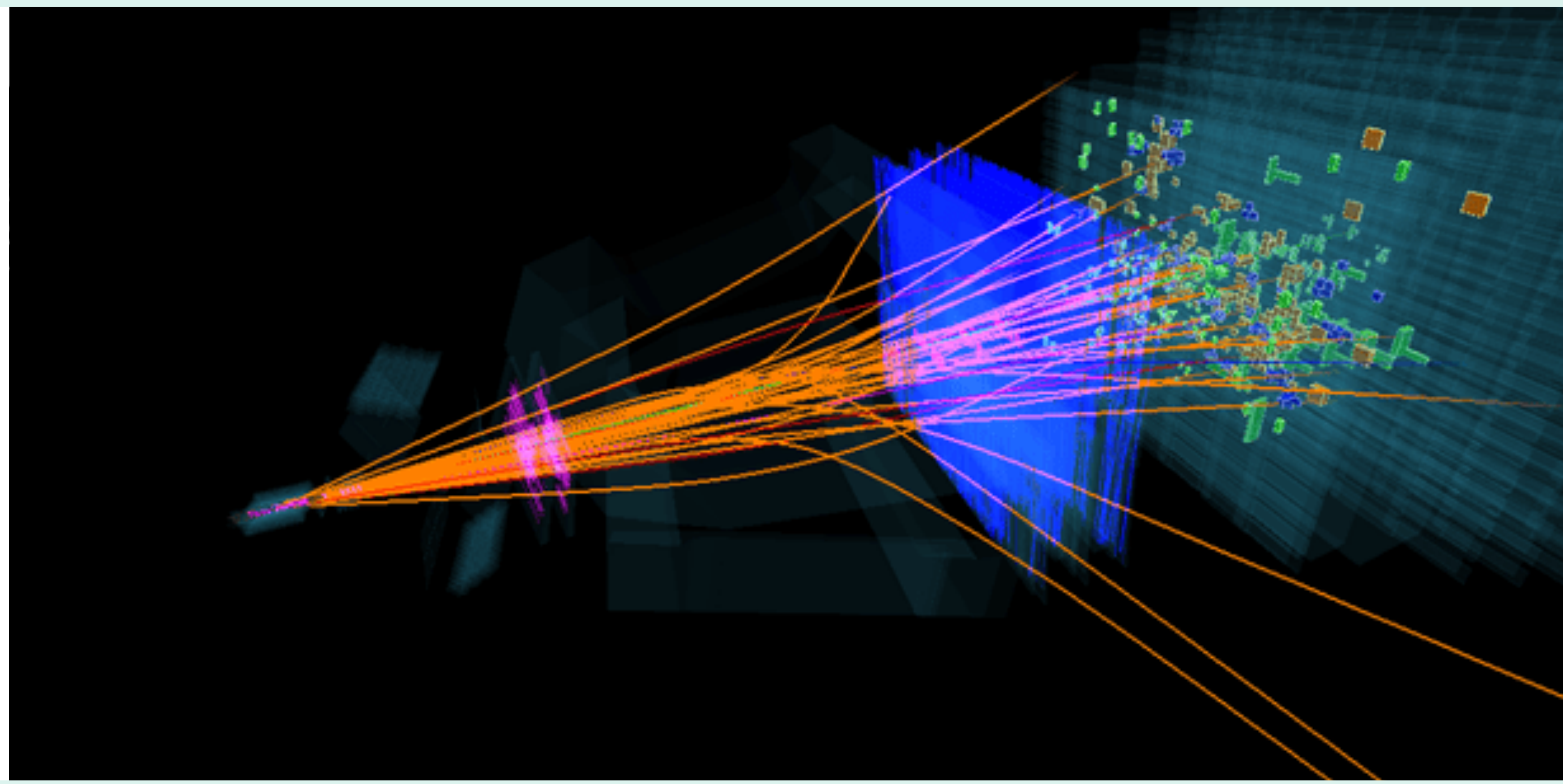
Graph Neural Networks for a Deep-learning based Full Event Interpretation (DFEI) at the LHCb trigger



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4th of November 2022

ML4Jets 2022

Outlook

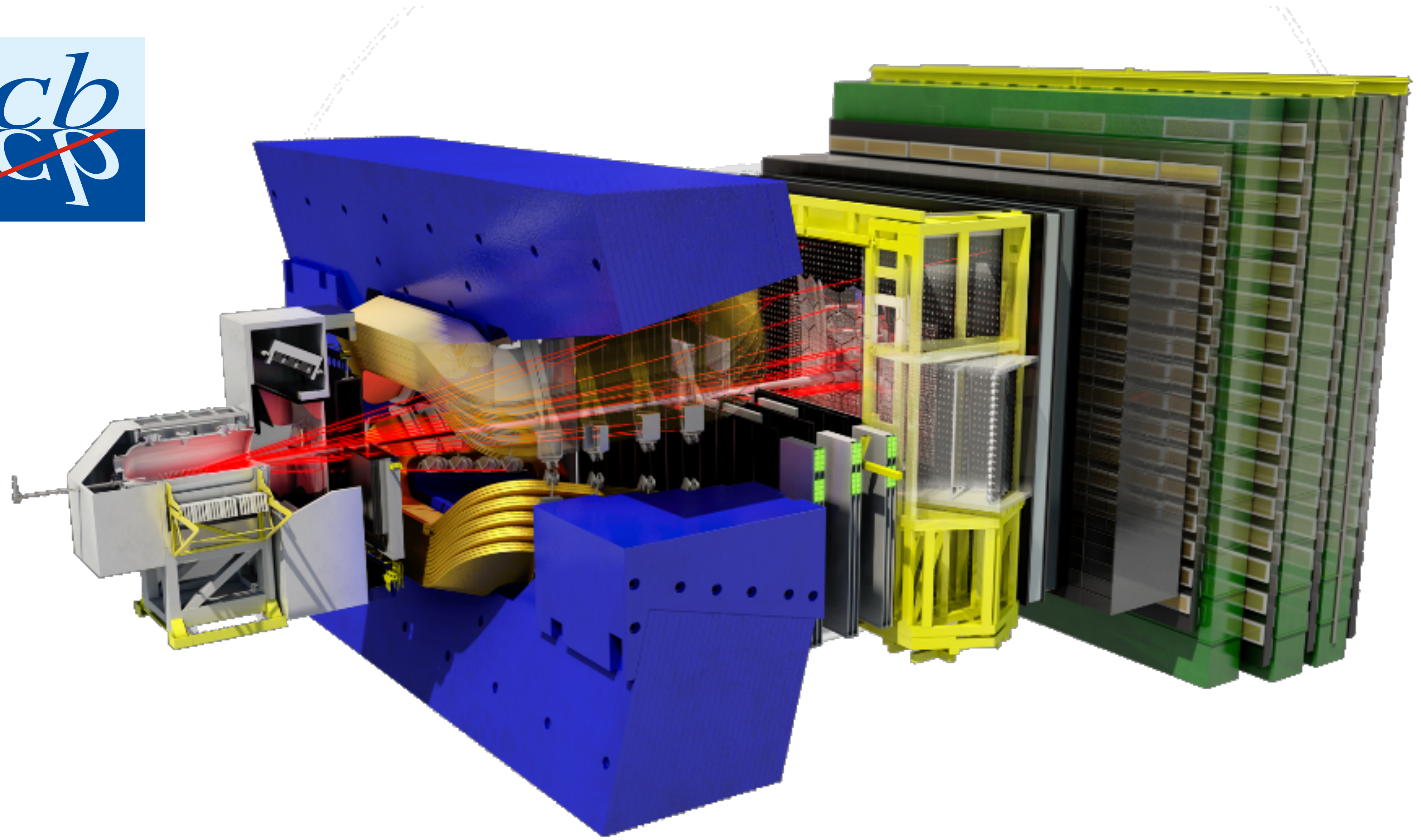
Performance (preliminary)

The algorithm

Motivation

The LHCb detector

Single-arm forward spectrometer, studying the **decays of beauty and charm hadrons**.
Very broad physics program. → To be maintained and expanded in future LHC runs.

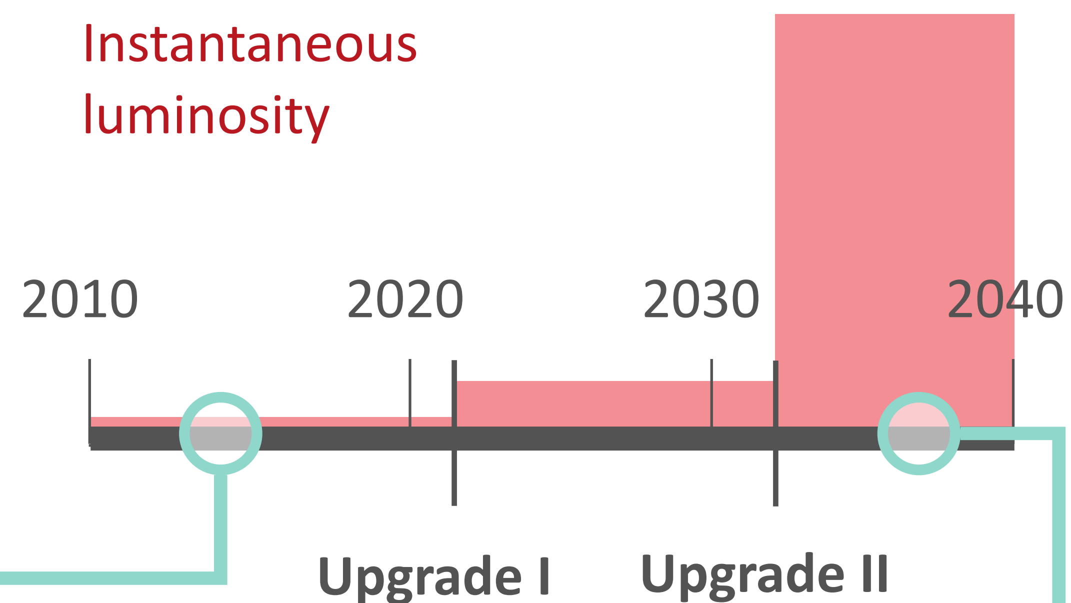


Excellent vertexing capabilities, momentum resolution and PID performance.

Evolution in the LHCb trigger

≪ 1 signal
~ 50 tracks

Which events are interesting?
⇓
Trigger strategy: signal based.



~ 5 signals
~ 1000 tracks

Which parts of the event are interesting?

New era for LHCb!

