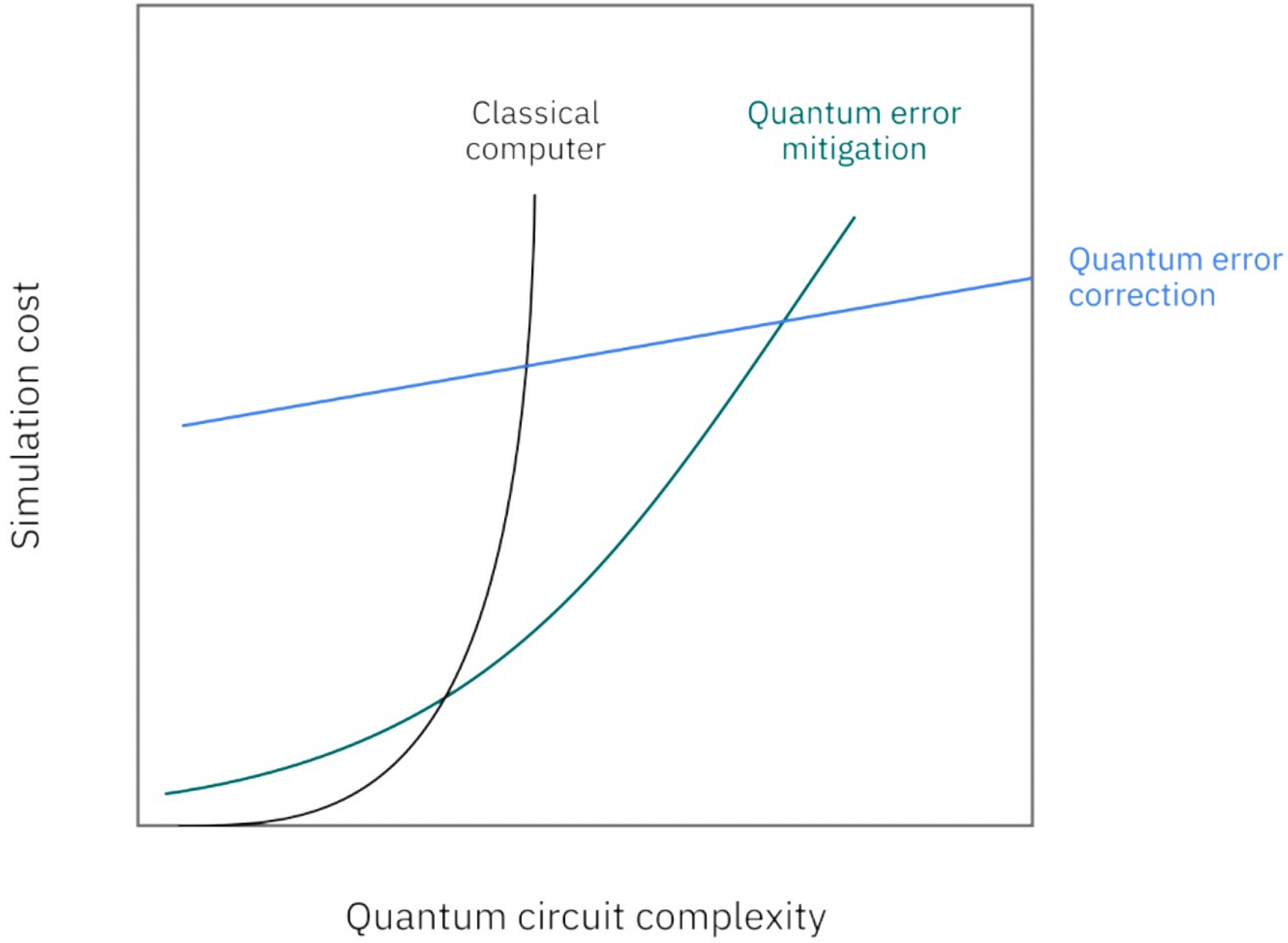
Quantum-centric Supercomputing
for physics research

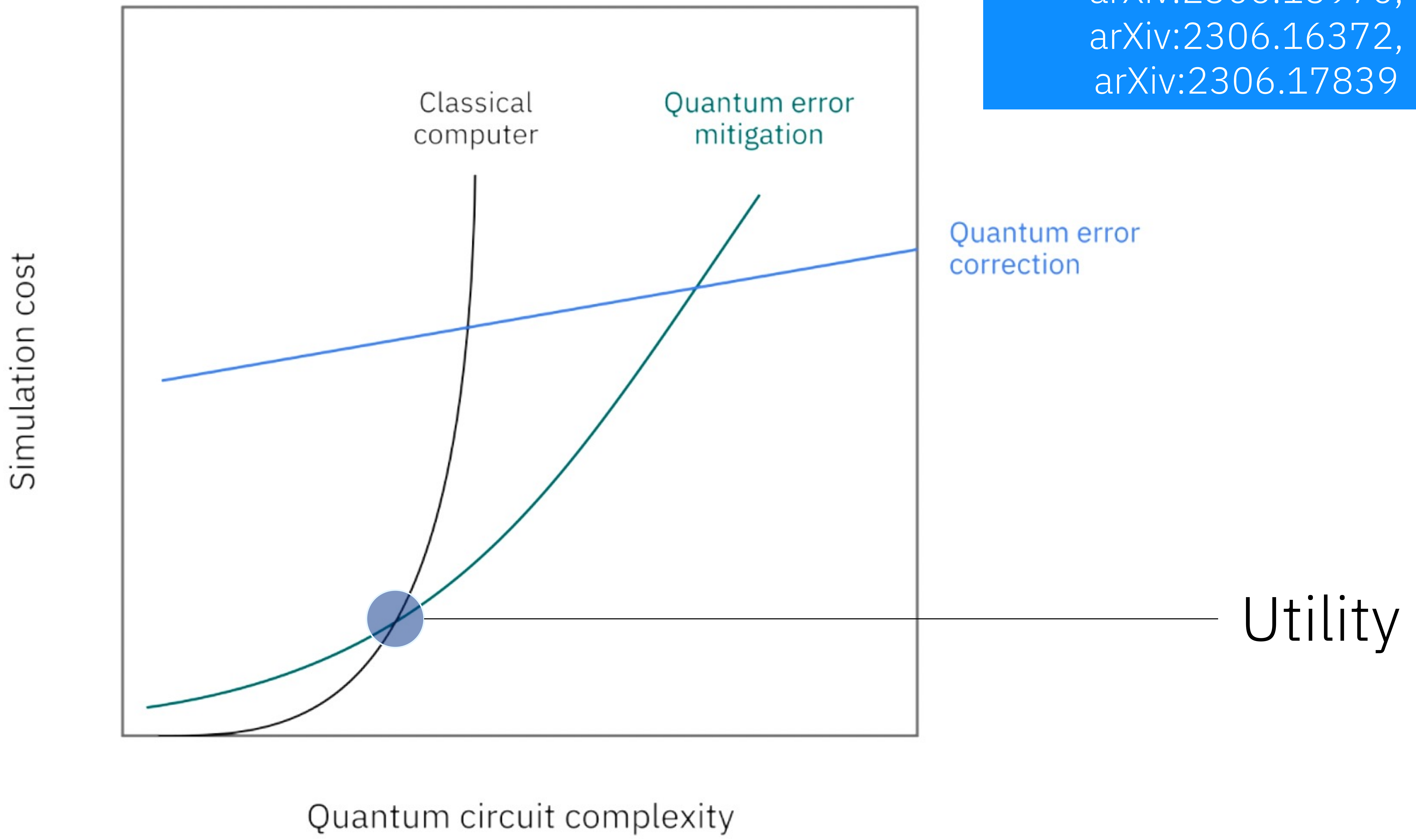
Vincent R. Pascuzzi
Quantum Compilation Engineer
IBM Quantum

Computational scaling of complex calculations



Computational scaling of complex calculations

Nature, **618**, 500-505 (2023)
arXiv:2306.14887,
arXiv:2306.15970,
arXiv:2306.16372,
arXiv:2306.17839



