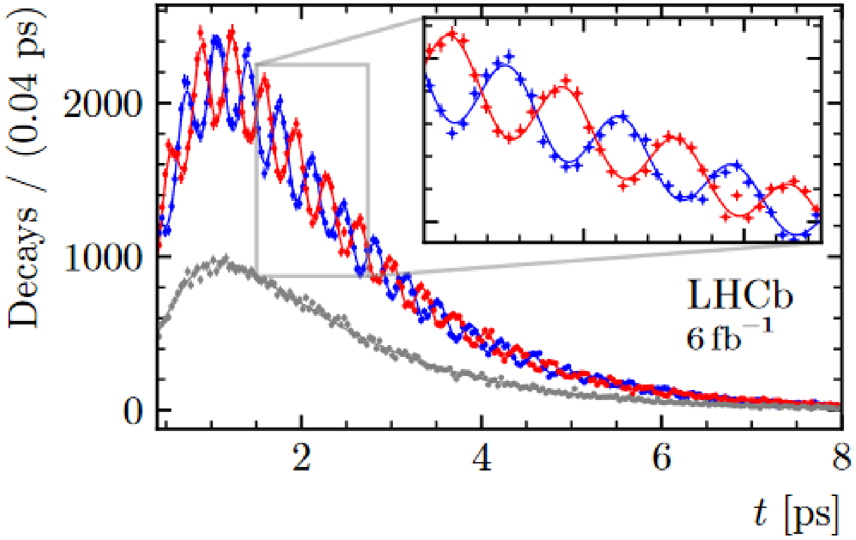
LHCB TRACKING

THE END IS THE BEGINNING

- Very often we see only the final results of complicated physics analyses…

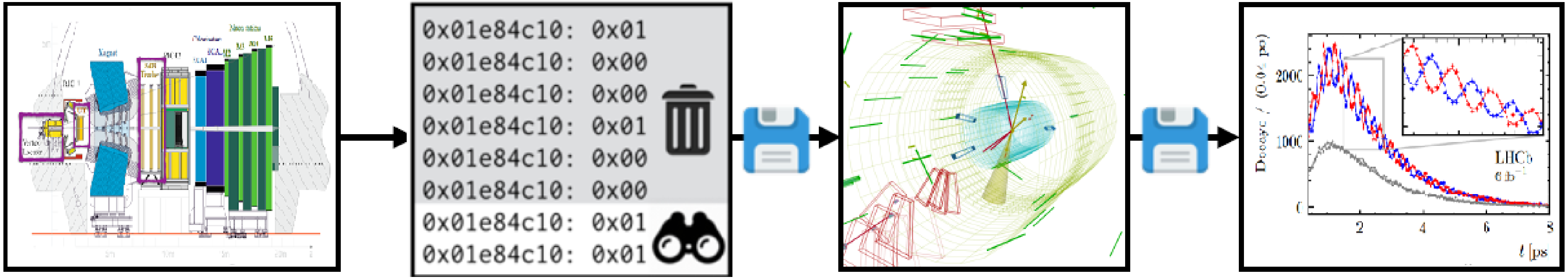


Flavour oscillations in $B_s^0 - \bar{B}_s^0$ system

- But before we can do that we need to push the RAW data through very complex processing pipelines, including trigger and tracking

THE END IS THE BEGINNING

- The typical data processing pipeline is as shown below:



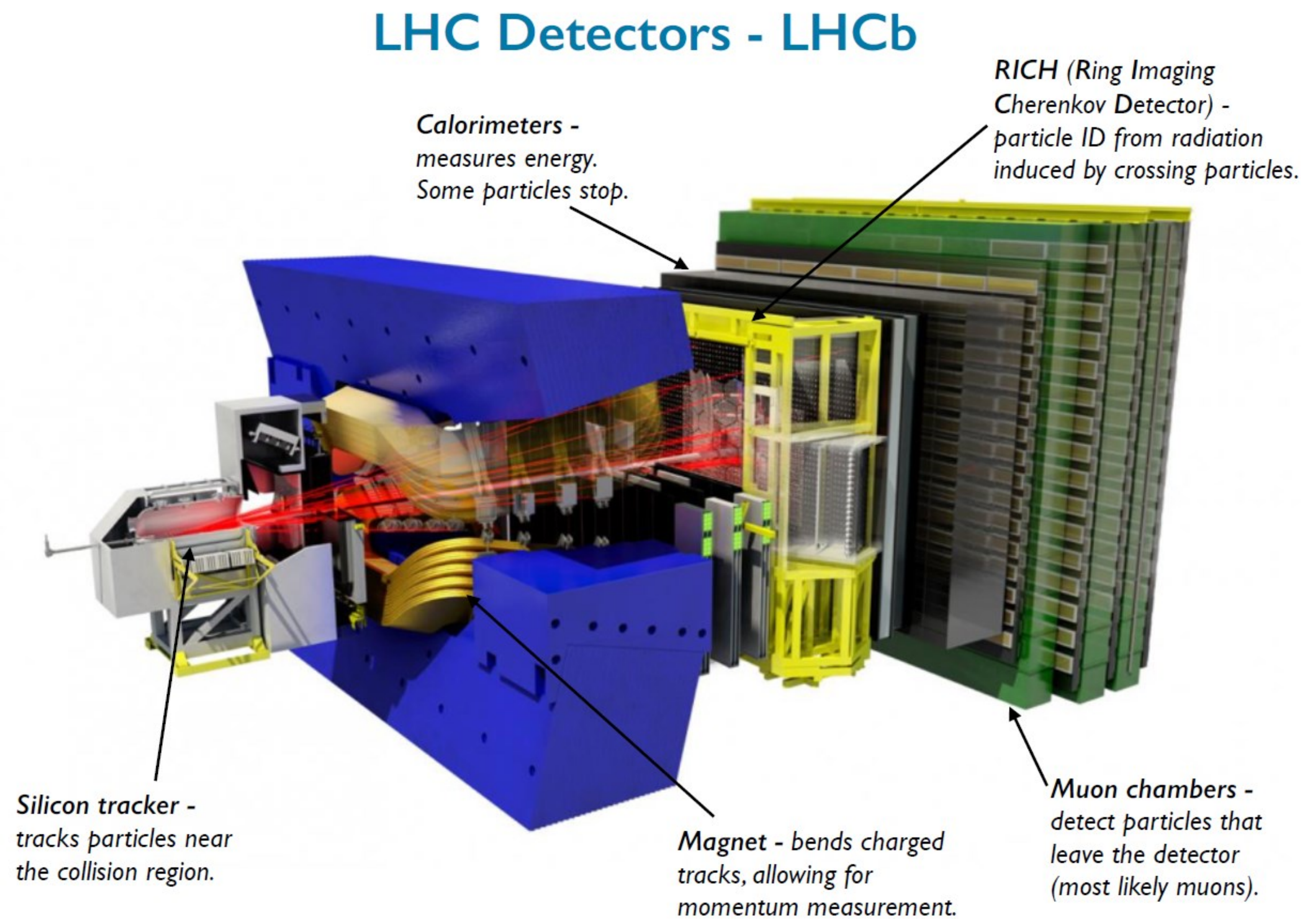
  - Detector collects data – radiation interaction with matter – loss of energy gives what we call „detector response"
  - Readout electronics interprets the detector response and convert it into (usually) voltages and may convert it to a digital signal
  - Then we combine the signals from different detectors, process with software to reconstruct particle trajectories (tracks) and vertices and…
  - Perform the physics analysis

LHC TRIVIA…

- There is approximately 100 billion protons circulating as bunches in LHC during the regular data taking runs
- Every 25 ns the bunches cross and interaction can occur (40 million times per second!)
- Typically 1 per million is useful for physics, the rest is consider the background or not interesting
- We need to be very clever to filter them out!
- Typically an LHC experiment produces a data stream of order of tens of GB/s
- Stored data are counted in tens of PB per year – these data are analysed by physicists

BE PRECISE…

- This is the LHCb detector
- It is over 20 m long and 3 stories high!!
- IT IS A BIG TOOL
- In a similar way as you may be interested in your PC screen resolution or your camera resolution we also need precise tools!



