Applications of Lipschitz monotonic NNs to the LHCb Run 3 trigger system

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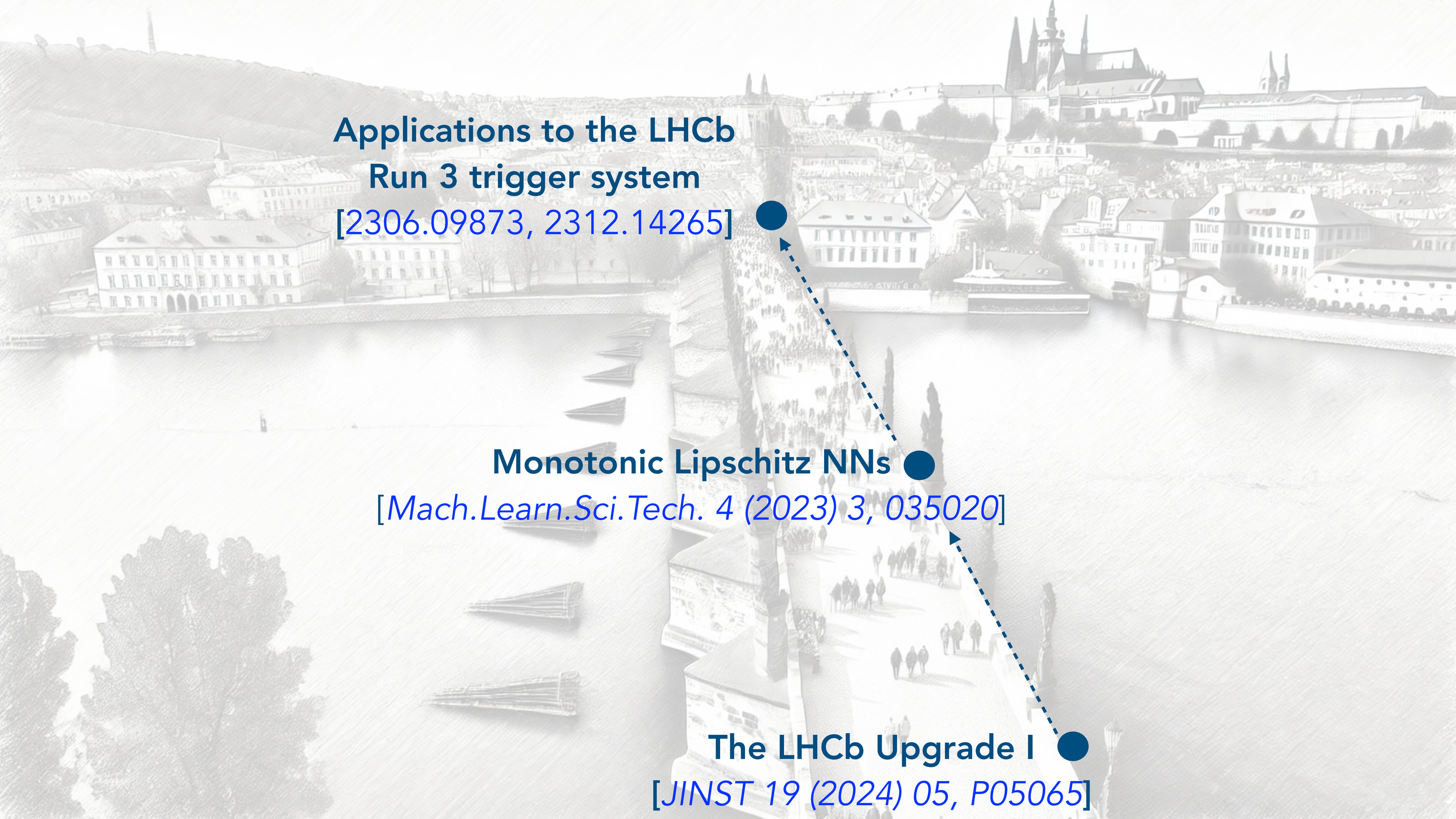
on behalf of the LHCb Collaboration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The LHCb Upgrade I
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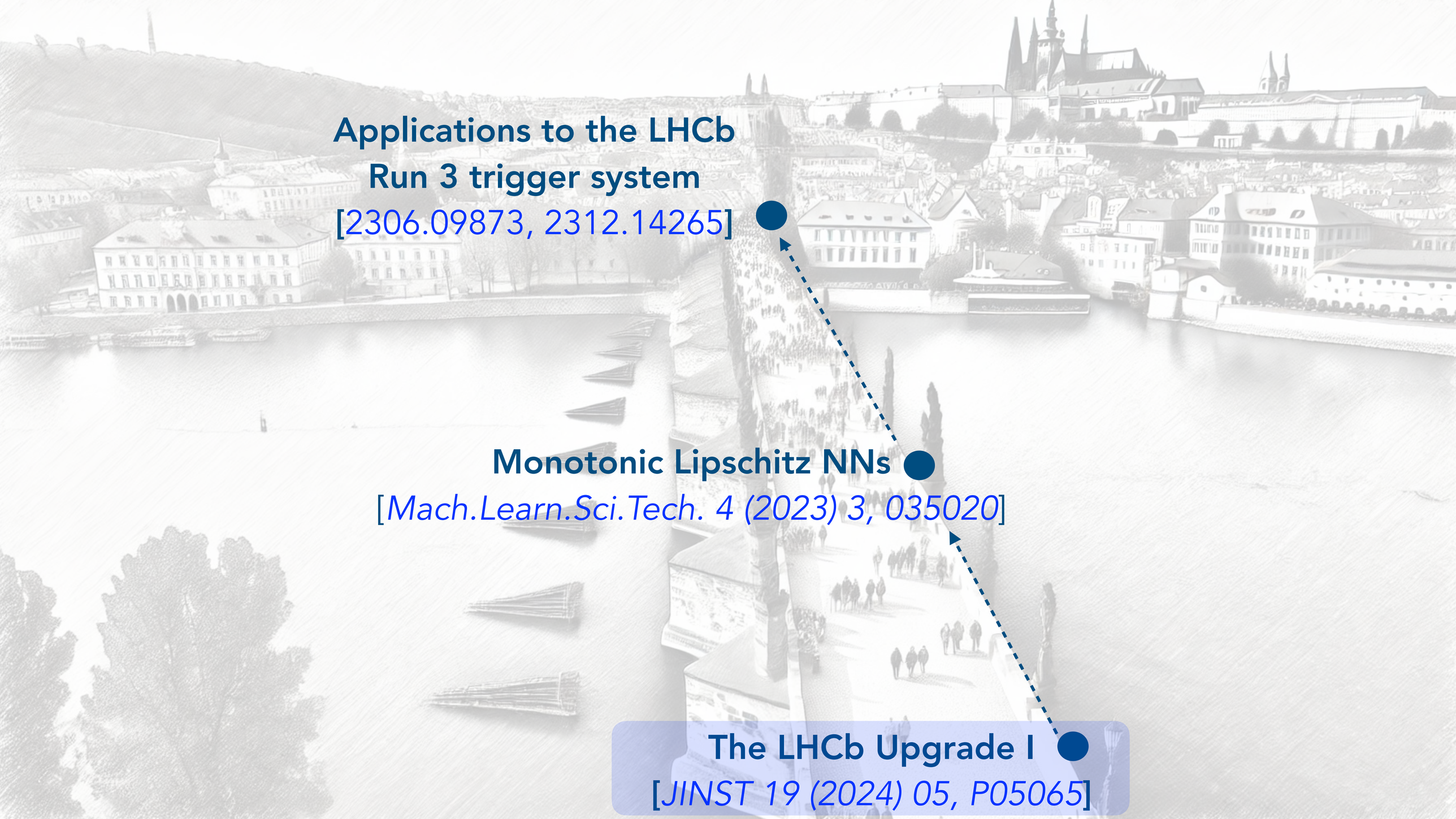
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The upgraded LHCb detector for Run 3

