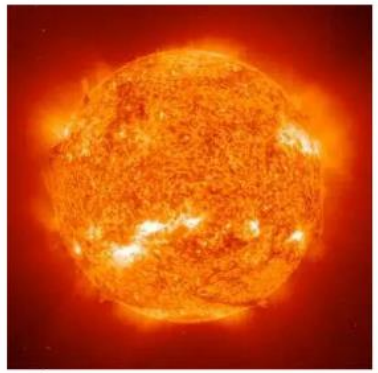
Enhanced Event Reconstruction at Hyper-Kamiokande using Graph Neural Networks at High Energy

Christine QUACH – Laboratoire Leprince-Rinquet & ILANCE

1 How does the detection work in HK



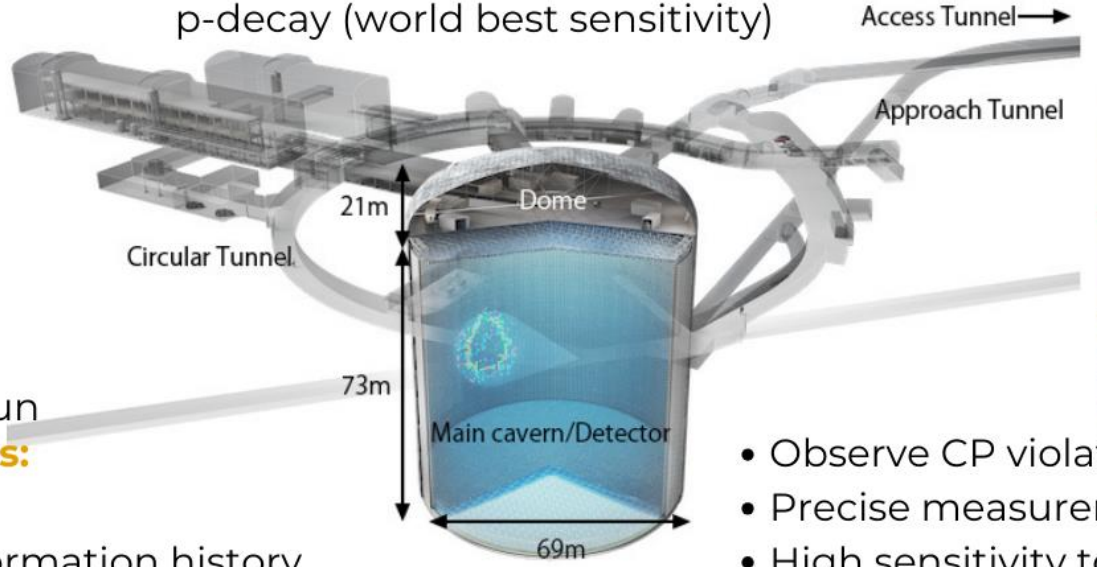
- MSW effect in the Sun
- Non-standard interactions in the Sun

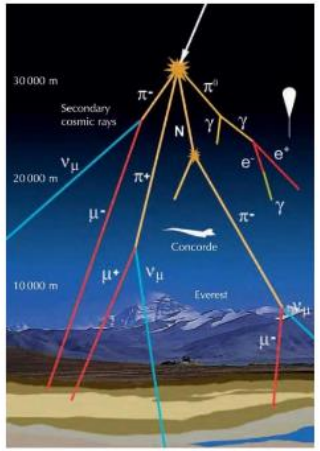
Supernovae neutrinos:

- Direct SNν: Constrains SN models
- Relic SNν: Constrains cosmic star formation history

Proton decay

Probe Grand Unified Theories through p-decay (world best sensitivity)





- Observe CP violation for lepton at 5 σ
- Precise measurement of δCP
- High sensitivity to ν mass ordering

	SK	HK
Site	Mozumi	Tochibora
Overburden	2700 m.w.e.	1700 m.w.e.
Number of ID PMTs	11129	20000
Photo-coverage	40%	20% (x2 efficiency)
Mass/Fiducial mass	50 kton / 22.5 kton	258 kton / 186 kton
Beam power	500 kW to 1 MW	1.3 MW

Parameters to reconstruct

- Flavor
- Direction
- Energy
- Vertex

1 How does the detection work in HK

a) Principle of event detection

Neutrino oscillation

$$\Delta m^2 \equiv m_2^2 - m_1^2$$

$$P(\nu_\alpha \to \nu_\beta)(L, E) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right) \approx \sin^2 2\theta \sin^2\left(1.3 \frac{\Delta m^2[\mathrm{eV}^2] L[\mathrm{km}]}{E[\mathrm{GeV}]}\right)$$

Two flavor approximation in vacuum

b) Event reconstruction key points

Parameters to reconstruct

- Flavor (PID)
- Direction
- Energy

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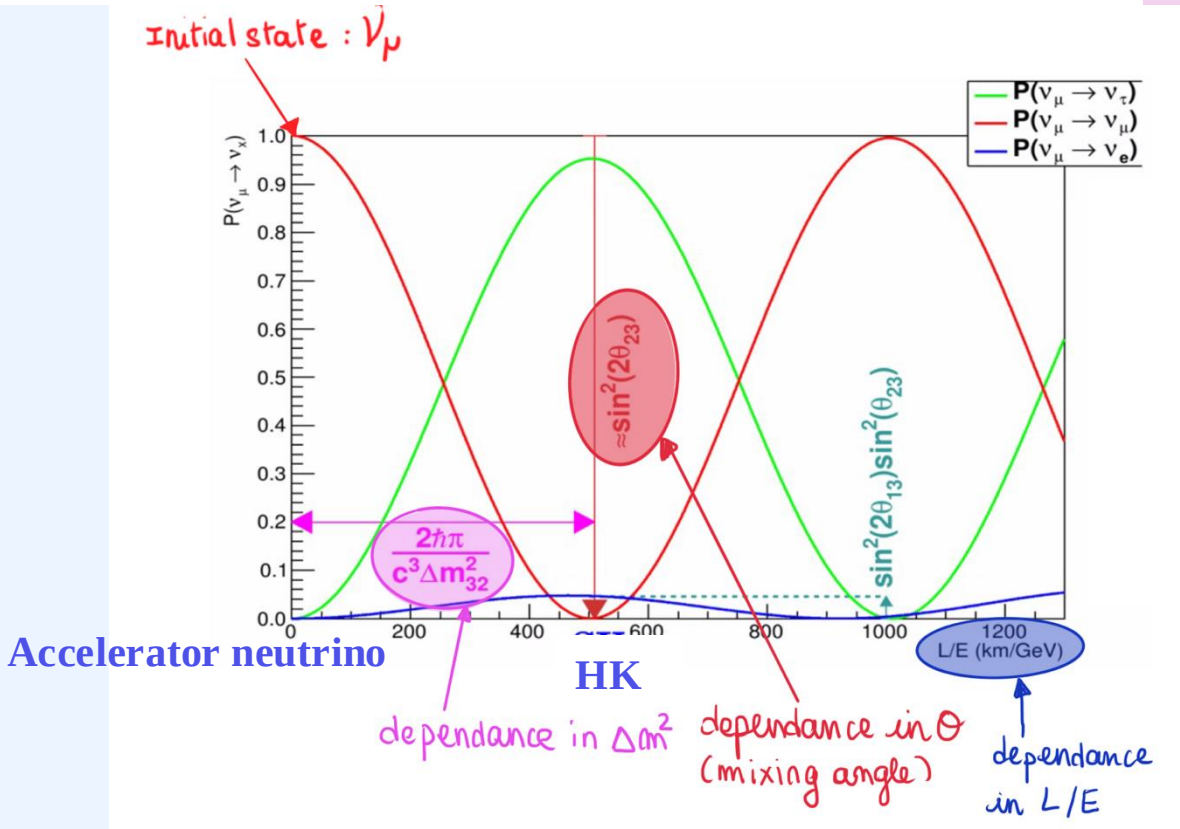

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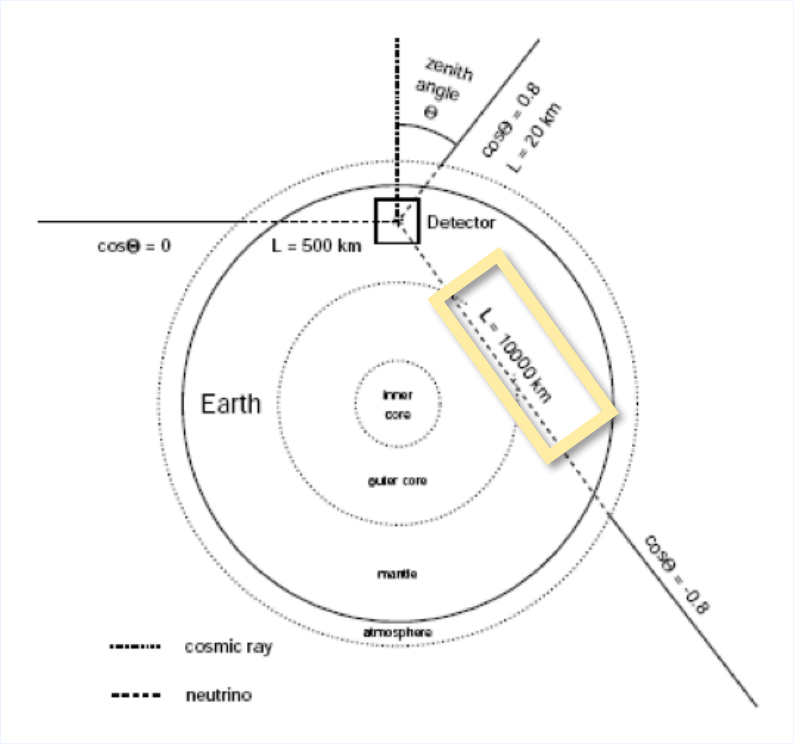
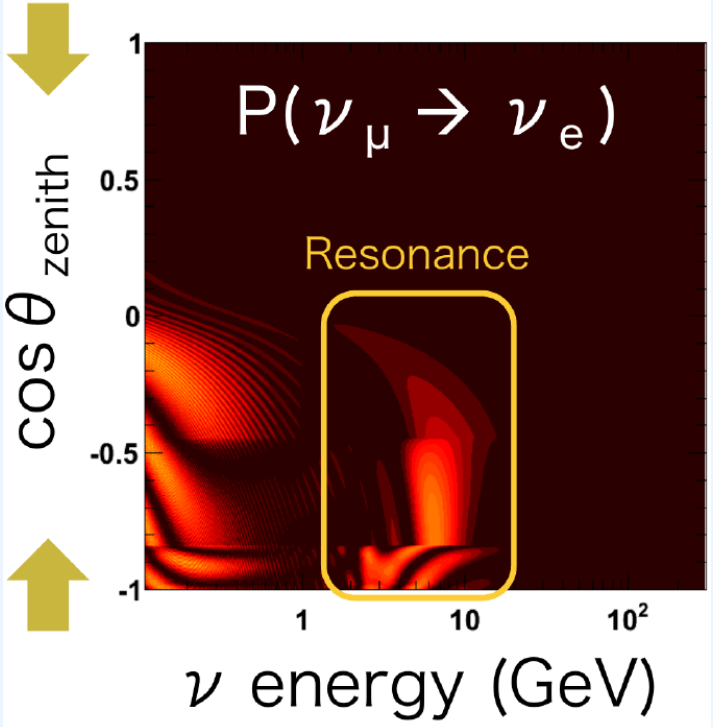




