QUANTUM TECHNOLOGY INITIATIVE
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QT4HEP 1 - 4 November, 2022

UNIVERSITÀ DEGLI STUDI DI PADOVA
INFN PADOVA

An LHC application of Quantum Machine Learning and INFN summary

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UNIVERSITY AND INFN OF PADOVA

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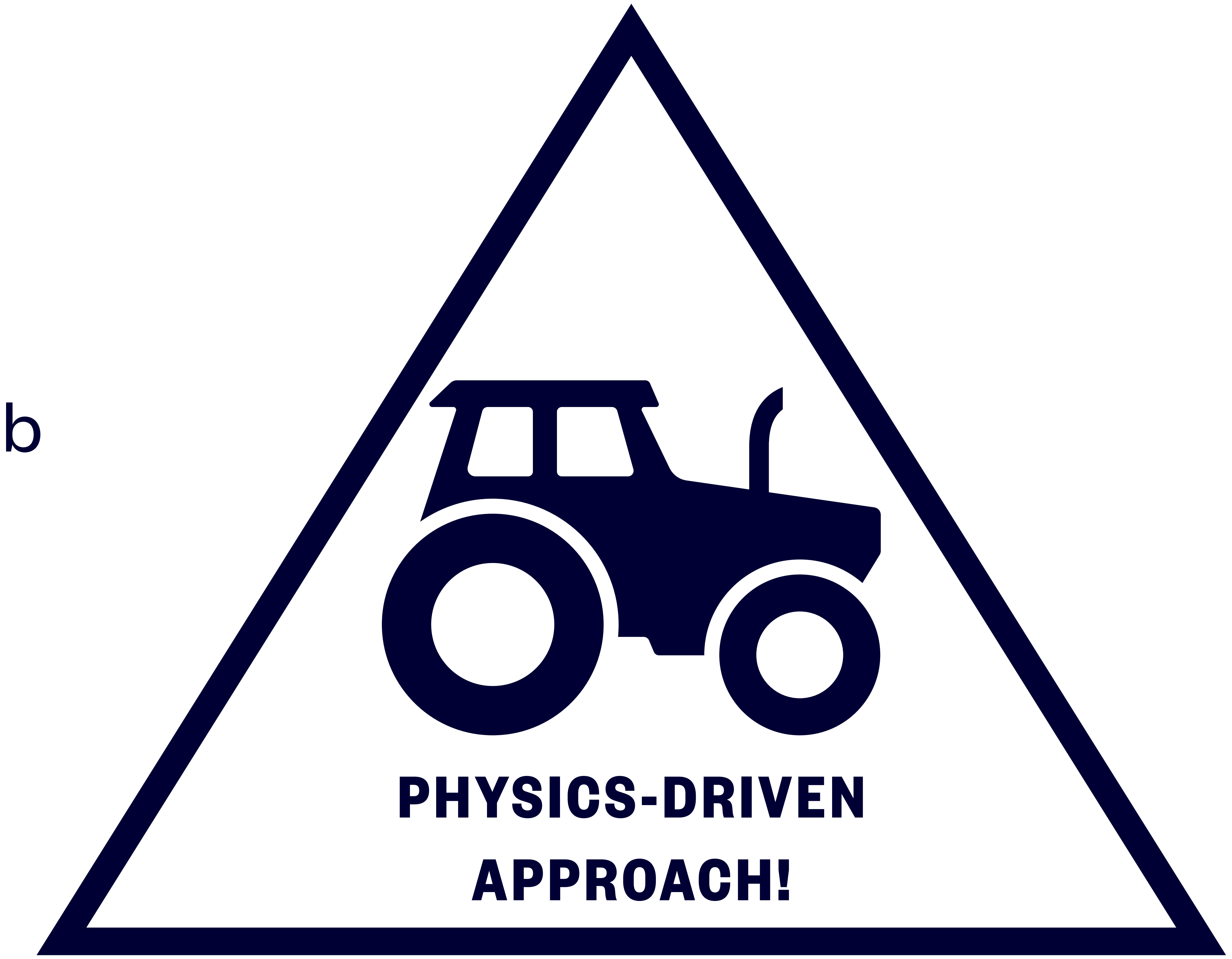
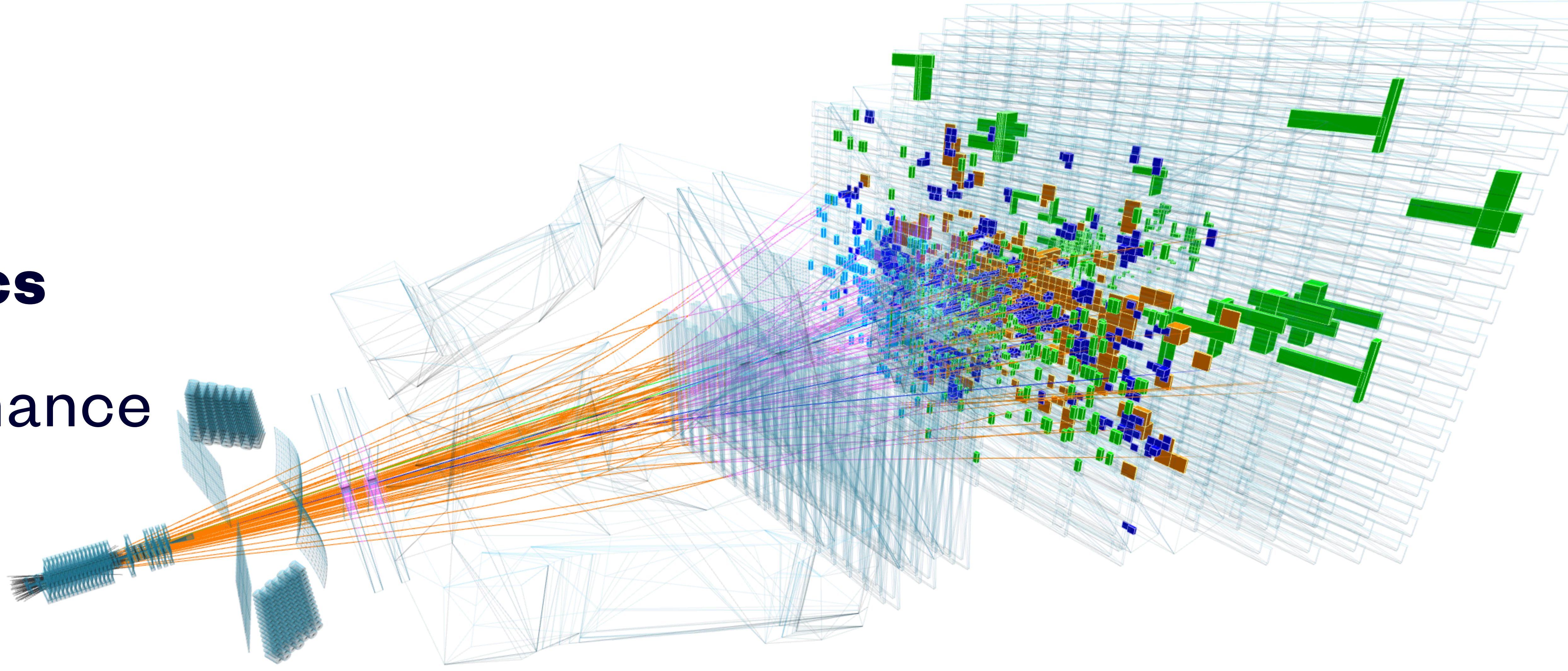


Phys. Rev. Lett. 113 (2014) 08

Application of QML at LHC

b-jet charge identification at LHCb



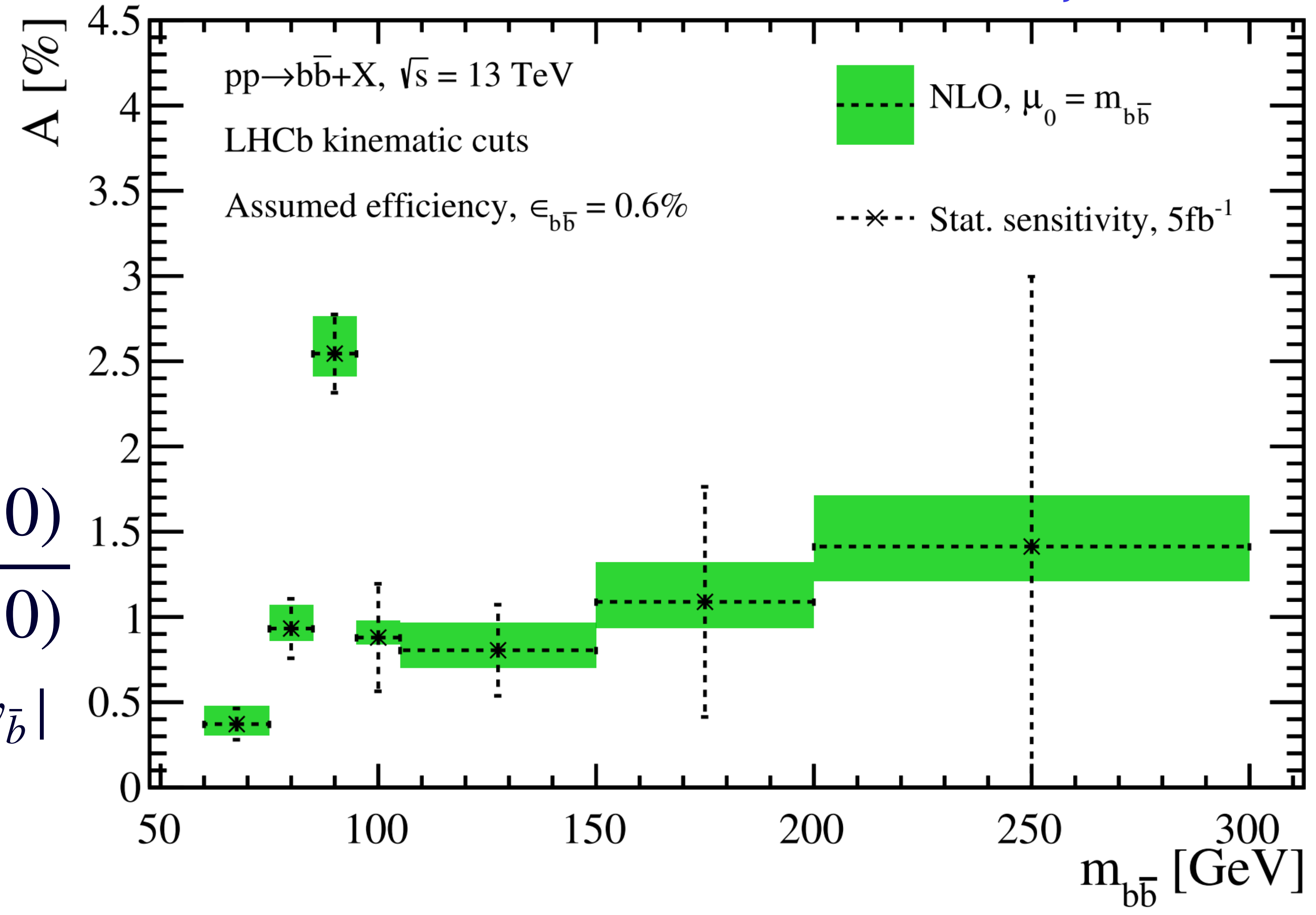
- LHC physics program heavily relies on **jets physics**
- Better jets reconstruction & identification performance
  $\rightarrow$ better results, but **very challenging**!

- Example: $b\bar{b}$ asymmetry at LHCb
  - **Tension from LEP** measurements makes it interesting to study $b\bar{b}$ charge asymmetry at LHC
  - **Statistical uncertainty** is directly related to the **identification algorithm performance**
    - Finer binning for $m_{b\bar{b}}$ around Z pole
    - Measure contribution from higher orders

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

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

JHEP 2019, 166 (2019)



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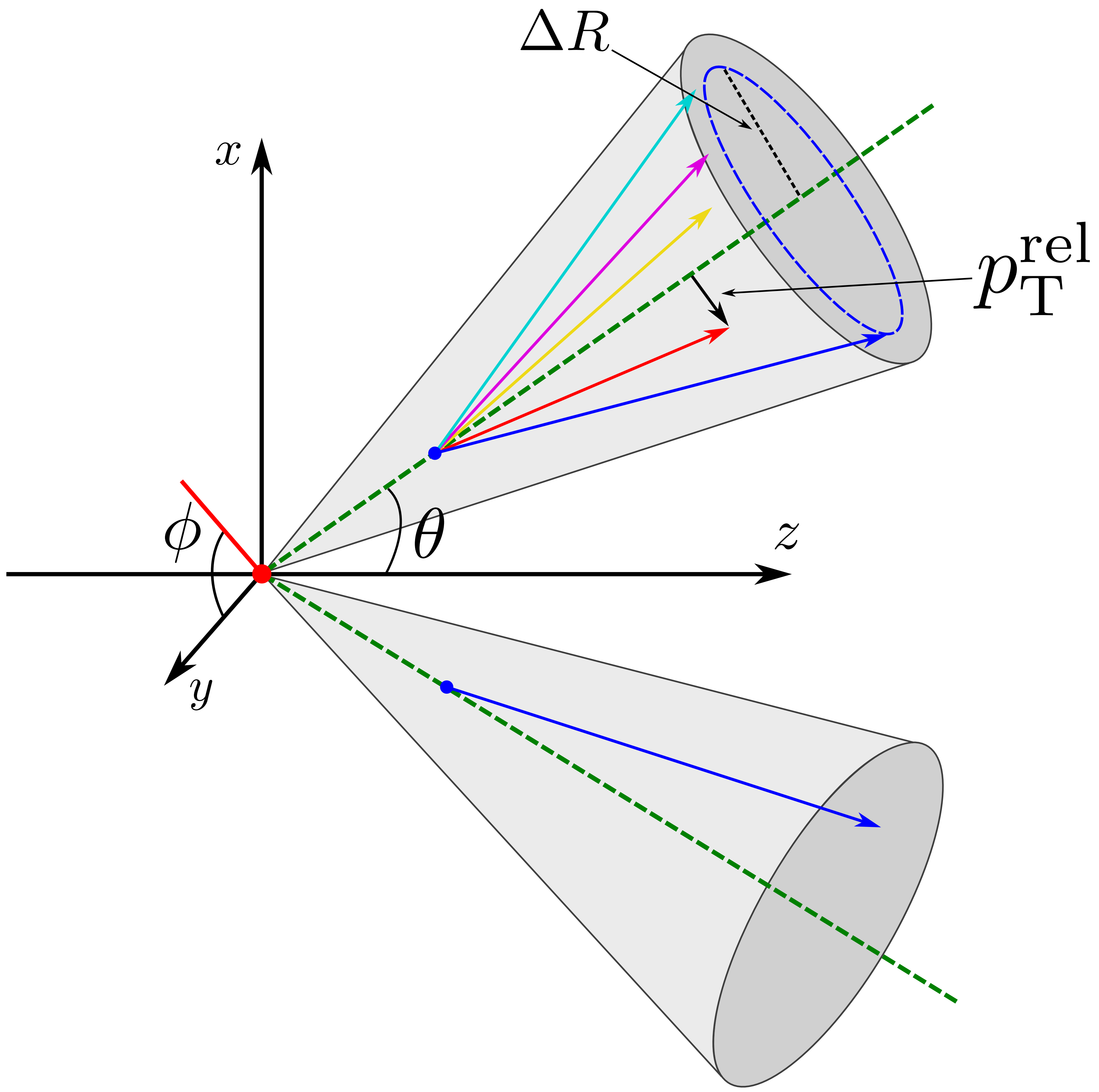
Application of QML at LHC

b-jet charge identification at LHCb

- How can we identify jet charge?



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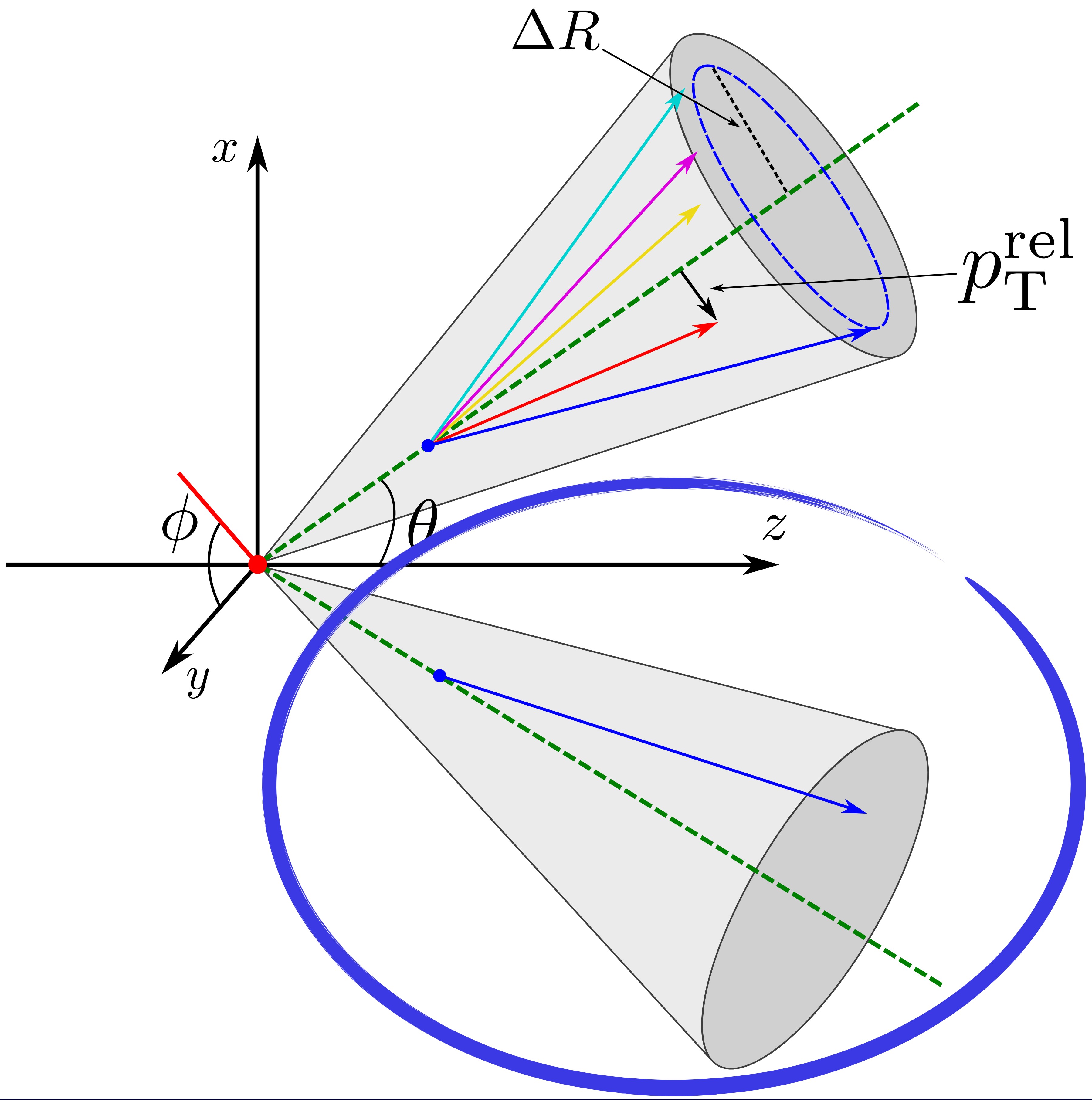

Exclusive approach

- 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 and discriminate between b and $\bar{b}$-jets

Application of QML at LHC

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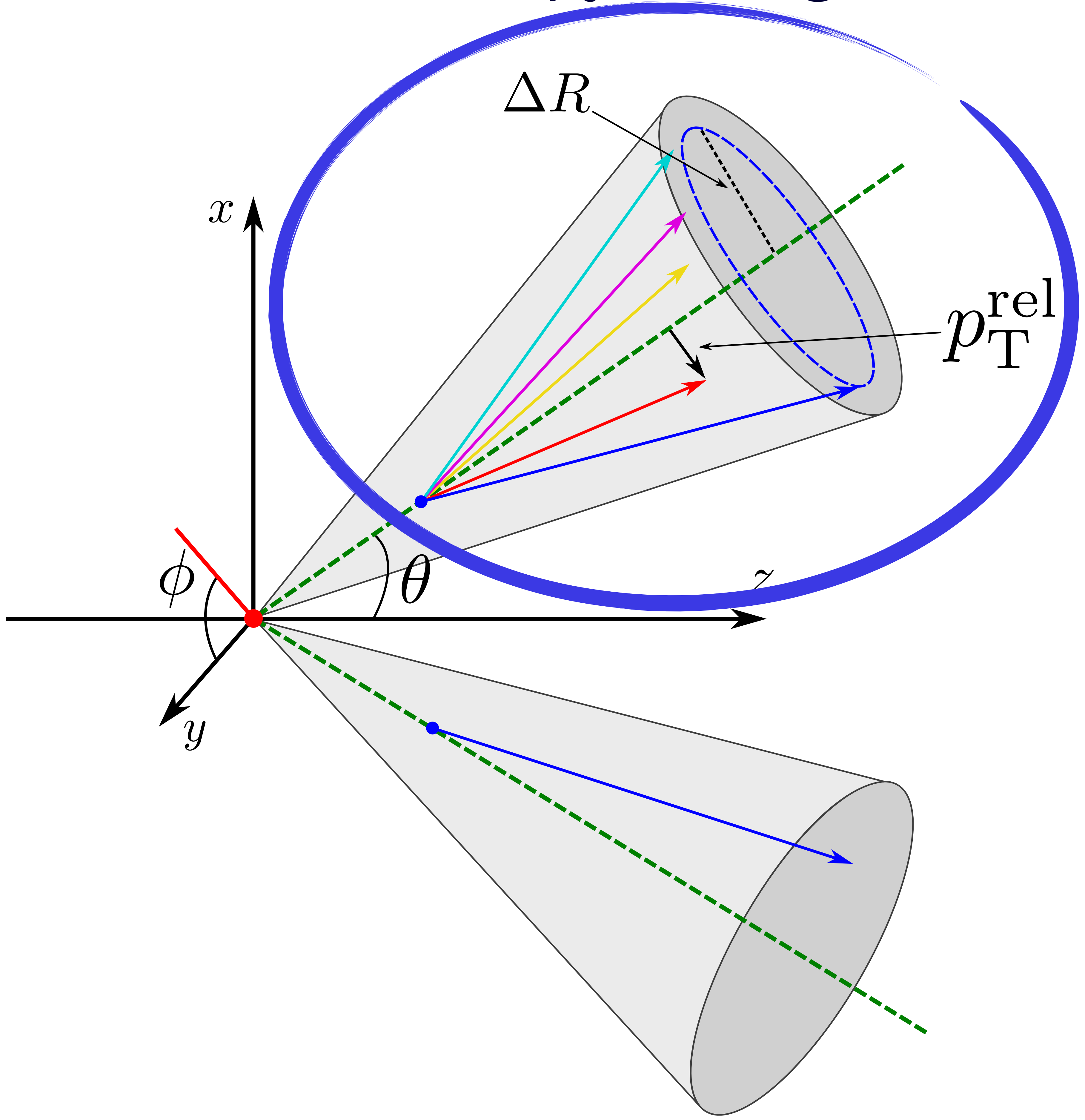

Inclusive approach

- 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** tools are well suited!