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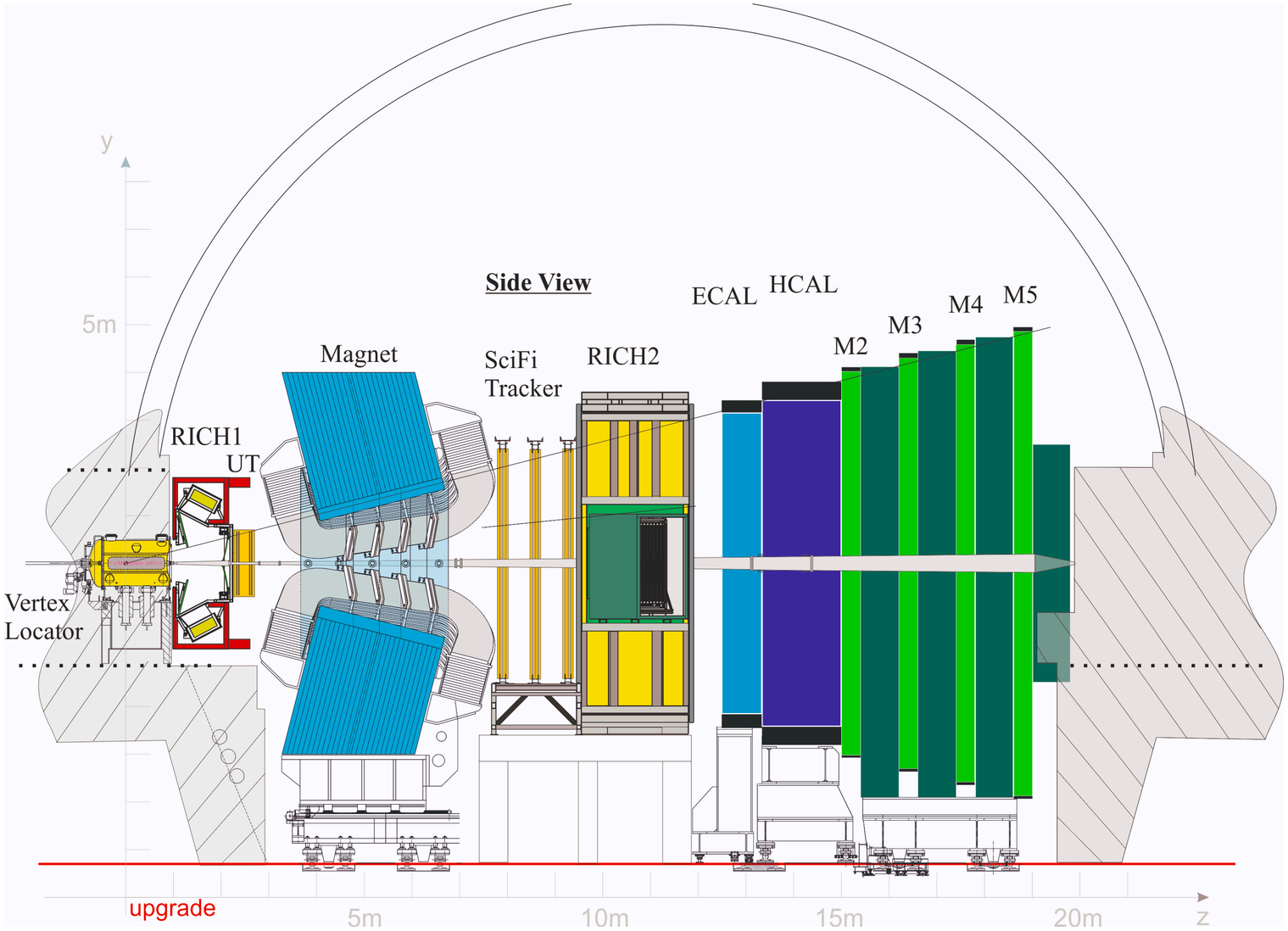

