Institute of High Energy Physics & China Spallation Neutron Source, Chinese Academy of Sciences

Postdoc mid-term evaluation: progress and plans

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Overview

- ☐ Research Objectives
- ☐ List of publications
- ☐ List of conferences and workshops
- ☐ Research summary:
  - Search for heavy resonances with the ATLAS experiment
  - The prospect of quantum machine learning in High Energy Physics
  - Quantum Particle transformer Algorithm
- ☐ Conclusion

Research objectives

- ☐ The first goal is to finalise the search for heavy resonances within the ATLAS experiment.
- ☐ Explore the prospect of quantum computing in High Energy Physics:
  - The study used CEPC features to demonstrate quantum and classical performance.
  - The support-vector machine algorithm was used as the basis for the study.
- ☐ Developing a quantum algorithm based on the transformer technology.

List of publications

- ☐ Fadol, Abdualazem, et al. "Application of quantum machine learning in a Higgs physics study at the CEPC." International Journal of Modern Physics A, Vol. 39, No. 01, 2450007 (2024), arXiv: 2209.12788.

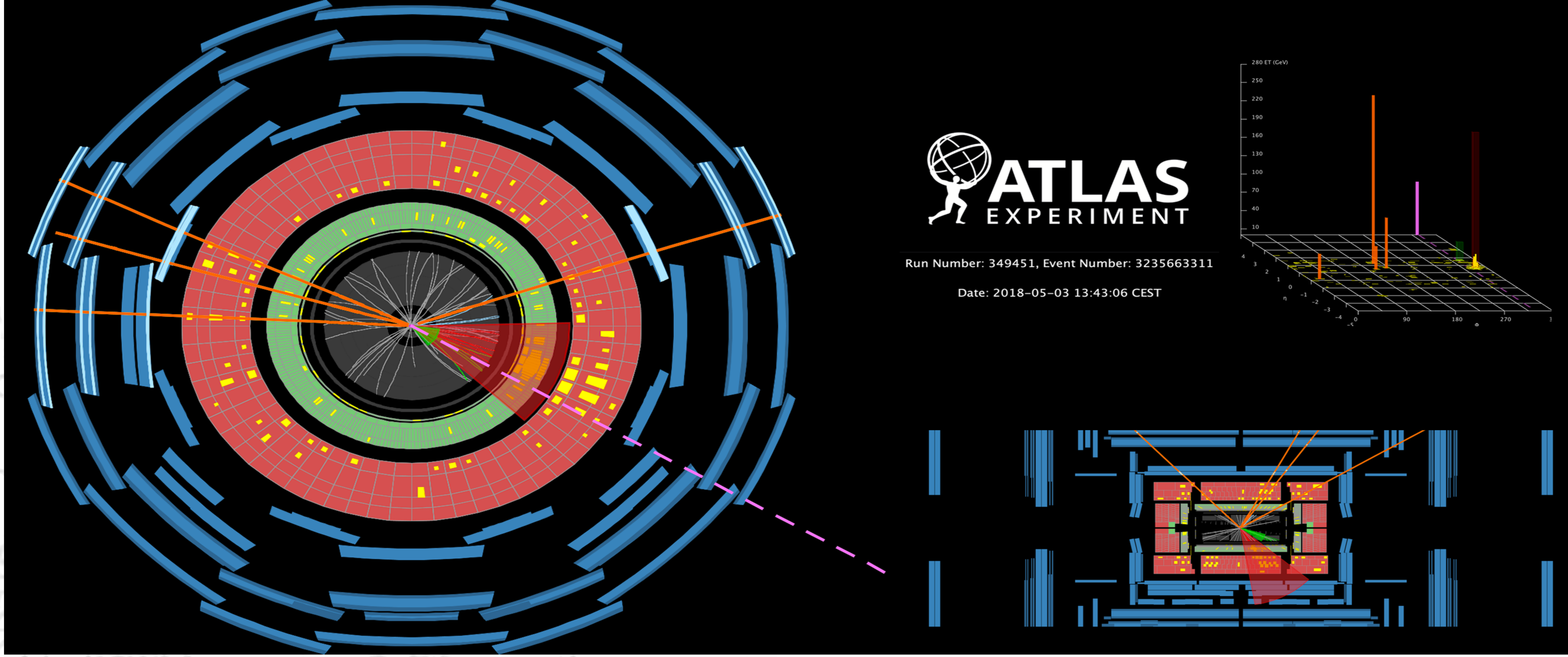
- ☐ ATLAS Collaboration. "Search for heavy resonances in final states with four leptons and missing transverse energy or jets in pp collision at $\sqrt{s} = 13$ TeV with the ATLAS detector." Submitted to the Journal of High Energy Physics (JHEP), arXiv: 2401.04742.

List of conferences and workshops

- ☐ BenchCouncil International Symposium of Intelligent Computers, Algorithms, and Applications, Sanya, China. December 3, 2023.
- ☐ Workshop on Computation in Experimental Particle Physics, Shanghai. July 16, 2023.
- ☐ IAS Program on High Energy Physics (HEP 2023), Hong Kong. February 14, 2023
- ☐ Miami 2022 Physics Conference, Miami, United States. December 17, 2022.

Miscellaneous

A scientific blog on the ATLAS Experiment Physics Briefing



ATLAS searches for new particles in familiar decays

5 March 2024 | By ATLAS Collaboration

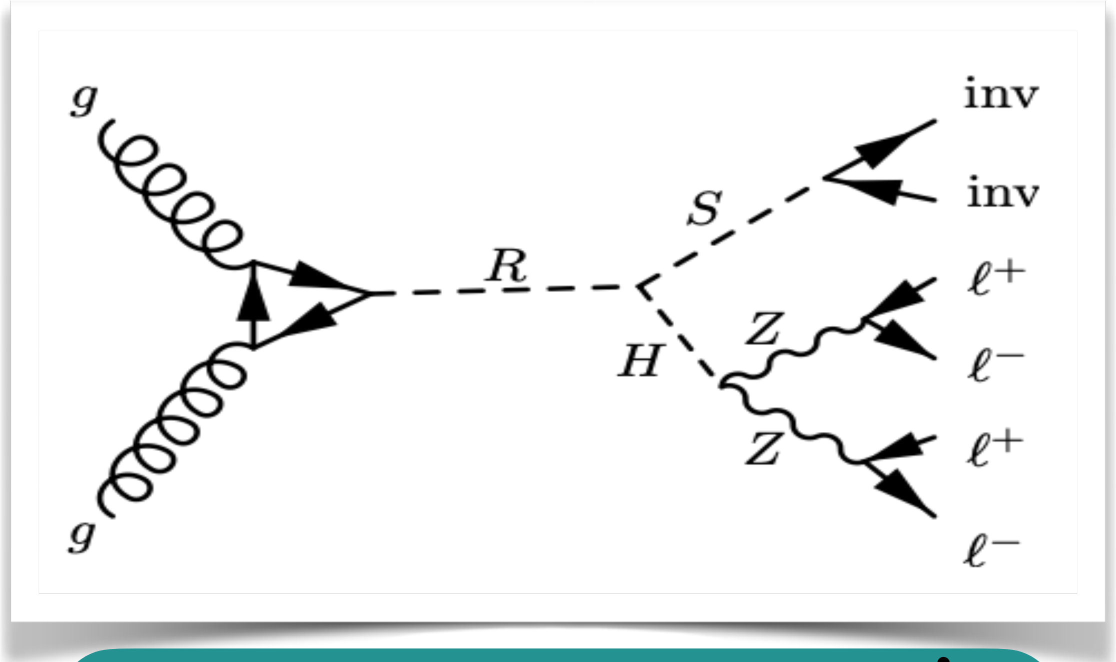
Could the Higgs boson be part of an extended family of particles? Could these new particles be the tools physicists need to discover dark matter? Or explain the matter-antimatter asymmetry of the universe? The two-Higgs-doublet model (2HDM) predicts the existence of a charged Higgs boson, and CP-even (H) and CP-odd (A) Higgs bosons. Expanding this model even further (2HDM+S), these new Higgs bosons could also have a scalar boson cousin (S) that decays into dark-matter particles.

Such theories help the ATLAS Collaboration create targeted searches of LHC collision data. In a new result, researchers conducted a novel search of data collected during Run 2 of the LHC, searching for heavy new particles that could fit the 2HDM or 2HDM+S models. One tested hypothesis considered whether another new scalar particle (R) could decay into H and S bosons, and thus interact with dark matter particles; they also tested whether the new H boson could be a source of matter-antimatter asymmetry. For the first time, researchers considered cases where the new particles decay into Z bosons, leaving a signature in the ATLAS detector with four leptons (electrons or muons) and missing

Search for heavy resonances with the ATLAS experiment

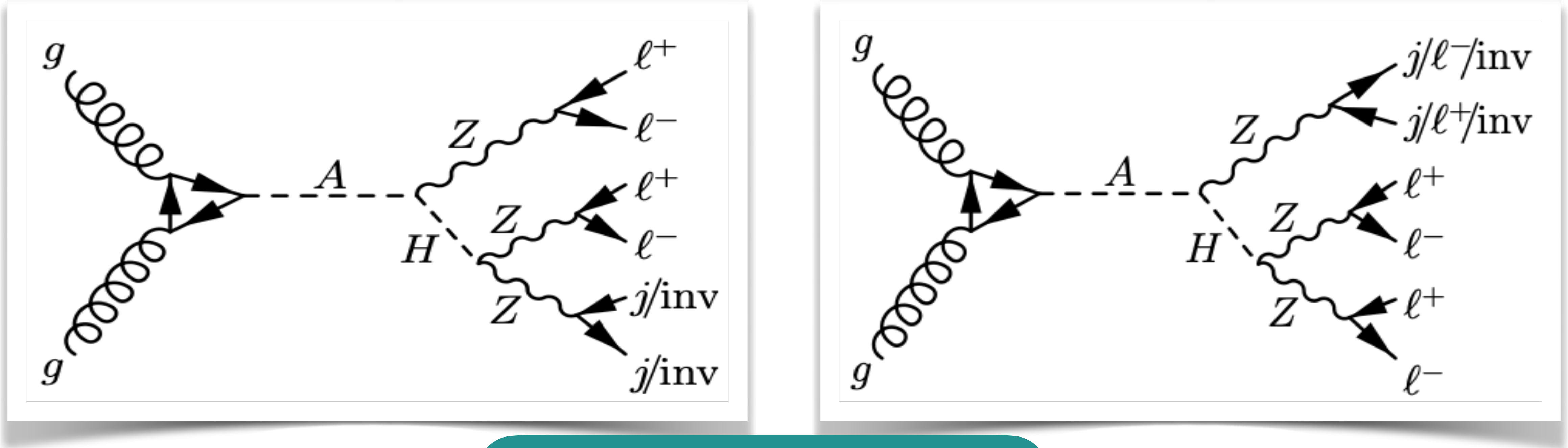
- ☐ Search for heavy resonances in final states with four-lepton and missing transverse momentum or jets.
- ☐ Complementing the $H \to ZZ \to 4\ell$ inclusive search and searches for models consistent with baryogenesis.
- ☐ Signal topology: two signal models are investigated.

2HDM+S



$R \to SH \to 4\ell + E_T^{miss}$

2HDM

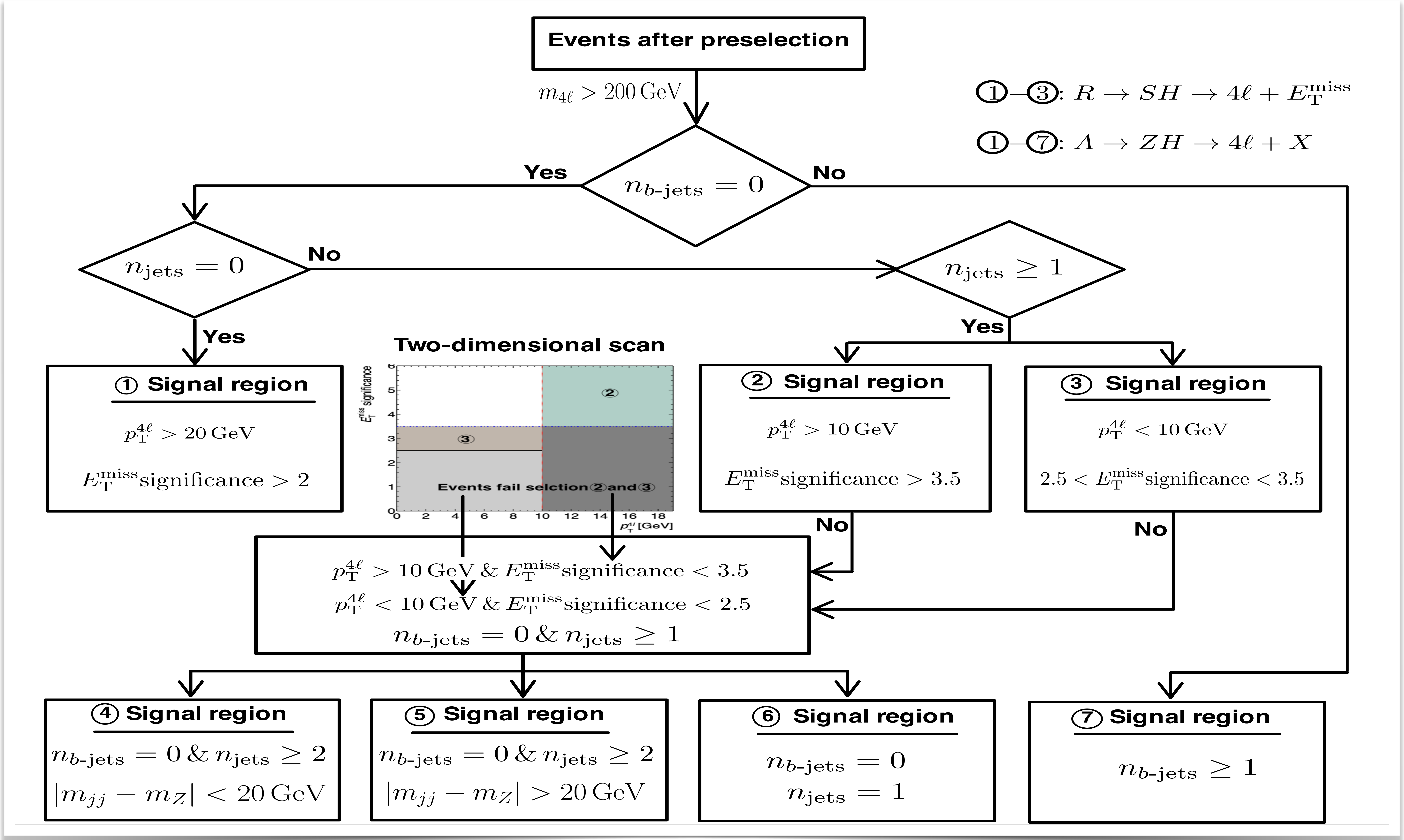


$A \to ZH \to 4\ell + X$

- ☐ The R (CP-even) and A (CP-odd) mass ranges are 390-1300 GeV and 320-1300 GeV, respectively.
- ☐ The mass of H (CP-even) is between 220 GeV and 1000 GeV. The S mass is 160 GeV.