b) Event reconstruction key points

Two flavor approximation in vacuum

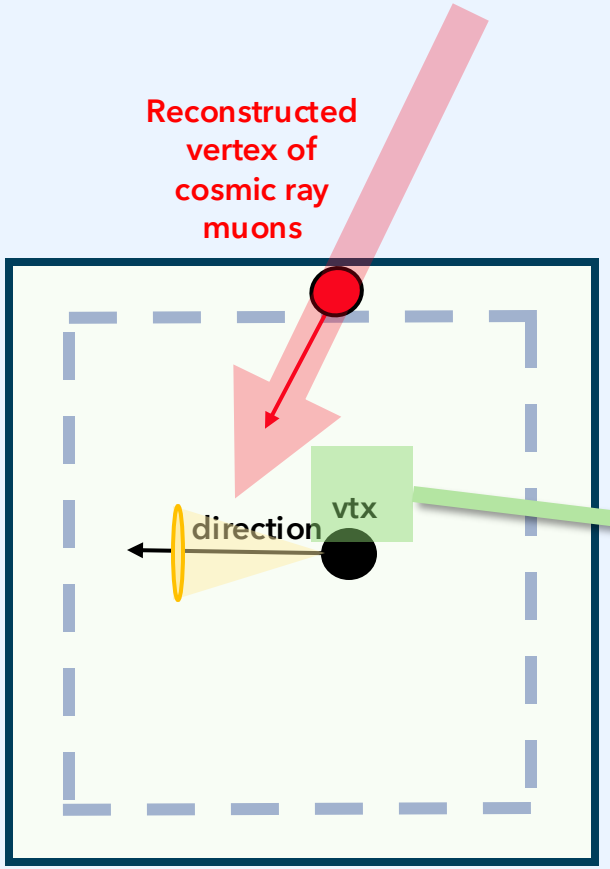
Parameters to reconstruct

- Flavor (PID)
- Direction
- Energy

1 How does the detection work in HK

a) Principle of event detection

Cosmic rays muon background



Pi0 background

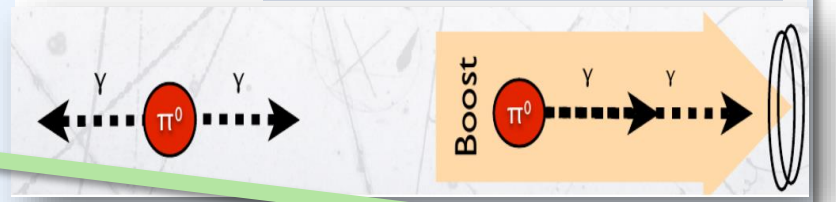
$$\nu + N \rightarrow \nu + N + \pi^0$$

Pi0 decays like an electron ! :

$$\pi^0 \rightarrow \gamma + \gamma$$

$$\rightarrow e^- + e^+$$

$$\rightarrow e^- + e^+$$



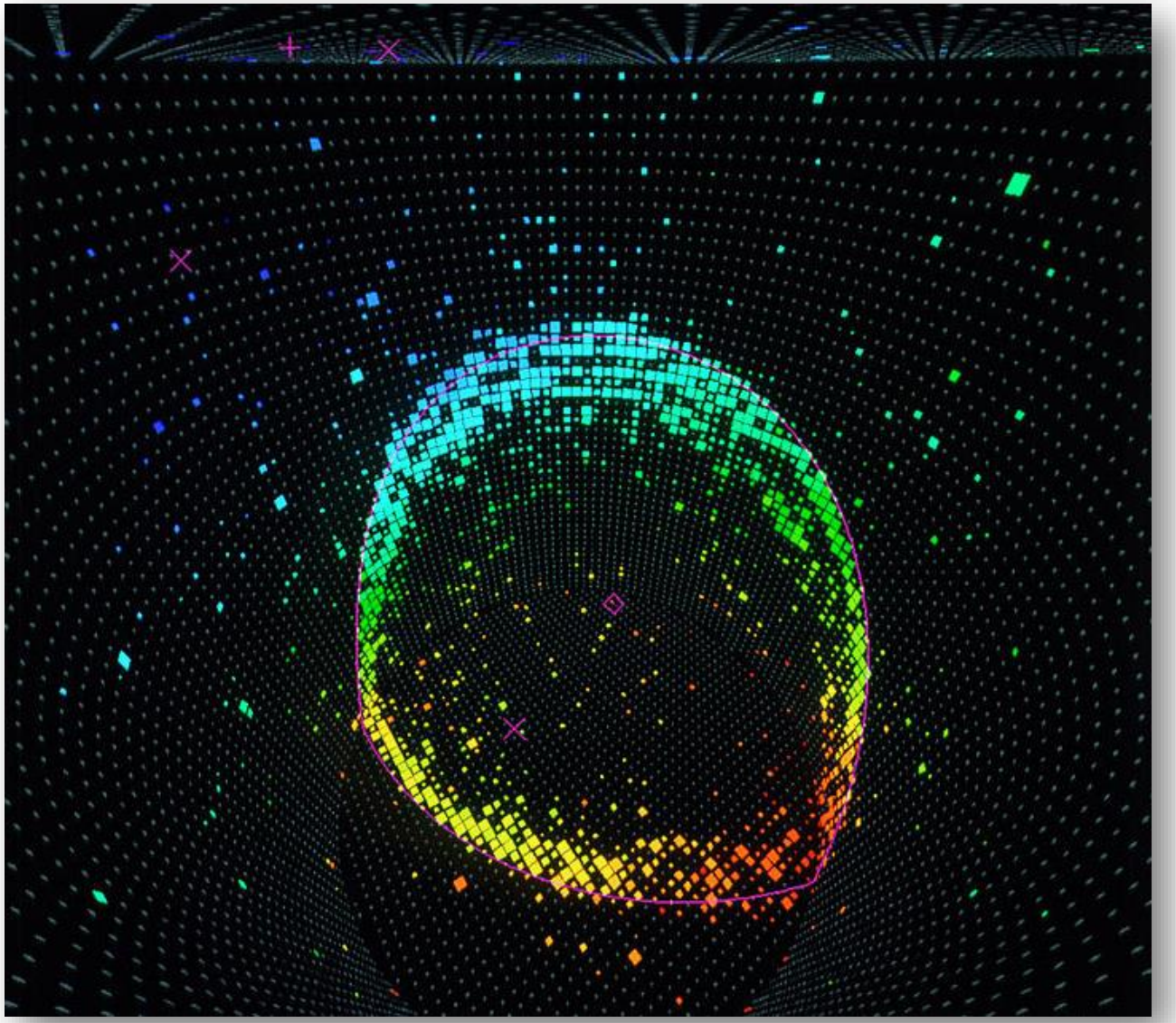
- At high momentum, the 2 **gammas decay are very boosted** and the rings of **e+/e- overlap**, giving a 2 e-like rings.
- In some cases, **the 2 e-like rings overlap**.

