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Quantum Circuit Optimization for Scientific Applications

W. Jang , K. Terashi, M. Saito, Y. Iiyama,

T. Kishimoto, R. Okubo, R. Sawada, J. Tanaka

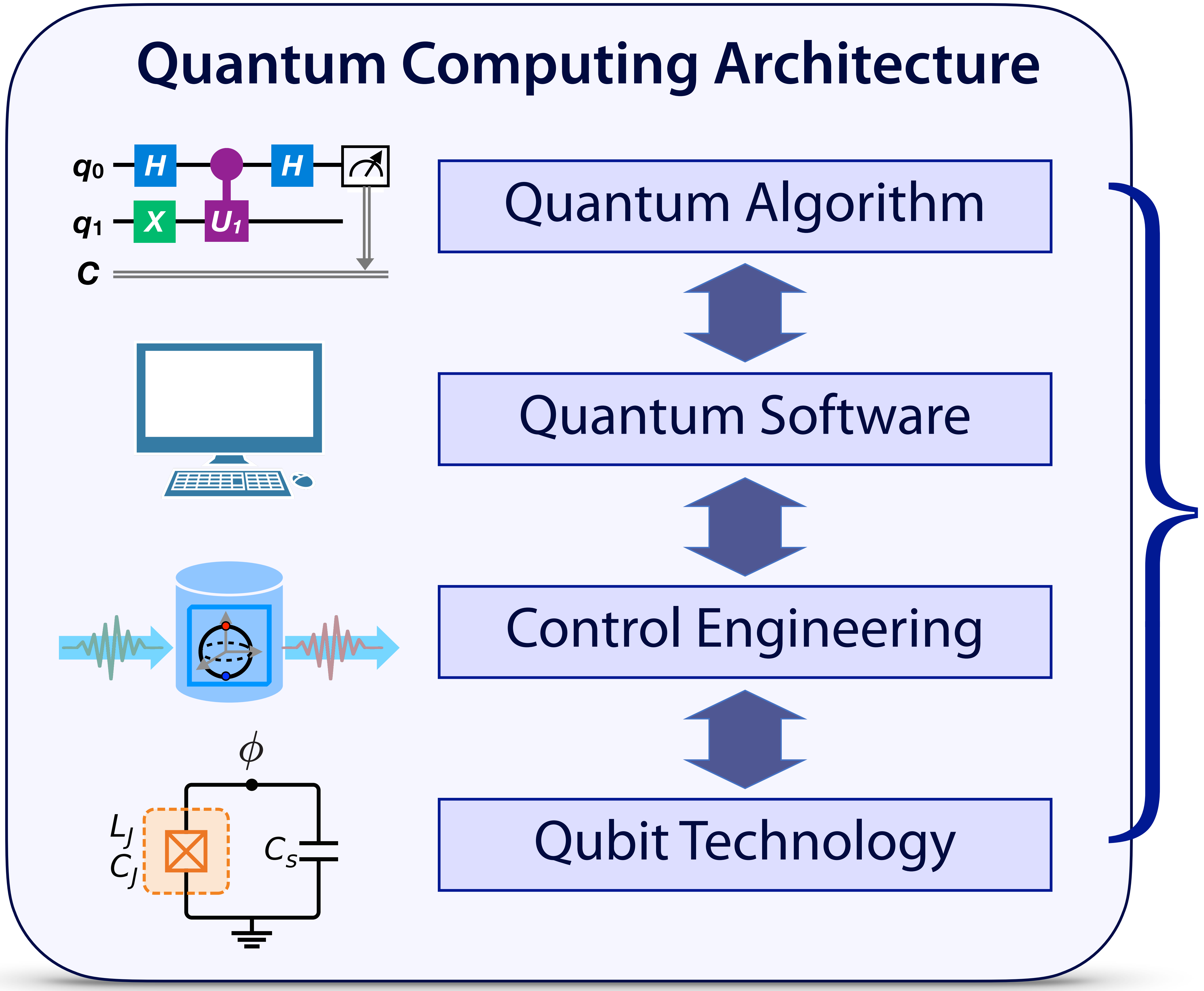
International Center for Elementary Particle Physics (ICEPP)

University of Tokyo

Quantum Computing and Artificial Intelligence

Envisioning artificial intelligence empowered by quantum information processing becoming a transformative technology in fundamental science and industry over next decade

➡ Realize ***Large-Scale Quantum AI*** for scientific discovery and industrial application



Co-designing quantum computing architecture from algorithm to hardware technology crucial for near-term NISQ application

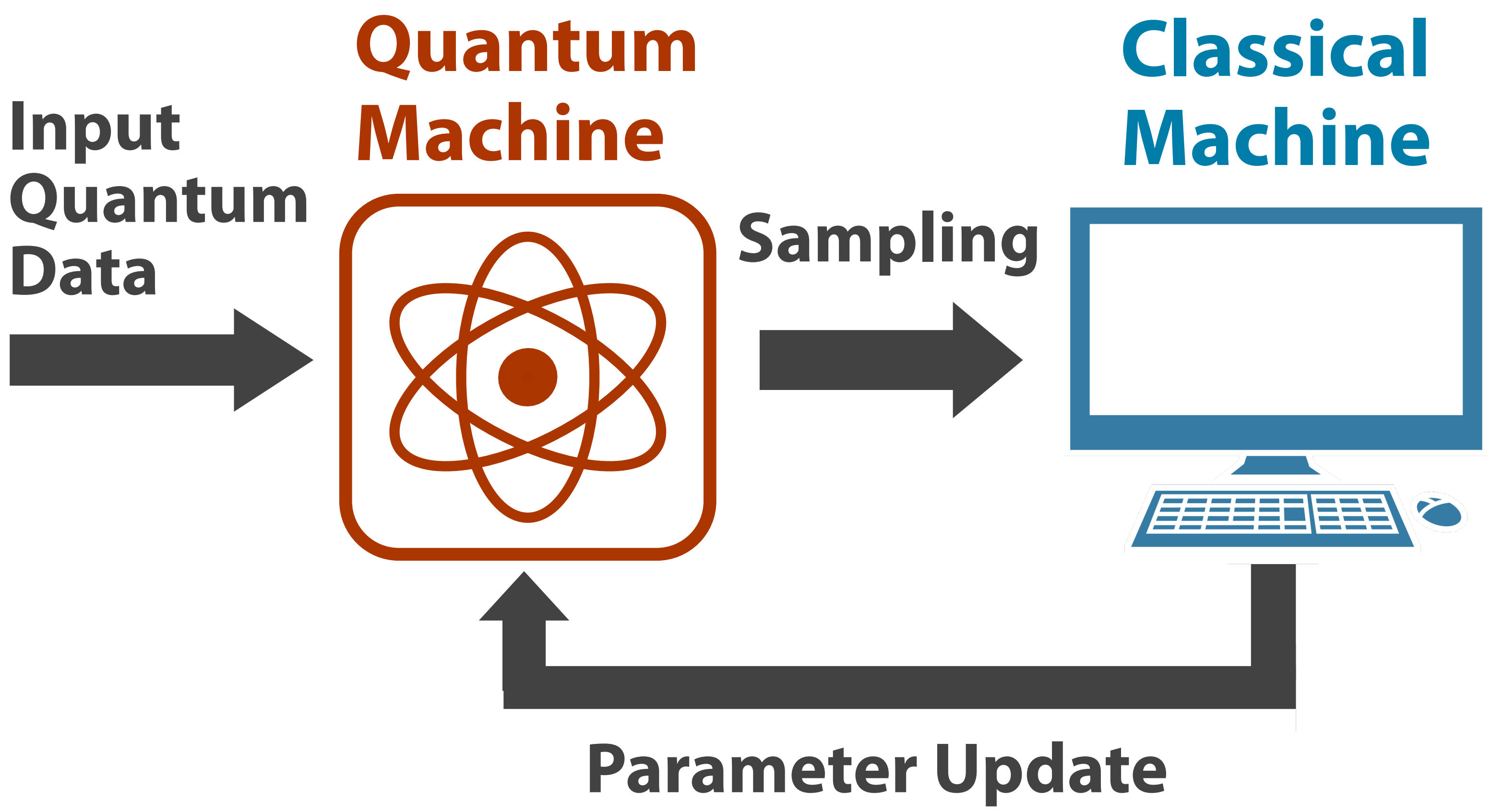
Towards Large-Scale Quantum Artificial Intelligence

