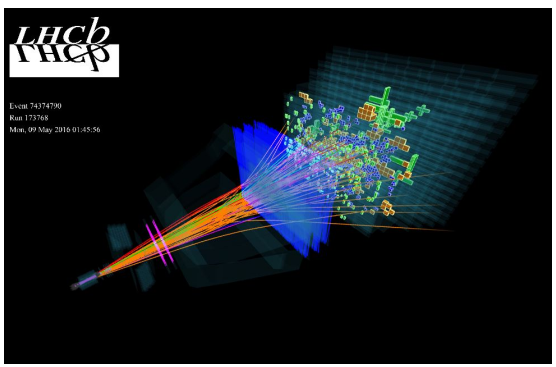
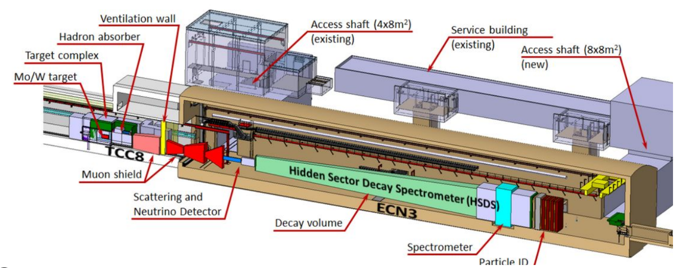
GNN event interpretations at LHCb and SHIP

William Sutcliffe





CHIPP AI/ML Workshop

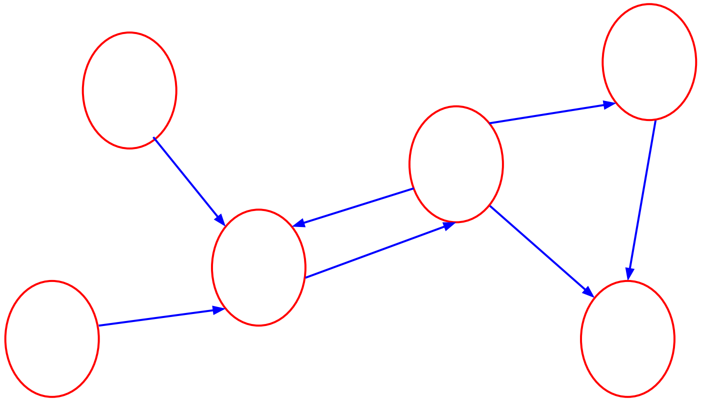
19/06/24

Universität Zürich UZH

Why Graph Neural Networks (GNNs)?

- Many neural network architectures are specialised for sequential and image-like data such as RNNs, Transformers and CNNs.
- GNNs can model more arbitrary relations between data objects by modelling them as edges between nodes in a graph.

Sharing of parameters across node and edge updates in the graph

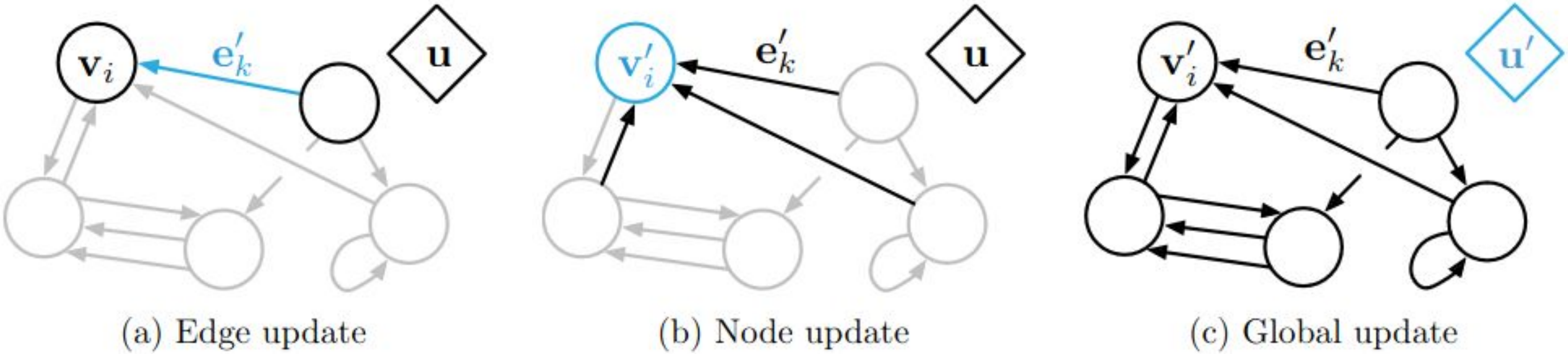


Invariance under node / edge permutations

- This is perfect for particle physics collision events where we deal with various objects like tracks and their relations to one another.

