Real Time Reconstruction developments for PbPb collisions at LHCb

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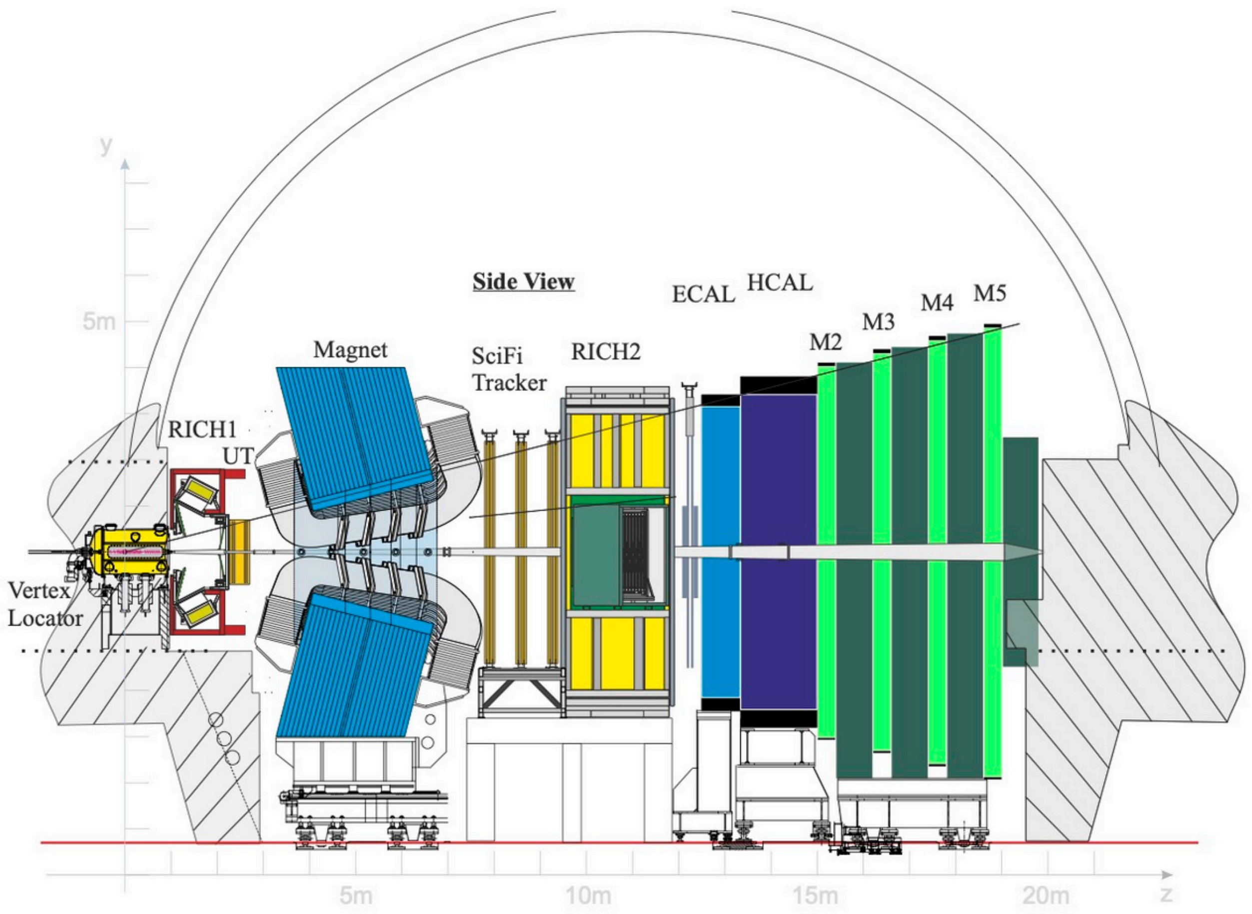
Outline

1. **Introduction**
    I. Upgrade I LHCb
    II. Heavy Ion physics at LHCb
2. **Challenges at trigger level for PbPb real time reconstruction**
3. **PbPb HLT2: reconstruction, optimisation and ghost rate studies**
4. **Velo-UT-Muon (VUM) tracking for muon reconstruction in PbPb**

LHCb Upgrade I detector

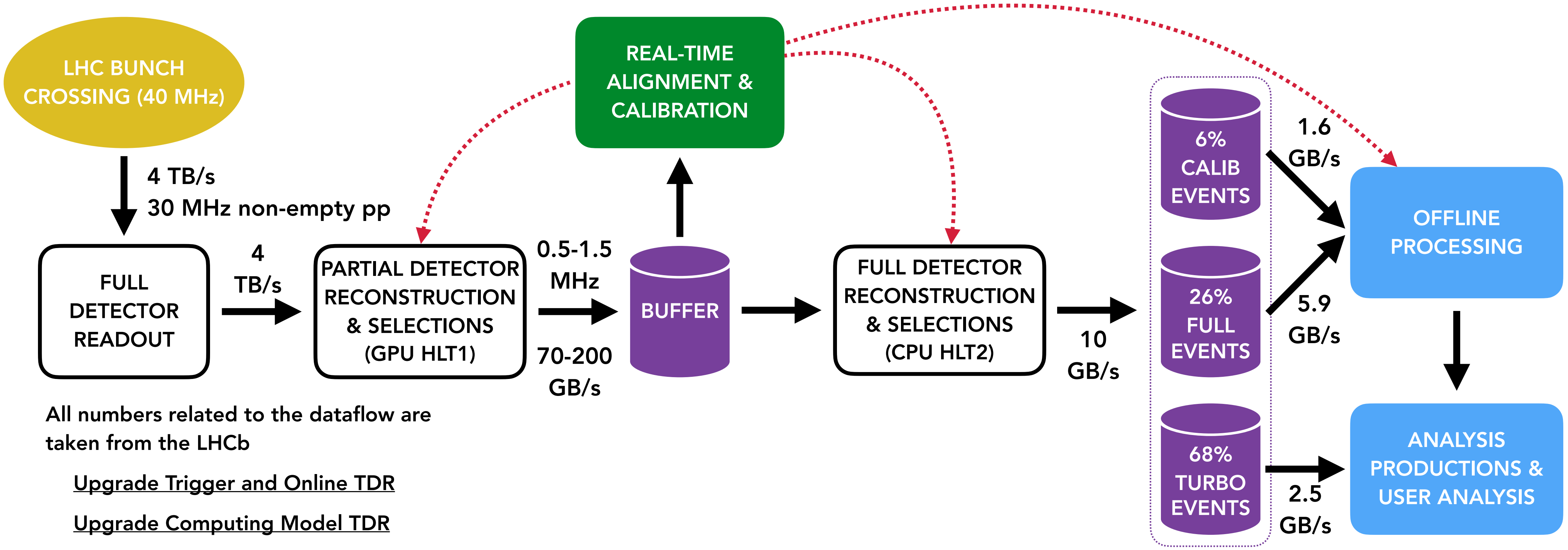
- General-purpose single-arm forward spectrometer
- Pseudorapidity coverage $2 < \eta < 5$
- Optimised for b and c physics. Now it is a general purpose detector
- Three tracking subdetectors:
  - VErtex LOcator (VELO) located around the beamspot
  - Upstream Tracker (UT) located before the magnet
  - 3 Scintillating Fibre tracking stations (SciFi) located after the magnet
- Also includes RICH, ECAL, HCAL and muon stations for PID
- New fully software based trigger
- New SMOG2 system for fixed target configuration

LHCB-TDR-15



LHCb Real Time Analysis (RTA) data flow for Run3

LHCb-FIGURE-2020-016



All numbers related to the dataflow are taken from the LHCb

Upgrade Trigger and Online TDR

Upgrade Computing Model TDR

Strategy based on **trigger lines**

HLT1
(Partial track reconstruction)

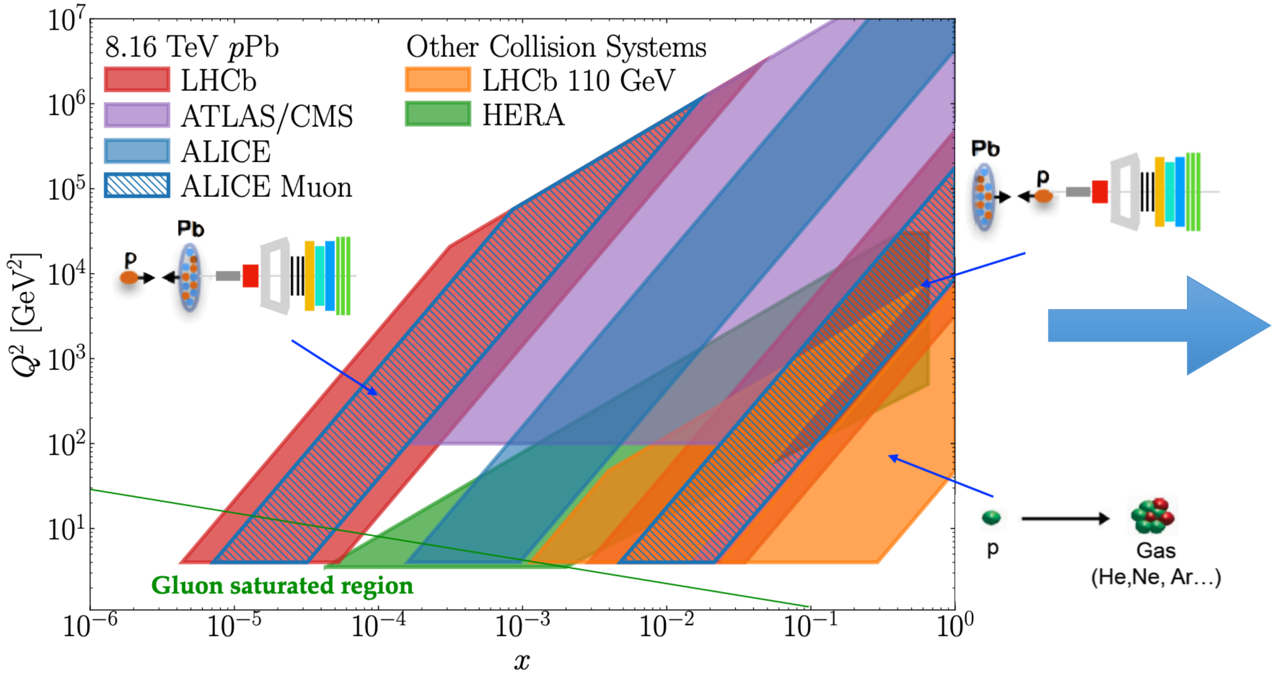
Lines for track quality conditions

HLT2
(Full track reconstruction and PID)