The LHCb experiment @ the LHC:
forward-arm spectrometer
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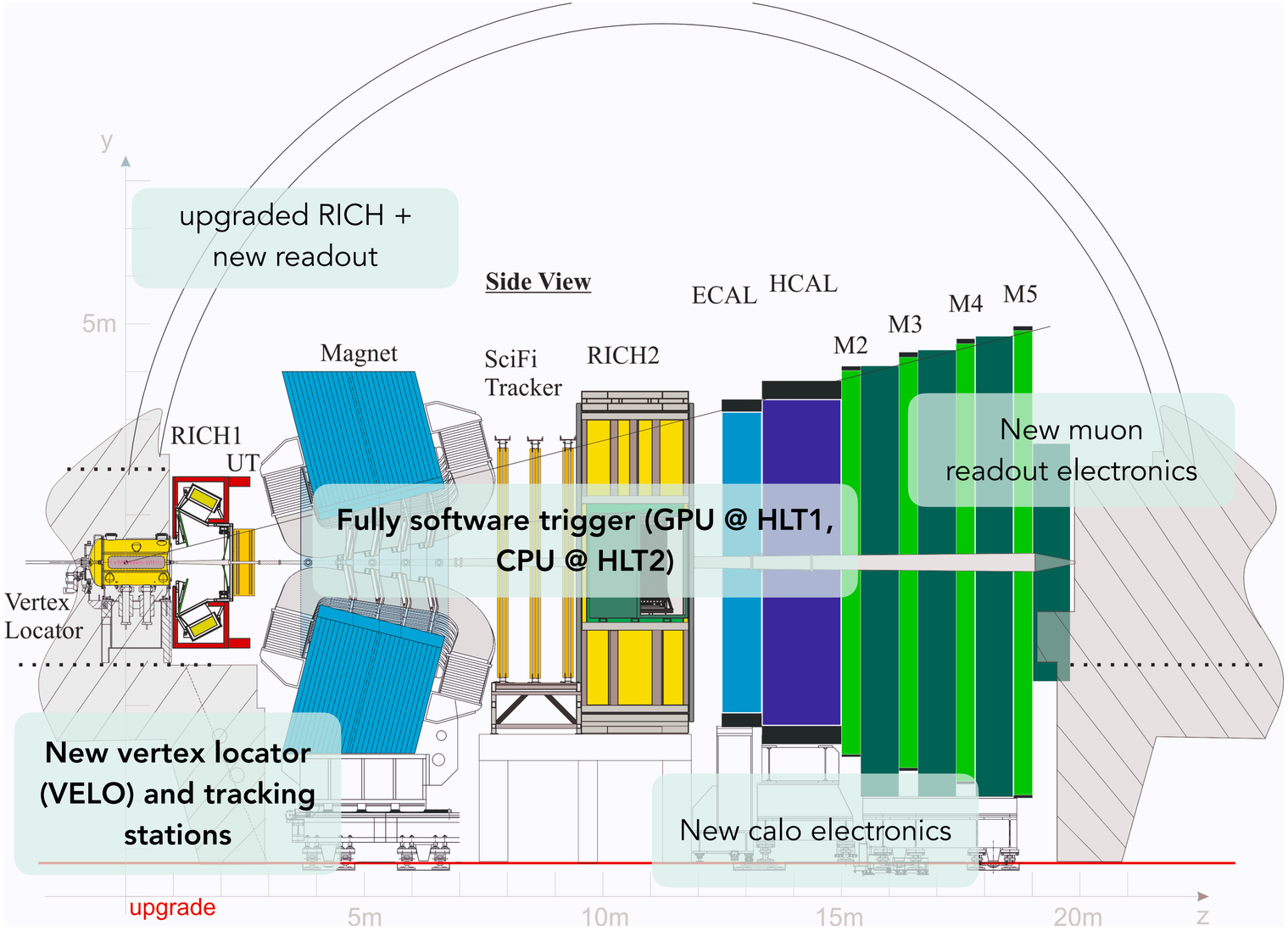

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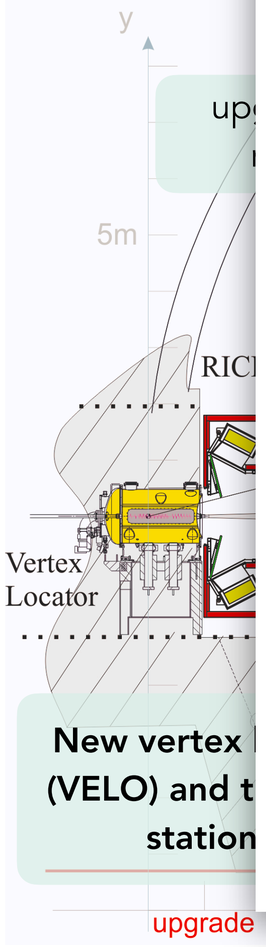
Unprecedented conditions in **Run 3**:

- Instantaneous $\mathcal{L} = 2 \times 10^{33} \mathrm{cm}^{-2} \mathrm{s}^{-1}$ → 5 × Run 2
- Redesigned tracking detectors & improved readout electronics @ pp bunch crossing rate of $30\,\mathrm{MHz}$
- Milestone: **fully software trigger**

The LHCb Run 3 trigger system

[CERN-LHCC-2018-014, LHCB-TDR-018]



