20 May 2021
vCHEP 2021

Quantum Circuit Optimization for Scientific Applications

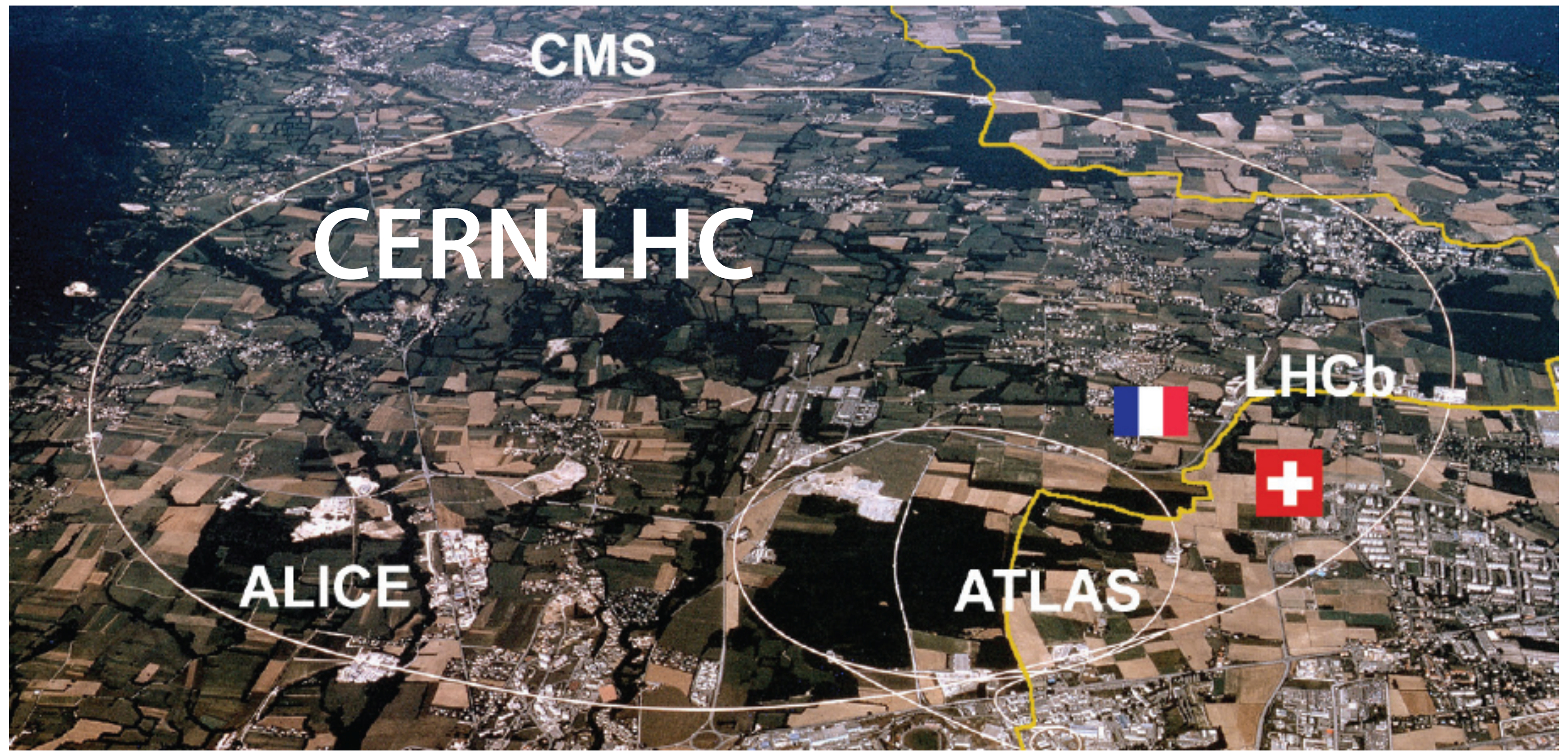
W. Jang[1] , K. Terashi[2], M. Saito[2], C. Bauer[3], B. Nachman[3], Y. Iiyama[2], T. Kishimoto[2], R. Okubo[1], R. Sawada[2], J. Tanaka[2]

[1] Department of Physics, University of Tokyo
[2] ICEPP, University of Tokyo
[3] Lawrence Berkeley National Laboratory

