# Quantum computing in particle physics

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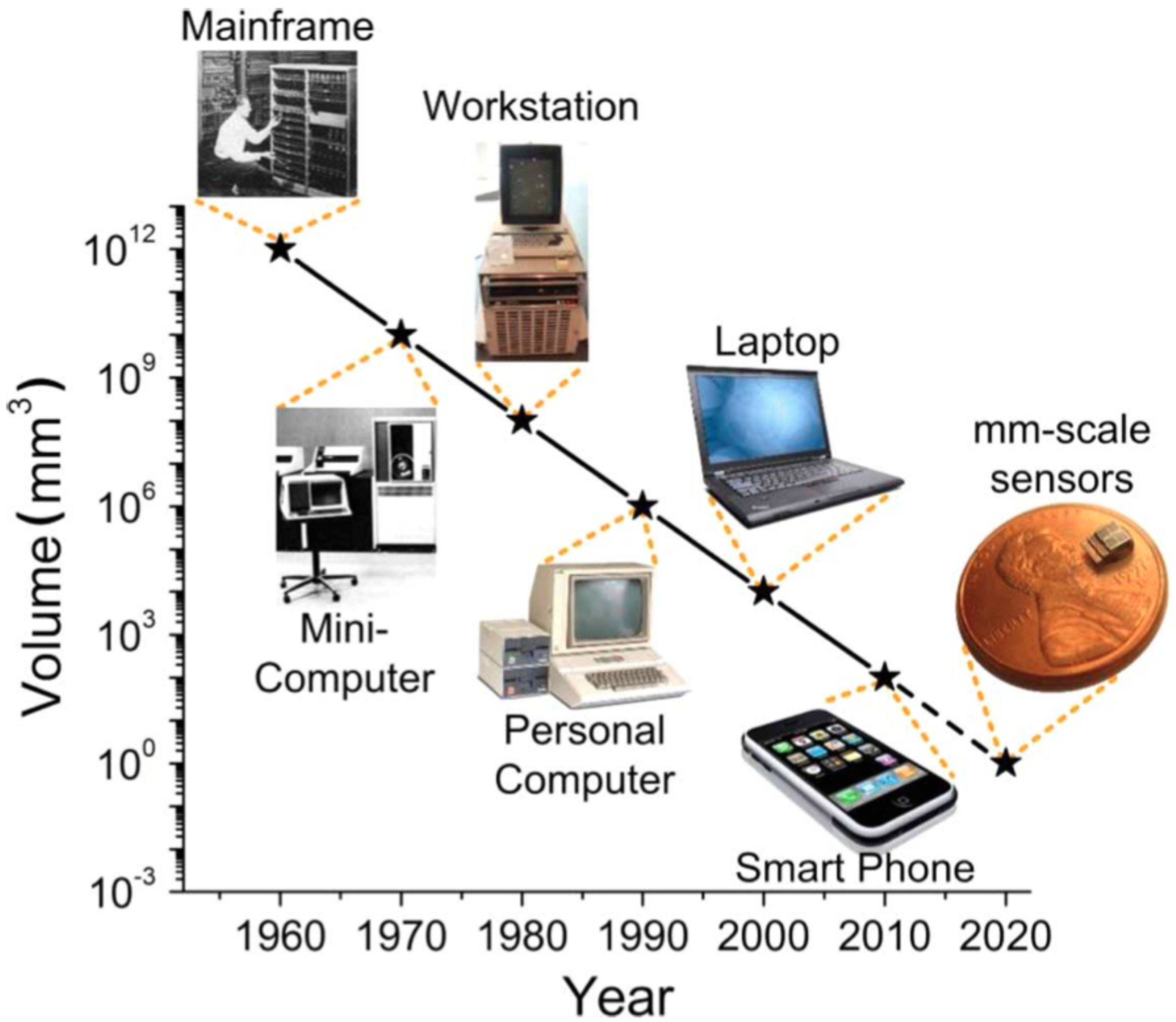
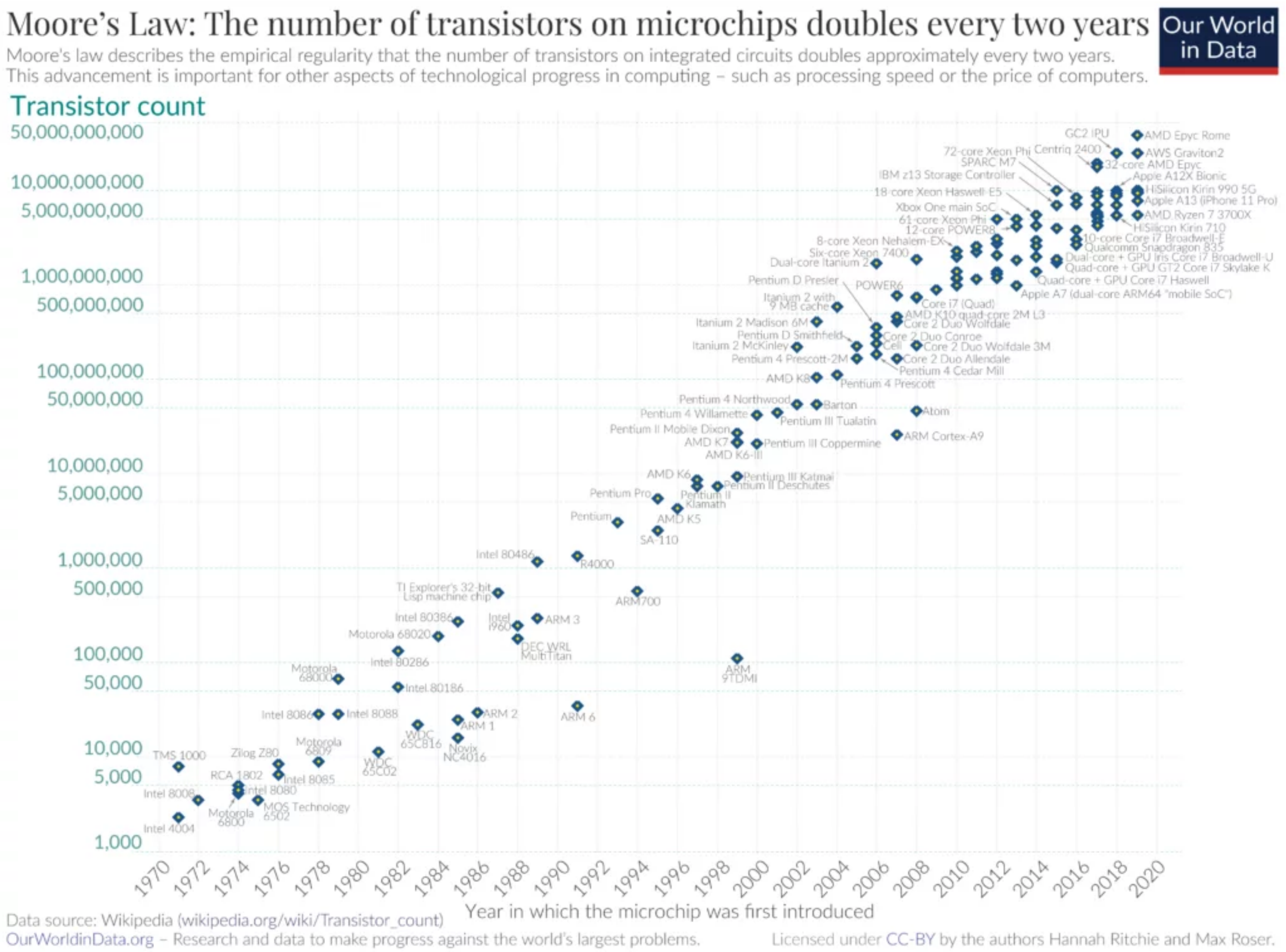
University College London

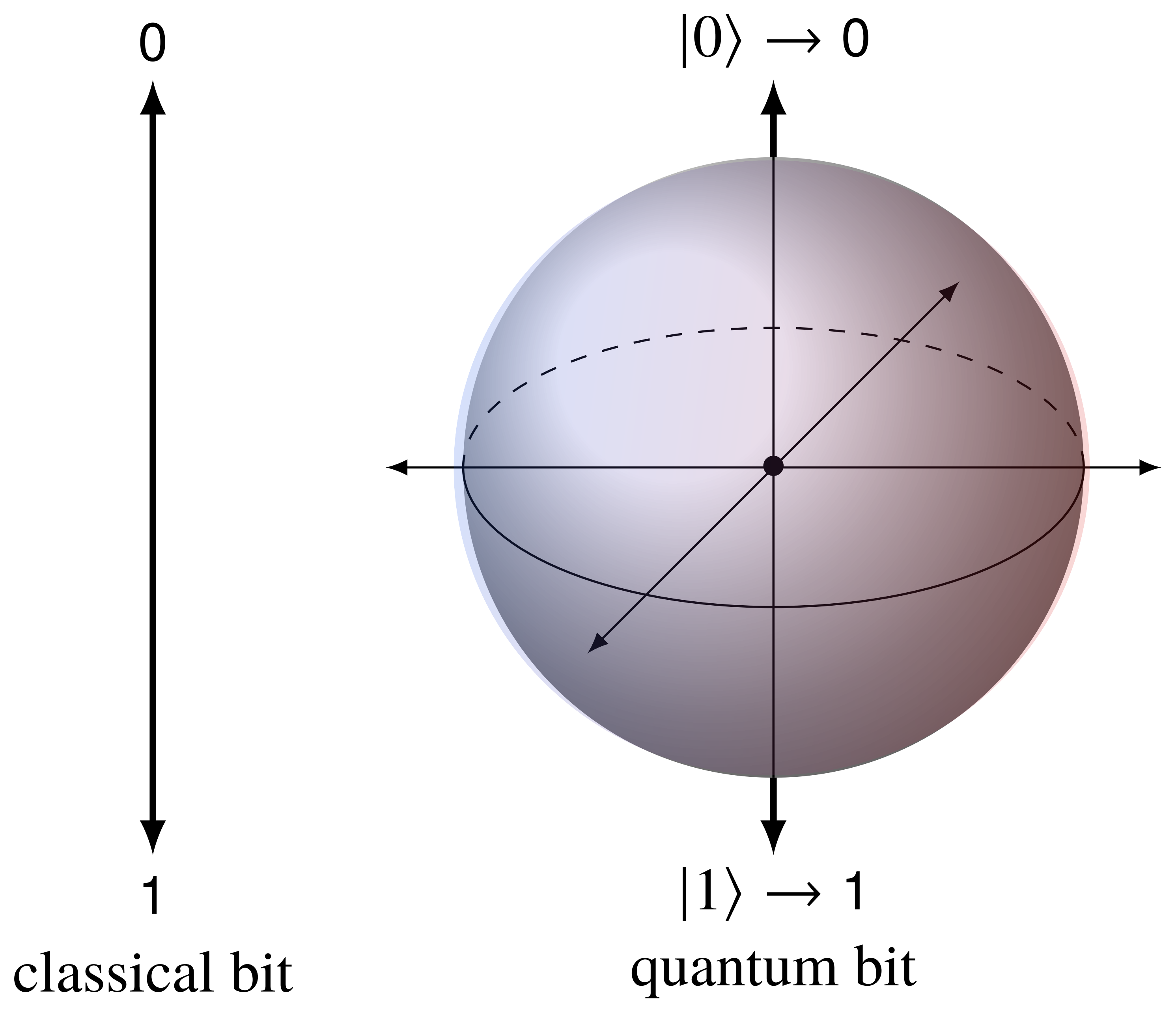
# Classical computing




- Trajectory of classical computers - could not have foreseen
- Quantum computer at similar stage of development as classical computers were in 1950s