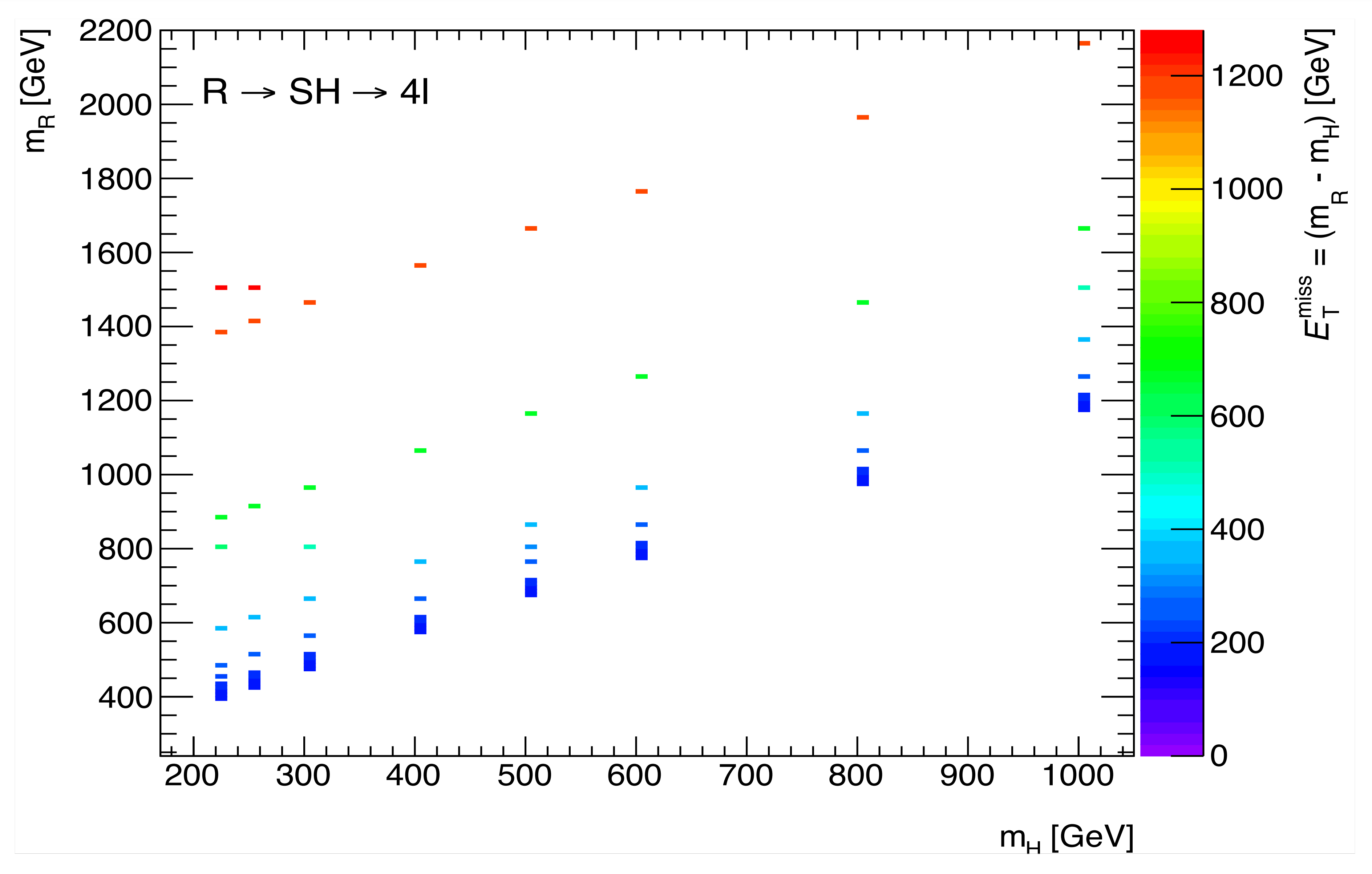
Analysis overview

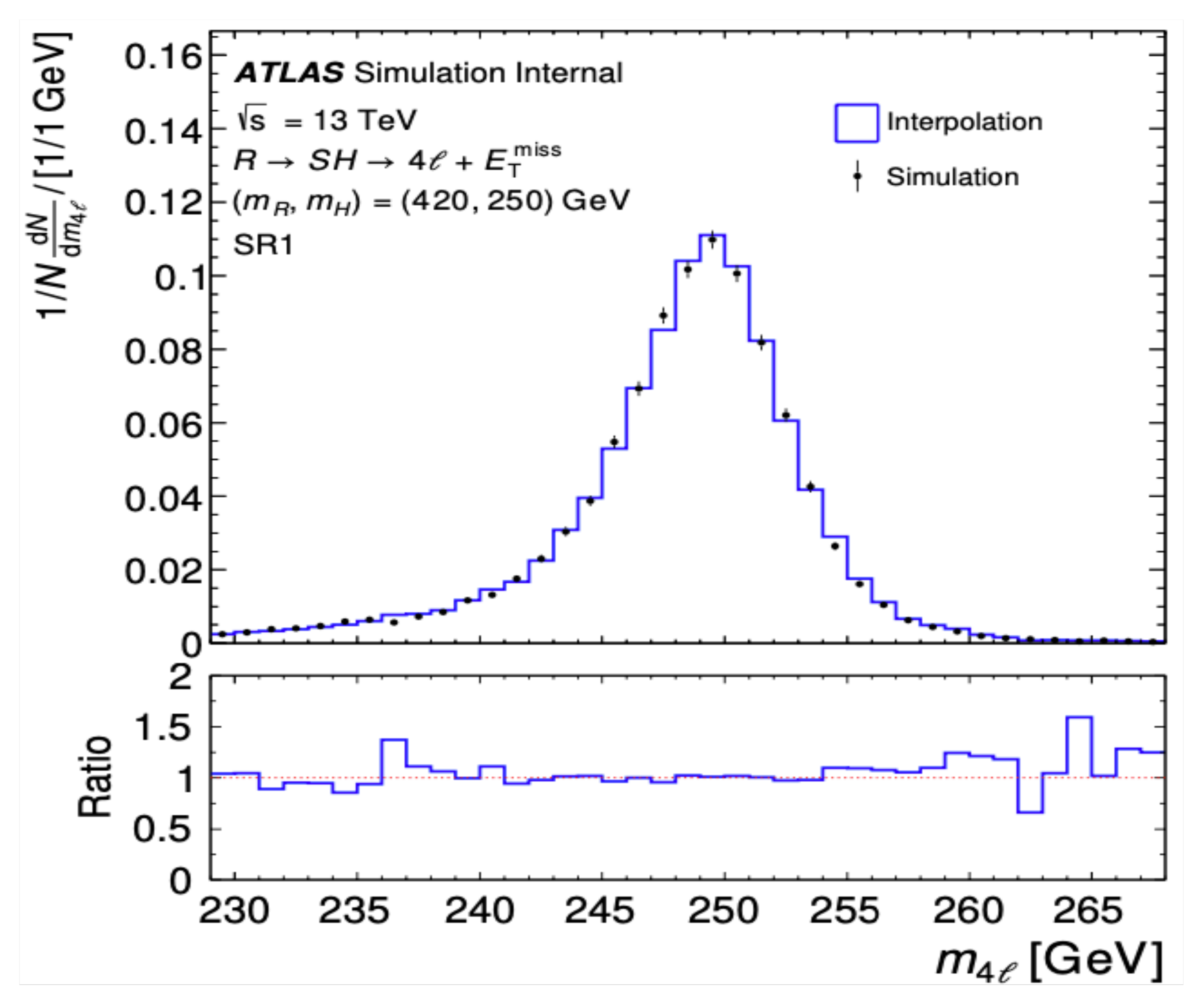
- Orthogonal signal regions were developed for both signals using a simple cut-based analysis selection: the four-lepton momentum, the significance of the missing transverse momentum, the number of jet multiplicity and the number of b-jets.

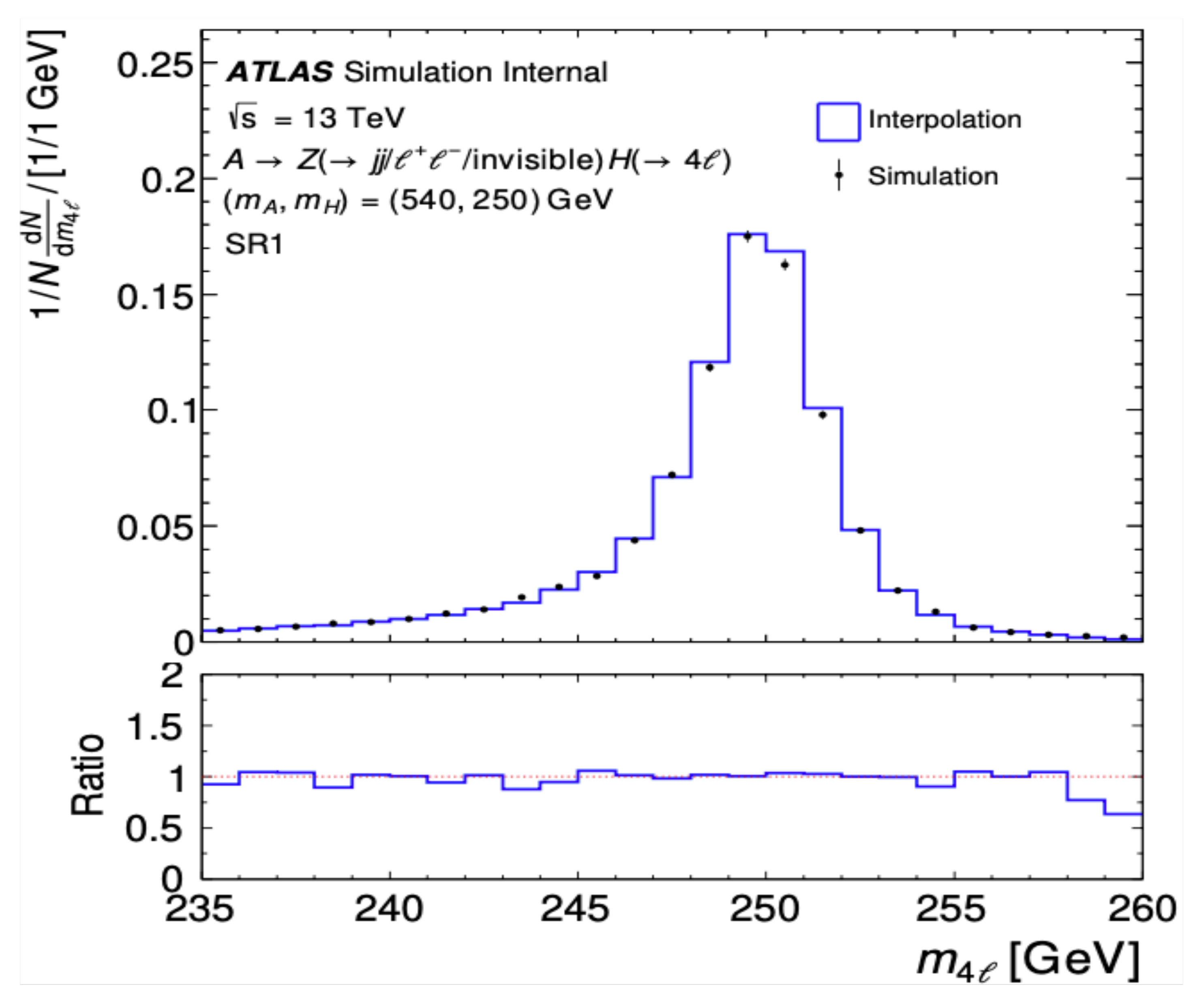


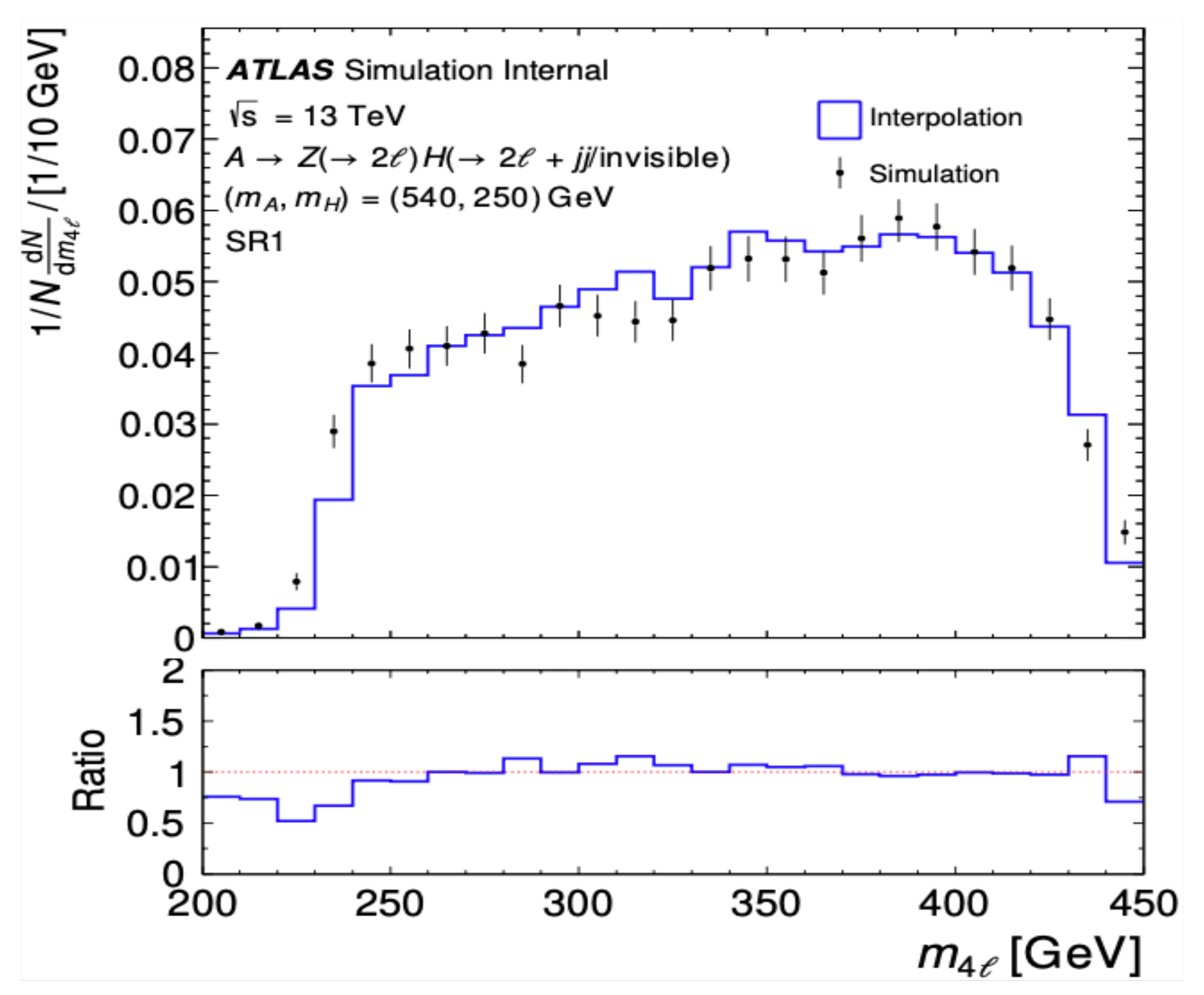
Signal modelling

- ☐ The **signals** used are from the simulation with:
  - Linear interpolation to obtain in-between masses
  - In a step of 10 GeV for (m_R, m_H) or (m_A, m_H)
- ☐ Interpolation was validated by comparing simulated and interpolated signal distributions.