BERKELEY LAB

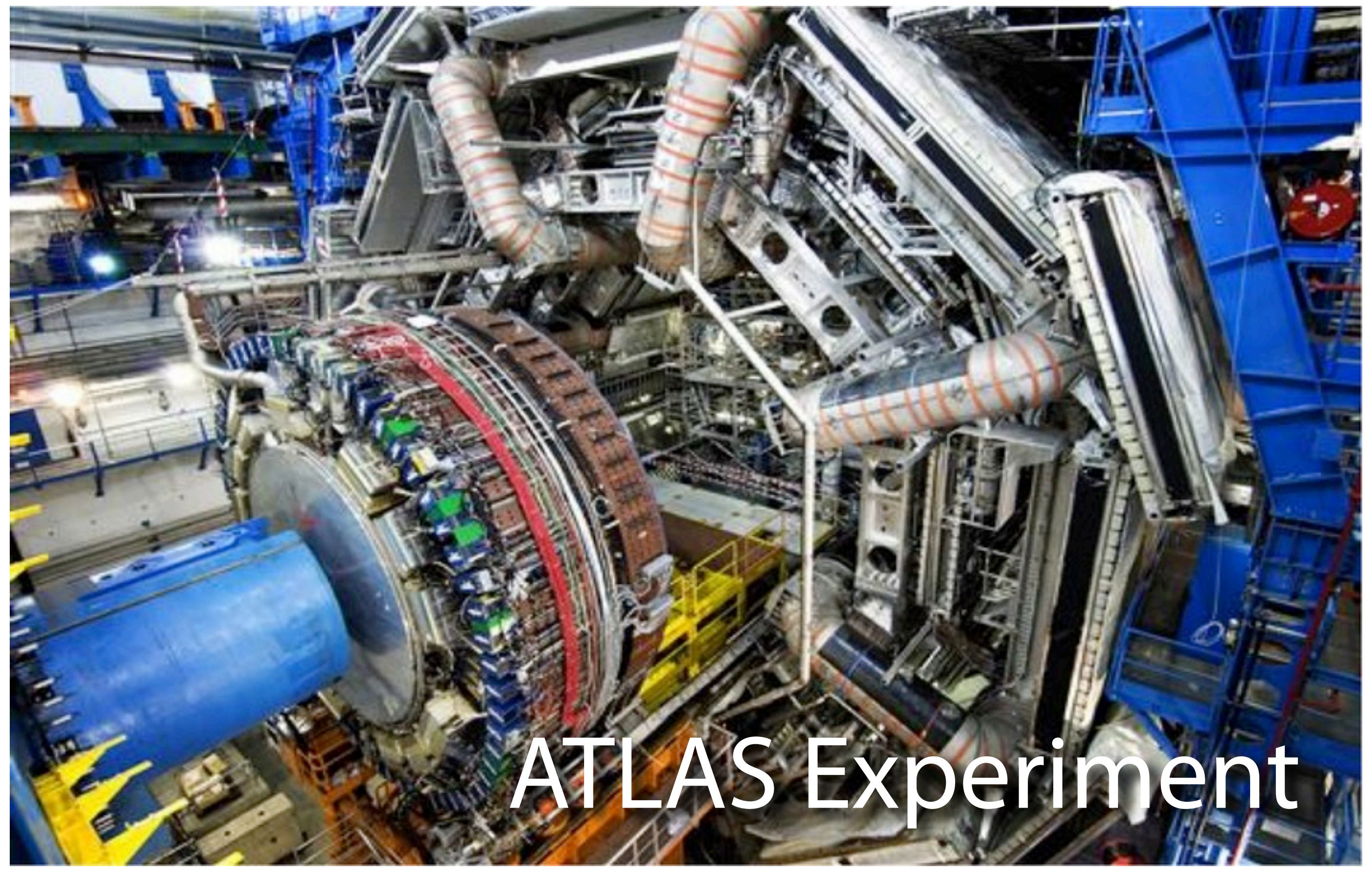
ICEPP
The University of Tokyo

HEP and Quantum Computing



- Particle Physics directly probing quantum properties of fundamental building blocks in nature
- Needs of large computing resources in HEP experiments

➡ Natural to explore quantum computing in particle physics



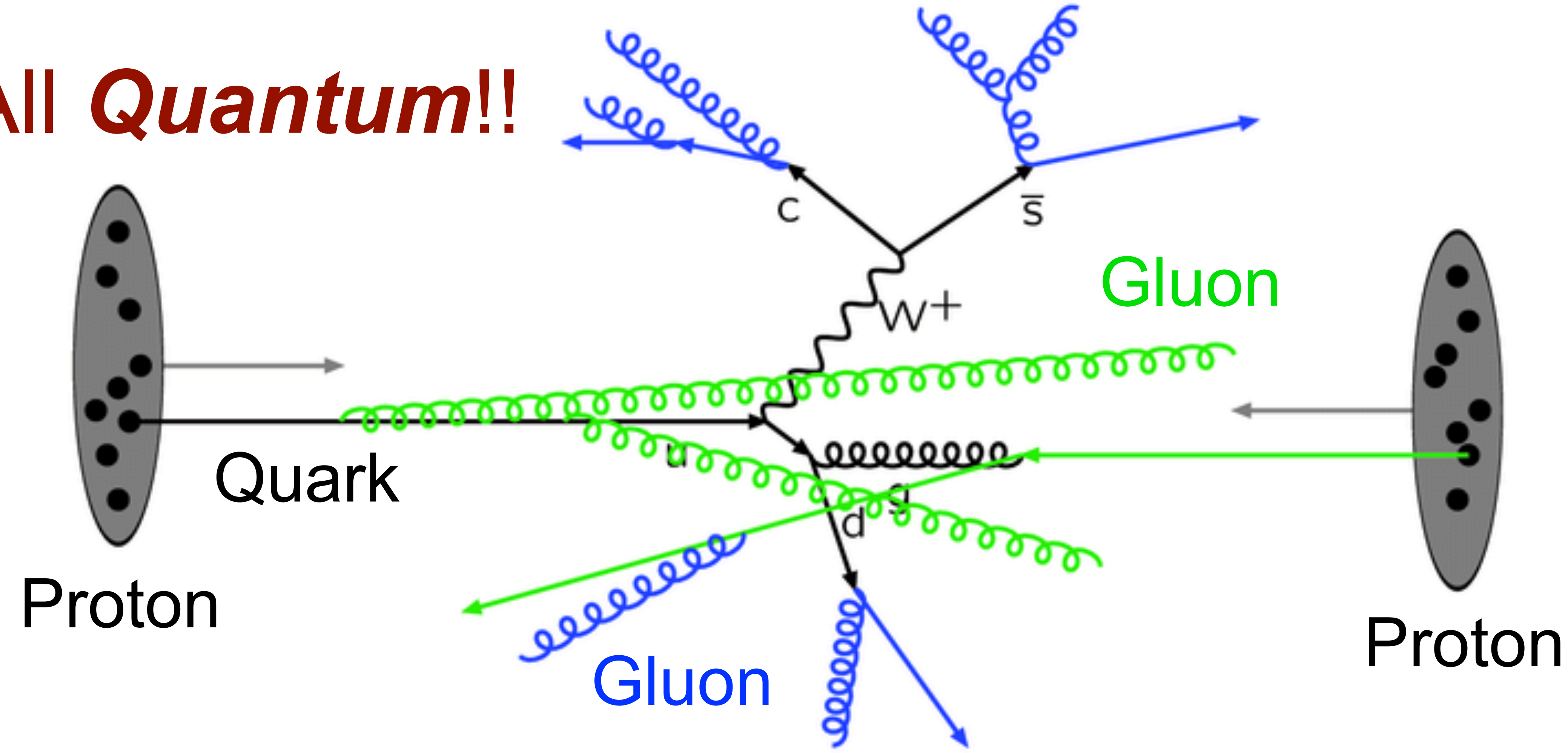
- Present quantum computer, called ***NISQ*** (*noisy intermediate-scale quantum device*), still at early stage for general use…