Quantum AI group in ICEPP at U. of Tokyo working on :

Quantum Algorithm

Advanced quantum-classical hybrid QML architecture

Quantum data learning

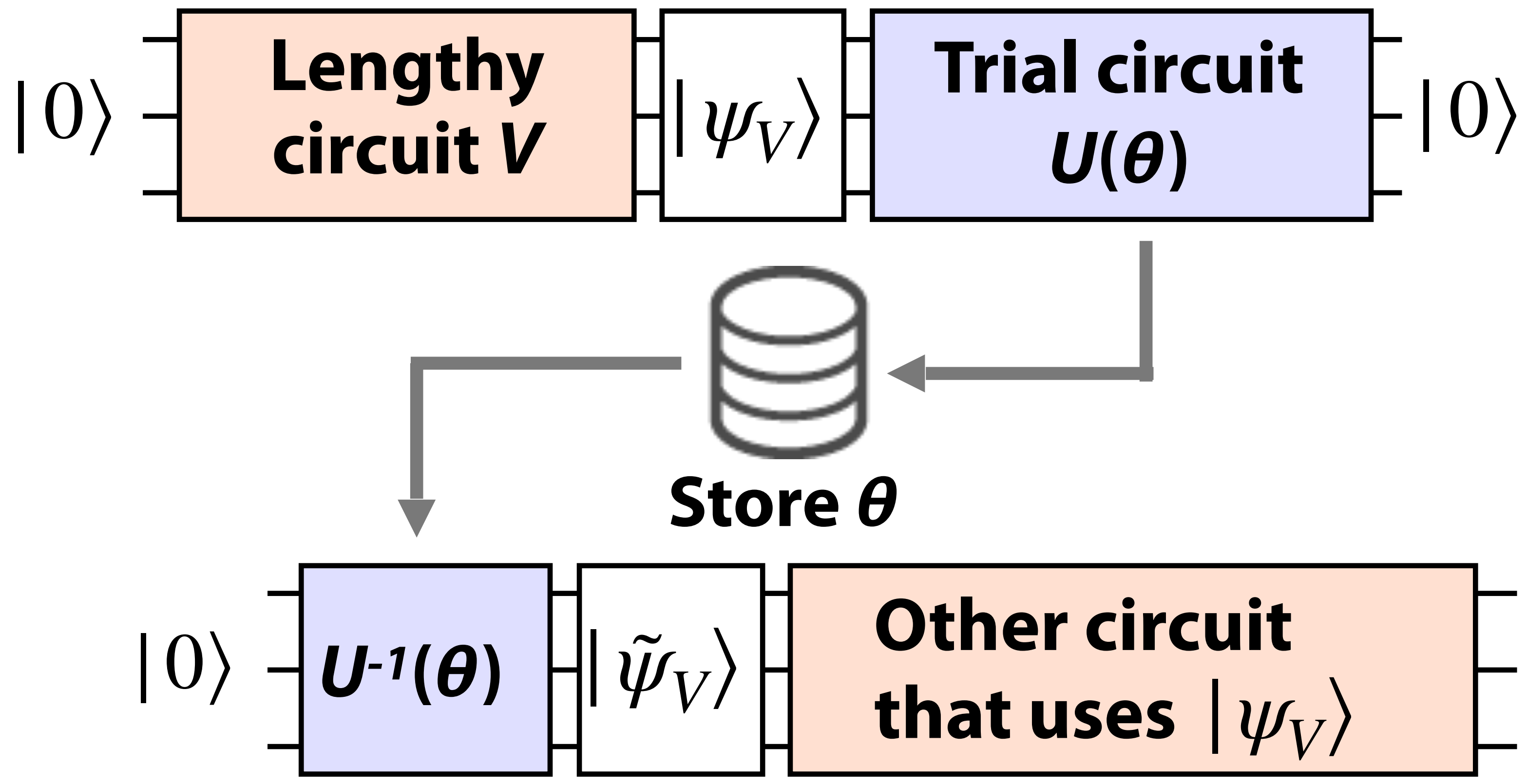


Open up a new way to design quantum experiment

Quantum Software

Efficient/Error-tolerant quantum circuit for NISQ

Pseudo quantum memory

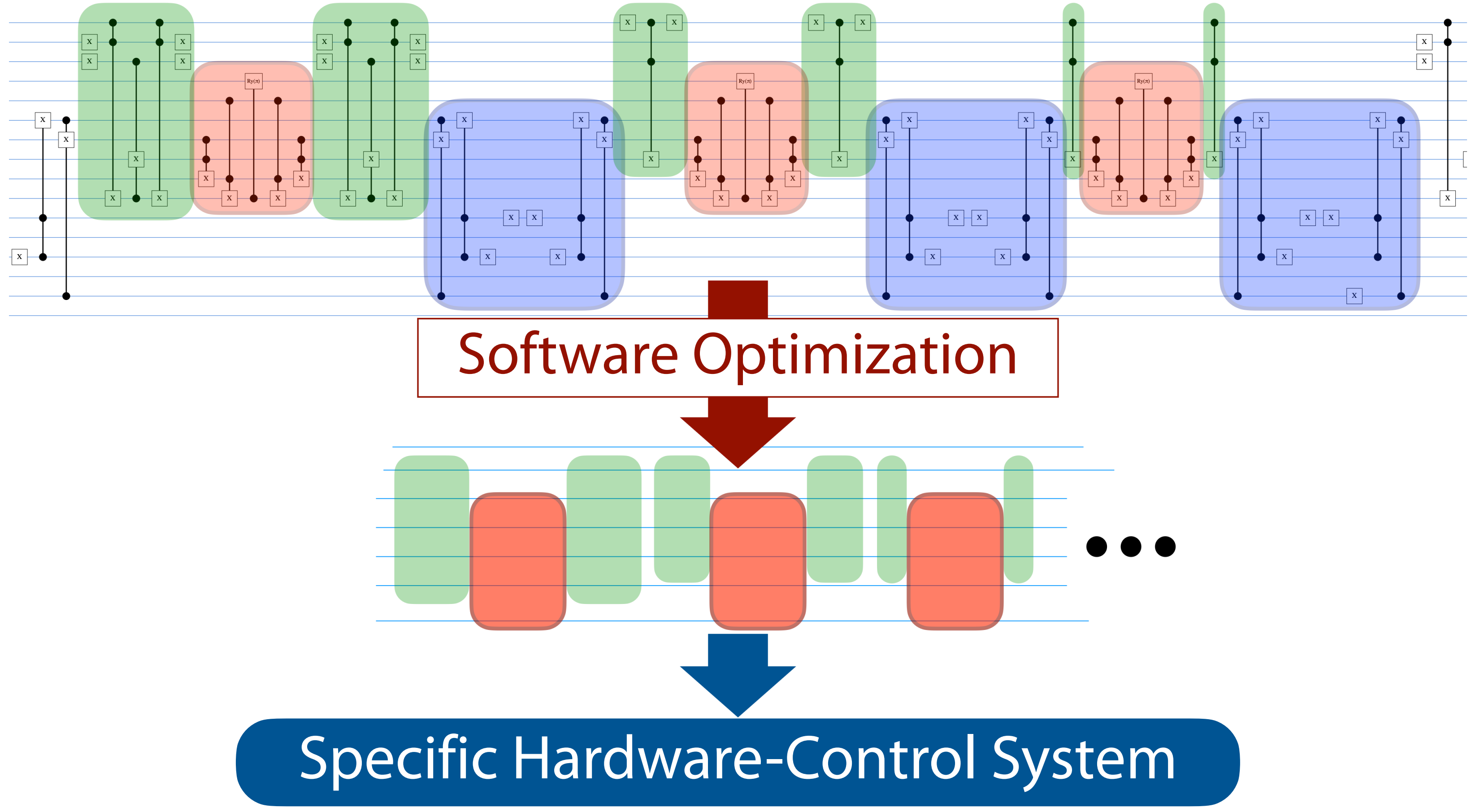


Allow complex quantum computation with NISQ machine

Quantum Software Control Engineering

Application-specific circuit optimization with hardware control

HEP-specific circuit optimization