LHCb raw data
15000 PB/year

500× reduction

LHCb storage capacity
30 PB/year

⇒ LHCb trigger: ***real-time* data reduction:** 5 TB/s → 10 GB/s

*image not to scale

The LHCb Run 3 trigger system

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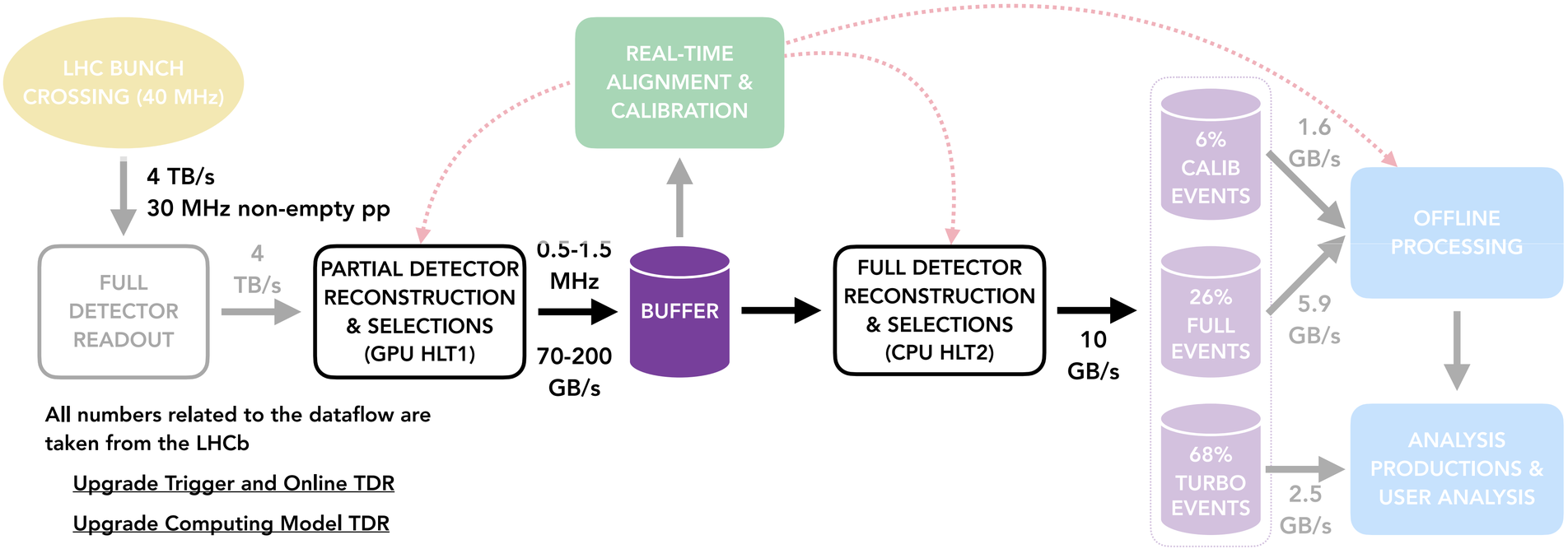
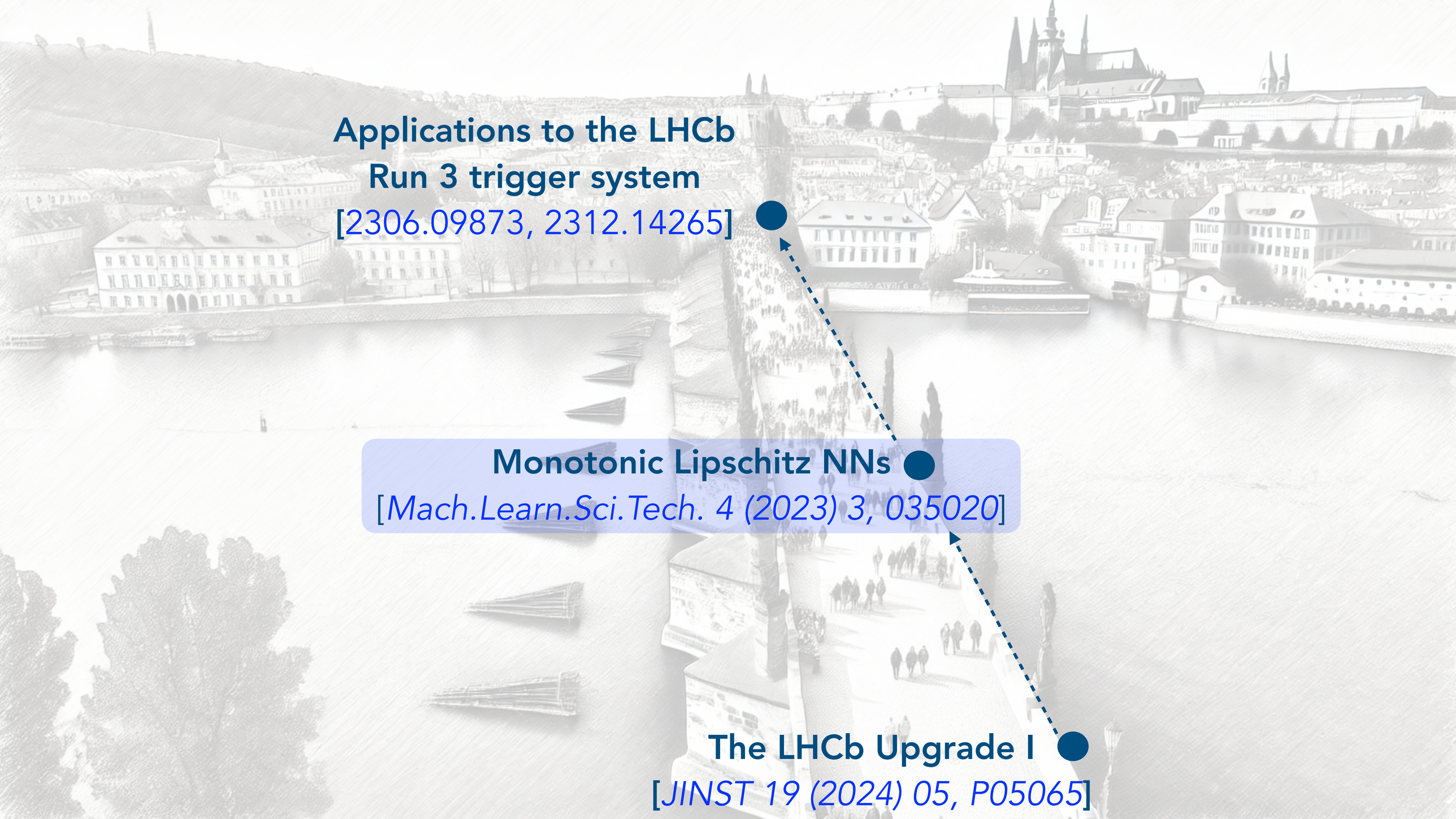
LHCb-FIGURE-2020-016



Fully software, two-staged trigger: select only *interesting* events via combination of *expert systems* and ***machine learning***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ML for trigger decisions

Criteria for reliable *real-time & irreversible* trigger decisions:

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Solution:

a) **certified** robustness and interpretability, *ie* via formal guarantees
→reliable performance on unseen data

b) **expressiveness and reduced complexity** for deployment in the trigger

Constraining the Lipschitz constant

- A formal guarantee for robustness is realised constraining of the gradient of the learnt decision boundary, $f(\vec{x})$, in any i^{th} feature direction,

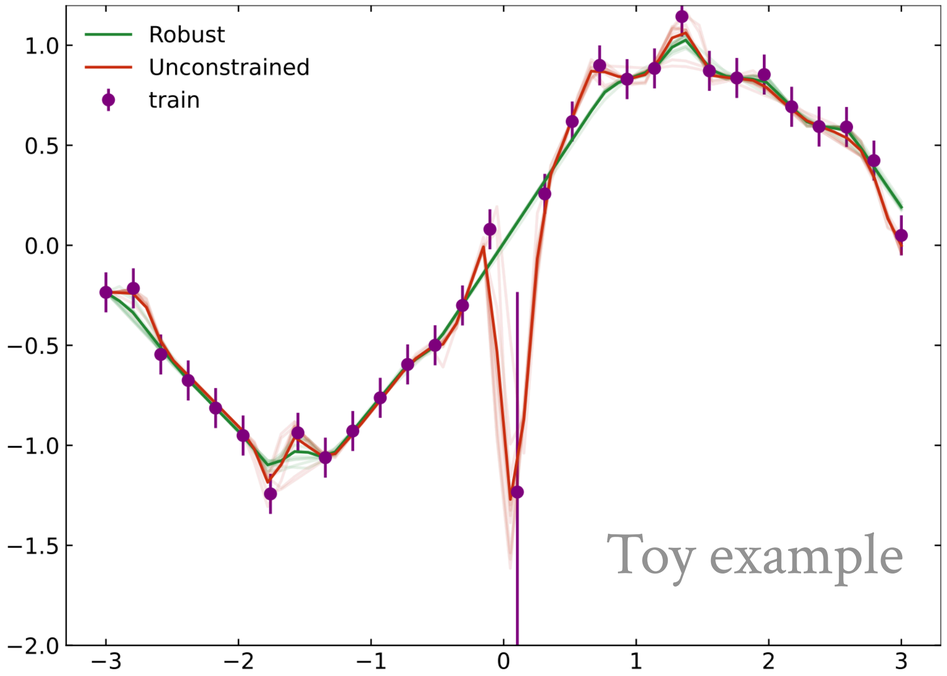
$$\underbrace{|f(\vec{x}+\vec{\varepsilon}) - f(\vec{x})|}_{\text{NN response variation due to feature variation}} \approx \left|\sum_i \frac{\partial f}{\partial x_i}\varepsilon_i\right|$$

$$\leq \lambda \|\vec{\varepsilon}\|_1 \qquad \Rightarrow \left|\frac{\partial f}{\partial x_i}\right| \leq \lambda$$