➡ Need 1) quantum applications with advantage over classical method, and 2) optimizations suitable for NISQ device

International Center for Elementary Particle Physics (ICEPP), University of Tokyo

- Working on LHC-ATLAS (CERN), MEG (PSI), ILC, …
- International collaboration with CERN & LBNL

All ***Quantum***!!



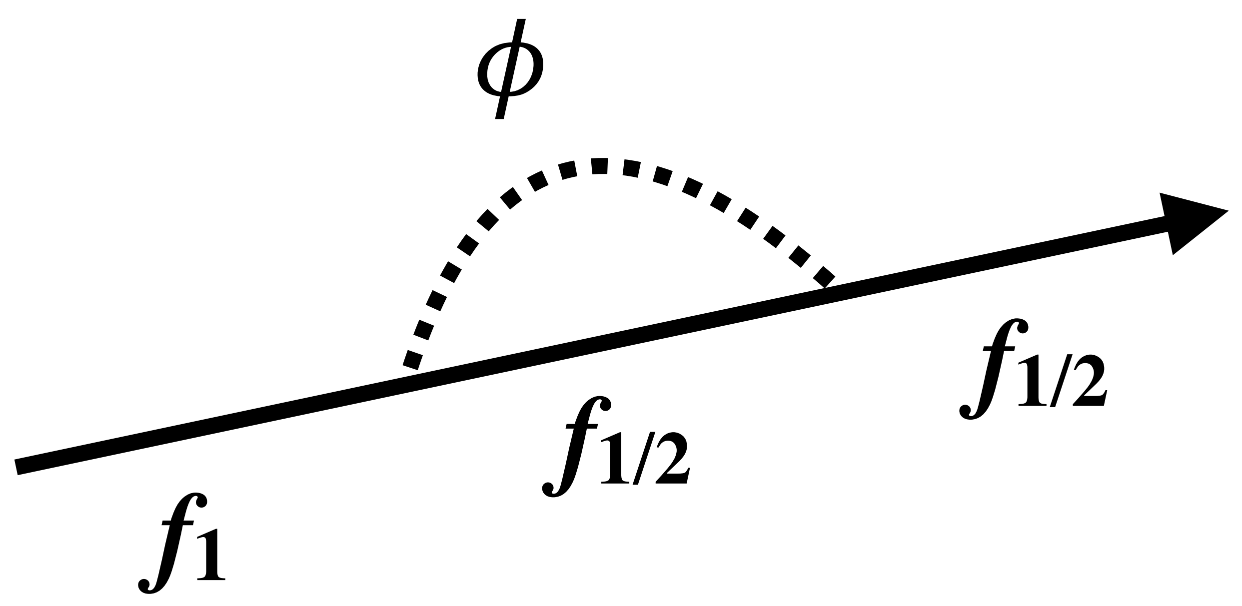
Quantum Algorithm for HEP Simulation

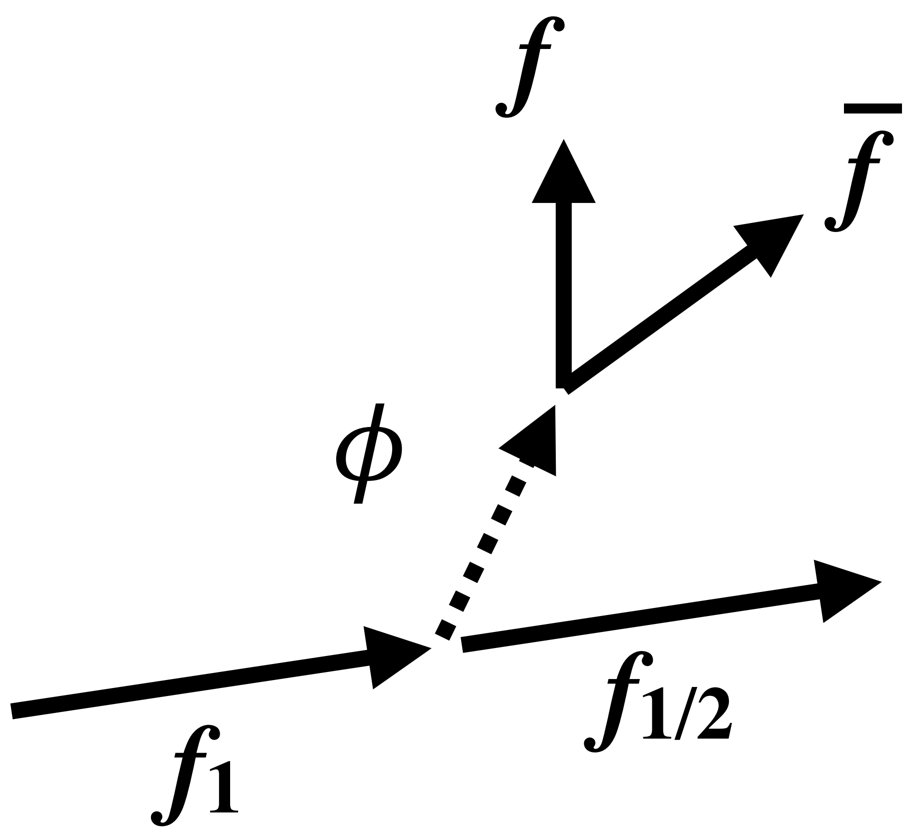
Parton shower processes typically simulated using probabilistic classical calculations (e.g., Markov-Chain MC)
➡ Impossible to include all amplitudes of contributing processes when the number of emissions grows

