Quantum Computing for High-Energy Particle & Nuclear Physics

26th international symposium on spin physics (SPIN2025),
Qingdao, Shandong, September 22-26, 2025

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Institute of High Energy Physics, Chinese Academy of Sciences

Picture credits: Qianhui Shi, Yan Liang

2025: 100th Anniversary of QM & Spin

INTERNATIONAL YEAR OF
Quantum Science
and Technology

Werner Heisenberg

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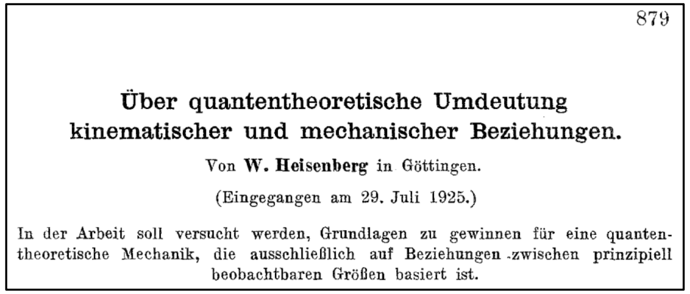
"Quantum-mechanical re-interpretation of kinematic and mechanical relations"
(translation used in "Sources of Quantum Mechanics, edited by B. L. van der Waerden (1967))



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Über quantentheoretische Umdeutung kinematischer und mechanischer Beziehungen.

Von **W. Heisenberg** in Göttingen.

(Eingegangen am 29. Juli 1925.)

In der Arbeit soll versucht werden, Grundlagen zu gewinnen für eine quantentheoretische Mechanik, die ausschließlich auf Beziehungen zwischen prinzipiell beobachtbaren Größen basiert ist.

Z. Physik 33, 879–893 (1925)

https://www.bnl.gov/centuryofspin/

- UNESCO proclaims 2025 as the **International Year of Quantum Science and Technology**, celebrating the **100th anniversary of the initial development of quantum mechanics (i.e. Heisenberg's paper accepted on 29 July, 1925)**
- It is also the **100th anniversary of spin introduced by Uhlenbeck and Goudsmit**.

2^{nd} Quantum Revolution: A New Era

- **1^{st} quantum revolution:** lasers, transistors, nuclear magnetic resonance, etc.
- **<u>2^{nd} quantum revolution</u>:** Identification and control of a single quantum bit for the first time in human history. **<u>Arrival of commercial quantum computers</u>.**
  - Quantum supremacy for random number generation in 2019/2020.
  - Recent significant speed-up in Willow/Zuchongzhi-3 & surface code implementation → a milestone towards large-scale quantum computers.

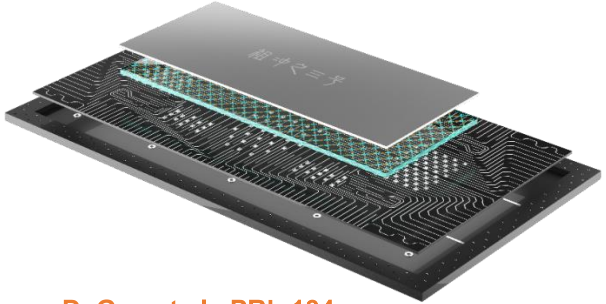
Google (2019)

Jiuzhang (九章) (2020)

Google (2024)

Google AI & collab., Nature 638 (2025) 920

Zuchongzhi-3 (祖冲之3号) (2024)

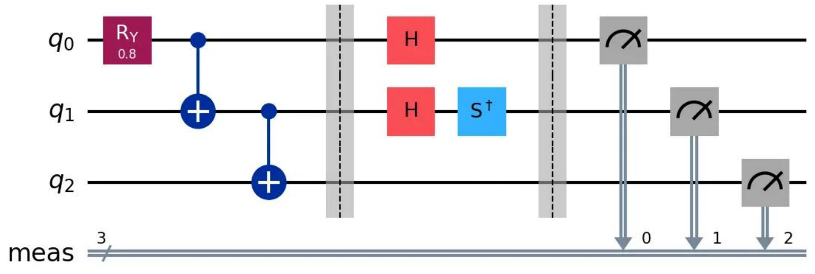


D. Gao et al., PRL 134 (2025) 090601

Quantum Computing Technologies

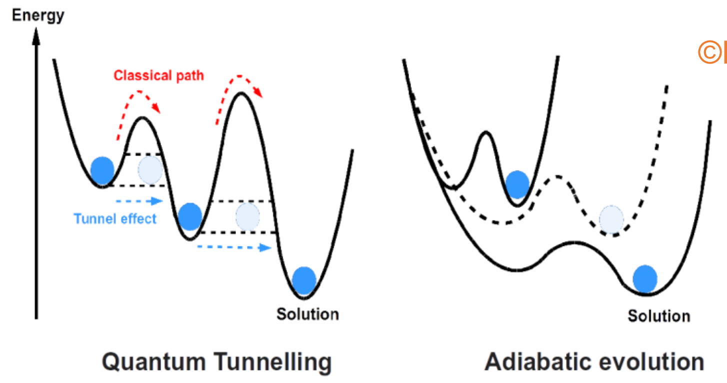
Quantum Gates

- Uses quantum logic gates. Is universal computing.
- **Most quantum computers adopt this approach**



Quantum Annealing

- Uses adiabatic theorem to seek for Hamiltonian ground state.
- Is non-universal, only applicable to optimization problems.



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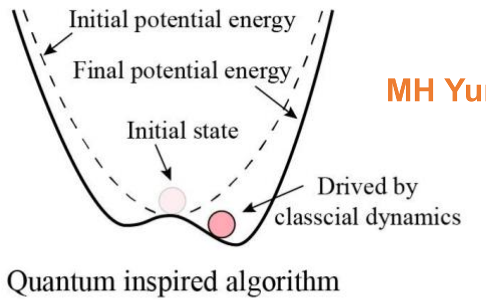
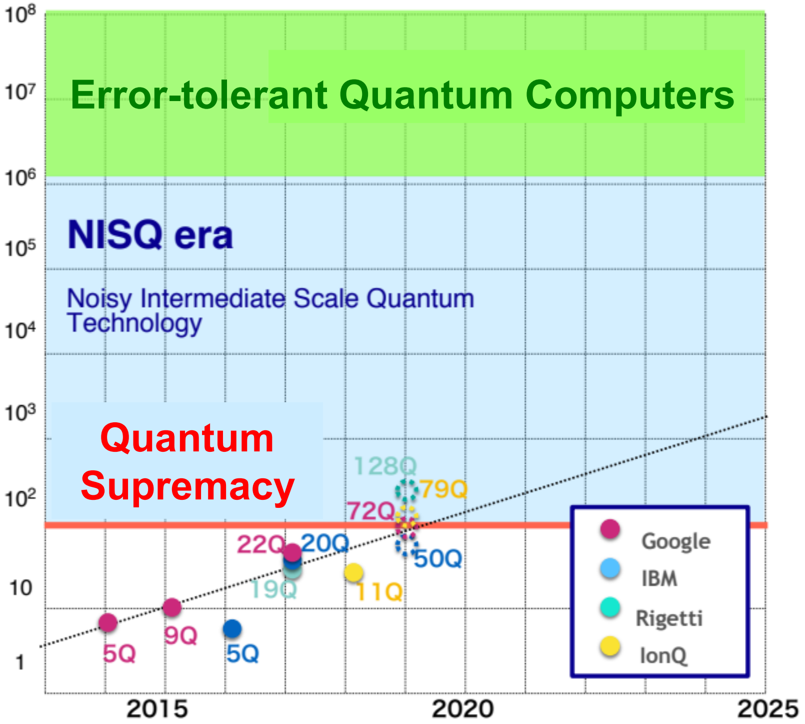
Quantum-inspired

- Classical algorithms: Simulated annealing, simulated coherent Ising machine, simulated bifurcation, tensor network, etc.



MH Yung

Noisy Intermediate Scale Quantum

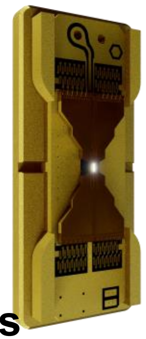


Modified from QunaSys

IBM

Superconductor
Heron 133 qubits

IonQ

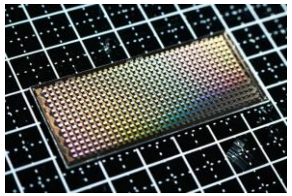


Ion Trap
Forte
32 qubits

QuEra

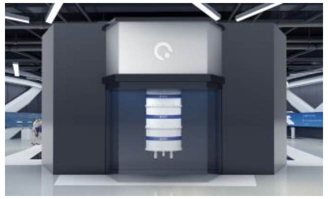
Neutral Atom
Aquila 256 qubits

QuantumCTek



Superconductor
Xiaohong
504 qubits

Origin Quantum



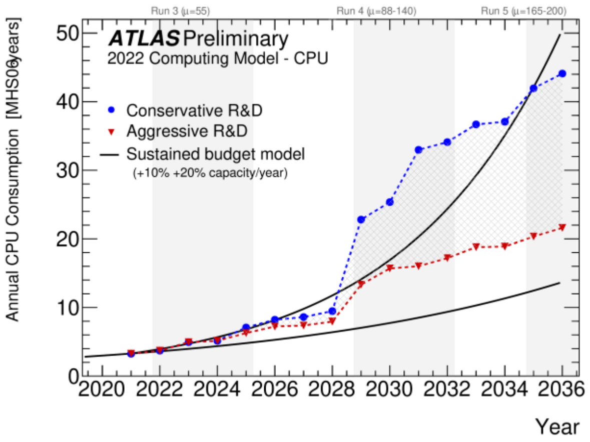
Superconductor
Wukong
72 qubits

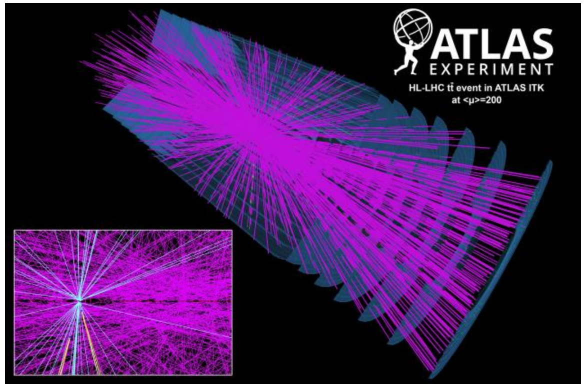
Photons
Jiuzhang-3 255 qubits

- Now is the era of Noisy Intermediate Scale Quantum (NISQ) computers **(>~50 qubits)**。
- **Error mitigation is actively introduced in various hardware. Error-tolerant quantum computers are starting to show up in ion-trap hardware.**

Why Quantum Computing?

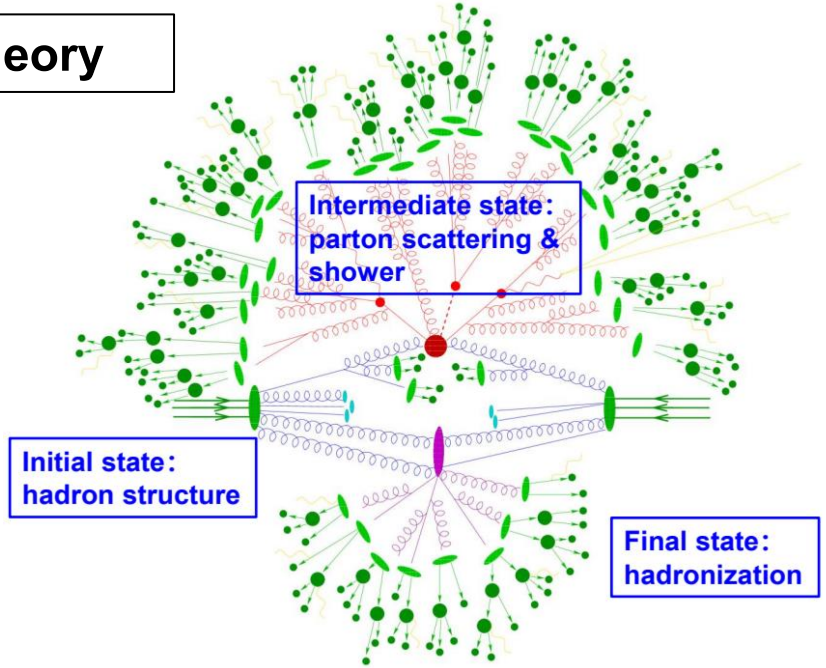
Experiments





- Future colliders (e.g. HL-LHC, CEPC, EIC) will enter **the EB era from the current PB-scale operation.**
- At the HL-LHC, annual computing cost will increase by a factor of 10-20. **CEPC Z-pole operation will experience similar challenges.**

Theory

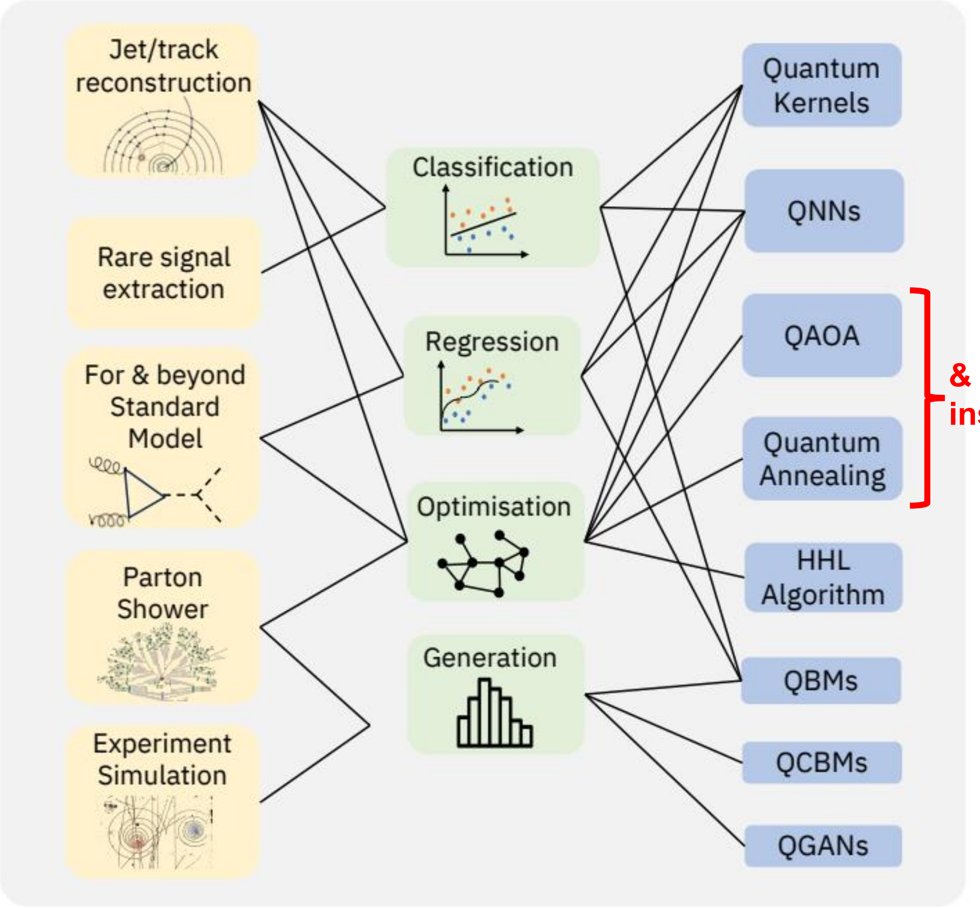


- Strong interaction dynamics is difficult to simulate classically from the first principles.
  - Non-equilibrium, non-perturbative, complexity of many-body quantum systems, quantum interference, sign problem, etc.

QC Applications in HEP

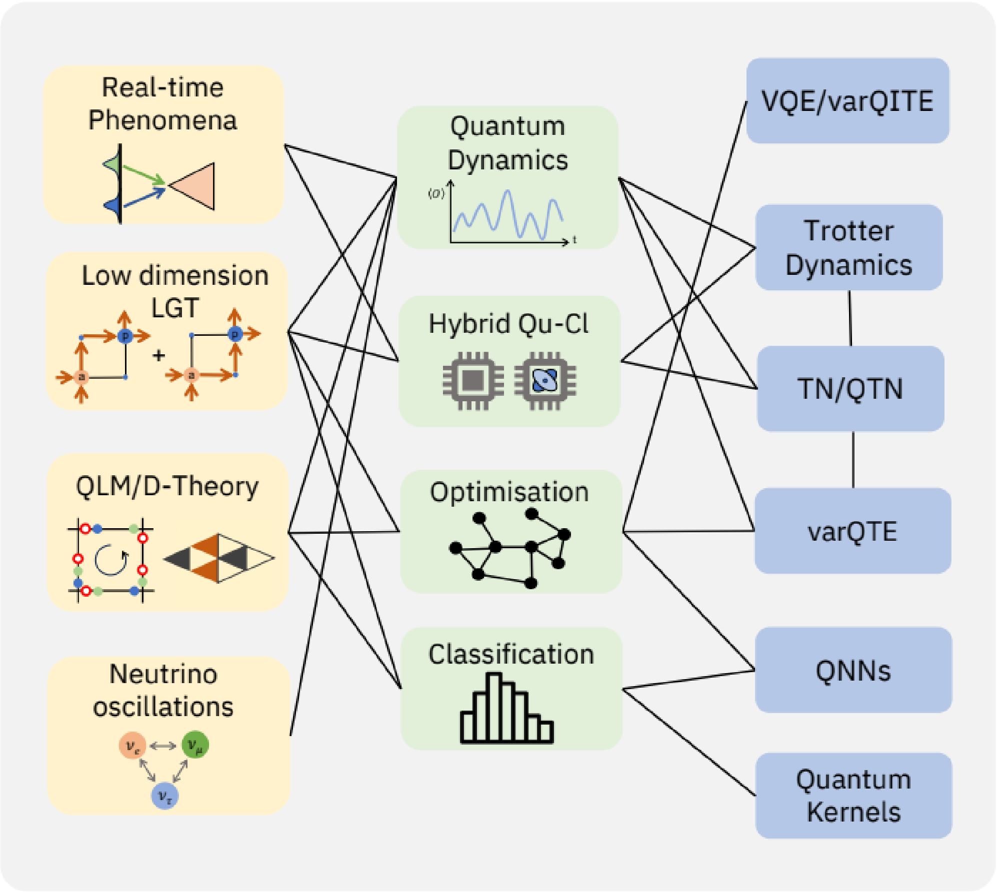
QC4HEP Whitepaper: A. Di Meglio et al., PRX QUANTUM 5, 037001 (2024)