$R \to SH \to 4\ell + E_T^{miss}$

$A \to ZH \to 4\ell + X$

Background modelling

- ☐ **Backgrounds modelled with an empirical function:**

$$f(m_{4\ell}) = H(m_0 - m_{4\ell})\, f_1(m_{4\ell})\, C_1 + H(m_{4\ell} - m_0)\, f_2(m_{4\ell})\, C_2.$$

$$f_1(m_{4\ell}) = \frac{a_1 \cdot m_{4\ell} + a_2 \cdot m_{4\ell}^2}{1 + \exp\left(\frac{m_{4\ell} - a_1}{a_3}\right)}$$

$$f_2(m_{4\ell}) = \left(1 - \frac{m_{4\ell}}{n_C}\right)^{b_1} \cdot \left(\frac{m_{4\ell}}{n_C}\right)^{\left(b_2 + b_3 \cdot \ln\left(\frac{m_{4\ell}}{n_C}\right)\right)}$$

$$C_1 = \frac{1}{f_1(m_0)}, \qquad C_2 = \frac{1}{f_2(m_0)}$$

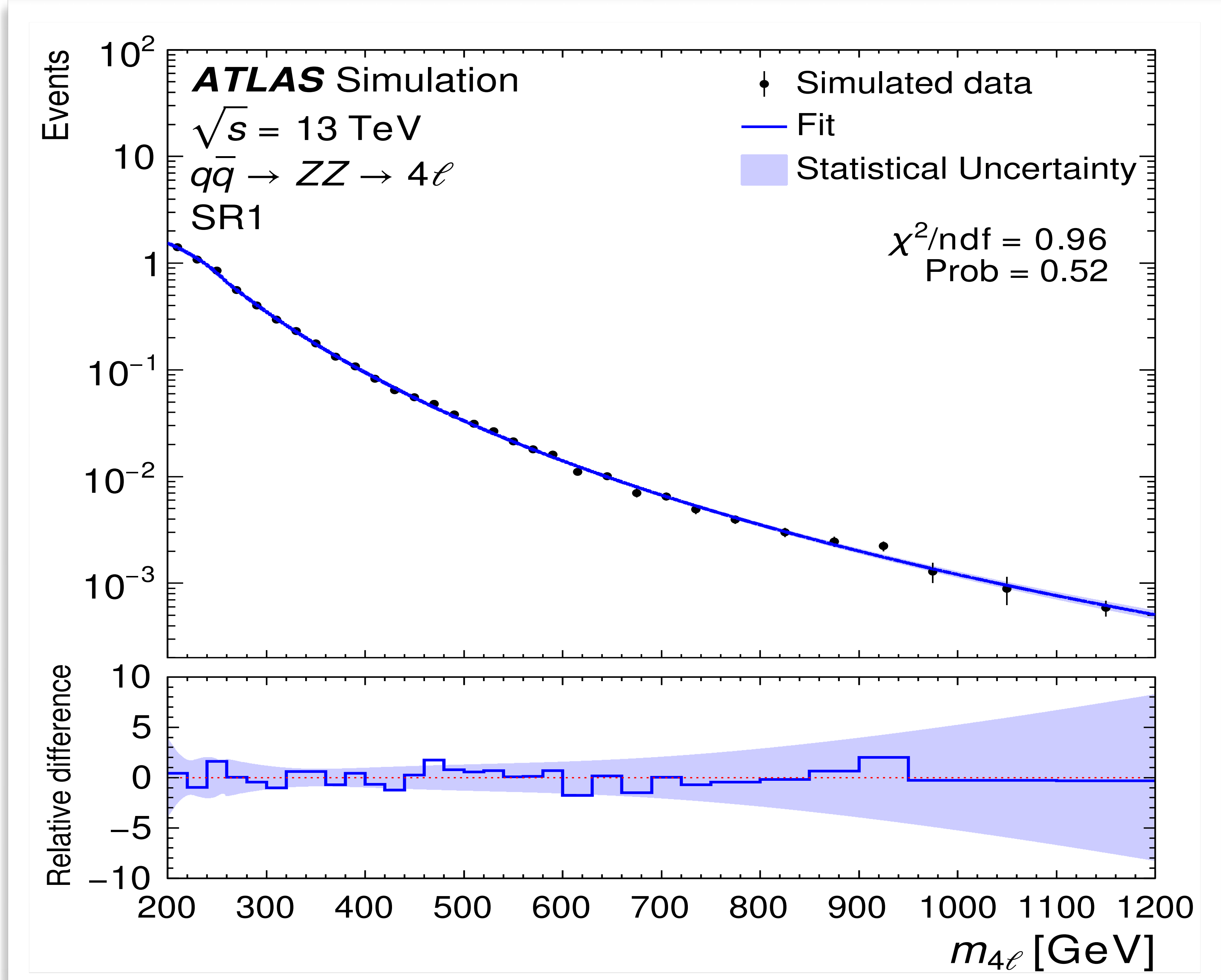
- $q\bar{q} \to ZZ$ **(~84.6%)**
- $gg \to ZZ$ **(~11.7%)**

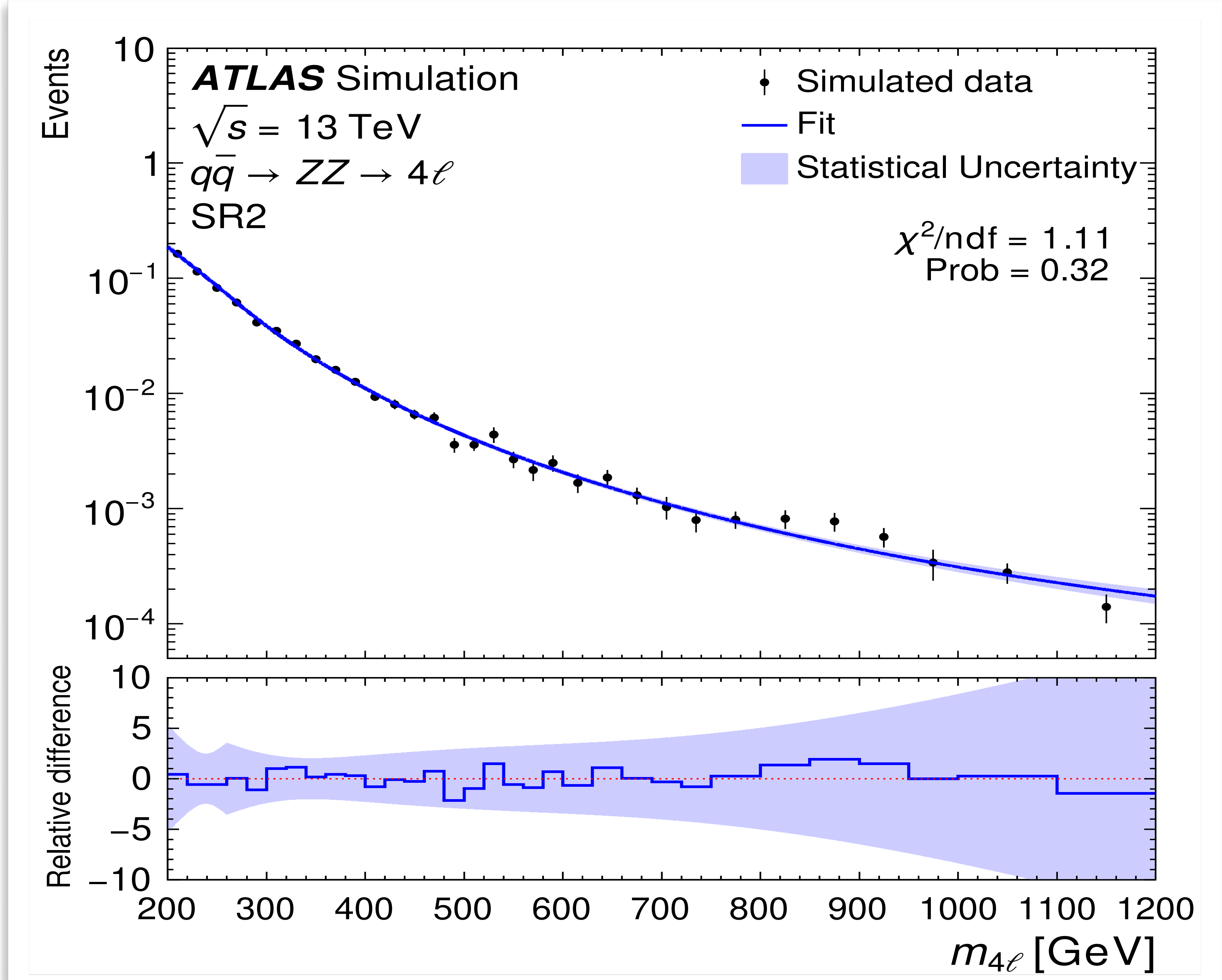
} **Share one free normalisation factor per each signal region.**

- VVV
- **Other** ($q\bar{q} \to ZZ$ (**EW**), $t\bar{t}$, $t\bar{t}V$, WZ)

} **The normalisation is fixed to the SM.**

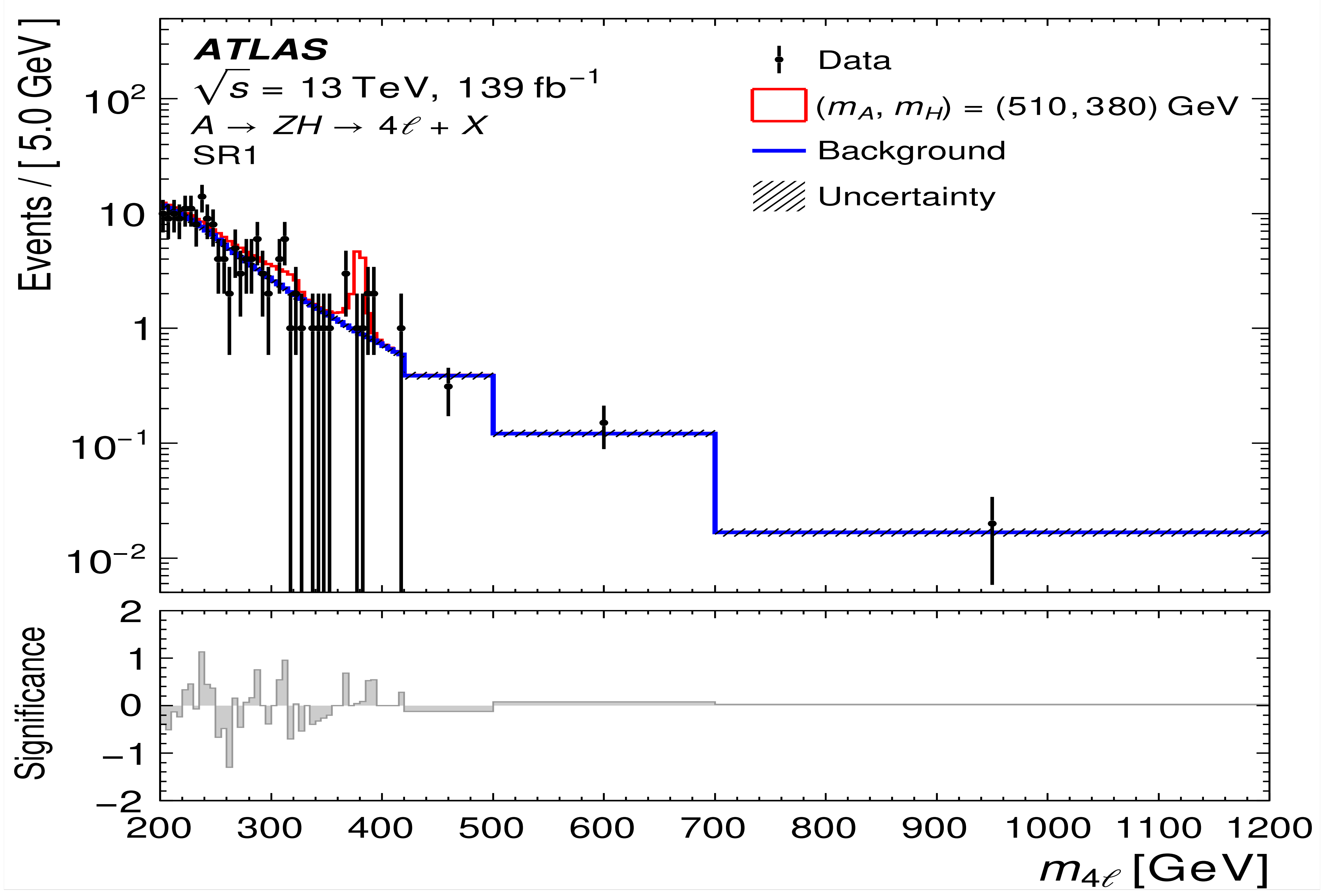
- ☐ **The parameters a_i are obtained by fitting the function into the simulation.**

