Quantum technologies meet high energy physics challenges

Michele Grossi, PhD

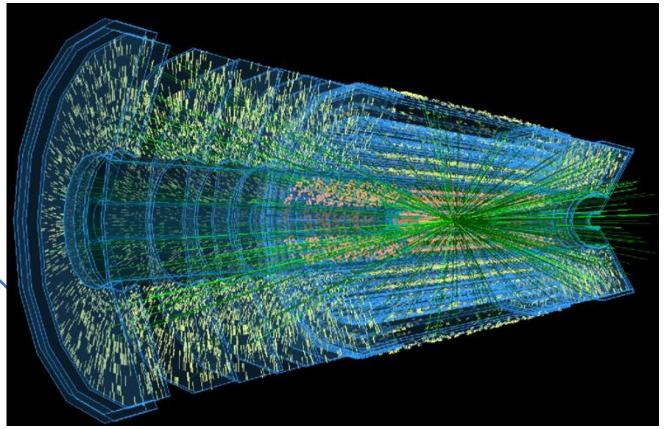
Hybrid Quantum Computing Infrastructures and Algorithms Coordinator

CERN

QUANTUM
TECHNOLOGY
INITIATIVE

HEP Pipeline

Theory

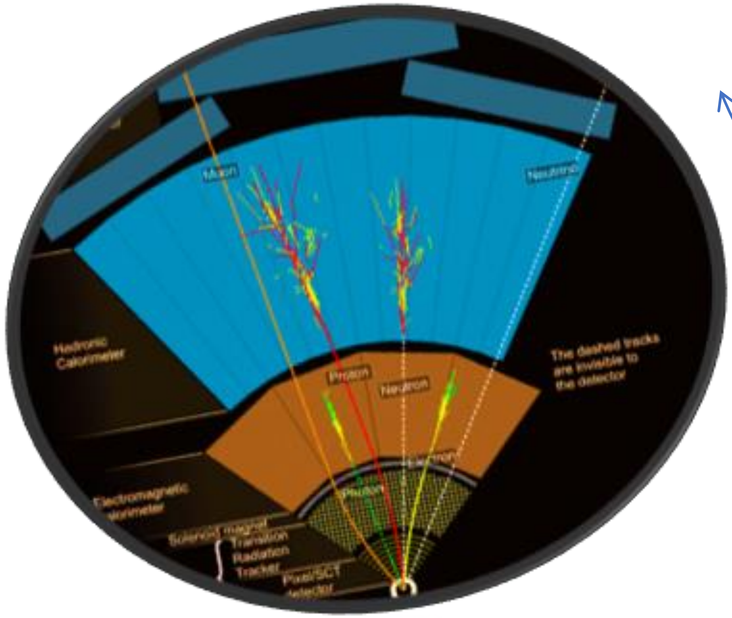


Calculate (differential) cross sections

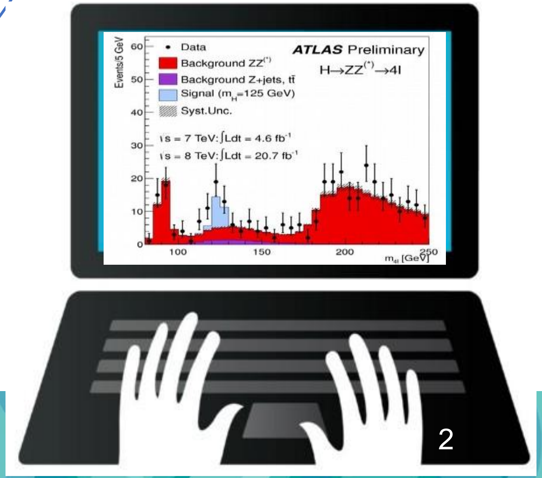
$$d\sigma = \frac{1}{\text{flux}} dx_a dx_b\, f(x_a) f(x_b)\, d\Phi_n \left\langle \, |M_{\lambda,c,\ldots}(p_a, p_b \mid p_1, \ldots, p_n)|^2 \, \right\rangle$$

Data Analysis

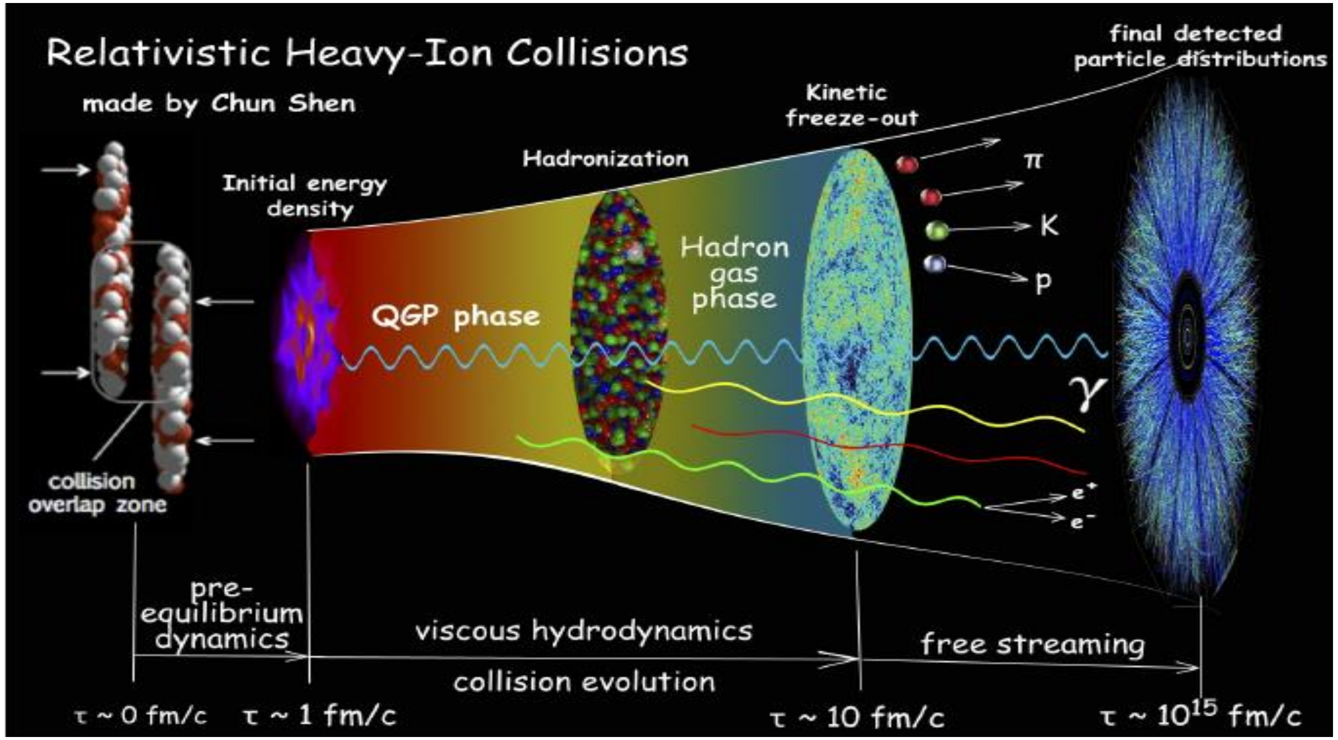
Data Generation



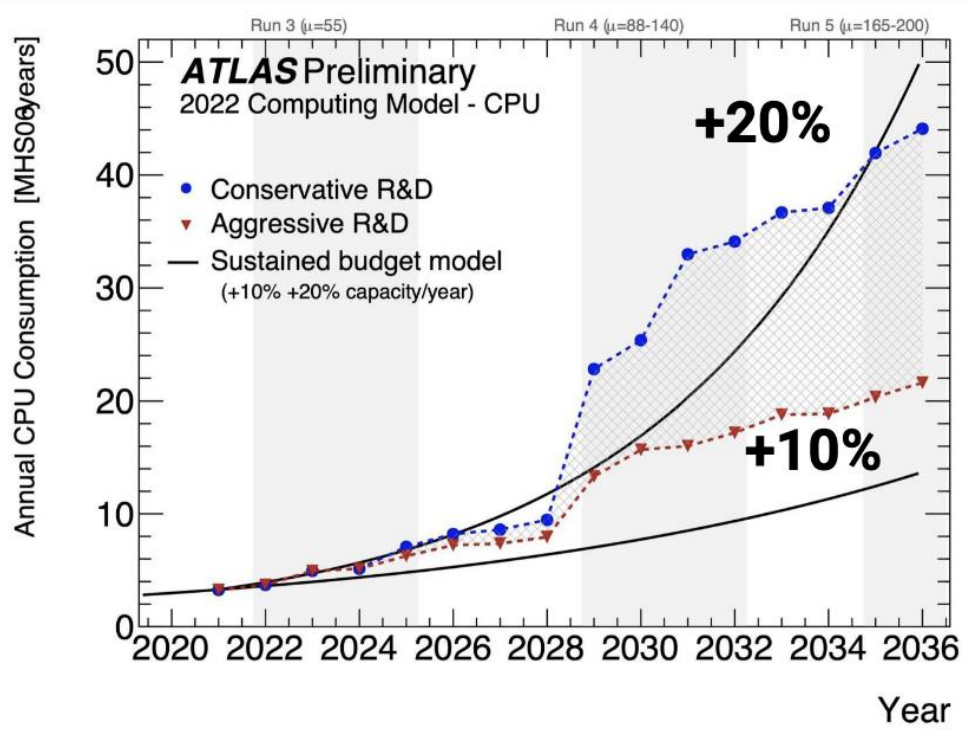
Feature Extraction



Motivation

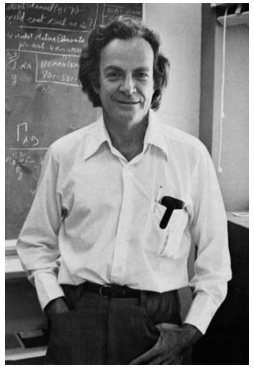


From: 10.1051/epjconf/20159700025
Cartoon of the time evolution of an ultra-relativistic heavy-ion collision