Development roadmap

Audiences: Data Scientists, Researchers, Quantum Physicists

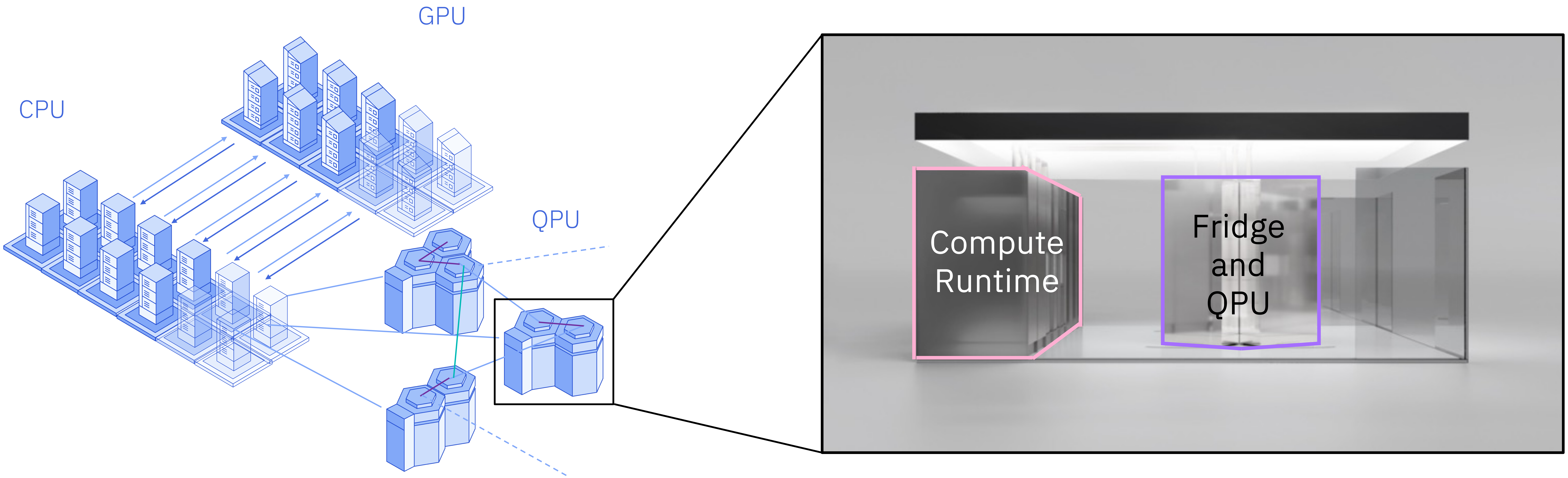
Year	Description	Platform (Data Scientists)	Middleware (Researchers)	Quantum Physicists	Processor
2016–2019 ✓	Run quantum circuits on the IBM Quantum Platform			IBM Quantum Experience ✓	Early ✓ Canary 5 qubits Albatross 16 qubits Penguin 20 qubits Prototype 53 qubits
2020 ✓	Release multi-dimensional roadmap publicly with initial aim focused on scaling			IBM Quantum Experience ✓	Falcon ✓ Benchmarking 27 qubits
2021 ✓	Enhancing quantum execution speed by 100x with Qiskit Runtime			Qiskit Runtime QASM3 ✓	Falcon ✓
2022 ✓	Bring dynamic circuits to unlock more computations			Qiskit Runtime Dynamic circuits ✓	Eagle ✓ Benchmarking 127 qubits
2023 ✓	Enhancing quantum execution speed by 5x with quantum serverless and Execution modes		Middleware Quantum Serverless ✓	Qiskit Runtime Execution Modes ✓	Eagle ✓
2024	Improving quantum circuit quality and speed to allow 5K gates with parametric circuits	Platform Code assistant (on target)	Middleware Transpiler Service (on target)	Qiskit Runtime	Heron (5K) (on target) Error Mitigation 5k gates 133 qubits Classical modular Up to 133x3 = 399 qubits
2025	Enhancing quantum execution speed and parallelization with partitioning and quantum modularity	Platform Functions	Middleware Resource Management	Qiskit Runtime	Flamingo (5K) Error Mitigation 5k gates 156 qubits Quantum modular Up to 156x7 = 1092 qubits
2026	Improving quantum circuit quality to allow 7.5K gates	Platform Mapping Collections	Middleware Circuit Knitting x P	Qiskit Runtime	Flamingo (7.5K) Error Mitigation 7.5k gates 156 qubits Quantum modular Up to 156x7 = 1092 qubits
2027	Improving quantum circuit quality to allow 10K gates	Platform Specific Libraries	Middleware Intelligent Orchestration	Qiskit Runtime	Flamingo (10K) Error Mitigation 10k gates 156 qubits Quantum modular Up to 156x7 = 1092 qubits
2028	Improving quantum circuit quality to allow 15K gates	Platform Specific Libraries	Middleware Intelligent Orchestration	Qiskit Runtime	Flamingo (15K) Error Mitigation 15k gates 156 qubits Quantum modular Up to 156x7 = 1092 qubits
2029	Improving quantum circuit quality to allow 100M gates	Platform Specific Libraries	Middleware Intelligent Orchestration	Qiskit Runtime	Starling (100M) Error Correction 100M gates 200 qubits Error corrected modularity
2033+	Beyond 2033, quantum-centric supercomputers will include 1000's of logical qubits unlocking the full power of quantum computing	Platform General purpose QC libraries	Middleware Circuit libraries	Qiskit Runtime	Blue Jay (1B) Error Correction 1B gates 2000 qubits Error corrected modularity

✓ Executed by IBM

On target

Quantum-centric Supercomputing (QCSC)

Delivering impactful quantum computing requires the interplay of quantum and classical resources at scale: HPC-assisted quantum computation to extract/boost useful signals in utility-scale experiments.



Quantum-centric Supercomputing (QCSC)

See also:
arXiv:2312.09733
arXiv:2312.05344

Quantum Computing for High-Energy Physics
State of the Art and Challenges
Summary of the QC4HEP Working Group

Alberto Di Meglio,[1,*] Karl Jansen,[2,3,†] Ivano Tavernelli,[4,‡] Constantia Alexandrou,[5,3] Srinivasan Arunachalam,[6] Christian W. Bauer,[7] Kerstin Borras,[8,9] Stefano Carrazza,[10,1] Arianna Crippa,[2,11] Vincent Croft,[12] Roland de Putter,[6] Andrea Delgado,[13] Vedran Dunjko,[12] Daniel J. Egger,[4] Elias Fernández-Combarro,[14] Elina Fuchs,[1,15,16] Lena Funcke,[17] Daniel González-Cuadra,[18,19] Michele Grossi,[1] Jad C. Halimeh,[20,21] Zoë Holmes,[22] Stefan Kühn,[2] Denis Lacroix,[23] Randy Lewis,[24] Donatella Lucchesi,[25,26,1] Miriam Lucio Martinez,[27,28] Federico Meloni,[8] Antonio Mezzacapo,[6] Simone Montangero,[25,26] Lento Nagano,[29] Vincent R. Pascuzzi,[6] Voica Radescu,[30] Enrique Rico Ortega,[31,32,33,34] Alessandro Roggero,[35,36] Julian Schuhmacher,[4] Joao Seixas,[37,38,39] Pietro Silvi,[25,26] Panagiotis Spentzouris,[40] Francesco Tacchino,[4] Kristan Temme,[6] Koji Terashi,[29] Jordi Tura,[12,41] Cenk Tüysüz,[2,11] Sofia Vallecorsa,[1] Uwe-Jens Wiese,[42] Shinjae Yoo,[43] and Jinglei Zhang[44,45]

arXiv:2307.03236

Quantum-centric Supercomputing for Materials Science:
A Perspective on Challenges and Future Directions

Yuri Alexeev,[1] Maximilian Amsler,[2] Marco Antonio Barroca,[3,4] Sanzio Bassini,[5] Torey Battelle,[6] Daan Camps,[7] David Casanova,[8,9] Young jai Choi,[10] Frederic T. Chong,[11] Charles Chung,[12] Christopher Codella,[12] Antonio D. Córcoles,[12] James Cruise,[13] Alberto Di Meglio,[14] Ivan Duran,[12] Thomas Eckl,[2] Sophia Economou,[15] Stephan Eidenbenz,[16] Bruce Elmegreen,[12] Clyde Fare,[12] Ismael Faro,[12] Cristina Sanz Fernández,[12] Rodrigo Neumann Barros Ferreira,[3] Keisuke Fuji,[17] Bryce Fuller,[12] Laura Gagliardi,[18,1] Giulia Galli,[11,1] Jennifer R. Glick,[12] Isacco Gobbi,[19] Pranav Gokhale,[20] Salvador de la Puente Gonzalez,[12] Johannes Greiner,[12] Bill Gropp,[21] Michele Grossi,[14] Emmanuel Gull,[22] Burns Healy,[23] Matthew R. Hermes,[18] Benchen Huang,[11] Travis S. Humble,[24] Nobuyasu Ito,[25] Artur F. Izmaylov,[26,27] Ali Javadi-Abhari,[12] Douglas Jennewein,[6] Shantenu Jha,[28,29] Liang Jiang,[11] Barbara Jones,[30] Wibe Albert de Jong,[31] Petar Jurcevic,[12] William Kirby,[32] Stefan Kister,[12] Masahiro Kitagawa,[17] Joel Klassen,[33] Katherine Klymko,[34] Kwangwon Koh,[35] Masaaki Kondo,[36,25] Doğa Murat Kürkçüoğlu,[37,38] Krzysztof Kurowski,[39] Teodoro Laino,[40] Ryan Landfield,[24] Matt Leininger,[41] Vicente Leyton-Ortega,[24] Ang Li,[42,43] Meifeng Lin,[28] Junyu Liu,[11,44,45] Nicolas Lorente,[46,8] Andre Luckow,[47] Simon Martiel,[12] Francisco Martin-Fernandez,[12] Margaret Martonosi,[48] Claire Marvinney,[24] Arcesio Castaneda Medina,[19] Dirk Merten,[19] Antonio Mezzacapo,[12,*] Kristel Michielsen,[49] Abhishek Mitra,[18] Tushar Mittal,[12] Kyungsun Moon,[10] Joel Moore,[50,51] Sarah Mostame,[12] Mario Motta,[12] Young-Hye Na,[12] Yunseong Nam,[12] Prineha Narang,[28,52] Yu-ya Ohnishi,[53] Daniele Ottaviani,[5] Matthew Otten,[54] Scott Pakin,[16] Vincent R. Pascuzzi,[12] Edwin Pednault,[12] Tomasz Piontek,[39] Jed Pitera,[55] Patrick Rall,[32] Gokul Subramanian Ravi,[22] Niall Robertson,[56] Matteo A. C. Rossi,[57] Piotr Rydlichowski,[39] Hoon Ryu,[58] Georgy Samsonidze,[59] Mitsuhisa Sato,[25] Nishant Saurabh,[60] Vidushi Sharma,[12] Kunal Sharma,[12] Soyoung Shin,[61] George Slessman,[62] Mathias Steiner,[3] Iskandar Sitdikov,[12] In-Saeng Suh,[24] Eric D. Switzer,[8] Wei Tang,[48] Joel Thompson,[63] Synge Todo,[64] Minh C. Tran,[32] Dimitar Trenev,[65] Christian Trott,[66] Huan-Hsin Tseng,[28] Norm M. Tubman,[67] Esin Tureci,[48] David García Valiñas,[12] Sofia Vallecorsa,[14] Christopher Wever,[68] Konrad Wojciechowski,[39] Xiaodi Wu,[69] Shinjae Yoo,[28] Nobuyuki Yoshioka,[64] Victor Wen-zhe Yu,[1] Seiji Yunoki,[25,70] Sergiy Zhuk,[56] and Dmitry Zubarev[12]

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arXiv:2312.09733

The coming together of a wide range of expertise across disciplines to solve domain-specific problems.