GNN architecture

Graph, G, defined by nodes with features v_i, edges with features e_k and global features u



$$\begin{aligned}
\mathbf{e}'_k &= \phi^e\left(\mathbf{e}_k, \mathbf{v}_{r_k}, \mathbf{v}_{s_k}, \mathbf{u}\right) \\
\mathbf{v}'_i &= \phi^v\left(\bar{\mathbf{e}}'_i, \mathbf{v}_i, \mathbf{u}\right) \\
\mathbf{u}' &= \phi^u\left(\bar{\mathbf{e}}', \bar{\mathbf{v}}', \mathbf{u}\right)
\end{aligned}$$

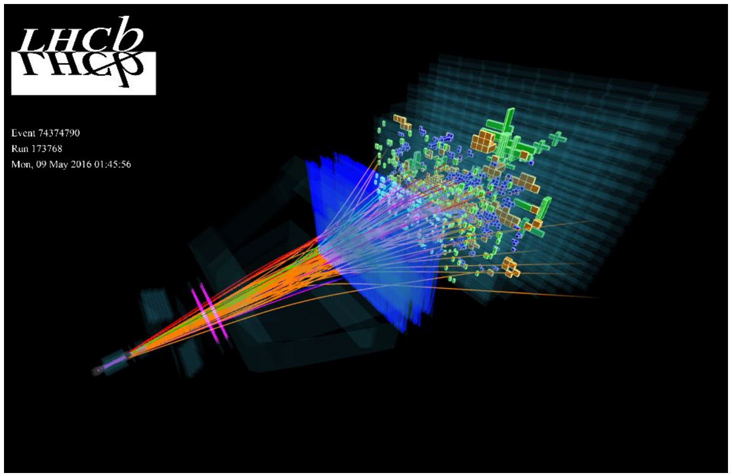
$$\begin{aligned}
\bar{\mathbf{e}}'_i &= \rho^{e\rightarrow v}\left(E'_i\right) \\
\bar{\mathbf{e}}' &= \rho^{e\rightarrow u}\left(E'\right) \\
\bar{\mathbf{v}}' &= \rho^{v\rightarrow u}\left(V'\right)
\end{aligned}$$

https://arxiv.org/pdf/1806.01261

Universität Zürich[UZH]

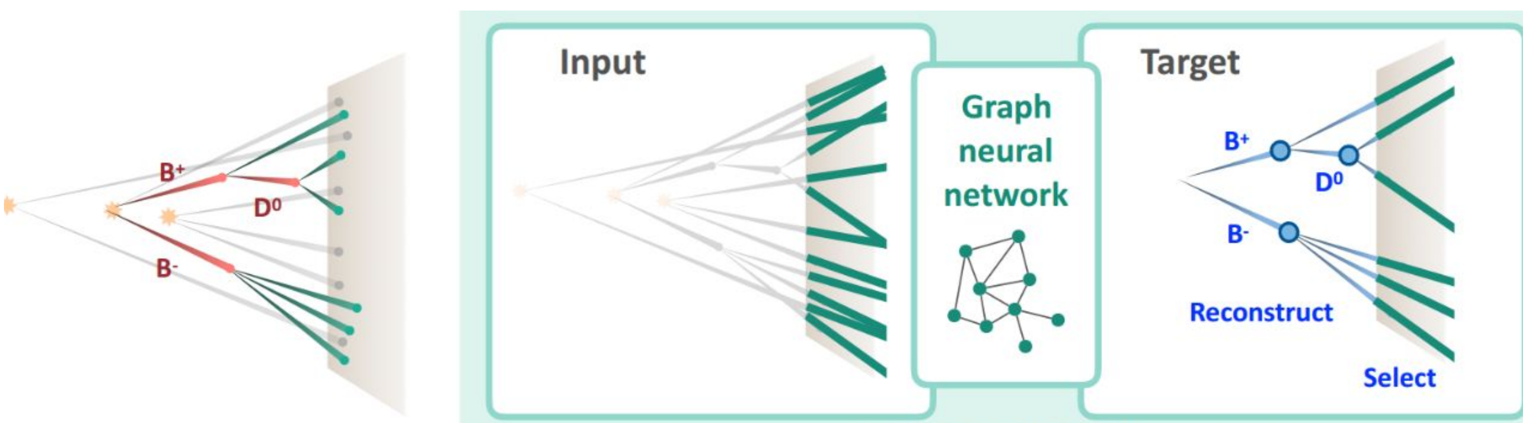
Deep Full Event Interpretation (DFEI)

Julian Garcia Pardinas, Marta Calvi, Rafael Silva Coutinho, Jonas Eschle, Abhijit Mathad, Andrea Mauri, Simone Meloni, Martina Mozzanica, Nicola Serra, Felipe Luan Souza De Almeida, William Sutcliffe, Azusa Uzuki