# Bit vs qubit



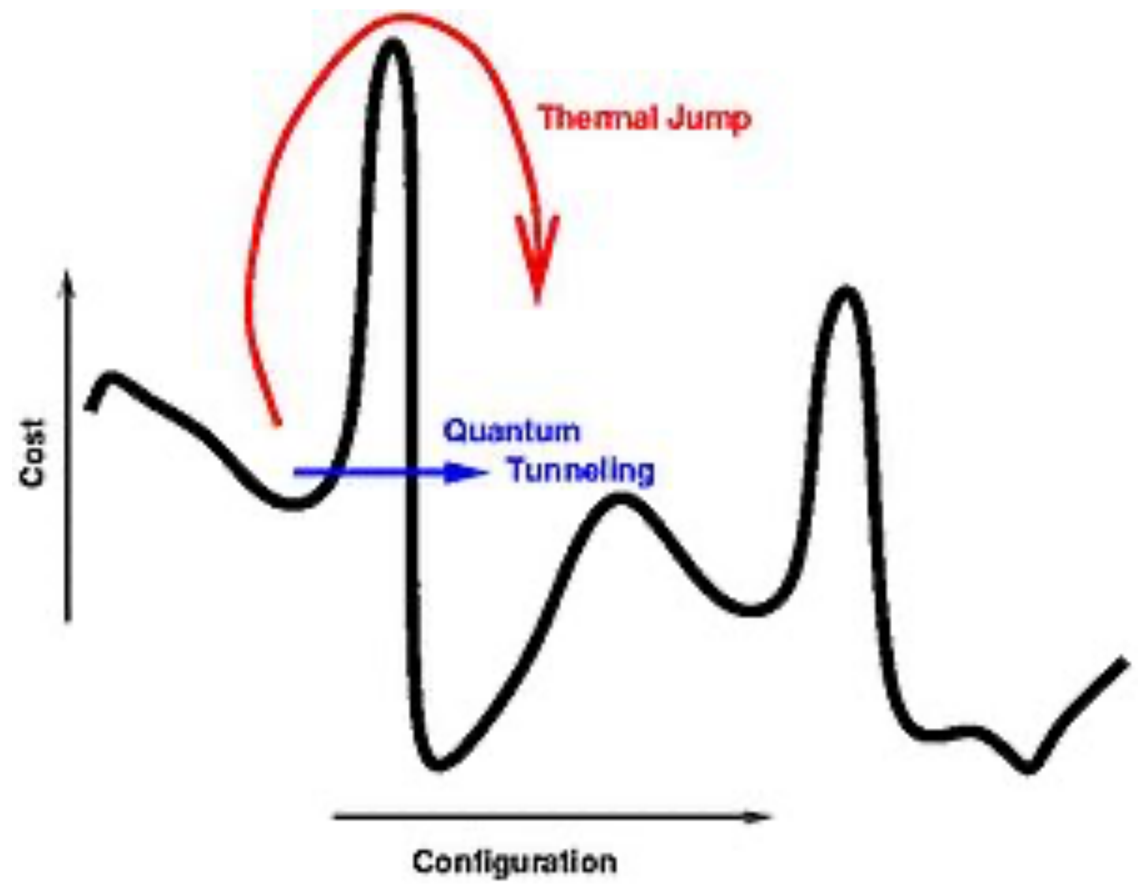

2-qubit system → 4 basis states $|00\rangle\,|01\rangle\,|10\rangle\,|11\rangle$

N qubits → $2^N$ dimensional Hilbert space

Power of quantum computing: this exponential increase in size of Hilbert space

# Quantum computing: Two classes/paradigms

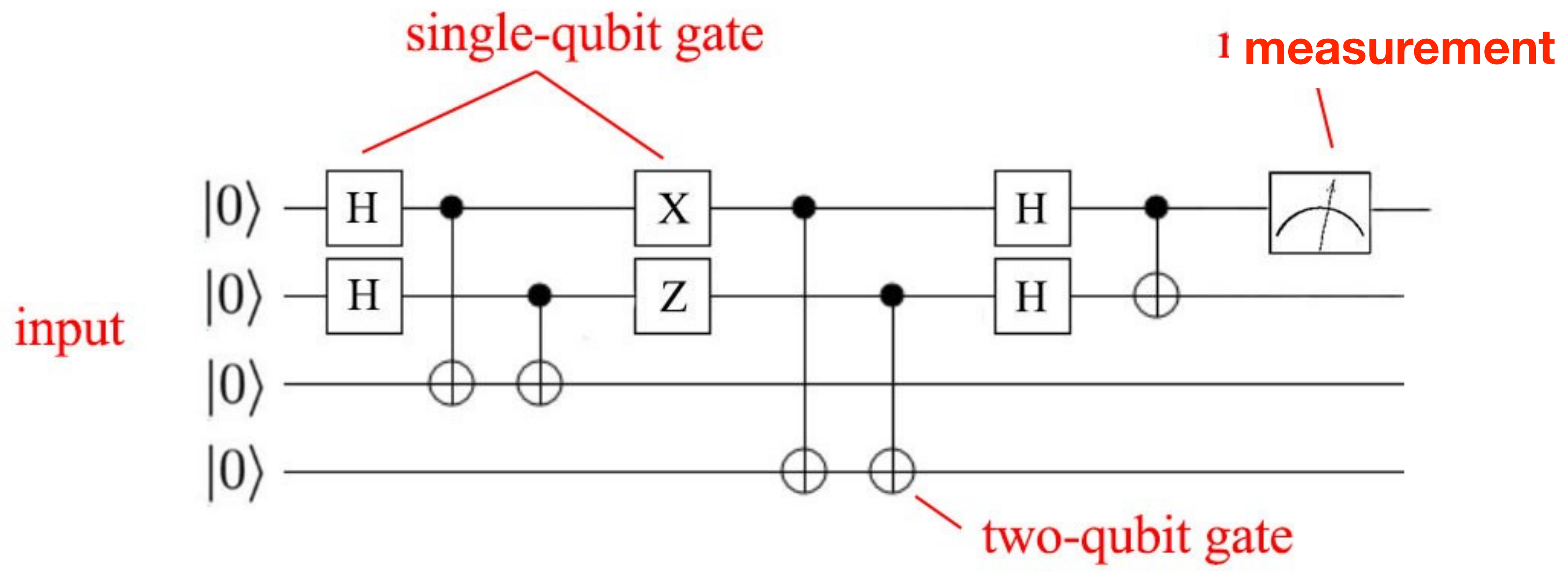
## Quantum Annealing




Find low-energy configurations of a complex energy landscape by using quantum tunnelling to escape local minima

- Large number of ‘noisy’ qubits
- Good for solving specific problems; for instance optimisation.
- D-Wave specialises in quantum annealers

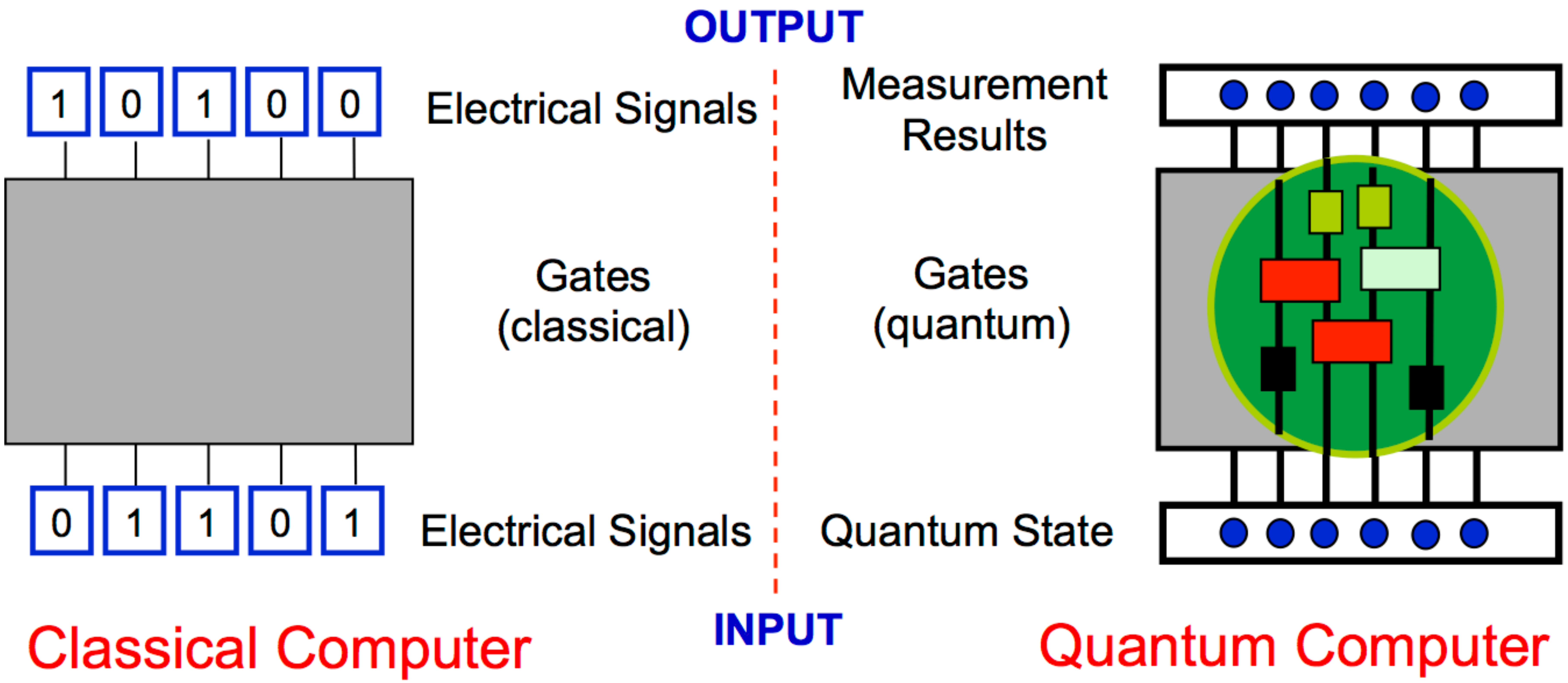
## Quantum Gate Circuit




Apply unitary transformations to qubits through discrete set of gates

- Small number of qubits but universal quantum computer
- Google, IBM, Microsoft, Rigetti focused on gate-based quantum computing

# Gate-based quantum computers




- similar structure, input is either classical bit, perform a series of gate based operations., both use logic gates. to manipulate the bits or qubits and then you make a measurement at the end.
- quantum gates operate on qubits and can leverage two key aspects of quantum phenomena that are not accessible to classical computers; superposition and entanglement.

# Quantum gates

### Hadamard gate

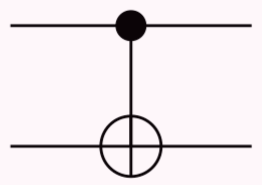
- One of the most frequently used and important gates in quantum computing
- Has no classical equivalent.
- It puts a qubit initialised in the $|0\rangle$ or $|1\rangle$ state into a superposition of states.

$$\mathrm{H}|0\rangle = \frac{1}{\sqrt{2}}\big(|0\rangle + |1\rangle\big), \qquad \mathrm{H}|1\rangle = \frac{1}{\sqrt{2}}\big(|0\rangle - |1\rangle\big).$$


### CNOT

- One of the most important gates
- 2-qubit operation, flips the state of a target qubit based on state of a control qubit.
- Used to create entangled qubits.

$$\mathrm{CNOT}|00\rangle = |00\rangle, \qquad \mathrm{CNOT}|01\rangle = |01\rangle,$$
$$\mathrm{CNOT}|10\rangle = |11\rangle, \qquad \mathrm{CNOT}|11\rangle = |10\rangle.$$

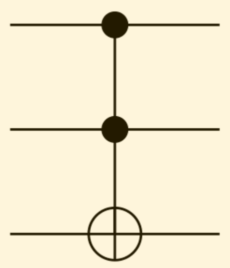


$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

### Toffoli (CCNOT)

- 3-qubit operation, an extension of CNOT but on 3 qubits
- Flips the state of a target qubit based on state of the 2 other control qubits

$$\mathrm{CCNOT}|000\rangle = |000\rangle, \qquad \mathrm{CCNOT}|001\rangle = |001\rangle,$$
$$\mathrm{CCNOT}|100\rangle = |100\rangle, \qquad \mathrm{CCNOT}|010\rangle = |010\rangle,$$
$$\mathrm{CCNOT}|110\rangle = |111\rangle, \qquad \mathrm{CCNOT}|111\rangle = |110\rangle.$$