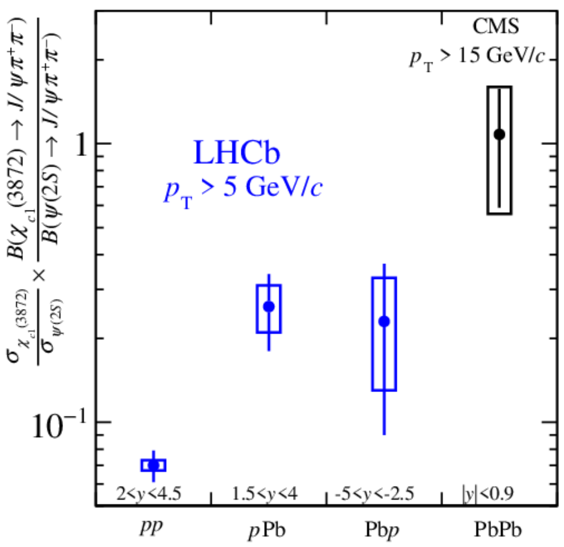
Lines for triggering specific decays

Motivation: Heavy ion physics at LHCb

Phys.: Conf. Ser. **1271** 012008



Phys. Rev. Lett. 132 (2024) 242301



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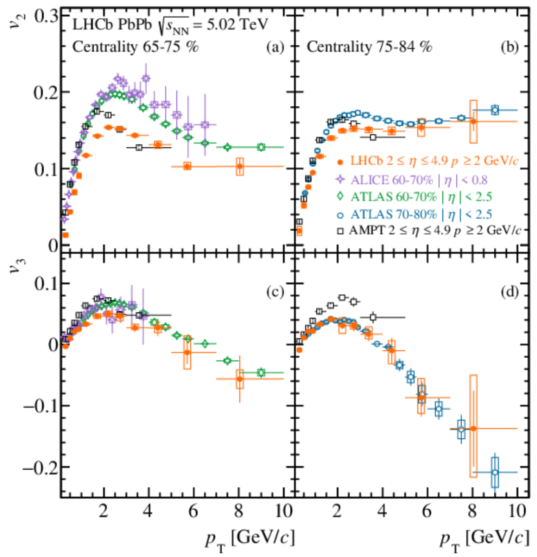

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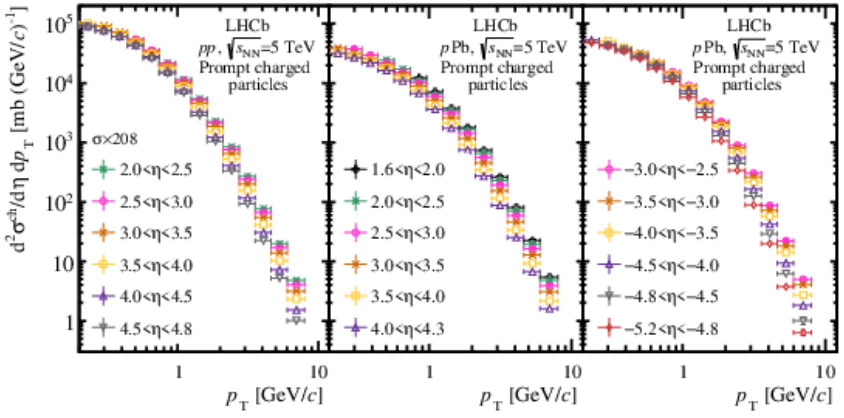
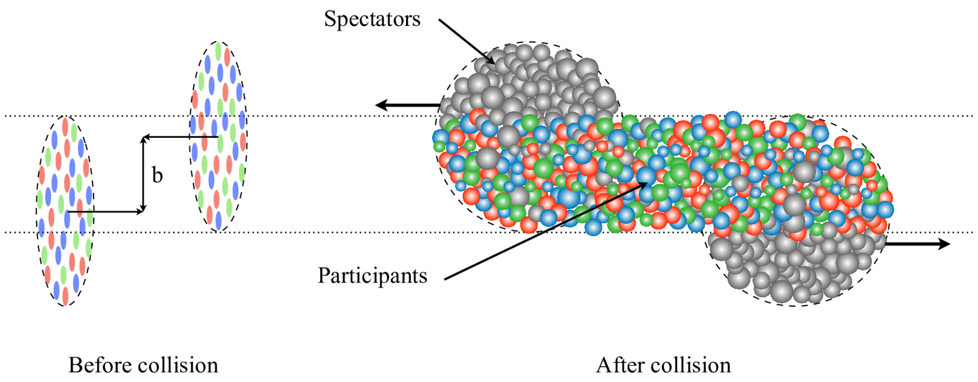


Really good por pA collisions, but also can be for AA (PbPb for this 2024 data-taken)

The difference with respect to pp collisions → Centrality



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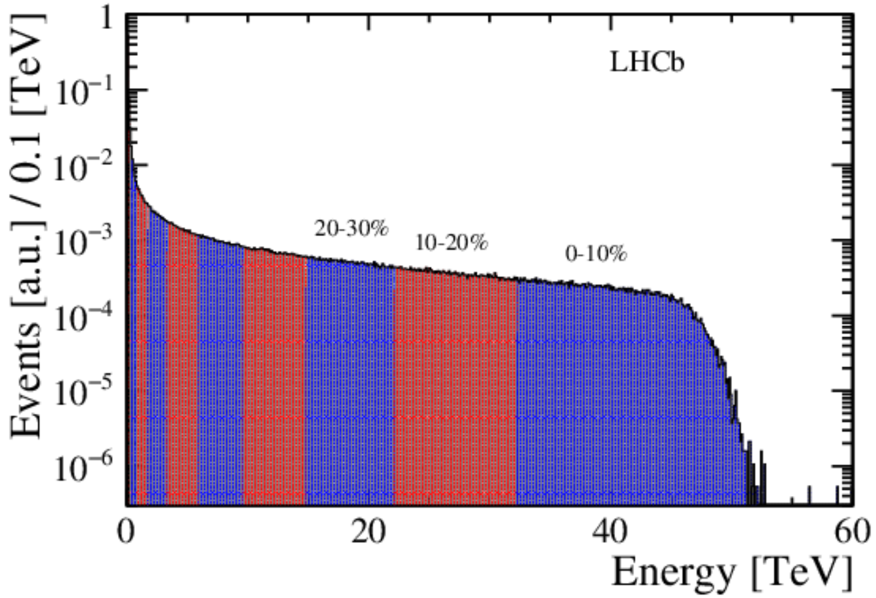


UPC Peripheral Central

Centrality %	E [GeV]	N_{part}	$\sigma_{N_{part}}$	N_{coll}	$\sigma_{N_{coll}}$	b	σ_b
100-90	0-310	2.9	1.2	1.8	1.2	15.4	1.0
90-80	310-800	7.0	2.9	5.8	3.1	14.6	0.9
80-70	800-1750	15.9	4.8	16.4	7.0	13.6	0.7
70-60	1750-3360	31.3	7.1	41.3	14.7	12.6	0.6
60-50	3360-5900	54.7	10.0	92.6	27.7	11.6	0.5
50-40	5900-9630	87.5	13.3	187.5	46.7	10.5	0.5
40-30	9630-14860	131.2	16.9	345.5	71.6	9.2	0.5
30-20	14860-22150	188.0	21.5	593.9	105.2	7.8	0.6
20-10	22150-32280	261.8	27.1	972.5	151.9	6.0	0.7
10-0	322980-∞	357.2	32.2	1570.3	236.8	3.3	1.2

- Low centrality events have more chances to create the **quark gluon plasma (QGP)**
- The number of nucleon participants increases while going down in centrality.
- That leads to a huge number of particles that produce a huge number of hits in the detectors

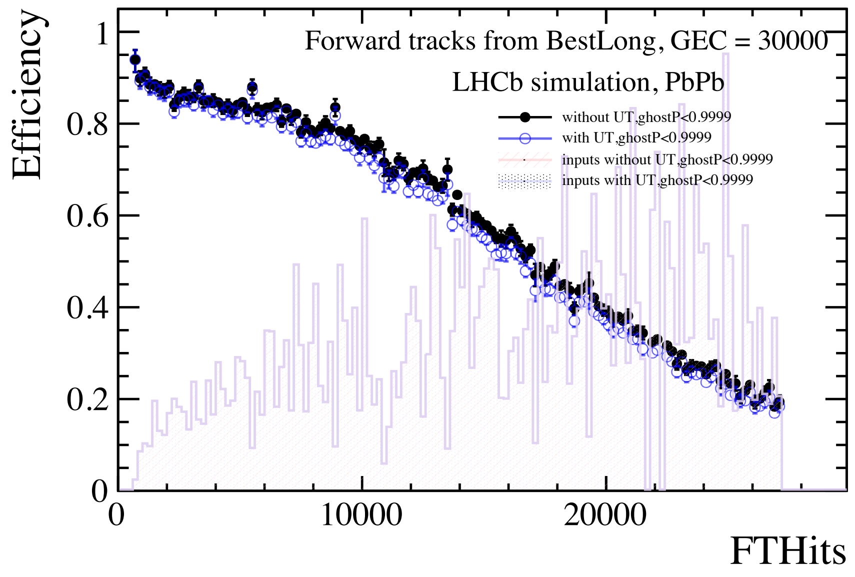
The main challenges: Reaching the 3 centrality ranges and dealing with the high detector occupancy

