# High-Throughput GNN-Based Track Reconstruction on GPUs at LHCb

arXiv.2407.12119

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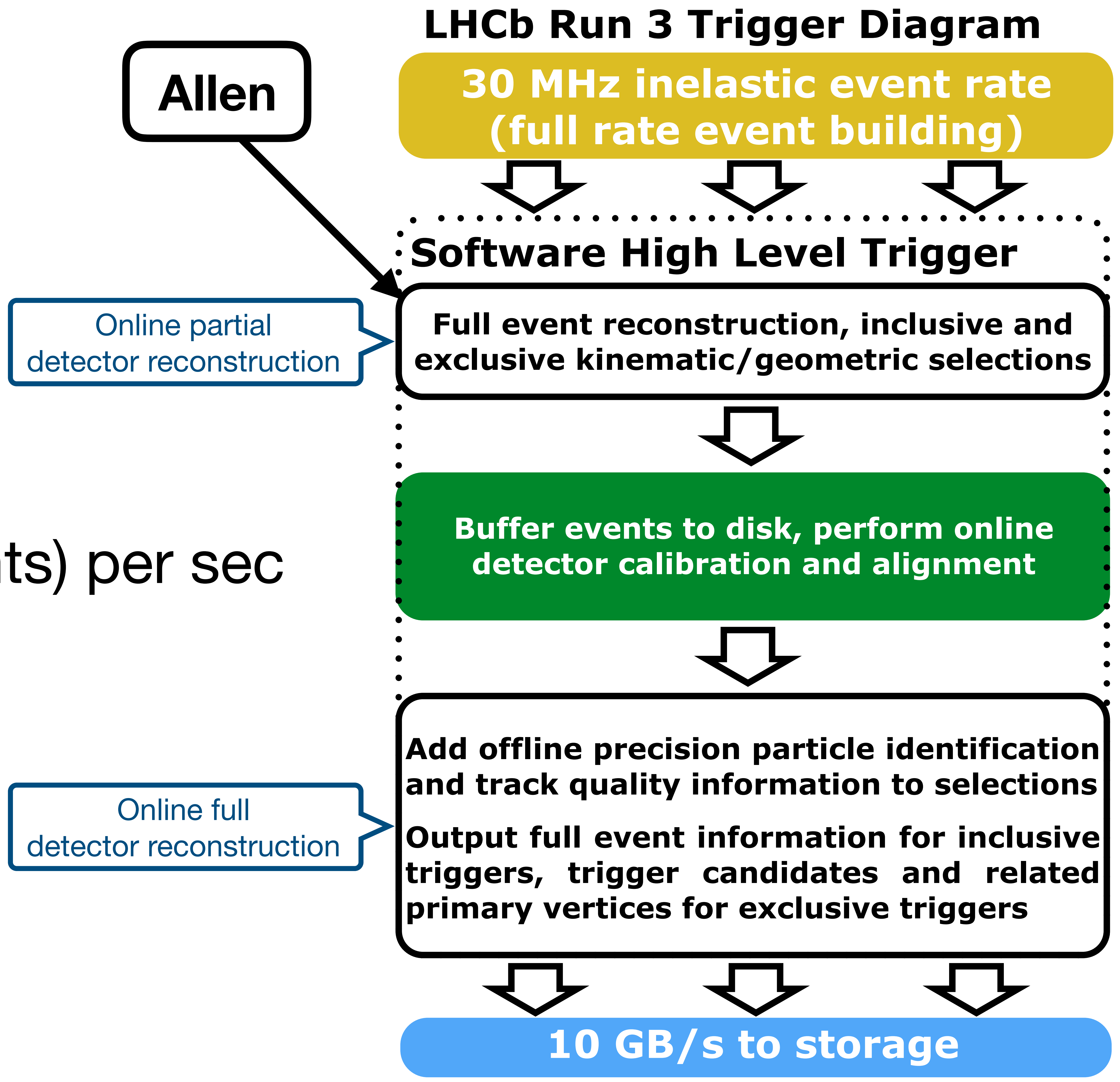
*On behalf of the LHCb Real-Time Analysis Project*

# LHCb Trigger

## Software trigger of LHCb

- Software high level trigger: 2 levels
- Allen: level 1 of the LHCb trigger
- Filters **30 million** bunch crossings (events) per sec
- Entirely on **GPUs**
- **Track reconstruction**
- Topological triggering on events

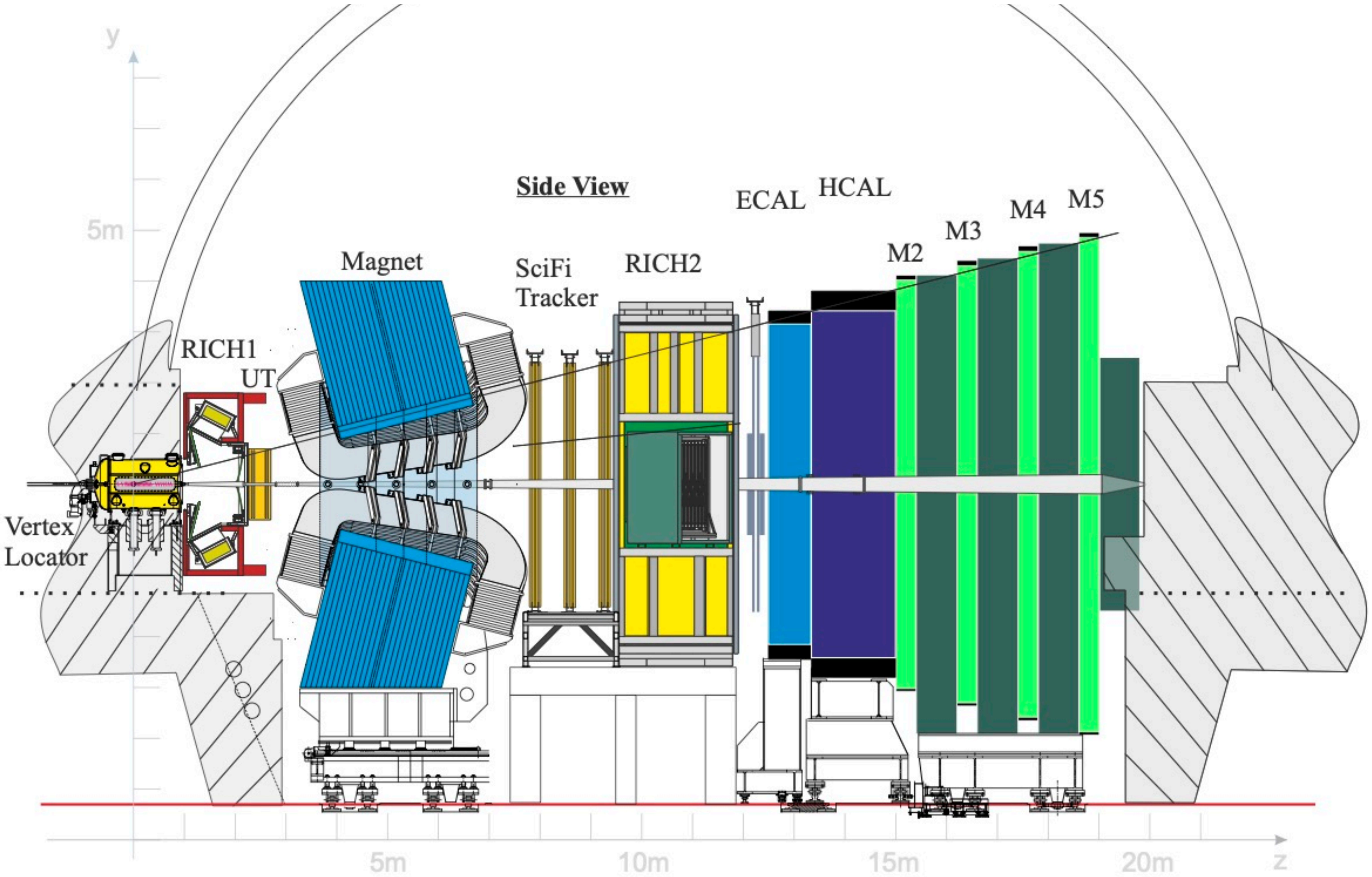



[LHCB-FIGURE-2020-016]

# LHCb Detector

## Focus: Vertex Locator (VELO)

- Momentum resolution: Δp/p ~ 0.5-1%
- B-meson decay time resolution: ~45 fs
- Impact parameter resolution: (15 +29/pT[GeV] ) μm




[LHCB-DP-2022-002]

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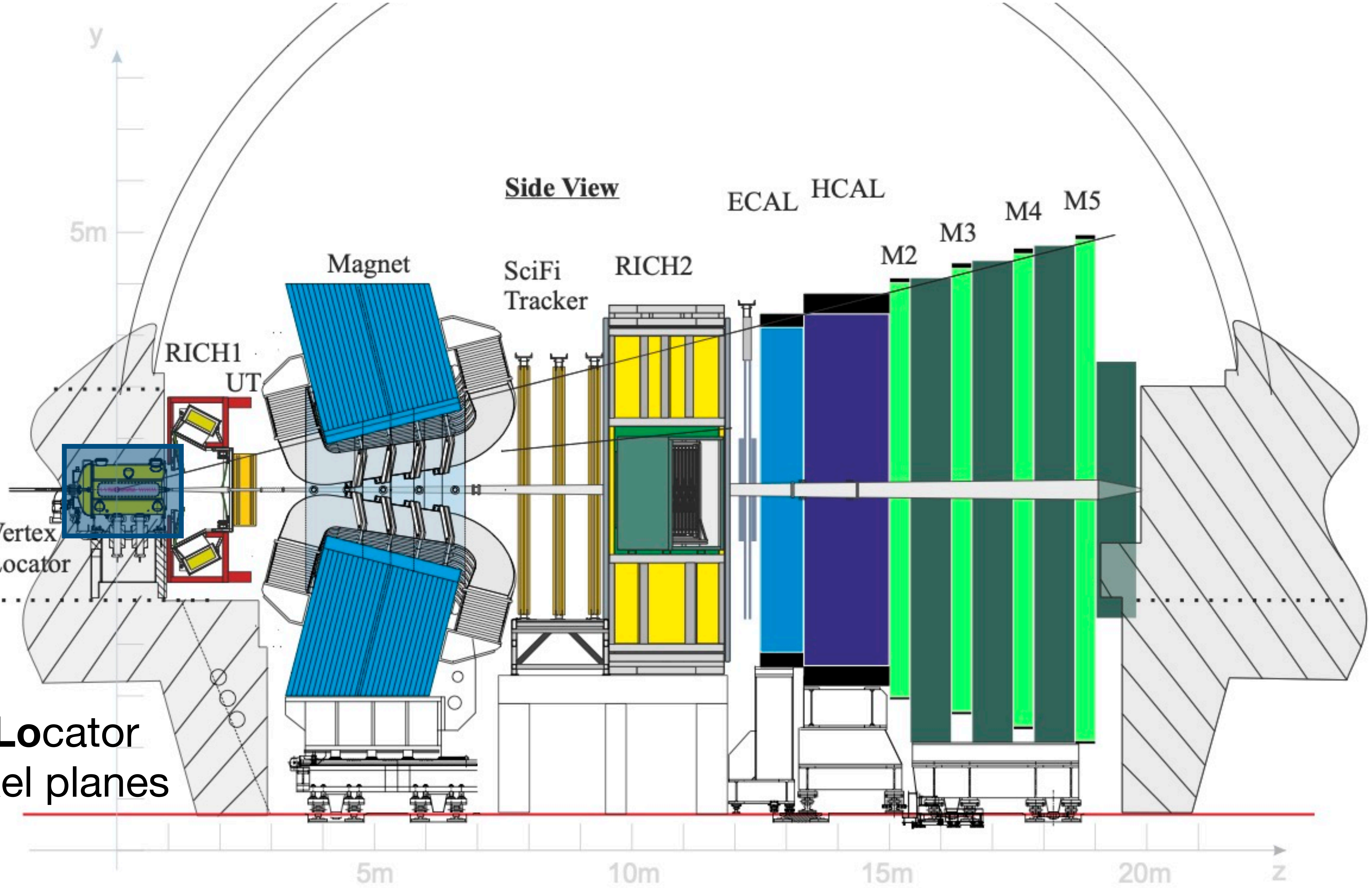


**VELO, Ve**rtex **Lo**cator
with silicon pixel planes

[LHCB-DP-2022-002]