Enforce NN is universal approximator of Lipschitz functions

λ bounds the NN response variation as a result of feature variations during detector operations

[*Mach.Learn.Sci.Tech. 4 (2023) 3, 035020*]



∴ Learn **smooth** functions at a **scale above detector resolution**

Interpretability by way of monotonicity

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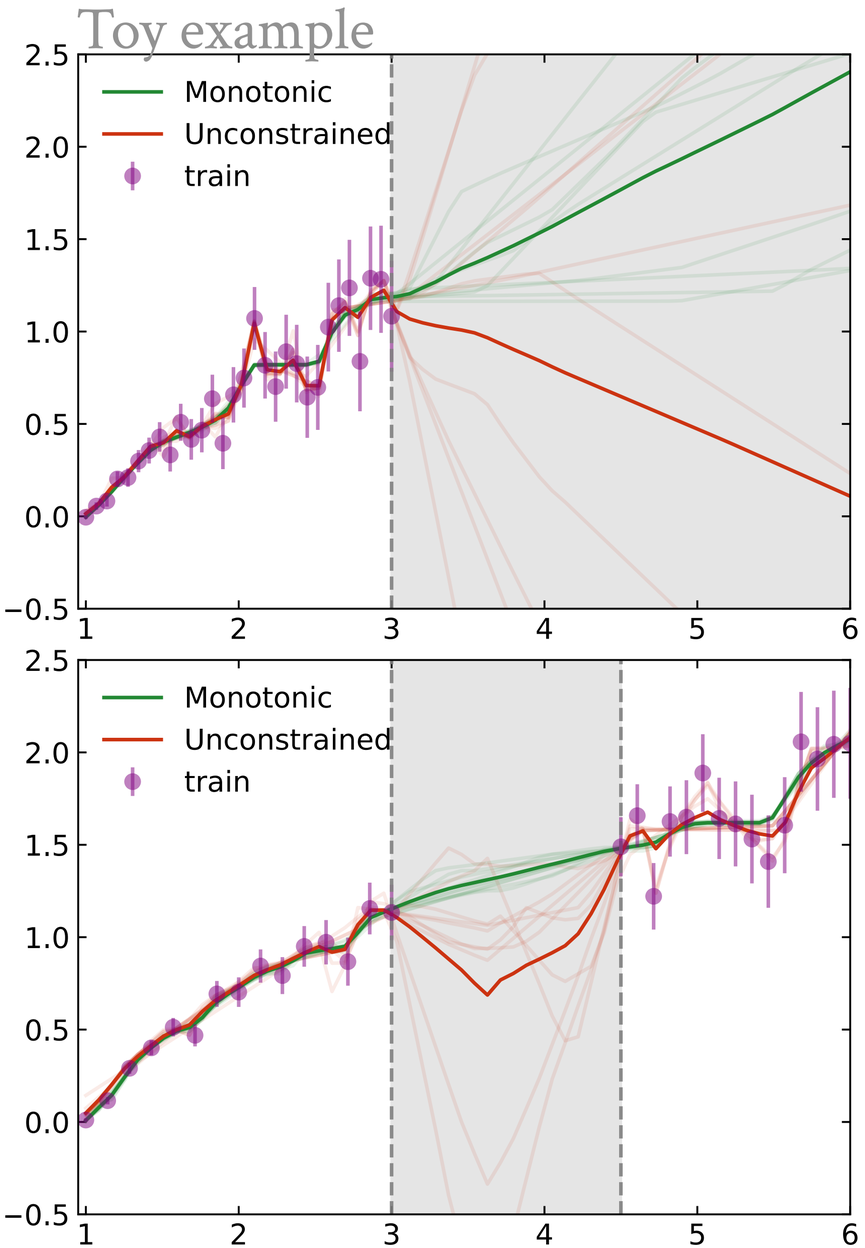
Residual connection in the response function learnt by the NN