The no-nonsense path to quantum advantage

1. Run quantum circuits faster on quantum hardware

   Chart a path to develop quantum technology (hardware + software) that runs noise-free estimators of quantum circuits faster than can be done using classical hardware alone

2. Map interesting problems to quantum circuits

   We need applications that can only be solved with quantum circuits that are known to be difficult to simulate. This must be done collaboratively, with our clients and users.

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Workload management

Hybrid classical-quantum workflows

Programmability

Use case in physics

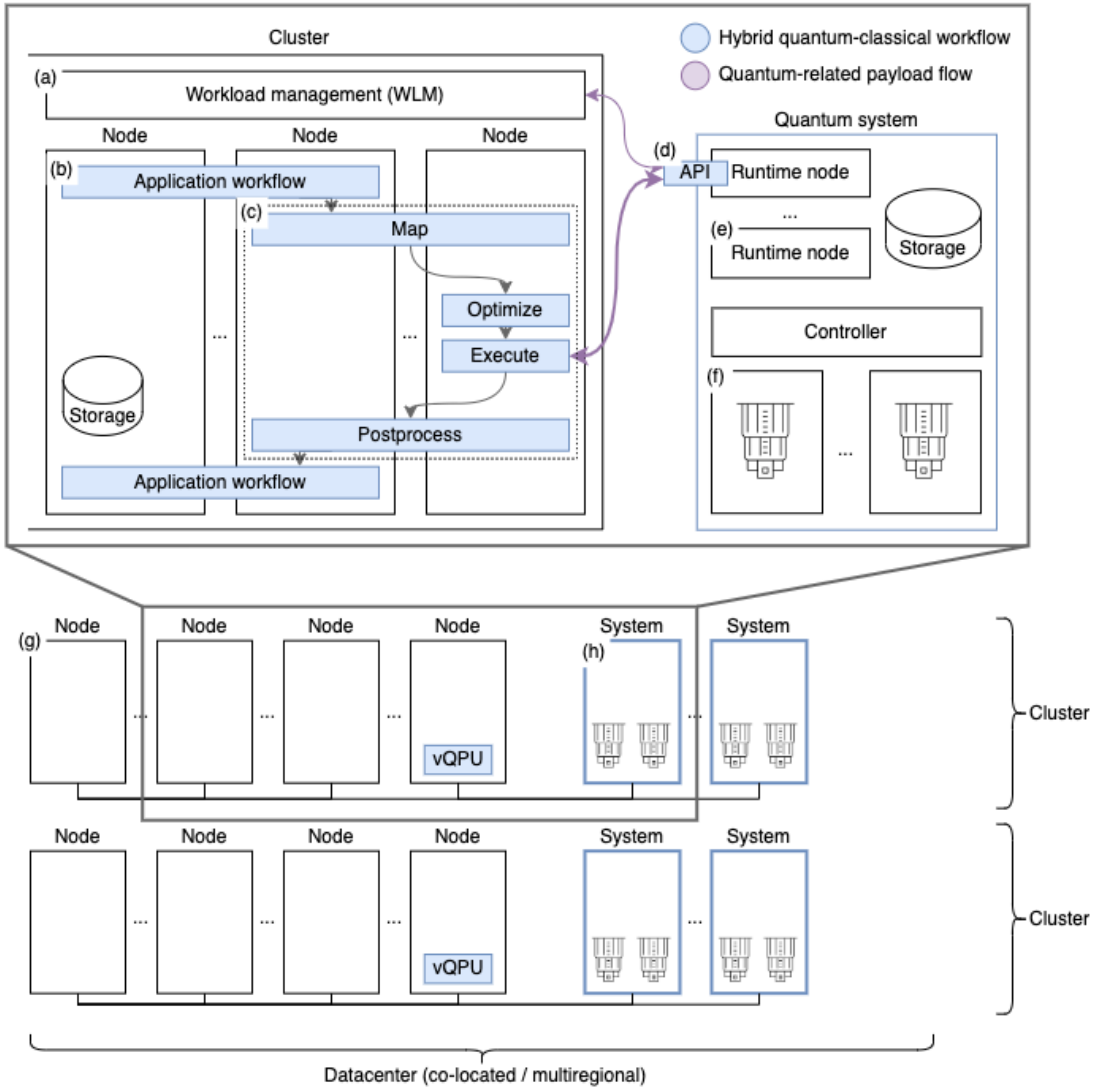
Workload management

QCSC comprises integrated classical and quantum resources

Consider WLM as conventional software system (e.g., SLURM) with extensions for interfacing to quantum devices

Worker nodes w/ ‘virtual’ QPU resource

Hybrid workfload spawned from login (classical) node; quantum circuit executed via low-latency, high-throughput interface (“Direct Access API”)



Hybrid classical—quantum workflows

Near-term

“Weakly-coupled” regime

Latency between classical and quantum devices beyond qubit coherence time; e.g., distributed or co-located with ‘slow’ interconnect

Workflows comprising temporally decoupled tasks

Far-term

“Strongly-coupled” regime

High-speed bus (latency ≪ coherence) connecting classical and quantum devices

Workflows, single large-scale hybrid applications with quantum accelerator complementing conventional HPC

Programmability

Near-term

"Loosely-coupled" regime

Trivially separable classical and quantum executables, functions, etc.; latencies insignificant

Language-agnostic: "bag of tasks" to be executed on available resources; e.g., C/C++, Python (Qiskit) for quantum and AI/ML

Far-term

"Tightly-coupled" regime

Desire is to offload quantum-accelerated kernels while classical task(s) execute in parallel and/or asynchronously

Single-source application(s) part of a larger workflow that pervade all available resources; compiled language (C/C++), potentially with bindings

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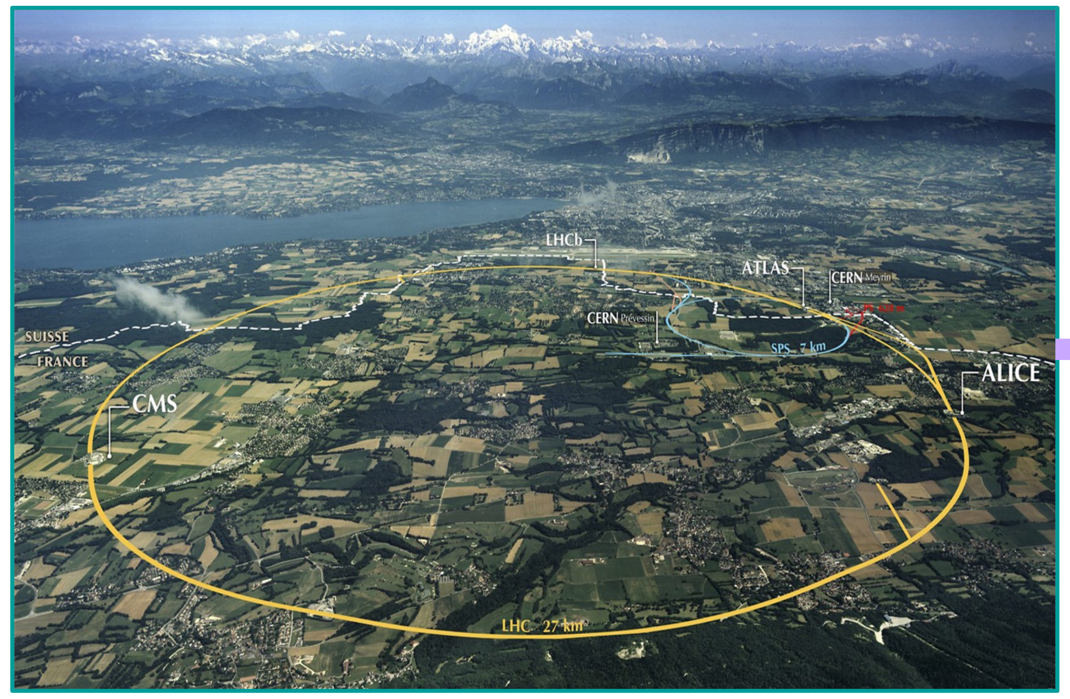
How will these systems be programmed?