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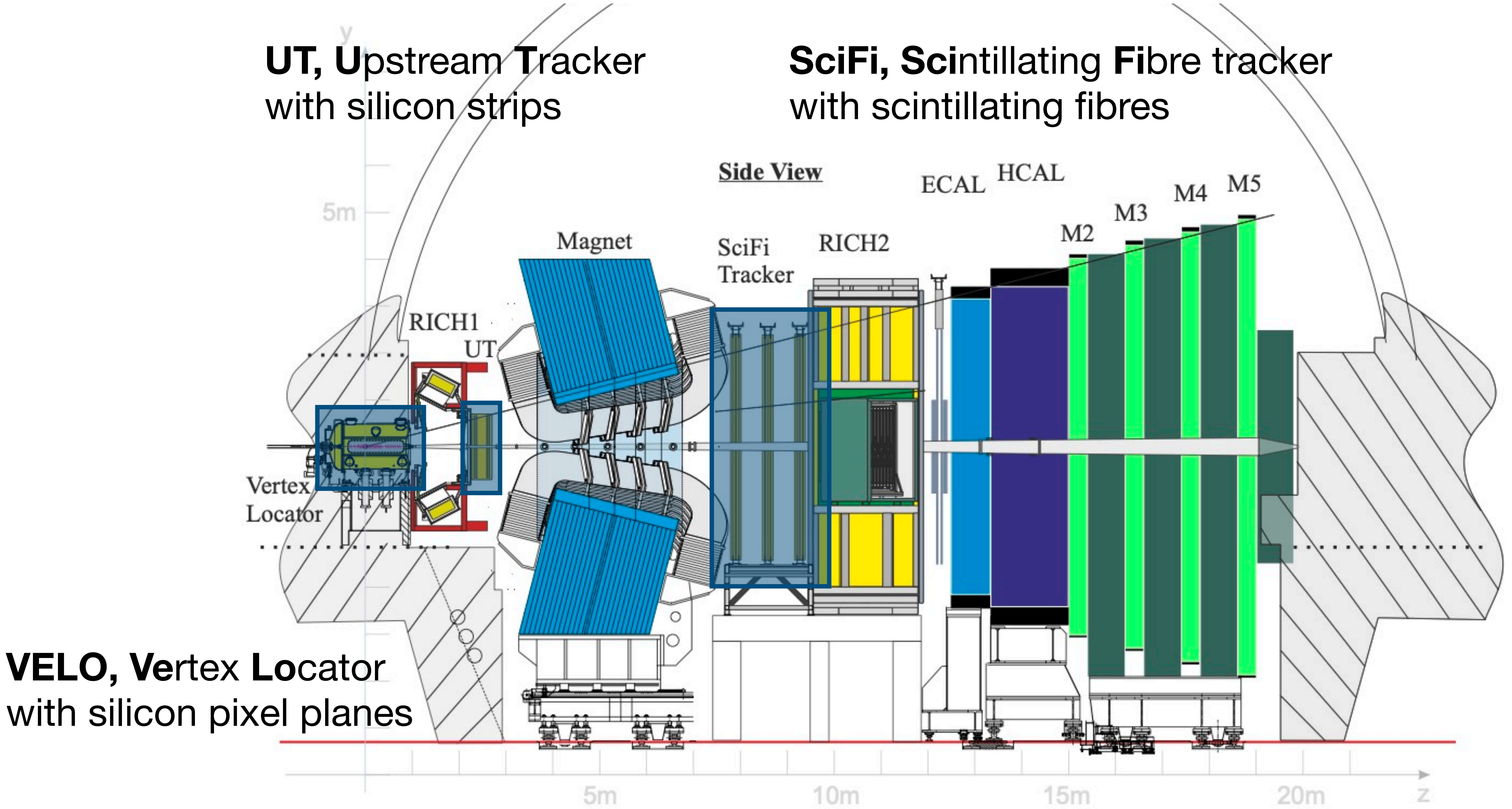


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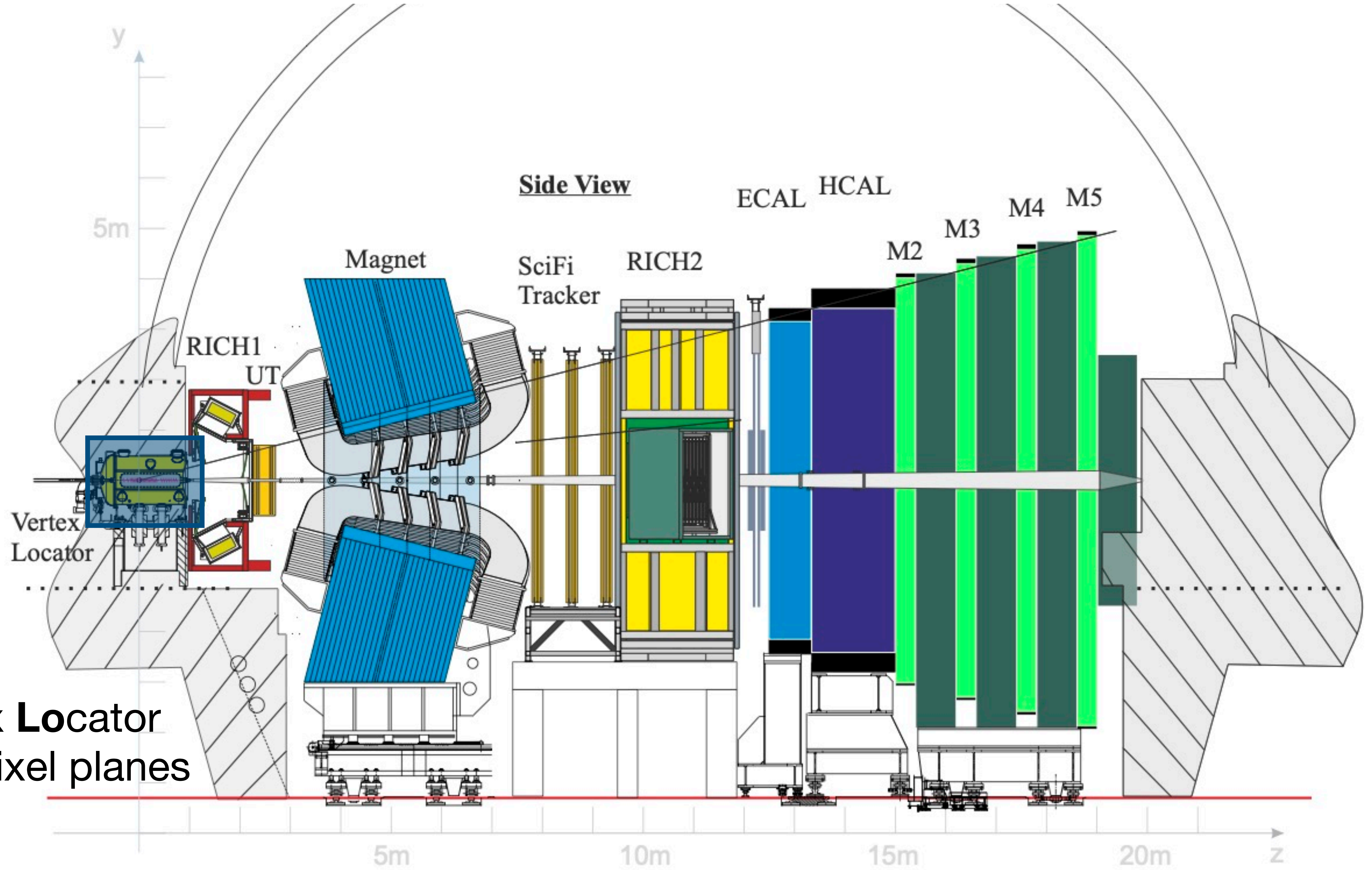


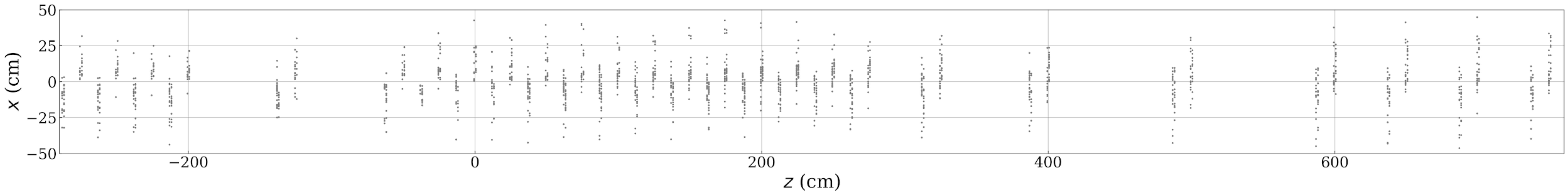

**VELO, Ver**tex **Lo**cator
with silicon pixel planes

[LHCB-DP-2022-002]

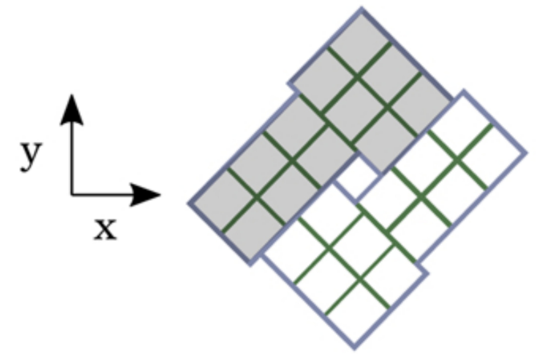
# Track Finding

## Finding tracks from the hits in the detector

“track reconstruction”, “tracking”

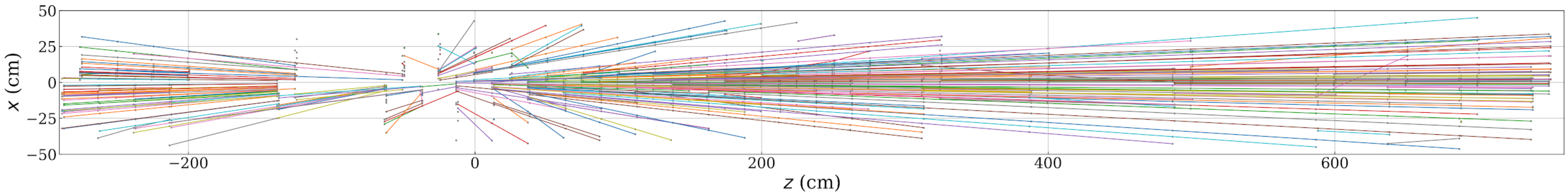



26 pairs of sensors




**Track finding**

**No magnetic field**



# ETX4VELO

## Tracking in the VELO with ETX4VELO

- Question: Will ML allow a more **efficient** use of computing resources?
- Expected increase in luminosity, next generation of detectors
- Inference time **close to linear** on # hits [DOI:10.1140/epjc/s10052-021-09675-8]
- vs classical **worse than quadratic** [DOI:10.48550/arXiv.2012.01563]

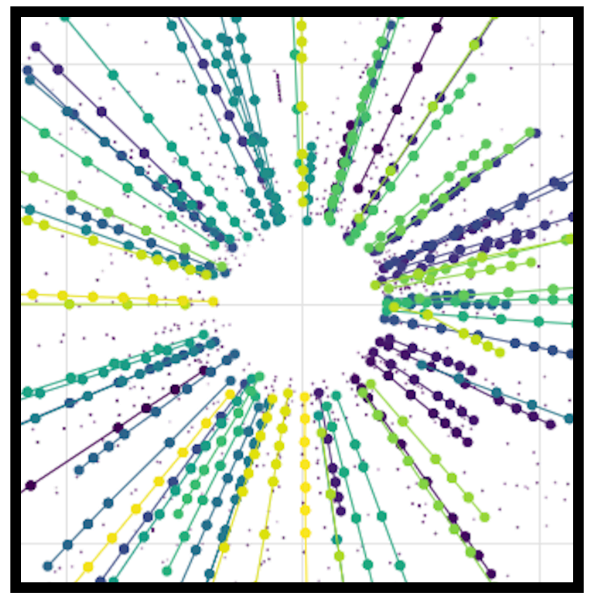
- Starting point: Exa.TrkX collaboration, talk@CHEP2021, PyTorch

# ETX4VELO

## Tracking in the VELO with ETX4VELO

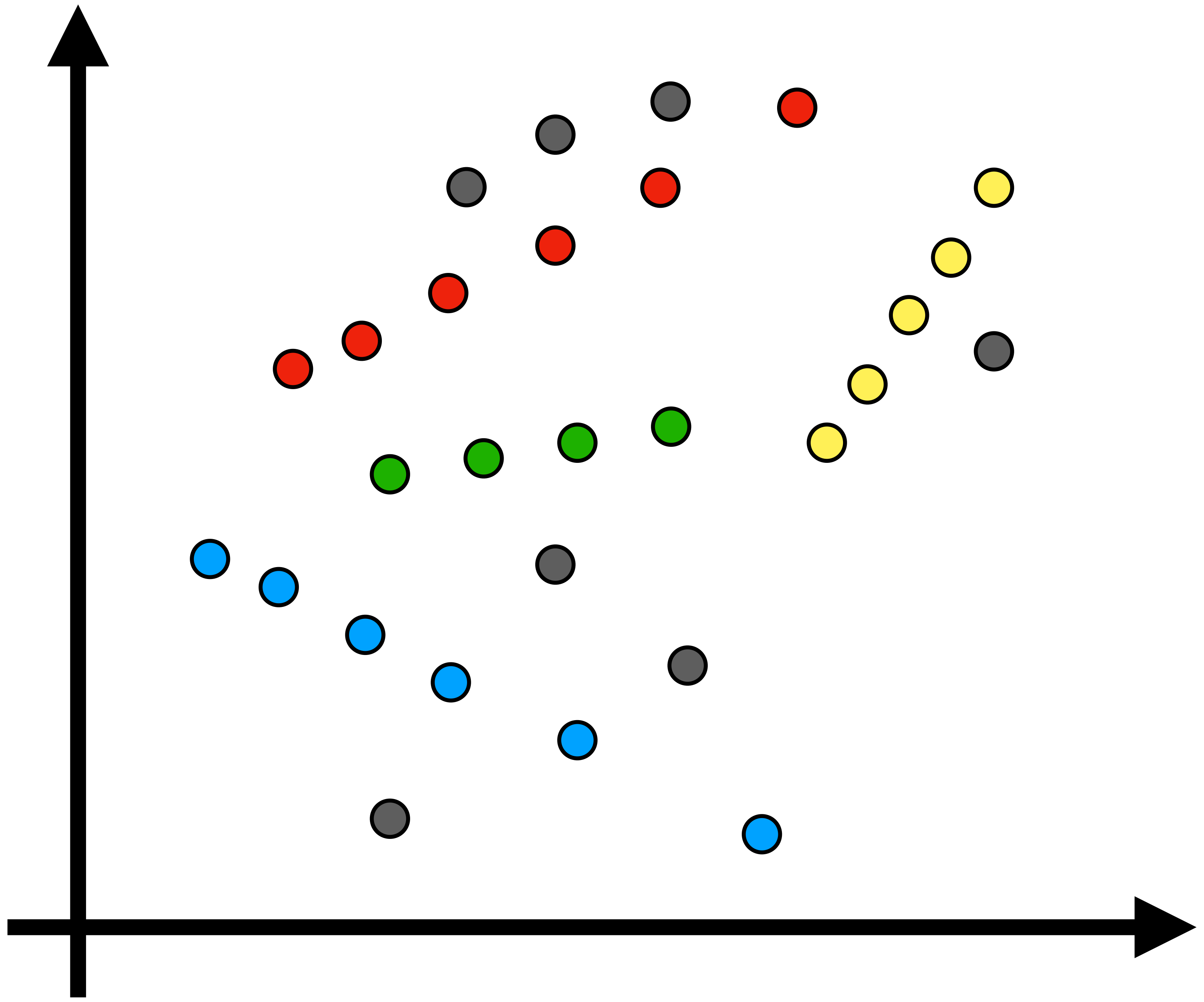
- Graph Neural Network-based pipeline for **track finding** in the VELO
- ETX4VELO, arXiv.2406.12869

