Università degli Studi di Padova

INFN Padova

LHCb

Quantum Machine Learning for b-jet charge identification

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On behalf of the **LHCb Collaboration**

CMS PAS HIG-21-008
JHEP 2019, 166 (2019)

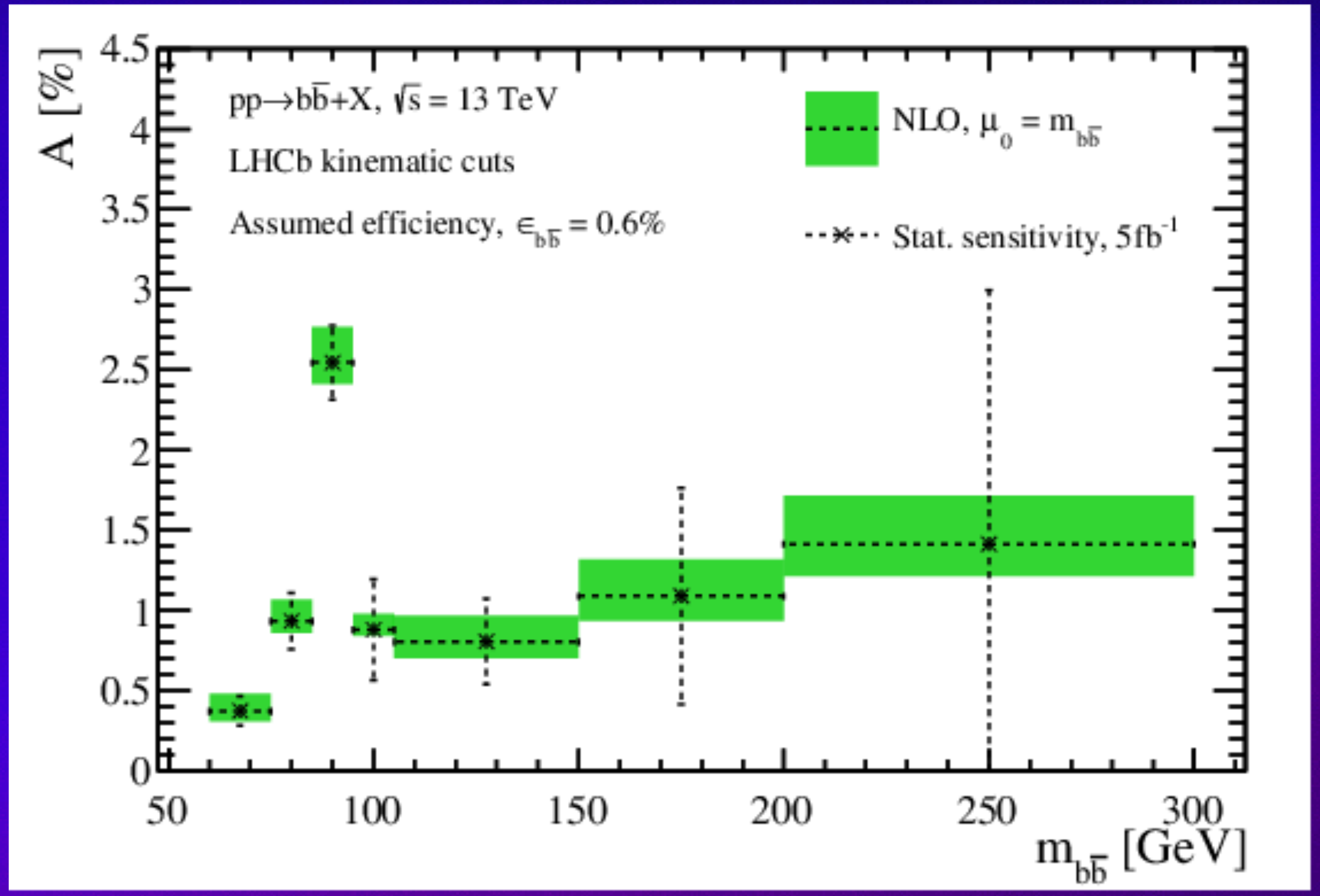
Jet identification

Aka “the problem”

- At hadron colliders it is mandatory to reconstruct and identify jets
- Several interesting physics studies, for example:
  - Angular asymmetries of b-quark pair production
  - Higgs identification
    - $h \to b\bar{b}$
    - $h \to c\bar{c}$

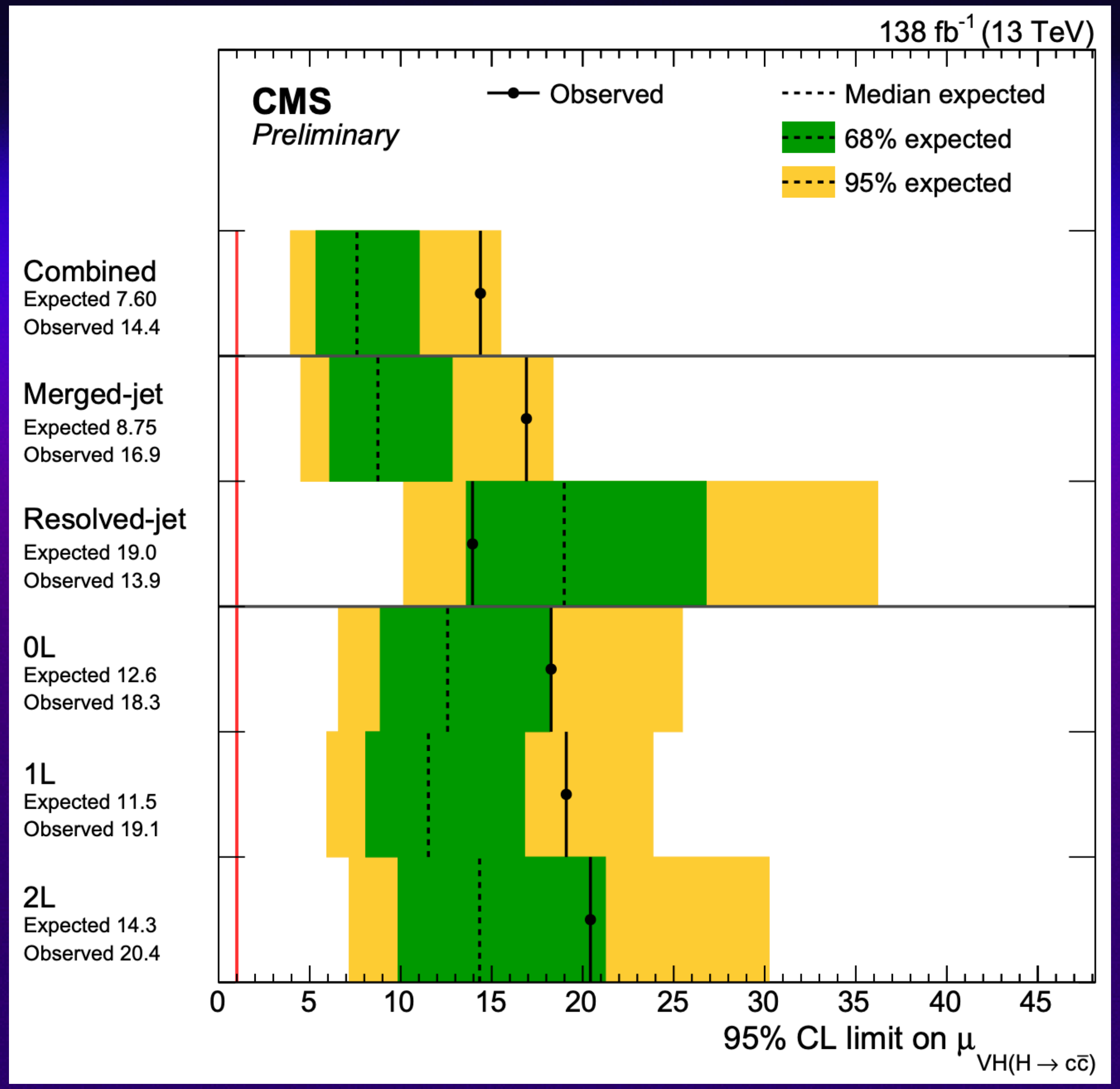
$$A^{C}_{b\bar{b}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

with $\Delta y = |y_b| - |y_{\bar{b}}|$



Jet charge identification

Jet flavour identification

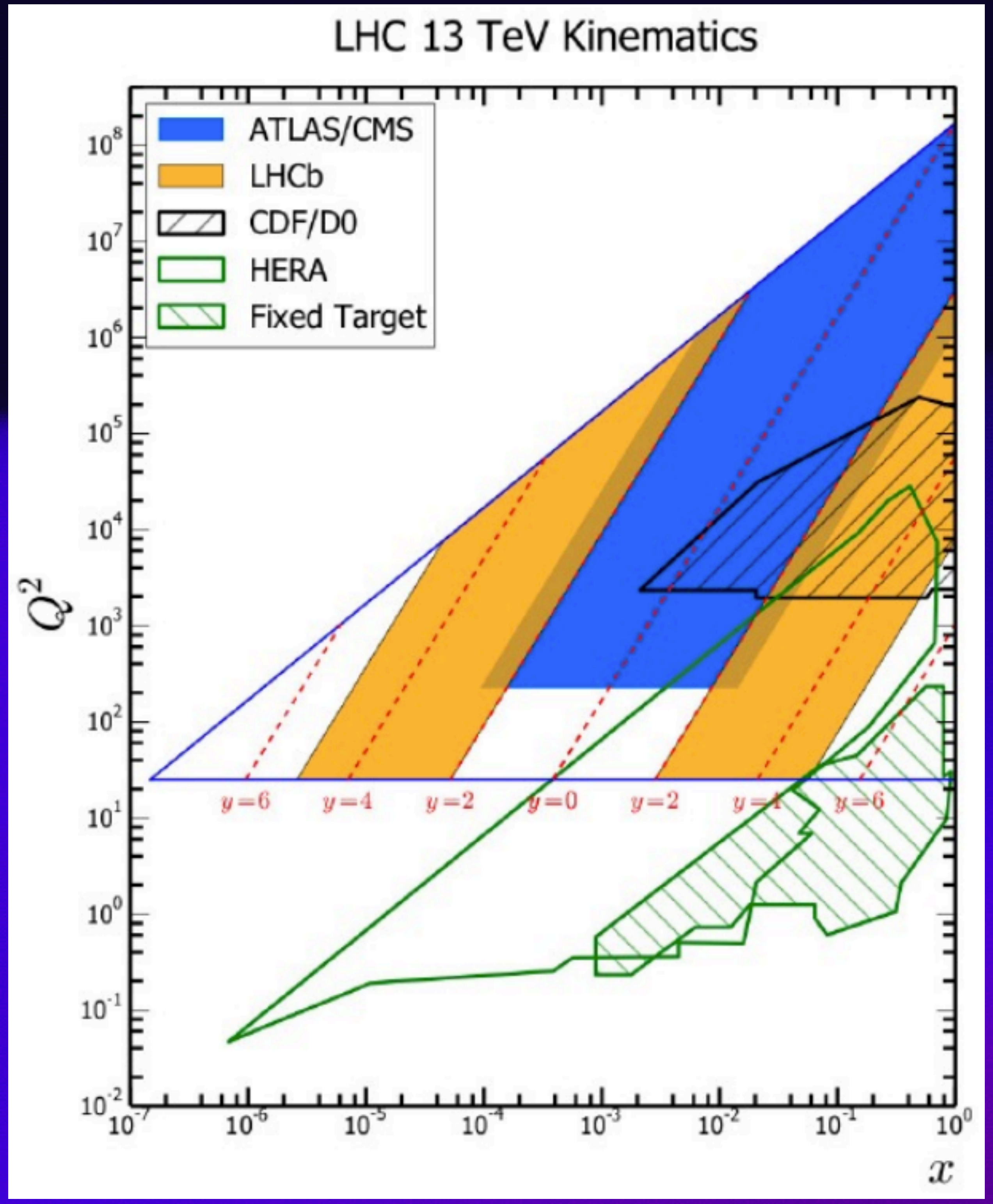


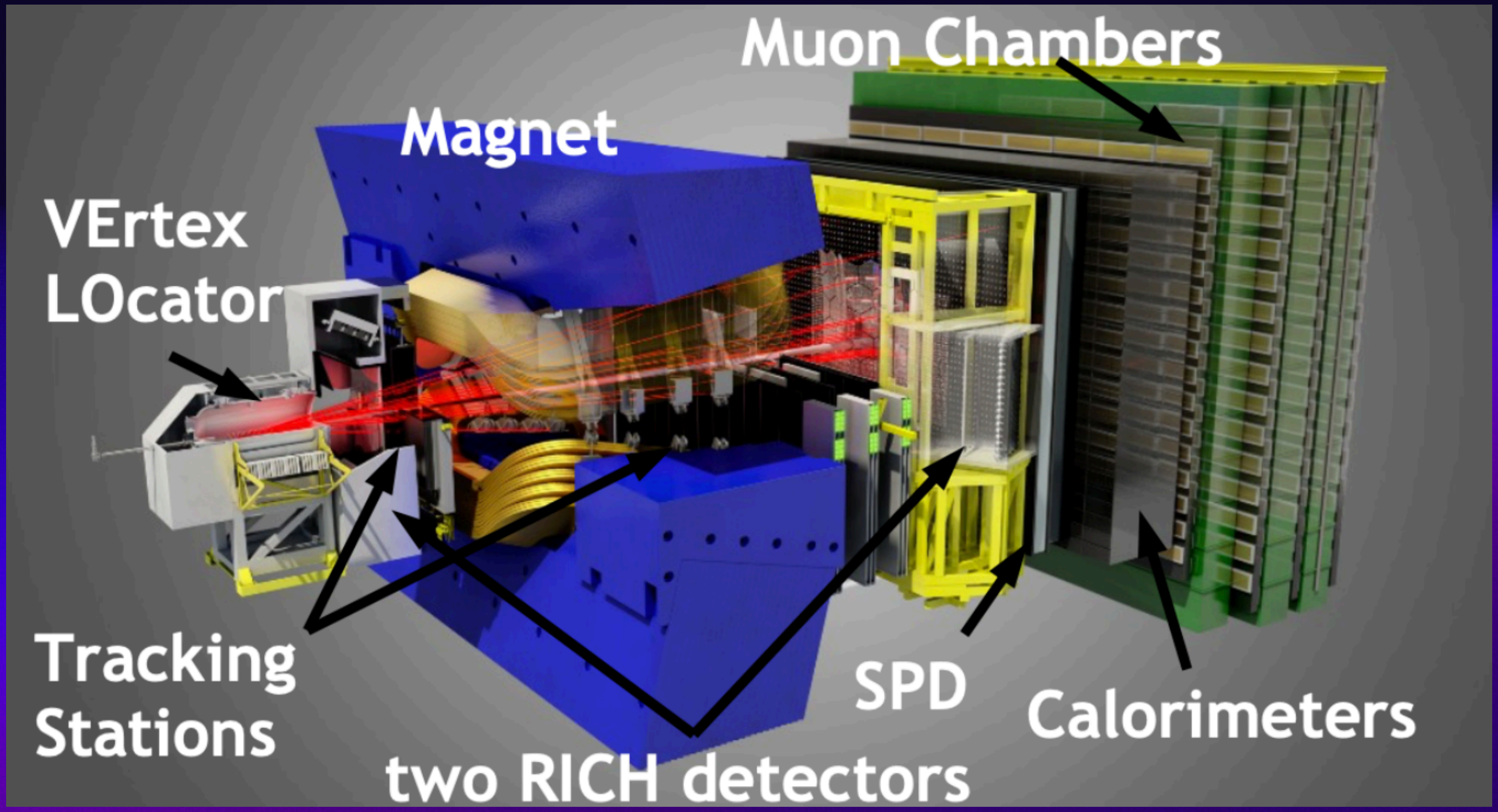
JINST 3 (2008) S08005
INT. J. MOD: PHYS. A 30, 1530022 (2015)
CERN-LPCC-2018-04