[LHCb-PUB-2014-027]

Evolution in the LHCb trigger

≪ 1 signal
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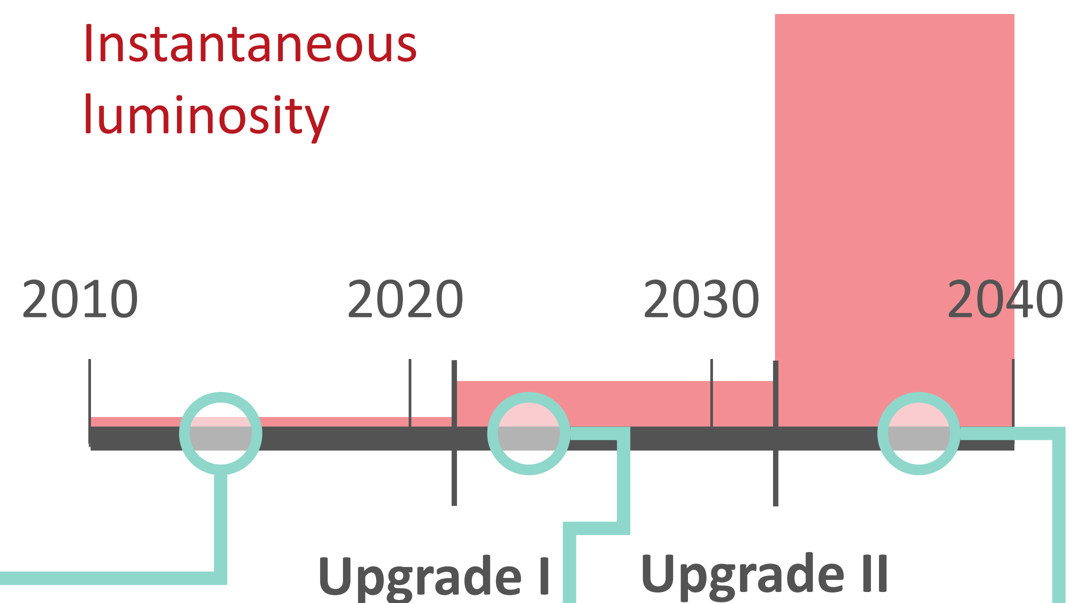


~ 5 signals
~ 1000 tracks

Which parts of the event are interesting?

New era for LHCb!

[LHCb-PUB-2014-027]

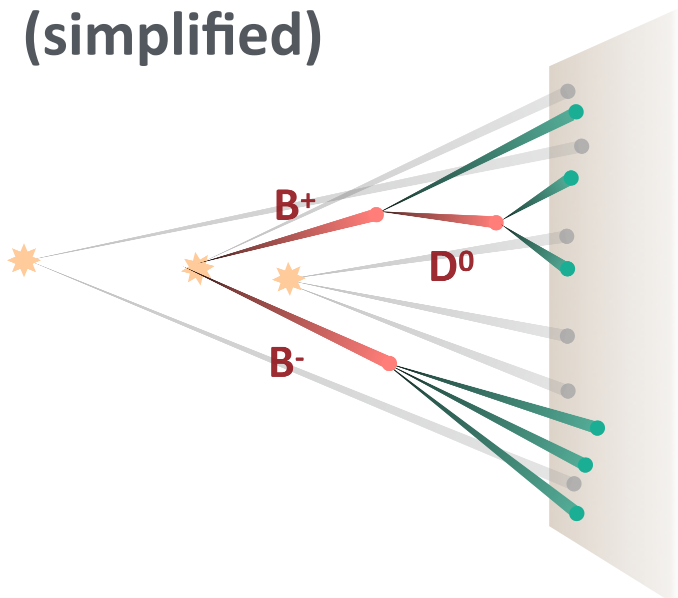
~ 0.5 signals
~ 140 tracks

- **Fully software trigger, CPU + GPU** [JINST 14 (2019) 04, P04006].
- Data buffer to enlarge the time window for online processing.
  ➡ Online alignment and calibration, **offline-quality online reconstruction**.

Key developments that enable more ambitious trigger strategies.

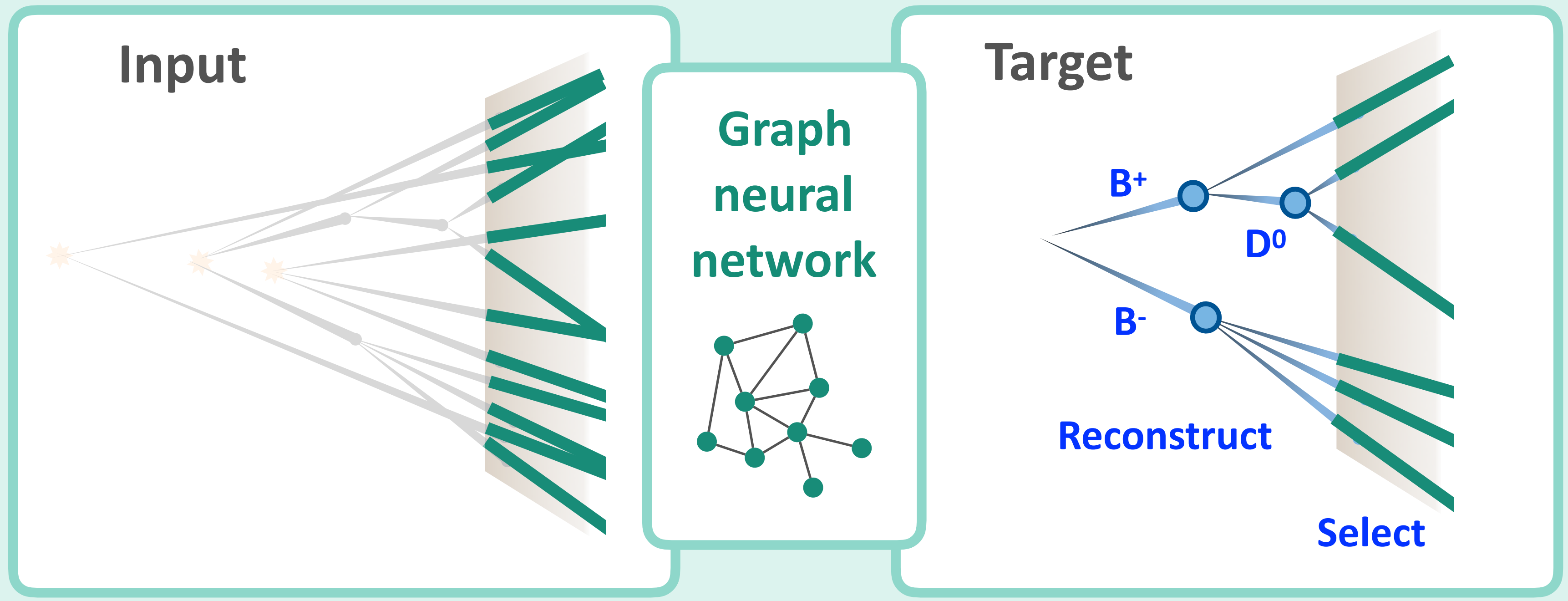
Facing the new era with machine learning

LHCb event (simplified)



Novel approach proposed

DFEI:
Deep-learning based
Full Event Interpretation



"Maximally efficient" trigger.

Similar developments in other experiments

Full Event Interpretation algorithm at an e+e- collider
[Comput.Softw.Big Sci. 3 (2019) 1 6], BELLE2-MTHESIS-2020-006].

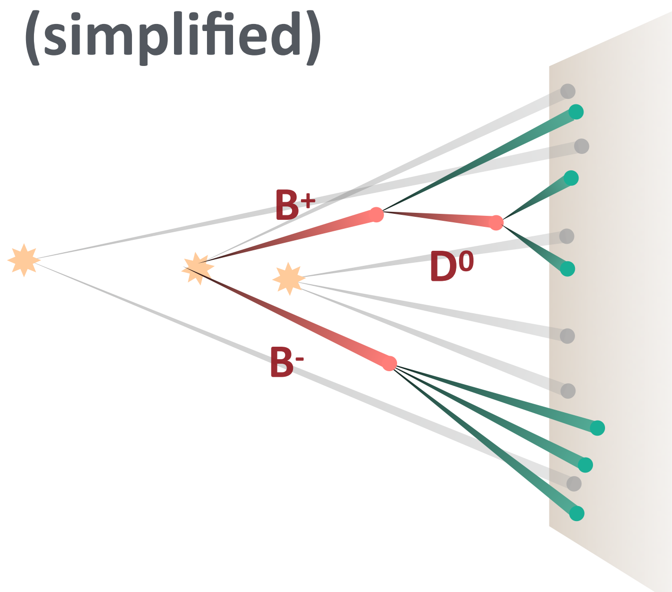
GNNs for trigger purposes
[see e.g. Eur.Phys.J.C 81 (2021) 5, 381, Frontiers in Big Data 3 (2021) 44].

Facing the new era with machine learning

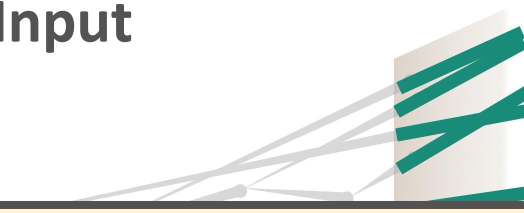
Novel approach proposed

DFEI:
Deep-learning based
Full Event Interpretation

LHCb event (simplified)

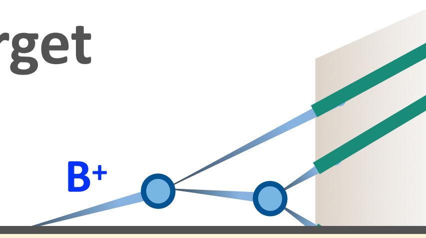


Input



Graph neural

Target



Belle II case	LHCb case
Only $B^0/B^\pm$ hadrons.	All b,c-hadron species.
e+e- environment.	pp environment.
Hermetic detector.	Non-hermetic detector.

ger.

Similar developments … **er experiments**

Full Event Interpretation algorithm at an e+e- collider
[Comput.Softw.Big Sci. 3 (2019) 1 6], BELLE2-MTHESIS-2020-006].

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Outlook

Performance (preliminary)

The algorithm

First prototype of DFEI for LHCb, focused on b-hadron decays and charged stable particles.

Motivation

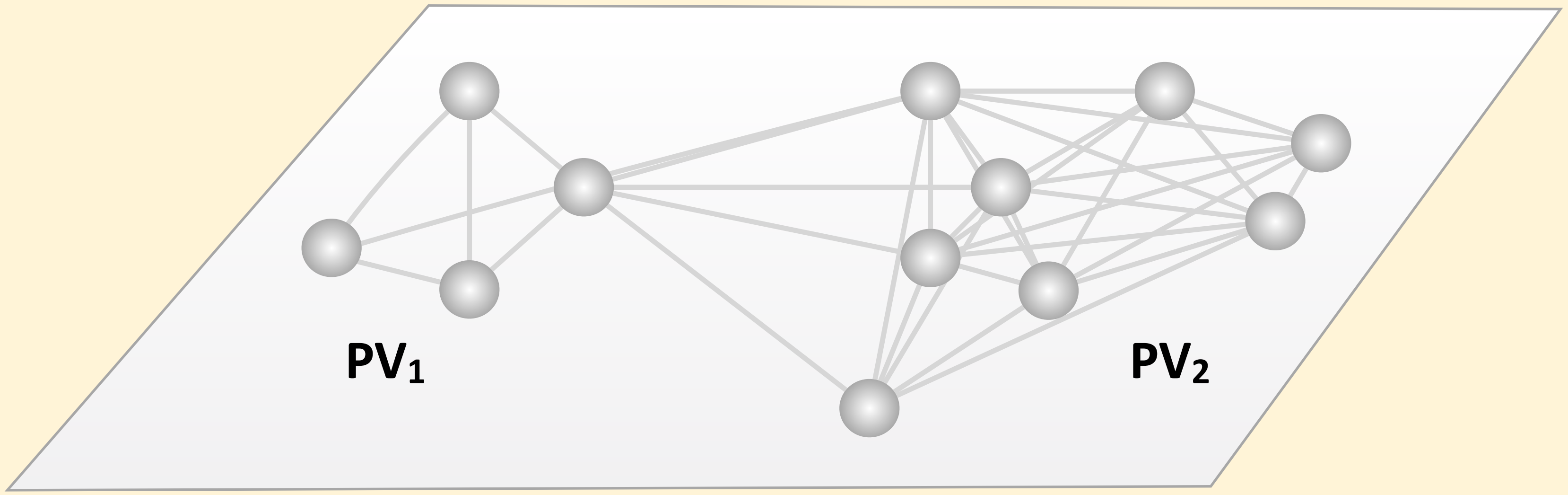
Input graph construction

Nodes: all the charged particles in the event.