Exclusive approach

- Use a **specific physics process** to infer the quark flavour
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Application of QML at LHC

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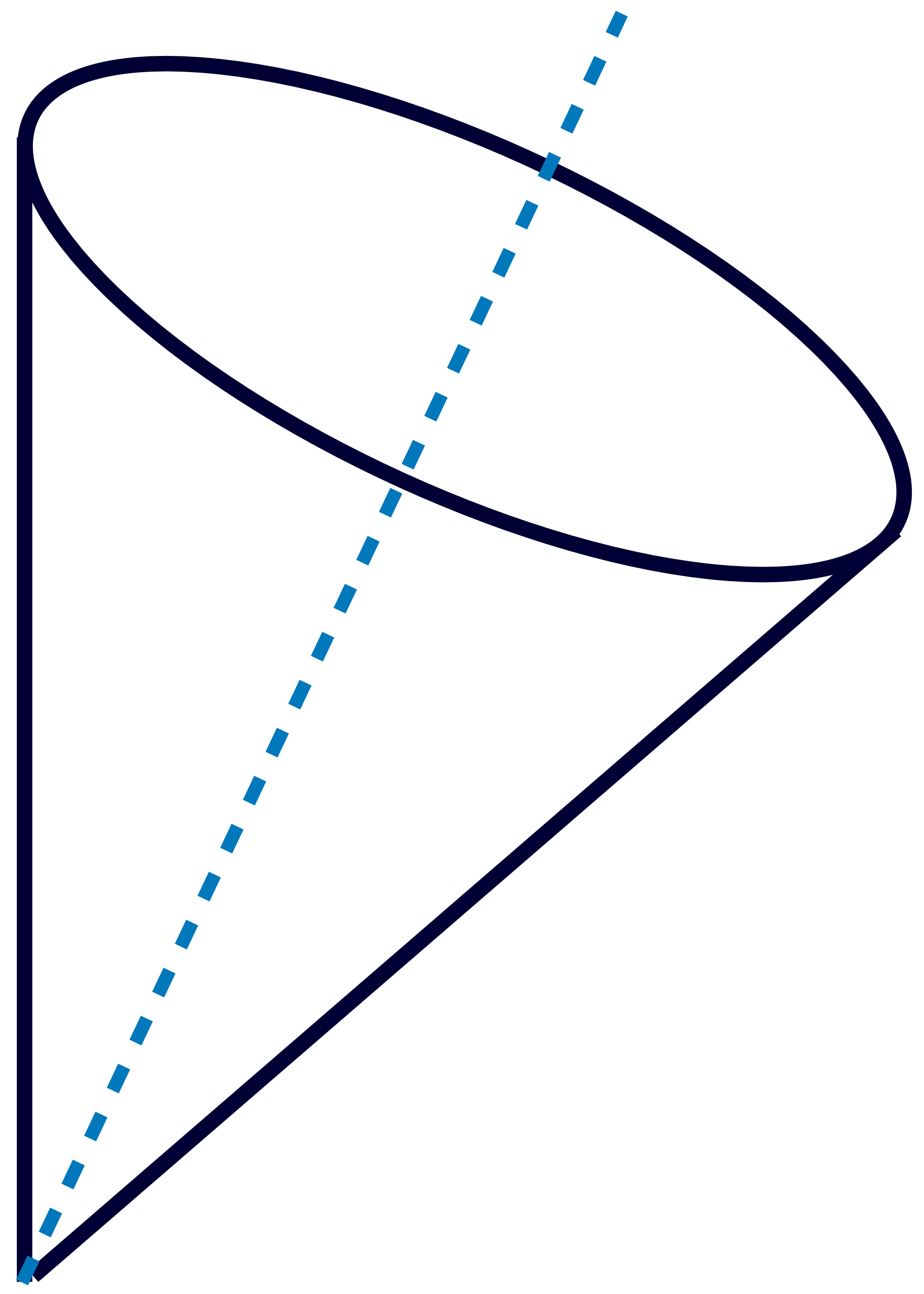

- Sample of $b\bar{b}$ di-jets events have been simulated with the **official LHCb simulation framework**

THEY RESEMBLE DATA!

- Run 2 condition ($\sqrt{s} = 13\ \mathrm{TeV}$)
- ~700.000 jets, divided into training, testing and evaluation

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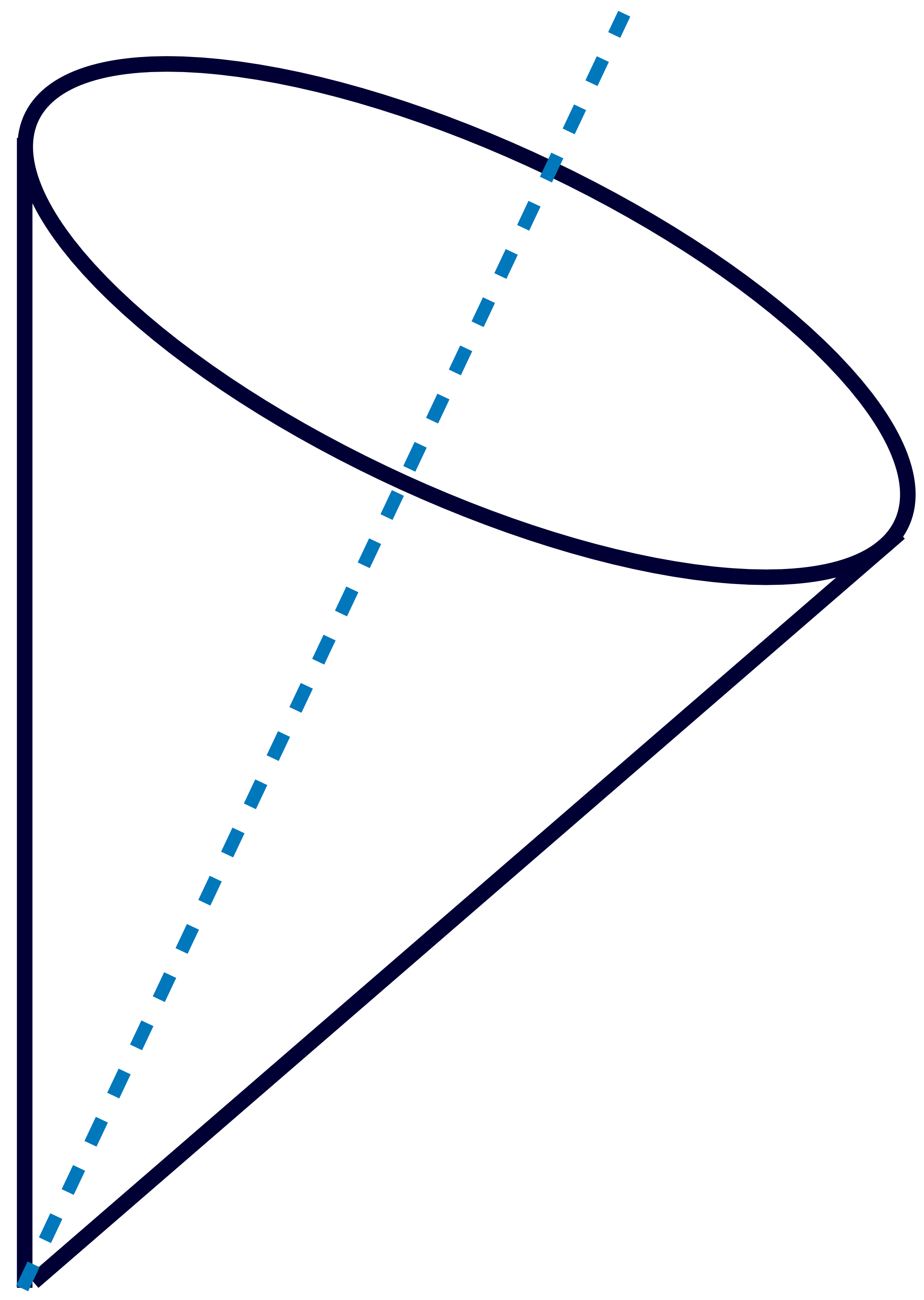
Application of QML at LHC

b-jet charge identification at LHCb



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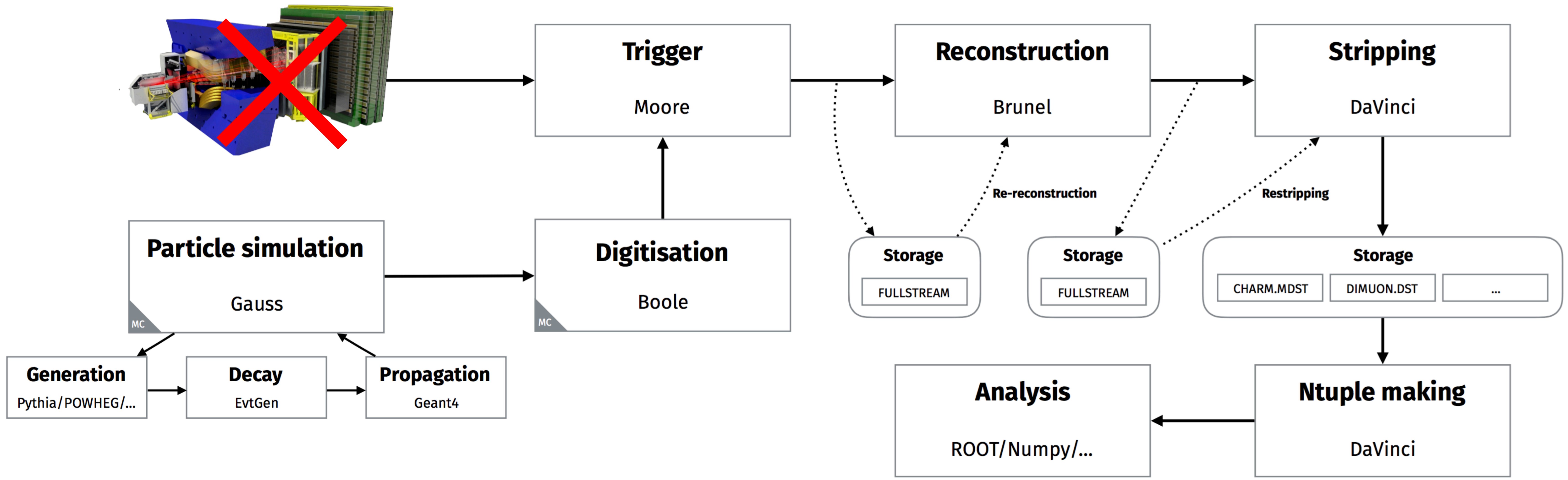

Image taken from https://lhcb.github.io/starterkit-lessons/first-analysis-steps/dataflow.html

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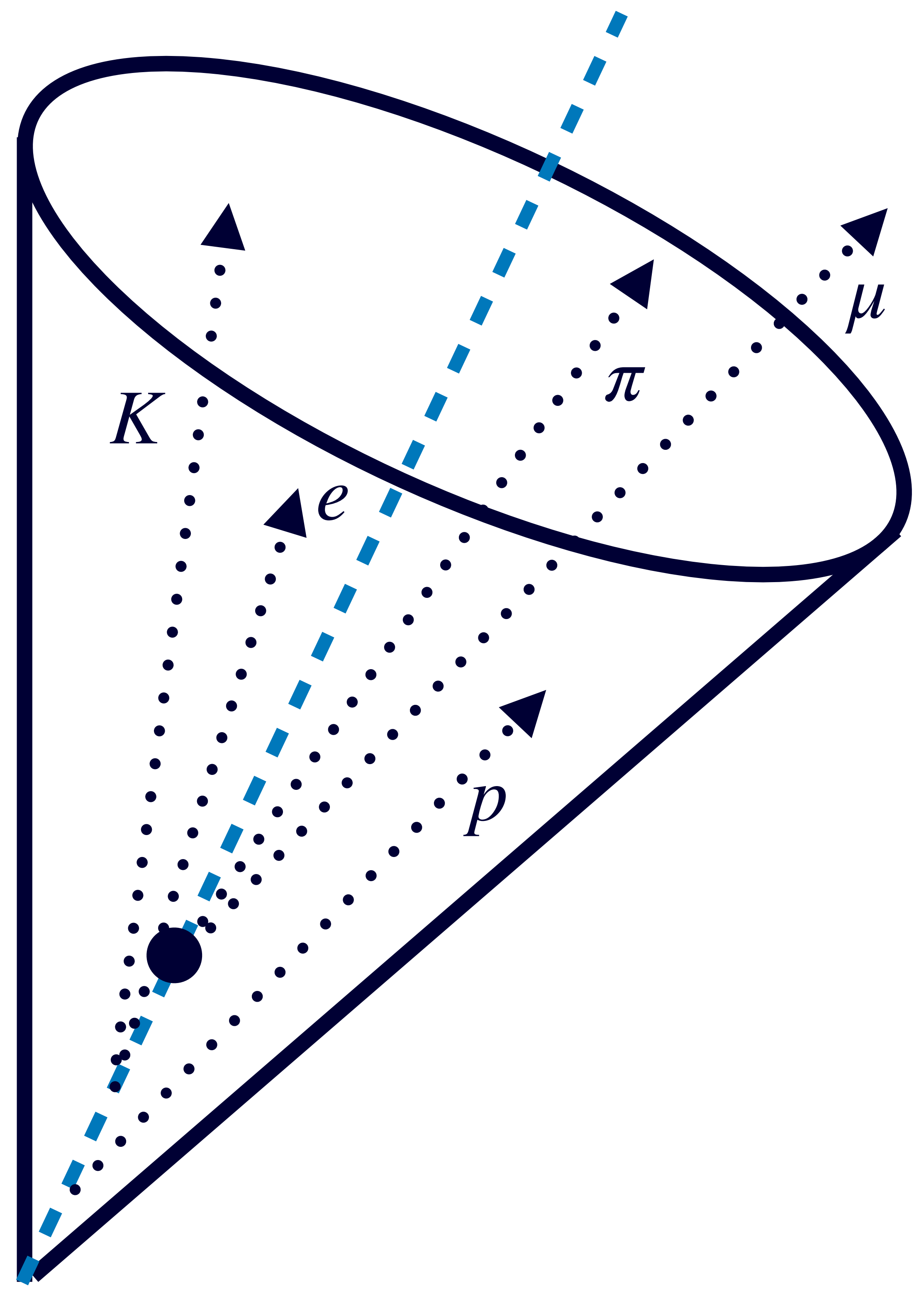

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muon electron pion kaon proton

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Application of QML at LHC

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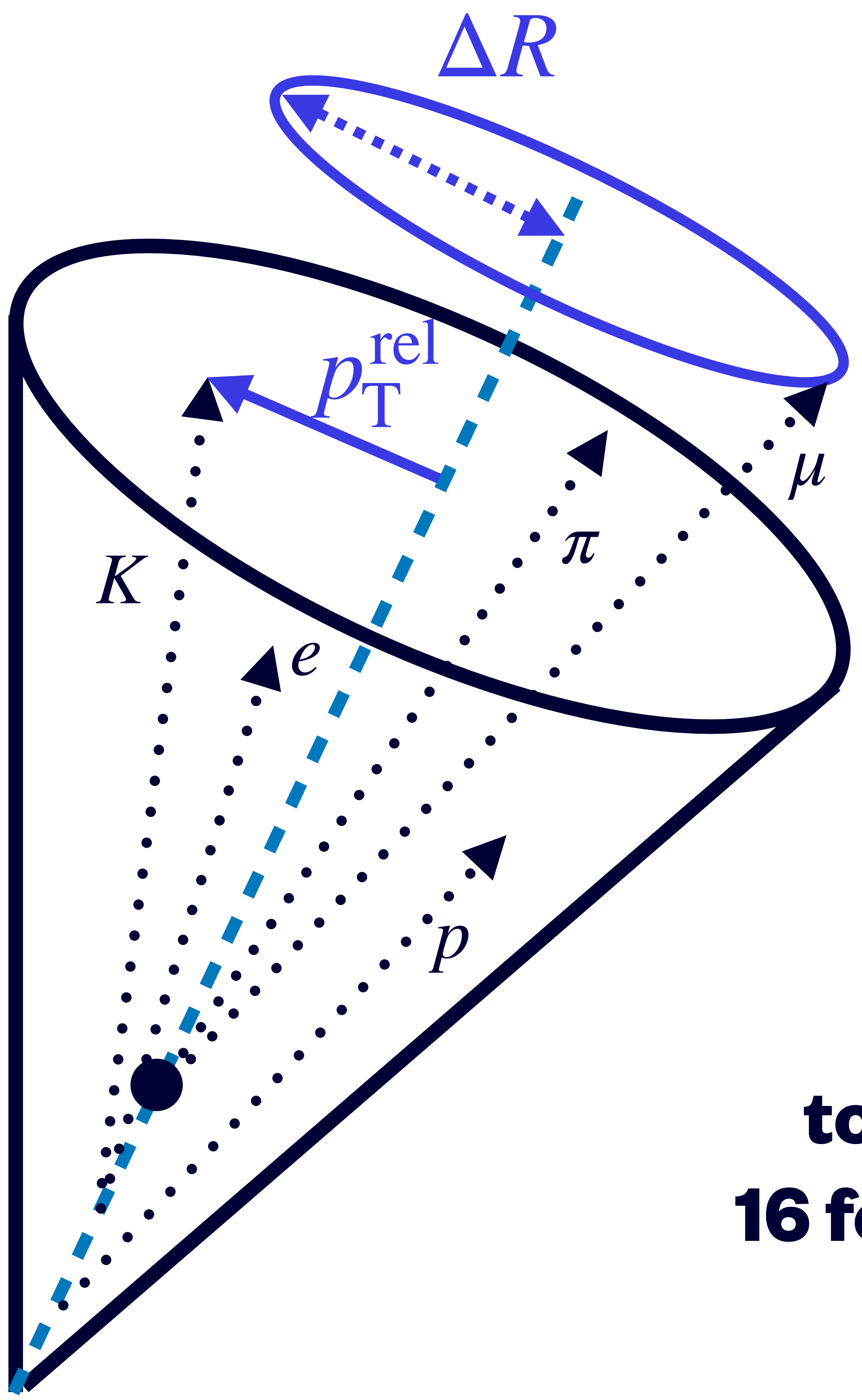