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

Quantum parton shower model:

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





- Many quantum gates required to calculate amplitudes at each emission step for every particles
- Algorithm designed to be generic to be able to simulate processes with different initial states

→ **Reduction of # of gates crucial for NISQ machine**

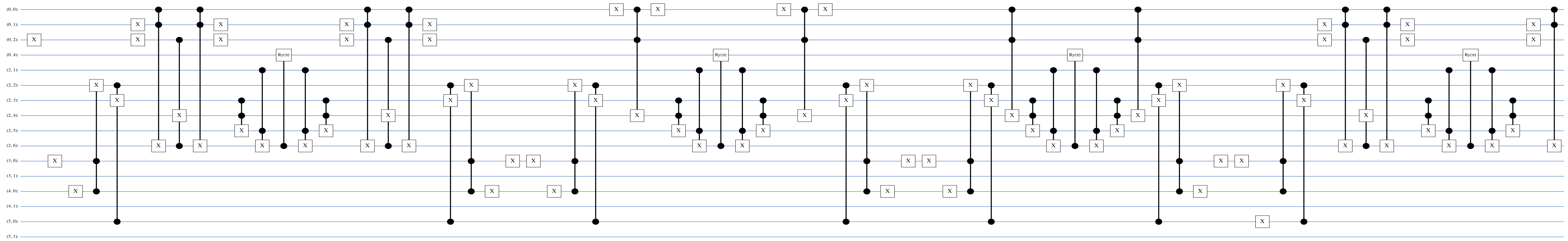
➡ Feasible to do that when focusing on specific initial states at run time