➥ On average **~140**.

Edges: connect particles which are topologically close (see backup for details).

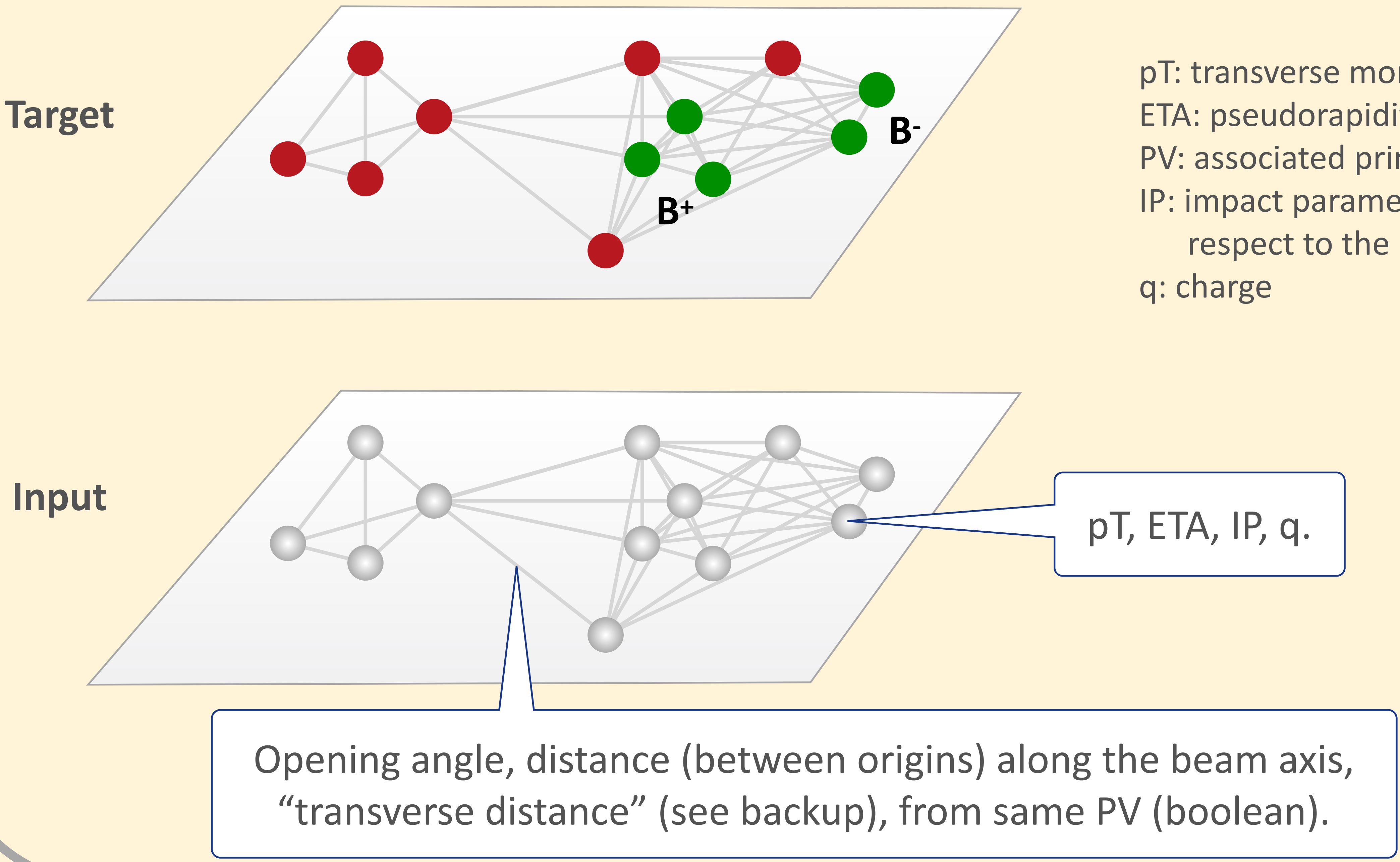
➥ On average **~10 000**.



PV_1, PV_2: different proton-proton primary vertices.

1st module: node pruning

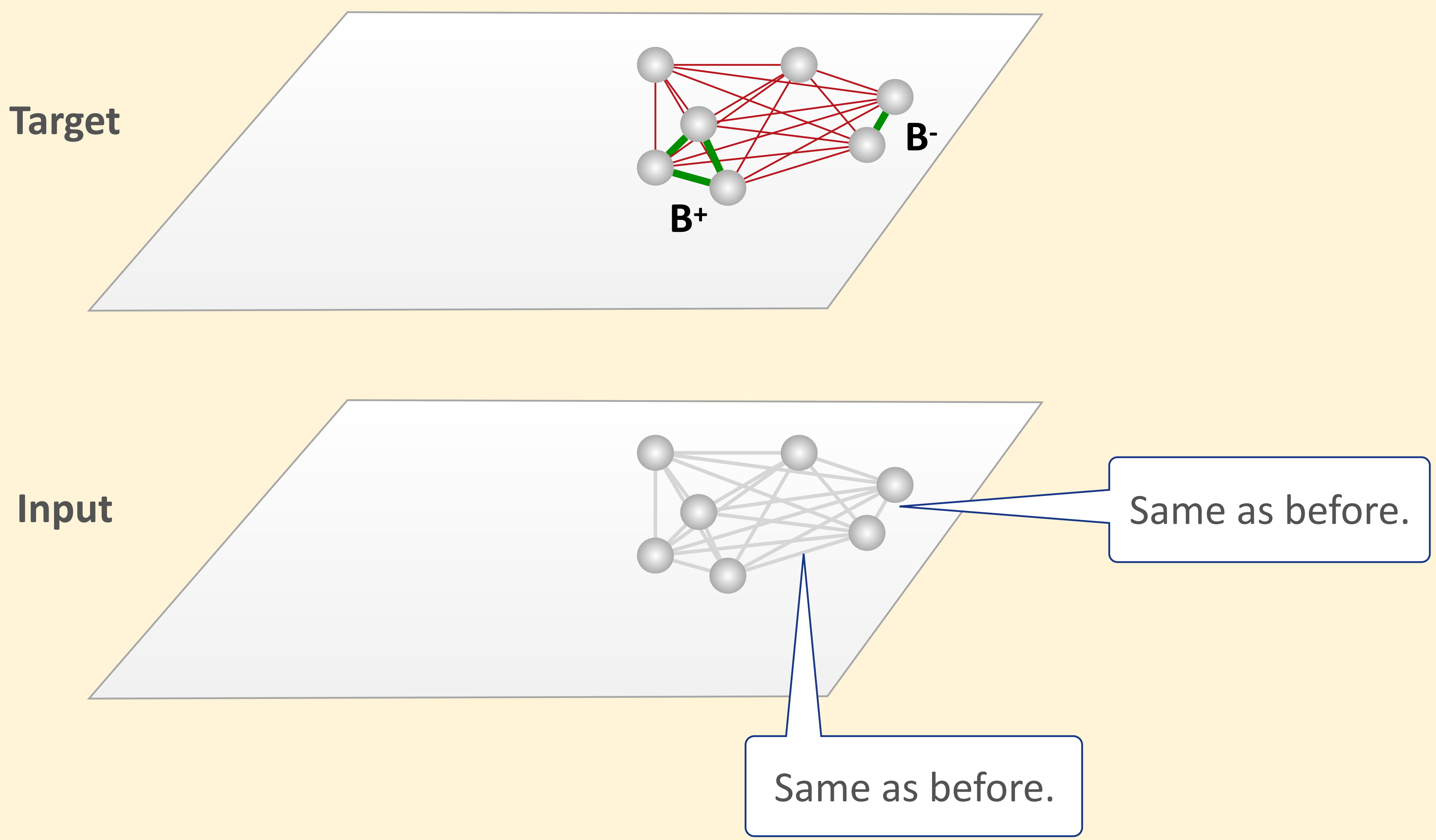
Signal nodes: particles from a b-hadron (any of them)
Background nodes: particles from the rest of the event



pT: transverse momentum
ETA: pseudorapidity
PV: associated primary vertex
IP: impact parameter with respect to the PV
q: charge

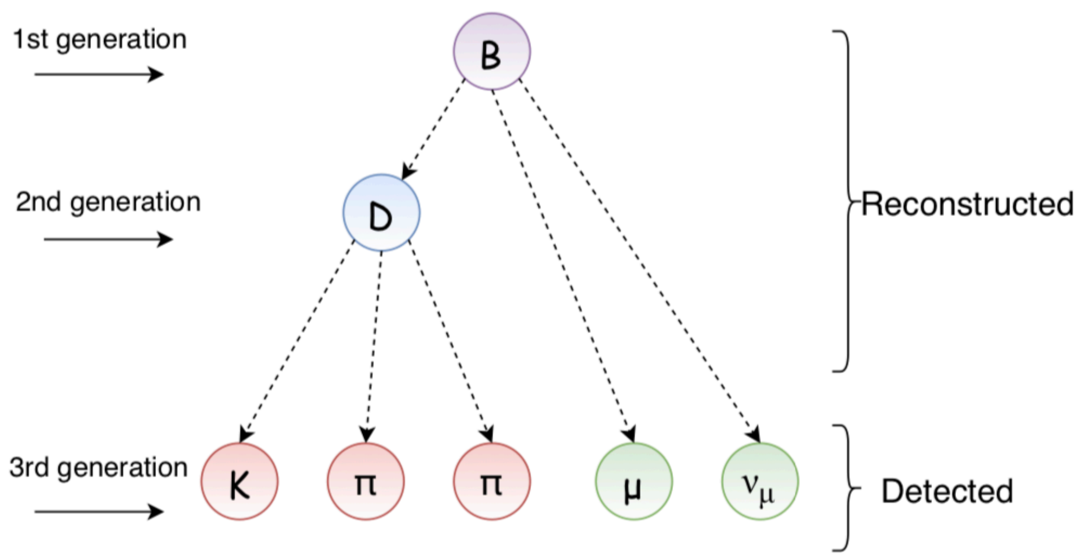
2nd module: edge pruning

Signal edges: pairs of particles with the same b-hadron ancestor
Background edges: any other pair of particles



3rd module: Lowest Common Ancestor (LCA) inference

From [BELLE2-MTHESIS-2020-006]:
(see also [James Kahn et al 2022 Mach. Learn.: Sci. Technol. 3 035012])



	B	D	K	π	π	μ	ν_μ
B	0	1	0	0	0	1	1
D	1	0	1	1	1	0	0
K	0	1	0	0	0	0	0
π	0	1	0	0	0	0	0
π	0	1	0	0	0	0	0
μ	1	0	0	0	0	0	0
ν_μ	1	0	0	0	0	0	0

	K	π	π	μ	ν_μ
K	0	1	1	2	2
π	1	0	1	2	2
π	1	1	0	2	2
μ	2	2	2	0	2
ν_μ	2	2	2	2	0

Problem reduced to **multi-class classification on edges**.