$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}$$

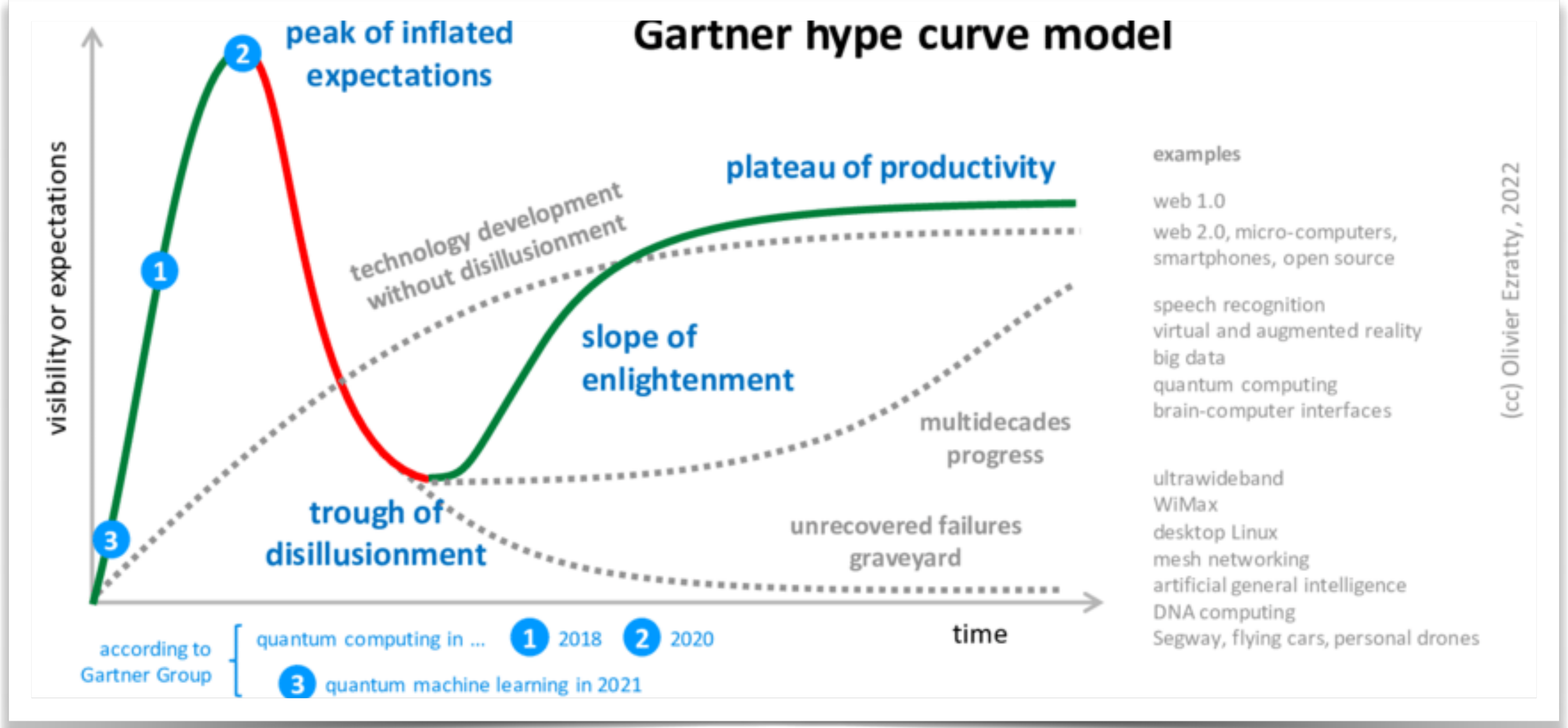
# Types of quantum computers

**A variety of different platforms with their own engineering challenges**

**No clear winner yet**

| Qubit Type | Pros/Cons | Select Players |
|---|---|---|
| **Superconducting** | ***Pros***: High gate speeds and fidelities. Can leverage standard lithographic processes. Among first qubit modalities so has a head start.<br>***Cons***: Requires cryogenic cooling; short coherence times; microwave interconnect frequencies still not well understood. | rigetti, Google, IBM Q, QuTech, OQC, IQM, qci Quantum Circuits, Inc, 本源量子 Origin Quantum |
| **Trapped Ions** | ***Pros***: Extremely high gate fidelities and long coherence times. Extreme cryogenic cooling not required. Ions are perfect and consistent.<br>***Cons***: Slow gate times/ operations and low connectivity between qubits. Lasers hard to align and scale. Ultra-high vacuum required. Ion charges may restrict scalability. | IONQ, AQT, QUANTINUUM, oxford ionics, Universal Quantum |
| **Photonics** | ***Pros***: Extremely fast gate speeds and promising fidelities. No cryogenics or vacuums required. Small overall footprint. Can leverage existing CMOS fabs.<br>***Cons***: Noise from photon loss; each program requires its own chip. Photons don't naturally interact so 2Q gate challenges. | PsiQuantum, XANADU, QuiX QUANTUM, ORCA Computing |
| **Neutral Atoms** | ***Pros***: Long coherence times. Atoms are perfect and consistent. Strong connectivity, including more than 2Q. External cryogenics not required.<br>***Cons***: Requires ultra-high vacuums. Laser scaling challenging. | ColdQuanta, QuEra Computing Inc., atom computing, PASQAL |
| **Silicon Spin/Quantum Dots** | ***Pros***: Leverages existing semiconductor technology. Strong gate fidelities and speeds.<br>***Cons***: Requires cryogenics. Only a few entangled gates to-date with low coherence times. Interference/cross-talk challenges. | intel, Silicon Quantum Computing, diraq, QUANTUM MOTION, QUANTUM BRILLIANCE |

# Quantum supremacy?





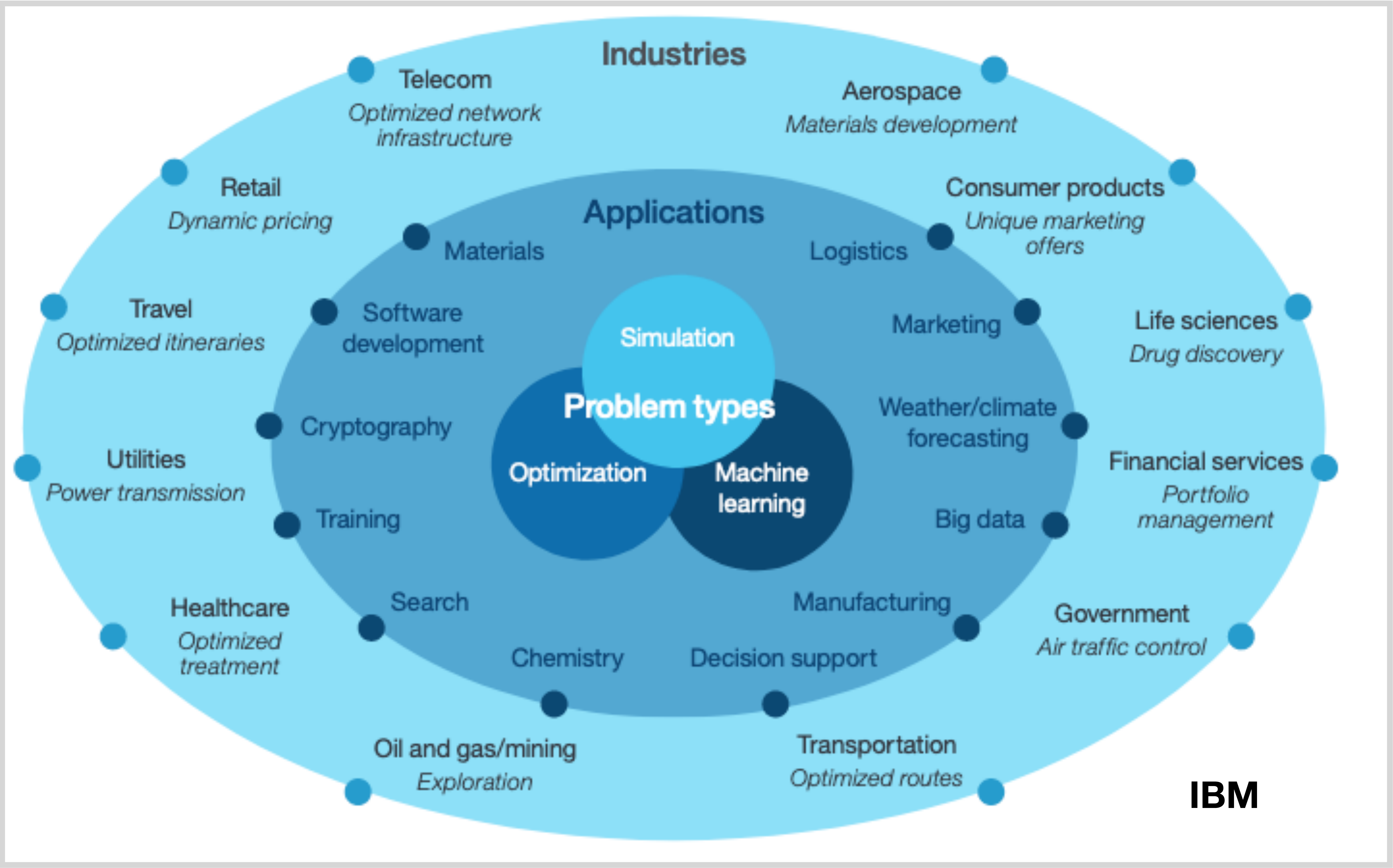
*Nature volume 574*

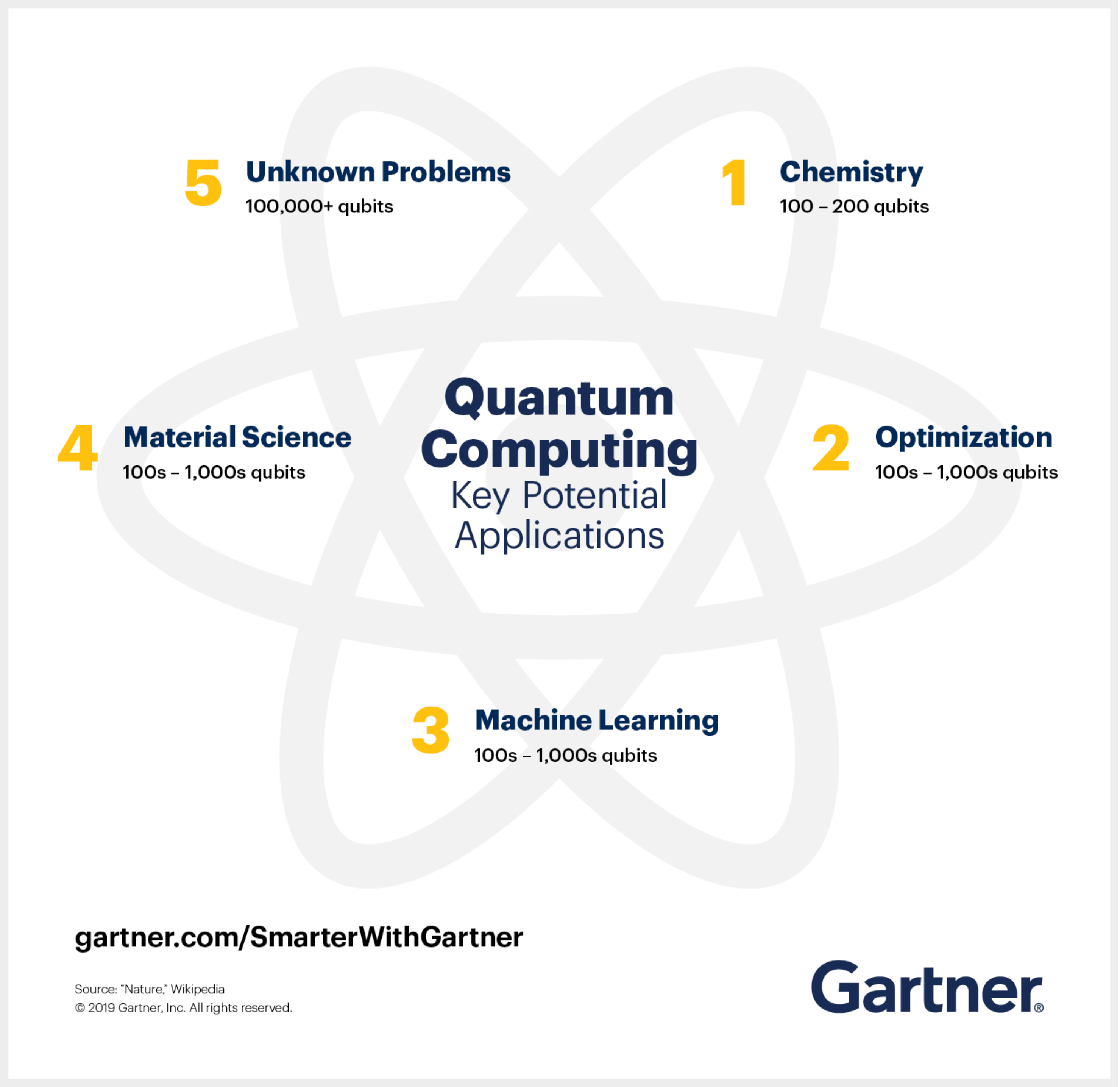
- **Google claimed quantum supremacy with 54-qubit quantum computer - performed a random sampling calculation in 3 mins, 20 sec.**

- **They claimed the this would take 10,000 years to do on classical machine.**

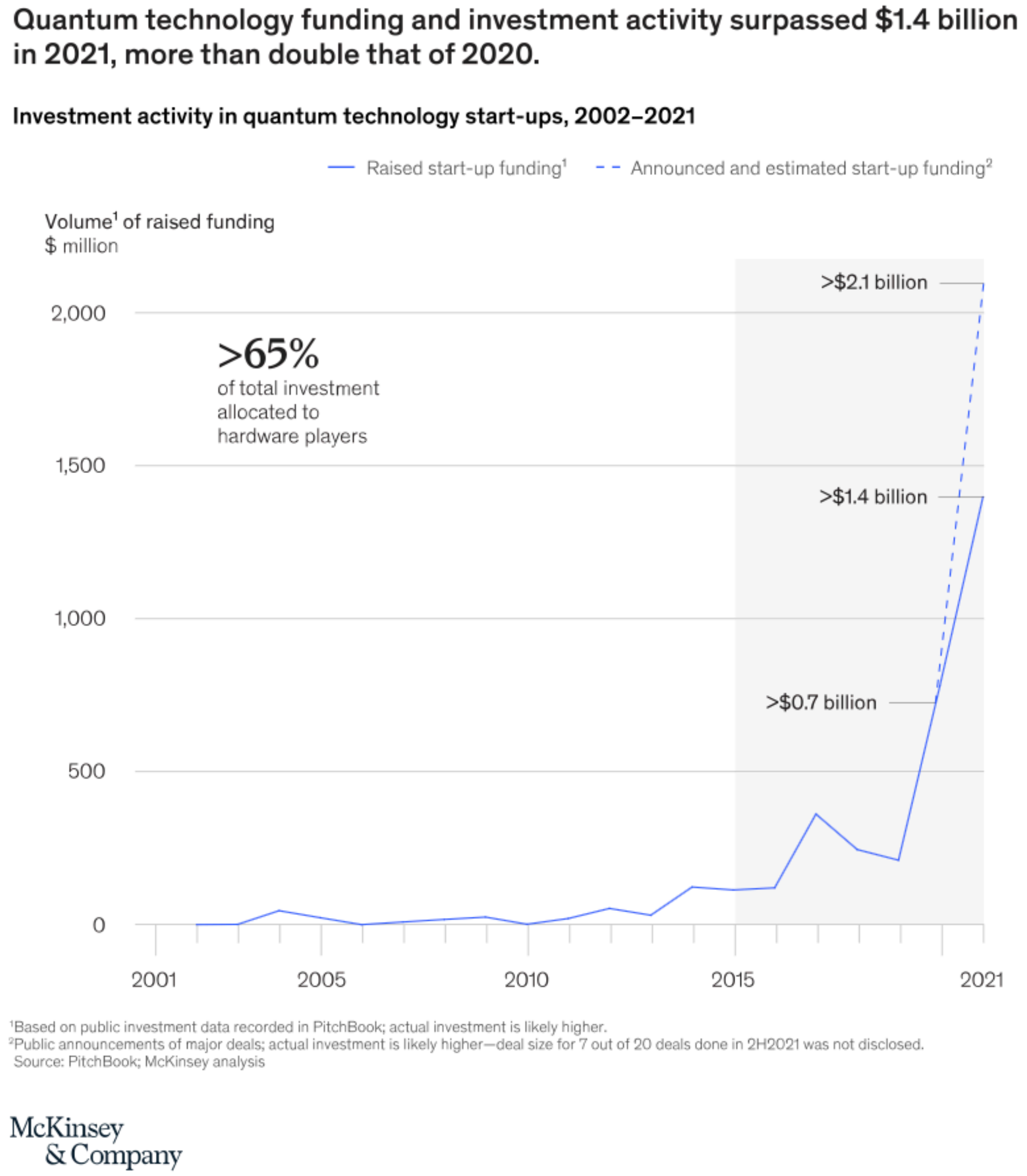
- **IBM counterclaim : can be done on classical machine in 2.5 days**

