Quantum computers: a breakthrough in information processing and application in High Energy Physics

Michele Grossi

IBM Tech Quantum Ambassador
Qiskit Advocate

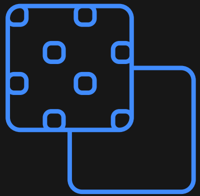
University of Pavia

IBM Quantum

With quantum computers, we will tackle problems in new ways

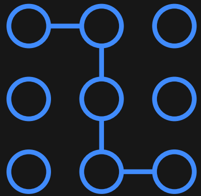
Model physical processes of nature

Find better patterns within AI/ML processes



Obtain better optimization solutions

Perform significantly more scenario simulations



Start thinking about quantum computing now

It’s moving fast

Talent is scarce

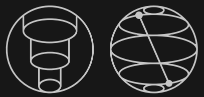
Patents are being filed

Strategizing takes time

IBM is defining the future of computing, again

Most advanced hardware supporting the full stack

14 systems
53 qubit system



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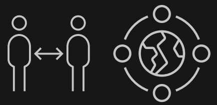
Trusted advisor with the broadest adoption

180k+ users
100B+ executions

qiskit.org

Built the network of experts defining the future together

80+ partners
200+ papers



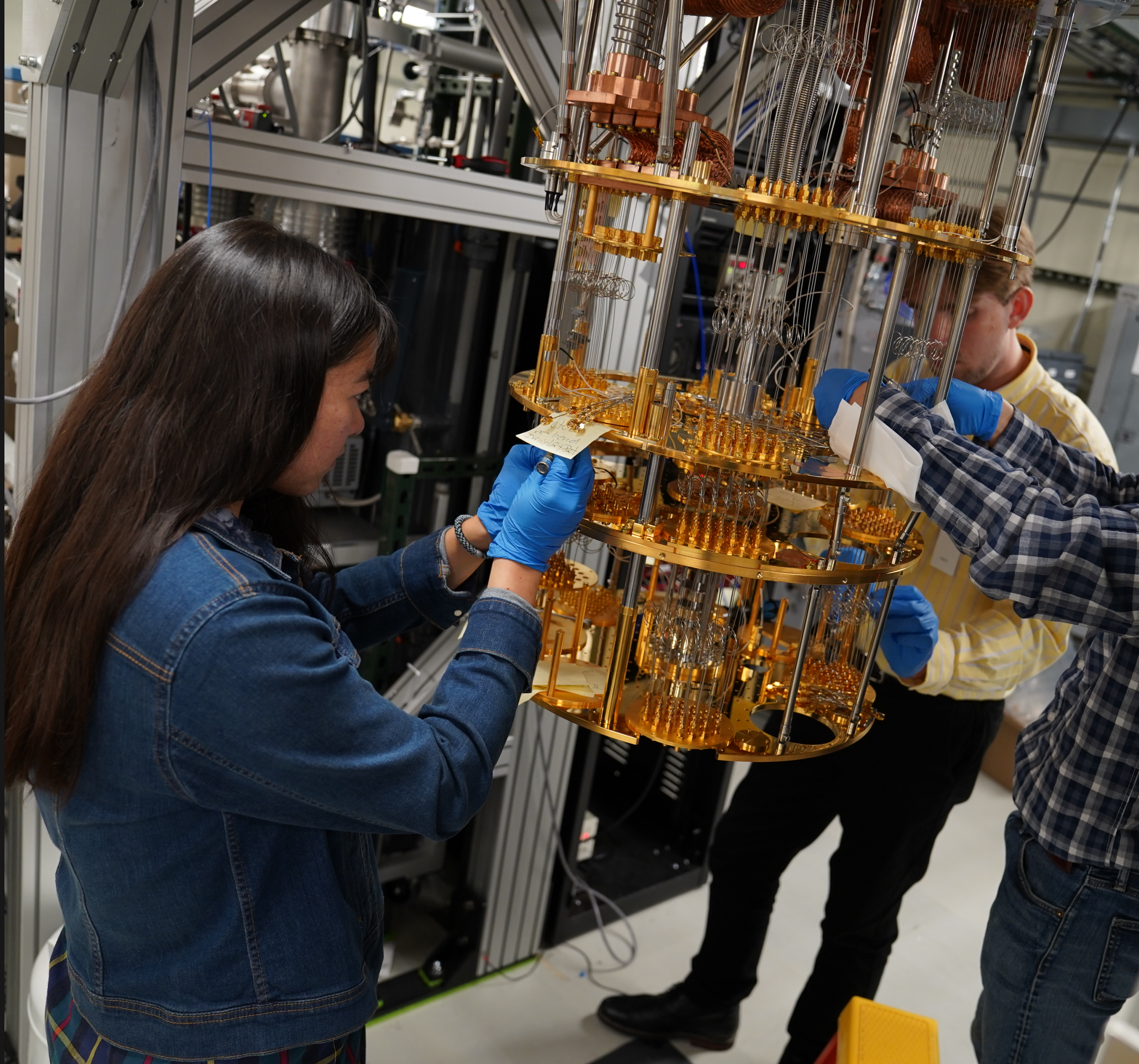
ibm.co/q-network

The future belongs to all of us

Giving students hands-on experience through internships

Offering open-access educational materials

community.qiskit.org/education



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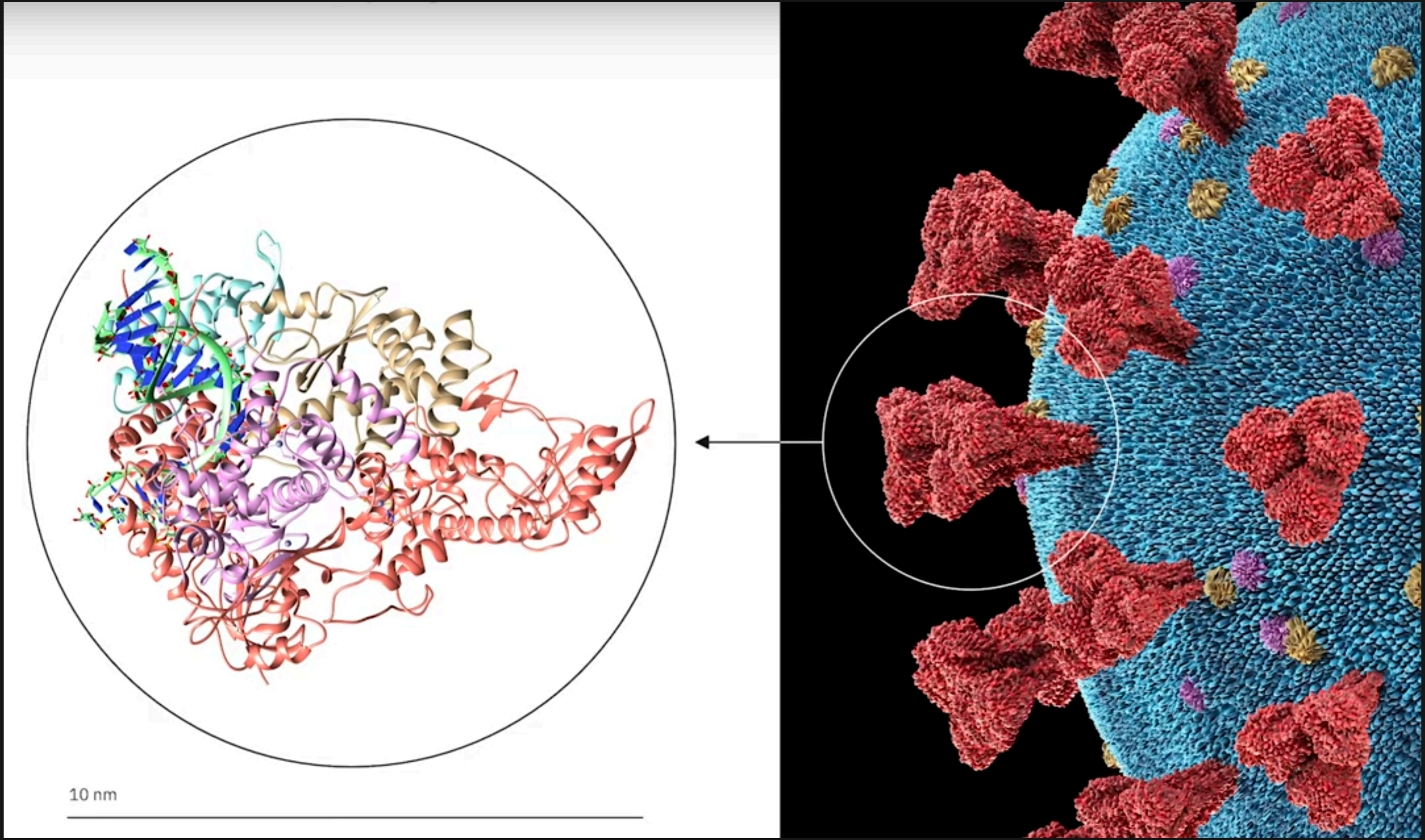
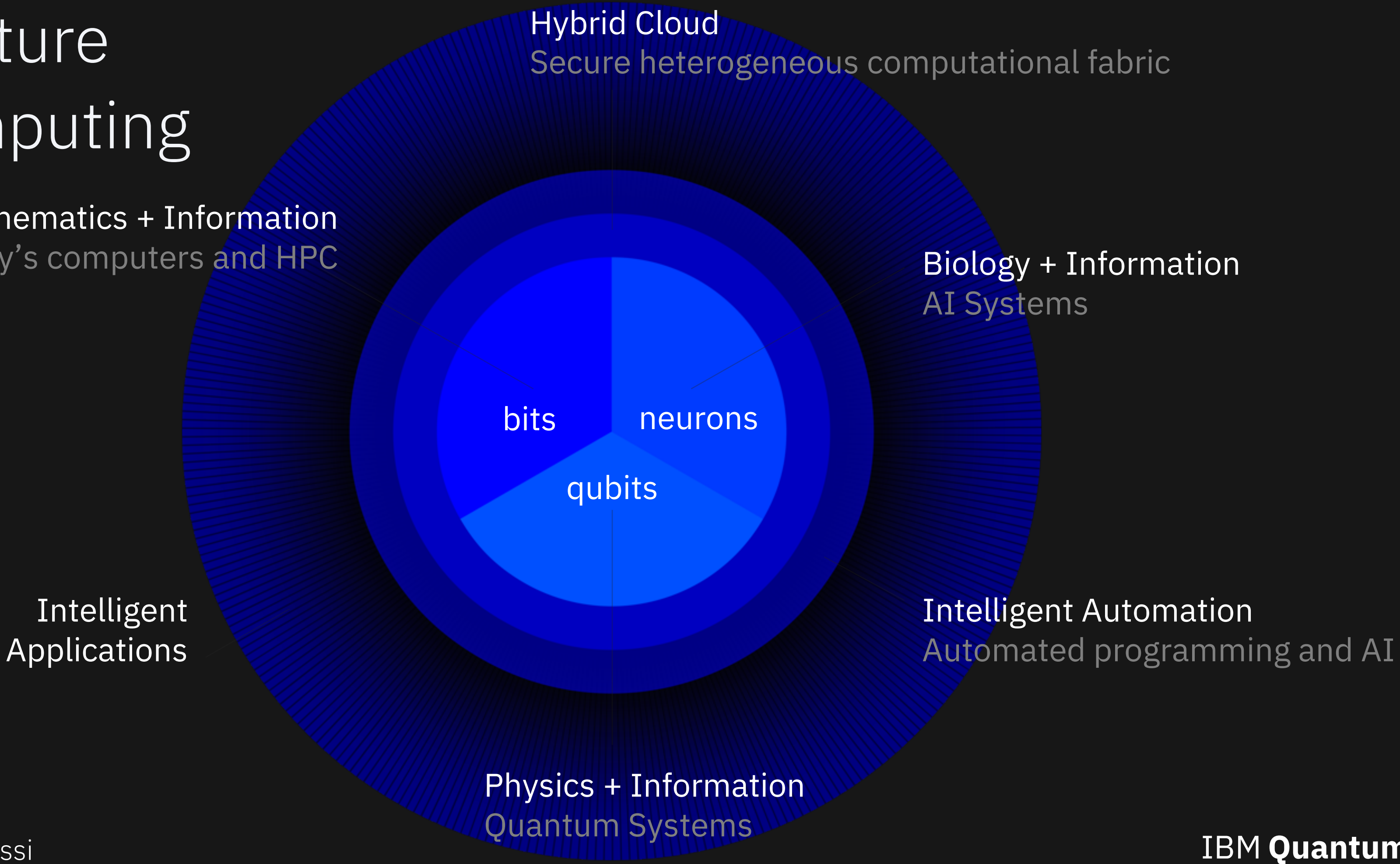
The motivation for quantum computing

IBM **Quantum**



The future of computing



