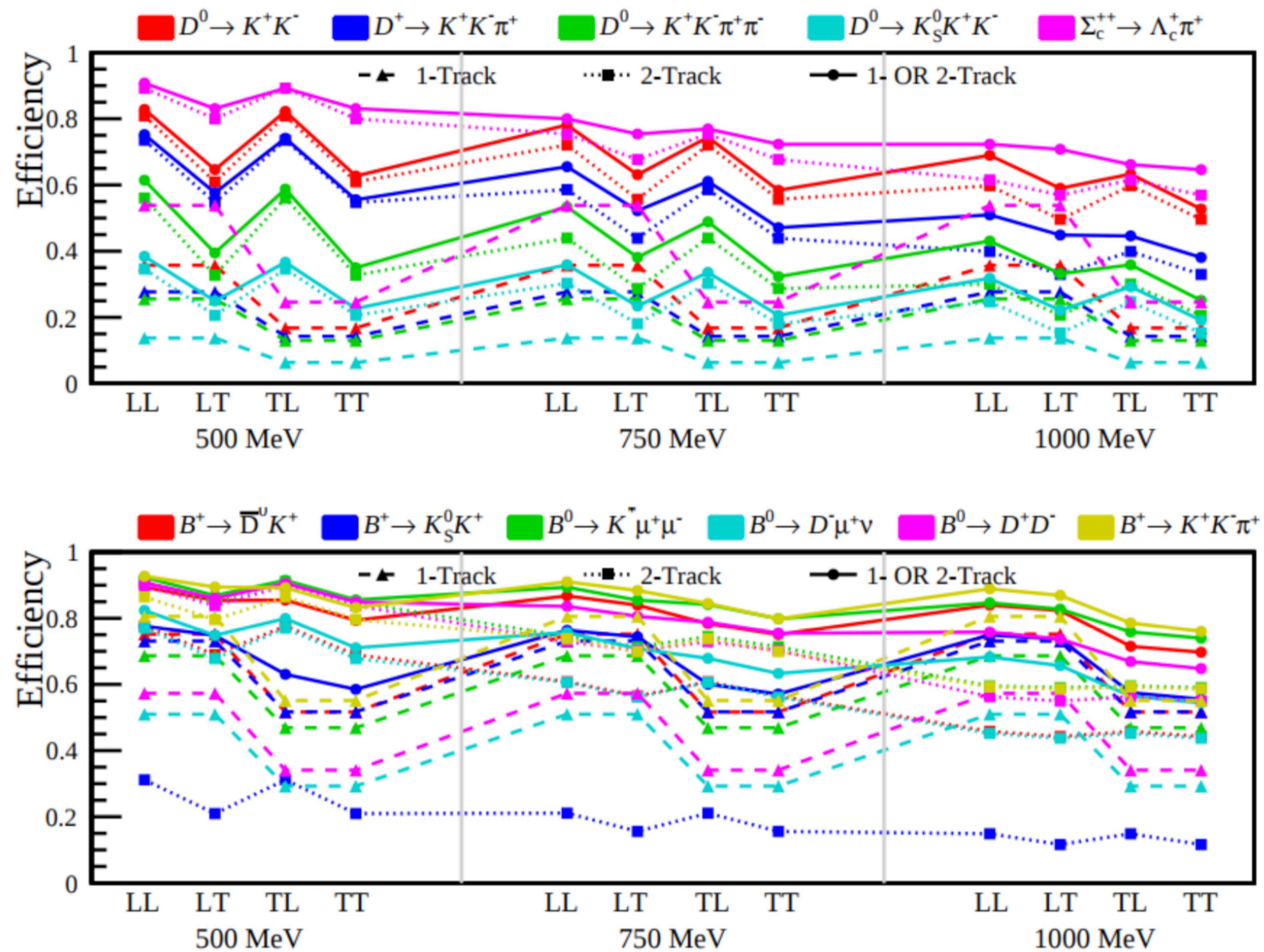
- ☞ **Parallel groups are also developing the HLT1 on GPU and part of data preparation with FPGA [not covered in the talk]**

Estimated HLT1 efficiency for Upgrade

Run 1 L0 efficiency



Hlt1 efficiency estimates for Upgrade

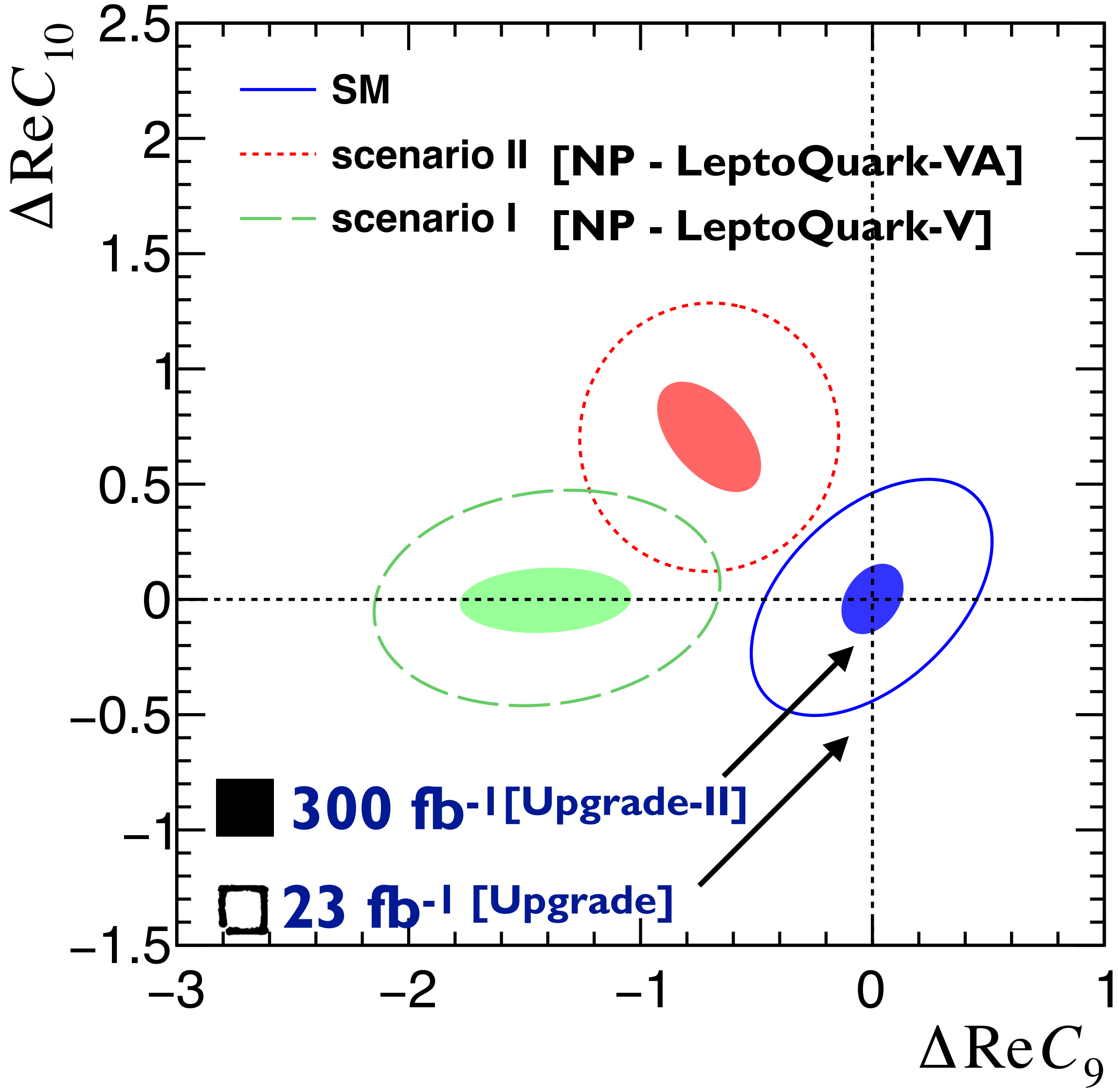


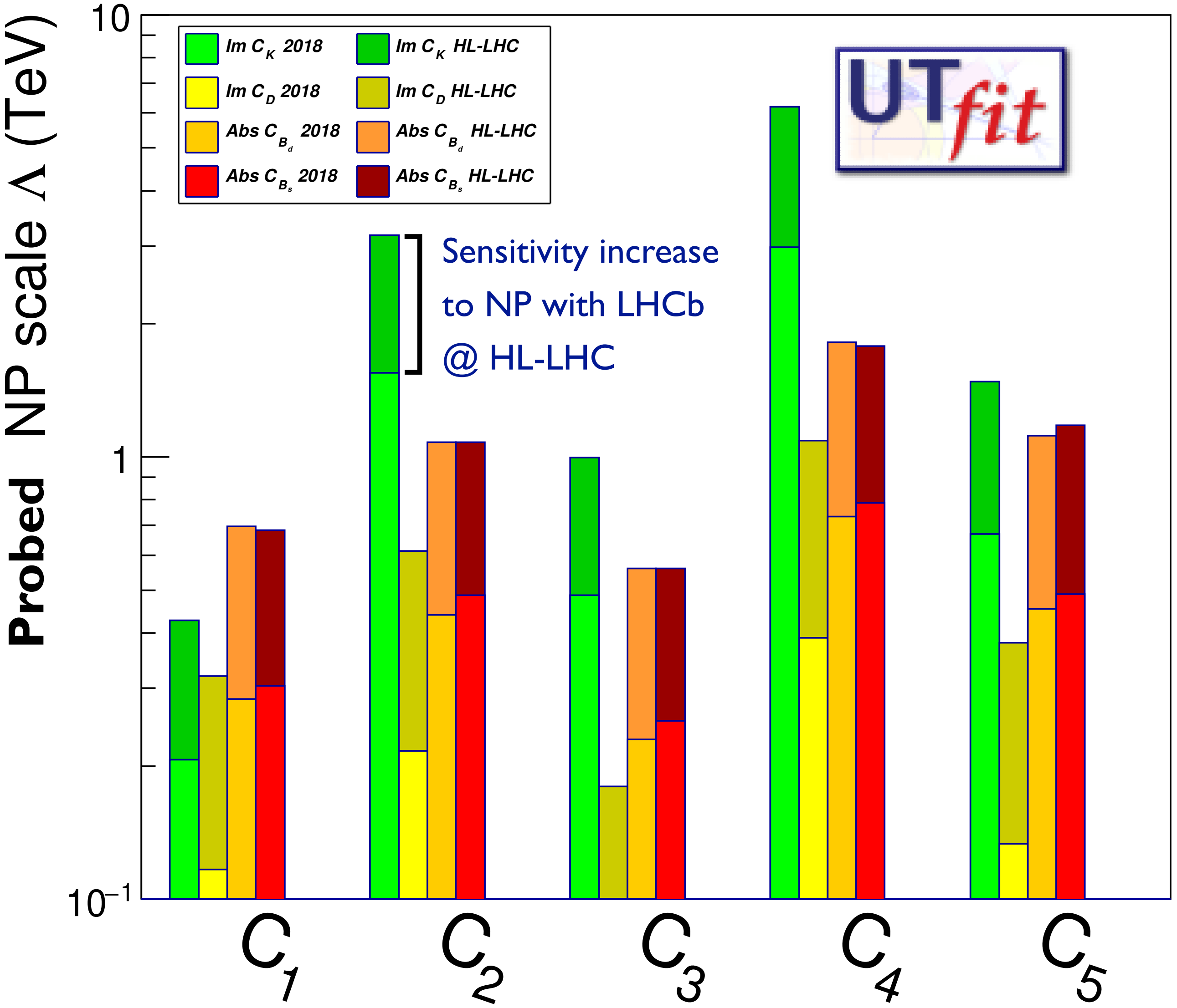
In whatever scenario, there is a significant gain in trigger efficiency, as expected

Road to the ultimate precision and the necessity of upgrade

from exploration and New Physics searches to precision and characterisation of New Physics?

Run II [8 fb^{-1}] — **Upgrade LHCb [50 fb^{-1}]** — **Upgrade II LHCb [300 fb^{-1}]**



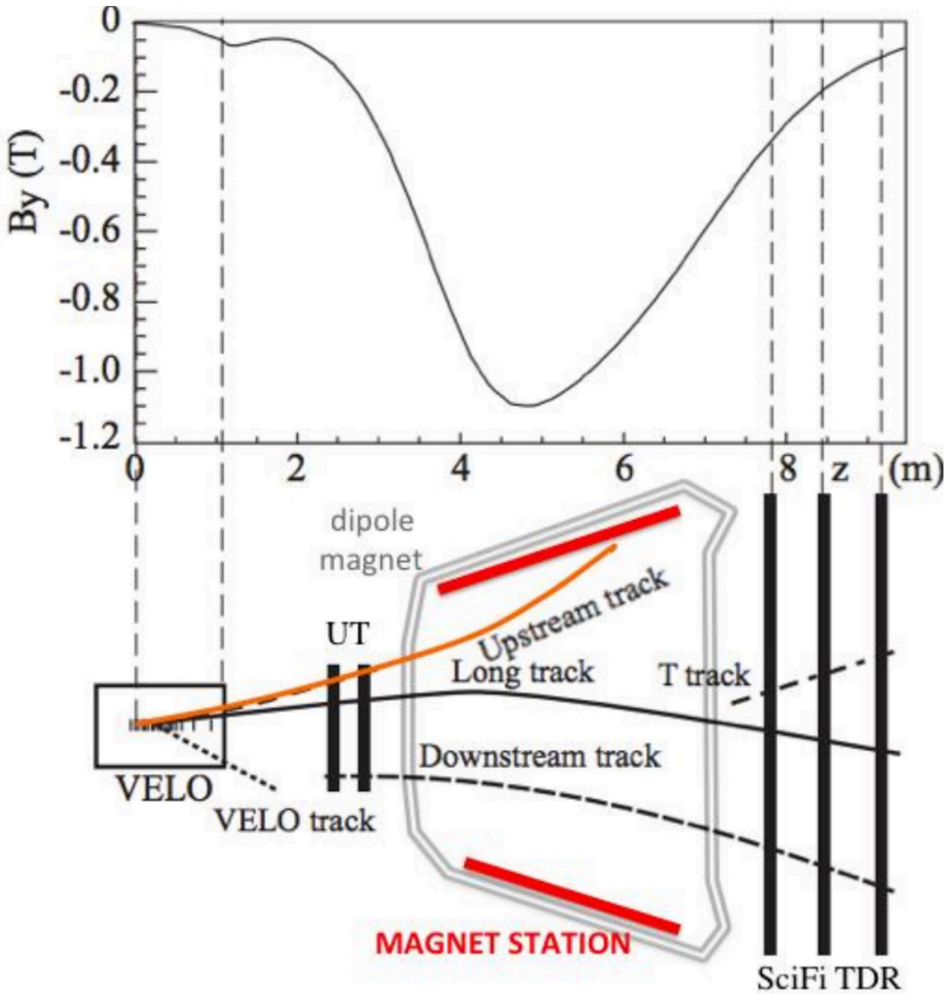


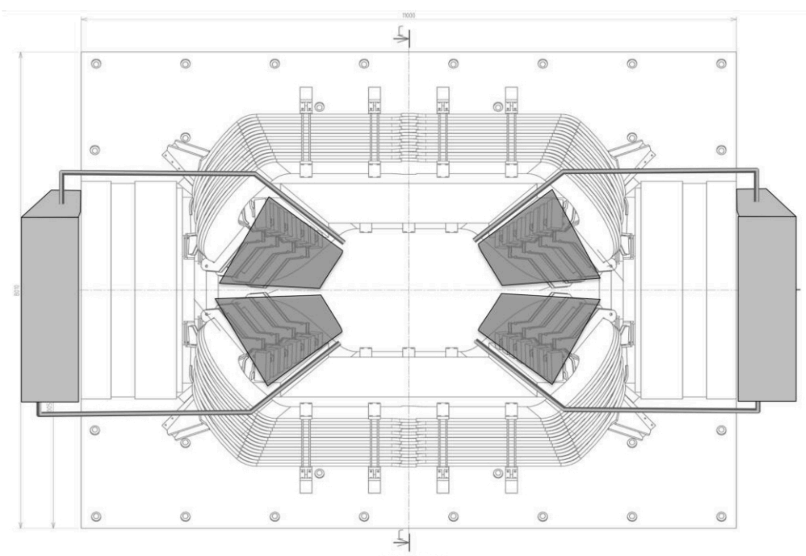
- Huge motivation for a flavour experiment at the ultimate precision
- Also an "ultimate" data and reconstruction challenge, as x 100 more complex event reconstrucion and data-selection

Road to the ultimate precision and the necessity of upgrade

Many ideas to fight the 100 times harder (w.r.t. Run III) challenge in signal rate

A unique opportunity to boost further the physics reach of the experiment





Magnet-side stations to boost physics using slow decay products

$D^* \to D(\pi K)\pi_{\text{slow}}$: gain 21 %.