➡ Developed a novel, generic *run-time* optimization protocol called **AQCEL**

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

Quantum Circuit for Parton Shower Simulation

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



• • •

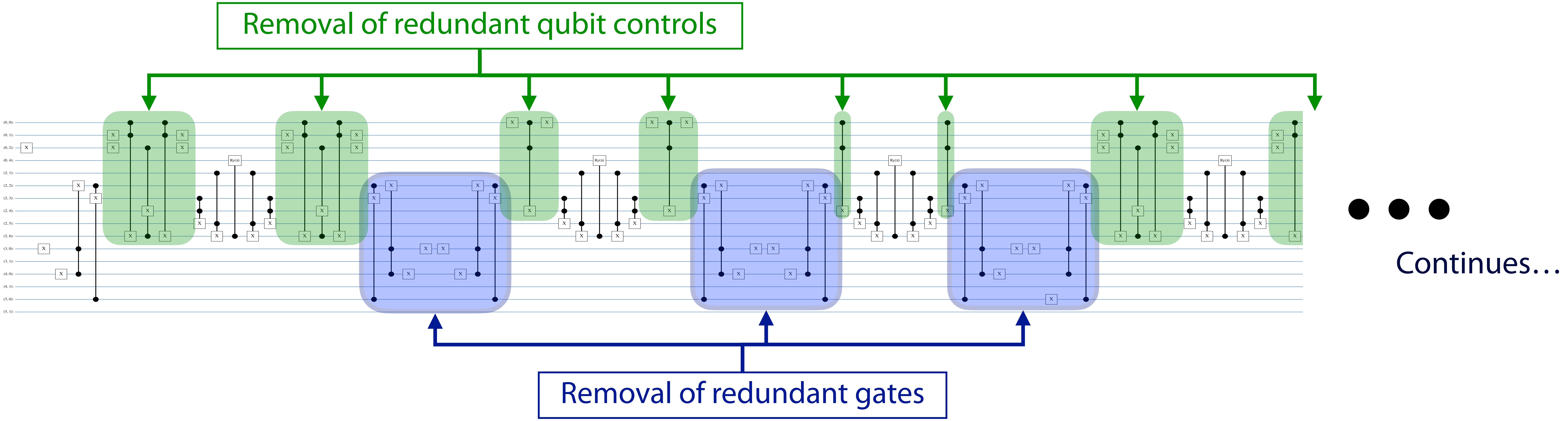
Continues…

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

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

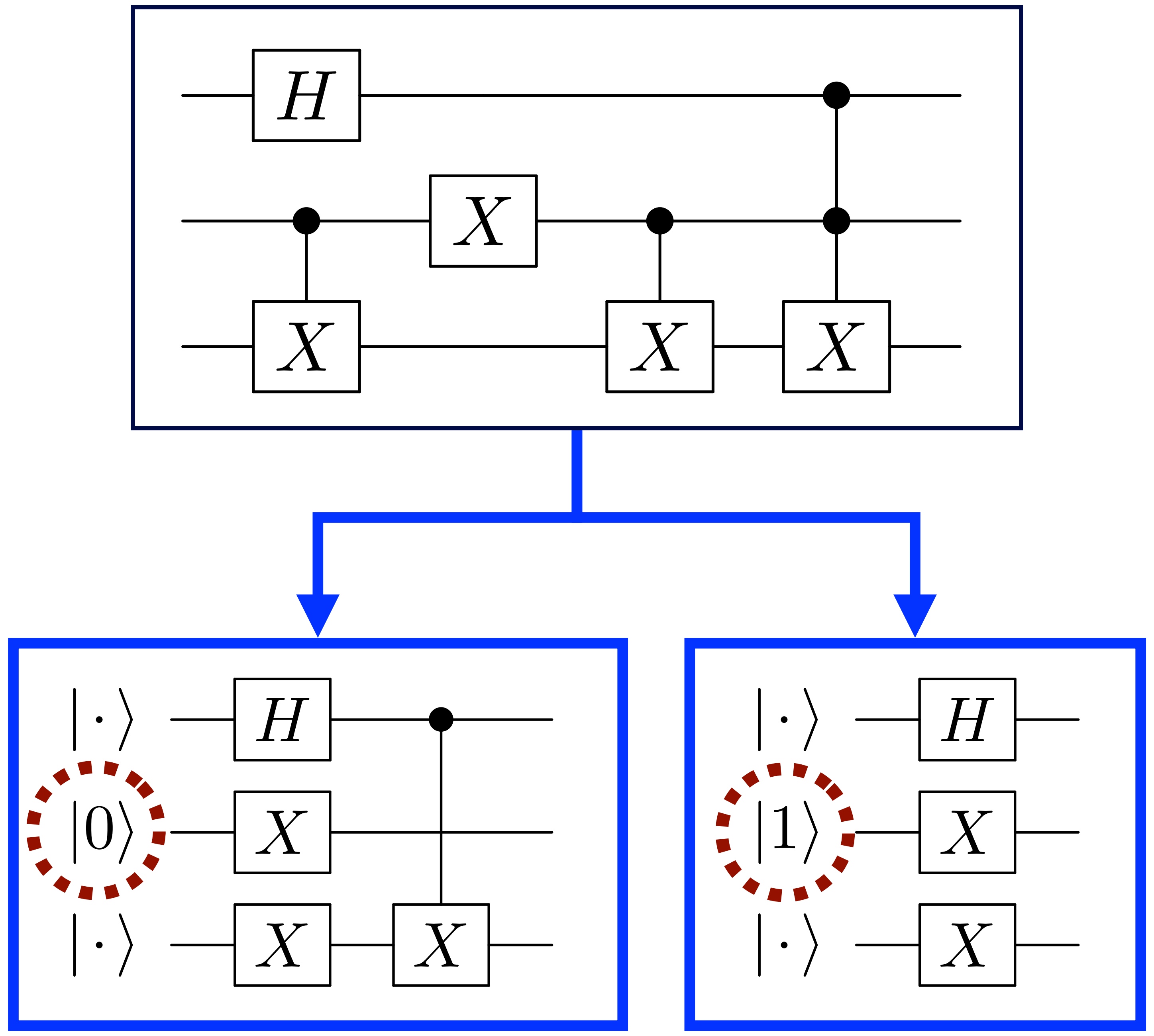


AQCEL Optimization Protocol

2 main ingredients for gate reduction:

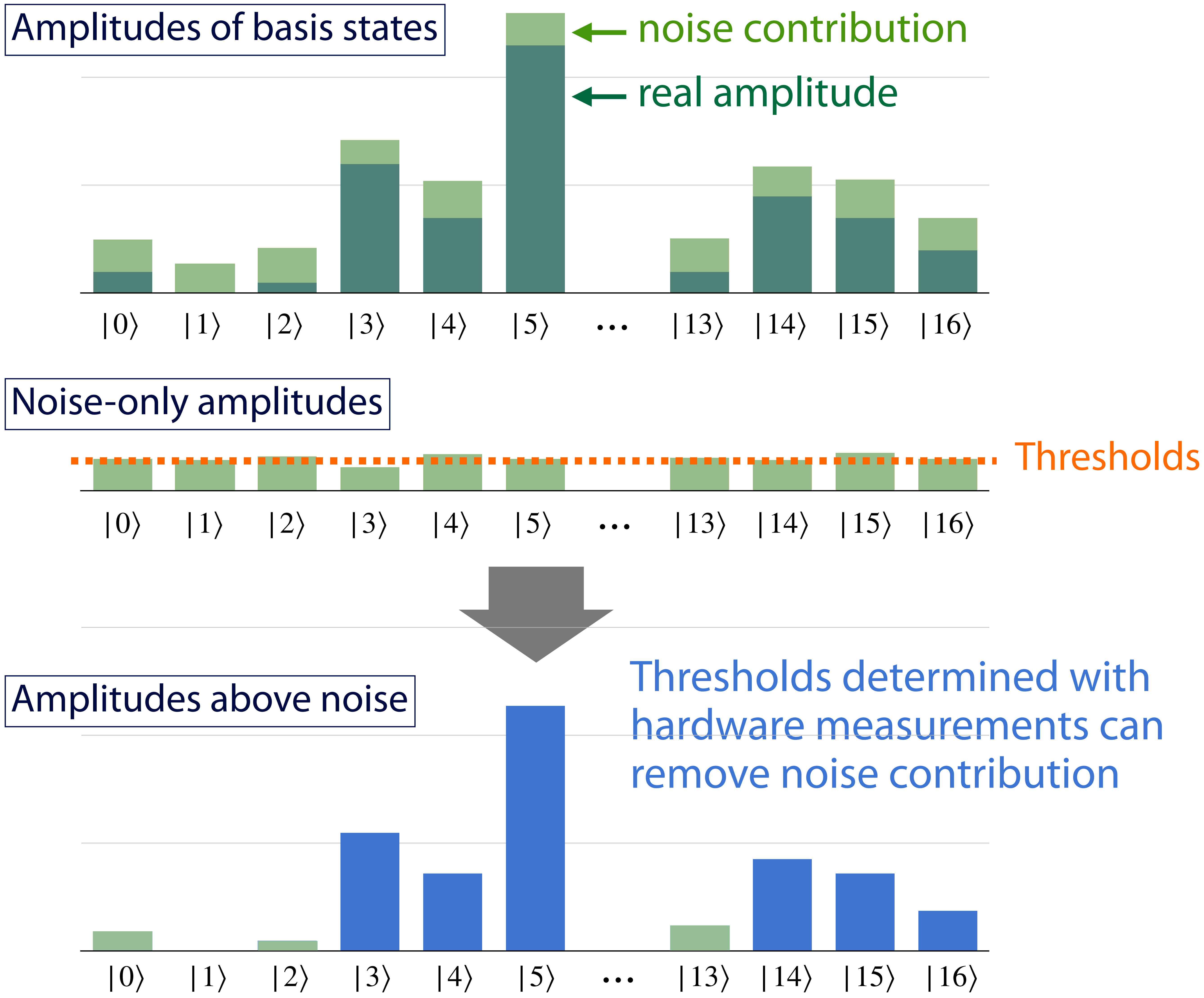
❶ Remove redundant qubit controls/gates with identified basis states