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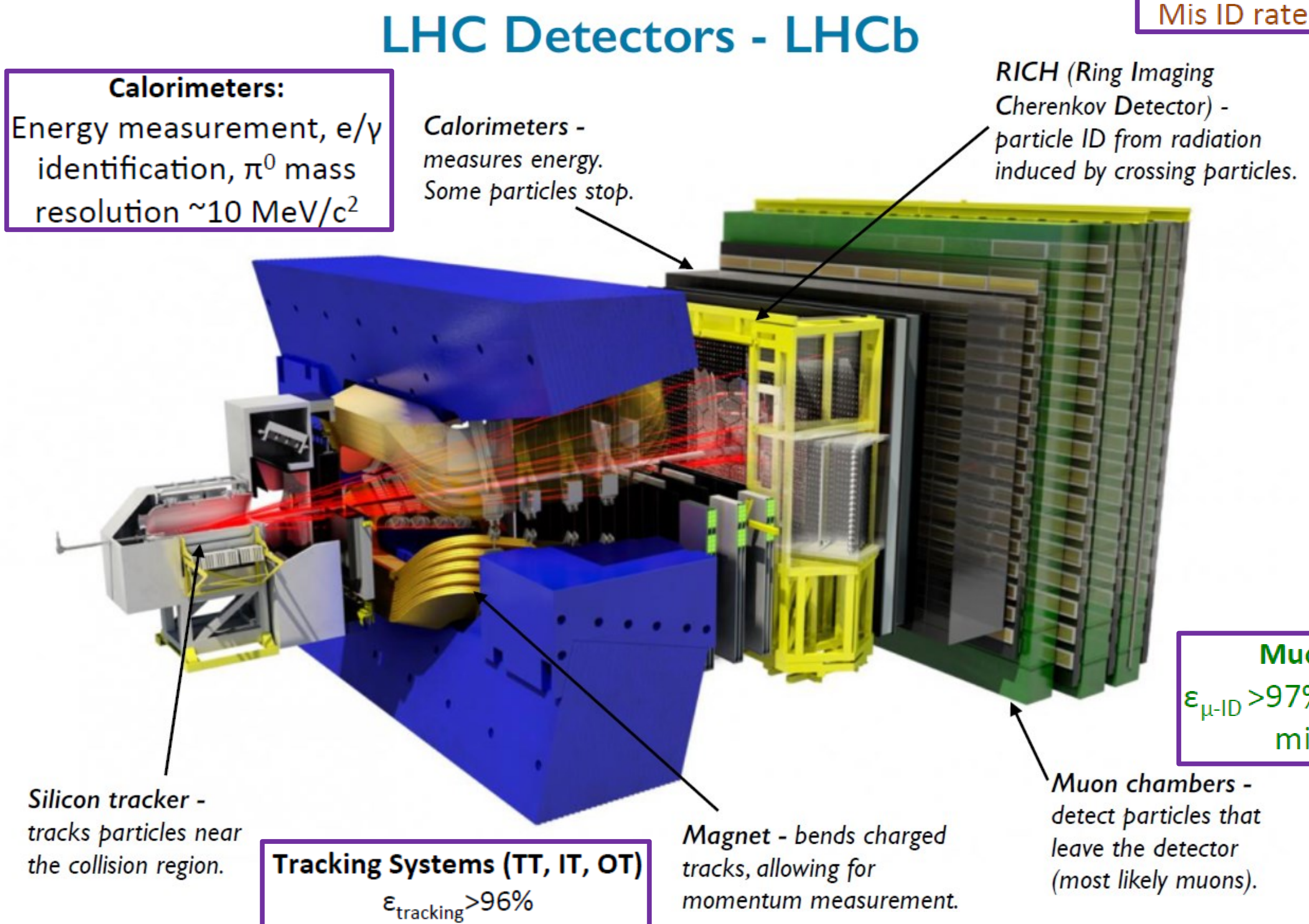
RICH:
Particle Identification
$\varepsilon_{k\text{-}ID}$ ~95%
Mis ID rate for π: ~10%

Calorimeters:
Energy measurement, e/γ identification, π^0 mass resolution ~10 MeV/c^2



Muon System:
$\varepsilon_{\mu\text{-}ID}$ >97% with <2.5% π mis-ID rate

VELO:
Distinguish primary and secondary vertices
$\sigma_{\tau\text{-decay}}$ ~45 fs for B mesons
σ_{IP} ~20µm

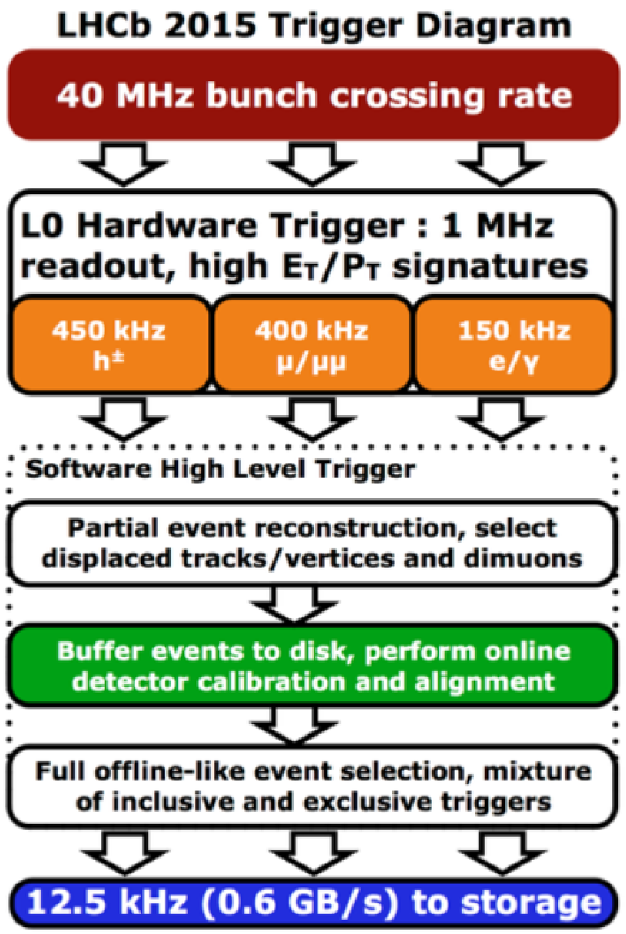
Tracking Systems (TT, IT, OT)
$\varepsilon_{tracking}$>96%
Δ_p/p~0.5 – 1.0%

LOOKING FOR A NEEDLE IN A HAY STACK

- Data rate of entire detector too high for all to be used in trigger:
  - Use a subset of information.
  - Introduce multiple levels of triggers → use more information in higher levels.

- May deliberately reduce resolution of detectors to reduce data size.
  - E.g. combine cells in tracker, or use a less precise data type.

- LHCb model is very efficient, allowing for physics analysis immediately after trigger - not always possible.



Particles cross each other every 25ns.

First trigger selects 1 in 40 events. Performed in hardware, using subset of detector data.

Software trigger selects 1 in 100 events. Since called less frequently, can use full detector information for full event reconstruction.

Combined trigger selects 1 in 40k events for physics analysis.

LHCB TRIGGER COMPRESSION

Level	Level0*	High Level Trigger*
Input rate	40 MHz	1MHz, 70GB/s
Hardware	FPGAs.	Local cluster using 20k[7] CPUs.
Output rate	1MHz	10kHz, 700MB/s[2]
Event filter factor	40x	100x
Notes	Uses subset of detector data (ECal and muons only).	Full reconstruction performed.

WHAT YOU REALLY NEED TO DO

- When we say: „reconstruction" we mean actually a lot of things on top of each other:
  - Particles are created in collisions – we need to know **where** they are produced, **what** types are produced and **follow them** to their parents
  - To make this happen we need: to reconstruct particles' **hits locally** in tracking detectors, **put the hits together** to form **tracks**, use tracks to reconstruct **vertices** and finally we need to **identify the type** of particles (PID)
- This complicated procedure is usually divided into steps:
  - Local hit reconstruction
  - Pattern recognition algorithms to assign hits to tracks
  - Fitting the trajectories to get the path of reconstructed particles inside detector
- No universal solution! Each experiment is unique and need a lot of studies. We need to tune the performance using:
  - **Efficiency of tracking**: how many tracks we can find compared to all re-constructible tracks
  - **Purity**: fraction of real tracks to all reconstructed
  - High quality MC samples are needed for this!!