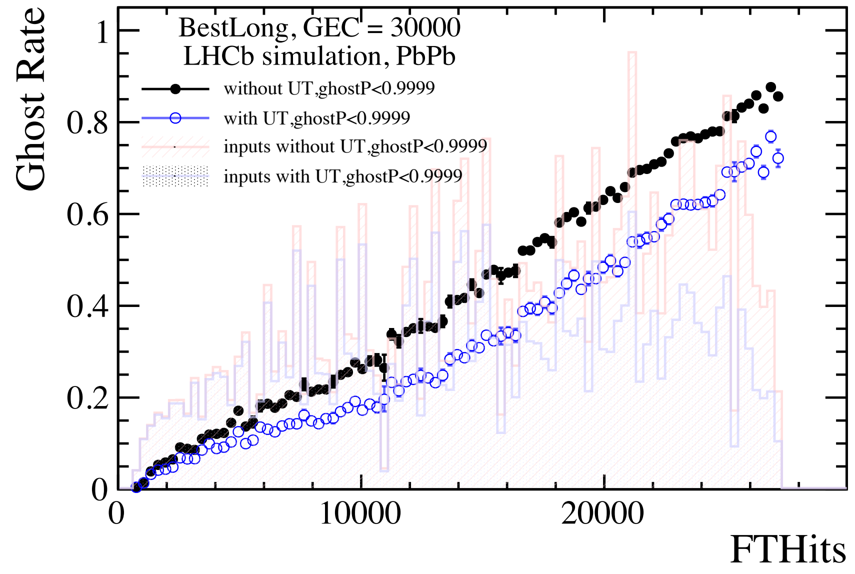
What are the challenges at software level compare to pp?

✤ Tracking efficiency and ghost rate

- ✳ The number of hits in the tracker detectors increases going down in centrality
- ✳ The tracking algorithms struggles to compute all possible combinations (**low efficiency**)
- ✳ Moreover, due to the huge number of hits, most of the hit patterns correspond to fake tracks (**high ghost rate**)
- ✳ Security global event cut (GEC) in 30000 SciFi-Hits (FTHits)

$$\varepsilon = \frac{N^{\text{tracks}}_{\text{reconstructed}}}{N^{\text{tracks}}_{\text{reconstructible}}} \qquad \text{Ghost Rate} = \frac{N^{\text{tracks}}_{\text{fake}}}{N^{\text{tracks}}_{\text{reconstructed}}}$$





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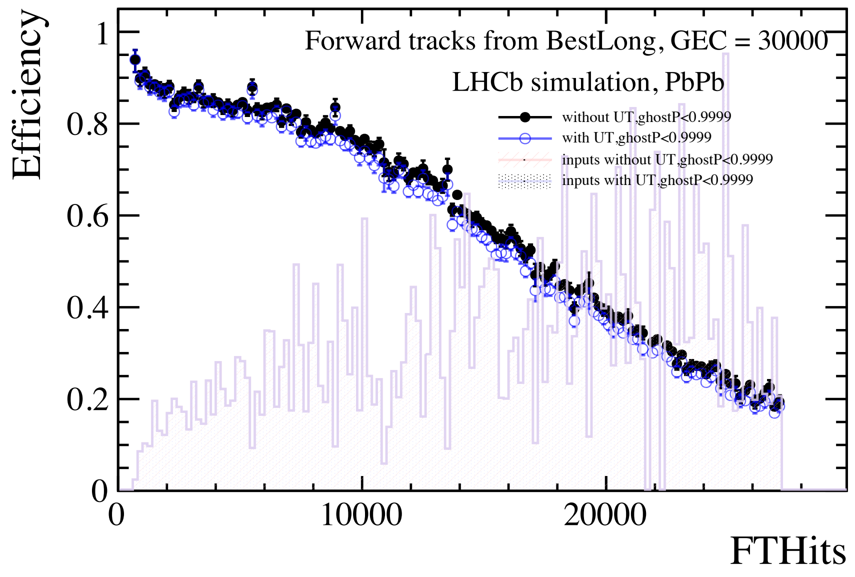

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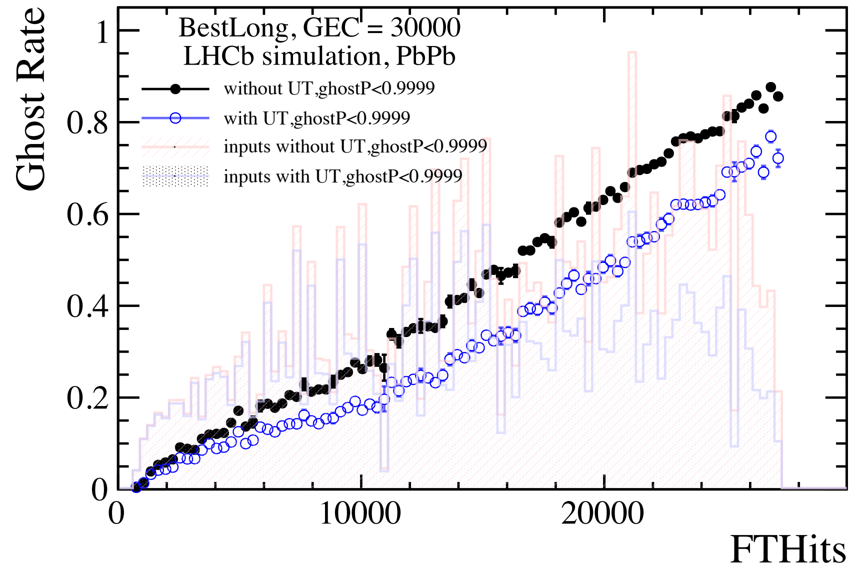


✤ Computational limitation and throughput

- ✳ The number of possible tracks limits the PID algorithms → the throughput becomes huge
- ✳ That limits the data-taken → **minimum bias strategy is chosen**

What can be improved for next 2024 PbPb data-taken?

Both HLT1 and HLT2 strategies are being developed simultaneously

In Santiago group, two tasks are proposed at HLT2 level

- Ghost Rate studies in expected 2024 PbPb collisions
  - ✓ Checking the ghost rate and efficiency for the new 2024 HLT2 PbPb strategy
  - ✓ Computing Neuronal-Network based ghost probability computing for PbPb samples
- VELO-UT-Muon tracking for 2024 PbPb collisions
  - ✓ Optimising the matching of Upstream Tracks with Muon chamber tracks for a new UpstreamMuon new track type
  - ✓ Creating HLT2 tracking efficiency lines for muons in PbPb

PbPb HLT2 reconstruction optimisation and ghost rate studies

What will be the difference between 2023 and 2024 in terms of HLT2 reconstruction

PbPb 2023

- No upstream tracker (UT) included
- Reconstruction option: the fastest one

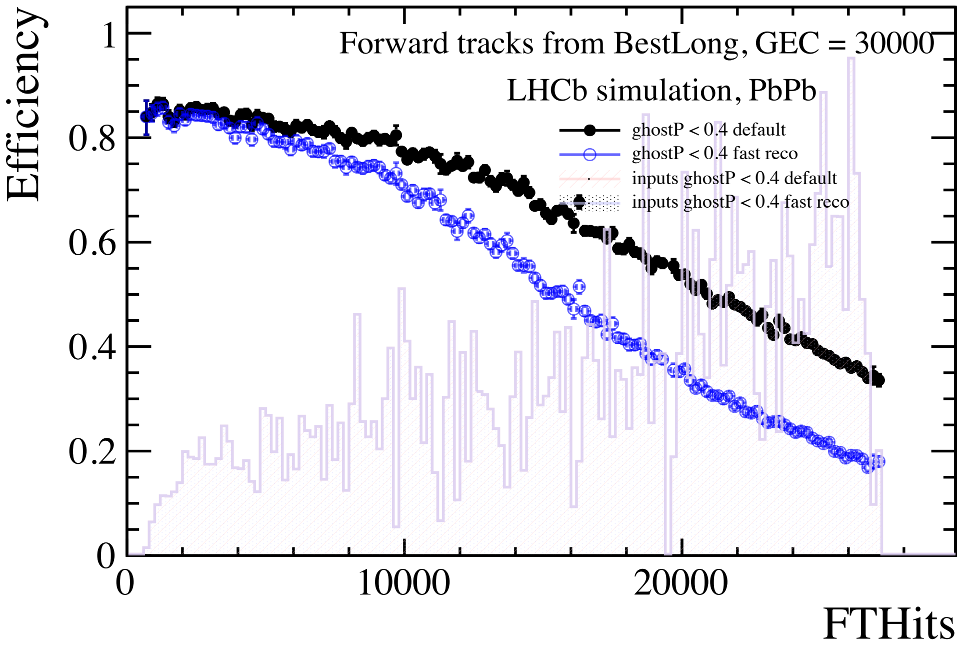
→

PbPb 2024

- UT included
- Reconstruction option: Baseline pp

Difference between fastest and baseline:

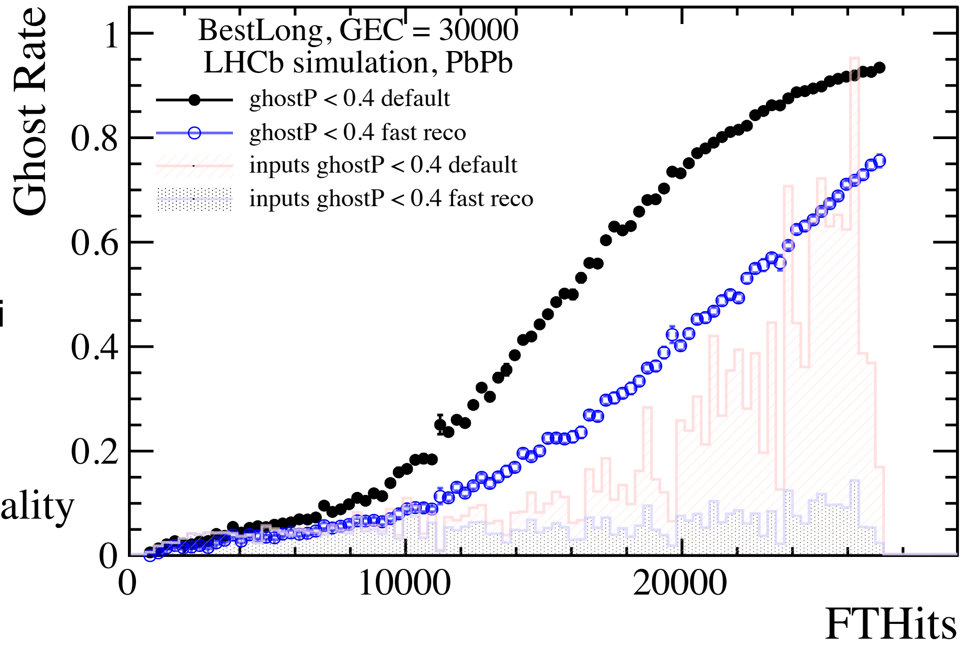
Sci-Fi Seed Track algorithm → x4 faster than baseline



FTHits: Hits in the Sci-Fi

BestLong: Best Long Tracks

$3 \cdot 10^5$ FTHits ≡ 30 % centrality



With the new reconstruction, the efficiency at low centrality is doubled

However, the ghost rate is huge at low centralities

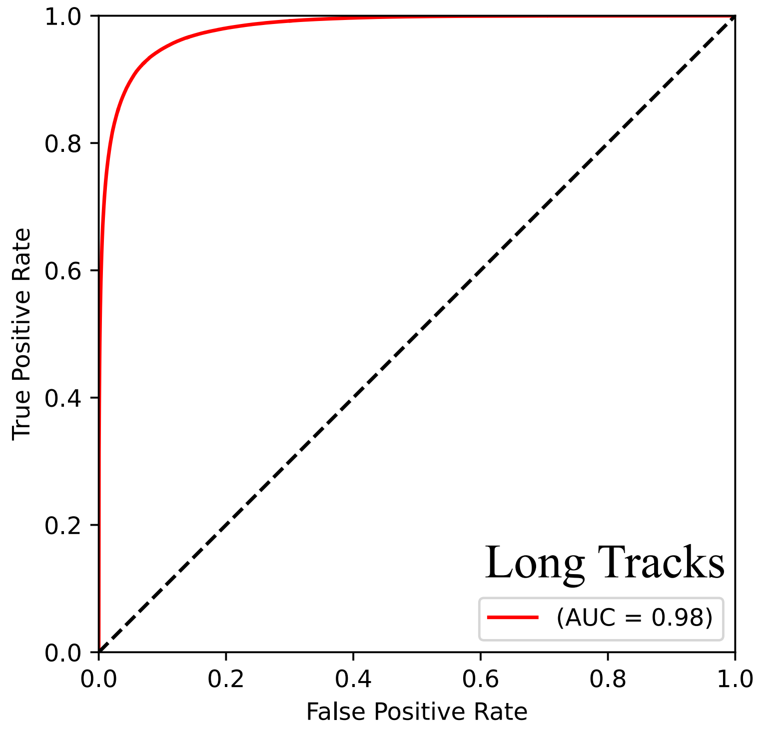
How can be reduced? → adding maximum ghost probability value of the tracks while doing the HLT2 reconstruction

How the ghost probability is computed? → through a Neuronal Network (NN) classifier trained with simulation samples → ProbNN_ghost

Problem → the NN training was made with pp simulation, which is not suited for PbPb due to the occupancy

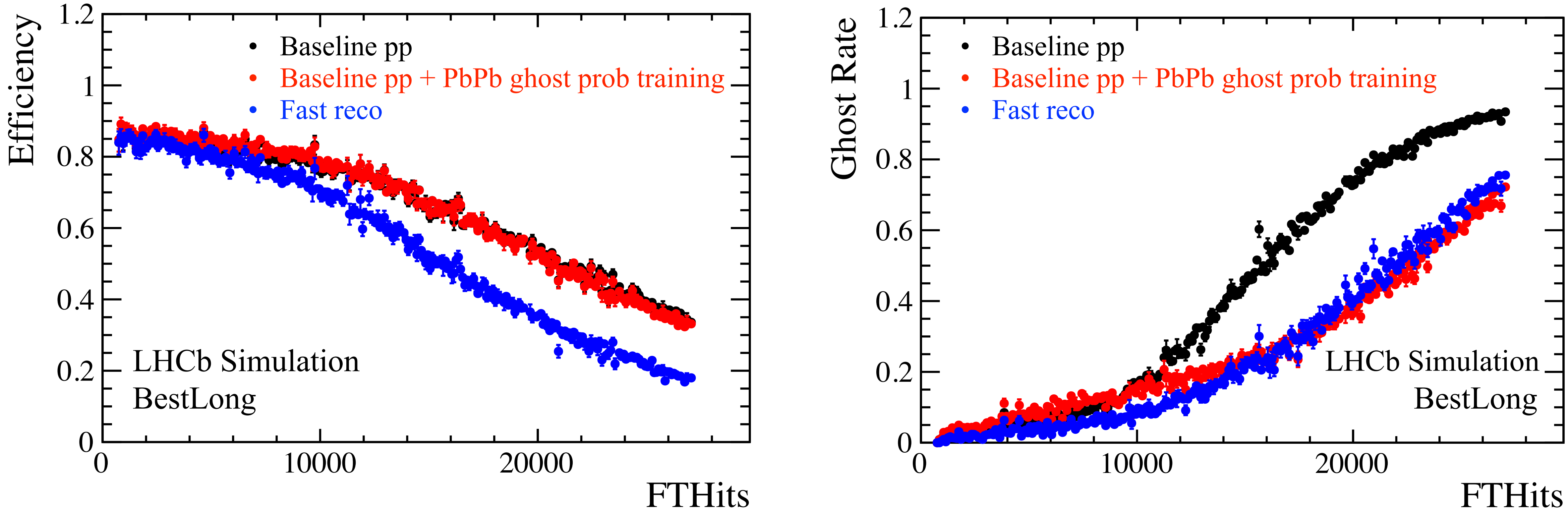
Solution → training new NN ghost classifiers for PbPb collisions

- Training sample → 2024 minbias PbPb peripheral MC
- Training-test split → 60%-40%
- Same NN structure and features as pp per track type



How the reconstruction changes with this new ghost probabilities

For PbPb we impose the same ghost probability cut as for pp → $\text{ProbNN}_{\text{ghost}}(\text{track}) < 0.4$



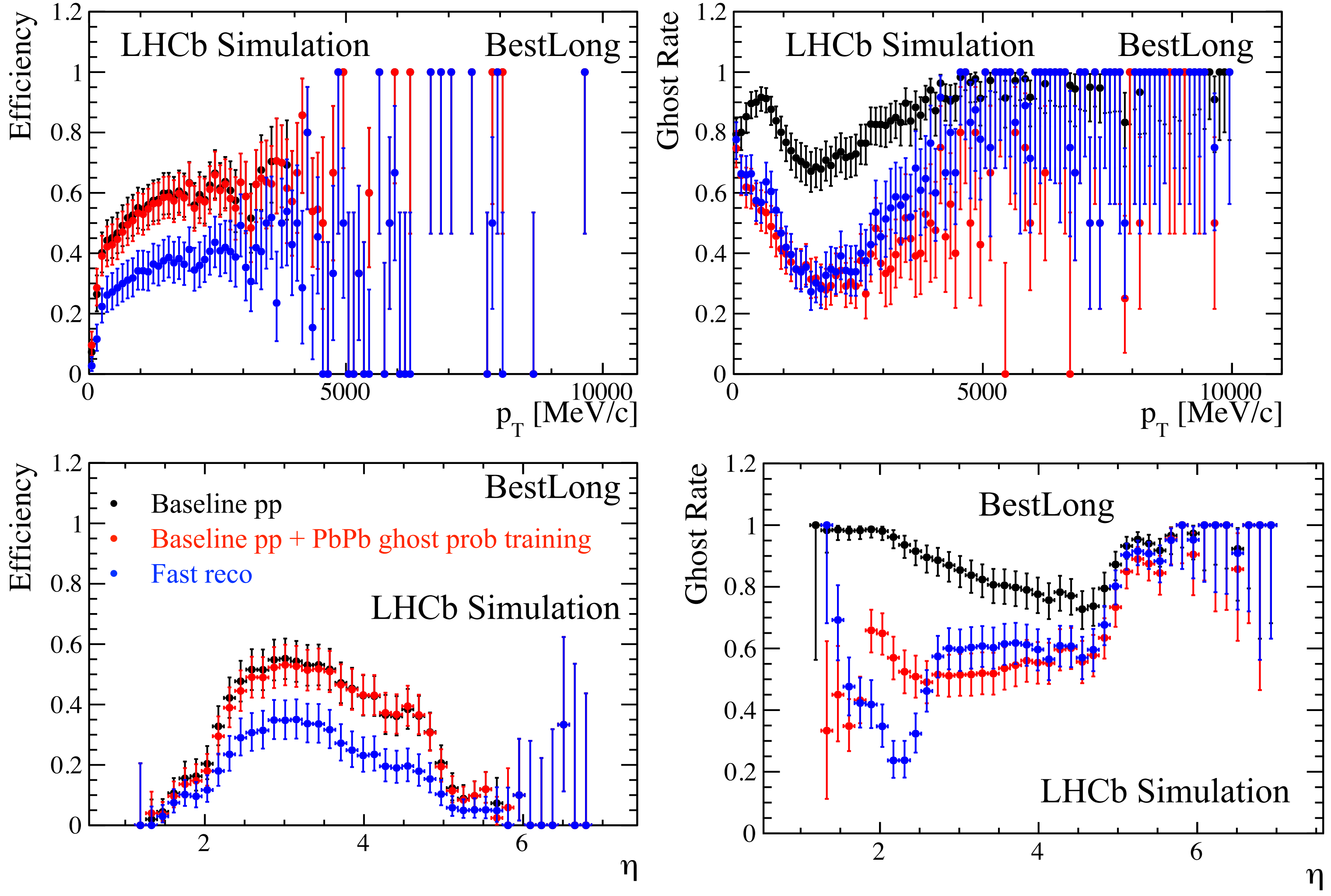
Significant improvement → the ghost rate is reduced $\sim 30\,\%$ at low centralities without loosing efficiency