b) Event reconstruction key points

Parameters to reconstruct

- **PID**
  - **Flavor**
  - **e/pi0**
- **Direction**
- **Energy**
- **Vertex**

2 GNN : Machine Learning based algorithm for reconstruction



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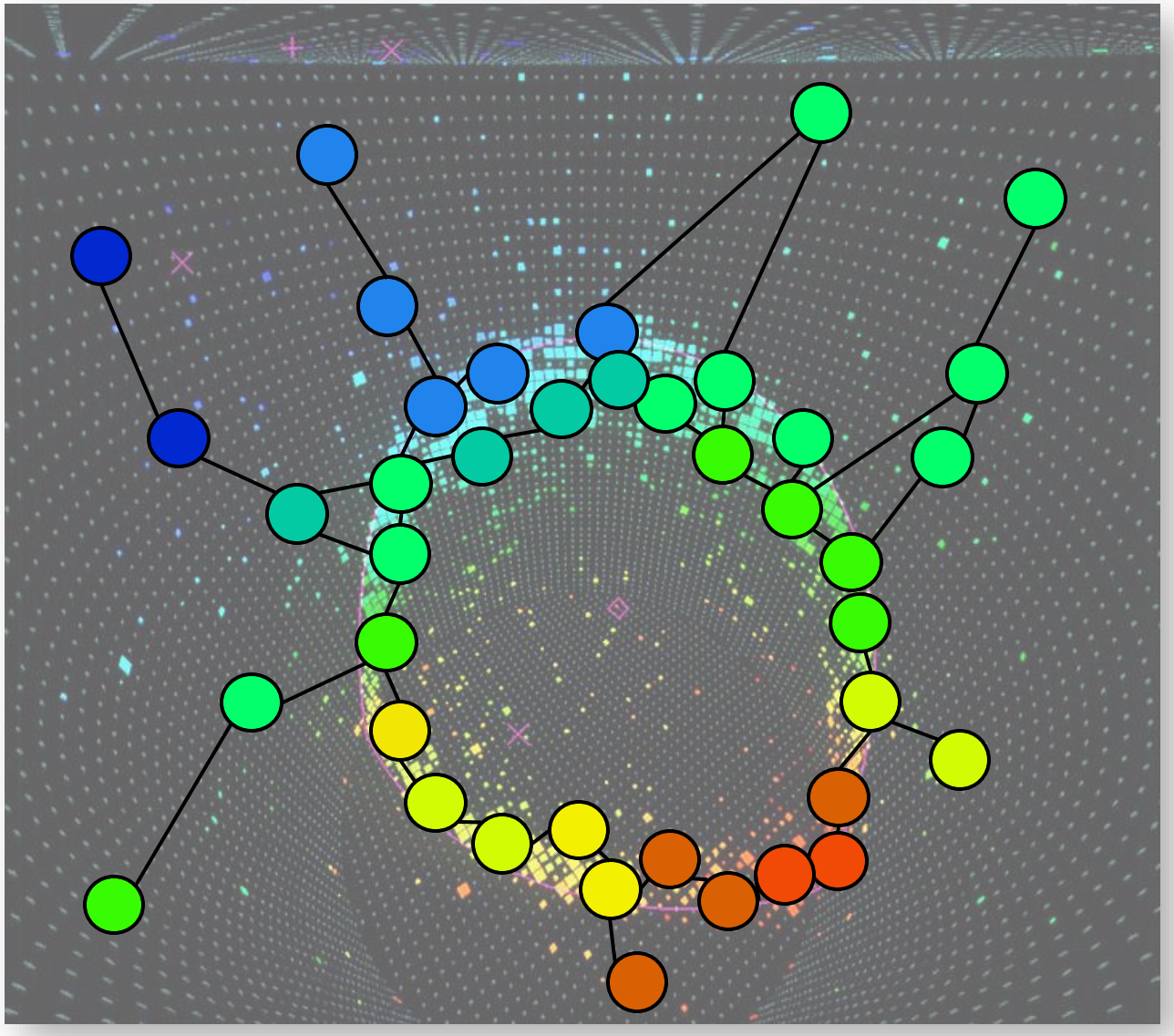

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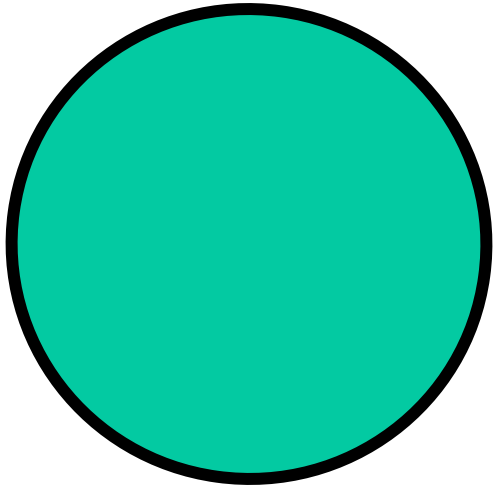
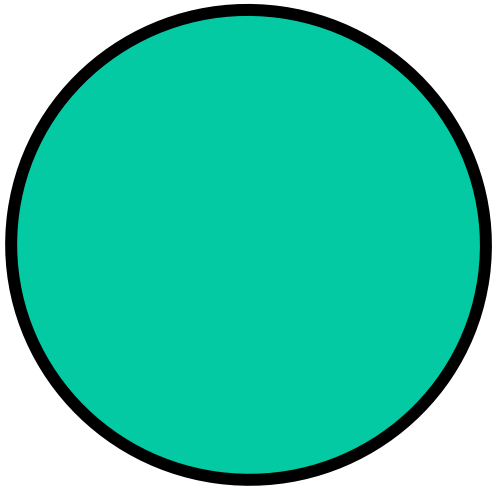


Node : Hit PMT

2 GRANT : Machine Learning based algorithm for reconstruction

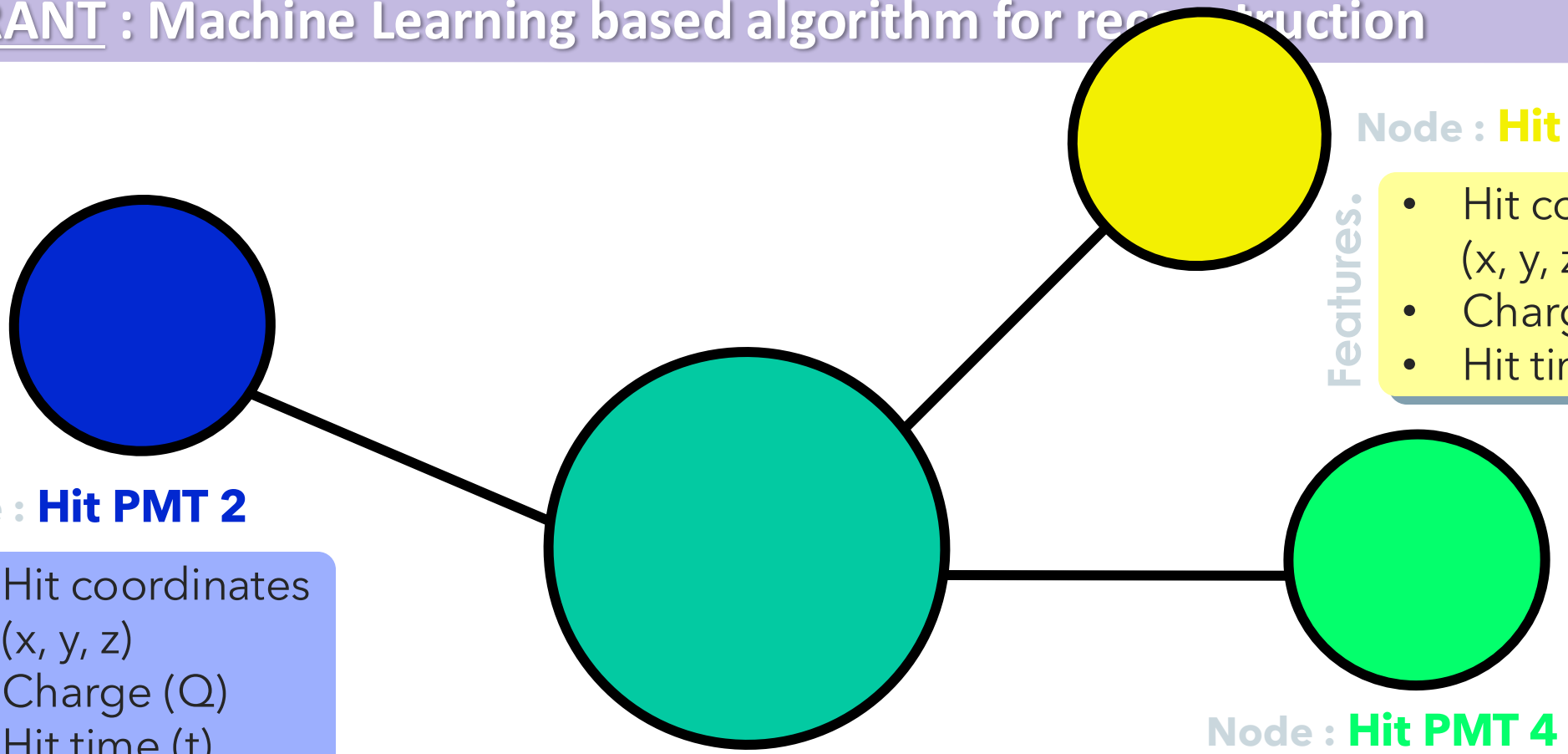


Node : **Hit PMT**

Features.

- Hit coordinates (x, y, z)
- Charge (Q)
- Hit time (t)

GRANT : Machine Learning based algorithm for reconstruction



Node : **Hit PMT 3**

Features.
- Hit coordinates (x, y, z)
- Charge (Q)
- Hit time (t)

Node : **Hit PMT 2**

Features.
- Hit coordinates (x, y, z)
- Charge (Q)
- Hit time (t)