- Comparable or superior physics performance to Allen
- Excellent **electron reconstruction** achieved using **triplets**
- Significantly reduced **fake rate**



# ETX4VELO

## How do we get a graph from the hits?



Hits in the detector

# ETX4VELO

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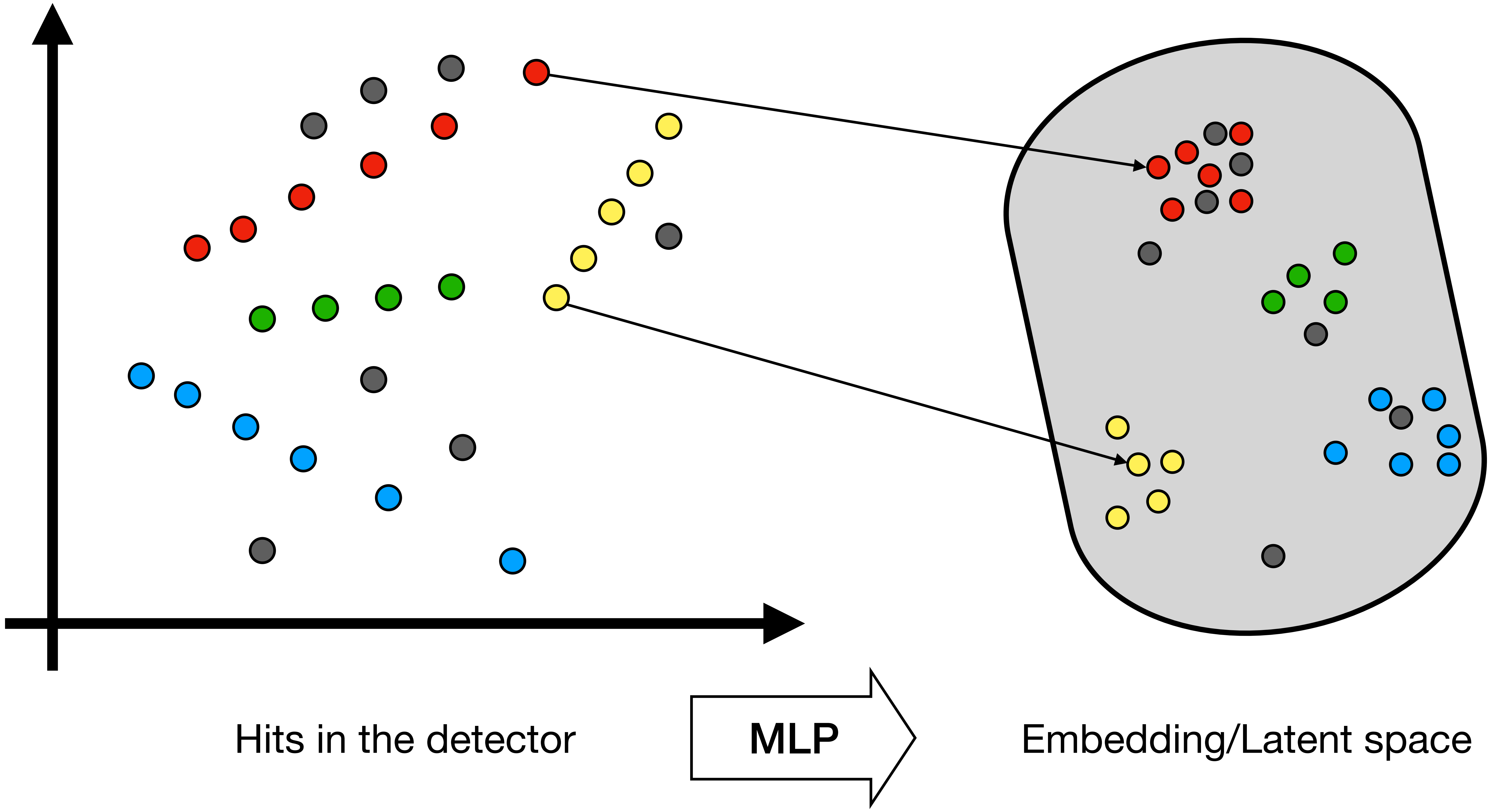

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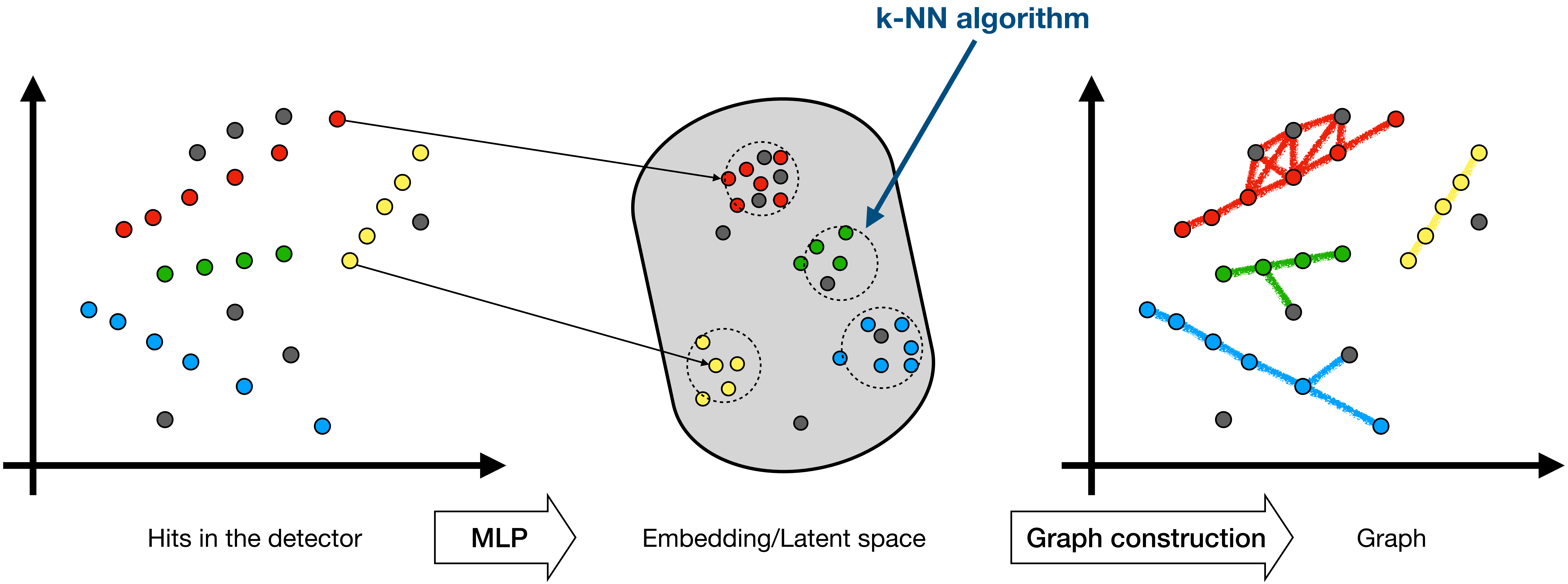

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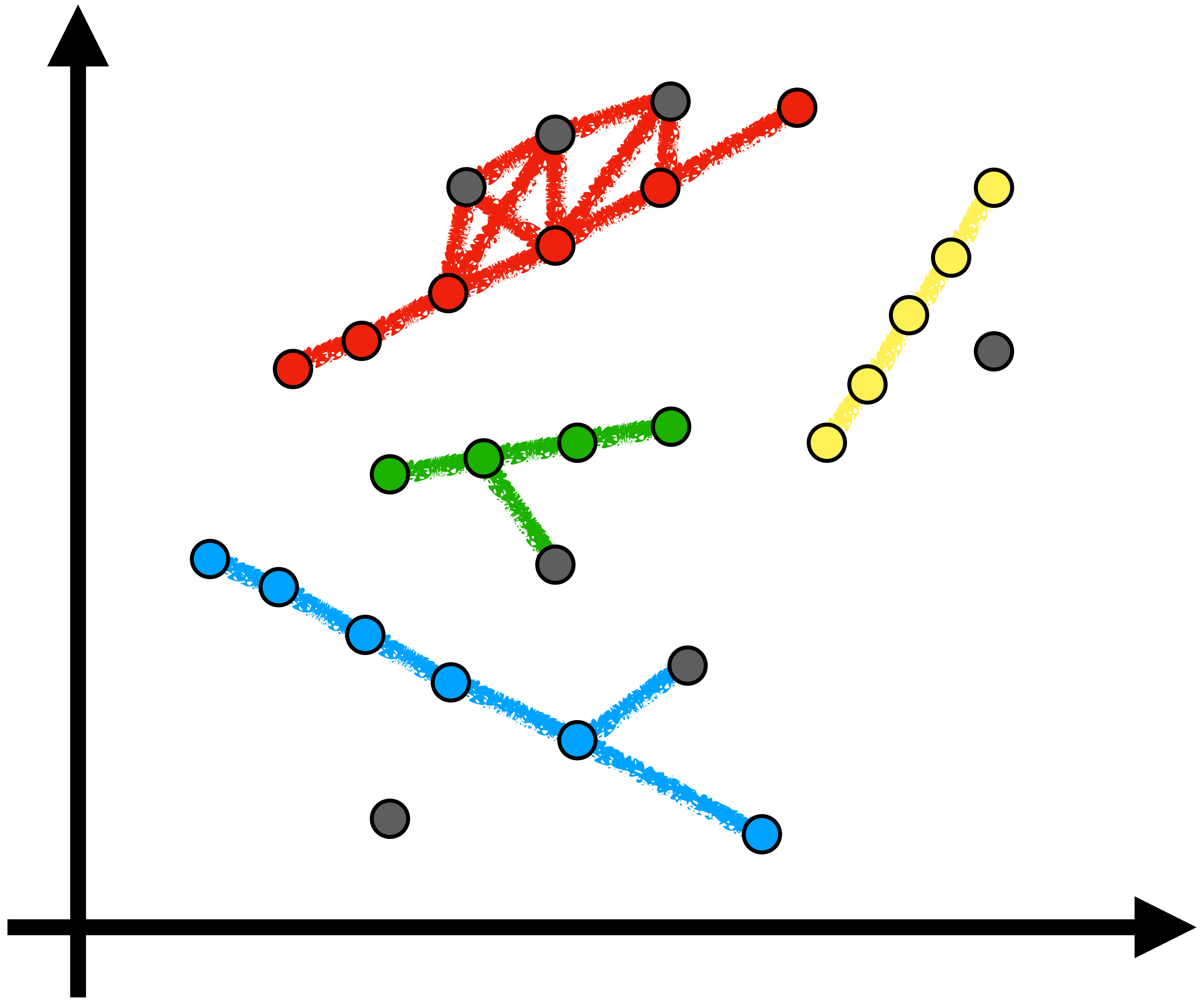