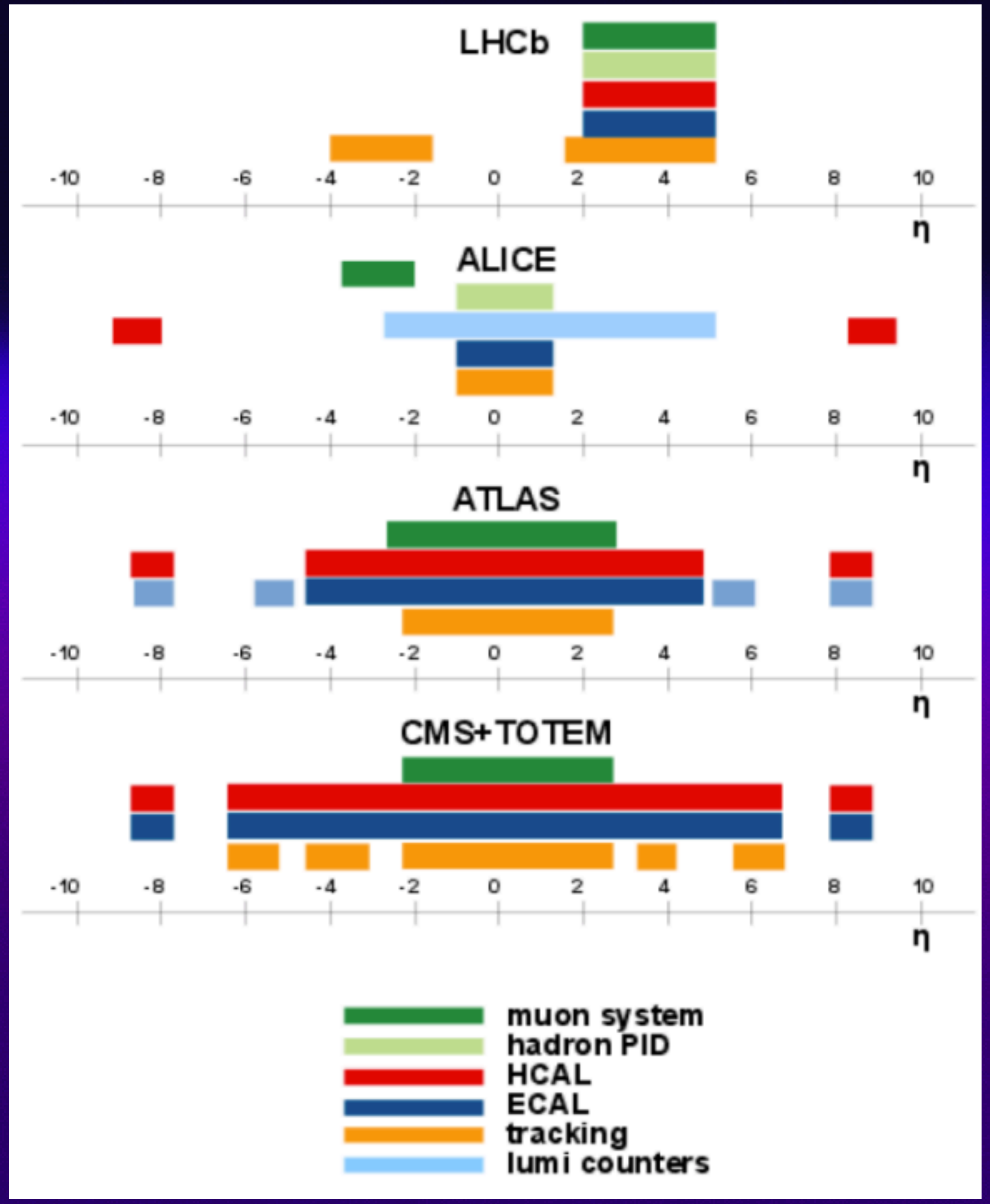
Jet charge identification at LHCb

Where and How

- LHCb is a **forward spectrometer** originally designed to study b- and c-hadron physics
- **Unique phase space region** $(2 < \eta < 5)$ **complementary** to ATLAS & CMS



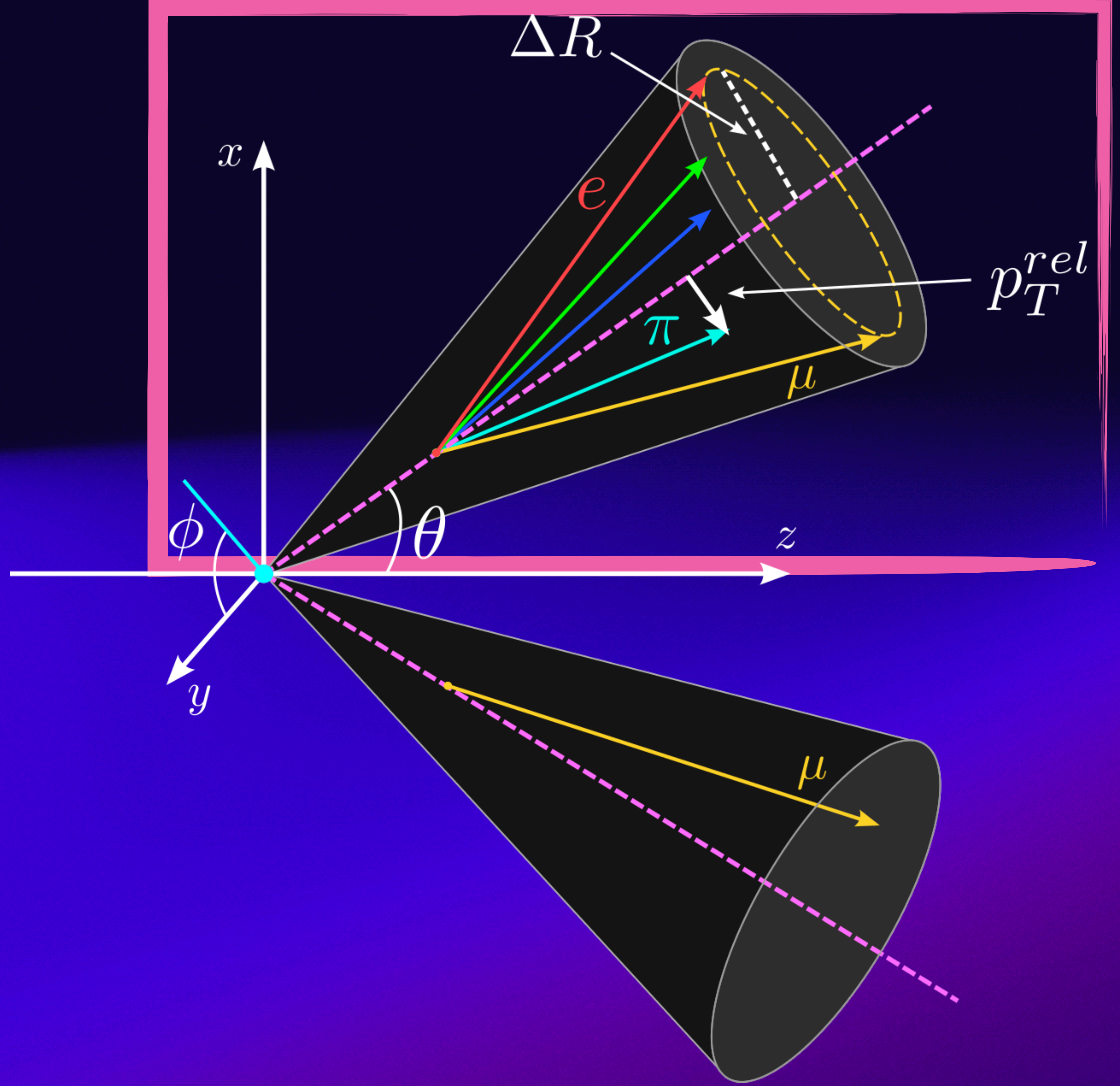




Jet charge identification at LHCb

Where and How

- In principle there are two different approaches to identify the charge of a jet



Inclusive approach

- It uses all the information coming from the jet substructure
- e.g. get the kinematic properties of all the particles inside the jet
- Given the amount of information → Machine Learning!

Exclusive approach

- Use a specific physics process to infer the quark flavour
- So far used at LHCb → "muon tagging"
- A muon coming from the semi-leptonic decay of a b quark ($\mathscr{B} = 10\ \%$) is used to tag the jet

NATURE 567, 209–212 (2019)