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IBM Quantum

“I’m not happy with all the analyses that go with just the classical theory, because nature isn’t classical, dammit, and if you want to make a simulation of nature, you’d better make it quantum mechanical …”

Richard P. Feynman
Department of Physics,
California Institute of Technology

International Journal of Theoretical Physics,
Vol 21, Nos. 6/7, 1982

The basics of quantum computing

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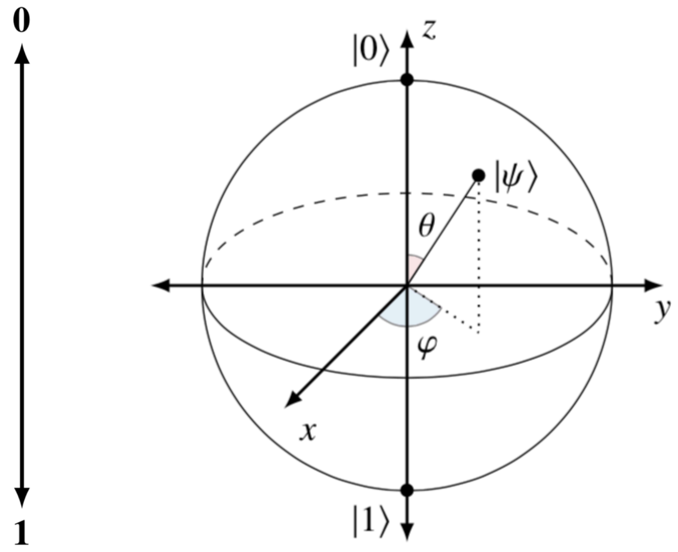
Bits and qubits

A classical bit can be **0** or **1**.

A quantum bit, or *qubit*, can take on those values but can represent a combination of **0** and **1** while we are computing.

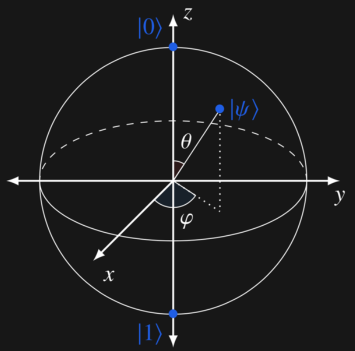
When we measure a qubit, it becomes **0** or **1** based on probability.



classical bit quantum bit analogy

Quantum computing uses essential ideas from quantum mechanics

Measurement



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Measurement is forcing the qubit's state

$$a\,|0\rangle + b\,|1\rangle$$

to |0> or |1> by observing it, where

$|a|^2$ is the probability we will get |0> when we measure

$|b|^2$ is the probability we will get |1> when we measure

Examples

$$\frac{\sqrt{2}}{2}\,|0\rangle + \frac{\sqrt{2}}{2}\,|1\rangle$$

has an equal probability of becoming |0> or |1>.

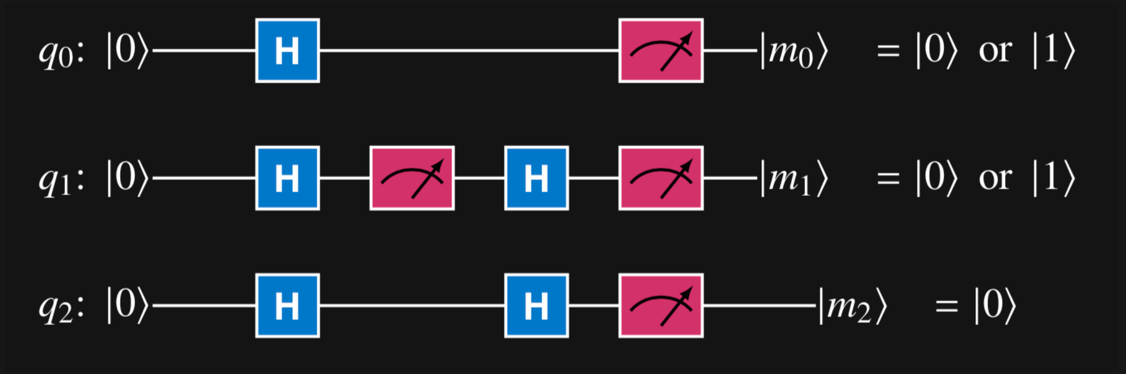
$$\frac{\sqrt{3}}{2}\,|0\rangle - \frac{1}{2}\,i\,|1\rangle$$

has a 75% chance of becoming |0>.