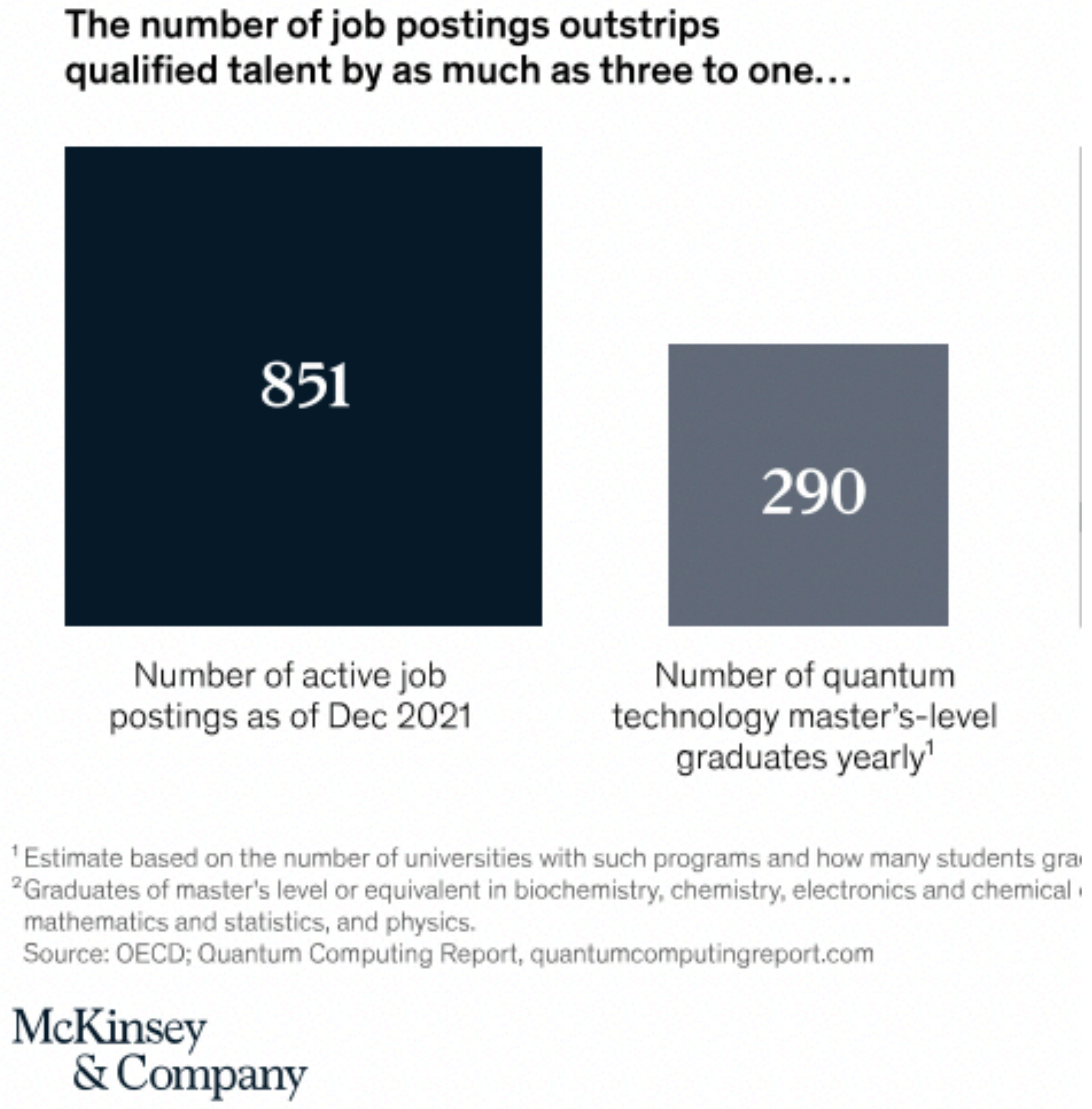
# Quantum computing : Potential applications



# Quantum computing : Investment & skills shortage




## UK to invest £2.5bn in quantum computing drive

Decade-long scheme intended to boost government pledge to make Britain 'next Silicon Valley'

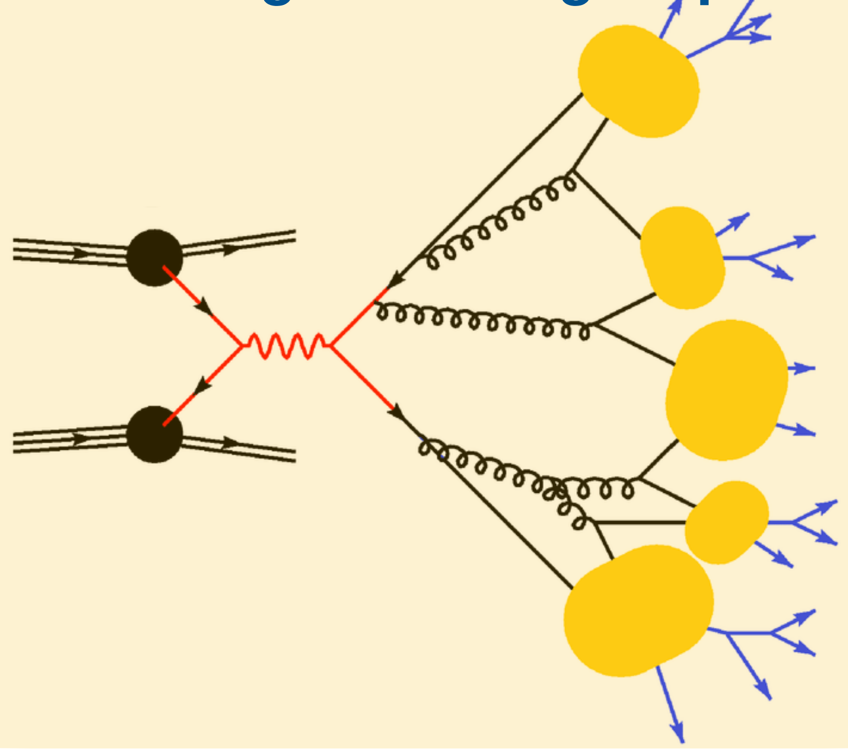
- £1 billion invested by UK govt, ~£200 million in venture capital and govt funding, ~40 UK SMEs
- Biggest bottleneck: acute skills shortage, need to have a 'quantum-ready' workforce

# Quantum computing in HEP

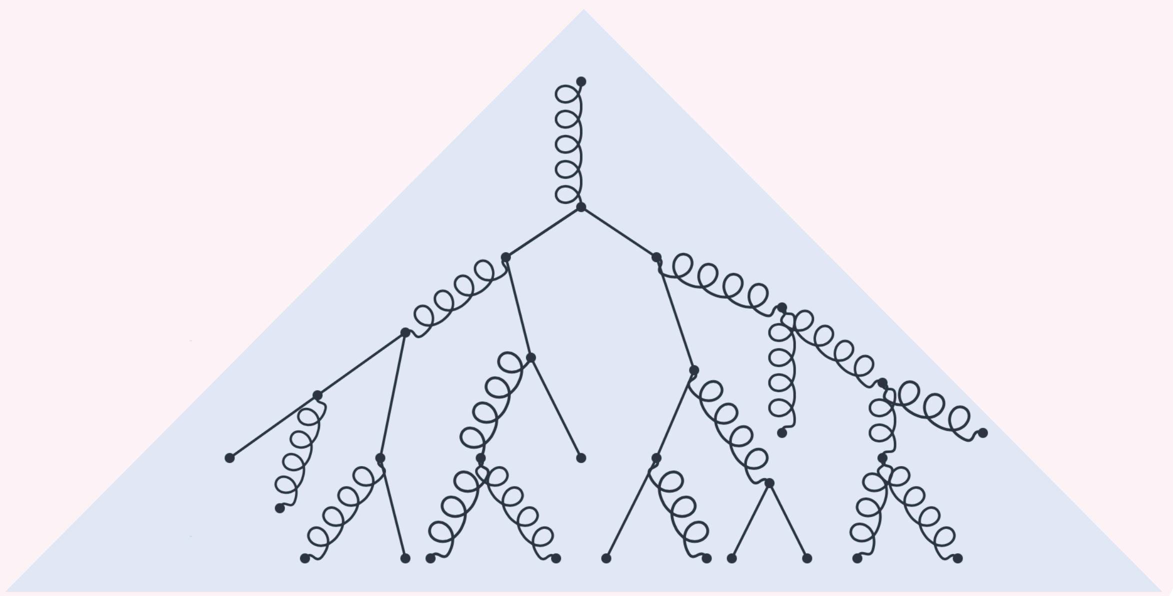
## Quantum computing approaches

- Quantum walk
- Support Vector Machine with quantum kernel
- Quantum Graph Neural Net
- Quantum-enhanced cellular automata
- *Quantum auto encoder*
- ……