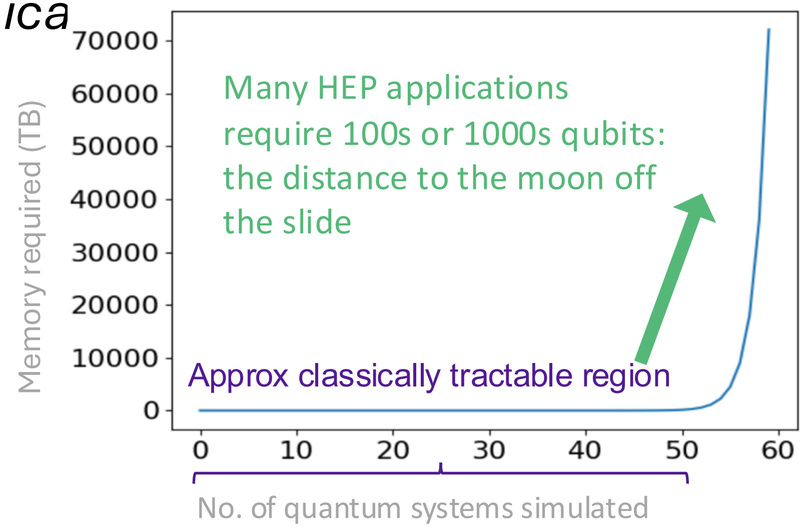
From HL-LHC Projections - ATLAS Software and Computing HL-LHC Roadmap

Motivation



One of the original motivations for quantum computing is still one of the best:

"Nature isn't classical, dammit, if you want to make a simulation of nature, you'd better make it quantum mechanical"
(Feynman)



How to study/simulate **Lattice Field Theories**?

- Analytic methods broadly limited to those accessible by perturbation theory (e.g. no predictions expected for QCD sector)
- Monte Carlo Methods excel at equilibrium phenomena but **struggle with out-of-equilibrium real time dynamics** due to sign problem.

Motivates instead simulating Heisenberg evolution of a quantum state.... But:

- **Classical** simulations of highly correlated quantum systems **grow exponentially** with system size.
- **Quantum** simulations of highly correlated quantum systems **only grow linearly** with system size.

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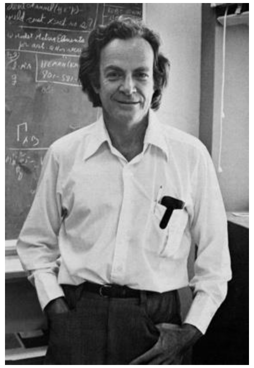
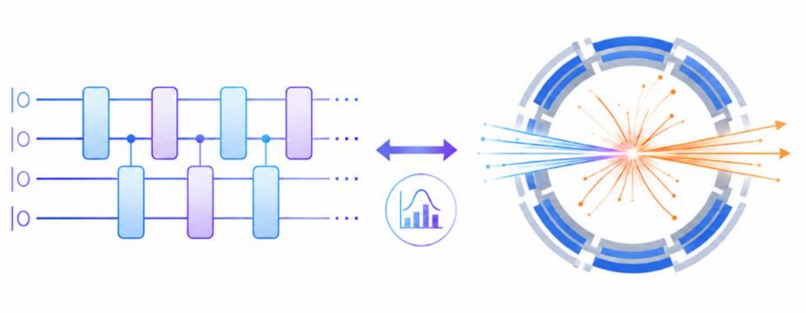


The dream: *Quantum simulations could give "access to **direct data from nonperturbative many-body real-time simulations of gauge theories** would enable a **complete paradigm shift**... we could **immediately compare them with** the observed statistics of collected **events from high-energy laboratories**"*



PRX QUANTUM 5, 037001 (2024)

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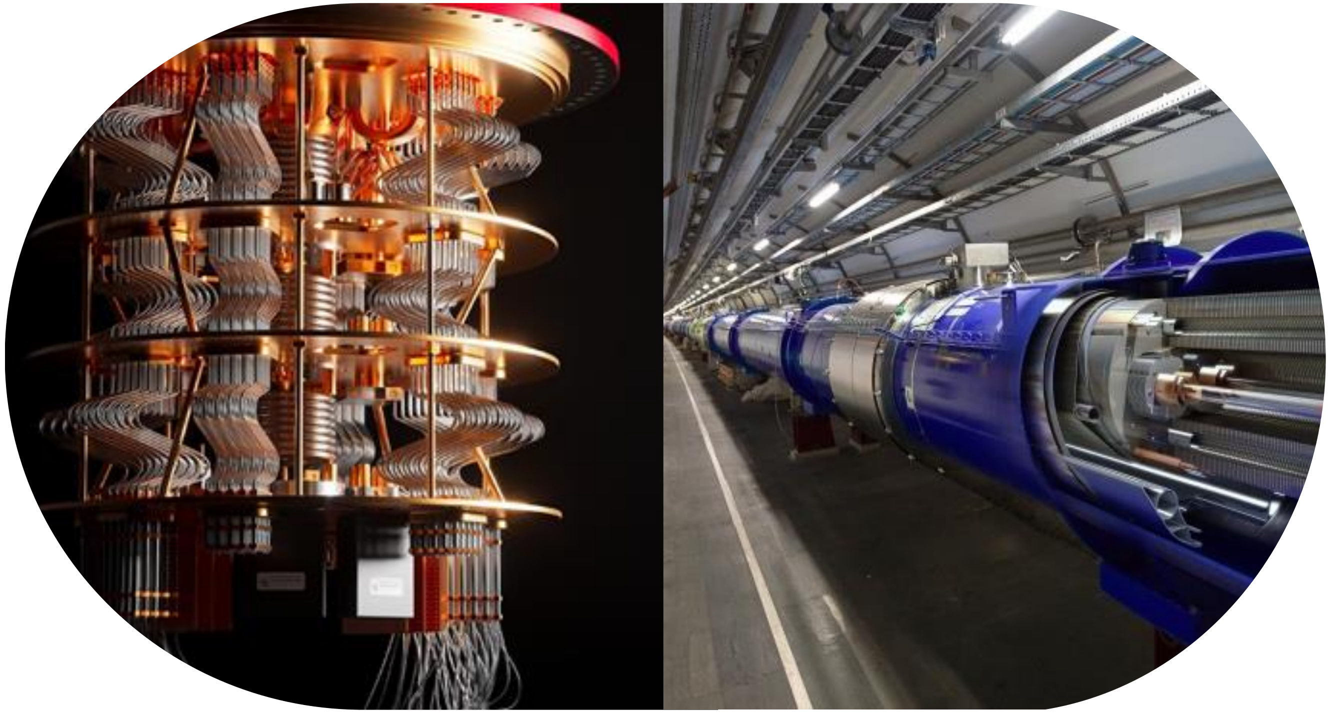
How does CERN engage in Quantum Technologies?



QT4HEP

Develop technologies required by the CERN scientific programme

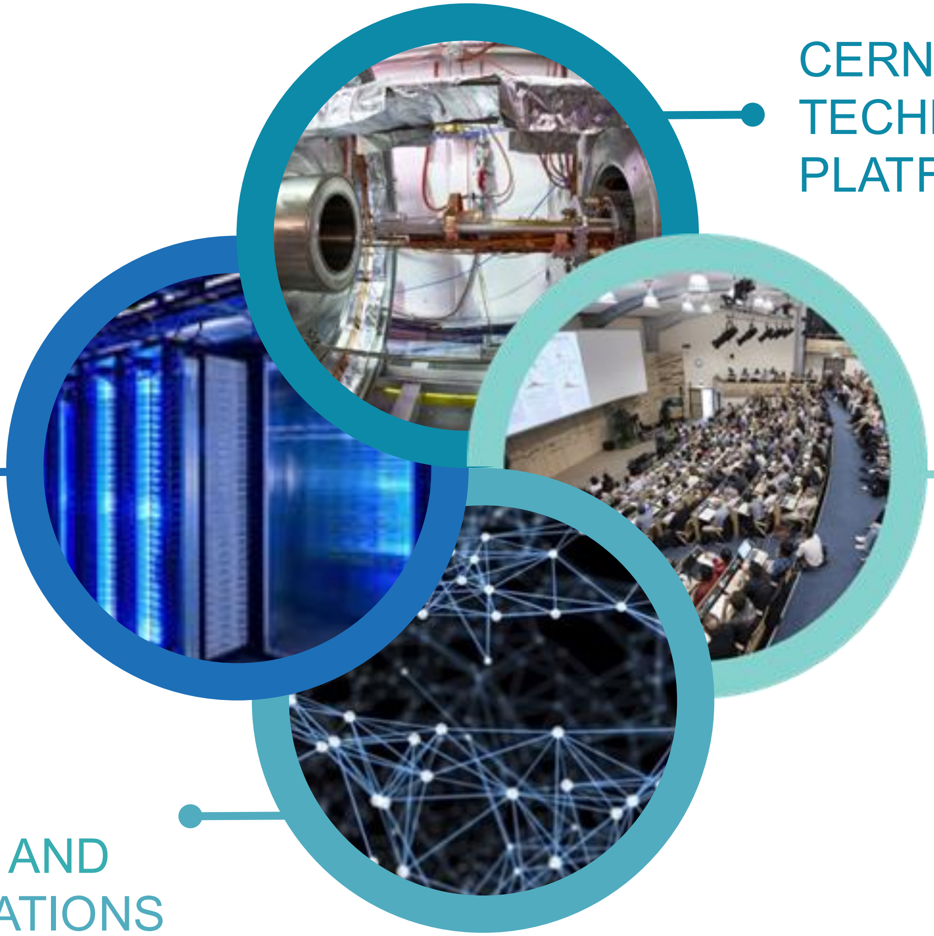
Integrate CERN to future quantum infrastructures