Experiment



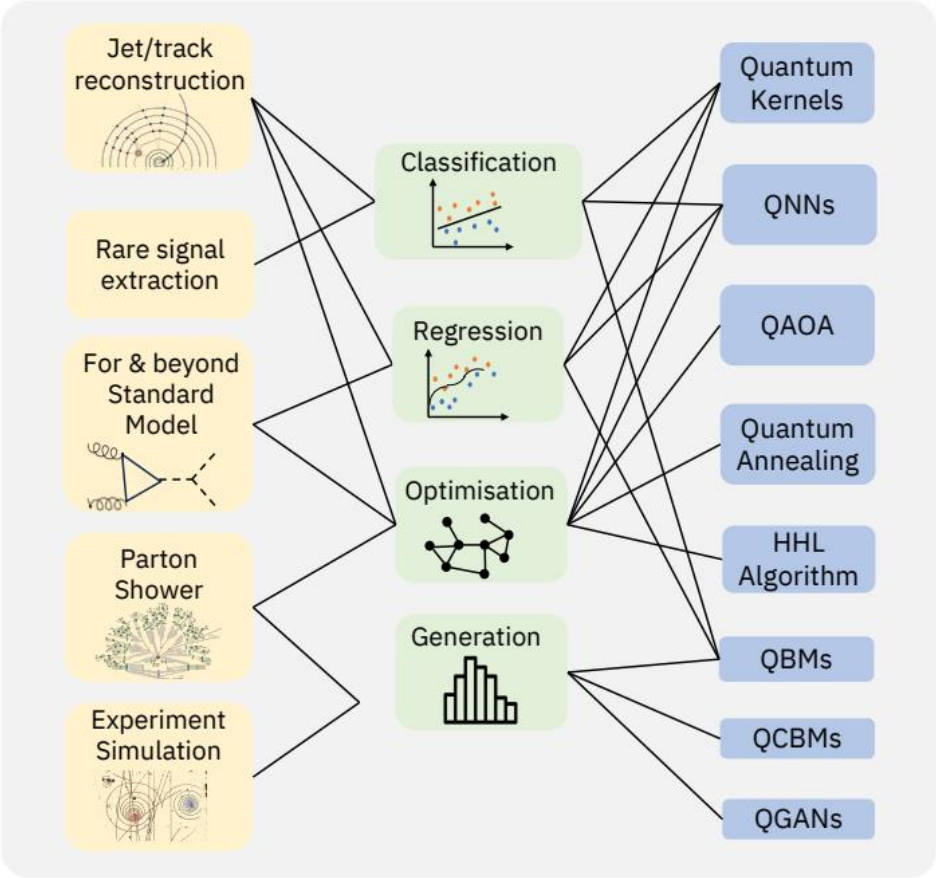
& Quantum-inspired

Theory

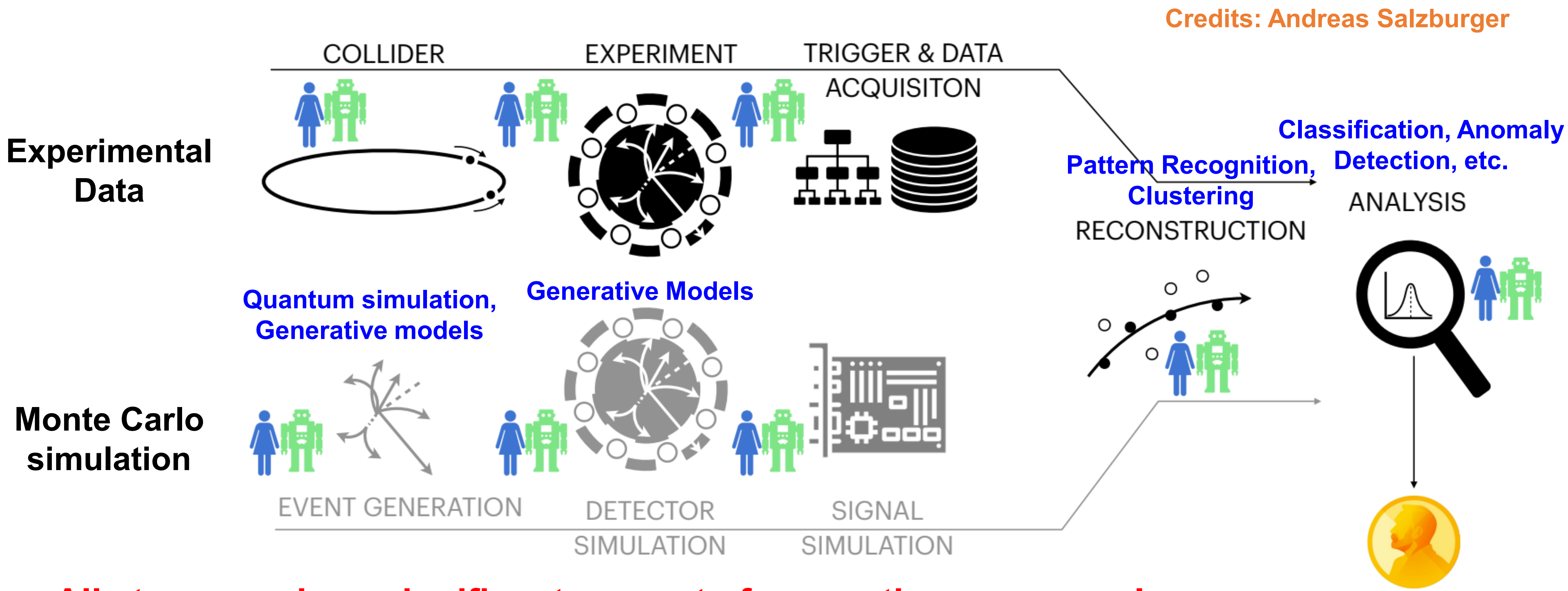


About quantum simulation, see also: C.W. Bauer et al., PRX Quantum 4 (2023) 2, 027001

Experimental Applications



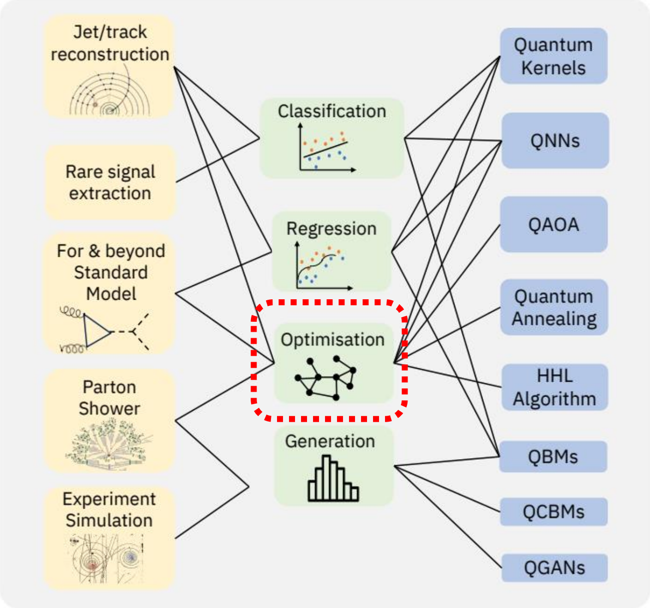
Full Experimental Workflow

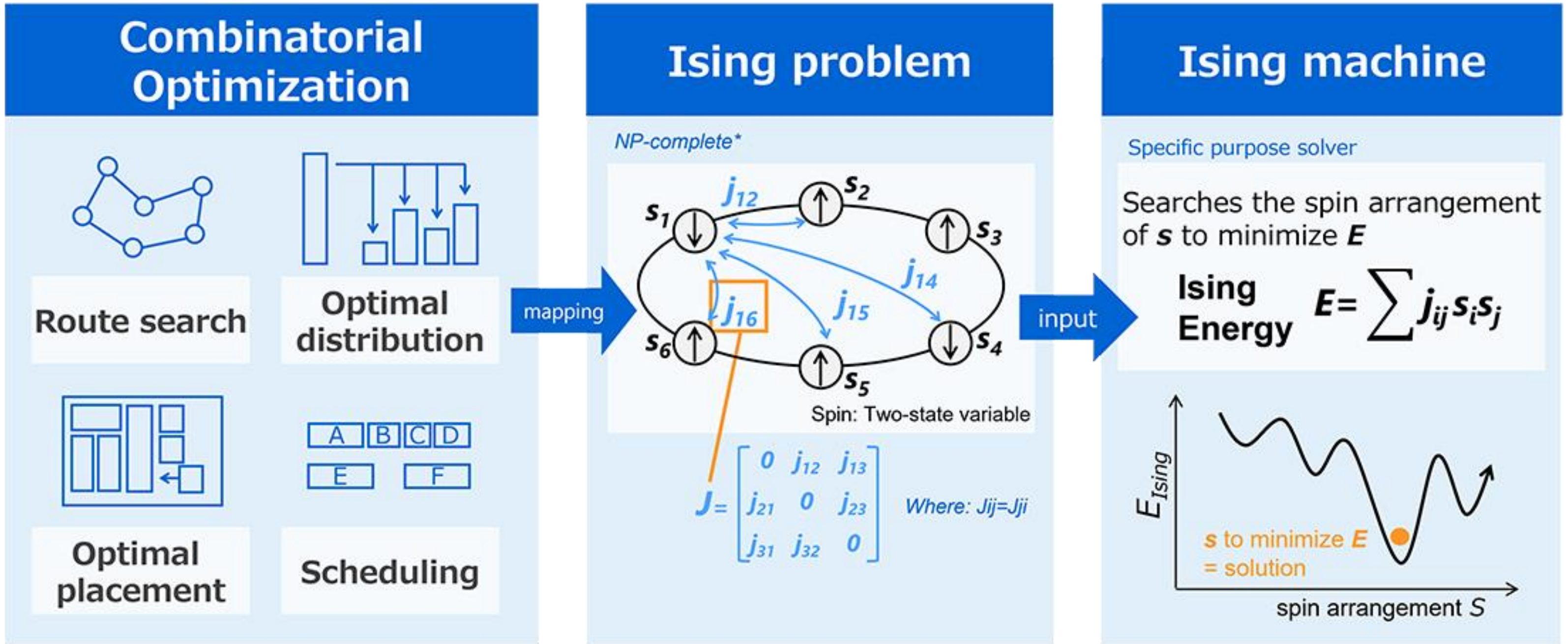


- **All steps require a significant amount of computing resources!**
- **State-of-the-art machine learning is currently being introduced/considered at all levels.**
- **Can we introduce quantum computing to these tasks?**

Combinatorial Optimization Problems

©TOSHIBA





- Practically complicated problems can often be formulated as combinatorial optimization problems/Ising problems → **Ground state of Ising Hamiltonian corresponds to the answer.**

Non-deterministic Polynomial time

- **They are generally NP-complete problem**: no efficient algorithm exists to find the solution.
  → But quantum approaches can provide quasi-optimal answers!

Tracking as Optimization Problem

- Tracks are formed by connecting silicon detector hits: e.g. triplets (segments w/ 3 hits).
- Doublets/triplets are connected to reconstruct tracks & it can be regarded as a **quadratic unconstrained binary optimization (QUBO)/Ising** problem.

$$O(a,b,T) = \sum_{i=1}^{N} a_i T_i + \sum_{i}^{N} \sum_{j<i}^{N} b_{ij} T_i T_j$$

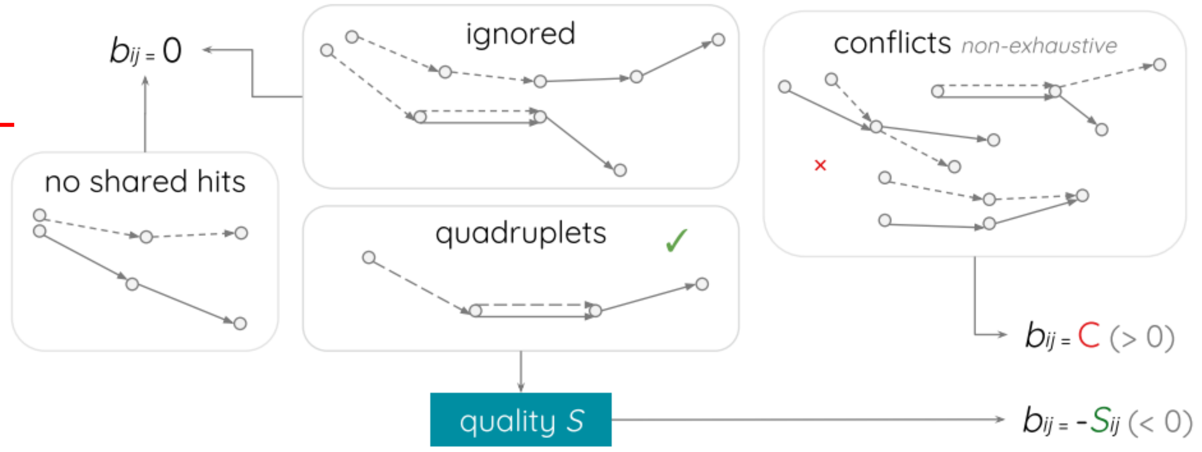
Quality of triplets — Compatibility b/w triplet pairs

$$a_i = \alpha \left(1 - e^{\frac{|d_0|}{\gamma}}\right) + \beta \left(1 - e^{\frac{|z_0|}{\lambda}}\right),$$

b_{ij} = 0 (if no shared hit), 1 (if conflict)
= $-S_{ij}$ (if two hits are shared)

$$S_{ij} = \frac{1 - \frac{1}{2}(|\delta(q/p_{Ti}, q/p_{Tj})| + max(\delta\theta_i, \delta\theta_j))}{(1 + H_i + H_j)^2},$$

F. Bapst et al. Comp. Soft. Big Sci. 4 (2019) 1

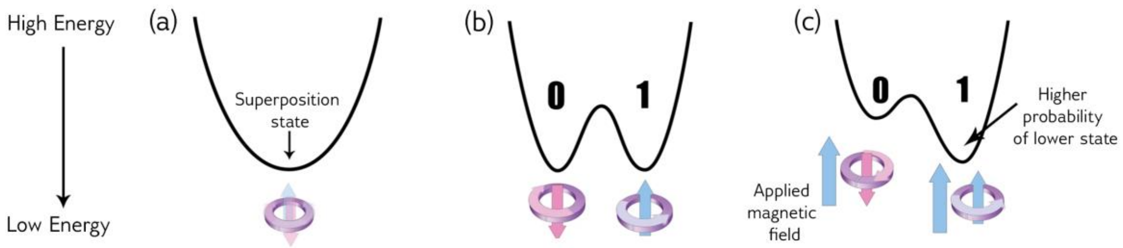


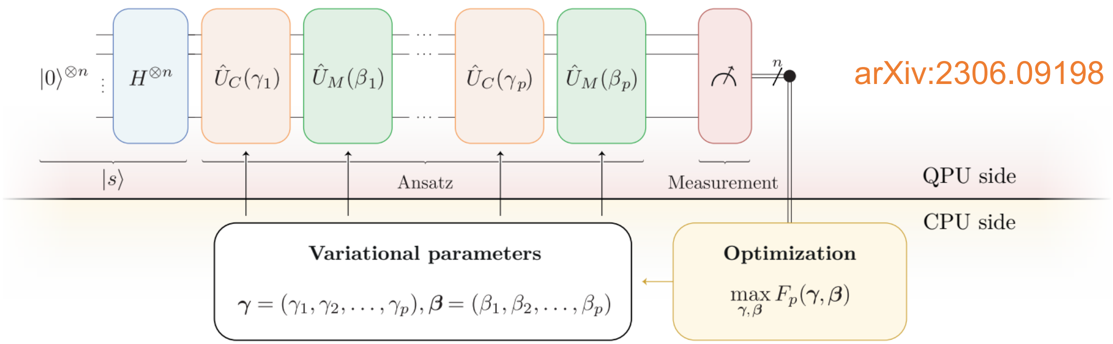
Minimizing QUBO is equivalent to searching for the ground state of the Hamiltonian.

Quantum Optimization Solvers

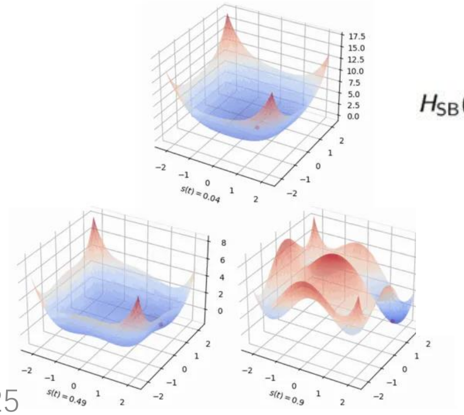
1. **Quantum annealer** looks for the global minimum based on the quantum adiabatic theorem (+quantum tunneling).
2. **Quantum gate** machines can also solve Ising problems with variational circuits & Trotterization; it is a hybrid with classical optimizers.
   - e.g. Variational Quantum Eigensolver (VQE), Quantum Approximate Optimization Algorithm (QAOA), imaginary Hamiltonian variational ansatz (iHVA), Imaginary Time Evolution-Mimicking Circuit (ITEMC).
3. **Quantum-inspired** algorithms search for ground state through the "**classical**" time evolution of differential equations.
   - e.g. Simulated annealing (SA), simulated bifurcation (SB)

©D-wave





arXiv:2306.09198



$$H_{SB}(\mathbf{x}, \mathbf{y}, t) = \sum_{i=1}^{N} \frac{\Delta}{2} y_i^2 + \sum_{i=1}^{N} [\frac{K}{4} x_i^4 + \frac{\Delta - p(t)}{2} x_i^2] - \frac{\xi_0}{2} \sum_{i=1}^{N} \sum_{j=1}^{N} J_{ij} x_i x_j$$

$$\dot{x}_i = \frac{\partial H_{SB}}{\partial y_i} = \Delta y_i$$

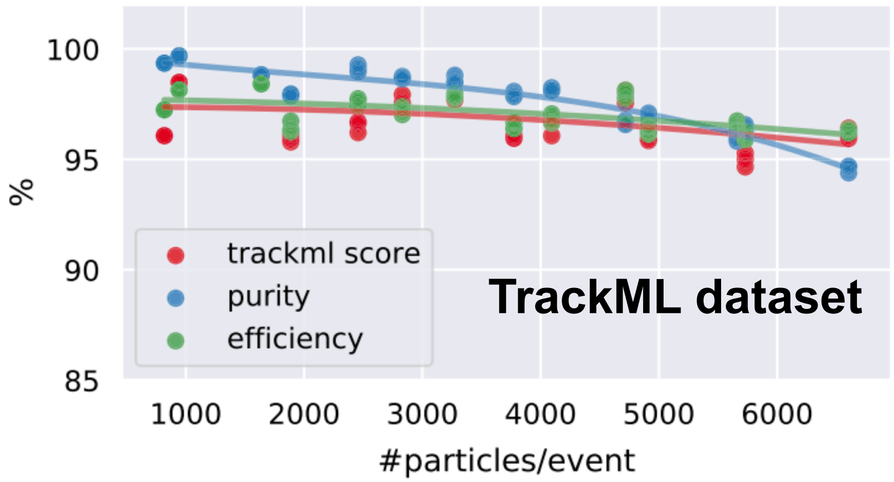
$$\dot{y}_i = -\frac{\partial H_{SB}}{\partial x_i} = -[K x_i^2 - p(t) + \Delta] x_i + \xi_0 \sum_{j=1}^{N} J_{i,j} x_j$$

See also I Shapoval, P Calafiura, EPJ Web Conf. 214 (2019) 01012; G Quiroz et al., NIM A 1010 (2021) 165557; D Magano et al., PRD 105 (2022) 076012; C Brown et al., Front. Artif. Intell. 7:1339785 (2024)

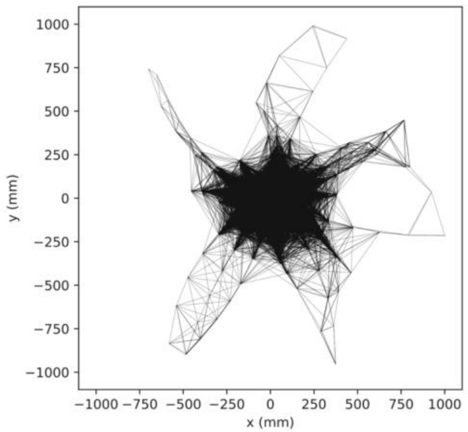
Tracking with Quantum Algorithms

Quantum annealing (w/ triplets)

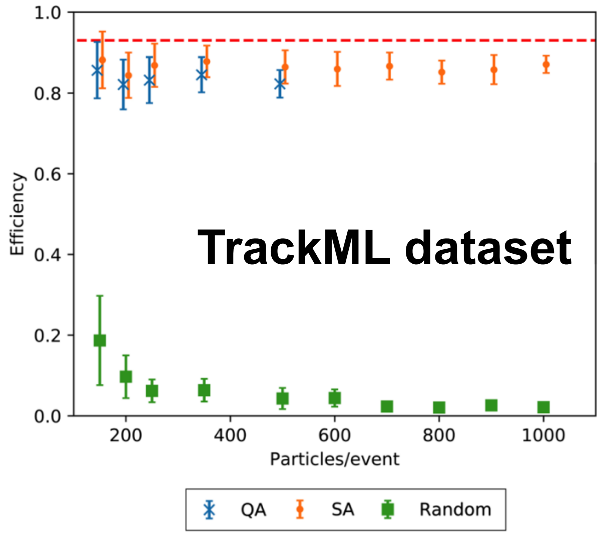
F. Bapst et al. Comp. Soft. Big Sci. 4 (2019) 1.