Example circuit



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

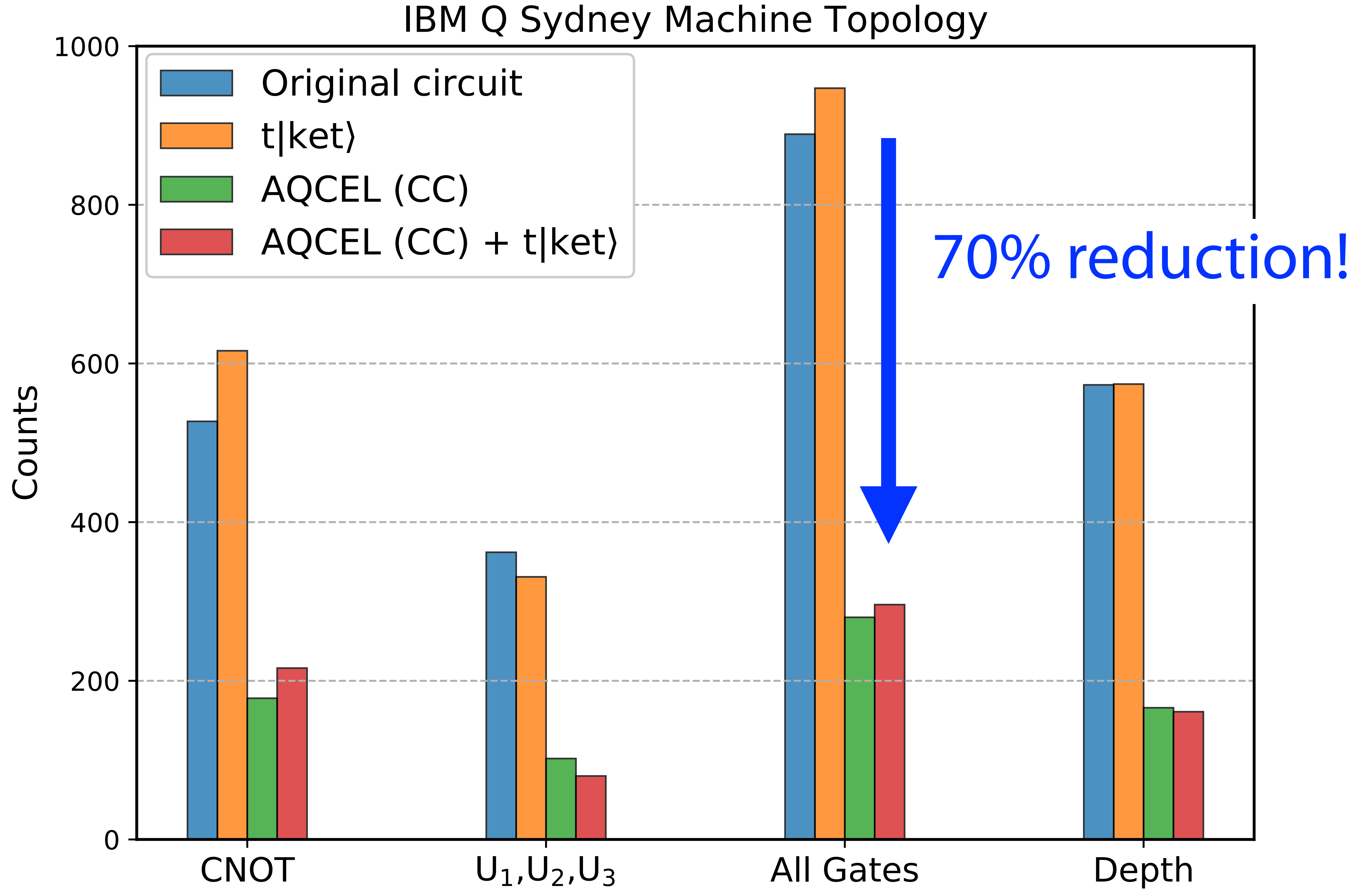
❷ Identify basis states with polynomial resources using quantum measurements



➡ Generic approach; Applicable to other algorithms

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 possible by AQCEL if circuit optimized using hardware measurements

→ Accuracy??