Graph

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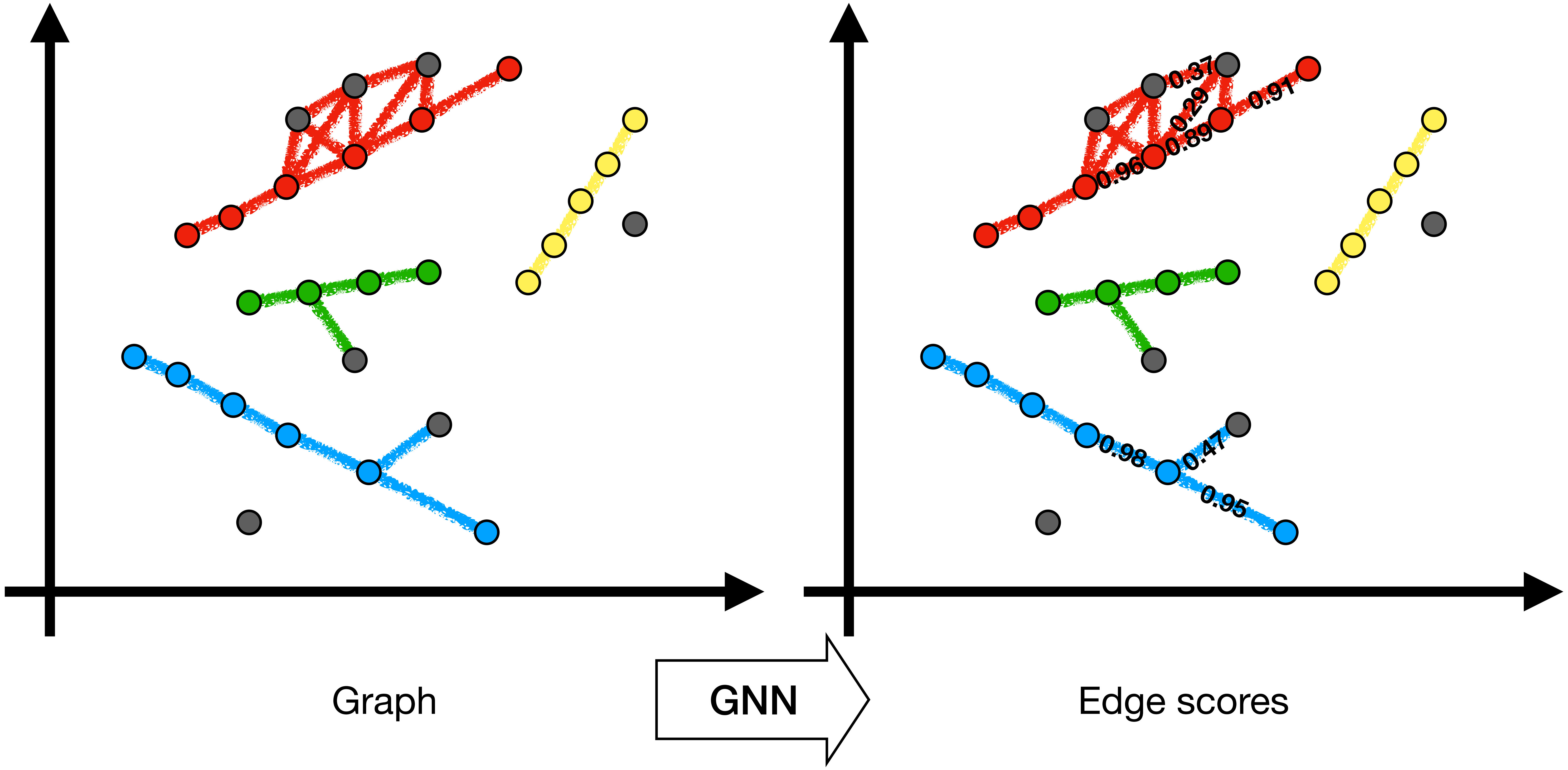

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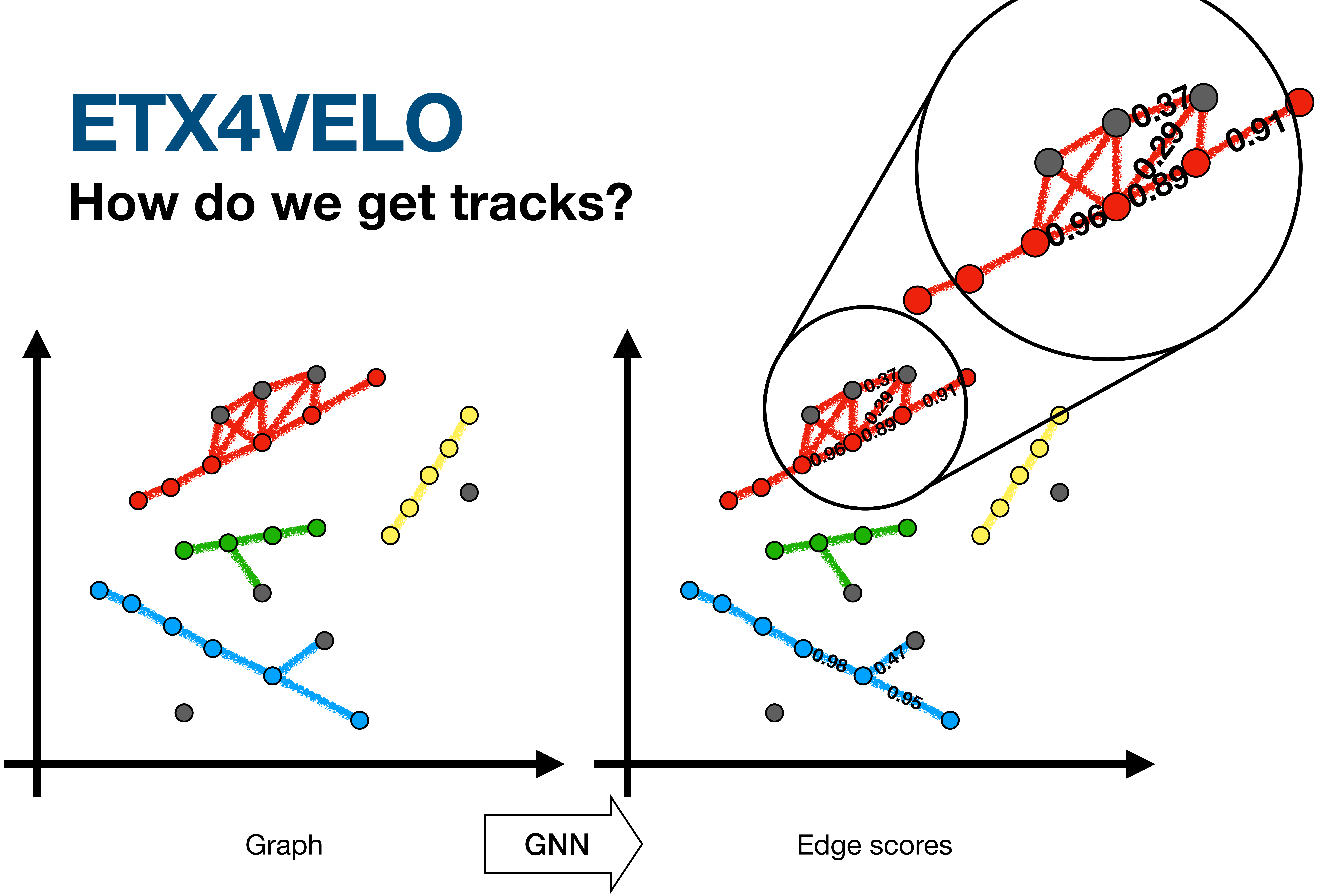

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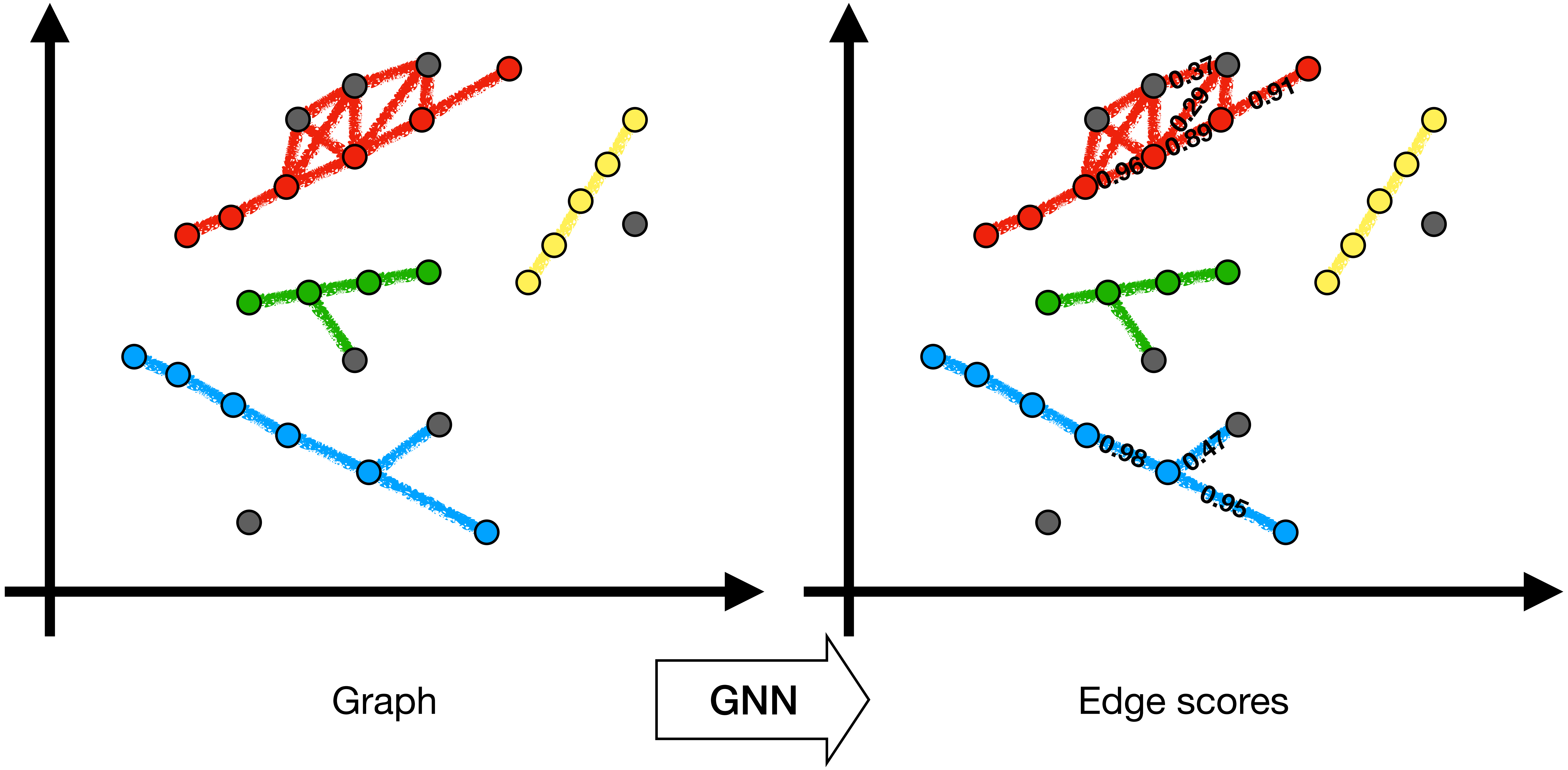

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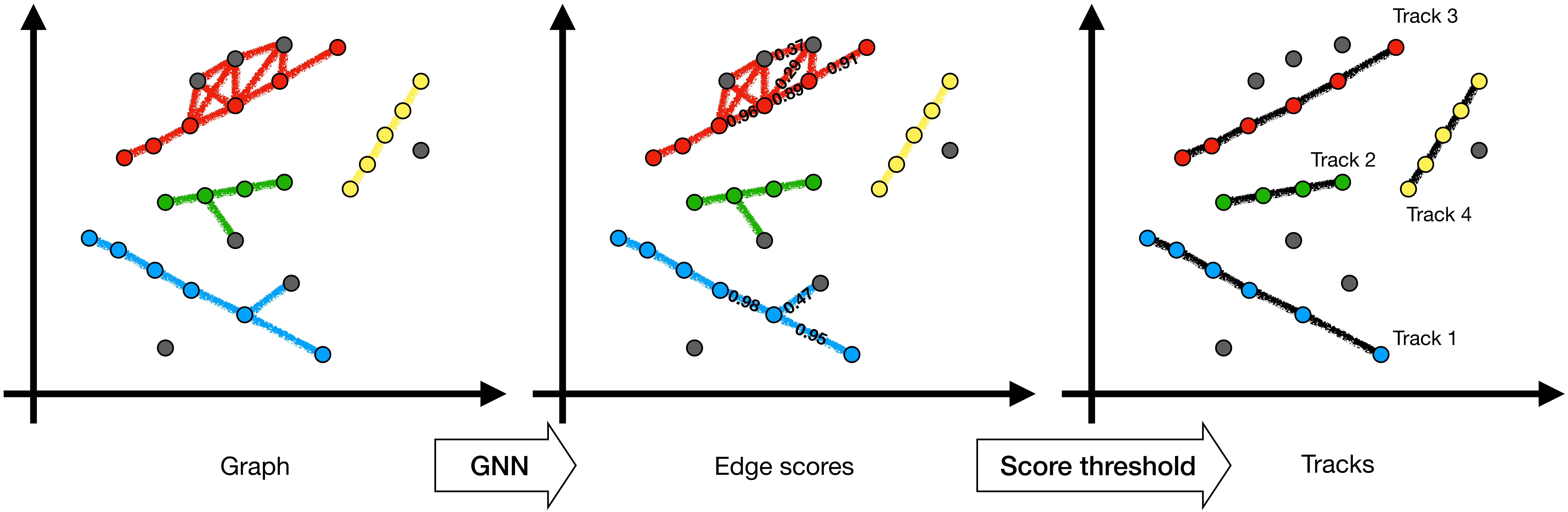