Use case: HEP data processing chain



Data Path

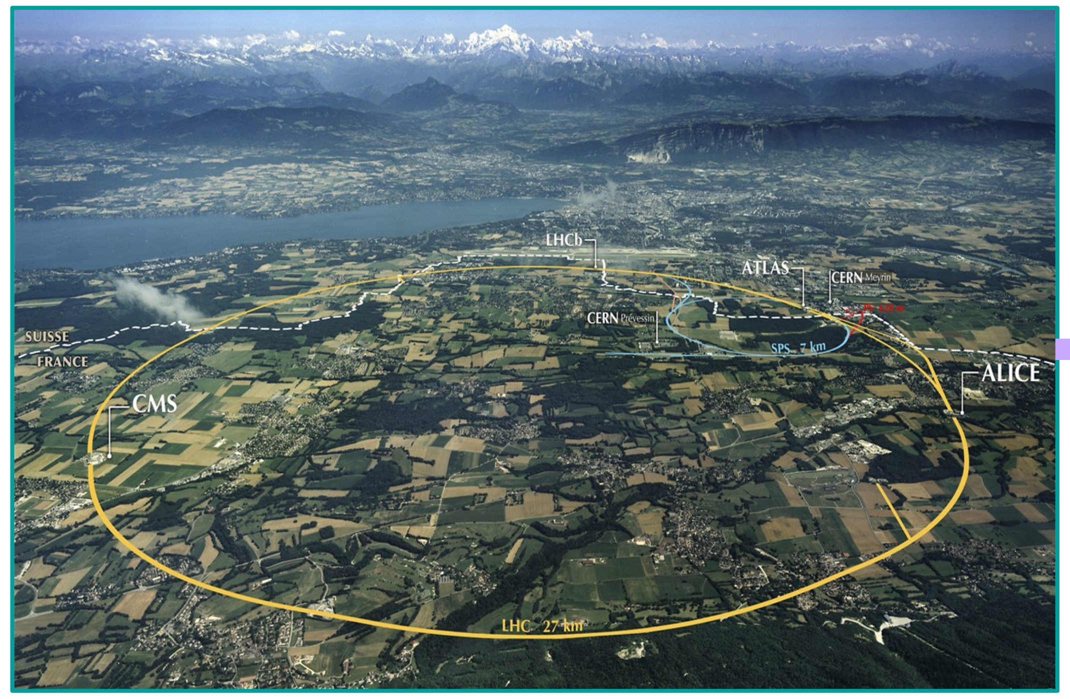
Trigger-1 → Trigger-2 → Reconstruction

Monte Carlo Path

Generation → Simulation → Reconstruction

Reconstruction → Derivation → Analysis

Use case: HEP data processing chain



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arXiv:2207.03473

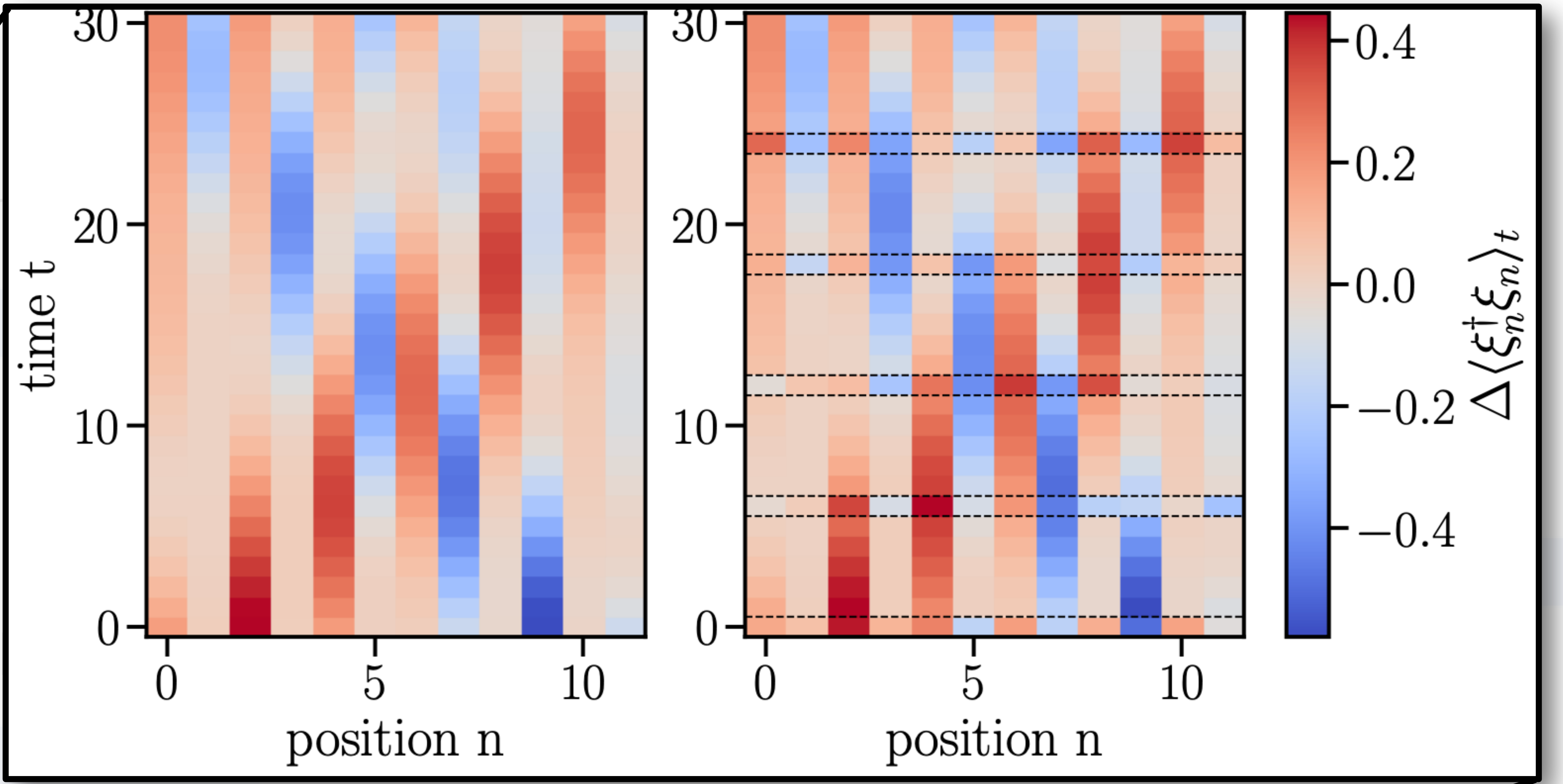
arXiv:2207.10694

arXiv:2312.02272

arXiv:2402.10265

Use case: HEP data processing chain

Y. Chai *et al.* (2023)



Generation

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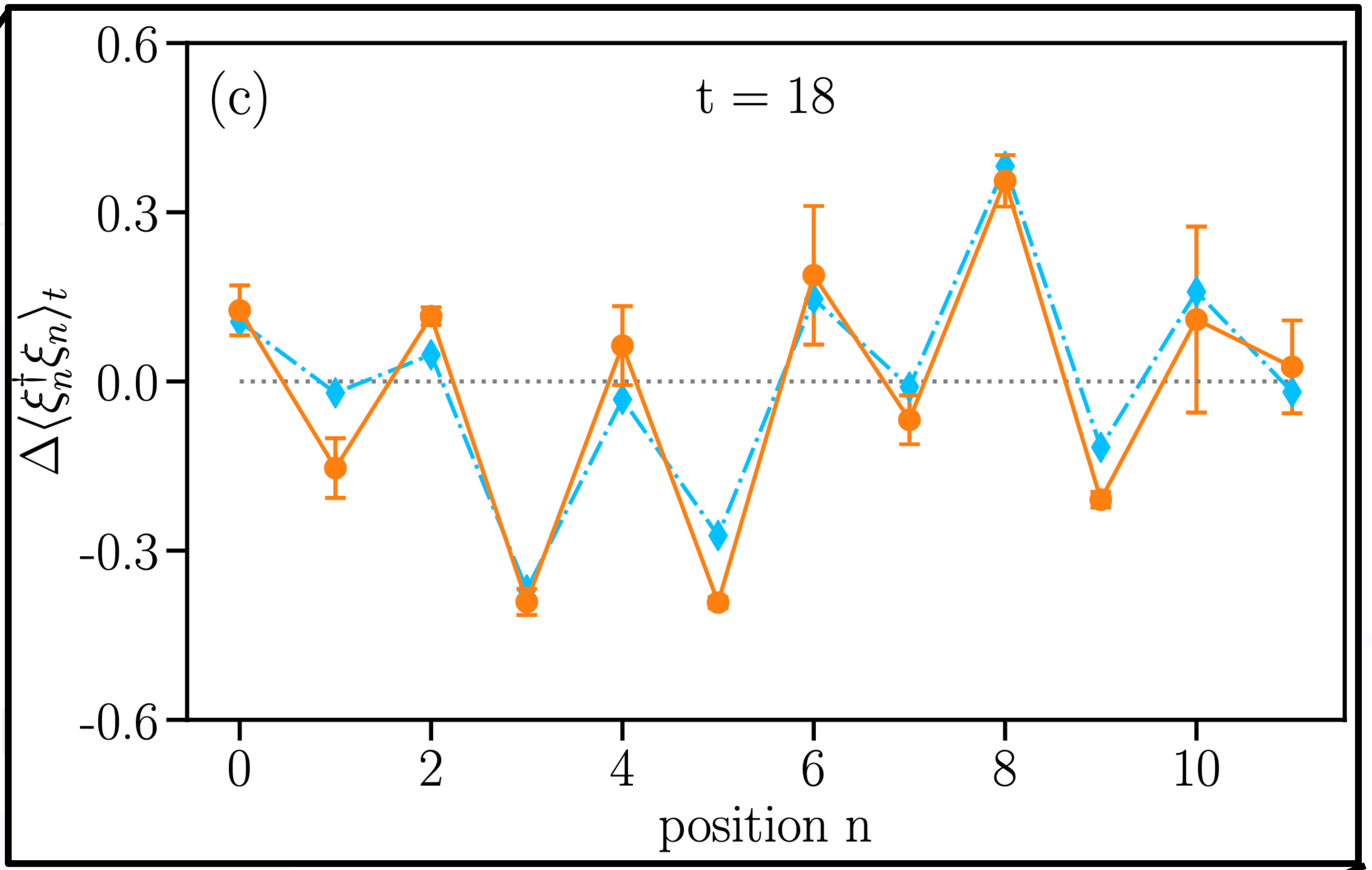