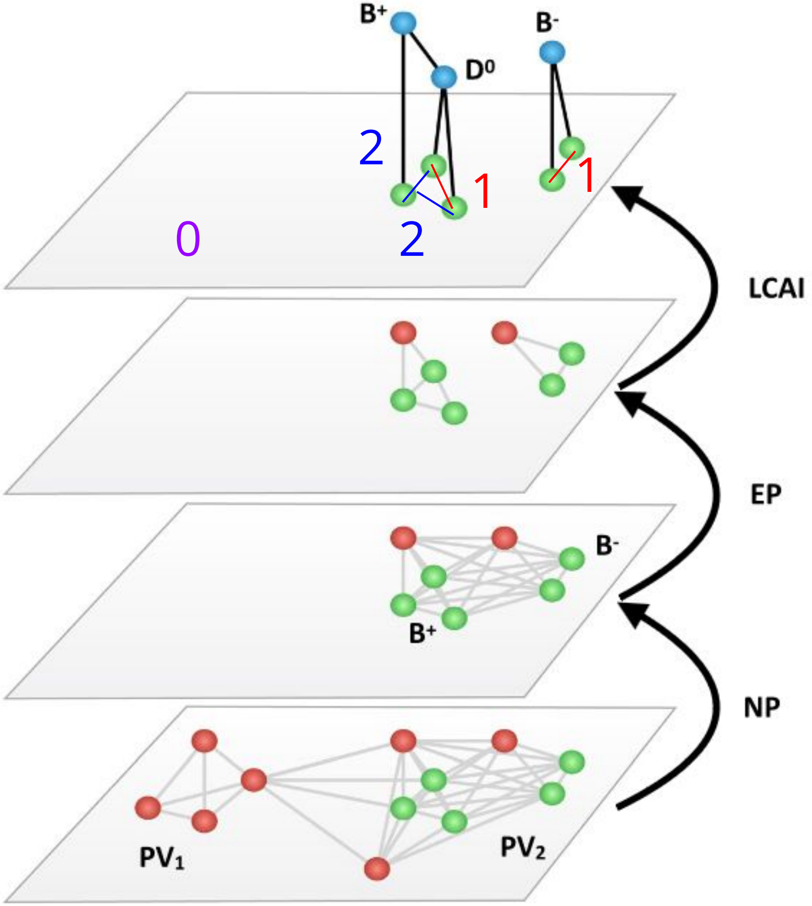
- R&D full event interpretation of heavy hadron decays at LHCb. [García Pardiñas, J., Calvi, M., Eschle, J. et al. Comput Softw Big Sci 7, 12 (2023).]

- Two main applications of trigger and offline analysis.



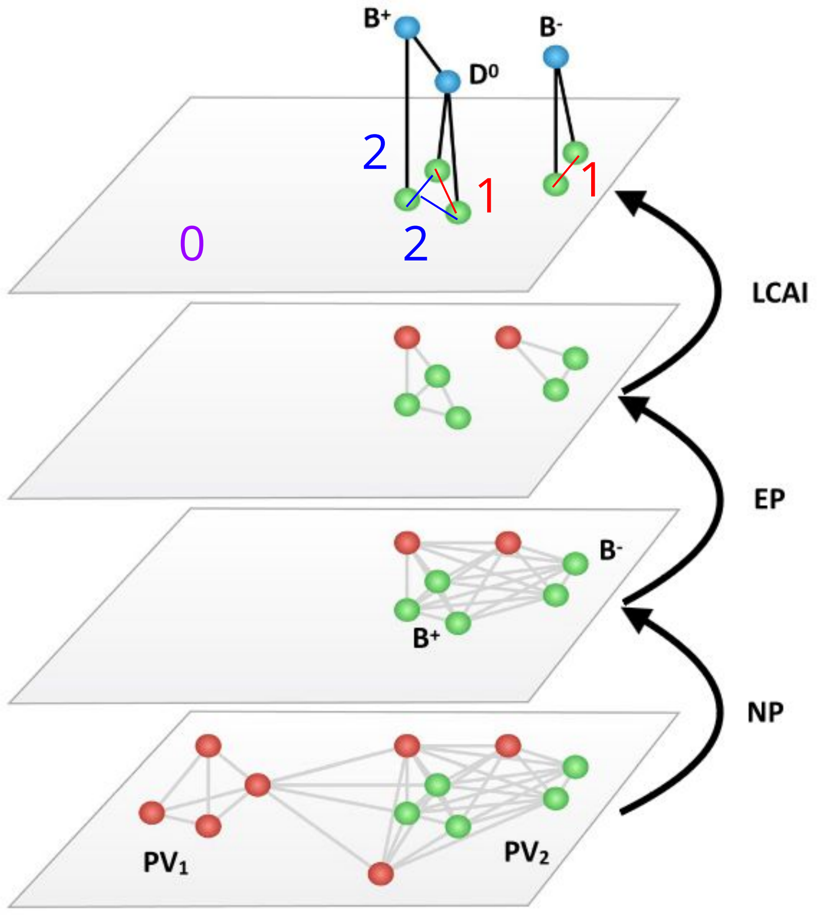
[arXiv:1806.01261v3]

Algorithm



- **Node pruning -** GNN classifies whether node particles are associated with a b-hadron.

Algorithm



- **Edge pruning -** GNN classifies whether the edges connect particles from the same b-hadron.