$\Lambda_b \to \Lambda_c^* \mu\nu$, $\Lambda_c^* \to p\pi_{\text{slow}}\pi_{\text{slow}}$: gain 60 %.

$B \to D^* \tau\nu$: gain 26 %.

$\Sigma_b \to \Lambda_b \pi_{\text{slow}}$: gain 29 %.

$B \to \tau\tau$: gain: 24 %.

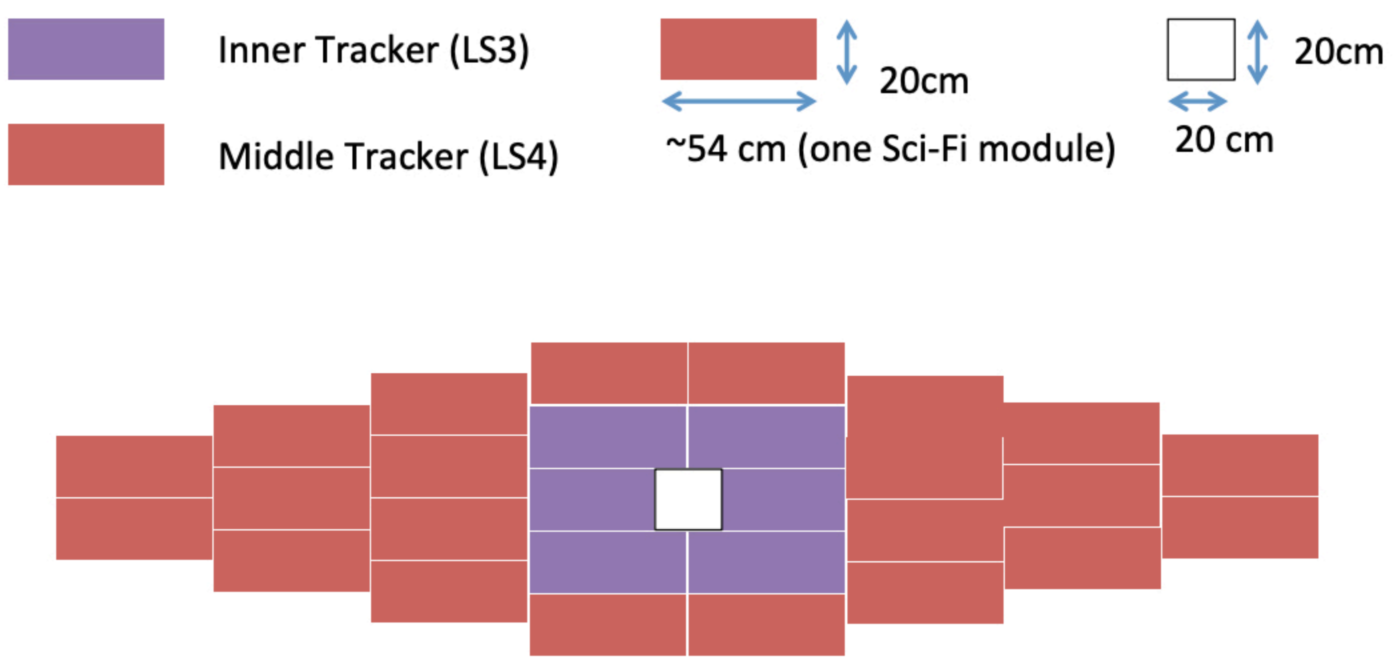
$B \to nK$: gain 10 – 50 %.

Road to the ultimate precision and the necessity of upgrade

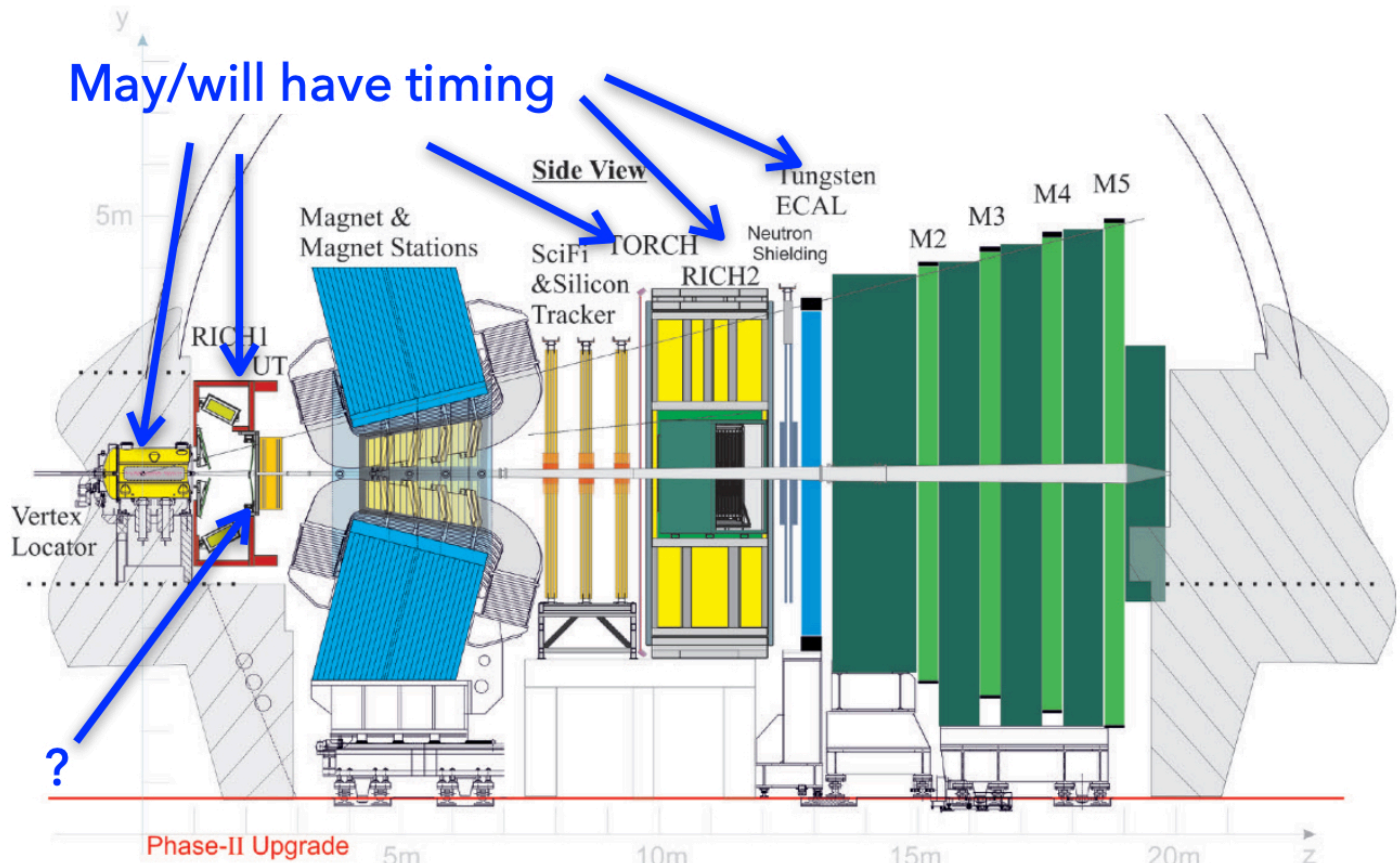
Many ideas to fight the 100 times harder (than Run III) challenge in signal input rate.

The **mighty tracker** (downstream the dipole). Pixel sensors + **Scintillating Fibers.**

A pixelled detector in the central region measuring x-y-z directly



Road to the ultimate precision and the necessity of upgrade



At 10 times higher luminosity than Run III, necessity of a PU suppression system, which can be achievable with high resolution timing detectors, especially in the Velo and T-Stations

R&D, design and studies on going.

Conclusions

- ☞ The LHCb trigger system has evolved a lot during data taking.
- ☞ This has been possible to the choice of making it fully "software-based"
- ☞ The Run II alignment and calibration and TURBO lines development is used as a proof of concept of the Run III trigger
- ☞ In Run III, a similar strategy to Run II will be used, but facing big challenges, which are not yet solved.
- ☞ Perform the reconstruction upfront at software level at an input rate of 30 MHz.
- ☞ LHCb is on the road to deliver the trigger system, aiming at not applying tight selections.
- ☞ LHCb has expressed interest for a further upgrade for the HL-LHC.

Backup

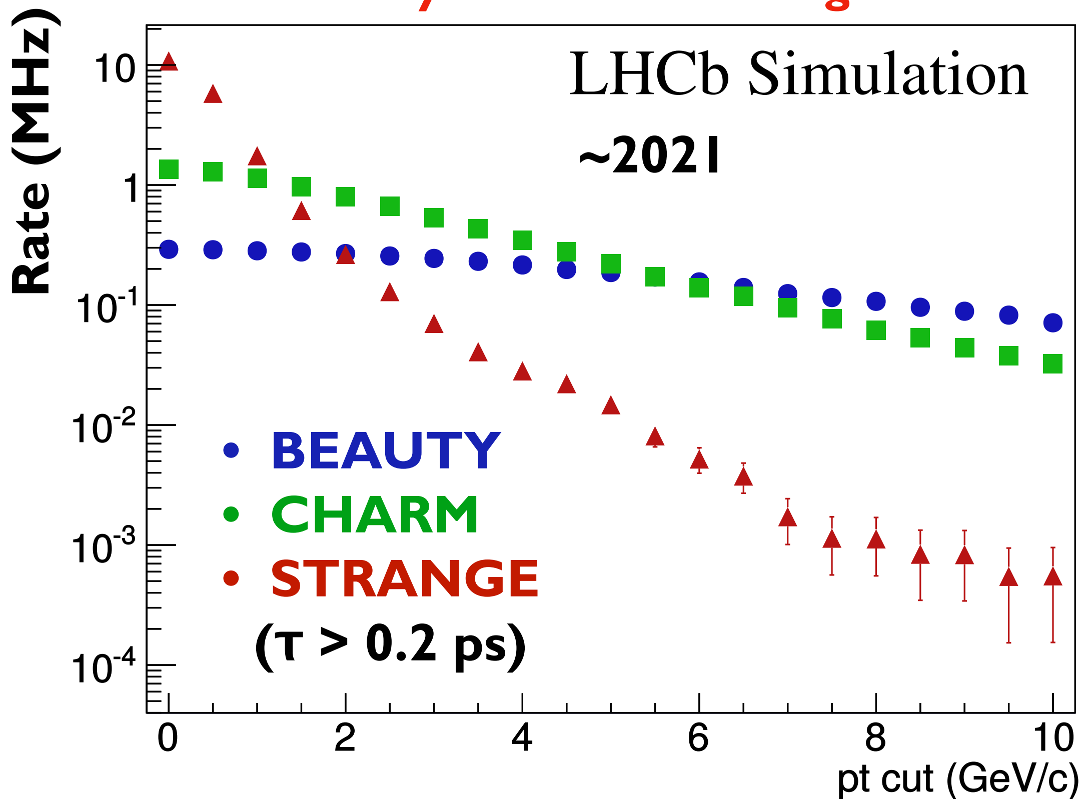
LHCb and triggering

Why triggering?