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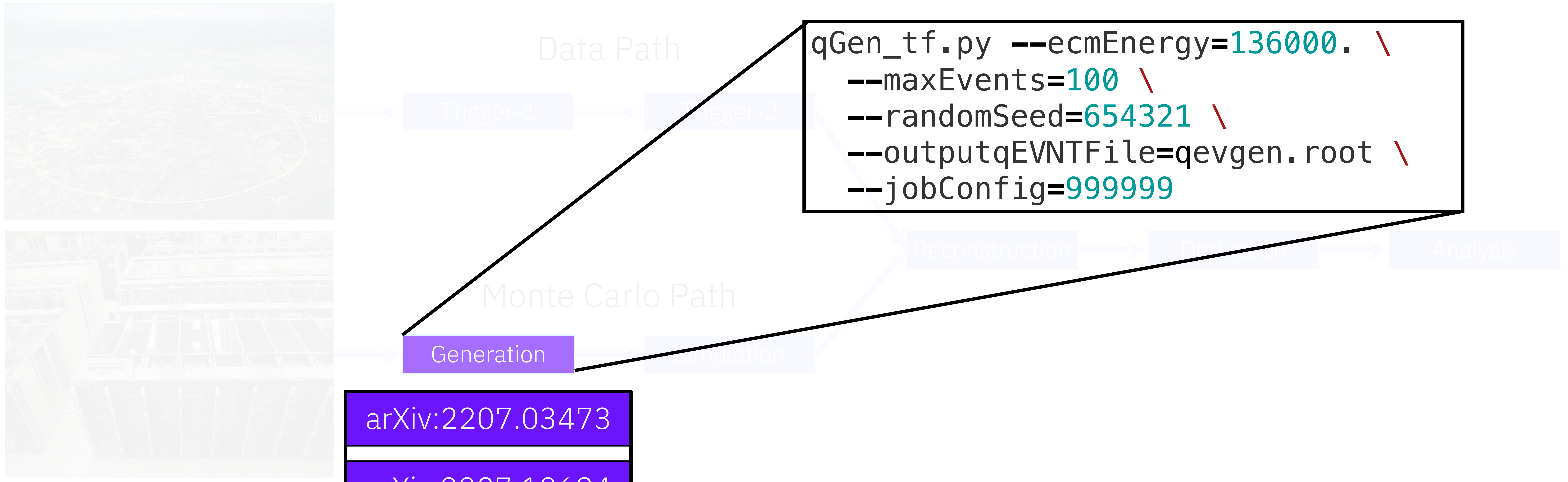


```
qGen_tf.py --ecmEnergy=136000. \
  --maxEvents=100 \
  --randomSeed=654321 \
  --outputqEVNTFile=qevgen.root \
  --jobConfig=999999
```

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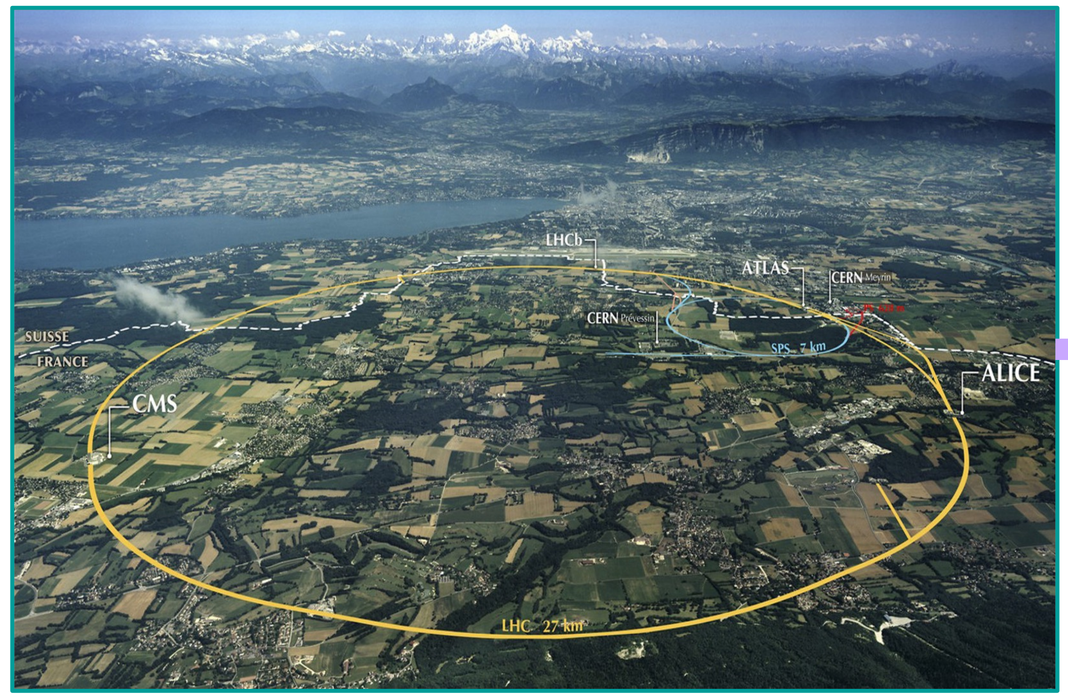

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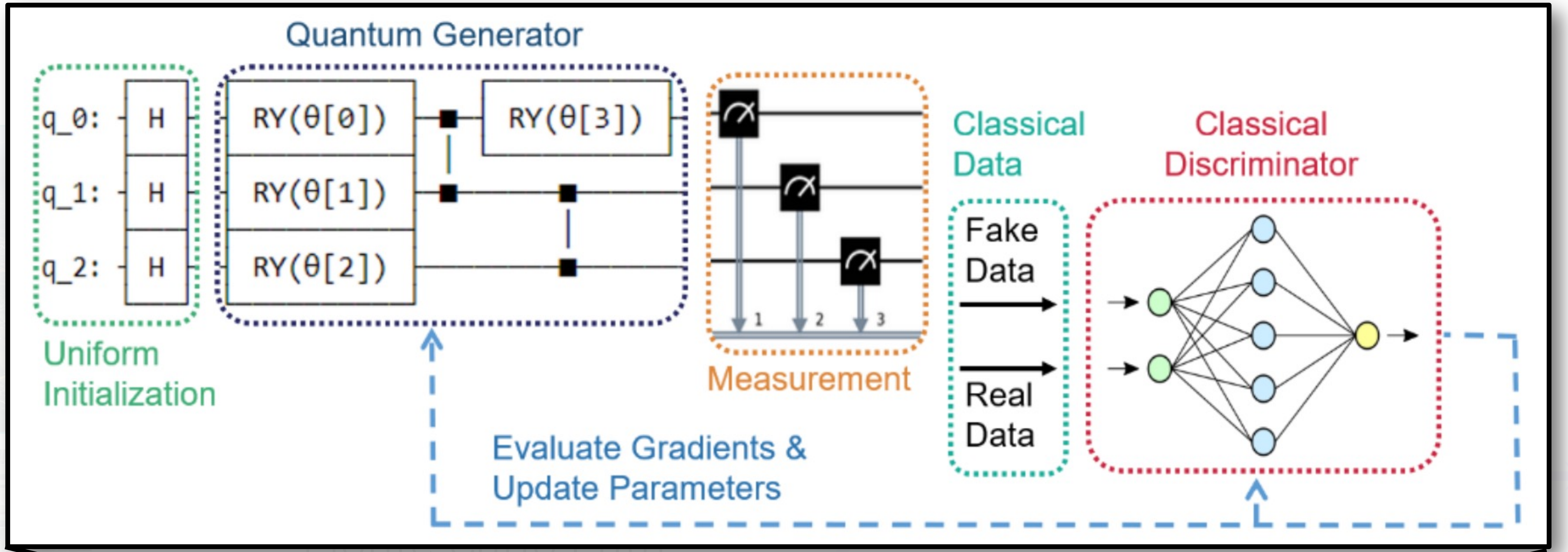
arxiv:2005.08582