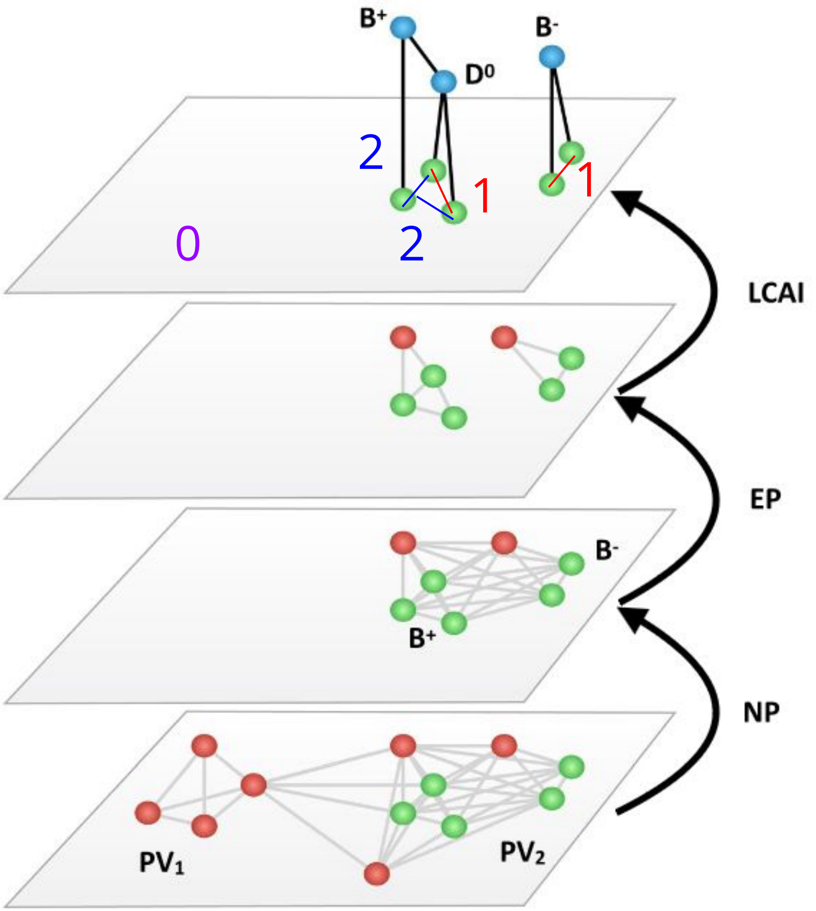
- **Node pruning -** GNN classifies whether node particles are associated with a b-hadron.

Algorithm

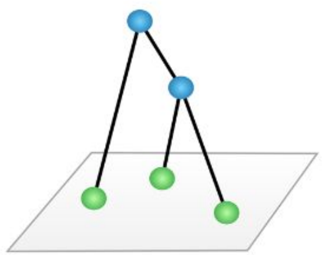
- **Lowest common ancestor prediction -** GNN classifies lowest common ancestor of remaining edges (classes 0,1,2,3).

- **Edge pruning -** GNN classifies whether the edges connect particles from the same b-hadron.

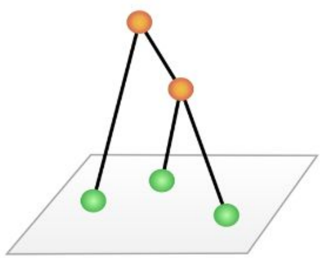
- **Node pruning -** GNN classifies whether node particles are associated with a b-hadron.



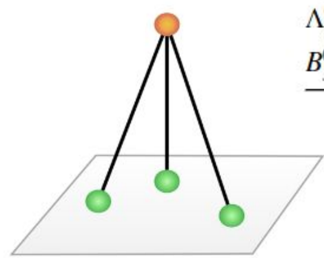
Performance



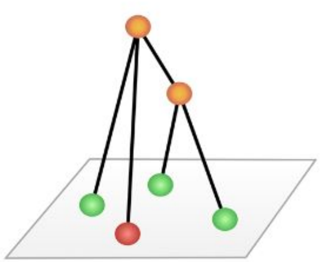
(a) True decay chain.



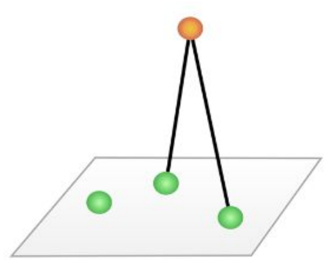
(b) Perfect reconstruction.



(c) Wrong hierarchy.

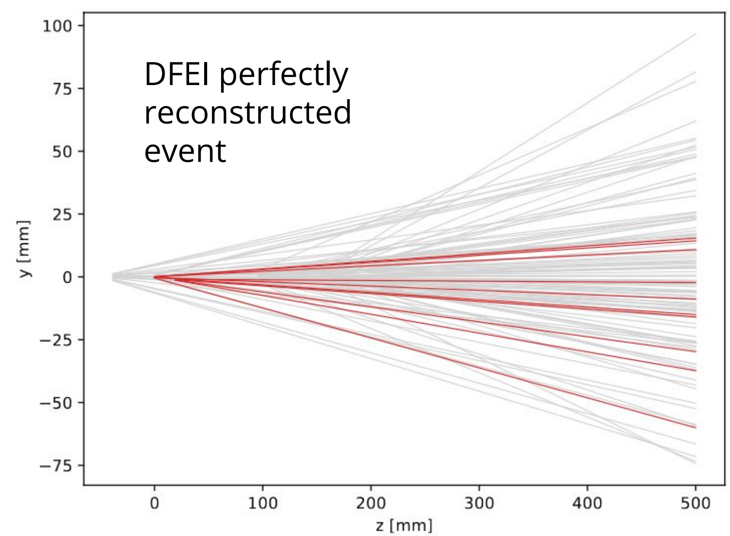


(d) Not isolated.



(e) Partially reconstructed.