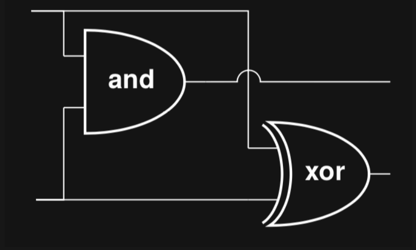
Quantum computing uses essential ideas from quantum mechanics

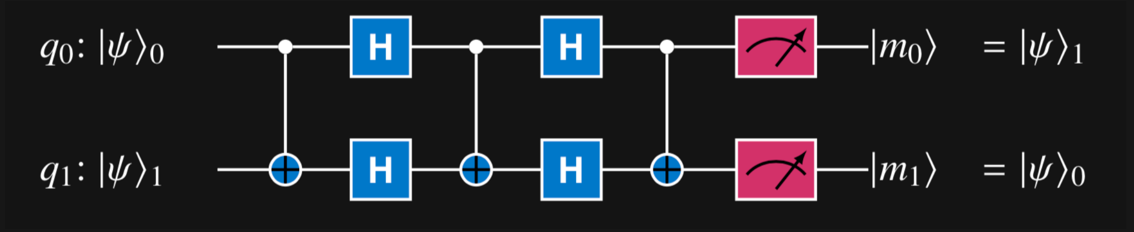
Classical logical circuits use operations like and, or, not, nand, and xor. We also call these gates.

Quantum circuits use reversible gates that change the quantum states of one, two , or more qubits.

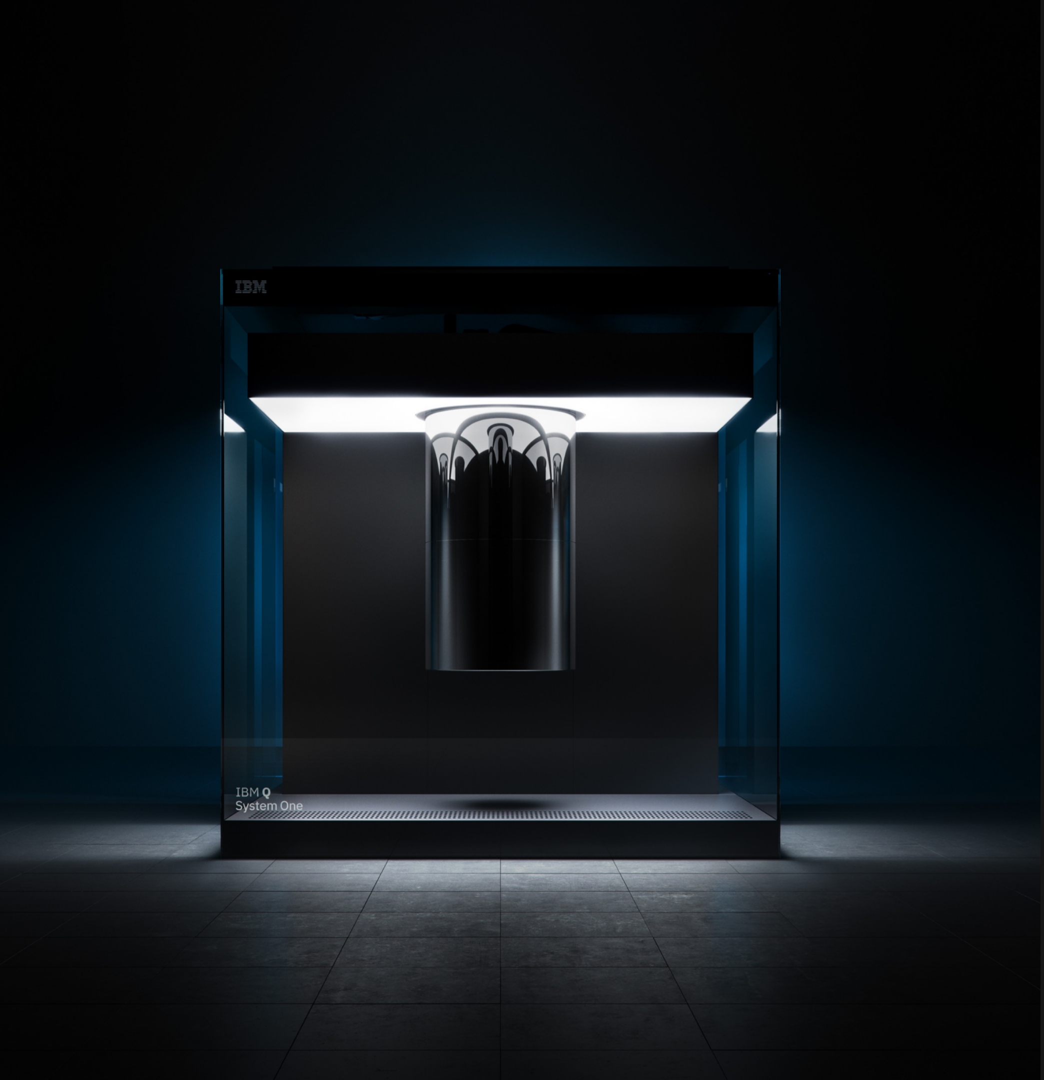


Gates / Operations



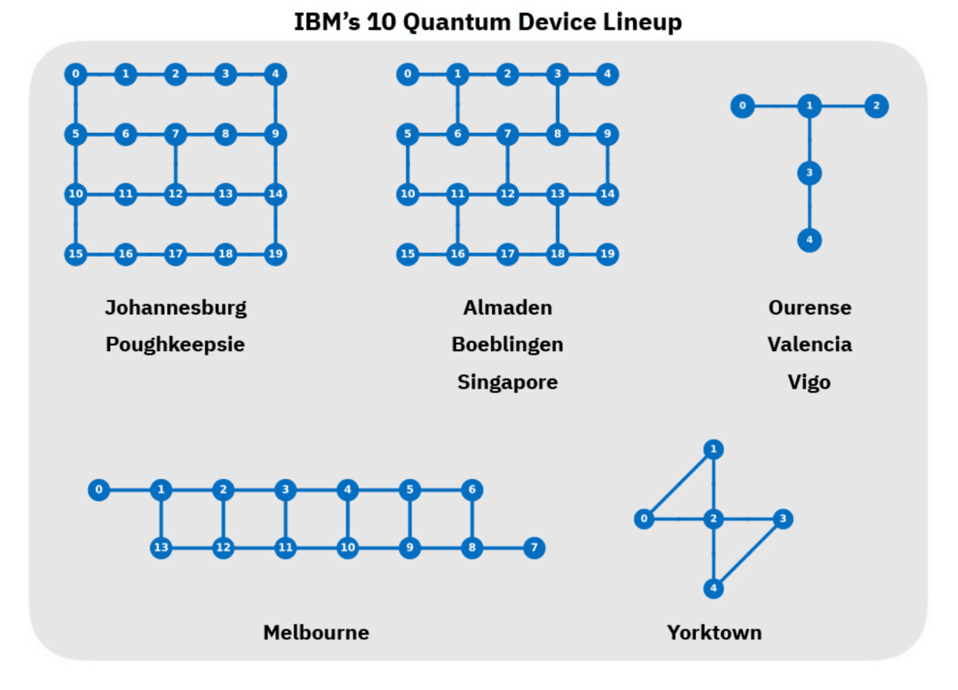


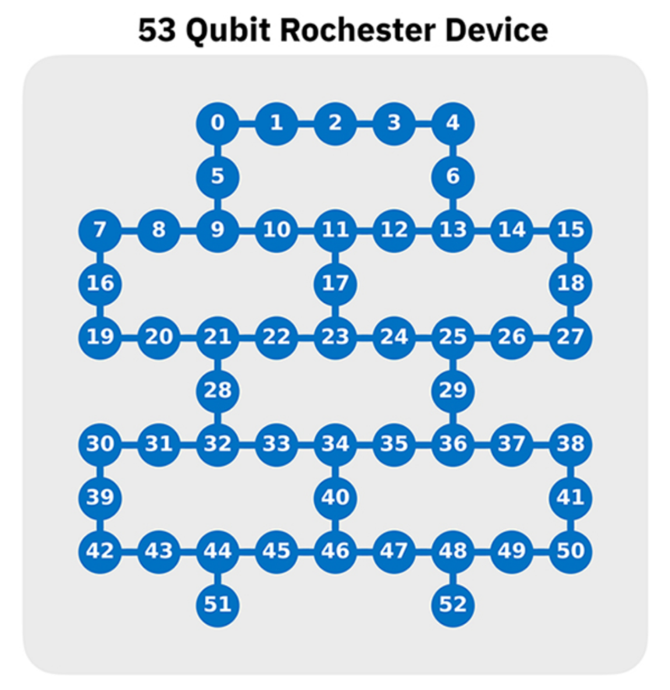
The hardware in an IBM Q quantum computing system