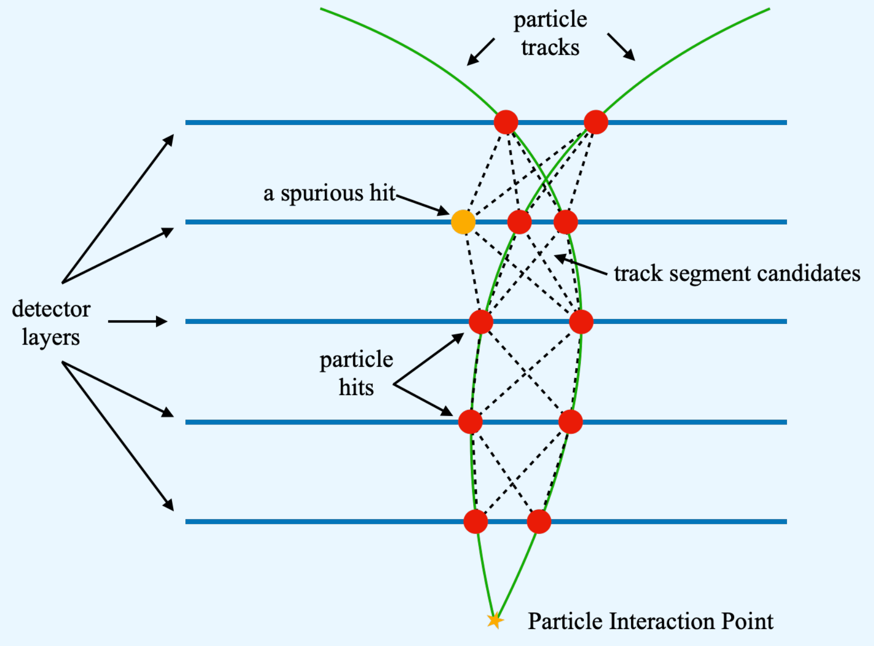
### Calculating scattering amplitudes



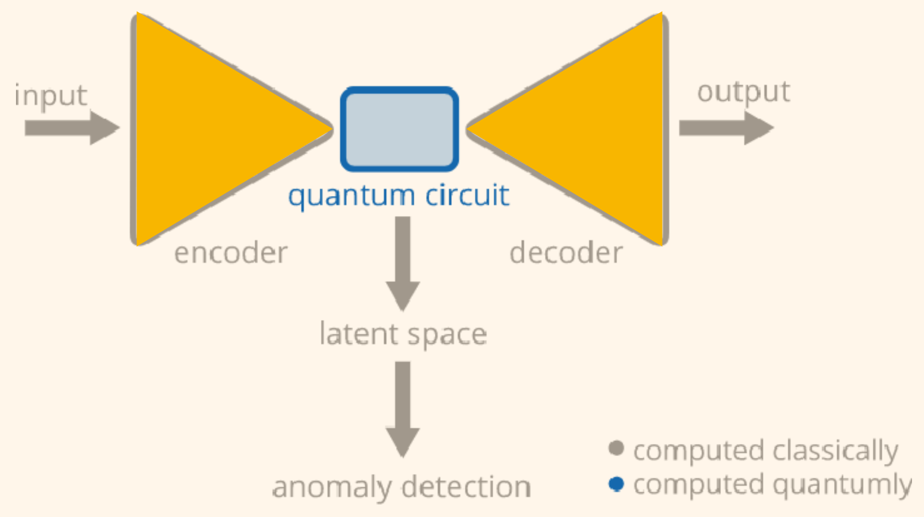
### Simulating parton shower



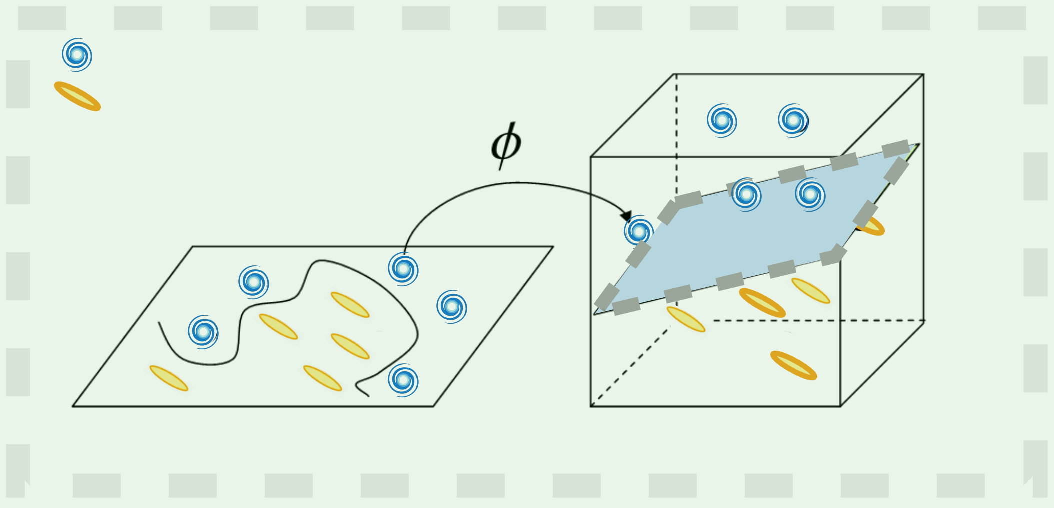
### Reconstructing particle tracks




### New physics search

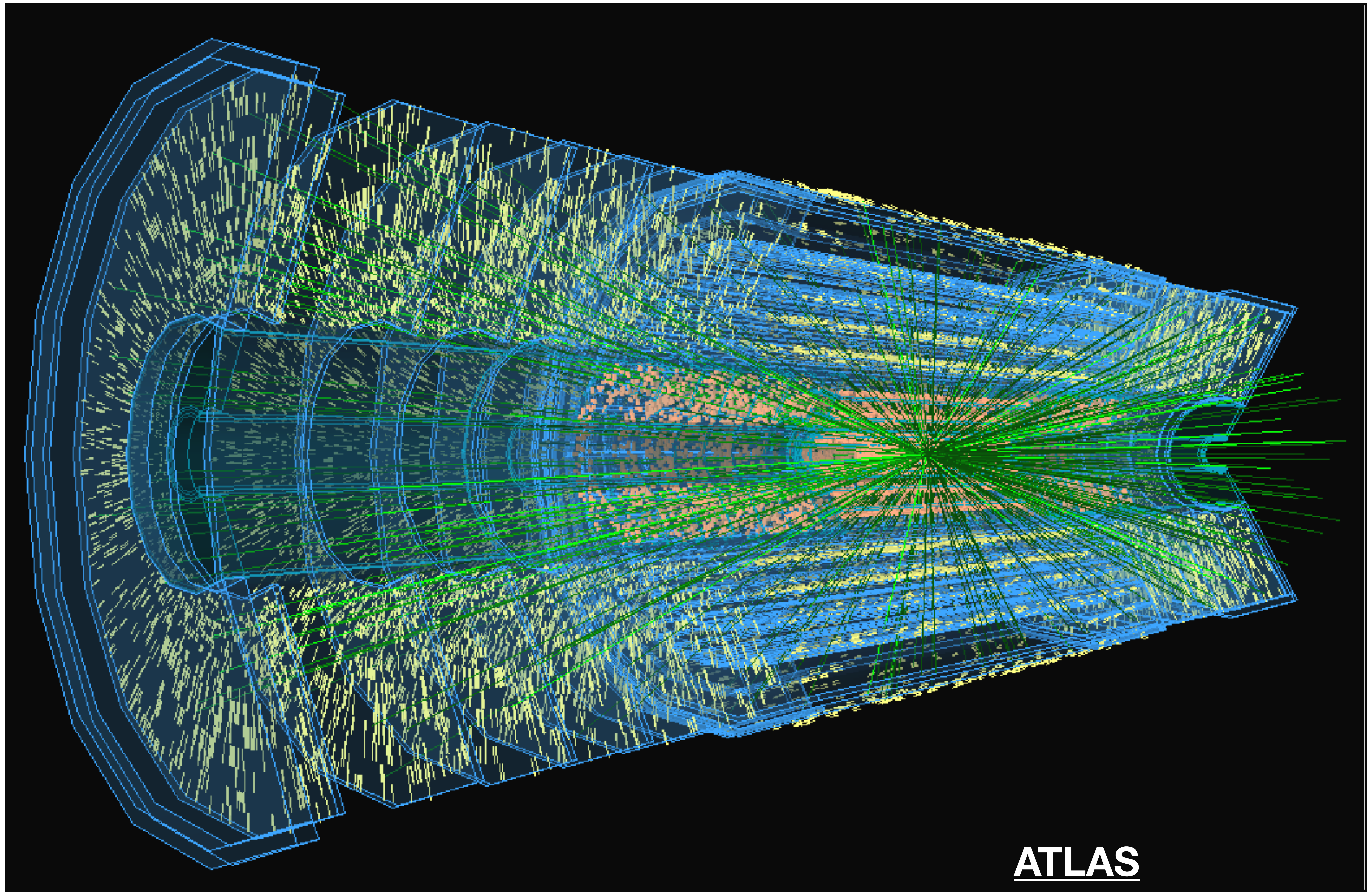



### Classifying galaxies



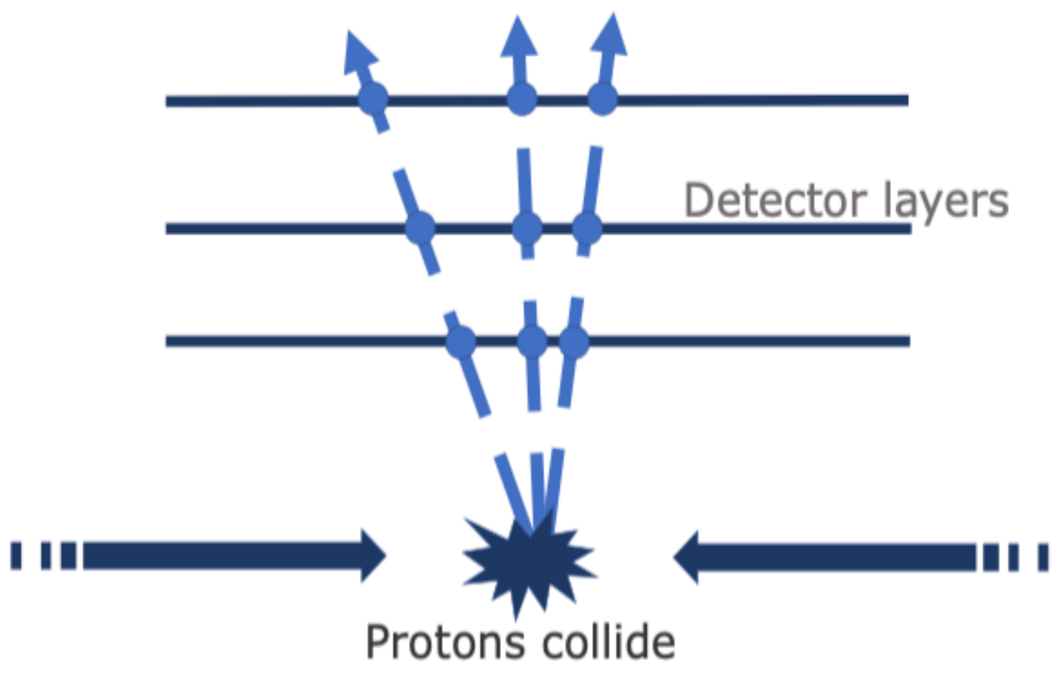
# Track reconstruction at upgraded LHC

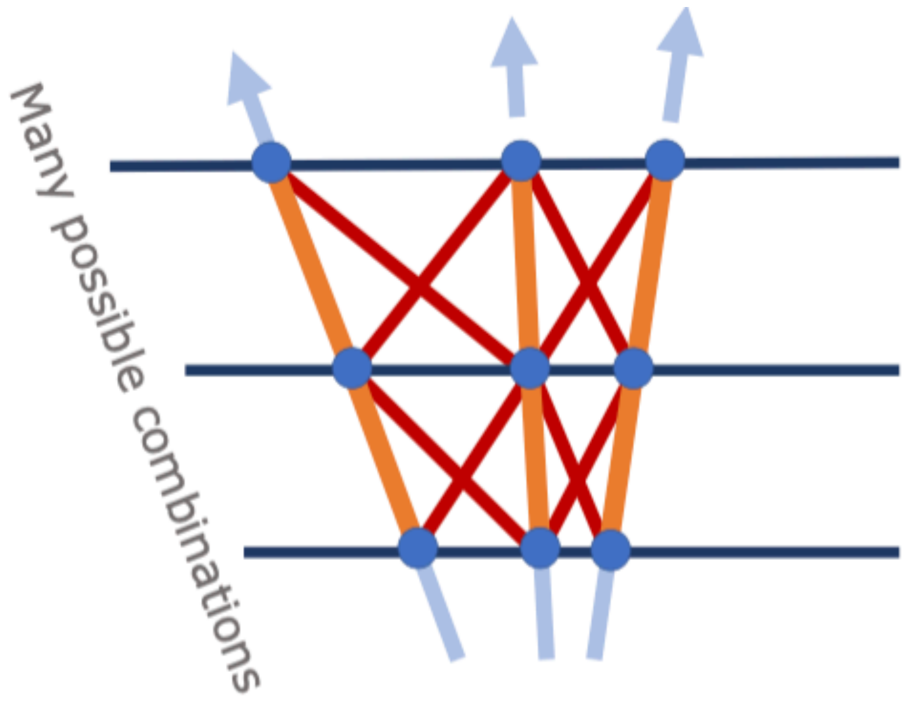
- One of the key challenges at upgraded LHC : track reconstruction in a very busy, high pileup environment (140 - 200 overlapping pp collisions)
- Much more CPU and storage needed
- Can quantum computers help?