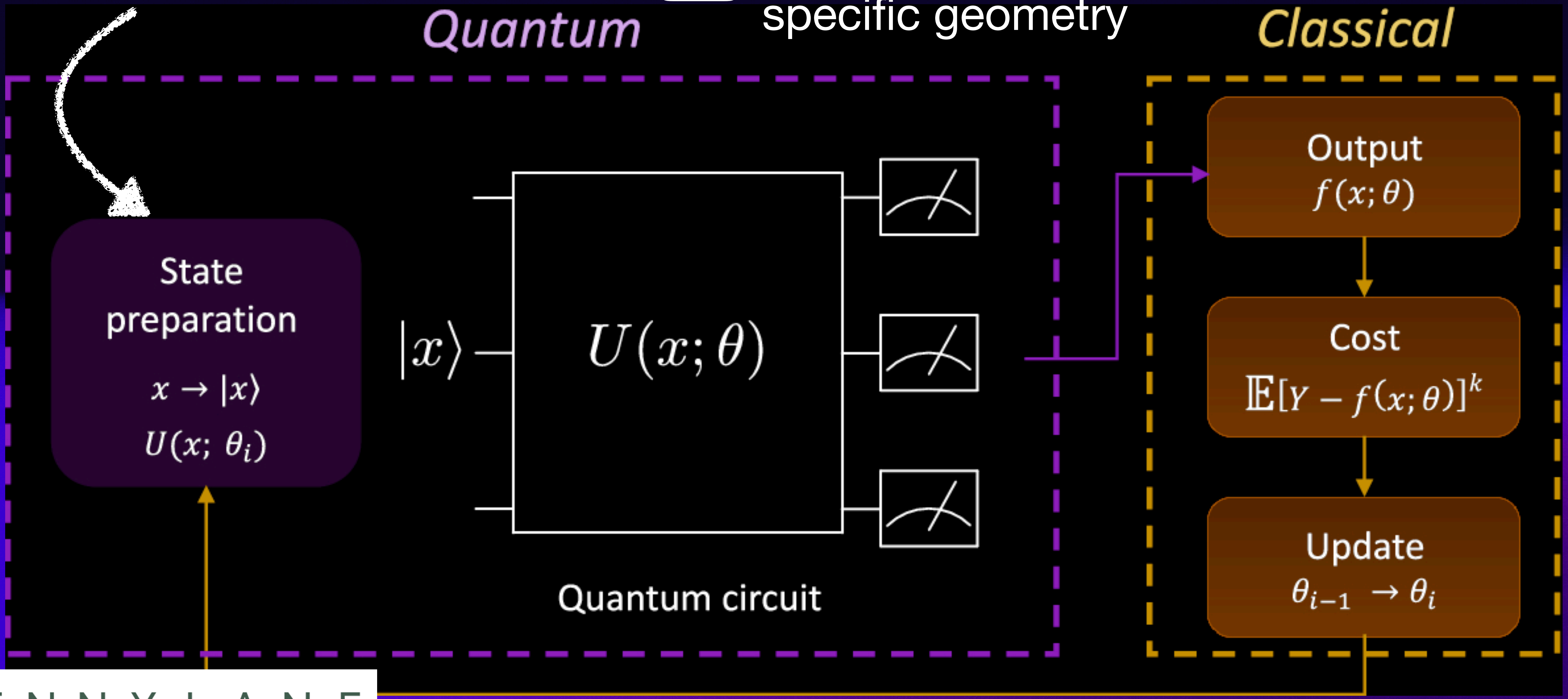
Going to quantum

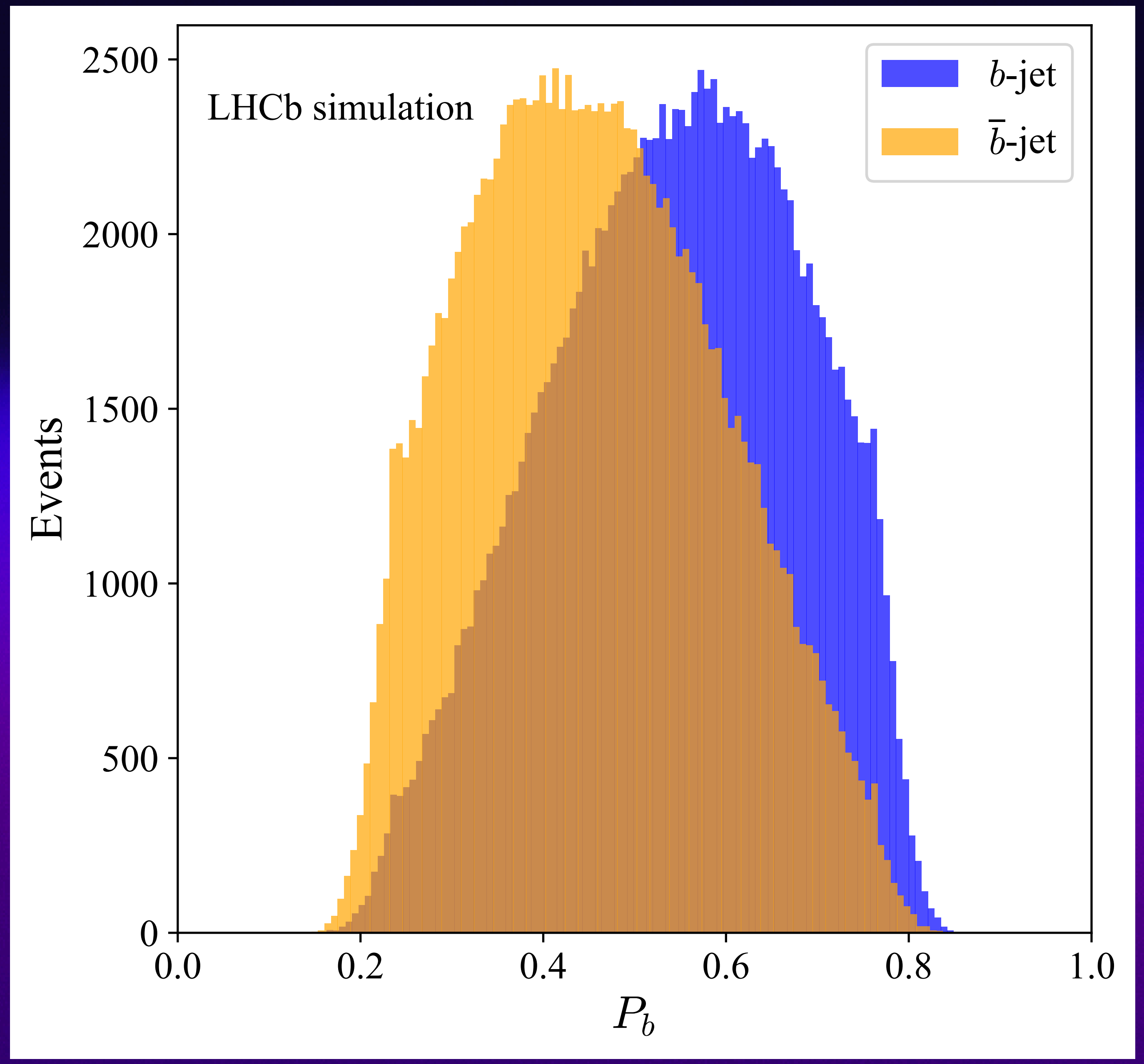
QML with Variational Quantum Classifier

1 Feed the data into a quantum state ("data embedding")

2 Create a quantum circuit with a specific geometry

3 Feed the output of the circuit to a classical optimization algorithm





PENNYLANE

4 Perform a training on a sample of data by optimizing circuit parameters

5 Get output distribution

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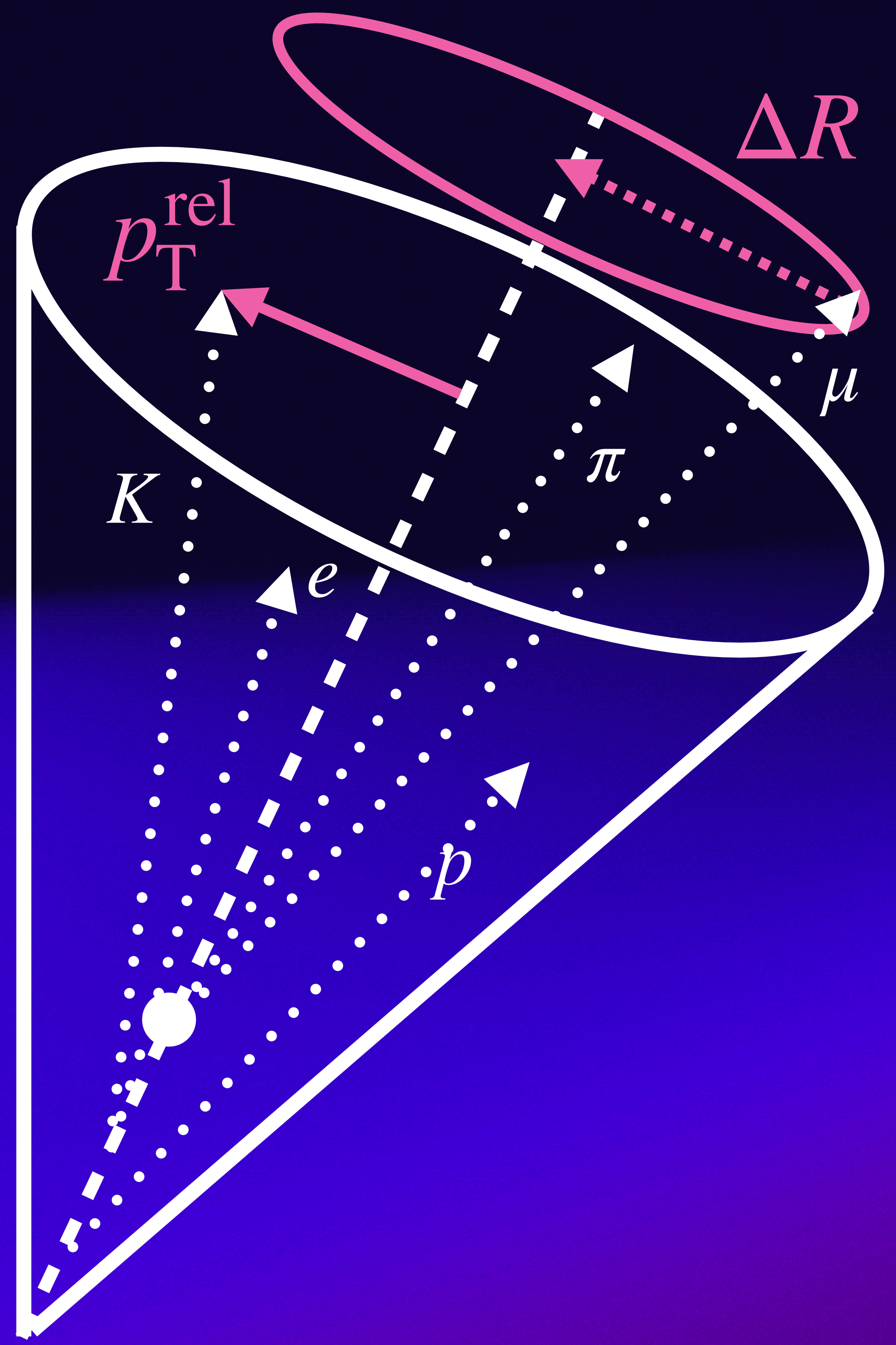
Going to quantum

The dataset



- Sample of $b\bar{b}$ di-jets events have been simulated with the official LHCb simulation framework
- Run 2 condition ($\sqrt{s} = 13$ TeV)
- ~700.000 jets, divided into training (60%) and testing (40%)

- For each jet, 5 types of particles are considered:

muon **electron** **pion** **kaon** **proton**

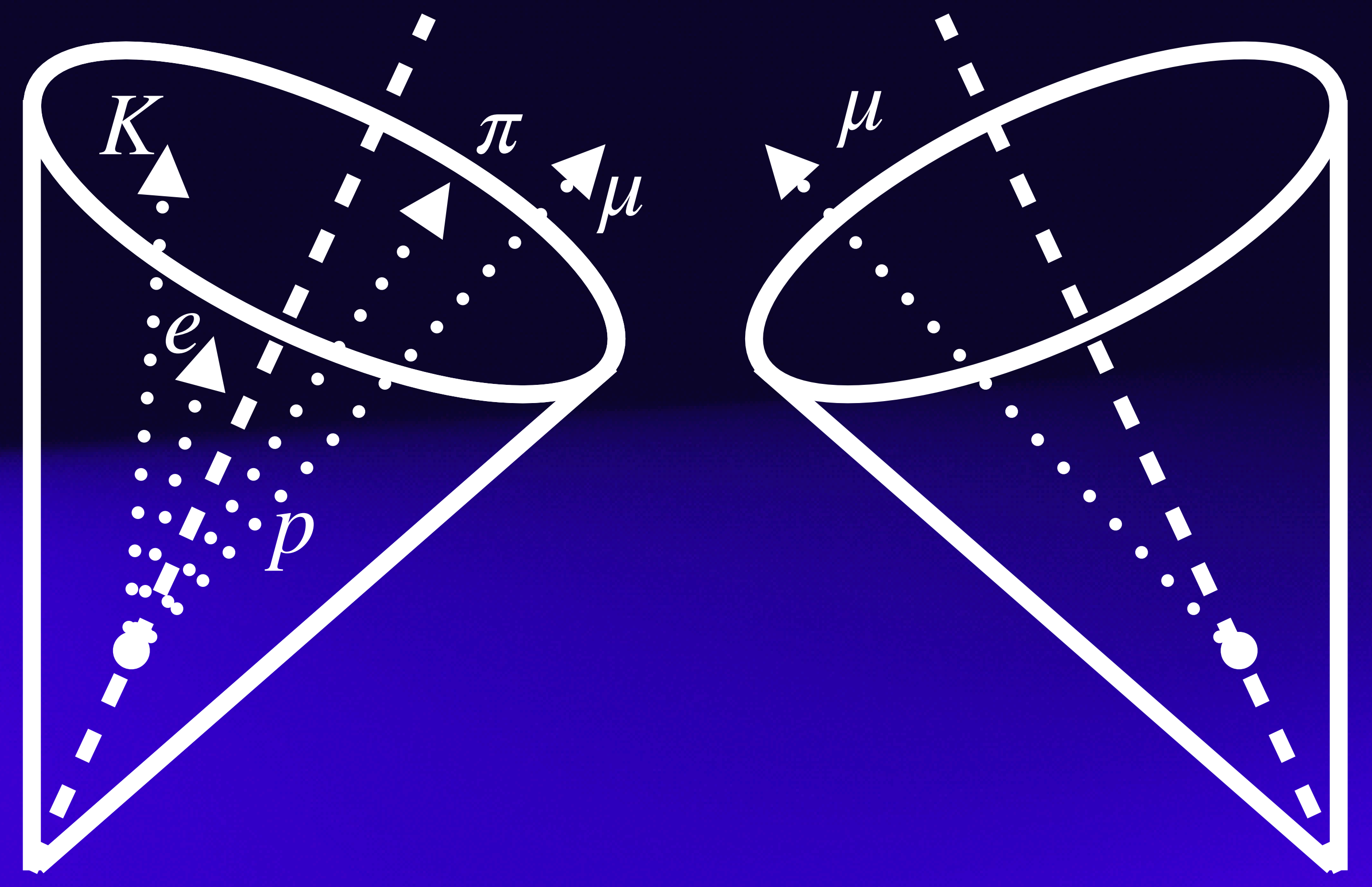
- And for each type of particle, three features are considered:
  - Transverse momentum relative to jet axis $p_{\mathrm{T}}^{\mathrm{rel}}$
  - Distance relative to jet axis ΔR
  - Charge of the particle q
- + a global variable, the total jet charge $Q = \dfrac{\Sigma(p_{\mathrm{T}}^{\mathrm{rel}})q}{\Sigma(p_{\mathrm{T}}^{\mathrm{rel}})}$

b-jet charge identification with QML

Try to get a complete study

- To perform a complete study of this algorithm and its application, we have considered several aspects

Different datasets

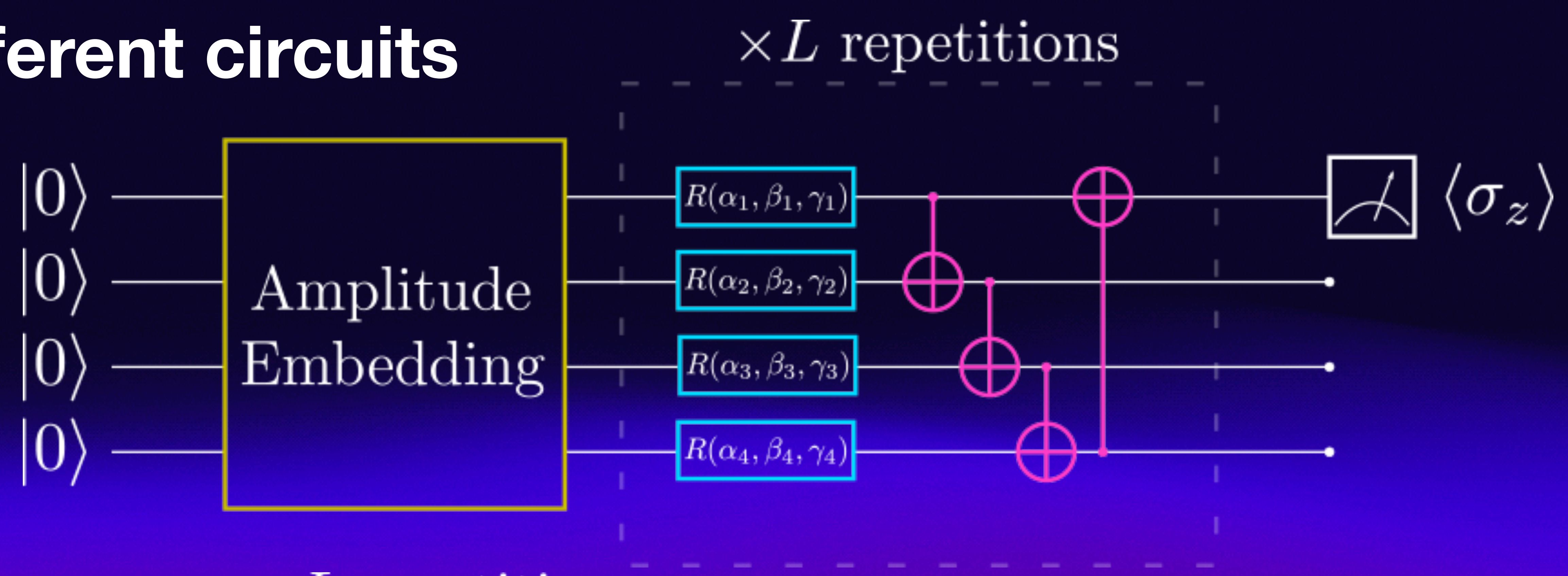


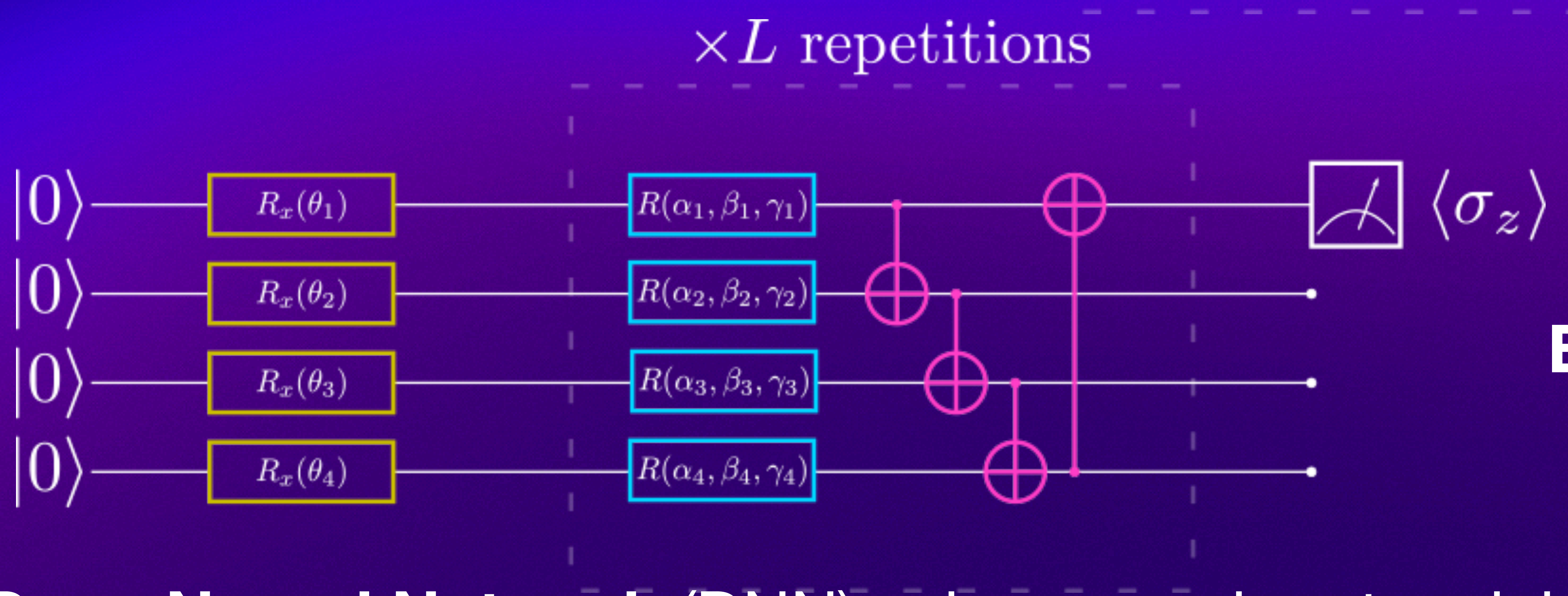
"Complete" dataset
16 variables

"Muon" dataset
$\mu + Q$ =
4 variables

Different circuits

Amplitude Embedding





Angle Embedding

- **Results are compared with a standard Deep Neural Network** (DNN) using same input variables