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- Run 2 condition ($\sqrt{s} = 13 \text{ TeV}$)
- ~700.000 jets, divided into training, testing and evaluation
- For each jet, 5 types of particles are considered:

muon electron pion kaon proton

total of 16 features

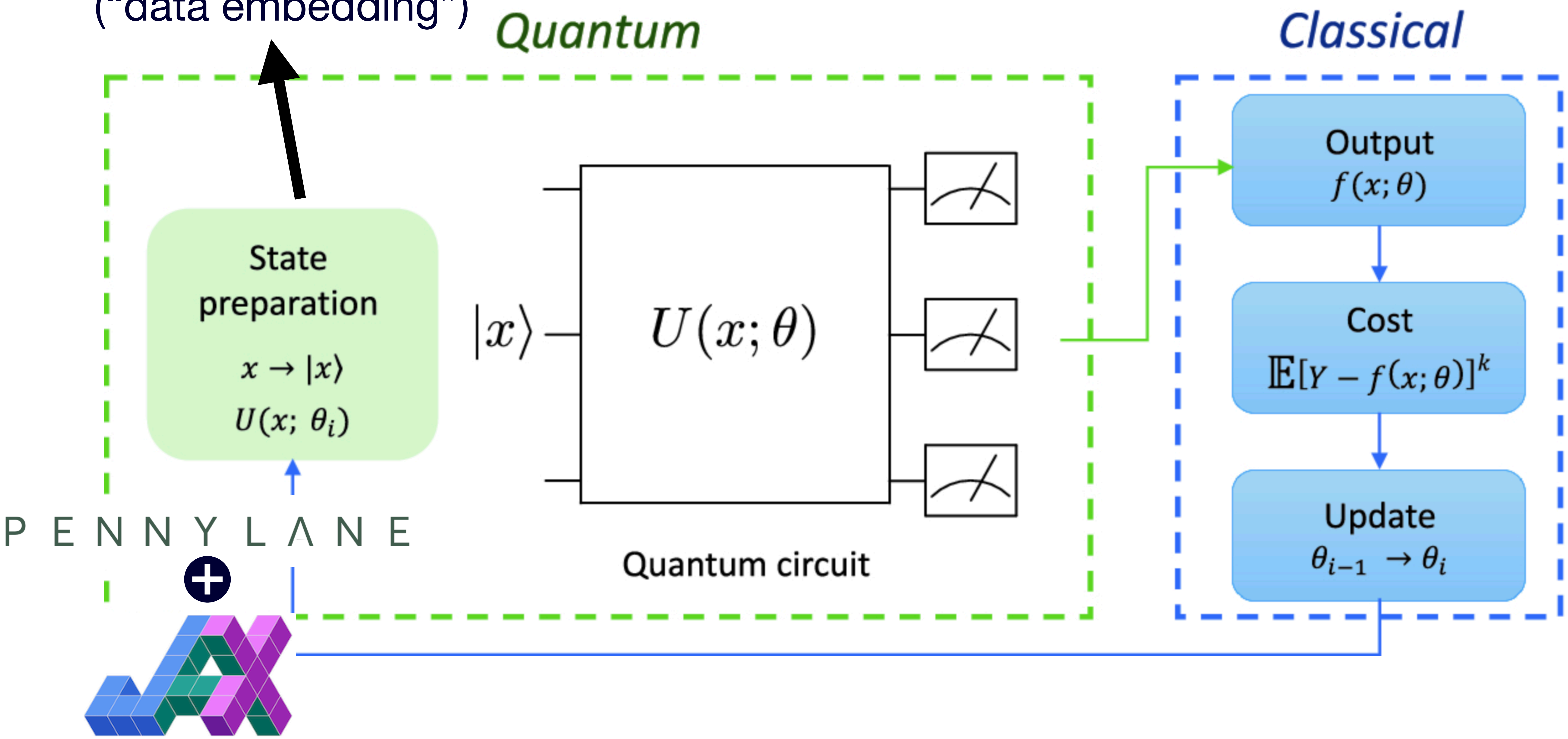
- And for each type of particle, three features are considered:
  - Transverse momentum relative to jet axis p_T^{rel}
  - Distance relative to jet axis ΔR in the (η, ϕ) plane
  - Charge of the particle q
- + a global variable, the total jet charge $Q = \frac{\Sigma(p_T^{rel})q}{\Sigma(p_T^{rel})}$

NATURE 567, 209–212 (2019)

Application of QML at LHC

Algorithm description, Variational Quantum Classifier (VQC)

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



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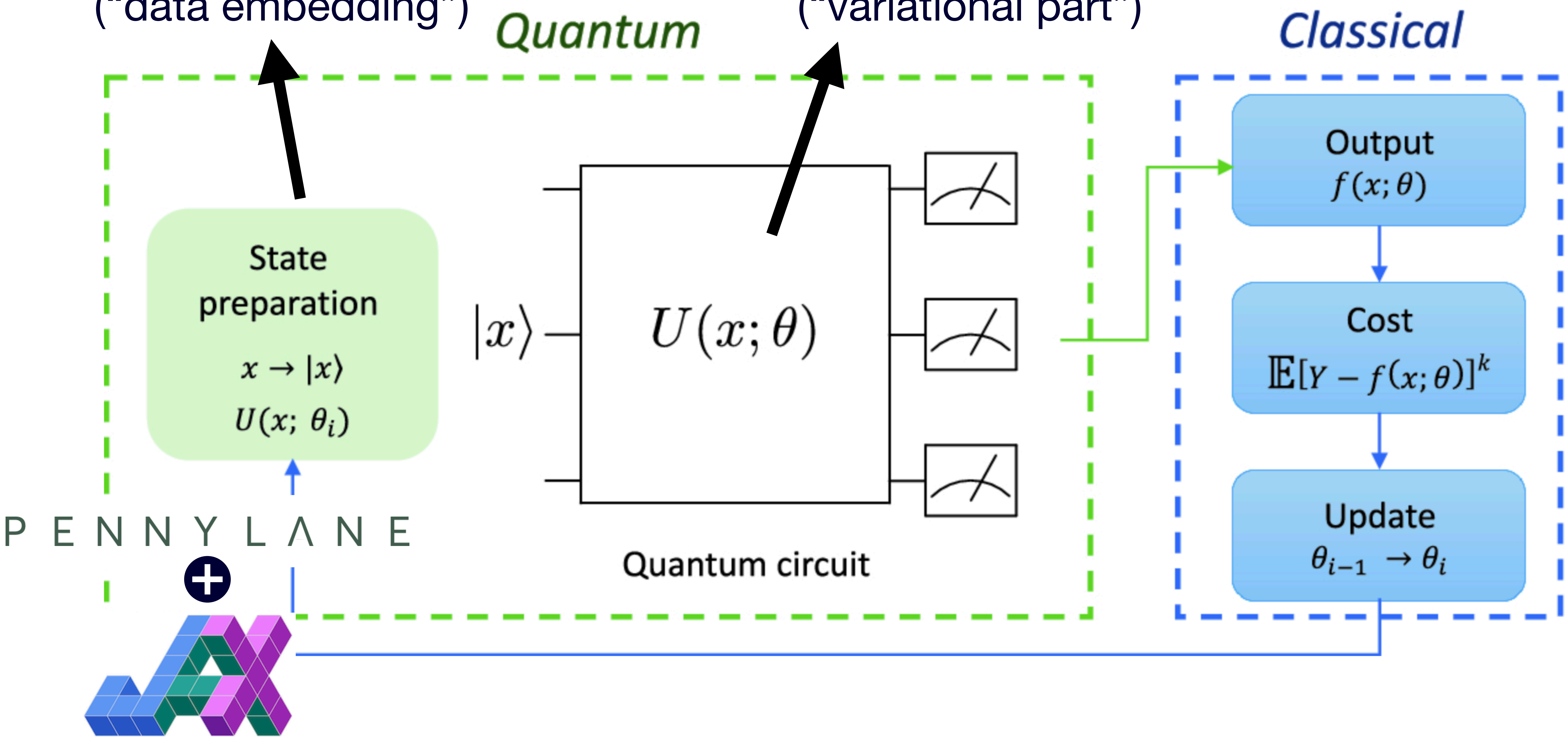

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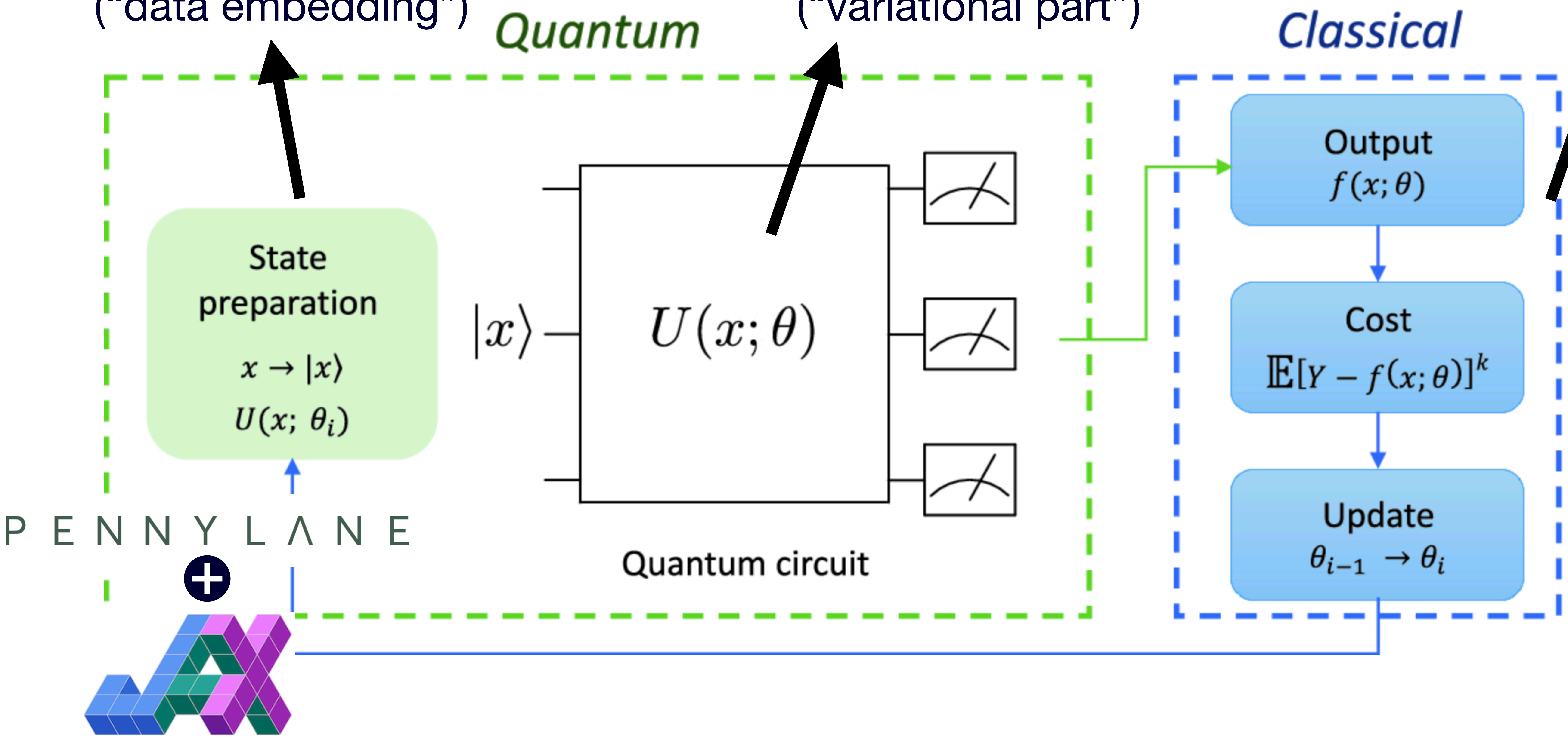

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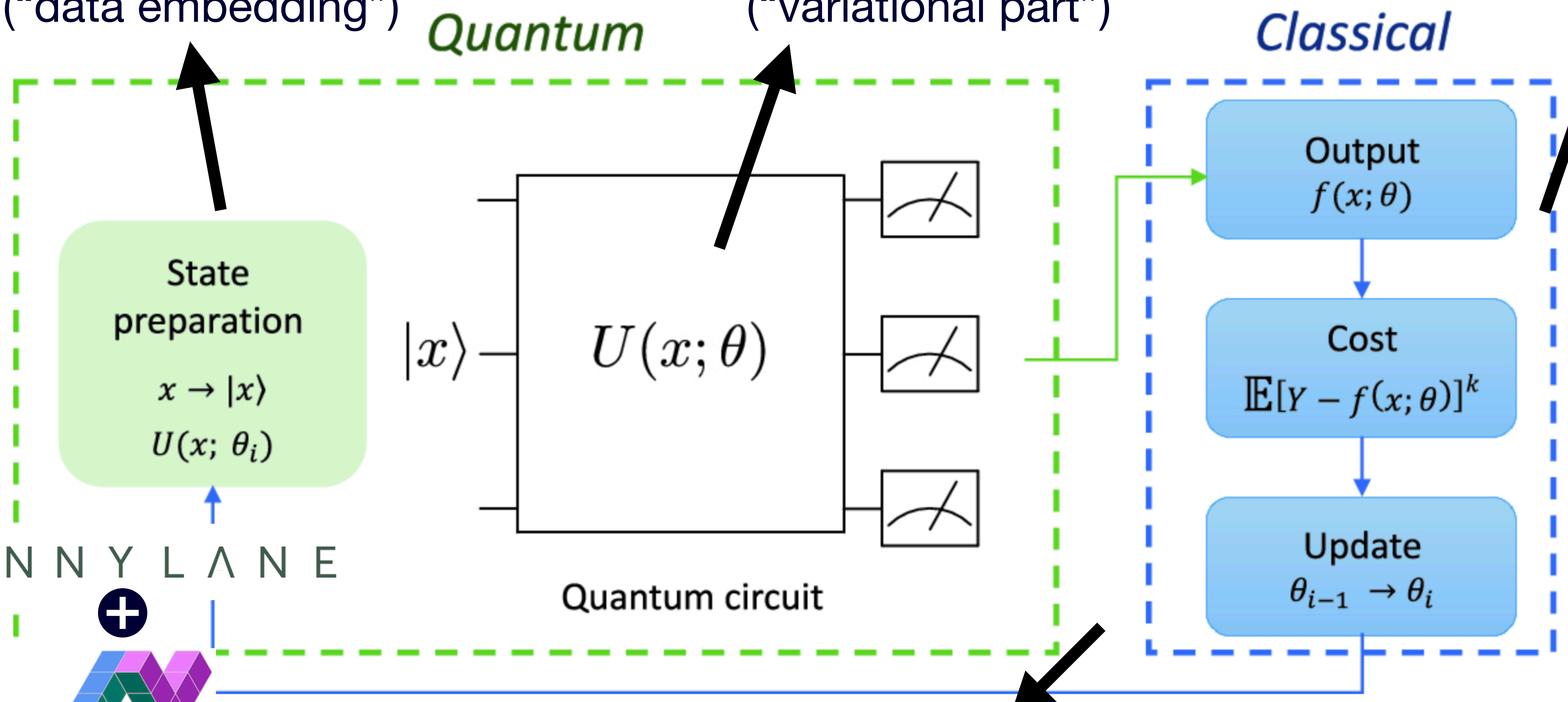

PENNYLANE +

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

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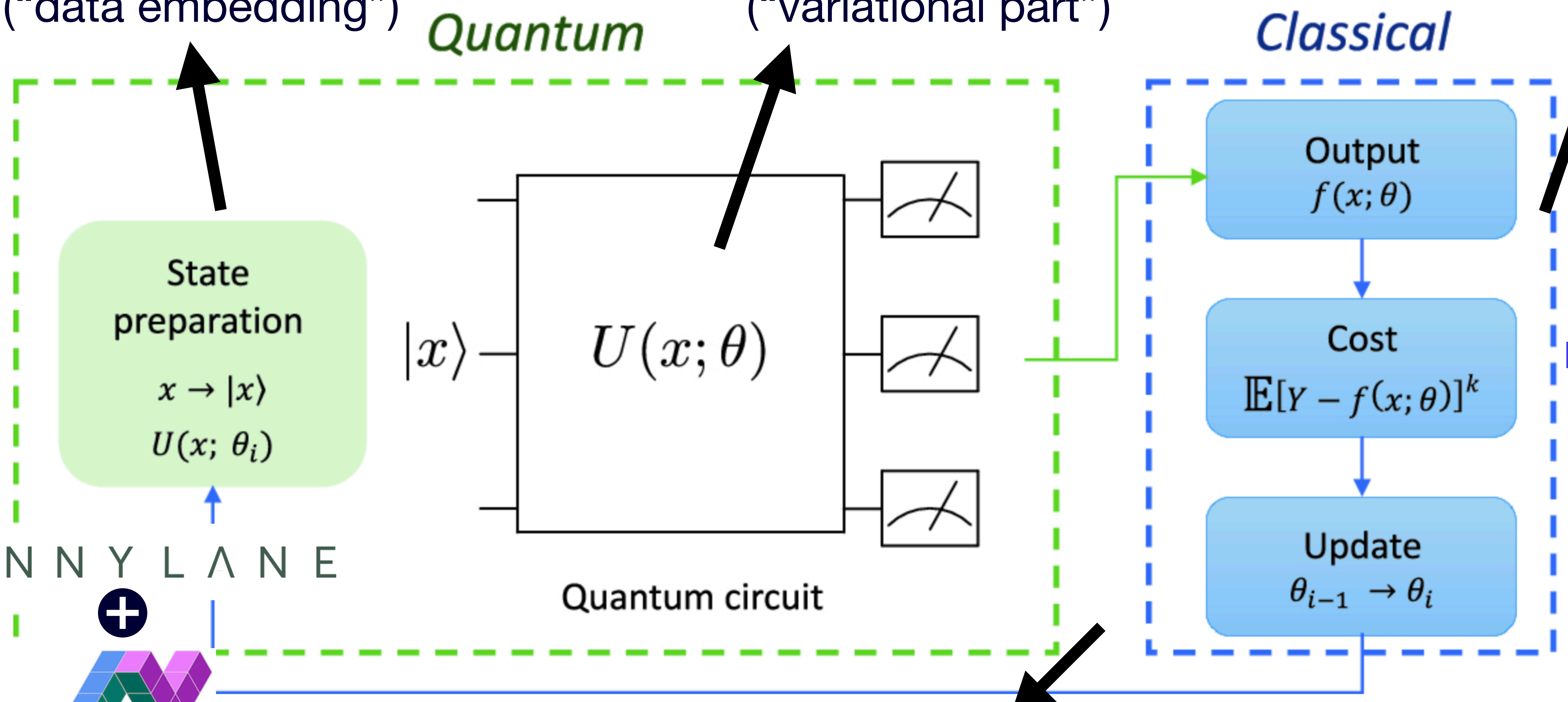