CDS 2824092

arxiv:2203.03578

Use case: HEP data processing chain

F. Rehm *et al.* (2021)



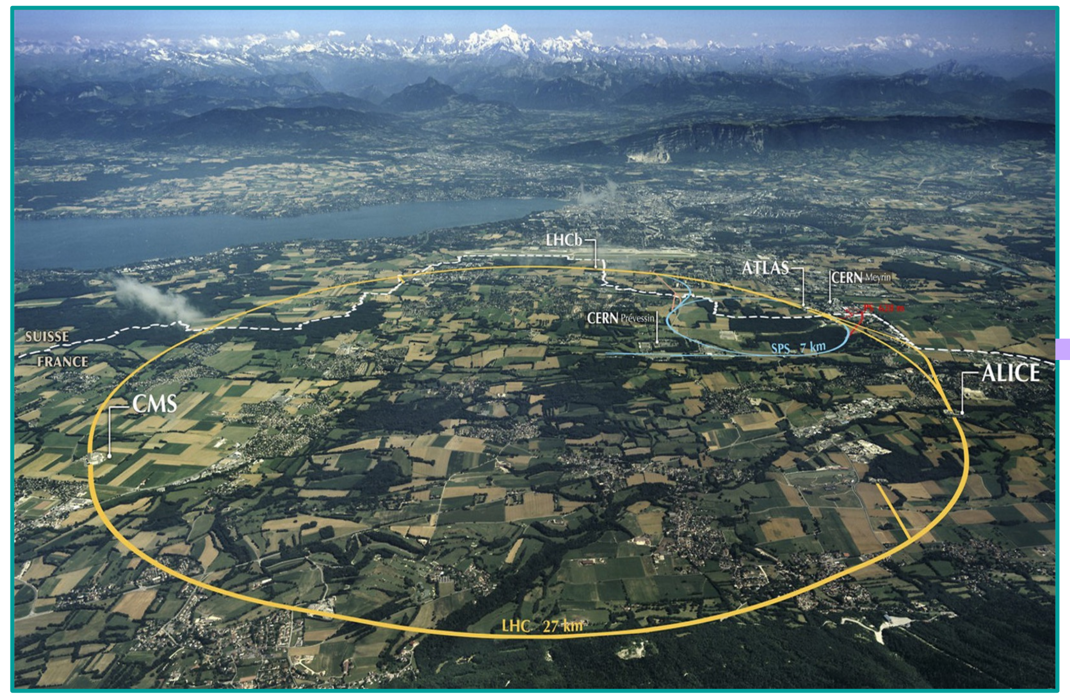
Simulation

arxiv:2005.08582

CDS 2824092

arxiv:2203.03578

Use case: HEP data processing chain



Data Path

Trigger-1 → Trigger-2

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Generation → Simulation

arXiv:2104.11583

arXiv:2204.06496

arXiv:2308.00619

Reconstruction → Derivation → Analysis

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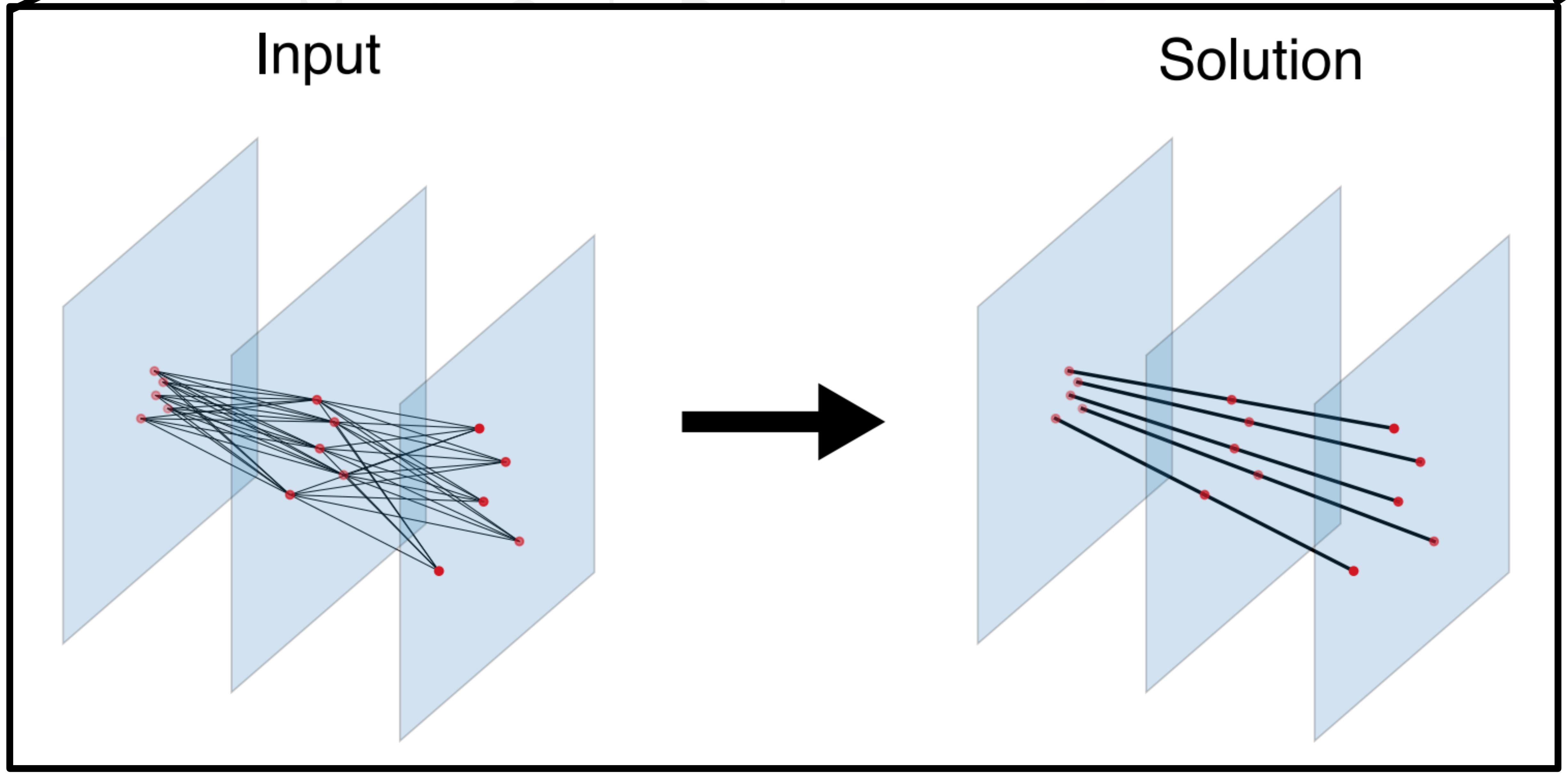
Reconstruction → Derivation → Analysis

D. Nicotra *et al.* (2023)



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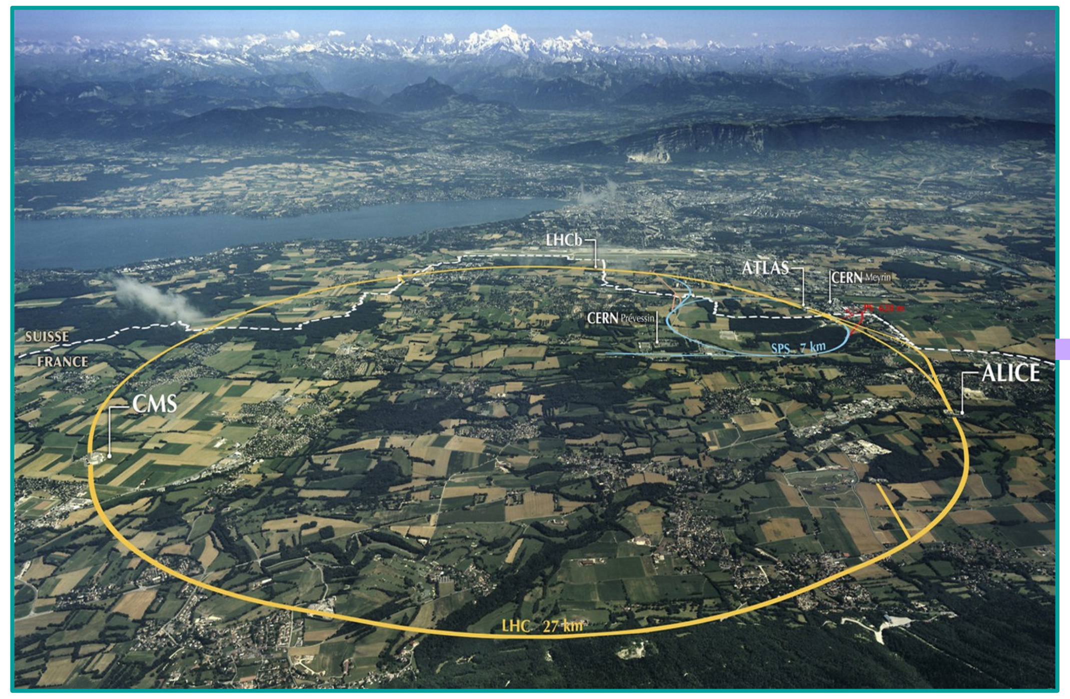
arXiv:2308.00619

D. Nicotra *et al.* (2023)

Layers	Particles	Doublets	Qubits	Depth	2-qubit gates
3	2	8	8	12 071	5 538
3	3	18	12	1 665 771	834 417
3	4	32	12	901 255	442 694
3	5	50	14	14 515 229	7 107 317
4	2	12	10	185 817	93 213
4	3	27	12	1 714 534	840 780
4	4	48	14	14 197 046	7 110 044