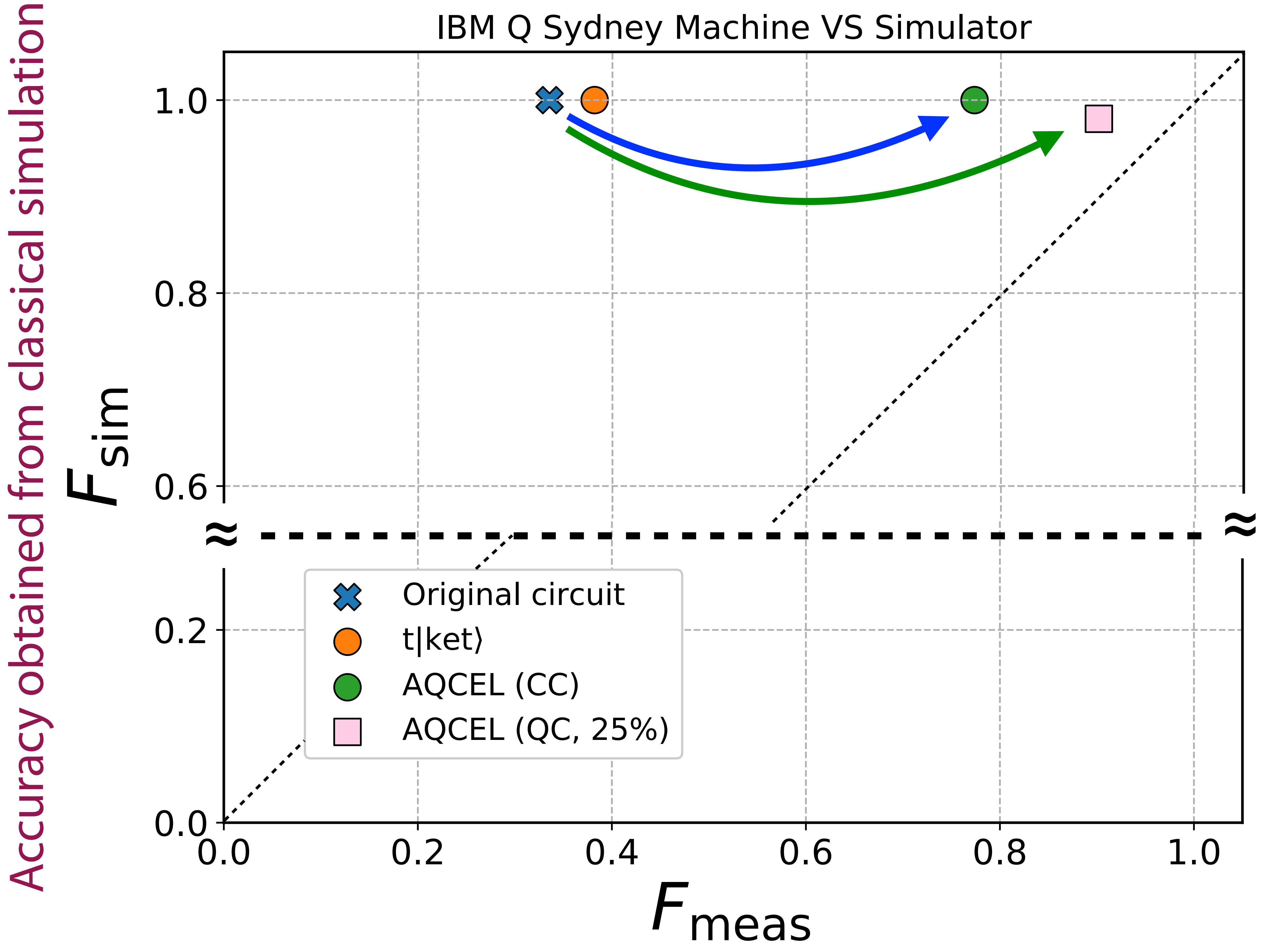
Circuit Optimization for Parton Shower Simulation

ibmq_**sydney** (27 qubits, Quantum Volume 32)

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

$$F = \sum_k \sqrt{p_k^{\text{orig}} p_k^{\text{opt}}}$$ (***Classical Fidelity***)

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



Accuracy obtained from quantum computer

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

More details in arXiv:2102.10008

Summary

- Working towards quantum computing applications to high-energy physics
- Working on application-specific circuit design/optimization (quantum parton shower simulation in HEP as a benchmark) for NISQ applications

AQCEL optimization protocol documented in arXiv:2102.10008

arXiv.org > quant-ph > arXiv:2102.10008

Search... | All fields | Search

Help | Advanced Search

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.

Download:

- PDF
- Other formats

(license)

Current browse context:
quant-ph

< prev | next >

new | recent | 2102

References & Citations

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

Code is made public at Github

GitHub

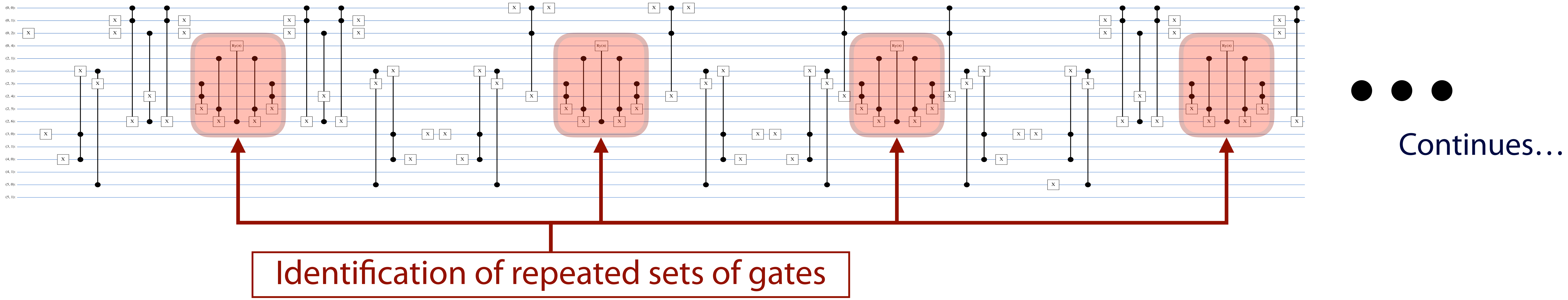
Feedback appreciated!