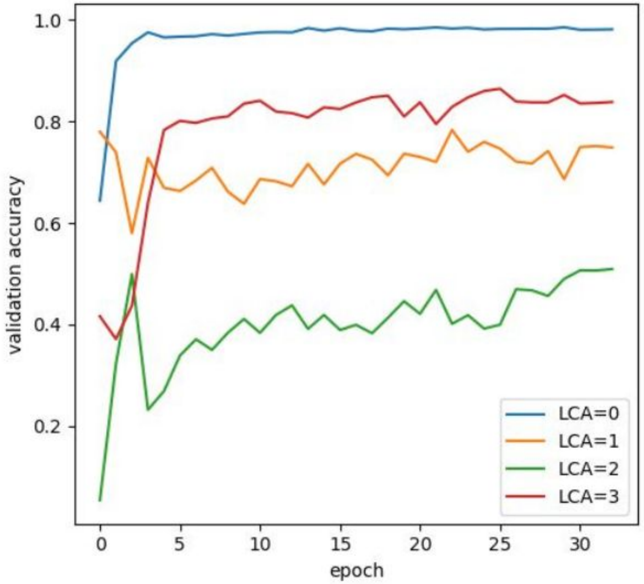
Decay mode	Perfect (%)	Wrong hierarchy (%)	Not iso. (%)	Part. reco. (%)
Inclusive H_b decay	4.6 ± 0.1	5.9 ± 0.1	76.0 ± 0.2	13.4 ± 0.1
$B^0 \to K^{*0}[K^+\pi^-]\mu^+\mu^-$	35.8 ± 0.7	19.2 ± 0.6	44.9 ± 0.7	<0.02
$B^0 \to K^+\pi^-$	38.0 ± 0.7	–	54.7 ± 0.7	7.2 ± 0.4
$B_s^0 \to D_s^-[K^-K^+\pi^-]\,\pi^+$	32.8 ± 0.7	7.1 ± 0.4	53.7 ± 0.8	6.4 ± 0.4
$B^0 \to D^-[K^+\pi^-\pi^-]D^+[K^-\pi^+\pi^+]$	22.7 ± 0.6	22.4 ± 0.6	54.9 ± 0.8	<0.02
$B^+ \to K^+K^-\pi^+$	35.7 ± 0.7	10.2 ± 0.4	46.4 ± 0.7	7.7 ± 0.4
$\Lambda_b^0 \to \Lambda_c^+[pK^-\pi^+]\,\pi^-$	21.7 ± 1.0	8.9 ± 0.7	36.8 ± 1.2	32.6 ± 1.1
$B_s^0 \to J/\psi[\mu^+\mu^-]\,\phi[K^+K^-]$	26.9 ± 0.6	20.5 ± 0.5	52.5 ± 0.6	<0.02

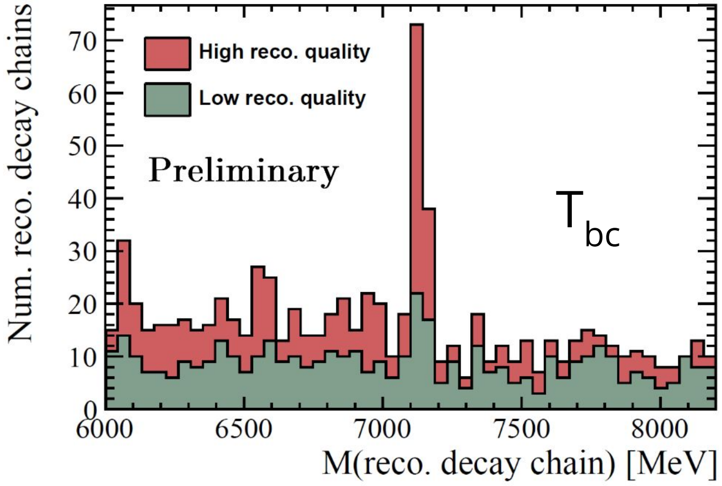


Universität Zürich[UZH]

Ongoing work

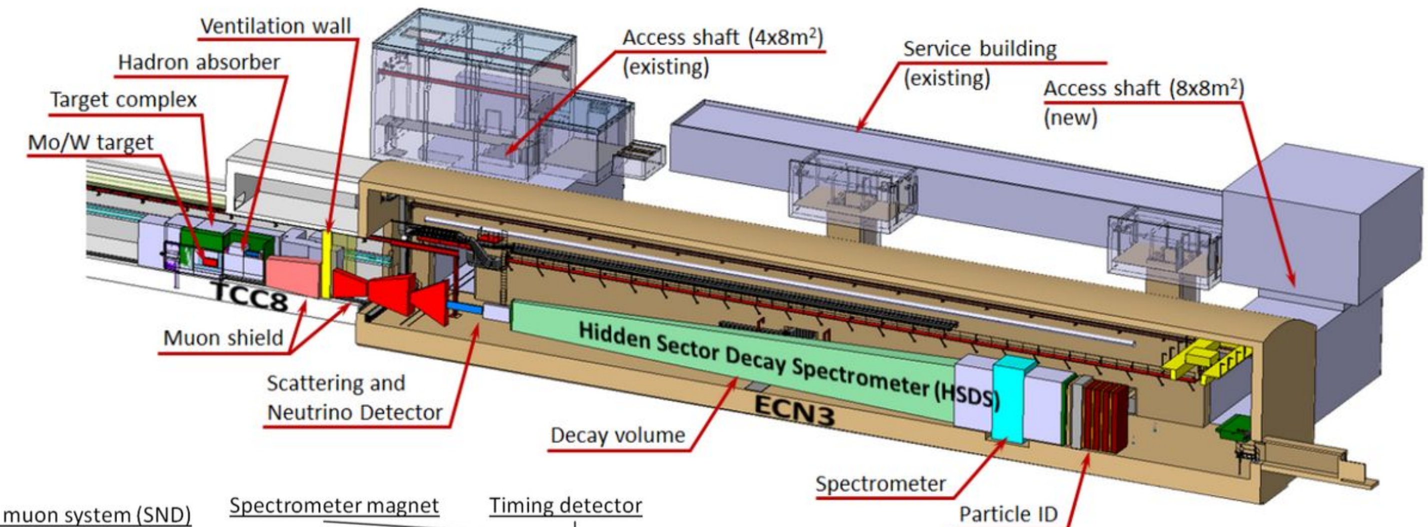
- Development of a new GNN architecture capable of node and edge pruning and with an improved LCA classification.
- Exploration of several physics use cases such as inclusive B -> $X_s$ll and tetraquark searches.
- Work towards deploying the existing algorithm in production with a C++ pipeline.