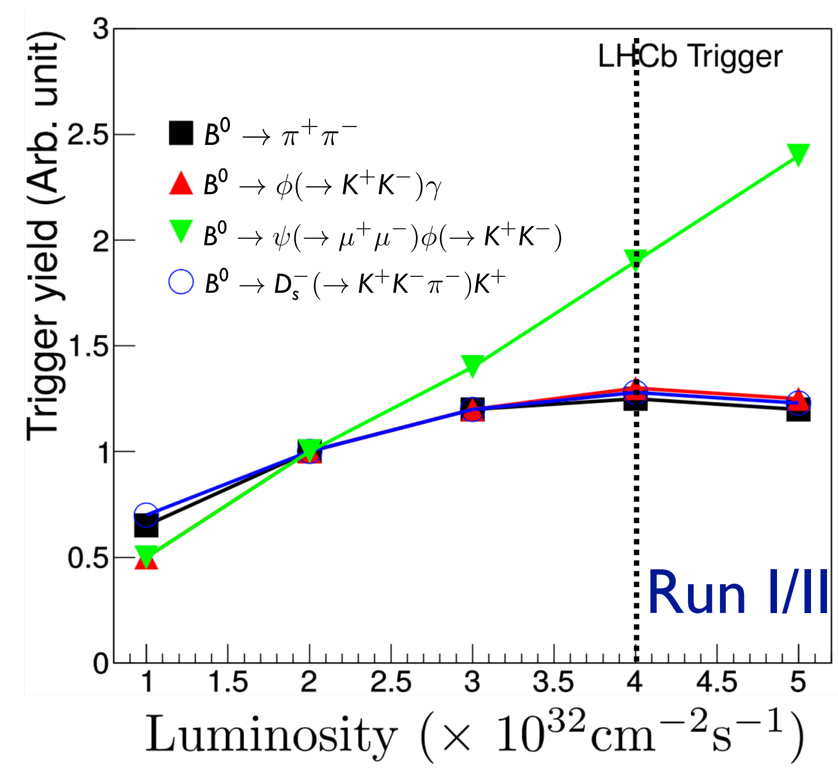
- **LHCb** produces ~ 1 TB/second : 15kPB/year with O(10) M€/year resources
    - LHCb data cost: **O(600€/PB)**
- By comparison, **Facebook** processes 180 PB/year with O(500) M€/year resources
    - Facebook data cost: **O(2.700.000€ / PB)**

A problem of signal saturation

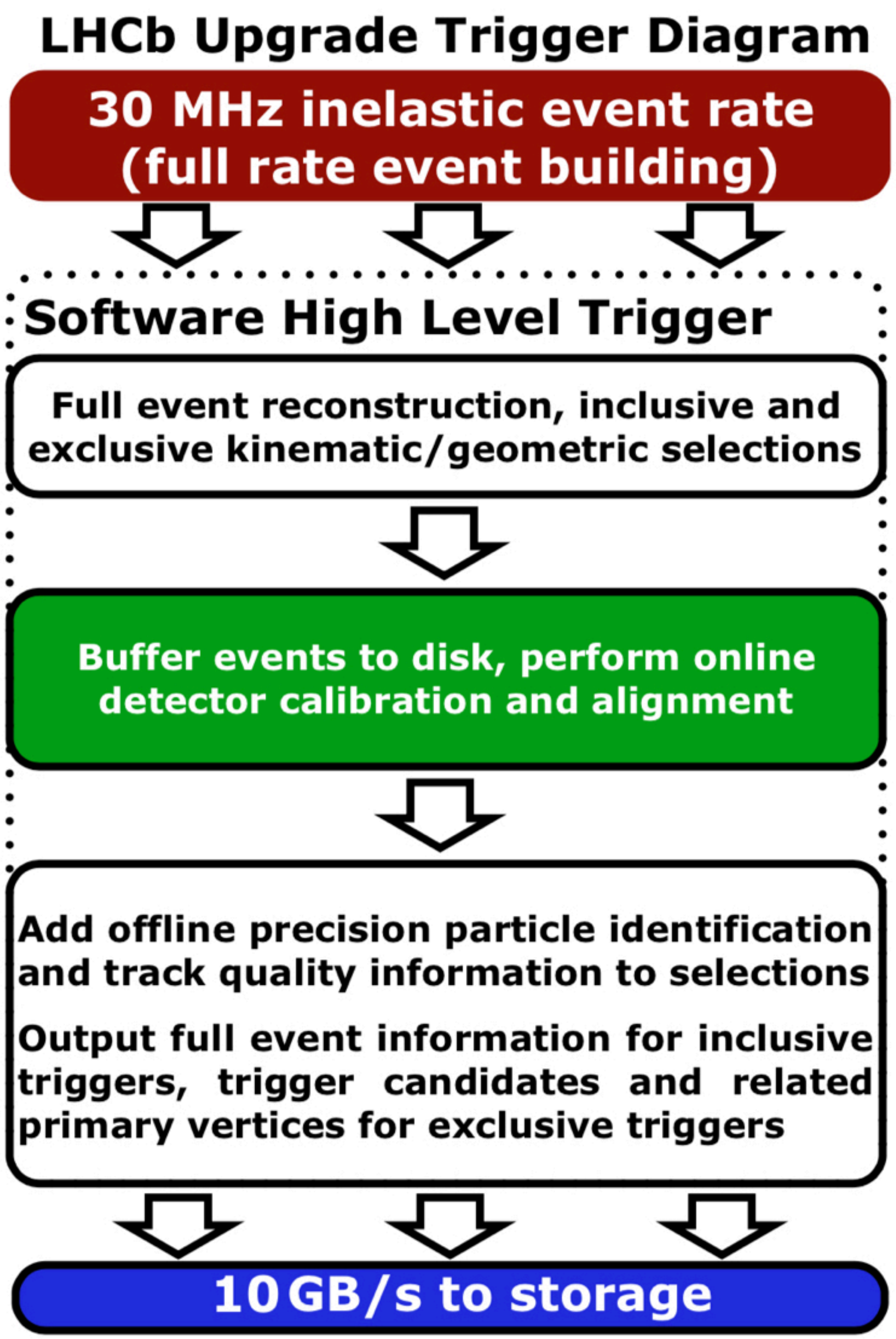
Partially reconstructed signals



Hardware triggers hit a limit of effectiveness!



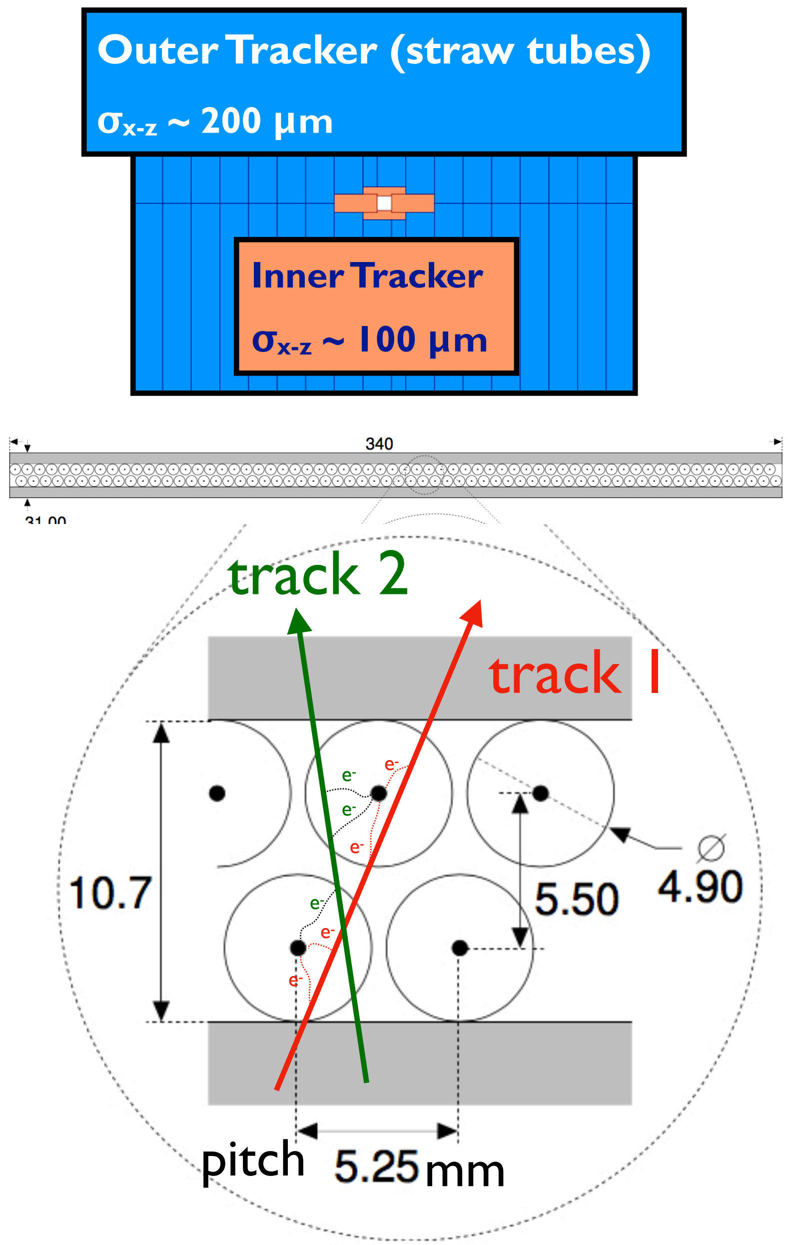
Run III trigger scheme



- ☞Run2 has proven the strategy at 1MHz with a PU level of ~1
- ☞Run3 must process full 30 MHz at 5x the PU of Run2
- ☞Overall strategy similar, but
  - ☞HLT1 output 100kHz —> 1 MHz
  - ☞Disk Buffer contingency of O(days) instead of weeks
  - ☞HLT2 affordable at 10GB/s : must do Real-time analysis with TURBO output
- ☞Full software based : max flexibility to physics needs
- ☞Huge challenge given available resources O(3M CHF) with off-the shelf computing units

Necessity of Upgrading the Downstream tracker

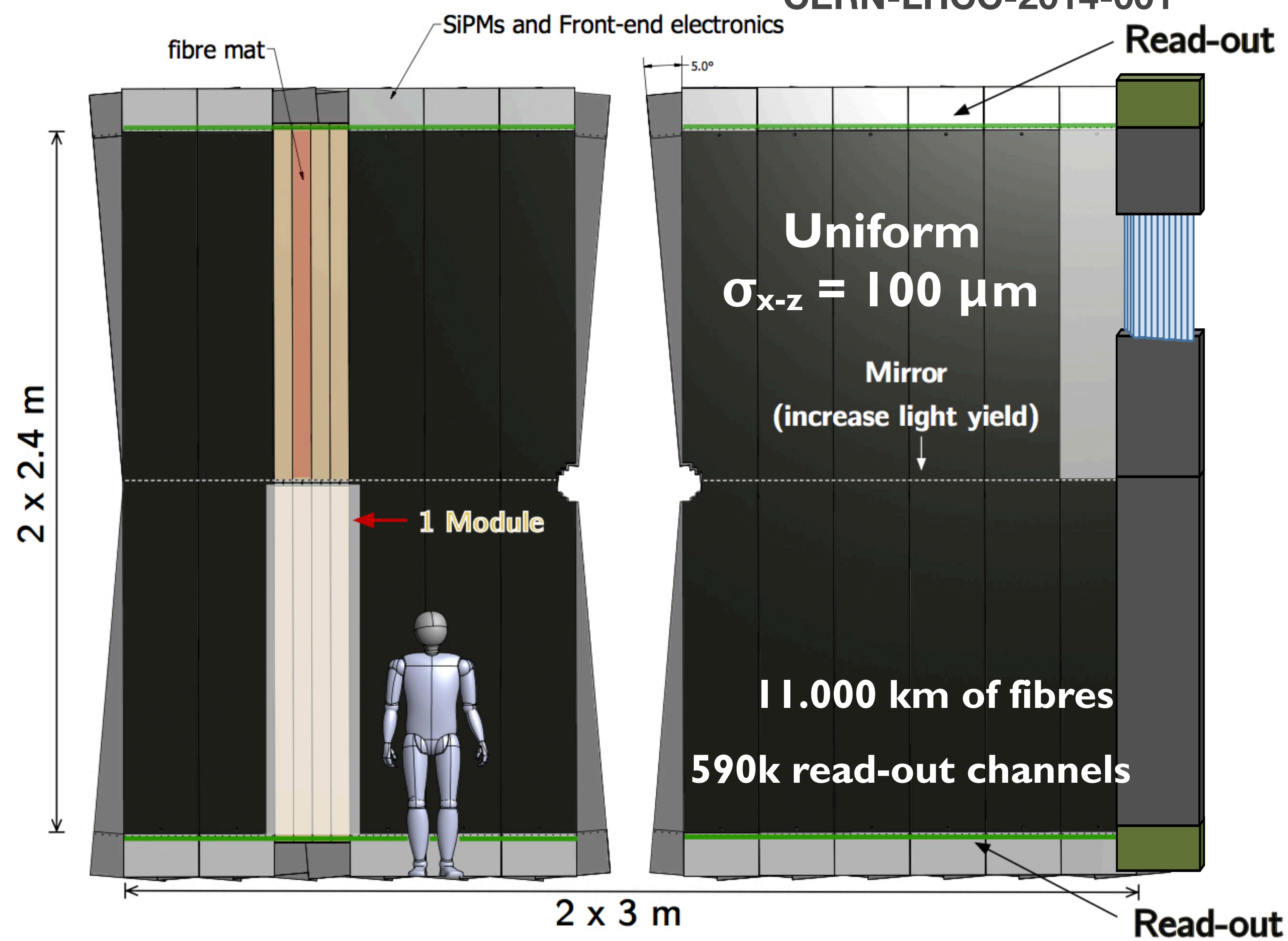
Current downstream tracker



☞ 40% occupancy expected in Outer Tracker

Scintillating Fibre Tracker (Sci-Fi)

CERN-LHCC-2014-001



☞ 3 stations x 4 planes (*x*/*u*/*v*/*x*) of 6 stacked 2.4 m long scintillating fibres.

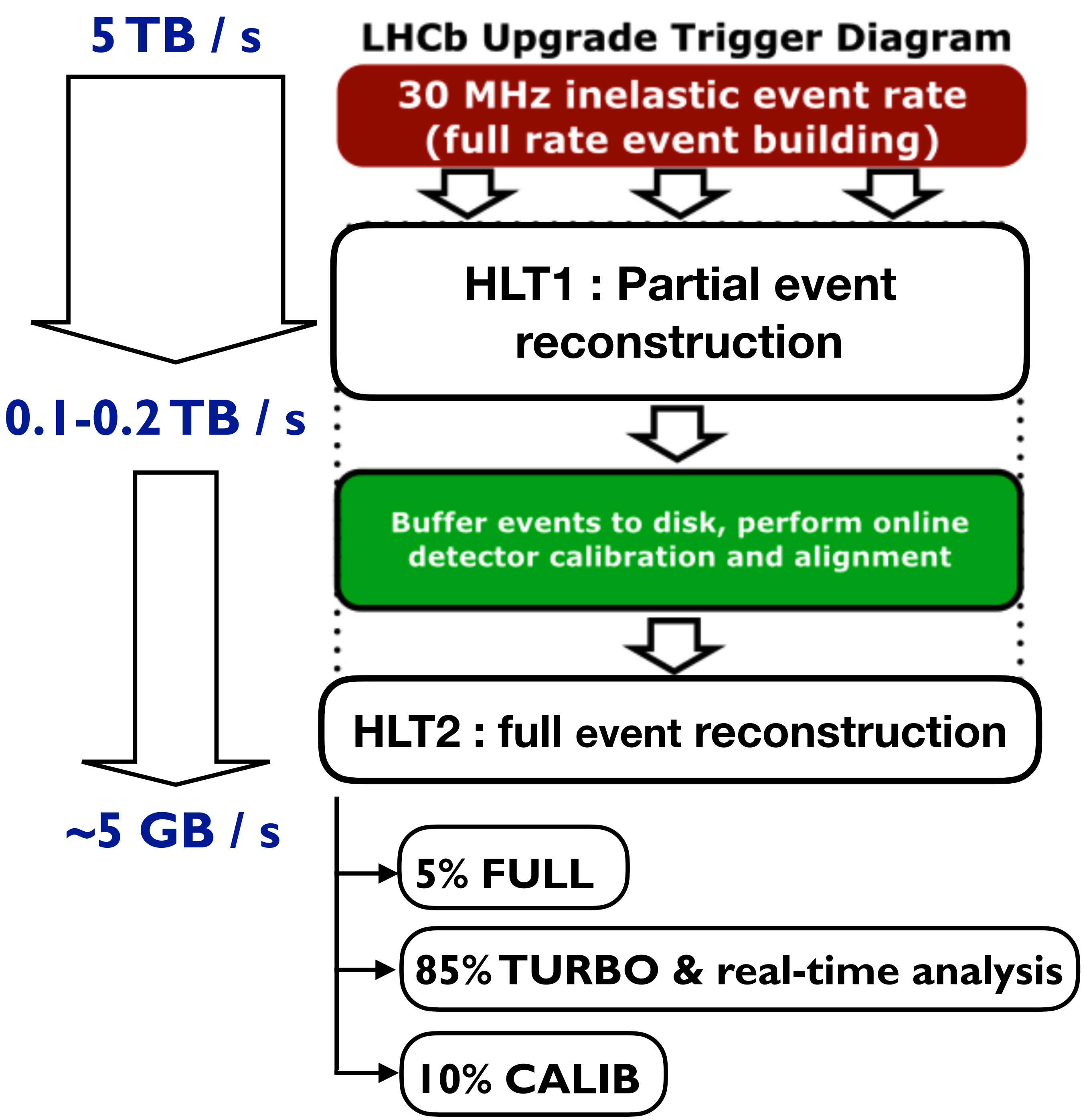
☞ Scintillating fibers diameter: 250 µm

☞ Read-out by Silicon-Photon multipliers (250 µm channel pitch)