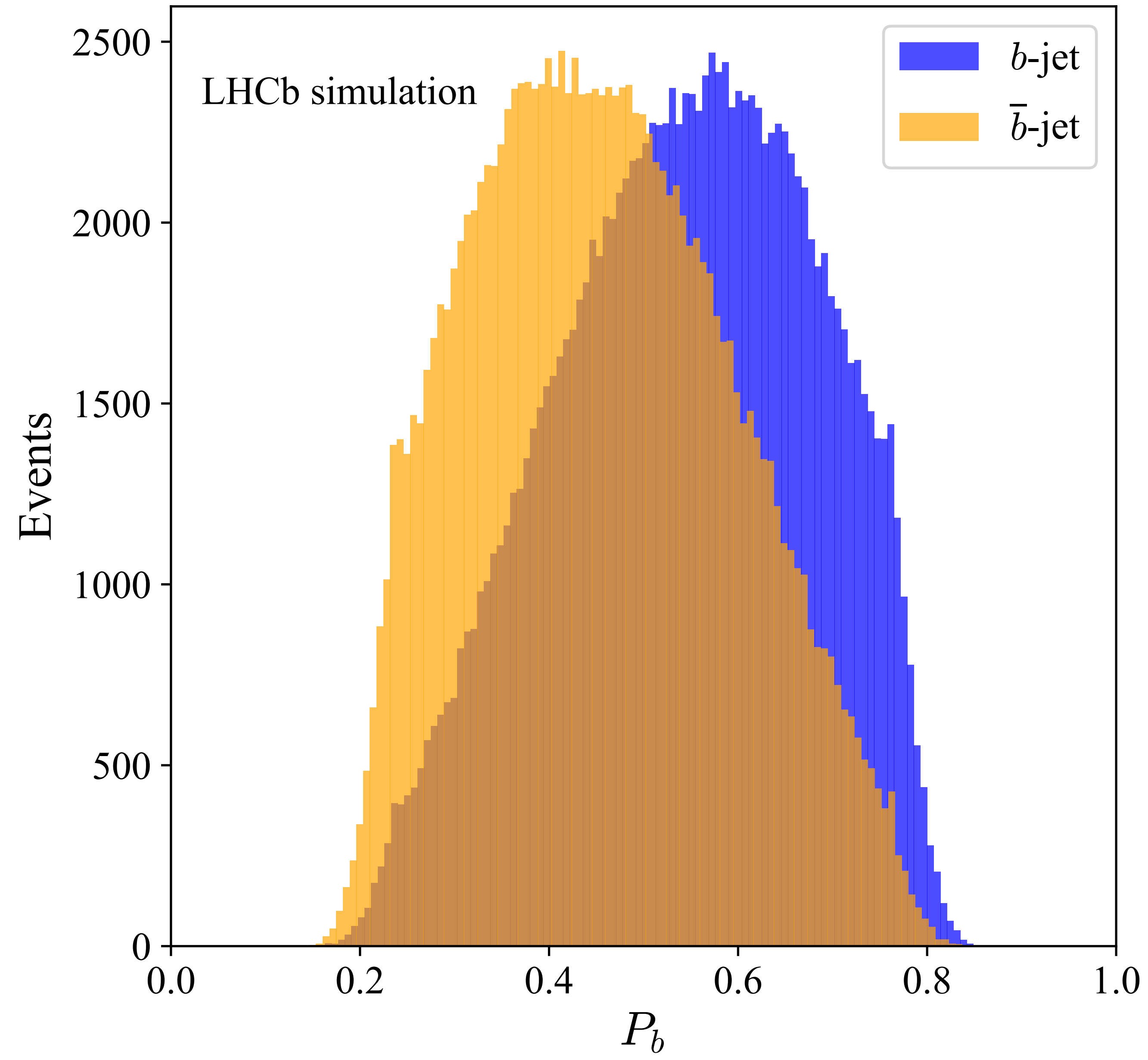

4 Perform a training on a sample of data by optimising circuit parameters

5 Get output distribution

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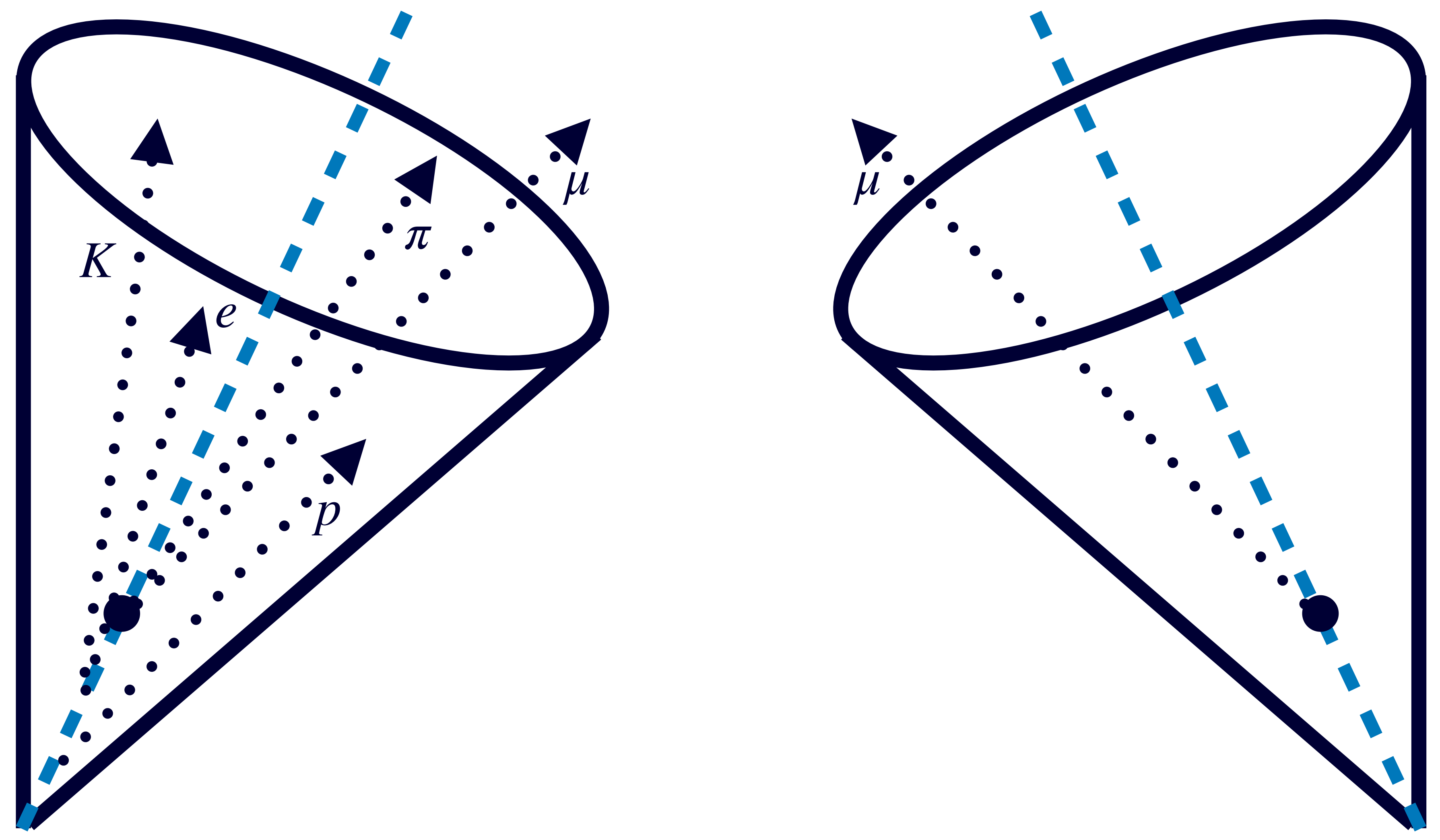
Application of QML at LHC

Algorithm description

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

Different sets of features



"complete" set of features
16 variables

"muon" set of features
$\mu + Q$ **= 4 variables**

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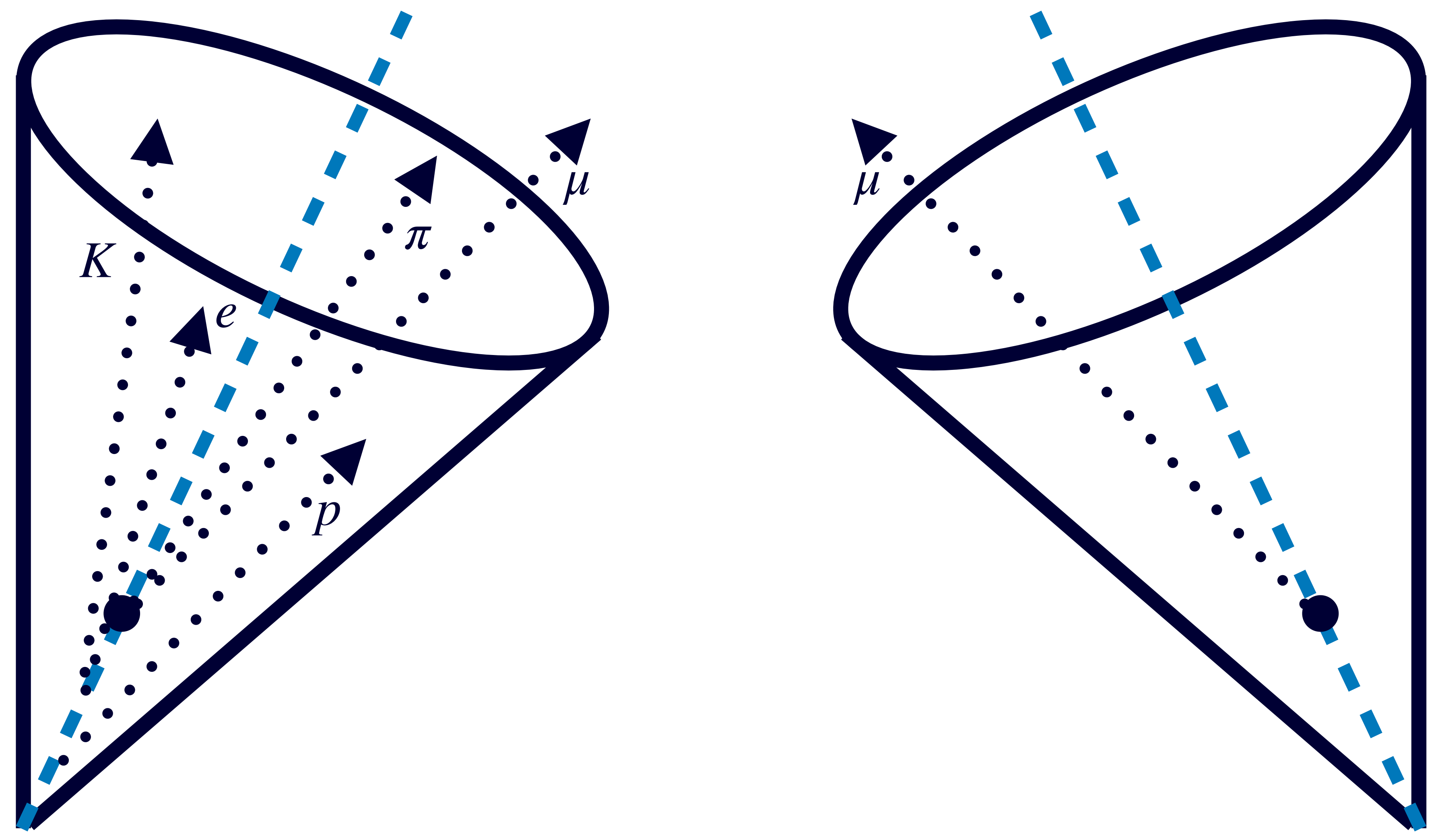

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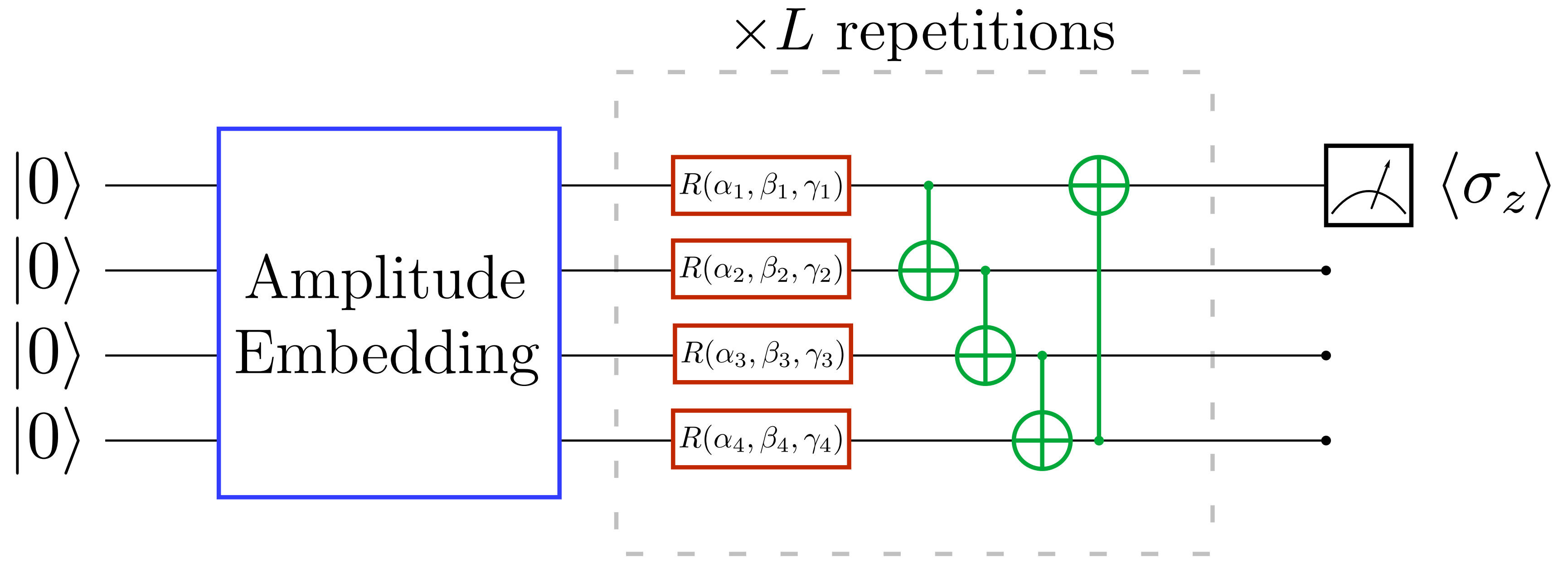
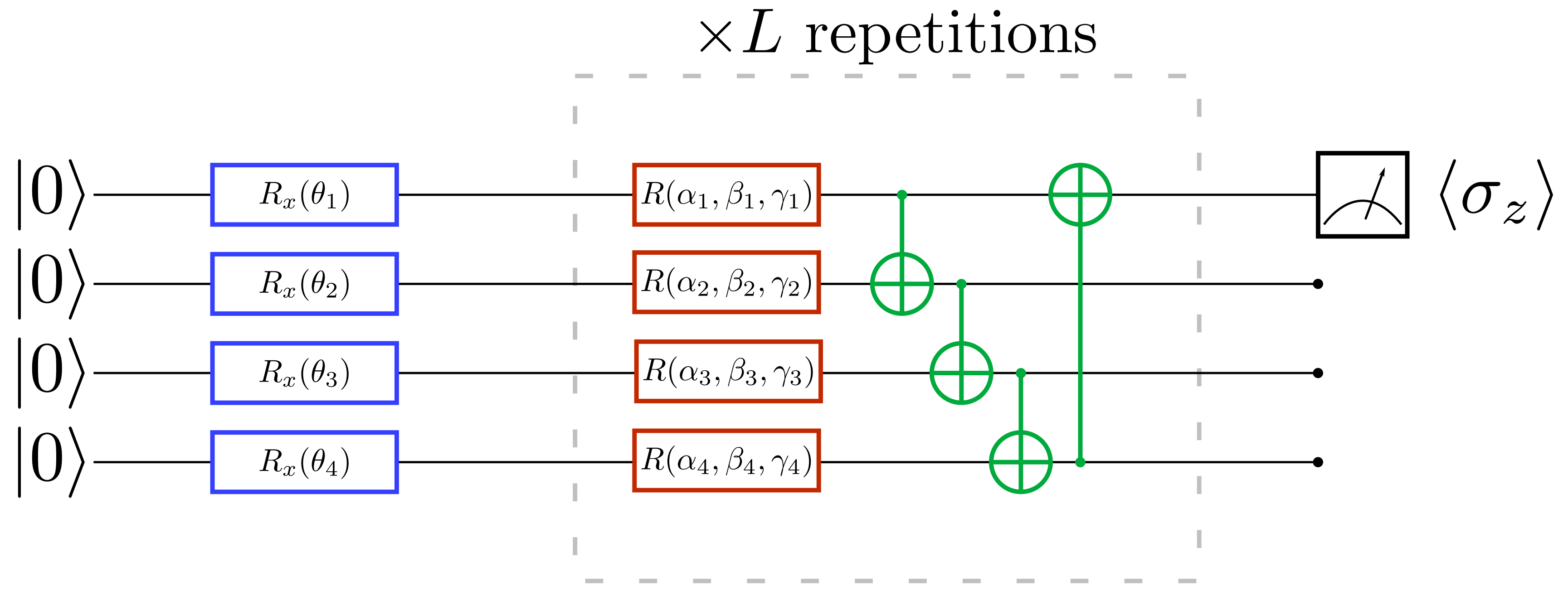
Different embedding circuits

Amplitude Embedding

$$|x\rangle = \sum_{i=1}^{2^n} x_i |n_i\rangle$$





Angle Embedding

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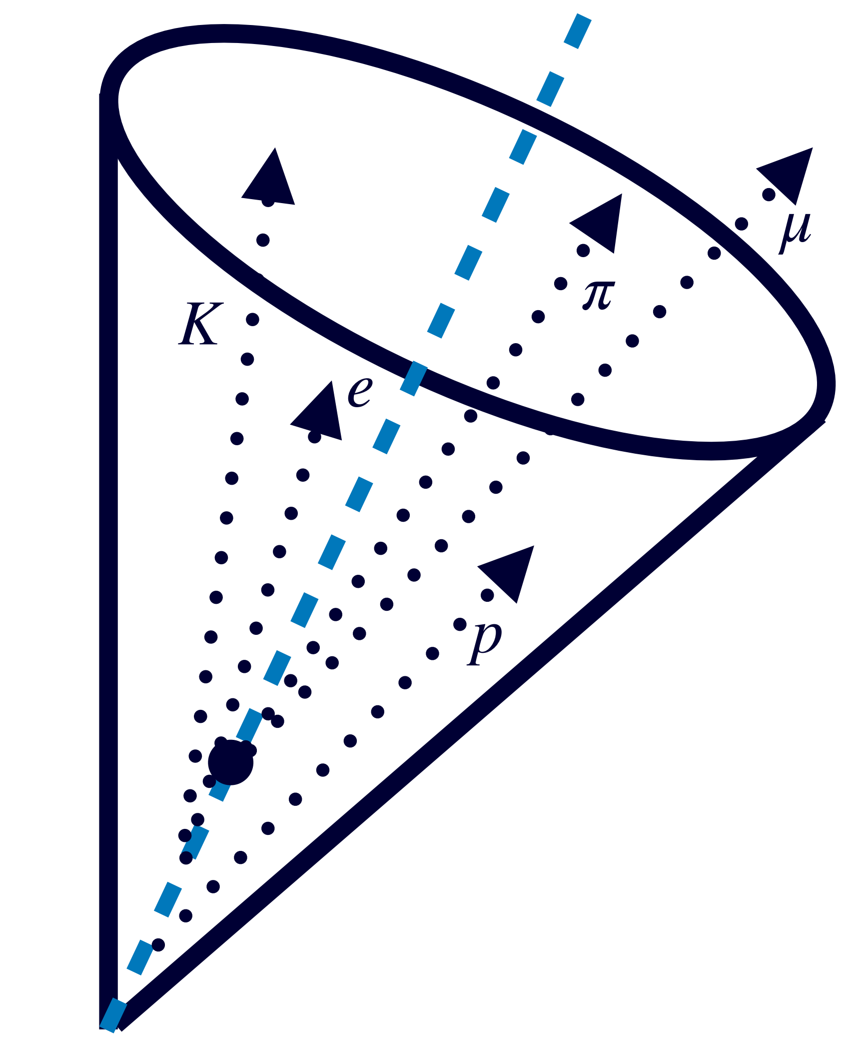

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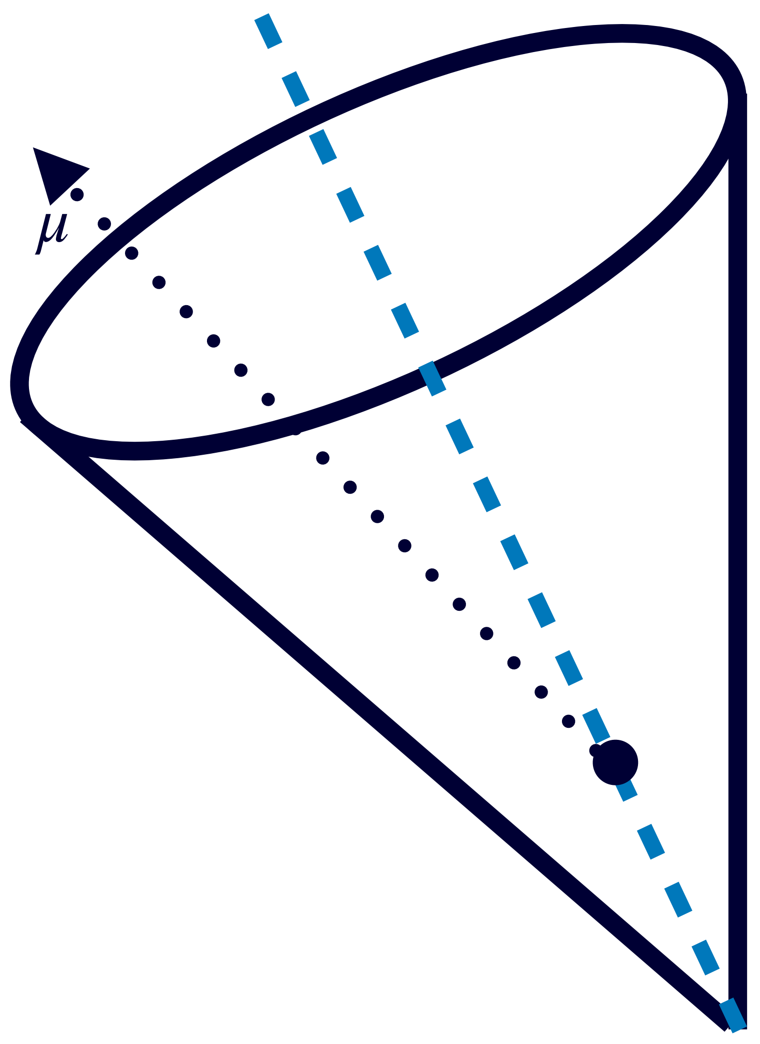

