

Qutrits for physics at the LHC

Miranda Carou¹ Veronika Chobanova² Miriam Lucio Martinez³

¹University of A Coruña, Rúa da Maestranza 9, 15001 A Coruña

²University of A Coruña, CITENI, Campus Industrial de Ferrol,
Campus de Esteiro, Rúa Doctor Vazquez Cabrera s/n, 15403 Ferrol, A Coruña

³Instituto de Física Corpuscular (IFIC), University of Valencia
Carrer del Catedratic José Beltrán Martínez, 2. Paterna

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Outline

1. Why qutrits?
2. Step 1: Choose a qubit-based reference model
3. Step 2: Face theoretical limitations and changes
4. Step 3: Implement the qutrit-based model
 - 4.1 Software
 - 4.2 Results
5. Conclusions
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Why qutrits?

Qutrits advantages

Higher storage capacity

$\log_2 3 \approx 1,56$ bits of information

Richer set of operations

$SU(2)$ algebra vs $SU(3)$ algebra

Real Hardware possibilities

- Quantum Error Correction of Qudits Beyond Break-even
- Quantum-Fourier-transform-based quantum arithmetic with qudits

Not as crazy as it may seem!!

Step 1: Choose a qubit-based reference model

Qubit-based reference model

One particle - one qubit: Particle physics data encoding for quantum machine learning

Aritra Banerjee[✉] and Markus Klute
*Institute of Experimental Particle Physics (ETP),
Karlsruhe Institute of Technology, Karlsruhe, DE*

Benedikt Maier[†], Melik Oughton, and Eric Pezone
Imperial-X and Department of Physics, Imperial College Of Science, Technology And Medicine, London, UK

Michael Spannowsky[‡]
Institute for Particle Physics Phenomenology (IPPP), Durham University, Durham, UK

We introduce 1P1Q, a novel quantum data encoding scheme for high-energy physics (HEP), where each particle is assigned to an individual qubit, enabling direct representation of collision events on quantum circuits without classical compression. We demonstrate the effectiveness of 1P1Q in quantum machine learning (QML) through two applications: a Quantum Autoencoder (QAE) for unsupervised anomaly detection and a Variational Quantum Circuit (VQC) for supervised classification of top quark jets. Our results show that the QAE successfully distinguishes signal jets from background QCD jets, achieving superior performance compared to a classical autoencoder while utilizing significantly fewer trainable parameters. Similarly, the VQC achieves competitive classification performance, approaching state-of-the-art classical models despite its minimal computational complexity. Furthermore, we validate the QAE on real experimental data from the CMS detector, establishing the robustness of quantum algorithms in practical HEP applications. These results demonstrate that 1P1Q provides an effective and scalable quantum encoding strategy, offering new opportunities for applying quantum computing algorithms in collider data analysis.

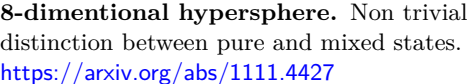
Published in: Physical Review D 112 (2025), 076004.

Reference paper: [arxiv.org:2502.17301](https://arxiv.org/abs/2502.17301)

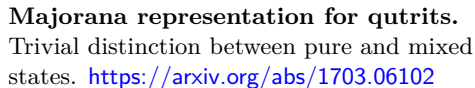
Key features:

- Great and robust performance.
- Developed in a framework with support for qutrits.
- With application for anomaly detection.
- Uses LHC open data.