HEP4QT

Extend and share technologies available at CERN

Boost development and adoption of QT beyond CERN

CERN QTI Phase 2



CERN QUANTUM TECHNOLOGY PLATFORMS

HYBRID QUANTUM COMPUTING AND ALGORITHMS

COLLABORATION FOR IMPACT

QUANTUM NETWORKS AND COMMUNICATIONS

CERN | QUANTUM TECHNOLOGY INITIATIVE

Integrate CERN into the emerging quantum communications infrastructure

QUANTUM COMMUNICATIONS AND NETWORKS

Geneva Quantum Network:

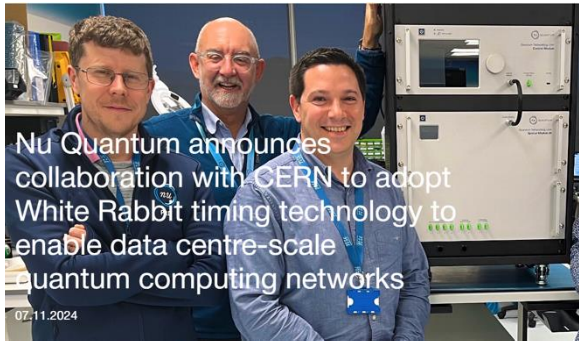
- Initial experiment within CERN CAMPUS (29 km)
- Entanglement distribution with White Rabbit: demonstrate the distribution of polarization entangled photon pairs multiplexed on the same optical fiber as the classical **White Rabbit** signal used for synchronization for longer-distance experiments

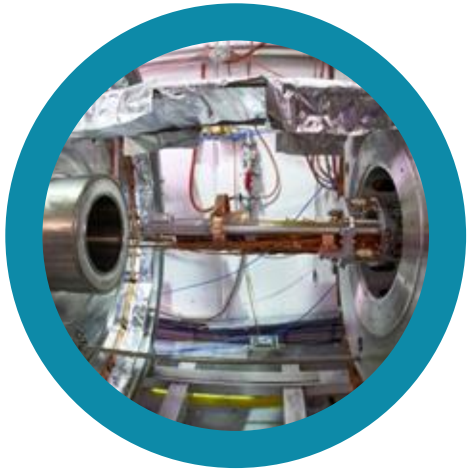
Already used in:

- *Deutsche Börse*
- *Fusion experiments*

White Rabbit applications to distributed quantum computing

nu QUANTUM

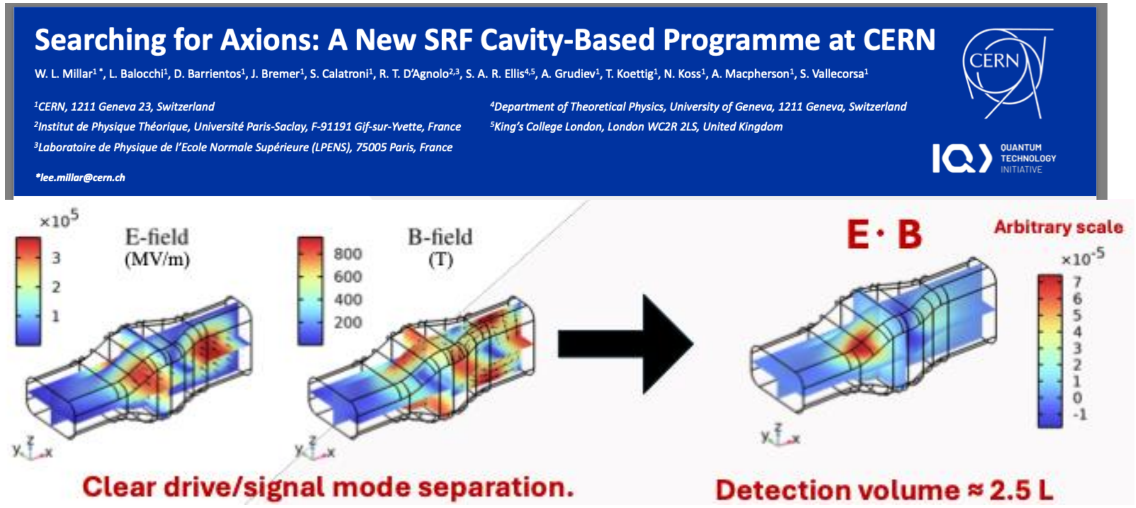




- Develop quantum sensors to provide new capabilities for particle physics research (dark matter search, axion search, gravitational wave detection…)
- Focus areas: Superconducting RF cavities, hydrogen-like Rydberg ions, and Transition Edge Sensors

CERN's broad expertise and experimental facilities in many areas (superconducting materials, magnets, radiation effects, cryogenics, controls etc.) could be useful to support developments.

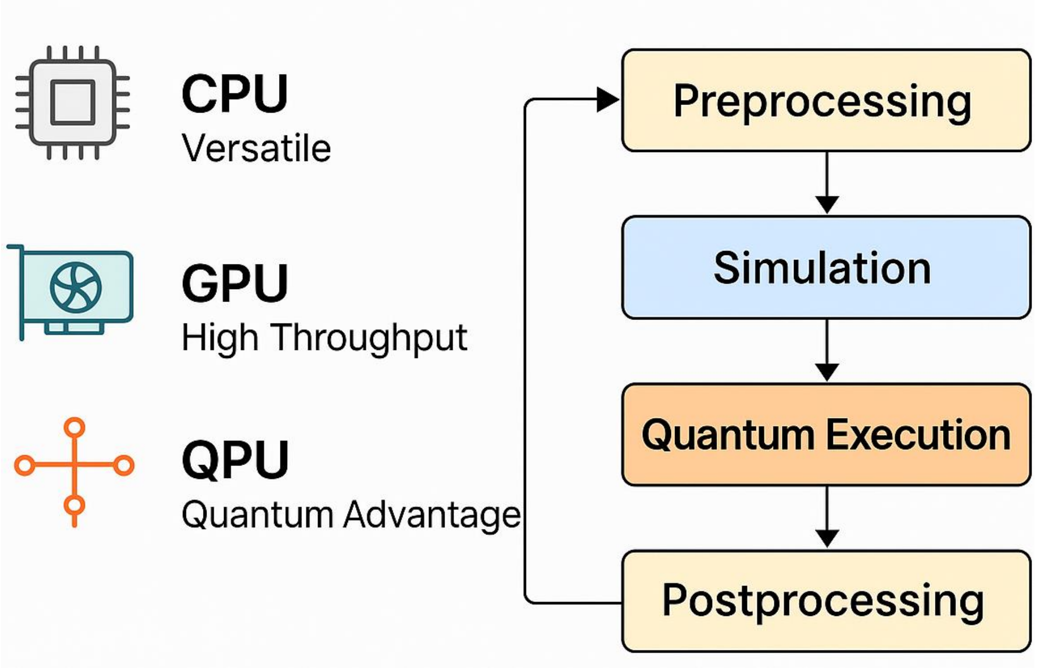
CERN QUANTUM TECHNOLOGY PLATFORMS



https://indico.cern.ch/event/1573467/

- Develop algorithms with a focus on distributed hybrid computing and Quantum Algorithms
- Achieve a robust understanding of the performance and optimal use of the (near-term) quantum infrastructure
- Provide use-cases for quantum algorithms and quantum computers

DISTRIBUTED QUANTUM COMPUTING AND ALGORITHMS



Kubernetes-Orchestrated Hybrid Quantum–Classical Workflows

Mar Tejedor*†, Michele Grossi‡, Cenk Tüysüz‡, Ricardo Rocha‡, Sofia Vallecorsa‡
*Barcelona Supercomputing Center (BSC), Barcelona, Spain
†Universitat Politècnica de Catalunya (UPC), Barcelona, Spain
‡European Organisation for Nuclear Research (CERN), Espl. des Particules 1211 Geneva 23, Switzerland