IBM
IBM Q
System One


IBM Q

IBM Q quantum devices

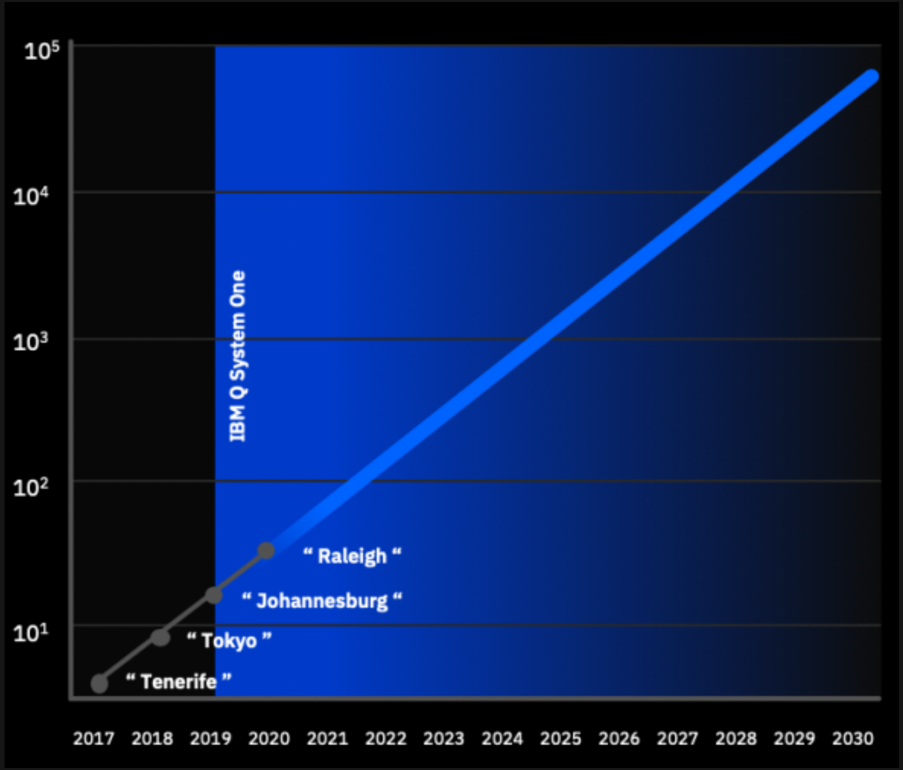




Quantum volume

Many factors contribute to the performance of the overall system

https://www.ibm.com/blogs/research/2020/01/quantum-volume-32/



IBM Q Experience is the quantum cloud services and software platform designed to take full advantage of IBM Q systems.

In collaboration with IBM Q Network partners we are driving advancements in quantum software and algorithms

IBM research towards the first use cases with quantum advantage...

Simulating Quantum Systems
- Quantum chemistry
- Material science
- **High energy physics**

Artificial Intelligence
- Better model training
- Pattern recognition
- Fraud detection

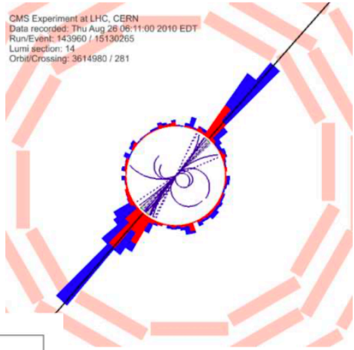
Optimization / Monte Carlo
- Portfolio optimization
- Risk analysis
- Loans & credit scoring
- Monte Carlo-like applications

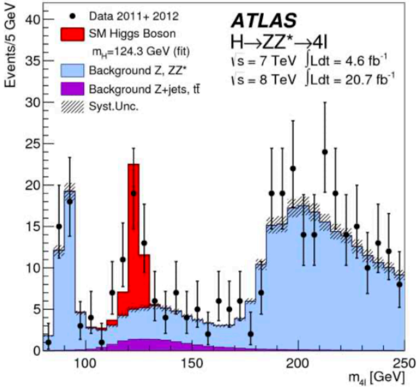
High Energy Physics

Classification (machine learning and SVM), select/identify relevant LHC events, reconstruction of tracks - jets tracking

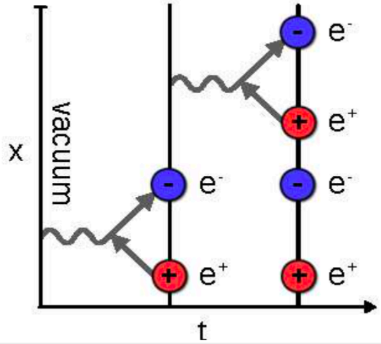
Quantum-Computing where Time-Evolution: lattice gauge theory (Schwinger's model and beyond)

Quantum Minimization VQE optimization in lattice gauge theory





E.A. Martinez et al., nature, 534, 516 (2016)



Simulating lattice gauge theories on a quantum computer

Tim Byrnes* Yoshihisa Yamamoto

2005

Quantum Computation of Scattering in Scalar Quantum Field Theories

Stephen P. Jordan,[†§] Keith S. M. Lee,[†§] and John Preskill [§ *]

2012

Atomic Quantum Simulation of $U(N)$ and $SU(N)$ Non-Abelian Lattice Gauge Theories

D. Banerjee[1], M. Bögli[1], M. Dalmonte[2], E. Rico[2,3], P. Stebler[1], U.-J. Wiese[1], and P. Zoller[2,3]

2013

2014

Towards Quantum Simulating QCD

Uwe-Jens Wiese

Quantum Simulations of Lattice Gauge Theories using Ultracold Atoms in Optical Lattices

Erez Zohar J. Ignacio Cirac Benni Reznik

2015

2016

Real-time dynamics of lattice gauge theories with a few-qubit quantum computer

Esteban A. Martinez,[1,*] Christine Muschik,[2,3,*] Philipp Schindler,[1] Daniel Nigg,[1] Alexander Erhard,[1] Markus Heyl,[2,4] Philipp Hauke,[2,3] Marcello Dalmonte,[2,3] Thomas Monz,[1] Peter Zoller,[2,3] and Rainer Blatt[1,2]

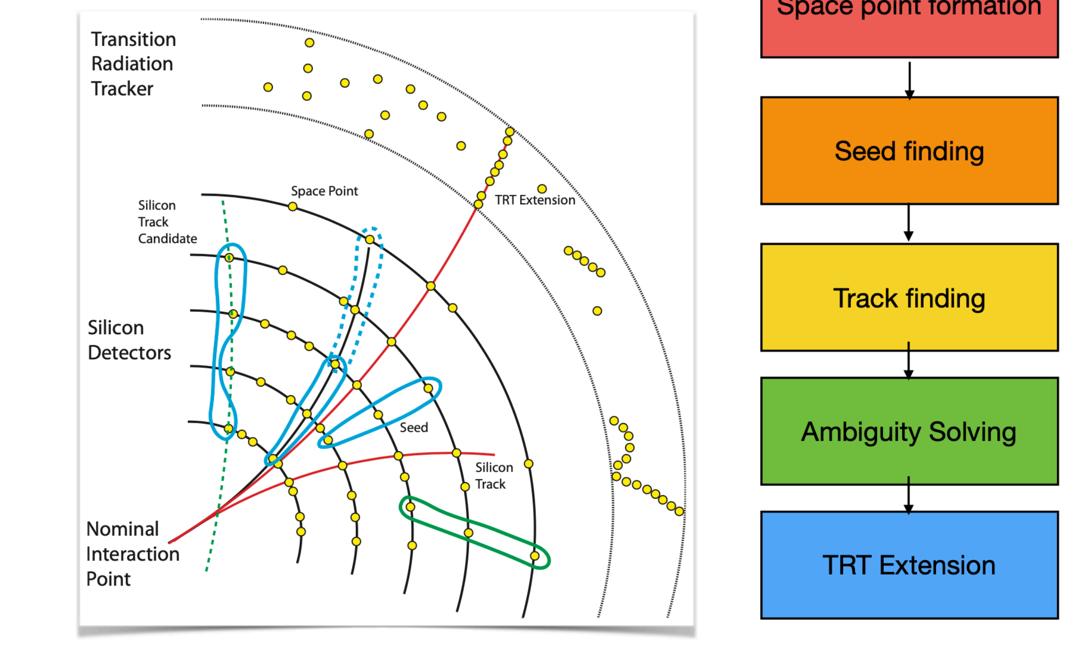
Quantum Sensors for the Generating Functional of Interacting Quantum Field Theories

A. Bermudez,[1,2,*] G. Aarts,[1] and M. Müller[1]

2017

Track Reconstruction – QUBO Algorithm

Multi-step iterative Kalman filter approach



Quadratic Unconstrained Binary Optimization QUBO

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https://sites.google.com/lbl.gov/hep-qpr

Mapping of QUBO to Hamiltonian

1. Set $x_i = \frac{z_i+1}{2}$, for $z_i \in \{-1, 1\}$
2. Replace z_i by σ_Z^i and $z_i z_j$ by $\sigma_Z^i \otimes \sigma_Z^j$ where

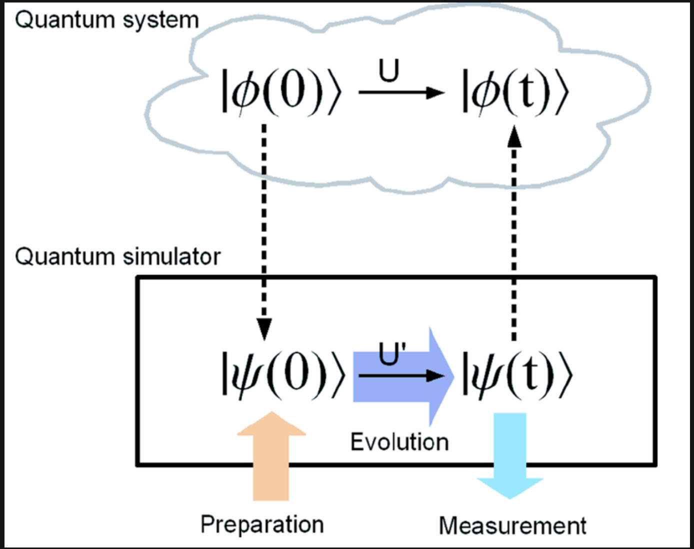
$$\sigma_Z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