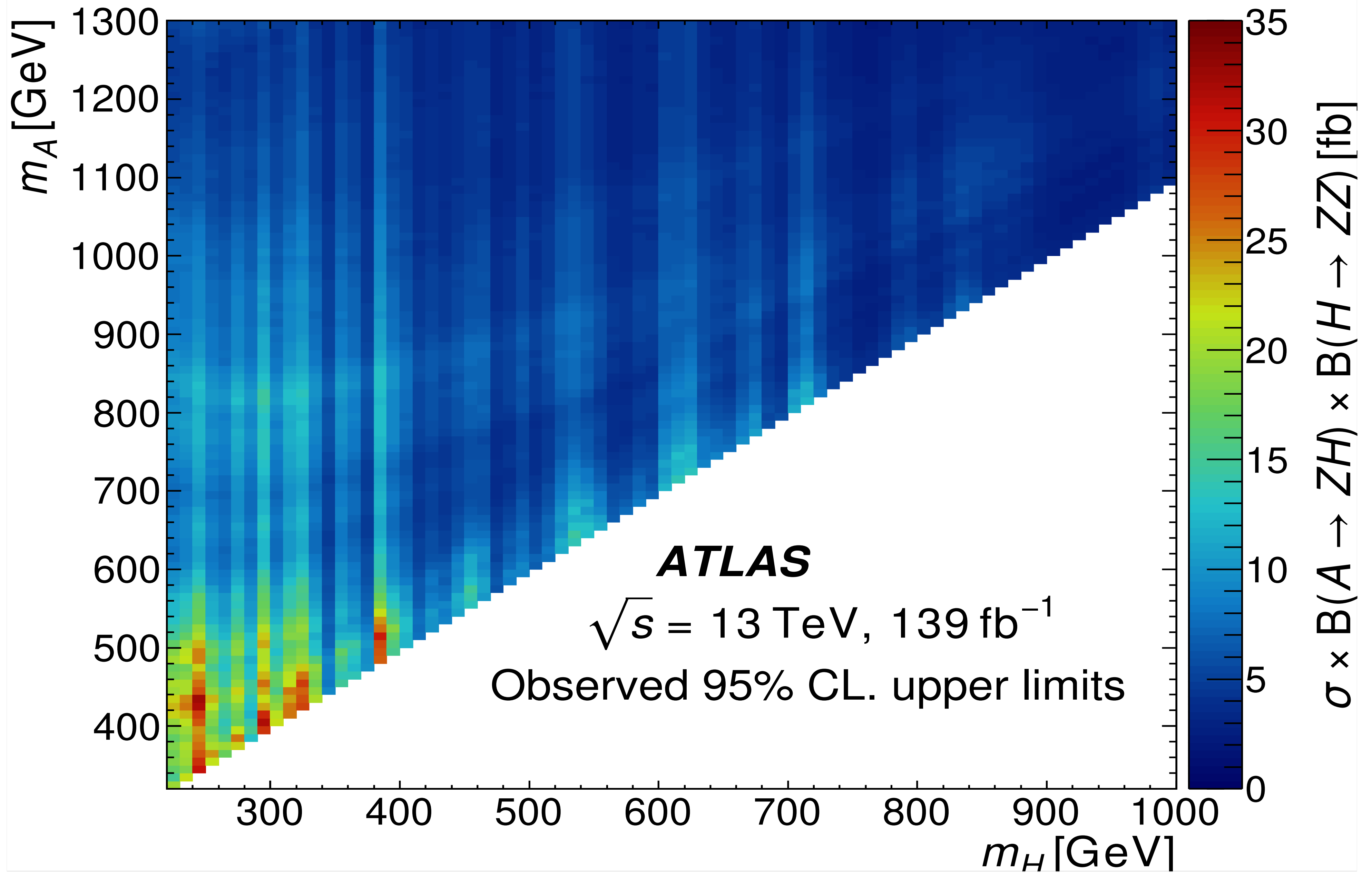




Results

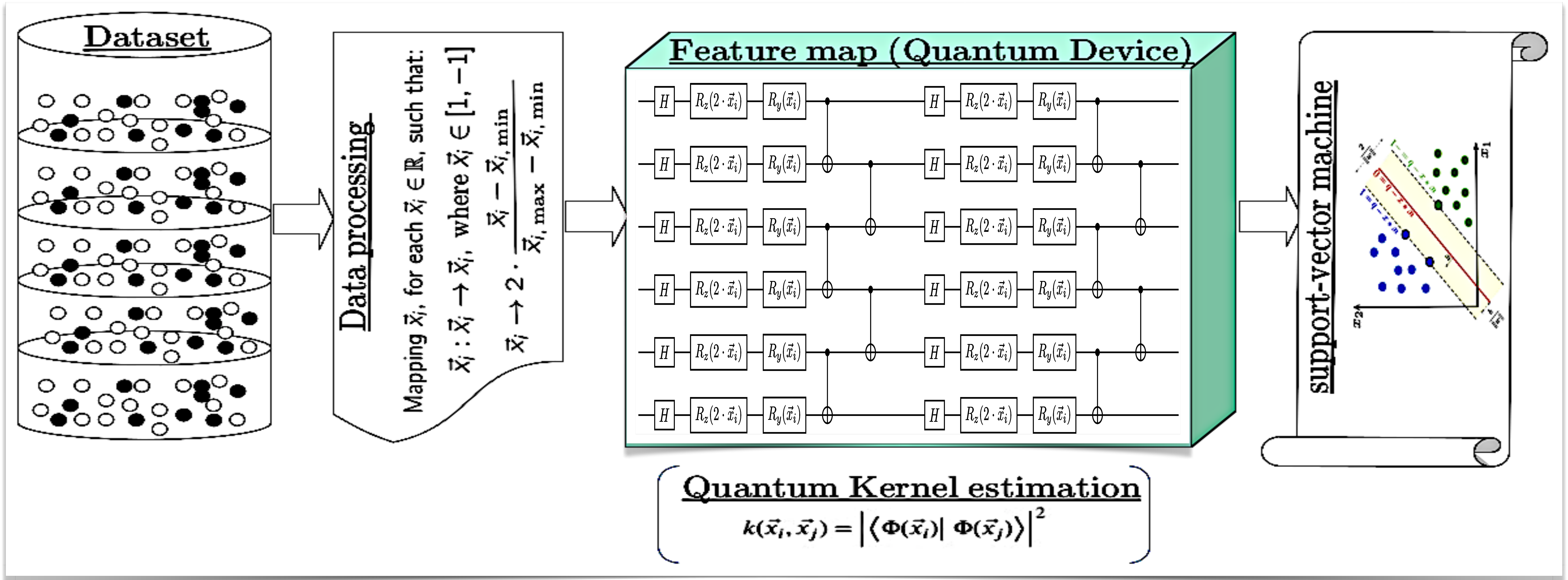
- ☐ No significant deviation above the Standard Model backgrounds was observed.
- ☐ The largest deviation is observed at $(m_A, m_H) = (510{,}380)$ GeV with local significance of 2.5σ.
- ☐ Upper limits were set on the cross-section times the branching ratio.
- ☐ The $R \to SH \to 4\ell + E_{\mathrm{T}}^{\mathrm{miss}}$ search:
  - The observed (expected) upper limit ranges from 6.8–119.2 (7.6–75.8) fb.
  - For m_H and m_R in (220, 100) and (390,1300) GeV.
- ☐ The $A \to ZH \to 4\ell + X$ search:
  - The observed (expected) upper limit ranges from 2.1–32.3 (2.7–25.8) fb.
  - For m_H and m_A in (220, 100) and (320,1300) GeV.





Application of quantum machine learning in HEP

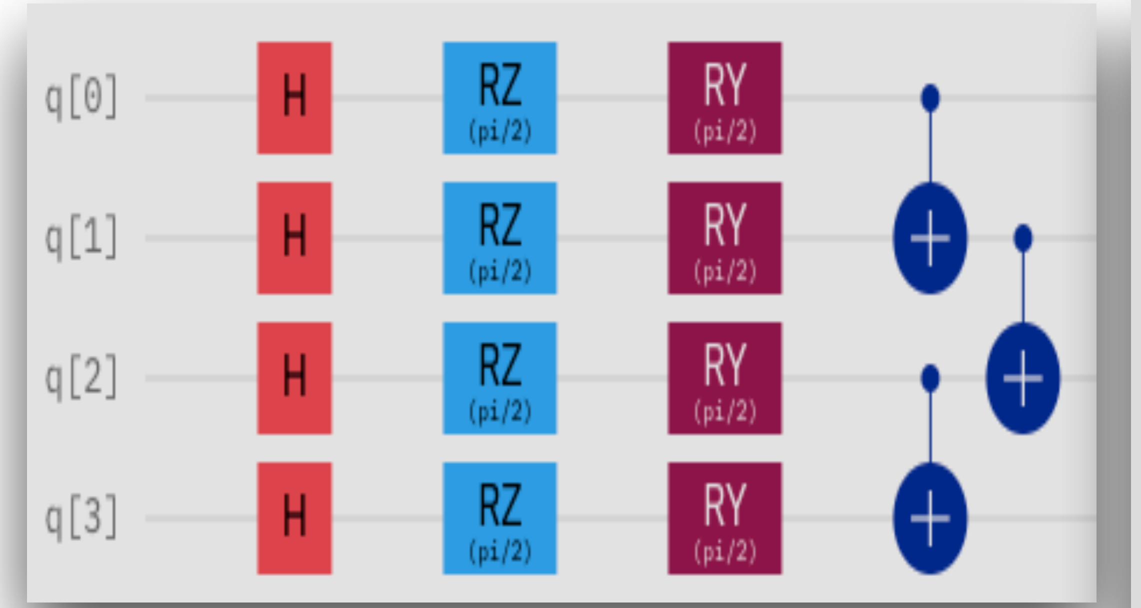
- Comparing the performance of the support-vector machines in quantum and classical hardware.
- With a simple classification problem using the CEPC signature ($e^+e^- \to ZH \to \gamma\gamma jj$).
- Data encoding and processing:

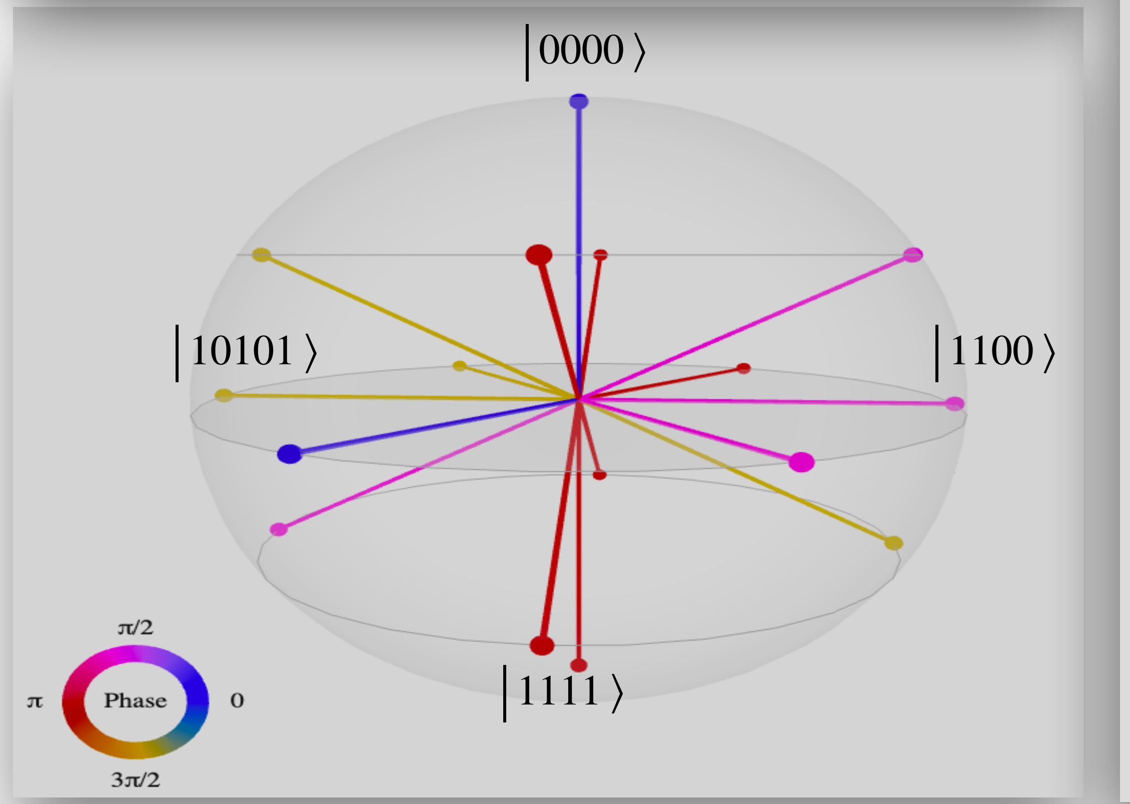


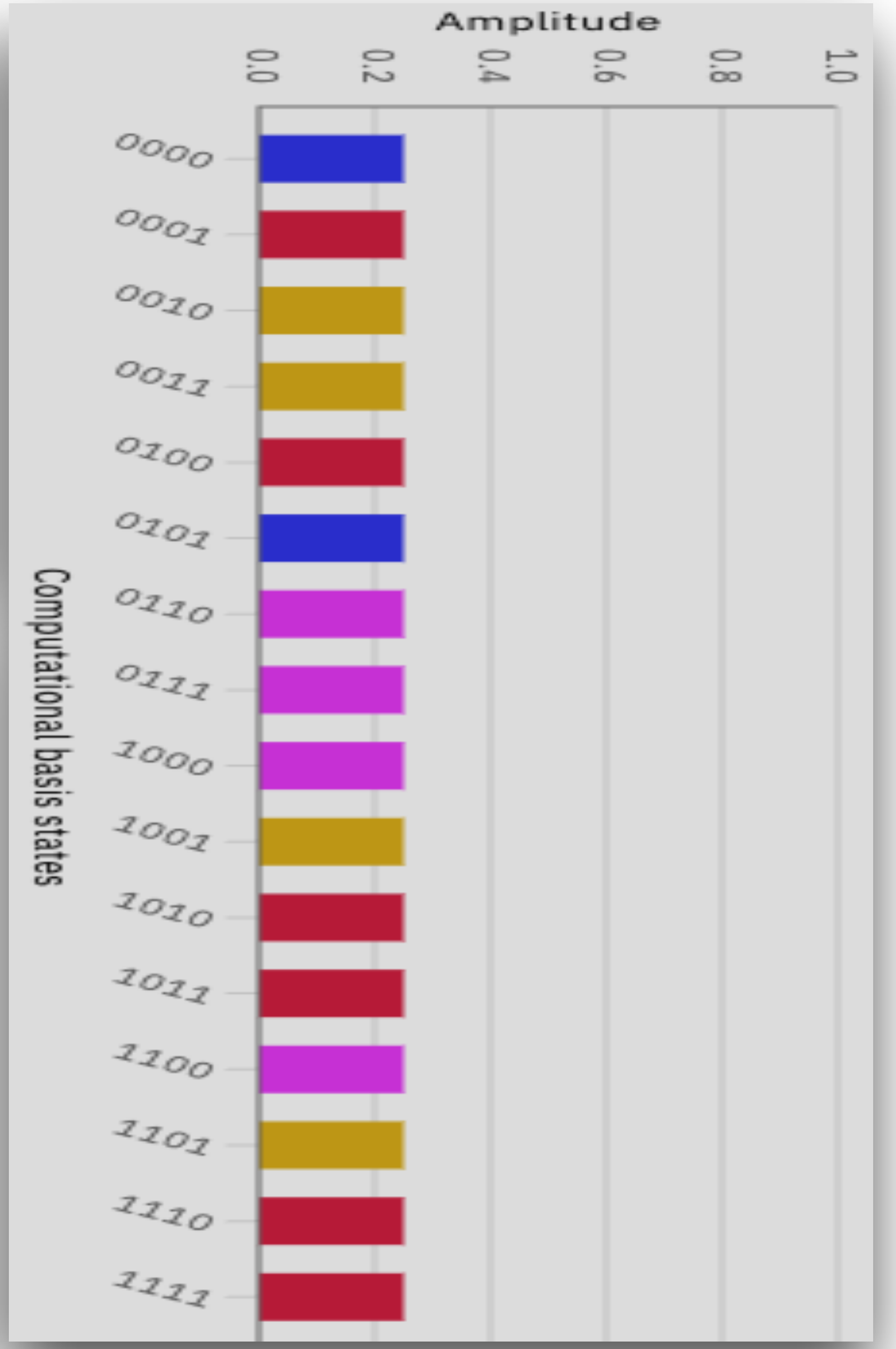
The performance of the quantum simulator