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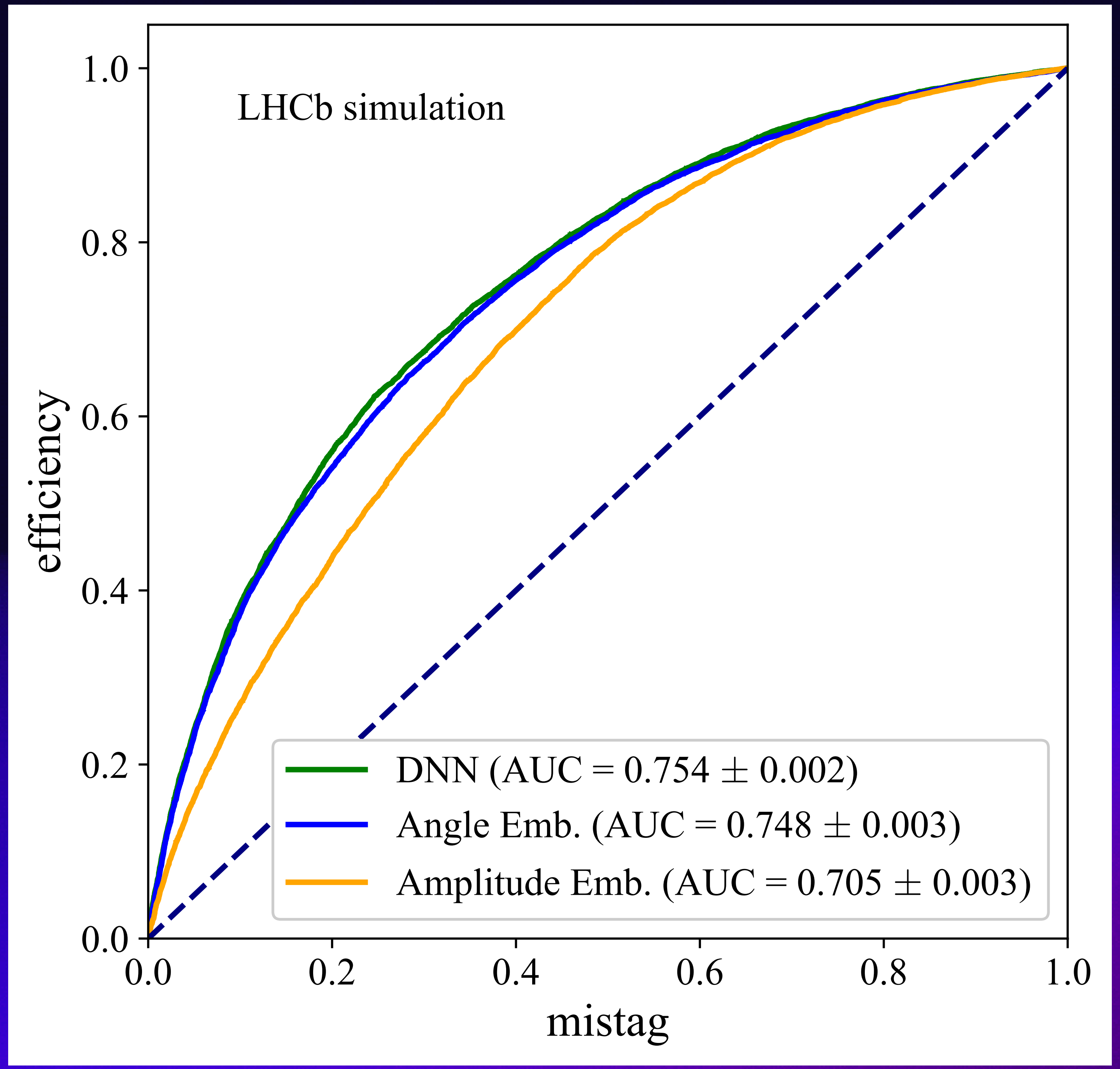
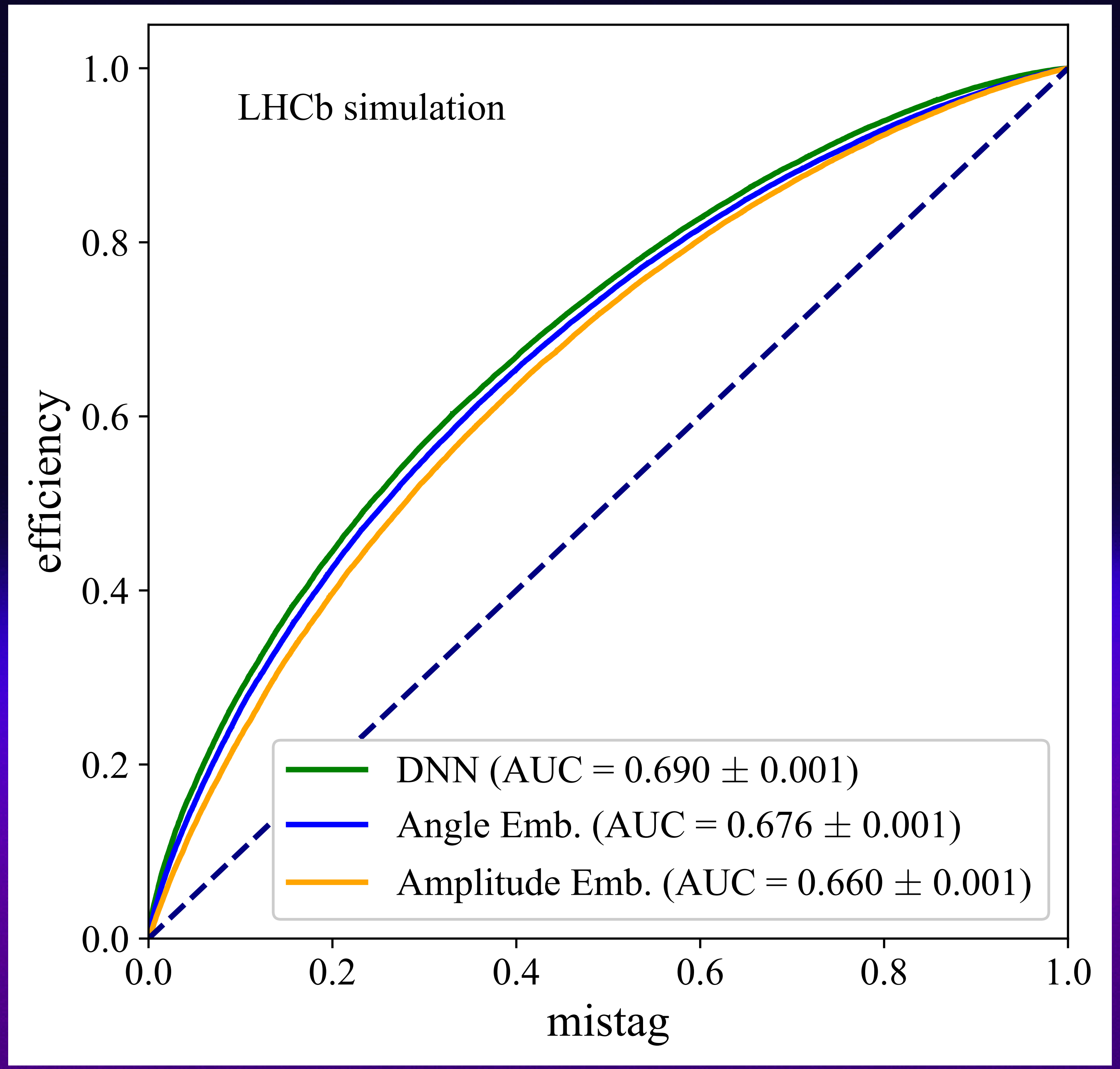
b-jet charge identification with QML

Algorithm performance

- A typical figure of merit for performance is the Receiving Operating Characteristic (ROC) curve

Muon dataset





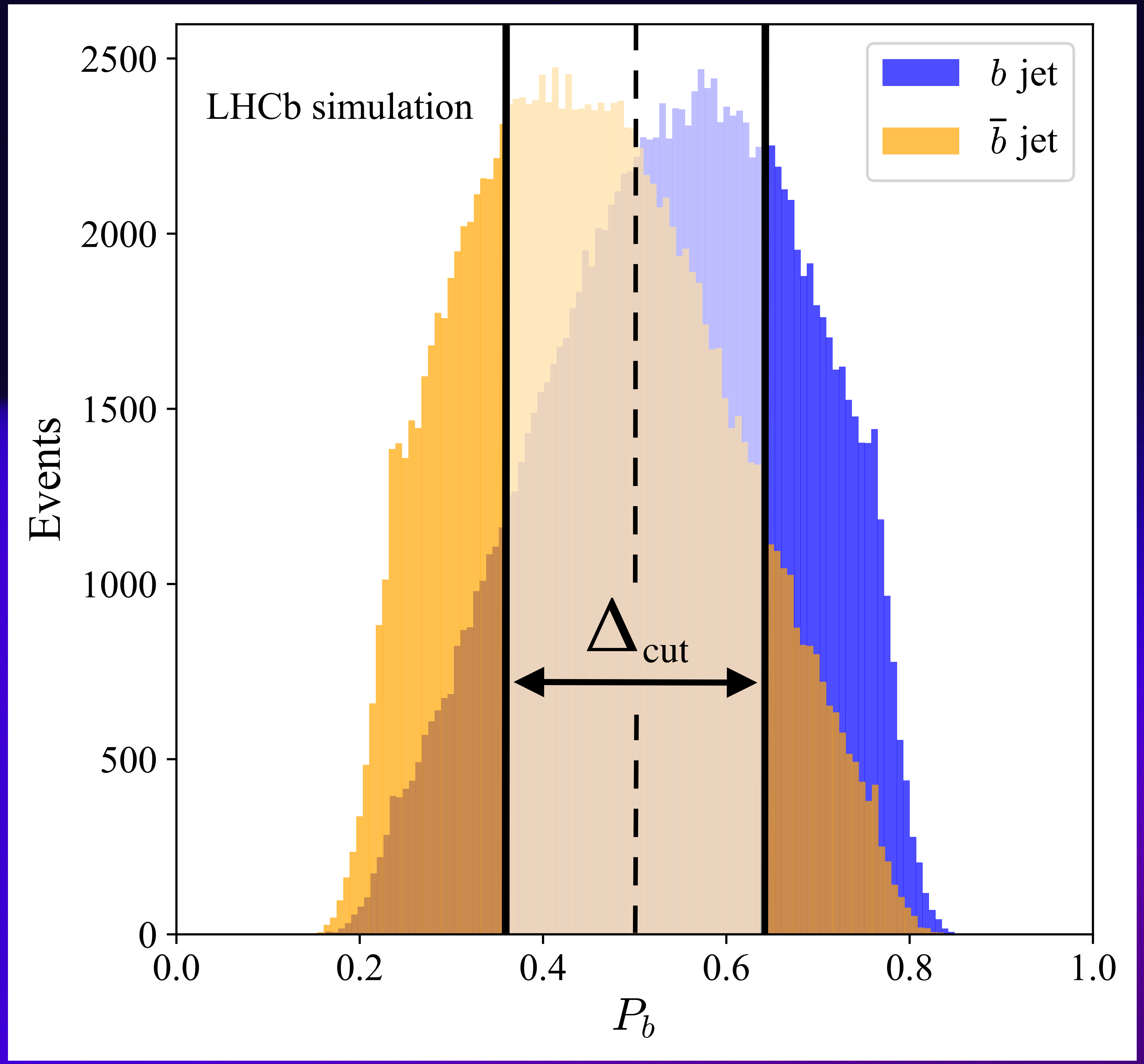
Complete dataset

- The Angle Embedding circuit performs better than the Amplitude Embedding circuit, for both the Muon and the Complete dataset
- For the Muon dataset the Angle Embedding circuit performs as good as the DNN

b-jet charge identification with QML

The physics perspective

- Once performance of the algorithm is assessed, we focus on the physical interesting quantities
- A typical figure of merit for this kind of problems is the **tagging power**



$$\epsilon_{tag} = \epsilon_{eff}(1 - 2\omega)^2$$

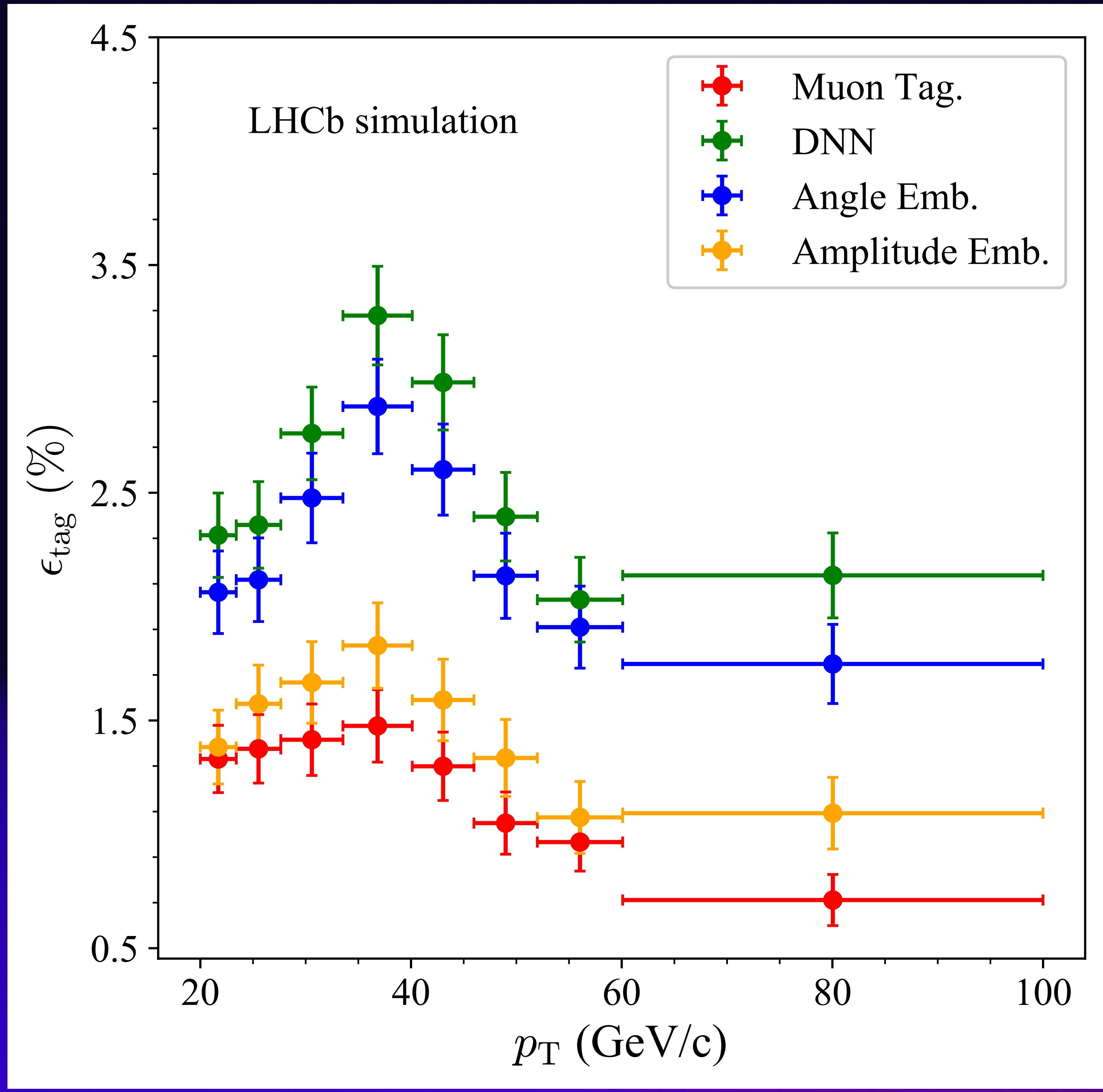
$$\epsilon_{eff} = \text{efficiency} = \frac{\#\text{ tagged jets}}{\#\text{ jets}} \qquad \omega = \text{mistag} = \frac{\#\text{ wrongly tagged jets}}{\#\text{ tagged jets}}$$