➔ Combinatorial optimization problem has been translated to ground state problem of Hamiltonian H as known from quantum chemistry

$$\min_{|\psi\rangle} \langle\psi|H|\psi\rangle$$

Quantum Simulation

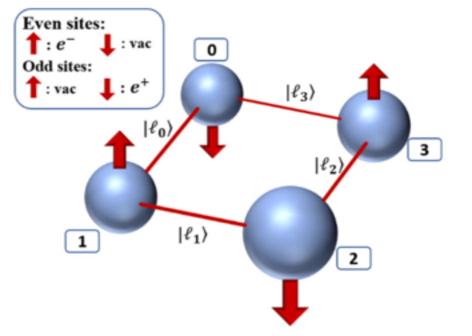
- Represent the system Hilbert space on the qubit space
- Implement a circuit to simulate the time evolution
- Field on a lattice
- The field amplitude is discretized at every lattice site



S. Lloyd, Science **273**, 1073 (1996)

Example: **Schwinger** model describes 2D QED with a Dirac fermion

→ toy QCD model:
- Charge screening
- SSB
- confinement

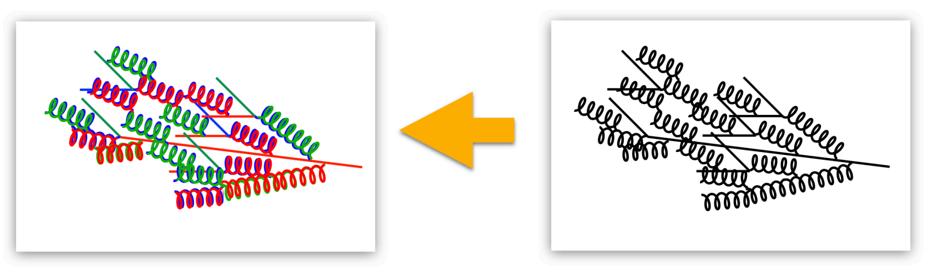


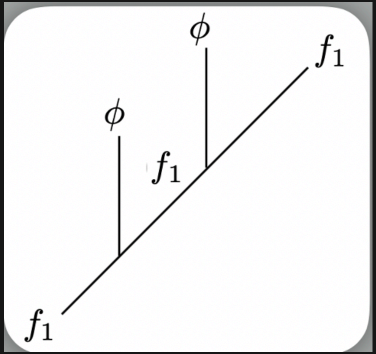
ϕ^4 - **quantum field theory**
S. Jordan, et al., **Science, 336, 1130 (2012)**

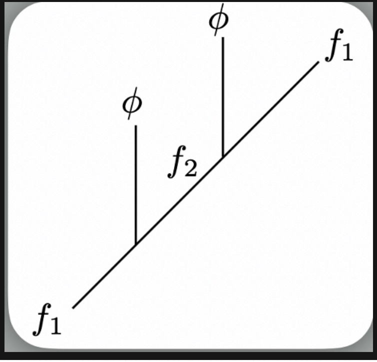
SU(2) non-Abelian gauge field theory in one dimension on digital quantum computers

Natalie Klco, Jesse R. Stryker and Martin J. Savage[1]
[1] *Institute for Nuclear Theory, University of Washington, Seattle, WA 98195-1550, USA*
(Dated: August 20, 2019 - 0:44)

Quantum Computing for Final State Radiation







Final State Radiation (FSR) is a complex many-body quantum system. Classic MC simulation cannot capture all quantum effects.

Parton shower models are implemented using classical Markov Chain MC (MCMC) algorithms to efficiently generate high multiplicity radiation patterns.

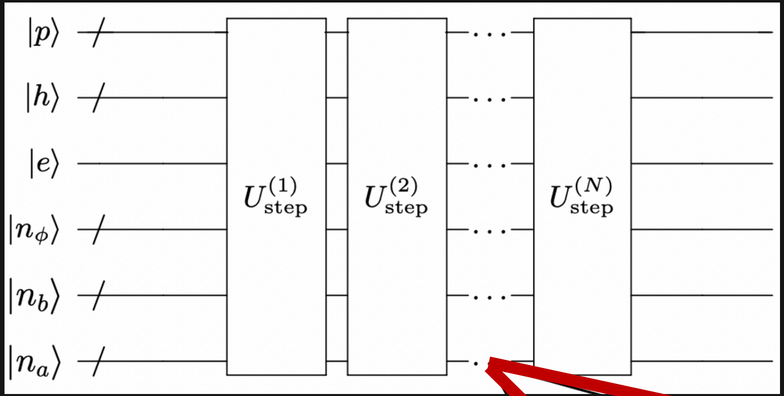
Perhaps quantum tools can be used to incorporate quantum degrees of freedom

Ref: 1904.03196 D.Provasoli, C. Bauer, W. de Jong

Like the SM Higgs when $g_{1,2} \sim m/v$ and $g_1 = g_2 = 0$

$$\mathcal{L} = \bar{f}_1 i(\not\partial + m_1) f_1 + \bar{f}_2 (i\not\partial + m_2) f_2 + (\partial_\mu \phi)^2 + g_1 \bar{f}_1 f_1 \phi + g_2 \bar{f}_2 f_2 \phi + g_{12} \left[\bar{f}_1 f_2 + \bar{f}_2 f_1\right] \phi$$

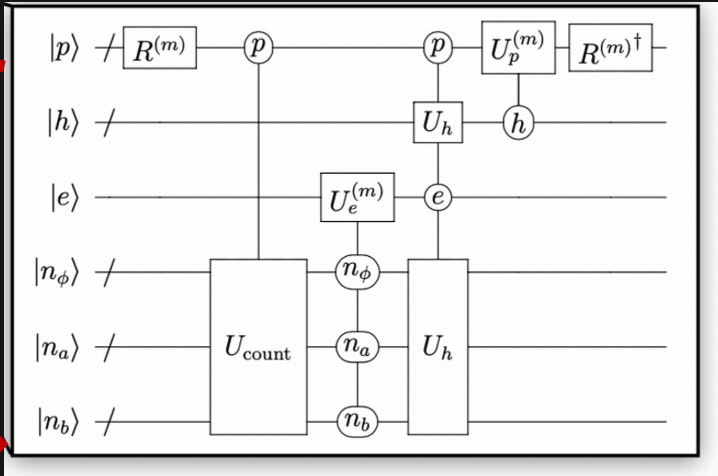
Quantum Computing for FSR: algorithm



The *algorithm* is able to keep track of amplitudes and not probabilities, it samples from the full probability distribution in polynomial time

Measurement: normalized differential cross section for log θmax and the number of emissions. Interference effects are turned on (g12 = 1) and off (g12 = 0), where the classical simulations/calculations are expected to agree with the quantum simulations and measurements.

Register	Purpose	# of qubits
$\|p\rangle$	Particle state	$3(N+n_I)$
$\|h\rangle$	Emission history	$N\lceil\log_2(N+n_I)\rceil$
$\|e\rangle$	Did emission happen?	1
$\|n_\phi\rangle$	Number of bosons	$\lceil\log_2(N+n_I)\rceil$
$\|n_a\rangle$	Number of f_a	$\lceil\log_2(N+n_I)\rceil$
$\|n_b\rangle$	Number of f_b	$\lceil\log_2(N+n_I)\rceil$