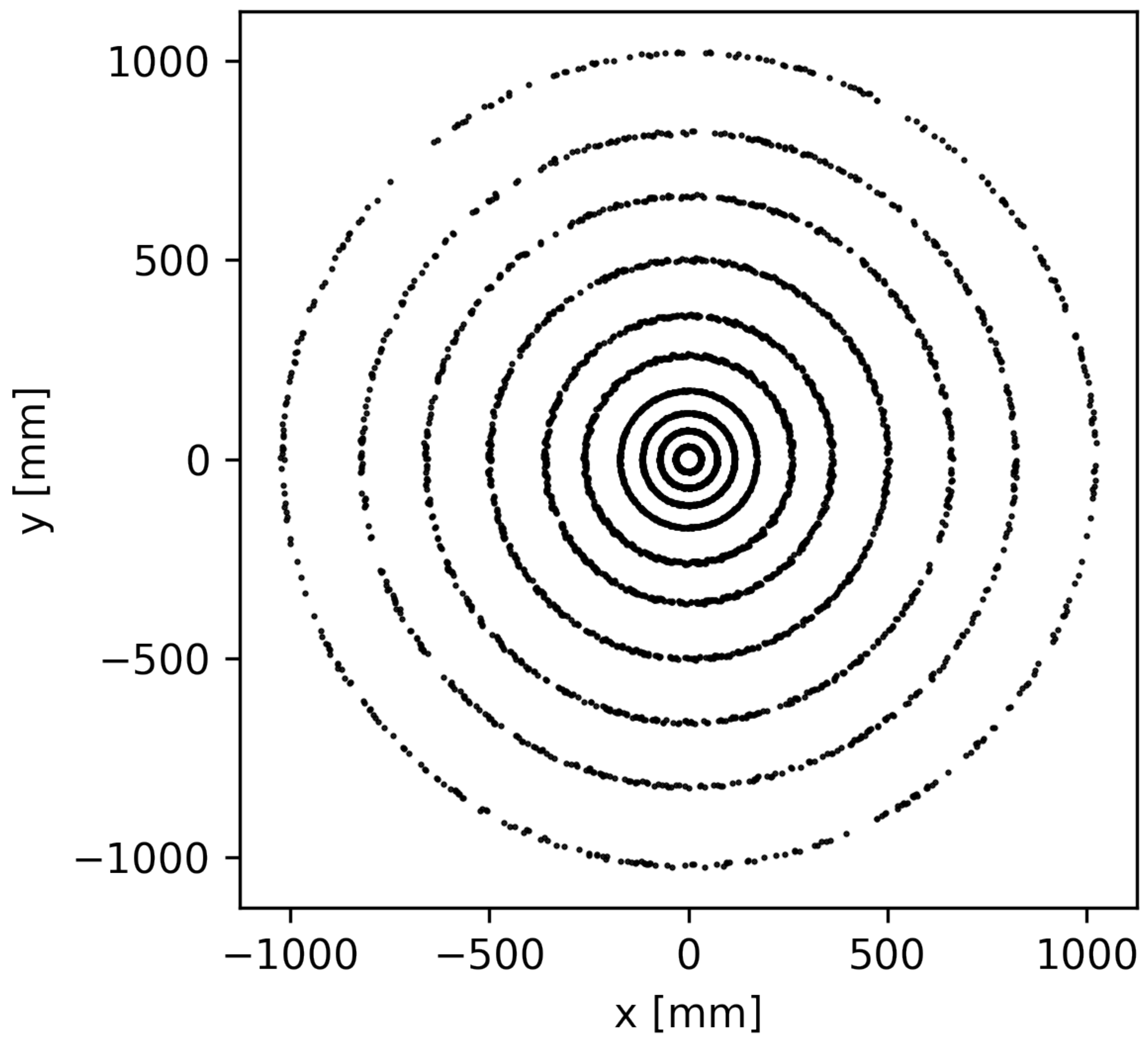


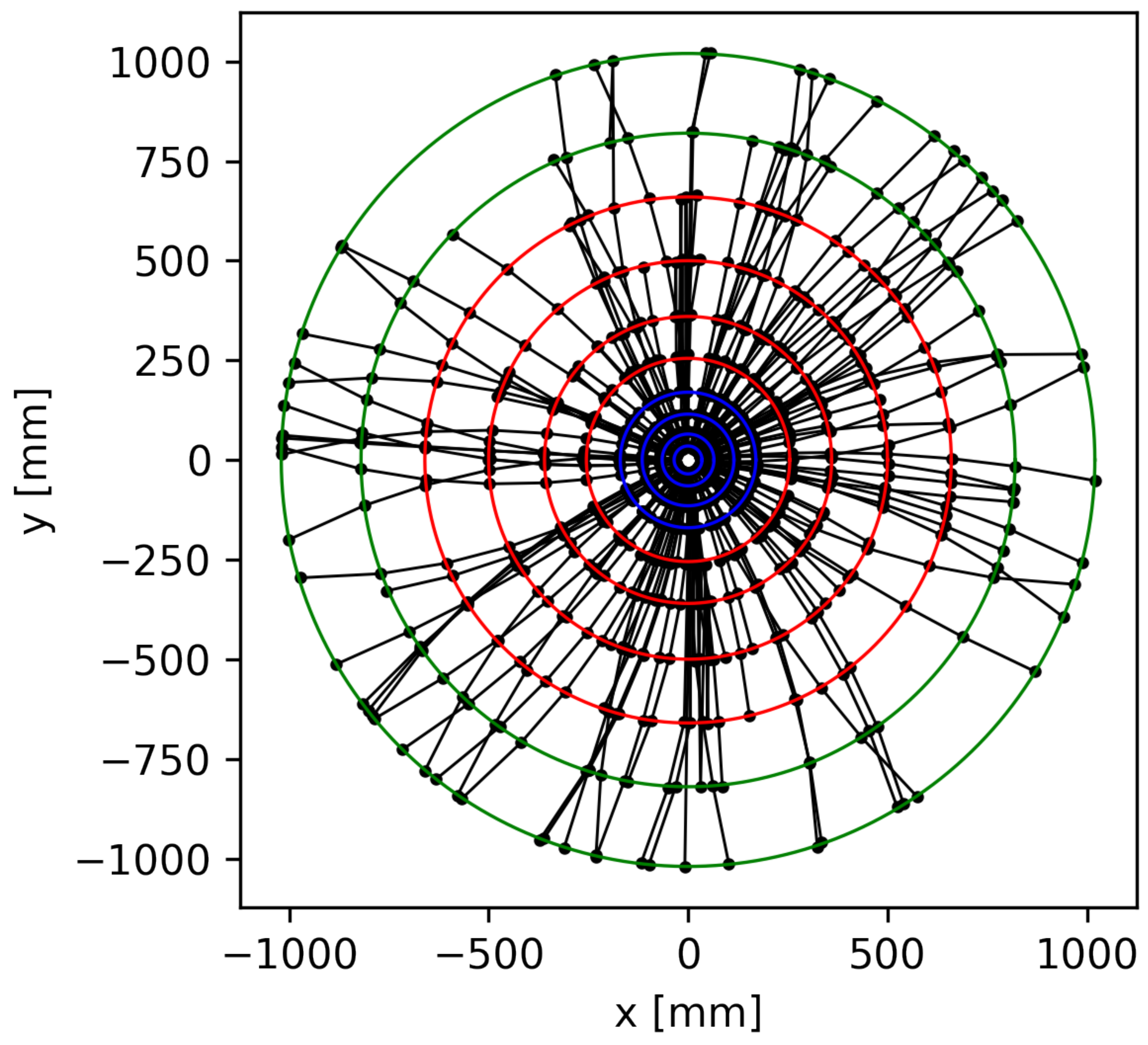
# Connecting the dots

*arXiv:2212.07279*



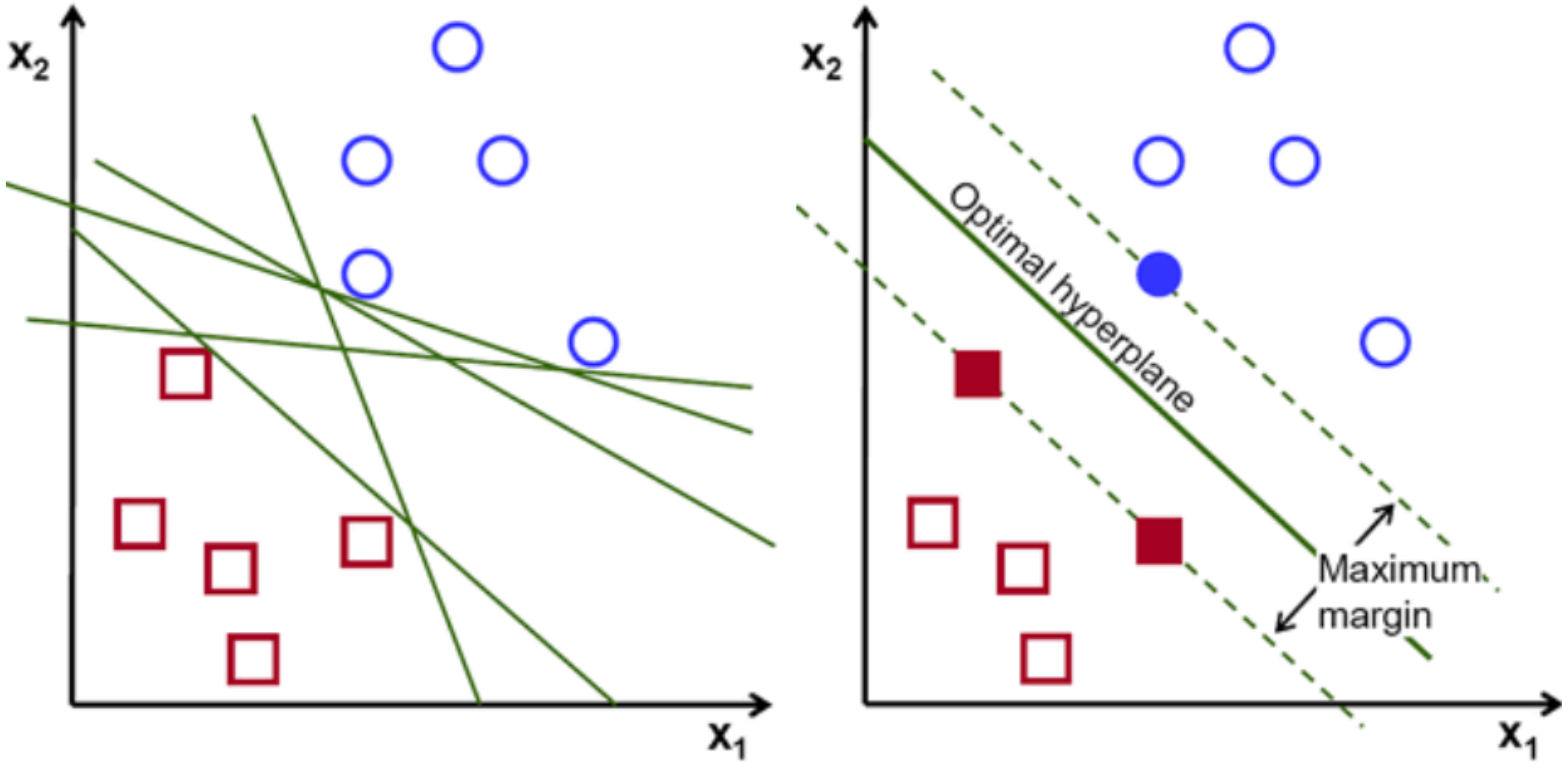

**100,000 hits in detector**

**10,000 particle tracks**

# Quantum machine learning

Reformulate as a classification task: Does a track segment (set of 3 consecutive hits) belong to a particle?

**Support vector machine**



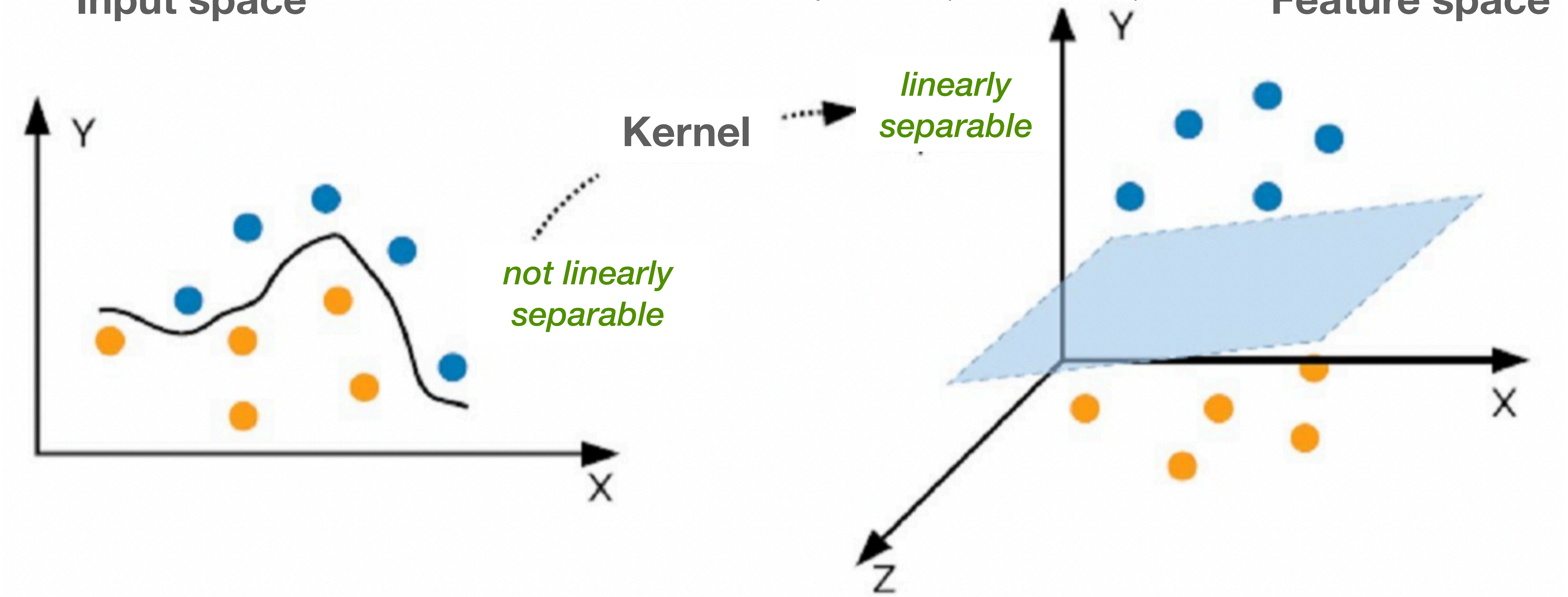

Support Vector Machine (SVM):

- Finds the optimal separating boundary between classes
- Uses only the closest data points (“support vectors”)
- Maximizes the margin for robust classification

# Quantum machine learning

Kernel:

- Measures similarity between data points
- Allows SVMs to operate in high-dimensional spaces implicitly
- Makes nonlinear classification possible (“kernel trick”)