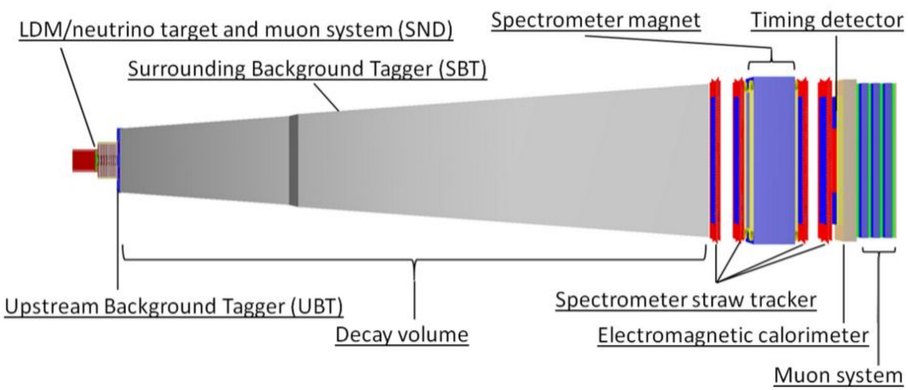




SHIP experiment

- SHIP - recently approved fixed target experiment.
- Will search for heavy neutral leptons, ALPs and dark matter.

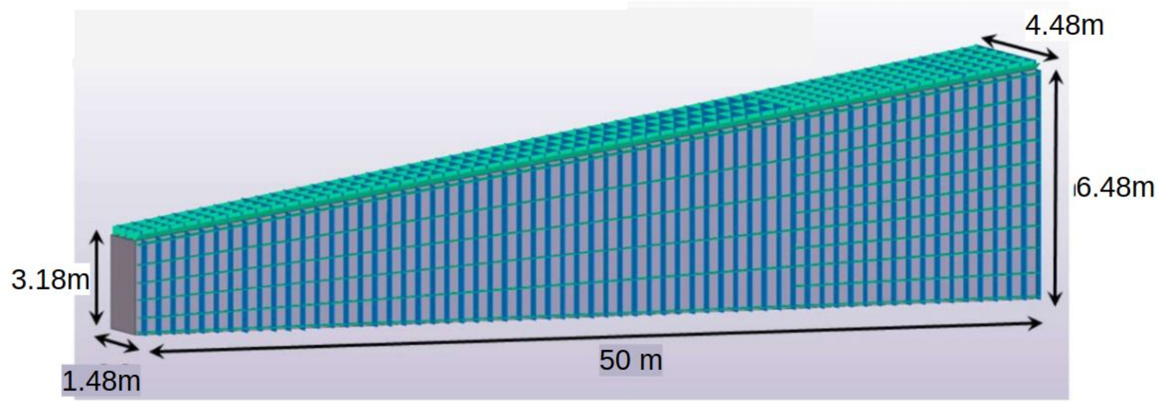


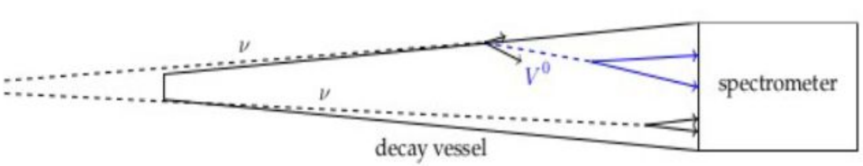


- Decay spectrometer has various veto systems (UBT and SBT)

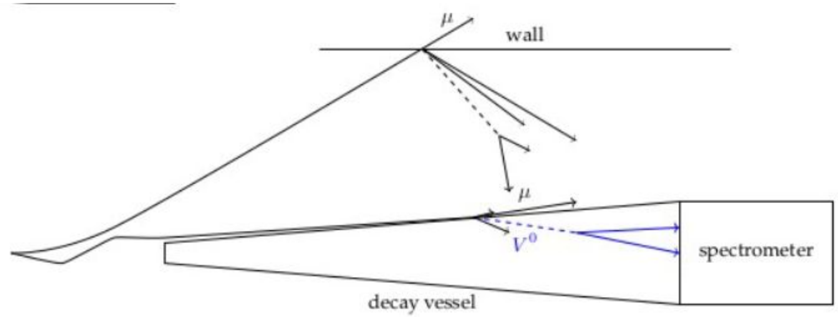
Surround Background Tagger (SBT)

- 2000 cells filled with liquid scintillator
- Tags charged particle entering decay vessel.
- Provides discrimination power against two key backgrounds (μDIS and νDIS)