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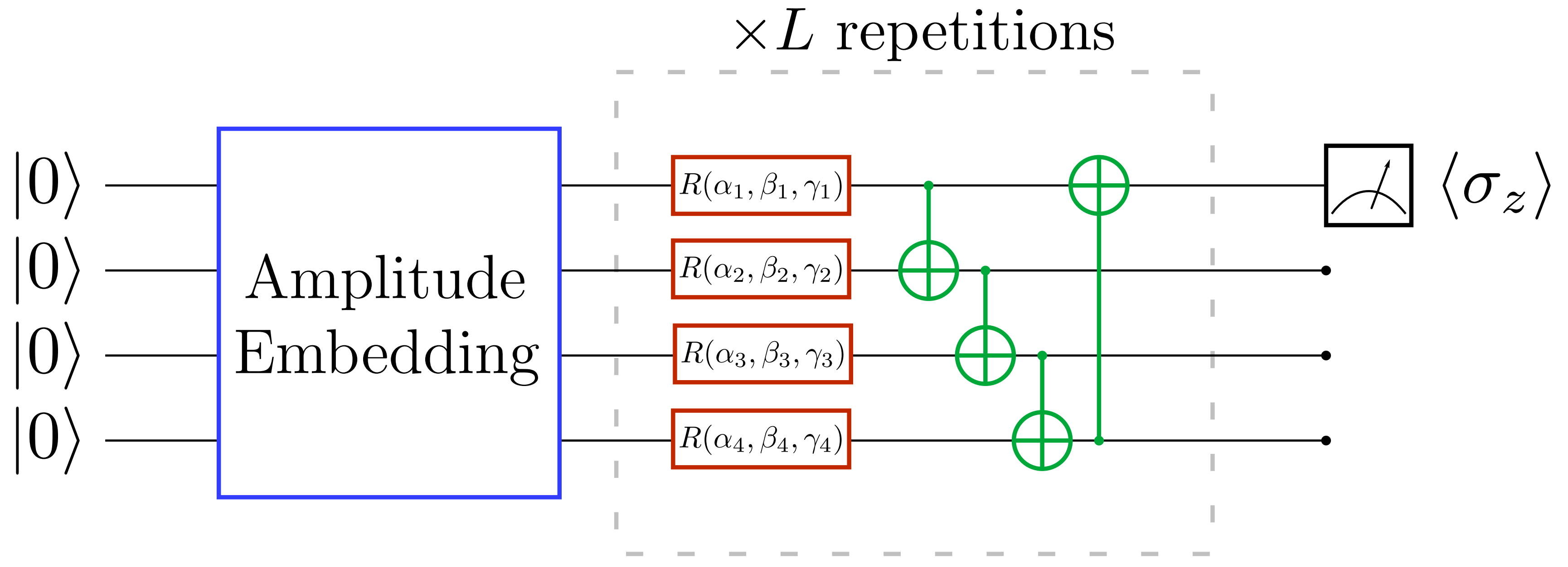

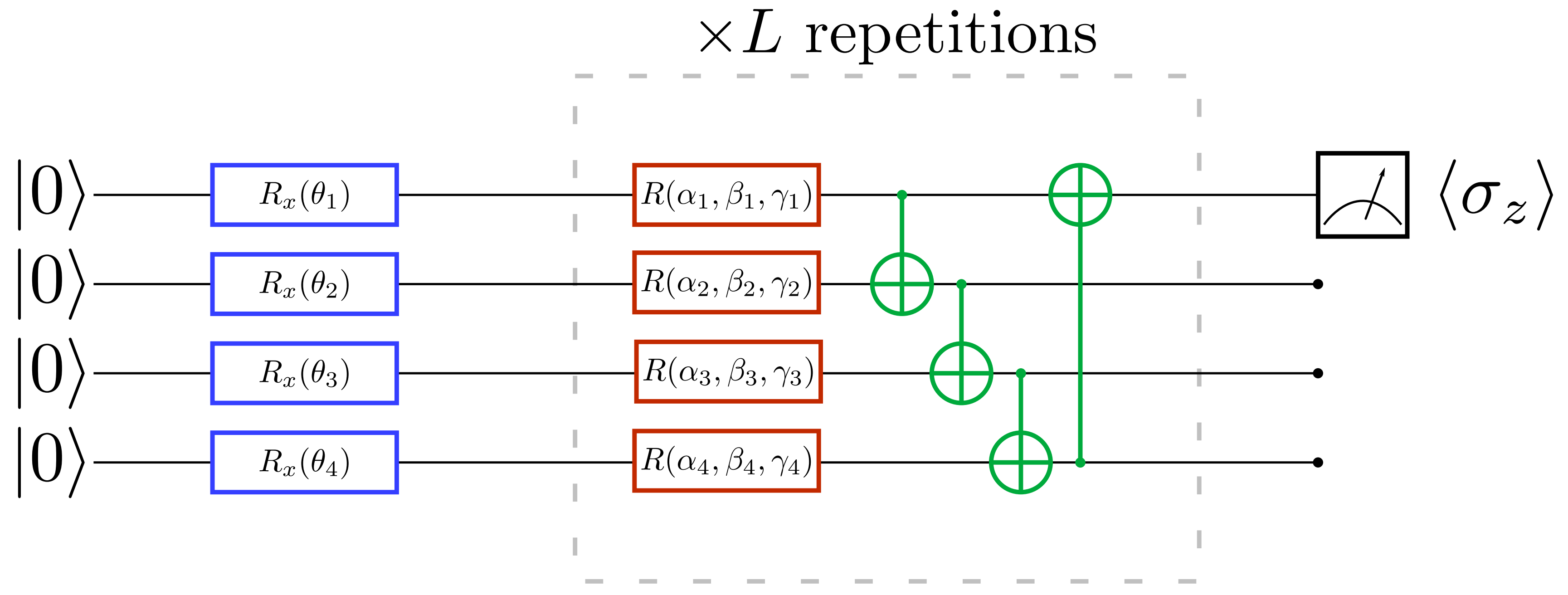

Angle Embedding

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

Application of QML at LHC

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Algorithm description

- A typical figure of merit for this kind of problems is the **tagging power**

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

$$\epsilon_{\text{eff}} = \text{efficiency} = \frac{\#\ \text{tagged jets}}{\#\ \text{jets}}$$

$$\omega = \text{mistag} = \frac{\#\ \text{wrongly tagged jets}}{\#\ \text{tagged jets}}$$

- It can be interpreted as the **effective fraction of correctly identified jets**, important for **asymmetry measurements**:

$$\sigma \propto \frac{1}{1 - 2\omega}$$

where σ = statistical uncertainty

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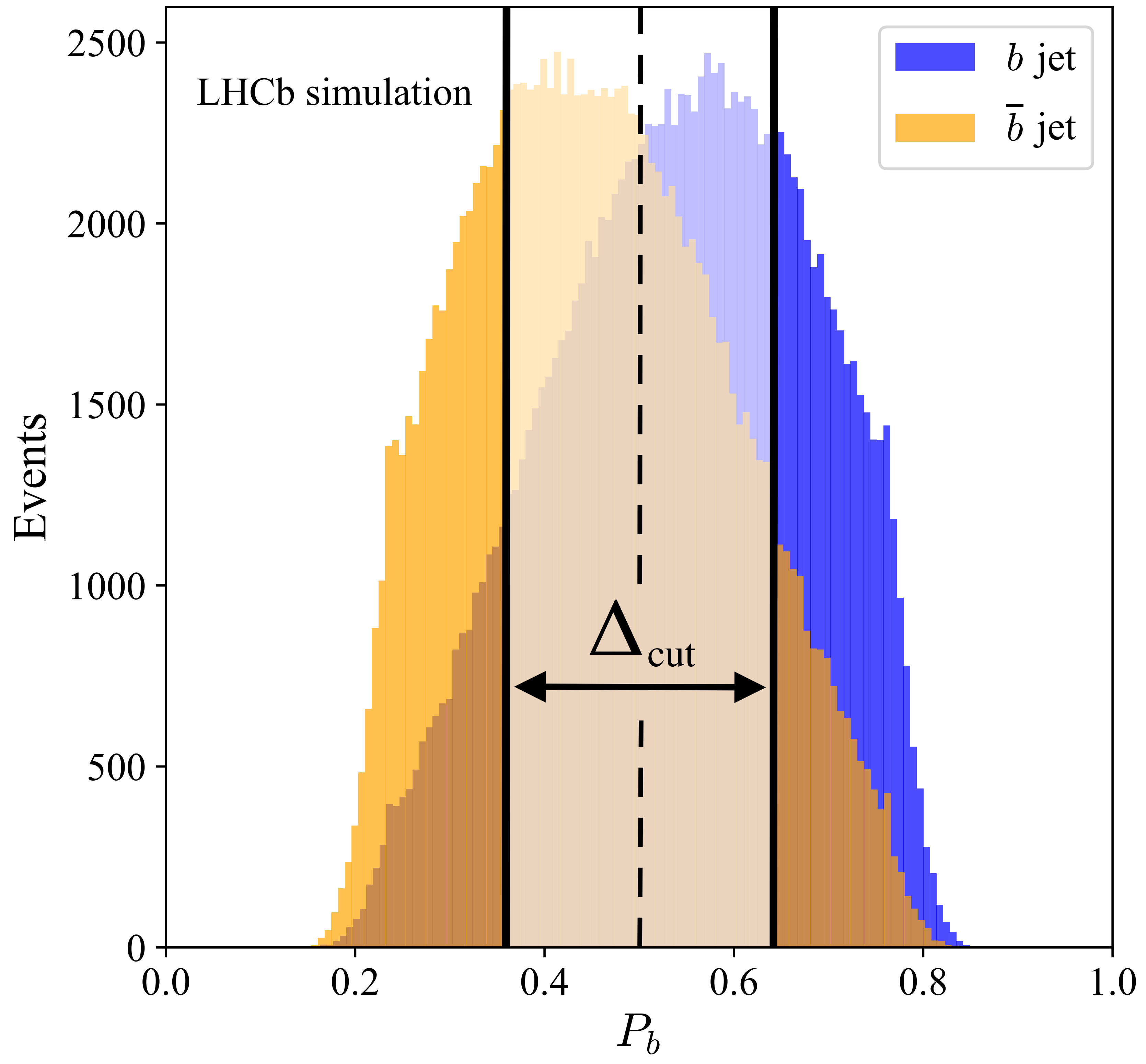

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- It can be interpreted as the **effective fraction of correctly identified jets**, important for **asymmetry measurements**:

$$\sigma \propto \frac{1}{1-2\omega}$$ where σ = statistical uncertainty

- **Optimised cut** Δ_{cut} over output distribution: reduce efficiency but also reduce mistag, therefore **increasing tagging power**

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

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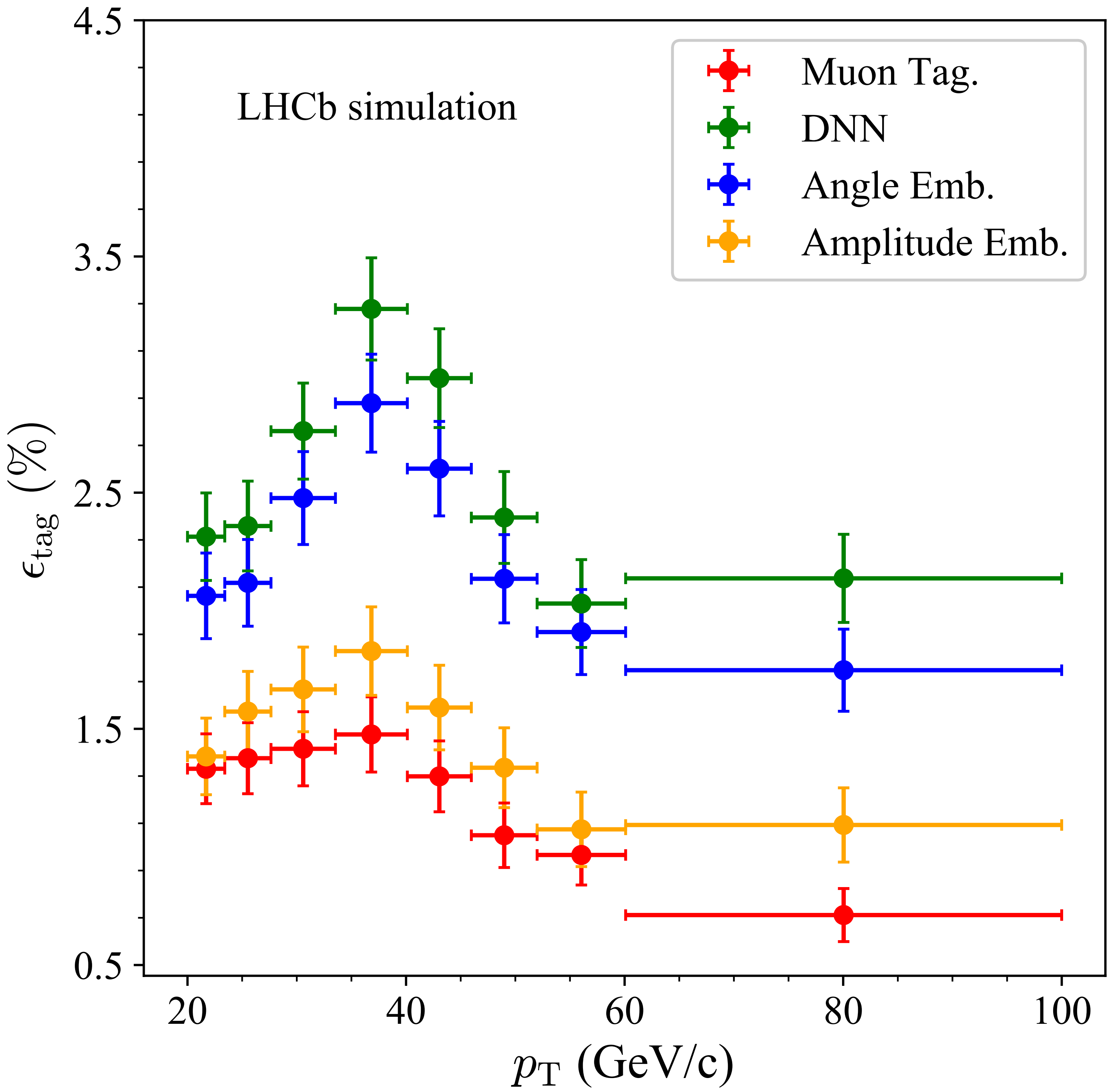
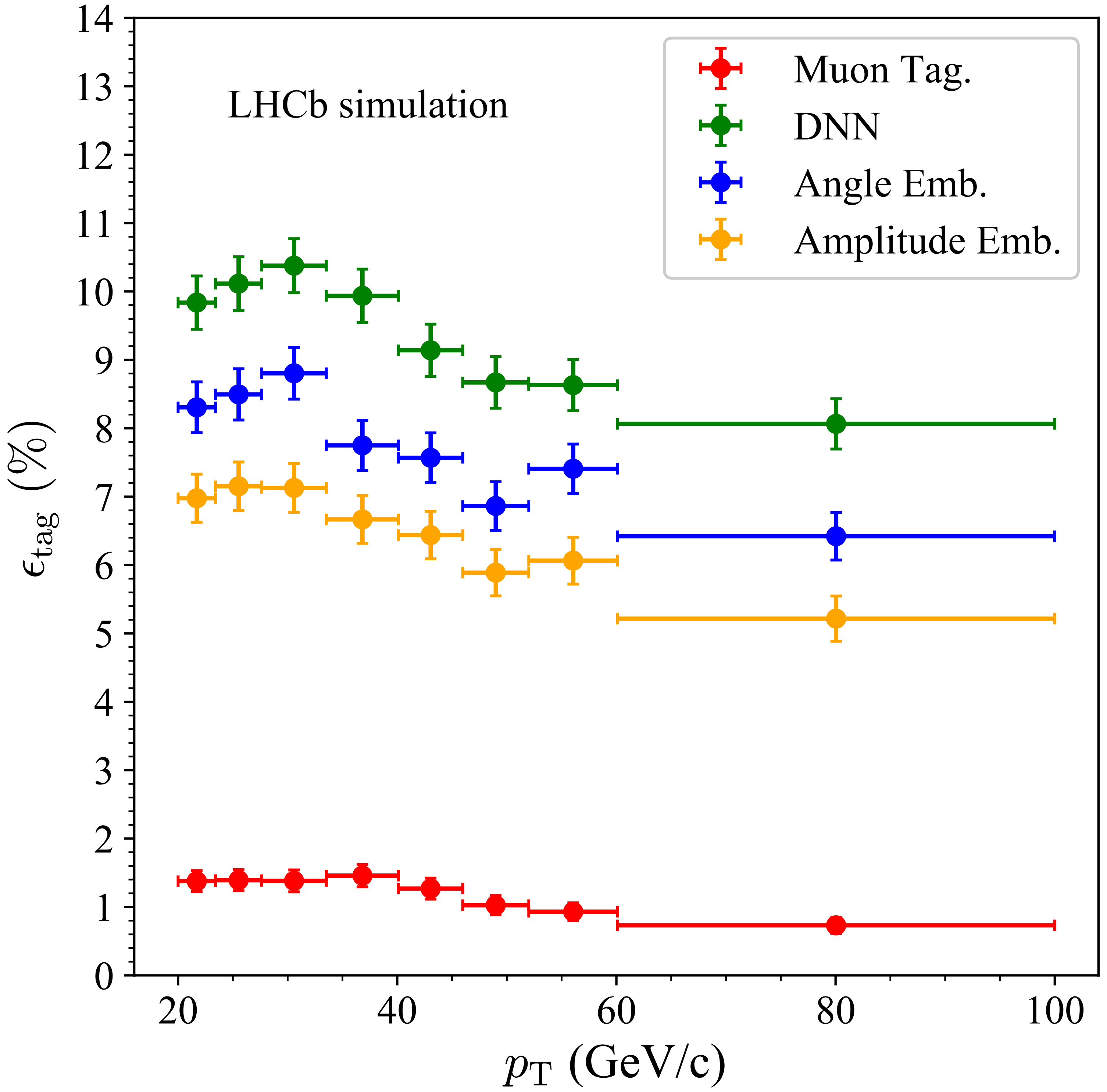
Application of QML at LHC

Results for tagging power

“muon” set of features





“complete” set of features

- For muon dataset (up to 4 qubits), Angle Embedding circuit is **comparable to DNN**, Amplitude Embedding not performing as good
- For complete dataset (up to 16 qubits), **QML performs slightly worse than DNN**

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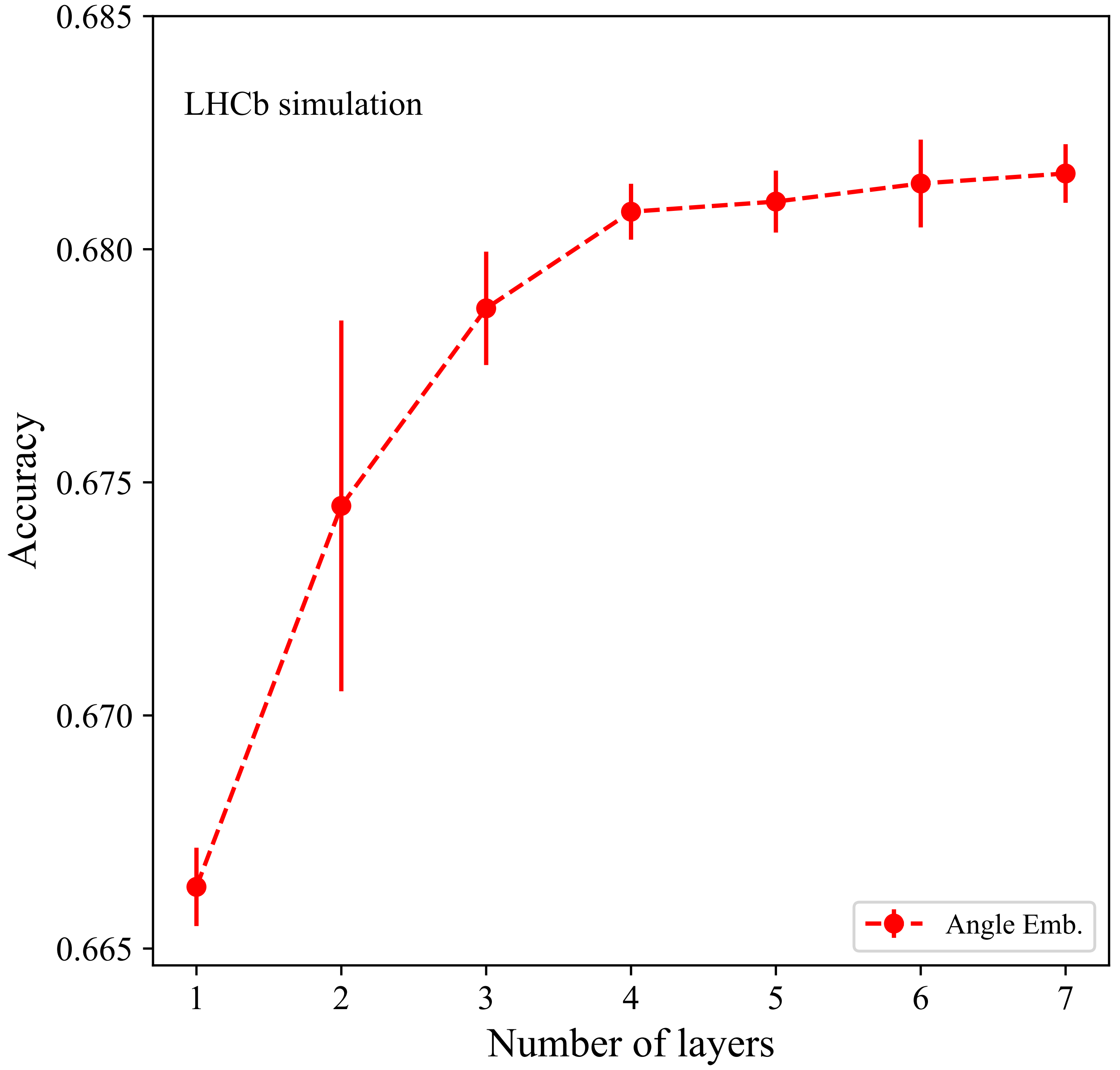
Application of QML at LHC