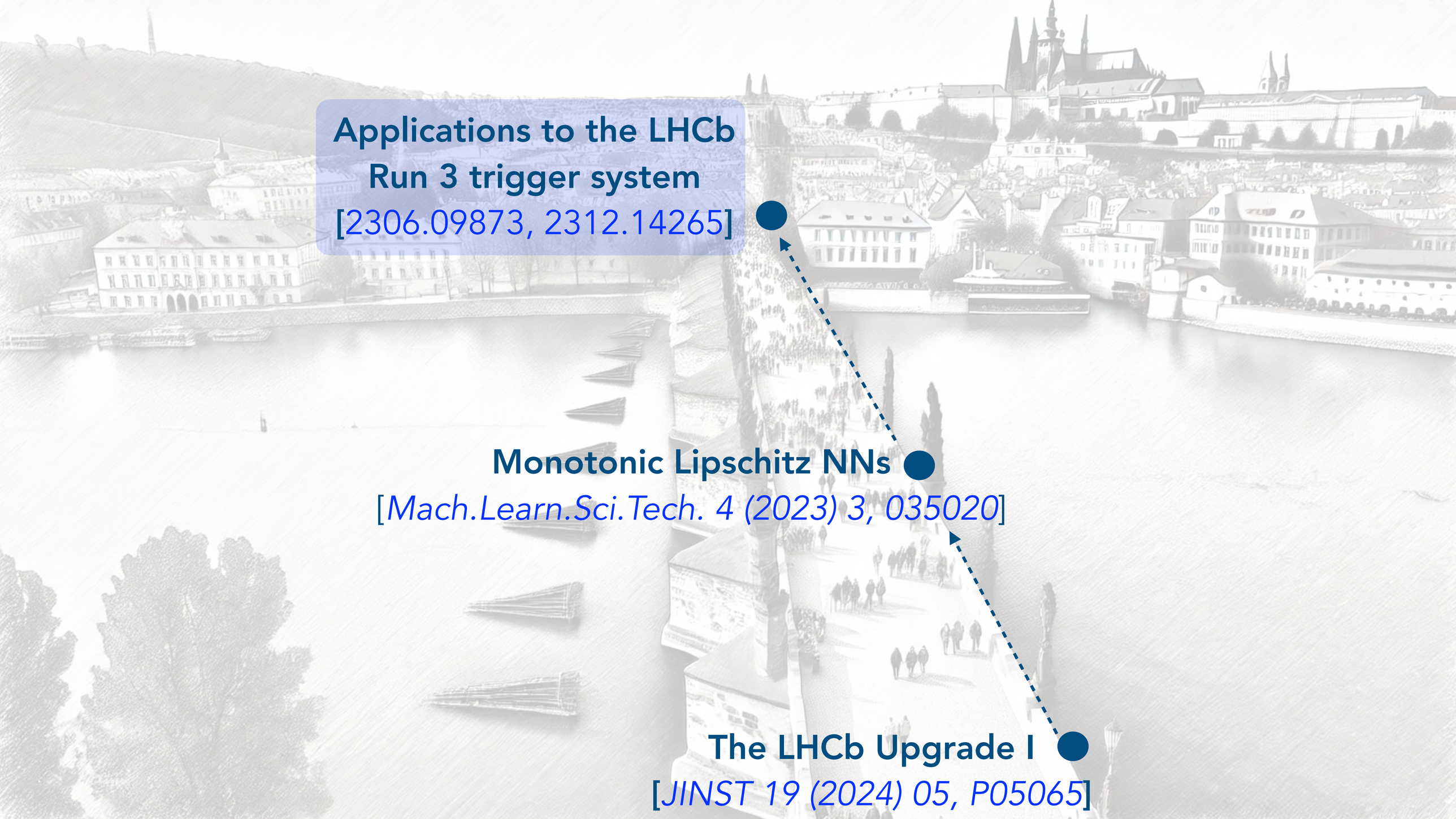
$$g(\vec{x}) = f(\vec{x}) + \lambda \sum_{i \in \mathcal{M}} x_i$$

$$\Rightarrow \frac{\partial g}{\partial x_i} = \frac{\partial f}{\partial x_i} + \lambda \geq 0 \quad \forall i \in \mathcal{M}$$

$\in [-\lambda, +\lambda]$ for Lipschitz functions

⇒ Monotonicity defined wrt any (sub) set of features, at the the level of feature-specific variations (*"all else being equal, an increase in a specific feature will be more signal-like"*)

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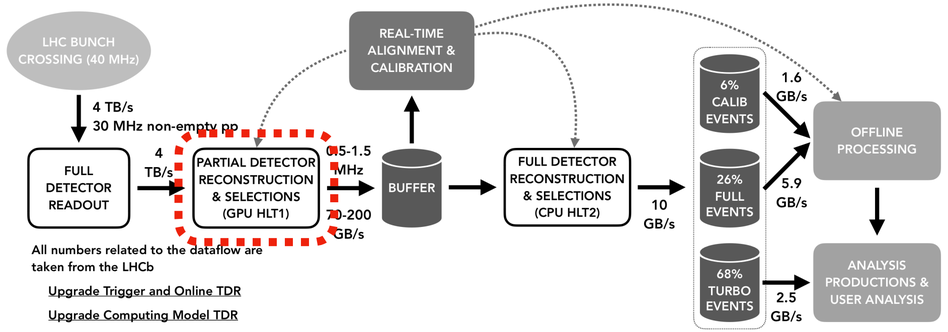
Electron Identification @ HLT1

[LHCB-FIGURE-2024-003]

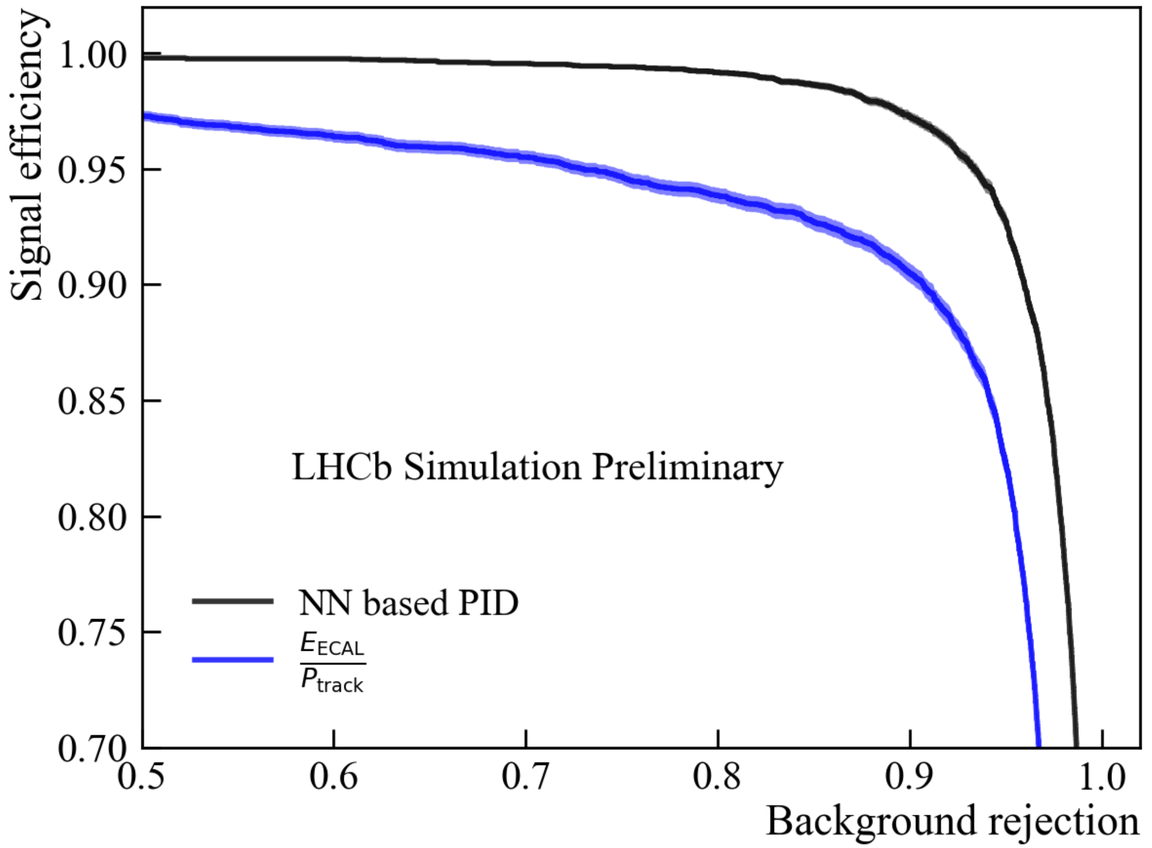


Expressiveness of Lipschitz NN → meet memory and compute requirements of the LHCb trigger