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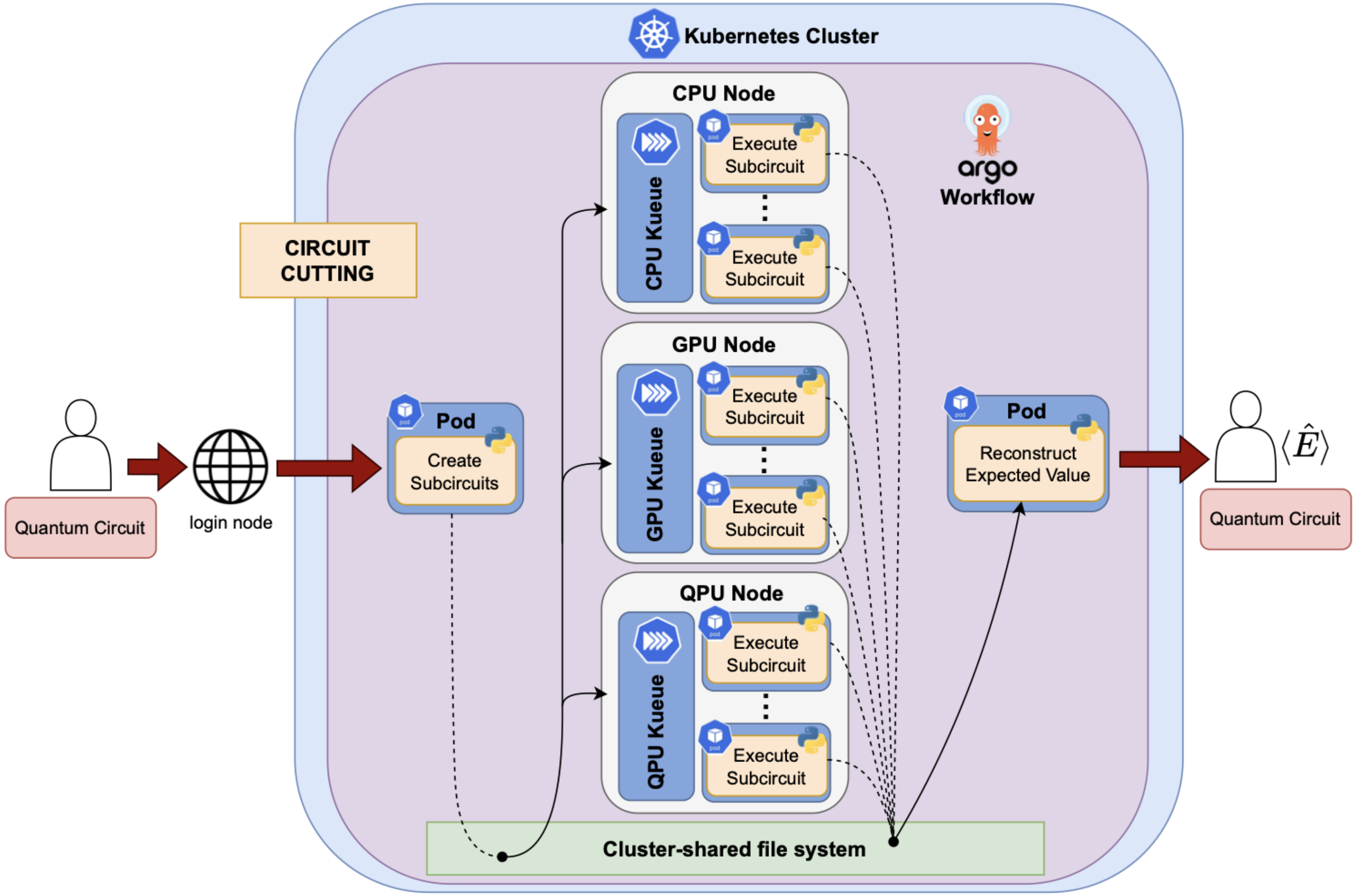

What is quantum simulation?

Use a controllable quantum system to compute the behaviour of another quantum system.

1. **Target model**

   Lagrangian / Hamiltonian

- Lattice gauge theory
- QFT-inspired toy model
- Many-body Hamiltonian

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Example model

Fermionic scattering via Thirring model:

$$H = \sum_n \left[\frac{i}{2a} \left(\xi^\dagger_{n+1}\xi_n - \xi^\dagger_n \xi_{n+1} \right) + (-1)^n m \xi^\dagger_n \xi_n \right] + \sum_n \frac{g(\lambda)}{a} \xi^\dagger_n \xi_n \xi^\dagger_{n+1} \xi_{n+1}.$$

Fermionic model is mapped to spin model:

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→ *qubits evolve under Hamiltonian*

[There are numerous well established quantum algorithms for this]

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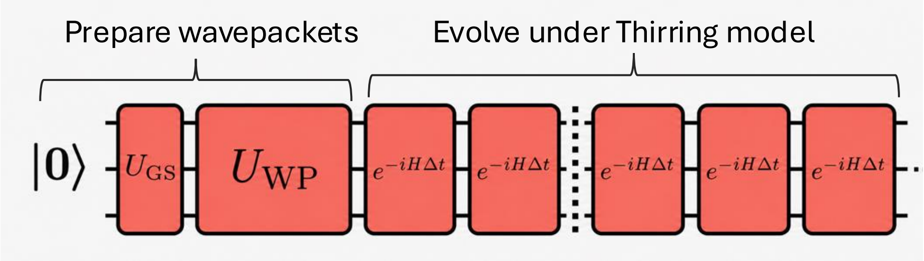
Initialize   Evolve



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3. Measure observables

estimate observables from shots

- Correlators, spectra, response functions, scattering-like quantities

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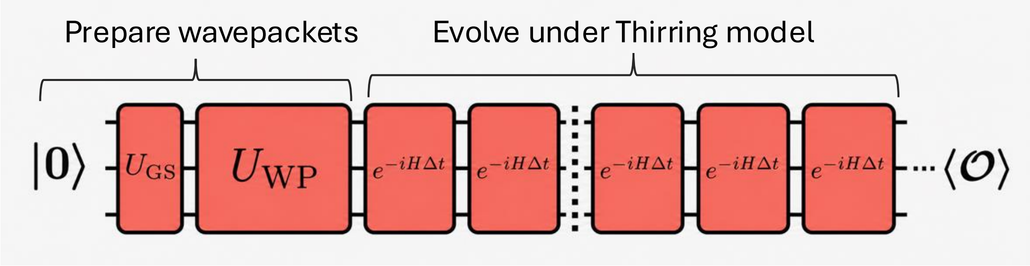

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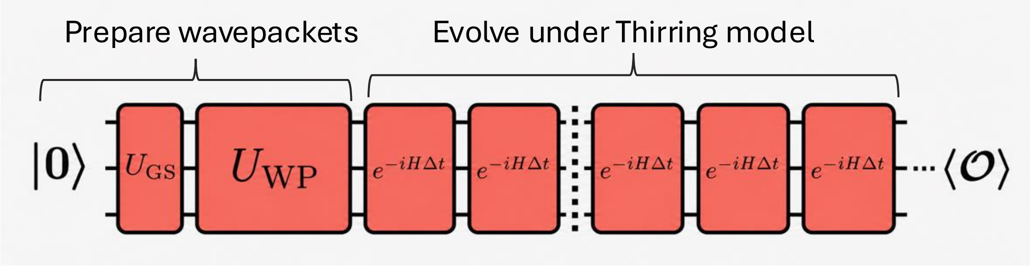
Initialize **Evolve**



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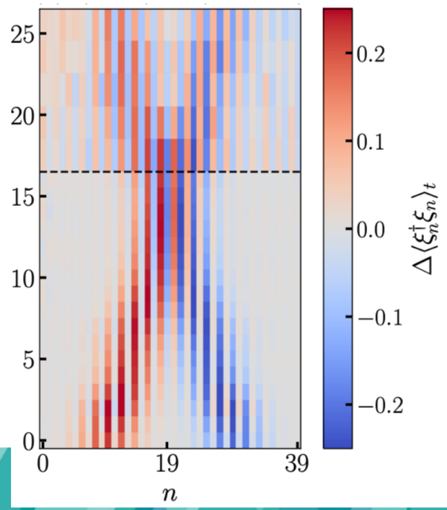


What has been achieved on quantum computers?

HW 127 qubits

arXiv > quant-ph > arXiv:2507.17832

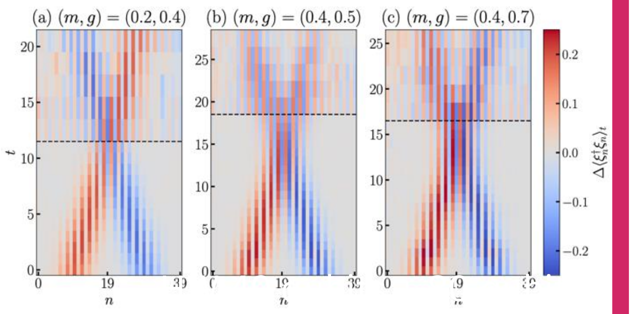
Quantum Physics

[Submitted on 23 Jul 2025]

Resource-Efficient Simulations of Particle Scattering on a Digital Quantum Computer

Yahui Chai, Joe Gibbs, Vincent R. Pascuzzi, Zoë Holmes, Stefan Kühn, Francesco Tacchino, Ivano Tavernelli

We develop and demonstrate methods for simulating the scattering of particle wave packets in the interacting Thirring model on digital quantum computers, with hardware implementations on up to 80 qubits. We identify low-entanglement time slices of the scattering dynamics and exploit their efficient representation by tensor networks. Circuit compression based on matrix product state techniques yields on average a reduction by a factor of 3.2 in circuit depth compared to conventional approaches, allowing longer evolution times to be evaluated with higher fidelity on contemporary quantum processors. Utilizing zero-noise extrapolation in combination with Pauli twirling, on quantum hardware we accurately simulate the full scattering dynamics on 40 qubits, and further demonstrate the wave packet state-preparation on 80 qubits.