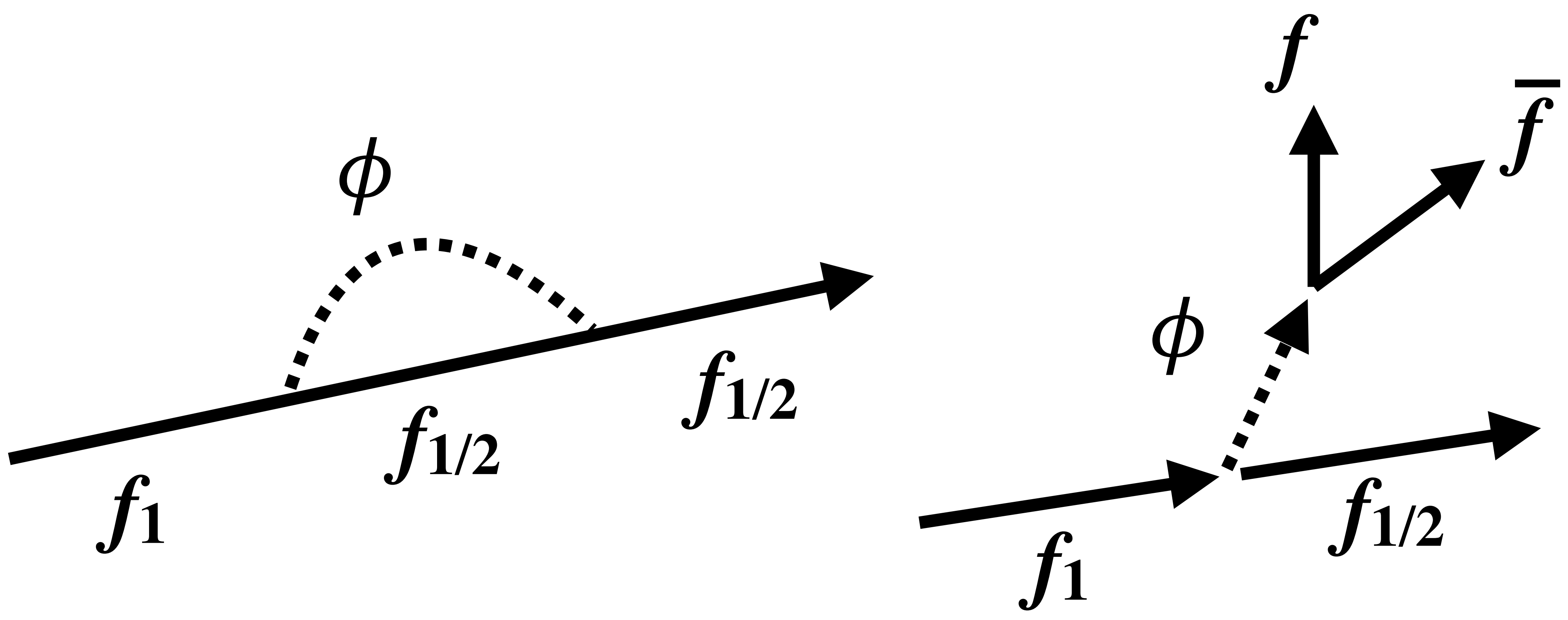
Co-design quantum circuit for specific application

Quantum Algorithm for HEP Simulation

C. W. Bauer, B. Nachman *et al.*
[Phys. Rev. Lett. 126, 062001 (2021)]

Quantum parton shower model:

- Emission of ϕ-boson ($f \rightarrow f\phi$) and splitting ($\phi \rightarrow f\bar{f}$)
- Interference due to two fermion flavors $\{f_1, f_2\}$ in the intermediate states



- Represent emission/splitting processes using matrices of coupling constants
- Emission/splitting probabilities using Sudakov factors
- Create superposition with emission histories and measure