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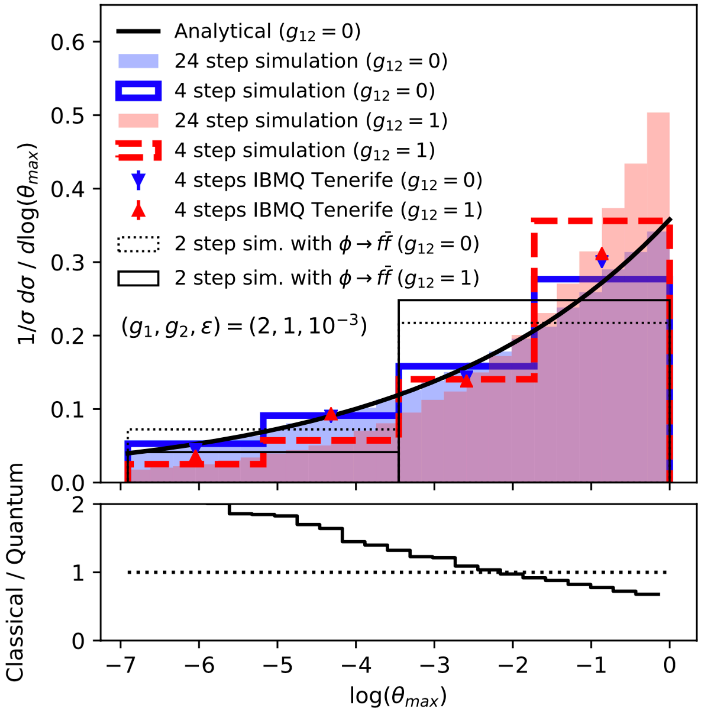
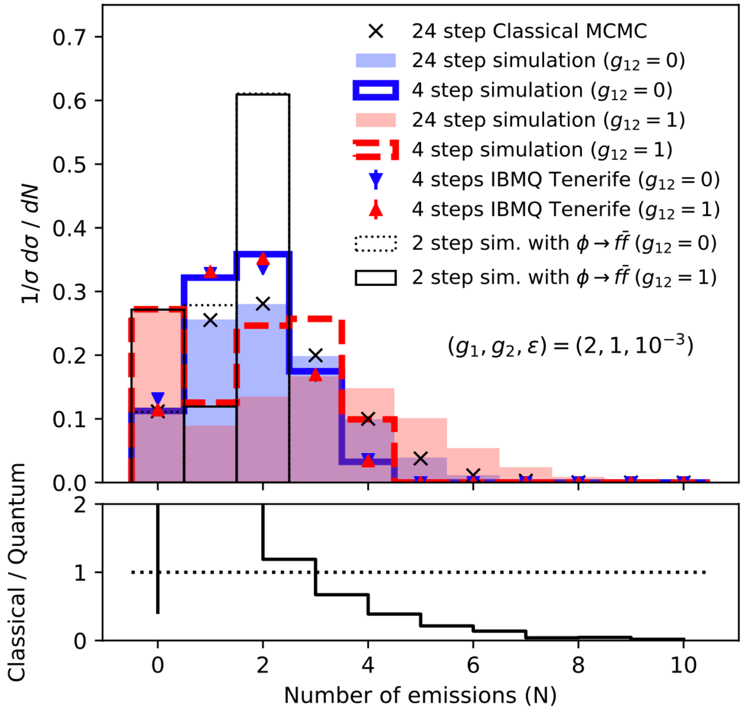
Ref: 1904.03196 D.Provasoli, C. Bauer, W. de Jong

no interference

with interference





angle of maximum emission

number of emissions

Quantum Generative Adversarial Networks

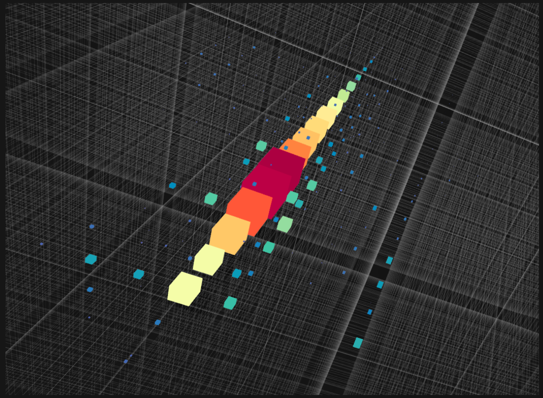
Use classical **Generative Adversarial Networks** to **simulate detector response**

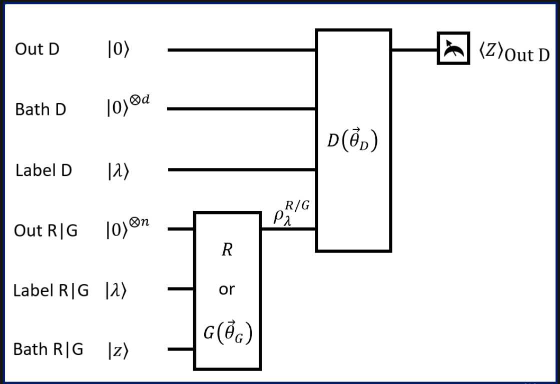
– Replace Monte Carlo simulation

Quantum GAN can have **larger representational power**

– Different hybrid classical-quantum algorithms for generative models exist

Train a quantum GAN to generate **few-pixels image**





Dallaire-Demers and Killoran, arxiv: 1804.08641

From Classics SVM to QSVM

Primal Problem

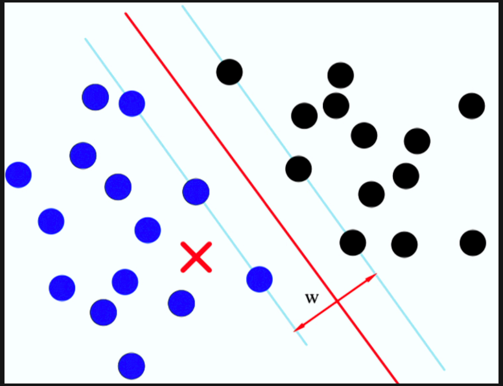
$$L_P = \frac{1}{2}\|\vec{w}\|^2 - \sum_{i \in T} \alpha_i \left[\, k_i(\vec{w} \cdot \Phi(\vec{x}_i) + b) - 1 \,\right]$$

minimize this to maximize the margin

Lagrange multipliers

class labels $\{+1, -1\}$

constraints



From Classics SVM to QSVM

Primal Problem

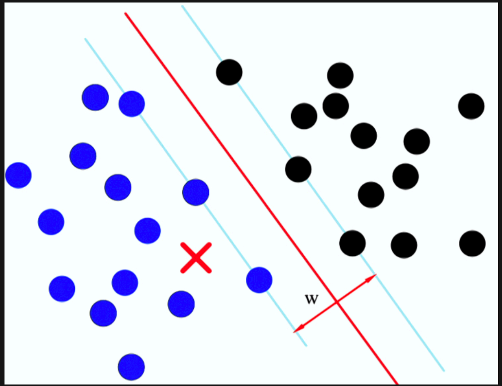
$$L_P = \frac{1}{2}\|\vec{w}\|^2 - \sum_{i \in T} \alpha_i \left[k_i(\vec{w} \cdot \Phi(\vec{x}_i) + b) - 1 \right]$$

$\frac{1}{2}\|\vec{w}\|^2$: minimize this to maximize the margin

α_i: Lagrange multipliers

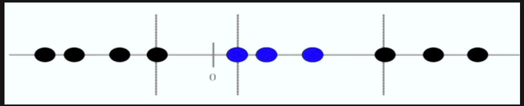
k_i: class labels $\{+1, -1\}$

$[\dots]$: constraints

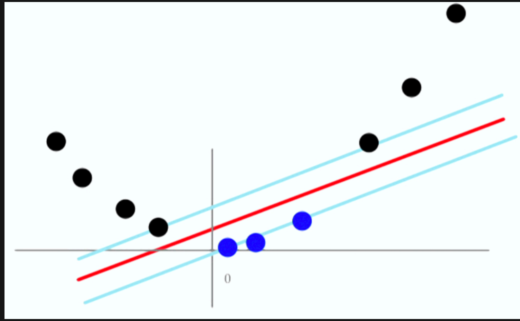


Dual Problem is useful because dot products can Be replaced by a **kernel** function

$$L_D(\alpha) = \sum_{i \in T} \alpha_i - \frac{1}{2} \sum_{i,j \in T} k_i k_j \alpha_i \alpha_j \underbrace{\boldsymbol{\Phi}(\vec{x}_i) \cdot \boldsymbol{\Phi}(\vec{x}_j)}_{\boldsymbol{K}(\vec{x}_i, \vec{x}_j)}$$