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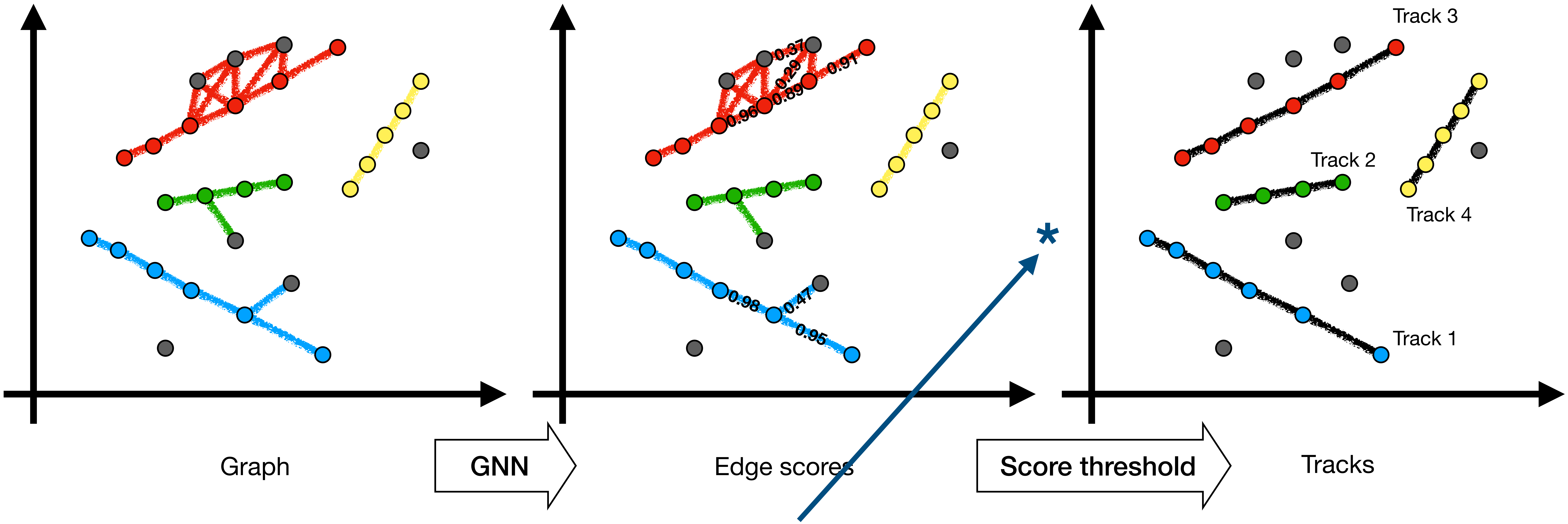



*** Triplet-based methodology to improve electron reconstruction, see backup**

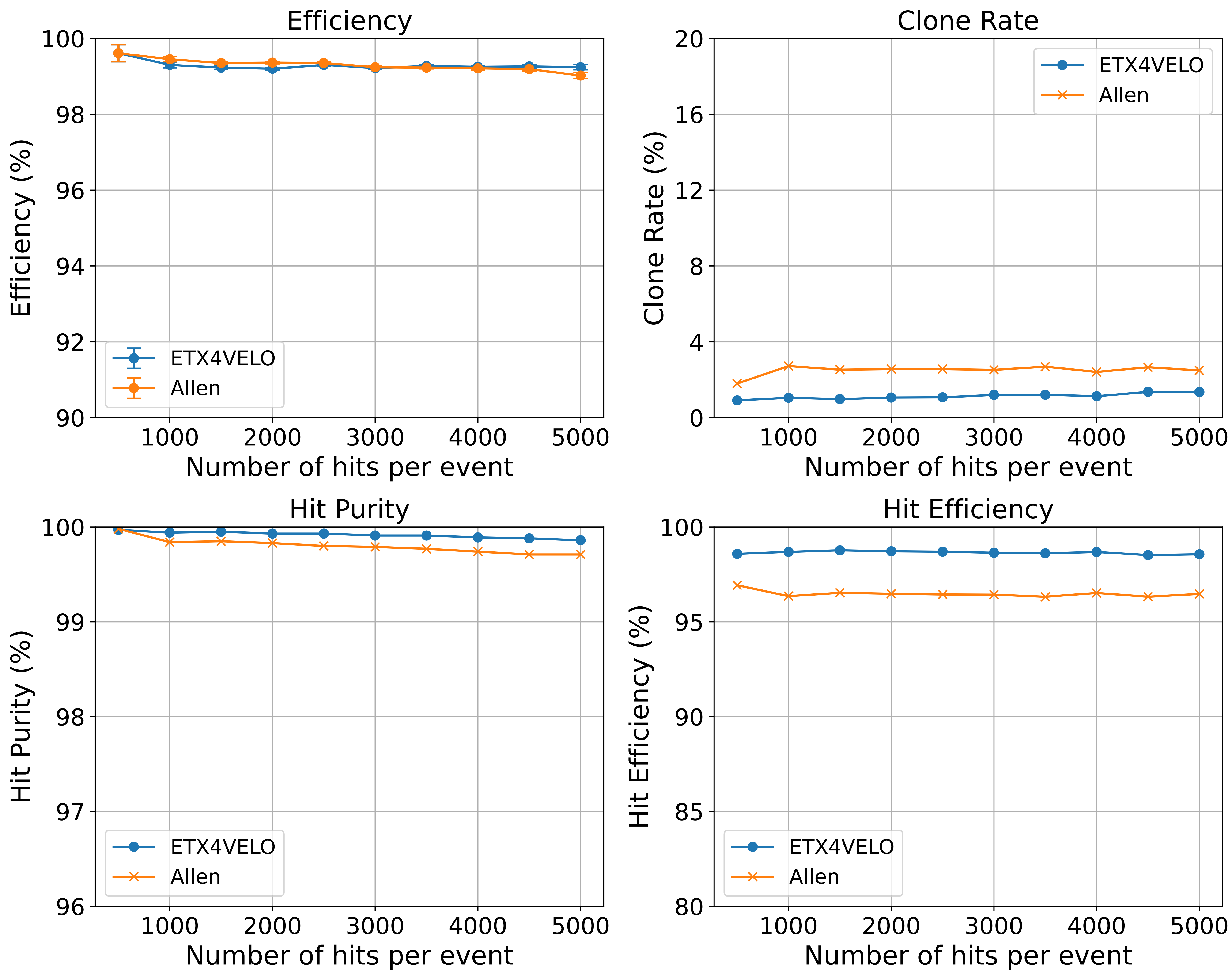
# ETX4VELO

## Physics performance

| | ALLEN | ETX4VELO |
|---|---|---|
| Fake rate | 2.17 % | 1.04 % |

*For particles leaving long tracks*

*For particles leaving long tracks, no electrons*



# ETX4VELO Main Objectives

- **Neural network for tracking with state-of-the-art physics performance** ✓
- High computational performance (throughput)

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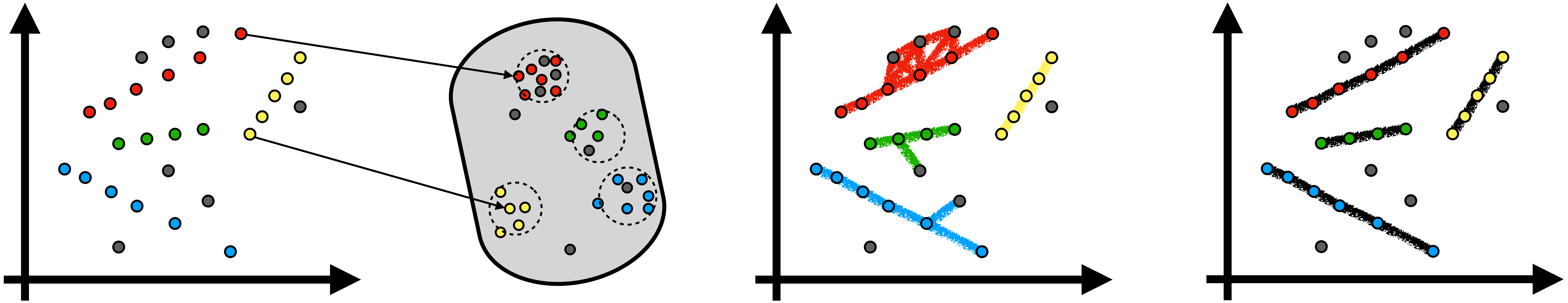
**ETX4VELO inside LHCb framework (Allen)**

# ETX4VELO GPU Version

## Inference steps



| | | | | |
|---|---|---|---|---|
| Hits in the detector | **MLP** | Embedding/Latent space | **Graph construction** | Graph |
| Graph | **GNN** | Edge scores | **Score threshold** | Tracks |

# ETX4VELO GPU Version

## Inference steps

Hits in the detector → **MLP** → Embedding/Latent space → **Graph construction** → Graph

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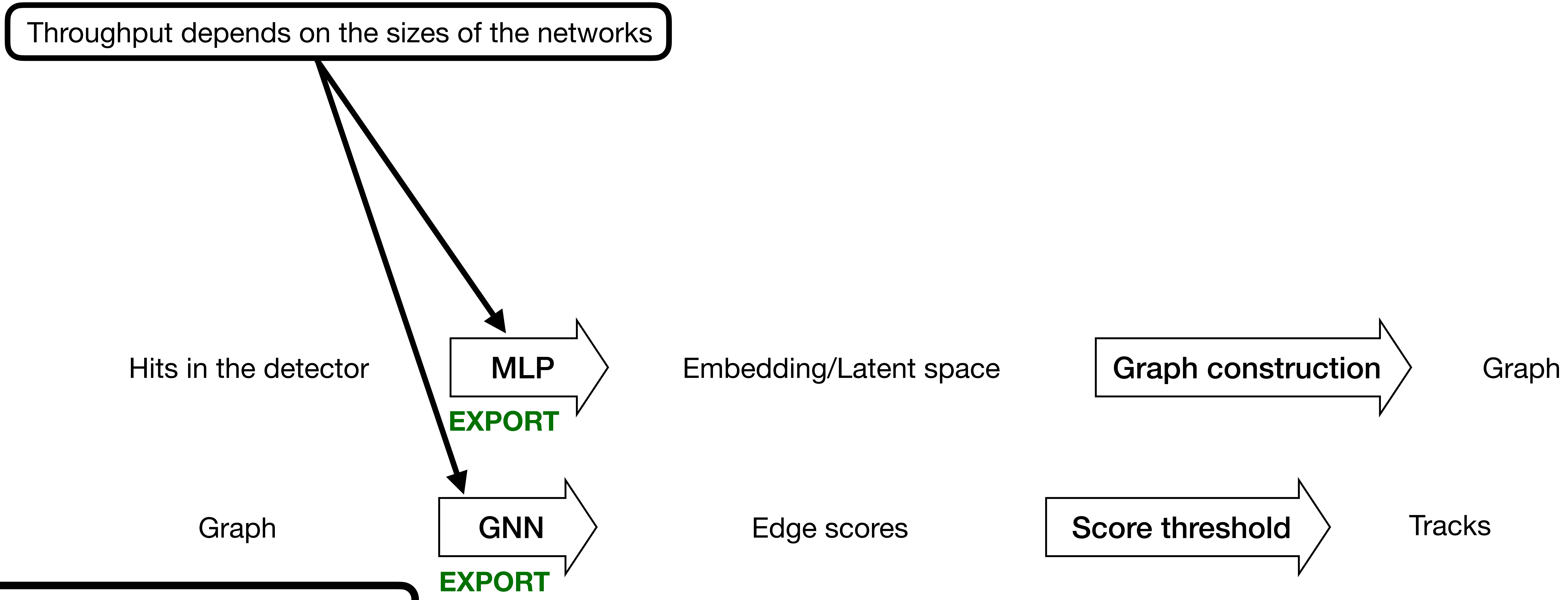


- **EXPORT: ONNX**
- **IMPLEMENT: C++/CUDA**

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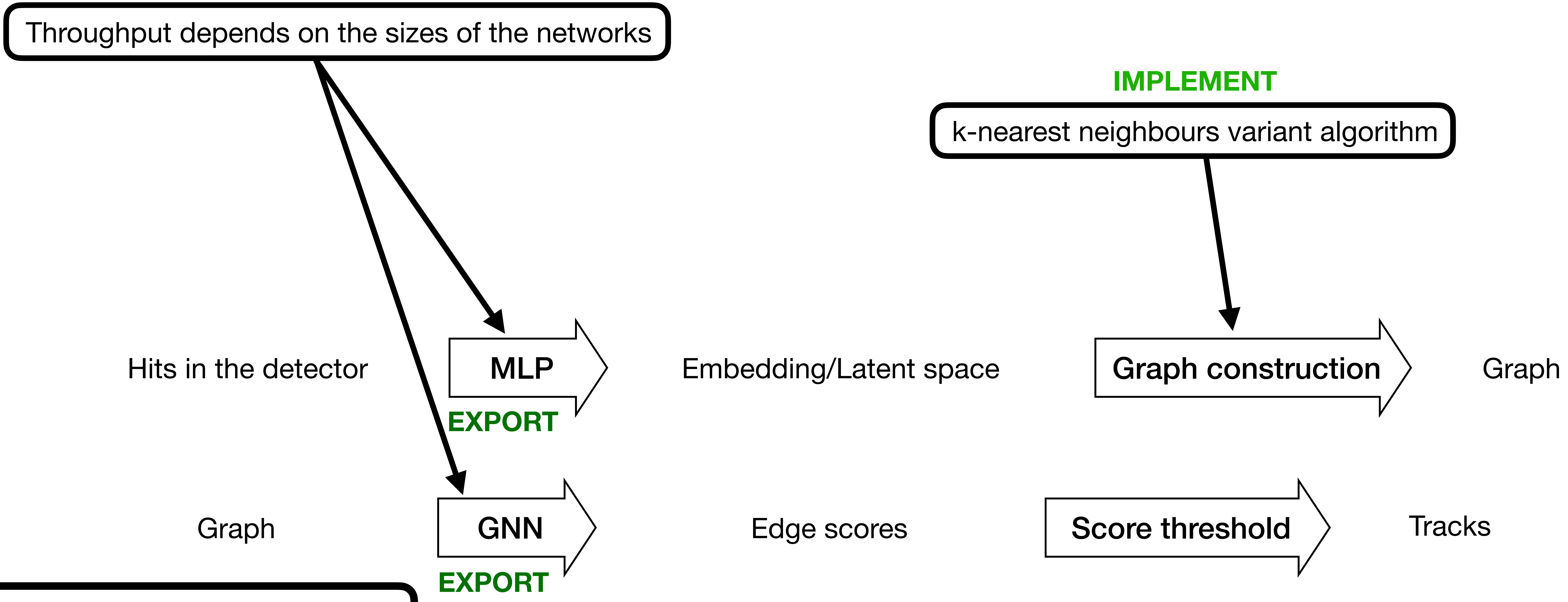