Also the input tracks is reduced → improvement in terms of throughput

How is the tracking performance at low centrality

Let's consider event with $\mathrm{FTHits} : 20000 - 30000$ (up to 30% centrality)

- The 20% improvement in efficiency of the baseline pp reconstruction is kept as function of p_T and η
- Same trend is seeing for the ghost rate. Mostly corrected with the new $\mathrm{ProbNN}_{\mathrm{ghost}}$ tuning



What implies this results

More statistics for events with higher chances of forming the QGP keeping the excellent LHCb behaviour

Velo-UT-Muon (VUM) tracking for muon reconstruction in PbPb

The idea

- Designing a new tracking strategy for muons at **HLT2**
- Only Velo-UT and Muon stations hits are used for doing the muon tracks

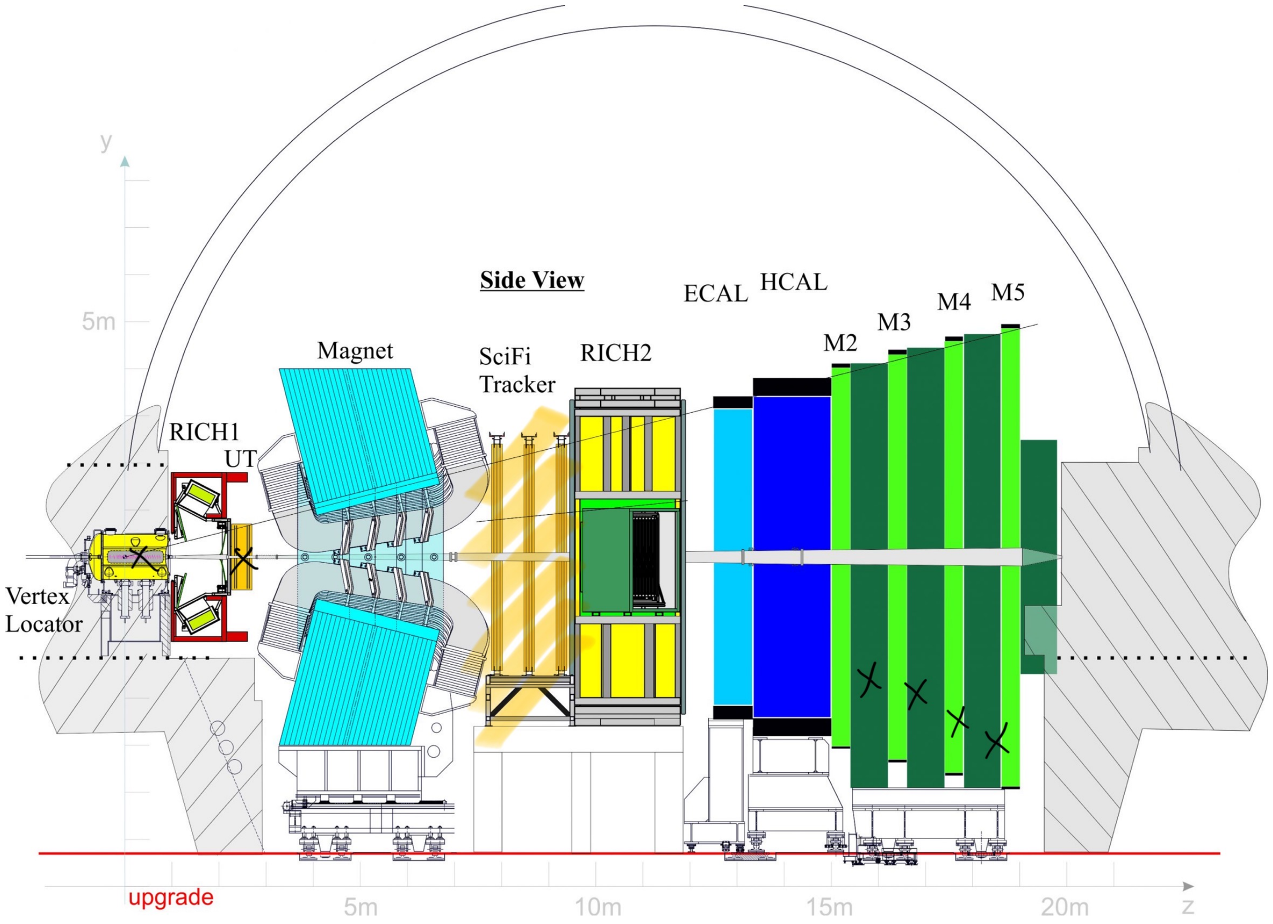
Why is this useful?

- New muon type for making HLT2 dimuon trigger lines, which can be used for:
- **Reconstruction efficiency**

  ✓ Tracking tables for MC tracking corrections in PbPb → not ready for Run 3 yet

- **Physics**

  ✓ It allows an alternative for dimuon decays for low centrality scenarios



The tracking algorithm → VeloUTMuonBuilder

(Based on the existing VeloMuonBuilder)

Inputs:

- HLT1 Upstream tracks and standalone muon tracks (tracks made only with muon chamber hits)

Algorithm:

- Both tracks are extrapolated to the plane at z_{mag} position
- $t_{y,\text{velout}} \approx t_{y,\text{Muon}} \rightarrow$ no bending in the ZY plane
- Matching condition in the ZX plane

$$s_x[t_{x,\text{velo}} - t_{x,\text{muon}}]^2 + (1 - s_x)[t_{y,\text{velo}} - t_{y,\text{muon}}]^2 < d^2_{cut}$$

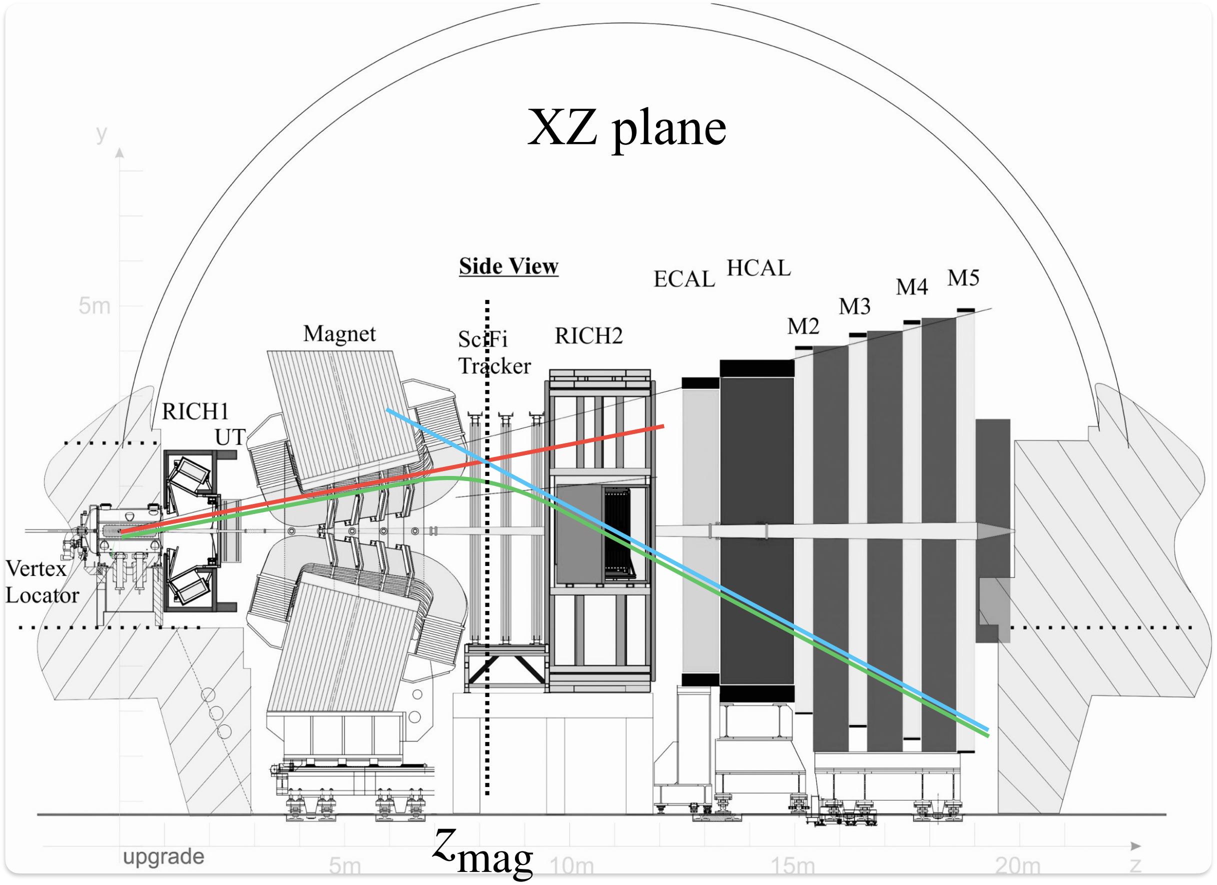
- First momentum estimation is made with $p_{\text{T,kick}}$ method.
- Finally, track refitting to improve the resolutions