3rd module: Lowest Common Ancestor (LCA) inference

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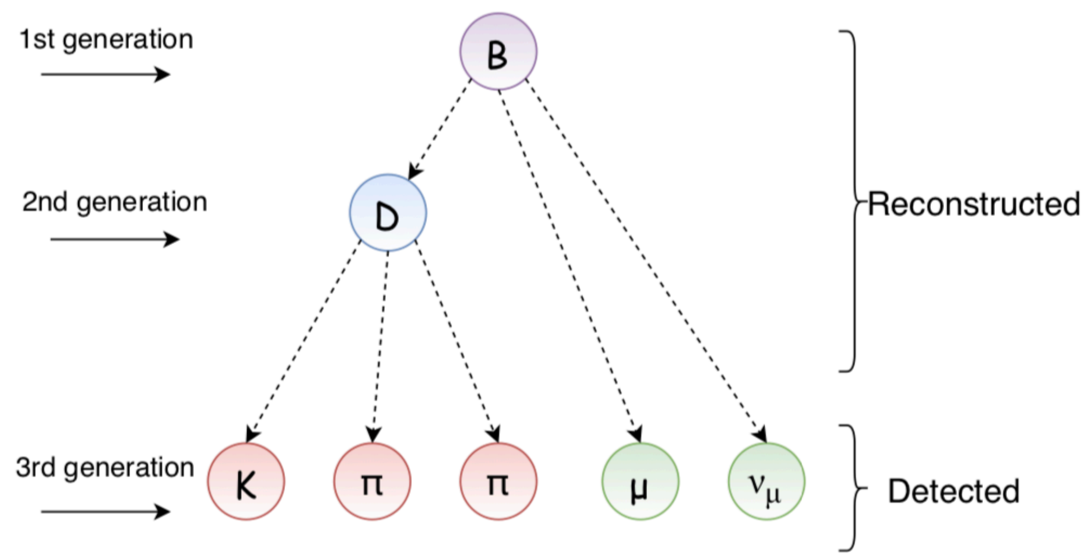


Adjacency Matrix

	B	D	K	π	π	μ	ν_μ
B	0	1	0	0	0	1	1
D	1	0	1	1	1	0	0
K	0	1	0	0	0	0	0
π	0	1	0	0	0	0	0
π	0	1	0	0	0	0	0
μ	1	0	0	0	0	0	0
ν_μ	1	0	0	0	0	0	0

LCA Matrix

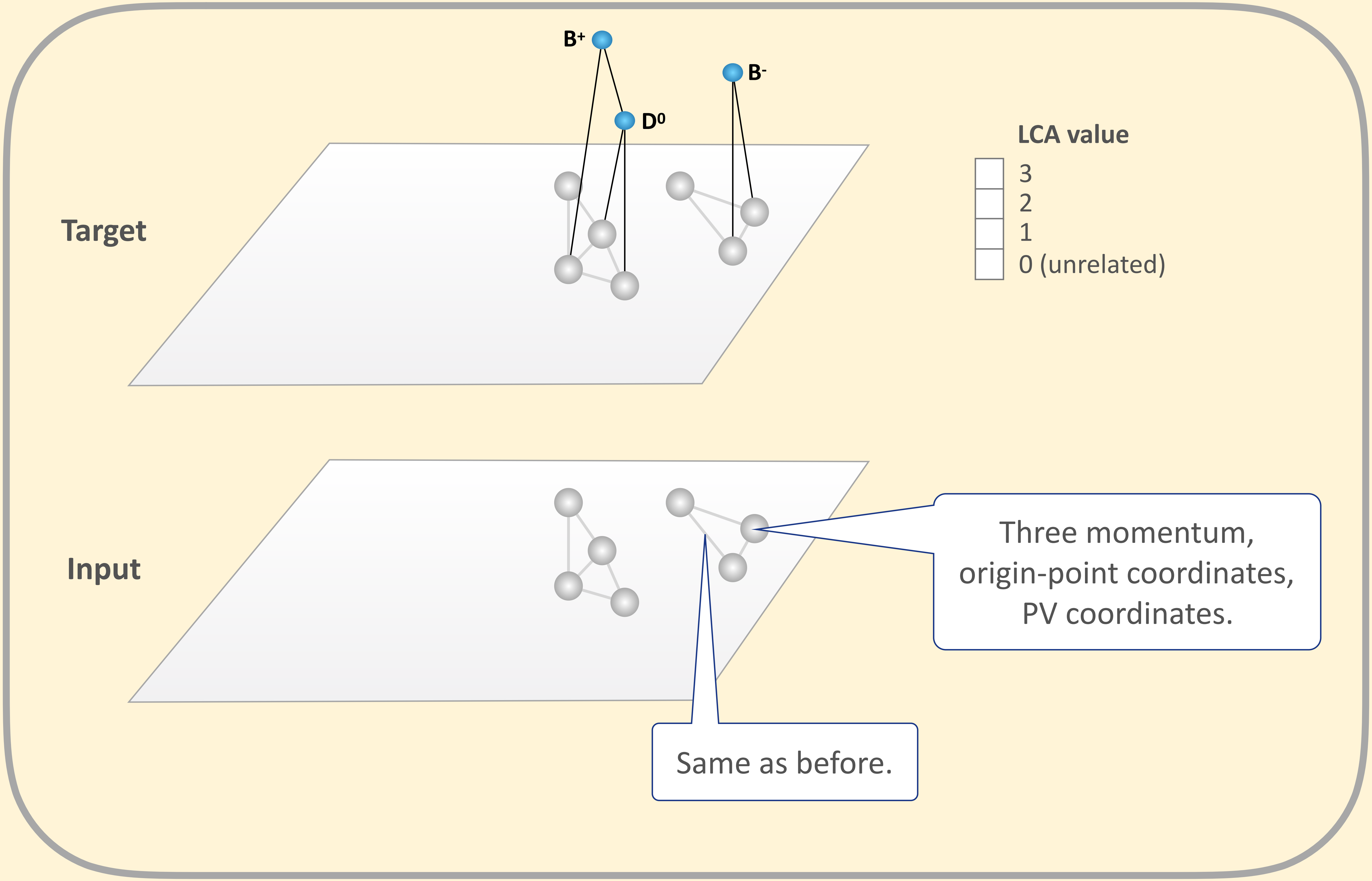
	K	π	π	μ	ν_μ
K	0	1	1	2	2
π	1	0	1	2	2
π	1	1	0	2	2
μ	2	2	2	0	2
ν_μ	2	2	2	2	0

Problem reduced to **multi-class classification on edges**.

For the prototype, use as target a **simplified version of the decay chain, based on the reconstructible vertices**.

- Very-short-lived resonances merged with the previous ancestor.
- Resonances with less than two charged descendants merged with the previous ancestor.