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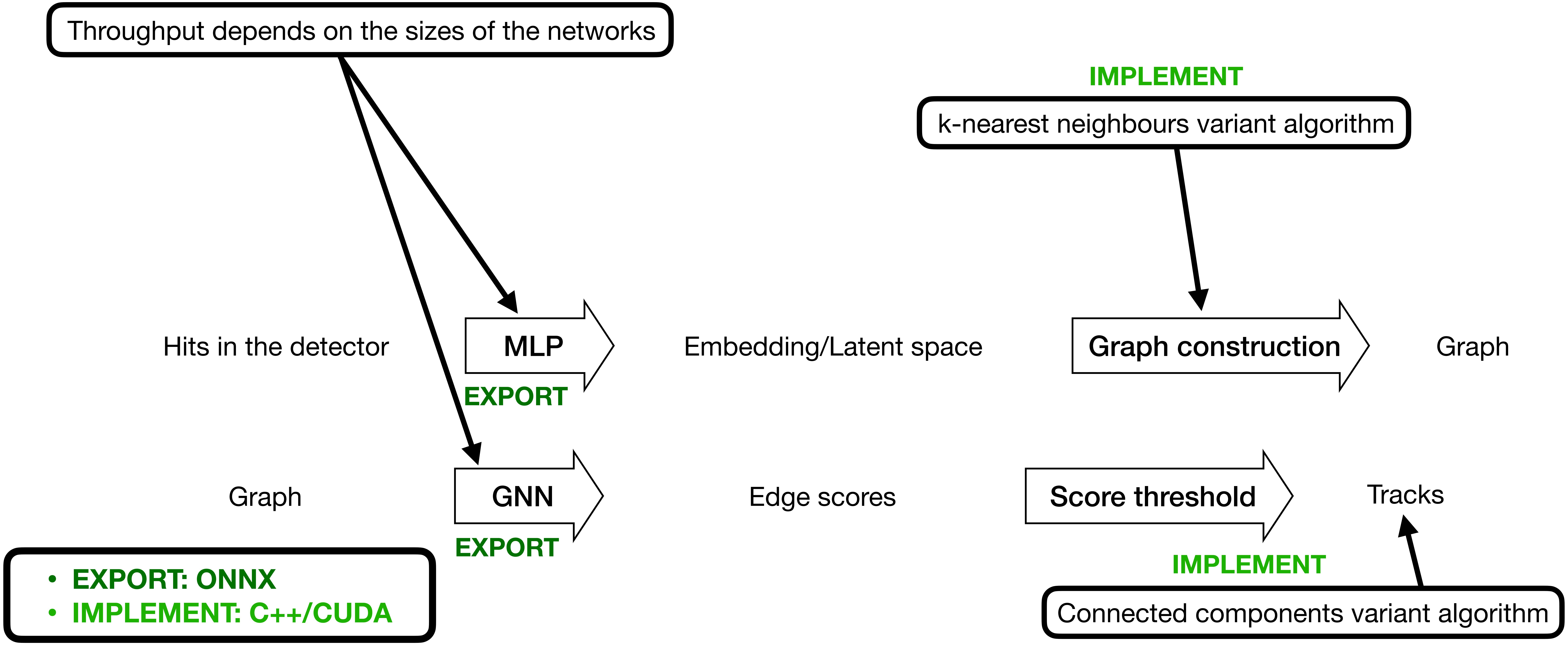
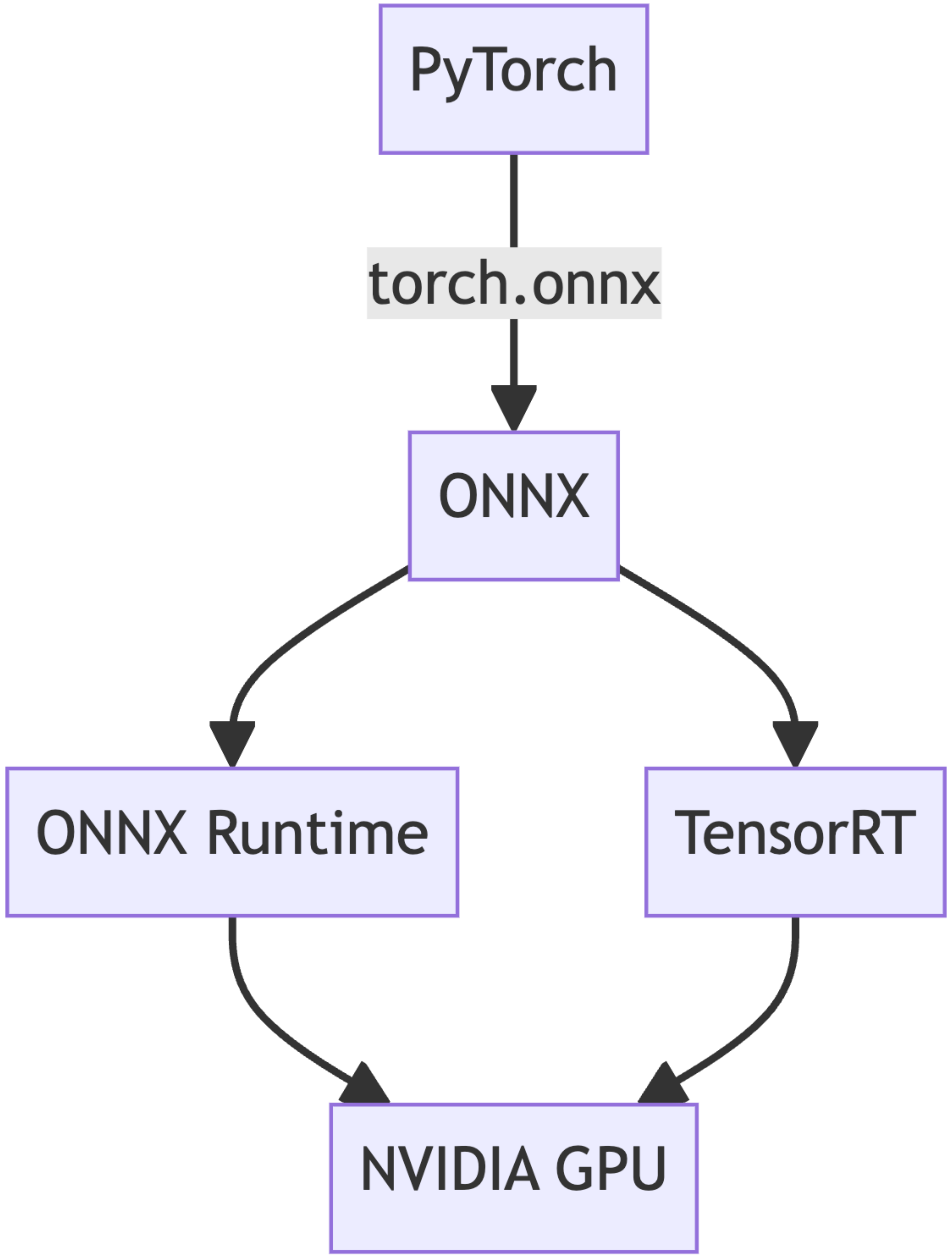


# ML Inference on GPU (Allen)

- Throughput: infer events in **batches**
- Maximum number allowed by GPU memory

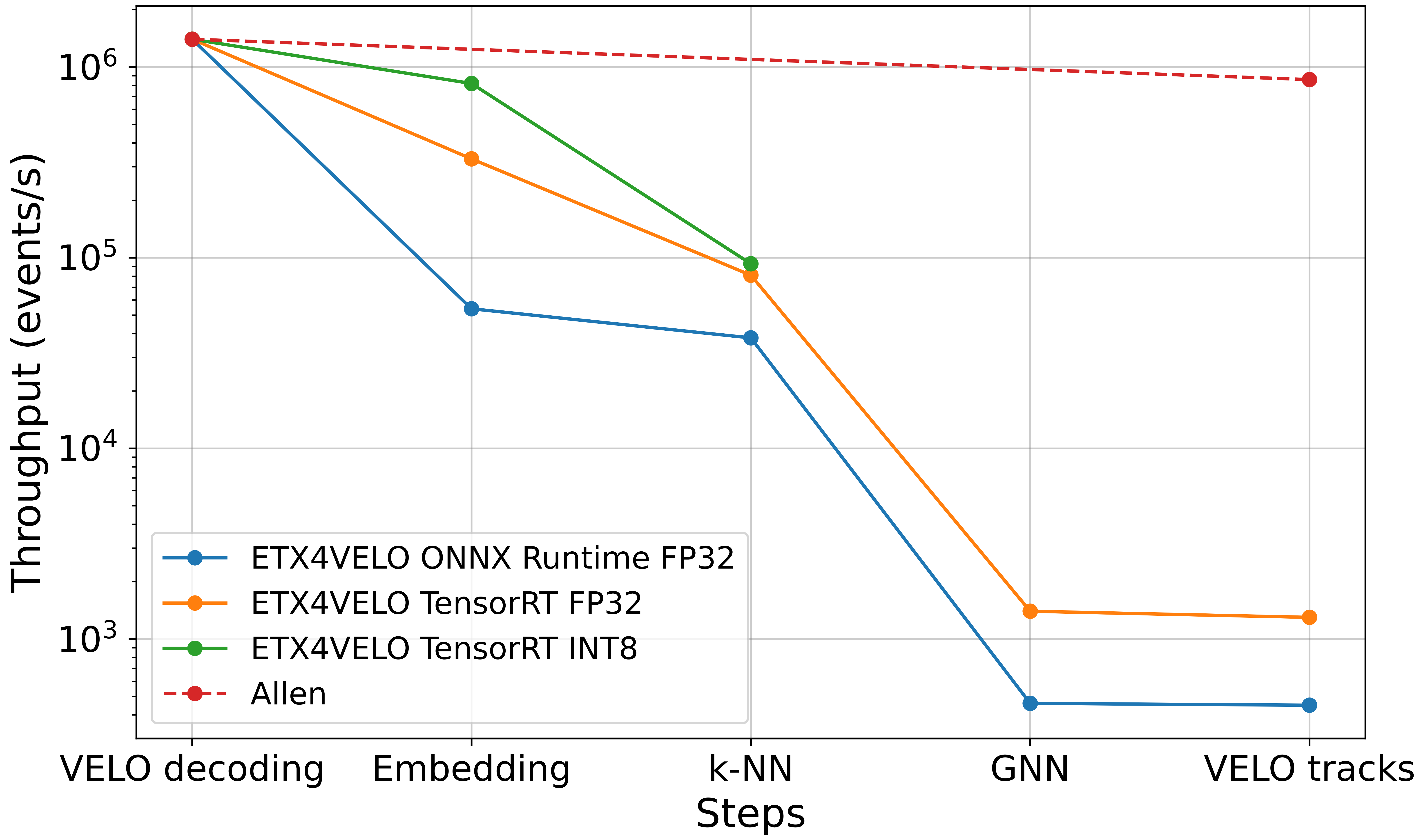



- **ONNX Runtime** + CUDA Execution Provider
- **TensorRT**

# ETX4VELO

## Computational performance

*NVIDIA GeForce RTX 3090*



# Conclusion

arXiv.2407.12119

**Track finding with ETX4VELO**

- **Superior physics performance** to state of the art reachable

**GPU version of ETX4VELO**

- **End-to-end** implementation in **LHCb** (Allen)

**Next steps**

- Quantization of the **GNN**
- Further optimization of the pipeline

## Thank you!

I would also like to thank the LHCb RTA reviewers, Núria Valls Canudas, Simon Akar, and Da Yu Tou, for their constructive comments

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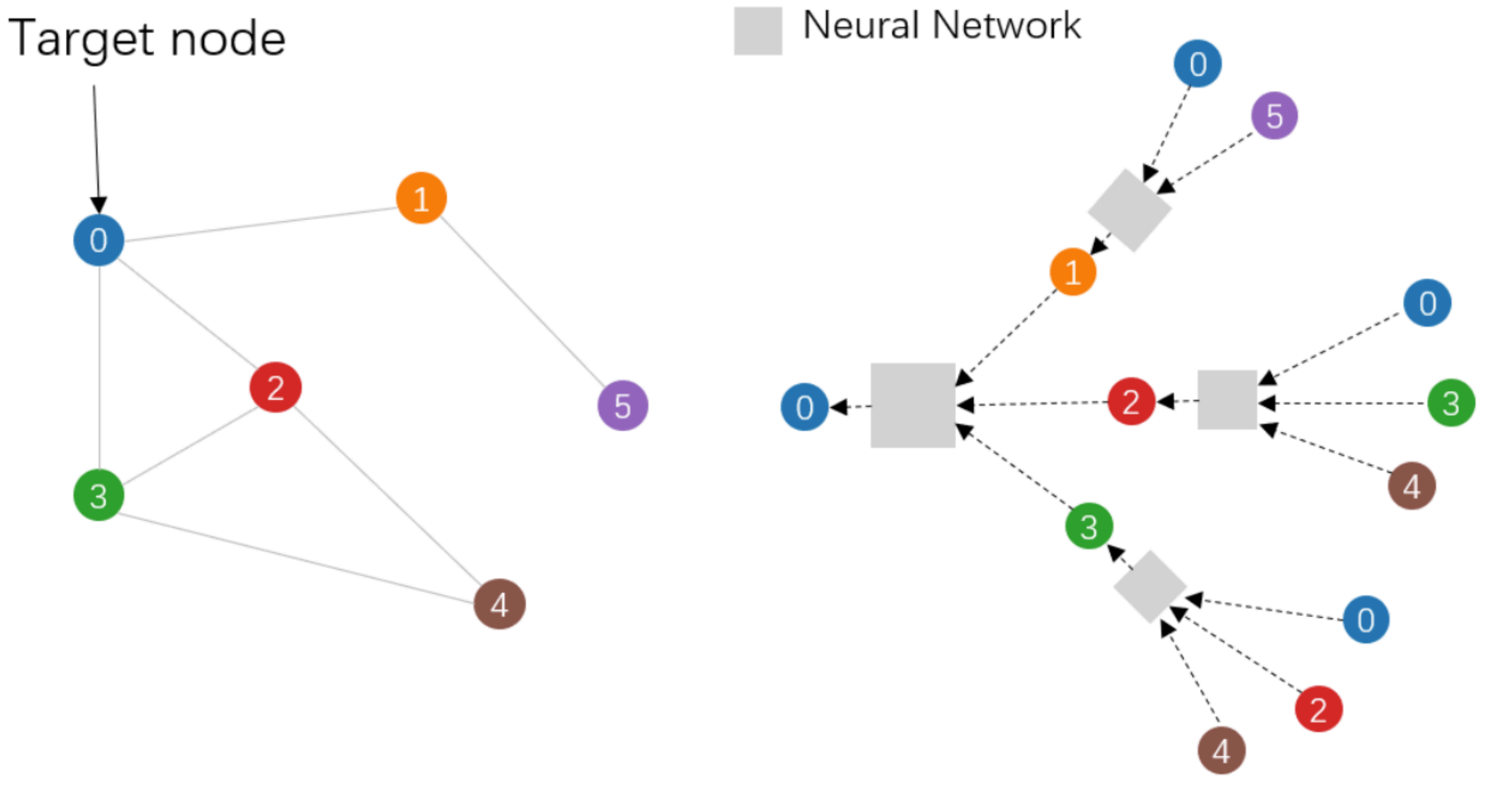
# Backup