VELO PATTERN RECOGNITION – SIMPLIFIED EXAMPLE (CSC)

inverted CSC
CERN School of Computing

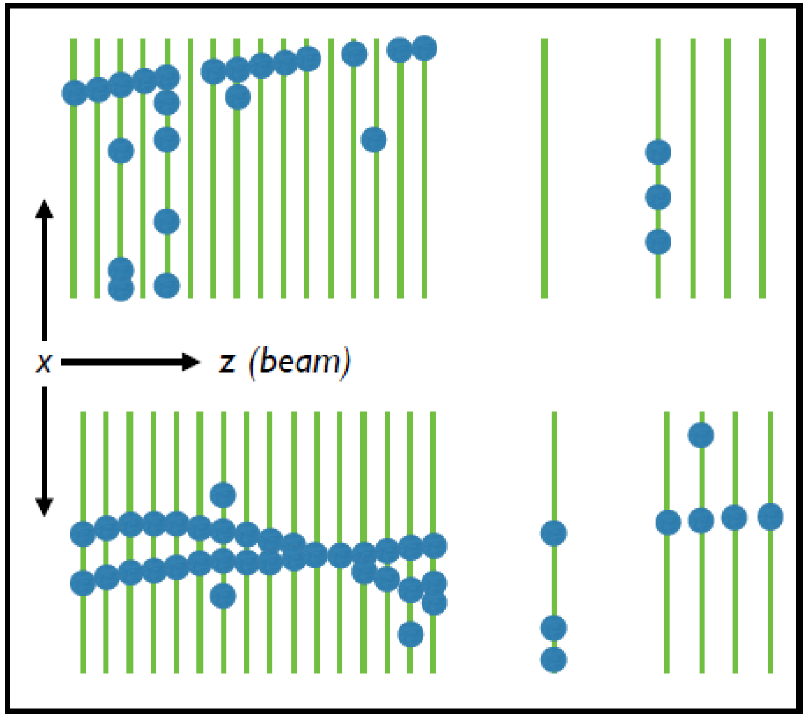
- Looking side on:
  - Particle tracks clearly visible to eye.
  - Extra hits present, typically electrical noise or secondary short tracks.

- Recall data points in the format:

  (x, y, z, ~~time~~)

  - Time resolution only accurate to which collision the particles come from (25ns, sometimes worse…).

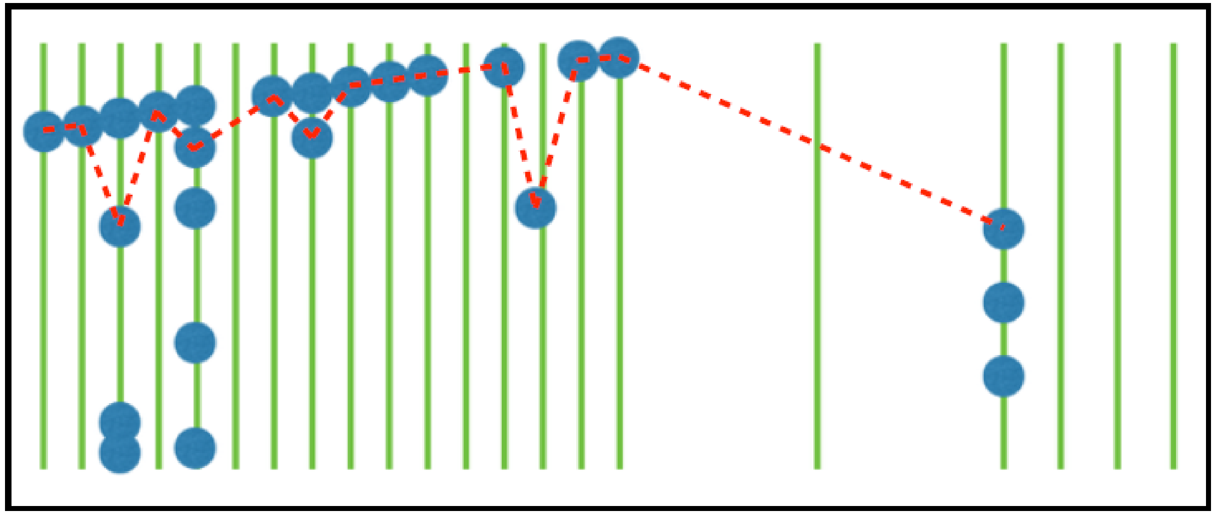
- Have to find an algorithm to track using this information and in these conditions. Many choices - consider the following (LHC) examples…



LHCb VELO data event (2d projection)

VELO PATTERN RECOGNITION – SIMPLIFIED EXAMPLE (CSC)

Name	Description	Scalability
Combinatorial	• Form every track from each possible combination of hits. • Access each track by quality (e.g. χ^2) and tag.	$n_{Tracks}!$



LHCb VELO data event (2d projection, top half)

VELO PATTERN RECOGNITION – SIMPLIFIED EXAMPLE (CSC)

inverted CSC CERN School of Computing

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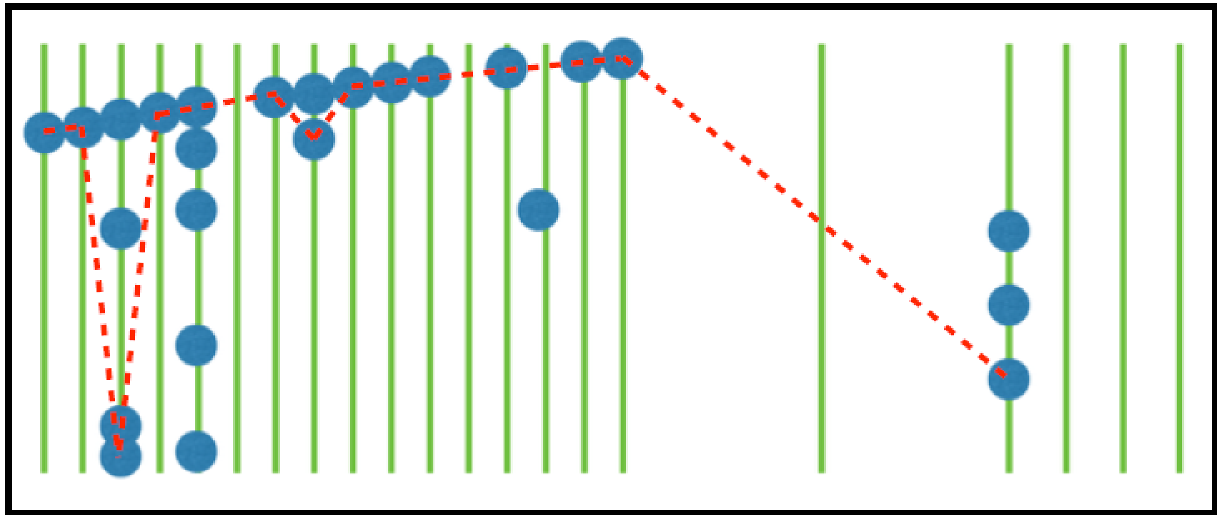

