Quantum computation for strong-force simulations at high energies

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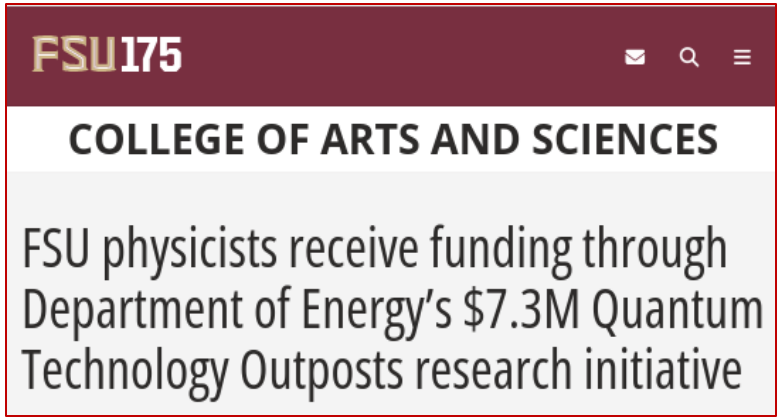
Wednesday October 28th 2026
ORNL Leadership Computing Facility User Call

Based upon:

- [arXiv:2303.04818] SciPost Phys. 15, 205 (2023) w/ M. Pellen
- [arXiv:2507.07194] Eur. Phys. J. C 86, 961 (2026) w/ M. Pellen & S. Williams
- and ongoing work

Acknowledgements

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- This research was supported by the U.S. Department of Energy under grant DE-SC0010102.



Outline

1. Introduction/motivation
2. Calculating colour part of a Feynman diagram on a quantum computer
3. Multiple Feynman diagrams and their quantum interferences
4. Efficient algorithm for Feynman diagrams with identical particles
5. Towards kinematics
6. Summary and outlook

Including demonstration on 56-qubit ion-trap quantum computer!

First hints of quantum advantage!

New 98-qubit ion-trap machine



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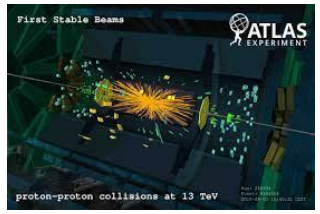
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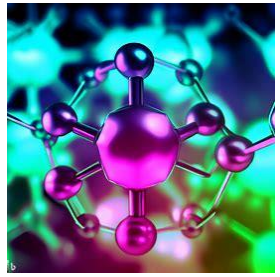
What can quantum computers do?

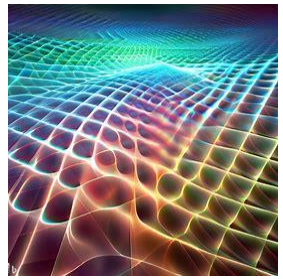
- Prime factorisation
- Unstructured search
  - e.g. searching abstract spaces
  - e.g. Monte-Carlo integration
- Simulating quantum systems
  - Computational chemistry
  - Condensed matter systems
  - Particle physics
- Linear equations, optimization, …











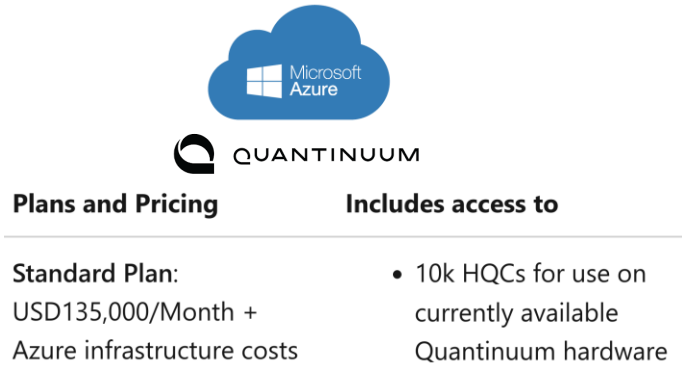


Why now?

- Hardware progress
  - Trapped ions
  - Neutral atoms
  - Photonic systems
  - Superconducting systems
  - …
- Software progress
  - e.g. Error-correcting codes (e.g. "surface codes")
- Commercial interest
- Government interest



Figure by IDTechEx



Why now?



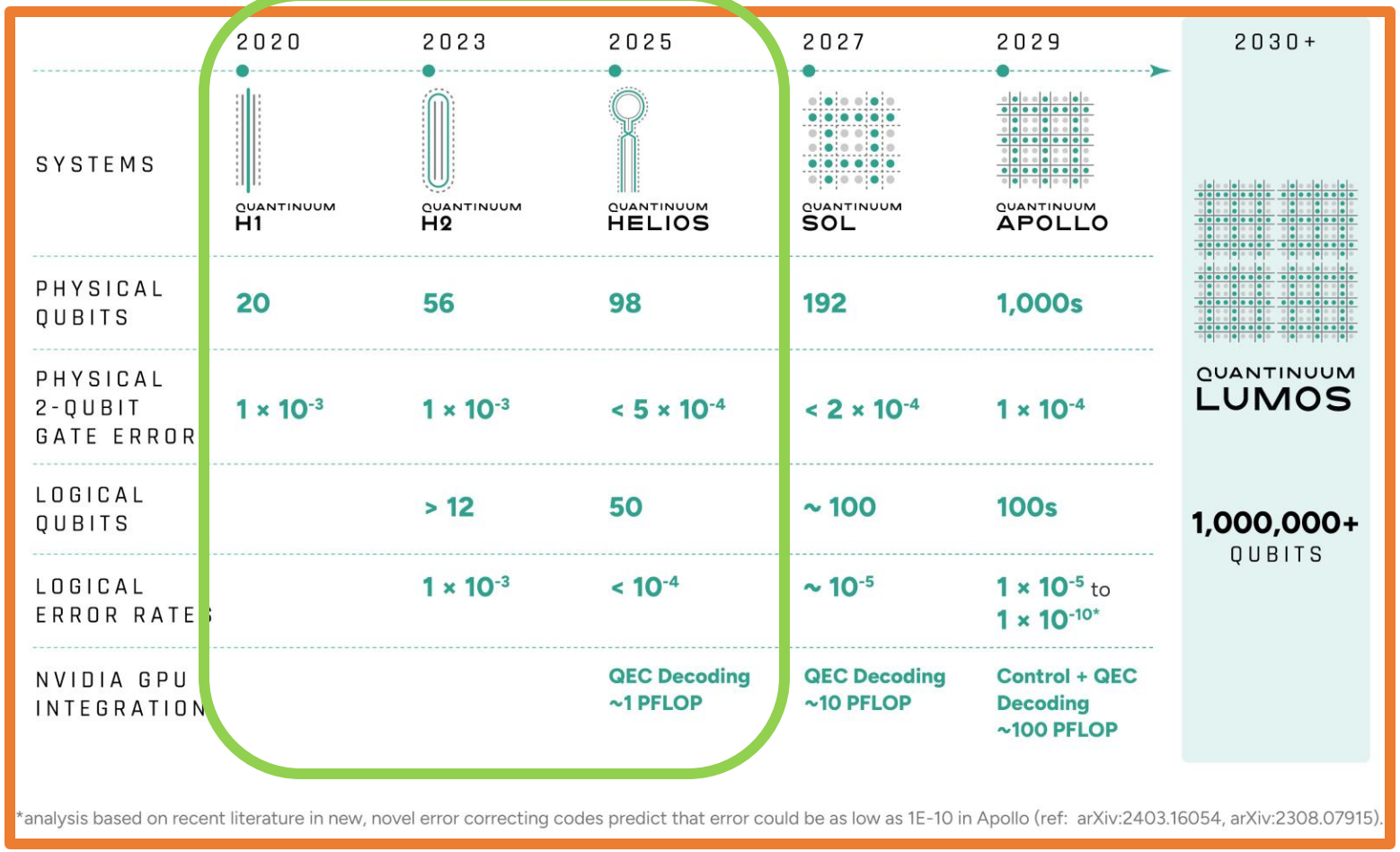
Quantum System Hardware Capability Progression

(Illustrative Ranges Across Platforms)

	2026 VERIFIED DEMONSTRATIONS	2027 SCALABLE SYSTEMS	2028 SCIENTIFIC-RELEVANT DEMONSTRATIONS	2030+ USER FACILITY CAPABILITY
LOGICAL QUBITS	~1 – 10 logical qubits	~10 – 50 logical qubits	~50 – 100+ logical qubits	~1,000 – 10,000 logical qubits for transformative campaigns
HARD LOGICAL OPERATIONS	Up to ~10^4 quantum operations in tightly controlled demonstrations	~10^3 – 10^4 hard logical operations	~10^4 – 10^5 hard logical operations	~10^9 – 10^{10} hard logical operations for large scientific applications
SPEED & TIME TO RESULT	~10 – 10^4 logical operations per second; much of the time spent resetting rather than computing	~10× more logical operations per hour at the same accuracy	A full scientific calculation returned within 24 hours	~10^9 – 10^{10} operation campaigns finished in days, computing >80% of the time
CONNECTIVITY BETWEEN QUBITS	Effective connectivity: linking distant qubits costs ~2 – 10× more time and error than neighbors; ~1× on small fully connected machines	Effective connectivity improved ~3× on machines of ~100+ qubits	Effective connectivity within ~2× of ideal across a ~1,000-qubit machine	Within ~1.5× of ideal across ~10^6 – 10^7 qubits; linked modules behave as one machine
ACCURACY & RELIABILITY	Logical operations demonstrated and classically benchmarked	Lower logical error rates; repeatable multi-logical-qubit workflows	Reliable fault-tolerant execution sufficient for end-to-end scientific calculation	Production-level reliability for sustained scientific campaigns
SYSTEM INTEGRATION	Early logical-qubit demonstrations	Integrated control, decoding, software, and calibration	End-to-end quantum–HPC–AI workflow with scientific validation	Results beyond routine classical reach, integrated with experiments and DOE user facilities
SCIENTIFIC VALIDATION	Direct classical verification	Classical verification or high-quality emulation where feasible	Independent validation against experiment, classical limits, or predictive scientific value	Results beyond routine classical reach, integrated with experiments and DOE user facilities

Why now?

Quantinuum Roadmap



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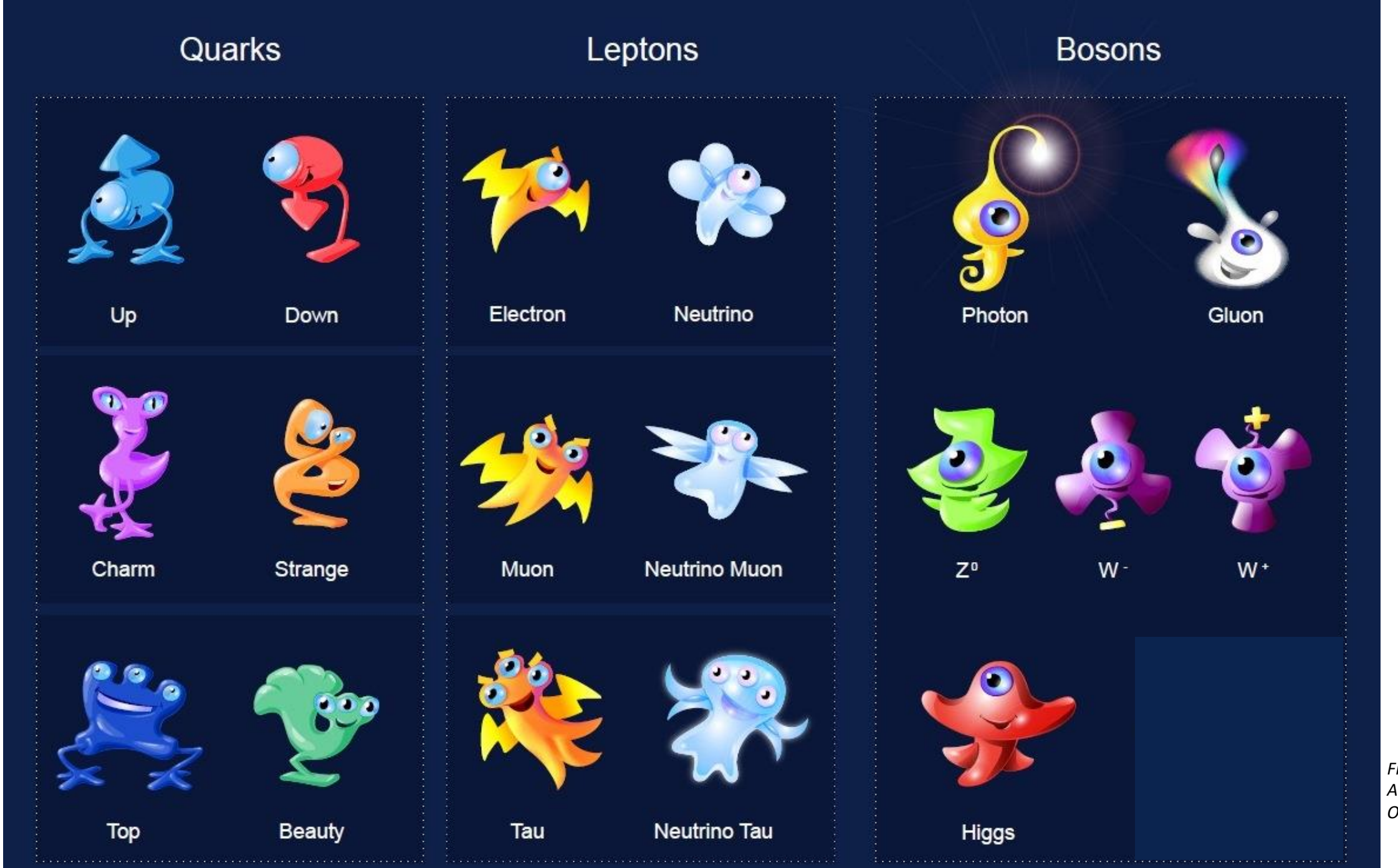