# Graph Neural Networks

## How?

- GNN architecture:
  - Node features
  - Aggregation
  - **Neural message passing**



(a) Input graph (b) Neighborhood aggregation

[DOI:10.1109/TVCG.2022.3148107]

# ETX4VELO

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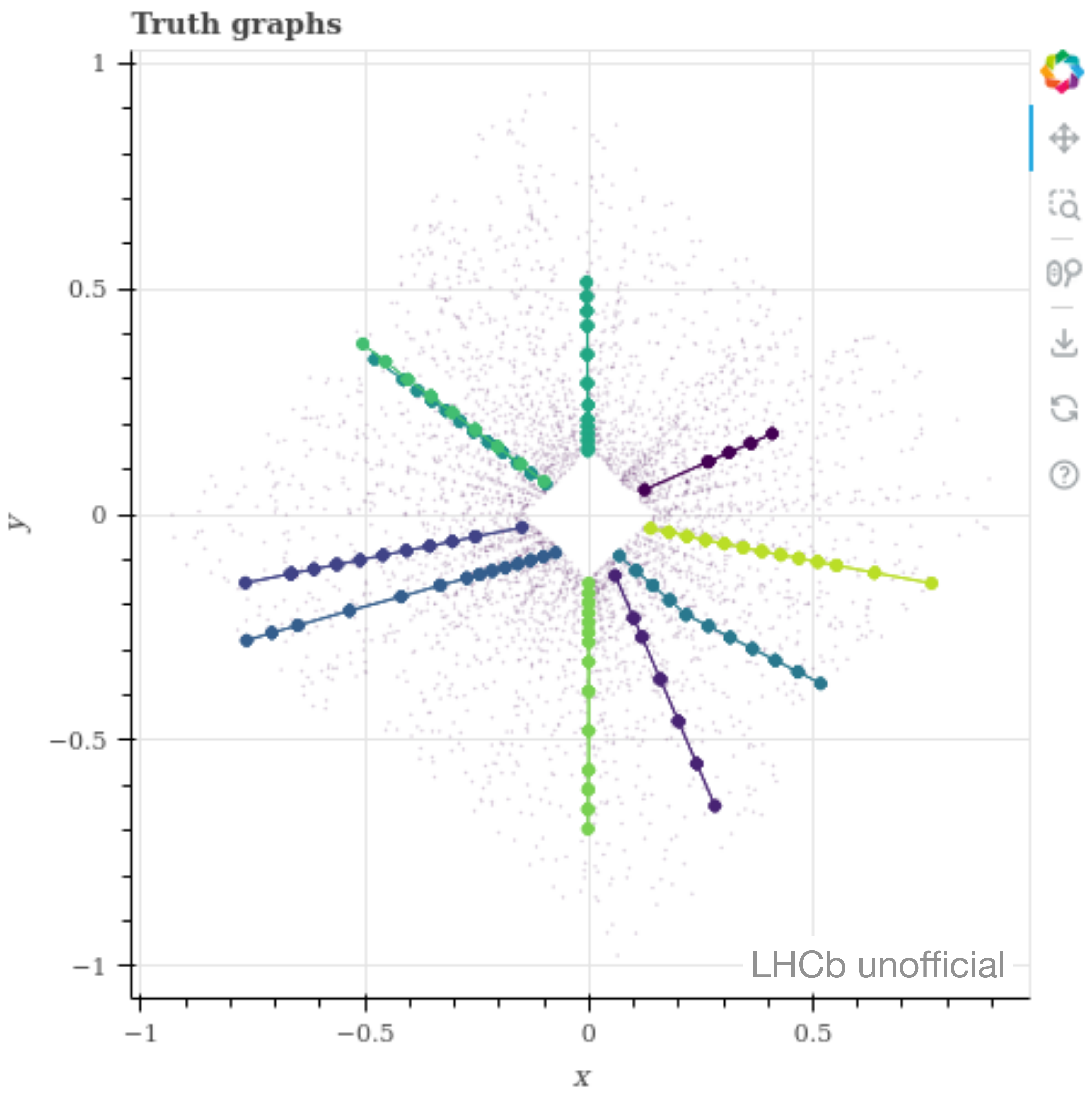
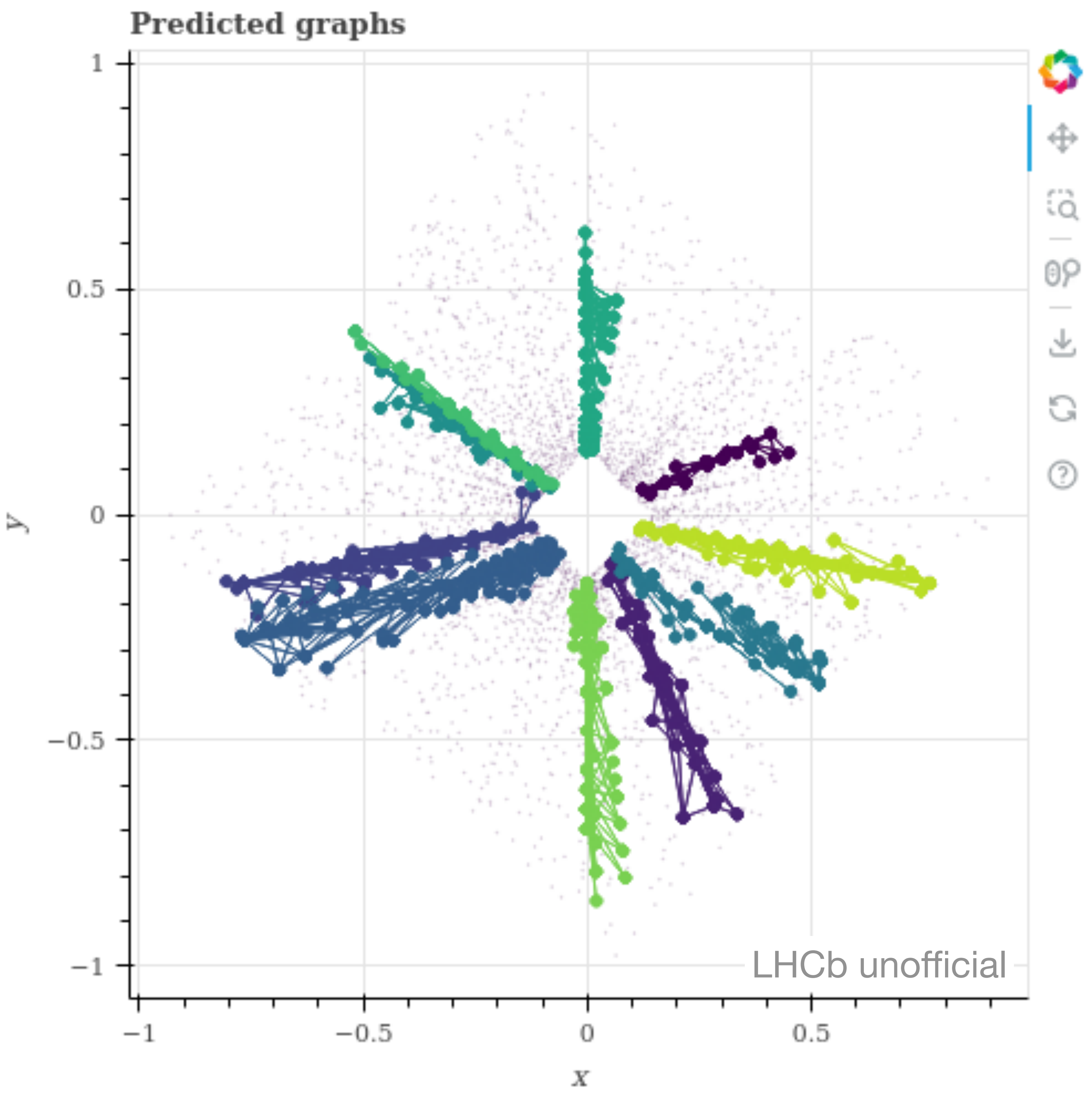
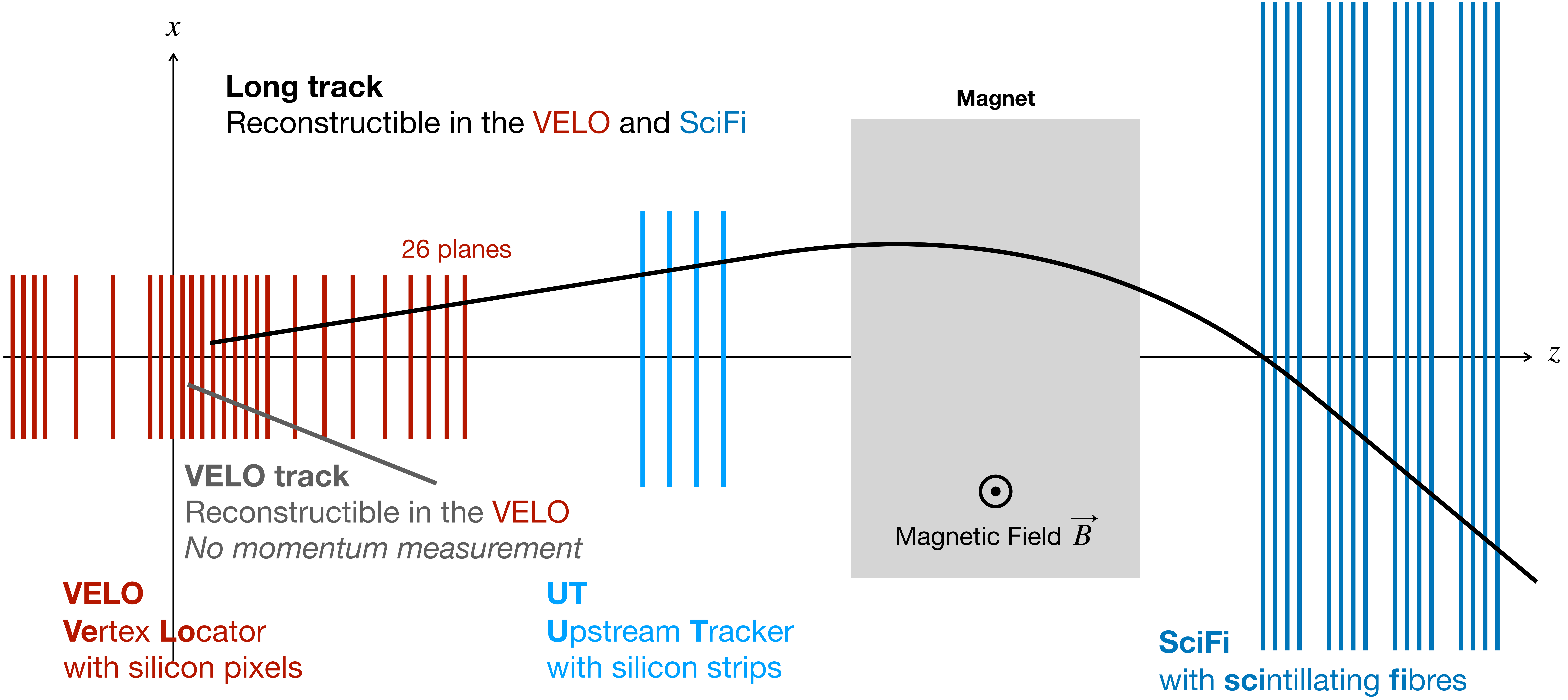


# The LHCb Detector

## Tracks in LHCb



# ETX4VELO

## Physics performance

| Proportion of | ALLEN | ETX4VELO |
|---|---|---|
| Reconstructed particles | 99.06 % | 99.23 % |
| Duplicate tracks | 2.63 % | 1.37 % |
| Fake tracks | 2.17 % | 1.04 % |