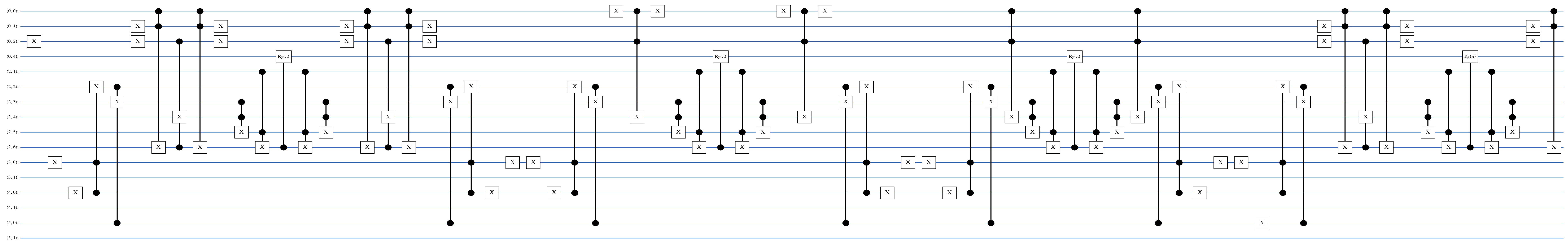
- Quantum circuit composed of many "*repeated*" sets of quantum gates
- Each repeated set represents an individual showering step in sequential Markov-Chain processes

➡ **Aim to design/optimize QPS algorithm for near-term NISQ machine**

- Quantum gate pattern recognition
  → Future hardware optimization for sequential algorithm
- Circuit optimization
  → Make circuit as short as possible to be compatible with present quantum device

Quantum Circuit for Parton Shower Simulation

Only a small fraction of representative quantum circuit for parton shower simulation



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Continues…

Actual circuit contains >1200 gates (after compiling to hardware native gates) just for 2 shower branching steps…

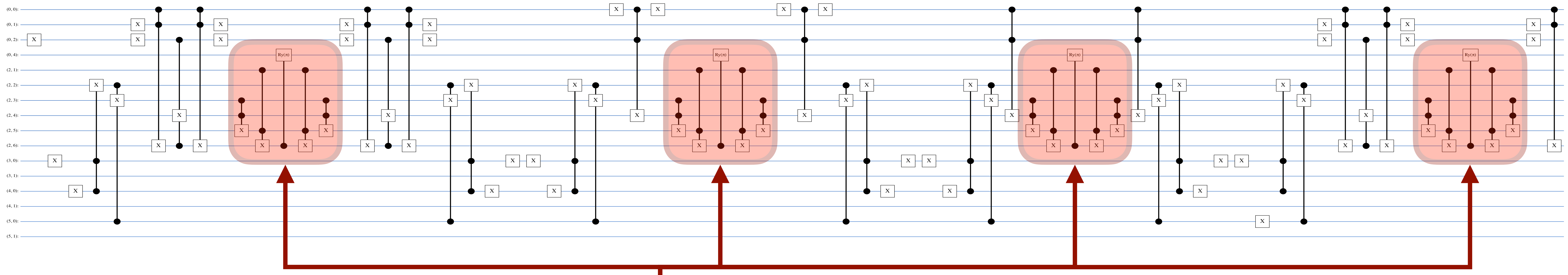
Quantum Gate Pattern Recognition

arXiv:2102.10008

***AQCEL** = **A**dvancing **Q**uantum **C**ircuit by ICE**PP** and **L**BNL*

Developed a novel optimization protocol called **AQCEL** :

- Identification of repeated sets of gates for application-specific gates/hardware control



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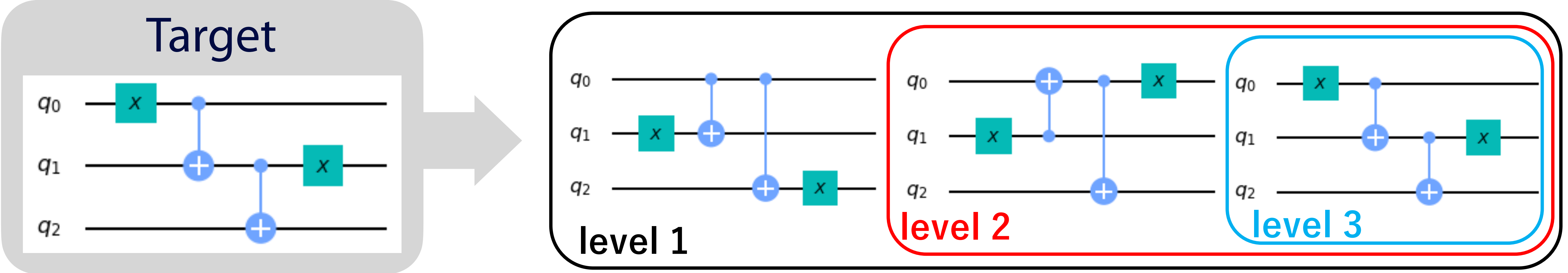
Continues…