Quantum annealing (w/ doublets)



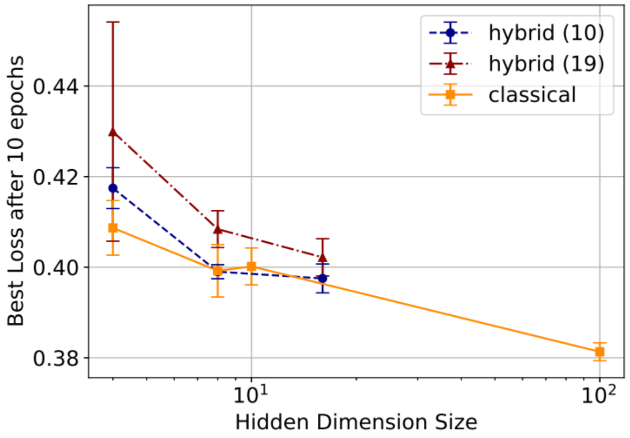
A. Zlokapa et al., Quantum Machine Intelligence (2021) 3:27



Quantum Gates (QGNN)

C. Tuysuz et al., Quantum Machine Intelligence (2021) 3:29

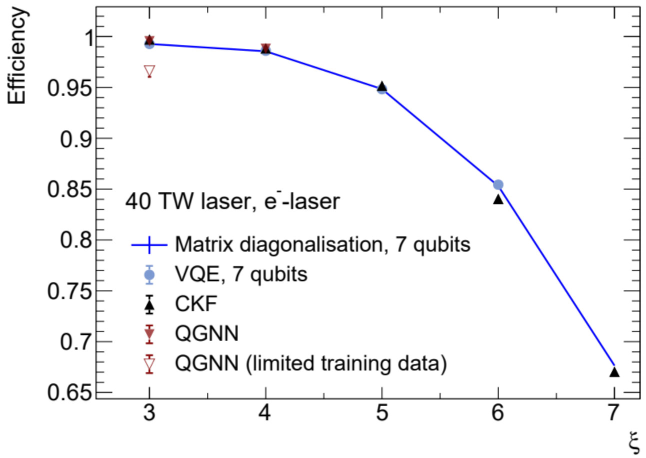
Conceptual stage



Quantum Gates (VQE w/ triplets, QGNN)

DESY-LUXE simulation dataset

Y.C. Yap et al., PoS EPS-HEP2023 (2024) 562

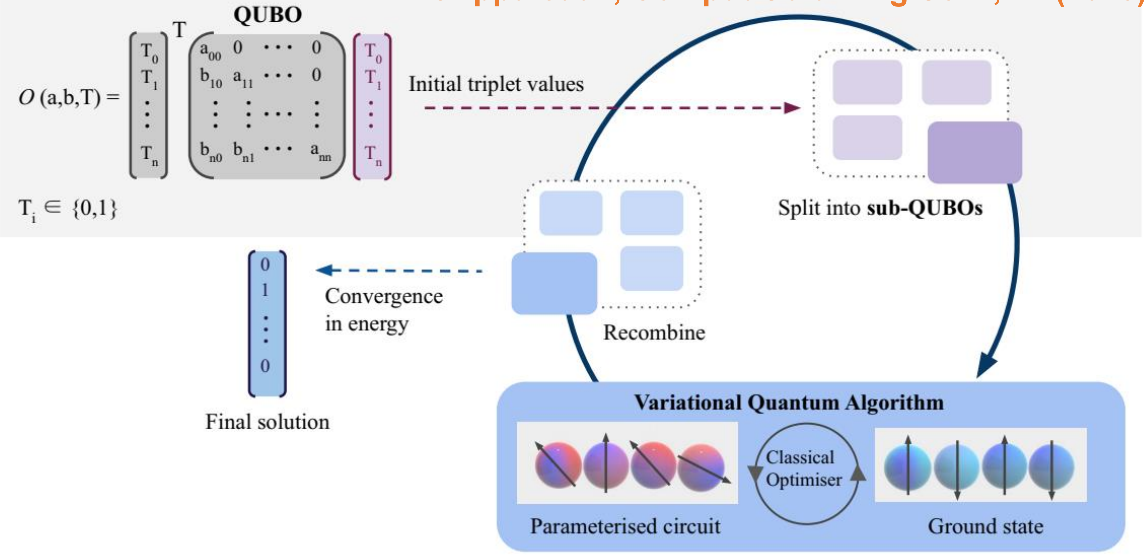


H. Okawa, Springer CCIS, 2036 (2024) 272–283, arXiv:2310.10255

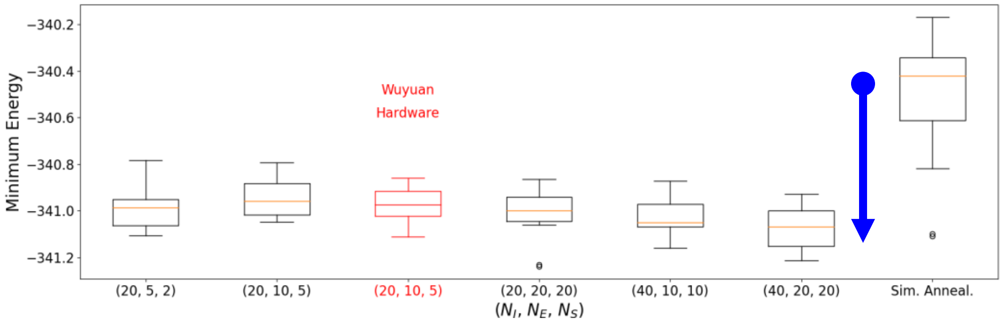
Tracking with Quantum Hardware

- # of triplet candidates determines # of qubits required → **HL-LHC conditions (~O(0.1M) qubits) do not fit into the current scale of quantum annealing & gate computers**
- **QUBO is split into sub-QUBOs.** There is no visible degradation in Ising solving precision, but **the computation speed degrades by a few orders of magnitude**.

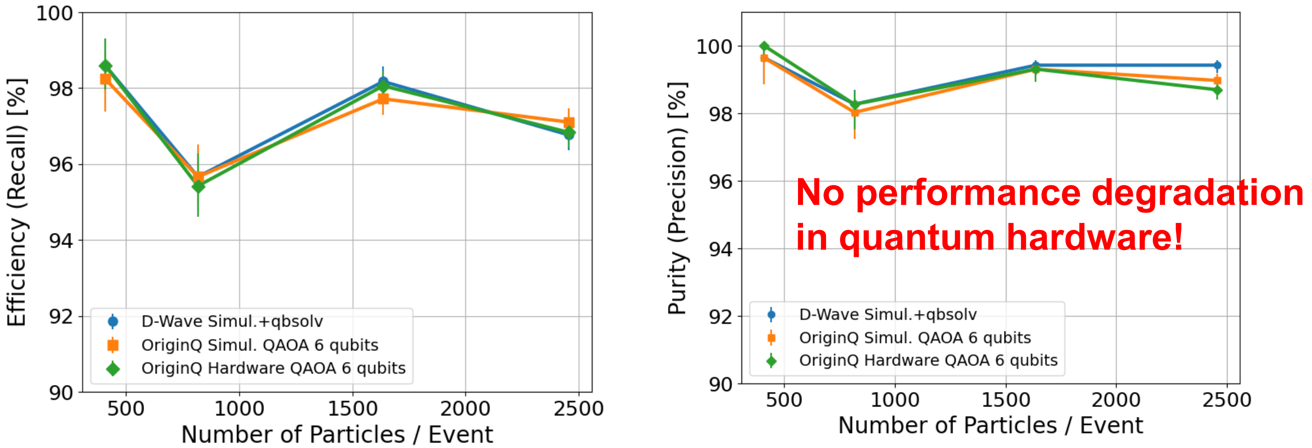
A.Crippa et al., Comput Softw Big Sci 7, 14 (2023)



Using theoretically robust sub-QUBO algorithm (Multiple Solution Instances)



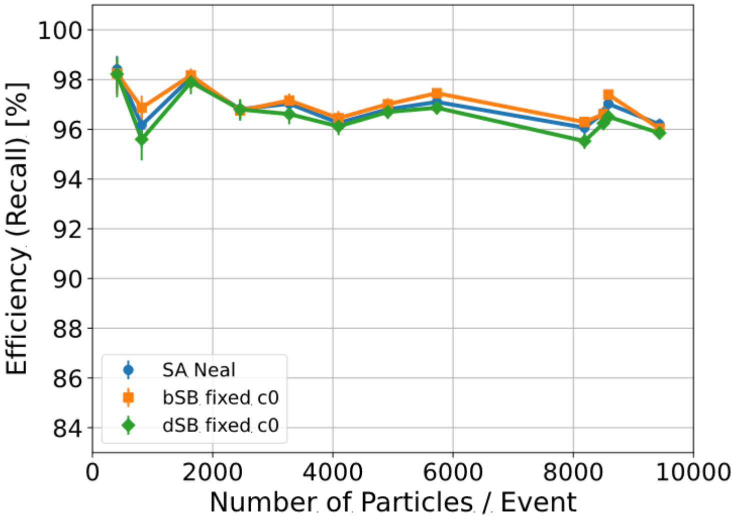
Track Finding with QAOA



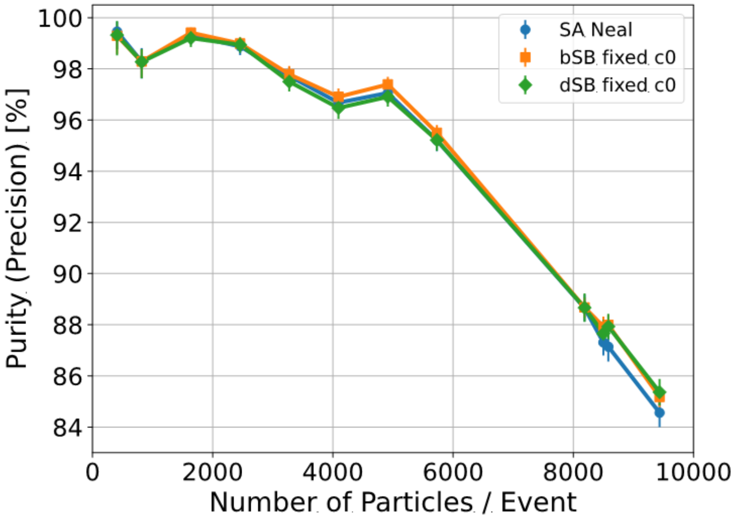
H. Okawa, Q.G. Zeng, X.Z. Tao, M.H. Yung, Springer Comput. Softw. Big Sci. 8, 16 (2024)

Quantum-Inspired Track Finding

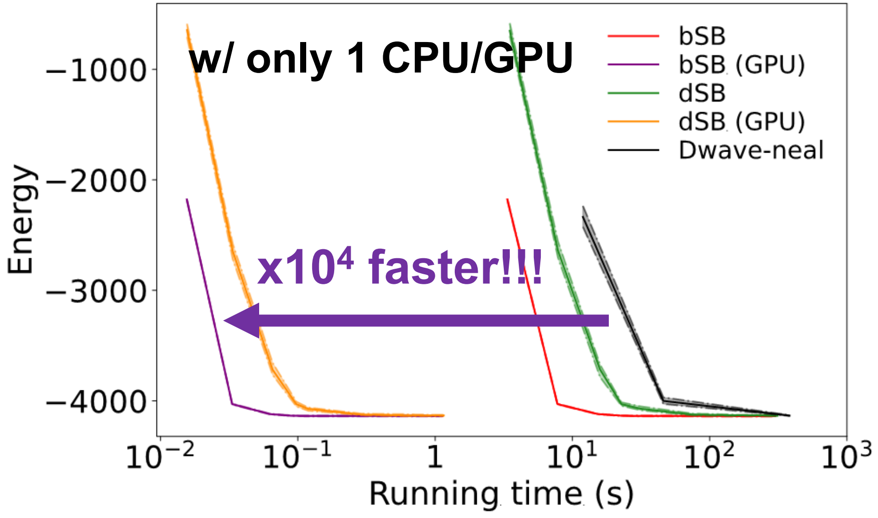
Efficiency



Purity

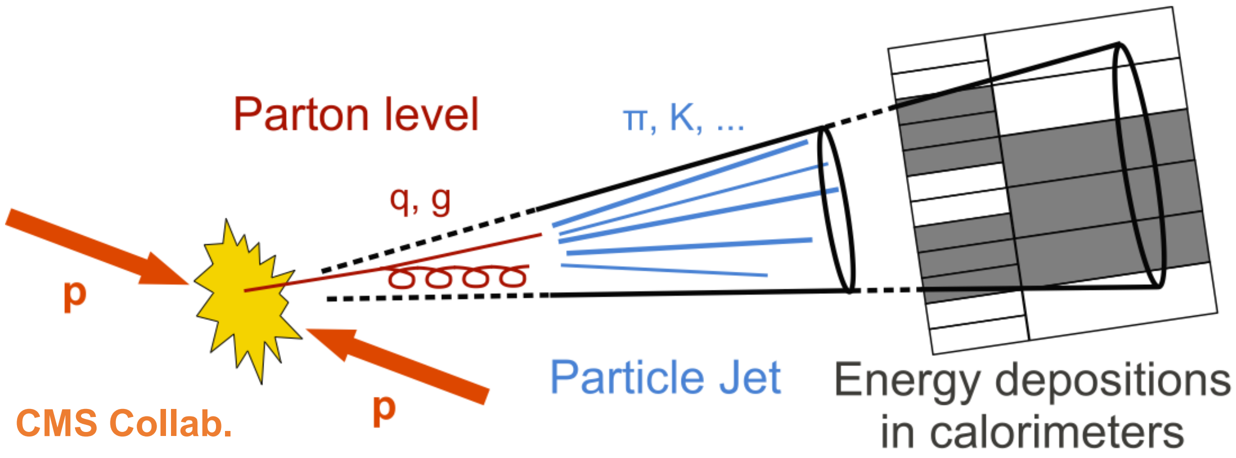


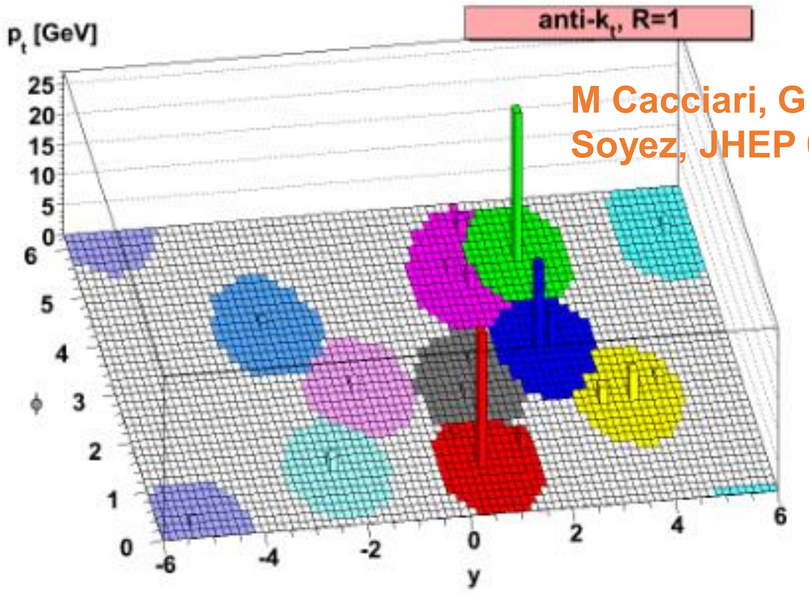
Ising Energy vs computing time



- **Quantum-annealing-inspired algorithm can DIRECTLY handle the HL-LHC dataset.**
- SB provides comparable or slightly better efficiency & purity than D-Wave Neal SA.
- bSB provides **4 orders of magnitude speed-up (23min → 0.14s) from D-Wave Neal** for HL-LHC data **(cf. D-Wave hardware with qbsolv is ~2 orders of magnitude slower than Neal)**.
- **SB can effectively run w/ multiple processing, GPU & FPGA → Perfect match with HEP!!**

Clustering Jets





M Cacciari, GP Salam, G Soyez, JHEP 0804:063 (2008)

- Due to color confinement, gluons & quarks cannot exist on their own; they spray **collimated arrays of particles**.
- **Clustering those particles as jets provides important proxies to understand the original quark/gluon kinematics** but is a non-trivial & CPU-consuming task.
- There have been numerous classical algorithms proposed & used for decades.

Quantum Approaches (Iterative)

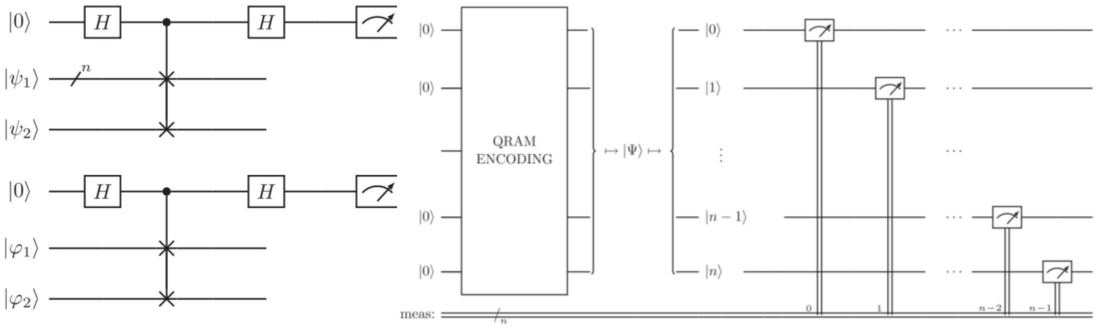
- Jet reconstruction is a clustering problem. Quantum algorithms may bring in acceleration.
- A few algorithms were considered to replace the traditional iterative calculation. Expected to bring in speed-up, but still at a conceptual stage.

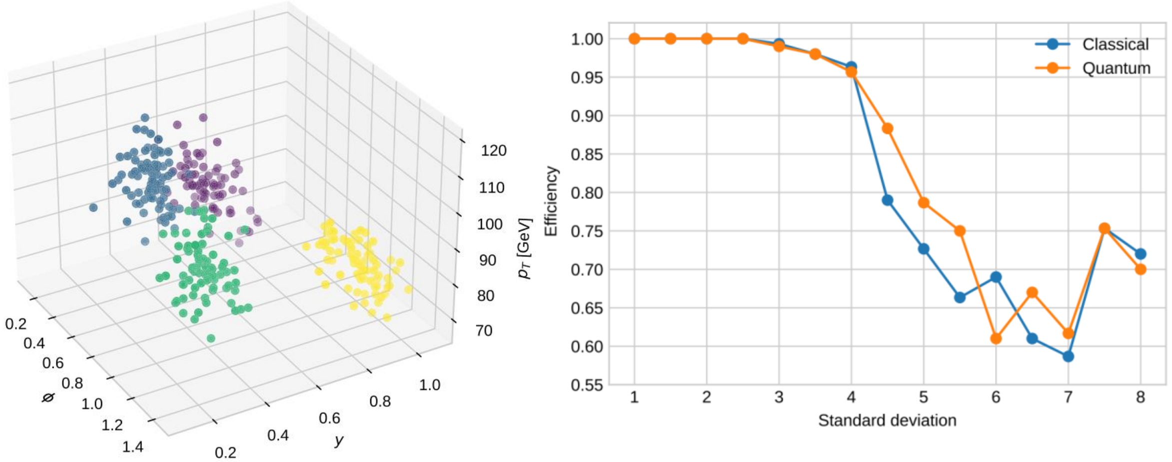
Quantum K-means， Quantum Affinity Propagation (AP)， Quantum k_t

J.J. Martinez de Lejarza, L. Cieri, G. Rodrigo, PRD 106 036021 (2022)

Computes distance in Minkowski space

Assigns each particle to the nearest centroid



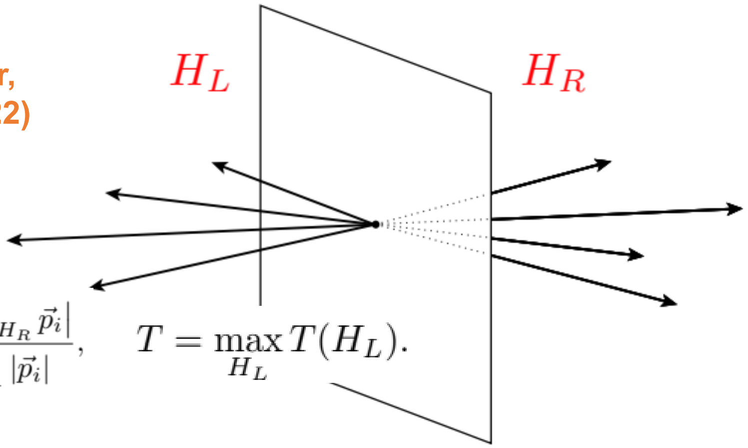


- Similar studies： Grover search **A. Wei, P. Naik, A.W. Harrow, J. Thaler, PRD 101, 094015 (2020),** quantum K-means **D. Pires, P. Bargassa, J. Seixas, Y. Omar, arXiv:2101.05618 (2021).**

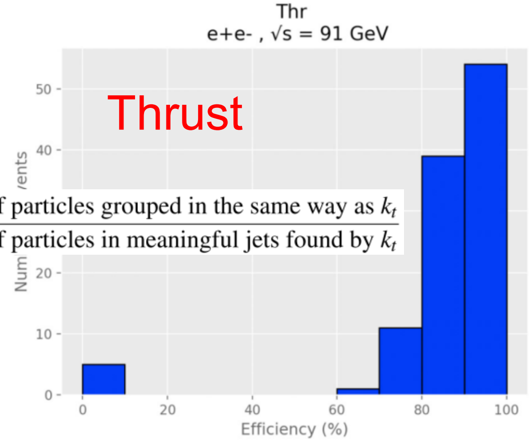
Quantum Approaches (Global)

Quantum Annealing (Thrust or Angle-based)

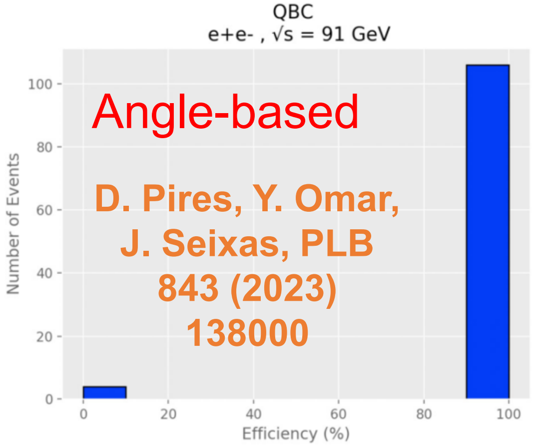
A. Delgado, J. Thaler, PRD 106, 094016 (2022)



$$T(H_L) = \frac{2\left|\sum_{i\in H_L}\vec{p}_i\right|}{\sum_{i=1}^{N}|\vec{p}_i|} = \frac{2\left|\sum_{i\in H_R}\vec{p}_i\right|}{\sum_{i=1}^{N}|\vec{p}_i|}, \quad T = \max_{H_L} T(H_L).$$



$$\varepsilon = \frac{\text{\# of particles grouped in the same way as } k_t}{\text{\# of particles in meaningful jets found by } k_t}$$

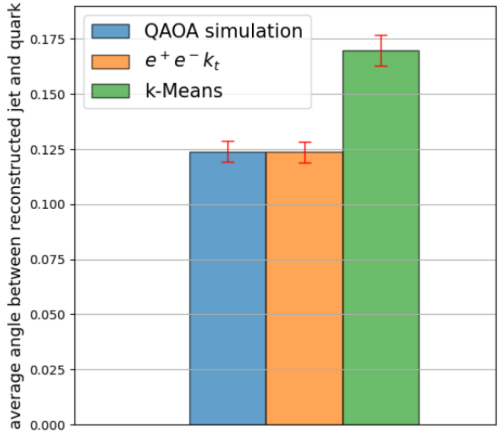


D. Pires, Y. Omar, J. Seixas, PLB 843 (2023) 138000

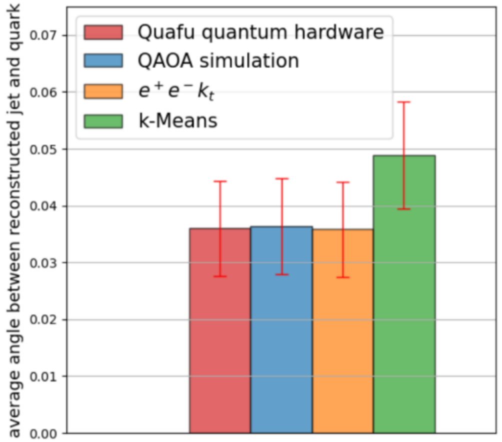
Quantum Gates (e.g. QAOA)

Y. Zhu et al., Sci. Bul. 70 (2025) 460

30-particle data ($e^+e^- \to ZH \to \nu\nu ss$)



6-particle data ($e^+e^- \to ZH \to \nu\nu ss$)



- **Jet reconstruction can also be considered as a QUBO problem.**
- D. Pires et al.: Angle-based method has better performance than the Thrust-based method, but **degrades in multijet (N_{jet}>2) events.**
- Y. Zhu et al.: Used small-size dataset & evaluated average angle w/ QAOA in Quafu (北京量子院夸父).