Figure by André-Pierre Olivier / CERN



Figure by Maximilien Brice / CERN

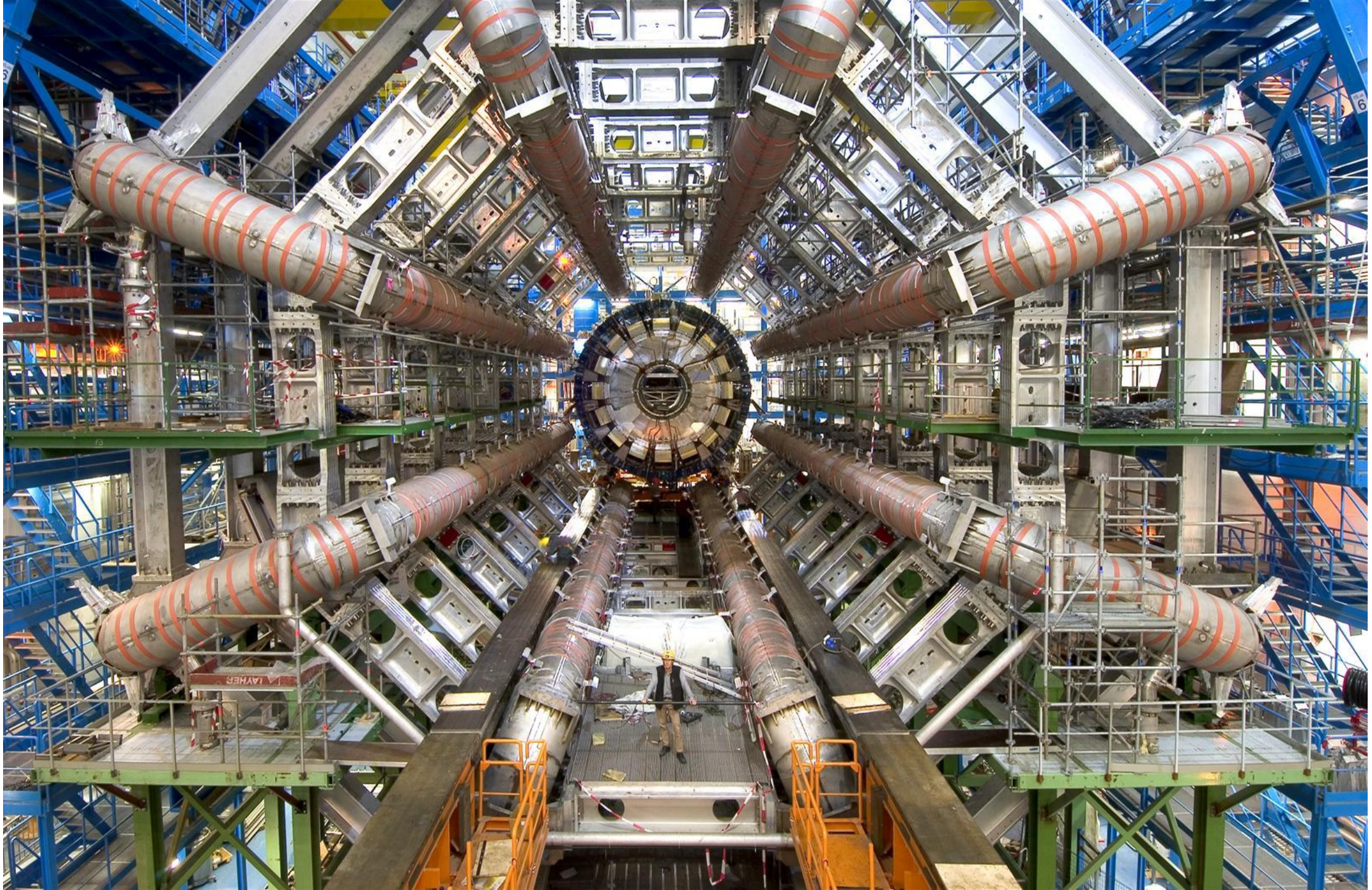


Image by Maximilien Brice / CERN

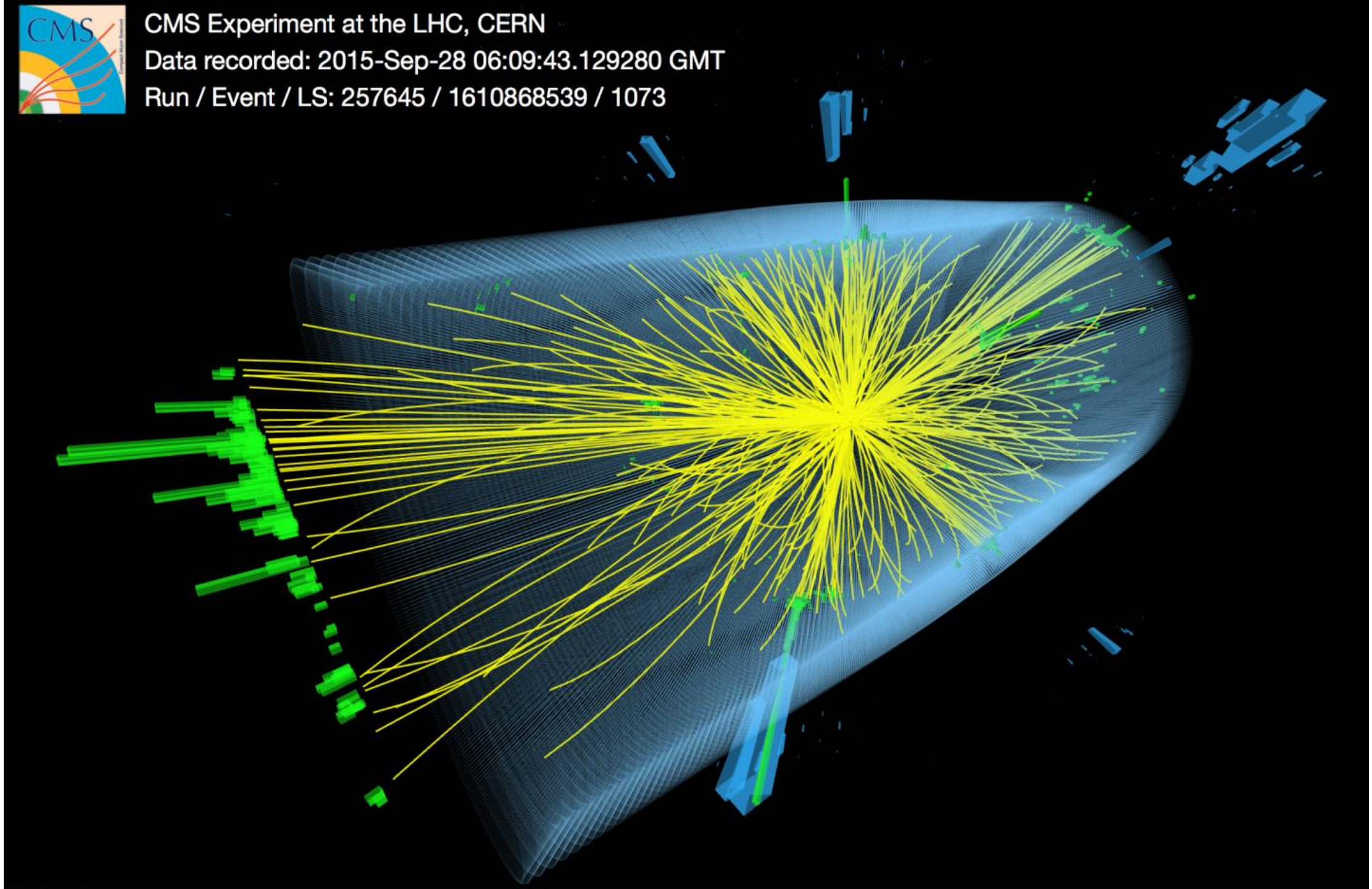
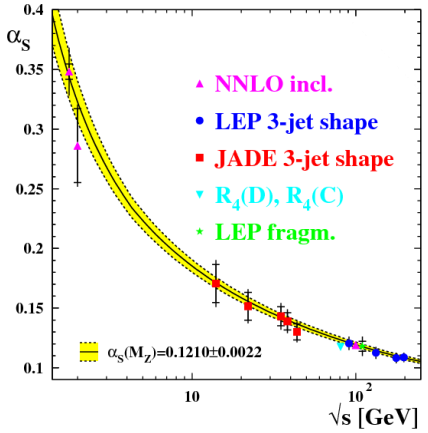


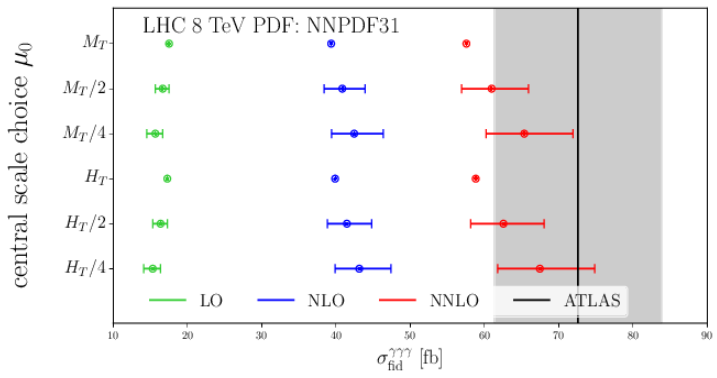
Image by T. McCauley and the CMS collaboration

Why simulate strong force at high energy?

- Simulations for precision measurements at colliders
  - Metrology for particle physics
    - Could give first hints of new particles awaiting discovery
- QCD at high energies becomes perturbative
  - Can use Feynman diagrams to calculate cross-sections / scattering rates
- Highly challenging and computationally intense
  - e.g. multi-loop amplitude calculations
  - e.g. Monte-Carlo integration of cross sections



HAC, Czakon, Mitov, Poncelet, [1911.00479]

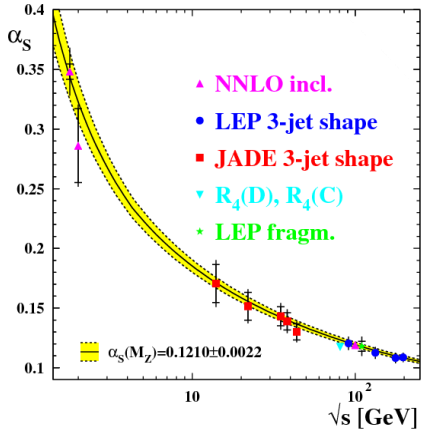


Why simulate perturbative QCD on a quantum computer?