1) Neutrino Deep Inelastic Scattering (**νDIS**)



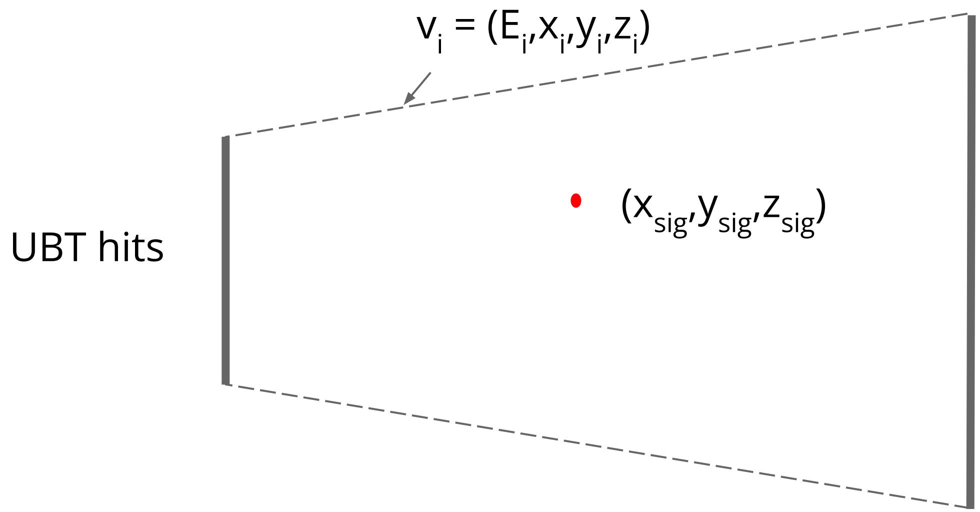
2) Muon Deep Inelastic Scattering **(μDIS)**

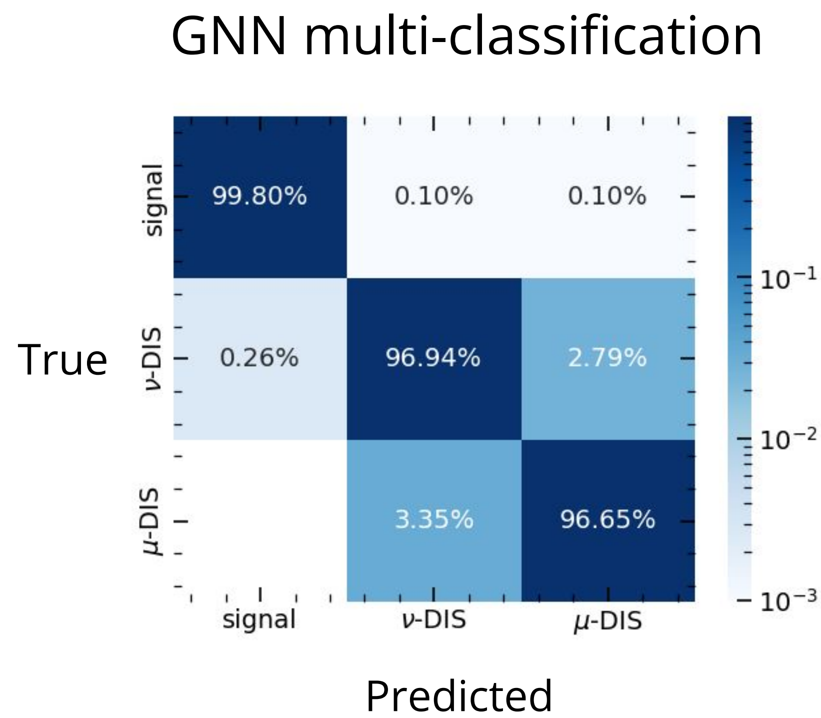
- Here consider signal of HNL -> $\mu\ \mu\ \nu$

Universität Zürich[UZH]

SBT GNN

Anupama Reghunath, Heiko Lacker, Patrick Owen, Nicola Serra, William Sutcliffe





- SBT cells (dashed line) are nodes, with $v_i = (E_i,x_i,y_i,z_i)$
- Edges defined via kNN clustering, k=20
- Global attributes, u = (no. UBT hits, no. SBT hits, x_{sig},y_{sig},z_{sig})

Universität Zürich[UZH]