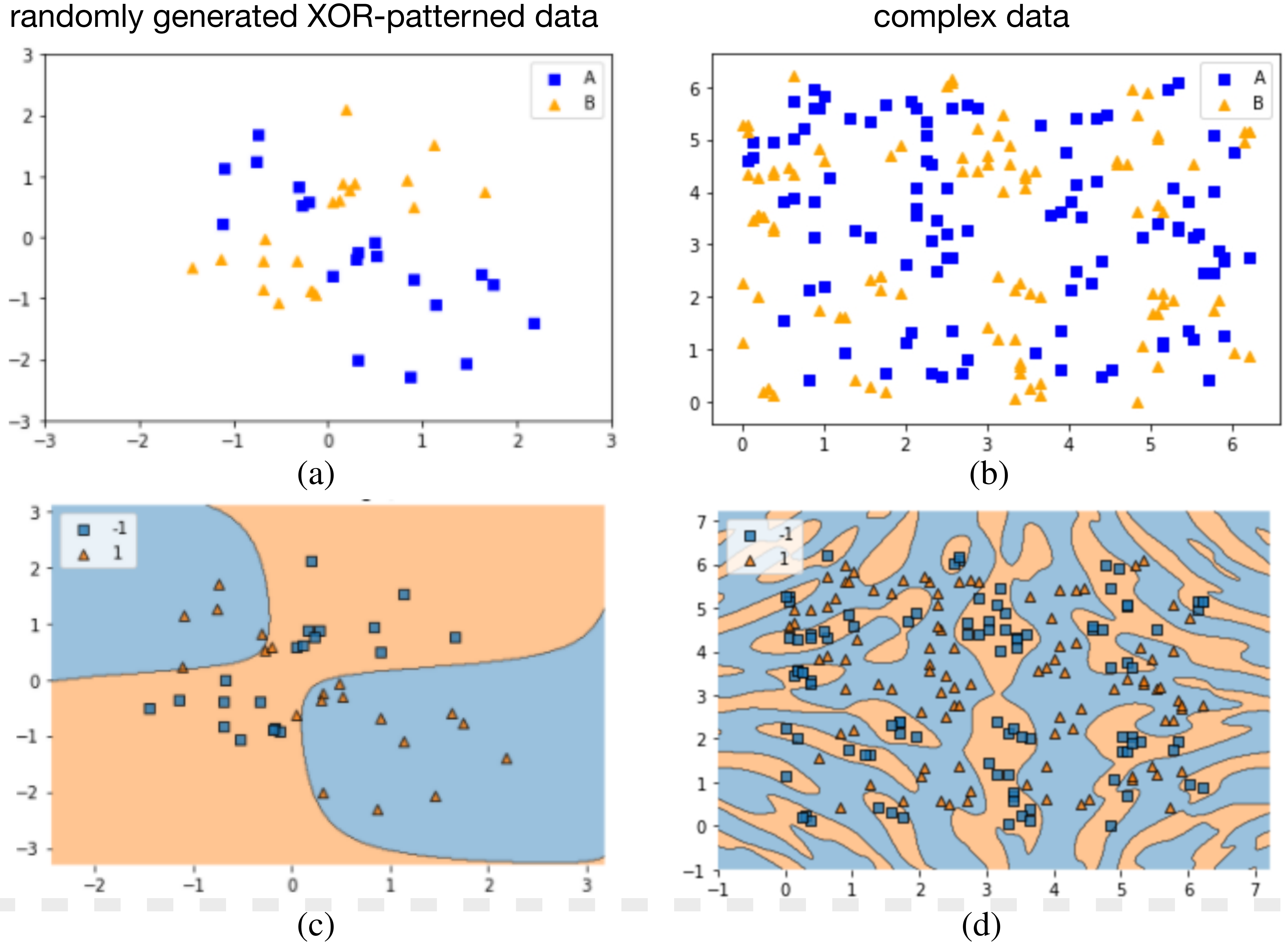



**Support vector machine with quantum kernel**

# Quantum SVM and kernels

arXiv:2012.07725

**Quantum SVM and kernels can efficiently exploit higher dimensional space and generate feature maps that are difficult for classical kernel functions**



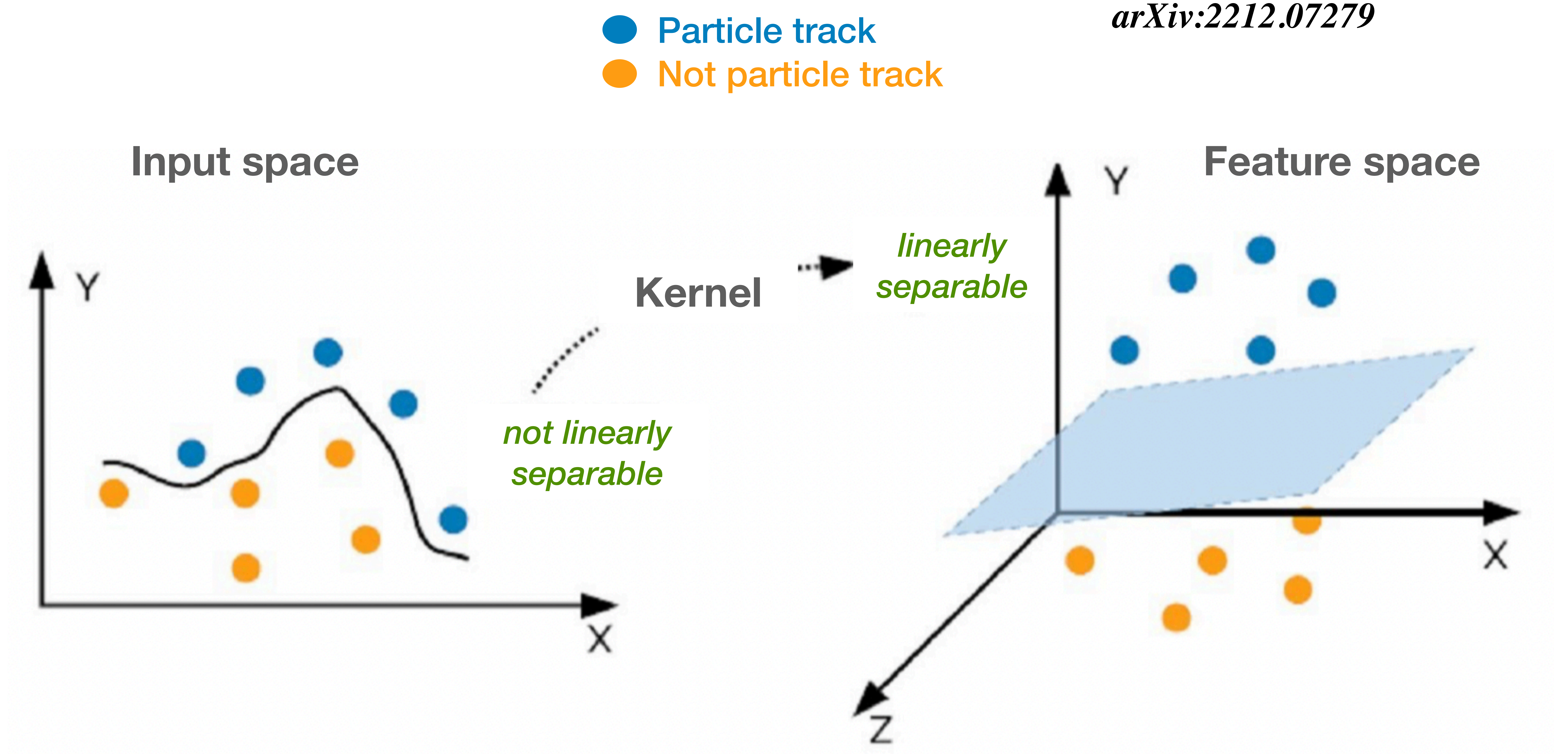

Comparing two artificially generated datasets with different levels of complexity

Quantum SVM flexible enough to get the decision boundary for simple and complex datasets.

# Quantum machine learning

Reformulate as a classification task: Does a track segment (set of 3 consecutive hits) belong to a particle?

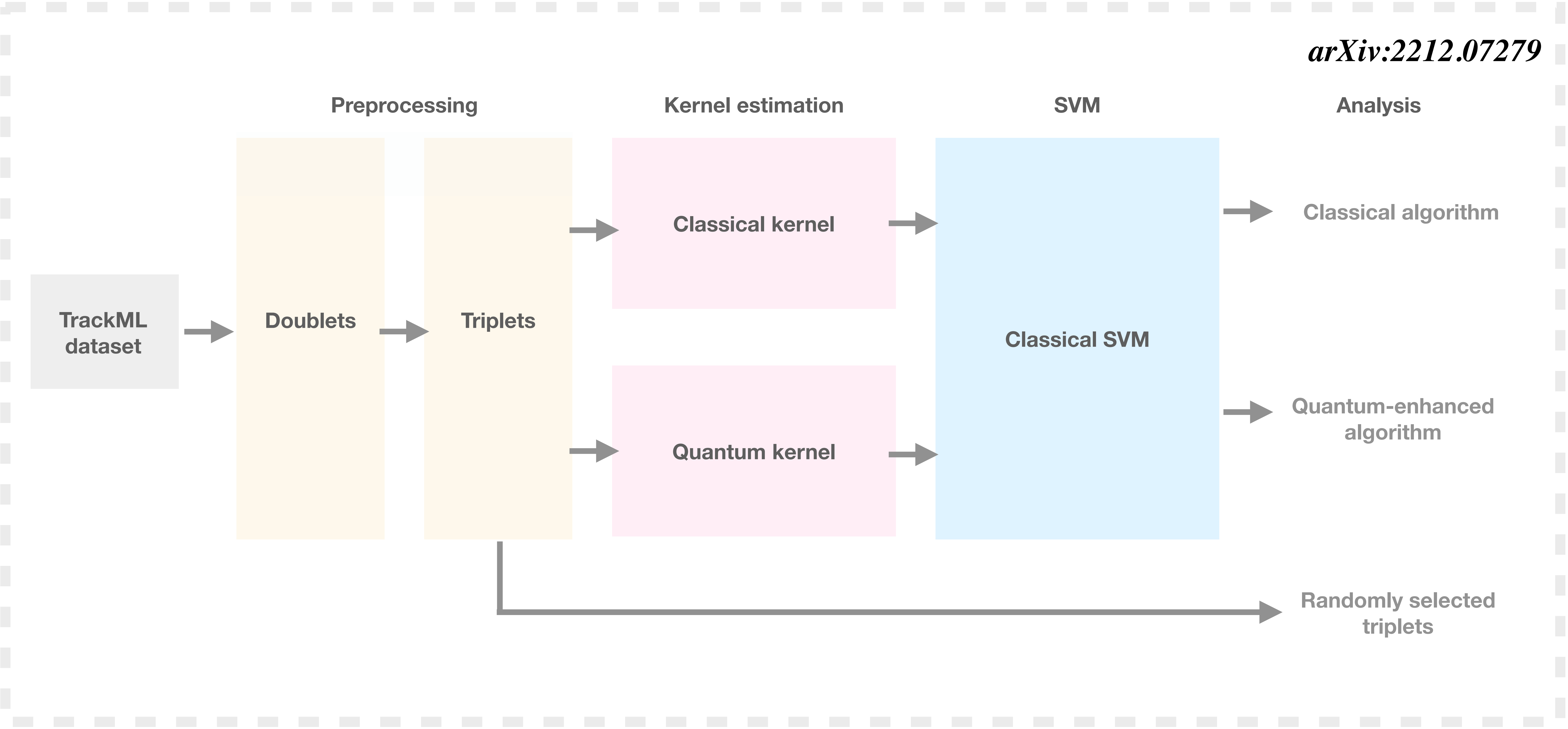
*arXiv:2212.07279*




**Support vector machine with quantum kernel**

# Quantum machine learning

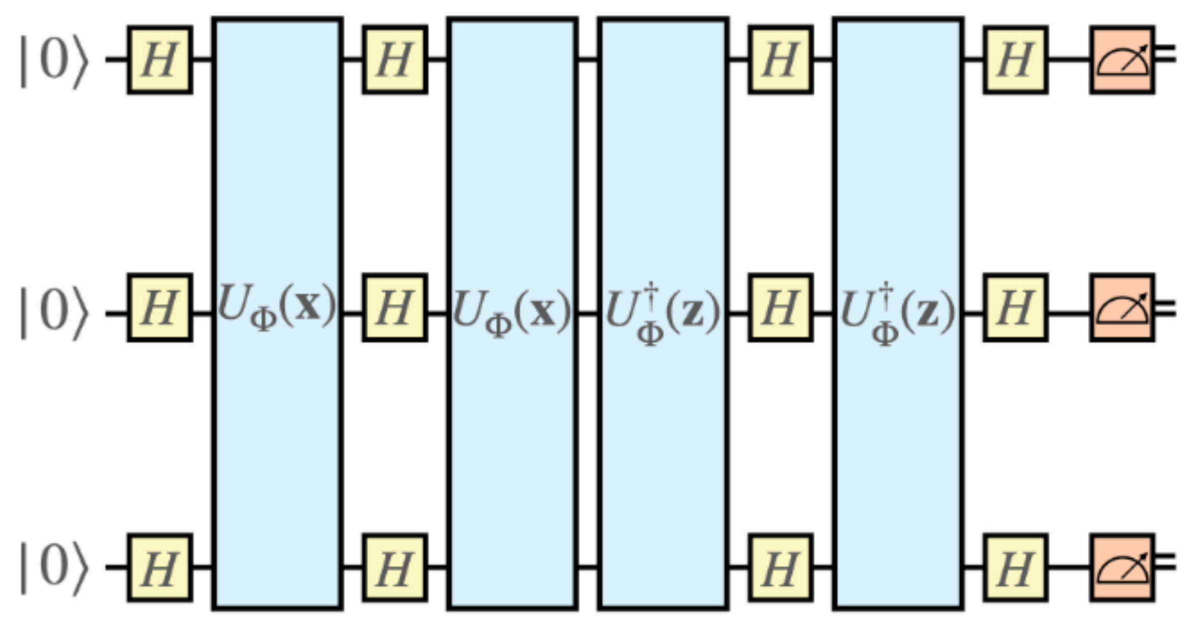
Reformulate as a classification task: Does a track segment (set of 3 consecutive hits) belong to a particle?



# Quantum machine learning

Reformulate as a classification task: Does a track segment (set of 3 consecutive hits) belong to a particle?