H Okawa, XZ Tao, QG Zeng, MH Yung, Phys. Lett. B, 864 (2025) 139393

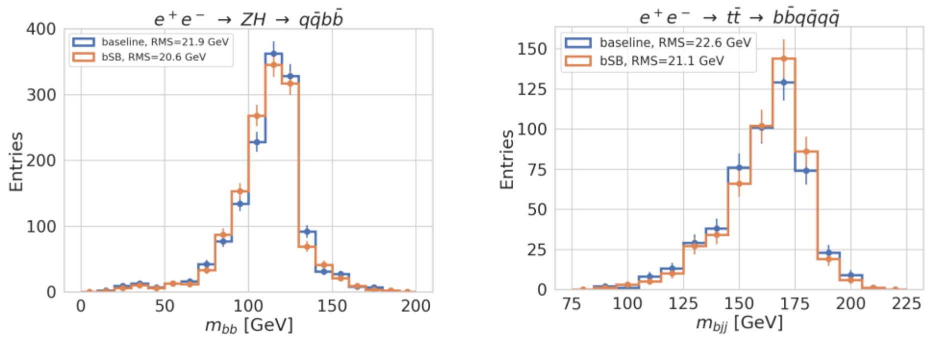
Quantum-inspired multijet clustering

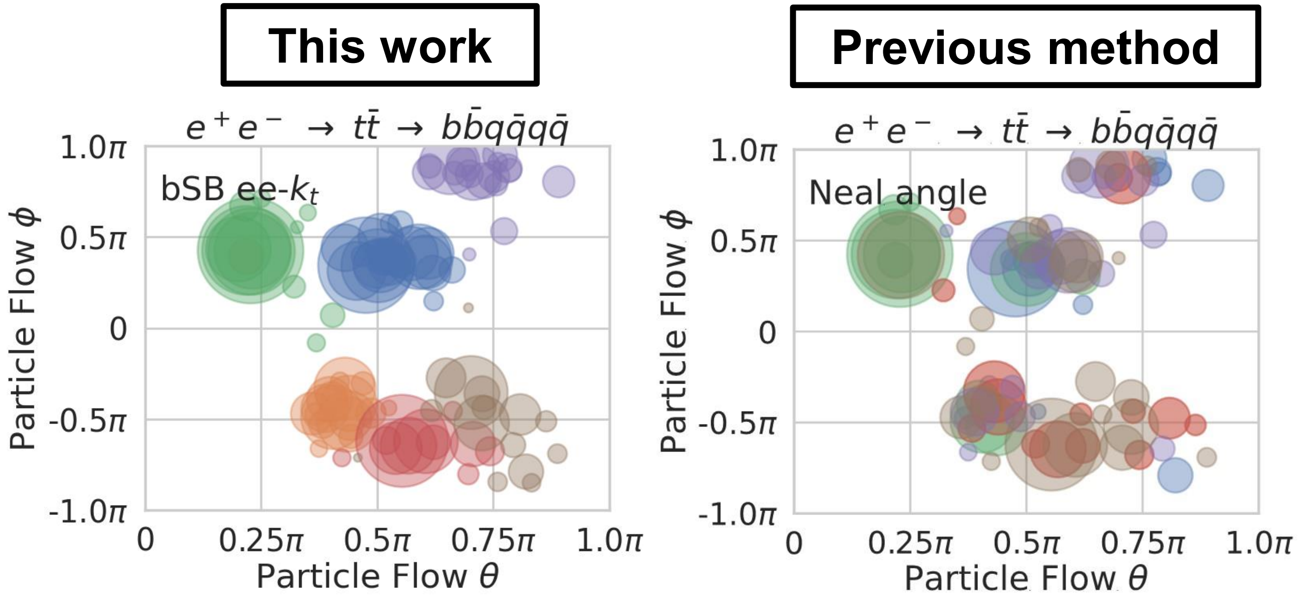
QUBO Formulation

$$O^{\mathrm{multijet}}_{\mathrm{QUBO}}(x_i) = \sum_{n=1}^{n_{\mathrm{jet}}} \sum_{i,j=1}^{N_{\mathrm{input}}} Q_{ij} x_i^{(n)} x_j^{(n)} + \lambda \sum_{i=1}^{N_{\mathrm{input}}} \left(1 - \sum_{n=1}^{n_{\mathrm{jet}}} x_i^{(n)}\right)^2 ,$$

Defines distances b/w particle flow candidates

Avoids double/none-assignment of particle flow candidates

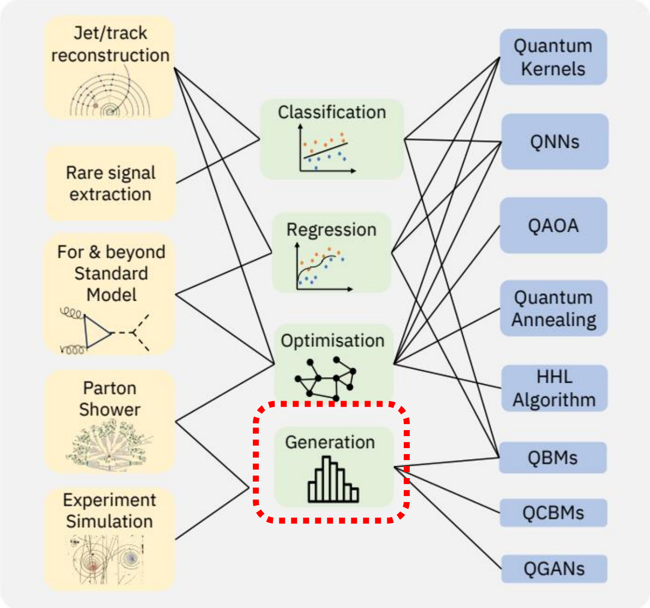


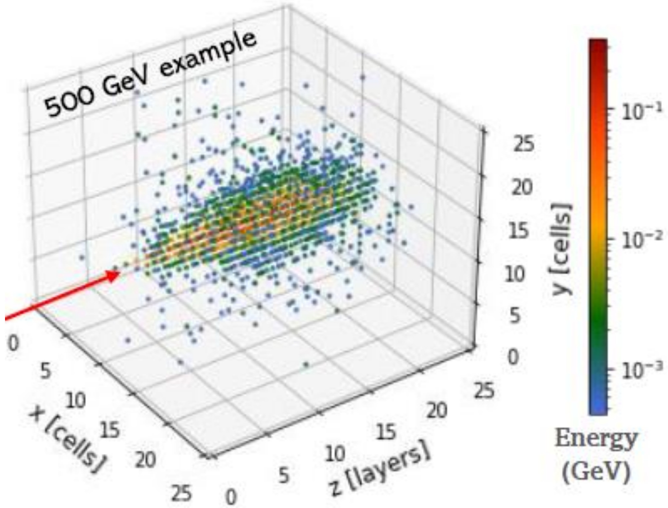


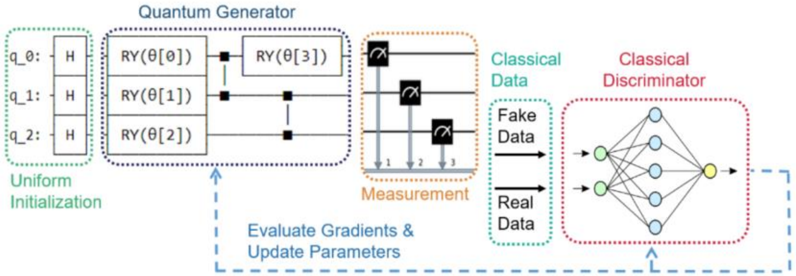
- **QUBO matrices for jet reconstruction are fully connected** unlike the track reconstruction, exceedingly difficult to solve.
- **1st successful global multijet clustering w/ bSB quantum-inspired algorithm.**
- **Invariant mass resolution improves by 6~7% for Higgs bosons/top-quarks.**

Generative Models

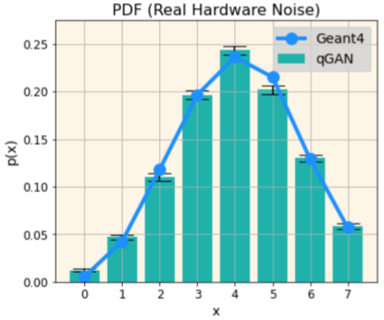
Quantum-classical hybrid GAN
(difficult to proceed beyond a simple generation from PDF)



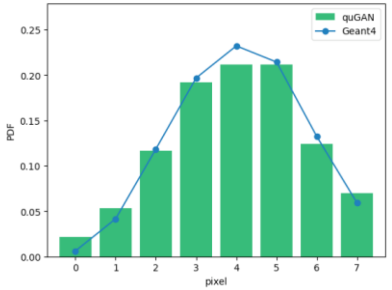




IBM (F. Rehm, S. Vallecorsa, K. Borras, D. Krücker)

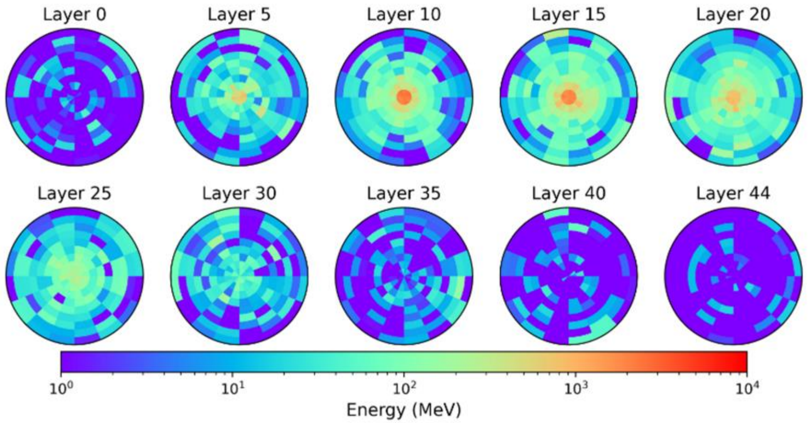


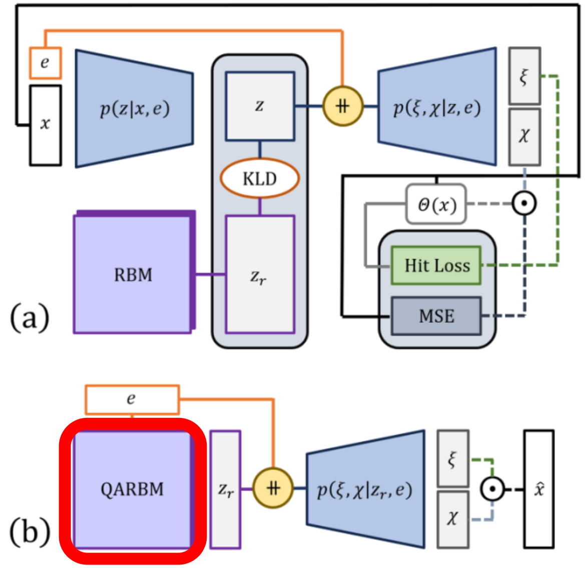
QuantumCTek (国盾) hardware (XZ Huang, WD Li)



- **Simulating particle shower development in calorimeter is very CPU-consuming.**
  Classical generative AI has been intensively introduced (GAN, VAE, diffusion etc.)
- Quantum AI may bring in training speed-up & performance improvement.
- Two strategies: (1) quantum-classical hybrid / quantum-assisted, (2) fully quantum.

Hybrid: Quantum-Annealing-Assisted VAE

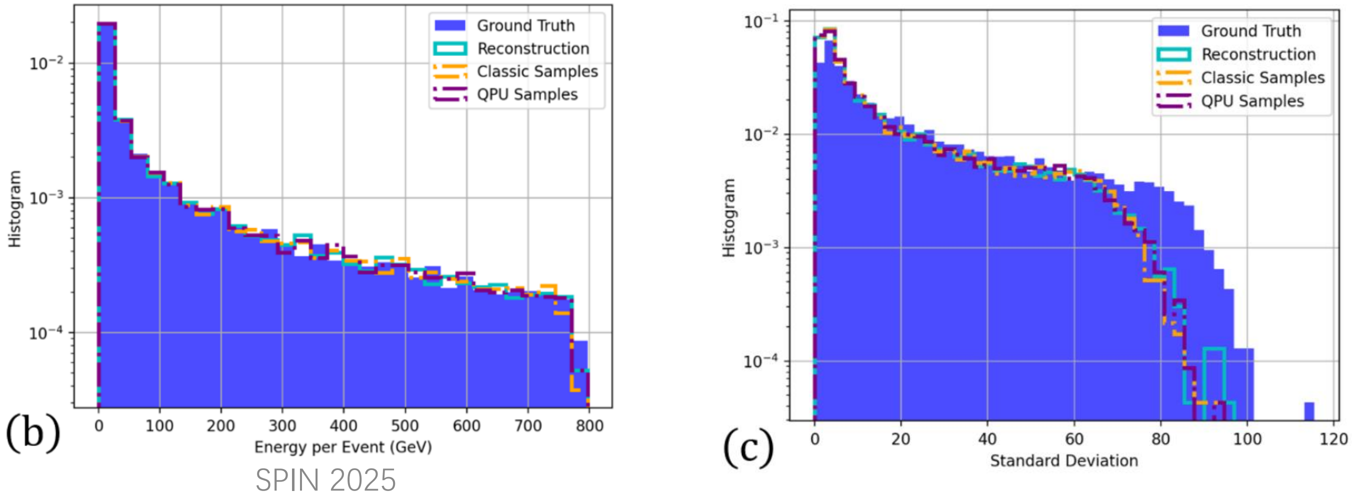




Quantum Annealing

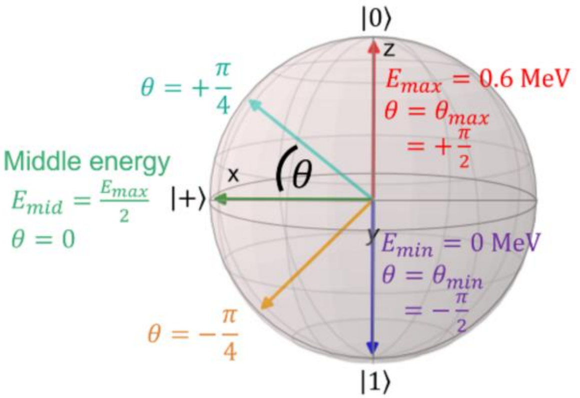
Quantum-assisted workflow:

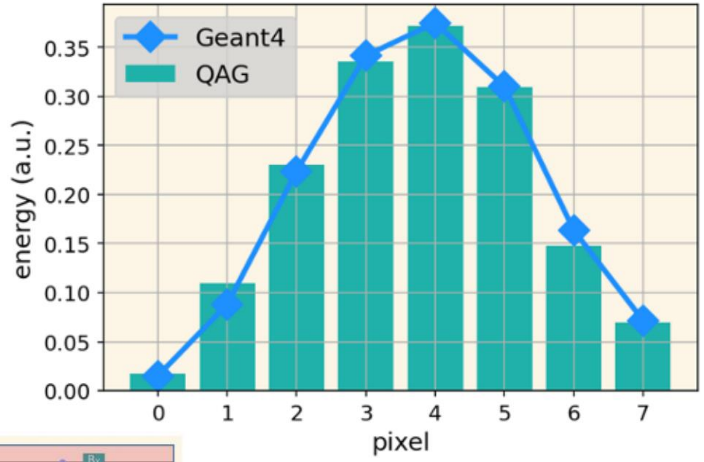
1. **[Classical]** Conditioned Restricted Boltzmann Machine (RBM) is trained to learn the representations compressed by the encoder.
2. **[Quantum] Classically trained RBM is loaded onto D-Wave Advantage quantum annealer.**
3. **[Classical]** Decoder generates events from quantum-annealing RBM sampling.



Full Quantum: QAG (Quantum Angle Generator)

F Rehm et al., Quantum Sci. Technol. 9 015009 (2023)

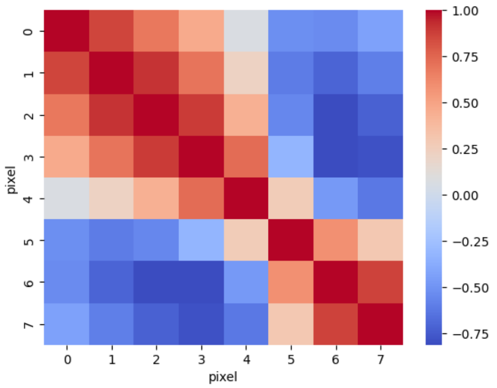




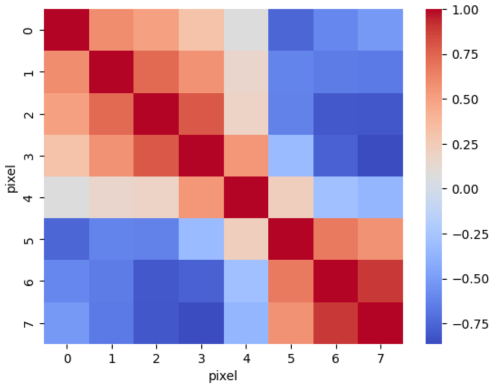
Inter-pixel correlations

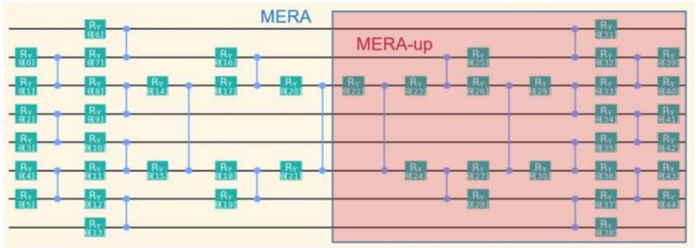
XZ Huang, WD Li

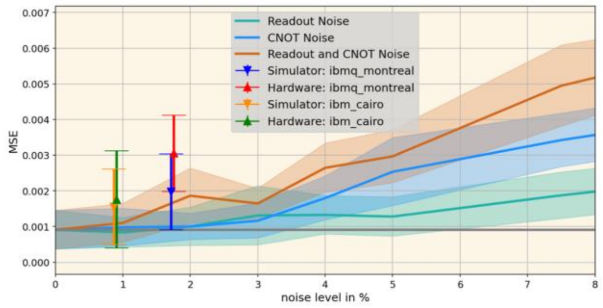
Geant4



QAG



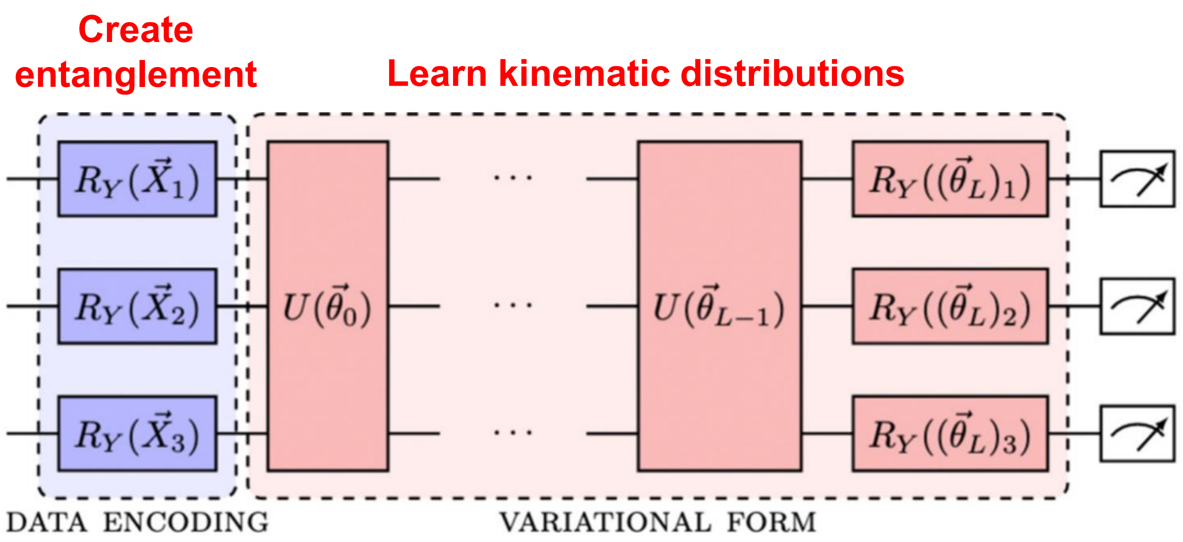


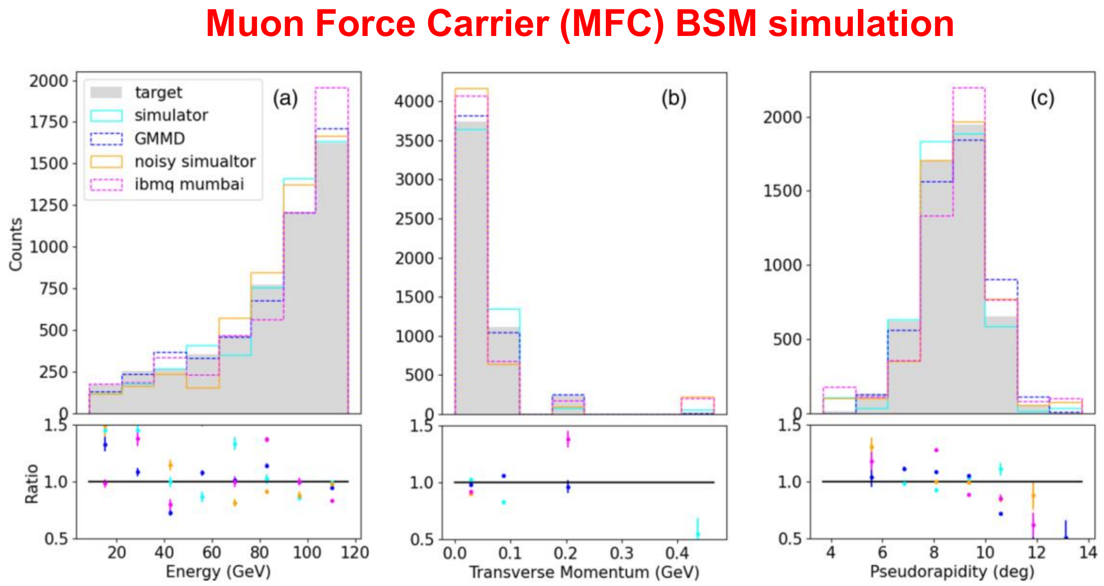


- Event-by-event generation is not straightforward with hybrid methods & performance is degraded. Dual-PQC GAN: S.Y. Chang et al., J. Phys. Conf. Ser. 2438 (2023) 1, 012062
- **Angle encoding with <u>full quantum implementation</u> overcomes the challenge.** Using two loss functions for event-wise generation & reproducing pixel correlation.
- The model can also learn noise & recover performance.
- XZ Huang & WD Li succeeded in improving the algorithm.