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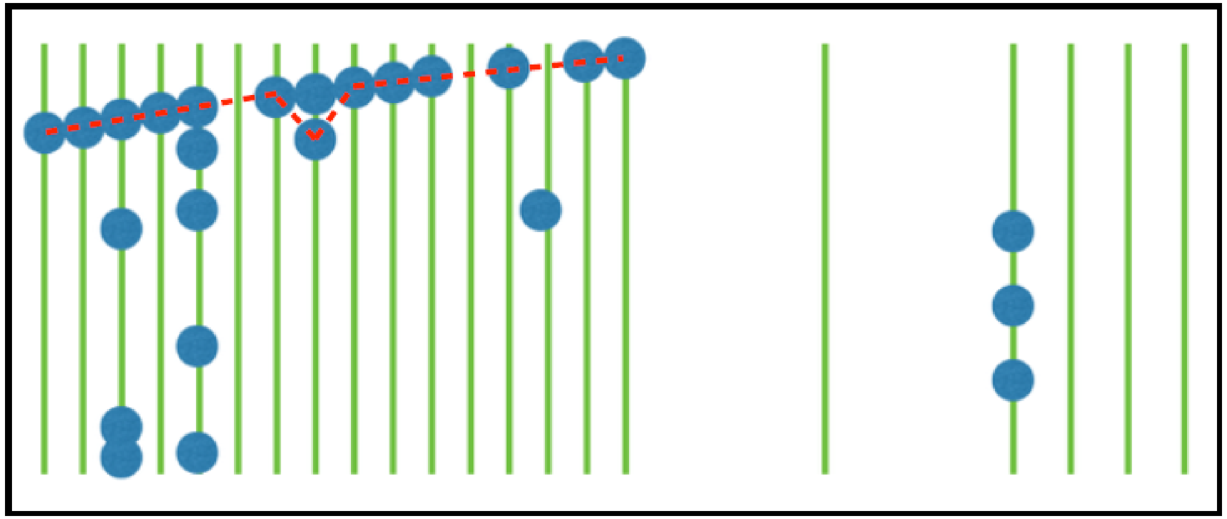

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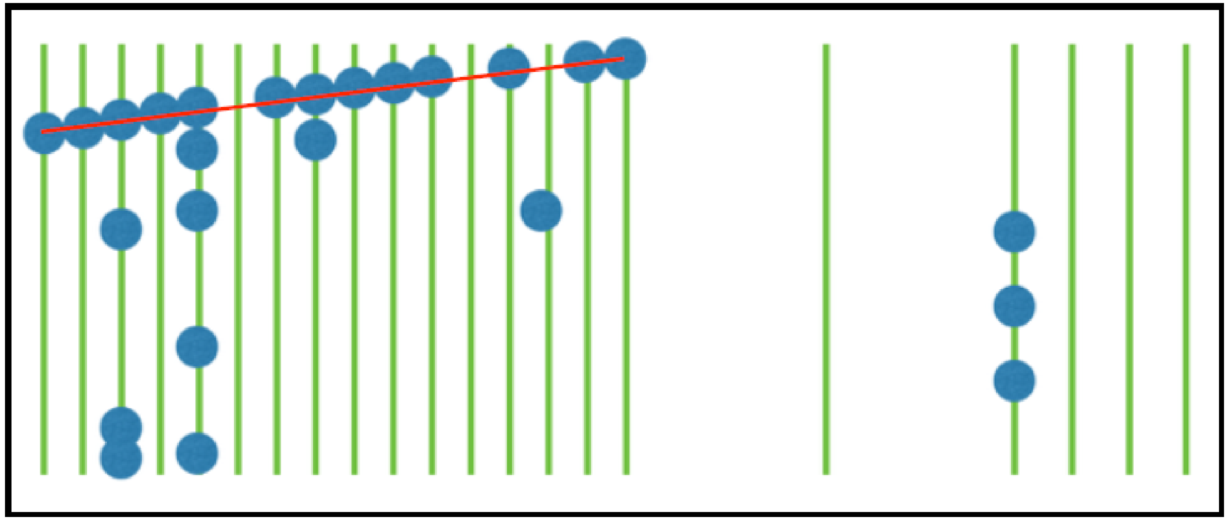
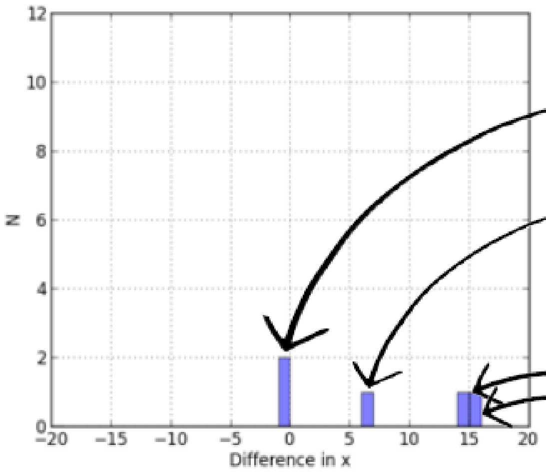
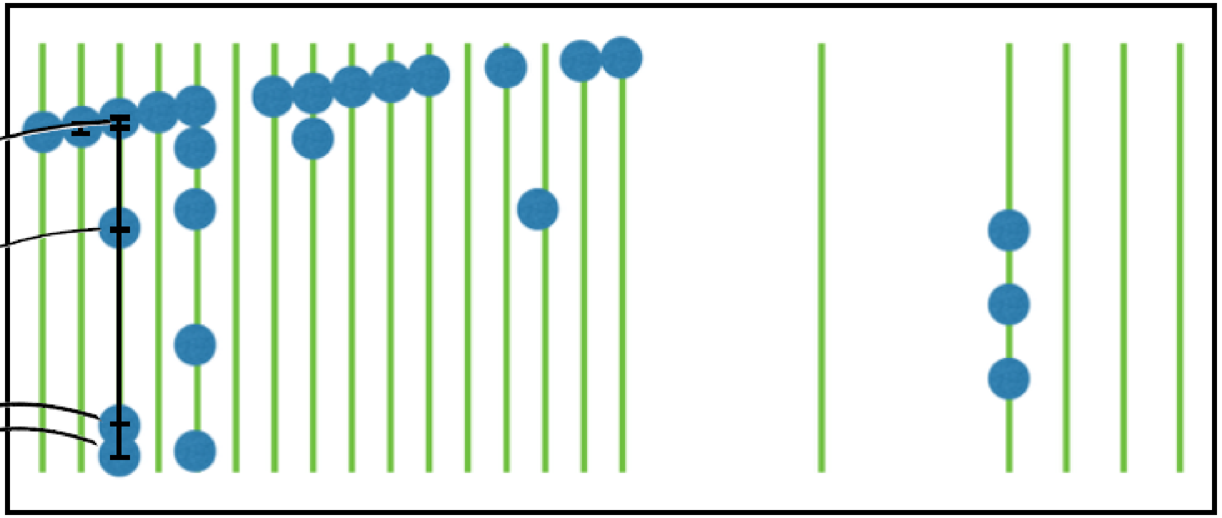


LHCb VELO data event (2d projection, top half)

VELO PATTERN RECOGNITION – SIMPLIFIED EXAMPLE (CSC)

Name	Description	Scalability
Combinatorial	• Form every track from each possible combination of hits. • Access each track by quality (e.g. χ^2) and tag.	$n_{Tracks}!$
Hough Transform	• Transform points into a system where clusters form. • If straight tracks, take the difference between consecutive hits. • Group (e.g. in a histogram) and tag peaks.	x





LHCb VELO data event (2d projection, top half)

VELO PATTERN RECOGNITION – SIMPLIFIED EXAMPLE (CSC)

inverted CSC
CERN School of Computing

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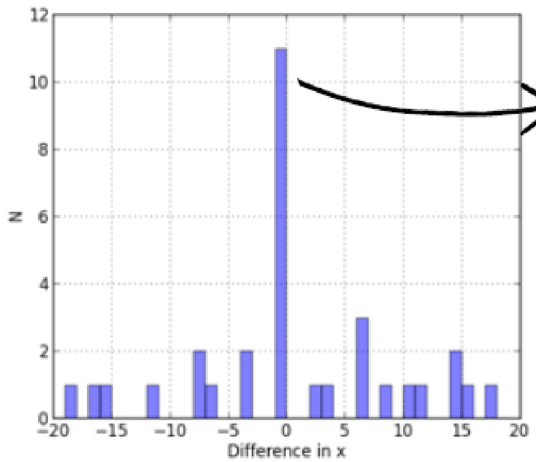