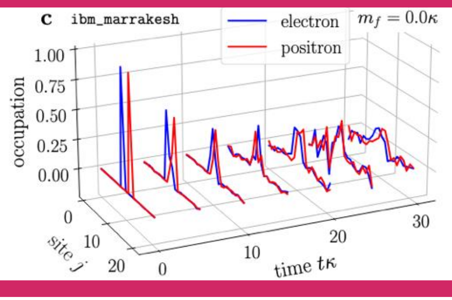
arXiv > quant-ph > arXiv:2505.20387

Quantum Physics

[Submitted on 26 May 2025]

Observation of hadron scattering in a lattice gauge theory on a quantum computer

Julian Schuhmacher, Guo-Xian Su, Jesse J. Osborne, Anthony Gandon, Jad C. Halimeh, Ivano Tavernelli



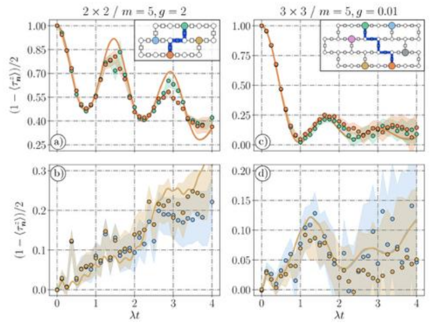
arXiv > quant-ph > arXiv:2507.08088

Quantum Physics

[Submitted on 10 Jul 2025]

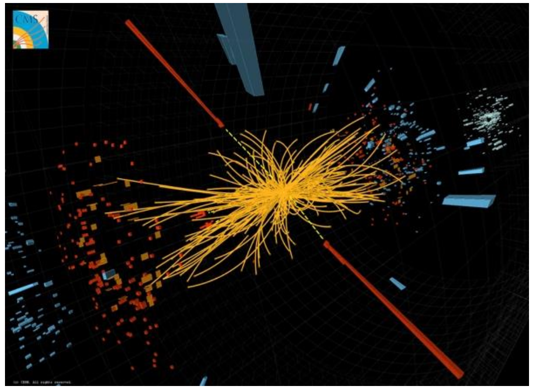
Real-Time Dynamics in a (2+1)-D Gauge Theory: The Stringy Nature on a Superconducting Quantum Simulator

Jesús Cobos, Joana Fraxanet, César Benito, Francesco di Marcantonio, Pedro Rivero, Kornél Kapás, Miklós Antal Werner, Örs Legeza, Alejandro Bermudez, Enrique Rico

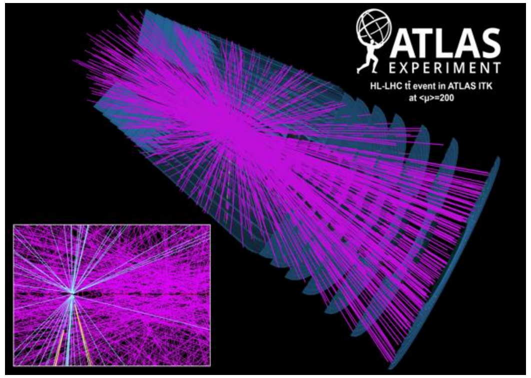


(HL-)LHC computing: complexity

Run-1 Higgs candidate

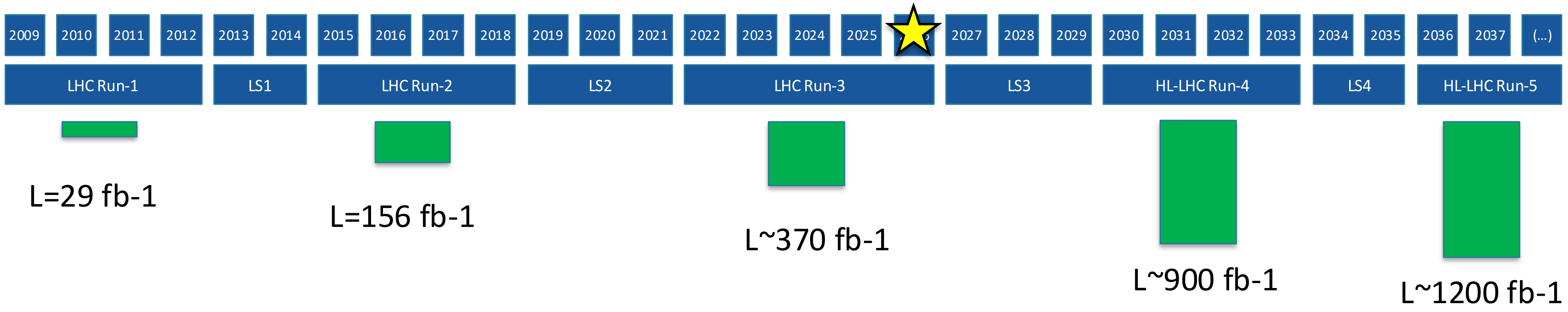


HL-LHC simulated event



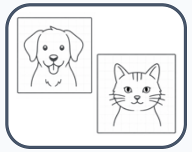
Increase in data volume, but also in **event complexity**

Major innovation needed in the experiments' software



Quantum computers to process data

classical access | **increasing quantumness of the data** | coherent quantum access

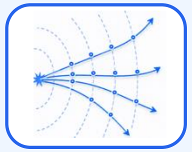


Classical data

Data is classical in origin & format

Images, text, tables, from `every day' problems

Analysis of standard data/ ML tasks

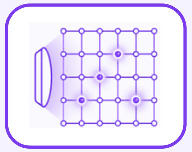


Classical data from quantum systems

The underlying process is quantum, but the recorded data is classical.

Detector hits, reconstructed particle tracks, spectra and correlations.

Analysis of standard HEP data



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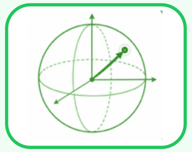
Tomographic data, Bell type observables, entanglement witnesses

Analysis of Quantum Information



Quantum data

The input itself is a quantum state, with coherent access before measurement.

Unknown states, many-copy access, encoded states, quantum memories.

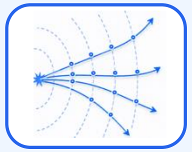
Coherent quantum processing

There are several distinct "learning" settings — depending on whether the data is classical, quantum-generated, or genuinely quantum.

Quantum computers to process data

increasing quantumness of the data

There is a community working on exploring applications of heuristic quantum machine learning algorithms to HEP data processing



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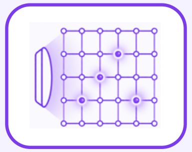

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Analysis of Quantum Information

We know quantum effects play a role (but could be partially washed out by complex classical processes)

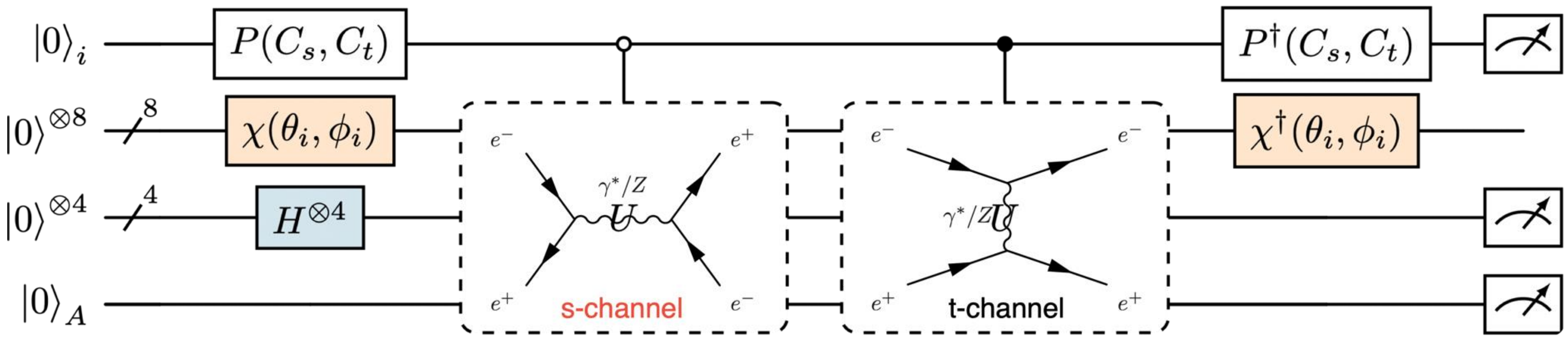
We know there is a simple underlying quantum model

Quantum computers to process data

Hamiltonian simulation approach
real-time dynamics, discretized fields)

Perturbative diagram simulation approach: Perturbative diagram simulation (amplitudes, interferences, helicity building blocks)

Coherent sum of Feynman diagrams with LCU



- reproduce the structure of perturbative scattering amplitudes Feynman-diagram
- provide a direct quantum-circuit interface to the amplitude-level
- calculate complex integrals and extract numbers that enter collider cross sections