Node : **Hit PMT 1**

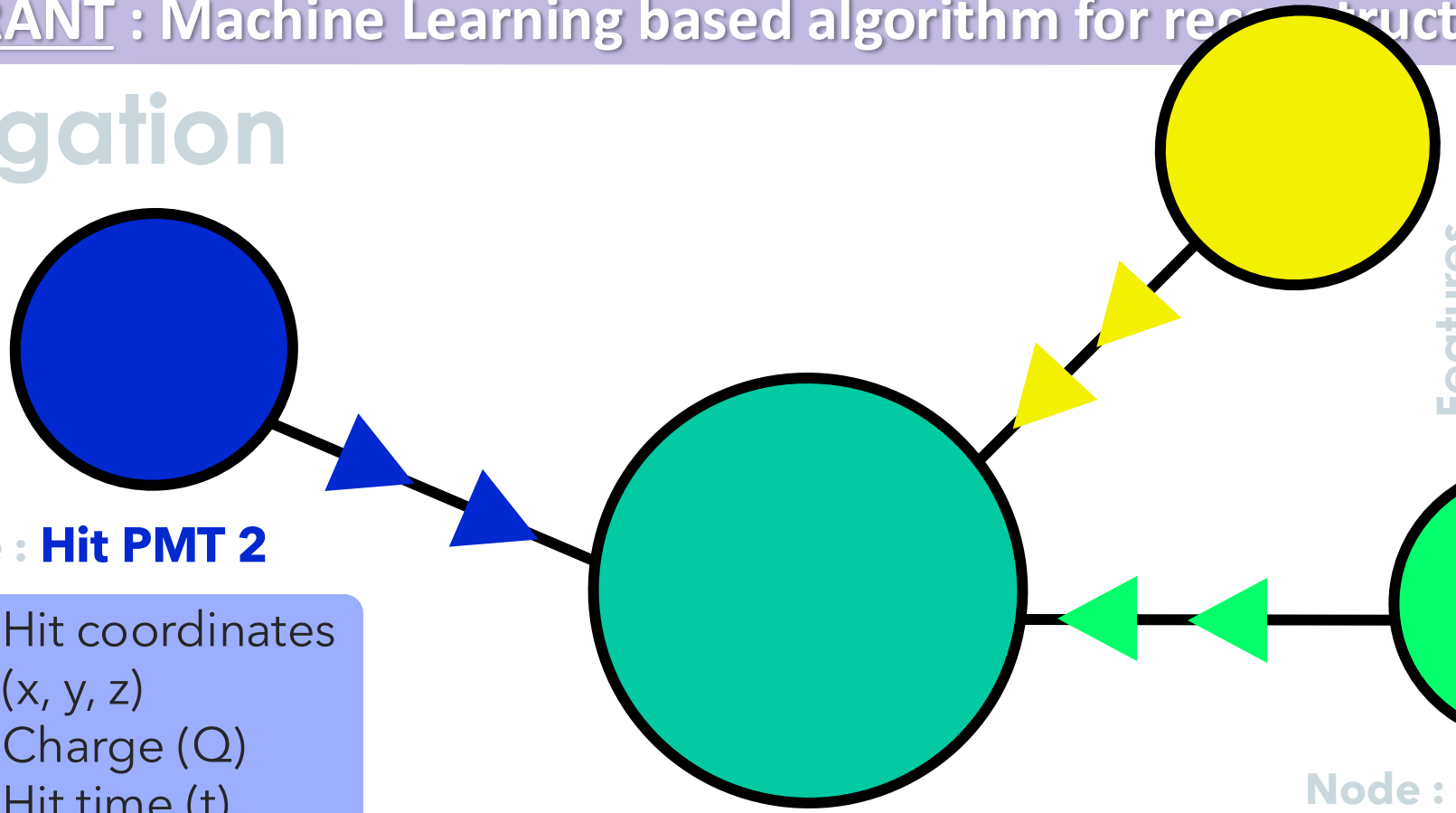
Features.
- Hit coordinates (x, y, z)
- Charge (Q)
- Hit time (t)

Node : **Hit PMT 4**

Features.
- Hit coordinates (x, y, z)
- Charge (Q)
- Hit time (t)

GRANT : Machine Learning based algorithm for reconstruction

Aggregation



Node : **Hit PMT 2**

Features.

- Hit coordinates (x, y, z)
- Charge (Q)
- Hit time (t)

Node : **Hit PMT 3**

Features.

- Hit coordinates (x, y, z)
- Charge (Q)
- Hit time (t)

Node : **Hit PMT 1**

Features.

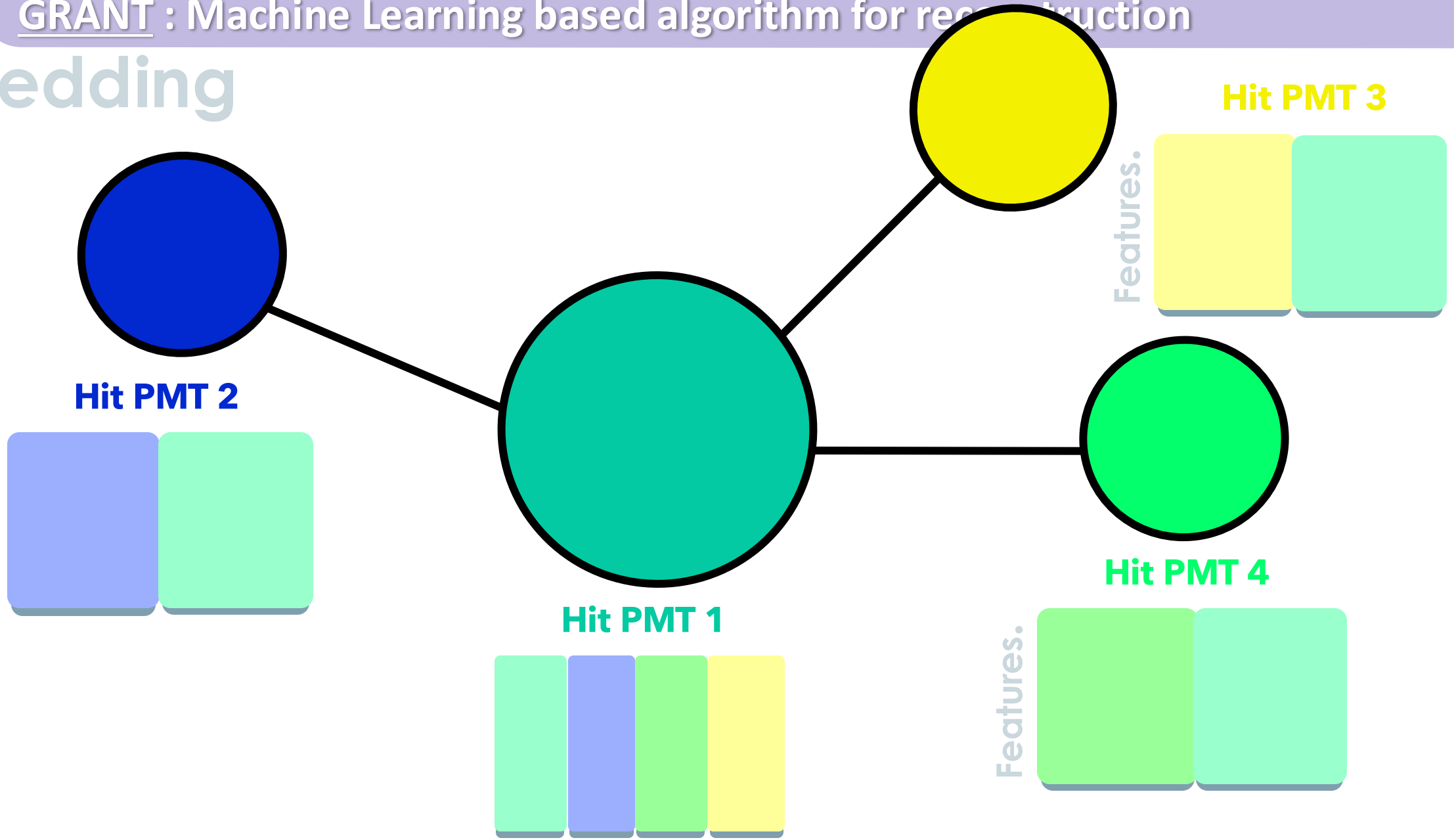
Node : **Hit PMT 4**

Features.

- Hit coordinates (x, y, z)
- Charge (Q)
- Hit time (t)

GRANT : Machine Learning based algorithm for reconstruction

Embedding



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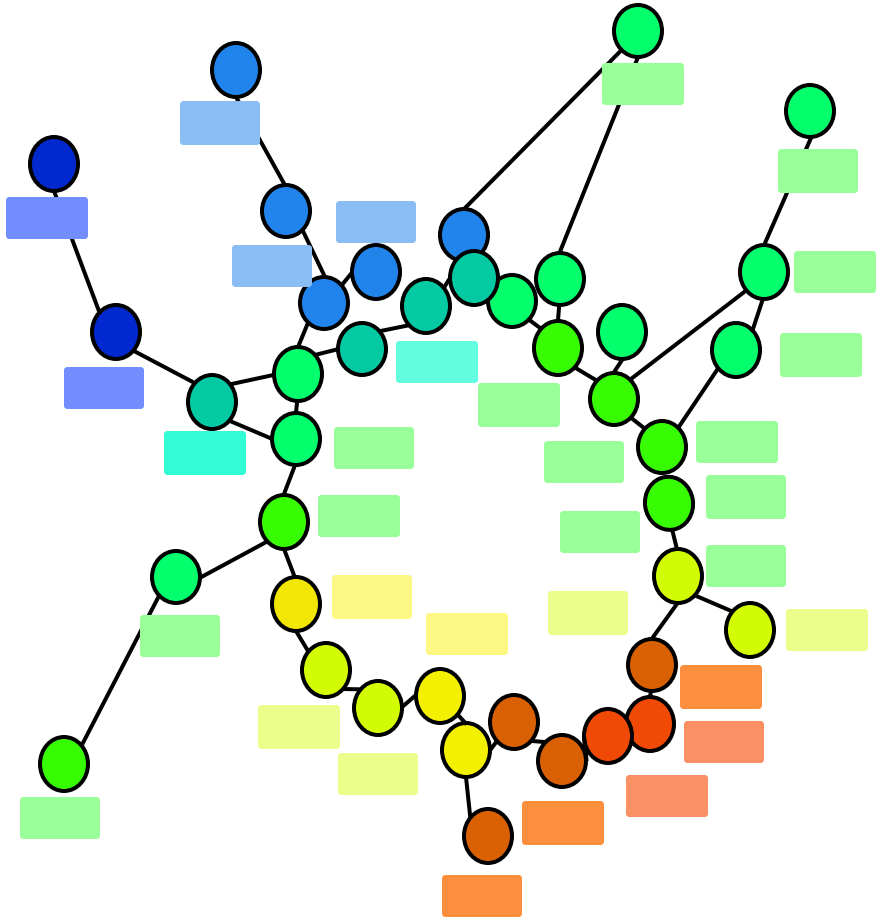