1. Perturbative QCD requires quantum-coherent combination of contributions from many unobservable intermediate states
   - natural candidate to exploit superpositions of quantum states in quantum computers and seek a quantum advantage (see later)
2. Processes with high-multiplicity final states, with full quantum interference effects
3. Improve speed/precision of perturbative QCD predictions by exploiting speed-ups of known quantum algorithms
   - e.g. quantum amplitude estimation
   - e.g. quantum Monte Carlo



Complementarity with lattice-based approaches



- Quantum simulation: a flagship application of quantum computers
- Recent years: proposals for quantum simulation of lattice QFTs (e.g. lattice QCD)
  - But lattice QCD requires lattice with $(Q/\Lambda)^3$ lattice sites
  - $\Lambda \sim 0.2$ GeV (fundamental QCD scale)
  - For the LHC, $Q \sim$ thousands of GeV

    So on a lattice, QCD at LHC energies would require trillions of lattice sites -> trillions of qubits!
- Fortunately, at high energies we can use perturbative methods instead of lattice.
  - Can use Feynman diagrams to calculate scattering amplitudes and cross sections
- Quantum simulation of perturbative QCD remains largely unexplored
  - Notable exception: several papers on parton showers
- This talk: towards simulation of generic perturbative QCD processes
- Conceptually distinct from typical quantum simulations



Quantum computing proposals in high-energy physics

- Experiments / data analysis
- PDFs [Pérez-Salinas, Cruz-Martinez, Alhajri, Carrazza, '20], [QuNu Collaboration, '21], [Robbiati, Cruz-Martinez, Carrazza, '23]
- EFTs [Bauer, Freytsis, Nachman, '21]
- Monte Carlo for cross-sections [Agliardi, Grossi, Pellen, Prati, '22] [Cruz-Martinez, Carrazza, '23] [Williams, Pellen, '25] [Lee, Lee, Kim, '25]
- Parton showers [Bauer, de Jong, Nachman, Provasoli, '19], [Bepari, Malik, Spannowsky, Williams, '20], [Gustafson, Prestel, Spannowsky, Williams, '22]
- Event generation [Gustafson, Prestel, Spannowsky, Williams, '22], [Bravo-Prieto, Baglio, Cè, Francis, Grabowska, Carrazza, '21], [Kiss, Grossi, Kajomovitz, Vallecorsa, '22]
- Lattice QCD (See reviews e.g. [Klco, Roggero, Savage, '21] and [Bauer et al., '22] and references therein)
- Many more [Cervera-Lierta, Latorre, Rojo, Rottoli, '17], [Ramírez-Uribe, Rentería-Olivo, Rodrigo, Sborlini, Vale Silva, '21], [Fedida, Serafini, '22], [Clemente, Crippa, Jansen, Ramírez-Uribe, Rentería-Olivo, Rodrigo, Sborlini, Vale Silva, '22], [Martínez de Lejarza, Cieri, Grossi, Vallecorsa, Rodrigo, '24], [Ramírez-Uribe, Rentería-Olivo, Rodrigo, '24], [Gálvez-Viruet, Llanes-Estrada, '24], [de Lejarza et al. '25], [Bashore, Moretti, Vitos, '25], …
- + QI studies, …

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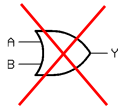
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Quantum circuit model

- Qubits
- Gates
  - Unitary, reversable 
  - Can be controlled by other qubits

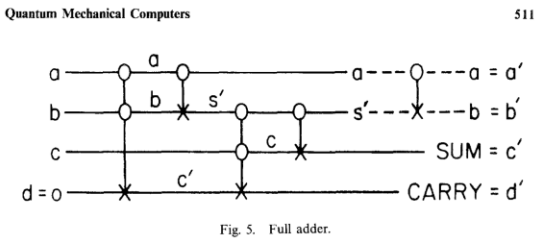
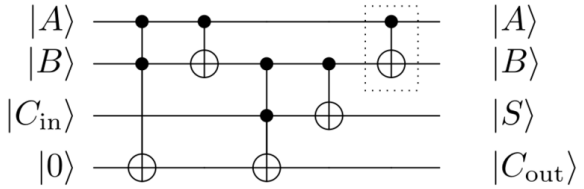
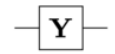
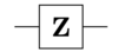
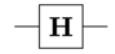
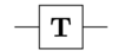
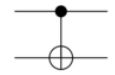
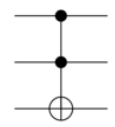


*Figure from: Feynman, R.P. Quantum mechanical computers. Found Phys **16**, 507–531 (1986)*

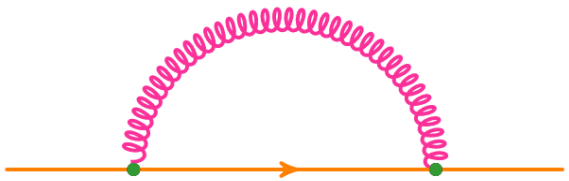


Operator	Gate(s)	Matrix
Pauli-X (X)		$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$
Pauli-Y (Y)		$\begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$
Pauli-Z (Z)		$\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$
Hadamard (H)		$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$
Phase (S, P)		$\begin{bmatrix} 1 & 0 \\ 0 & i \end{bmatrix}$
$\pi/8$ (T)		$\begin{bmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{bmatrix}$
Controlled Not (CNOT, CX)		$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$
Controlled Z (CZ)		$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}$
SWAP		$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$
Toffoli (CCNOT, CCX, TOFF)		$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$

QCD Feynman diagrams 101

- Physical observables ~ $|\mathcal{A}|^2$
- Scattering amplitude $\mathcal{A}$ can be written as sum over Feynman diagrams
  - Colour factors C_n and kinematic factors K_n

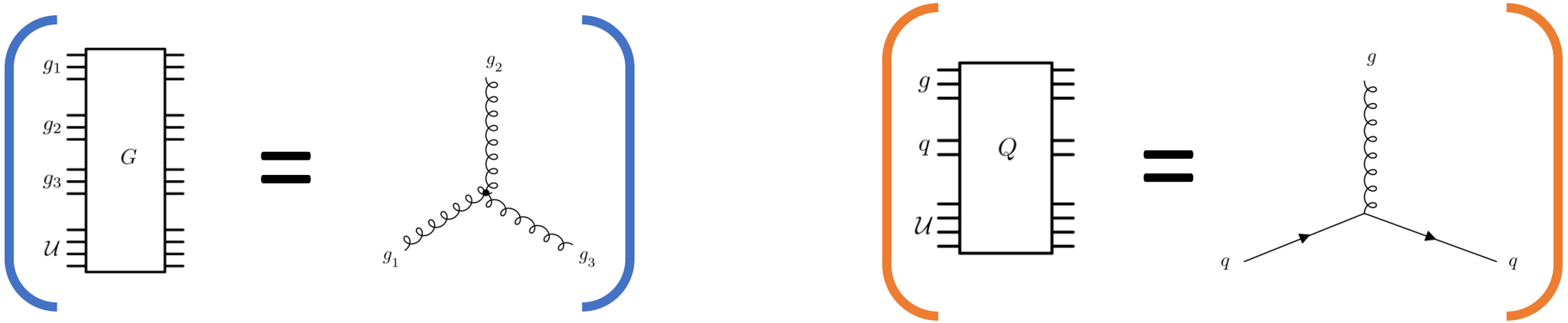
$$\mathcal{A} = \sum_n C_n K_n \qquad \mathcal{A}^{a_1 a_2 \ldots}_{i_1 i_2 \ldots, j_1 j_2 \ldots} = \sum_n C^{a_1 a_2 \ldots}_{n, i_1 i_2 \ldots, j_1 j_2 \ldots} K_n$$

- SU(3) structure function f^{abc} at each triple-gluon vertex
  - (4-gluon vertex can be written as linear combination of 3-gluon vertices)
- SU(3) generator T^a_{ij} at each quark-gluon vertex
- Trace over unmeasured (unmeasurable) colours
- e.g. colour factor of  is $\sum_{\substack{a\in\{1,\ldots,8\} \\ j\in\{1,2,3\}}} T^a_{ij} T^a_{jk}$
- Note: the large-N_c approximation is <u>not</u> required in this work



Key result of 2303.04818

- Two quantum gates (***G*** and ***Q***) to simulate color parts of the interactions of quarks and gluons

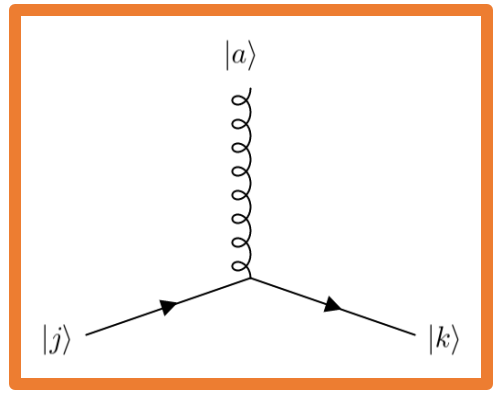


- Explicit construction of these gates: see 2303.04818 or backup slides

Implementation

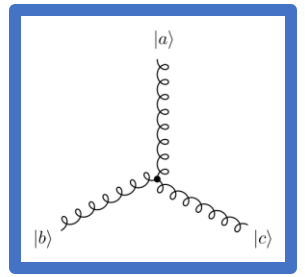
- Quark colors: represented by 2 qubits ($2^2 = 4$ basis states, of which 1 is unused)
- Gluon colors: represented by 3 qubits ($2^3 = 8$ basis states)
- Quark-gluon interaction gate is designed such that

$$Q\,|a\rangle_g\,|k\rangle_q\,|\Omega\rangle_{\mathcal{U}} = \sum_{j=1}^{3} T^a_{jk}\,|a\rangle_g\,|j\rangle_q\,|\Omega\rangle_{\mathcal{U}} + (\text{terms orthogonal to } |\Omega\rangle_{\mathcal{U}})$$



- Triple-gluon interaction gate is designed such that

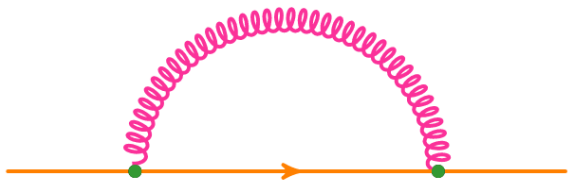
$$G\,|a\rangle_{g_1}\,|b\rangle_{g_2}\,|c\rangle_{g_3}\,|\Omega\rangle_{\mathcal{U}} = f^{abc}\,|a\rangle_{g_1}\,|b\rangle_{g_2}\,|c\rangle_{g_3}\,|\Omega\rangle_{\mathcal{U}} + (\text{terms orthogonal to } |\Omega\rangle_{\mathcal{U}})$$

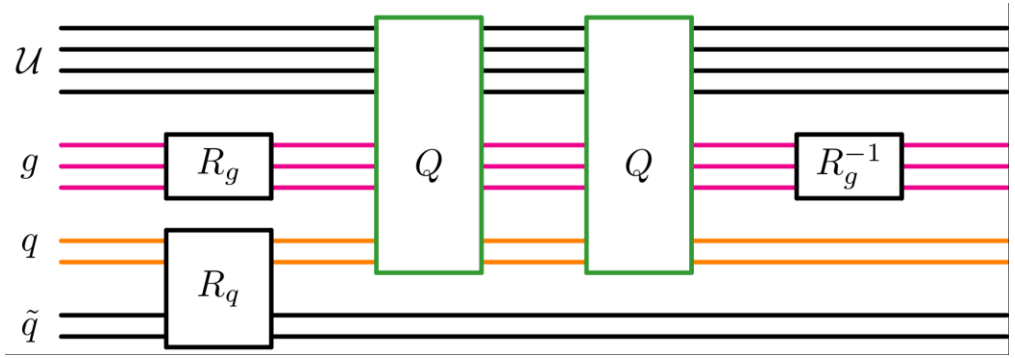


- Note: $|\Omega\rangle_{\mathcal{U}}$ is a reference state of a "Unitarization register", which we introduce because in SU(3), T^a_{jk} and f^{abc} are non-unitary.

Simulating colour: illustrative example

(See later slides for general case)