3rd module: Lowest Common Ancestor (LCA) inference



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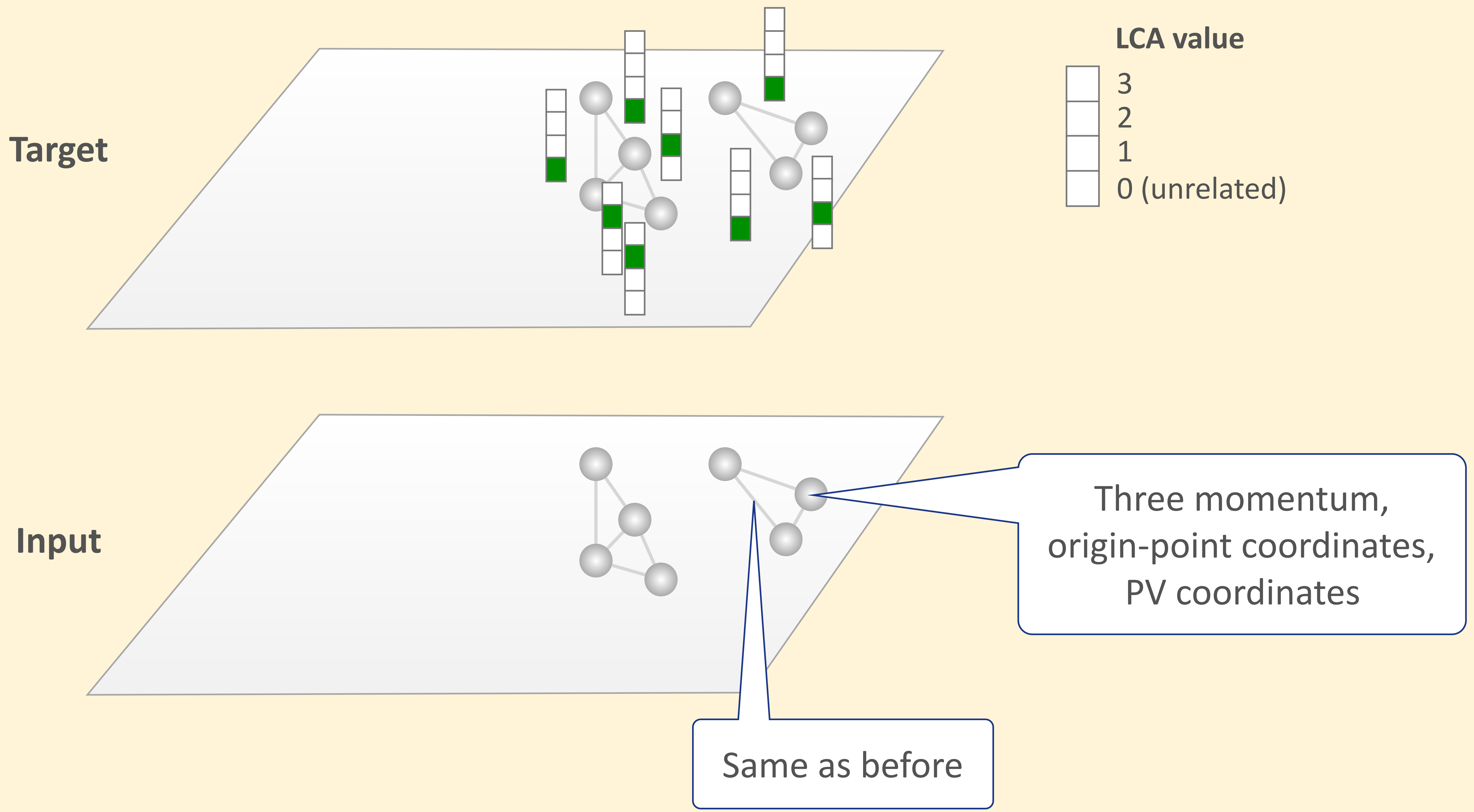
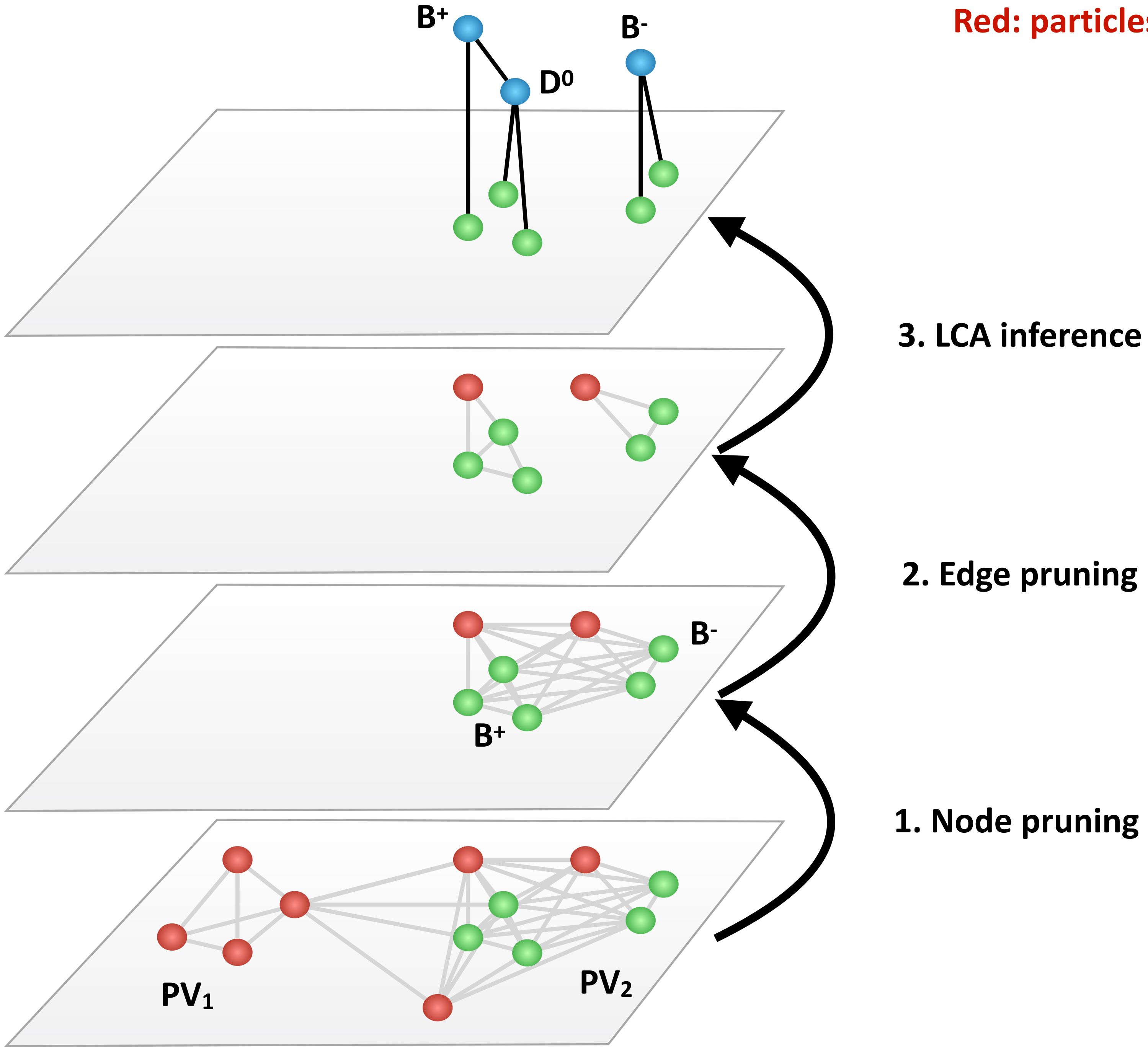


Global overview of the algorithm

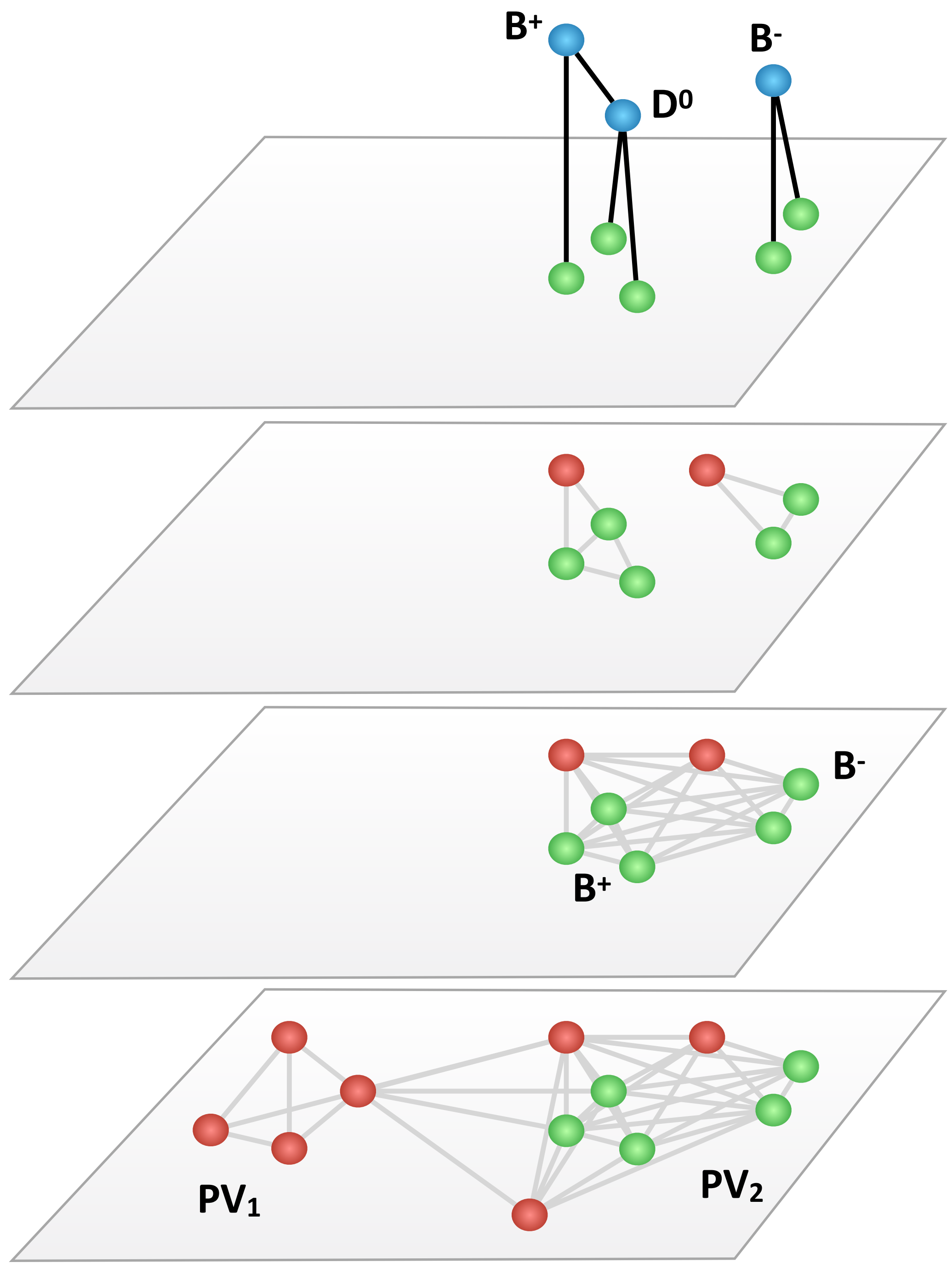


Blue: reconstructed ancestors.
Green: particles from a b-hadron
Red: particles from the rest of the event

Training

Dataset:

- PYTHIA-based simulation, Run 3 conditions, approximated emulation of LHCb reconstruction.
- Events required to contain at least one b-hadron (inclusive decay).



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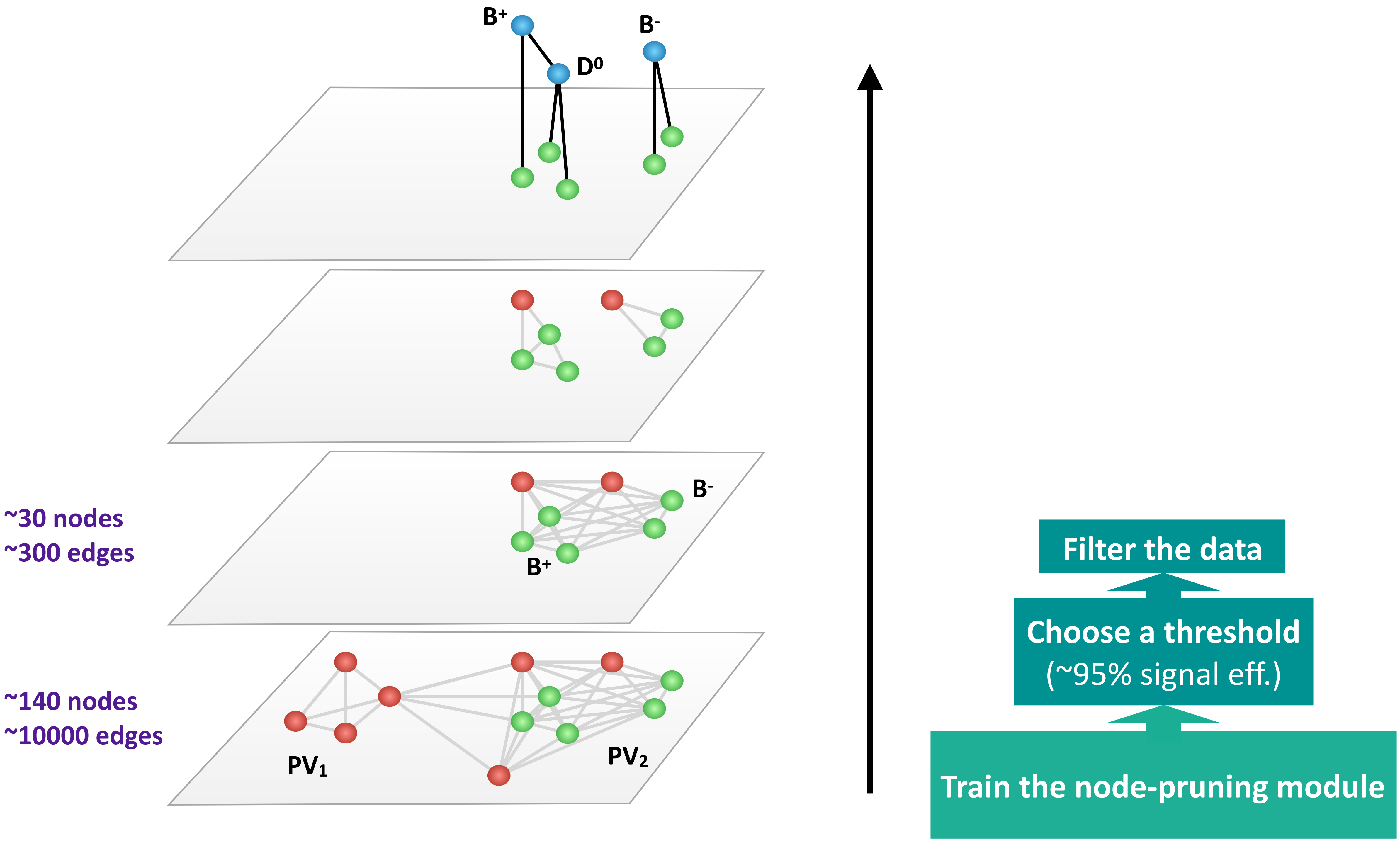