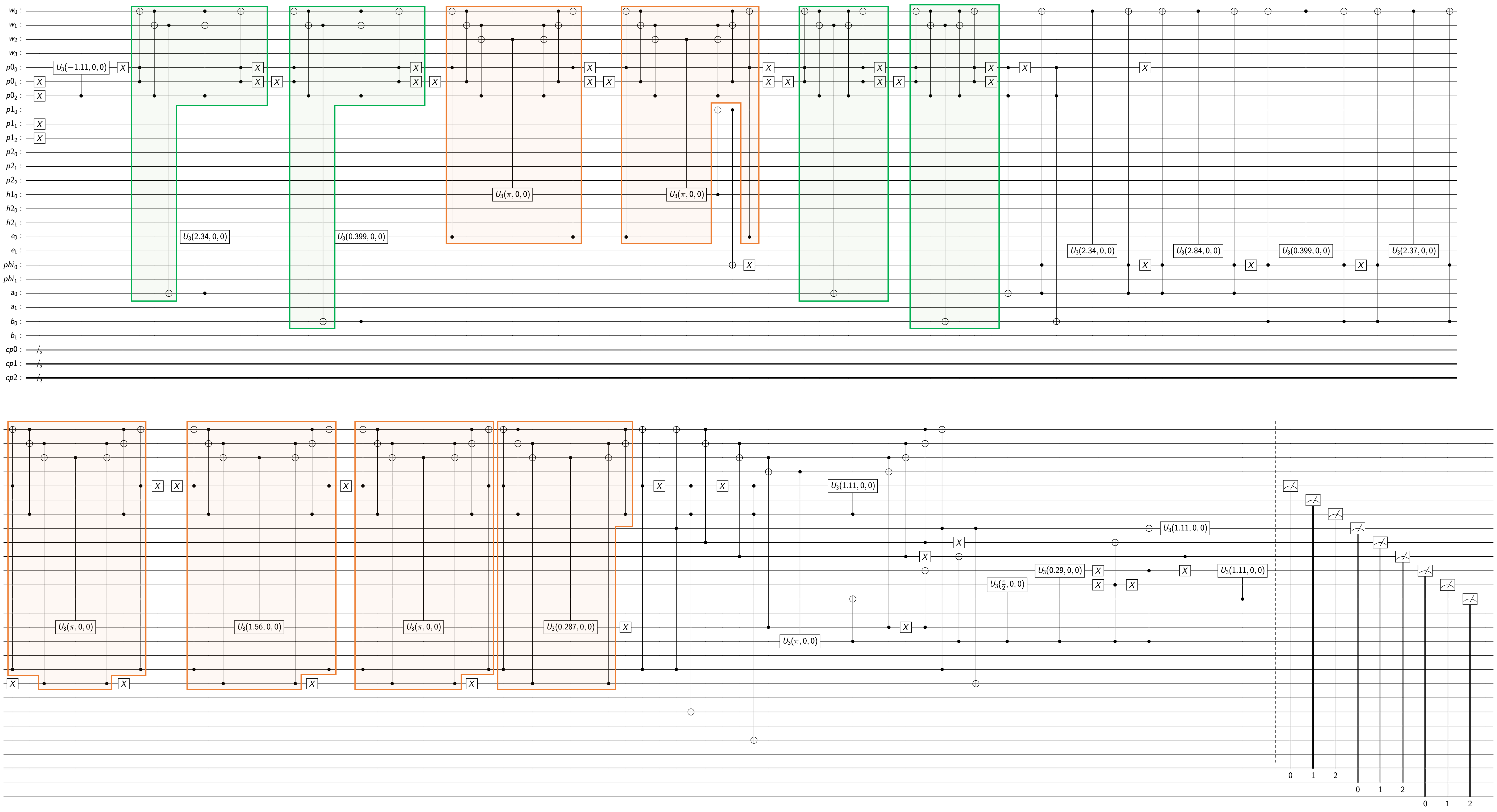
Identification of repeated sets of gates



- Analyze circuit structure using directed acyclic graph
- 3-level pattern matching to identify repeated gates

Recognized Gate Sets for Parton Shower Simulation

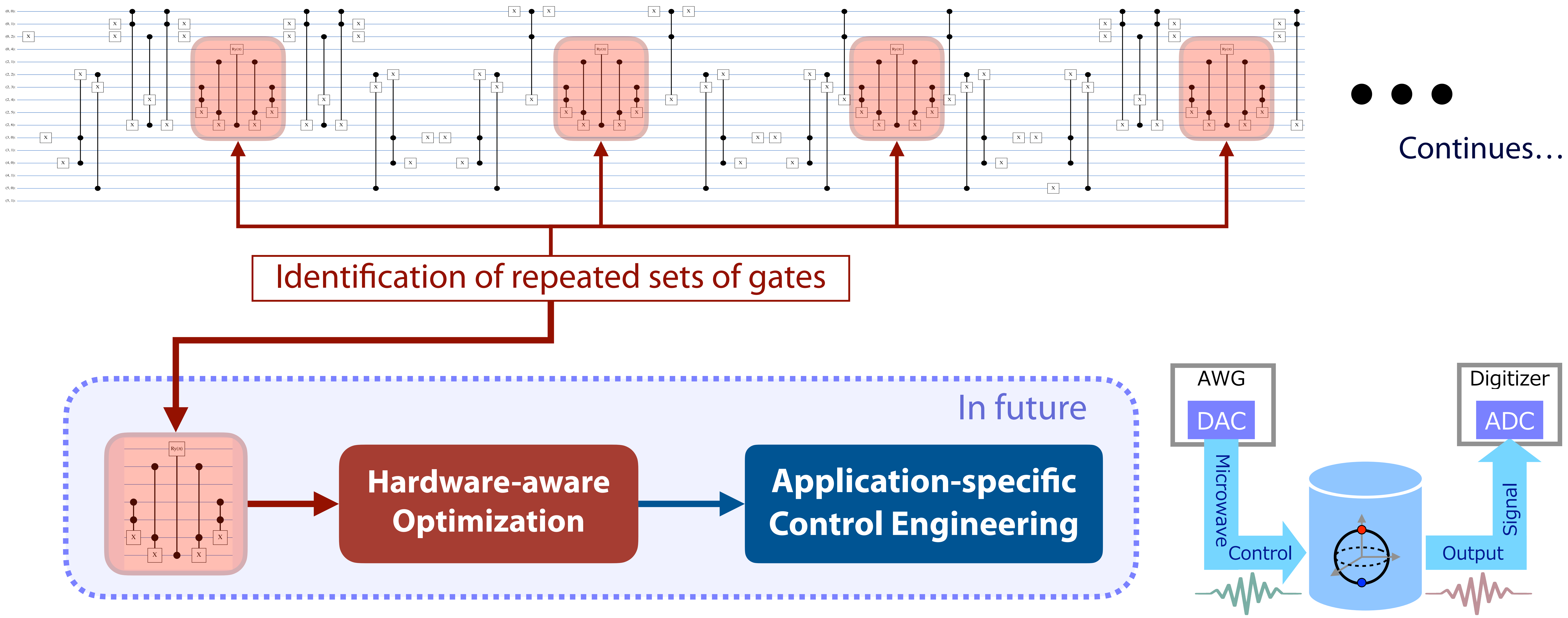
Level-2 matching



Quantum Gate Pattern Recognition

Developed a novel optimization protocol called **AQCEL** :