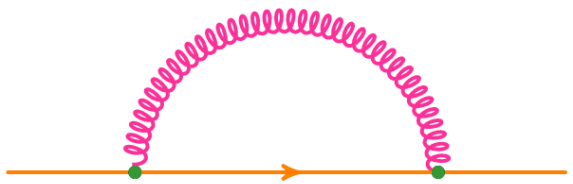


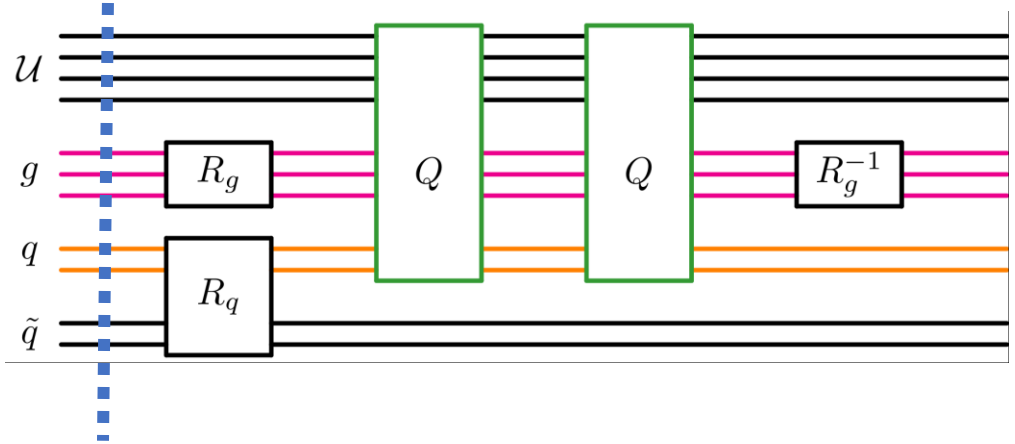


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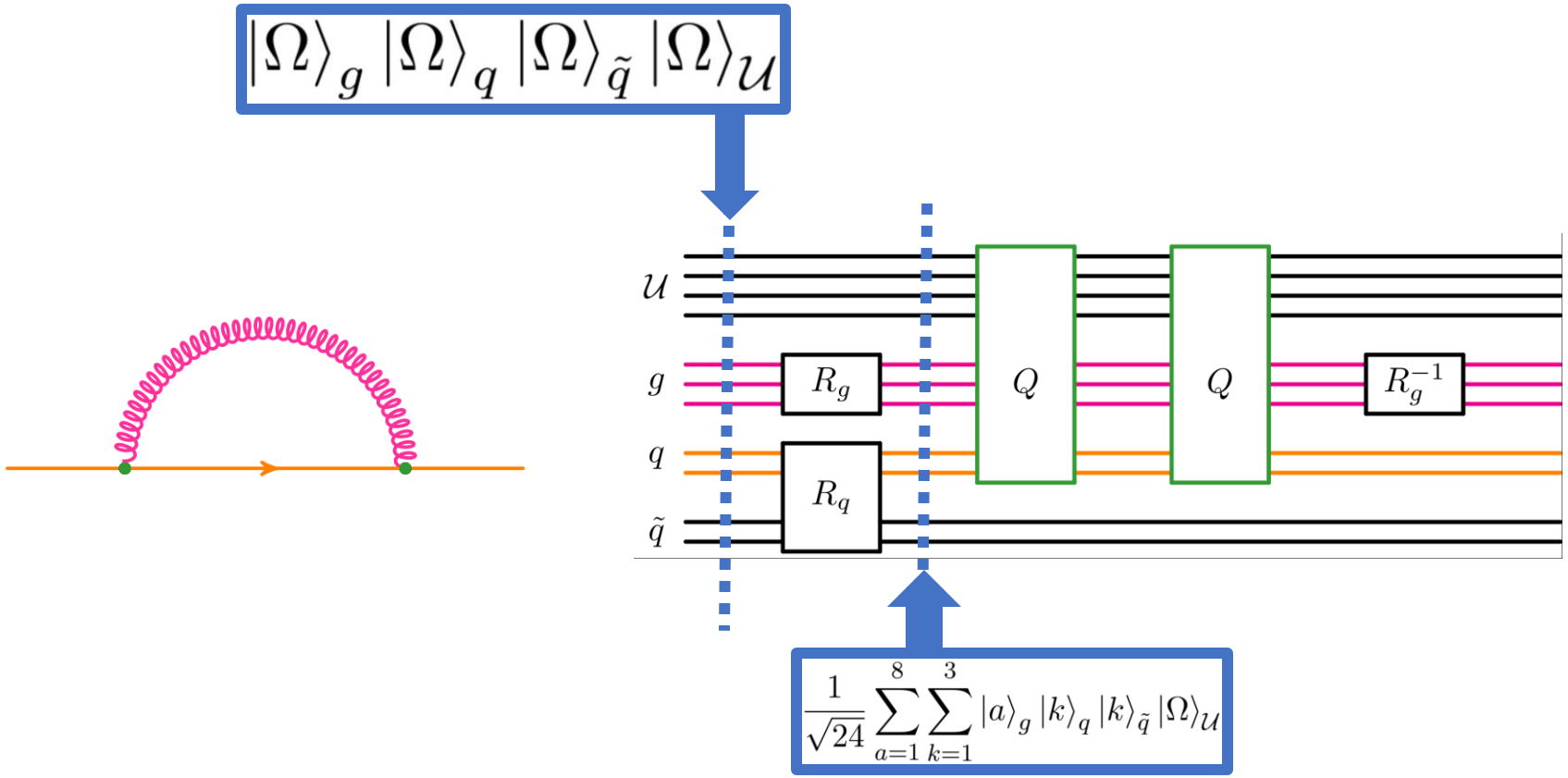
$$|\Omega\rangle_g \, |\Omega\rangle_q \, |\Omega\rangle_{\tilde{q}} \, |\Omega\rangle_{\mathcal{U}}$$





Simulating colour: illustrative example

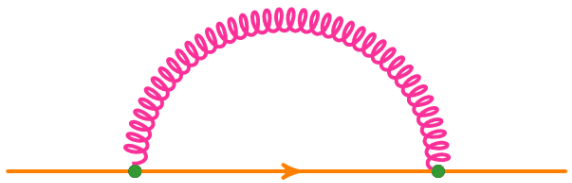
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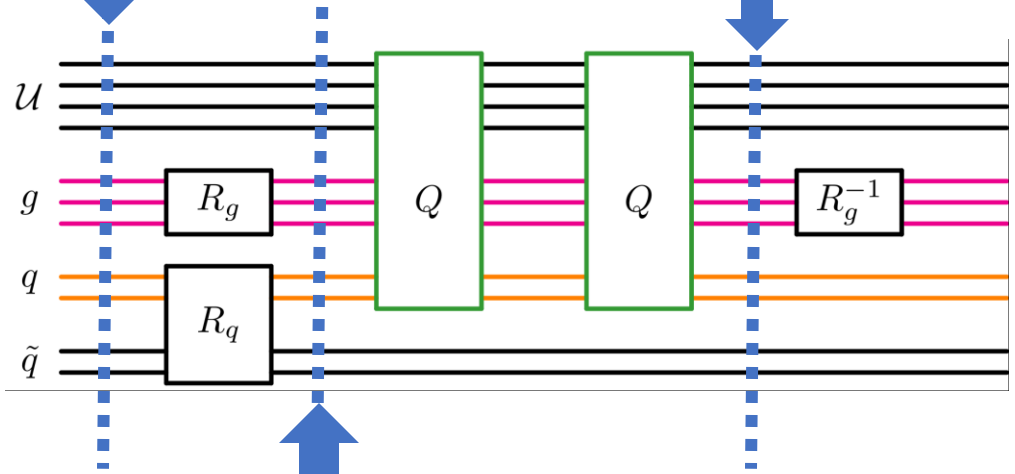


Simulating colour: illustrative example

$$|\Omega\rangle_g \, |\Omega\rangle_q \, |\Omega\rangle_{\tilde{q}} \, |\Omega\rangle_{\mathcal{U}}$$

$$\frac{1}{\sqrt{24}} \sum_{\substack{a\in\{1,\ldots,8\} \\ i,j,k\in\{1,2,3\}}} T^a_{ij} T^a_{jk} \, |a\rangle_g \, |i\rangle_q \, |k\rangle_{\tilde{q}} \, |\Omega\rangle_{\mathcal{U}} + (\text{terms orthogonal to } |\Omega\rangle_{\mathcal{U}})$$



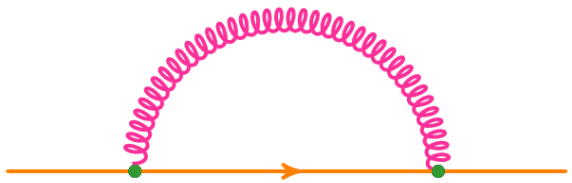


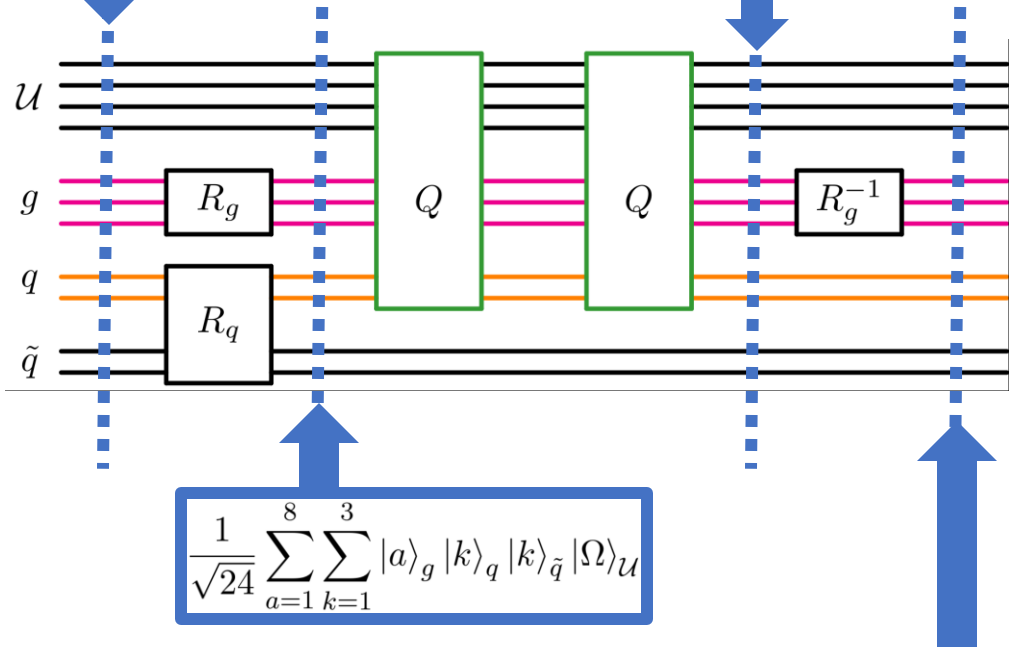
$$\frac{1}{\sqrt{24}} \sum_{a=1}^{8} \sum_{k=1}^{3} |a\rangle_g \, |k\rangle_q \, |k\rangle_{\tilde{q}} \, |\Omega\rangle_{\mathcal{U}}$$

Simulating colour: illustrative example

$$|\Omega\rangle_g\,|\Omega\rangle_q\,|\Omega\rangle_{\tilde{q}}\,|\Omega\rangle_{\mathcal{U}}$$

$$\frac{1}{\sqrt{24}}\sum_{\substack{a\in\{1,\ldots,8\}\\ i,j,k\in\{1,2,3\}}} T^a_{ij}T^a_{jk}\,|a\rangle_g\,|i\rangle_q\,|k\rangle_{\tilde{q}}\,|\Omega\rangle_{\mathcal{U}} + (\text{terms orthogonal to } |\Omega\rangle_{\mathcal{U}})$$





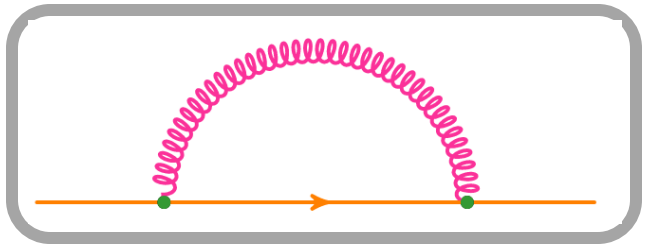
$$\frac{1}{\sqrt{24}}\sum_{a=1}^{8}\sum_{k=1}^{3}|a\rangle_g\,|k\rangle_q\,|k\rangle_{\tilde{q}}\,|\Omega\rangle_{\mathcal{U}}$$

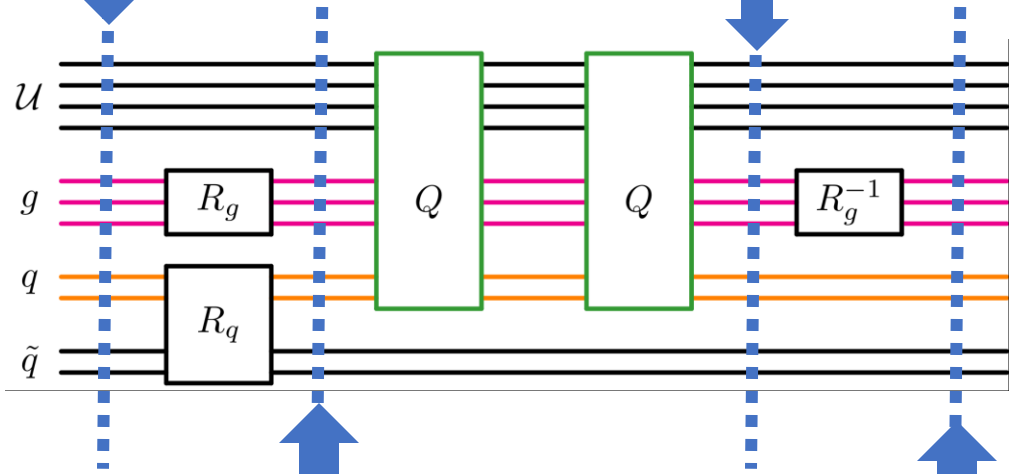
$$\frac{1}{8\sqrt{3}}\left(\sum_{\substack{a\in\{1,\ldots,8\}\\ i,j,k\in\{1,2,3\}}} T^a_{ij}T^a_{jk}\,|i\rangle_q\,|k\rangle_{\tilde{q}}\right)|\Omega\rangle_g\,|\Omega\rangle_{\mathcal{U}} + \Big(\text{terms orthogonal to } |\Omega\rangle_g\,|\Omega\rangle_{\mathcal{U}}\Big)$$

Simulating colour: illustrative example

$$|\Omega\rangle_g\,|\Omega\rangle_q\,|\Omega\rangle_{\tilde{q}}\,|\Omega\rangle_{\mathcal{U}}$$

$$\frac{1}{\sqrt{24}}\sum_{\substack{a\in\{1,\ldots,8\}\\ i,j,k\in\{1,2,3\}}} T^a_{ij}T^a_{jk}\,|a\rangle_g\,|i\rangle_q\,|k\rangle_{\tilde{q}}\,|\Omega\rangle_{\mathcal{U}} + (\text{terms orthogonal to } |\Omega\rangle_{\mathcal{U}})$$