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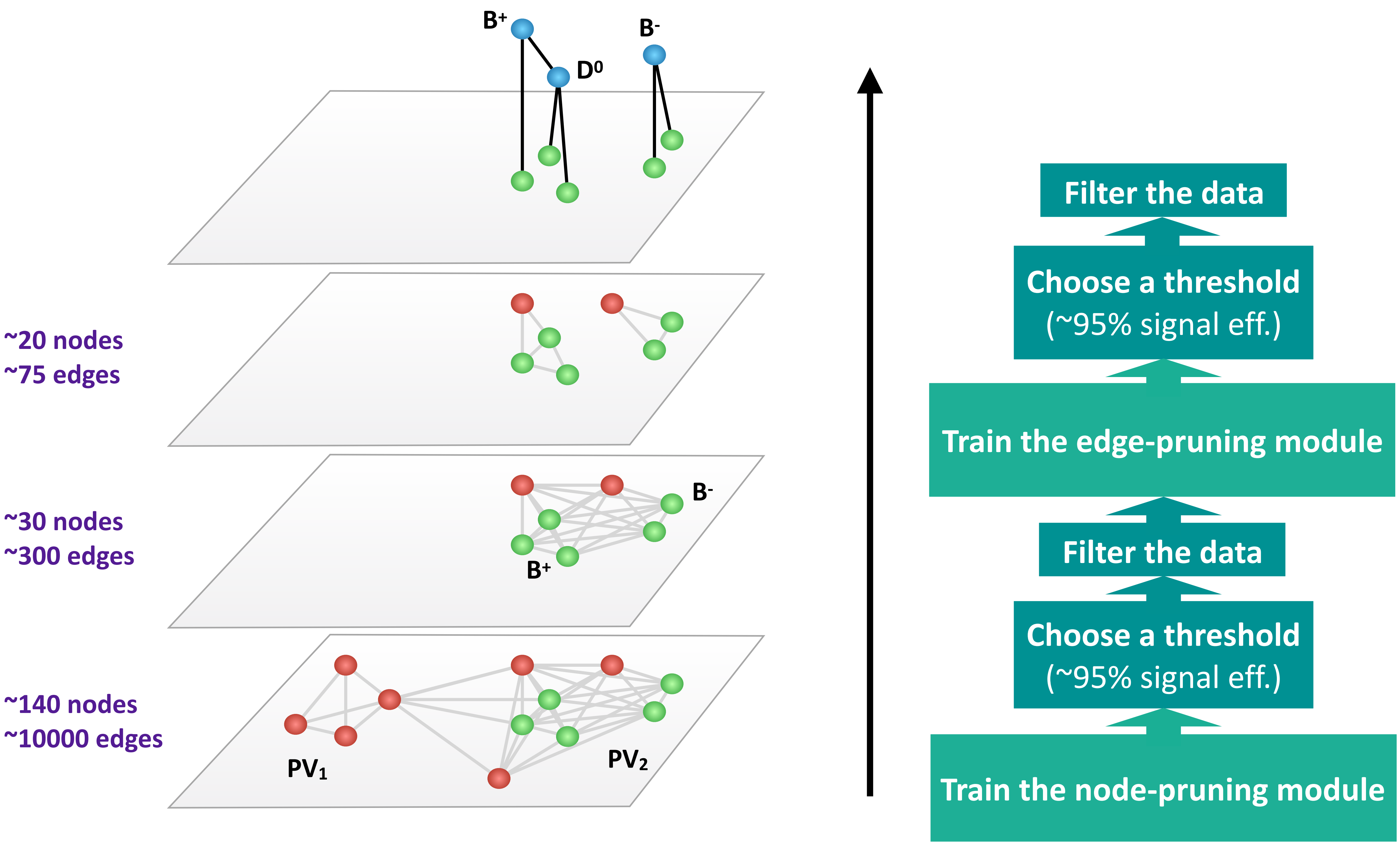

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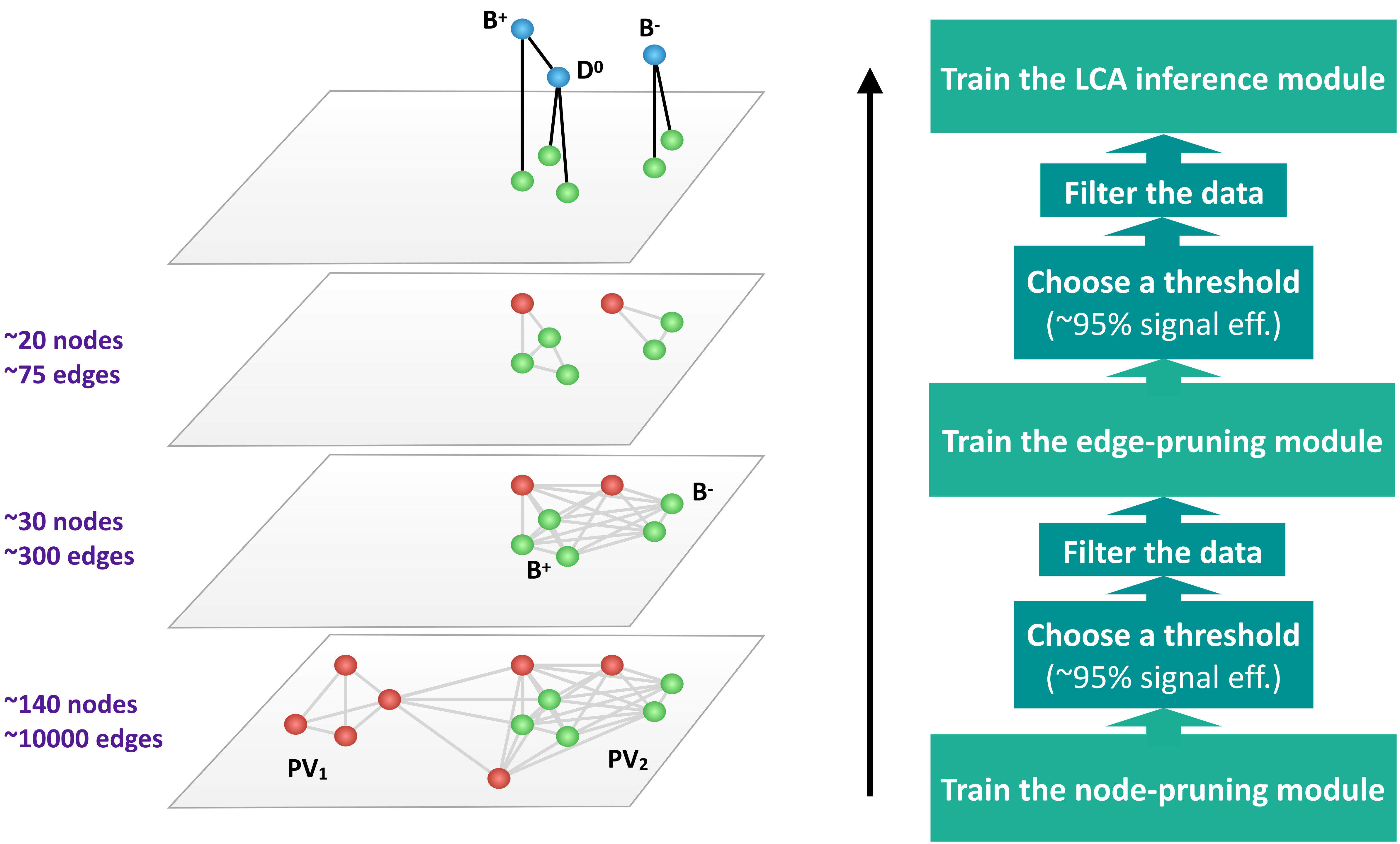


Outlook

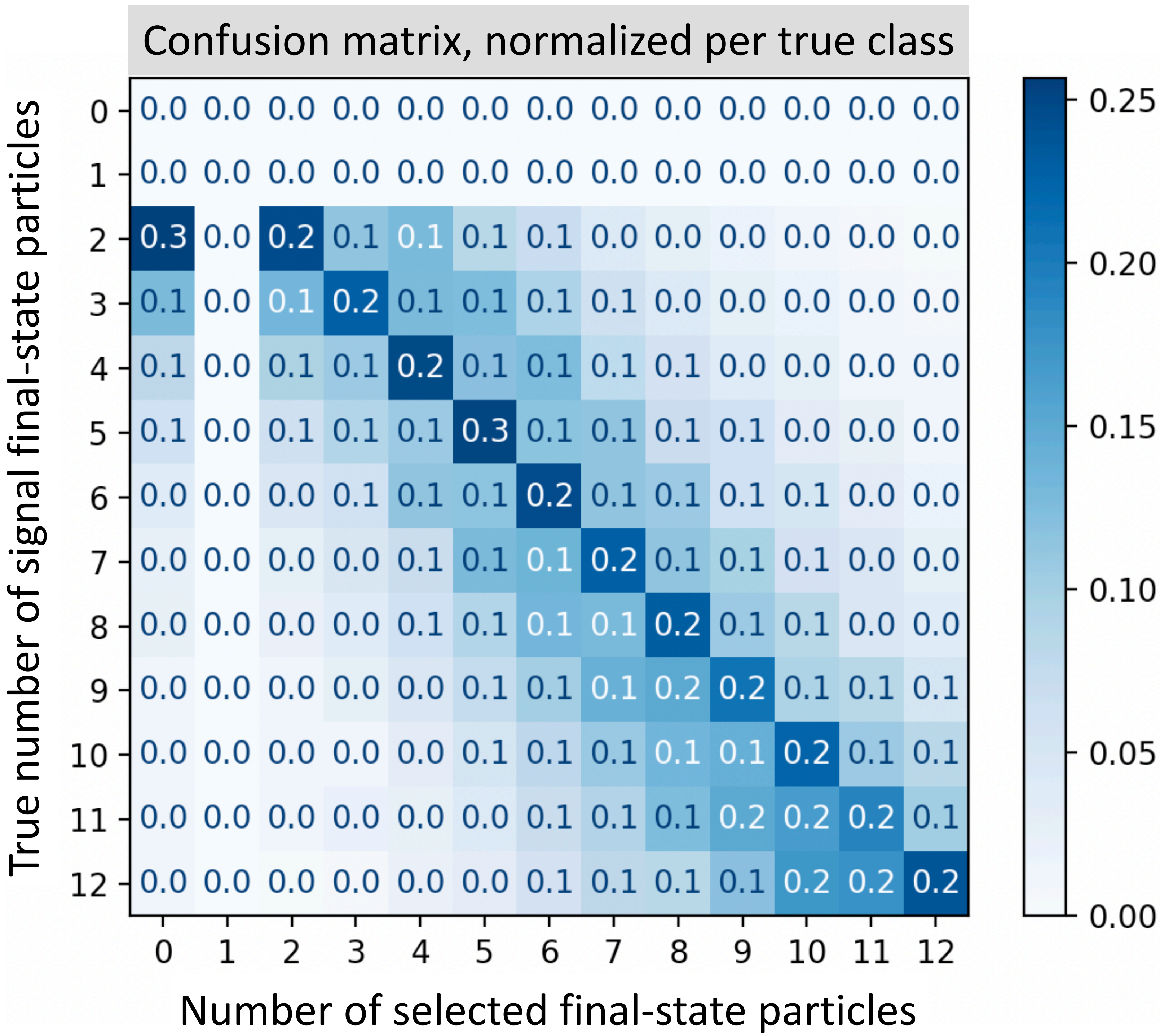
Performance (preliminary)