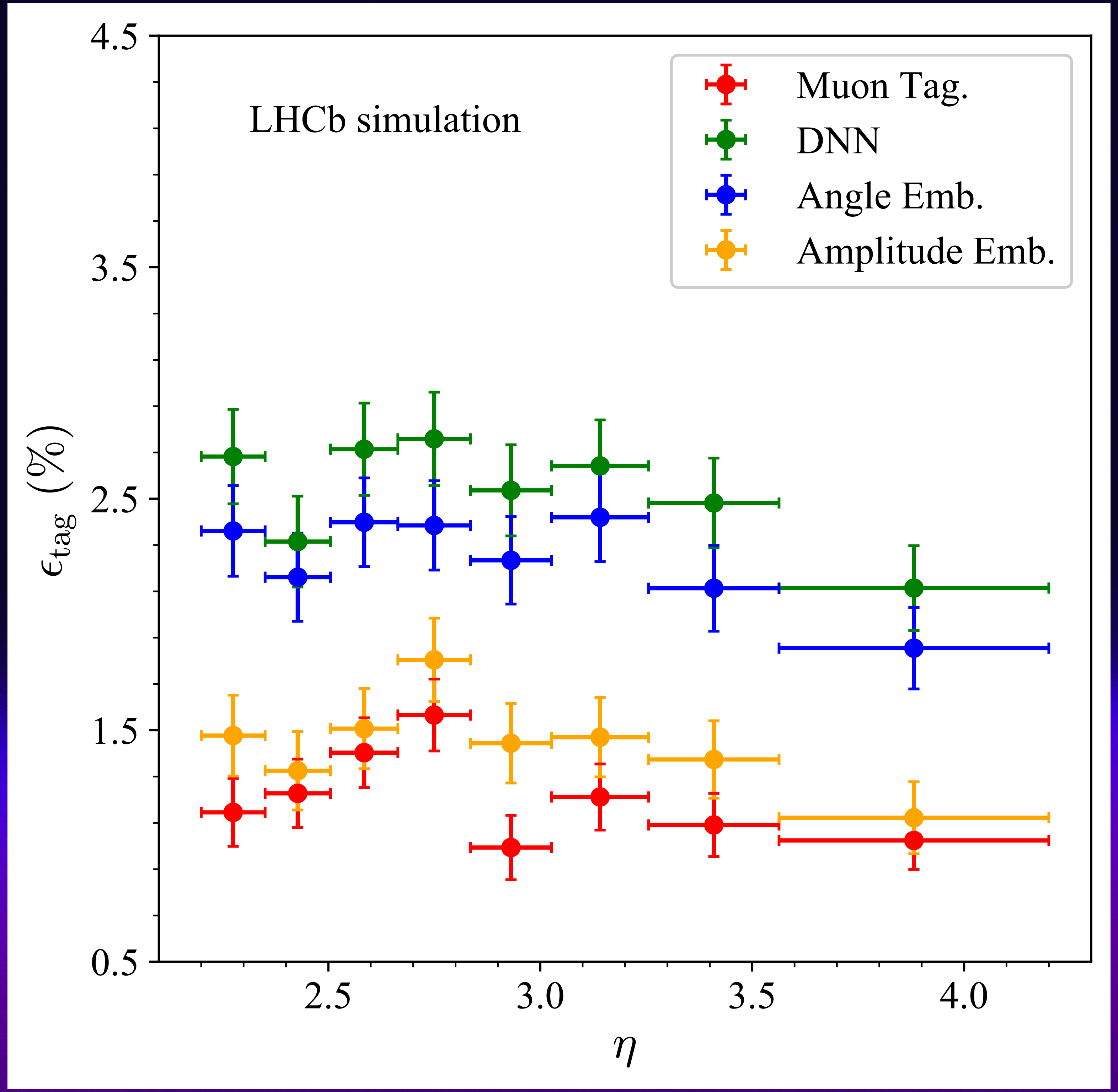
- It can be interpreted as the effective fraction of correctly identified jets (e.g. relevant for asymmetry measurements)
- Optimized cut Δ_{cut} over output distribution: reduce efficiency but also reduce mistag, therefore increase tagging power

	Classifier		
Dataset	DNN	Angle Embedding	Amplitude Embedding
Muon	0.30	0.25	0.16
Complete	0.21	0.19	0.12

b-jet charge identification with QML

Results for tagging power — muon dataset





- Tagging power is shown as function of jet p_{T} and pseudorapidity η
- Angle Embedding circuit is comparable to DNN, Amplitude Embedding not performing as good

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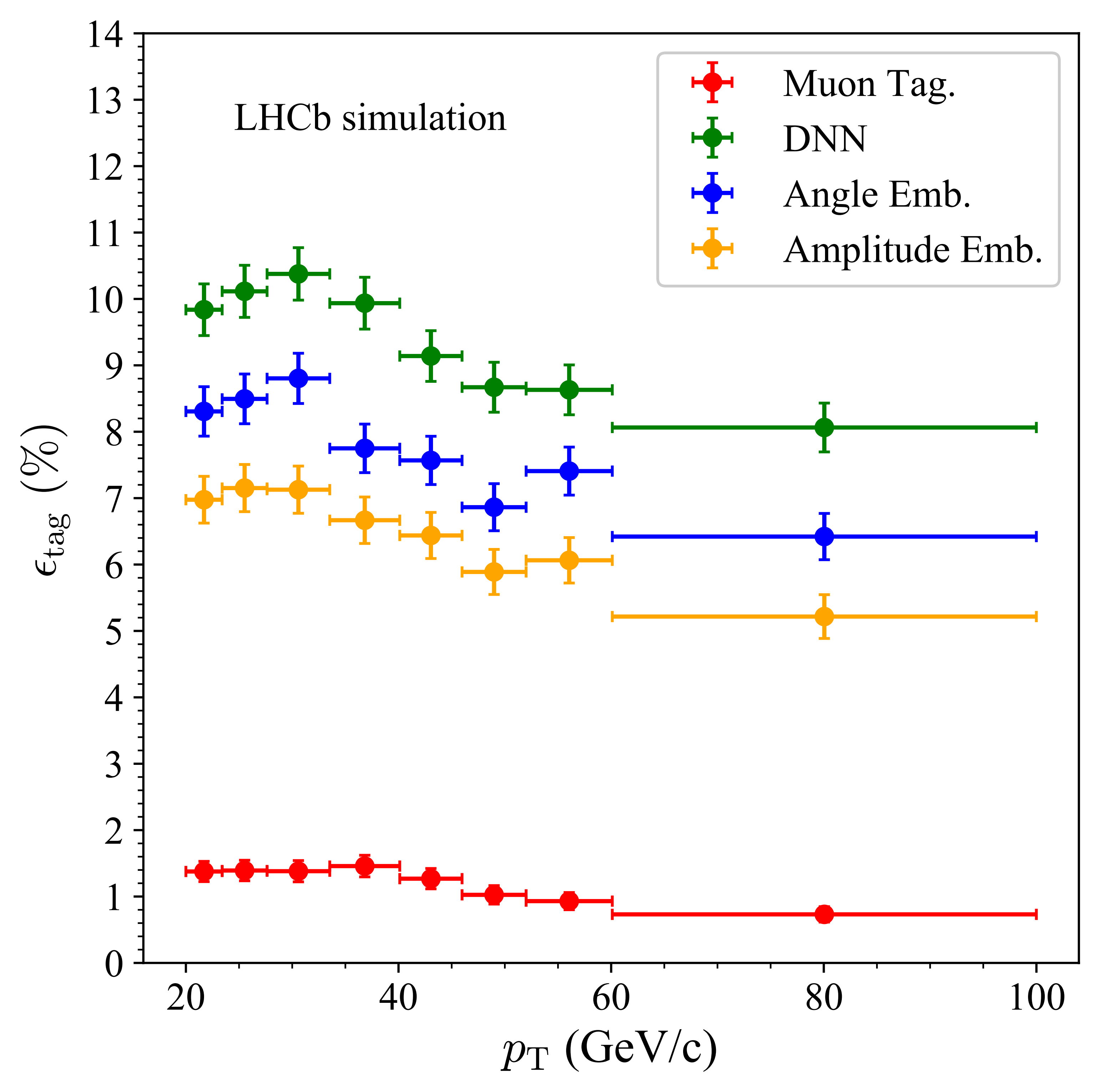
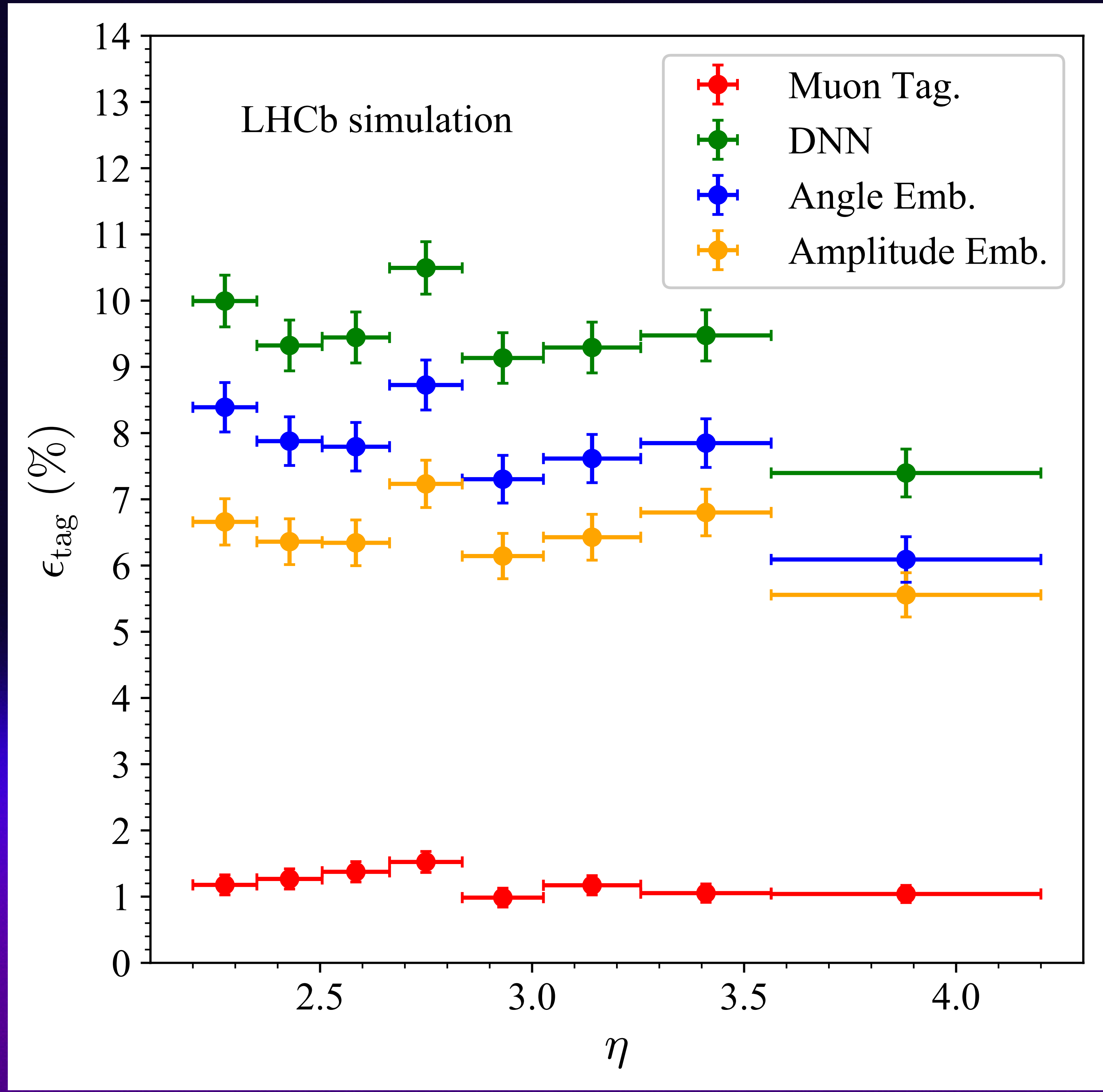
b-jet charge identification with QML

Results for tagging power — complete dataset





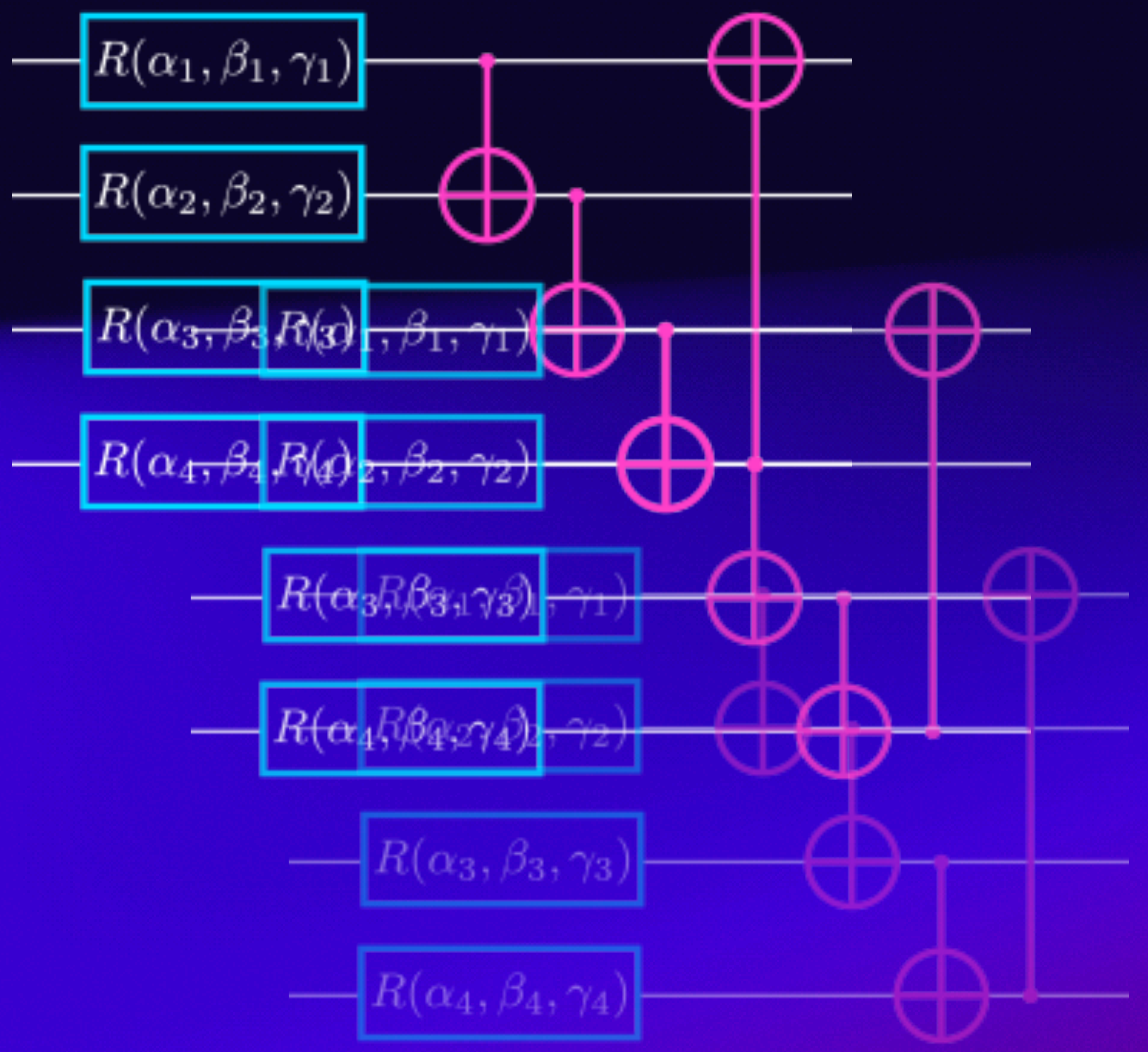
- Tagging power is shown as function of jet p_{T} and pseudorapidity η
- Both quantum circuits have lower performance → room for improvement!

b-jet charge identification with QML

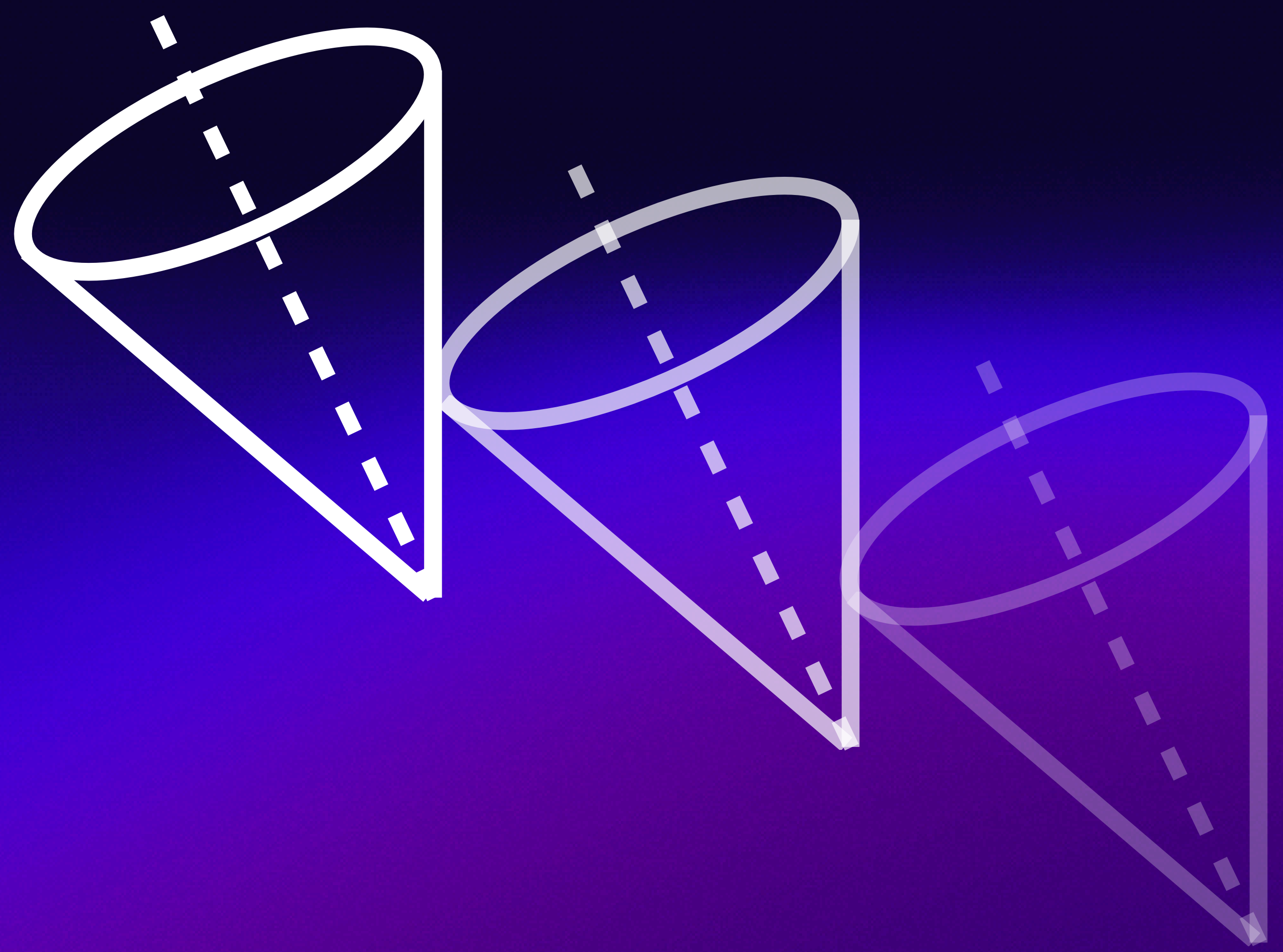
Try to get a complete study (2)