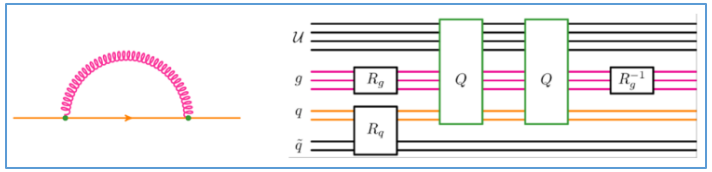
$$\frac{1}{\sqrt{24}}\sum_{a=1}^{8}\sum_{k=1}^{3}|a\rangle_g\,|k\rangle_q\,|k\rangle_{\tilde{q}}\,|\Omega\rangle_{\mathcal{U}}$$

$$\frac{1}{8\sqrt{3}}\left(\sum_{\substack{a\in\{1,\ldots,8\}\\ i,j,k\in\{1,2,3\}}} T^a_{ij}T^a_{jk}\,|i\rangle_q\,|k\rangle_{\tilde{q}}\right)|\Omega\rangle_g\,|\Omega\rangle_{\mathcal{U}} + \Big(\text{terms orthogonal to } |\Omega\rangle_g\,|\Omega\rangle_{\mathcal{U}}\Big)$$

Simulating colour for an arbitrary Feynman diagram

- Build a quantum circuit with:
  - For each gluon, 1 gluon register, with 3 qubits per register
  - For each quark line, a pair of quark registers: q and $\tilde{q}$, with 2 qubits per register
  - A unitarization register with $N_{\mathcal{U}} = \lceil \log_2(N_V + 1) \rceil$ qubits
- Initialise each register r into the state $|\Omega\rangle_r$
- For each gluon, apply R_g
- For each quark line, apply R_q
- For each quark-gluon vertex, apply Q gate to the corresponding g and q registers (not $\tilde{q}$)
- For each triple-gluon vertex, apply G gate to the corresponding g registers
- For each internal gluon, apply $(R_g)^{-1}$
- For each closed quark line, apply $(R_q)^{-1}$
- Colour factor $\mathcal{C}$ is found encoded in the final state of the quantum computer, which is:

Recall the illustrative example:



$$|\Psi\rangle = \frac{1}{\mathcal{N}} |\xi_n\rangle_E |\Omega\rangle_{I+U} + (\text{terms orthogonal to } |\Omega\rangle_{I+U})$$

$$|\xi_n\rangle = \sum_{\substack{a_1,a_2,\ldots \in \{1,\ldots,N_c^2-1\} \\ i_1,i_2,\ldots \in \{1,\ldots,N_c\} \\ j_1,j_2,\ldots \in \{1,\ldots,N_c\}}} C^{a_1 a_2 \ldots}_{n, i_1 i_2 \ldots, j_1 j_2 \ldots} (|a_1\rangle |a_2\rangle \ldots)(|i_1\rangle |i_2\rangle \ldots)(|j_1\rangle |j_2\rangle \ldots)$$

$$\mathcal{N} = N_c^{(2N_{q_I} + N_{q_E})/2} (N_c^2 - 1)^{(2N_{q_I} + N_{q_E})/2}$$

Validation

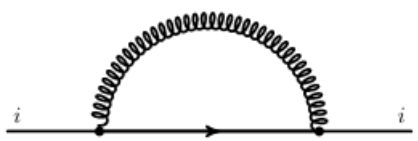
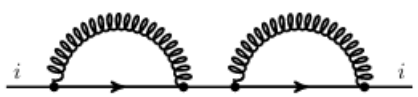
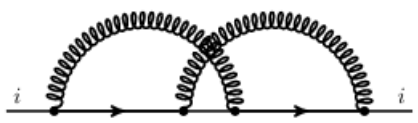
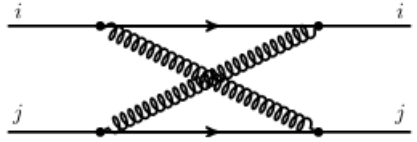
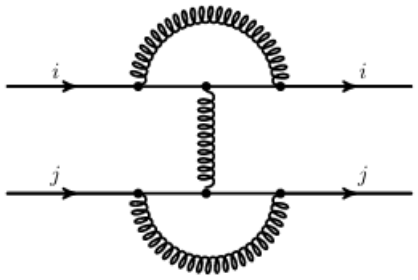
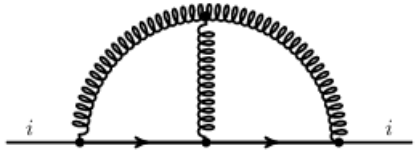
[2303.04818]

Simulating single Feynman diagrams

- Implemented using Qiskit
- Simulated colour for various diagrams
  - Working in SU(3)
  - Traced also over external lines, to obtain a single number for each colour factor
  - Noiseless quantum simulator
    - These examples use up to 30 qubits
  - Ran each diagram for 10^8 shots (subsequently reduced)
  - Measured output to infer colour factor

$$\frac{1}{\mathcal{N}}\mathcal{C}\,|\Omega\rangle_{all} + (\text{terms orthogonal to } |\Omega\rangle_{all})$$

  - Full agreement with analytic expectations

Diagram	Analytical	Numerical
	$C_F N = 4$	3.9988 ± 0.0012
	$C_F{}^2 N = \frac{16}{3}$	5.331 ± 0.010
	$\frac{C_F}{2} = \frac{2}{3}$	0.673 ± 0.010
	$N(N^2-1) = 24$	23.95 ± 0.03
	$\frac{(N^2-1)}{4} = 2$	2.00 ± 0.03
	0	$0.0^{+0.5}_{-0.0}$
	$\frac{C_F N^2}{2} = 6$	5.92 ± 0.08

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3. Multiple Feynman diagrams and their quantum interferences
4. Efficient algorithm for Feynman diagrams with identical particles
5. Towards kinematics
6. Summary and outlook

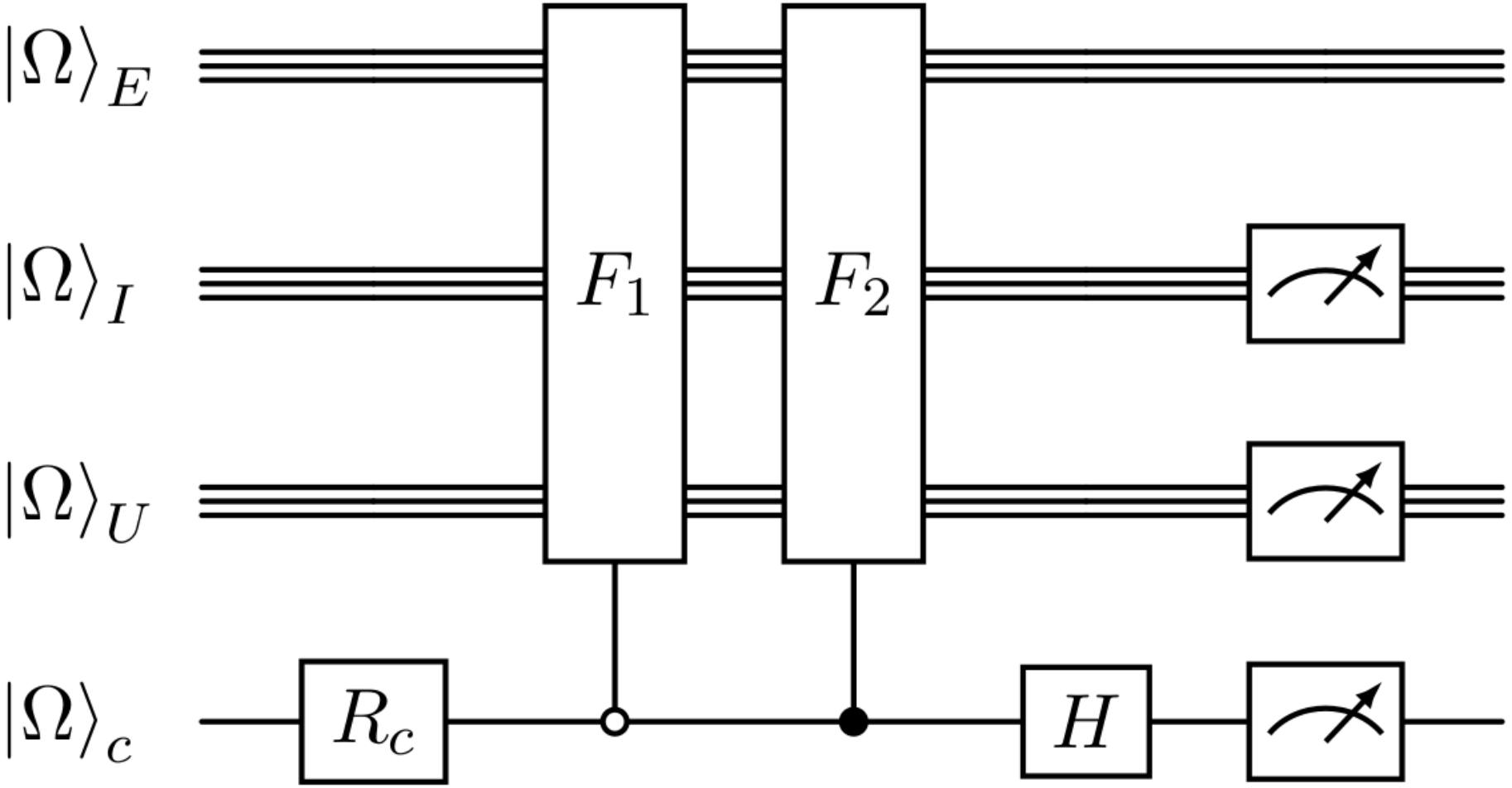
Including demonstration on 56-qubit ion-trap quantum computer!

First hints of quantum advantage!

New 98-qubit ion-trap machine

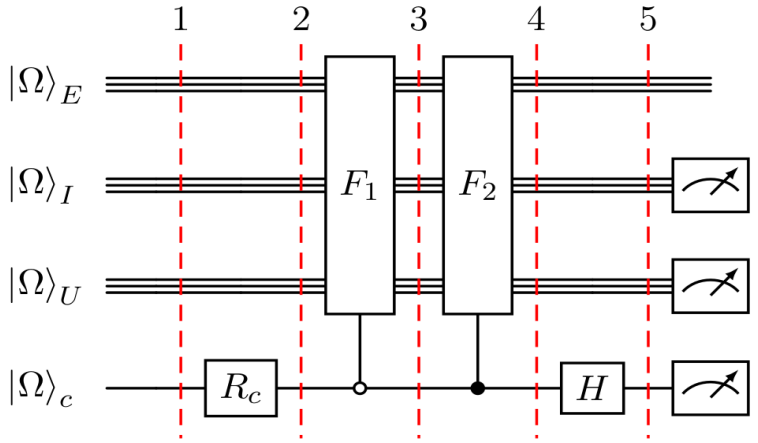


Quantum-coherent sum of multiple Feynman diagrams



Quantum-coherent sum of multiple Feynman diagrams

1. $|\Omega\rangle_E\,|\Omega\rangle_I\,|\Omega\rangle_U\,|\Omega\rangle_c$
2. $|\Omega\rangle_E\,|\Omega\rangle_I\,|\Omega\rangle_U\left(\frac{K_1|0\rangle_c+K_2|1\rangle_c}{\sqrt{|K_1|^2+|K_2|^2}}\right)$
3. $\frac{|\Omega\rangle_I|\Omega\rangle_U}{\sqrt{|K_1|^2+|K_2|^2}}\left(K_1\frac{|\xi_1\rangle_E}{\mathcal{N}}\,|0\rangle_c+K_2\,|\Omega\rangle_E\,|1\rangle_c\right)+(\text{terms orthogonal to }\,|\Omega\rangle_I\,|\Omega\rangle_U)$
4. $|\Omega\rangle_I\,|\Omega\rangle_U\left(\frac{K_1|\xi_1\rangle_E|0\rangle_c+K_2|\xi_2\rangle_E|1\rangle_c}{\mathcal{N}\sqrt{|K_1|^2+|K_2|^2}}\right)+(\text{terms orthogonal to }\,|\Omega\rangle_I\,|\Omega\rangle_U)$
5. $\frac{1}{\mathcal{N}\sqrt{2}}\left(\frac{K_1|\xi_1\rangle_E+K_2|\xi_2\rangle_E}{\sqrt{K_1^2+K_2^2}}\right)|\Omega\rangle_I\,|\Omega\rangle_U\,|\Omega\rangle_c+(\text{terms orthogonal to }\,|\Omega\rangle_I\,|\Omega\rangle_U\,|\Omega\rangle_c)$



$$P\left(|\Omega\rangle_I\,|\Omega\rangle_U\,|\Omega\rangle_c\right)=\frac{|K_1|^2\langle\xi_1|\xi_1\rangle+K_1^*K_2\langle\xi_1|\xi_2\rangle+K_2^*K_1\langle\xi_2|\xi_1\rangle+|K_2|^2\langle\xi_2|\xi_2\rangle}{2(|K_1|^2+|K_2|^2)\mathcal{N}^2}$$