Quantum computers to process data

~~**Hamiltonian simulation approach**
real-time dynamics, discretized fields)~~

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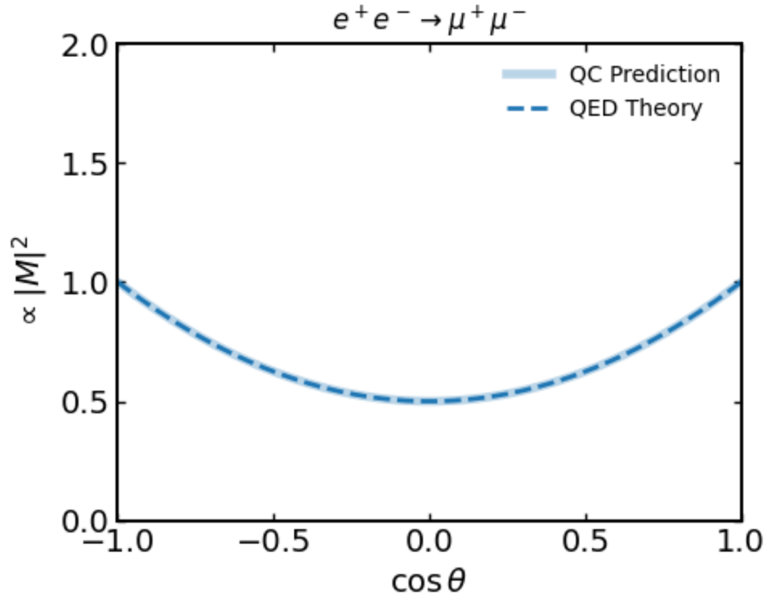
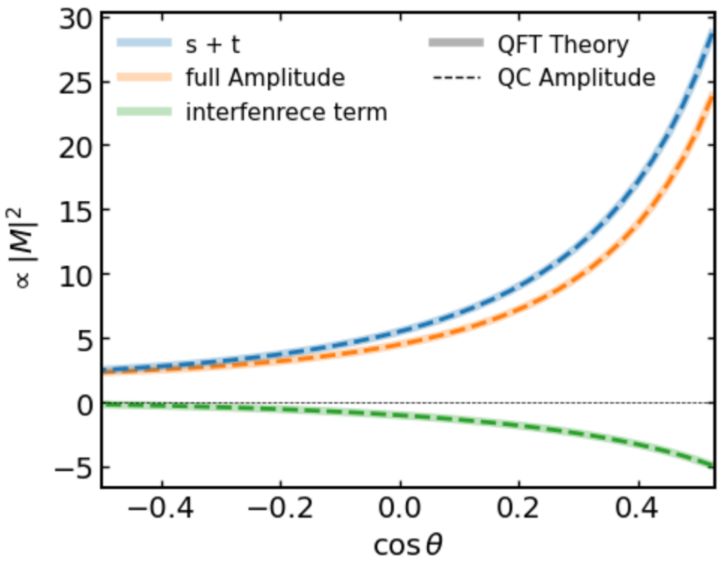
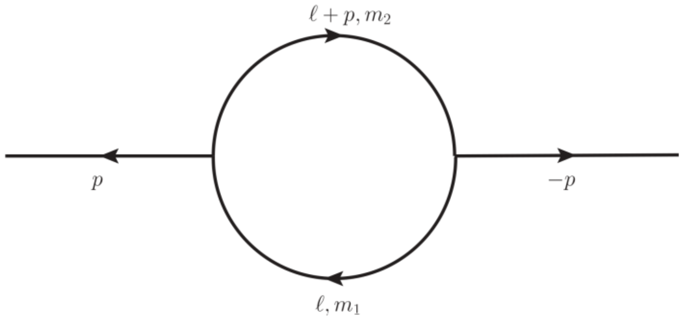


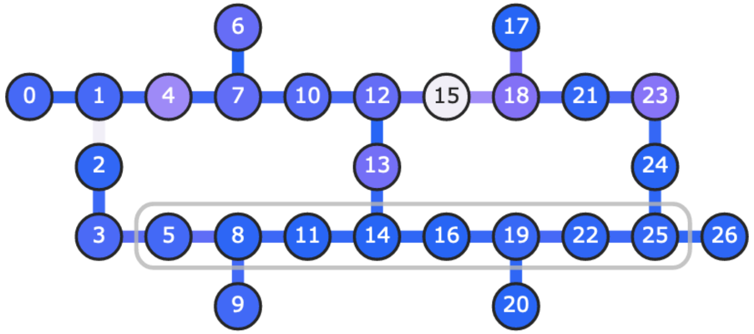


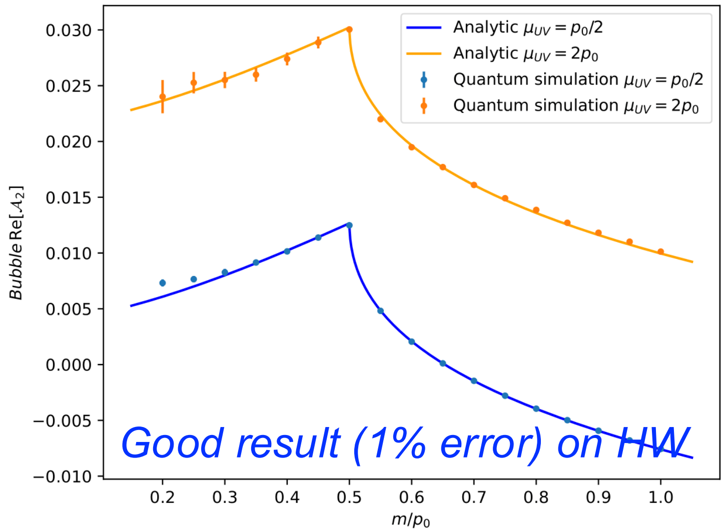
Quantum for integration



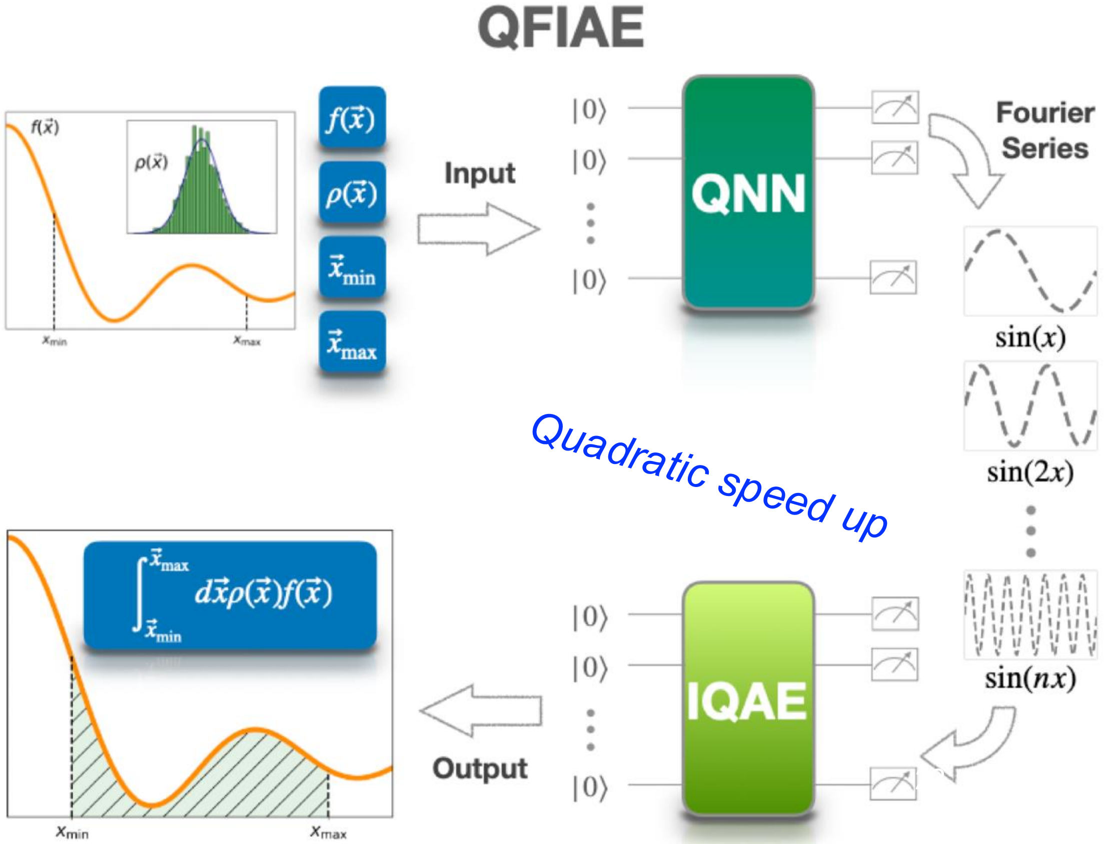
Loop Feynman integral (Bubble)

$$\mathcal{A}_2^{(1)}(p, m_1, m_2) = \int_\ell \prod_{i=1}^{2} G_F(q_i) = \int_\ell \frac{1}{(\ell^2 - m_1^2 + \imath 0)\left((\ell + p)^2 - m_2^2 + \imath 0\right)}$$