Step 2: Face theoretical limitations and changes



<https://arxiv.org/abs/1111.4427>



Majorana representation for qutrits.
Trivial distinction between pure and mixed states. <https://arxiv.org/abs/1703.06102>

Main differences qubits vs qutrits

Qubits

- 4 Pauli Matrices
- Rotation gates = Pauli matrix exponentiation
- Hadamard gate
- Standard Swap gate

Qutrits

- 8 Gell-Mann matrices
- Rotation gates $\neq$ Gell-Mann matrix exponentiation
- Chereston gate
- Specific SWAP gate

Generalized gates

$$Ch = \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & 1 & 1 \\ 1 & e^{2\pi i/3} & e^{4\pi i/3} \\ 1 & e^{4\pi i/3} & e^{2\pi i/3} \end{bmatrix}$$

<https://arxiv.org/abs/1703.06102>

$$U_{\text{SWAP}} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}.$$

<https://arxiv.org/abs/0811.1545>

Step 3: Implement the qutrit-based model

More data in the encoding

$$f \cdot \frac{p_T}{p_{T,\text{jet}}} \cdot (\eta - \eta_{\text{jet}}) \rightarrow \theta$$

$$f \cdot \frac{p_T}{p_{T,\text{jet}}} \cdot (\phi - \phi_{\text{jet}}) \rightarrow \varphi$$

$$f \cdot \frac{p_T}{p_{T,\text{jet}}} \cdot d_0 \rightarrow \varrho_0$$

$$f \cdot \frac{p_T}{p_{T,\text{jet}}} \cdot d_z \rightarrow \varrho_z$$

$$f \cdot \frac{p_T}{p_{T,\text{jet}}} \cdot (E - E_{\text{jet}}) = \varepsilon$$

$$f \cdot \frac{p_T}{p_{T,\text{jet}}} \cdot \tau_{12} = \tau_{12}$$

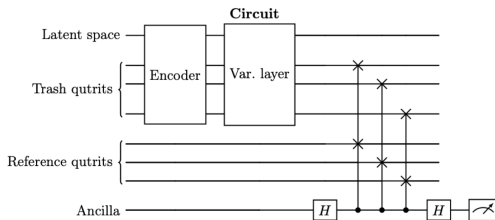
$$f \cdot \frac{p_T}{p_{T,\text{jet}}} \cdot (E - E_{\text{jet}}) = \varepsilon$$

$$f \cdot \frac{p_T}{p_{T,\text{jet}}} \cdot \tau_{23} = \tau_{23}$$

$$f \cdot \frac{p_T}{p_{T,\text{jet}}} \cdot (E - E_{\text{jet}}) = \varepsilon$$

$$f \cdot \frac{p_T}{p_{T,\text{jet}}} \cdot \tau_{34} = \tau_{34}$$

Implementation



More limitations

1. Library → PennyLane.
2. Simulators → "Default.qutrit" and "Default.qubit".
3. Circuit size → 8 qutrit/qubits
 - 1 latent space
 - 3 trash qubits/qutrits
 - 3 reference qubits/qutrits
 - 1 ancilla

Results I - AUC Scores

Model	$W \rightarrow q\bar{q}$	$H \rightarrow b\bar{b}$	$t \rightarrow bq\bar{q}$
4-Qb Our Ref.	0.7343	0.7755	0.8460
4-Qt ($\varphi, \vartheta, \varrho_0, \varrho_z$)	0.7258	0.7677	0.8366

Table: AUC Scores for the different models with flat distribution in jet p_T , in the range $[500, 1000]$ GeV. 'Qb' = Qubit Model, 'Qt' = Qutrit Model

Results II - Fidelity distribution

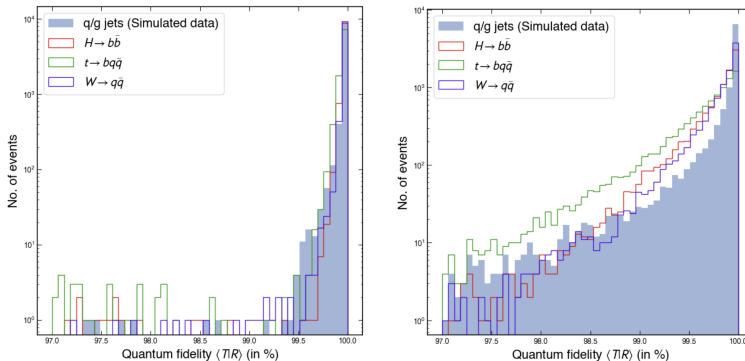


Figure: (Left) Fidelity distribution obtained by the qubit-based QAE model. (Right) Fidelity distribution obtained by the qutrit-based QAE model with $\phi_1 = \varrho_0$, $\phi_2 = \varrho_z$.