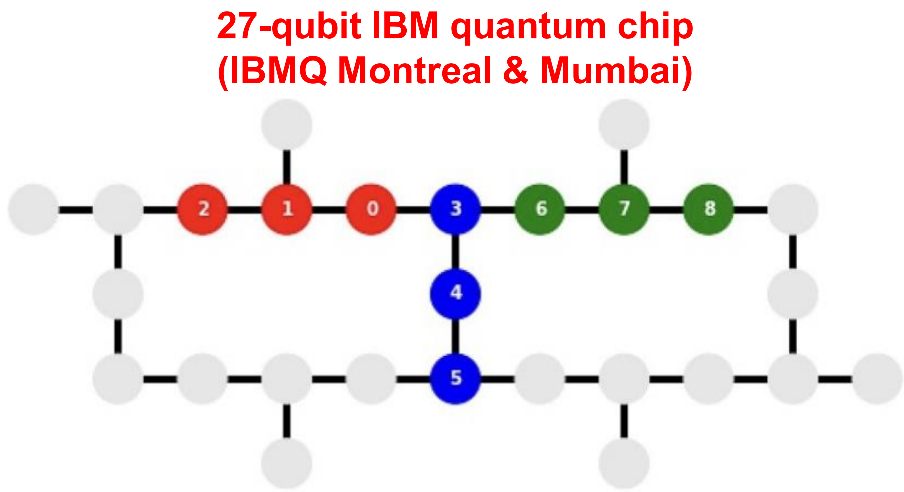
O. Kiss, M. Grossi, E. Kajomovitz, S. Vallecorsa, PRA 106, 022612 (2022)

Full Quantum: QCBM (Quantum Conditional Born Machine)

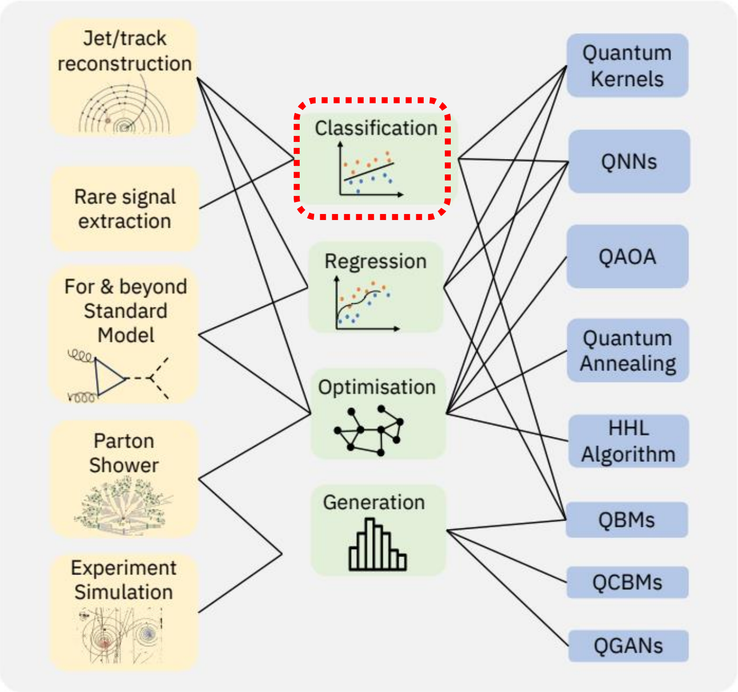




- A fully quantum algorithm that can generate event-by-event with correlations. Learnability of hardware noise.
- Does not yet exceed classical algorithms, but **is more expressive**, considering its simple circuit design with very few parameters.

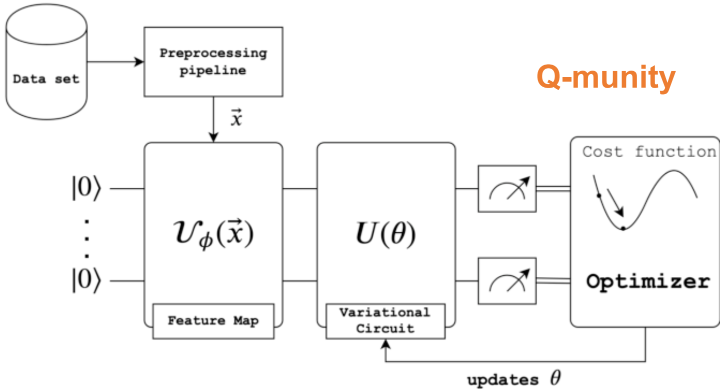


Classification



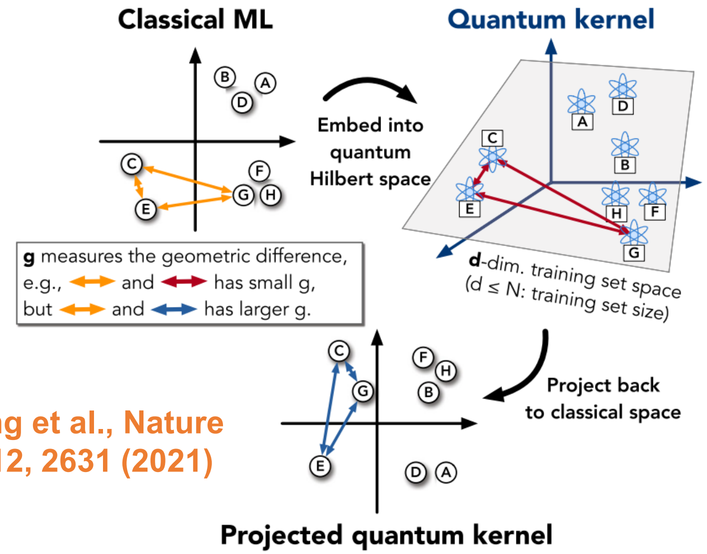
Variational quantum algorithms (hybrid)

- Use variational quantum circuit, but update parameters with a classical optimizer.



Quantum kernel methods

- Embed feature map into quantum kernel → using rich Hilbert space



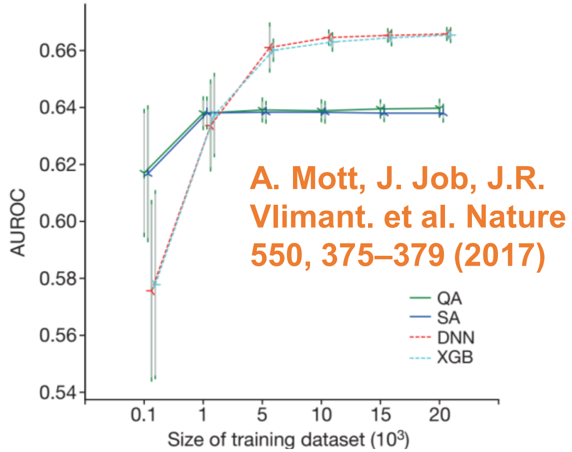
HY Huang et al., Nature Comm. 12, 2631 (2021)

Quantum annealing

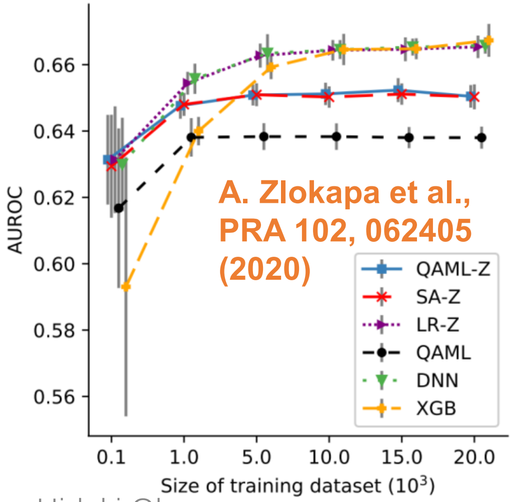
- Map machine learning into optimization problems (QBoost, QAML, QAML-Z etc.)

Classification

Quantum Annealing

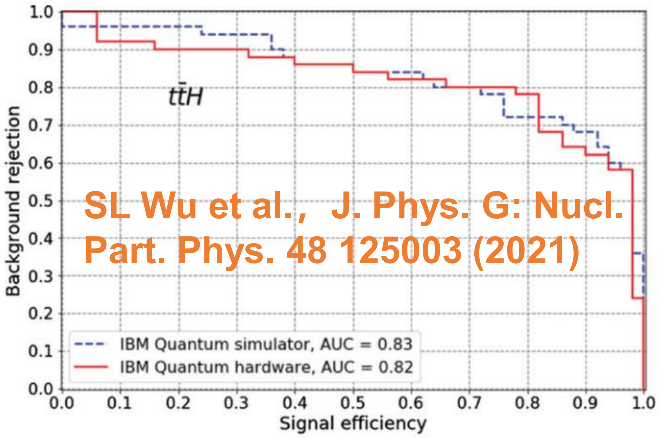


A. Mott, J. Job, J.R. Vlimant. et al. Nature 550, 375–379 (2017)

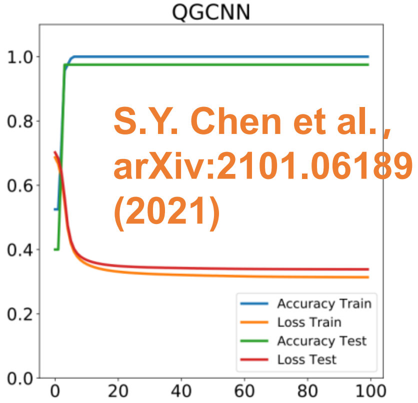


A. Zlokapa et al., PRA 102, 062405 (2020)

Quantum Gates (Variational quantum algorithms)

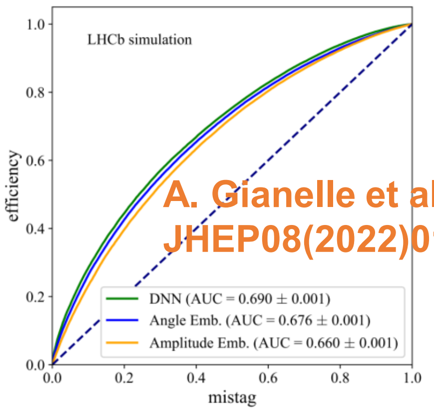


SL Wu et al., J. Phys. G: Nucl. Part. Phys. 48 125003 (2021)



S.Y. Chen et al., arXiv:2101.06189 (2021)

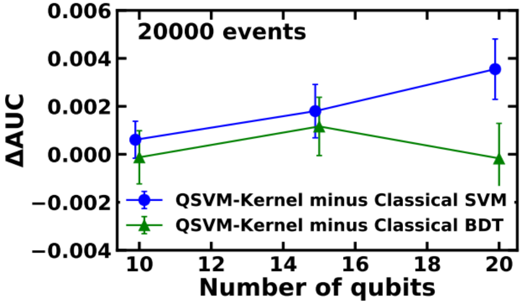
LHCb b-tag (VQC)



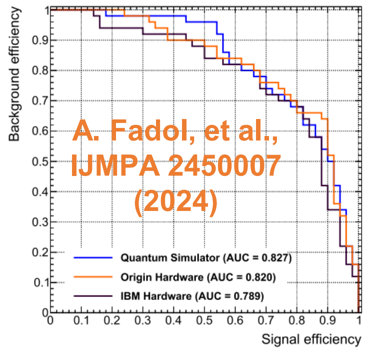
A. Gianelle et al., JHEP08(2022)014

Quantum Gates (Quantum Kernel methods)

SL Wu et al., Phys. Rev. Research 3, 033221 (2021)



CEPC event classification

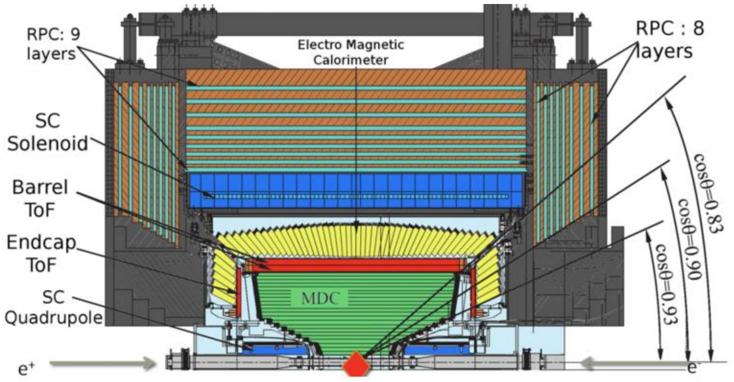


A. Fadol, et al., IJMPA 2450007 (2024)

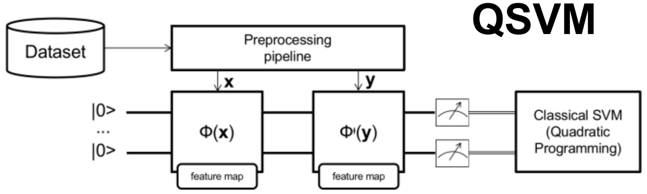
- A. Mott et al.: First QML applications in HEP using quantum annealing.
- Various QML algorithms are actively tested.

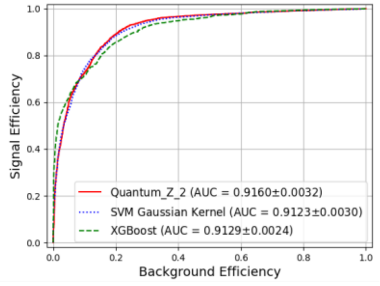
Classification (Particle ID)

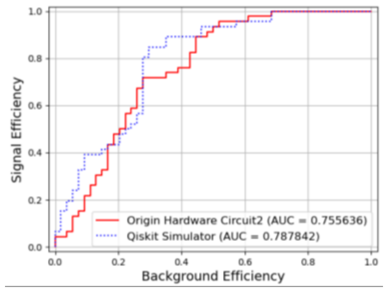
Z.P. Yao et al., EPJ Plus (2024) 139:356,
T. Li et al., J. Phys. Conf. Ser. 2438 (2023) 1, 012071



QSVM

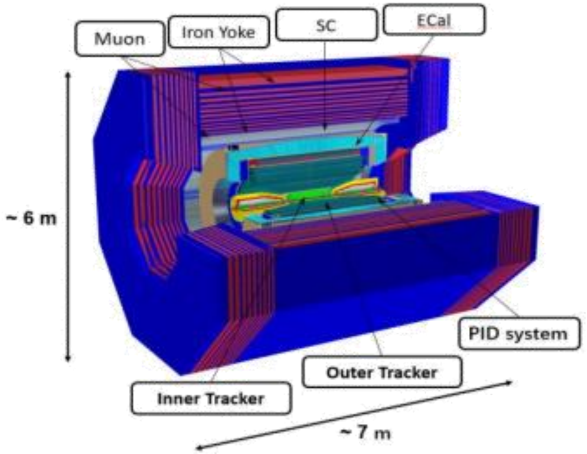


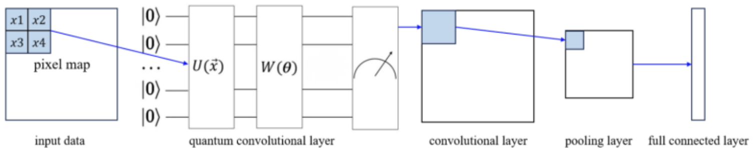




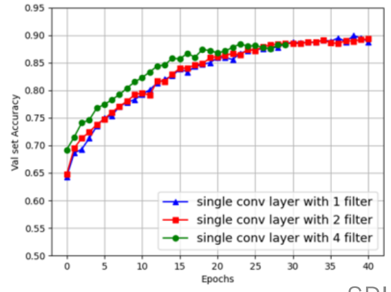
- QSVM & VQC for μ/π ID in BES3.
- Comparable QSVM performance in Origin Quantum (本源) hardware & simulator.

Z.P. Yao, T. Li, X.T. Huang, EPJ Web Conf. 295 (2024) 09030

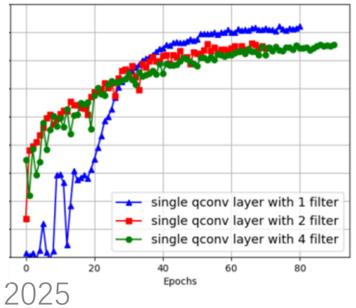




CNN



Quantum CNN

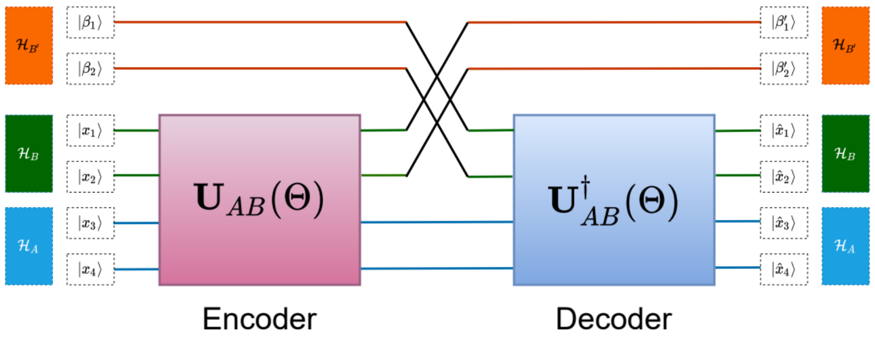


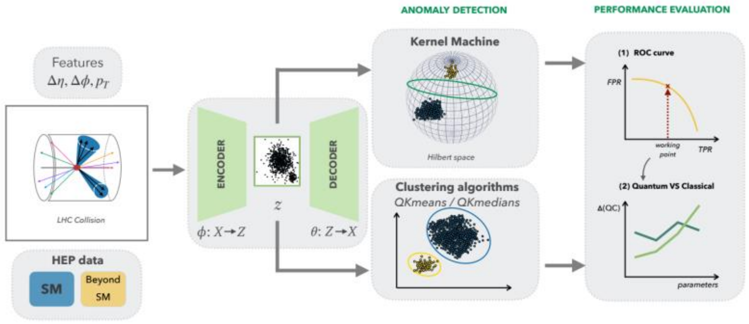
- π/K ID with QCNN in Super Tau Charm Factory (STCF) simulation.
- QCNN provides comparable performance to CNN in feature extraction and learning ability.