Good result (1% error) on HW



Quadratic speed up

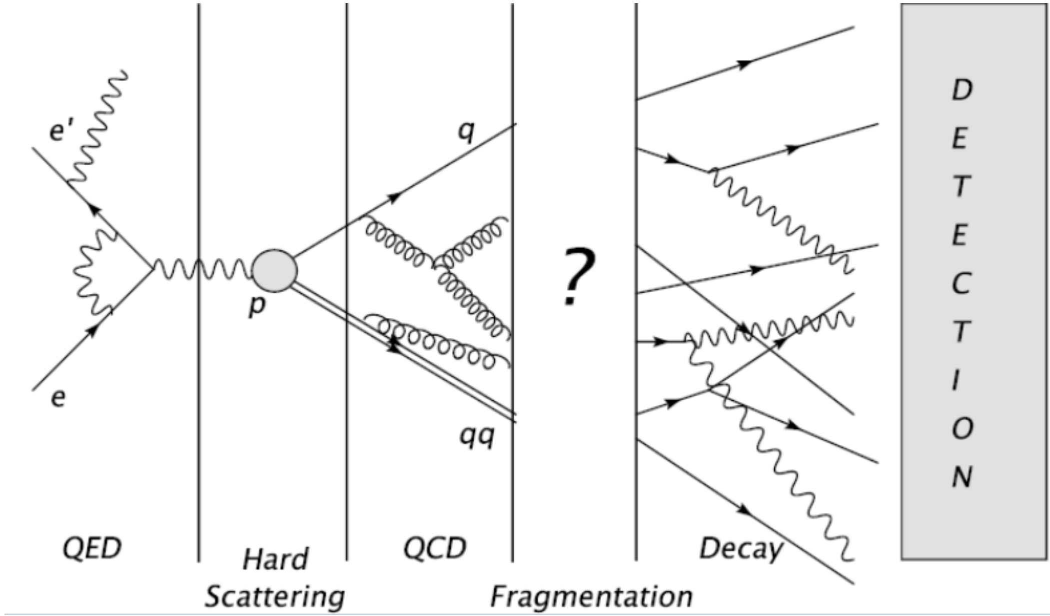
"Loop Feynman integration on a quantum computer
" De Lejarza, MG et al. - Phys. Rev. D 110, 074031

Fragmentation Functions

Def: Fragmentation functions encode the information on how partons produced in hard-scattering processes are turned into an observed colorless hadronic bound final-state

$$D_i^h(z,Q) \propto Prob(parton(i) \rightarrow hadron(h))$$

$z \equiv$ momentum fraction $\quad Q \equiv$ energy scale



Why are they important?

- **Non-Perturbative and Universal**→ predictions of observables (cross-sections)

How are they determined?

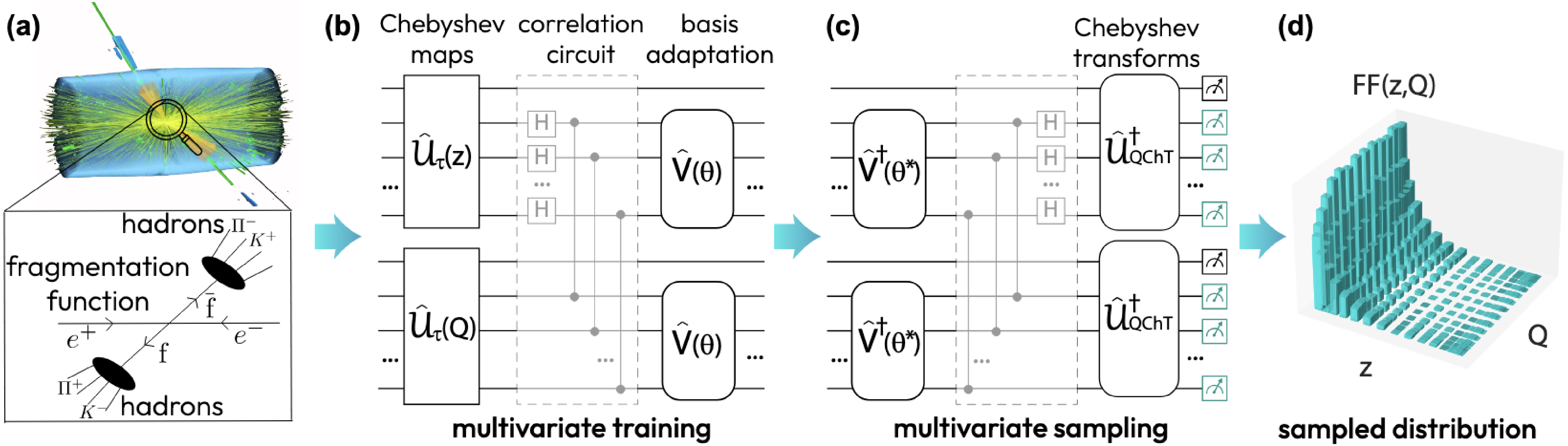
- Statistical and ML methods to **learn** FFs from data
- $D_i^h(z,Q_0) \propto z^{\alpha}(1-z)^{\beta}$

Caveat: Interpolation for Q solving DGLAP evolution equations

Quantum Chebychev GM for FF

Learn fragmentation functions from data using **quantum probabilistic models based on Chebyshev polynomials**.

Quantum Chebyshev Probabilistic Models for Fragmentation Functions - Commun Phys 8, 448 (2025)



What has been achieved on quantum computers?

arXiv > quant-ph > arXiv:2605.06789

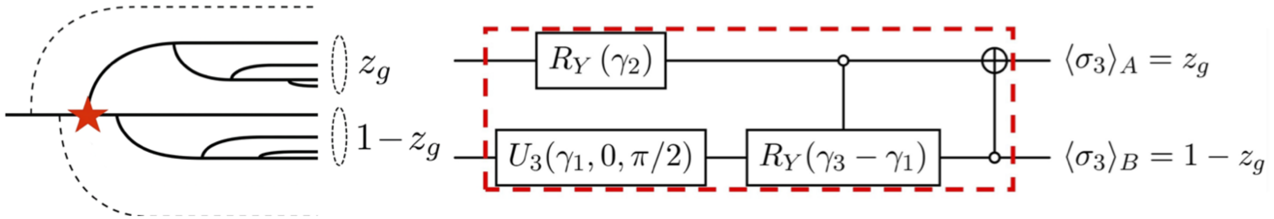
Quantum Physics

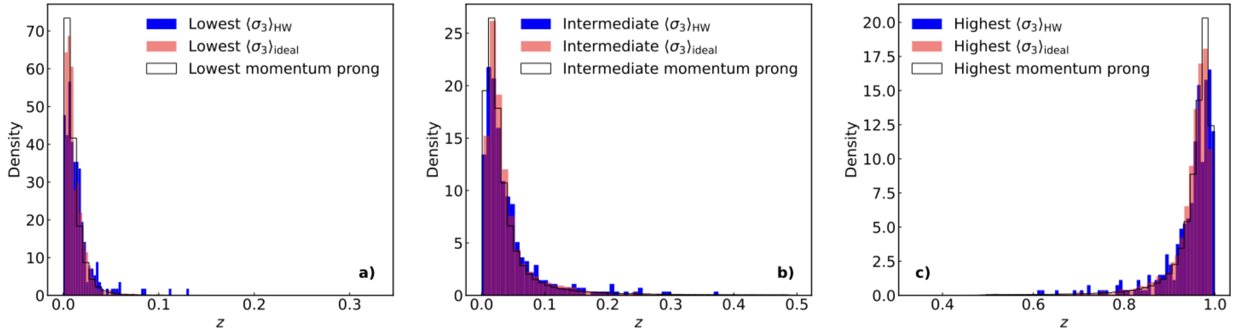
[Submitted on 7 May 2026 (v1), last revised 22 May 2026 (this version, v2)]

Physics inspired quantum algorithm for QCD splitting functions

Gabriel Rouxinol, Yacine Haddad, Cenk Tüysüz, Sofia Vallecorsa, Michele Grossi

We introduce a modular quantum circuit primitive to model entanglement dynamics in QCD parton splitting and use it as a composable building block for data-driven, physics-consistent event generation. For the pure-gluon channel, we derive an analytic expression for the helicity entanglement generated at the splitting vertex, quantified via the concurrence, and construct a two-qubit circuit whose measurement outcomes encode the momentum shared between outgoing gluons while reproducing the QCD-predicted entanglement structure. Calibrating the circuit parameters to LHC jet substructure data maps, reconstructed momentum-sharing fractions are directly related to circuit rotation angles. Composing multiple splitting primitives yields multi-prong momentum-fraction distributions; we validate the three- and four-prong cases against experimental data and find good agreement. For the three-prong configuration, we execute the circuit on superconducting quantum hardware and obtain results consistent with simulation after standard quality cuts, enabled by the low qubit count and shallow circuit depth. This work provides a concrete framework for quantum-native parton-shower modules that encode quantum correlations at the level of splitting dynamics, and offers physics-informed ansätze for future quantum algorithms for QCD.