New in Run 3: **electron ID @ HLT1**

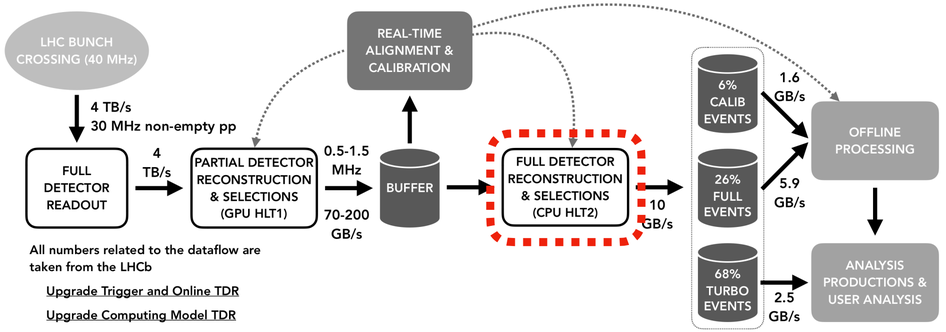
Reconstruction exploiting electron features:

- $E_{\mathrm{ECAL}}/p_{\mathrm{Track}}$
- Electron cluster dispersion
- Electron cluster barycentre



The topological triggers @ HLT2

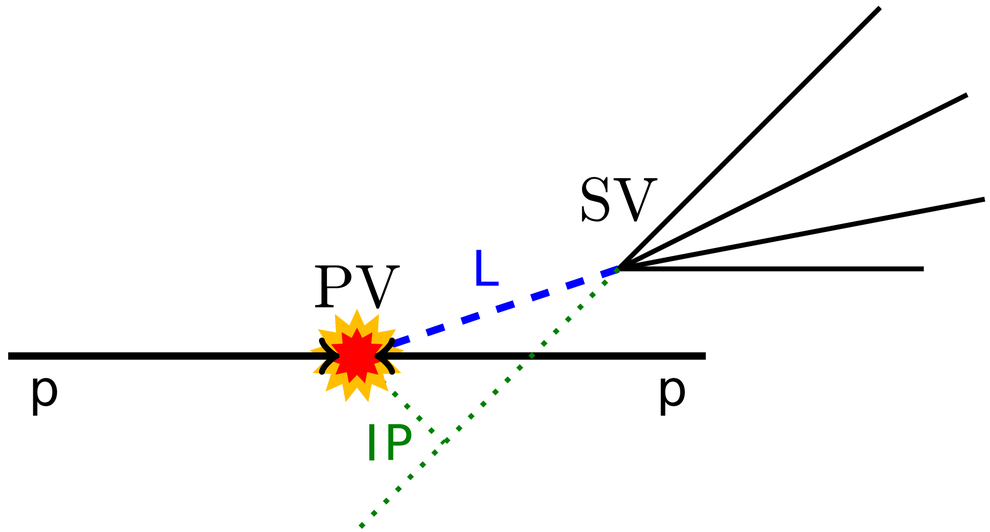
[2306.09873, 2312.14265]



- Higher-level (HLT2) trigger for **inclusive** selection of **beauty decays**

⇒ select multi-body candidates with b-hadron decay topologies:

- B mass $\mathcal{O}(5\ \text{GeV})$ → high transverse momentum, p_T
- Lifetime of $\mathcal{O}(1\ \text{ps})$ → displaced decay vertex
- Boosted in forward direction → $\mathcal{O}(1\ \text{cm})$ before decay vertex (DV)



Beauty decay topology

[Credit: D. Vom Bruch]

The topological triggers @ HLT2

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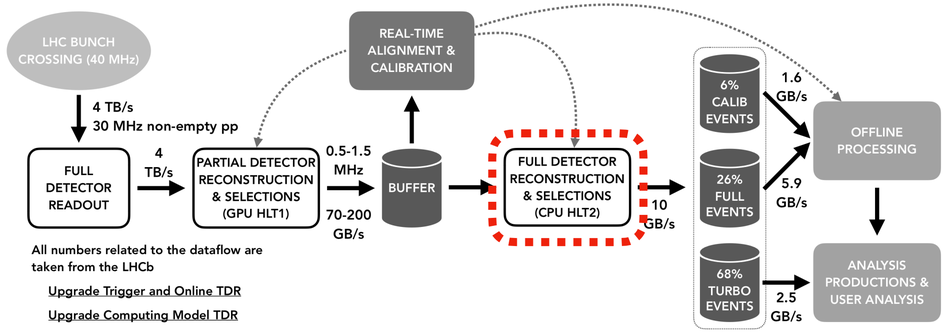

New in Run 3: Monotonic Lipschitz NN to identify **2- and 3-body *b*-candidates** using

- Kinematics
- Decay topology
- Monotonically increasing features:
  - a) candidate p_T
  - b) candidate flight distance
  - c) χ^2 of the impact parameter (IP)

Sensitivity to:

- Beauty candidates
- Potential feebly interacting BSM

The topological triggers @ HLT2

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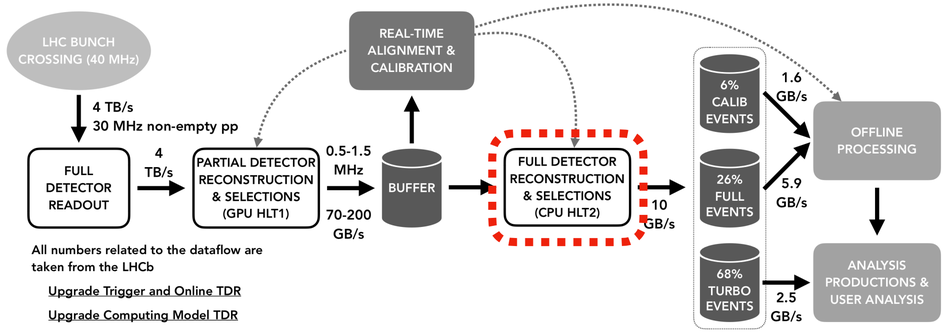