Default parameters:

$$z_{mag} = 5400 \text{ mm} \qquad p_{\text{T,kick}} = 1265 \text{ MeV}$$

$$s_x = [0.06, 0.1, 0.15, 0.15]$$

$$d_{cut} = [30, 60, 110, 200]$$

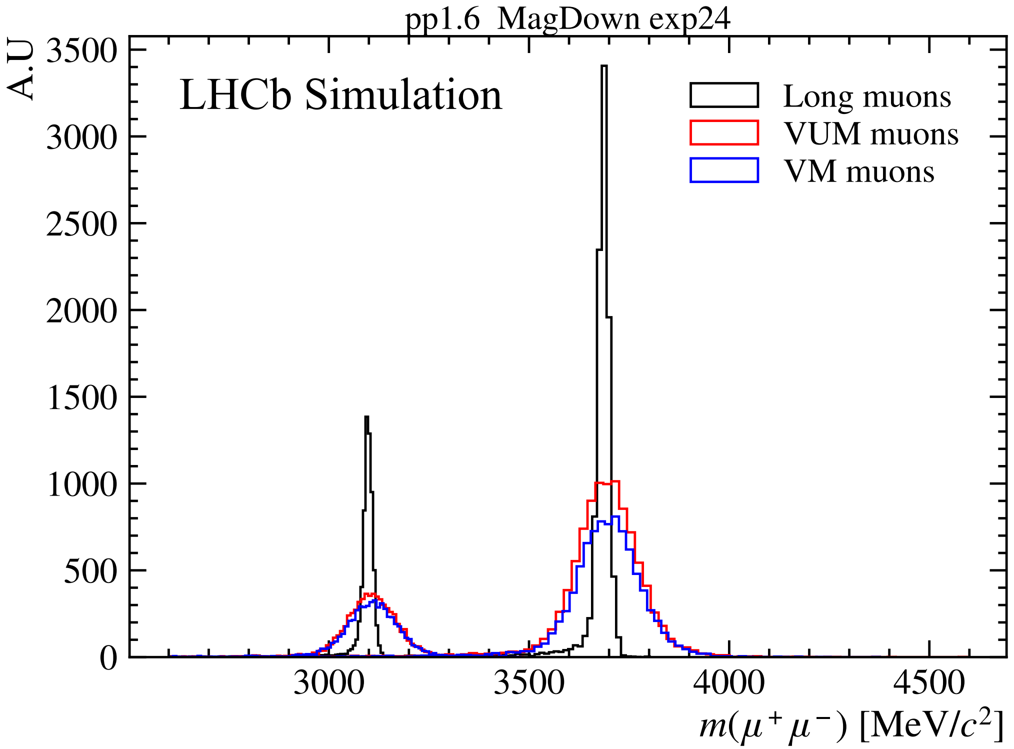


$$\frac{q}{p} = \frac{(x_{muon} - x_{velo})/p_{\text{T,kick}}}{z_{muon} - z_{magnet}}$$

proton-proton tests

- To test this HLT2 algorithm, the VeloUTMuon tracks are used for doing $X \to \mu^+\mu^-$ reconstruction
- Not additional cuts to the tracks are applied. First, this is going to be tested in pp simulation samples

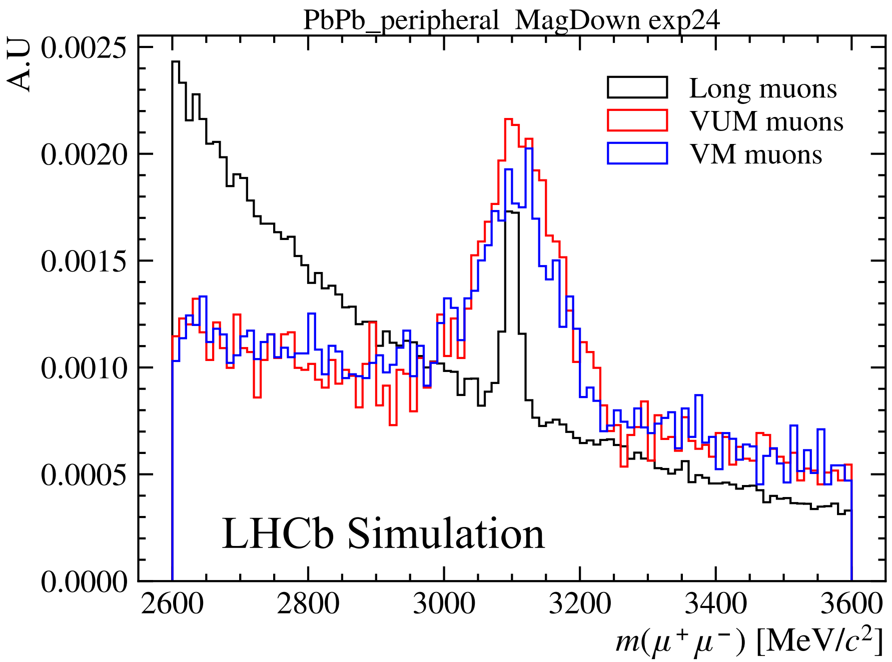
Muon track type	Triggered $J/\psi \to \mu^+\mu^-$ events over 20000 pp $\nu = 1.6$
Long	9553
Velo-UT-Muon (VUM)	6835
Velo-Muon (VM)	5631

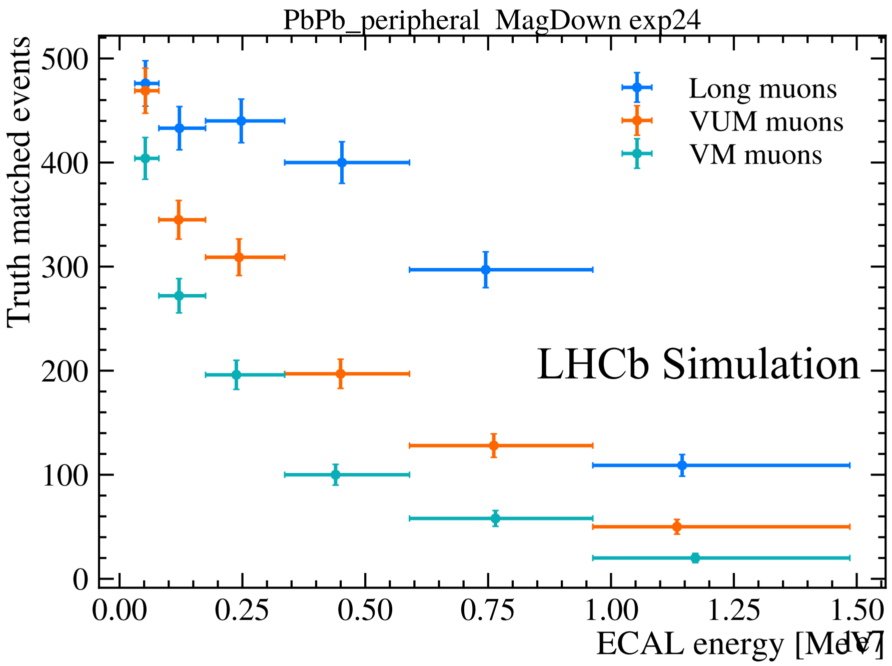


- Able to separate the J/ψ from the $\psi(2S)$ according to MC
- No improvement in resolution with respect to Velo-Muon (VM) matching → **expected**
- Improvement in terms of triggering → more efficient

PbPb tests

- The test is repeated for PbPb peripheral $J/\psi \to \mu^+\mu^-$ simulation



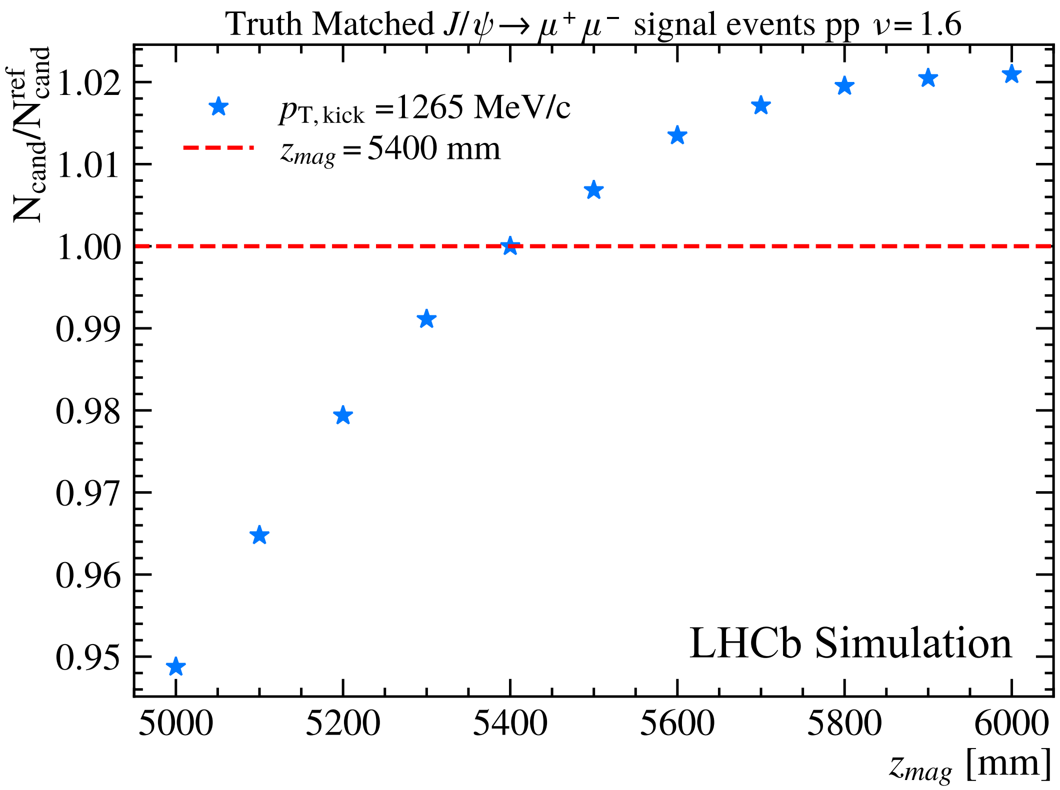


Centrality (%)	ECAL Energy [GeV]
90-80	310-800
80-70	800-1750
70-60	1750-3360
60-50	3360-5900
50-40	5900-9630
40-30	9630-14860
30-20	14860-22150
20-10	22150-32280
10-0	32280-1e12