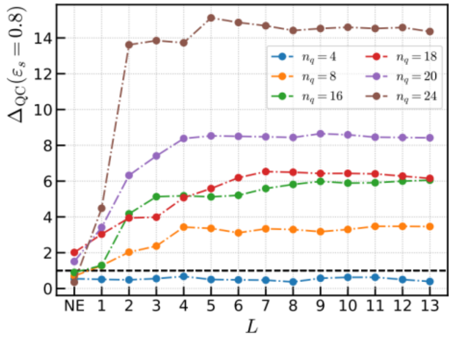
See also: S. Alvi, C.W. Bauer, B. Nachman, JHEP02(2023)220

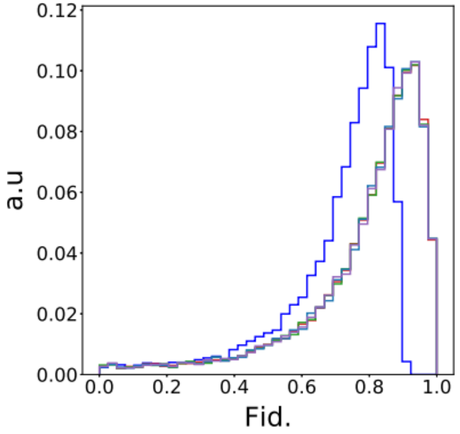
Anomaly Detection

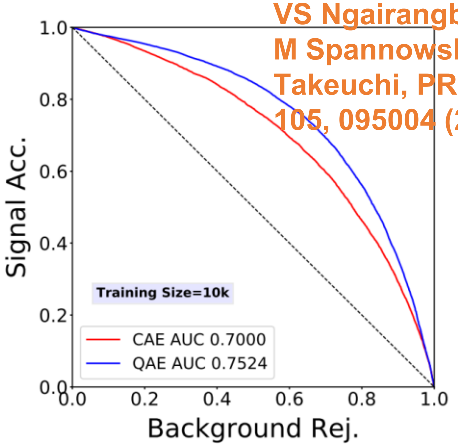
V. Belis et al., Comm. Phys. 7, 334 (2024)





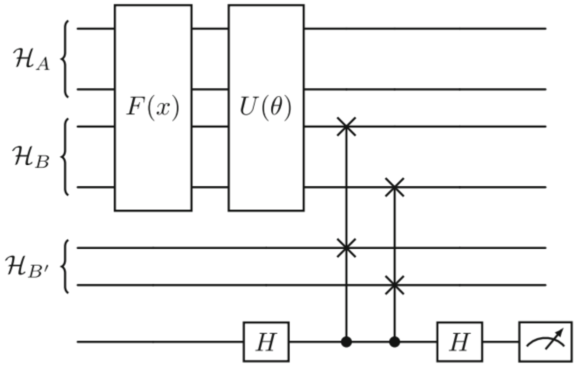


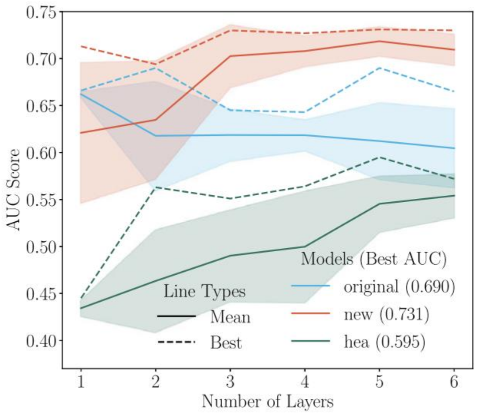




VS Ngairangbam, M Spannowsky, M Takeuchi, PRD 105, 095004 (2022)

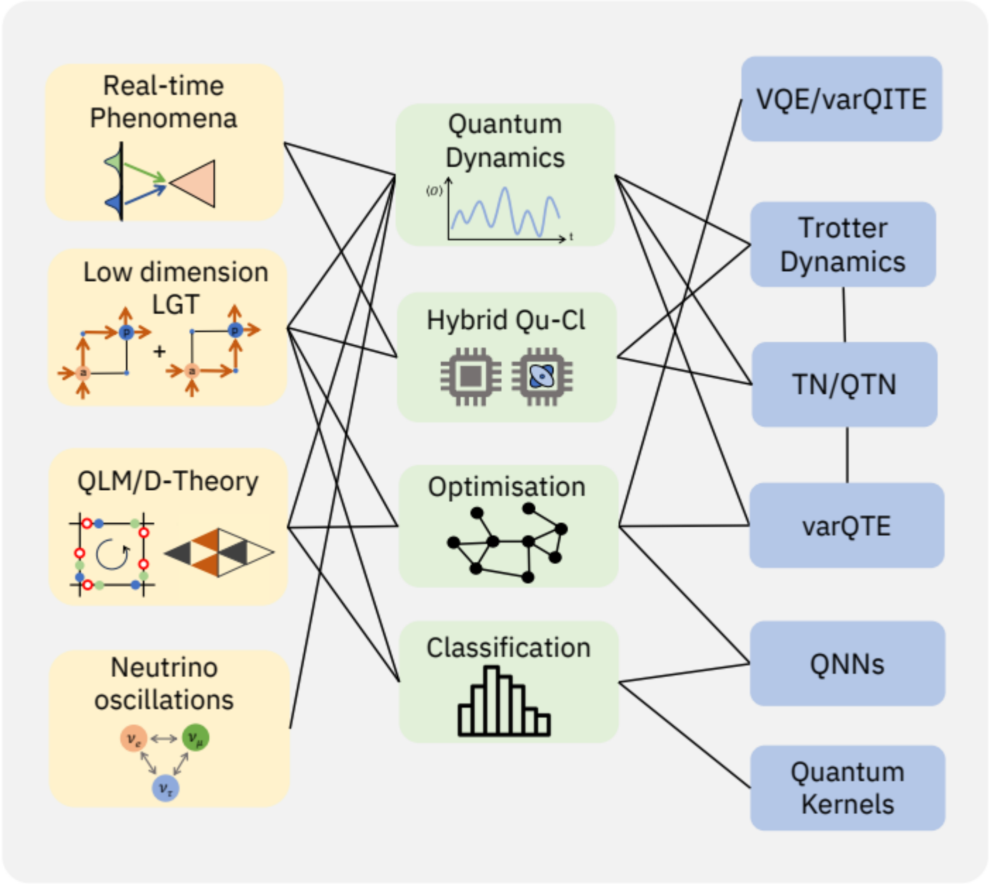
C. Duffy, et al. Quantum Mach. Intell. (2025) 7:41





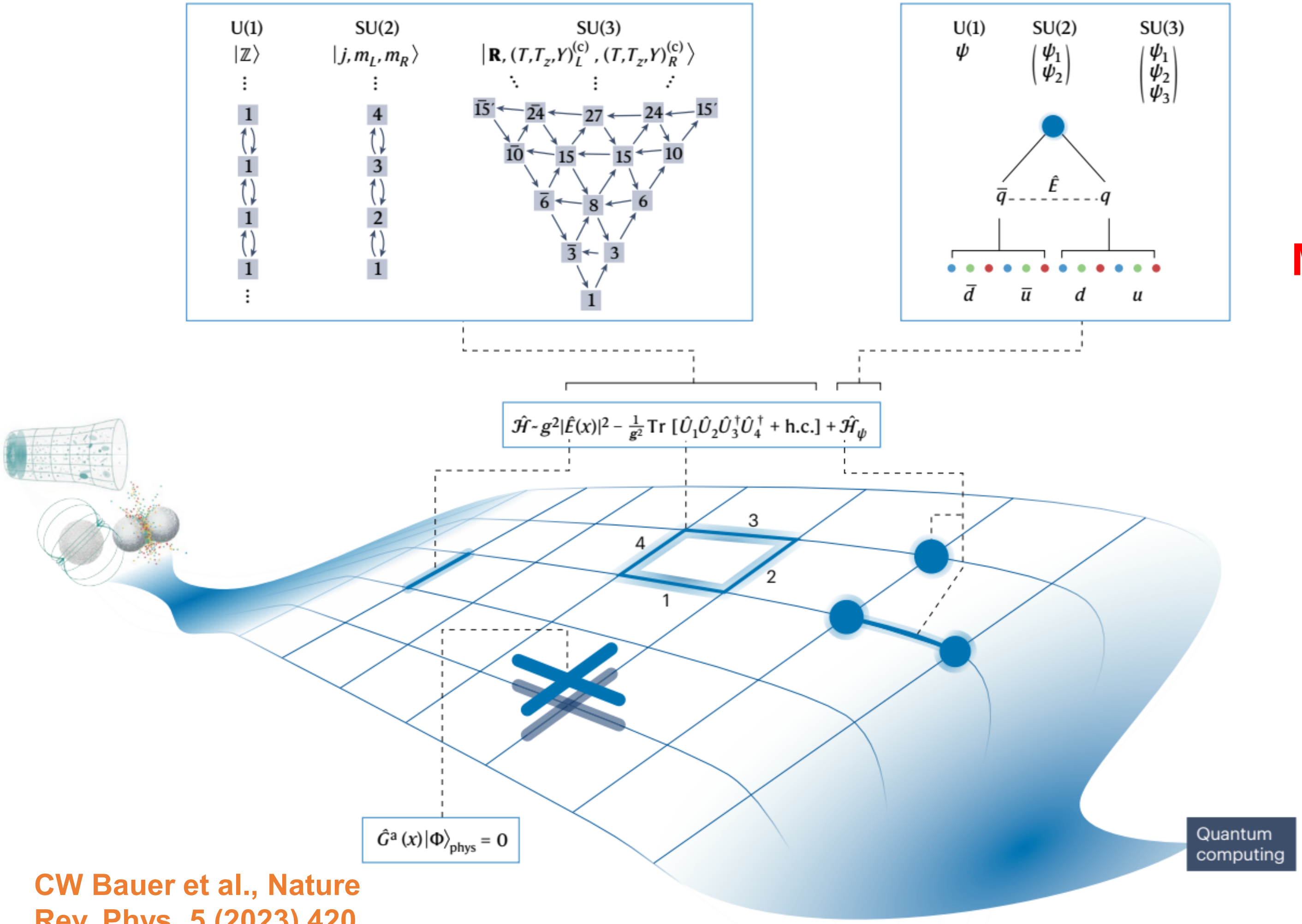
- V.S. Ngairangbam et al.: Quantum algorithm maintains performance with small datasets.
- V. Belis et al.: Performance enhances with more features & entanglement.
- C. Duffy et al.: Proposed scalable quantum circuit ansatz & demonstrated impact of ansatz design.

Theoretical Applications



See also parallel talks by Tianyin Li, Guofeng Zhang & Dairui Zou

Mapping Lattice Field Theory to QC



CW Bauer et al., Nature Rev. Phys. 5 (2023) 420

What we calculate

CW Bauer

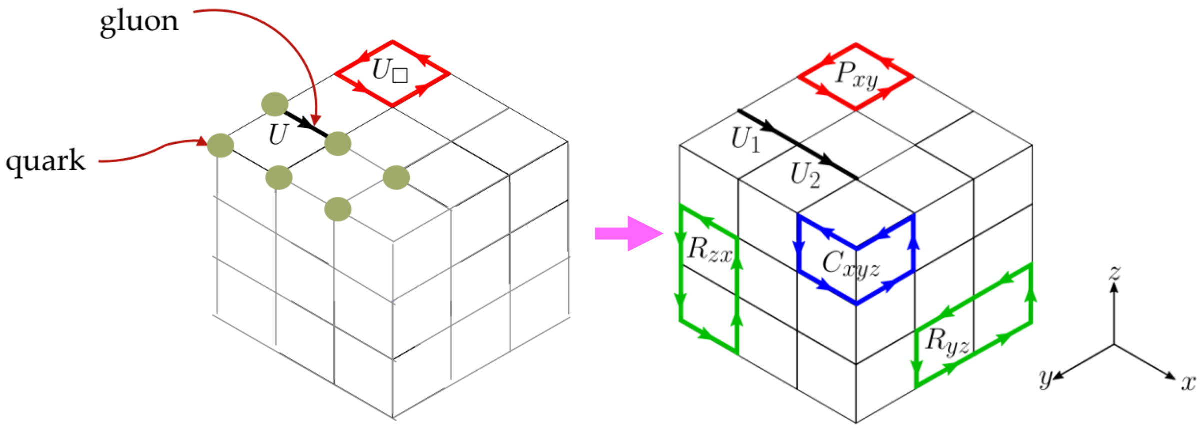
$$\left| \langle X(T) \,|\, U(T,-T) \,|\, pp(-T) \rangle \right|^2$$

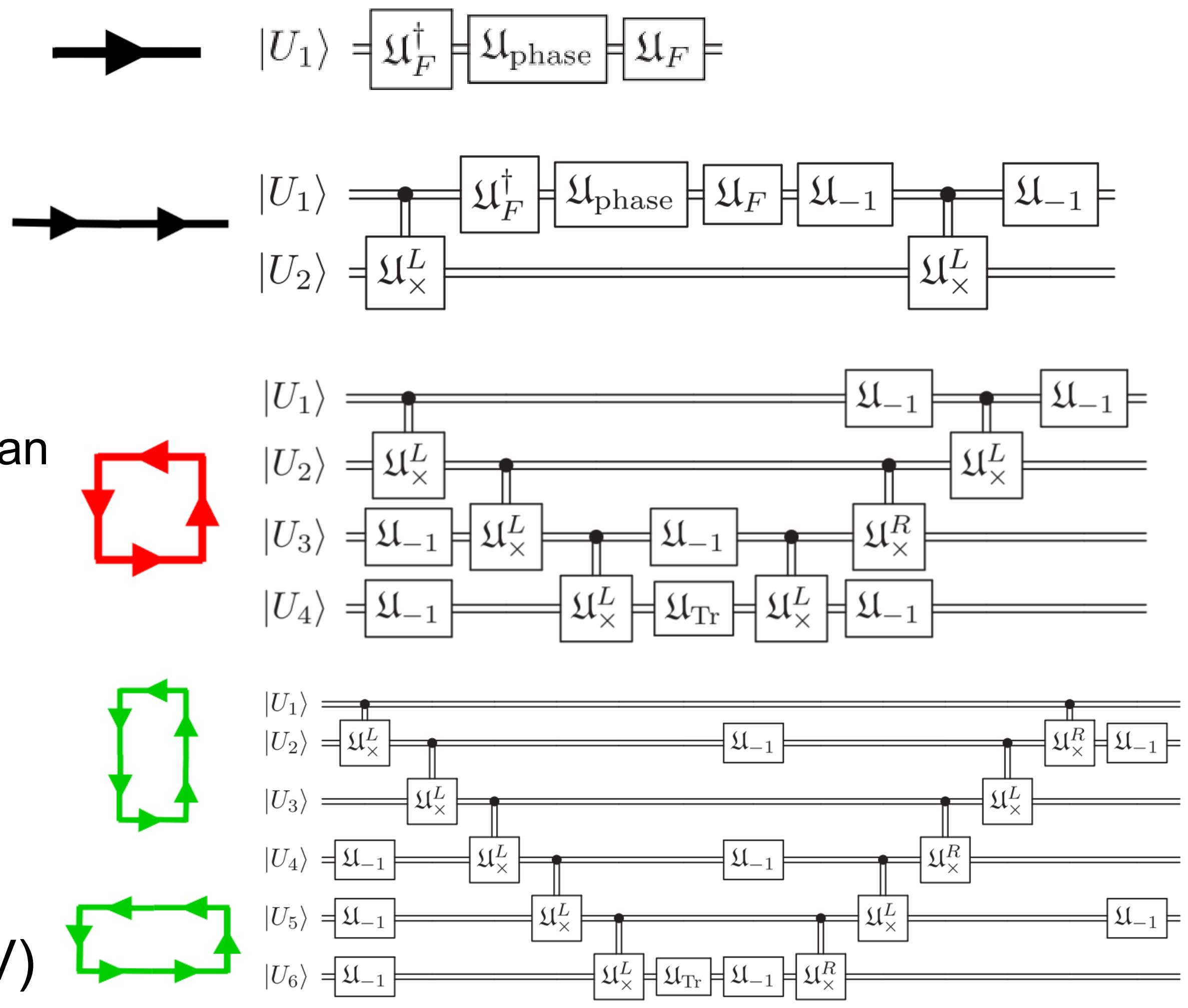
Measurement **Time evolution** **Initial state vector**

- Lattice field theory allows us to compute non-perturbative phenomena by discretizing space-time.
- **# of qubits required depends on the maximum & minimum energy scales** of the problem under consideration.

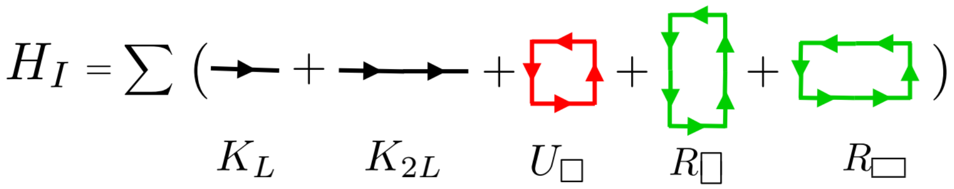
M. Carena, H. Lamm, Y.Y. Li, W. Liu, PRL. 129, 051601 (2022)

Hamiltonian Formulation





KS Hamiltonian PRD 11, 395 (1975) → Improved Hamiltonian

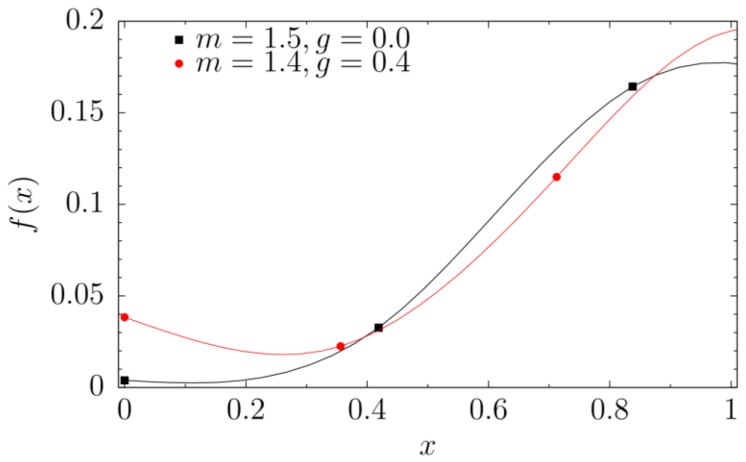


- This new Hamiltonian more efficiently uses quantum computing resources, and bring smaller discretization errors：
n_{qubits}~$1000n_{g+q}$→$125n_{g+q}$ (E~100-1000MeV)

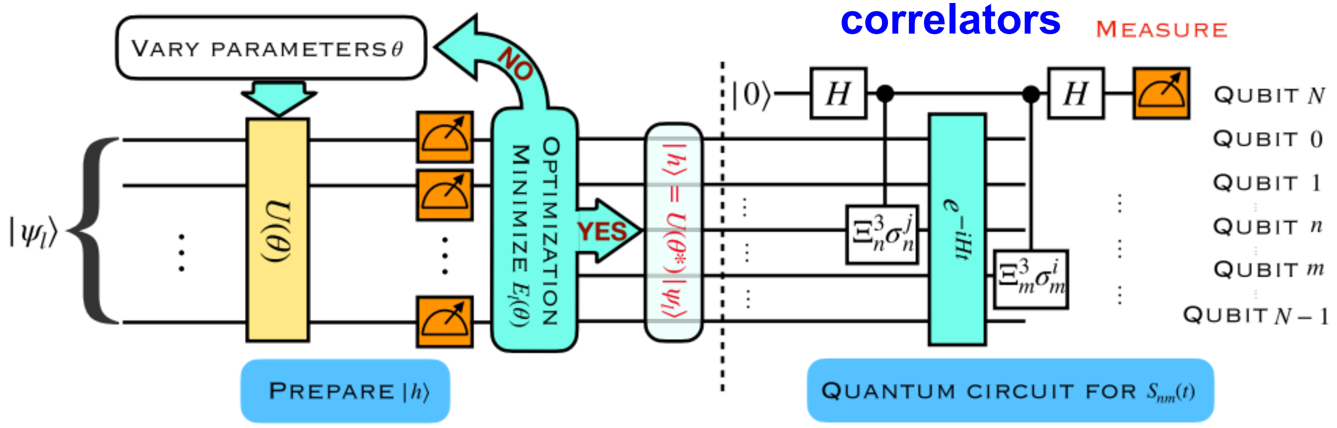
Initial State: Parton Distribution Function

- **H. Lamm et al.**: Predicted PDF & hadronic tensor w/ (1+1)D Thirring Model. PDF best obtained by fitting hadronic tensor.
- **T. Li et al.**: Predicted quark PDF in π^0 w/ (1+1)D Nambu-Jona-Lasinio model. Consistent results b/w quantum simulation and classical method (exact diagonalization [ED]).
- Related studies: global fit w/ QC (not quantum simulation)
  A. Salinas, J. Cruz-Martinez, A.A. Alhajri, S. Carrazza, PRD 103, 034027 (2021)