ArXiv: 2209.12788

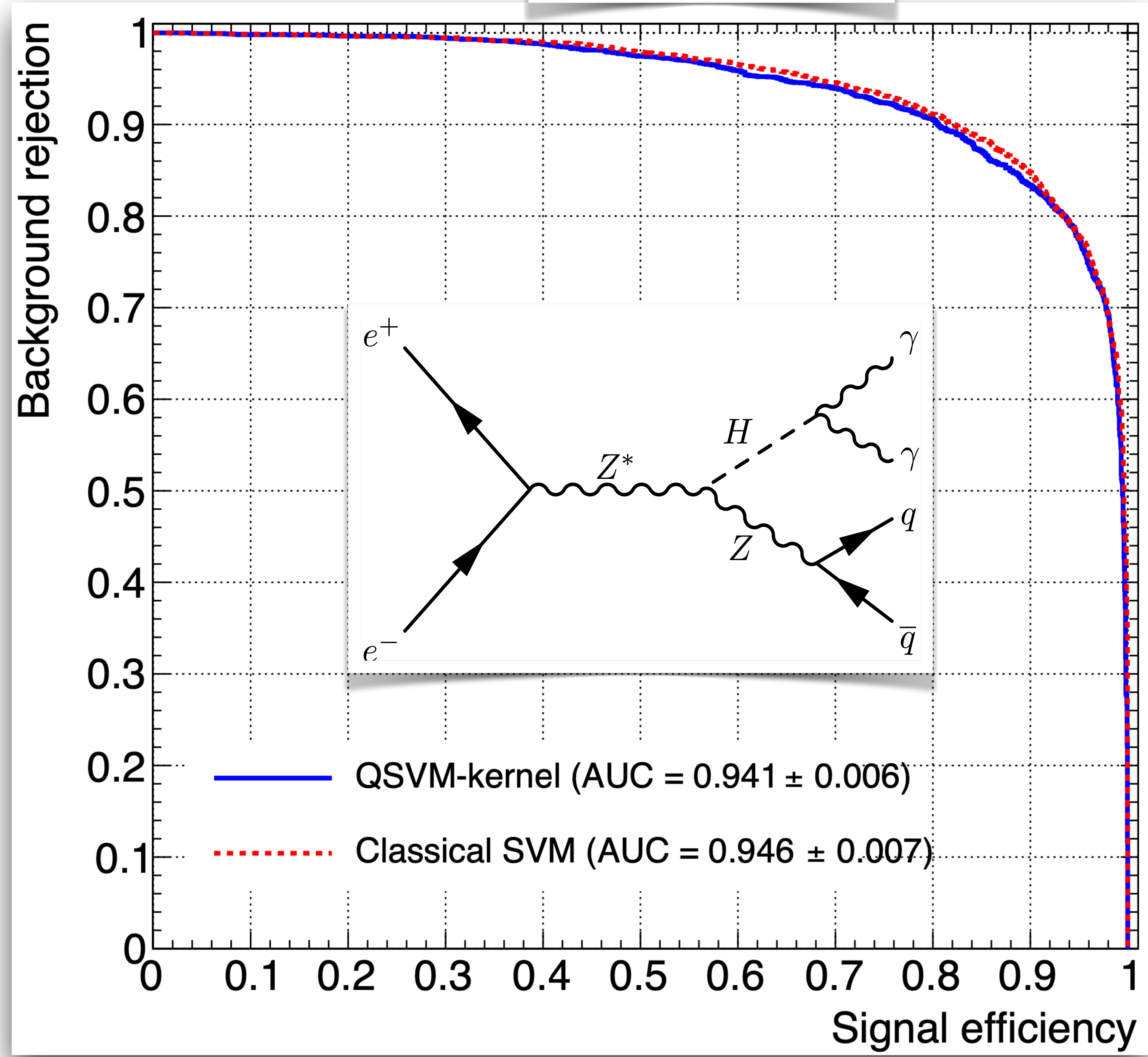
- ☐ **The quantum simulator has the following:**
  - ○ Statevector Simulator developed by the **Qiskit software package**



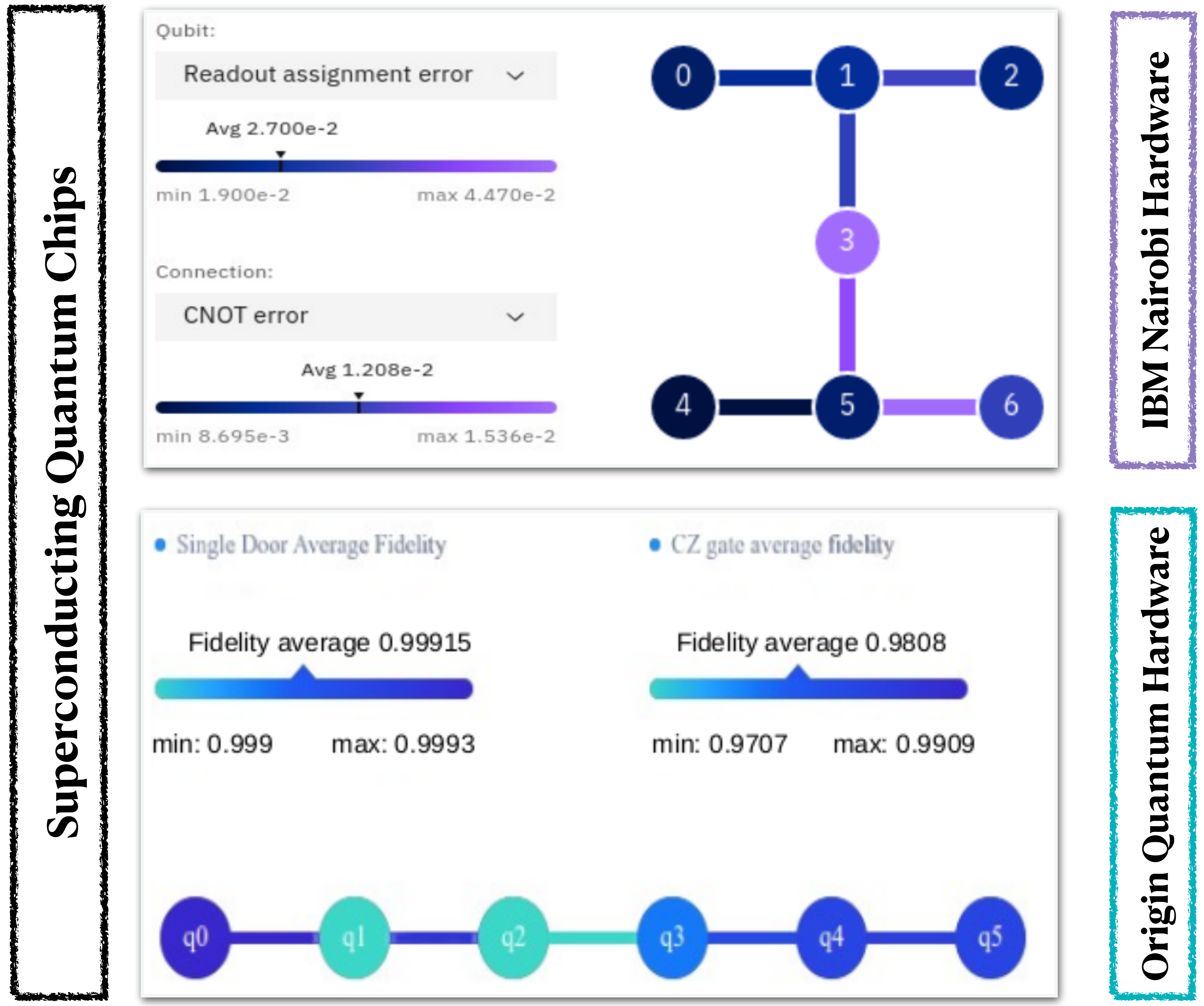




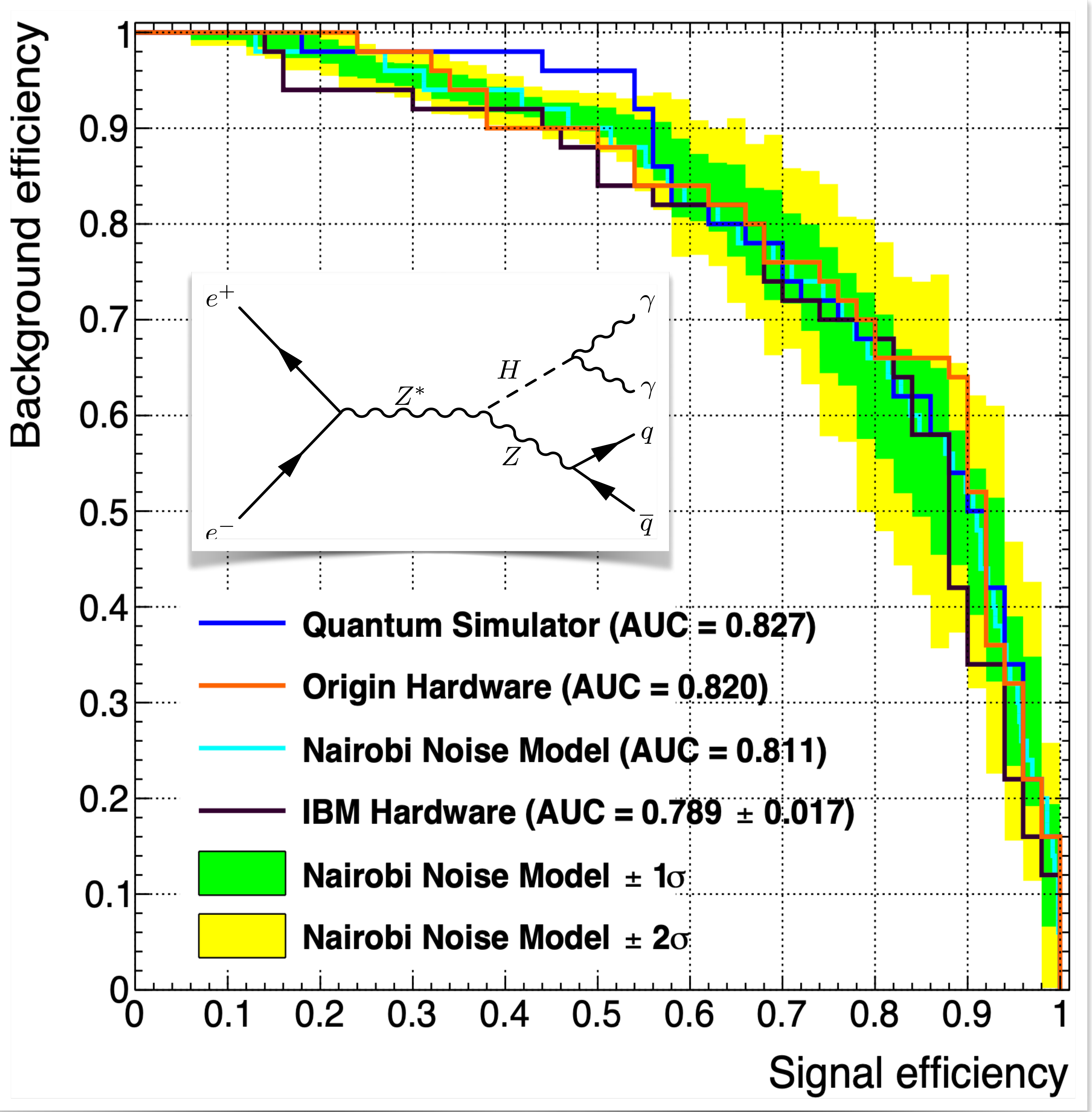
  - ○ Six quantum bits or simply qubits
- ☐ A total of 12000 events were used.



The performance of quantum computers

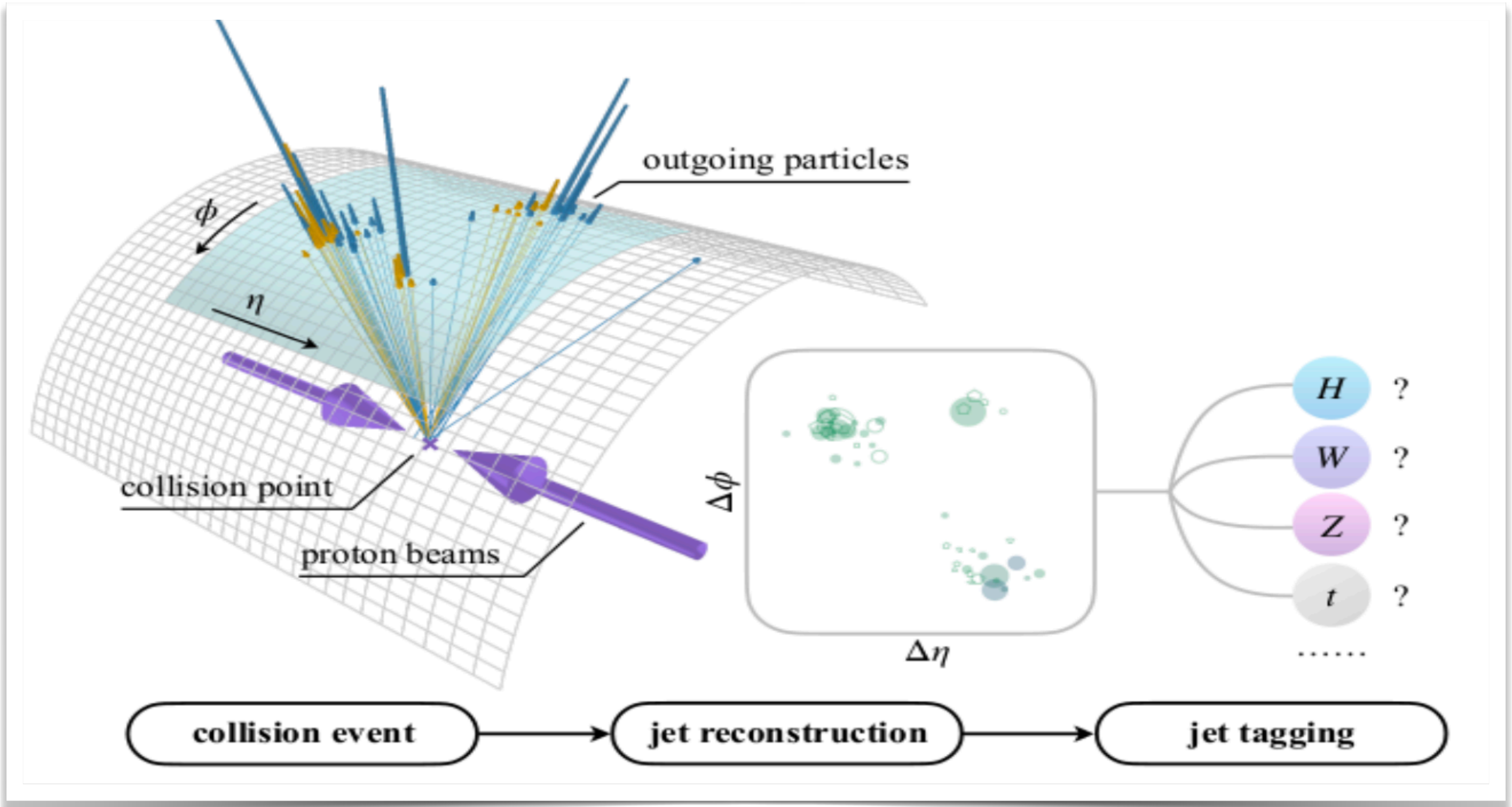


- ☐ Six qubits were used for both quantum hardware.
- ☐ 100 events were used for the training and testing.
- ☐ Comparable performance is observed between the IBM and Origin quantum hardware.