Results III - Separation between signals

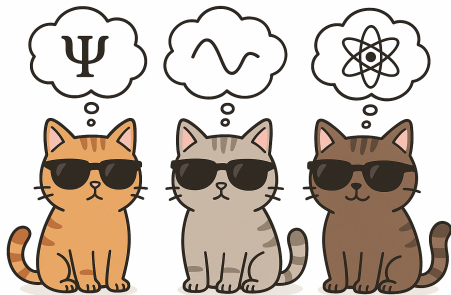
Table: Comparison of mean and median **absolute** fidelity differences between signals for qutrit- and qubit-based models over 100 executions.

Models	Comparison	Mean $ \Delta F $	Median $ \Delta F $
Qubits	$F(H \rightarrow b\bar{b}) - F(W \rightarrow q\bar{q})$	0.0227	0.00226
	$F(H \rightarrow b\bar{b}) - F(t \rightarrow bq\bar{q})$	0.0526	0.00756
	$F(W \rightarrow q\bar{q}) - F(t \rightarrow bq\bar{q})$	0.0752	0.00983
Qutrits	$F(H \rightarrow b\bar{b}) - F(W \rightarrow q\bar{q})$	0.8541	0.05527
	$F(H \rightarrow b\bar{b}) - F(t \rightarrow bq\bar{q})$	0.7097	0.19981
	$F(W \rightarrow q\bar{q}) - F(t \rightarrow bq\bar{q})$	1.5638	0.25508

All fidelity differences are reported in absolute value.

Conclusions

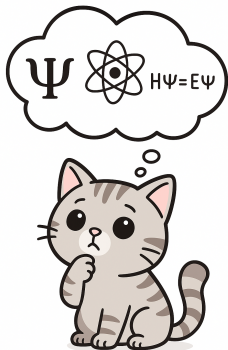
Conclusions



- ✓ The Majorana representation is an effective representation for qutrits within unit spheres.
- ✓ Comparable performance with the qubit-based model.
- ✓ Greater capacity to discriminate between signals.

Outlook

Outlook



Generalization to:

- Mixed states:
<https://arxiv.org/abs/1909.07740>
- Ququarts:
<https://arxiv.org/abs/2304.11159>



PhD Miriam Lucio Martínez



PhD Veronika Chobanova



PhD Candidate Miranda Carou Laiño

Thank you!



arxiv.org/2510.14001

Qutrit-based model implementation II

Gell-Mann matrices.

$$\begin{aligned}\lambda_1 &= \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} & \lambda_2 &= \begin{bmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} & \lambda_3 &= \begin{bmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{bmatrix} \\ \lambda_4 &= \begin{bmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix} & \lambda_5 &= \begin{bmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{bmatrix} & \lambda_6 &= \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix} \\ \lambda_7 &= \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{bmatrix} & \lambda_8 &= \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{bmatrix}\end{aligned}$$

Qutrit-based model implementation III

$SO(3)$ rotation matrices

$$\Sigma_1 = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}$$

$$\Sigma_2 = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 & -i & 0 \\ i & 0 & -i \\ 0 & i & 0 \end{bmatrix}$$

$$\Sigma_3 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -1 \end{bmatrix}$$

$$R_i(\xi) = e^{i\xi\Sigma_i} = I + (\cos \xi - 1) \Sigma_i^2 + i \sin \xi \Sigma_i.$$