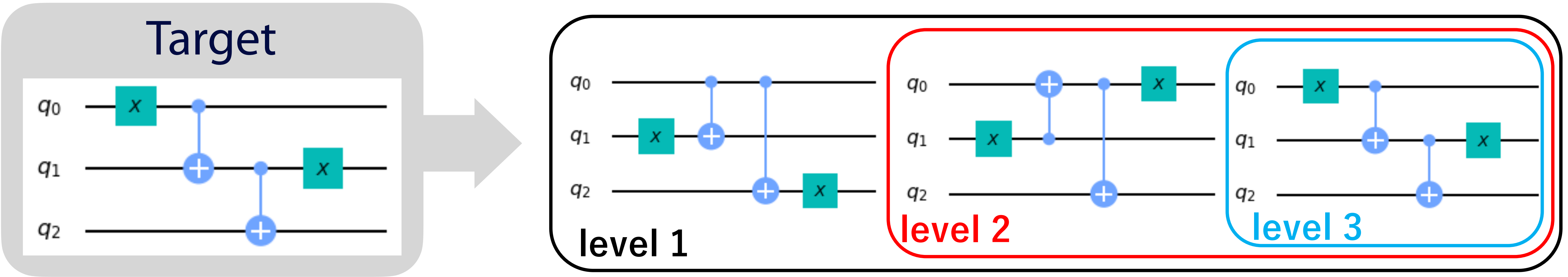
Backup

Quantum Gate Pattern Recognition

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

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

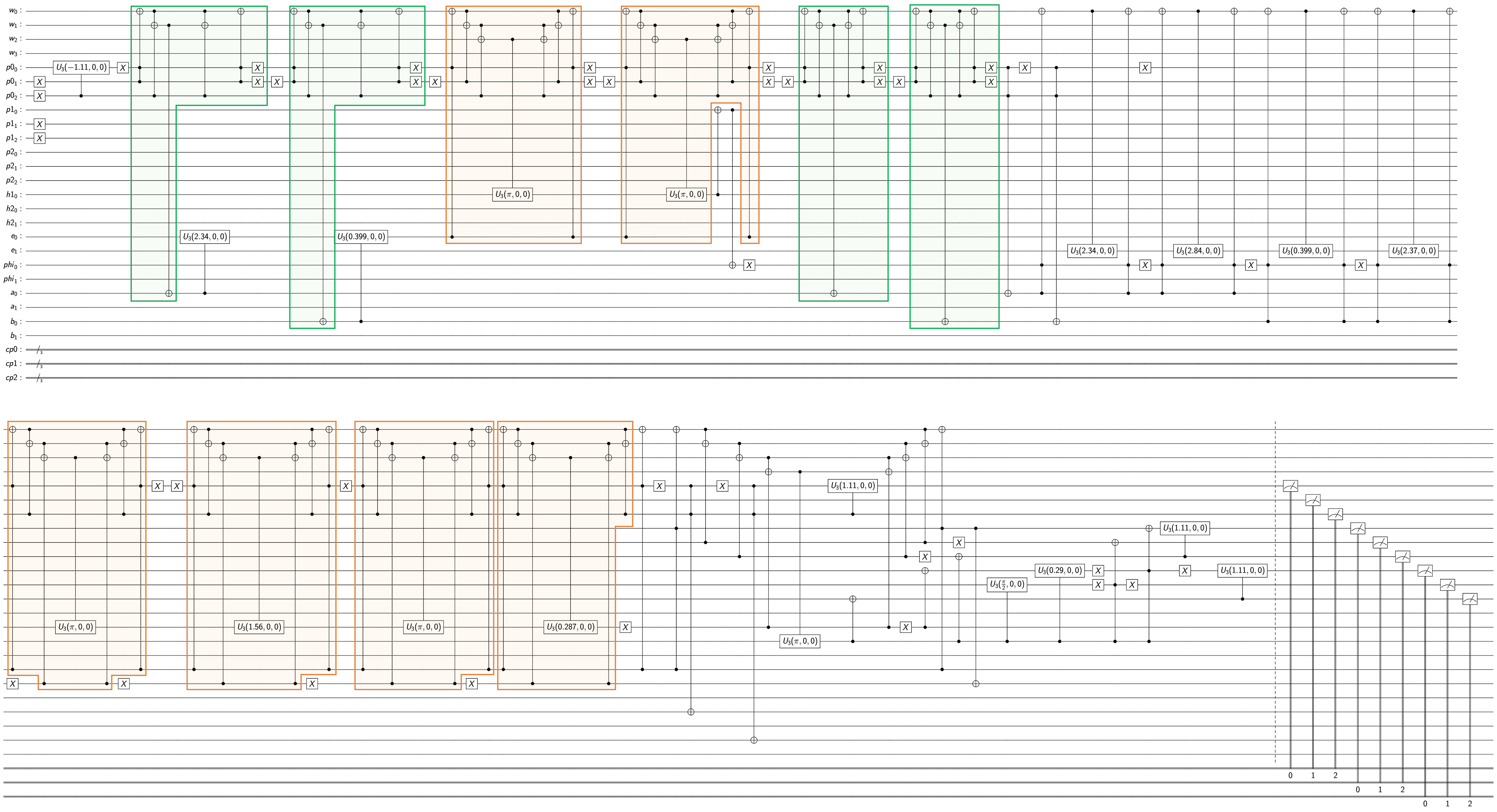




- Analyze circuit structure using directed acyclic graph
- 3-level pattern matching to identify repeated gates

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