Recall:

$$\mathcal{A}=\sum_n C_nK_n$$

Generalises straight-forwardly to arbitrary number N_D of diagrams (see article for details):

$$P\left(|\Omega\rangle_I\,|\Omega\rangle_U\,|\Omega\rangle_D\right)=\frac{1}{\mathcal{N}_{N_D}^2}\left|\sum_n K_n\,|\xi_n\rangle_E\right|^2$$

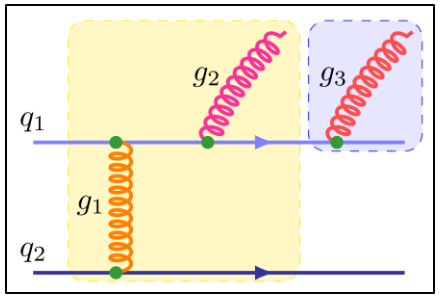
$$\mathcal{N}_{N_D}=\mathcal{N}\sqrt{N_D}\sqrt{\textstyle\sum_m|K_m|^2}$$

$$\mathcal{A}^{a_1a_2\ldots}_{i_1i_2\ldots,j_1j_2\ldots}=\sum_n C^{a_1a_2\ldots}_{n,i_1i_2\ldots,j_1j_2\ldots}K_n$$

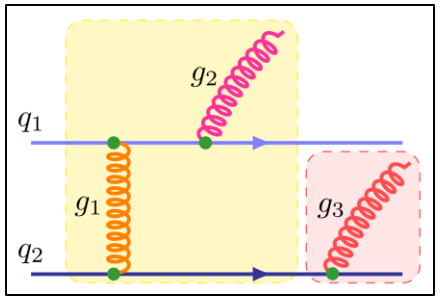
$$|\xi_n\rangle=\sum_{a_1,a_2,\ldots;i_1,i_2,\ldots;j_1,j_2,\ldots}C^{a_1a_2\ldots}_{n,i_1i_2\ldots,j_1j_2\ldots}\left(|a_1\rangle\,|a_2\rangle\ldots\right)\left(|i_1\rangle\,|i_2\rangle\ldots\right)\left(|j_1\rangle\,|j_2\rangle\ldots\right)$$

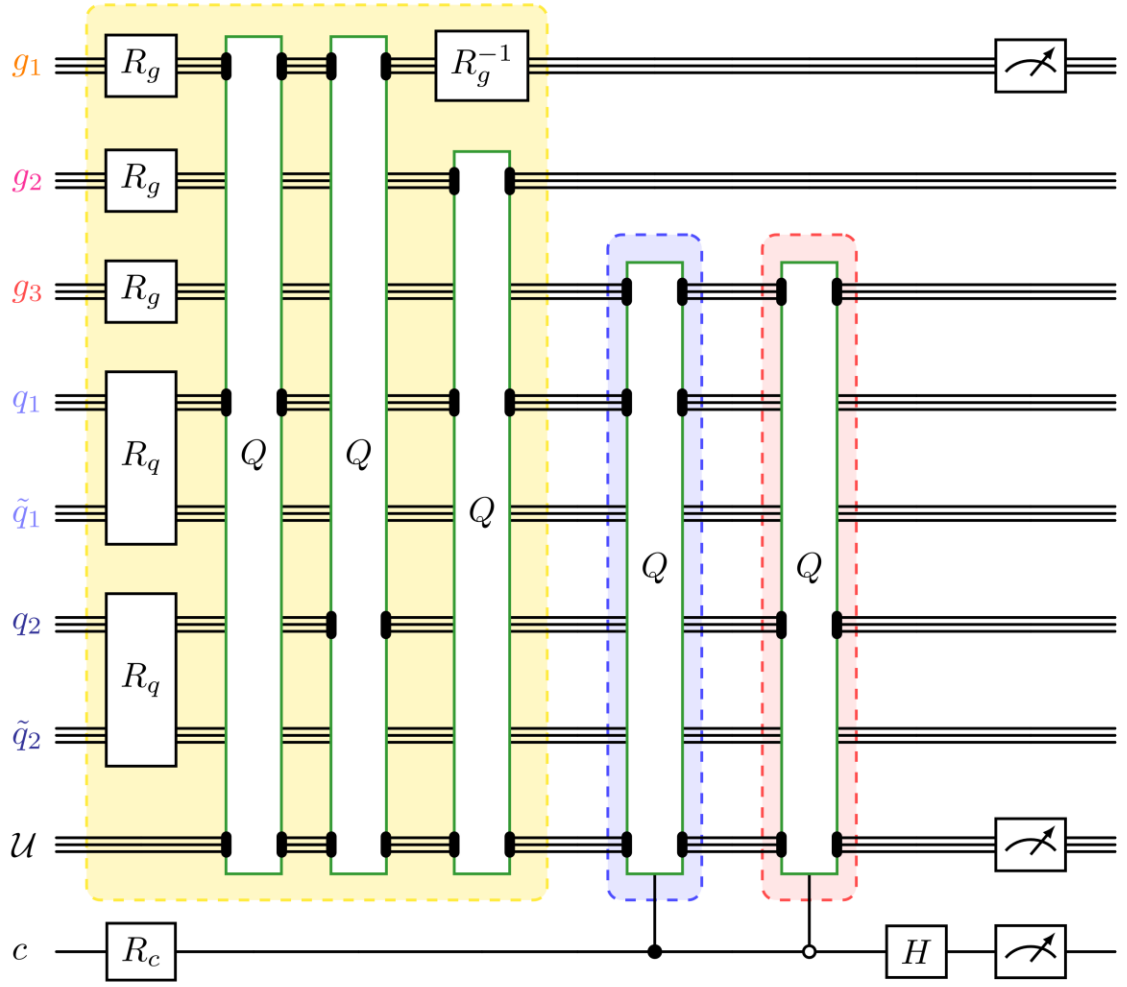
Quantum-coherent sum of multiple Feynman diagrams

- Example:

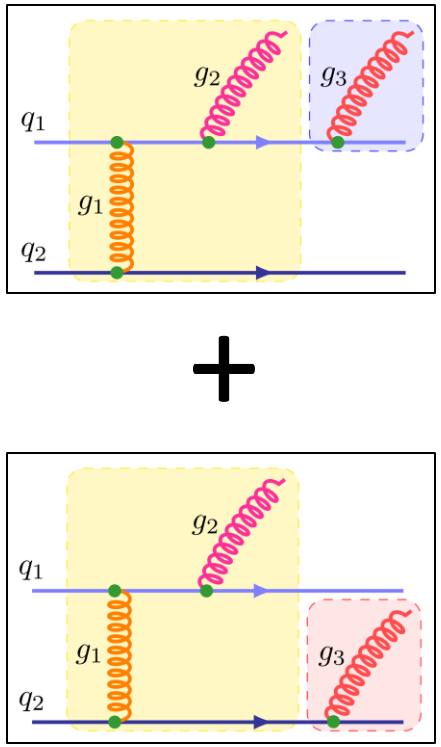


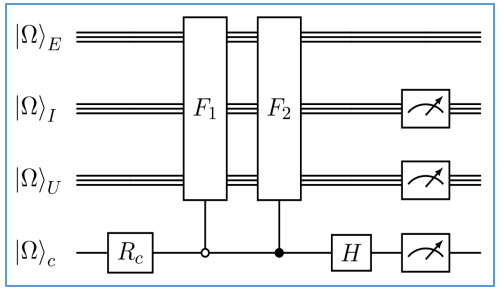
+

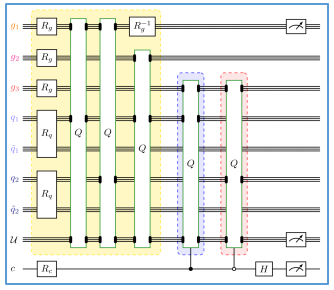




Validation
Interferences



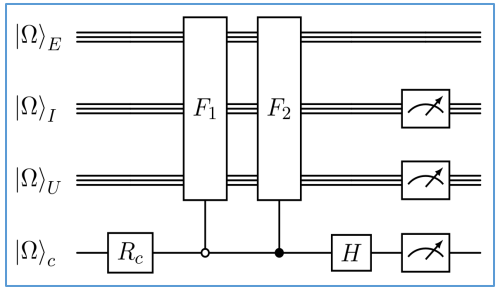


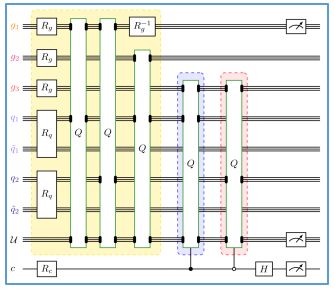


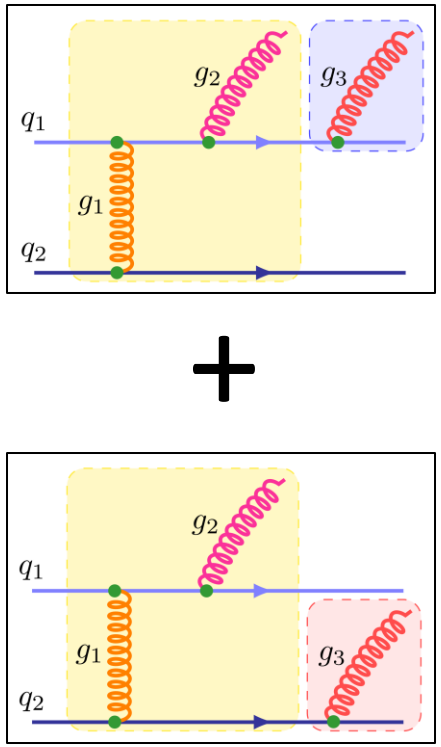
- QCD gauge group: SU(3)
- IBM Qiskit noiseless simulator
- Set kinematic factors $K_1 = K_2 = 1$
- Ran 10^8 shots
- Results for $\langle|F_1+F_2|^2\rangle$
  - Analytic: 22/3 ≈ 7.33
  - Noiseless simulator: 7.65 +/- 0.34

Validation

Interferences – on physical devices







- Now gauge group: SU(2)
- Quantinuum H1 and H2 ion-trap quantum computers
- Compiler optimization level 0
- Set kinematic factors $K_1 = K_2 = 1$
- Ran 1,000 shots
- Results for $\langle |F_1+F_2|^2 \rangle$
  - Analytic: 11/6 ≈ 1.83
  - Noiseless simulation: 1.93 +/- 0.12
  - Physical device (H1) 1.63 +/- 0.11
  - Physical device (H2) 1.95 +/- 0.12

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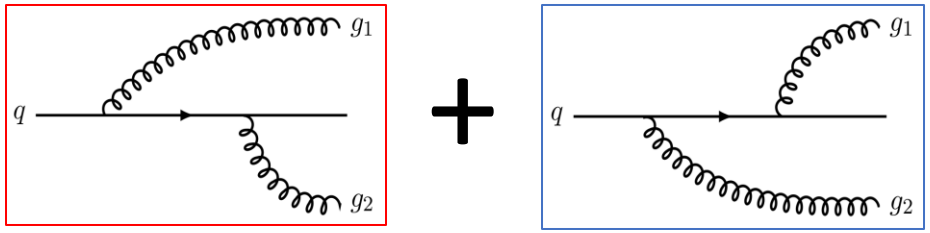
Including demonstration on 56-qubit ion-trap quantum computer!

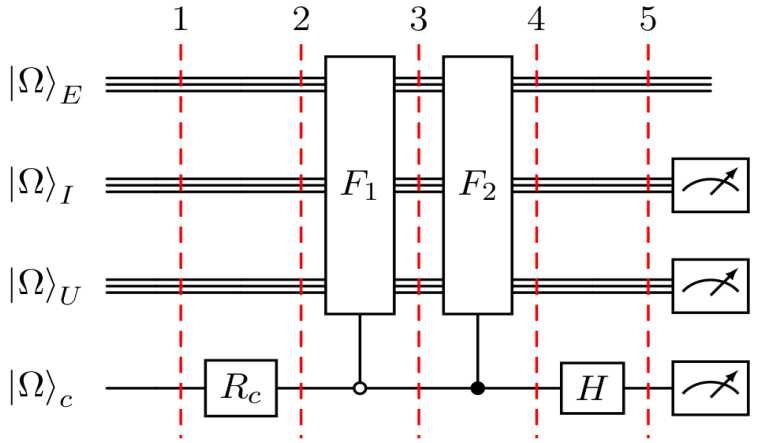
First hints of quantum advantage!