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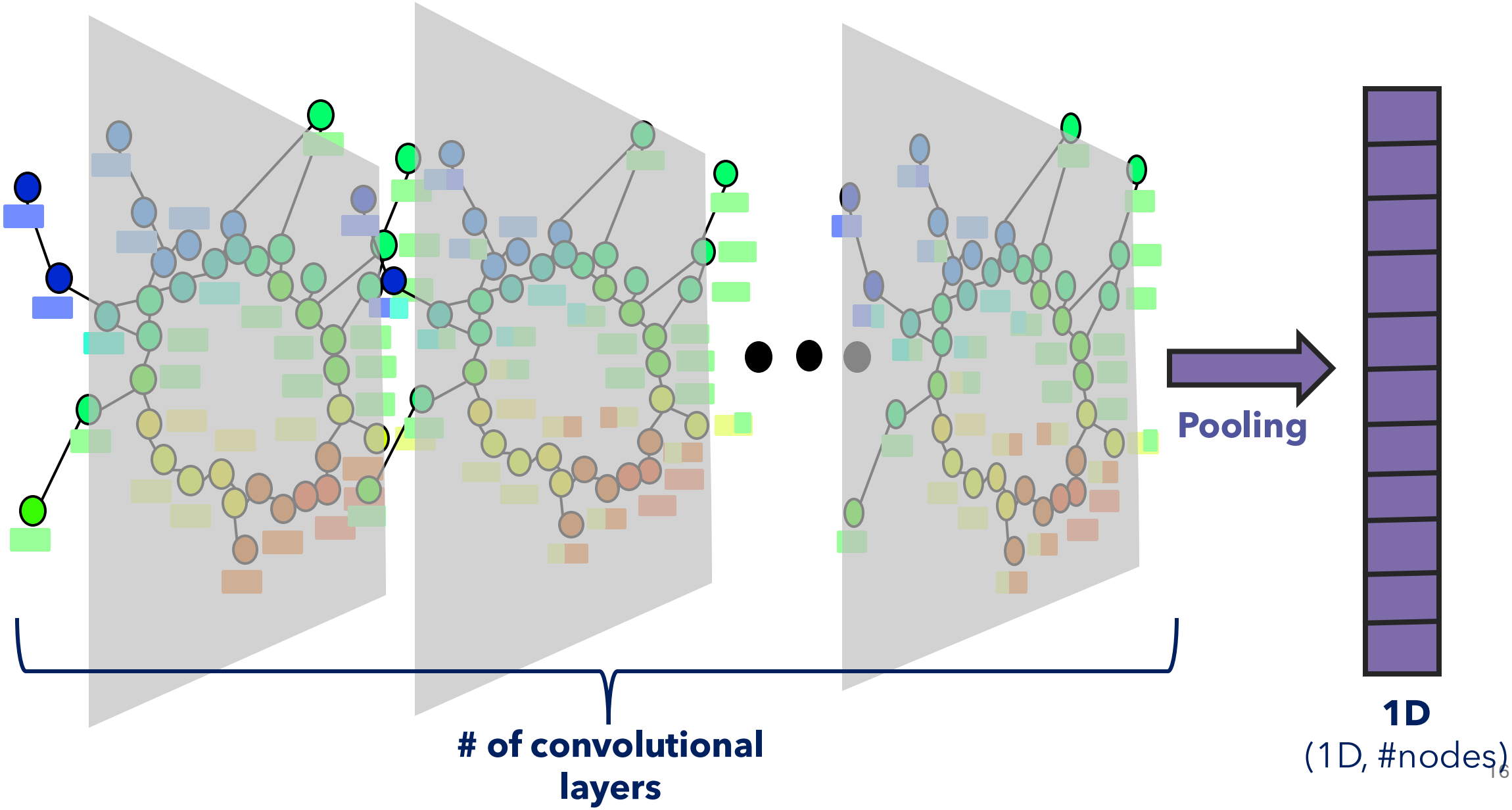

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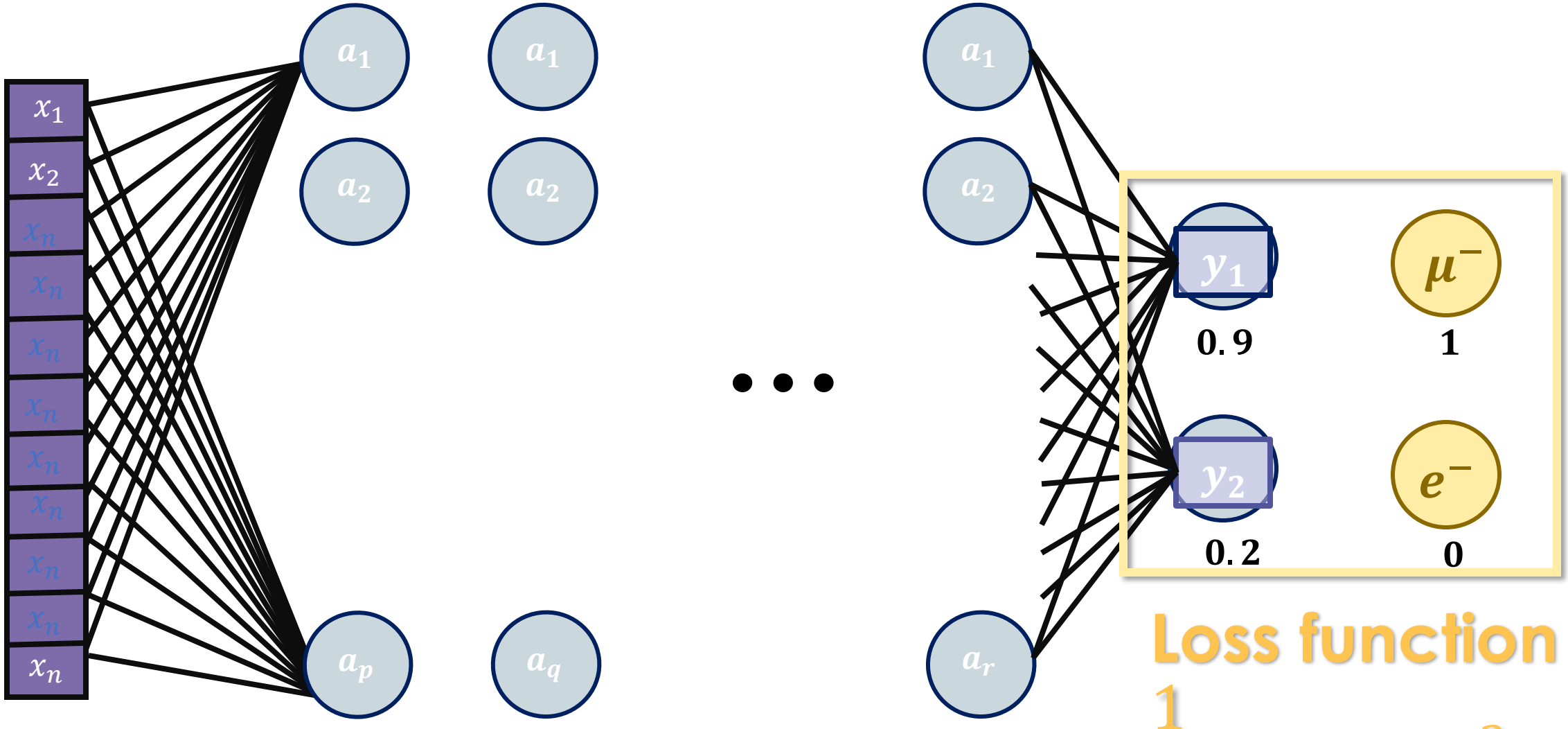


INPUT
(Graph representation as 1D vector)

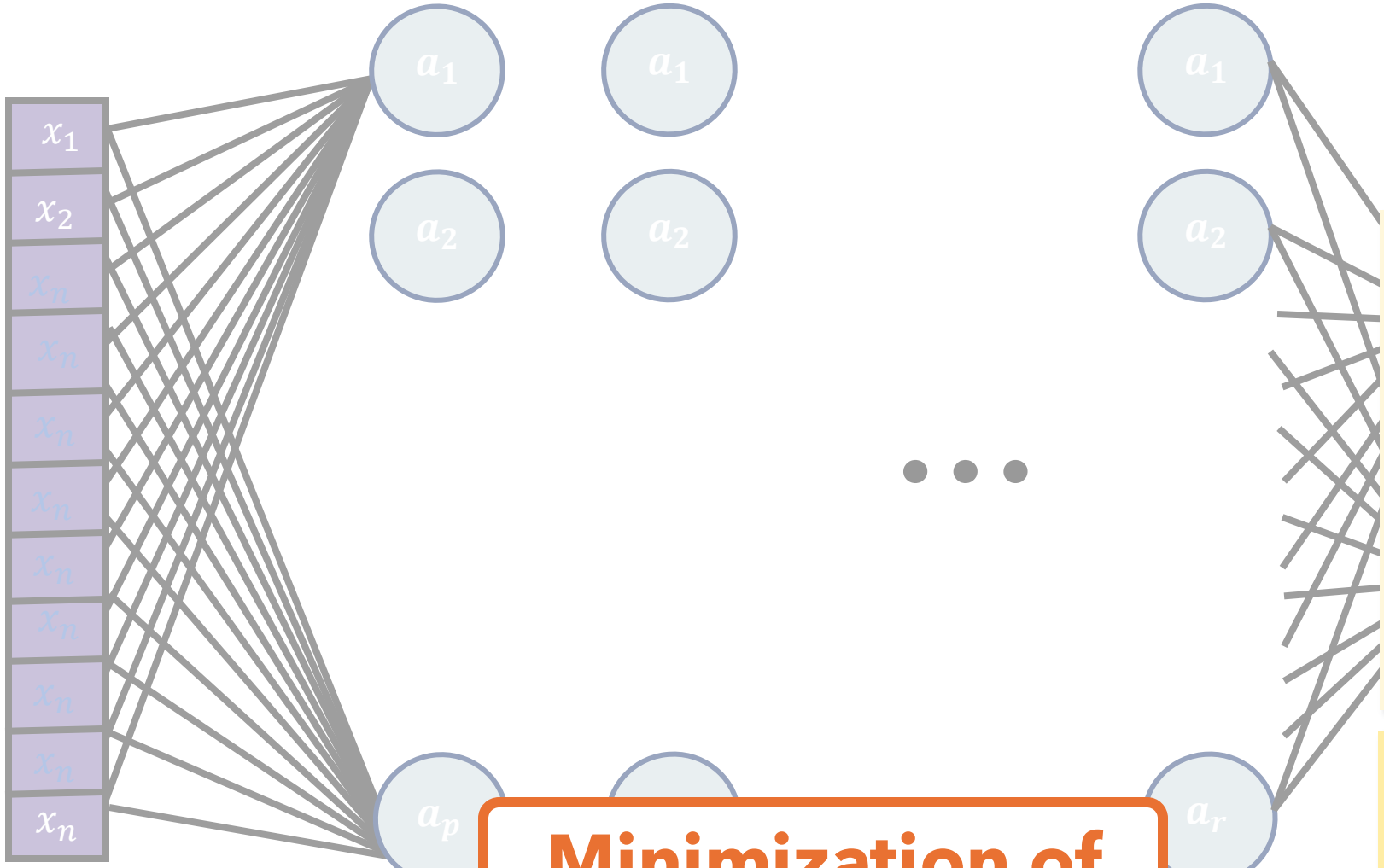
NEURONS **NEURONS** **NEURONS**

# of hidden layers

Loss function :

$$\frac{1}{n}\Sigma(y_i - \hat{y}_i)^2$$

2 GRANT : Machine Learning based algorithm for reconstruction



INPUT
(Graph representation as 1D vector)

NEURO

URONS

# of hidden layers

Minimization of the loss function !