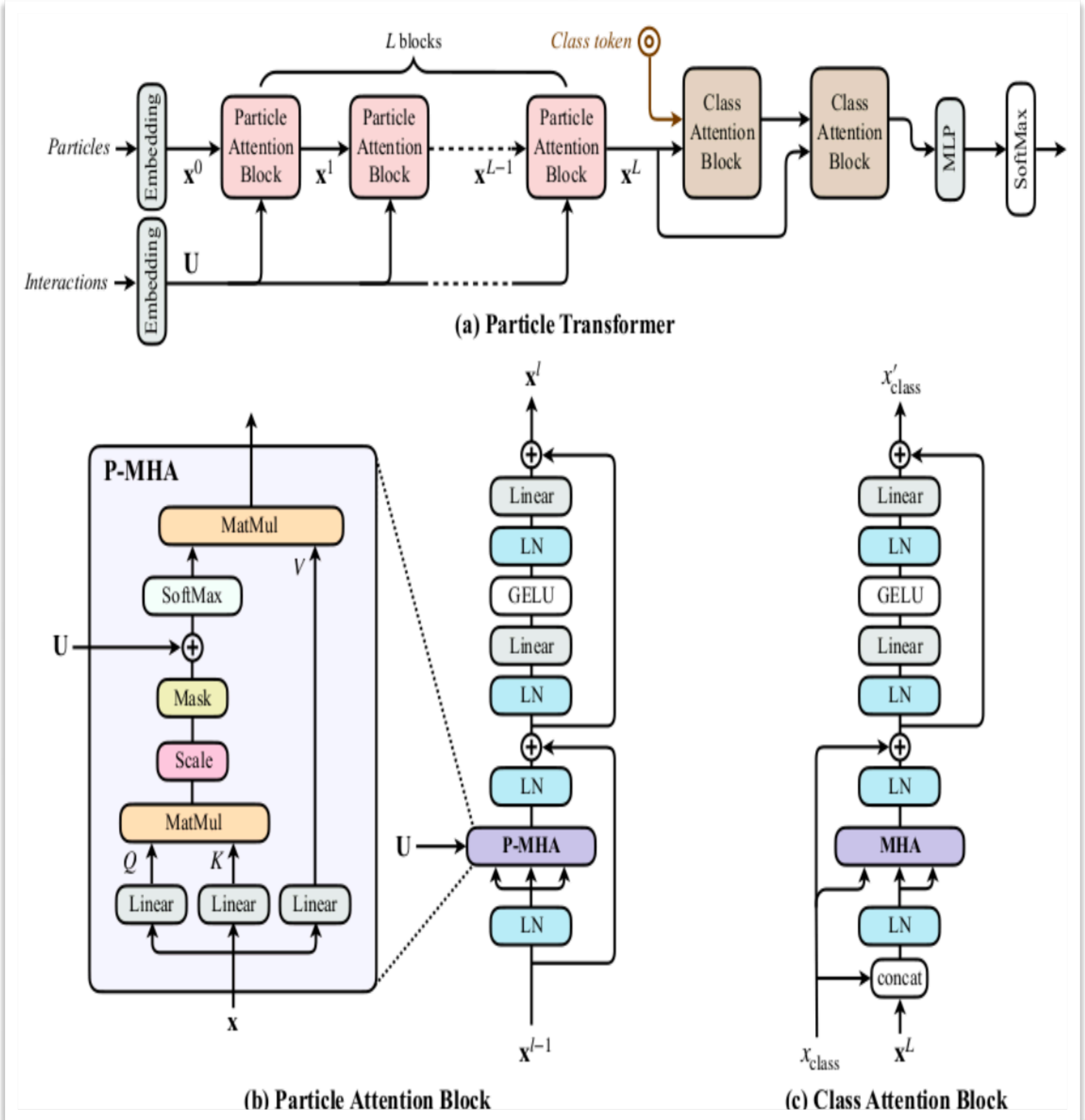
The Quantum Particle Transformer

- ☐ Jet tagging classification in particle physics



- ☐ Particle: a list of features for each particle
- ☐ Interactions: features involving a pair of particles
- ☐ Passing through a series of "attention" to MLP
- ☐ ArXiv: 2202.03772: Particle Transformer

Particle Transformer

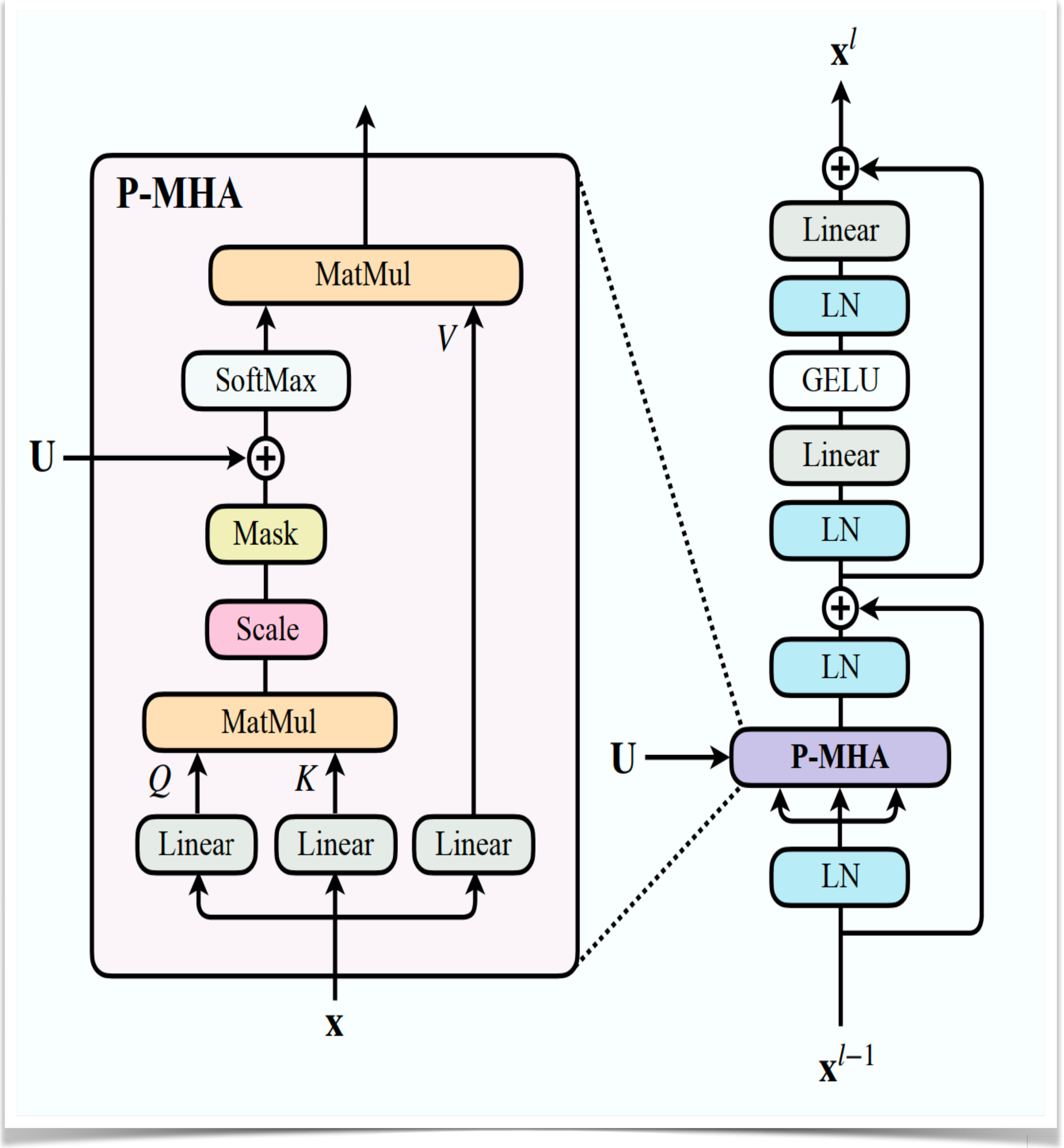


The Quantum Particle Transformer

- **Simplified version of the transformer**
  - **Multihead-Attention based on PyTorch**
  - **Three different linear transformations:**
    - W_Q, W_K, **and**, W_V

$$\text{P-MHA}(Q, K, V) = \text{SoftMax}\left(\frac{QK^T}{\sqrt{d_k}}\right) \cdot V$$

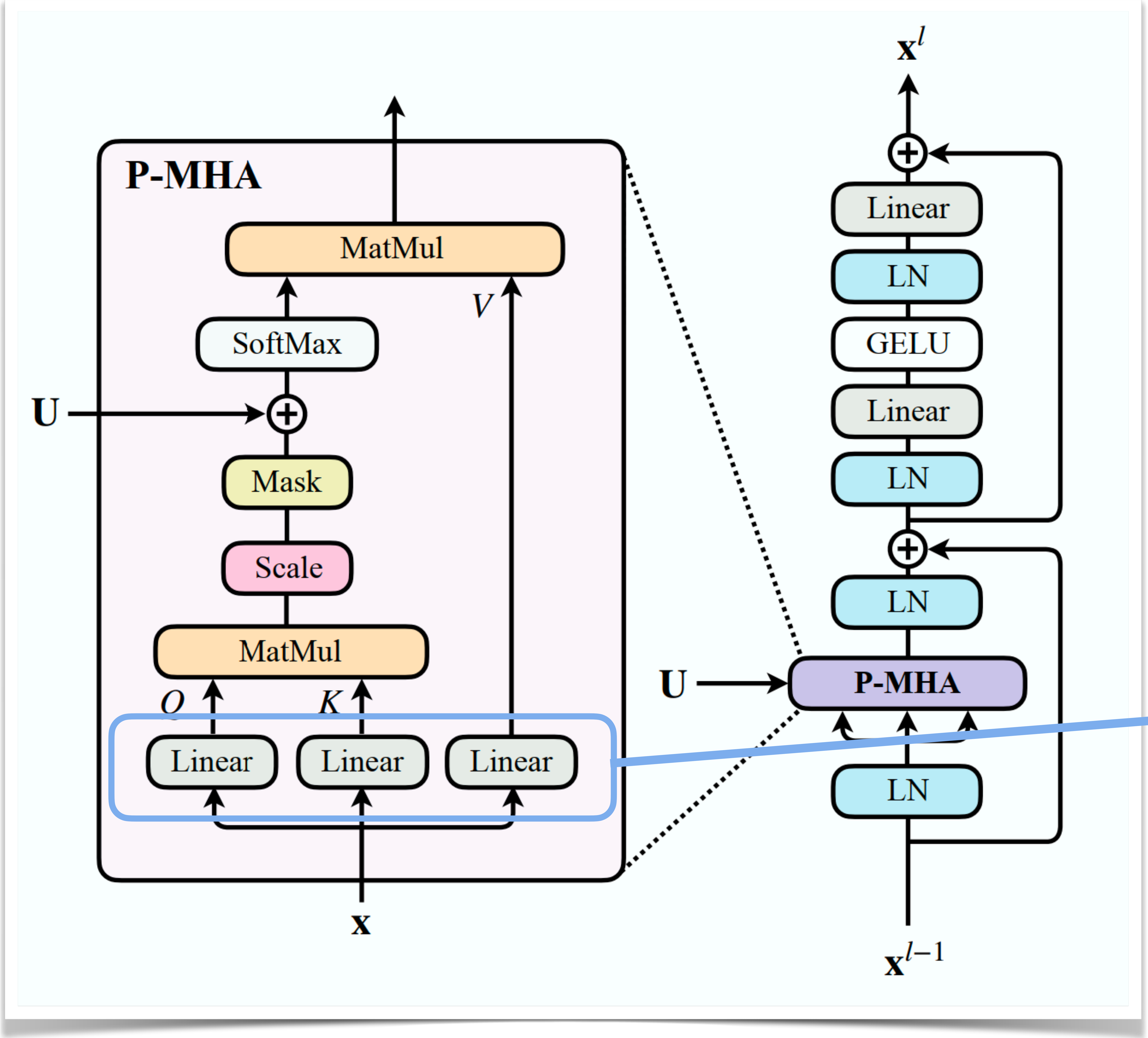
  - **Where Q, K, and V are linear projections of the input.**
- **Going to the quantum version, one could replace the linear transformation with a quantum one.**