☞ SiPM + FE electronics + cooling in "Read-out box"

Data Rate and the PRECISE revolution

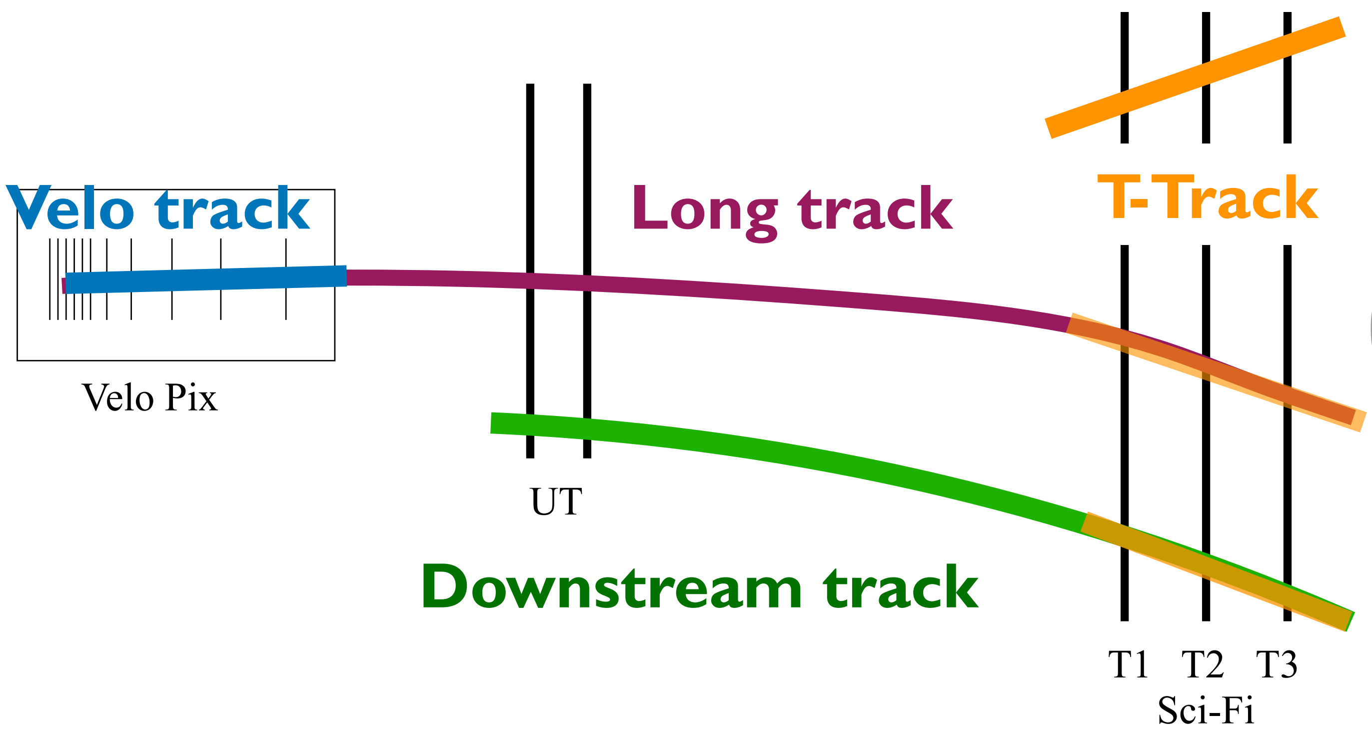
Necessity of a PRECISE revolution



- **Full detector : 30 MHz readout**
- **Full tracker reconstruction : 30 MHz in off-the-shelf x86 processing units**
- **Not only suppress background, but distinguish signal from signal**

- **LHCb** signal rates and precision physics program require a **real-time** alignment and calibration of the detector!
- **Run II [2015-2018]: first** real time alignment and calibration, as proof of concept for the upgrade.
- **Run III [2021 - 2025++] :** real time event reconstruction (at collision rate) and analysis. A **100** times bigger data challenge!

Track reconstruction at LHCb



For the HLT1: partial reconstruction

Daughters of b and c hadron decays (long)

No needs to be efficient in all the phase space, identify signature is enough.

For the HLT2 : full reconstruction

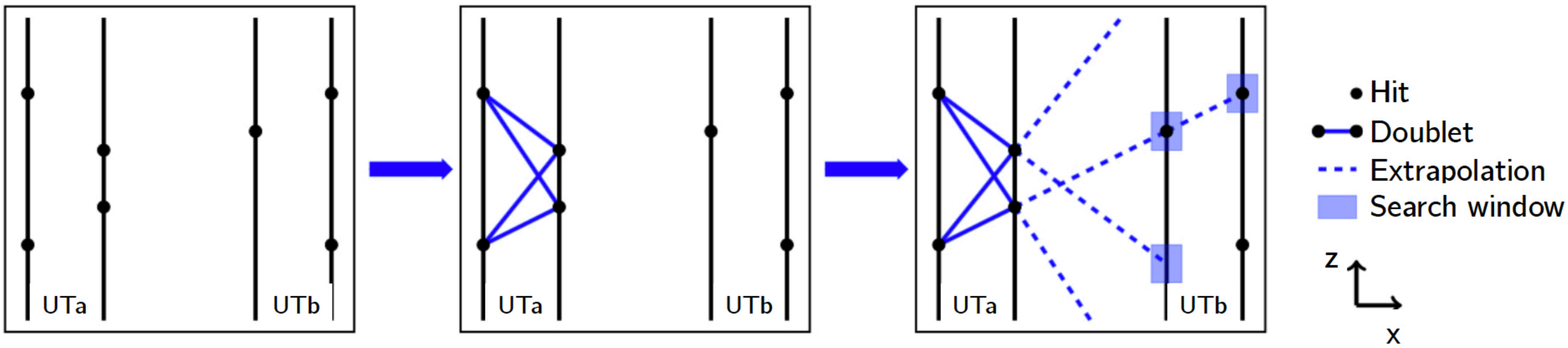
All Daughters of b and c hadron decays (long)

T-Tracks seed the reconstruction of

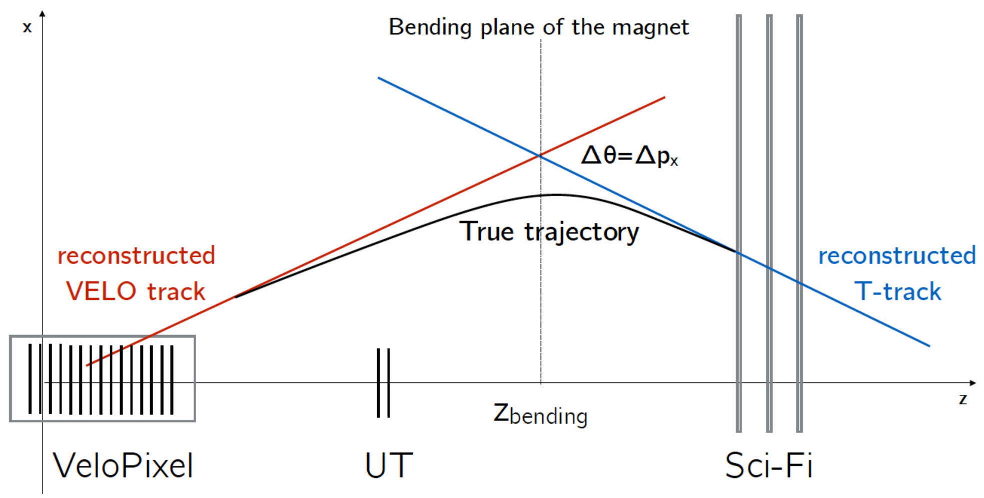
Daughters of long-lived particles such as K_s and Λ^0 (downstream)

- 2 Crucial algorithms for the partial event reconstruction and the full Event reconstruction:
- **VELO** tracking and **T-Tracks** finding algorithm : I am the author of both of them
- **The physics reach of the upgrade depends on how well those 2 performs in terms of tracking efficiencies and timing!**

Velo-UT tracking

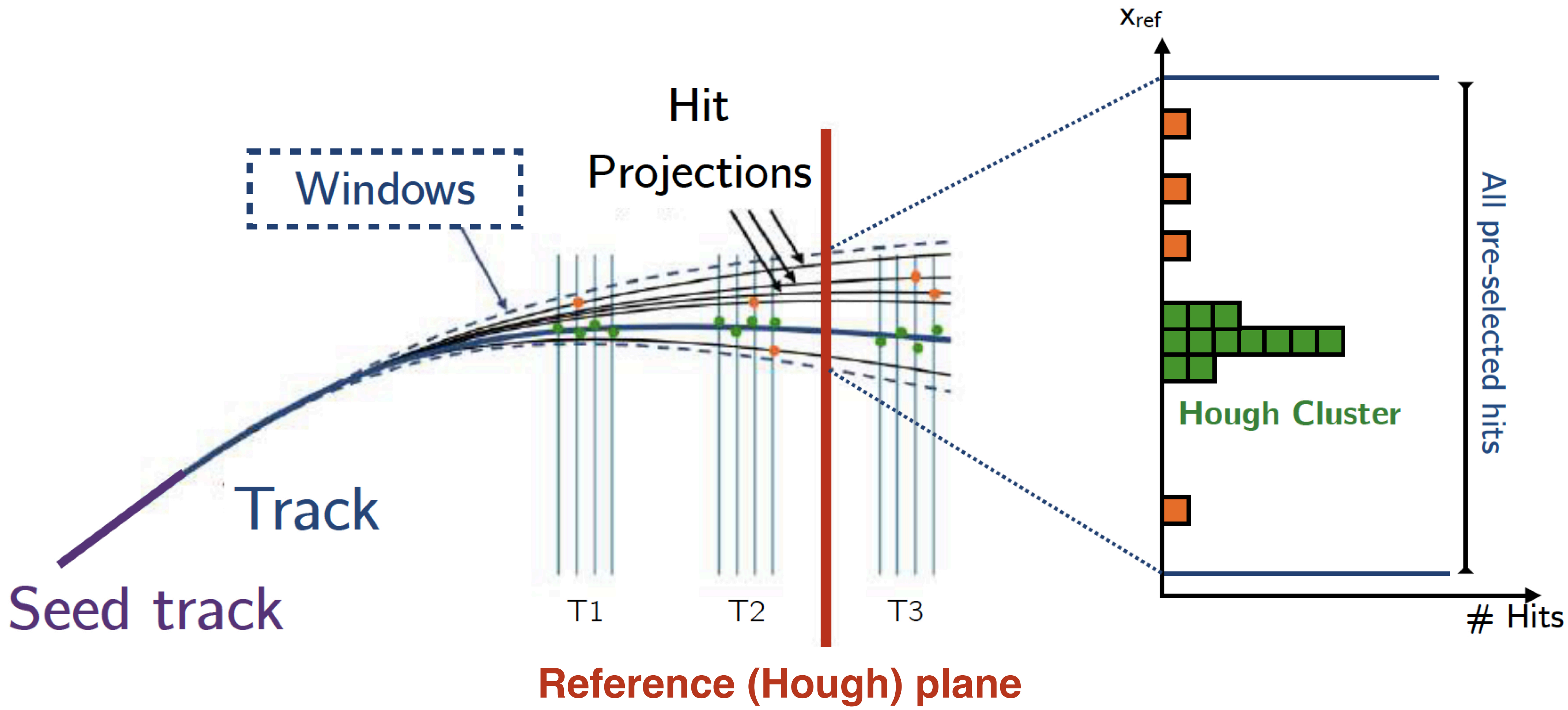


- **Propagate VELO track to UT correcting for integrated B field**
- Search for doublets and propagate
- Find 3-4 hits matching predictions using also y-z plane information
- Estimation of q/p



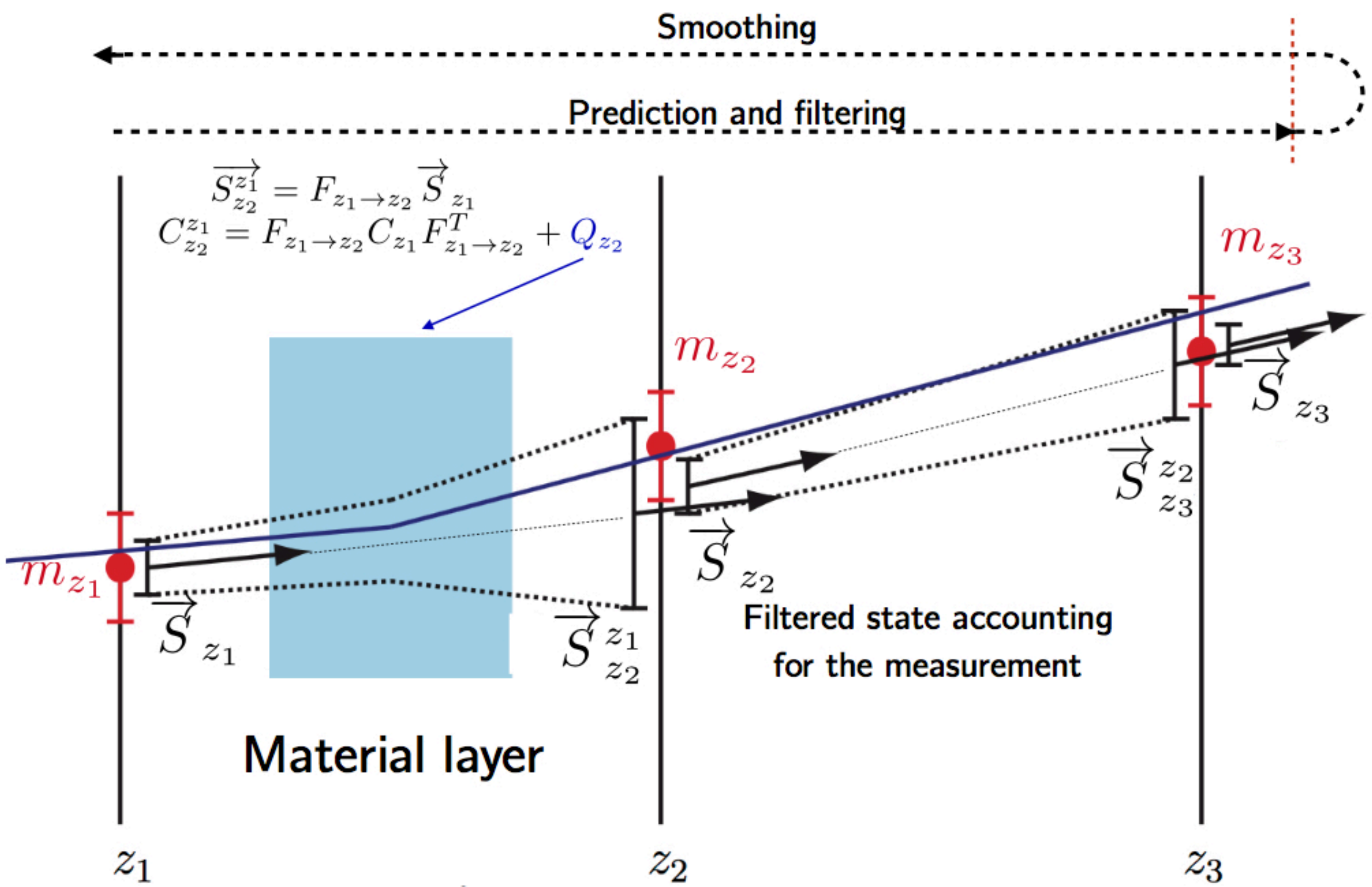
$$\frac{q}{p} = \frac{1}{\int \left| d\vec{l} \times \vec{B} \right|_x} \cdot \left(\frac{t_{x,f}}{\sqrt{1 + t_{x,f}^2 + t_{y,f}^2}} - \frac{t_{x,i}}{\sqrt{1 + t_{x,i}^2 + t_{y,i}^2}} \right)$$

The forward Tracking



- Hits are pre-selected according to the min p_T requirement
- The lower the min p_T requirement, the wider the window, the larger the amount of hits used for each seed track, the slower the algorithm.
- For each seed track, all p_T compatible hits are projected to a reference place and a cluster search is performed to find the matching SciFi hits.