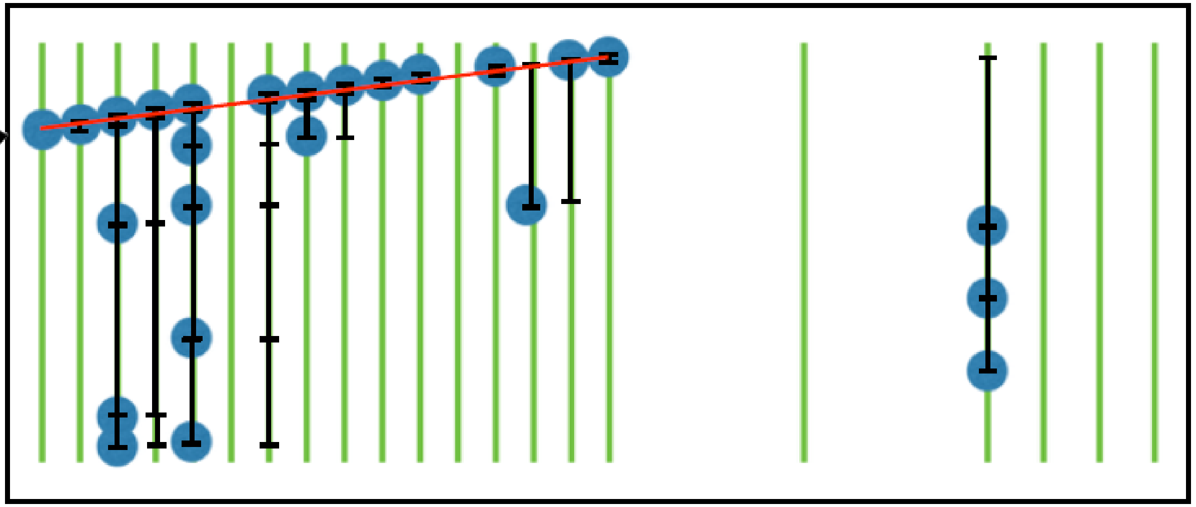

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VELO PATTERN RECOGNITION – SIMPLIFIED EXAMPLE (CSC)

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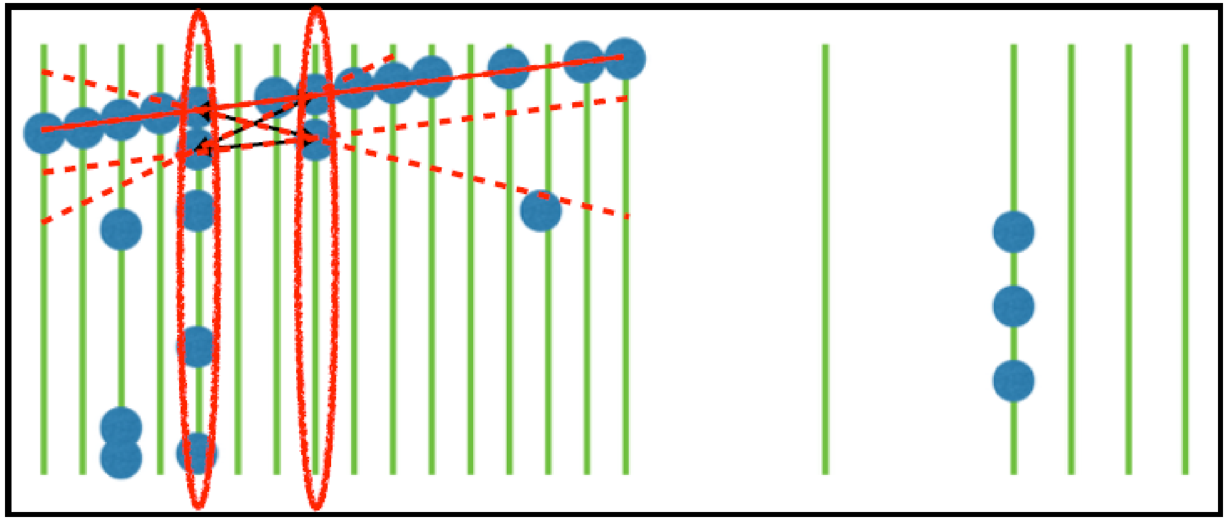
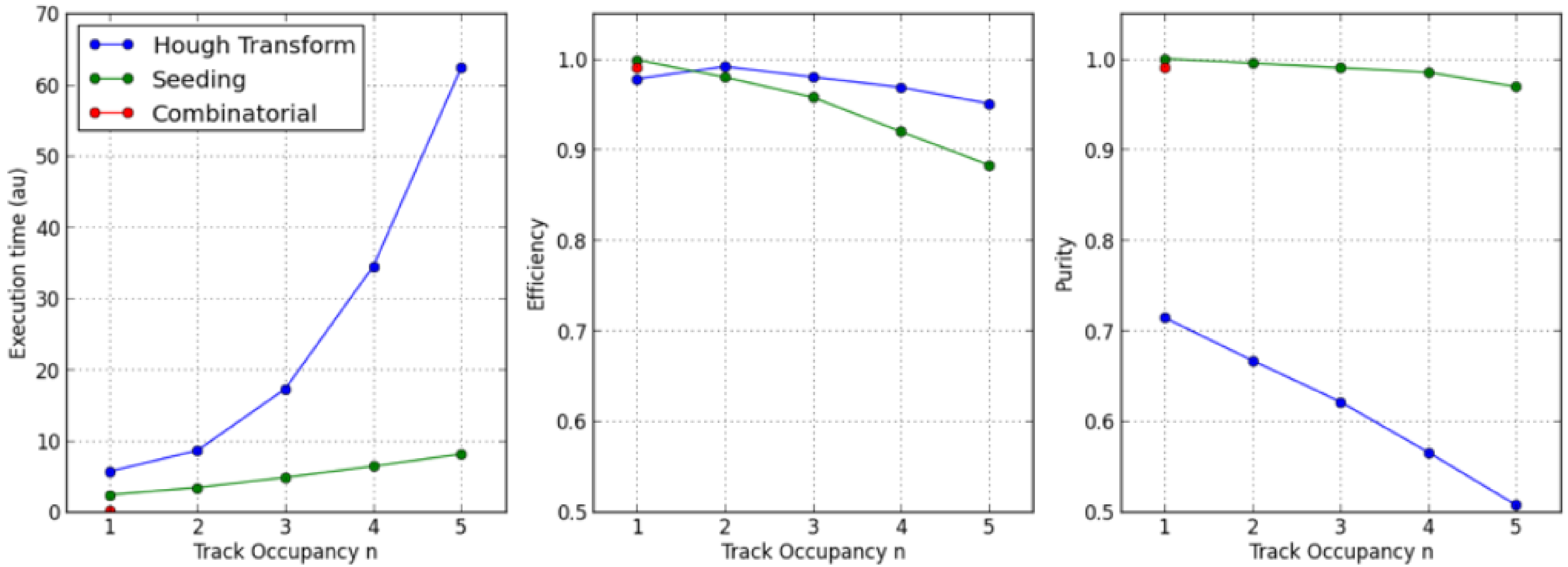
Hough Transform	• Transform points into a system where clusters form. • E.g. for straight tracks, take the difference between consecutive hits. • Group (e.g. in a histogram) and tag peaks.	x
Seeding	• Form seeds from pairs of hits on a sub set of the detector. • Extrapolate the seed and count hits intercepted. • Tag if sufficient number of hits.	nlog(n)



LHCb VELO data event (2d projection, top half)

VELO PATTERN RECOGNITION – SIMPLIFIED EXAMPLE (CSC)

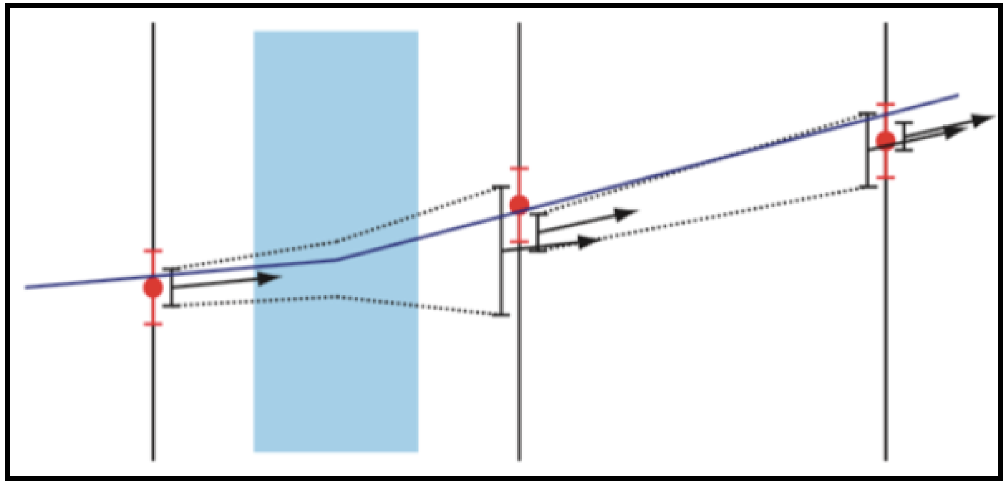
- Once we picked up an algorithm we need to understand its performance
- It is a complicated thing!