Run3-like conditions

The algorithm

Motivation

Preliminary performance: final-state particle filtering

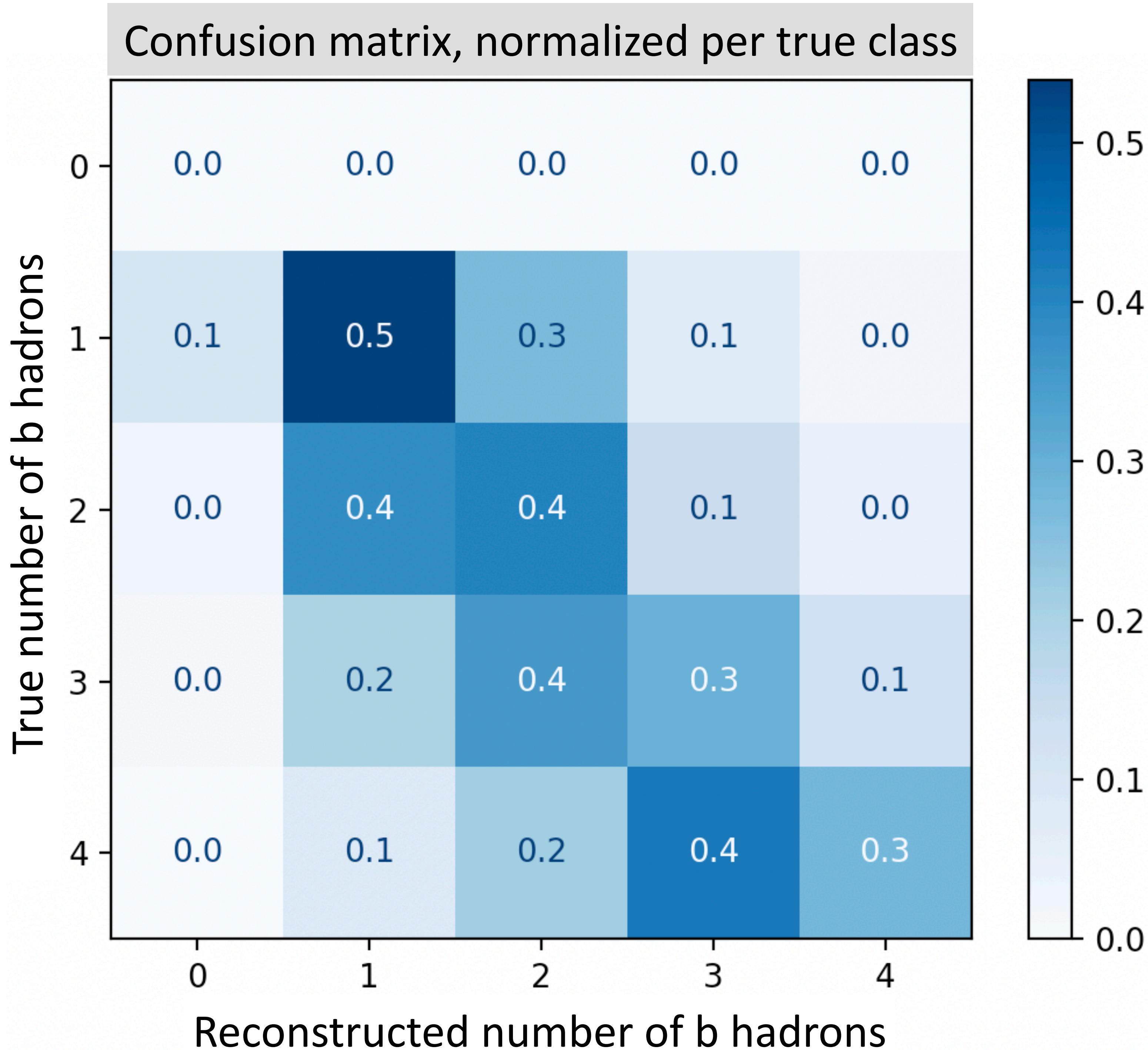


- Consistently good performance for events with different number and type of b-hadron signals.
- If restricted to the "single-b-hadron-signal" approach, performance comparable to the envisaged nominal LHCb strategy for Run 3 [JINST 14 (2019) 04, P04006].

DFEI capability #1

Powerfull event size reduction in a multi-signal environment.

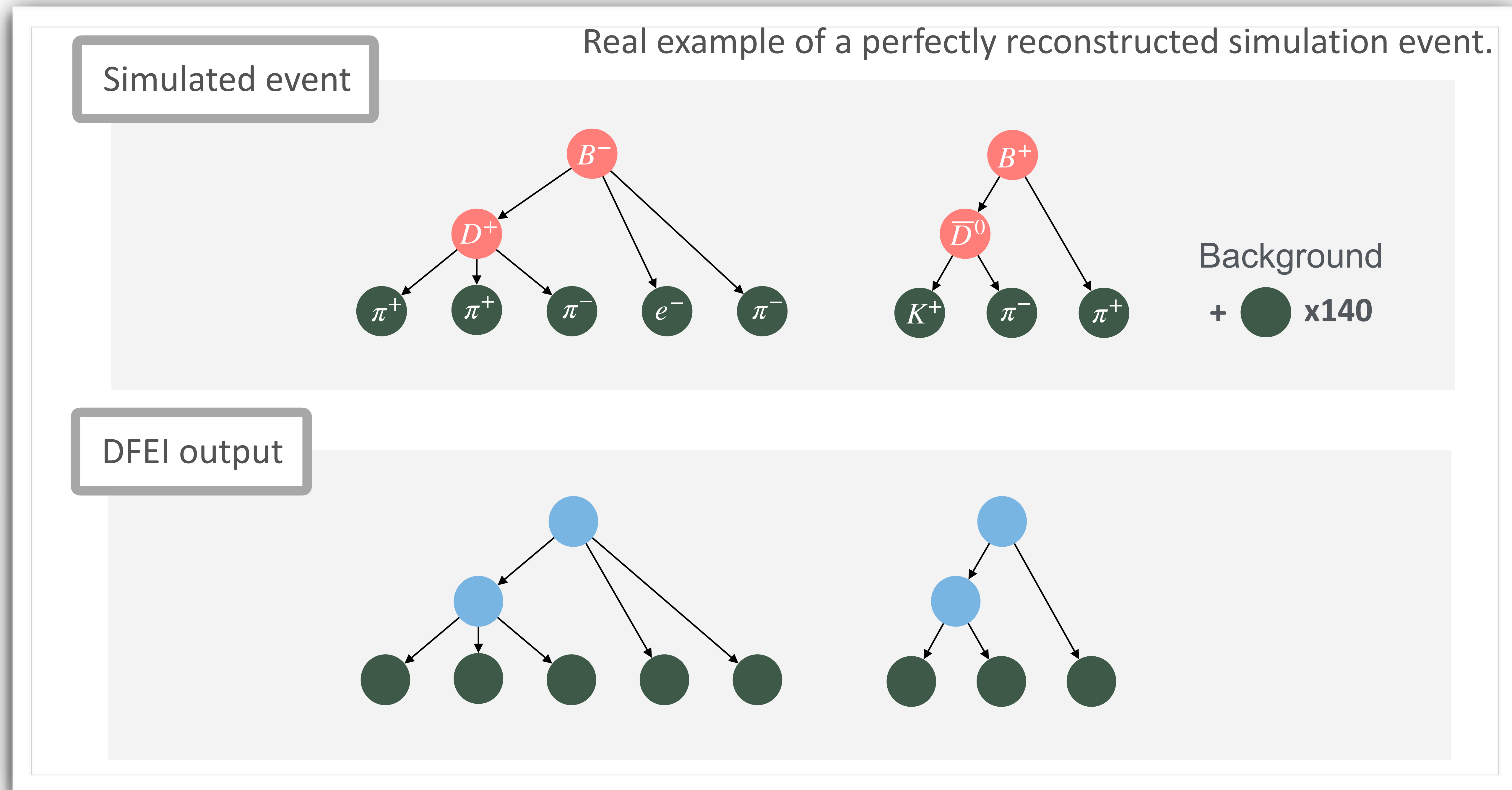
Preliminary performance: separation between b hadrons



- Good clustering of the final-state particles according to their b-hadron ancestor.

DFEI capability #2
Separation/study of multiple b-hadron decays per event.

Preliminary performance: perfect event reconstruction (PER)



- PER efficiency in the ballpark of the tag-side efficiency for Belle (II) [Comput.Softw.Big Sci. 3 (2019) 1 6].

DFEI capability #3
Automatised and inclusive reconstruction of decay chains.

Motivation

The algorithm

Performance (preliminary)

Outlook

Summary

Unprecedented computational challenges for the future **Upgrade II of LHCb**. Paradigm change needed: from **“which events are interesting?”** to **“which parts of the event are interesting?”**.

As a solution, we propose a novel approach: change from the signal-based trigger strategy to a **Deep-learning based Full Event Interpretation**.

- ➥ Automatic and accurate identification and reconstruction of all the heavy-hadron decay chains per event.
- ➥ Allows to discard the rest of the event, with minimal loss for offline analyses.

We have developed the first prototype of the DFEI algorithm, focused on b-hadron decays and charged stable particles.

- ➥ **Very promising performance in realistic conditions!**

Next steps

Further improvements to the algorithm, expansion in functionality.