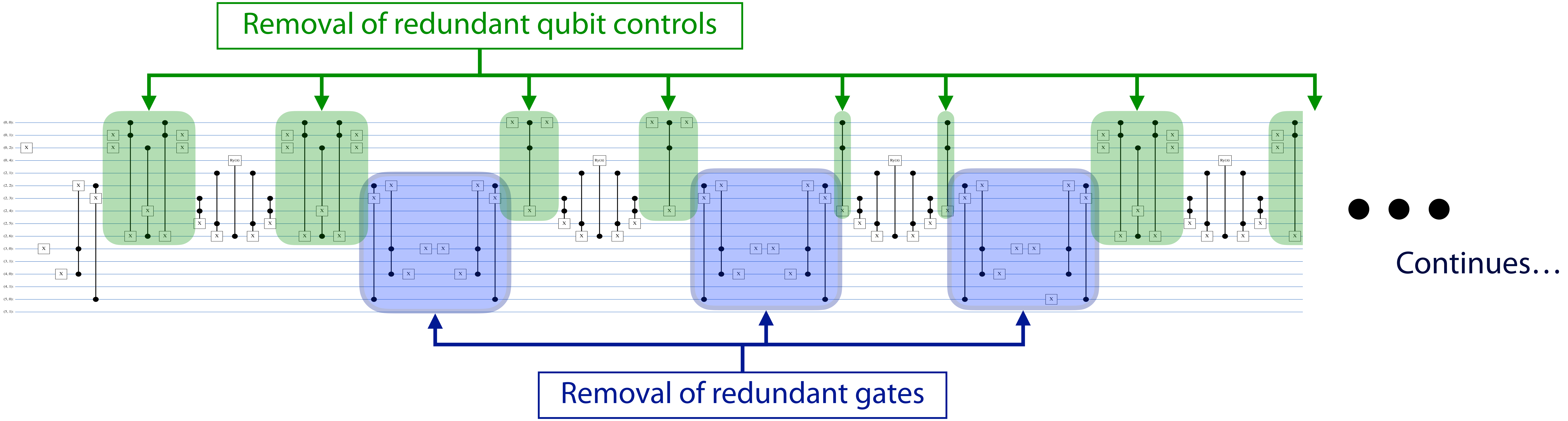
- Identification of repeated sets of gates for application-specific gates/hardware control



Quantum Circuit Optimization

Developed a novel optimization protocol called **AQCEL** :

- Removal of redundant qubit controls by identifying zero- or low-amplitude basis states
- Removal of redundant gates

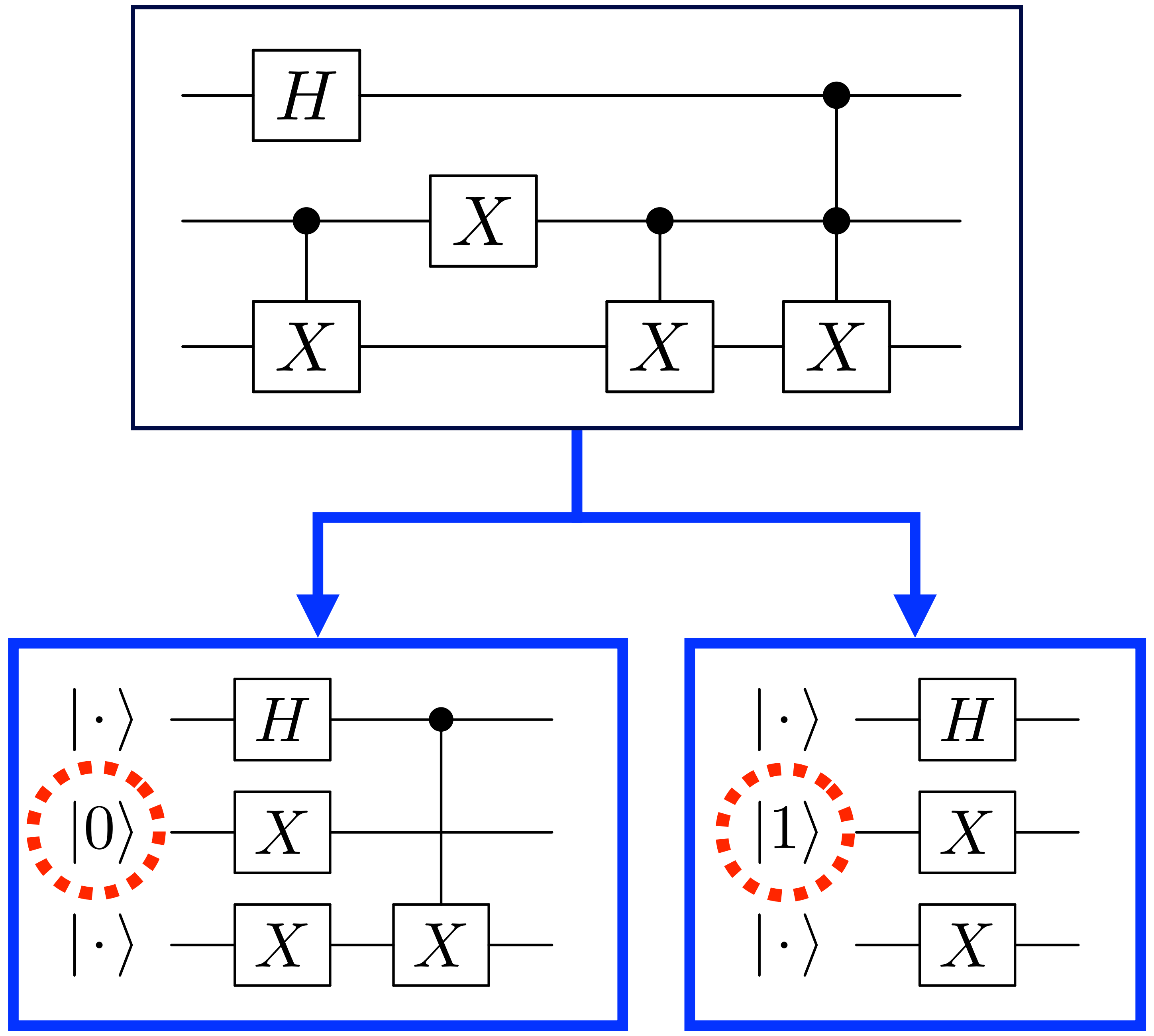


AQCEL Optimization Protocol

2 main ingredients for gate reduction:

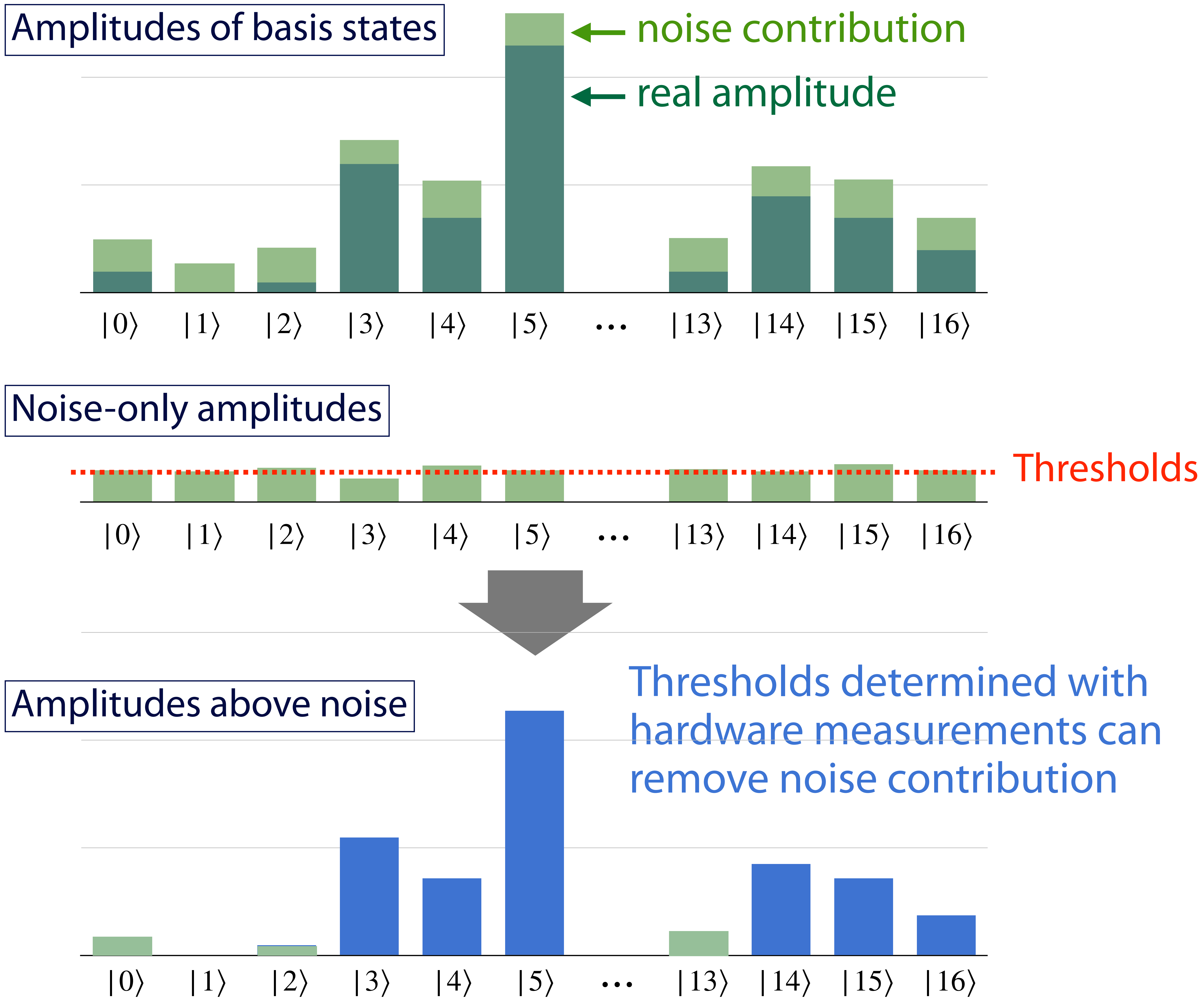
1) Remove redundant qubit controls/gates with identified basis states

Example circuit



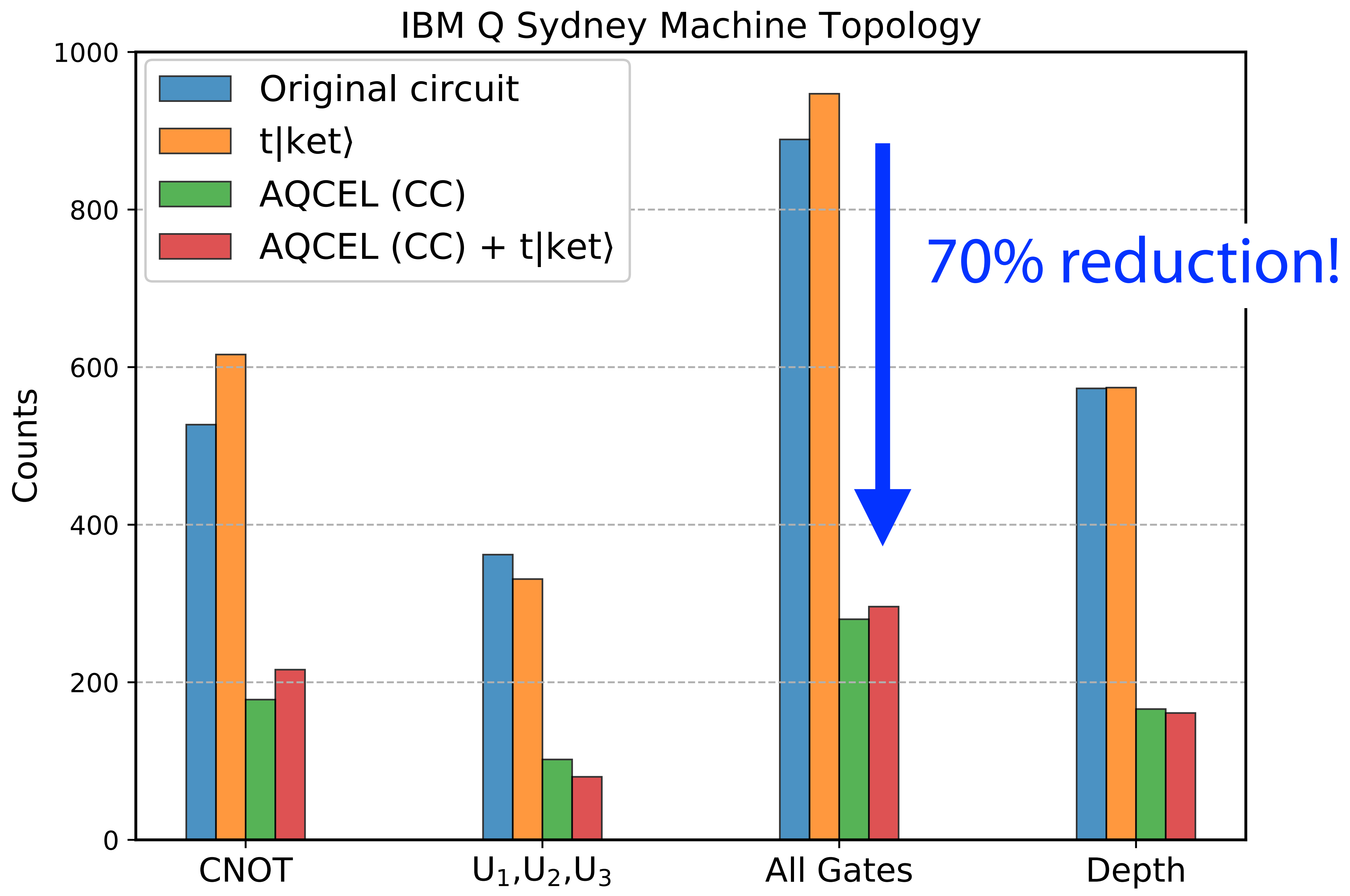
Circuit designed with generic initial states (*a la* parton shower algorithm) can be simplified when running on specific initial state

2) Identify basis states with polynomial resources using quantum measurements



Circuit Optimization for Parton Shower Simulation

Compared the optimization performance between **AQCEL** and **t|ket⟩** from Cambridge Quantum Computing



Number of native gates in quantum parton shower circuit*

#Gates	Original	t|ket⟩	AQCEL (Classical)	AQCEL (Quantum)
CNOT	527	616	178 (34%)	64 (12%)
$U_{1,2,3}$	362	331	102 (28%)	24 (7%)
All	889	947	280 (31%)	88 (10%)

* 1 splitting step only

- Significant gate reduction achieved for parton shower simulation by AQCEL
- Further gate reduction with AQCEL if circuit optimized using hardware measurements

⟶ Accuracy??