Qutrit-based model implementation V

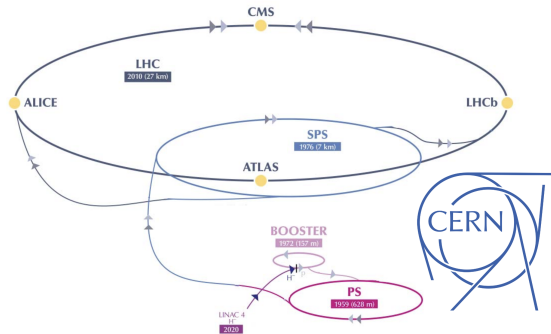
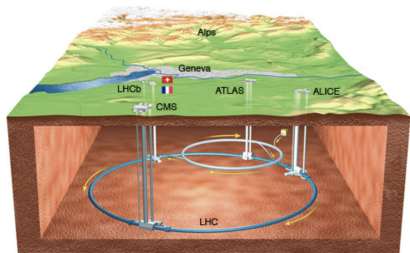
$$Ch = \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & 1 & 1 \\ 1 & e^{2\pi i/3} & e^{4\pi i/3} \\ 1 & e^{4\pi i/3} & e^{2\pi i/3} \end{bmatrix}$$

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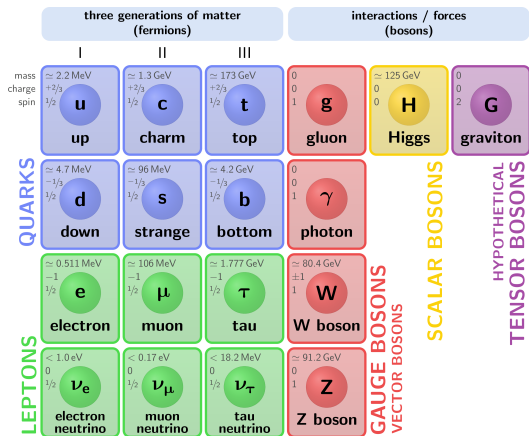
$$U_{\text{SWAP}} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}.$$

<https://arxiv.org/abs/0811.1545>

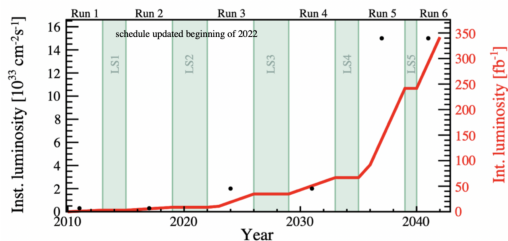
What's the LHC?



Anomaly detection



Example of BSM particle content



Datasets

Methods

Dataset

Real Data



Aspen Open Jets: a real-world ML-ready dataset for jet physics

Amram, Oz; Anzalone, Luca; Birk, Joschka; Faroughy, Darius A.; Hallin, Anna; Kasieczka, Gregor; Krämer, Michael; Pang, Ian; Reyes-Gonzalez, Humberto; Shih, David

This dataset contains approximately 180 M boosted jets, derived from open data collected by the CMS experiment at the Large Hadron Collider (LHC) in 2016 — specifically the JetHT datastream — and presented in a format suitable for Machine Learning (ML) applications. A detailed description of the dataset and how it was produced can be found in the companion paper, arxiv [2412.10504](https://arxiv.org/abs/2412.10504).

JetClass: A Large-Scale Dataset for Deep Learning in Jet Physics

Qu, Huilin¹ ; Li, Congqiao² ; Qian, Sitian²

Show affiliations

JetClass is a new large-scale dataset to facilitate deep learning research in jet physics. It consists of 100M jets for training, 5M for validation and 20M for testing. The dataset contains 10 classes of jets, simulated with MadGraph + Pythia + Delphes.

A detailed description of the JetClass dataset is presented in the paper [Particle Transformer for Jet Tagging](#). An interface to use the dataset is provided in https://github.com/jet-universe/particle_transformer.