Kalman Filter

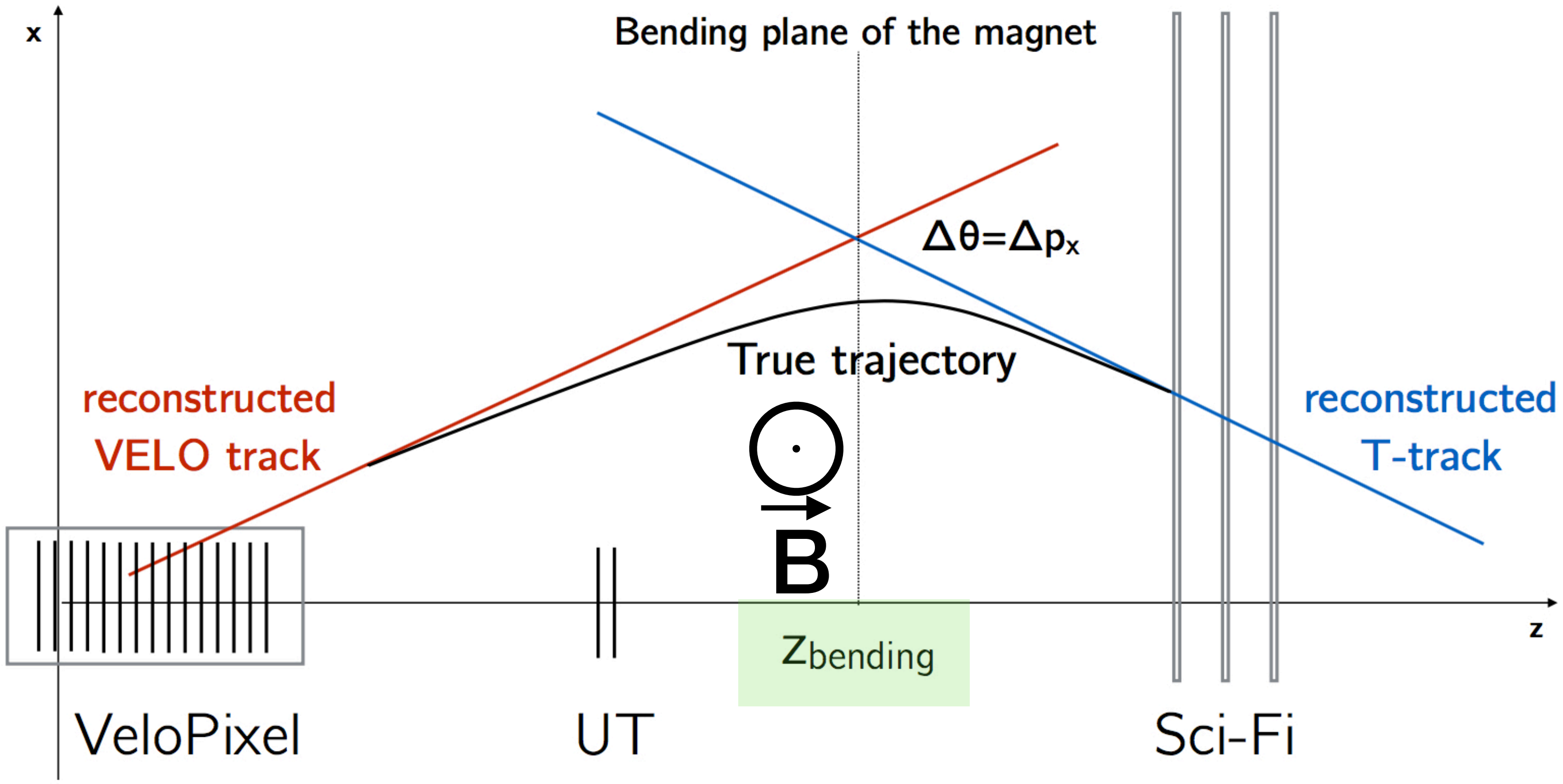


- **Prediction**: propagate a track state to another track state
- **Filtering**: compare propagated track state to actual measurement. Minimisation of χ^2 based on residual.
- Evaluate best estimate of new track state (also reject/accept measurement)
- Iterate over all measurements
- **Smoothing**: perform previous steps in the opposite direction using the prediction and filtering
- **Material interactions accounted for enlarging the errors when propagating states**

Tracks behaviour in LHCb and pattern recognition

p_T-kick method is heavily used in LHCb for patter recognition (PR).

(typically B_x and B_z assumed to be negligible at any z in pattern recognition)

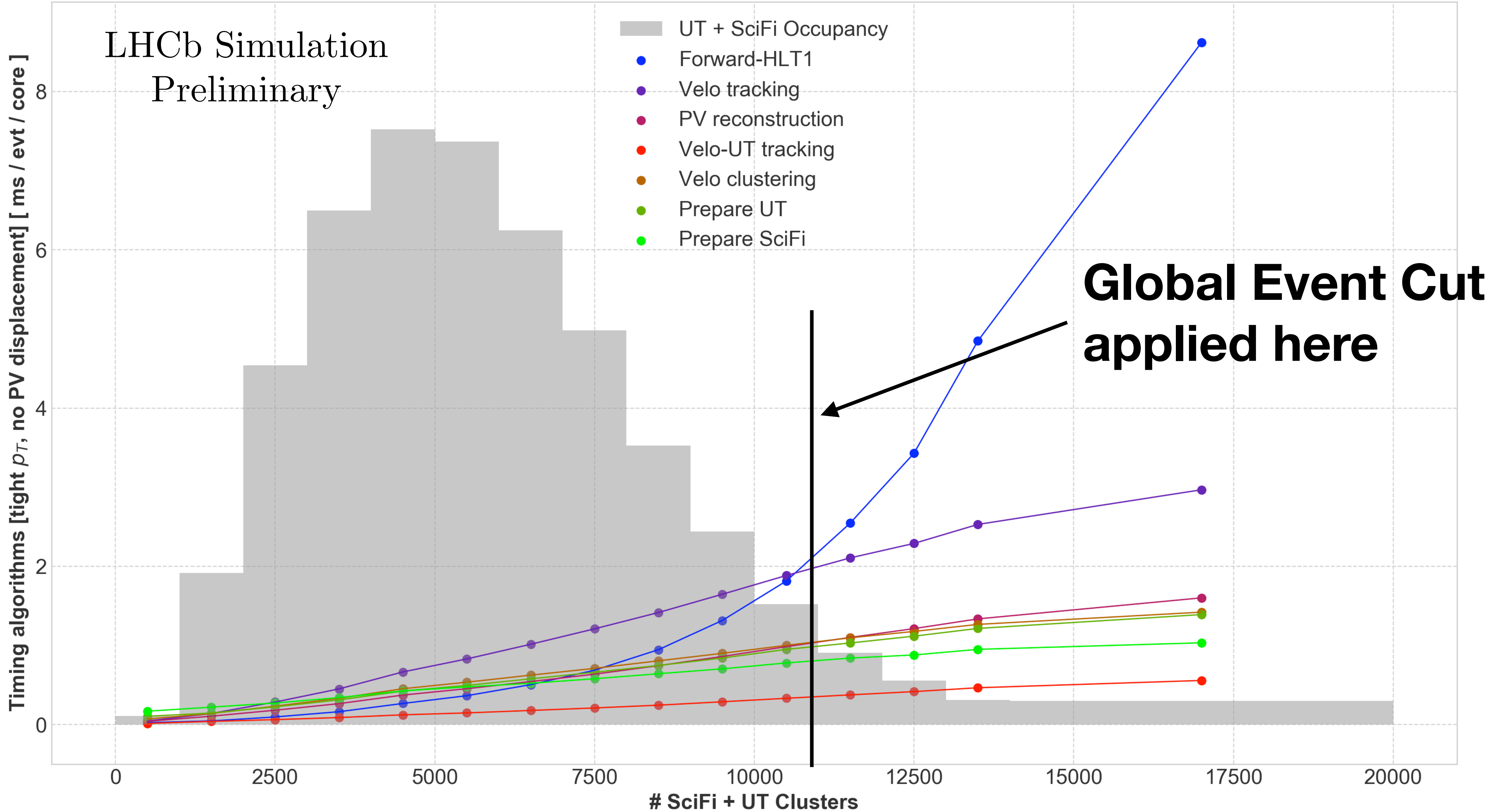


Example of the p_T-kick used in the matching algorithm

$$\frac{q}{p} = \frac{1}{\int \left| d\vec{l} \times \vec{B} \right|_x} \cdot \left(\frac{t_{x,f}}{\sqrt{1 + t_{x,f}^2 + t_{y,f}^2}} - \frac{t_{x,i}}{\sqrt{1 + t_{x,i}^2 + t_{y,i}^2}} \right)$$

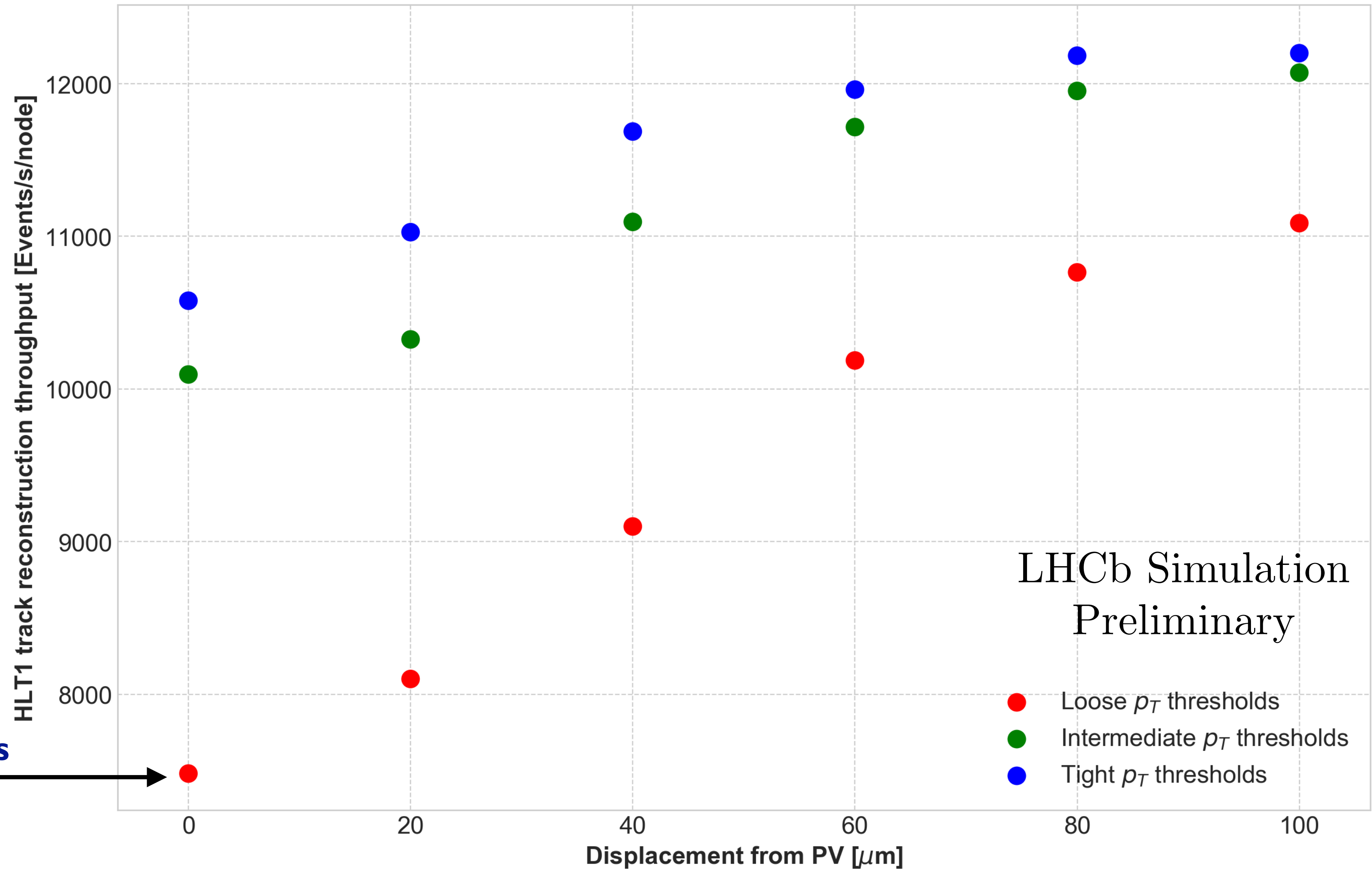
- ☞Used to estimate q/p.
- ☞Used to open search windows according to momentum requirements.
- ☞Used to quantify matching quality of reconstructed segments.

Throughput dependence on detector occupancy



- ☞ Almost all algorithms scales linearly with the occupancy.
- ☞ Exception done for the forward tracking, which is currently implementing a tracking strategy oriented for HLT2 purposes.

Throughput dependence on tracking scenario



Same working point as
[LHCb-PUB-2017-005]
(used to be 3500 evt/s/node)

- The displaced-tight p_T track reconstruction scenario is almost fitting in the 30 MHz computing budget and it fulfills the B physics scientific program.
- Prompt physics and multi-hadron final state B physics will suffer in tightest scenario.
- Factor 2 in throughput gained since biannual upgrade review document thanks to the optimization of the various algorithms.