Quantum computers to process data

classical access — **increasing quantumness of the data** — coherent quantum access

An exciting paradigm in the quantum computing community:

Quantum advantage in learning from experiments

HSIN-YUAN HUANG, MICHAEL BROUGHTON, JORDAN COTLER, SITAN CHEN, JERRY LI, MASOUD MOHSENI, HARTMUT NEVEN, RYAN BABBUSH, RICHARD KUENG, [...], AND JARROD R. MCCLEAN +1 authors Authors Info & Affiliations

SCIENCE • 9 Jun 2022 • Vol 376, Issue 6598 • pp. 1182-1186 • DOI: 10.1126/science.abn7293

Power of data in quantum machine learning

Hsin-Yuan Huang, Michael Broughton, Masoud Mohseni, Ryan Babbush, Sergio Boixo, Hartmut Neven & Jarrod R. McClean

Nature Communications 12, Article number: 2631 (2021) | Cite this article

The idea is excitedly discussed in the quantum computing HEP community but very early days….

arXiv > quant-ph > arXiv:2603.03157

Search... Help |

Quantum Physics

[Submitted on 3 Mar 2026]

Achieving speedup in Dark Matter search experiments with a transmon-based NISQ algorithm

Roberto Moretti, Pietro Campana, Rodolfo Carobene, Alessandro Cattaneo, Marco Gobbo, Danilo Labranca, Matteo Borghesi, Marco Faverzani, Elena Ferri, Sara Gamba, Angelo Nucciotti, Andrea Giachero

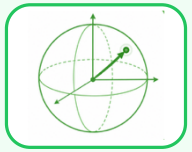
Coherent detection of ultralight bosonic dark matter can be achieved by monitoring slow Rabi oscillations in superconducting qubits. We introduce an ancilla-assisted, gate-based protocol that enhances sensitivity to the hidden photon kinetic mixing parameter ϵ using a single two-qubit gate, bypassing the need to maintain long-lived multi-qubit entangled states and remaining compatible with the limitations of modern quantum hardware. We characterized the increase in sensitivity accounting for decoherence, thermal occupation, errors in readout and reset, indicating up to a ten-fold reduction in the required integration time to reach the same exclusion limit on ϵ achievable via Rabi-sampling experiments. Under plausible hardware assumptions and three years of data taking, the projected 95% C.L. exclusion limit on the hidden photon mixing parameter reaches $\epsilon \approx 1 \times 10^{-14}$ across 2.5–6.0 GHz (10–25 \textmu eV).

Full idea would need bold hardware developments…
But has links with more modest quantum sensing ideas

SEARCHING FOR AXIONS:
A NEW SRF CAVITY-BASED PROGRAMME AT CERN

W. L. Millar[1]*, L. Balocchi[1], D. Barrientos[1], J. Bremer[1], S. Calatroni[1], R. T. D'Agnolo[2,3], S. A. R. Ellis[4,5], A. Grudiev[1], T. Koettig[1], N. Koss[1], A. Macpherson[1], S. Vallecorsa[1]
[1]CERN, European Organization for Nuclear Research, Geneva, Switzerland
[2]Institut de Physique Théorique, Université Paris-Saclay, Gif-sur-Yvette, France
[3]Laboratoire de Physique de l'Ecole Normale Supérieure (LPENS), Paris, France
[4]Department of Theoretical Physics, University of Geneva, Geneva, Switzerland

Simple measurements on a quantum state



Quantum data

The input itself is a quantum state, with coherent access before measurement.

Unknown states, many-copy access, encoded states, quantum memories.

Coherent quantum processing

Complex measurements on quantum state and/or state processed by a quantum computer

Key theoretical challenges:

Quantum Algorithm Development:

Peter Shor (the godfather of quantum algorithm design) wrote a comment piece in 2003 with the title:

"Why haven't more quantum algorithms been found?"

Some more have by now been found but the zoo of quantum algorithms is still relatively small!

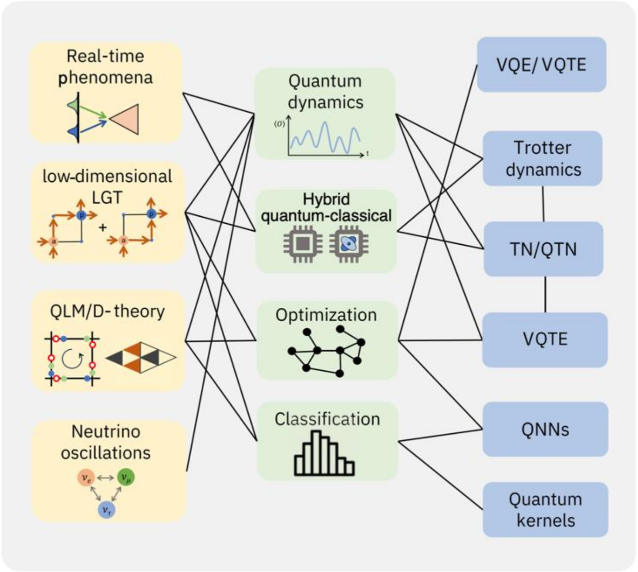
- Lack of large reliable devices makes it hard!
- Not many classical algorithms were found before we had classical computers…. Machine learning only took off once we had more compute power…
- Should get easier as hardware improves

Summary

A healthy community working on how quantum computers can be used in high energy physics...

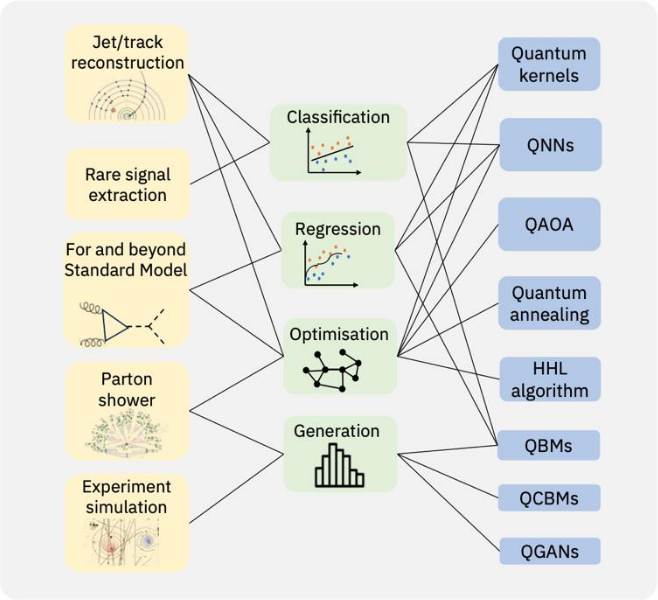
But a tiny percentage compared to the efforts in more 'commercial applications'

Applications for Simulations



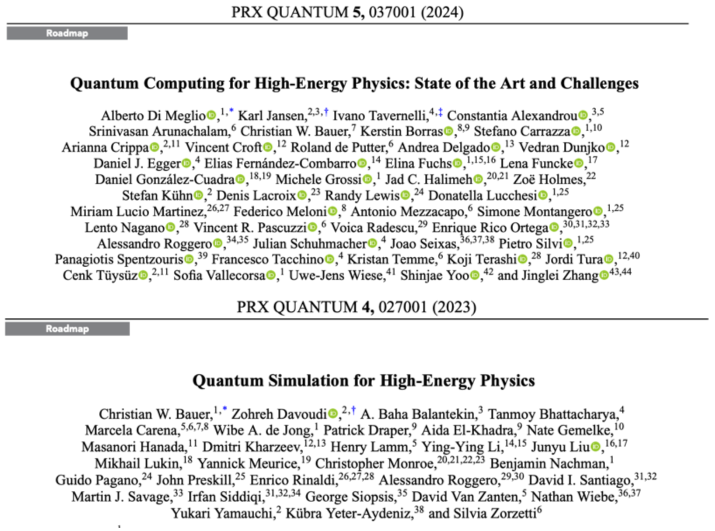
Quantum algorithms ready,
Hardware getting ready...
End-to-end applications needed!

Applications for Data Processing



Early stages: careful algorithm / protocol development needed.

Collaboration between HEP and quantum computing researchers is essential for this to work.



PRX QUANTUM **5,** 037001 (2024)

Roadmap

Quantum Computing for High-Energy Physics: State of the Art and Challenges

Alberto Di Meglio,[1,*] Karl Jansen,[2,3,†] Ivano Tavernelli,[4,‡] Constantia Alexandrou,[3,5] Srinivasan Arunachalam,[6] Christian W. Bauer,[7] Kerstin Borras,[8,9] Stefano Carrazza,[1,10] 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,[1,25] Miriam Lucio Martinez,[26,27] Federico Meloni,[8] Antonio Mezzacapo,[6] Simone Montangero,[1,25] Lento Nagano,[28] Vincent R. Pascuzzi,[6] Voica Radescu,[29] Enrique Rico Ortega,[30,31,32,33] Alessandro Roggero,[34,35] Julian Schuhmacher,[4] Joao Seixas,[36,37,38] Pietro Silvi,[1,25] Panagiotis Spentzouris,[39] Francesco Tacchino,[4] Kristan Temme,[6] Koji Terashi,[28] Jordi Tura,[12,40] Cenk Tüysüz,[2,11] Sofia Vallecorsa,[1] Uwe-Jens Wiese,[41] Shinjae Yoo,[42] and Jinglei Zhang[43,44]

PRX QUANTUM **4,** 027001 (2023)

Roadmap

Quantum Simulation for High-Energy Physics

Christian W. Bauer,[1,*] Zohreh Davoudi,[2,†] A. Baha Balantekin,[3] Tanmoy Bhattacharya,[4] Marcela Carena,[5,6,7,8] Wibe A. de Jong,[1] Patrick Draper,[9] Aida El-Khadra,[9] Nate Gemelke,[10] Masanori Hanada,[11] Dmitri Kharzeev,[12,13] Henry Lamm,[5] Ying-Ying Li,[14,15] Junyu Liu,[16,17] Mikhail Lukin,[18] Yannick Meurice,[19] Christopher Monroe,[20,21,22,23] Benjamin Nachman,[1] Guido Pagano,[24] John Preskill,[25] Enrico Rinaldi,[26,27,28] Alessandro Roggero,[29,30] David I. Santiago,[31,32] Martin J. Savage,[33] Irfan Siddiqi,[31,32,34] George Siopsis,[35] David Van Zanten,[5] Nathan Wiebe,[36,37] Yukari Yamauchi,[2] Kübra Yeter-Aydeniz,[38] and Silvia Zorzetti[6]

And to train future researchers that comfortably straddle both fields…