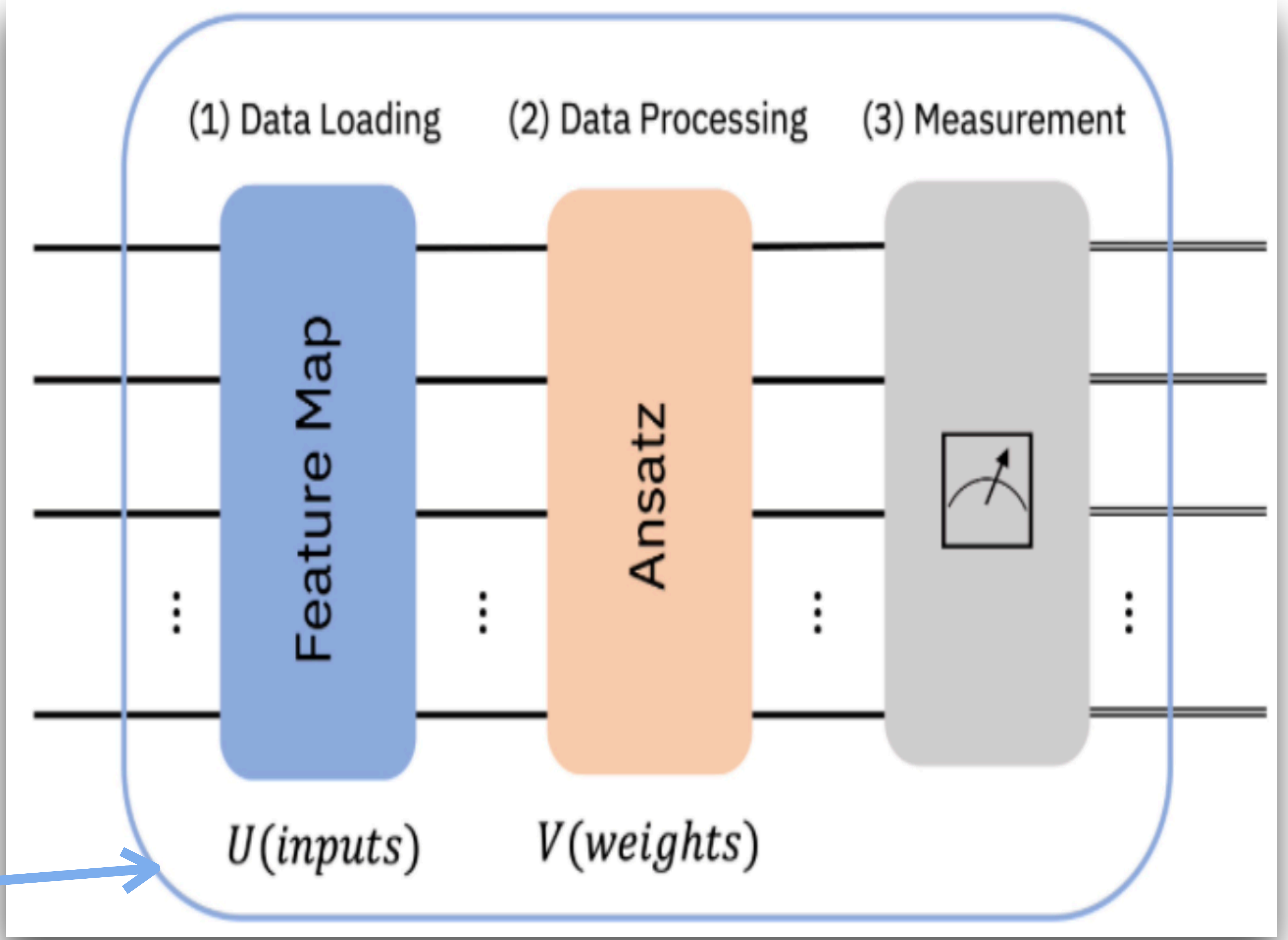


The Quantum Particle Transformer

Quantum Neural Network

- ☐ **Implementing quantum layer instead**

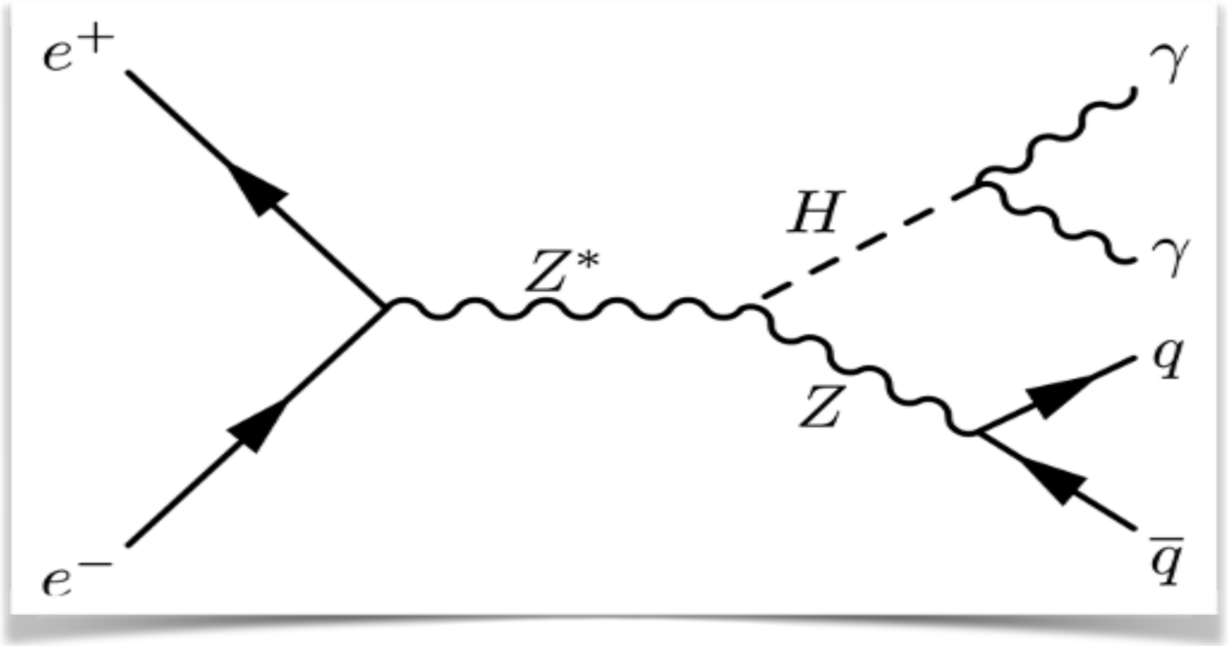




- ☐ **The trainable parameters are added using the Anzatz with a feature-map that acts as an encoder.**

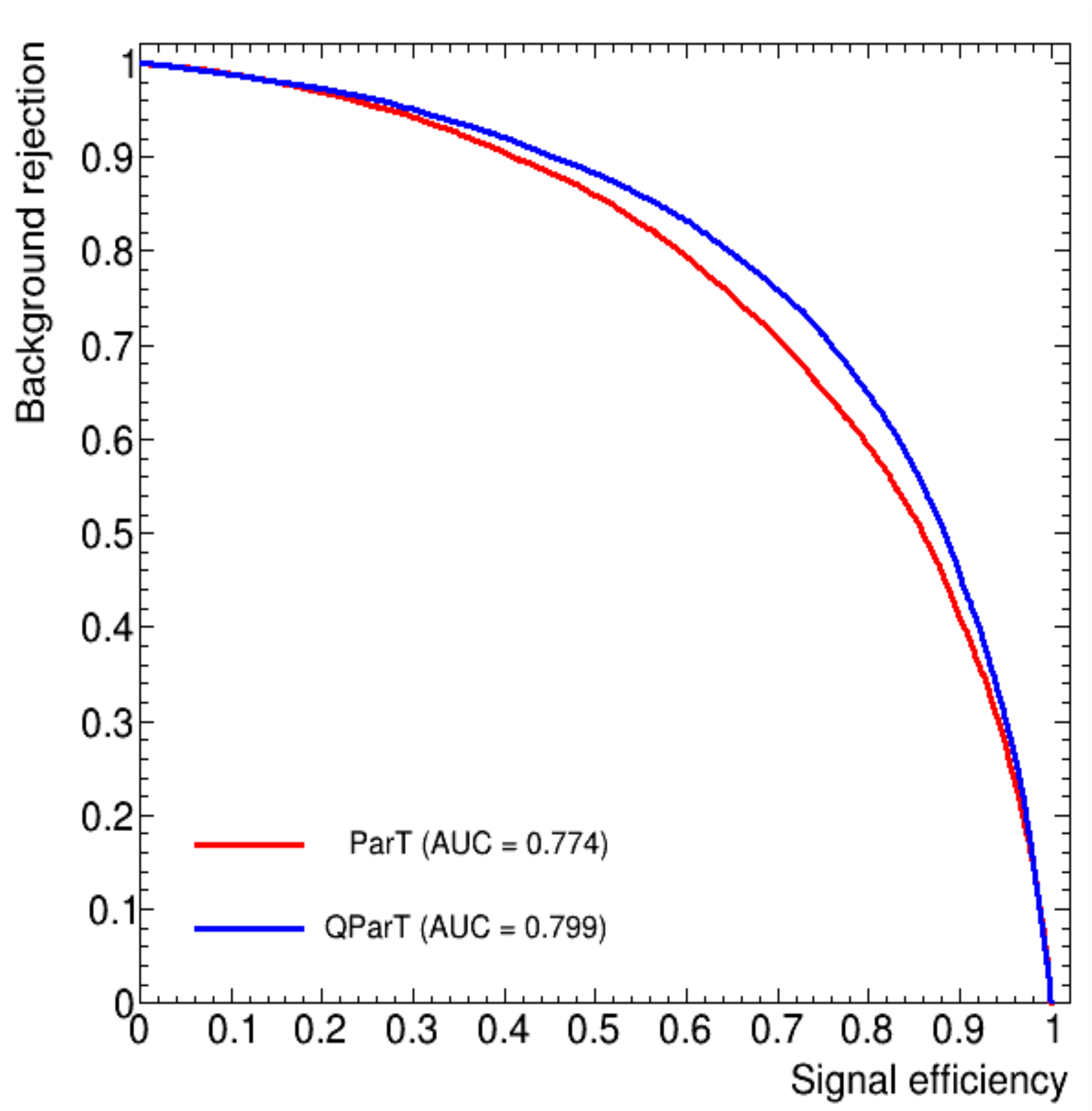
The Quantum Particle Transformer

- Using the Particle Transformer as signal and background classifier for:



- Kinematics of photons, jets and their combination were used as input:
  - $p_{\mathbf{T}}$, p_x, p_y, p_z, E, η, and ϕ

- Training size: 15k entries for each class.
- Testing size: 10k entries for each class.



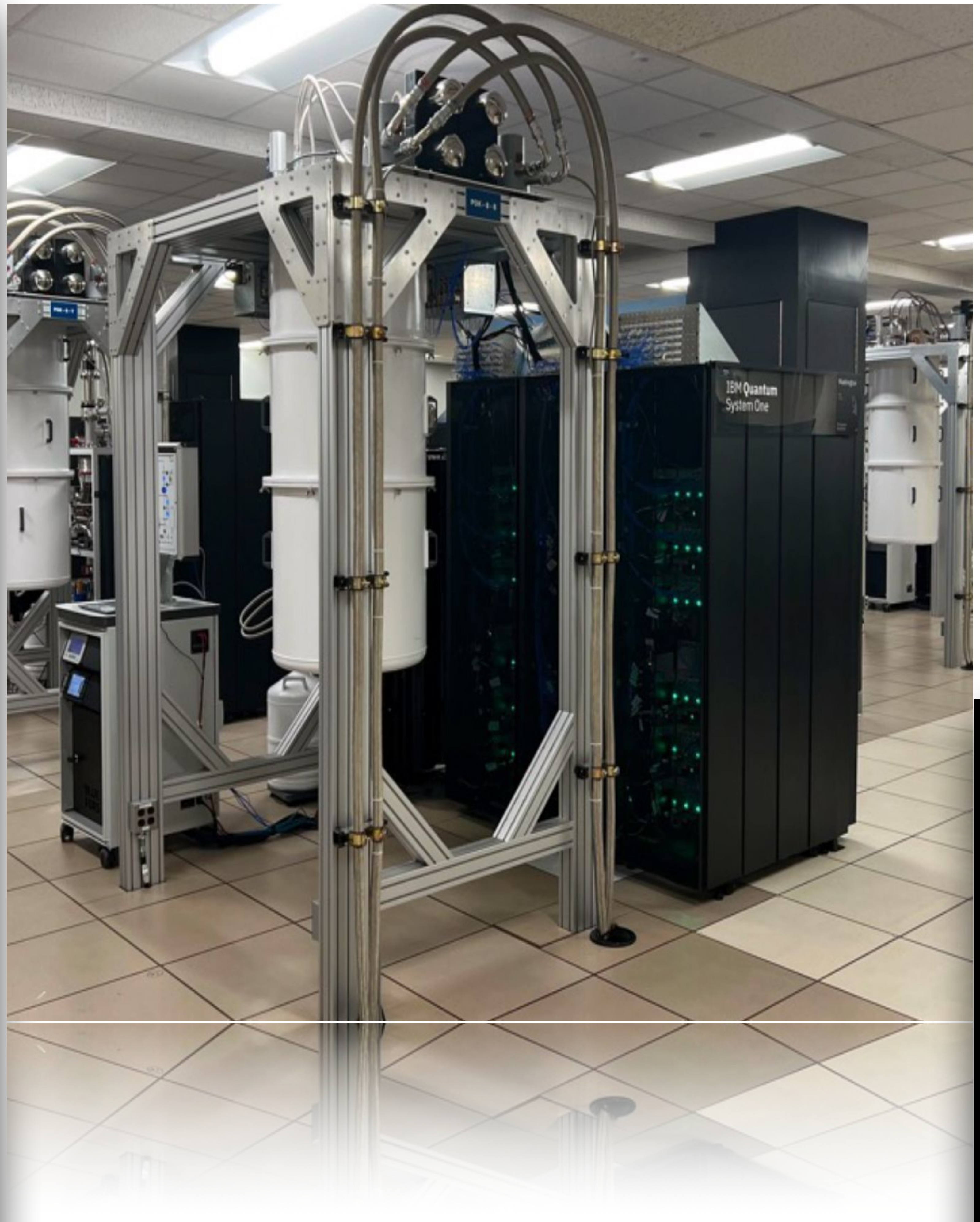
Conclusion

- Provided a quick overview of the research performed within the past year.
- One paper comparing the performance of a support-vector machine was published:
    - A similar performance between classical and quantum was obtained.
    - Study the noise effect with a simplified model.
- The ATLAS physics analysis paper was submitted to the Journal of High Energy Physics.
- We constructed a quantum self-attention based on a quantum neural network.
- Which is then used to build a Quantum Particle algorithm.
- We submitted a grant application to the NSFC under the Research Fund for International Young Scientists (RFIS-I).
- Plans and goals:
    - Optimise the performance of both Particle Transformer and Quantum Particle Transformer.
    - Figuring out the optimal way to use the available quantum hardware as they are very expensive.
    - Generating more events to improve the statistics.
    - Publishing the results in a peer-reviewed journal.