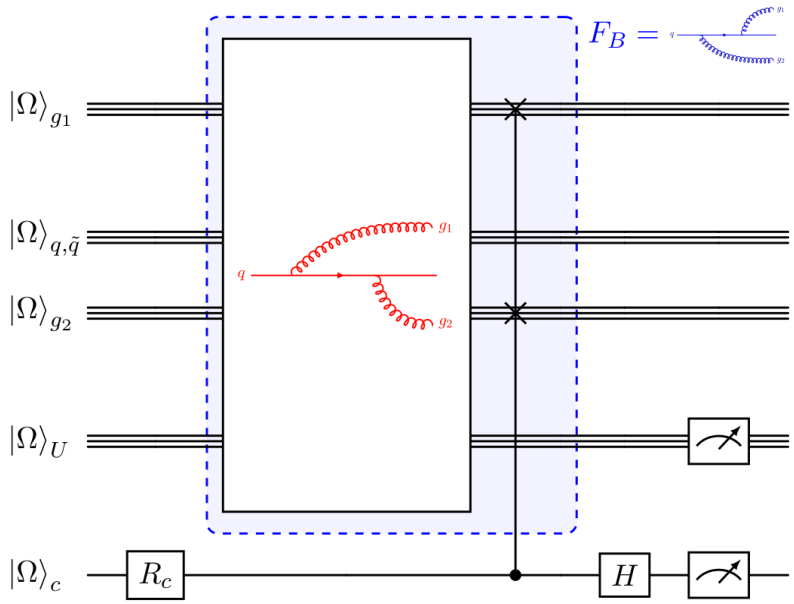
New 98-qubit ion-trap machine



Permutations of identical particles







$$\frac{1}{\mathcal{N}\sqrt{2}} \sum_{a,b,i,j,l} \left(\frac{K_1 T^a_{il} T^b_{lj} + K_2 T^b_{il} T^a_{lj}}{\sqrt{|K_1|^2 + |K_2|^2}} \right) |a\rangle_{g_1} |b\rangle_{g_2} |i\rangle_q |j\rangle_{\tilde{q}} |\Omega\rangle_U |\Omega\rangle_c + (\text{terms orthogonal to } |\Omega\rangle_U)$$

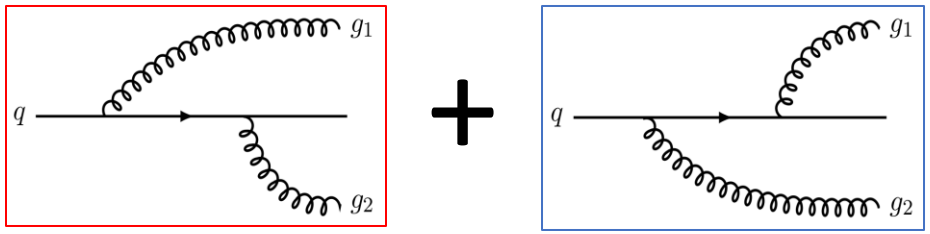
Recall:

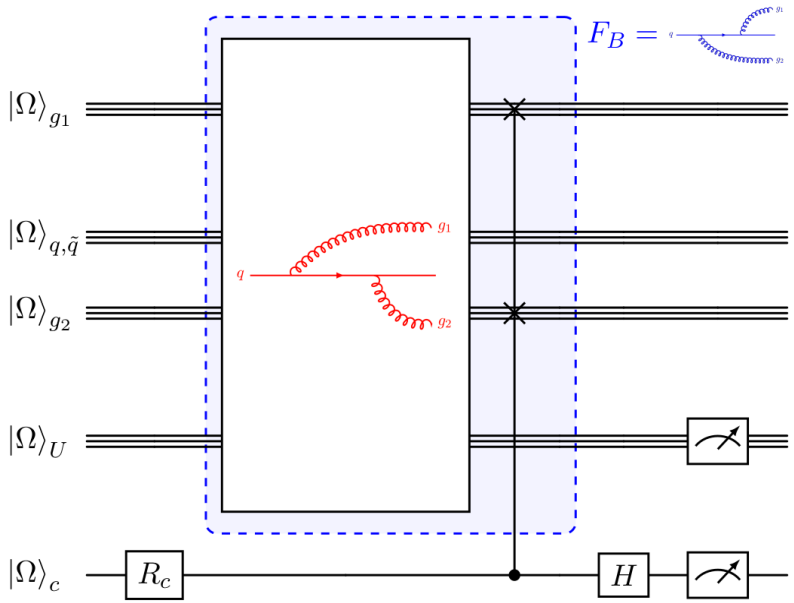
$$\mathcal{A} = \sum_n C_n K_n$$

$$\mathcal{A}^{a_1 a_2 \ldots}_{i_1 i_2 \ldots, j_1 j_2 \ldots} = \sum_n C^{a_1 a_2 \ldots}_{n, i_1 i_2 \ldots, j_1 j_2 \ldots} K_n$$

$$|\xi_n\rangle = \sum_{a_1, a_2, \ldots; i_1, i_2, \ldots; j_1, j_2, \ldots} C^{a_1 a_2 \ldots}_{n, i_1 i_2 \ldots, j_1 j_2 \ldots} (|a_1\rangle |a_2\rangle \ldots)(|i_1\rangle |i_2\rangle \ldots)(|j_1\rangle |j_2\rangle \ldots)$$

Validation
Permutations

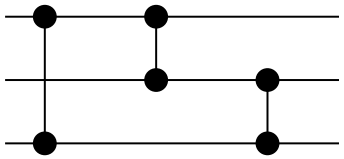




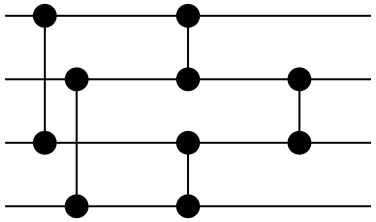
- Gauge group: SU(2)
- Quantinuum H1 quantum computer
- Compiler optimization level 0
- Set kinematic factors $K_1 = K_2 = 1$
- Ran 1,000 shots
- Results for $\langle|F_1+F_2|^2\rangle$
  - Analytic: $1/3 \approx 0.333$
  - Noiseless simulation: 0.330 +/- 0.015
  - Physical device (H1): 0.342 +/- 0.015

Generalization to many particles

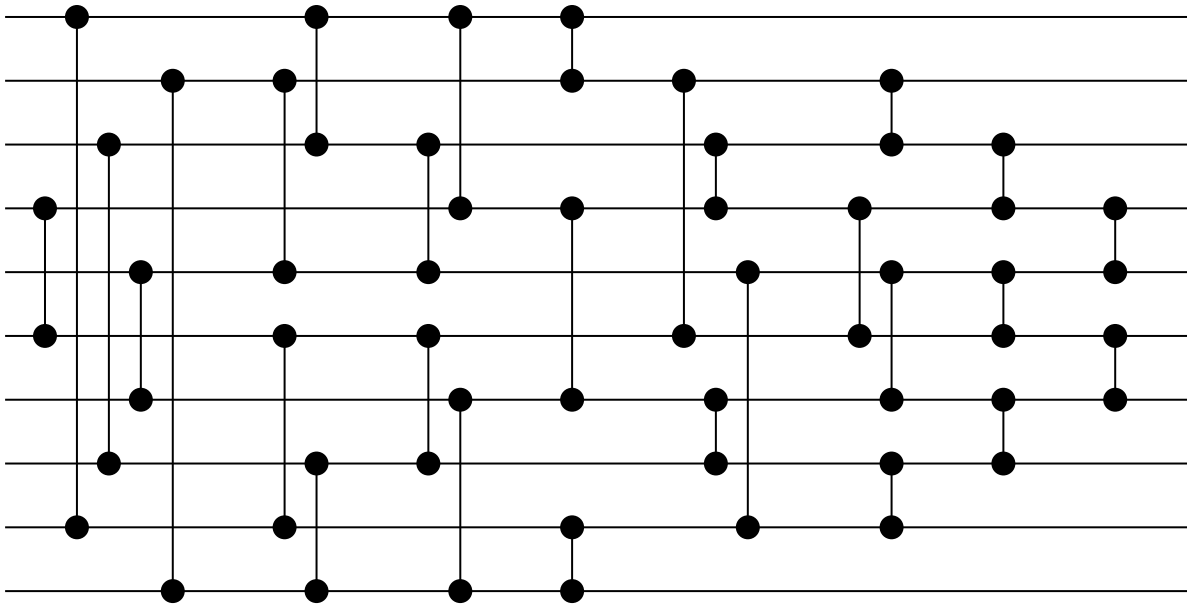
- Generalizes nicely to *N* particles
  - Employ *sorting networks* – well-studied in computer science *see also [arXiv:quant-ph/9703054]*
  - *N* = 3:



  - *N* = 4:



N = 10:



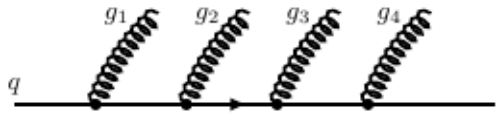
Symmetrise with 29 swaps instead of (10! ≈ 3*10^6) separate Feynman diagrams!

Figures from https://bertdobbelaere.github.io/sorting_networks.html

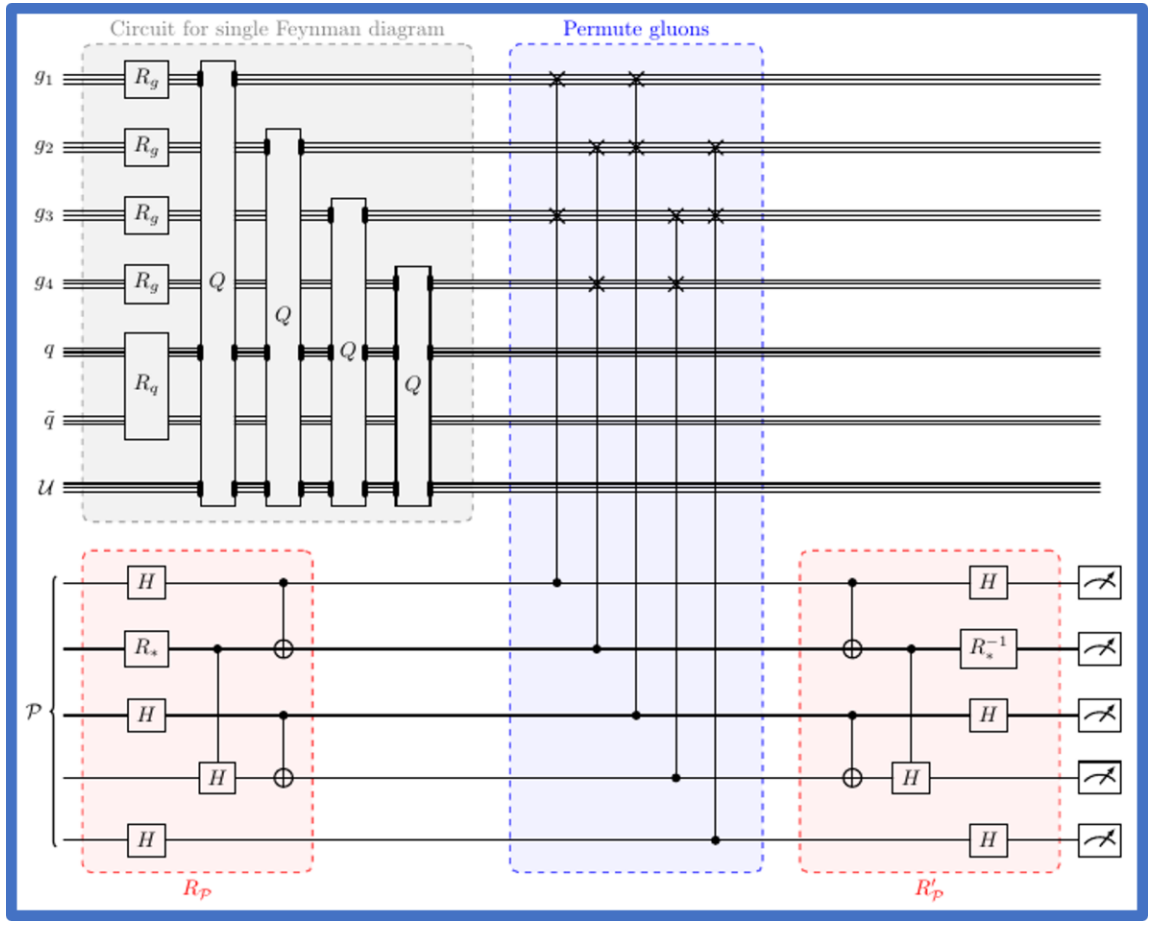
N=10 circuit by Waksman (1969). Optimality proof by Codish et al. (2016)

Generalization to many particles

- N=4 example:

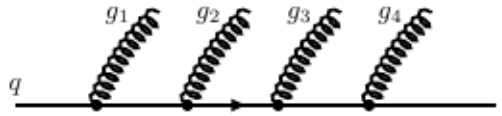


+ 23 more Feynman diagrams

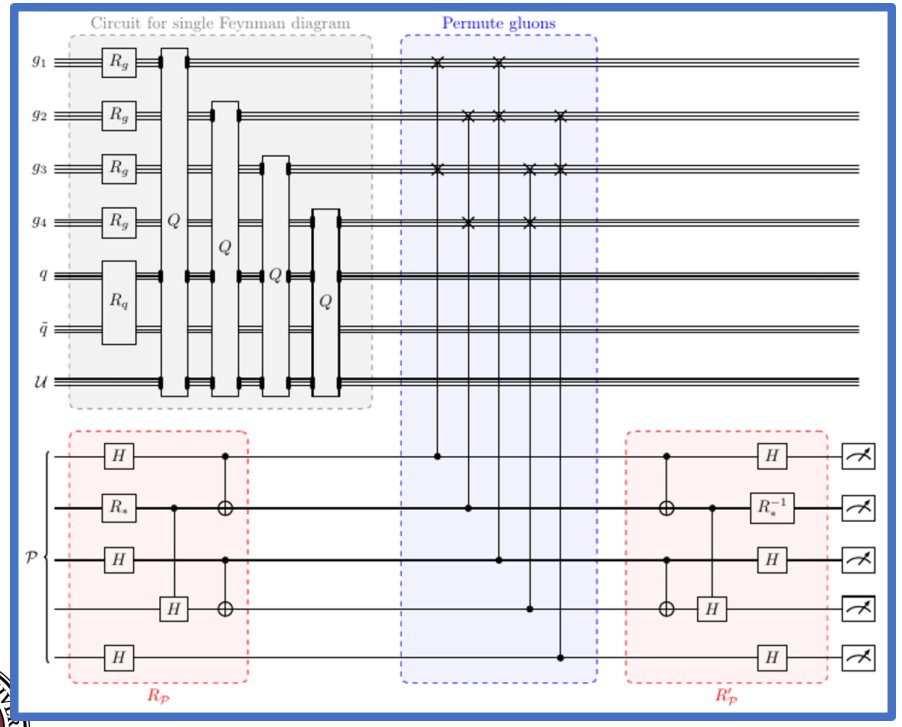


Validation

Diagrams with many identical particles



+ 23 more



- Gauge group: SU(2)
- Quantinuum H2 ion-trap machine
- Optimization level 0
- Set kinematic factors $K_1 = \ldots = K_{24} = 1$
- Ran 1,000 shots
- Results for $\langle | F_1 + F_2 + \ldots + F_{24} |^2 \rangle$
  - Analytic: 45/4 = 11.25
  - Physical device (H2-1): 11.12 +/- 1.42

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4. Efficient algorithm for Feynman diagrams with identical particles
5. Towards kinematics
6. Summary and outlook

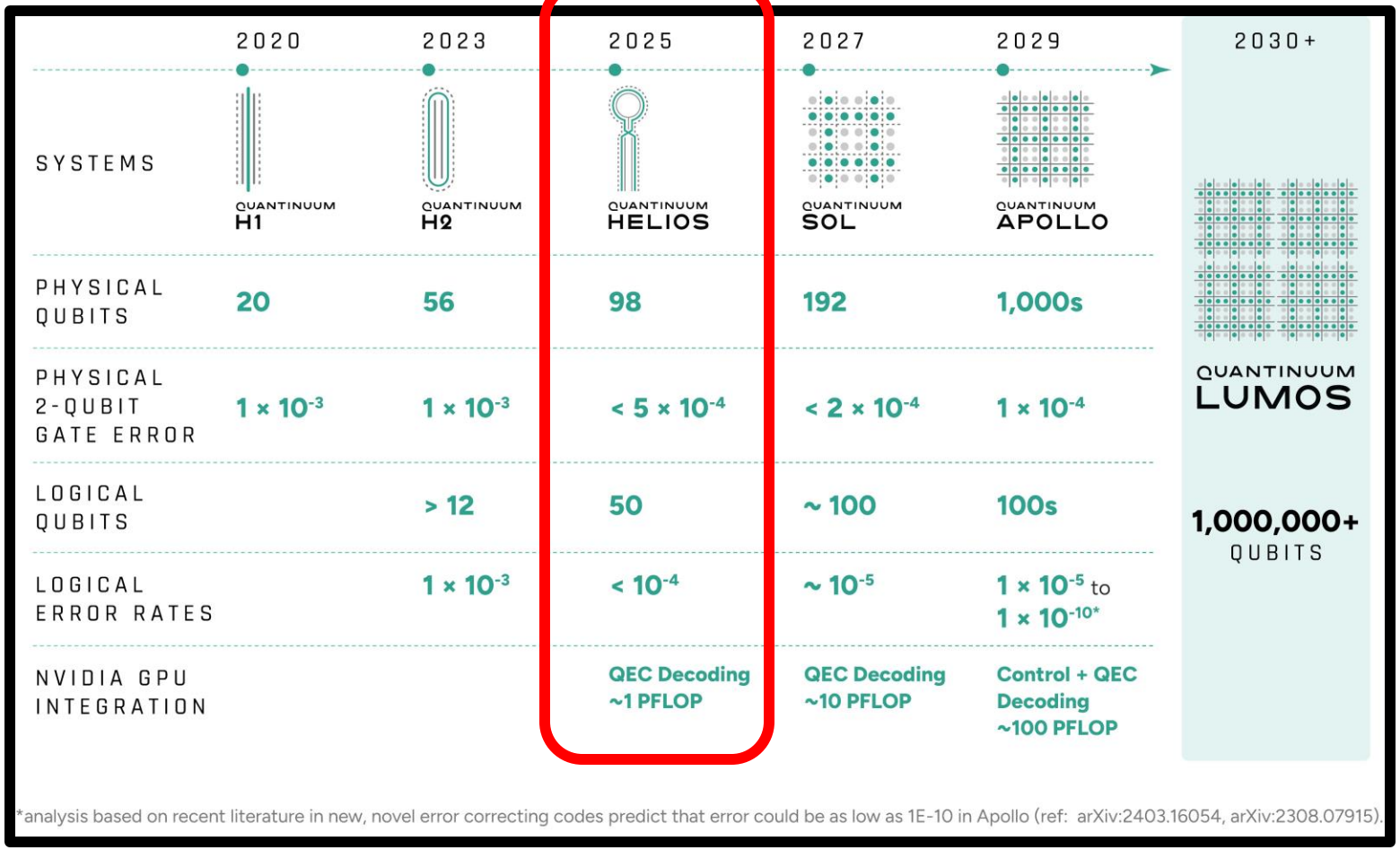
Including demonstration on 56-qubit ion-trap quantum computer!

First hints of quantum advantage!

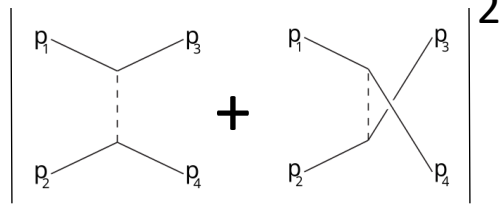
New 98-qubit ion-trap machine

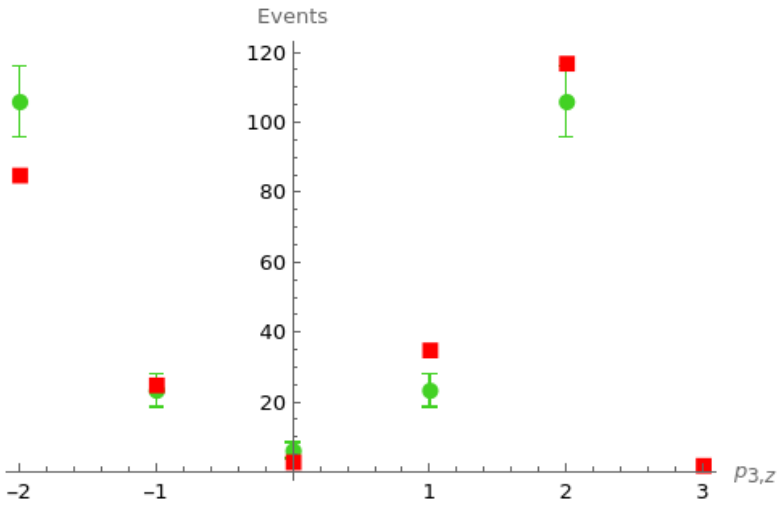


Quantinuum Roadmap



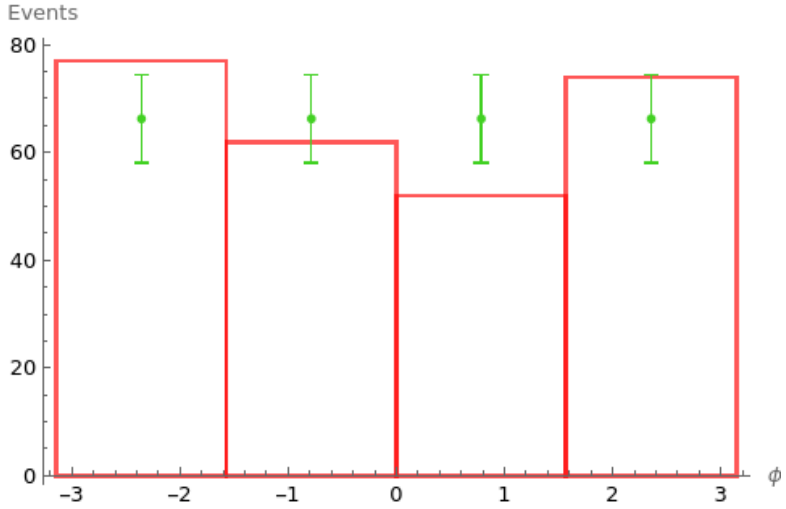
Towards kinematics - PRELIMINARY!!





Analytic expectation*

10k shots on 98–qubit machine



p_3									p_4									k									k^2					...
x			y			z			x			y			z			x			y			z								
↑	↓	↑	↑	↓	↓	↓	↓	↓	↑	↓	↓	↑	↓	↑	↓	↑	↑	↑	↓	↓	↑	↓	↑	↑	↑	↓	↑	↑	↑	↓	↓	(10+)
0	1	0	0	1	1	1	1	1	0	1	1	0	1	0	1	0	0	0	1	1	0	1	0	0	0	1	0	0	0	1	1	(10+)
2			−2			−1			−2			2			1			−2			2			4			24					
$p_3 = (2, -2, -1)$									$p_4 = (-2, 2, 1)$									$k = (-2, 2, 4)$									$k^2 = 24$					...

Aside - get in touch to discuss:

- Mid-circuit measurement + feedforward: algorithmic applications?
  - (Apart from error correction)
- Encoding schemes for error detection, with lower overhead than full error-correction?
- Quantifying systematic uncertainties resulting from hardware noise
- Optimization with quantum circuits



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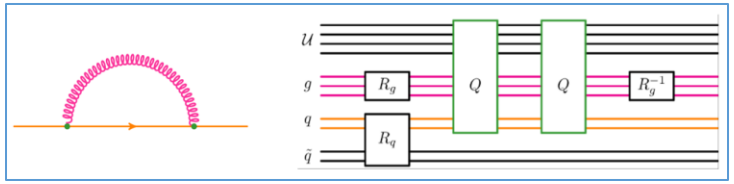


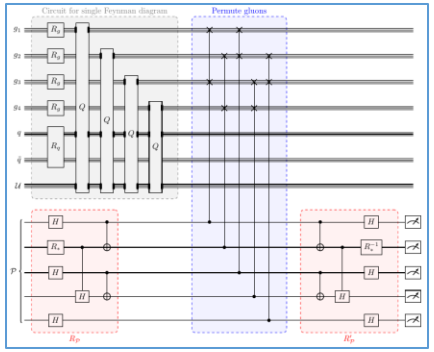
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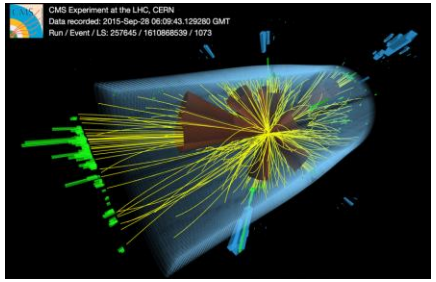


Summary and outlook





- Quantum algorithms for efficient high-energy strong-force simulations
  - Complex physical system – classically hard to compute
  - Important for precision measurement science program
  - First signs of quantum advantage (Feynman diagrams with identical particles)
  - Validation on state-of-the-art ion-trap machines with up to 98 qubits
- Unlocks several natural avenues for follow-up work:
  - Faster quantum circuits to generate multi-particle quantum states
  - Opens new paths to beyond-classical capabilities for quantum sensing and metrology
  - Quantum error correction/mitigation; quantum optimization
  - Faster Monte Carlo calculations of cross-sections
  - Broader applications outside of high-energy physics



Want to know more? Email me: hchawdhry@fsu.edu