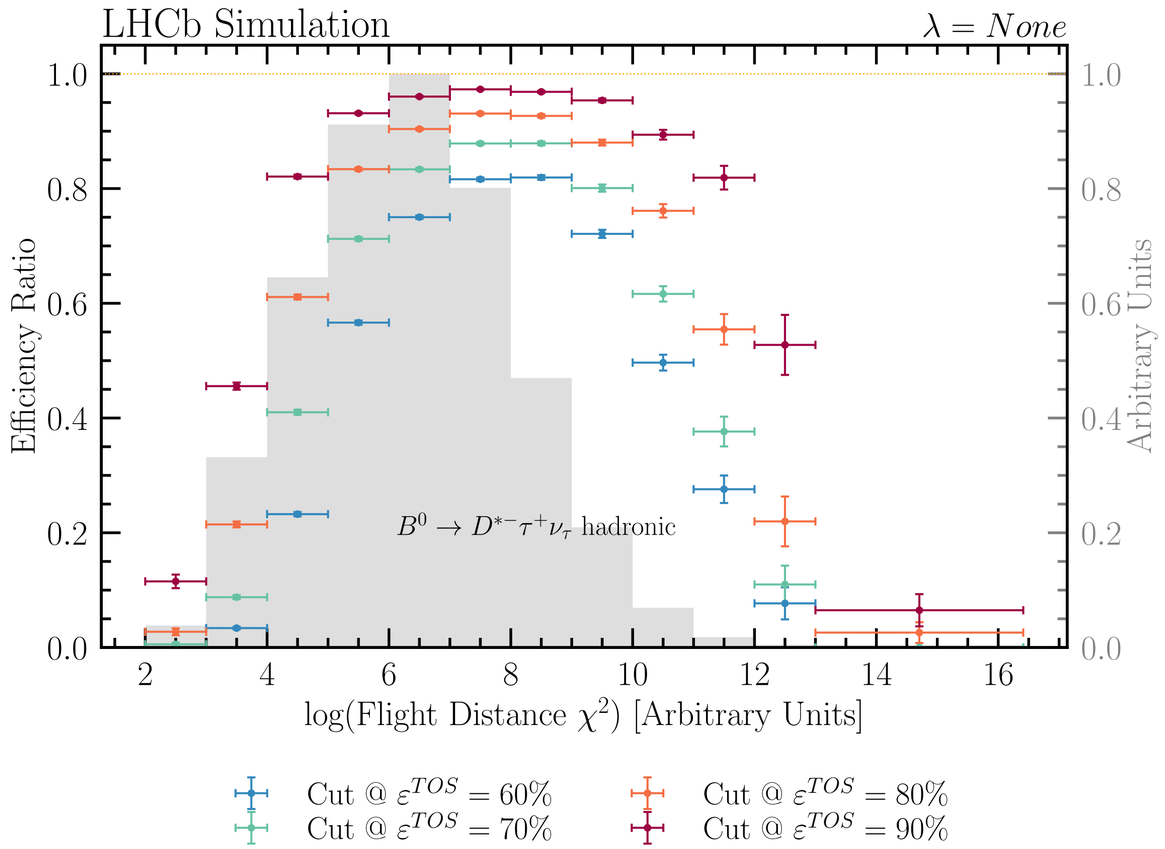

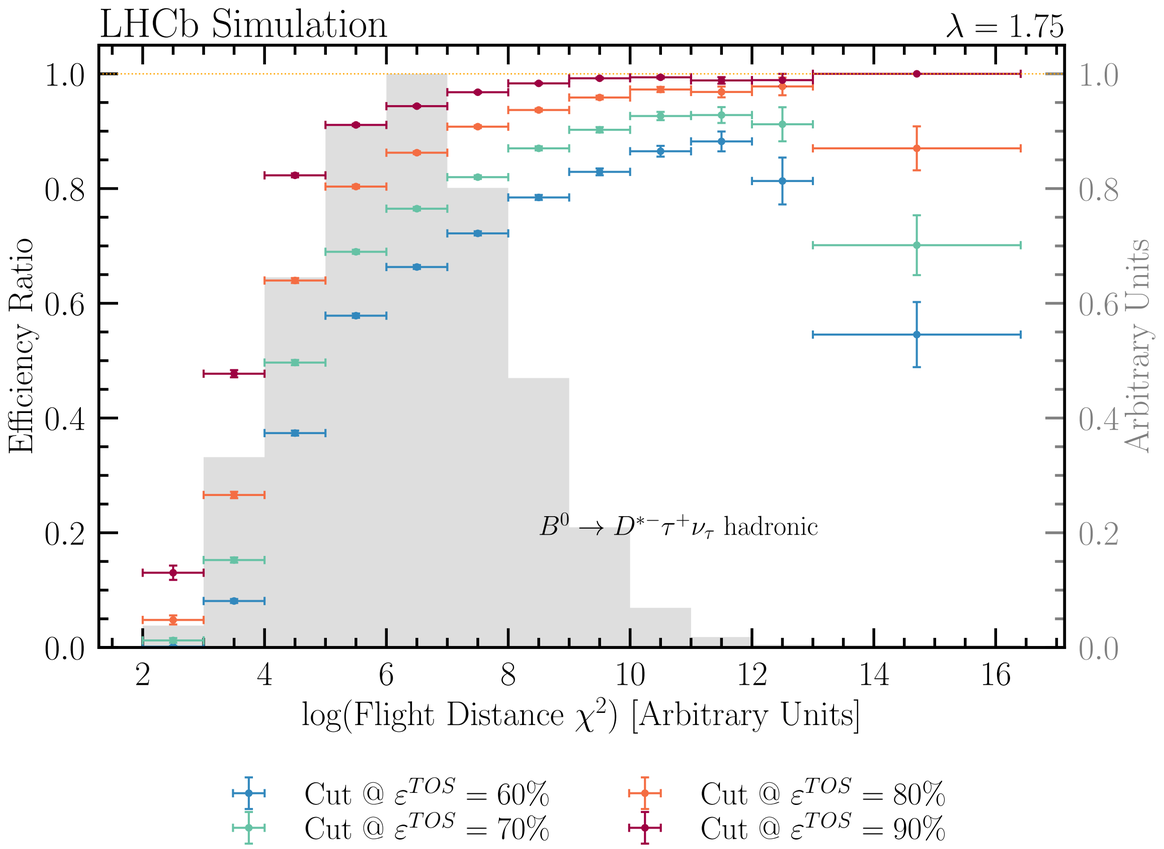

Unconstrained NN

Lipschitz Monotonic NN

Summary & outlook

- Lipschitz monotonic NNs offer a prescription to perform **physics-informed (irreversible) decisions**:
  - certified robustness and interpretability: formal guarantees at the level of the architecture design
  - expressiveness enabling deployment in high-throughput environments, such as the *fully software* LHCb Run 3 trigger
- Commissioning with 2024 LHCb data squarely in progress

Appendix

The LHCb Trigger