- To perform a complete study of this algorithm and its application, we have considered several aspects

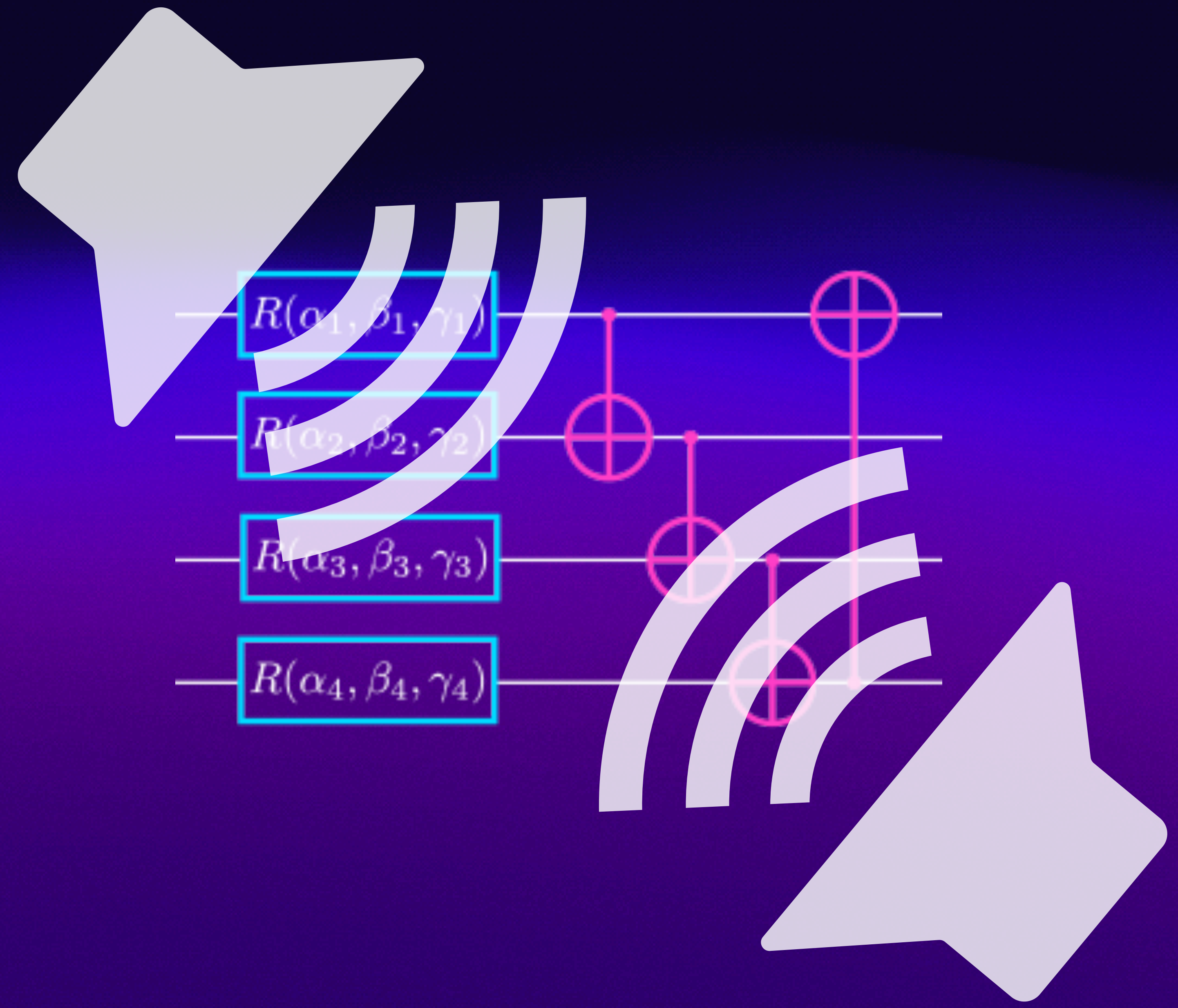
Number of variational layers



Number of training events

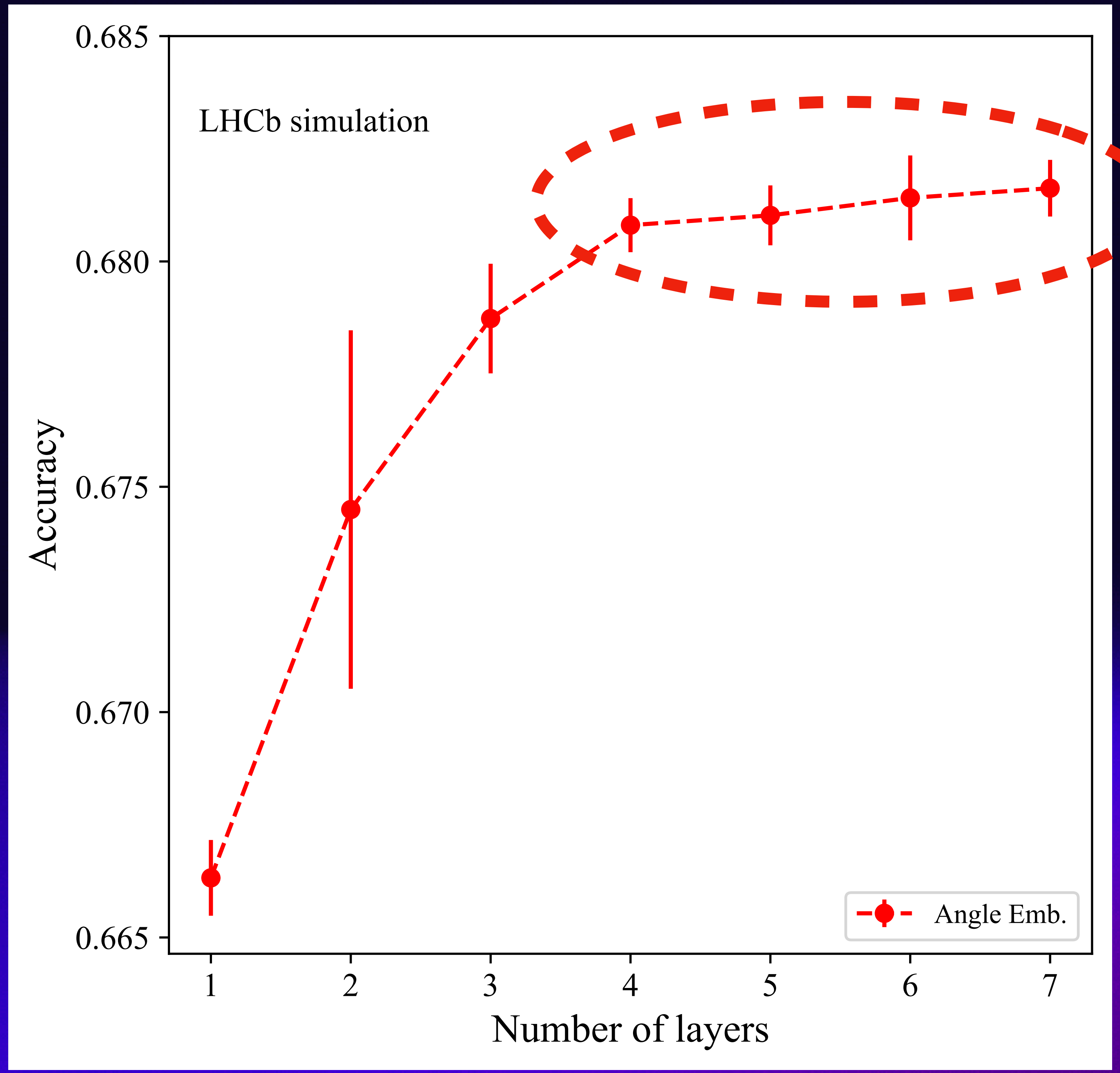


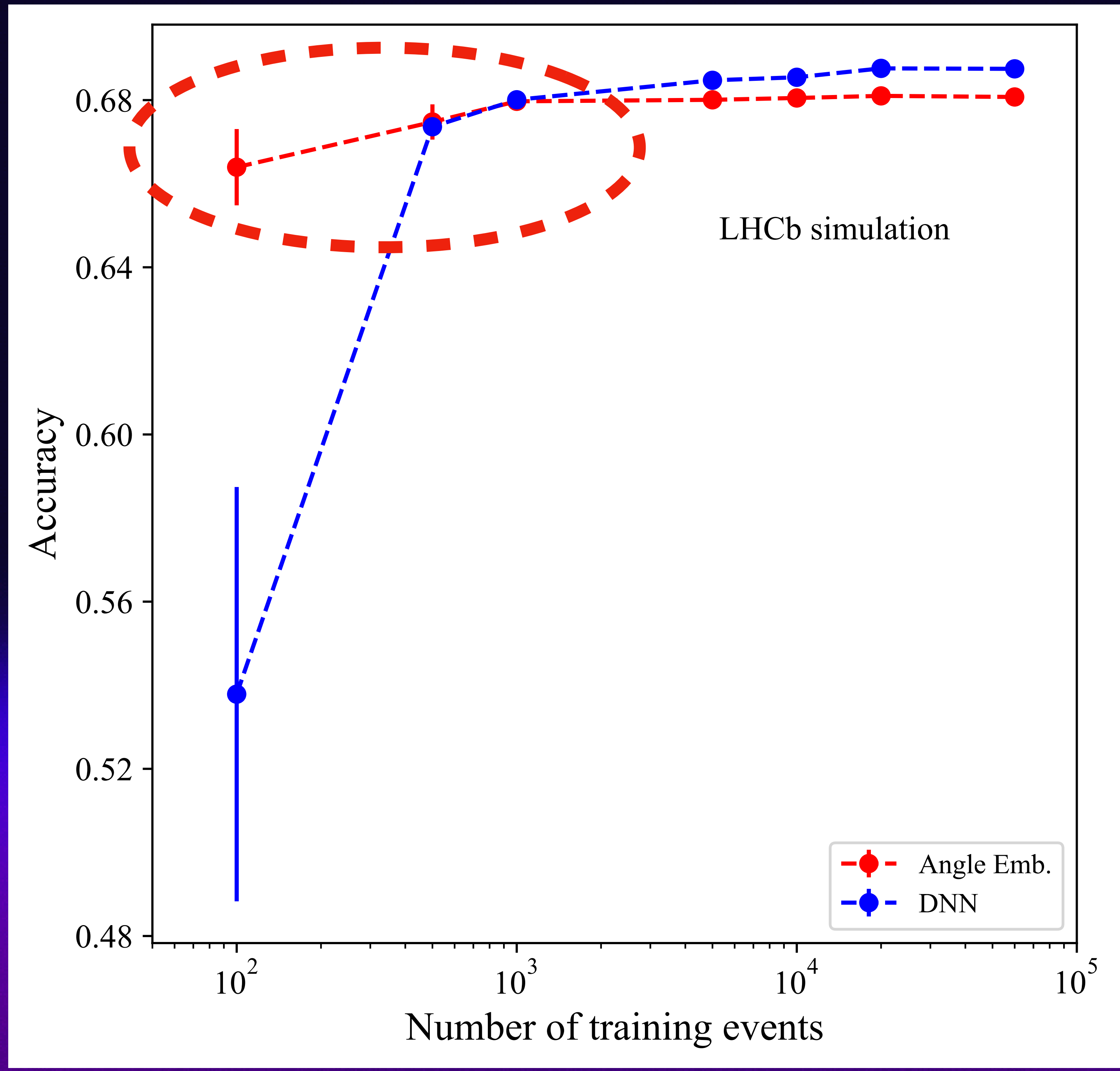
Noise



b-jet charge identification with QML

Try to get a complete study — performance





- Accuracy computed using the muon dataset (4 qubits)
- **Accuracy saturates for >5 variational layers**
- For a low number of training events, the Angle Embedding performs better than the DNN