*For particles leaving long tracks*

# ETX4VELO

## Problem with electrons: shared hits

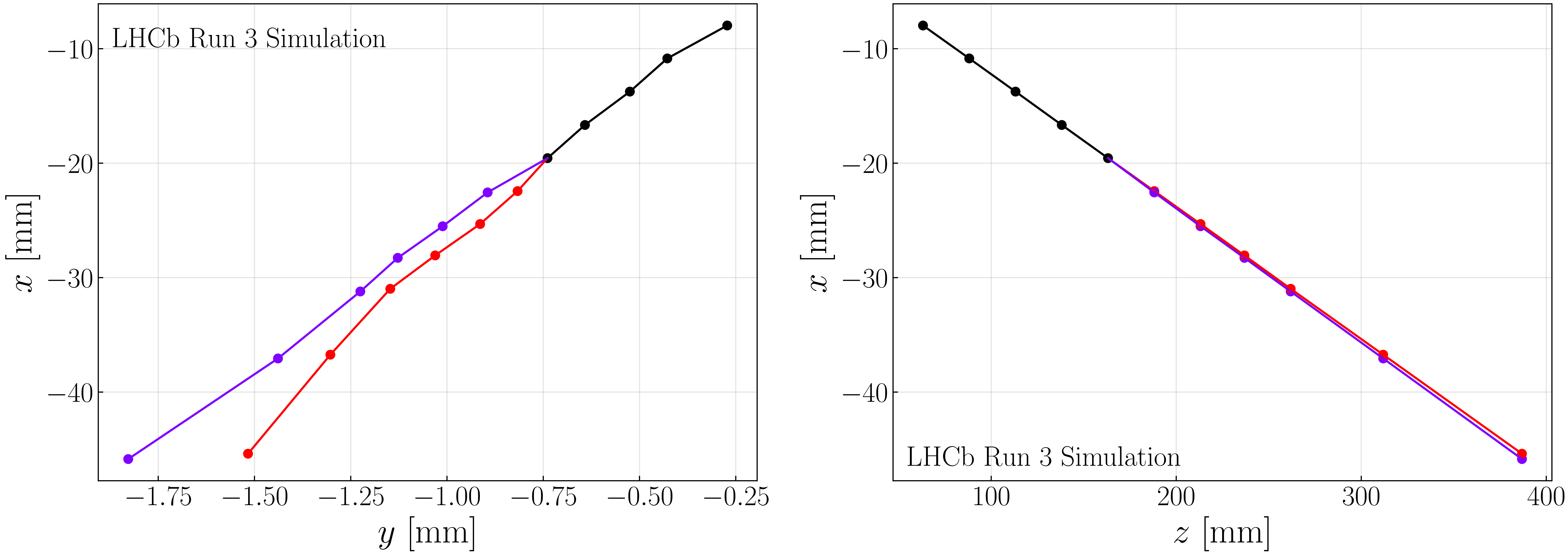
- Problem with electrons:
  - Material interactions —> positron-electron pairs
  - ~ **55%** electrons/positrons share hits with one another
  - Then split up
  - Electrons with “long tracks” = **“long electrons”**
  - Important for the LHCb physics program
- Solution: use edge-edge connections (triplets)

```
TrackChecker output                          :     38049/  1117828   3.40% ghost
01_velo                                      :    491643/   520515  94.45% ( 95.
02_long                                      :    286719/   296345  96.75% ( 97.
03_long_P>5GeV                               :    185866/   189727  97.96% ( 98.
04_long_strange                              :     13654/    15243  89.58% ( 90.
05_long_strange_P>5GeV                       :      6606/     7229  91.38% ( 92.
06_long_fromB                                :       497/      513  96.88% ( 96.
07_long_fromB_P>5GeV                         :       335/      343  97.67% ( 97.
08_long_electrons                            :     16634/    21330  77.98% ( 78.
09_long_fromB_electrons                      :        41/       58  70.69% ( 76.
10_long_fromB_electrons_P>5GeV               :        30/       38  78.95% ( 81.

*** Benchmark score:  94.01

| Categories             | Efficiency    | Average efficiency    | % clones    | Average h
|:-----------------------|:--------------|:----------------------|:------------|:---------
| Velo                   | 90.37%        | 91.08%                | 1.41%       | 99.03%
| Long                   | 95.49%        | 95.97%                | 0.97%       | 99.33%
| Velo, no electrons     | 94.45%        | 95.11%                | 0.89%       | 99.30%
| Velo, only electrons   | 69.30%        | 69.84%                | 4.91%       | 97.15%
| Long, only electrons   | 77.98%        | 78.93%                | 3.54%       | 97.36%

| Categories    | # ghosts    | # tracks    | % ghosts    |
|:--------------|:------------|:------------|:------------|
| Everything    | 38,049      | 1,117,828   | 3.40%       |
```

LHCb unofficial

# ETX4VELO

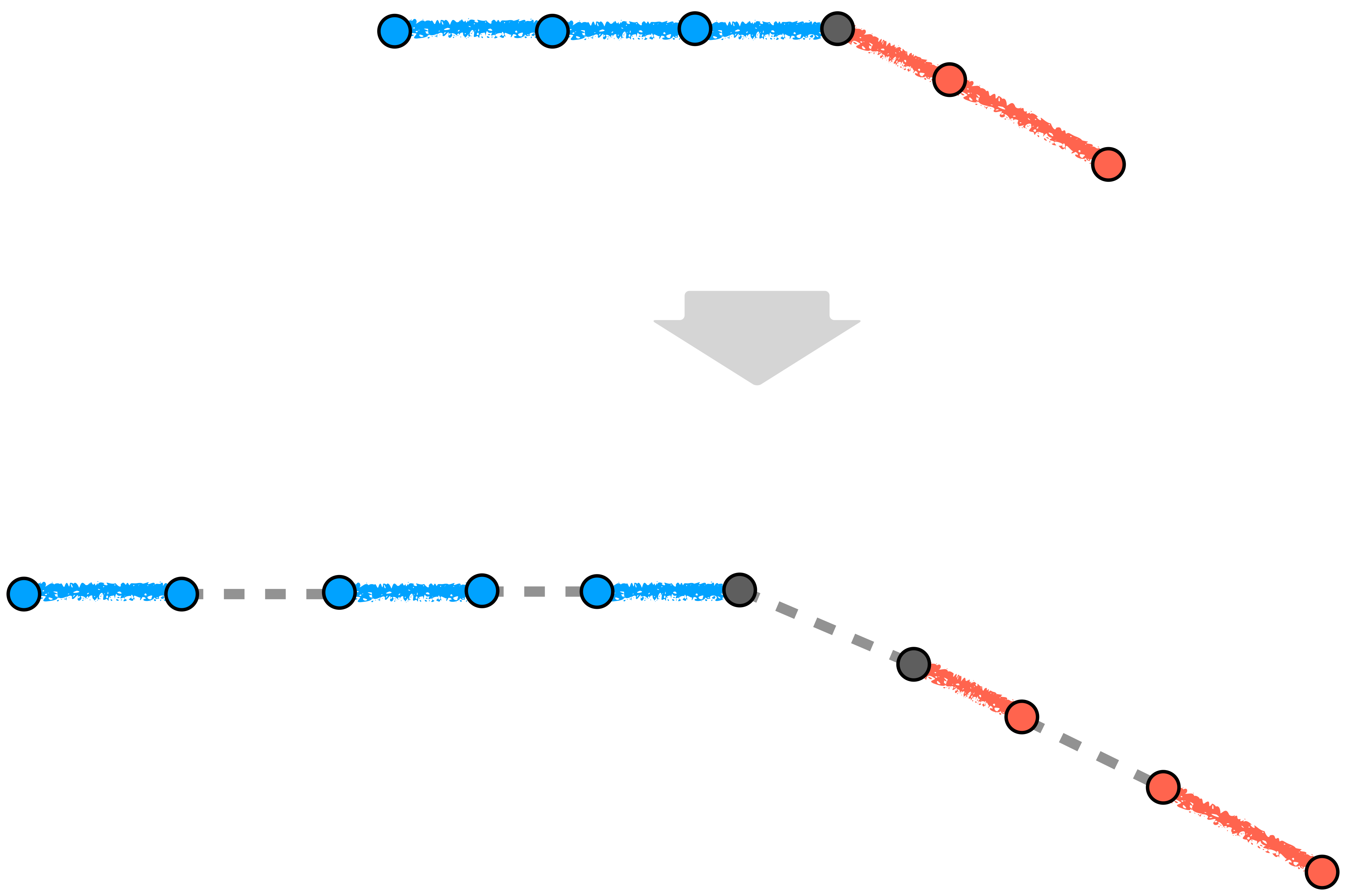
## Problem with electrons: shared hits



# ETX4VELO

## Problem with electrons: the solution

- Problem with electrons:
  - Pipeline cannot separate particle with shared edges
  - **Hit-hit** connections are not enough
  - Solution:
  - Use **edge-edge** connections (**triplets**)
  - Use GNN again on triplets



# ETX4VELO

## Computational performance

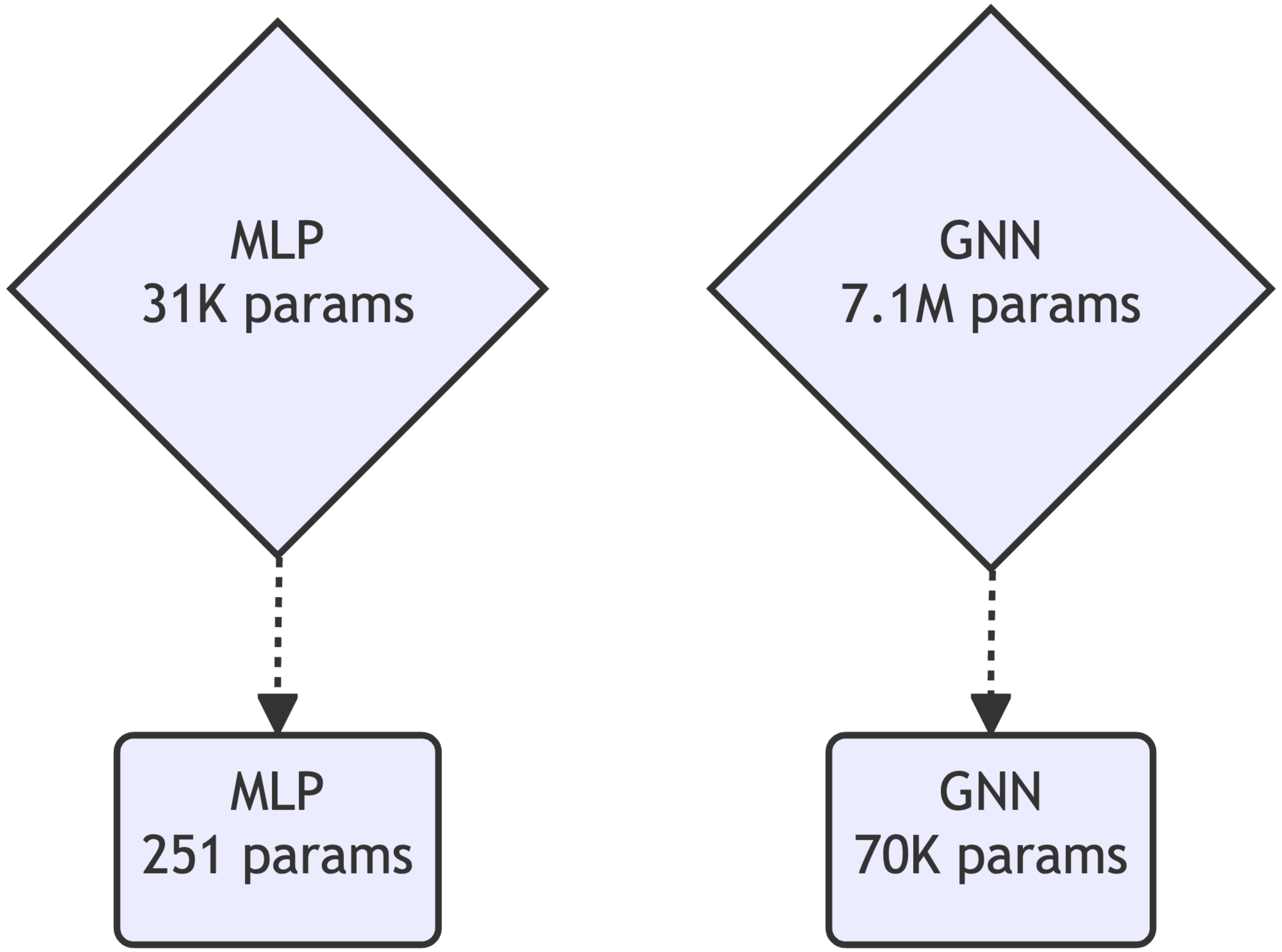
*NVIDIA GeForce RTX 3090, 500 events, 50 repetitions*

| Pipeline | Up to step | Throughput (events/s) | | |
|---|---|---|---|---|
| | | **ONNX Runtime FP32** | **TensorRT FP32** | **TensorRT INT8** |
| **ETX4VELO** | VELO decoding | 1,400k | | |
| | Embedding | 54k | 330k | **820k** |
| | k-NN | 38k | 81k | 93k |
| | GNN | 0.46k | 1.4k | - |
| | VELO tracks | 0.45k | **1.3k** | - |
| **ALLEN** | VELO tracks | **860k** | | |

# ETX4VELO GPU Version

## Implementation details

- Global nearest neighbour search vs **using only adjacent planes**
- Unidirectional vs bidirectional graph
- General connected components algorithm vs **geometry-specific**
- TensorRT plugin for GNN operation
- Custom **memory allocator** for the inference engine



# ETX4VELO GPU Version

## ONNX Runtime vs TensorRT implementation

| ONNX Runtime | TensorRT |
| --- | --- |
| Better out-of-the-box support | Better documentation |
| CPU backend | Lower memory footprint |
| | Higher throughput |
| | Memory managers reconciled more easily |