TRACK FITTING

- Tracking particles through detectors involves two step.
  - Pattern recognition: identifying which detector hits for a track.
  - Track fit: approximate the path of the particle with an equation.

- Typically use a Kalman filter. Basic steps:
  - Track is approximated as a 'zig-zag' (fewer free parameters than co-ordinates!).
  - Start with seed or estimate of track parameters (e.g. straight line fit).
  - Propagate to the next plane (approximating B field, account for scattering in material).
  - Predict position of next particle, weighting by closest hits (needs too be tuned).



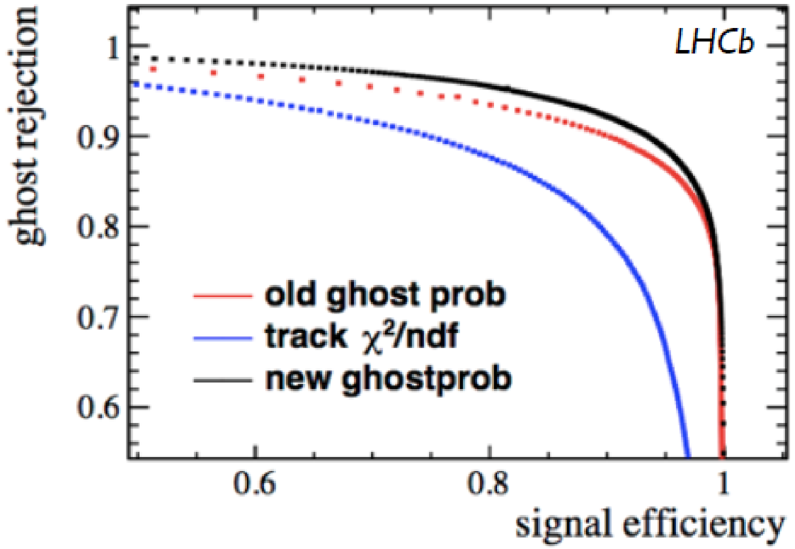
Kalman Filter Example

TRACK FITTING

- Common to tune pattern recognition to be efficient and impure → refine selection later using full particle information.

  - Can use χ^2 to find well fitting tracks.
  - Can also use/combine with other parameters:
    - Number of hits (complimentary information to χ^2).
    - Fits from different sub detectors

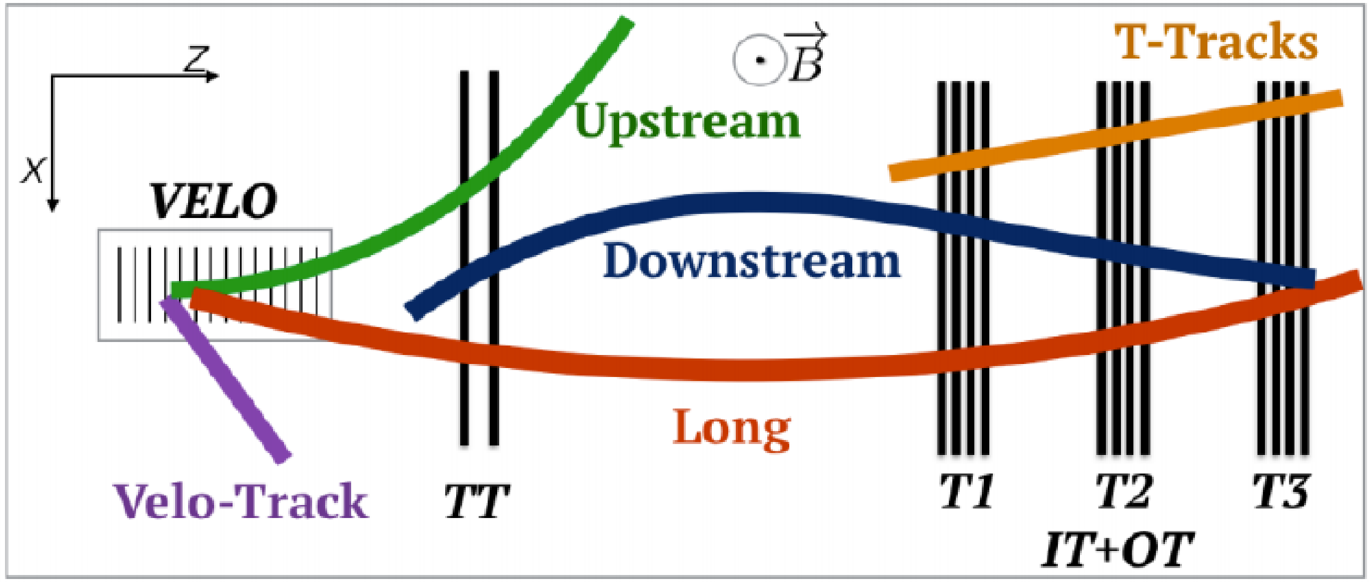
  - Typically build an MVA out of different quality parameters - LHCb uses a neutral net.



- Caution: if fake/ghost tracks are formed from parts of real tracks, they may be lost.

CALIBRATION – SUPER CRUCIAL PART

- Stop for one more minutes… We need to make sure our tracks are the high quality
  - Time alignment
  - Spatial alignment
  - PID calibration
- Then we finally have physics quality tracks!



SPACE ALIGNMENT

Track reconstruction using current alignment constants

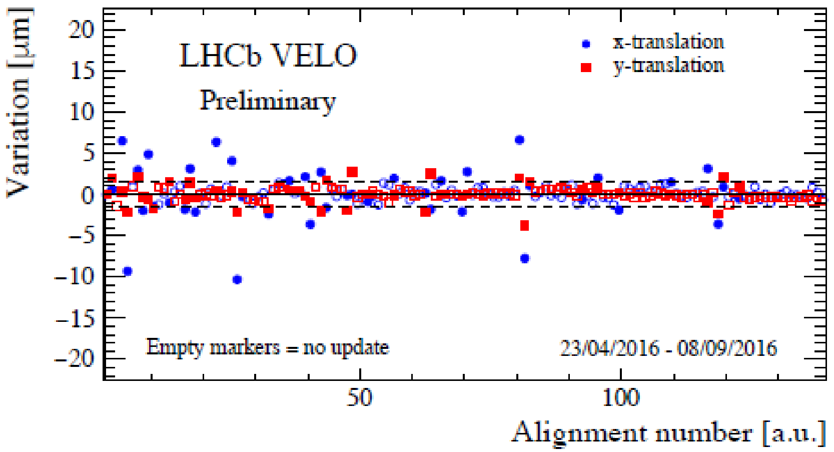
$$\frac{d\chi^2}{d\alpha} = \sum_{\text{tracks}} \frac{dr}{d\alpha}^T V^{-1} r$$