Loss function :

$$\frac{1}{n}\Sigma(y_i - \hat{y}_i)^2$$

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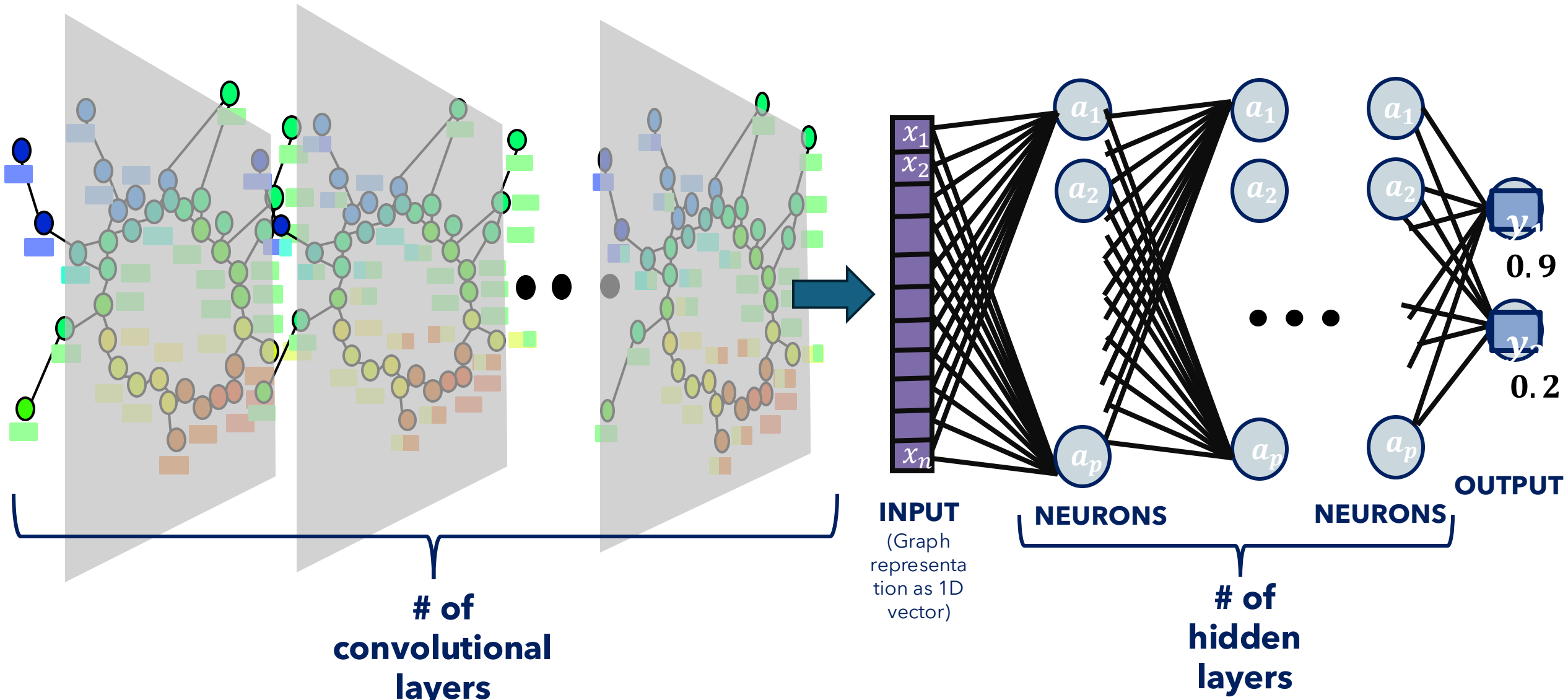


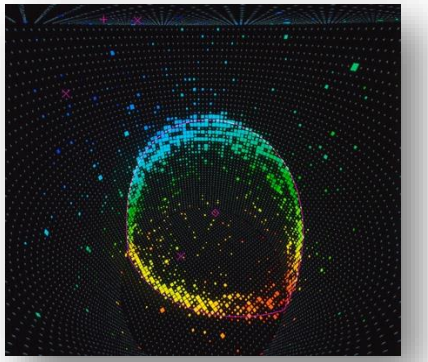
3

Performance comparation: GNN vs existing software

	GRANT	Existing software
e/mu		
e/pi0		
Energy reconstruction for e & mu (1D)		
Vertex reconstruction for e & mu (3D)		

3 Performance comparation: GNN vs existing software

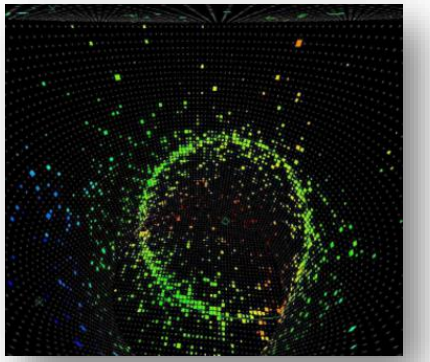
	GRANT	Existing software
e/mu	**99% electron efficiency** at 5% muon bg acceptance, Dwall, towall analysis: After 2 m, efficiency above 99.4% !	**99% electron efficiency** at 5% muon bg acceptance,



Sharp ring

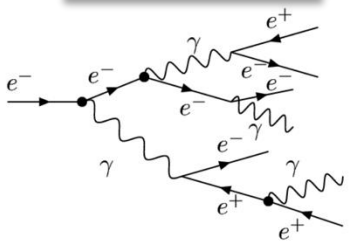
Muon

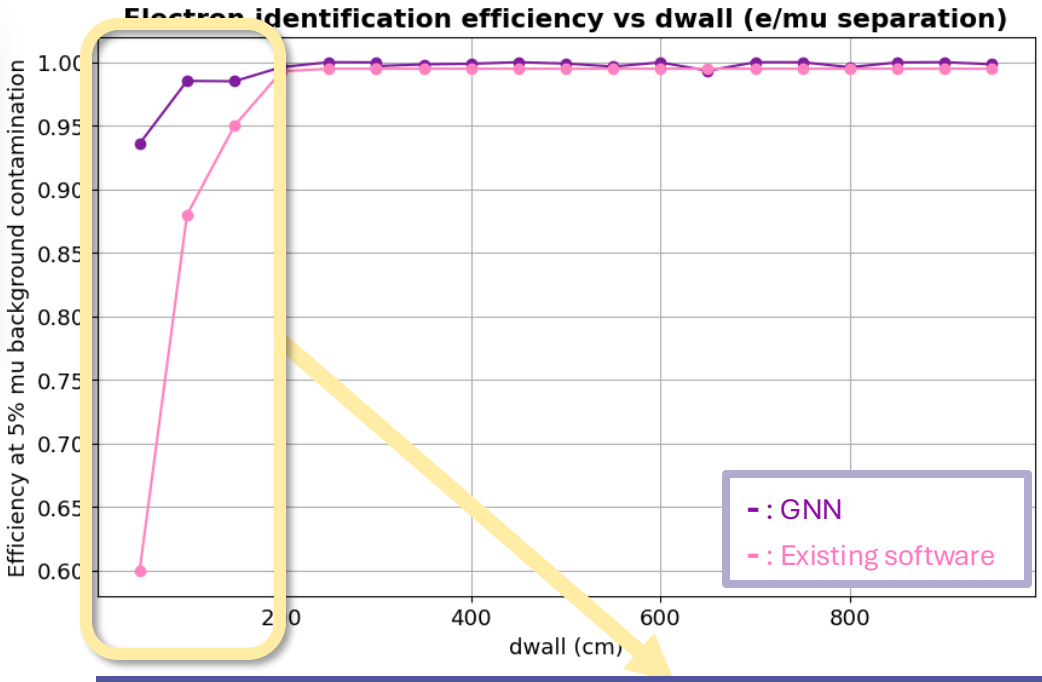
μ^-

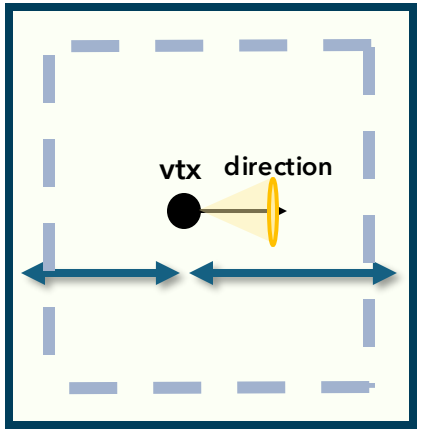


Fuzzy ring

Electron



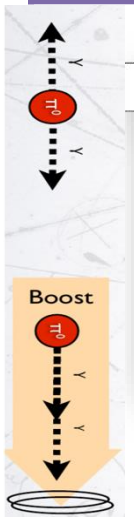


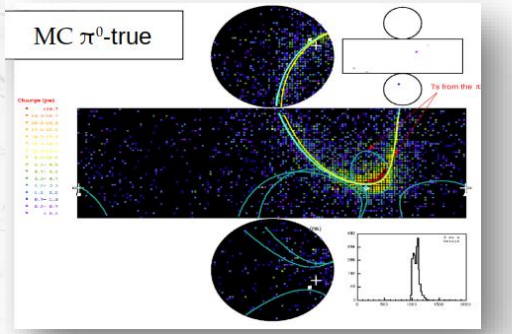


For events close to the wall : GNN > existing software
=> potentially increase FV