IBM QUANTUM
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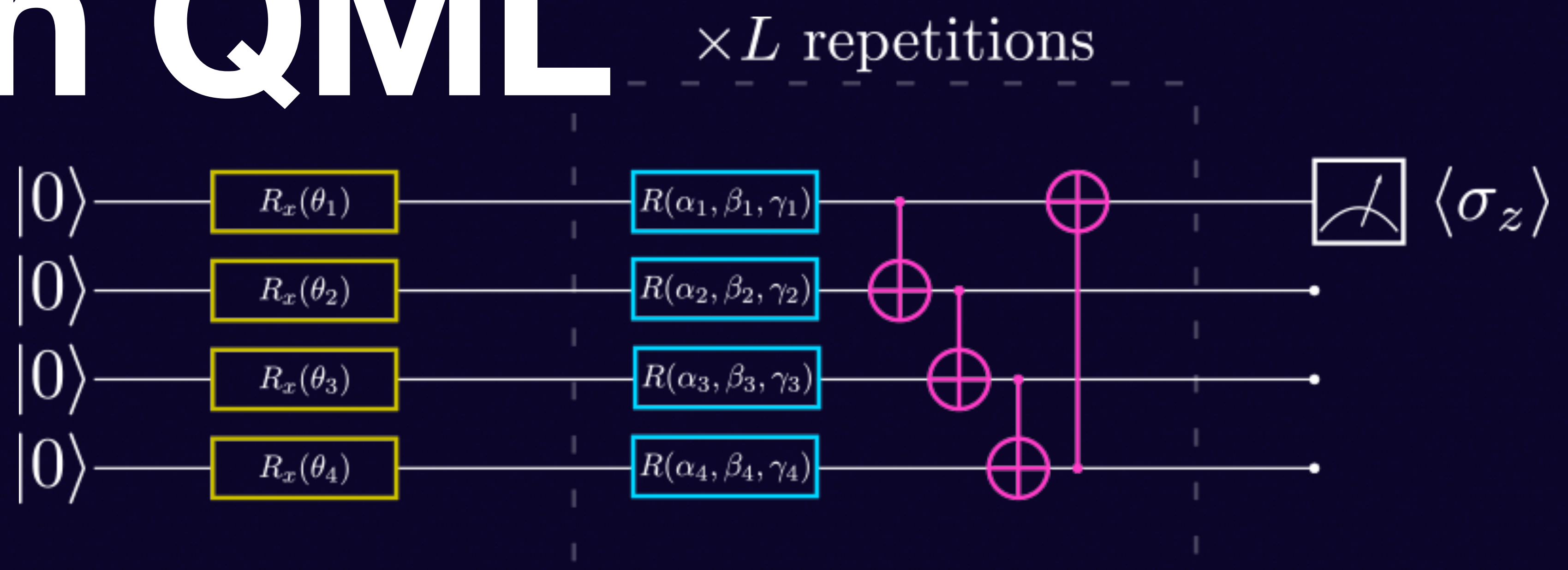
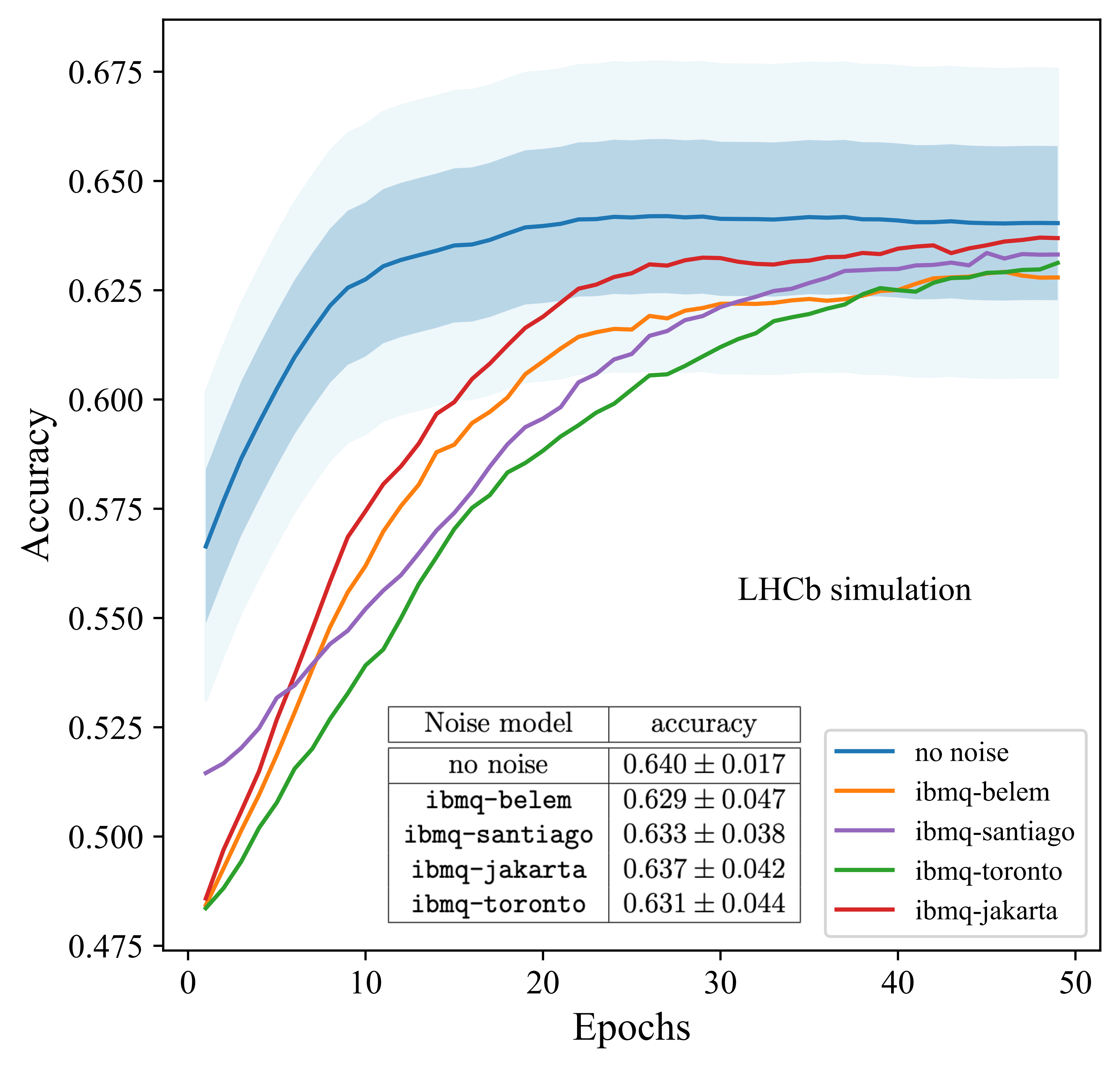
b-jet charge identification with QML

Try to get a complete study — noise





- Finally, the impact of noise has been studied for the 4 qubit circuit
- Using the *pennylane-qiskit* library, it's possible to simulate noise coming from different IBMq machines

PENNYLANE + Qiskit

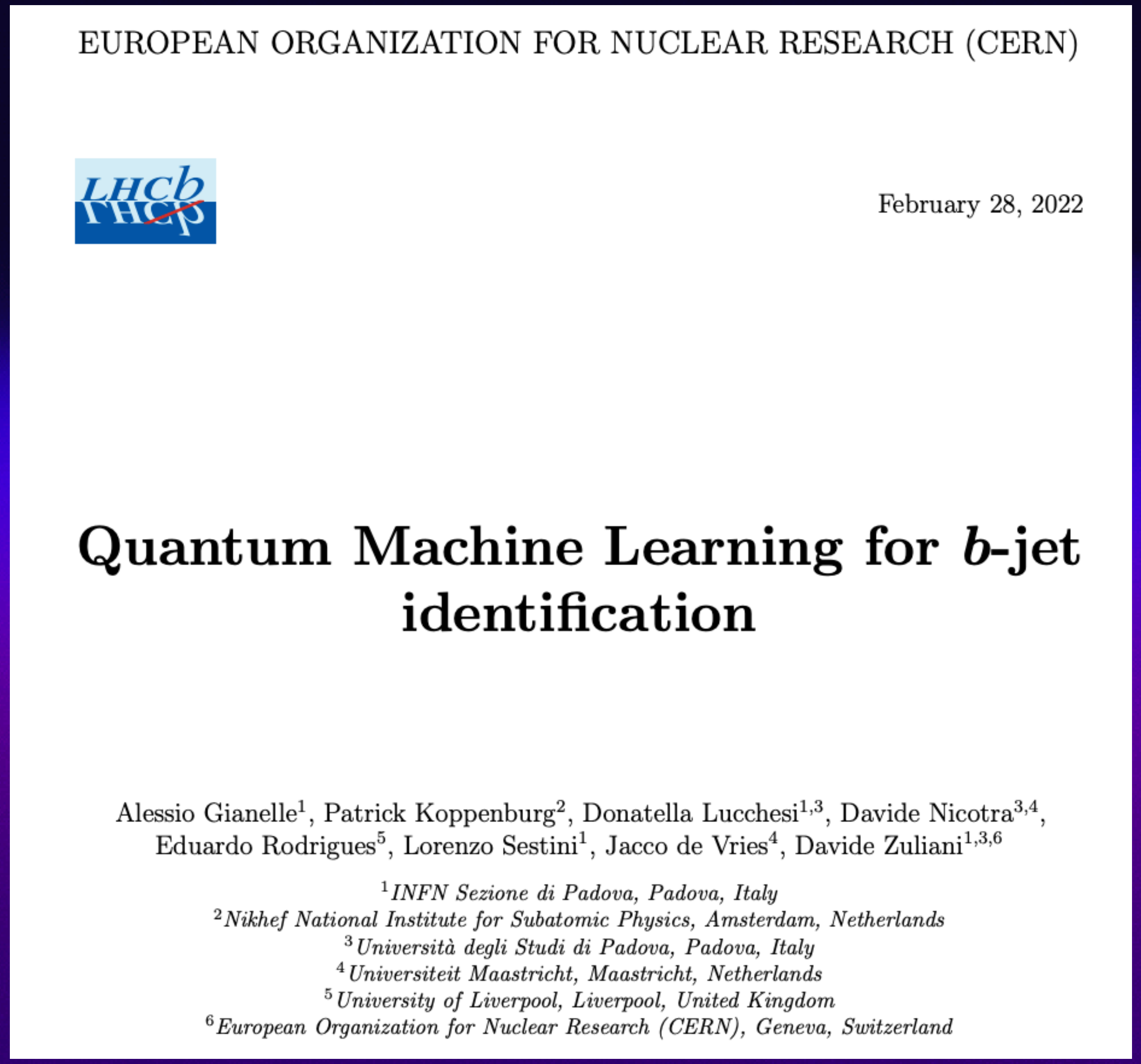
- Results are averaged over five rounds of training, using five independent training subsets of 1000 jets each
- Simpler Angle Embedding circuit, with just 3 variational layers
- Noisy simulations take more epochs to perform training
- Structure quite robust to noise, accuracy within error

Conclusions

Or maybe just the beginning

- A first, exploratory but “real-life” study of QML for b-jet charge identification at LHCb has been presented
- The problem has been studied by considering several aspects:
  - For the muon dataset, QML approaches standard DNN
  - Dependence on # layers and # training events has been assessed
  - Simple structures have been proven to be robust to noise

- Continue to explore this exciting (and fairly new) topic:
  - Possibly access hardware (at first for testing, but also for training)
  - New “exercises” (e.g. b- vs c-jet identification)
  - Different architectures (annealing?)



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

February 28, 2022

Quantum Machine Learning for *b*-jet identification

Alessio Gianelle[1], Patrick Koppenburg[2], Donatella Lucchesi[1,3], Davide Nicotra[3,4], Eduardo Rodrigues[5], Lorenzo Sestini[1], Jacco de Vries[4], Davide Zuliani[1,3,6]

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Paper accepted by JHEP!

Thank you for your attention

Questions, comments?

Backup slides

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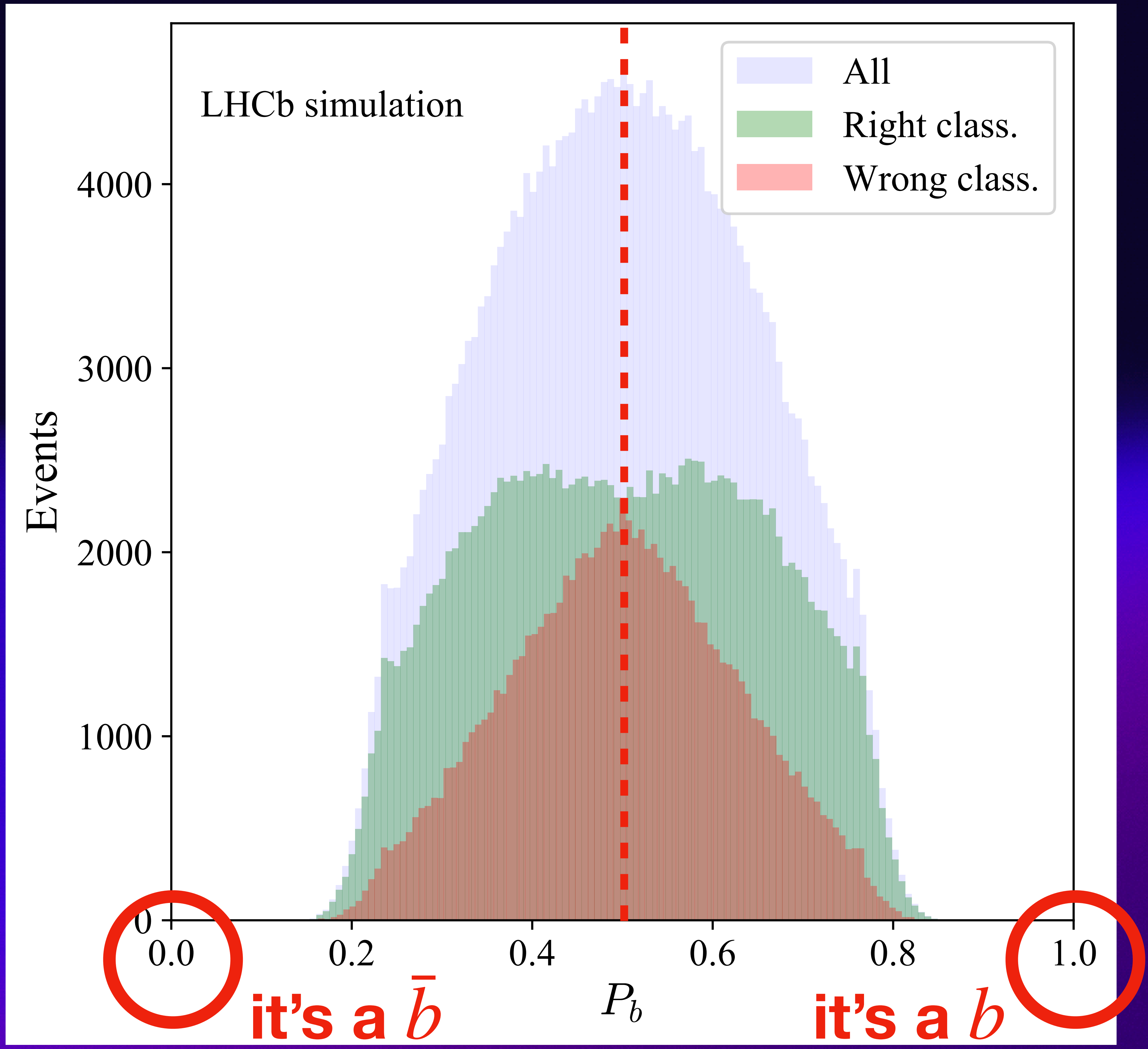
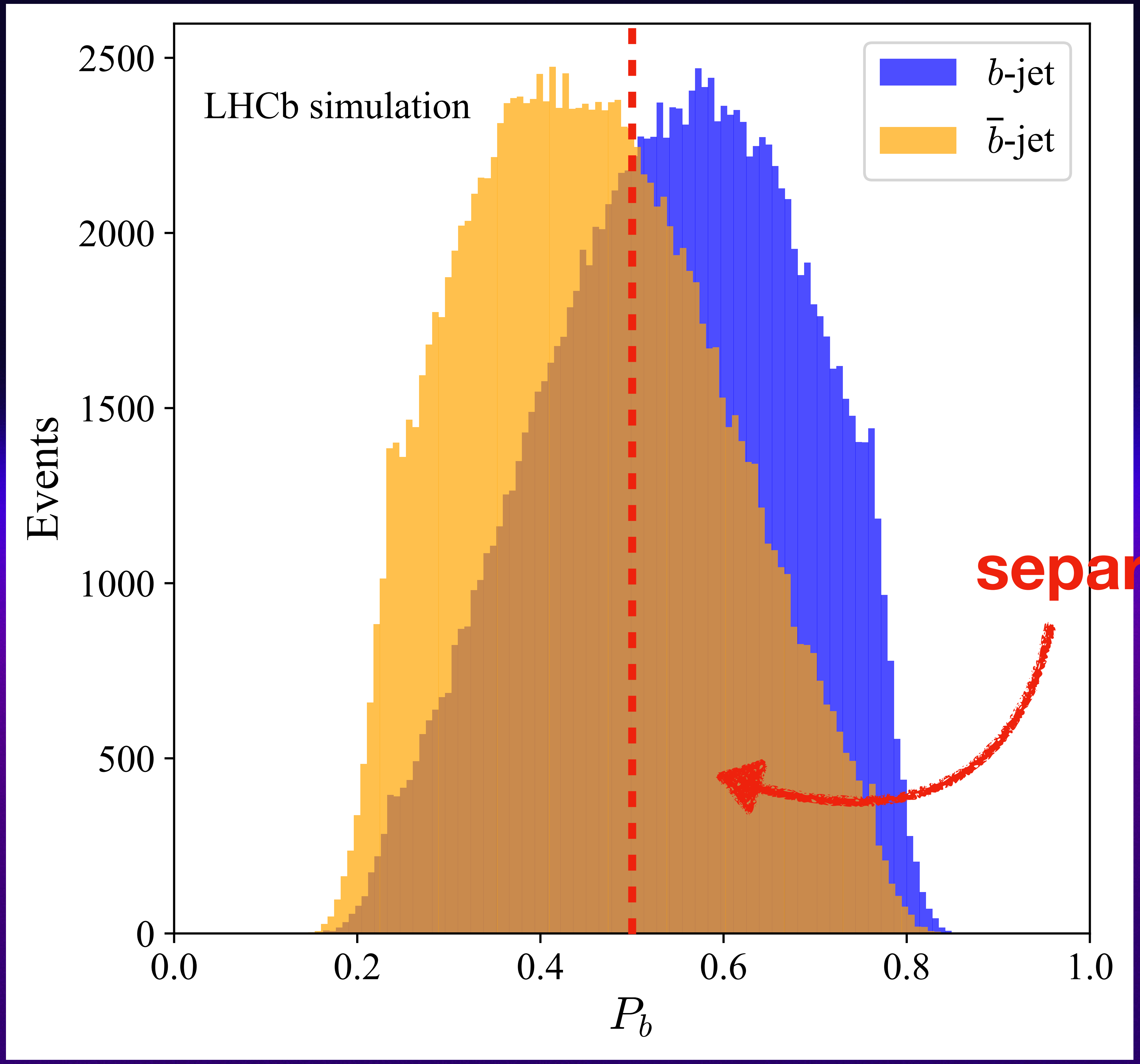
b-jet charge identification with QML