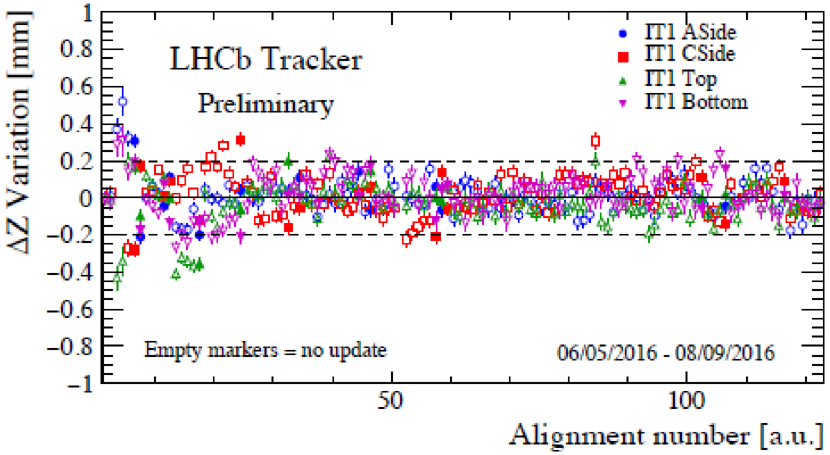
$$\frac{d^2\chi^2}{d\alpha^2} = \sum_{\text{tracks}} \frac{dr}{d\alpha}^T V^{-1} \cdot R \cdot V^{-1} \frac{dr}{d\alpha}$$

New set of alignment constants α from global χ^2 minimisation:

$$\alpha = \alpha_0 - \left(\frac{d^2\chi^2}{d\alpha^2}\right)^{-1}_{\alpha_0} \cdot \frac{d\chi^2}{d\alpha^2}_{\alpha_0}$$