Other results for 4 qubits circuit (muon set of features)

number of variational layers



- Accuracy saturates after 5/6 variational layers
- A **trade-off** between performance and complexity

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Application of QML at LHC

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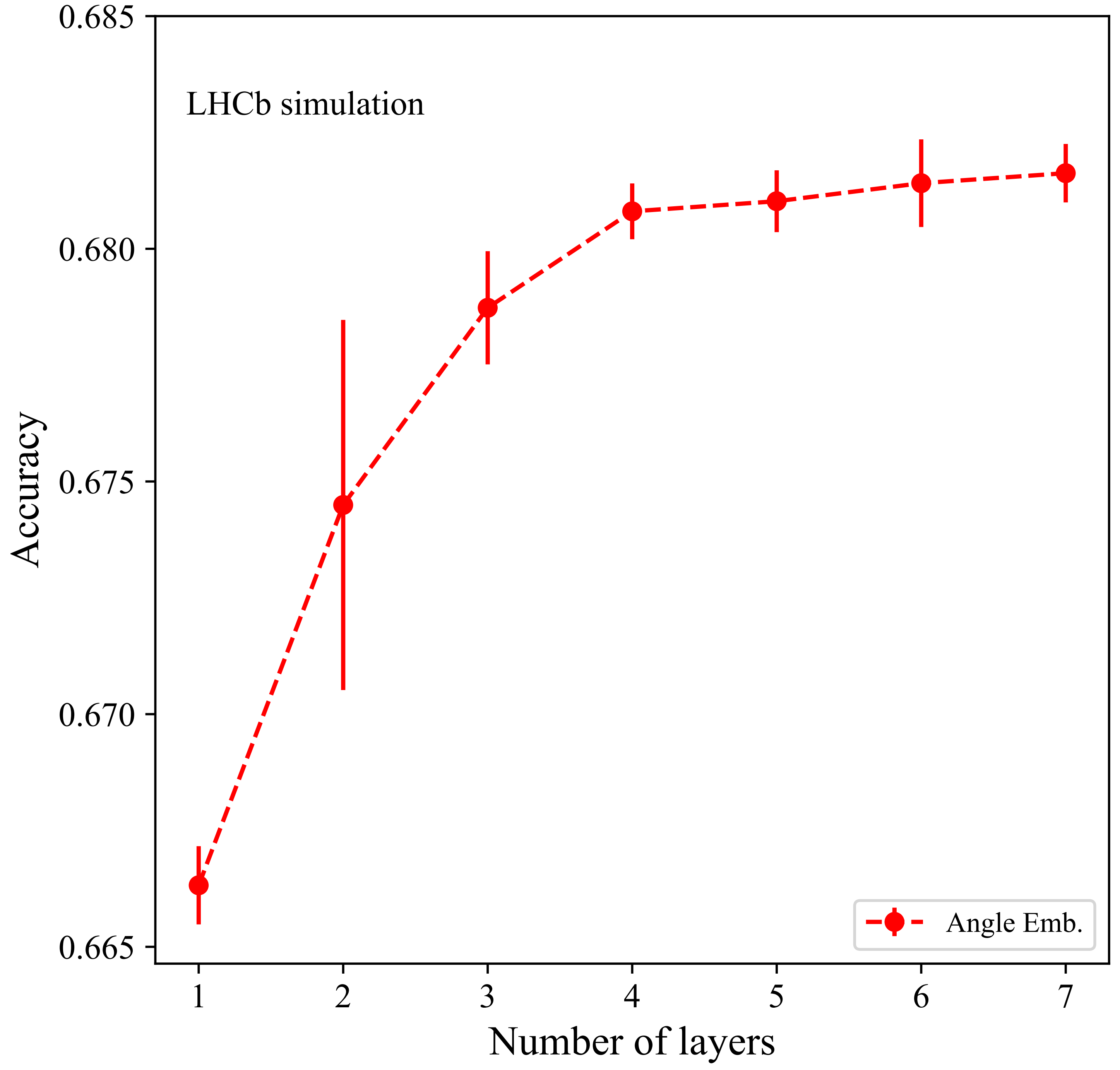
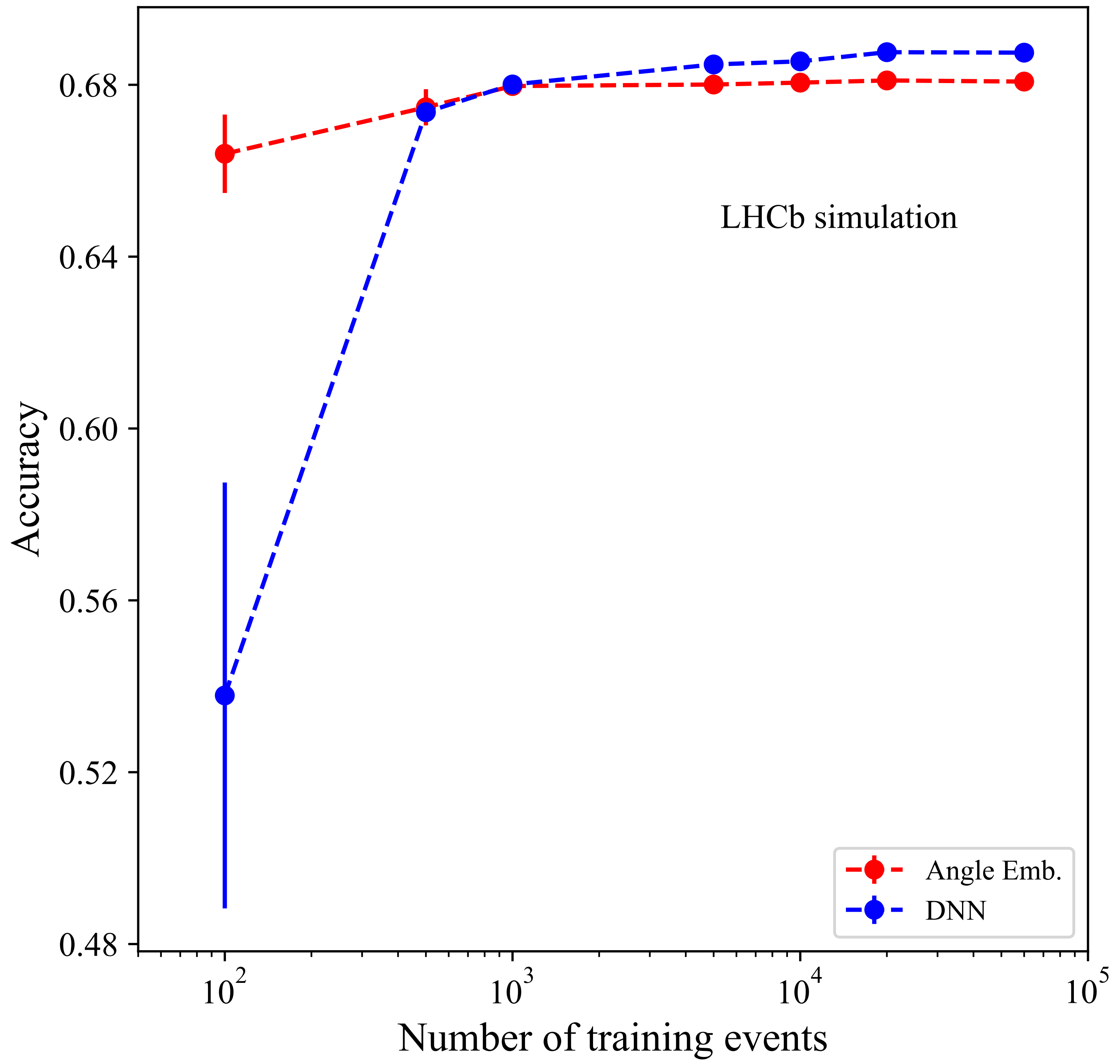


number of training events



- Accuracy saturates after 5/6 variational layers
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- For a low number of training events, the Angle Embedding **performs better** than the DNN

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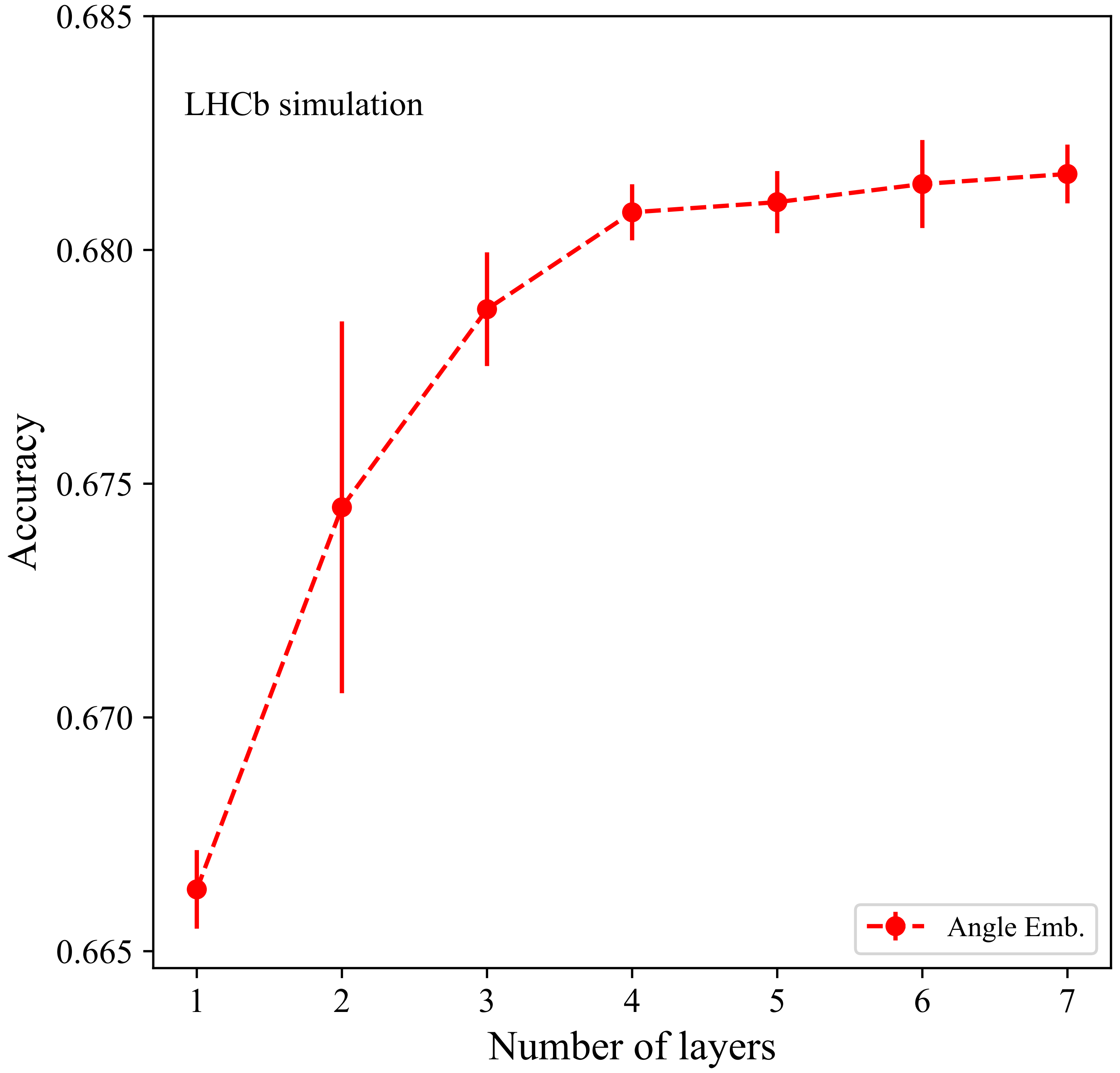

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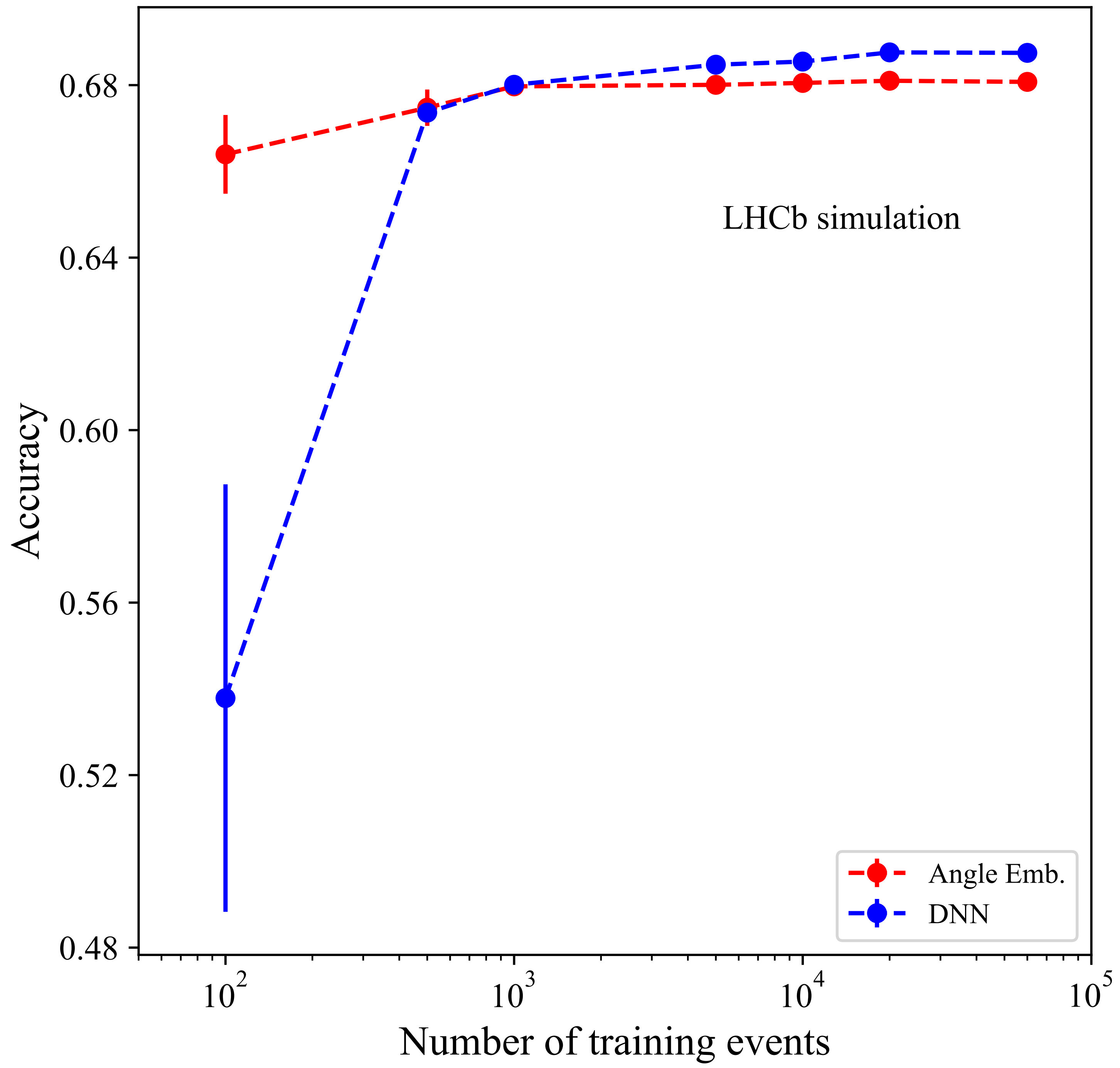

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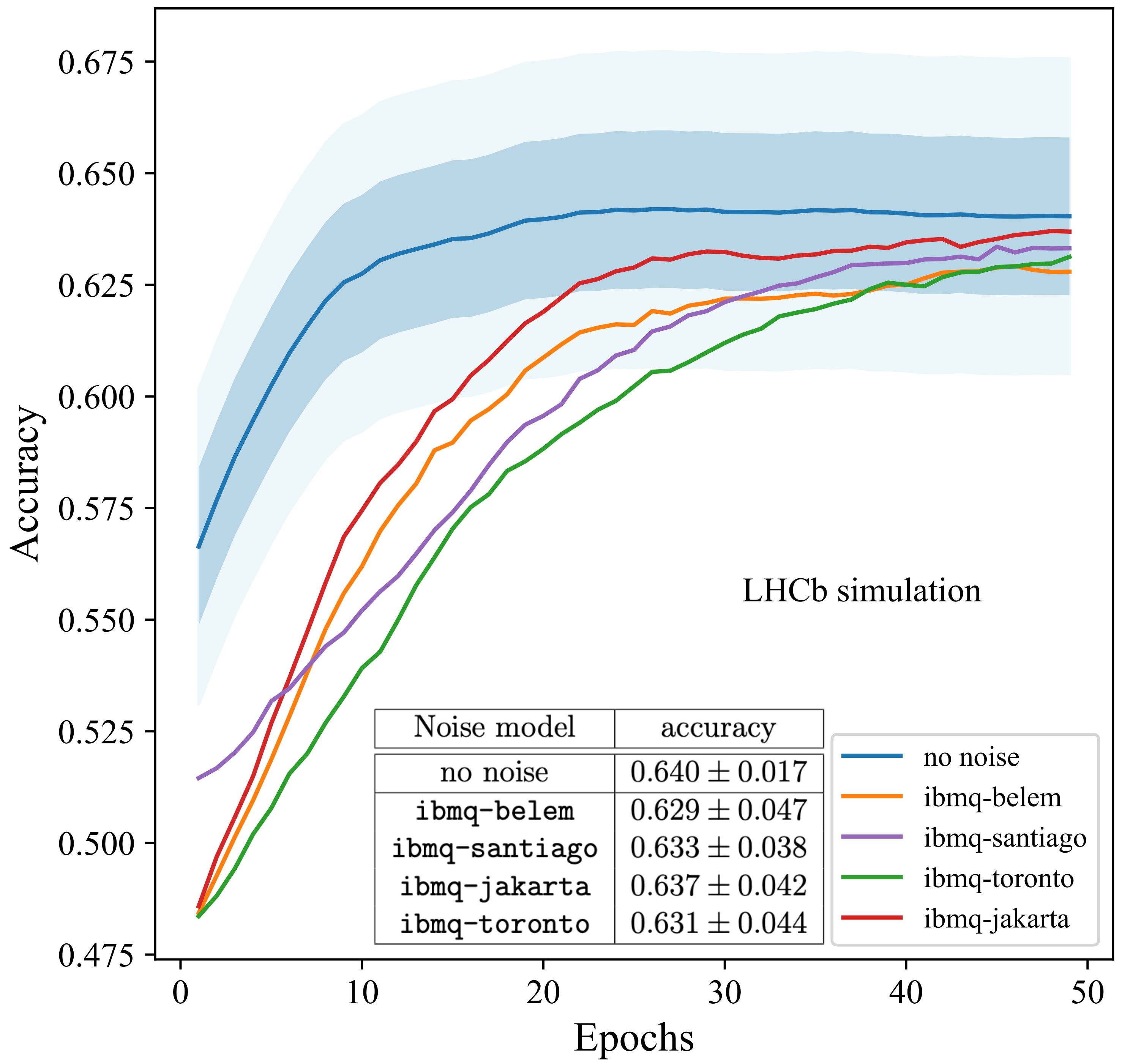
noise contribution



- Simulate noise contribution from several IBM backends
- **Simpler structures are robust to noise**

Future studies and ideas

What to expect in the next months

tests on hardware preliminary

MODEL4f 3Layers	Accuracy	AUC ROC	Secs. x jet	
Simulator	0.78	0.82	0.01	
Manila Opt 2 Shots 1024	0.74	0.79	0.12	MANILA 5 Qubits 32 QV 2.8K CLOPS Processor type: Falcon r5.11L
Manila Opt 2 Shots 10240	0.75	0.80	0.97	
Oslo Opt 2 Shots 1024	0.69	0.74	0.12	OSLO 7 Qubits 32 QV 2.6K CLOPS Processor type: Falcon r5.11H
Oslo Opt 2 Shots 10240	0.69	0.74	0.96	
Oslo Opt 2 Shots 1024 Mitigated	0.72	0.74	0.12	
Oslo Opt 3 Shots 1024	0.65	0.69	0.12	
Nairobi Opt 2 Shots 1024	0.57	0.59	0.13	NAIROBI 7 Qubits 32 QV 2.6K CLOPS Processor type: Falcon r5.11H
Nairobi Opt 3 Shots 1024	0.72	0.77	0.12	

- Several tests on different IBM machines
- Transpiling and error mitigation studies
- **Preliminary performance similar to simulations**

MORE IN THE FUTURE...