Forward Tracking algorithm

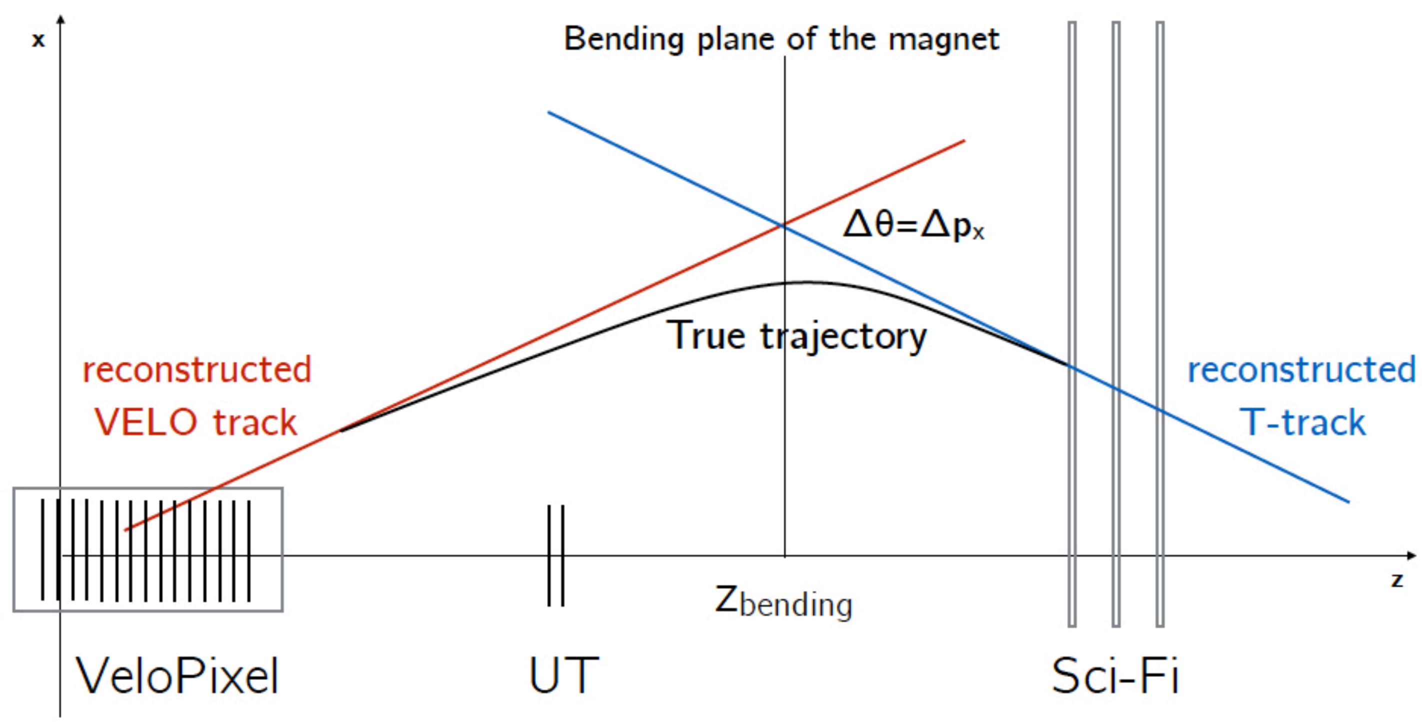
Seed track: VELO or VELO-UT depending if fast (HLT 1) or best (HLT2) sequence

Search windows based on p-kick method

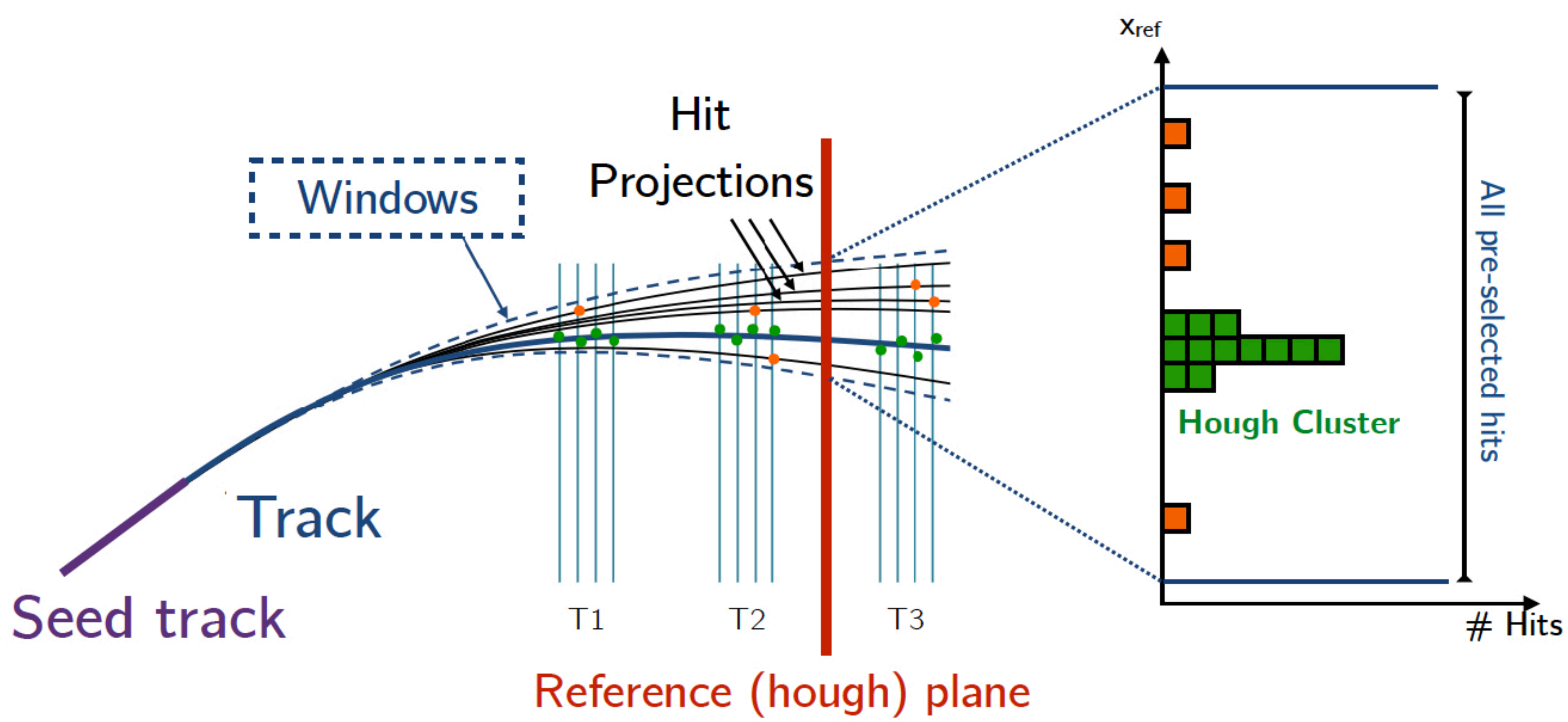
1 hit + Seed track: allows to know expected track motion in bending plane in all T-stations.

Hough-Clusters: project all measurements to reference plane and find accumulation of them

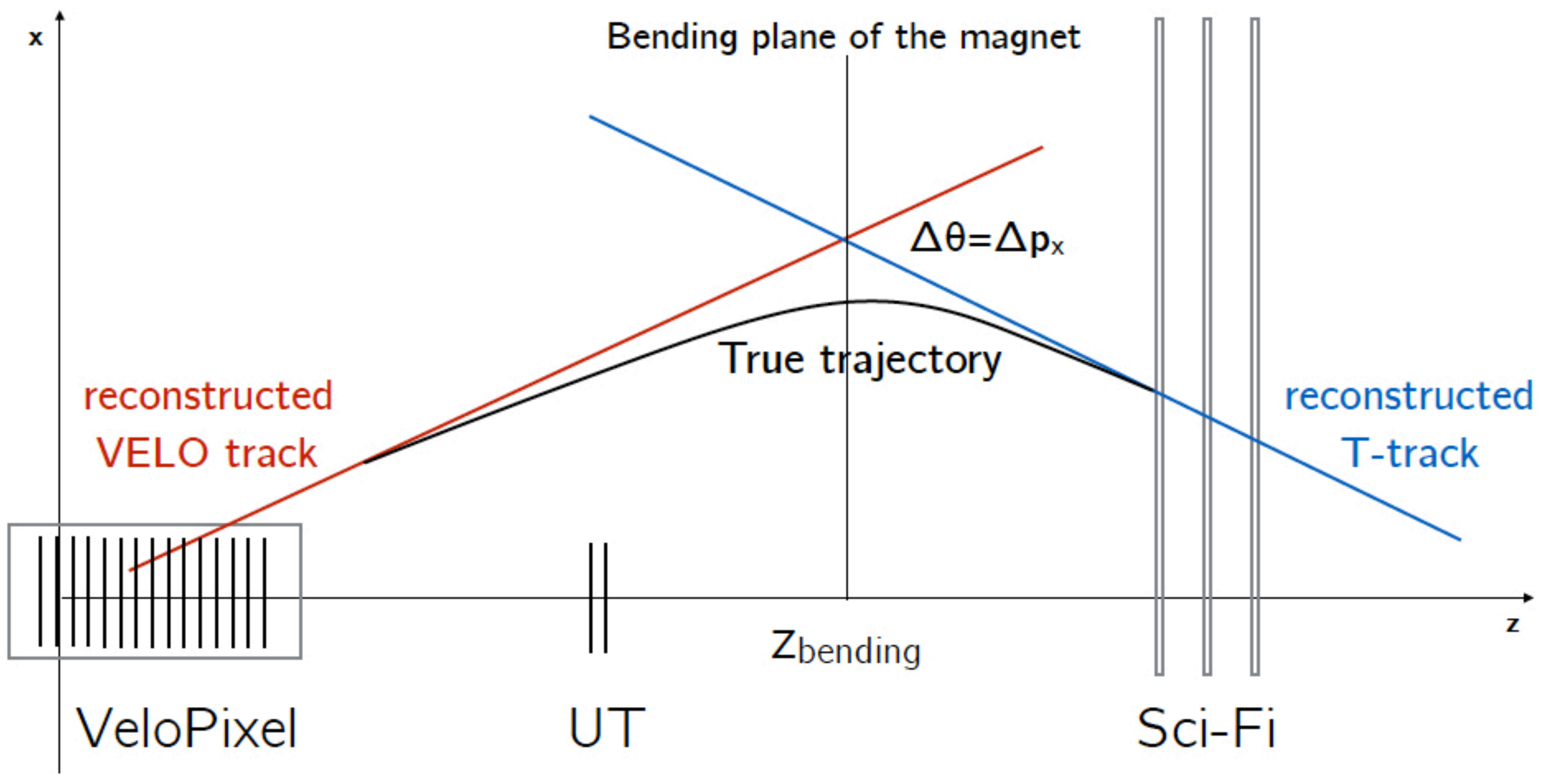
p_T-kick method



Forward tracking and Hough Clustering (1D)



Matching algorithm

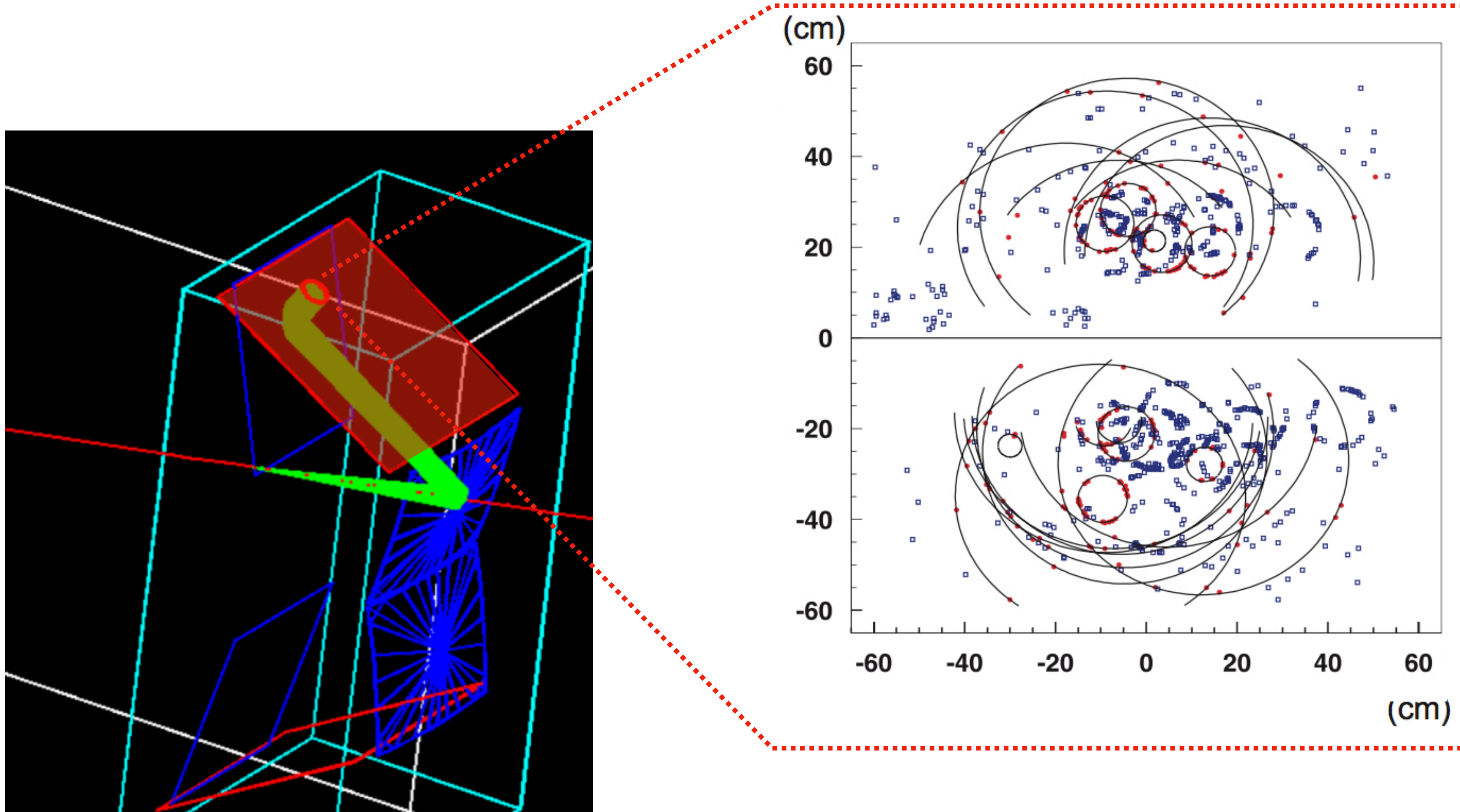


- **Seed tracks: T-Track state (S_T) from Seeding and Velo Track state from Velo Tracking (S_V)**
- **Matching of them building a χ^2 matching at $z_{bending}$ plane and Neural Net based selection**

$$\chi^2_{match'} = \left(\vec{S}^K_V(z_{mag}) - \vec{S}^K_T(z_{mag})\right)^T \cdot \left(C^K_{VELO} + C^K_T\right)^{-1} \cdot \left(\vec{S}^K_V(z_{mag}) - \vec{S}^K_T(z_{mag})\right)$$