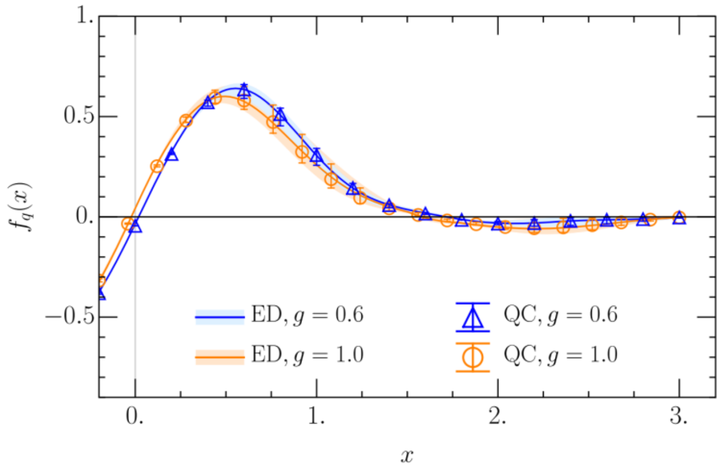
H. Lamm, S. Lawrence, Y. Yamauchi (NuQS Collaboration)
PR Research 2, 013272 (2020)



Hadronic state preparation **Real-time evolution of correlators**

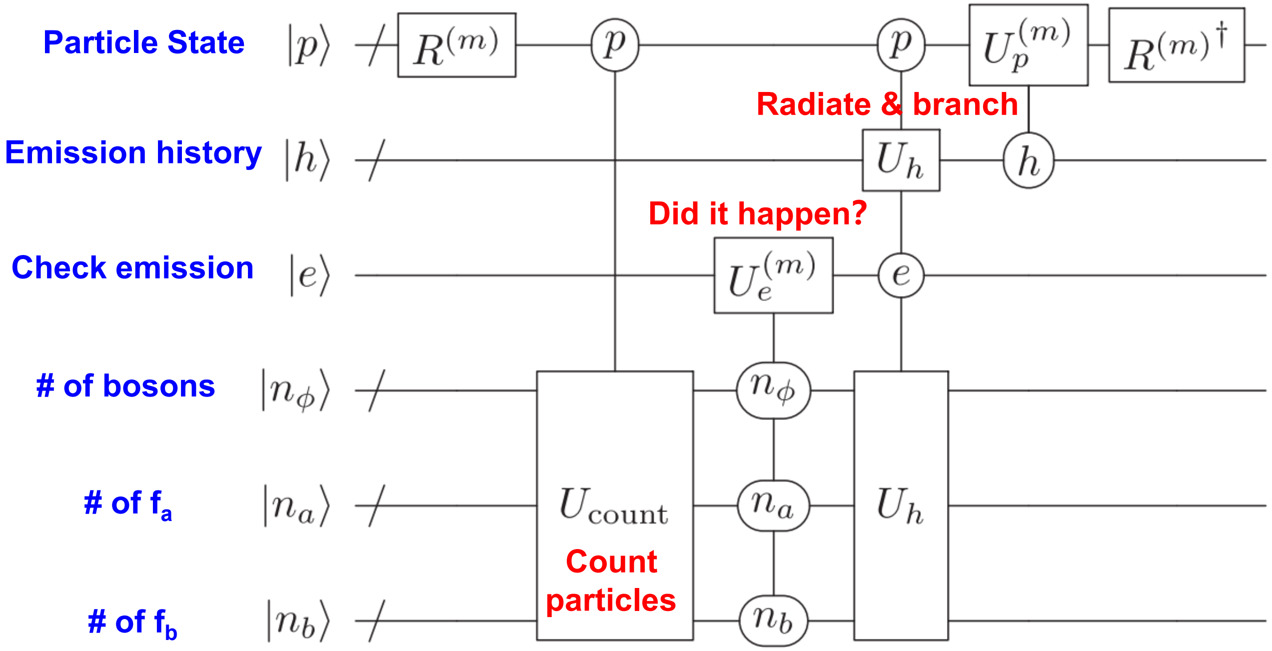


T. Li et al. (QuNu Collab.), PRD105 L111502 (2022)



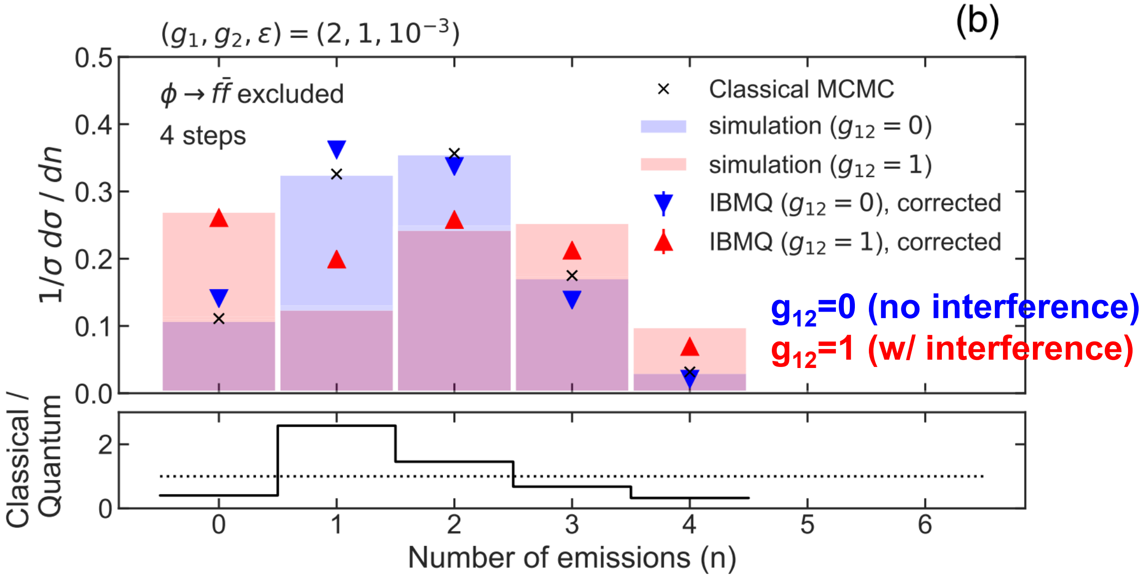
B. Nachman, D. Provasoli, W.A. de Jong, C.W. Bauer, PRL 126, 062001 (2021)

Intermediate State: Parton Shower



Simplified Lagrangian (2 fermions,1 gauge boson, 2D radiation)

$$\mathcal{L} = \bar{f}_1(i\partial\!\!\!/ + m_1)f_1 + \bar{f}_2(i\partial\!\!\!/ + m_2)f_2 + (\partial_\mu\phi)^2 + g_1\bar{f}_1 f_1\phi + g_2\bar{f}_2 f_2\phi + g_{12}[\bar{f}_1 f_2 + \bar{f}_2 f_1]\phi.$$

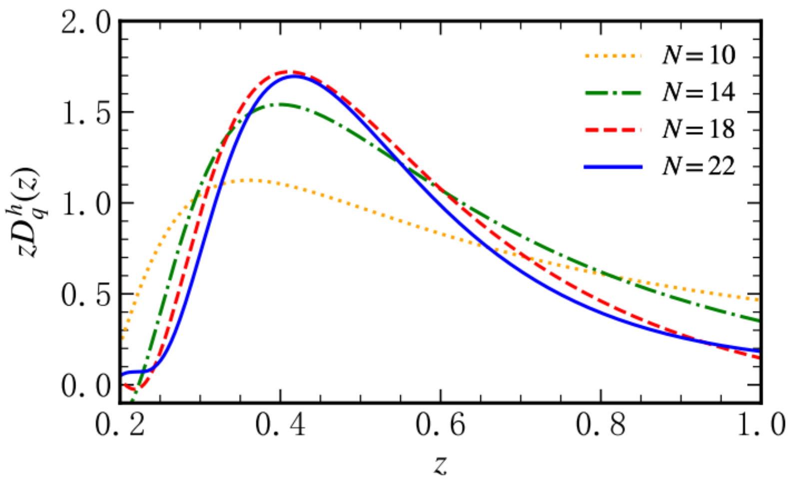


- Simulated parton shower from a simplified Lagrangian.
- **QC can calculate particle interference in a polynomial time.** Expects quantum advantage for # of emission>O(10).
- Related studies using quantum walk: G. Gustafson, S. Prestel, M. Spannowsky, S. Williams, JHEP11(2022)035; K. Bepari, S. Malik, M. Spannowsky, S. Williams, PRD 103 (2021) 076020 & PRD 106 (2022) 056002

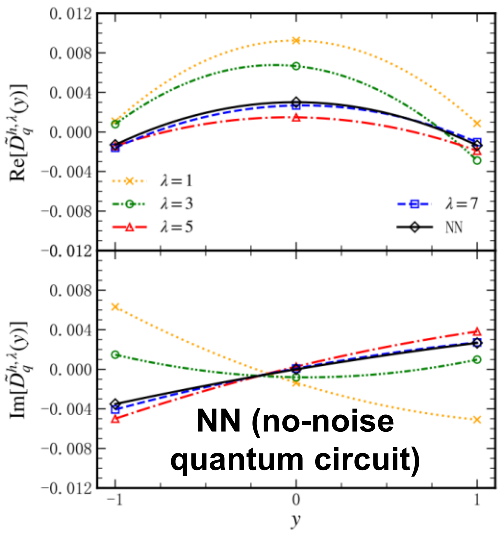
Final State: Fragmentation, Hadronization

Quark Fragmentation

T. Li et al., (QuNu), arXiv:2406.05683



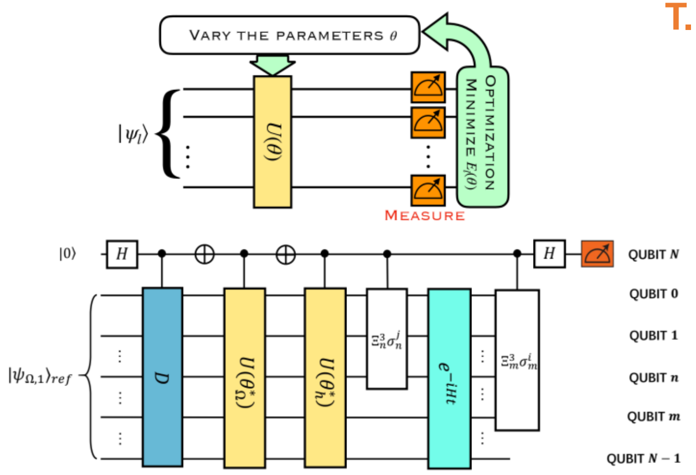
Impact of error mitigation



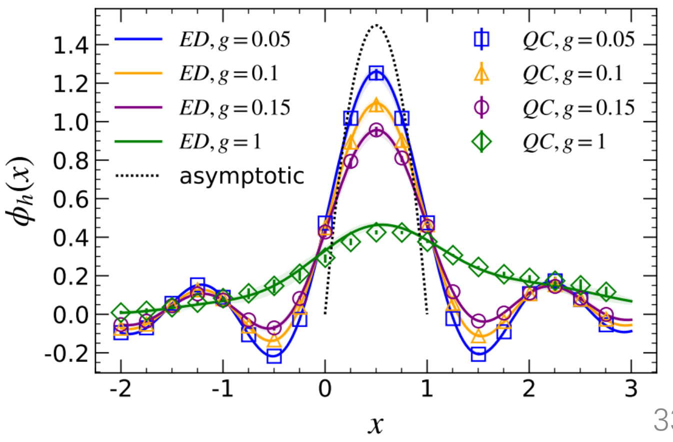
- Directly calculated fragmentation function (FF) with a quantum algorithm based on (1+1)D Nambu-Jona-Lasinio model.
- Qualitative agreement with classical extraction of FF.
- Also demonstrated that error mitigation is crucial for hardware.

Hadronization

- Light-cone distribution amplitudes (LCDAs) describe non-perturbative aspects of bound states.
- Developed a quantum algorithm to simulate LCDA. Very good agreement with classical prediction.

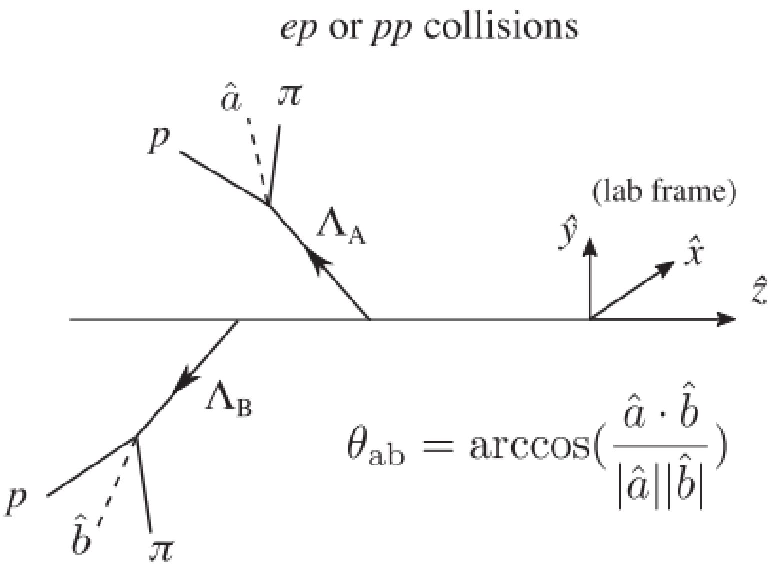


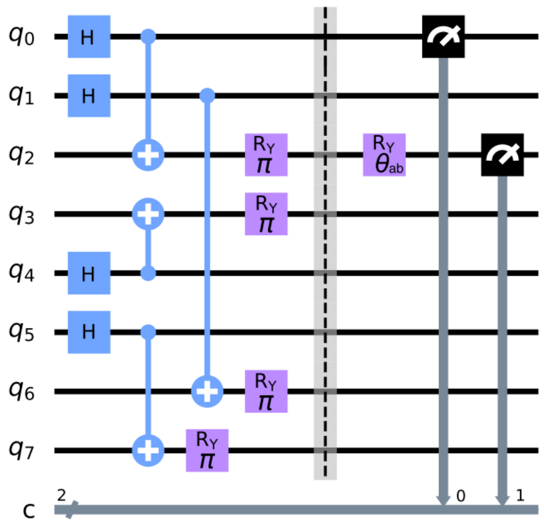
T. Li et al (QuNu), SCPMA 66 (2023) 8, 281011

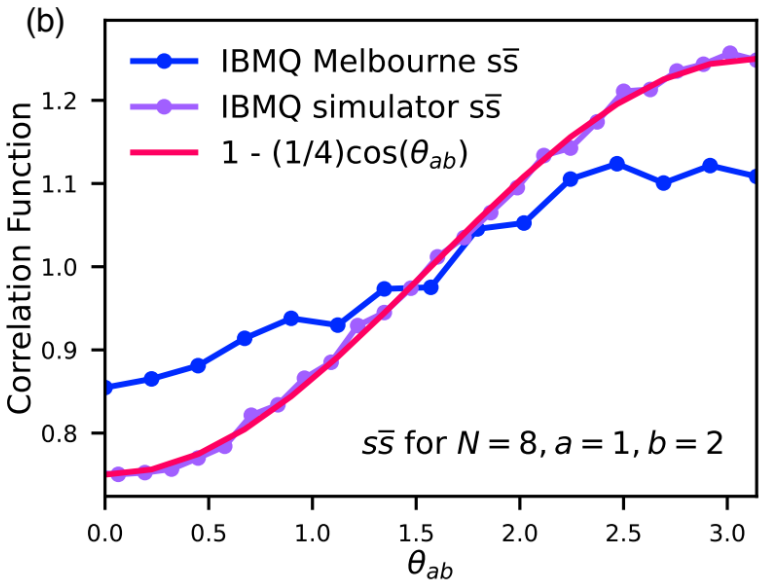


Final State: $\Lambda\bar{\Lambda}$ Spin Correlation

W Gong, G Parida, Z Tu, R Venugopalan, PRD 106 (2022) L031501



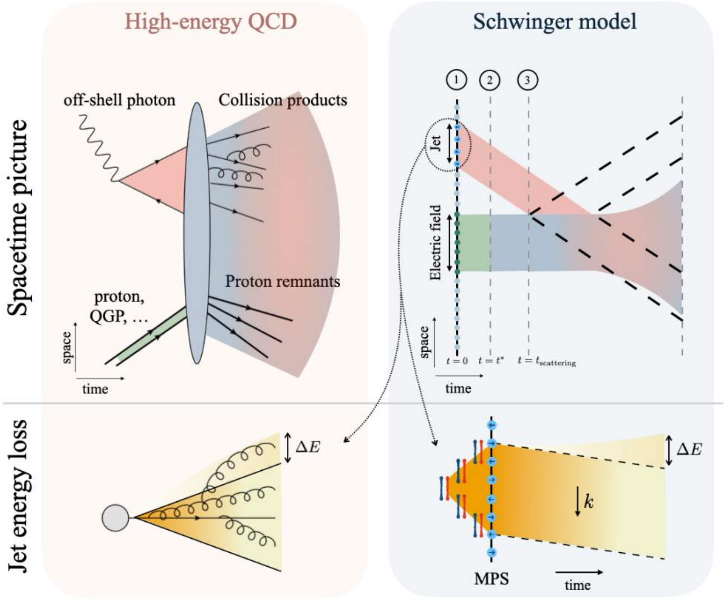




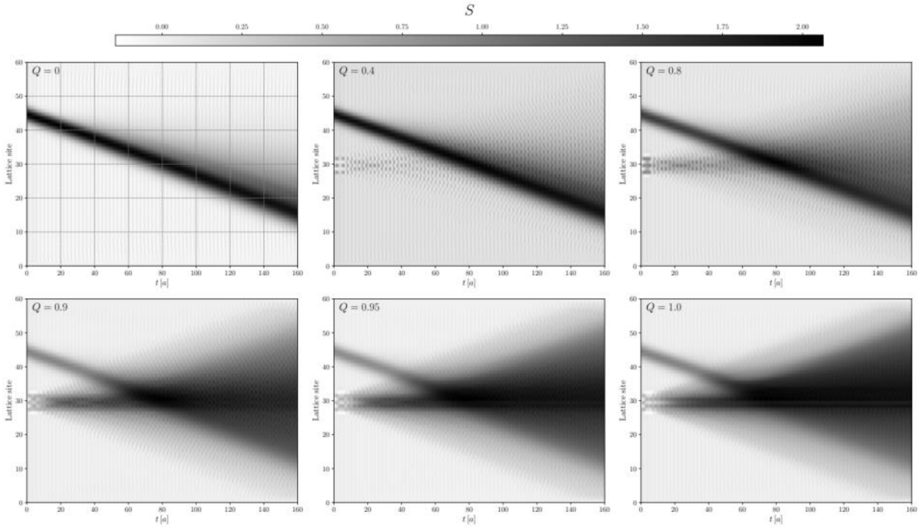
- Simulated a QCD string model with singlets of two fermion flavors. IBMQ circuit simulator reproduces the $s\bar{s}$ correlation function very well.
- Results from quantum hardware deviates from the circuit simulator and classical predictions due to noise. → **error mitigation is crucial**
- 4-flavor Schwinger model (1+1D QED) has been studied with TN. Quantum hardware may allow us to scale the computation to larger lattices. (J. Barata, W. Gong, R. Venugopalan, PRD **109** (2024) 116003)

Final State: Jet Dynamics

J Barata, E Rico, arXiv:2502.17558 (2025)

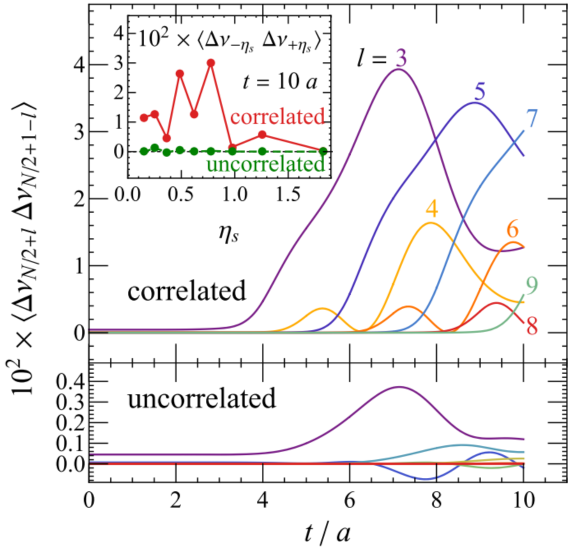


Entropy evolution



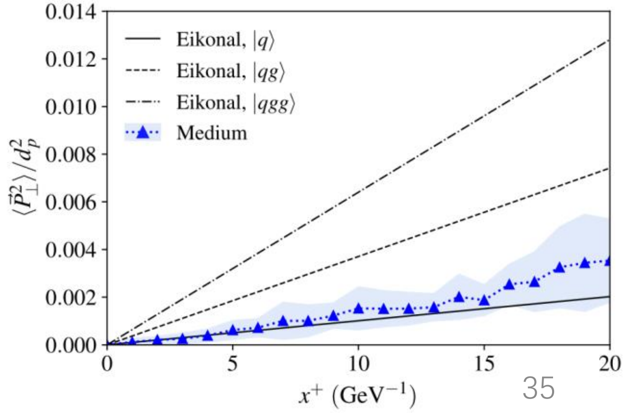
A Florio et al., PRL 131, 021902 (2023)

Quantum entanglement of fragmenting jets



W Qian, M Li, CA Salgado, M Kreshchuk, PRD 111, 096001 (2025)