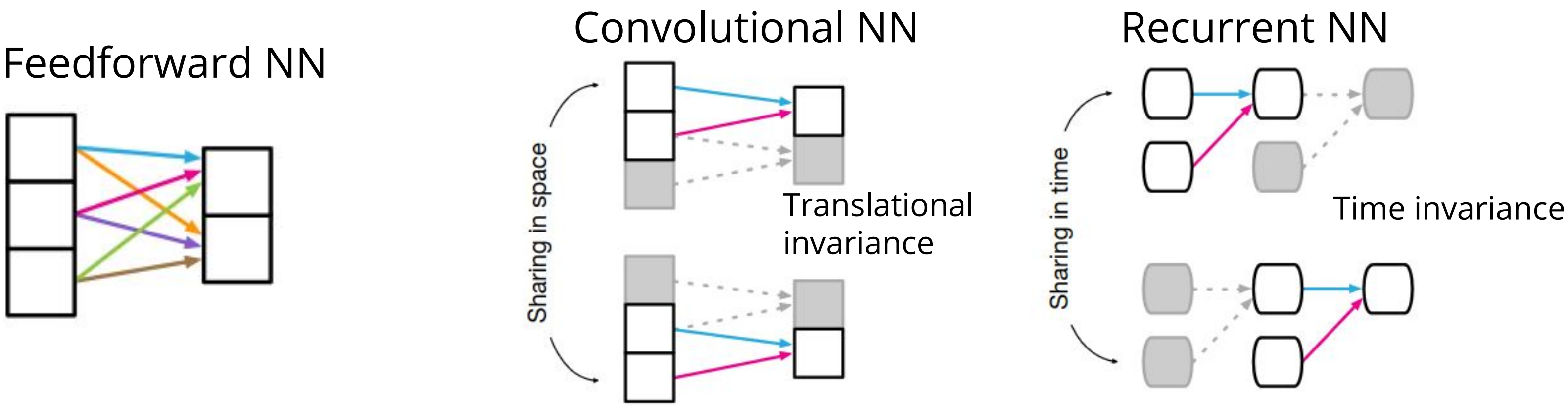
Conclusion

- GNNs can represent complex relations between particle physics data objects enabling sophisticated event interpretations.
- The deep full event interpretation (DFEI) Comput Softw Big Sci 7, 12 (2023) employs a novel GNN based edge classification of lowest common ancestors of heavy hadron b-decays.
- Meanwhile, at SHIP GNNs allow for a more complete exploitation of discrimination power from the surround background tagger.

Universität Zürich[UZH]

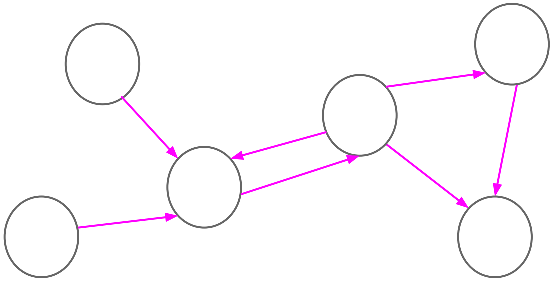
Why Graph Neural Networks (GNNs)?

- Several neural network architectures for exploiting the spatial and sequential structure of data (CNNs, RNNs and transformers).



- GNNs can model arbitrary relations between data objects by treating these as nodes and edges in graph.

Sharing across nodes and edges in the graph

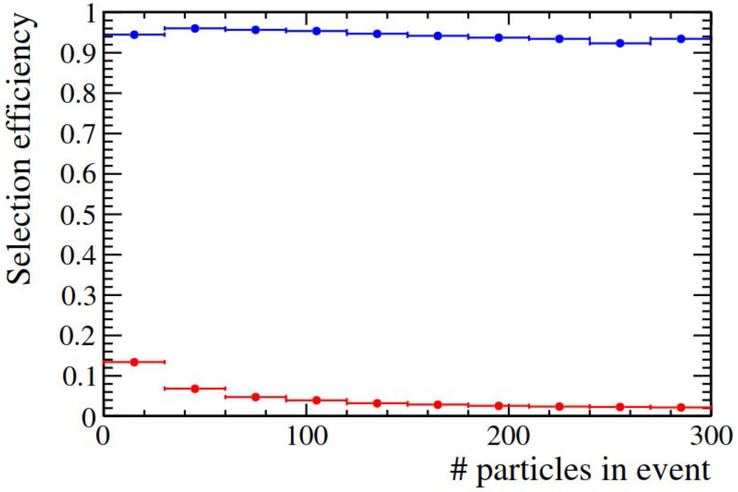


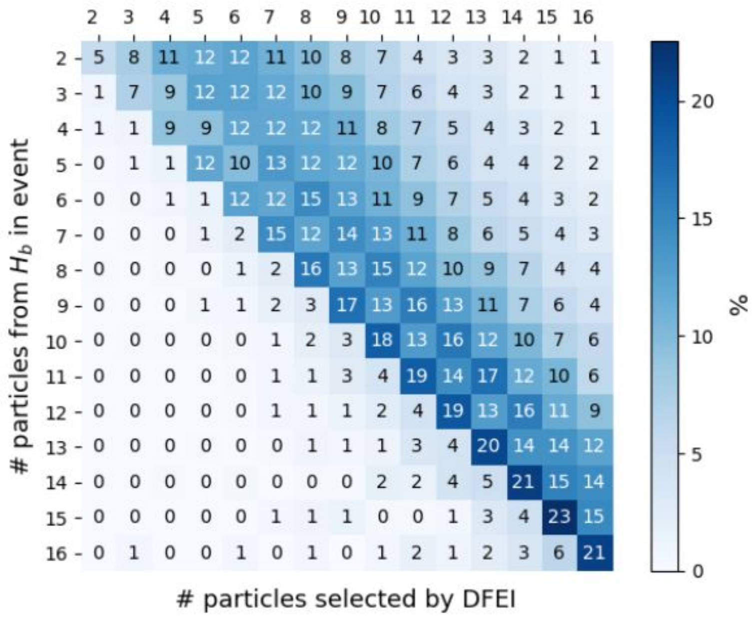
Invariance under node / edge permutations

Additional DFEI performance plots

- Selection efficiency for B particles and particles from the rest of the event.

- Confusion matrix shown below.





Universität Zürich[UZH]