PID using RICH detectors

Add *PID* information to tracks using RICH detectors



$$m = \frac{p}{c\beta\gamma} \qquad \cos\theta_C = \frac{1}{n\beta}$$

from tracking (p)

ring radius (θ_C)

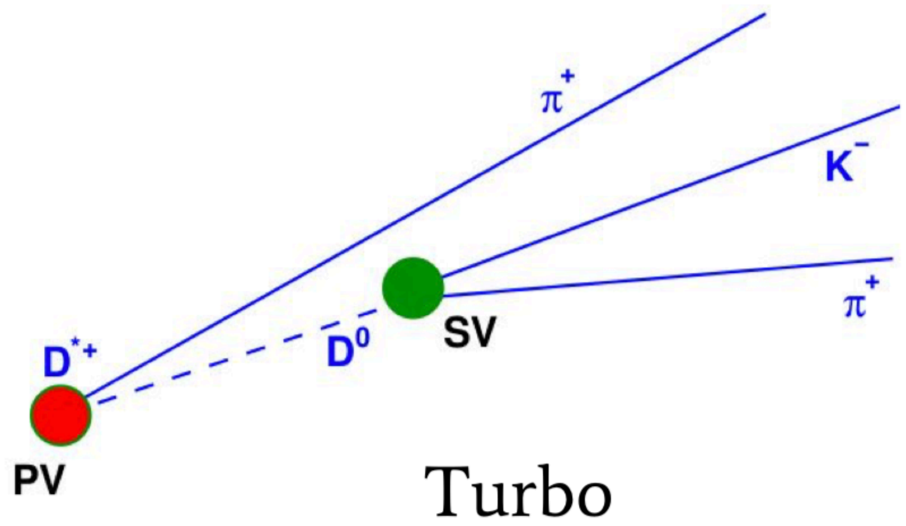
- Rings used to assign PID likelihood.
- (offline) Info combined with other sub-detectors into a Neural Net PID probability

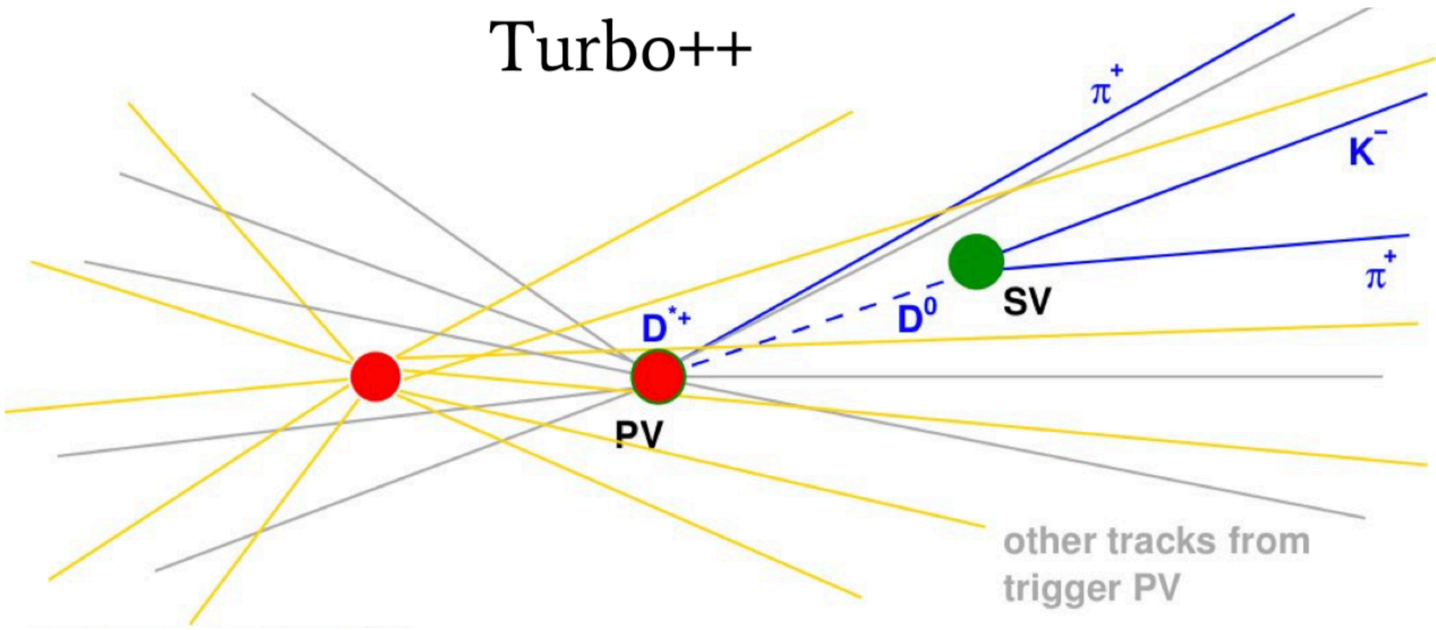
		SSE4		AVX2	
		time (s)	Speedup	time (s)	Speedup
double	scalar	233.462		228.752	
	vectorized	122.259	1.90	58.243	3.93
float	scalar	214.451		209.756	
	vectorized	55.707	3.85	26.539	7.90

Table 3.2: Performance of vectorized Rich's Ray Tracing

- Vectorization leads to around a factor 8 speed-up.

TURBO and TURBO ++





Store on disk only high level object for the decay mode of interest.

Turbo worked quite well in Run II : few analysis published after 1 week of data taking.

☞ **Towards the upgrade: Turbo++ introduced in 2016**

Turbo++ able to persist arbitrary variables on any reconstructed object

Can save HLT candidate + any reconstructed objects

Custom binary serialization and compression per event

Event size of 50 kB including minimal subset of raw data

Allow to do new things on HLT output

Run II trigger

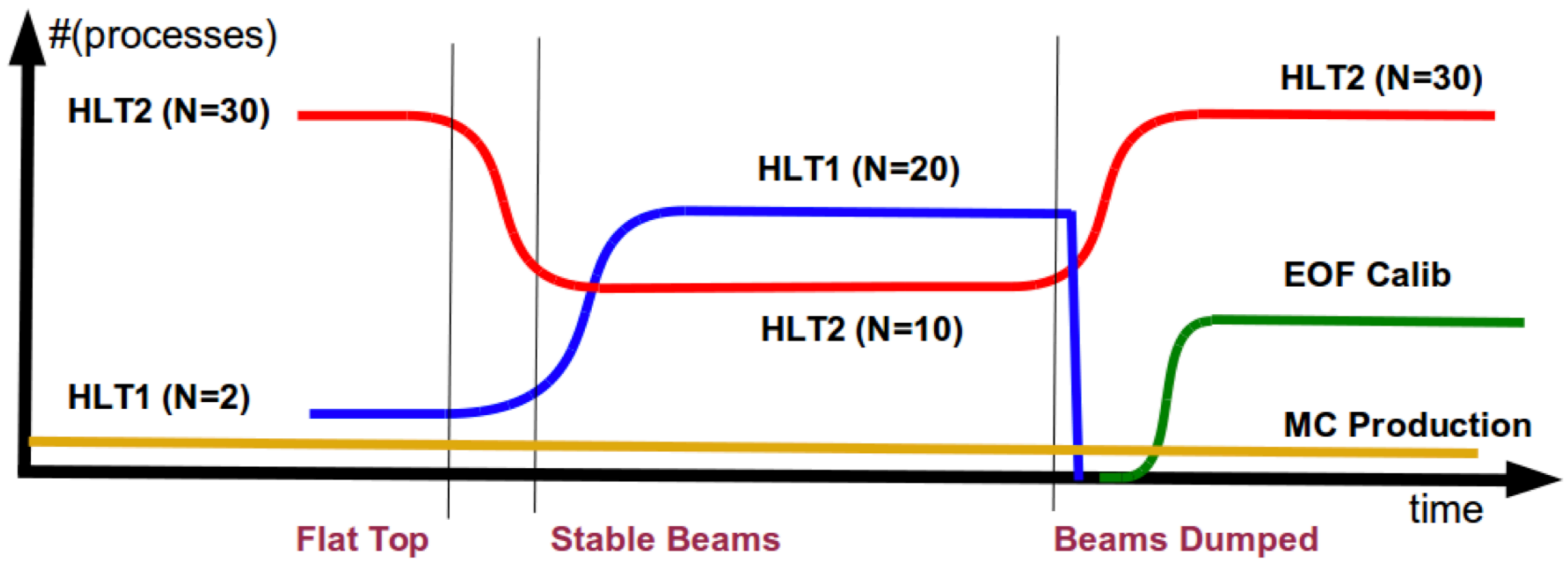
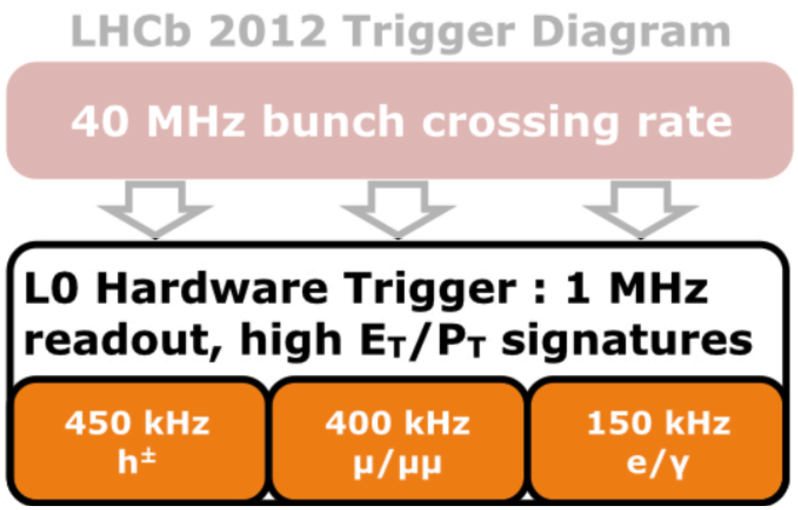


Figure 2.1: A schematic diagram showing the amount of CPU dedicated to the HLT1 and HLT2 activity during various states of the LHC collider.

- Stable beams ~50% of the time
- Buffer events to disk and process between fills

- Run II
  - Defer 100% of HLT 1 accepted events
  - More efficient use of buffers due to larger real-time reduction
  - Save 100% of events at 150 kHz instead of 20% at 1 MHz
  - Use HLT 1 output for calibration and alignment
  - 10 PiB in farm (half in 2015)

LHCb L0 trigger in Run I

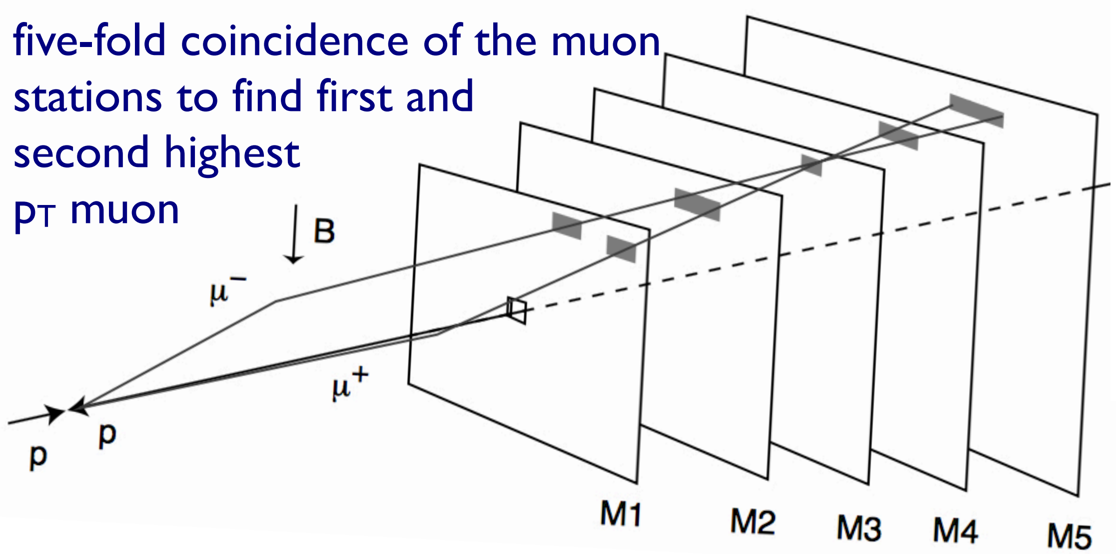


L0 Hardware trigger

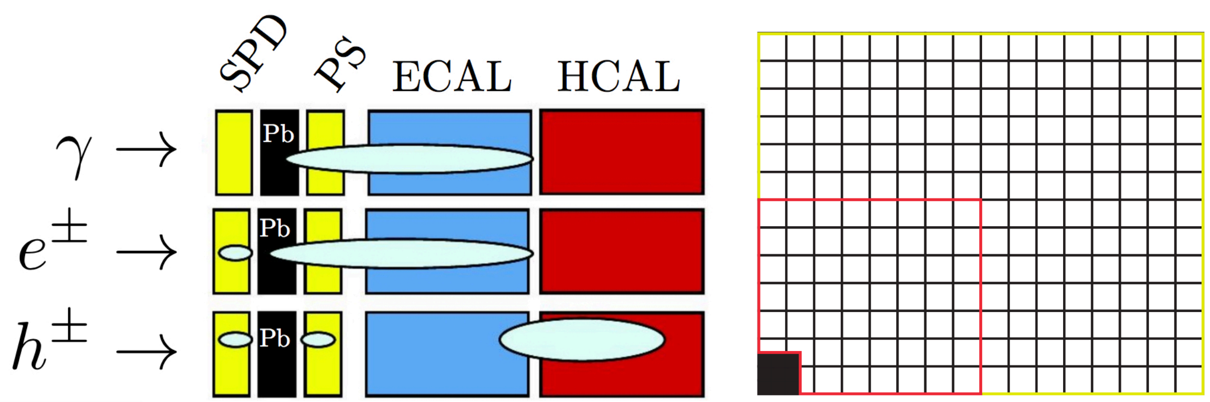
- Reduce 40 MHz input rate to 1 MHz.
- Selection performed at Hardware level using information from Muon Stations (p_T muons), hadronic & electromagnetic Calorimeters (HCAL and ECAL) + Scintillating Pad Detector (SPD) and pre-shower (PS) measure the E_T and event multiplicity.