- Enough resolution to reach a peak in PbPb collisions (worst resolution expected due to occupancy)
- In terms of centrality, the Velo-UT-Muon is always better than Velo-Muon (**specially for low centrality regions**). That is great for tracking efficiency calibration

What can be changed/improved

1. **Fit parameters**
   - The fixed parameters of the algorithm can be different for Upstream tracks
   - $p_{\mathrm{T,kick}}$ do not affect since it is the first estimation of the track momentum
   - Our studies show that we gain 2% of triggered candidates by increasing z_{mag}
2. **Fit tools**
   - The matching is made through lineal extrapolation. Other extrapolator could suit better for Upstream tracks
3. **Code scheme**
   - The code works is made for track fitting
   - Adapt it to pattern recognition and Kalman filter could improve the HLT2 lines triggering



Conclusions

- The main aspects of the heavy ion data-taken in LHCb has been shown as well as its software challenges and possible fixes regarding HLT2

- The new reconstruction strategy showed big increase in efficiency for low centrality. Even if the ghost rate increases with it, the new proposed ghost probability optimised for PbPb solves the problem

- The Velo-UT-Muon matching algorithm has been shown and how it would be perfect suit for HLT2 tracking efficiency lines for PbPb

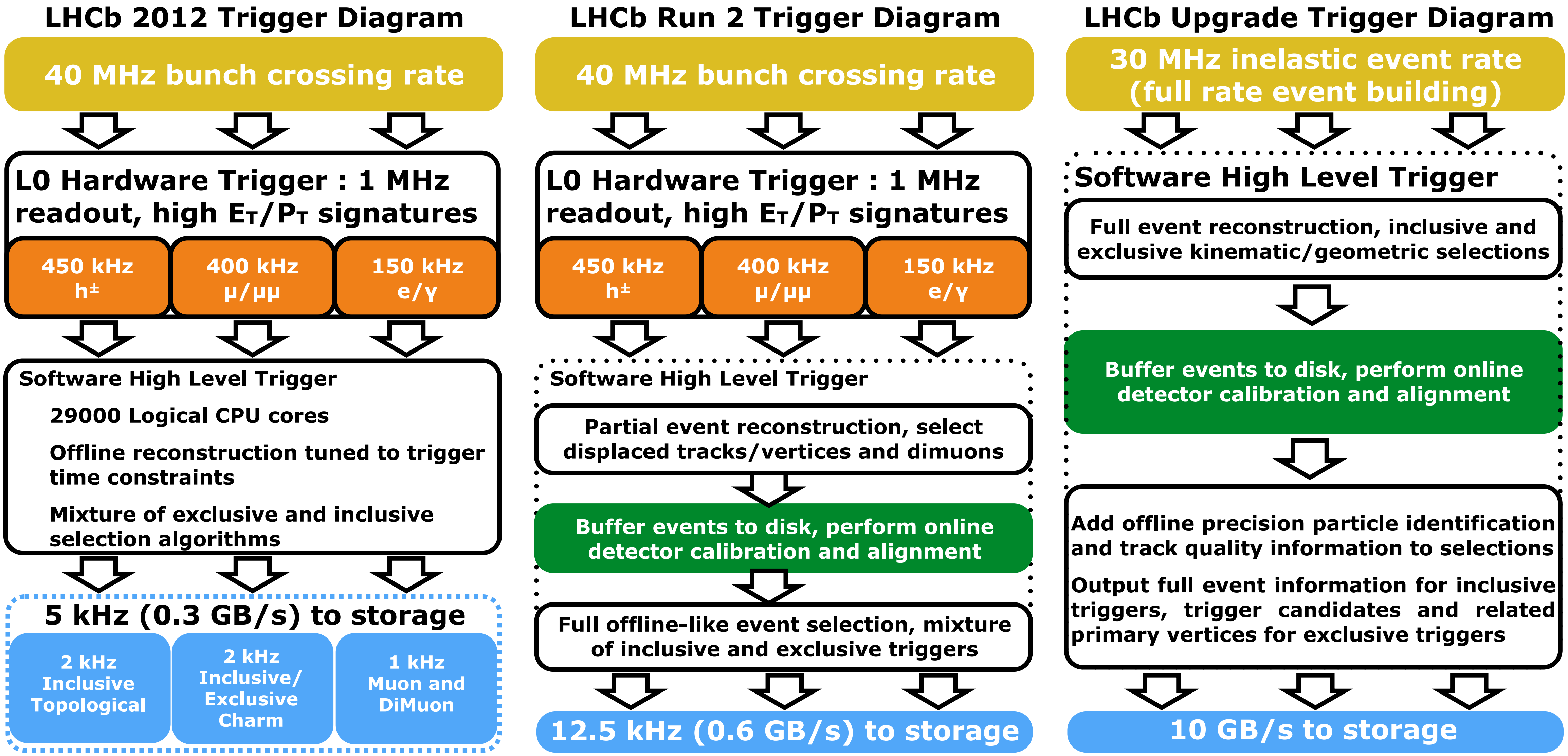
- Finally, all the presented changes are expected to be included in the LHCb software sequence for the next heavy ion data-taken

Thank you all for you attention

Backup

LHCb Real Time Analysis (RTA) data flow evolution comparison

LHCb-FIGURE-2020-016



LHCb track types

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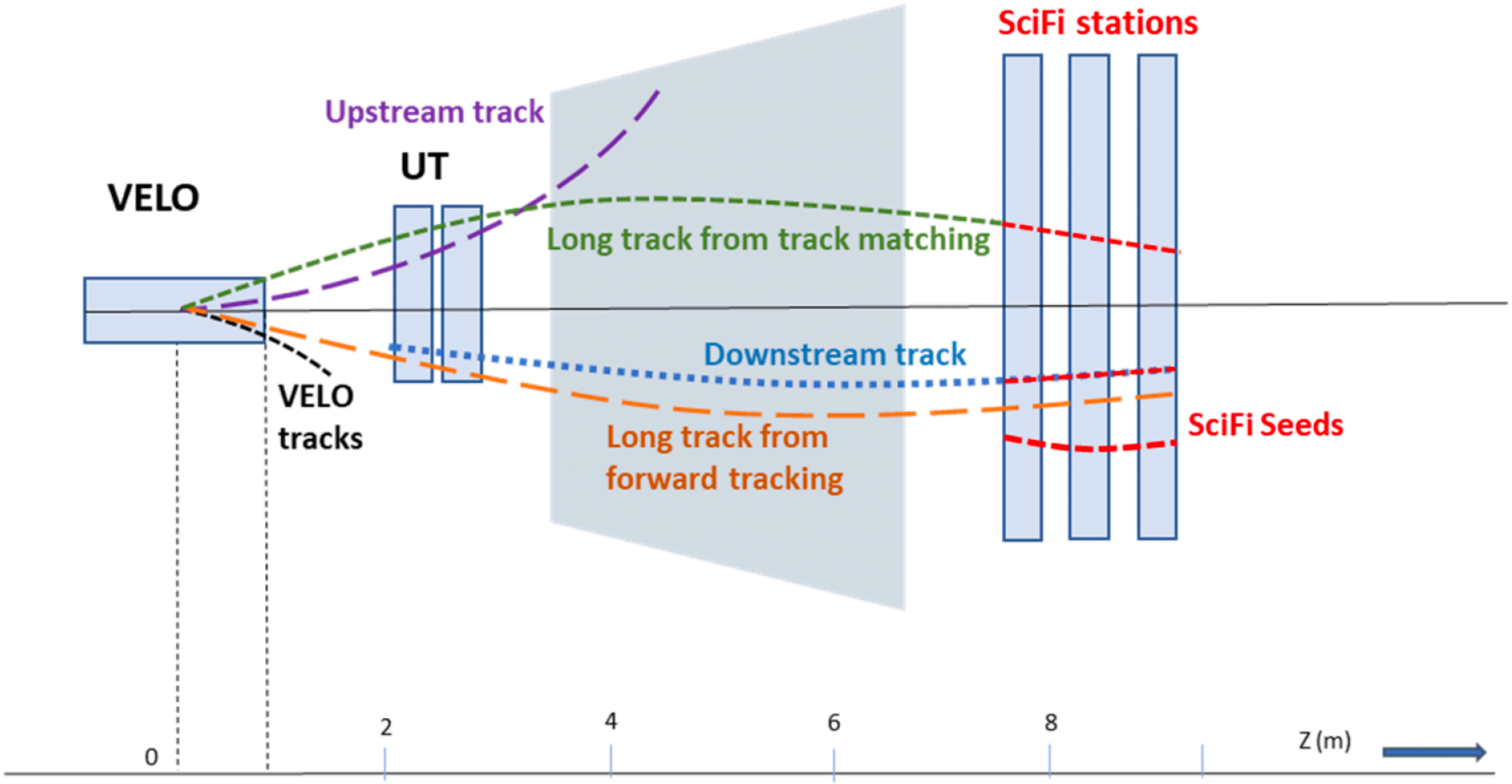
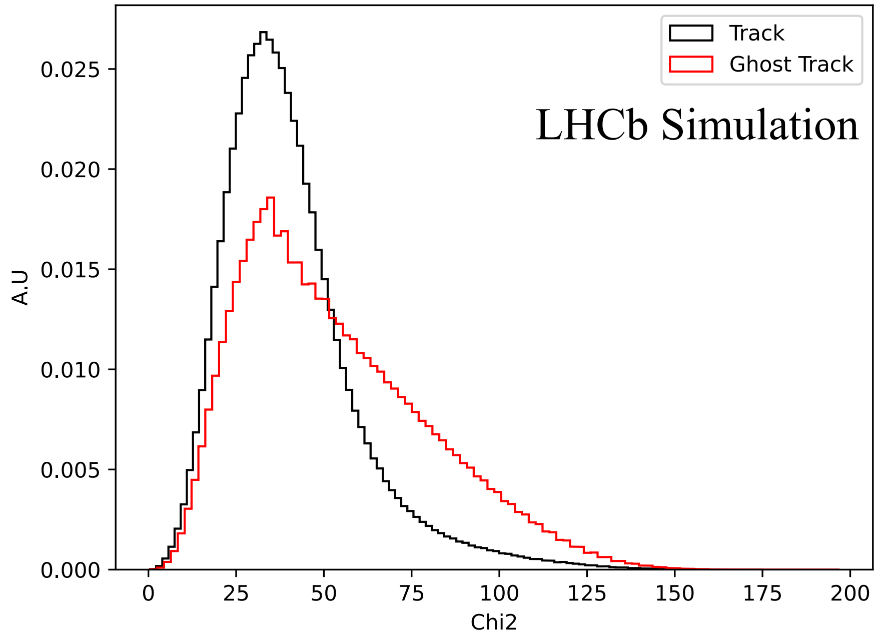