Use case: HEP data processing chain



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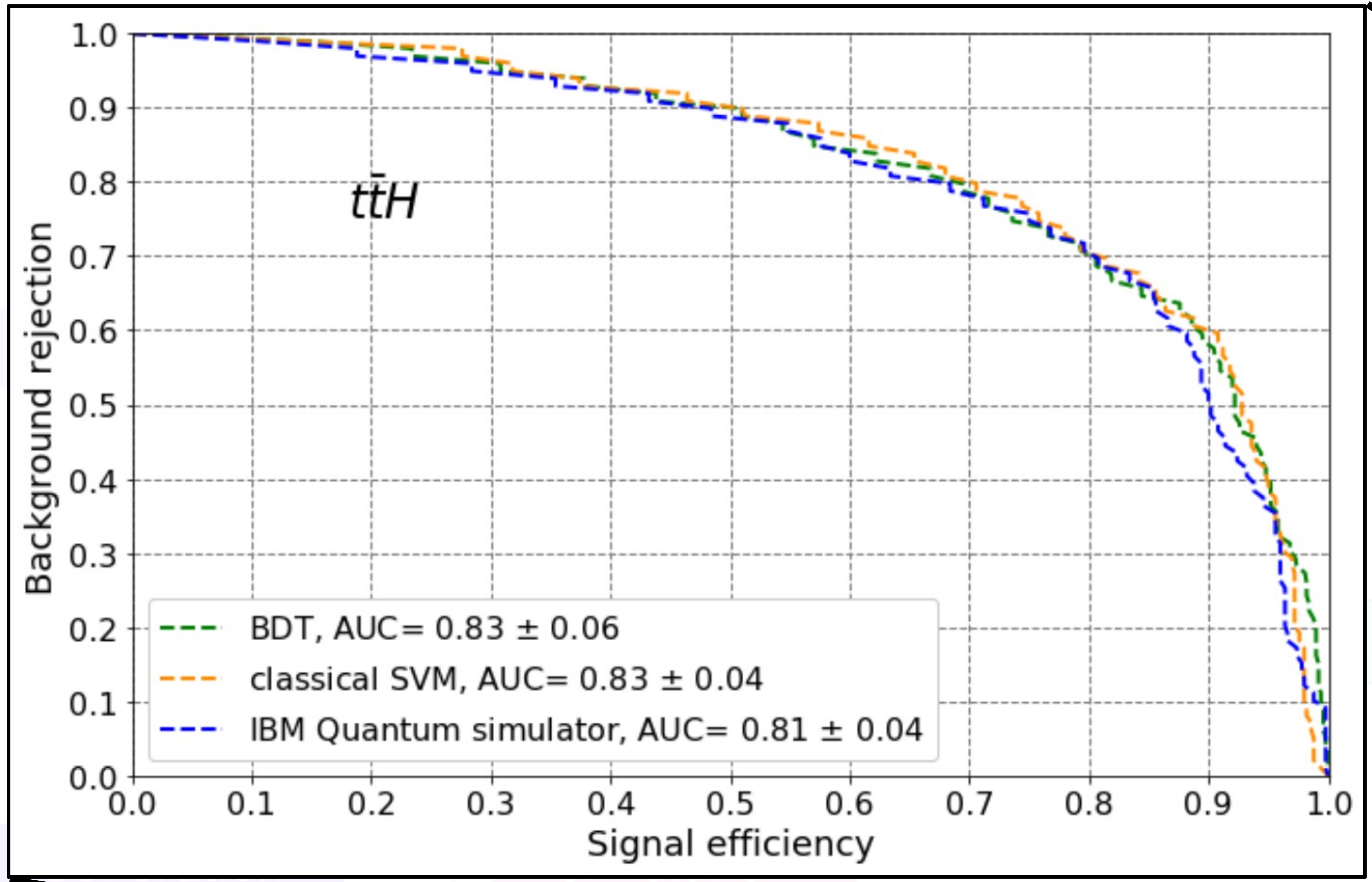
arXiv:2104.05059

arXiv:2203.08805

arXiv:2206.08391

Use case: HEP data processing chain

S.L. Wu *et al.* (2023)



Derivation → Analysis

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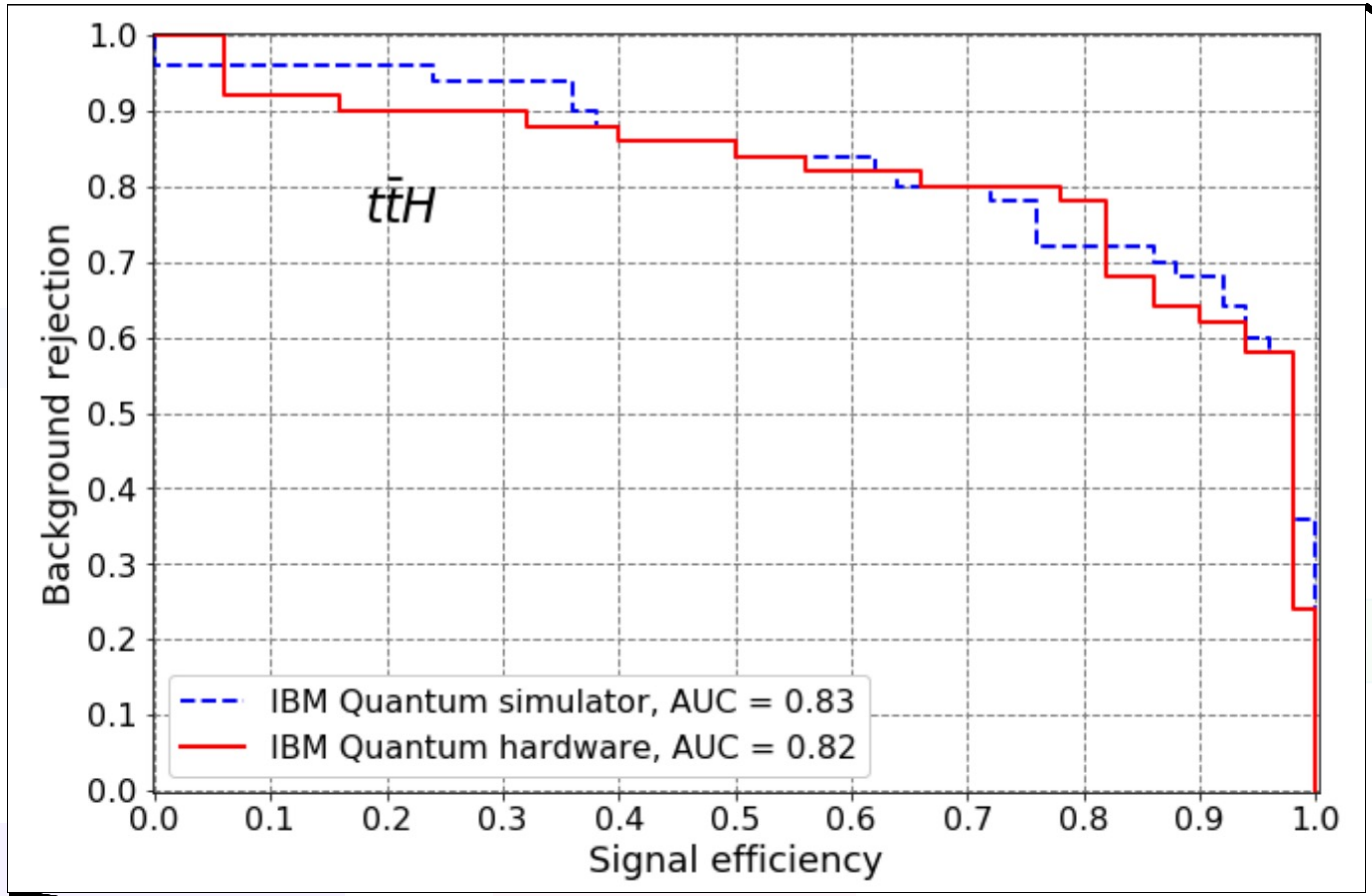

Derivation

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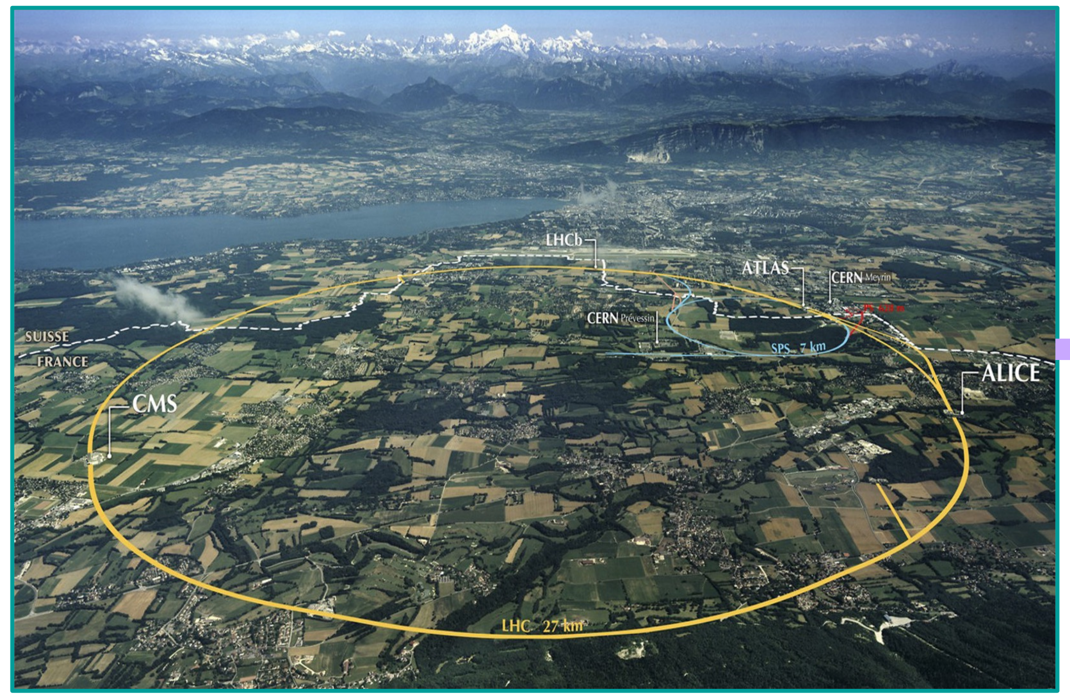

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Likely most promising avenue for quantum advantage.