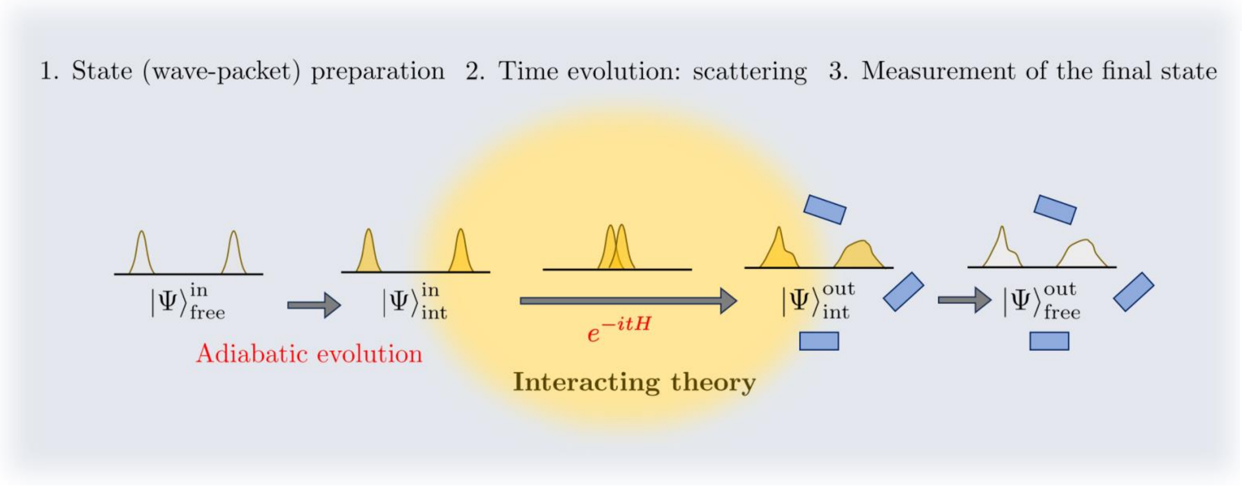
Transverse momentum broadening of quark jets in medium



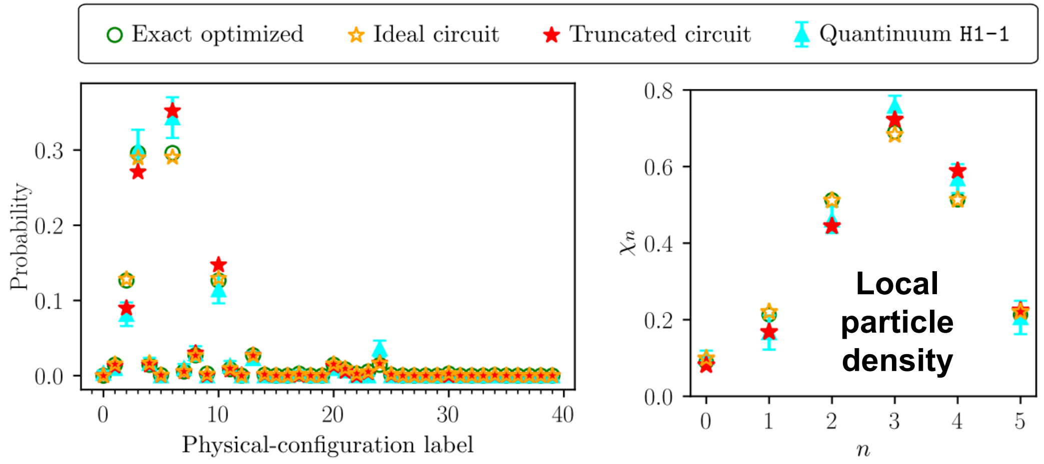
- First QC calculation of quenching parameter pursued in J. Barata et al., PRD 106, 074013 (2022).
- Real-time non-perturbative dynamics (quantum entanglement between fragmenting jets & medium interaction) has been investigated with Schwinger model.
- A 3+1D scalable approach with non-perturbative light-front Hamiltonian is also proposed and evaluated transverse momentum broadening of quark and gluon jets in medium.

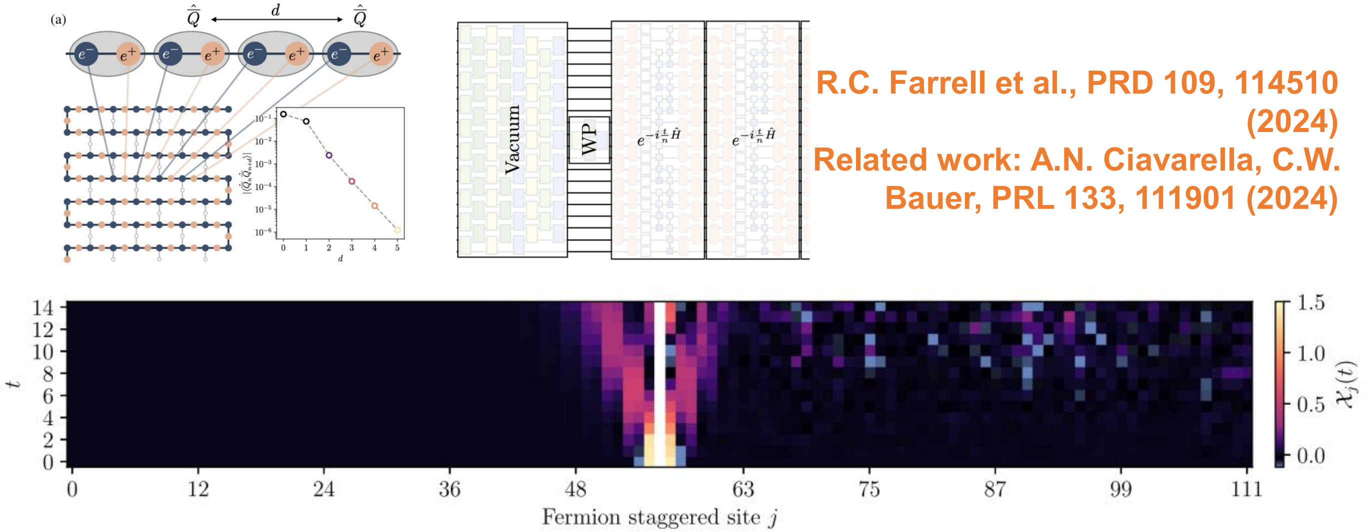
Towards Collision Dynamics

Wave-packet evolution



Z Davoudi, CC Hsieh, SV Kadam, Quantum 8 (2024) 1502





R.C. Farrell et al., PRD 109, 114510 (2024)
Related work: A.N. Ciavarella, C.W. Bauer, PRL 133, 111901 (2024)

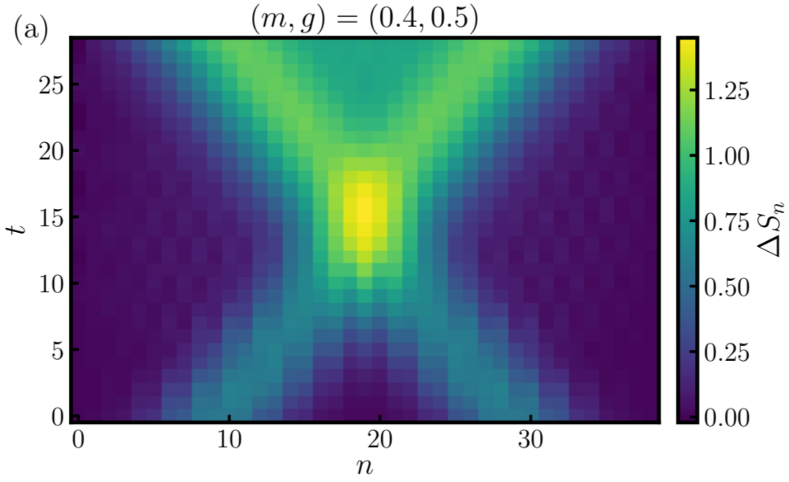
- Meson wave packets in Z_2 gauge theory are simulated with Quantinuum Ion-trap hardware (13 qubits).
- Similarly, meson wave packets with Schwinger model are evolved in **IBM superconducting hardware (112 qubits).**
- Results match well with the exact prediction or TN. **Error mitigation is particularly crucial for the 112-qubit machine.**

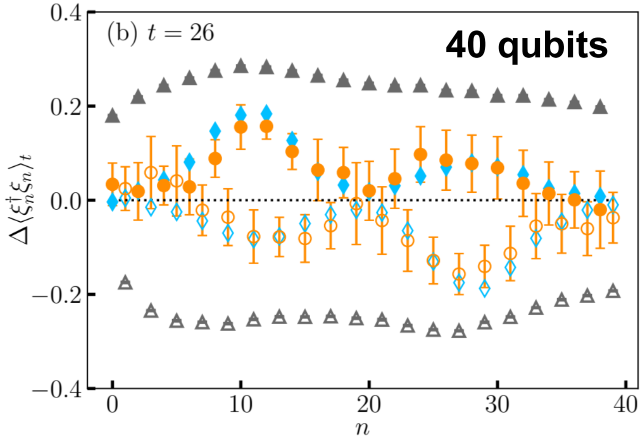
See also: RC Farrel et al., arXiv:2505.03111; Y Chai, Y. Guo, S. Kuehn, arXiv:2505.21240

Towards Collision Dynamics Scattering

Fermion-antifermion wave-packet scattering

Y. Chai et al., arXiv:2507.17832; related work: Y. Chai et al. Quantum 9 (2025) 1638

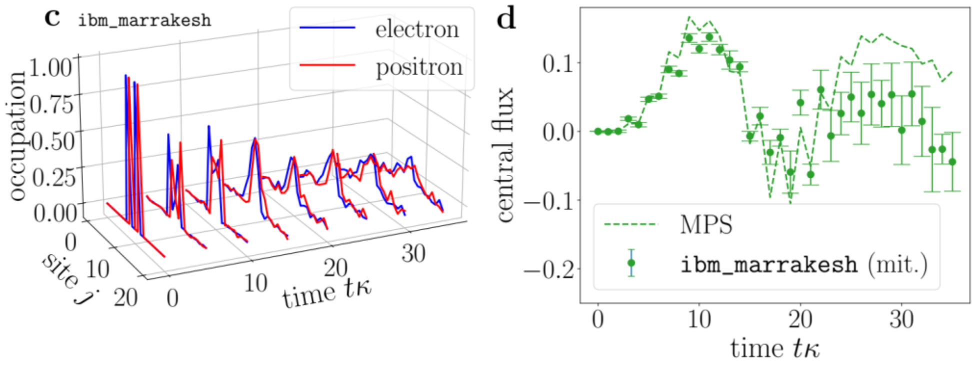




- Simulated (1+1)D Thirring model with 40 and 80 qubits on IBM hardware.
- Consistent with TN predictions after error mitigation.

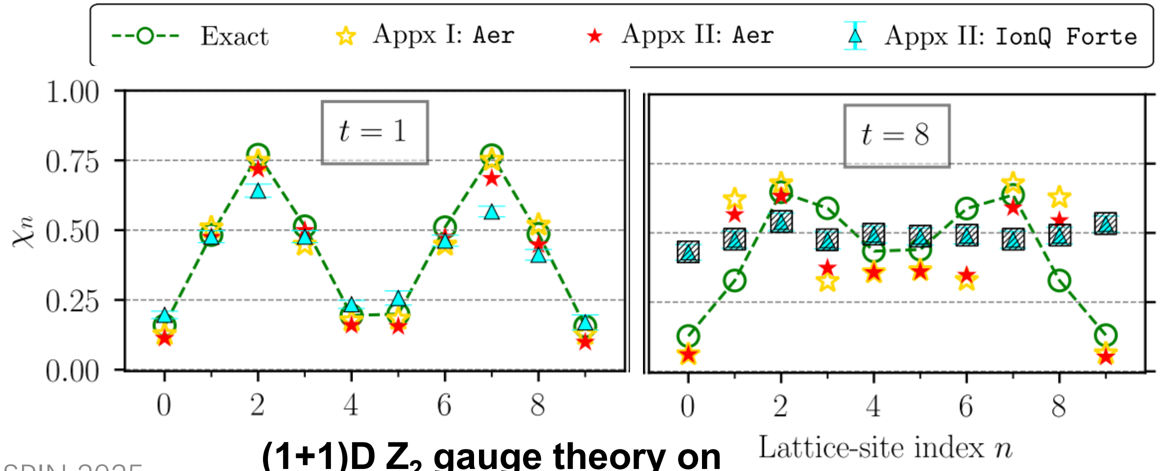
Meson wave-packet scattering

J. Schuhmacher et al., arXiv:2505.20387



(1+1)D U(1) on IBM hardware (45 qubits)

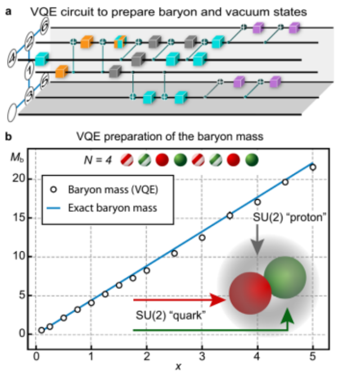
Z. Davoudi, CC Hsieh, SV Kadam, arXiv:2505.20408



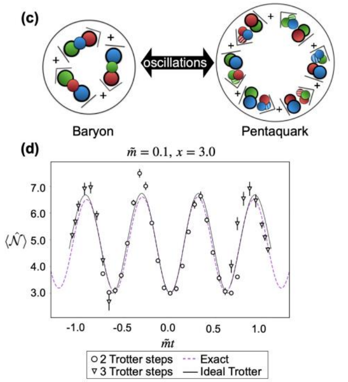
(1+1)D Z_2 gauge theory on IonQ Ion-trap hardware (11, 27 qubits)

Other Highlights

Hadron mass spectrum in (1+1)D

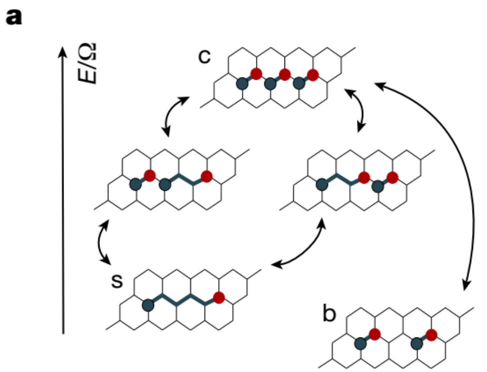


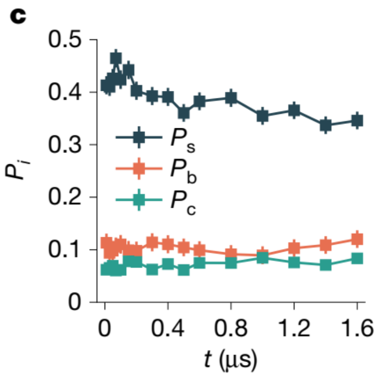
YY Atas et al., Nat Commun 12, 6499 (2021)



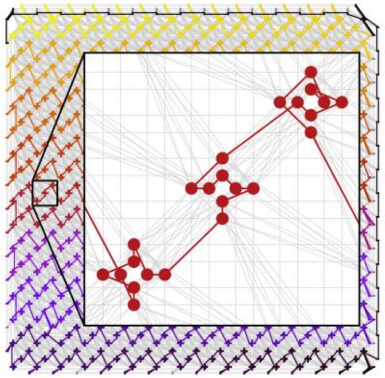
YY Atas et al., PR RESEARCH 5, 033184 (2023)

String breaking



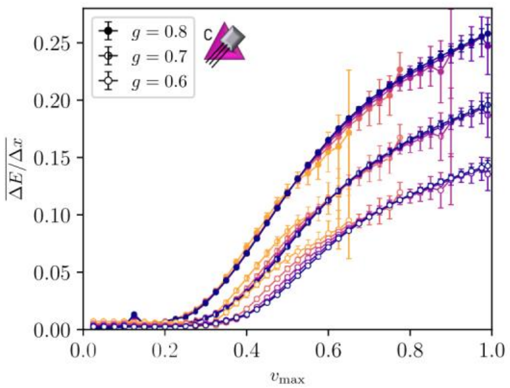


D González-Cuadra et al., Nature 642, 321 (2025)



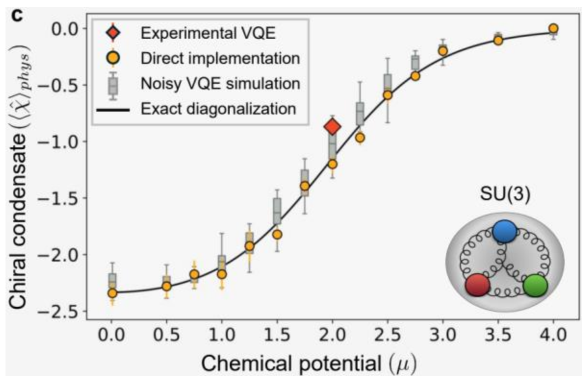
J Vodeb et al., Nature Physics 21, 386 (2025)

Heavy quark energy loss in medium



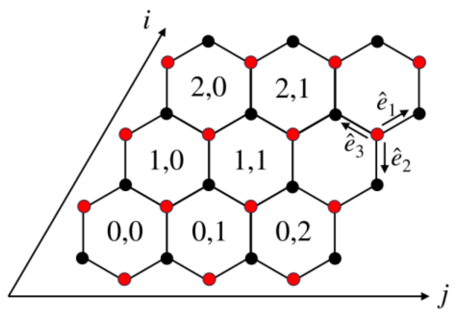
RC Farrell, M Illa, MJ Savage, PRC 111 (2025) 1, 015202

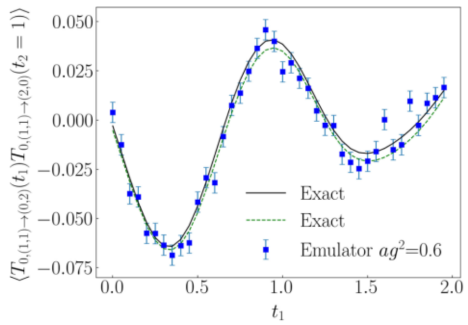
QCD phase diagram in (1+1)D



AT Than et al., arXiv:2501.00579

Energy-energy correlator in (2+1)D SU(2)





K Lee, F Turro, X Yao, PRD 111 (2025) 054514

Prospects

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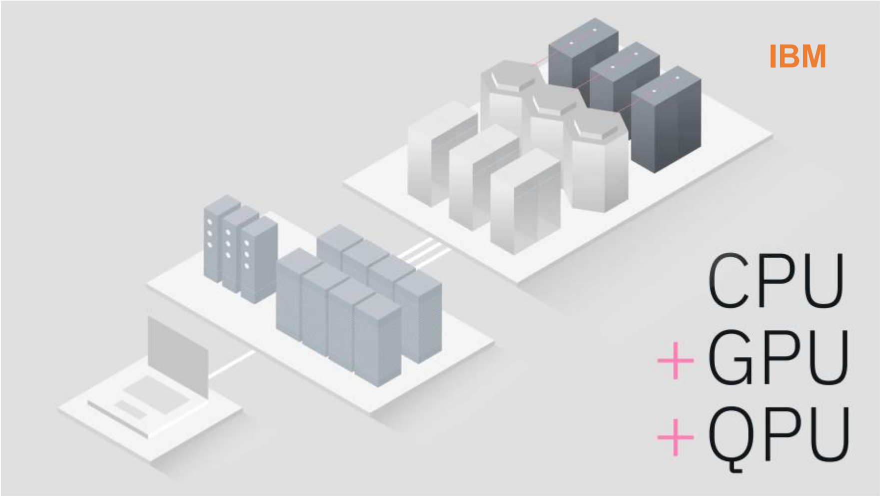
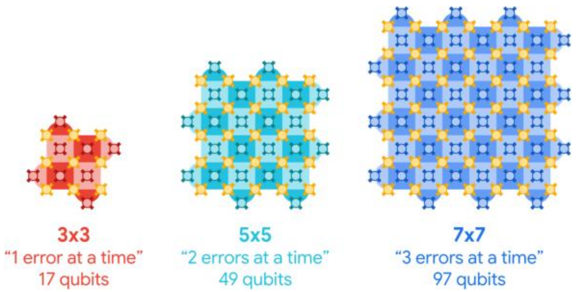
Towards Practical Applications

- Quantum computing combined with High Performance Computing has started to operate (Quantum-centric supercomputing).
- O(~100)-qubit level error-tolerant quantum computers will likely show up around 2030.
  - IBM aims for error-tolerant quantum computers by 2029 (100M gates, 200 logical qubits)
- In any case, some components of HEP experimental workflow require $O(10^6)$ qubits.
- Quantum-inspired techniques are also likely to stay valuable.

Quantum-centric supercomputing



Surface code logical qubits



Google Quantum AI

QuantumCtek (国盾量子)

Summary

- Quantum computing applications are an emerging field in high energy particle and nuclear physics.
- Quantum machine learning and quantum simulation are actively investigated for experimental tasks and theoretical calculations.
- Three quantum technologies exist: (1) universal quantum gate machines, (2) quantum annealing & (3) quantum-inspired algorithms.
- Each approach has its pros/cons and appropriate use cases.
- With the rapid development of quantum hardware and quantum-inspired algorithms, **it would be really exciting to see how all of our efforts converge in the end & understand how practical quantum advantages can be realized.**

Picture credits: Qianhui Shi, Yan Liang

Thank you for listening!