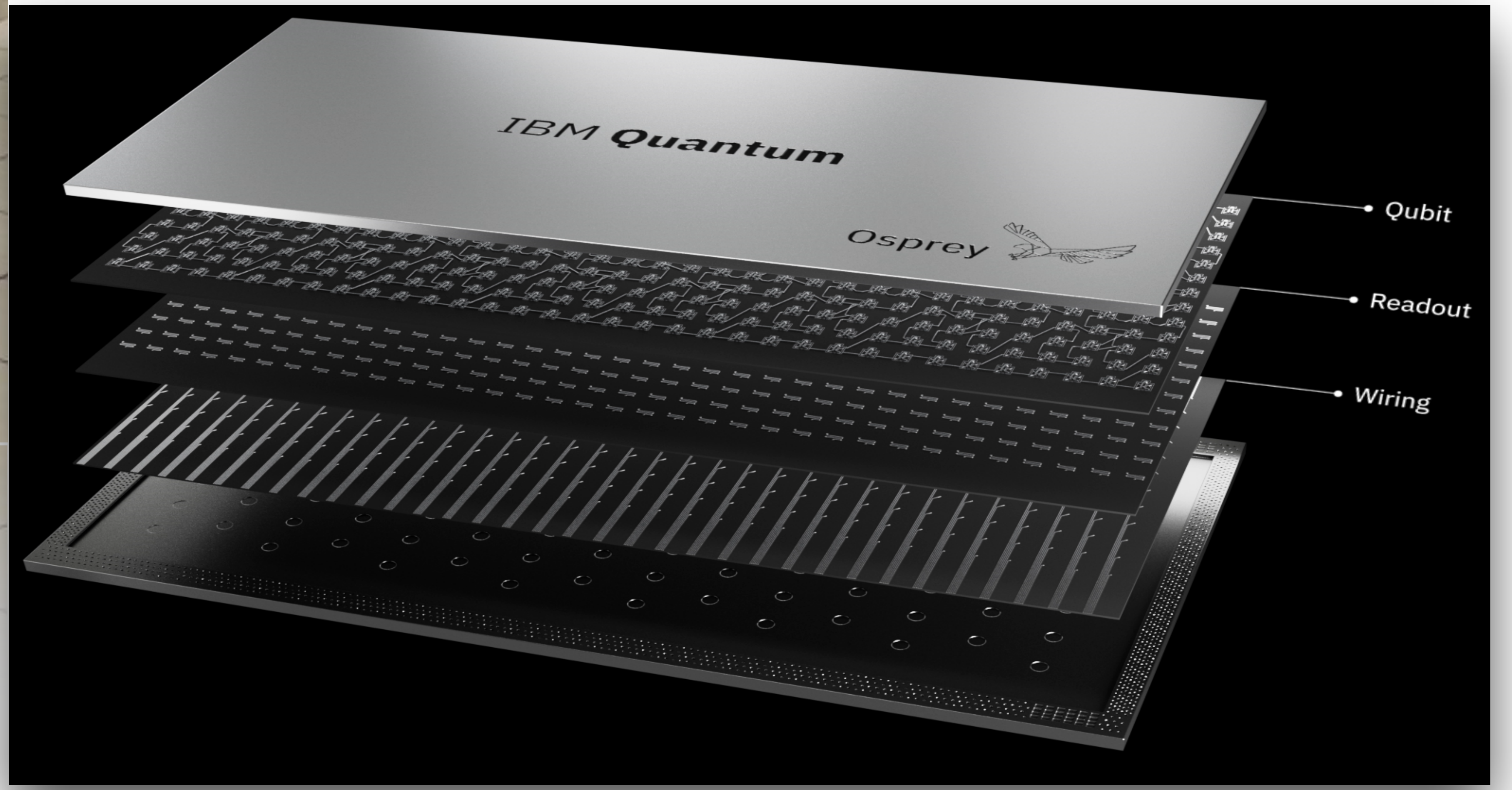
Additional Slides

IBM quantum computer

Credited to Thomas Prior for TIME

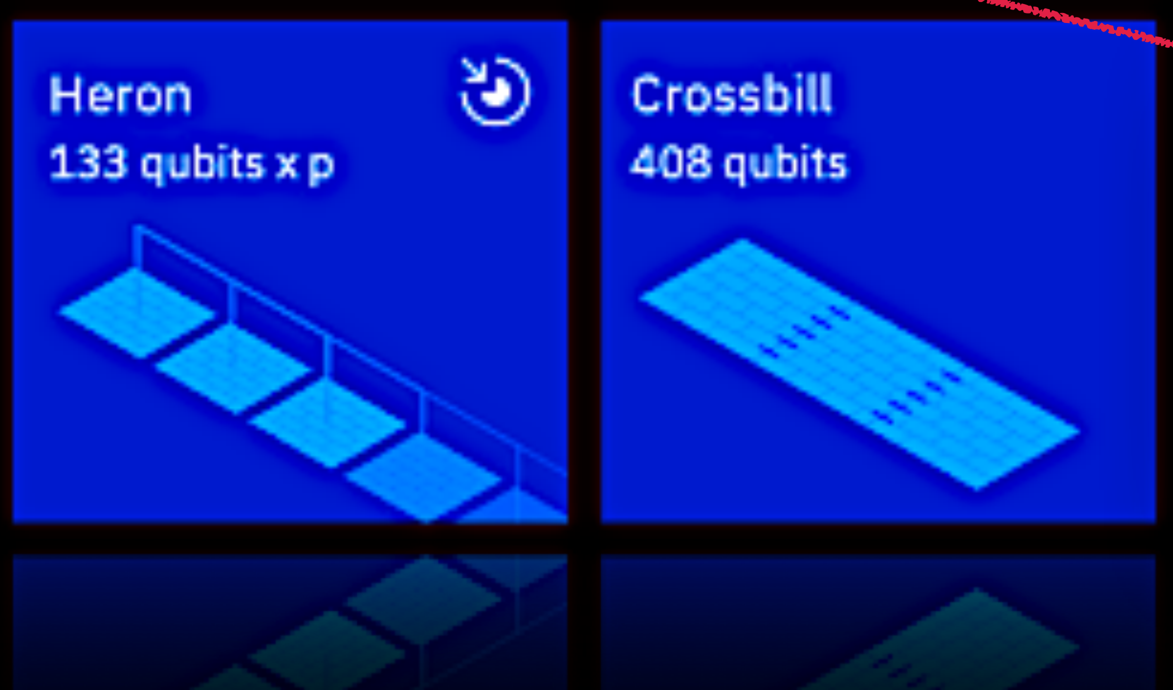


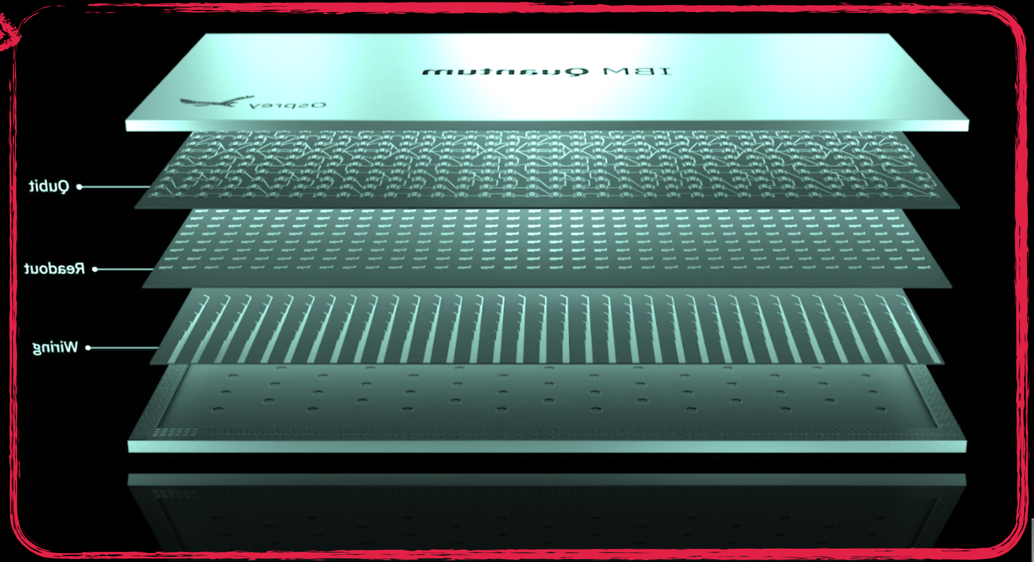
- Taking quantum computing out of the lab:
  - NY Computing Data Centre.
  - It provides over 20 computers.
  - Scales the processor's availability.
  - It provides over 20 comput



- IBM provides up to 7 qubits for free with an opportunity to apply for a researcher account with more qubits.

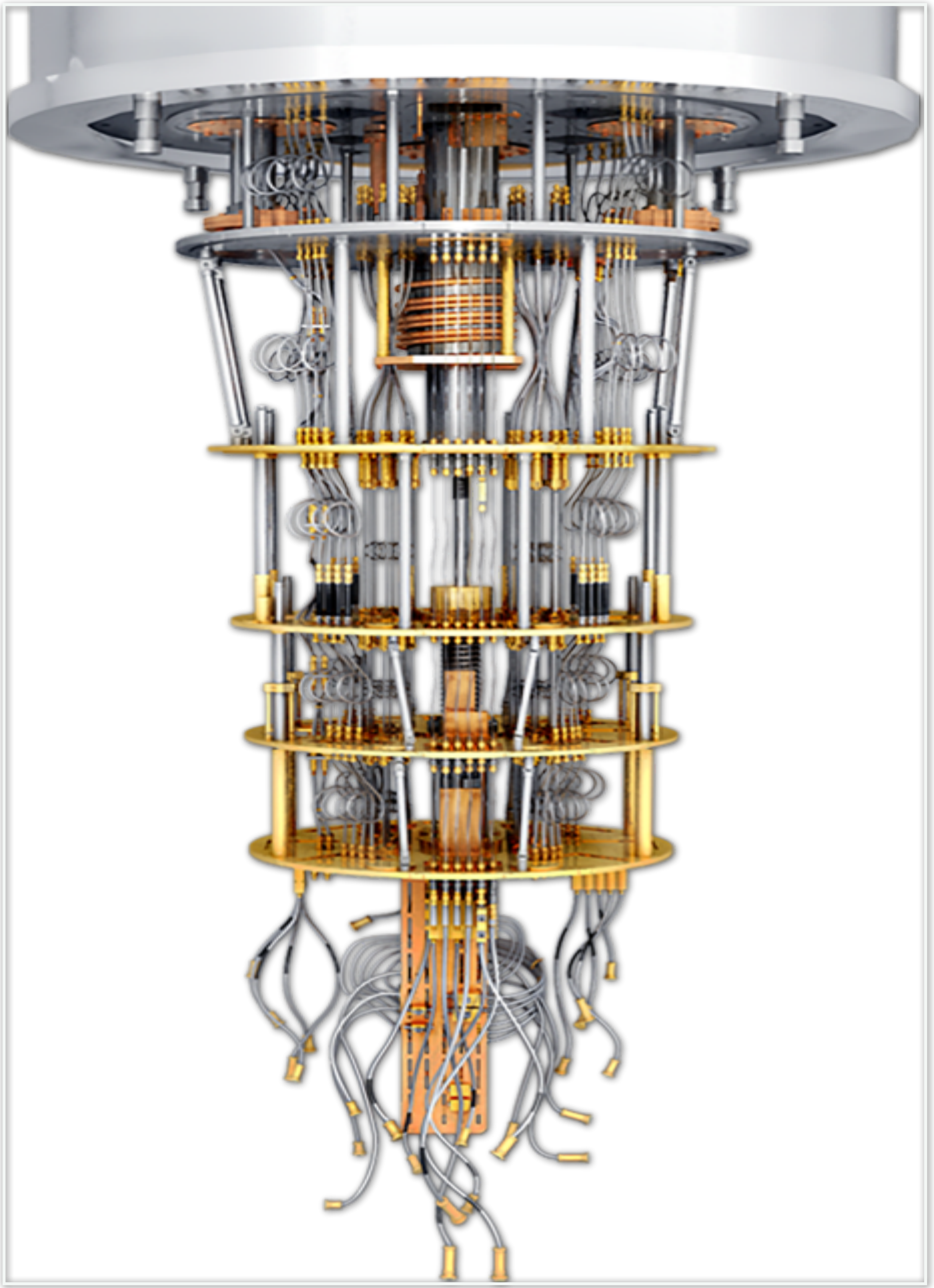
IBM quantum computer roadmap





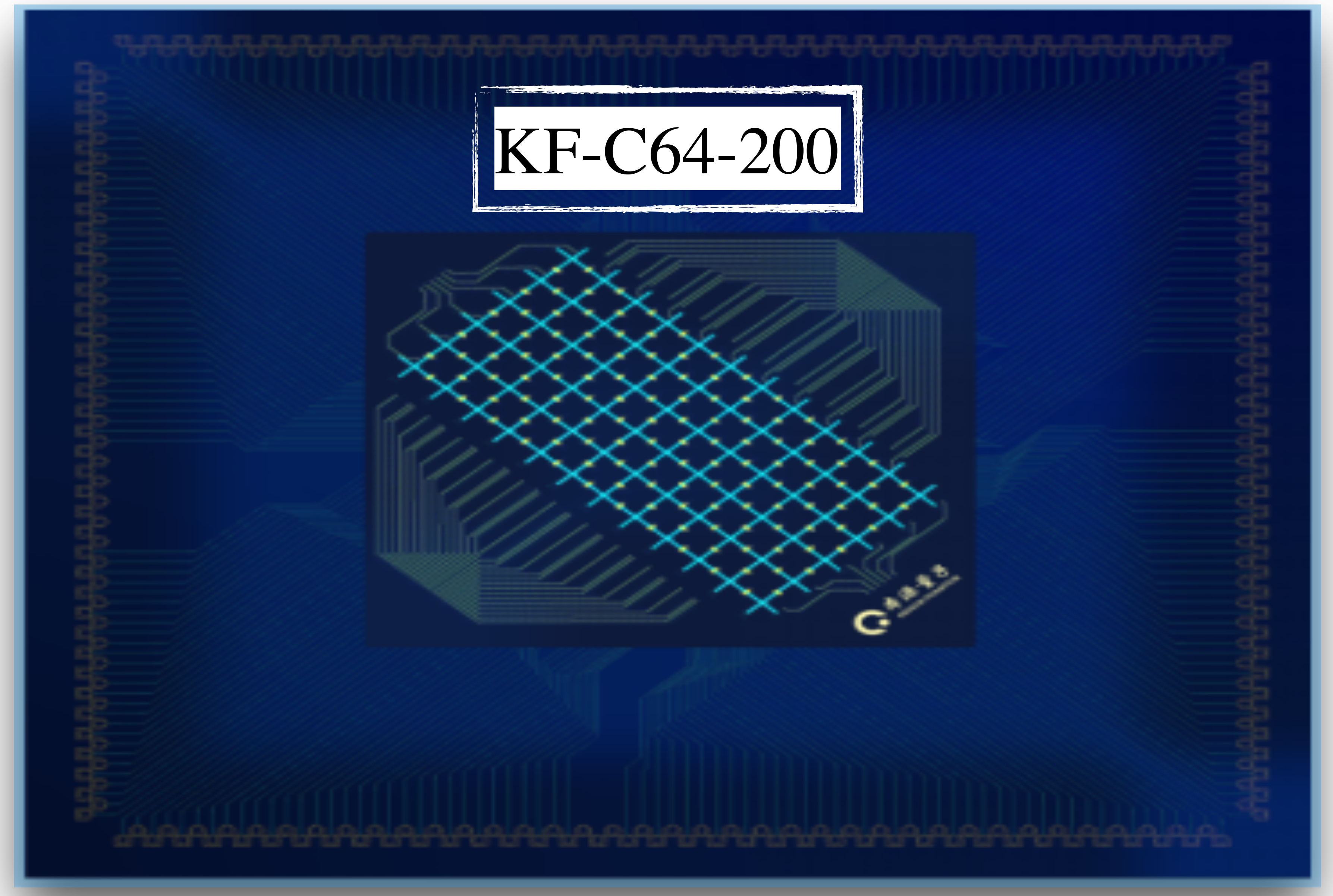
- IBM has ambitious pursuits:
  - 433-qubit IBM Quantum Osprey
  - three times larger than the Eagle processor
  - going up to 10k-100k qubits

Origin quantum computer



Taken from Origin web page

- Origin launched 64-qubit QPU:
  - Single-qubit gate fidelity > 99.9 % .
  - Double-qubit gate fidelities > 98 % .
  - Readout fidelities > 96 % .



- Origin quantum computer provides up to 6 qubits for free. However, another hardware called Quafu provides up to 136 qubits. The Beijing Academy of Quantum Information Sciences maintains it.