Summary

We are now in the era of utility, where quantum computing can provide reliable solutions at-par or beyond brute force classical computing methods.

QCSC to leverage quantum and classical computing devices to enable execution of hybrid workloads at utility-scale.

Domain scientists must find the hard problems to solve, cross-cutting expertise required to work on a solution.

Focus areas include workload management, HPC-quantum workflows, programmability, and use cases, all in the near- and far-term.

Many areas of physics already looking to quantum; theory or where quantum manifests in the problem are promising.

Keen to discuss with the community has in mind about other ideas and interests.

IBM **Quantum**

Backup

“Nature isn’t classical, dammit, and if you want to make a simulation of Nature, you’d better make it quantum mechanical...”

Richard P. Feynman
Simulating Physics with Computers, 1981

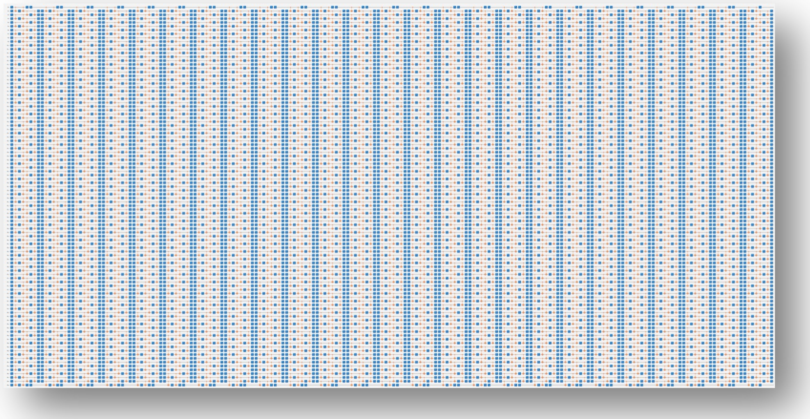
Error-resilience and time scales

- 🟢 QEC
- 🟦 QEM Unbiased
- 🟥 QEM Biased

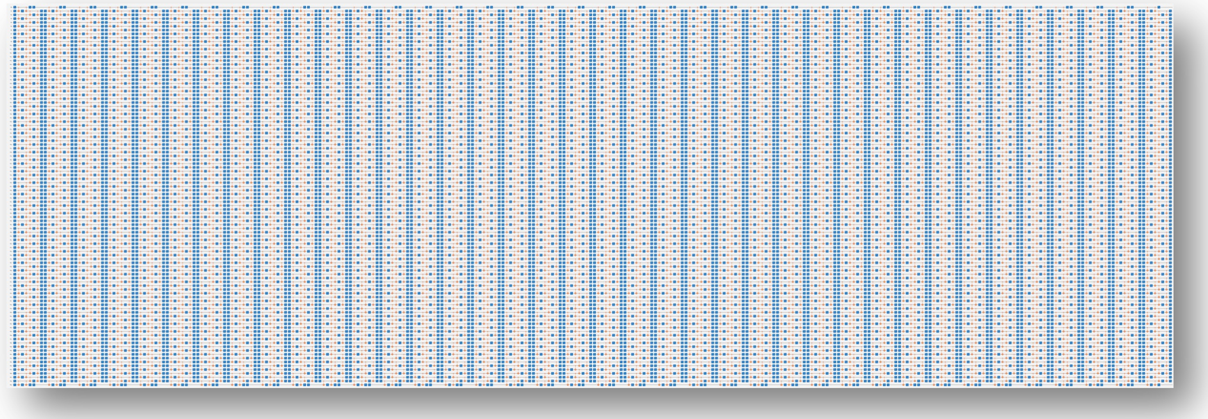
	Middleware		Qiskit Runtime		Quantum Hardware
Timescale	Cloud loop time	Server loop time	Near-time		Real-time
	hours – minutes	seconds	ms	µs-ns	ns
Error resilience related function	Unitary parameter update Custom QPU info share Logical circuit schedule and compile optimization Final decode/reconstruct/correction	Compile probabilistic circuits (🟦) Noise model update (🟦 🟥) Optimal qubit maps (🟦 🟥) Multi-QPU job optimization	Physical parameter update Decoder update (🟢) Decode/Correct (🟢)	Probabilistic gates (🟦🟥) Stretched gates (🟥) Dynamic logical ops (🟢) Fast decode, high BW (🟢) Decode data compression (🟢)	Mid-circuit measurement and feedforward (🟢) Non-local real-time operations (🟢)
Hardware challenges	Pipelining with QPUs Low latency HPC optimization Final level of decoding	Parallel QPU utilization Data BW Decode compute	FPGA Update AoT compiling	Fast reinitialization (🟦🟥) Intra-qubit comm Local decode and compress	Local memory size High-BW acquisition Intra-qubit latency

Quality and cost-effectiveness

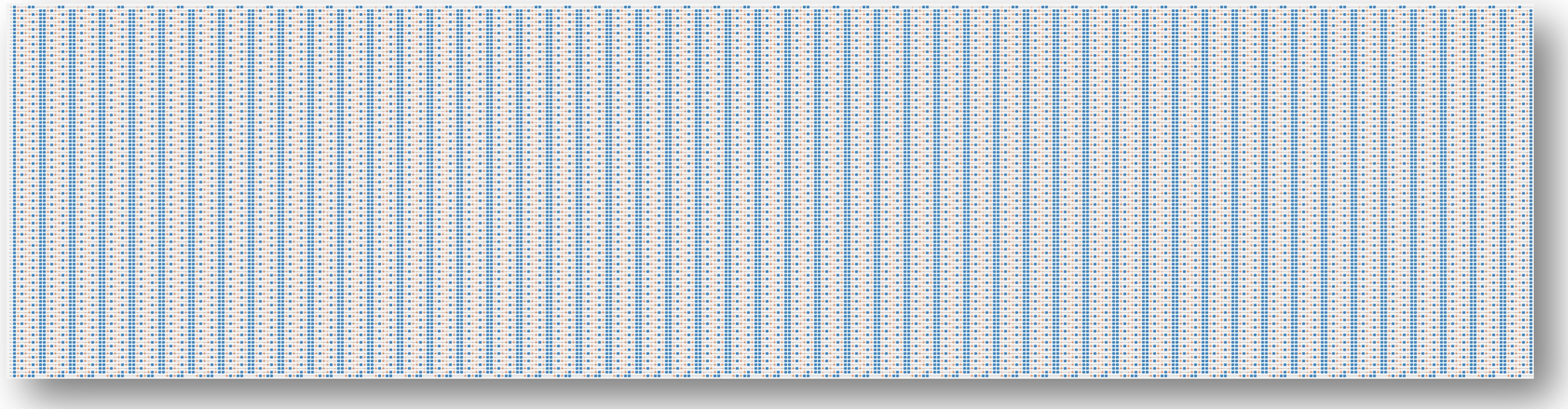
2024 – 5K gates 2Q error rate: 5×10^{-4} ($\bar{\gamma} = 1.002$)



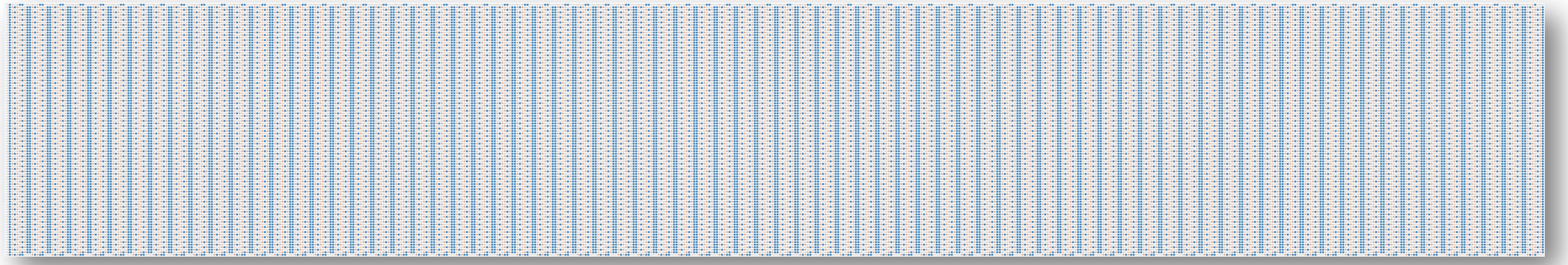
2026 – 7.5K gates 2Q error rate: 3.3×10^{-4} ($\bar{\gamma} = 1.001$)



2027 – 10K gates 2Q error rate: 2.5×10^{-4} ($\bar{\gamma} = 1.0009$)



2028 – 15K gates 2Q error rate: 1.6×10^{-4} ($\bar{\gamma} = 1.0006$)



Exponential growth of problem dimensionality places strict limits on classical compute scaling, and cost effectiveness of deploying ever growing resources; **effective limit of ~50 qubits for direct simulation**

There is no long-term value in CPU, GPU, or any other classical simulation of quantum circuits

Computations becomes more cost-effective to run on quantum hardware as error rates decrease

Crossover points for quantum cost effectiveness vs. GPUs

2023: **46Q** $\bar{\gamma} = 1.01$ Internal Nvidia 4x DGX GH200 capable of 46Q direct simulation

2026: **32Q** $\bar{\gamma} = 1.001$

By 2026 it will be cheaper to run even trivial circuits on quantum hardware vs. GPUs