Choose the right feature map



Supervised learning with quantum enhanced feature space

I

Map the data

II

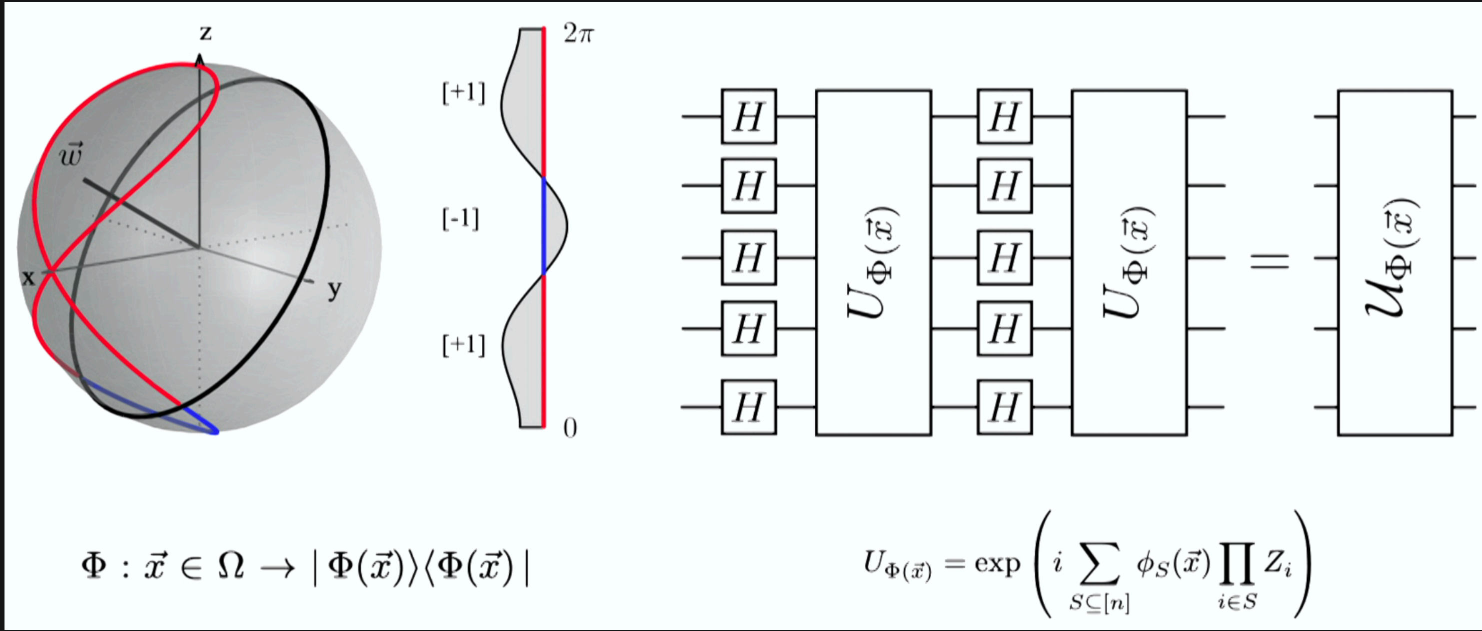
Apply short-depth circuit

III

Measure in canonical basis

IV

Assign label



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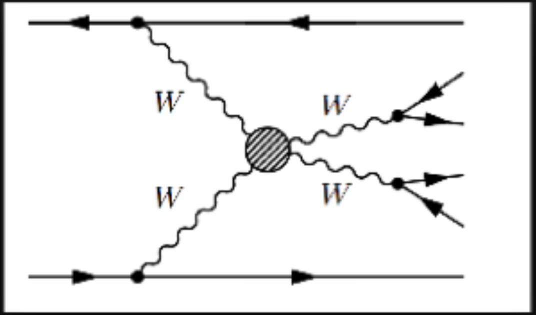
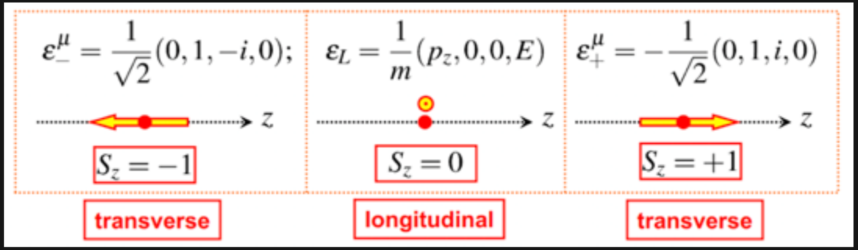
Havlicek, Córcoles, Temme, Harrow, Kandala, Chow, Gambetta, Nature vol. 567, 209–212 (2019)

Vector Boson Scattering



- Unitarity at high energies requires presence of the SM Higgs boson
- Sensitivity grows with energy of vector bosons
- Self-interaction of heavy gauge bosons
- Search for anomalous quartic-gauge-boson couplings

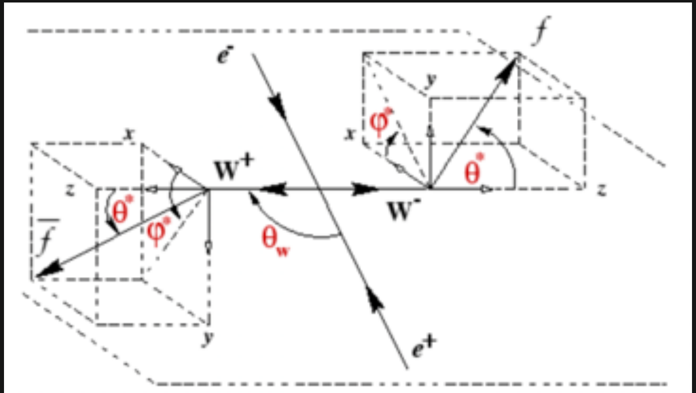
- The cross-section and angular distribution of longitudinal polarisations are particularly sensitive to beyond standard model (BSM) physics
- Boson polarisation can be measured as angular distributions of particles produced in the decay process



$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta}(W^{\pm} \to l^{\pm}\nu) = \frac{3}{4} f_0 \sin^2\theta + \frac{3}{8} f_R (1 \pm \cos\theta)^2 + \frac{3}{8} f_L (1 \mp \cos\theta)^2$$

Ref: M. Grossi et all in preparation

Vector Boson Scattering



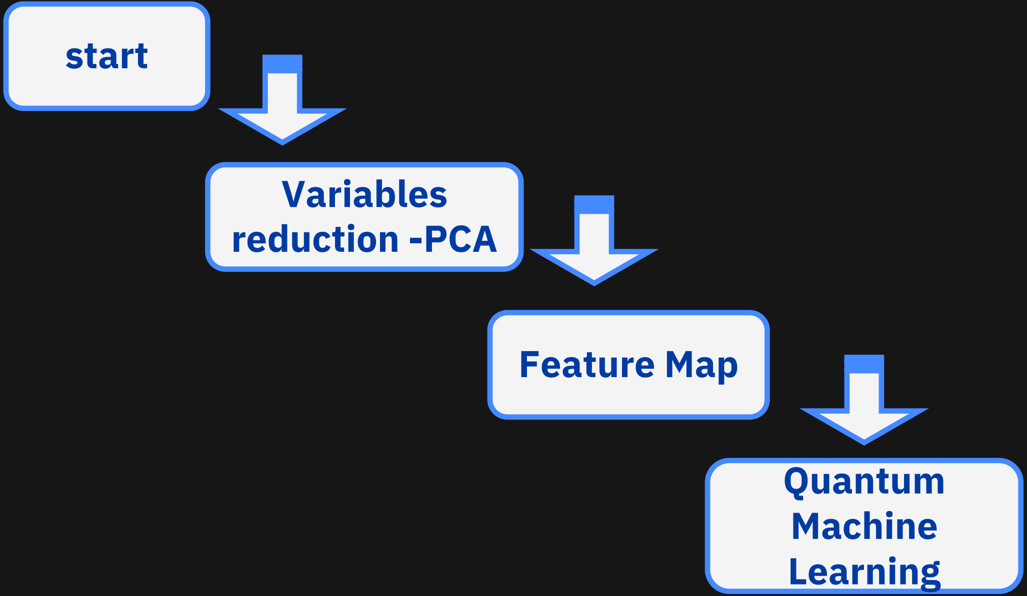
- Events with first solution closer to truth solution (1)
- Events with second solution closer to truth (0)
- Events with negative discriminant are discarded

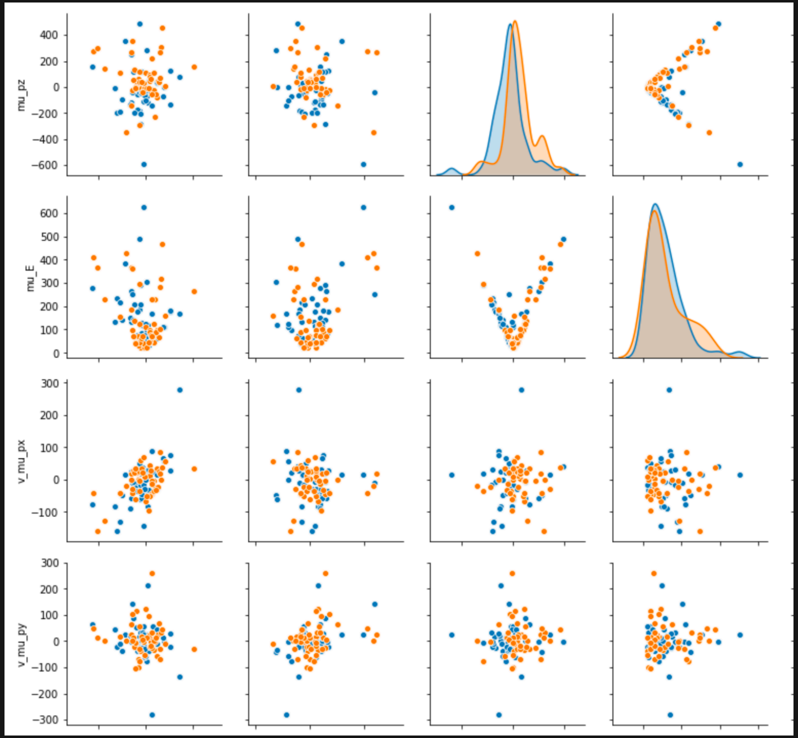
$$\underbrace{\left(p_{\ell L}^2 - E_\ell^2\right)}_{a} p_{\nu L}^2 +$$
$$\underbrace{\left(m_{\mathrm{W}}^2 p_{\ell L} + 2 p_{\ell L} \vec{p}_{\ell T} \vec{p}_{\nu T}\right)}_{b} p_{\nu L} +$$
$$\underbrace{\frac{m_{\mathrm{W}}^4}{4} + \left(\vec{p}_{\ell T} \vec{p}_{\nu T}\right)^2 + m_{\mathrm{W}}^2 \vec{p}_{\ell T} \vec{p}_{\nu T} - E_\ell^2 \vec{p}_{\nu T}^{\,2}\Big)}_{c} = 0$$