Simulated data



Dataset II

DATA SETS

Aspen Open Jets (CMS data 2016)

- transverse momentum $p_{T,jet}$
- pseudorapidity η_{jet}
- azimuthal angular coordinate ϕ_{jet}
- mass m_{jet} , groomed with softdrop algorithm
- jet constituents PF candidates

jet information jet kinematics

- 4 momentum stored in format (p_x, p_y, p_z, E)
- transversal impact parameter d_0
- longitudinal impact parameter d_z

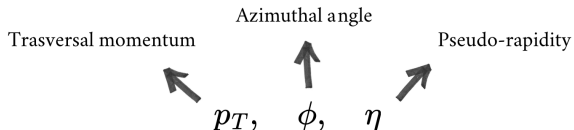
For each constituent we calculate:

$$p_T = \sqrt{p_x^2 + p_y^2} \quad m = \sqrt{\text{Max}(0, E^2 - (p_x^2 + p_y^2 + p_z^2))}$$
$$\eta = -\ln \tan(\eta/2) = \frac{1}{2} \ln \left(\frac{|\vec{p}| + p_z}{|\vec{p}| - p_z} \right)$$
$$\phi = \text{atan}(p_x, p_y) \quad |\vec{p}| = \sqrt{p_x^2 + p_y^2 + p_z^2}$$

Reference model

Methods

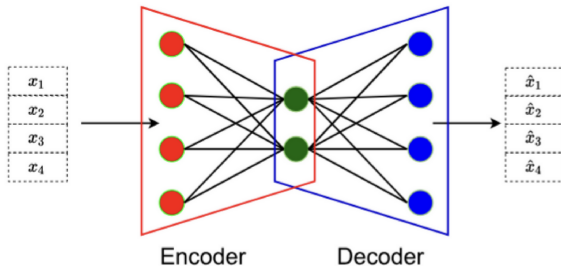
Reference model structure Ref. [15]



$$U(\Theta) = \left(\bigotimes_{i=1}^N R_X(\phi_i) R_Z(\theta_i) R_Y(\omega_i) \right) \otimes \left(\bigotimes_{1 \leq i < j \leq N} C_{ij} \right)$$

Autoencoders

¿What's a
autoencoder?



Qutrits - Pros and Cons

- ✓ More data with fewer physical systems = less depth in the circuits = less number of logic gates = less cumulative decoherence.
- ✓ Promising quantum error codes for qudits. <https://arxiv.org/abs/2409.15065>
- ✗ Higher number of levels = More complex gates errors.
- ✗ More complex implementation in hardware.