3 Performance comparation: GNN vs existing software

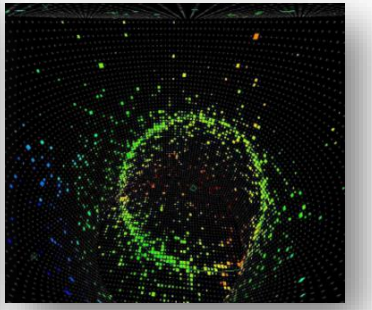
	GRANT	Existing software
e/pi0	**99% electron efficiency** at 25% pi0 bg acceptance Dwall, towall analysis: After 2 m, efficiency above 99% !	**94% electron efficiency** at 25% pi0 bg acceptance





Fuzzy ring

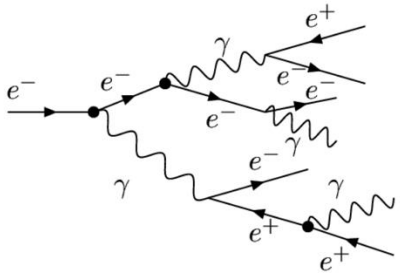
Pi0

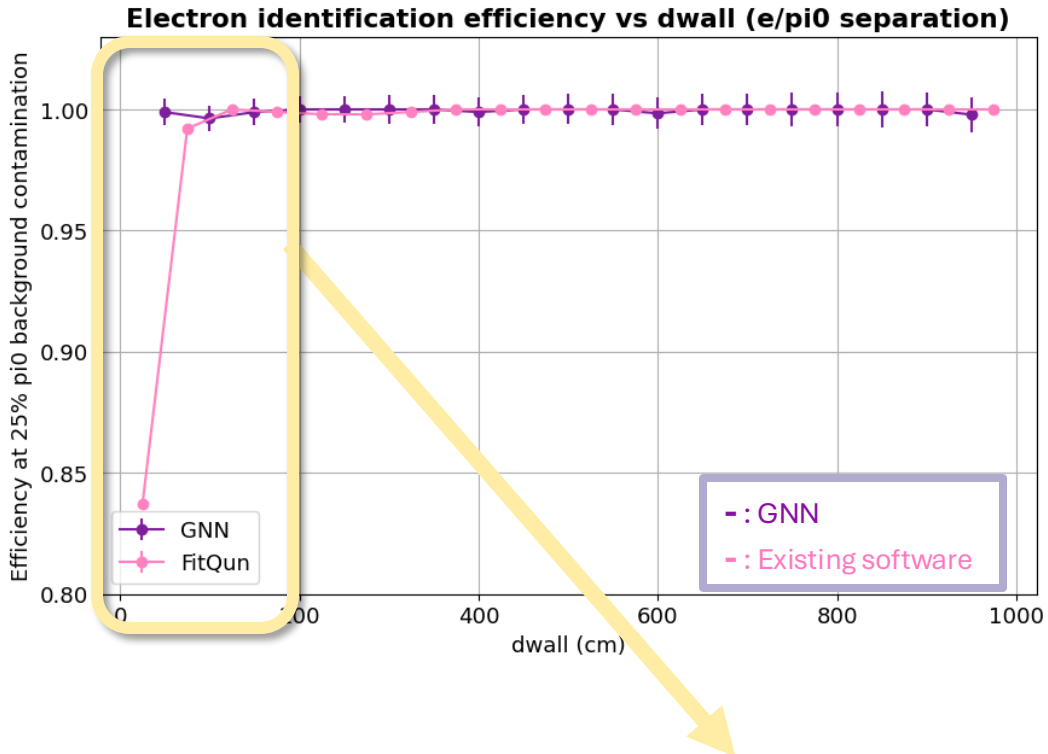


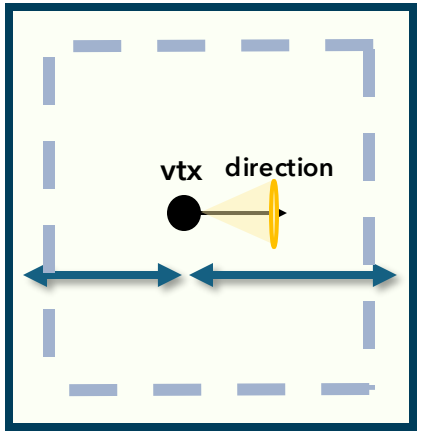
Fuzzy ring

Electron

$$\pi^0 \rightarrow \gamma + \gamma$$
$$\rightarrow e^- + e^+$$
$$\rightarrow e^- + e^+$$







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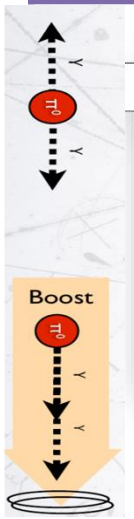
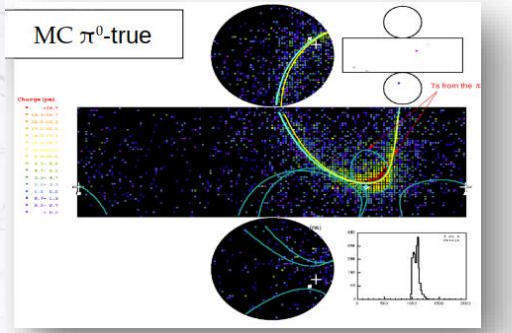
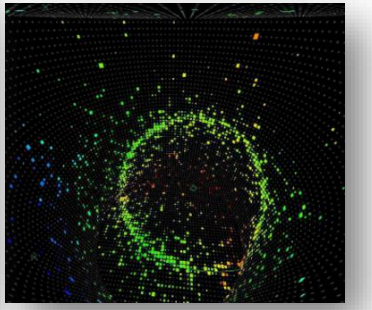




Fuzzy ring

Pi0



Fuzzy ring

Electron

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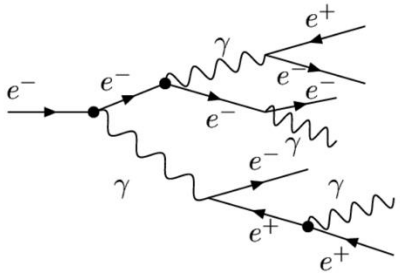
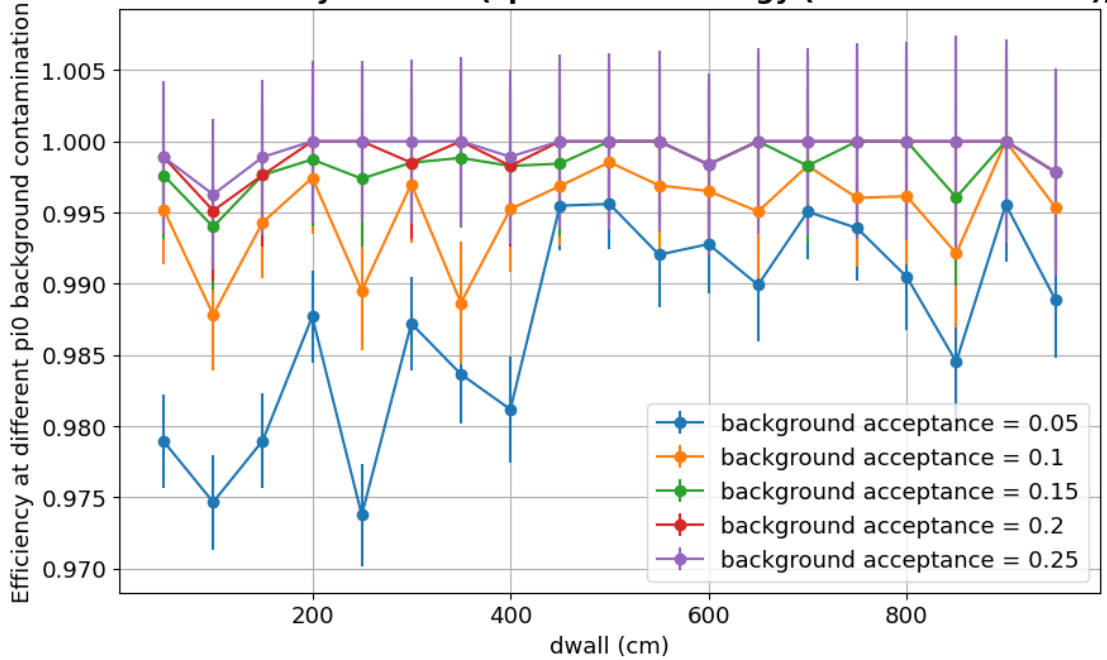