Extensive performance studies.

- ➡ In simulation.
- ➡ In real data.

Integration in the trigger

- ➡ Adaptation to the LHCb trigger framework.
- ➡ Algorithm optimisation in terms of speed.
- ➡ Study on the usage of hardware accelerators for Upgrade II (FPGA, GPU, etc.).

Backup slides

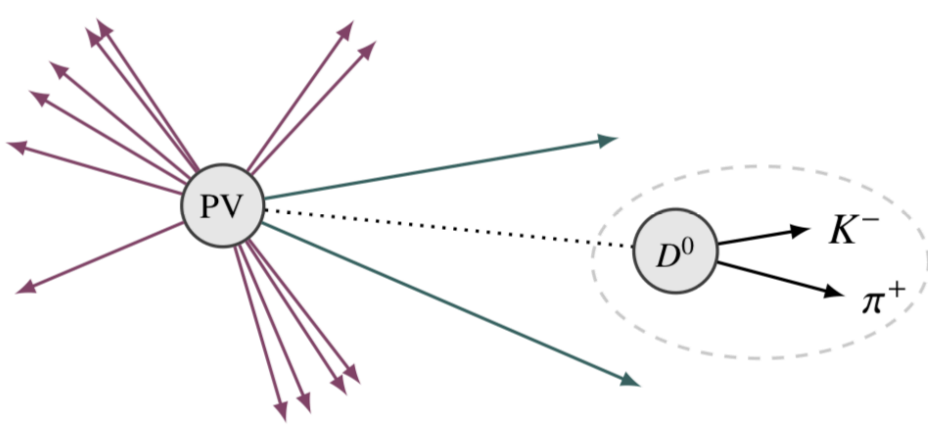
Signal-based trigger vs Full Event Interpretation (FEI)

Signal based

The current LHCb trigger is an **OR between many decay-mode selection lines**.

Since Run2, to reduce the event size, some lines **store only parts of the event which are related** to the specific signal. [JINST 14 (2019) 04, P04006]

E.g.: store the signal + the tracks in the same primary vertex (PV).



FEI

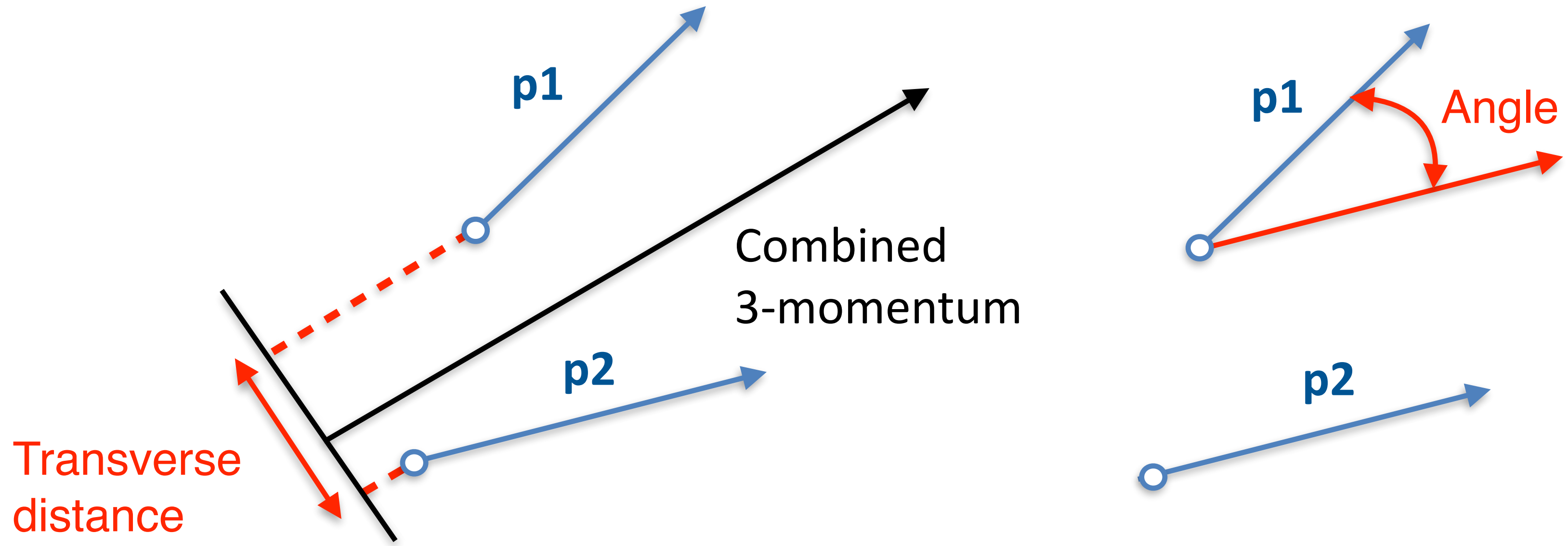
New proposal: try to **reconstruct the b- and c- hadron decay chains in the event**, in a hierarchical-clustering manner (cluster → unstable particle), **and discard the rest**.

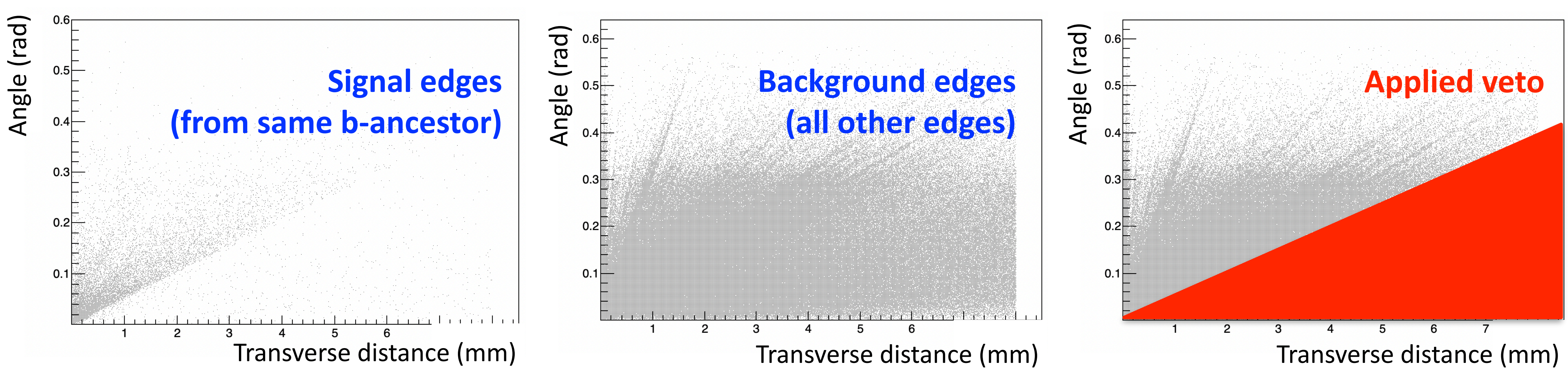
Advantages:

- **Exploit extra correlations** between objects in the event.
- **Bandwidth oriented**: focus on storing as much "useful" information as possible.
- Case of several signals per event as an integral part of the approach.
- Establishment of a basis for an expanded functionality of the trigger: inclusive selections, study of anomalous events ...

Cut-based edge pruning

Define two adequate topological variables for each edge (pair of particles)





This veto reduces on average 60% of the total number of edges in the graph. It also reduces connections between signal tracks, but it only leaves ~2% of the signal tracks fully disconnected.

Training dataset: emulating Run3 conditions

Particle collision&decay

The training and performance studies are currently done using **PYTHIA**, with the following configuration:

- Proton-proton collisions at 13 TeV.
- Average number of collisions per event: 7.6.
- Selecting **events with at least one b-hadron produced (inclusive decay)**.

"Detection and reconstruction"

We require all the tracks and the b-hadrons to be **inside the LHCb geometrical acceptance**.

In addition, we **emulate the reconstruction of the following quantities**, using publicly available expectations for the LHCb performance in Run3 (see backup):

- **Origin point of the tracks** (first measurement in the Vertex Locator).
- **Three-momentum of the tracks**.
- **Position of the primary vertices**.

Example of decay-tree simplification used in the prototype

Original chain of ancestors:

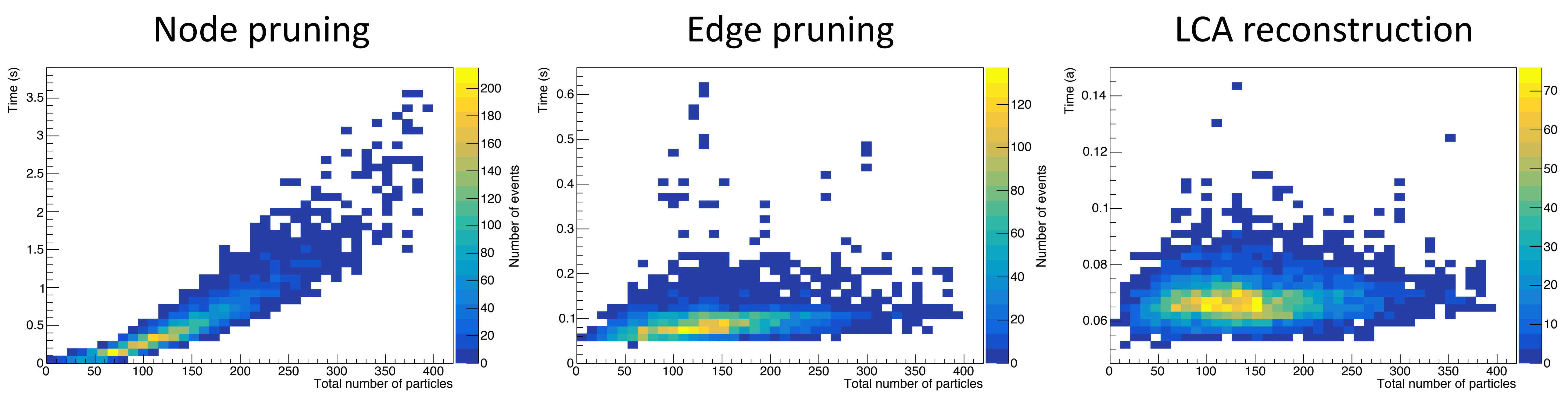
$\pi^+ \leftarrow \rho(770)^0 \leftarrow \phi(1020) \leftarrow D^+ \leftarrow B^0 \leftarrow B^{*0}$

Simplified chain of ancestors (based on reconstructible vertices):

$\pi^+ \leftarrow D^+ \leftarrow B^0$

Performance: timing

Simplistic study (no parallelisation, no hardware accelerators*, algorithm to be further optimised), to **understand which are the slowest parts of the algorithm and how they scale with the total number of particles per event.**



The slowest part is the node pruning, which also has the strongest dependency on the number of particles. → Many possible ways of optimisation.

The processing time of the subsequent algorithms is quite stable regarding changes in event complexity.

(*) Study done on a darwin-x86_64 architecture with a 2.8 GHz Intel Core i7 processor.