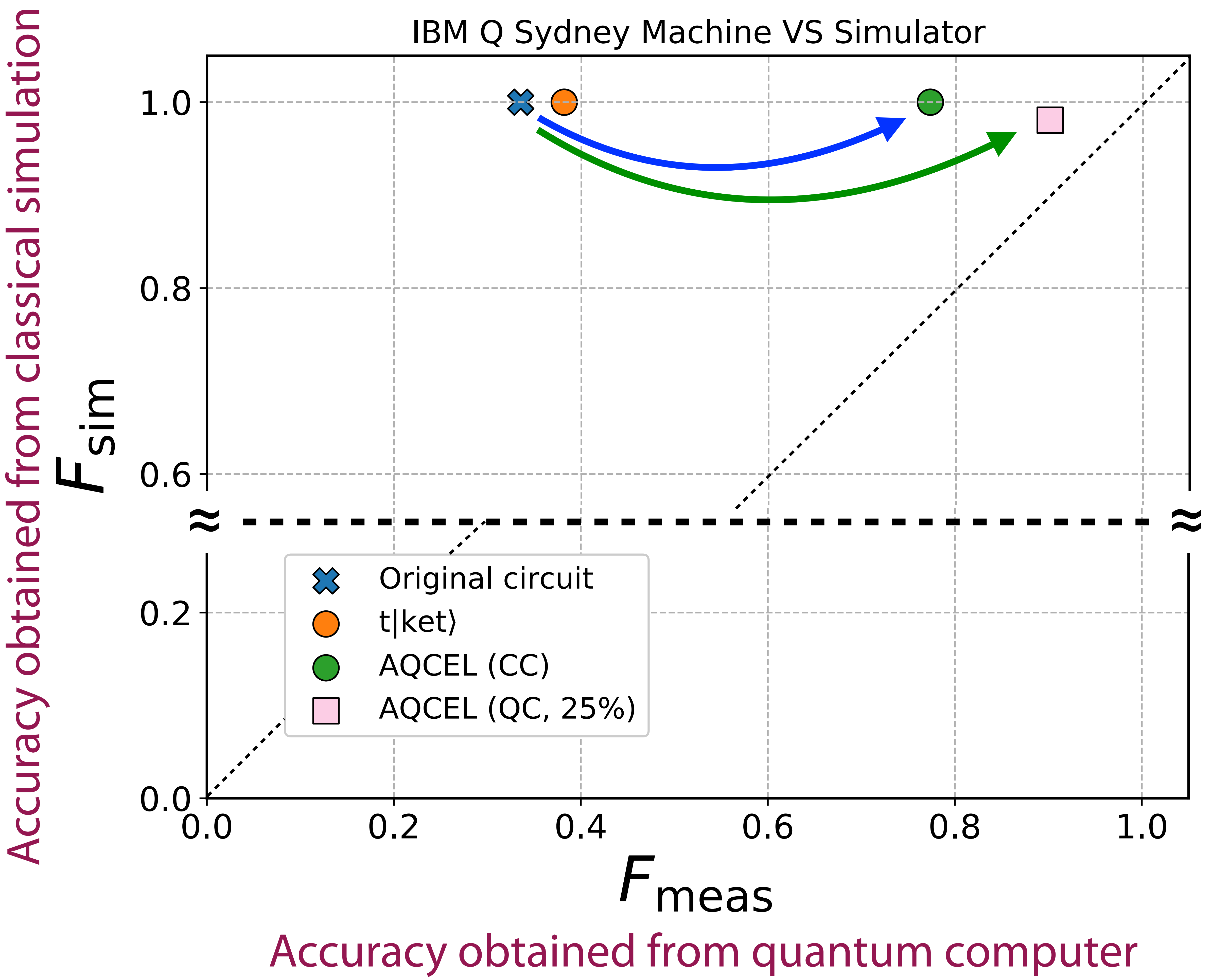
Circuit Optimization for Parton Shower Simulation

ibmq_**sydney** (27 qubits, QV32)

Computational accuracy quantified using probability distributions of measured output bit-strings:

$$F = \sum_k \sqrt{p_k^{\mathrm{orig}} p_k^{\mathrm{opt}}} \quad (\textit{\textbf{Classical Fidelity}})$$

$p_k^{\mathrm{orig\,(opt)}}$ = Probability of k computational basis state before (after) optimization



- AQCEL circuit maintains computational accuracy if circuit optimized classically
- Algorithm performance further improved on quantum computer due to noise suppression if AQCEL circuit optimized using hardware measurements

More details in arXiv:2102.10008

Summary

- Working towards ***large-scale Quantum AI*** for scientific discovery and industrial application
- Exploring ***co-designing quantum computing architecture*** for near-term NISQ application
- Working on application-specific circuit design/optimization for HEP application

AQCEL optimization protocol documented in arXiv:2102.10008

arXiv.org > quant-ph > arXiv:2102.10008

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Quantum Physics

[Submitted on 19 Feb 2021]

Quantum Gate Pattern Recognition and Circuit Optimization for Scientific Applications

Wonho Jang, Koji Terashi, Masahiko Saito, Christian W. Bauer, Benjamin Nachman, Yutaro Iiyama, Tomoe Kishimoto, Ryunosuke Okubo, Ryu Sawada, Junichi Tanaka

There is no unique way to encode a quantum algorithm into a quantum circuit. With limited qubit counts, connectivities, and coherence times, circuit optimization is essential to make the best use of near-term quantum devices. We introduce two separate ideas for circuit optimization and combine them in a multi-tiered quantum circuit optimization protocol called AQCEL. The first ingredient is a technique to recognize repeated patterns of quantum gates, opening up the possibility of future hardware co-optimization. The second ingredient is an approach to reduce circuit complexity by identifying zero- or low-amplitude computational basis states and redundant gates. As a demonstration, AQCEL is deployed on an iterative and efficient quantum algorithm designed to model final state radiation in high energy physics. For this algorithm, our optimization scheme brings a significant reduction in the gate count without losing any accuracy compared to the original circuit. Additionally, we have investigated whether this can be demonstrated on a quantum computer using polynomial resources. Our technique is generic and can be useful for a wide variety of quantum algorithms.

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References & Citations

- INSPIRE HEP
- NASA ADS
- Google Scholar
- Semantic Scholar

Code made public at Github

GitHub

Feedback appreciated!