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tests on hardware **preliminary**

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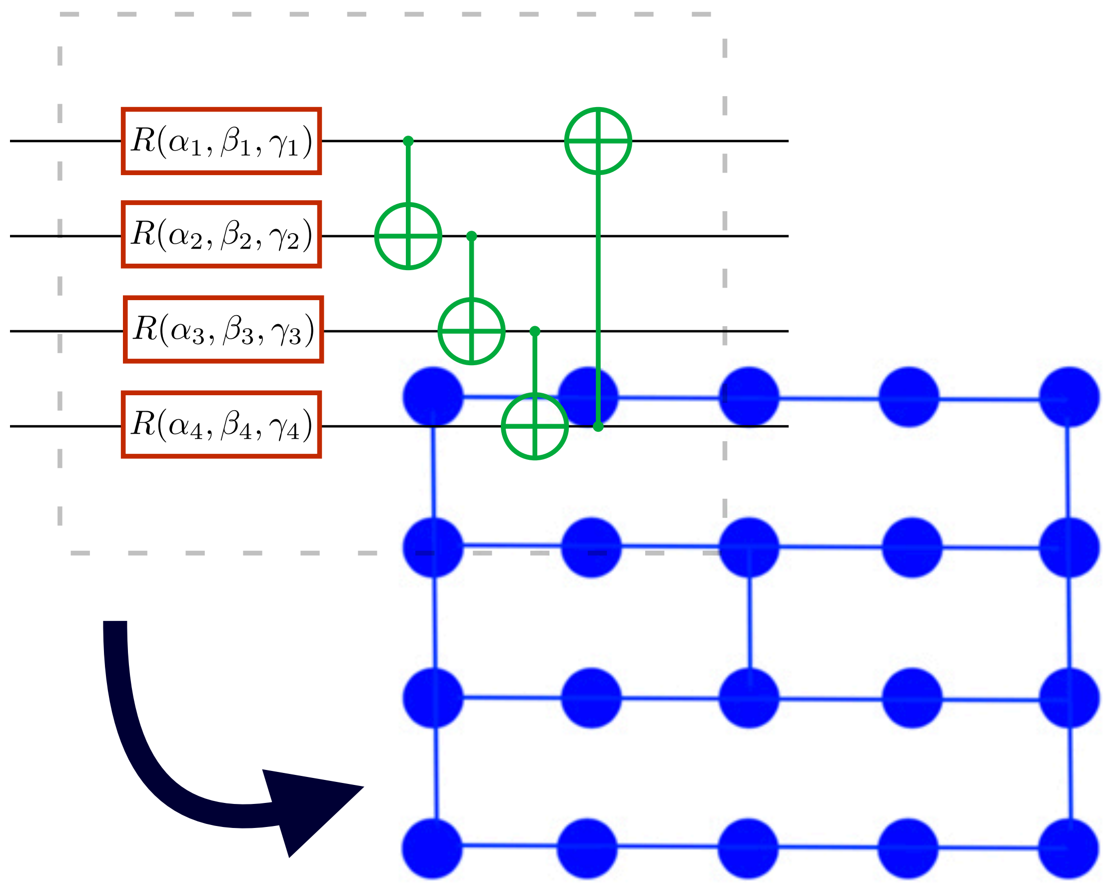
intelligent circuit design



- Can't scale up to many layers
- Is there a clever way to build our circuit?
- **Quantum TTN** show interesting features in this sense

MORE IN THE FUTURE...

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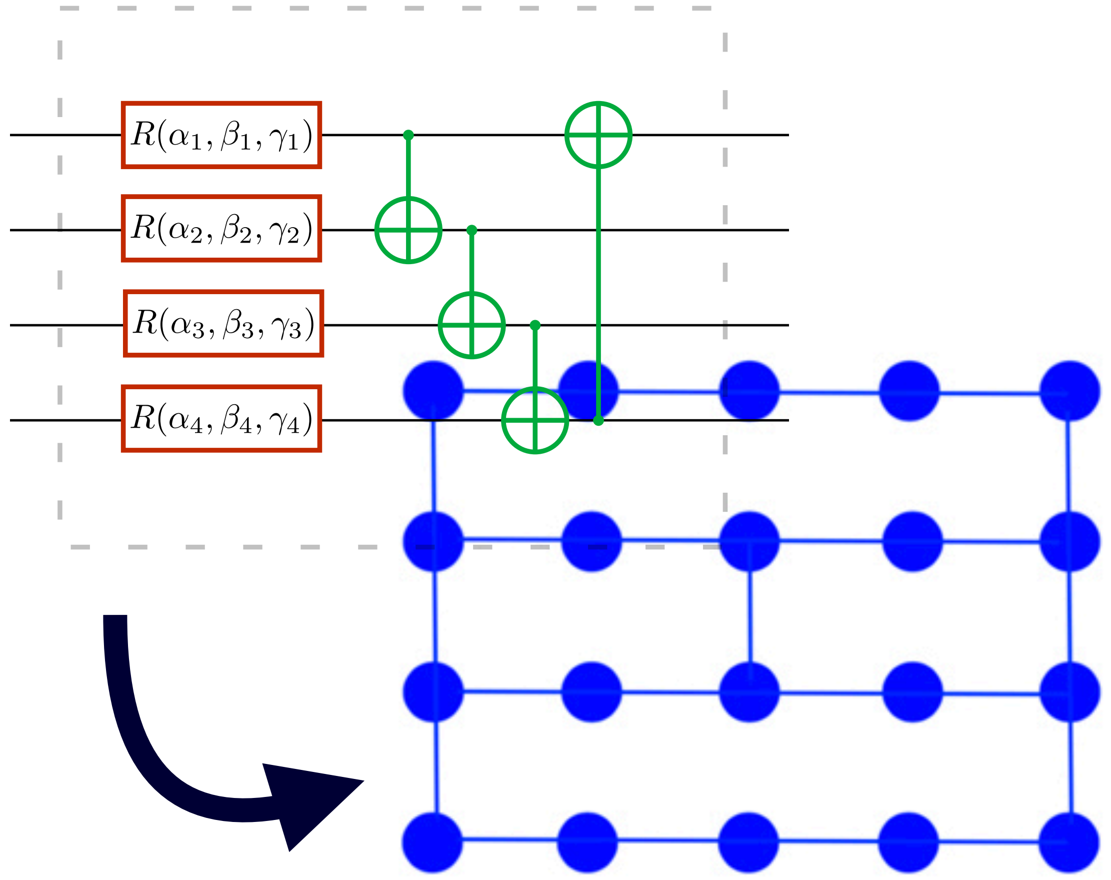
intelligent circuit design



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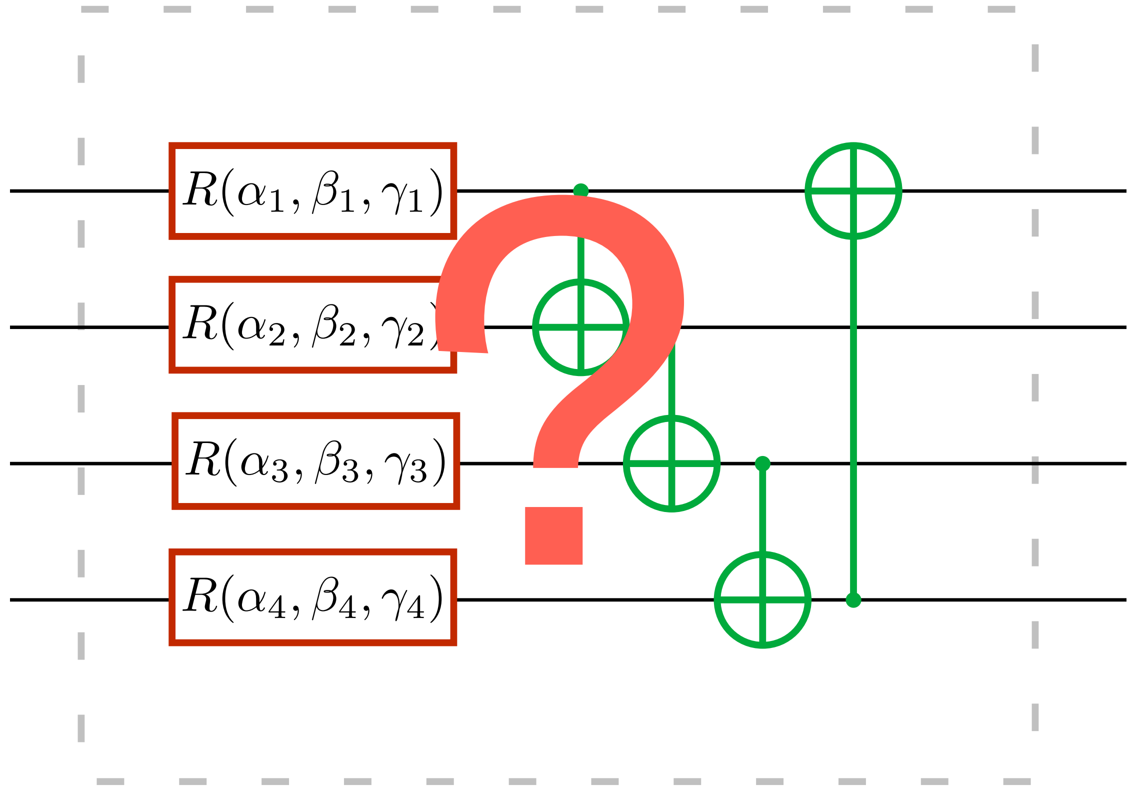
correlations between qubits



- What (and where) is the quantum advantage?
- Can we measure **correlations** between qubits?
- How to use this information?

MORE IN THE FUTURE…

Overview of INFN activities

- INFN is deeply involved in **many QC activities for HEP**

CERN welcomes INFN and IIT as new members of its IBM Quantum Network hub

15 JULY, 2022 **RATHER NEW!**

SQMS

- Ongoing projects in different areas of interest and expertise

SIMULATION AND THEORY — SEE TALK BY A. ROGGERO

QUANTUM COMPUTING ALGORITHMS

QUANTUM SENSING AND COMMUNICATION — SEE TALK BY C. BRAGGIO

- Early involvement already in 2018 (**QT @ INFN**)
- INFN is also part of the **QuantERA programme**

QUANTERA

The European Physics Journal D 74, 165 (2020)
Nature Communications 12, 3600 (2021)

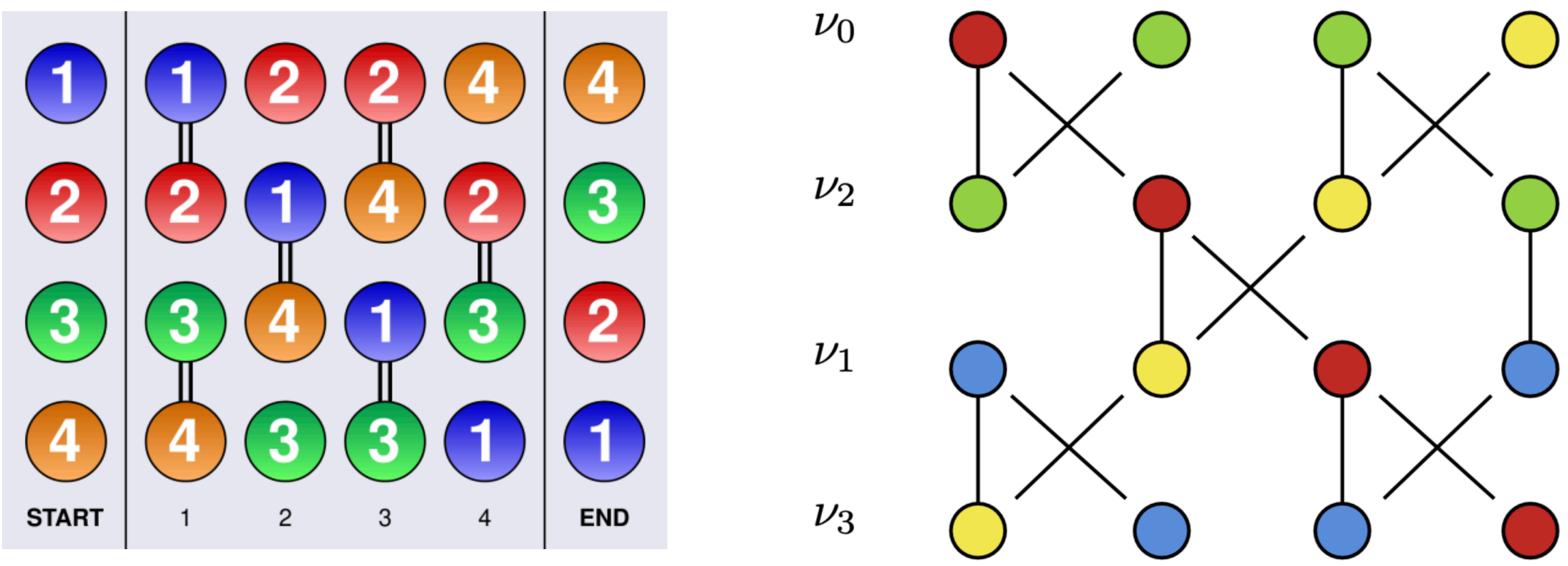
Overview of INFN activities

Simulation and theory

- Describe N interacting neutrinos with Hamiltonian by means of quantum simulations

$$H = \sum_i \frac{\Delta m^2}{4E_i}\vec{B}\cdot\vec{\sigma}_i + \lambda\sum_i \sigma_i^z + \frac{\mu}{2N}\sum_{i<j}(1-\cos(\phi_{ij}))\vec{\sigma}_i\cdot\vec{\sigma}_j$$

- Simulate one- and two-body interactions with SWAP network



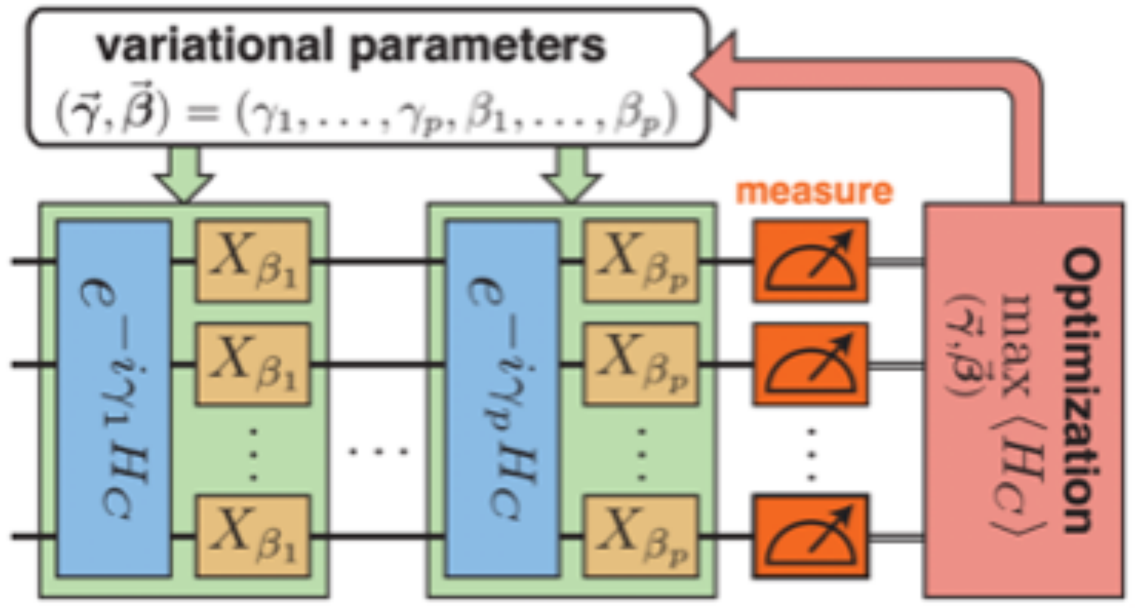
- Recent progress using trapped ions with all-to-all connectivity show very low infidelities

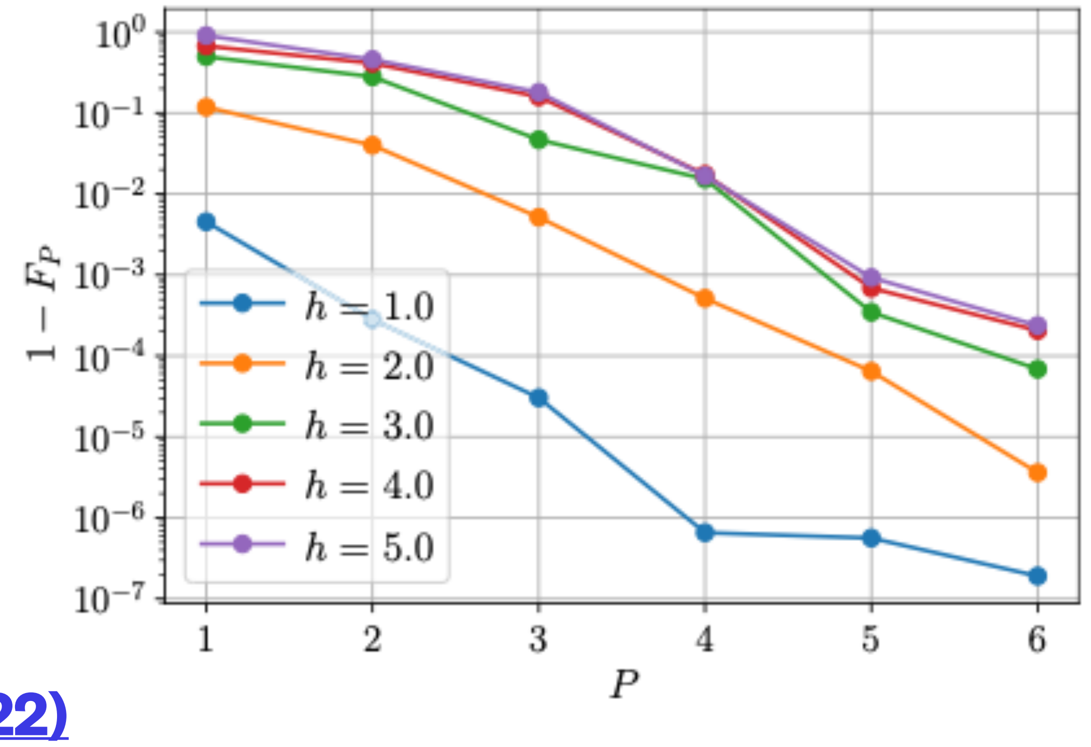
by V. Amitrano et al., arXiv:2207.03189 (2022)

- Quantum simulation of lattice gauge models on a real quantum computer
- Overcome old idea of classical approximation and numerical methods

High Energy Quantum Field Theory ⟷ Quantum Many Body Model on a Lattice

- Recent results on a near-term quantum simulator



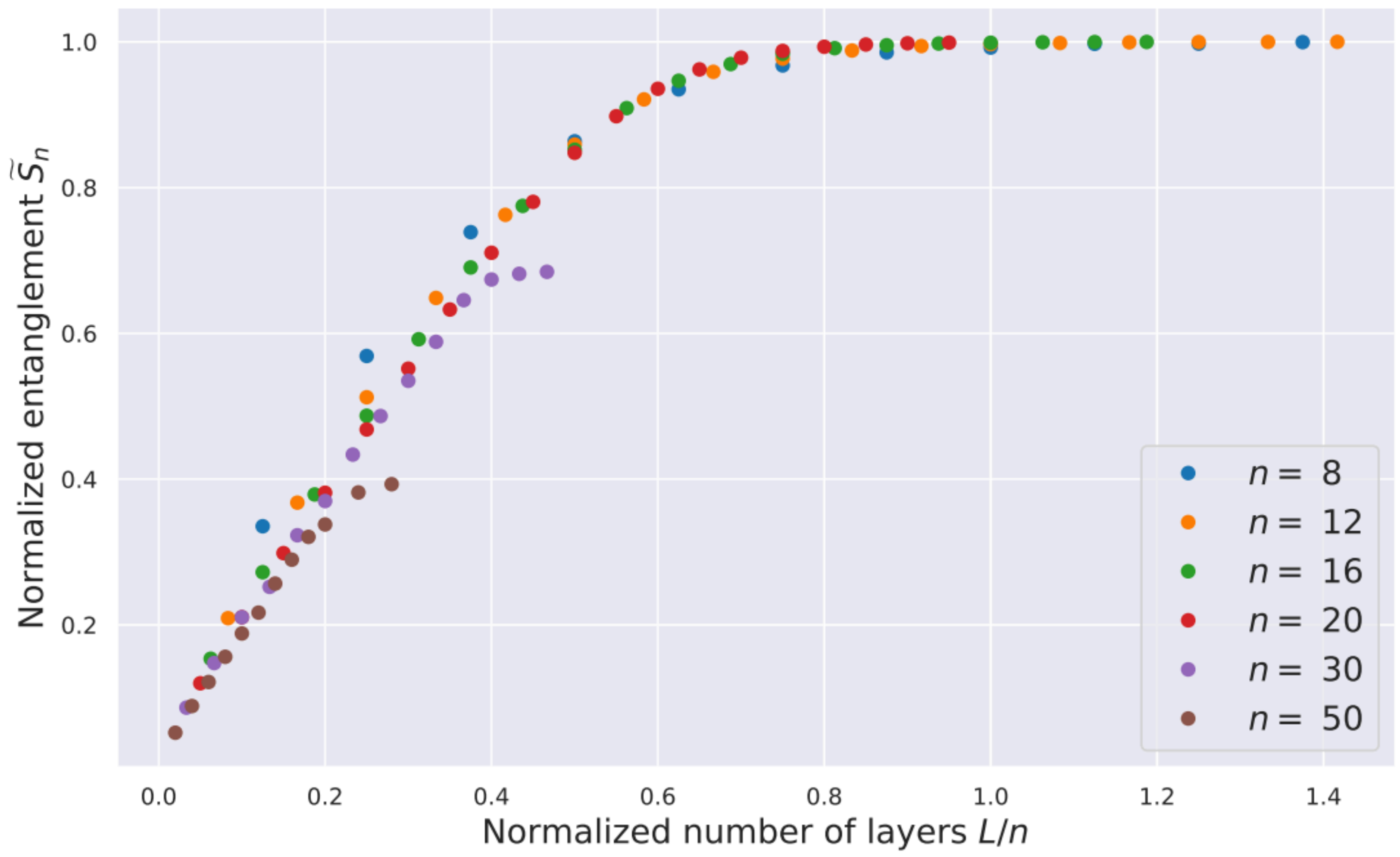


by L. Lumia et al., PRX Quantum 3, 020320 (2022)