Muon Stations

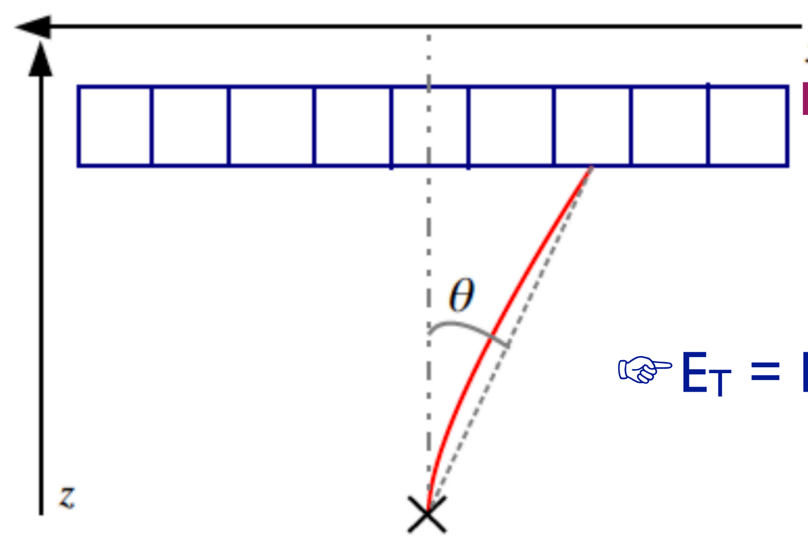
five-fold coincidence of the muon stations to find first and second highest p_T muon



Calorimeters



highest 2x2 ECAL/HCAL cluster to build candidate and perform L0 trigger



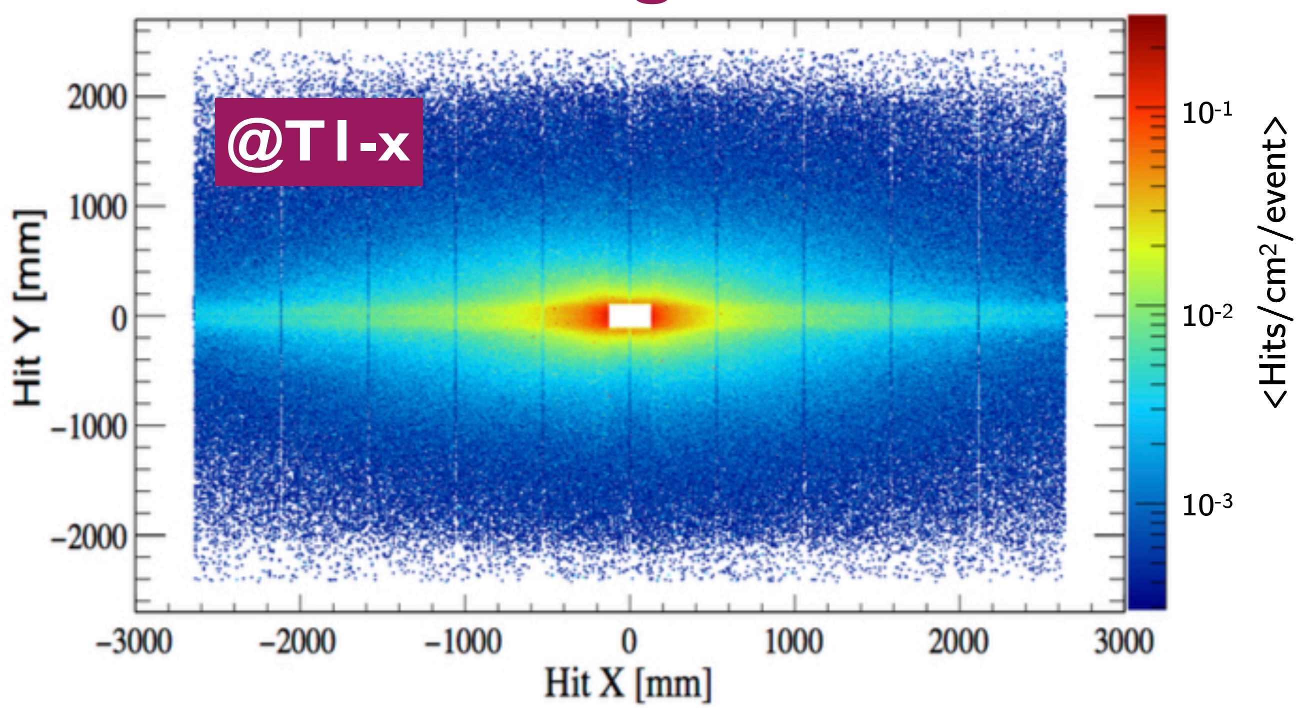
- $E_T = E \times \sin(\theta)$

Multiplicity

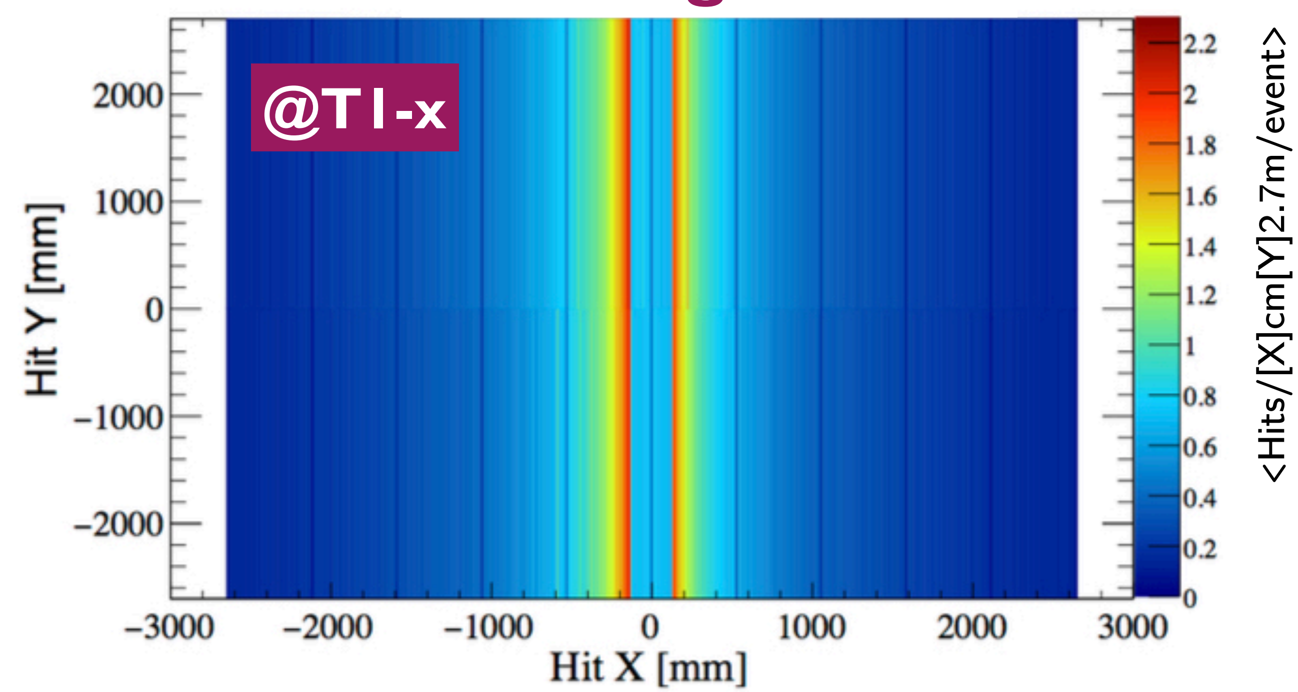
L0 Decision	2011 thresholds	2012 thresholds	SPD multiplicity
L0Muon	$p_T > 1.48$ GeV/c	$p_T > 1.76$ GeV/c	< 600
L0DiMuon	$p_T^{12} > 1.296$ GeV/c	$p_T^{12} > 1.6$ GeV/c	< 900
L0Hadron	$E_T > 3.6$ GeV	$E_T > 3.5 - 3.74$ GeV/c	< 600
L0Electron	$E_T > 2.5$ GeV	$E_T > 2.5 - 2.86$ GeV/c	< 600
L0Photon	$E_T > 2.5$ GeV	$E_T > 2.5 - 2.96$ GeV/c	< 600

Why a mighty tracker for HL-LHC and even before?

Before digitisation



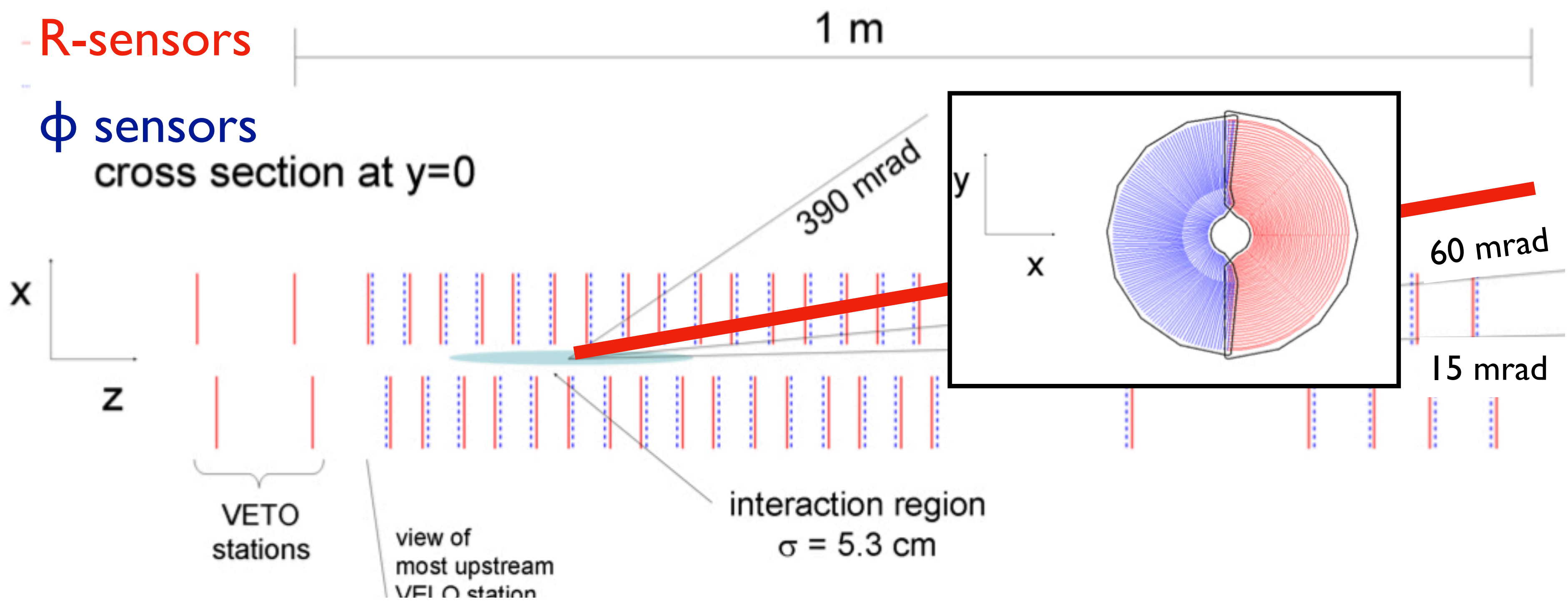
After digitisation



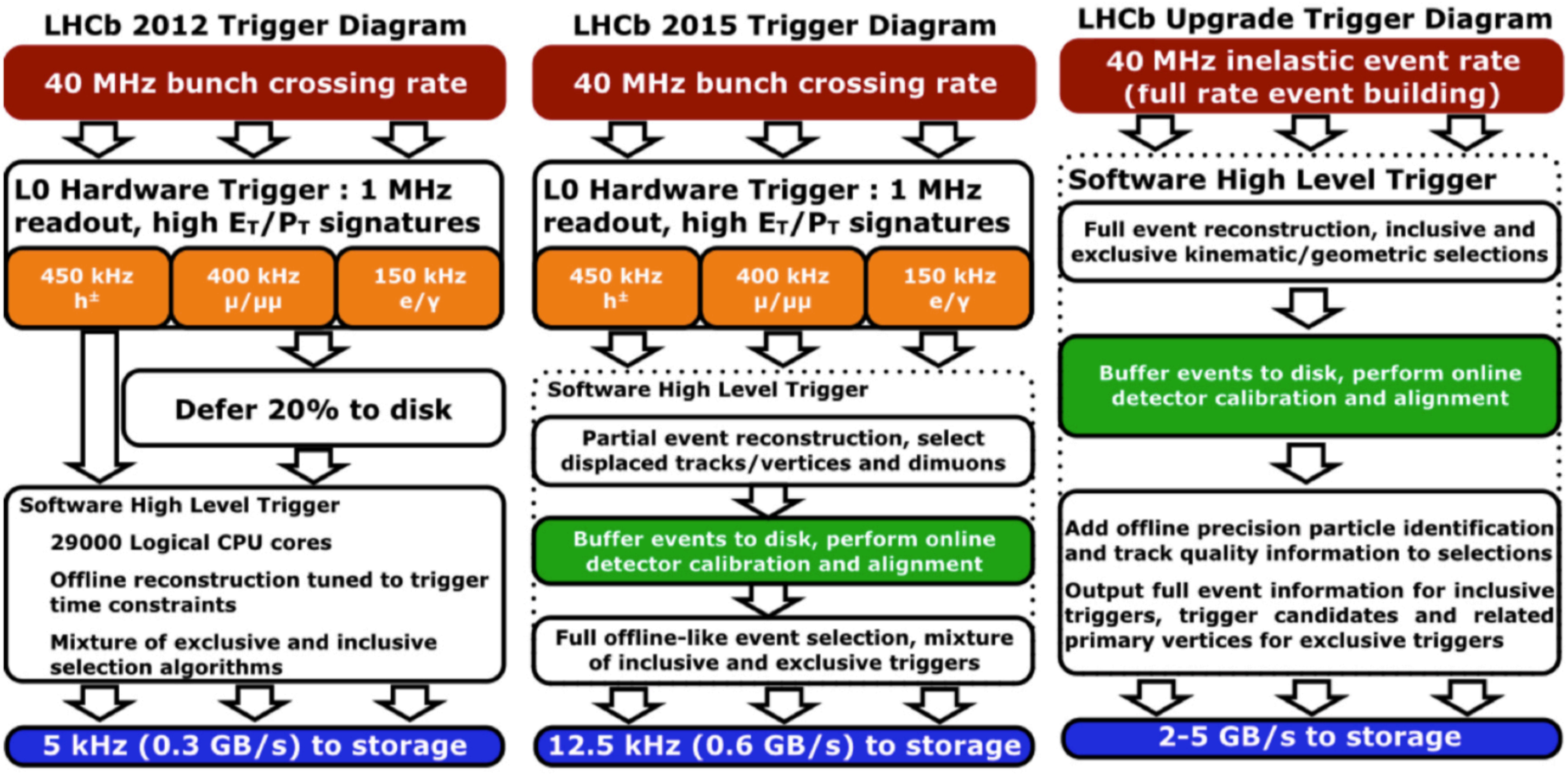
Integrated inefficiencies effects.

- Light attenuation.
- Irradiation damage.
- Clustering inefficiencies.
- Dead-regions.
- Noise and spill-over.
- ....

Current Velo



The 3 triggers comparison



maybe 10