α → alignment constants, r → track residuals, V → covariance matrix



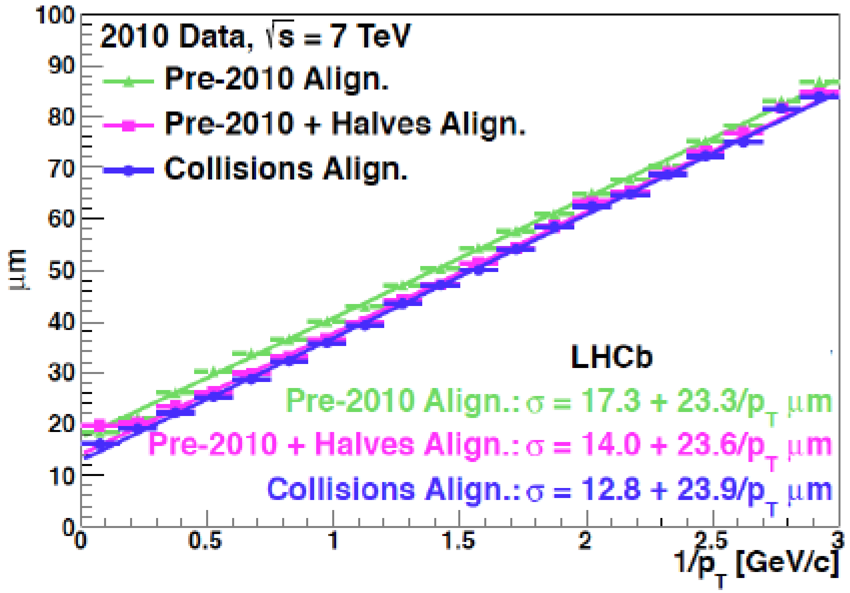


SPACE ALIGNMENT

- Impact on impact parameter… quality – critical for trigger selections

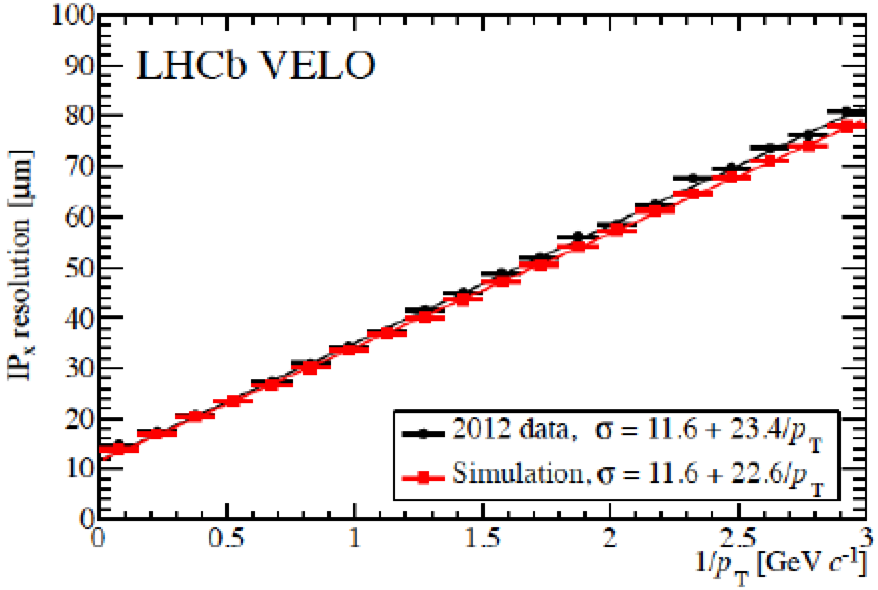
First alignment

σIP (high pT) = **14.0 µm**



Latest alignment

σIP (high pT) = **11.6 µm**

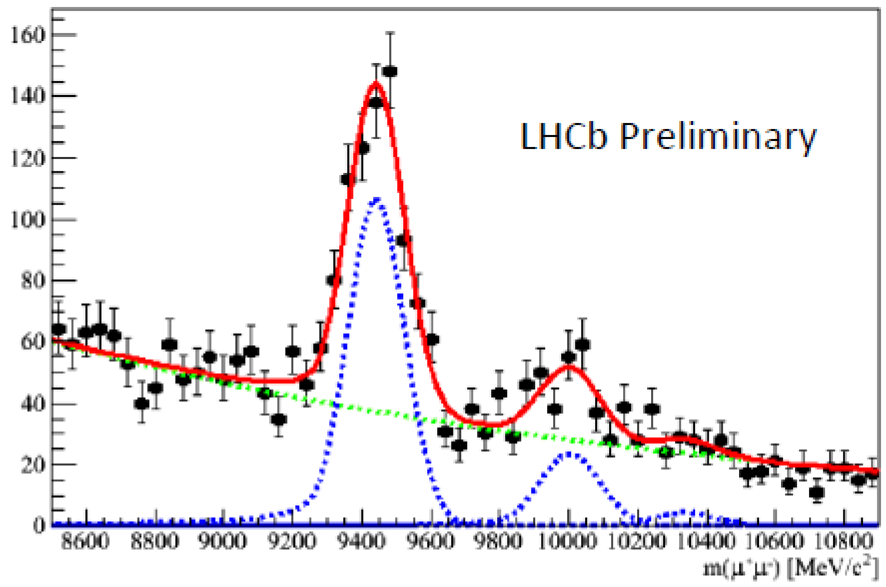


SPACE ALIGNMENT

- Mass resolution… $\Upsilon \rightarrow \mu^+\mu^-$

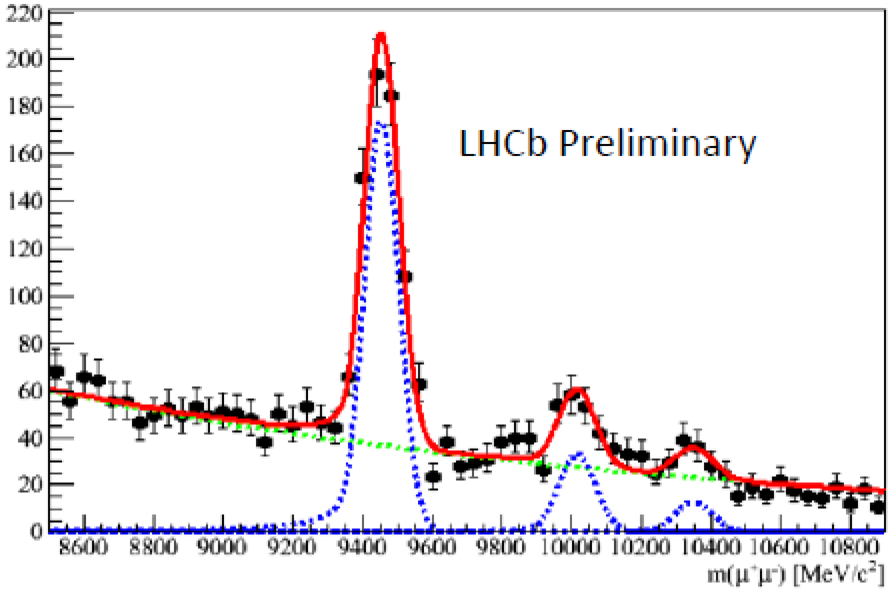
First alignment

σ_Υ = **92 MeV/c²**



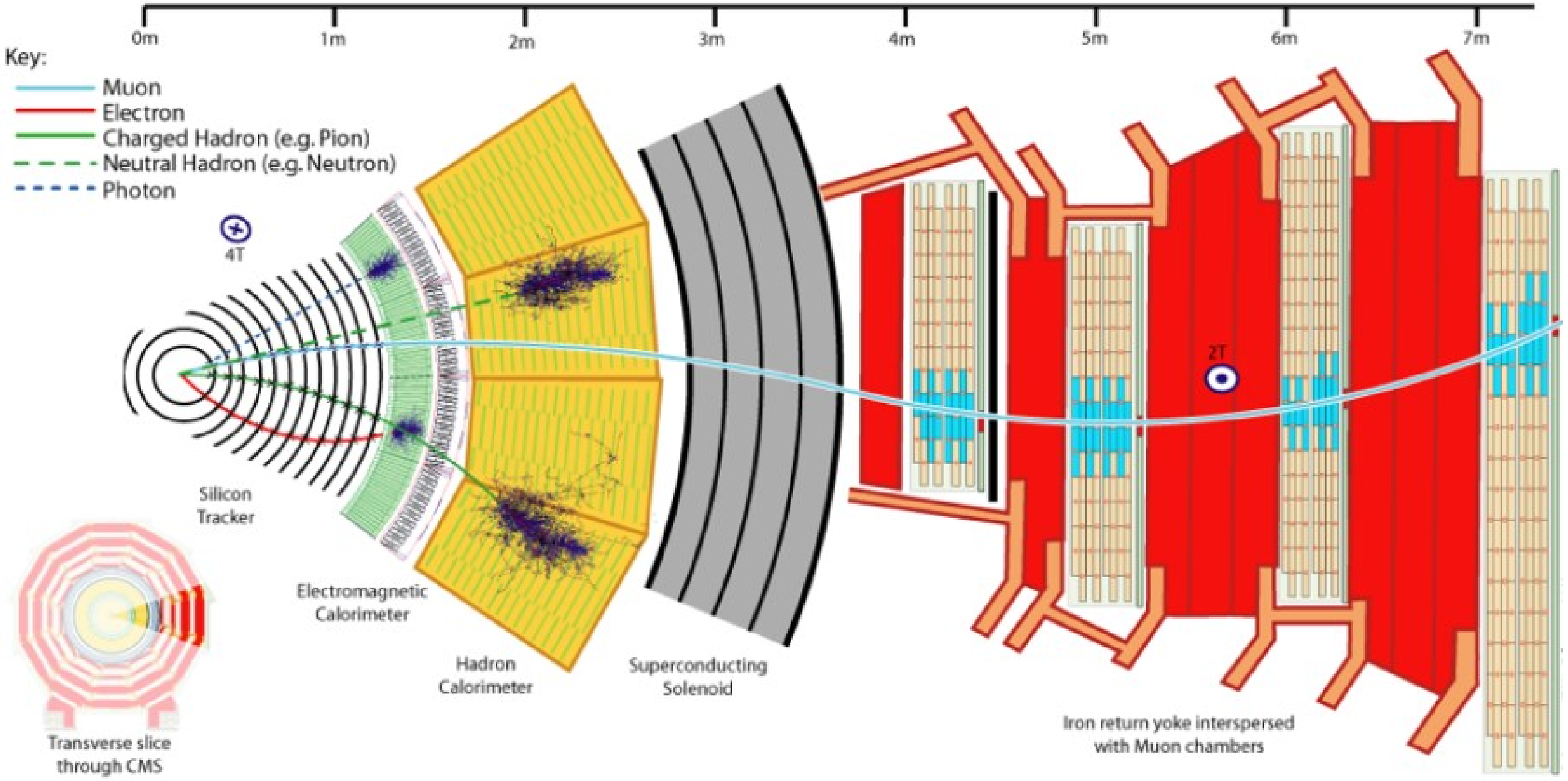
Better alignment

σ_Υ = **49 MeV/c²**



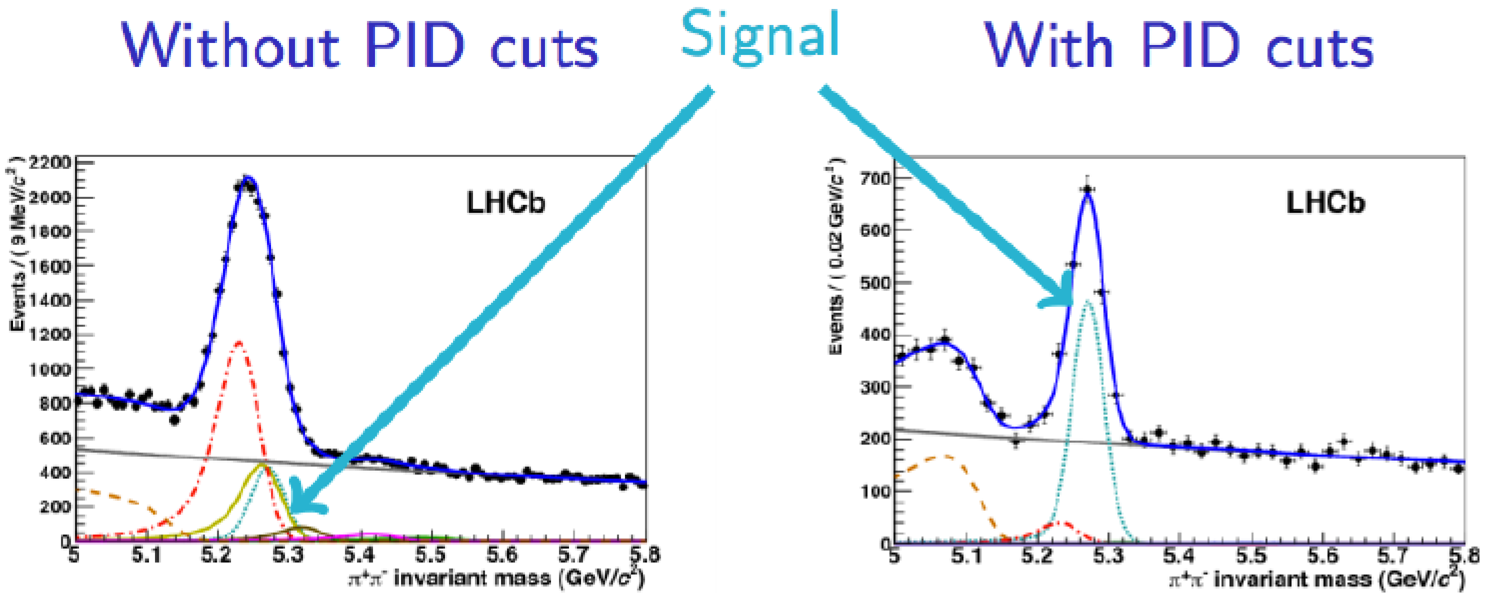
PID

- So, you say you reconstructed a track… what track…?
- PID dectectors – pure physics of radiation interaction with matter!



PID

- Exclusive selections with complicated final states



Invariant mass distribution for $B^0 \to \pi\pi$ decay ($B^0 \to \pi\pi$, $B^0 \to K\pi$, $B^0 \to$ 3-bodies, $B_s \to KK$, $B_s \to K\pi$, $\Lambda_b \to pK$, $\Lambda_b \to p\pi$)