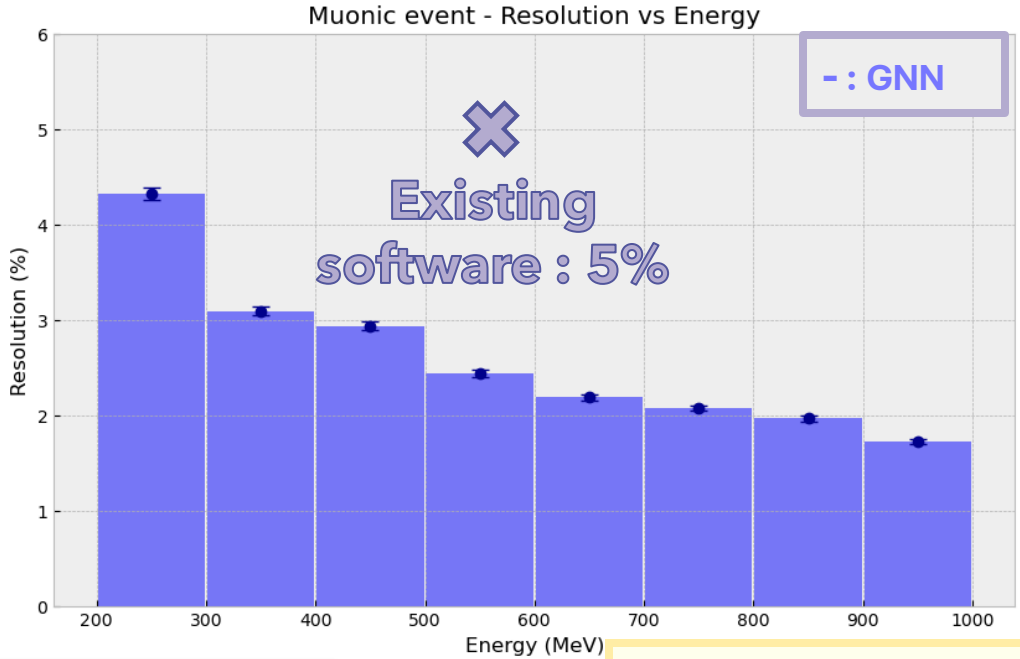
Electron identification efficiency vs dwall (spectrum of evergy (100 MeV to 1 GeV), e/pi0 separation)

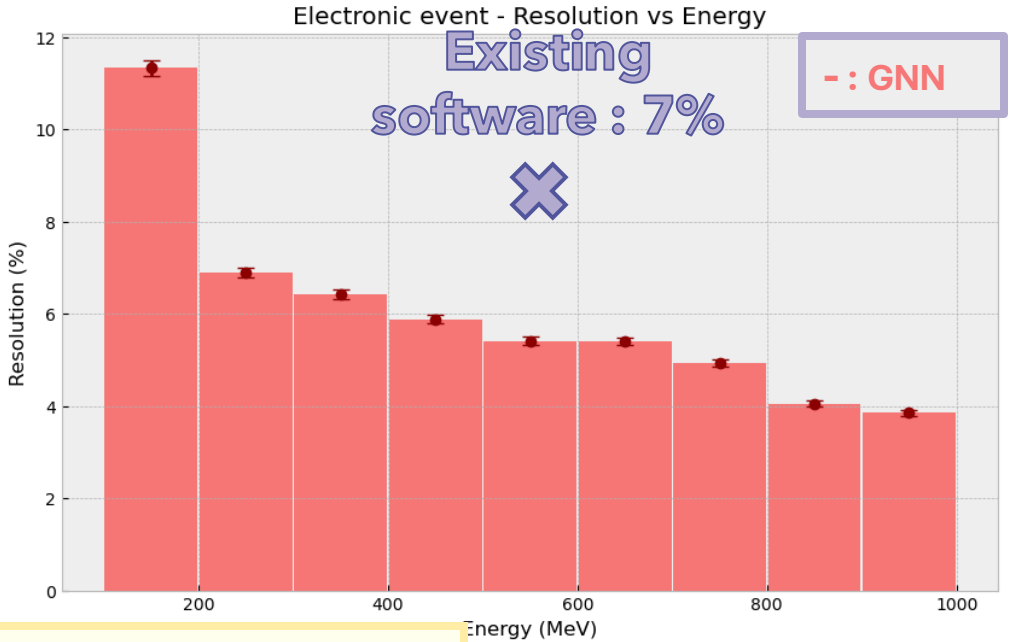


Decrease pi0 background acceptance => reduce systematic errors!

3 Performance comparation: GNN vs existing software

	GNN	Existing software
Energy reconstruction for e & mu (1D)	**Electron : 5.5% resolution** at 500 MeV, **energy bias at ~1.5%** **Muon : 2.5% resolution** at 500 MeV, **energy bias at ~0.5%**	**Electron : 7% resolution** at 500 MeV, **energy bias at ~0%** **Muon : 6% resolution** at 500 MeV, **energy bias at ~0%**





GNN : 2.5% at 500 MeV,

0.06 s per event (GNN)
1min30 (Existing software)

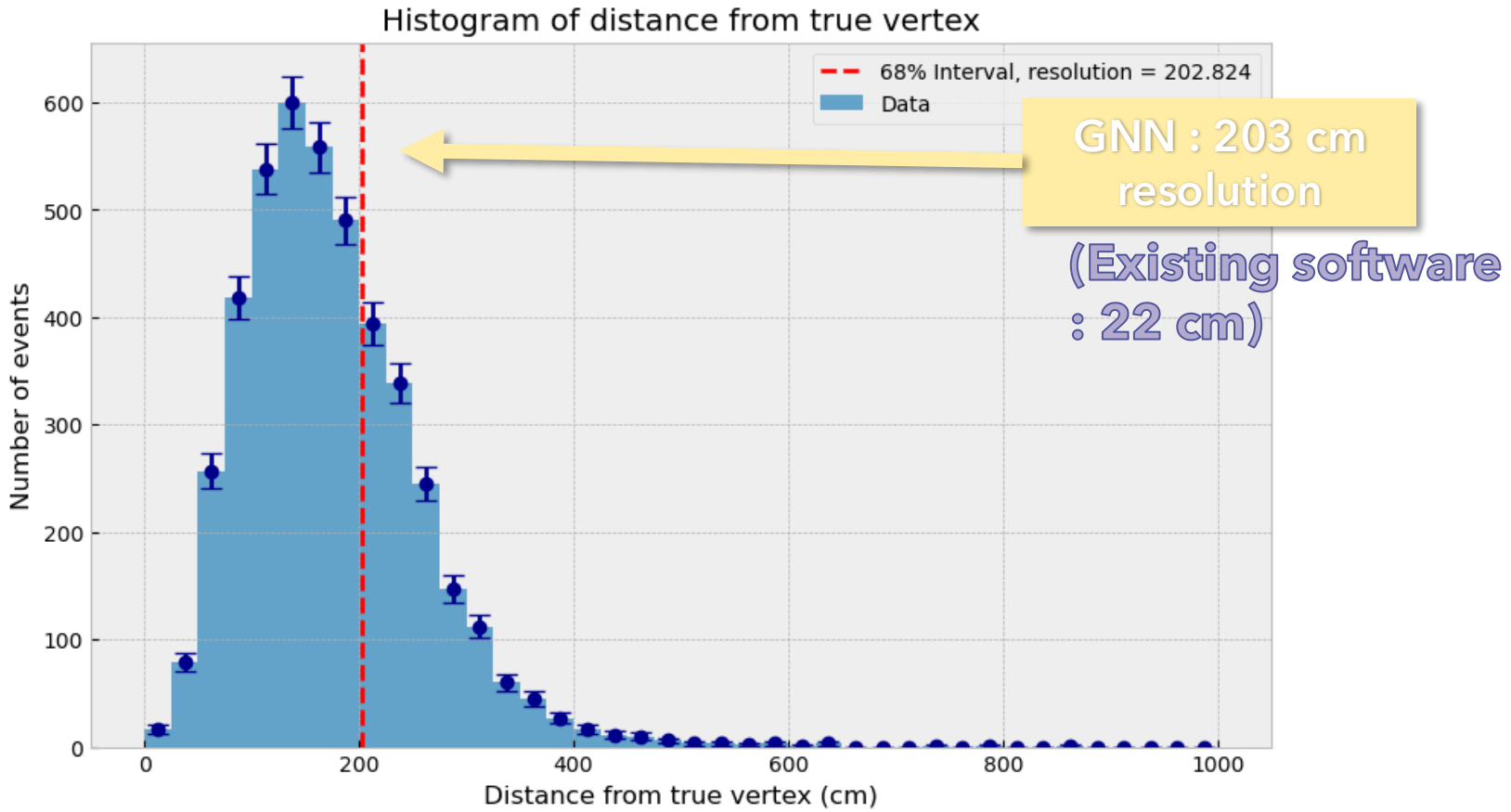
BUT : the GNN has a biais ☹
(1.5% electron, 0.5% muon at 500 MeV)

Existing software : 0% biais !

GNN : 5.5% at 500 MeV,

3 Performance comparation: GRANT vs existing software

	GNN	Existing software
Vertex reconstruction for e & mu (3D)	**Electron :** 203 cm **Muon:** None	**Electron :** 22 cm **Muon :** 28 cm



GNN : 203 cm resolution

(Existing software : 22 cm)

0.07 s per event (GNN)
1min30 (Existing software)

3 Performance comparation: GRANT vs existing software

	GNN	FitQun
e/mu	**99% electron efficiency** at 5% muon bg acceptance,	**99% electron efficiency** at 5% muon bg acceptance,
e/pi0	**99% electron efficiency** at 25% pi0 bg acceptance	**94% electron efficiency** at 25% pi0 bg acceptance
Energy reconstruction for e & mu (1D)	**Electron : 5.5% resolution** at 500 MeV, **energy bias at ~1.5%** **Muon : 2.5% resolution** at 500 MeV, **energy bias at ~0.5%**	**Electron : 7% resolution** at 500 MeV, **energy bias at ~0%** **Muon : 6% resolution** at 500 MeV, **energy bias at ~0%**
Vertex reconstruction for e & mu (3D)	**Electron :** 203 cm **Muon:** None	**Electron :** 22 cm **Muon :** 28 cm

0.1 s per event (GNN)
1min30 (Existing software)

Conclusion.

- **Hyper-Kamiokande** is the next-generation neutrino detector, designed with **unparalleled precision**.
- To fully exploit its potential, we need to **push our reconstruction techniques** to the next level.
- That's why we're relying on **machine learning,** which is proving to be a powerful tool for enhancing precision and unlocking HK's **full potential for groundbreaking discoveries in neutrino physics**.

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- That's why we're relying on **machine learning,** which is proving to be a powerful tool for enhancing precision and unlocking HK's **full potential for groundbreaking discoveries in neutrino physics**.

Thank you for your attention !! ☺