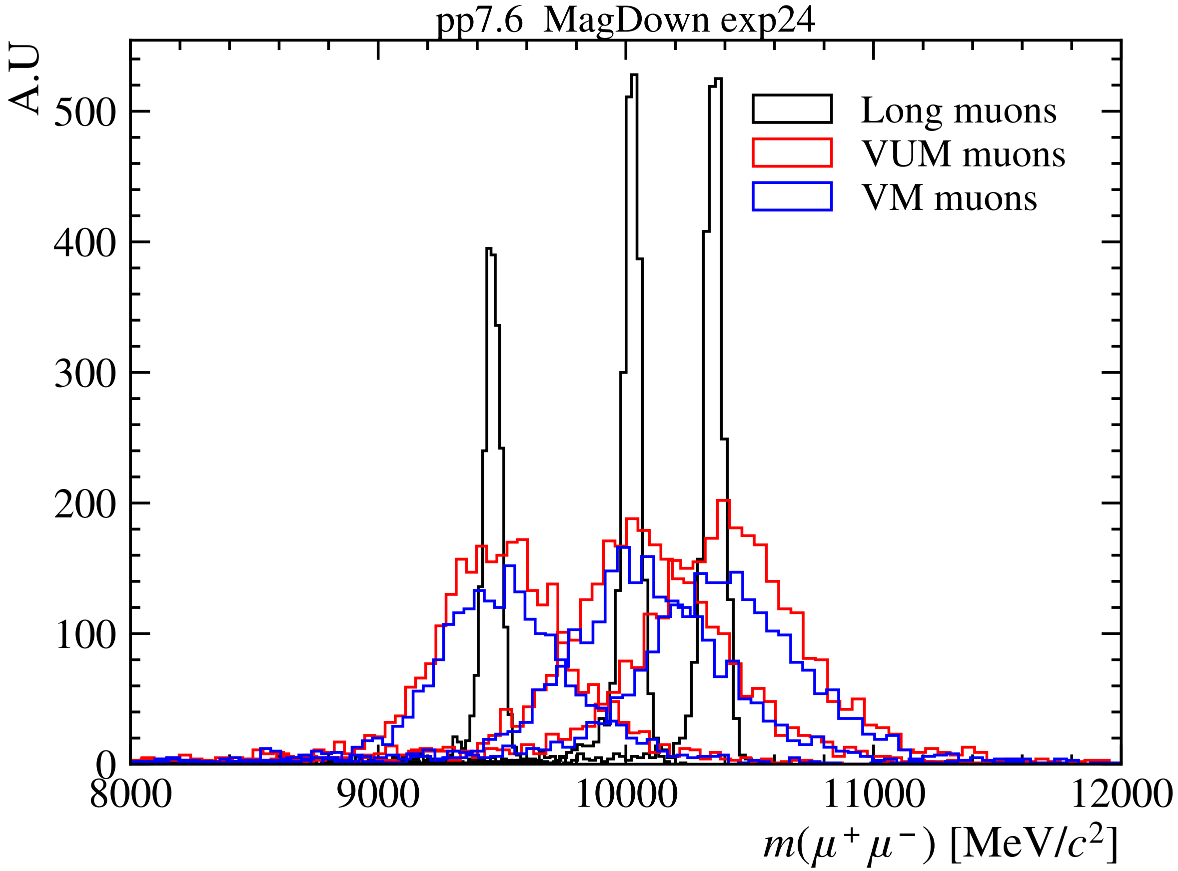
Training configuration for ghost probability calculation for LongTracks

- **Machine Learning algorithm:**

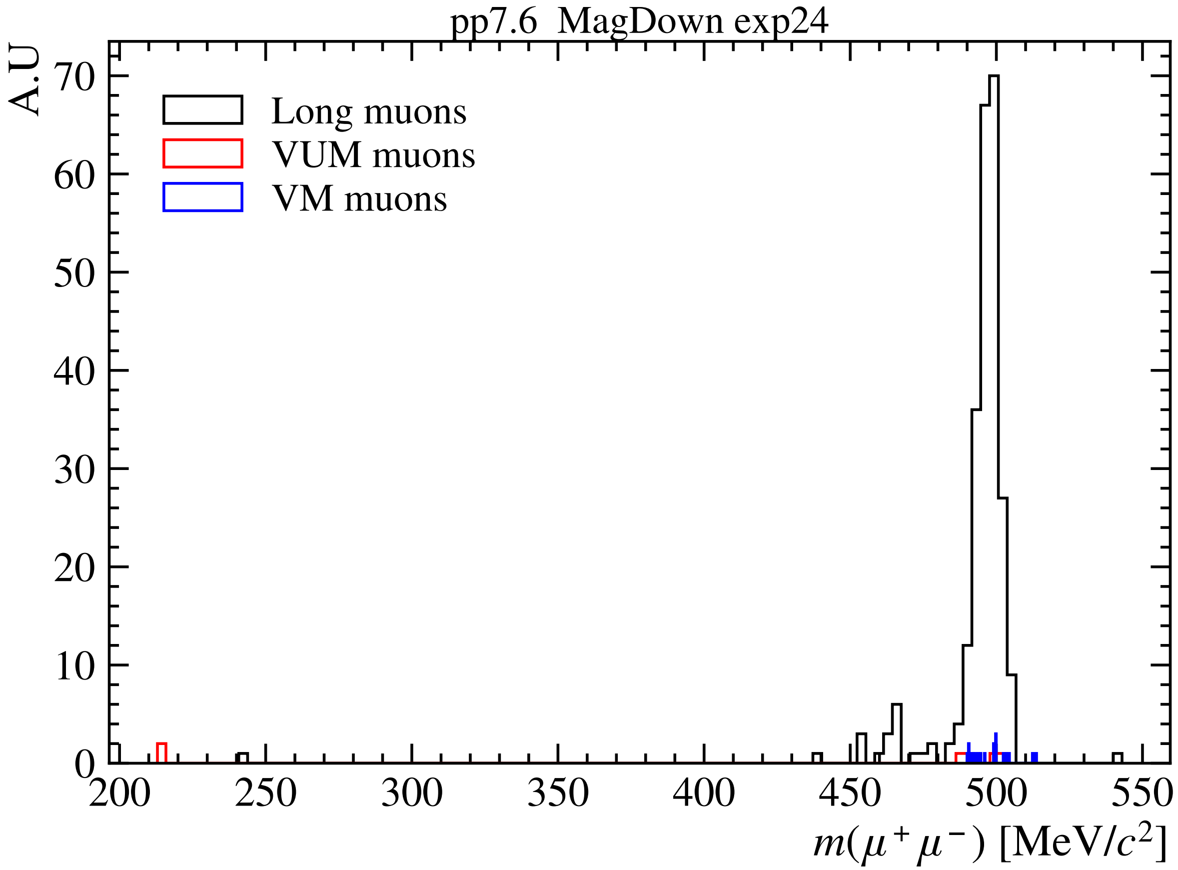
- **Training features:**
  - Track fitting: $\chi^2_{Long}, \chi^2_{Velo}, \chi^2_{seed}, \chi^2_{match}$, ndof, ndof_{seed}
  - Track kinematics: $\log(p_{\mathrm{T}}), \eta$
  - Track hits: nUTHits, nUTOutliers



VUM tracking performance for dimuon decays



$\Upsilon(1,2,3S) \to \mu^+\mu^-$



$K_S \to \mu^+\mu^-$