Algorithm performance

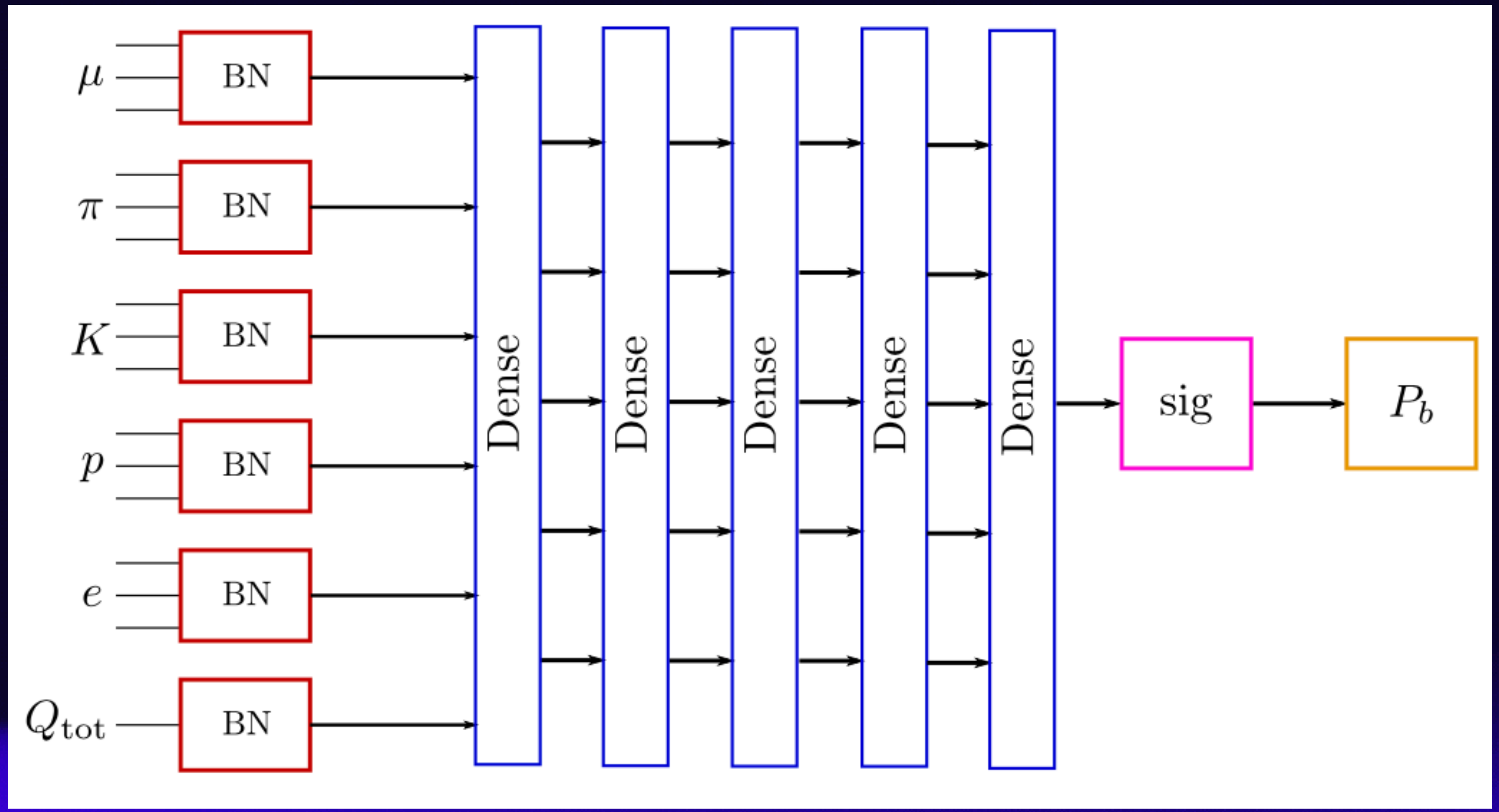
- A look at the output distribution gives an idea of the goodness of the algorithm

Angle Embedding complete dataset (16 qubit)



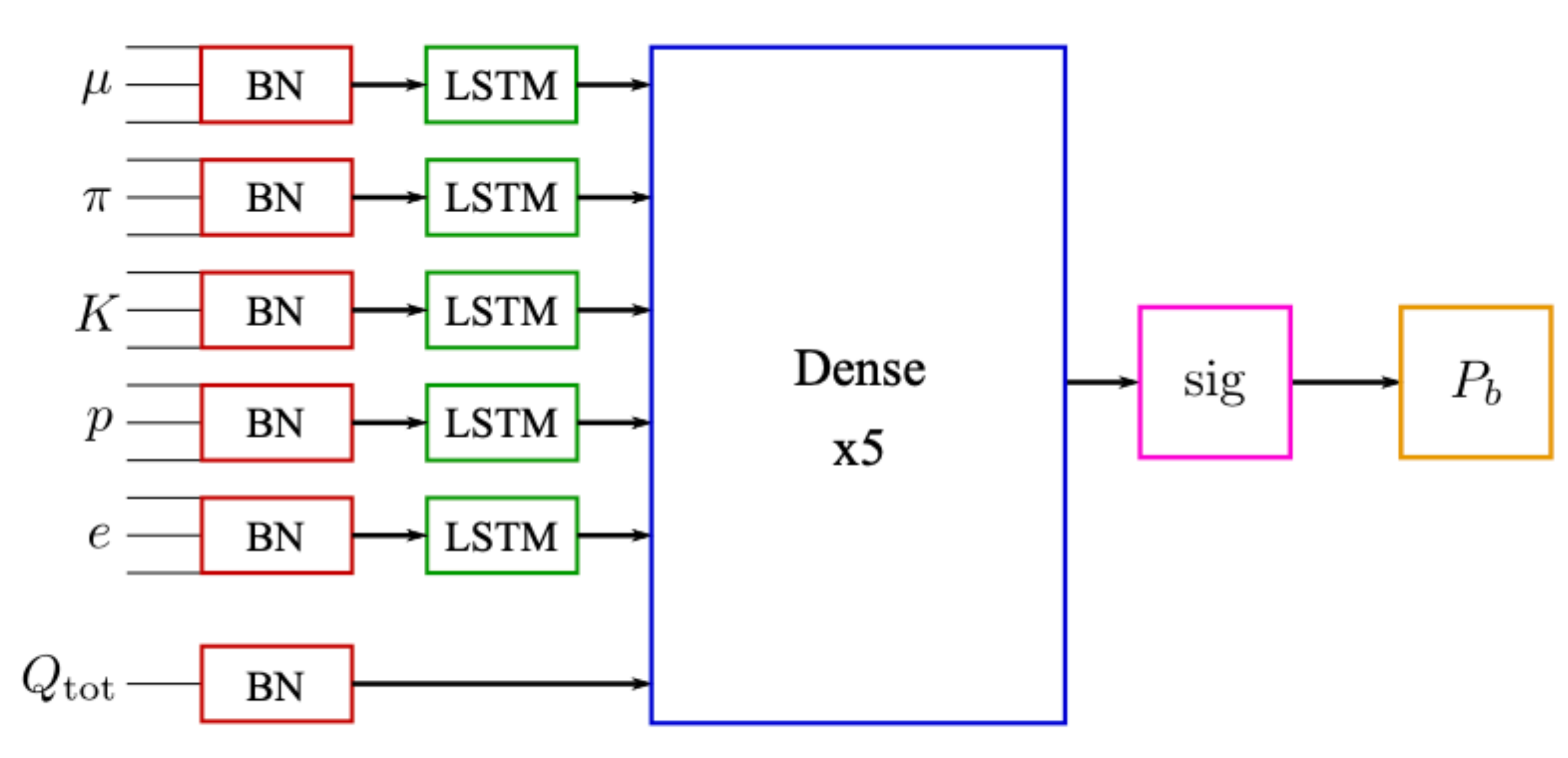


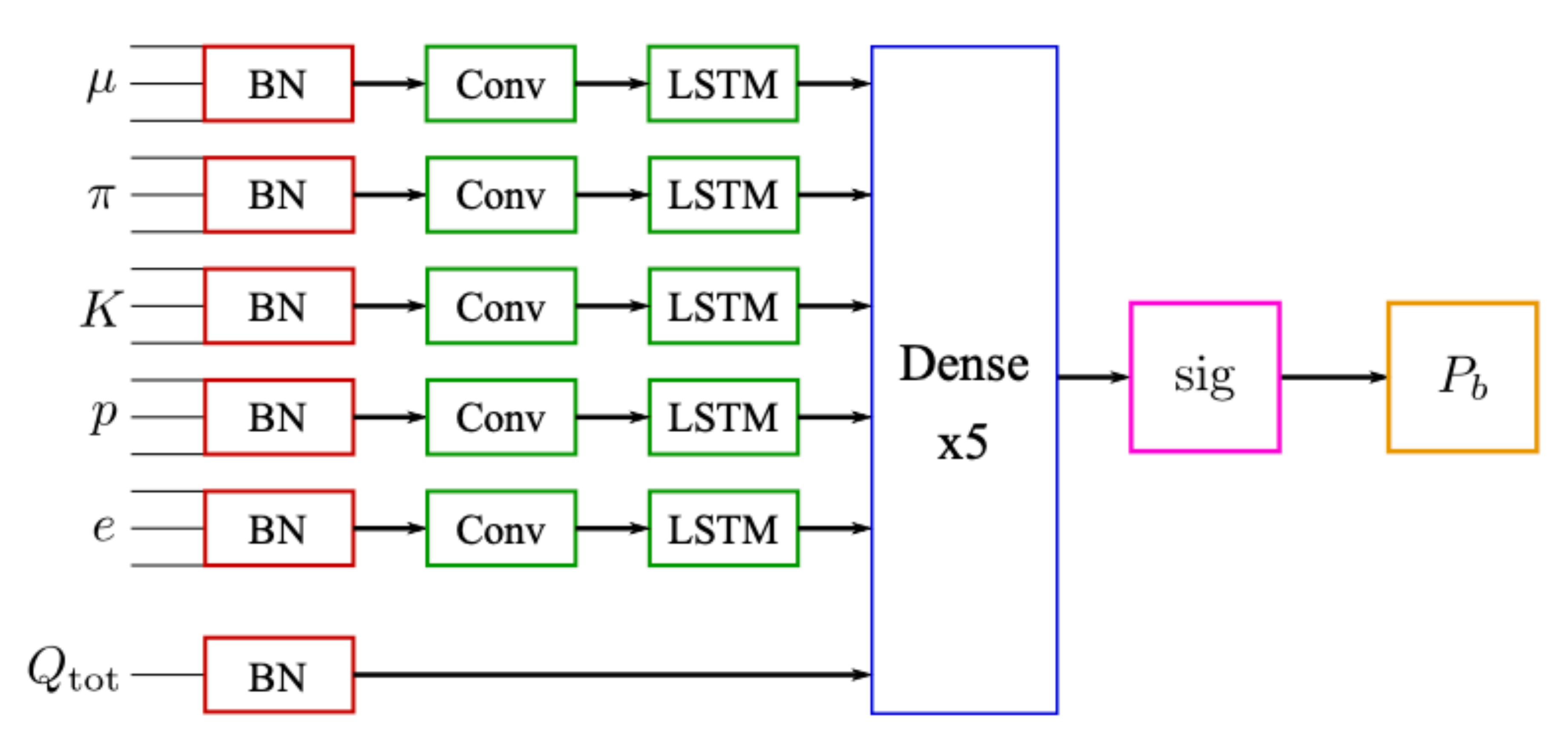
DNN structures



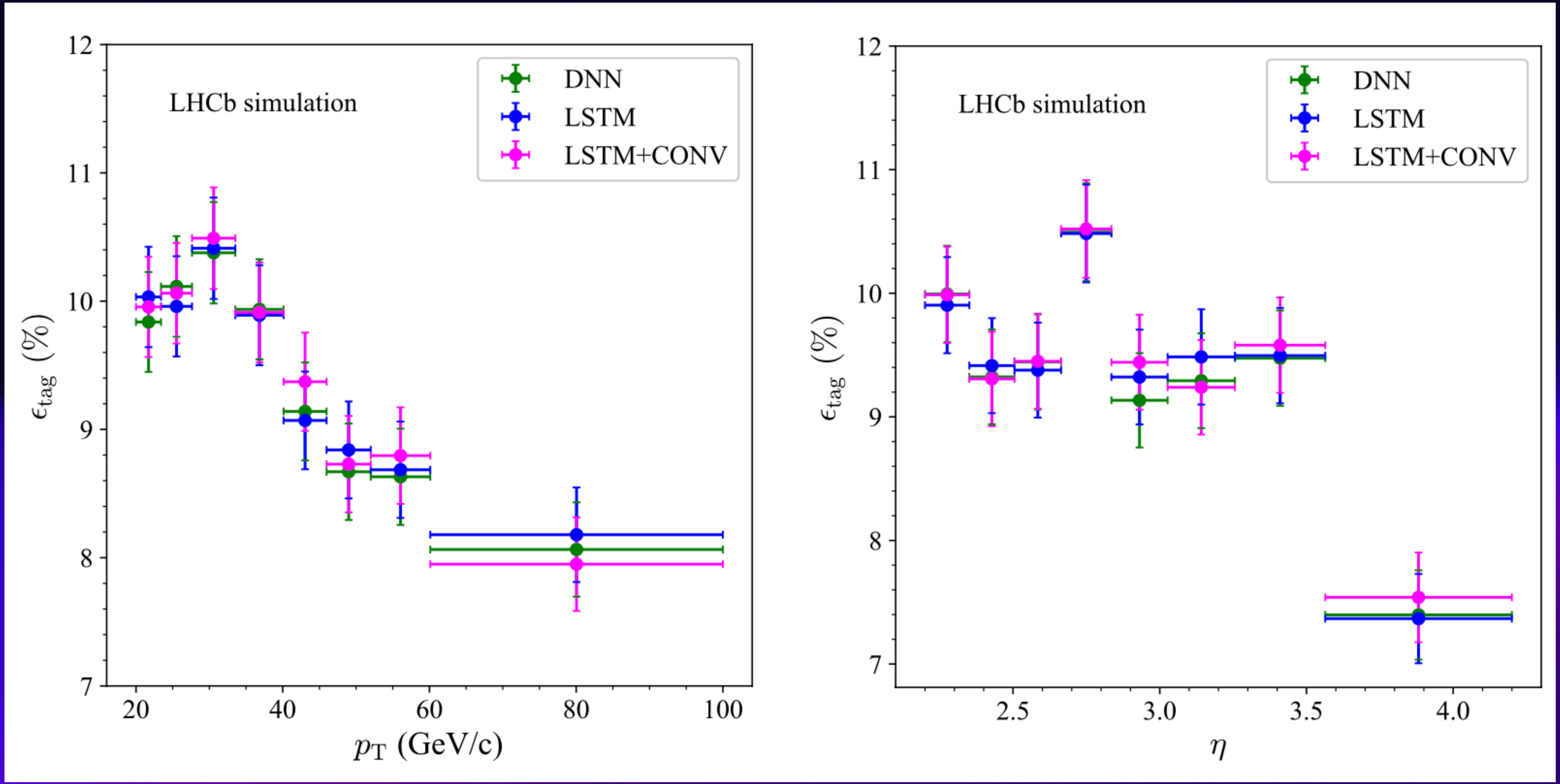
"Standard" DNN

DNN with LSTM and CONV





DNN performance



Unoptimised tagging power