$$p_{\nu L} = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

Ref: M. Grossi et all in preparation

Vector Boson Scattering – QSVM Flow

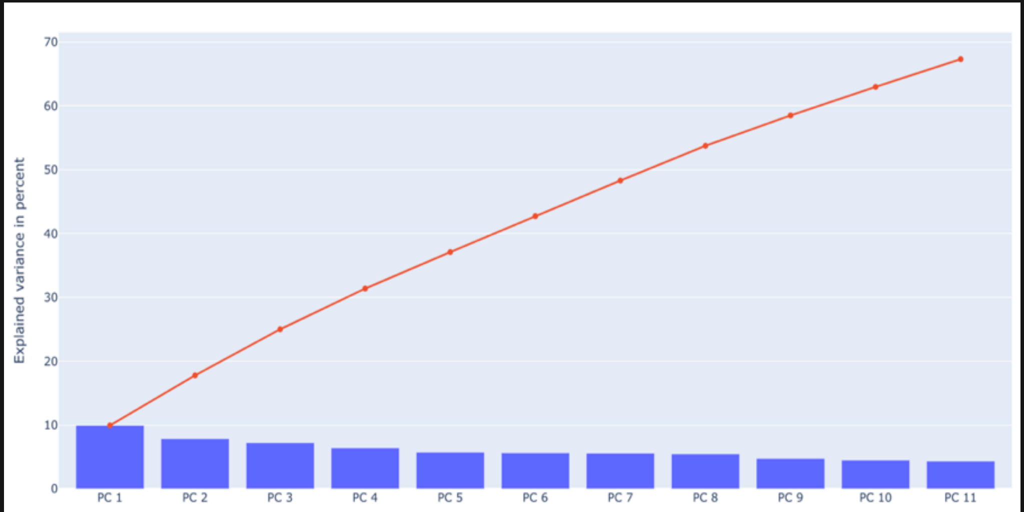


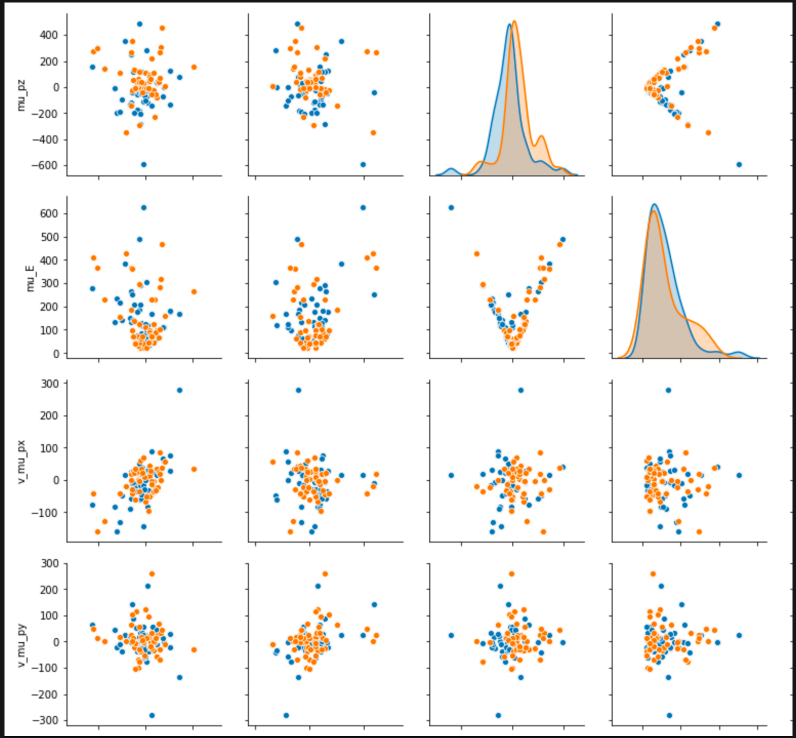


Given the current status of NISQ device we are limited in the number of features to map for our problem. To reduce the dimension of this space we apply the PCA analysis. We need to find balance between number of PCA and total variance explained

Ref: M. Grossi et all in preparation

Vector Boson Scattering – QSVM Flow





Given the current status of NISQ device we are limited in the number of features to map for our problem. To reduce the dimension of this space we apply the PCA analysis. We need to find balance between number of PCA and total variance explained

Ref: M. Grossi et all in preparation

Vector Boson Scattering – Angular Distribution

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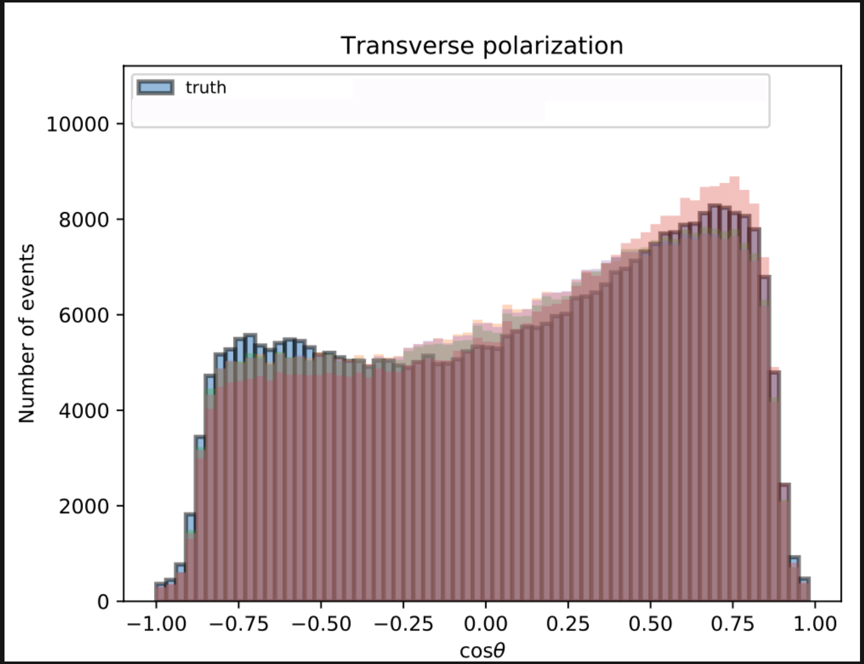

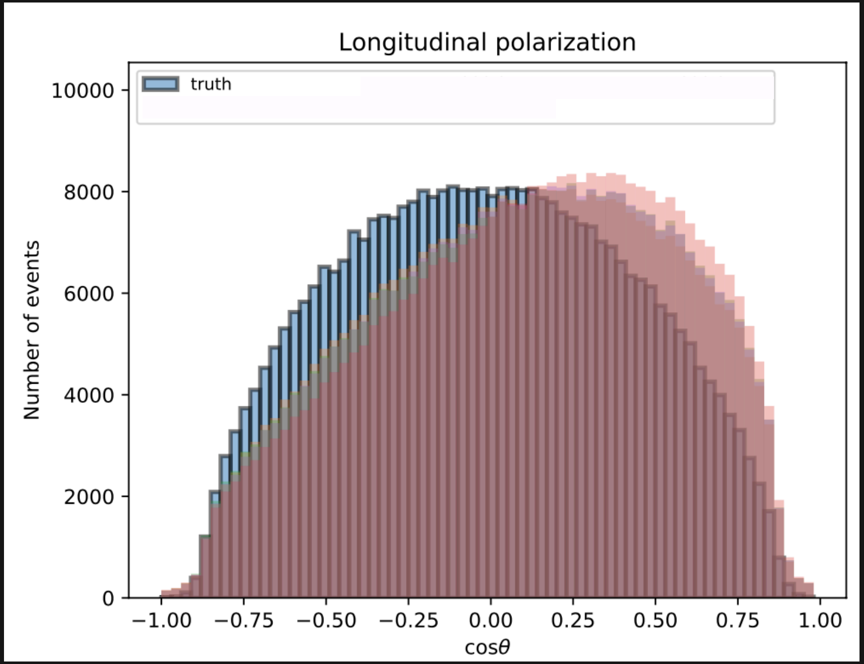

Ref: M. Grossi et all in preparation

Thank you!

There is a long road ahead, but quantum algorithms are very promising for modelling high energy scattering processes.

Michele Grossi

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