HL-LHC Context

LHC

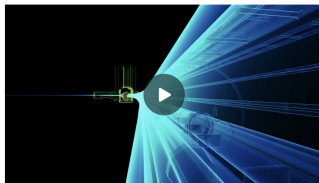
40 Colitions

1.000 Millions de colitions/second

HL-LHC

140 Colitions

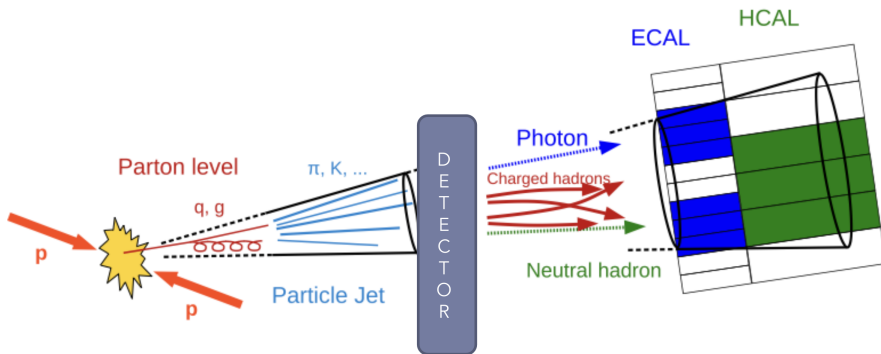
3.500 Millions de colitions/second



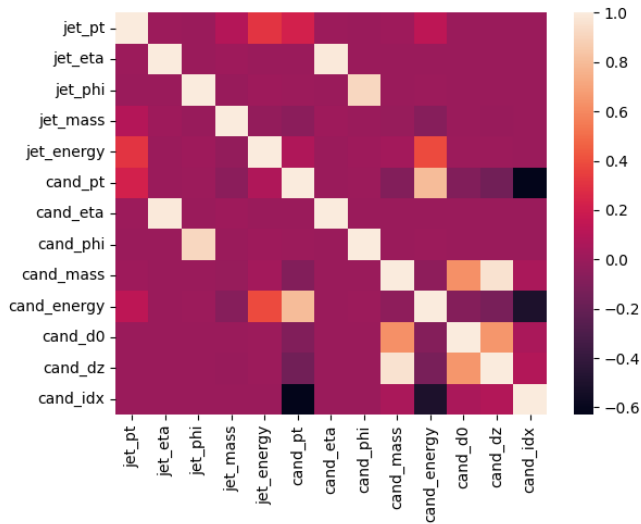
Gell-Mann Matrices

Matriz Gell-Mann	Matriz de Pauli	Subespacio	Equivalencia
$\lambda_1 = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$	$\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$	$\{ 0\rangle, 1\rangle\}$	Puerta X
$\lambda_2 = \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$	$\sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$	$\{ 0\rangle, 1\rangle\}$	Puerta Y
$\lambda_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$	$\sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$	$\{ 0\rangle, 1\rangle\}$	Puerta Z
$\lambda_4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix}$	$\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$	$\{ 0\rangle, 2\rangle\}$	Puerta X
$\lambda_5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix}$	$\sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$	$\{ 0\rangle, 2\rangle\}$	Puerta Y
$\lambda_6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$	$\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$	$\{ 1\rangle, 2\rangle\}$	Puerta X
$\lambda_7 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix}$	$\sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$	$\{ 1\rangle, 2\rangle\}$	Puerta Y
$\lambda_8 = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix}$	Sin equivalencia	$\{ 0\rangle, 1\rangle, 2\rangle\}$	Puerta de Fase

Jets

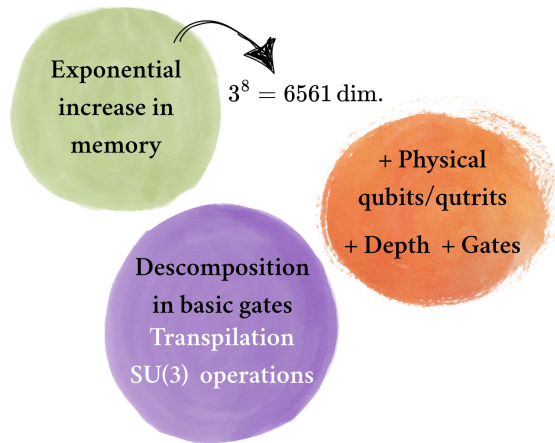


Data correlations



Gate-Based problems for realistic anomaly detection in HEP

- ✗ Gate-based model.
- ✗ Low hardware scalability.
- ✗ Optimization process.
- ✗ High computational cost.



Reframing the problem as QUBO

- ✓ Better scaling, no Barren Plateaus.
- ✓ Global analysis.
- ✓ Problem fragmentation and physical restrictions.
- ✓ Annealing can search solutions which maximize the fidelity inside real hardware.

$$f(x) = \sum_{i=0}^{N-1} Q_{i,i} x_i + \sum_{\substack{i,j=0 \\ i \neq j}}^{N-1} Q_{i,j} x_i x_j$$

<https://arxiv.org/abs/2311.03227>,
<https://arxiv.org/abs/2207.01827>

QUBO formulation for anomaly detection in LHC data?