Overview of INFN activities

Simulation and theory

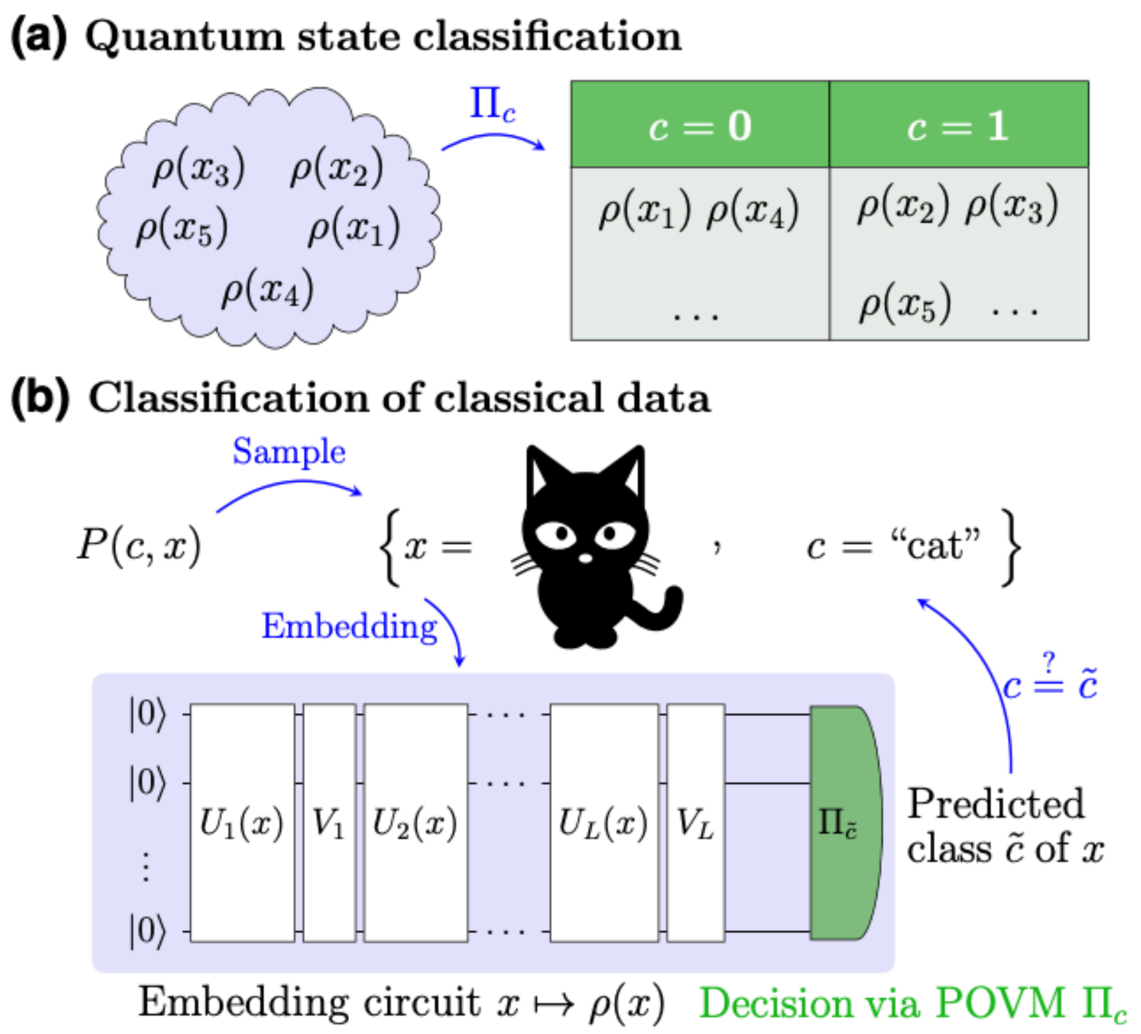
- **Entanglement entropy production in QNN**
- QNN characterisation by means of Tensor Networks tools

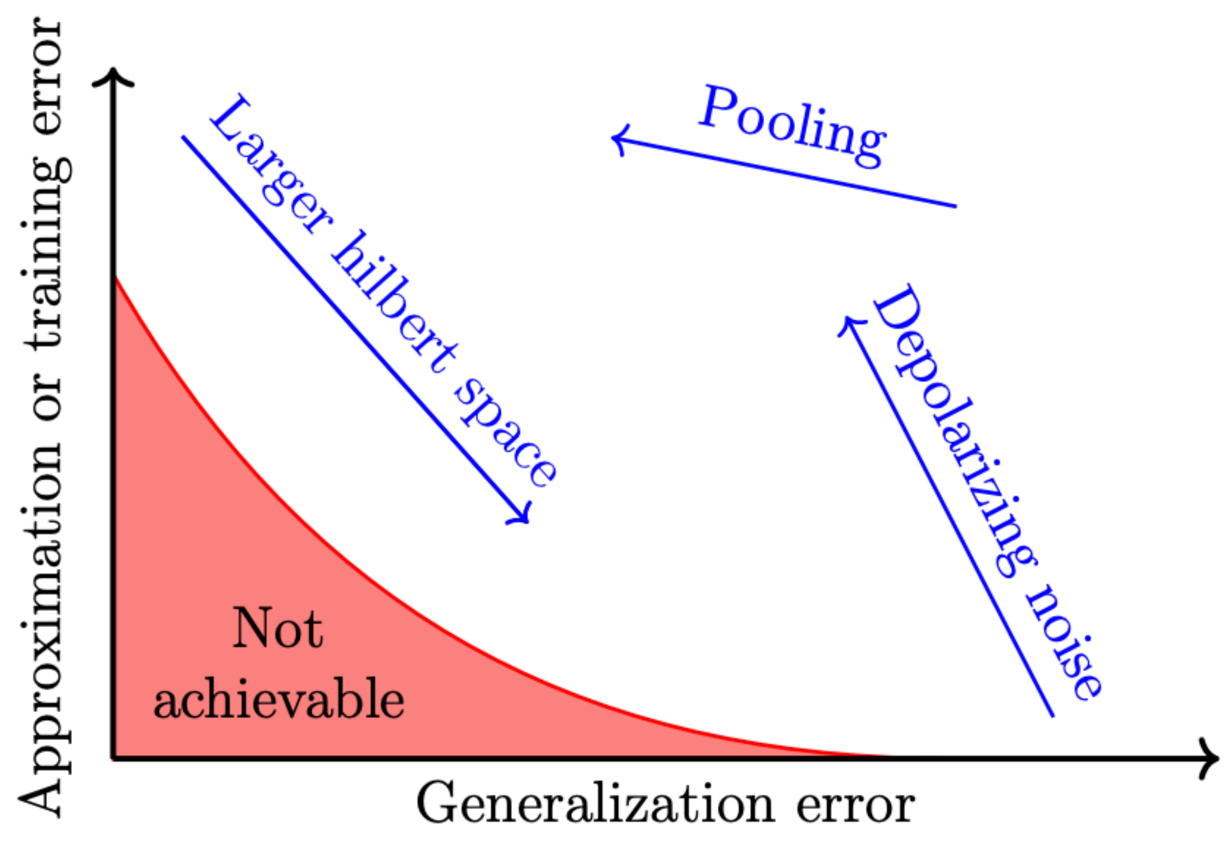


- The most promising regime for quantum advantage is a **trade-off** between high **entanglement** and **expressibility**

by M.Ballarin et al., arXiv:2206.02474

- **Study generalisation in QML**
- Quantify the generalisation and approximation capability of QML classification problems





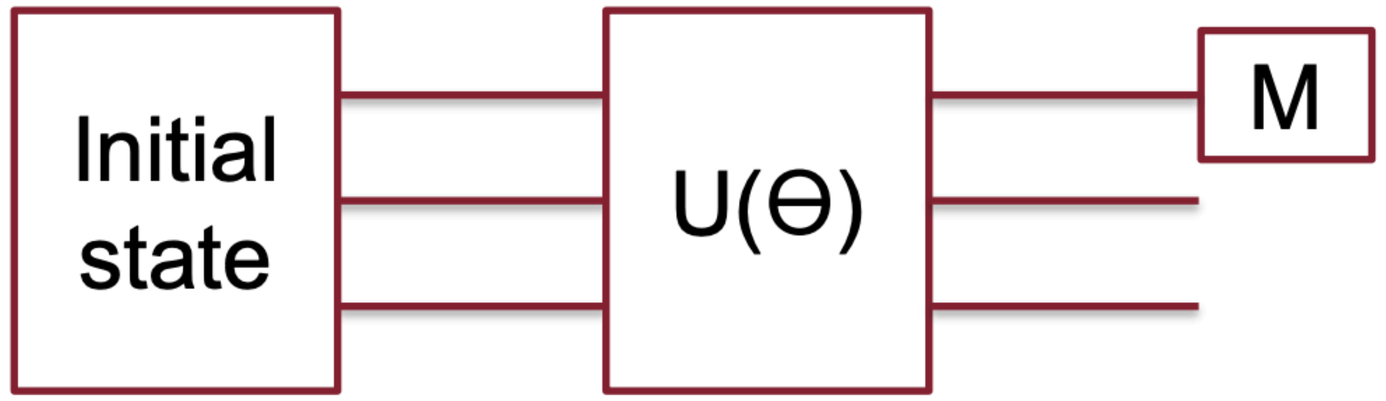
- Analysis can be applied to models of moderate complexity

by L.Banchi et al., PRX Quantum 2.040321 (2021)

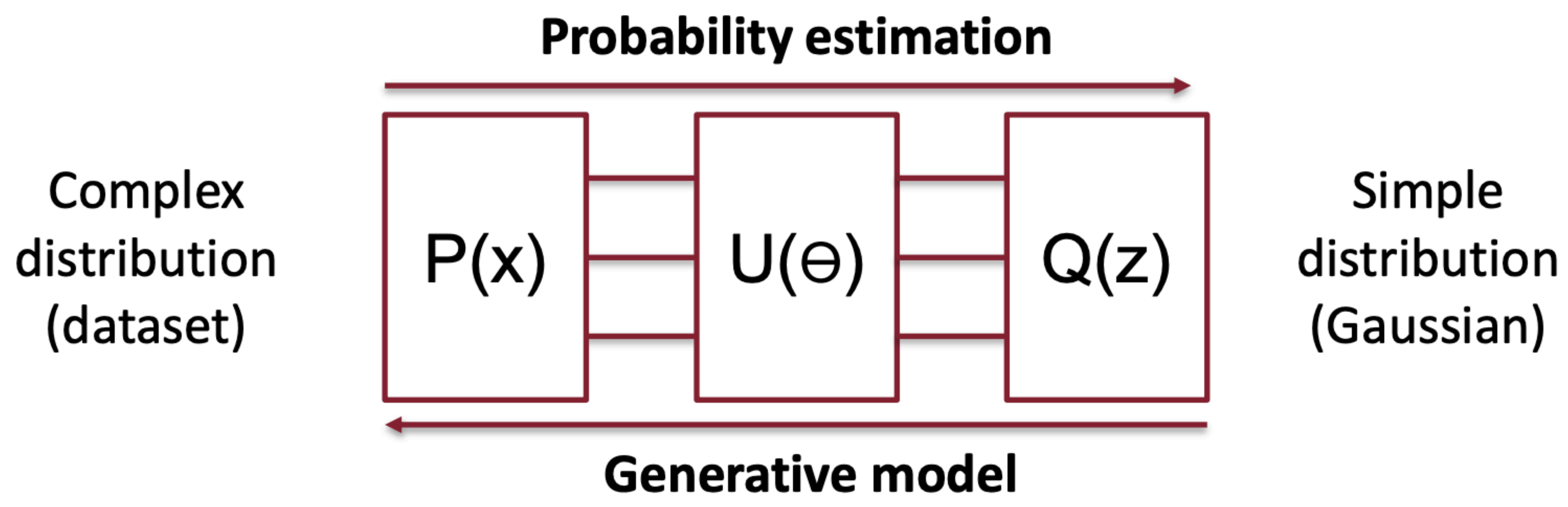
Overview of INFN activities

Classification in HEP and Gravitational Waves

- **Anomaly detection task**
  - Identification of long-lived particles in ATLAS



- **Generative models**
  - Simulation of particles-matter interaction



by S. Bordoni, D. Stanev, S. Giagu — INFN Roma and University Sapienza

- GW signals are deeply embedded in **detector noise**
- Matched filtering between data and signal templates
  - **Computationally not feasible**

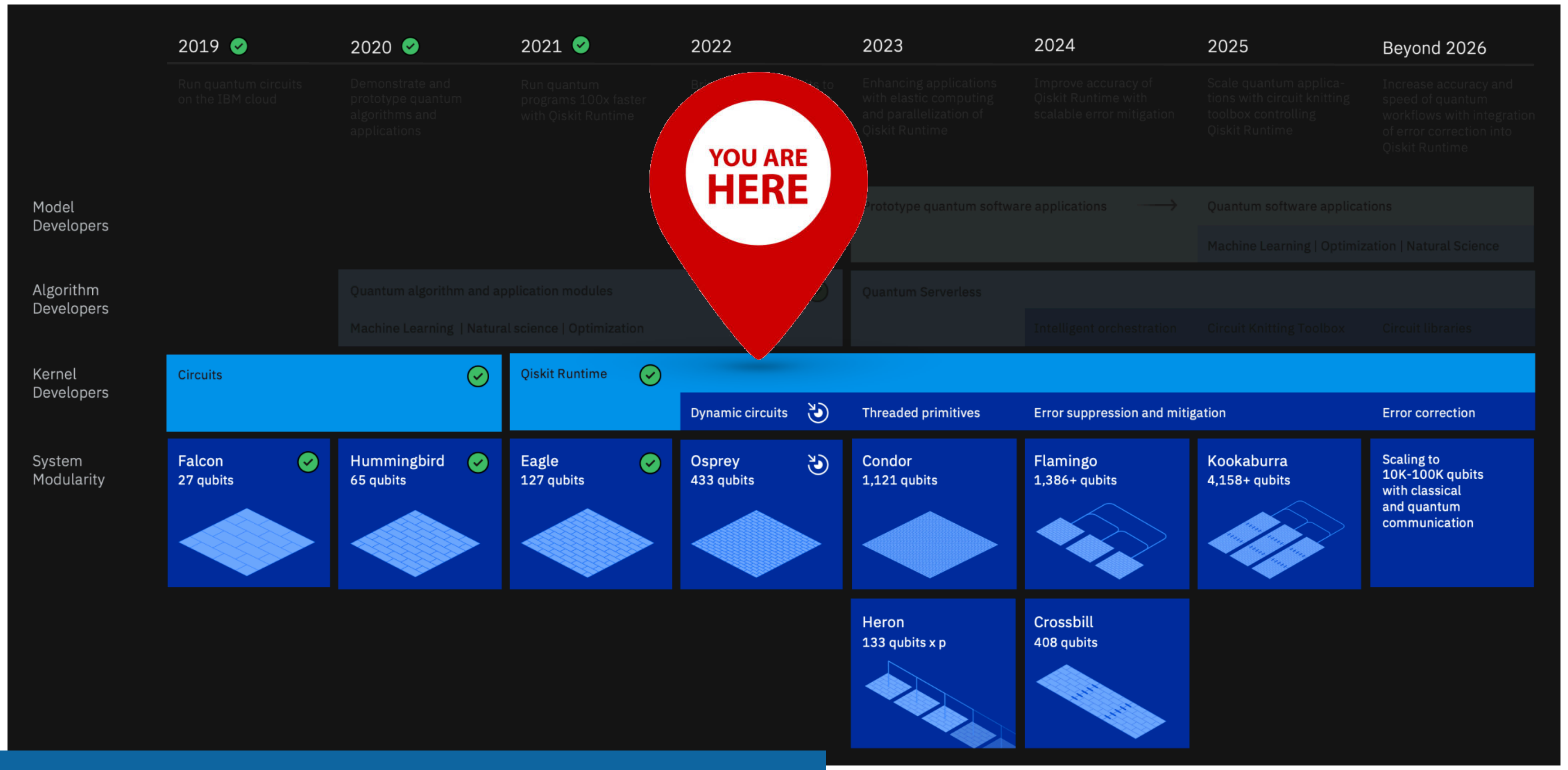
$$N_{\text{tot}} \approx 5.6\pi \times 10^{-9} K_f K_{\text{sky}} \left(\frac{T_{\text{FFT}}}{\delta t}\right)^{3+j_{\max}} \prod_{j \leq j_{\max}} \left(\frac{T_{\text{obs}}}{\tau_{\min}}\right)^{j} \approx 10^{21}$$

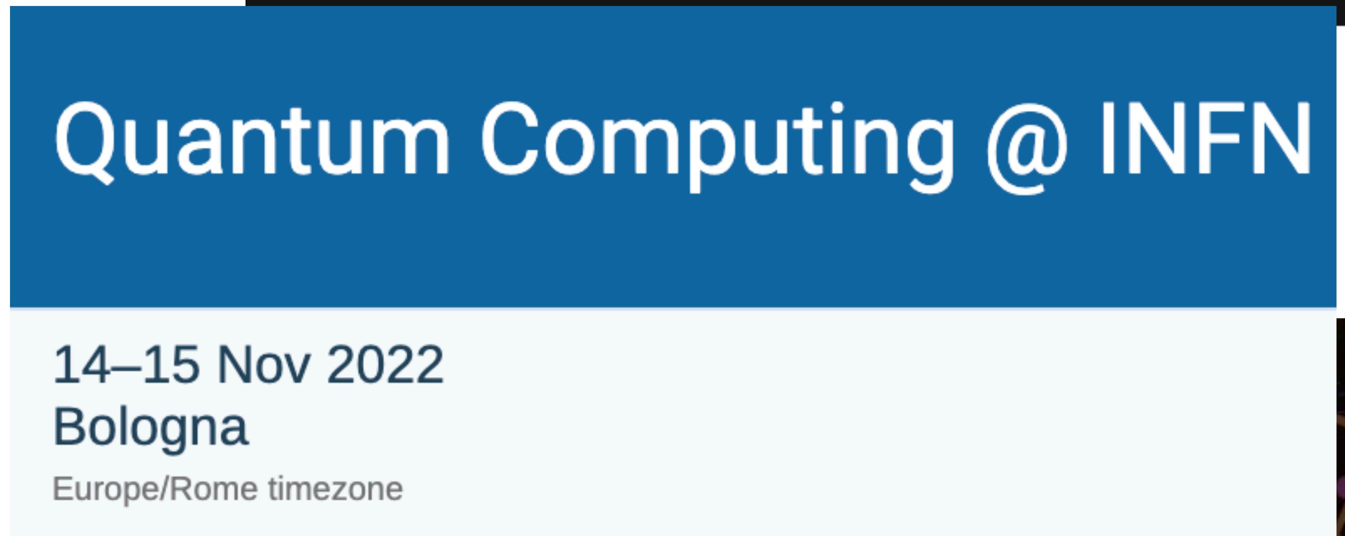
- Several proposals to use quantum algorithms
  - Quantum Hough Transform
    - Polynomial speed-up w.r.t. classical
  - QML
    - Already classical ML seems promising

by C. Palomba, P. Astone, F. Muciaccia — INFN Roma

Conclusions

- An application of QML to a **real LHC physics** case has been presented
  - While QML doesn't show any advantage, it behaves **almost as good as classic ML**
  - Nice PoC for future studies and application
  - Possible **new ideas** on
    - Leveraging **quantum** aspects of QML
    - Applicability to **near-term devices**
- **Many INFN activities** of QC for HEP in **different areas of interest**
- Significant boost expected from the **national center for HPC and QC**, currently being built





Thank you for your attention!