Quantum circuit to compute kernel

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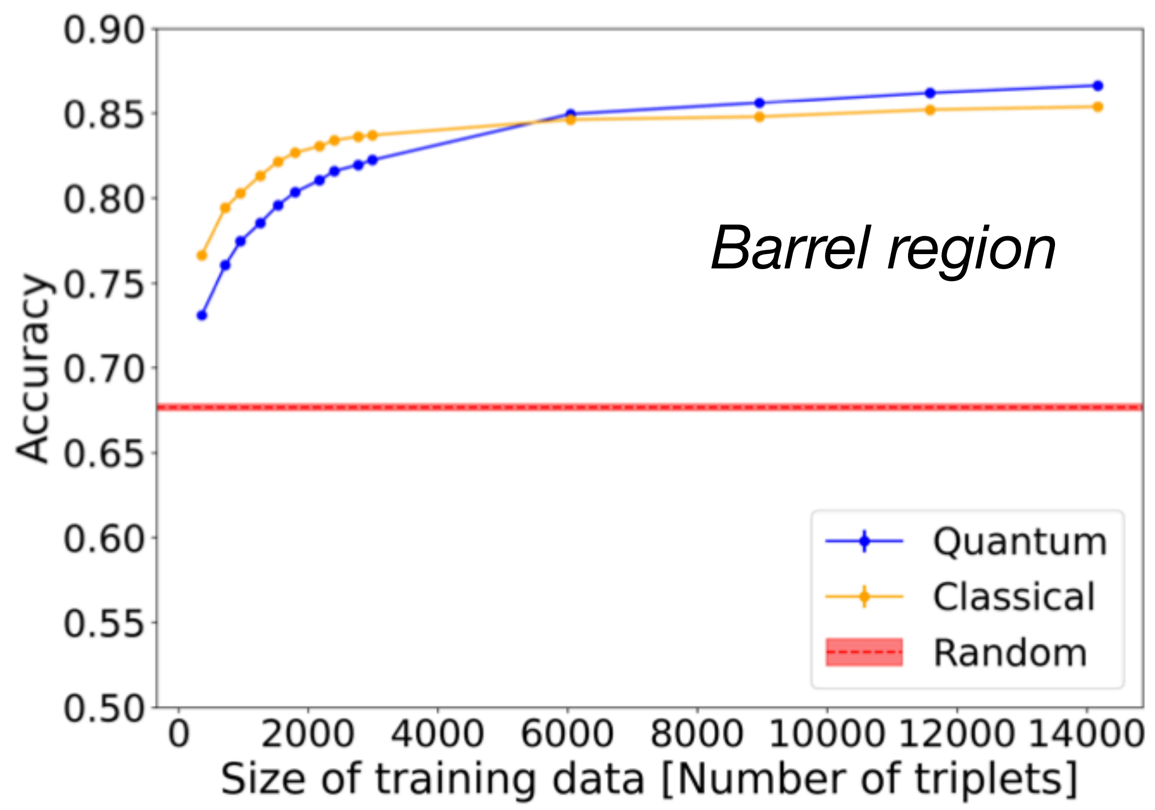
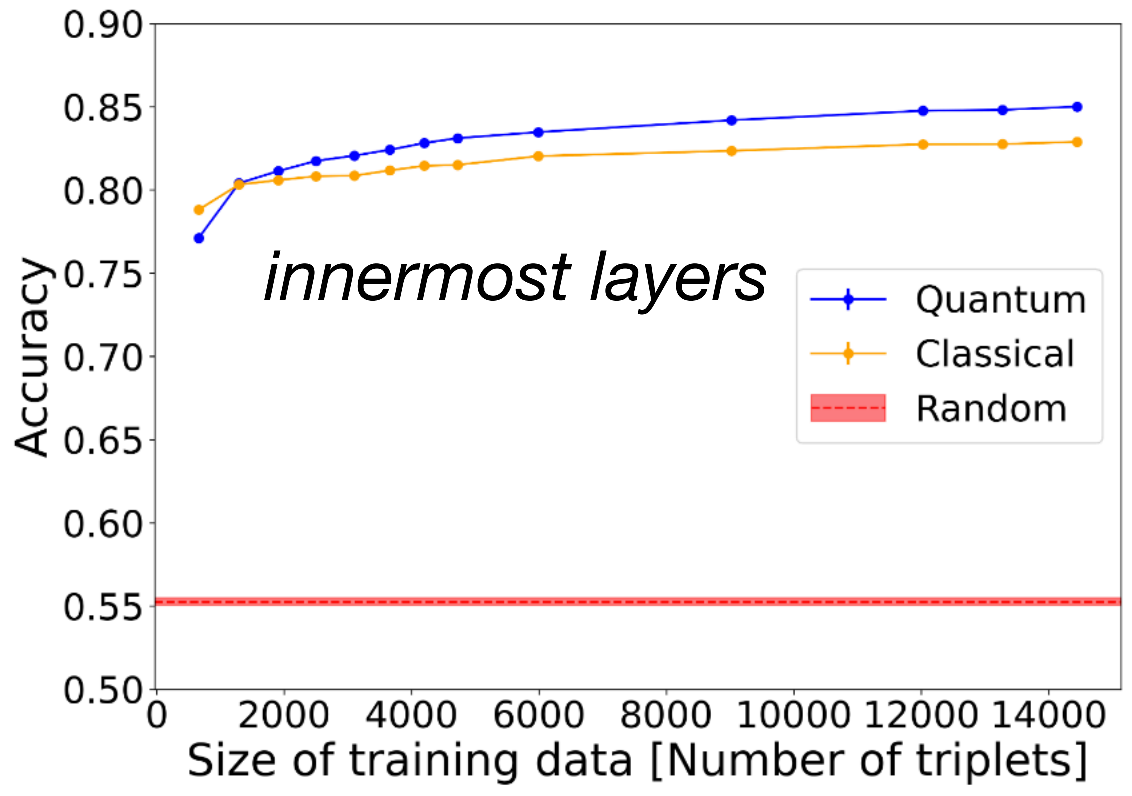
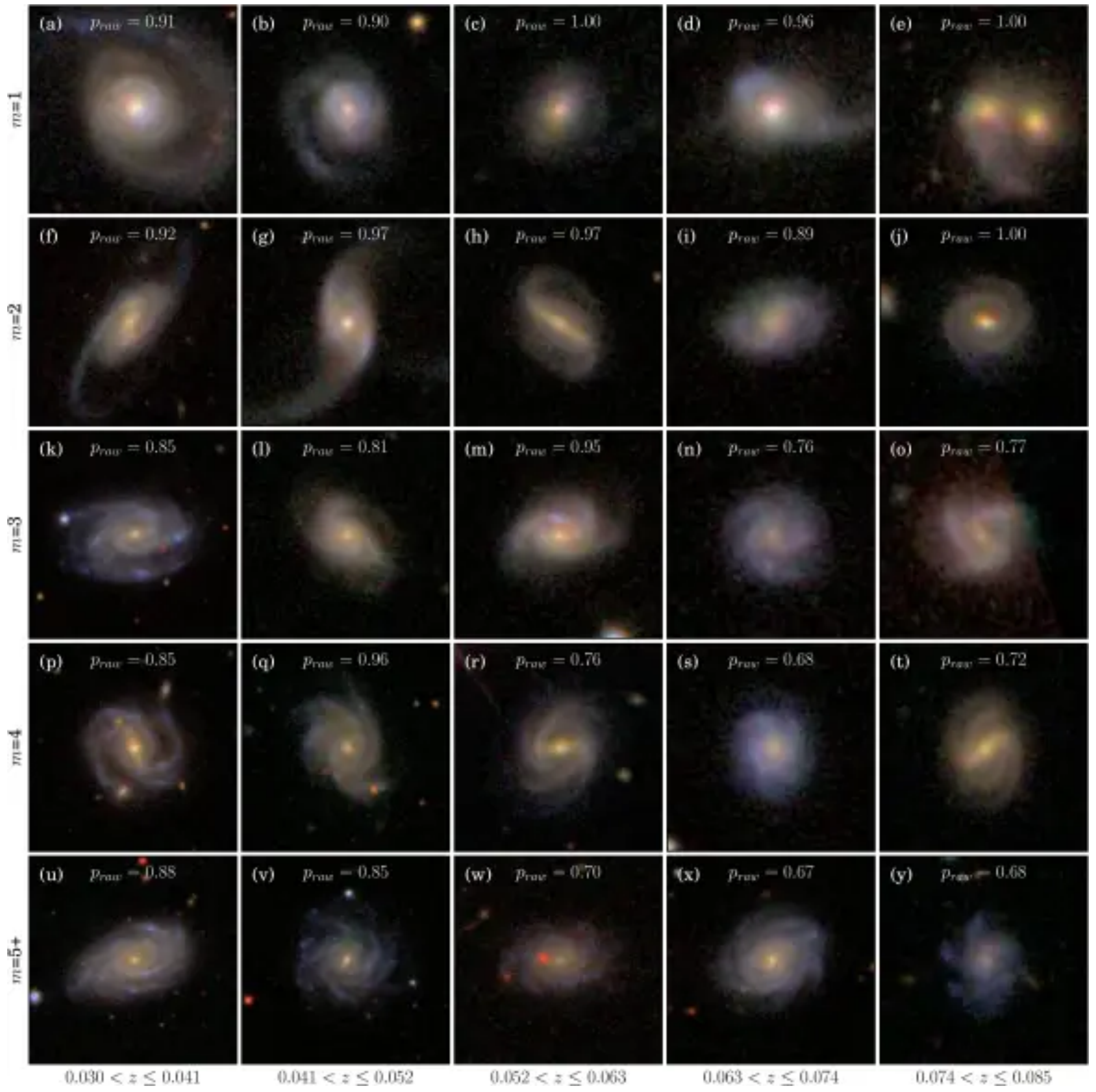


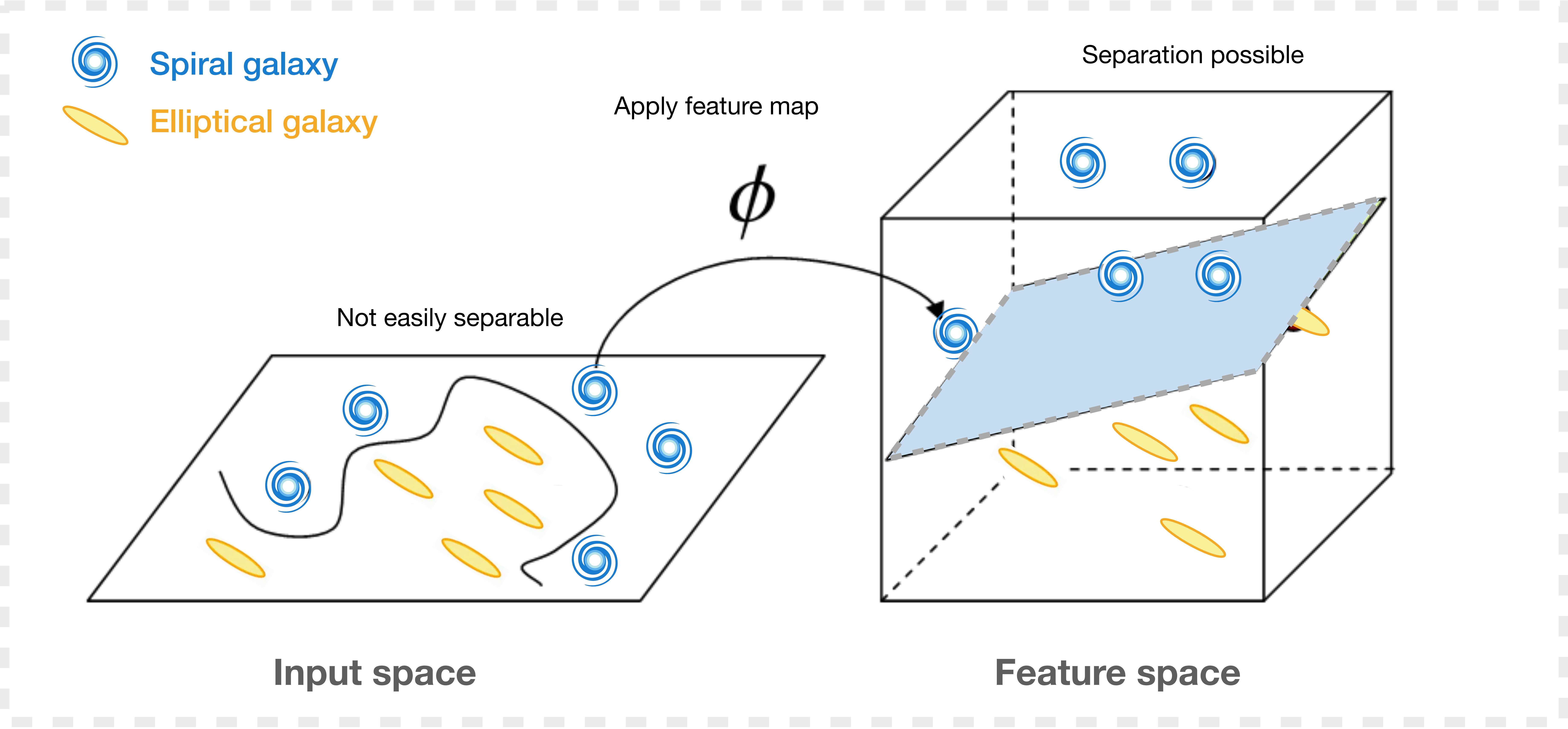

**Support vector machine with quantum kernel**

# Quantum machine learning for galaxy classification

- Shape of galaxy —> formation and evolution
- Sky surveys provide many more images than we can classify
- Galaxy zoo - citizen science project to classify galaxies
- Use machine learning to automate classification



# Quantum machine learning for galaxy classification



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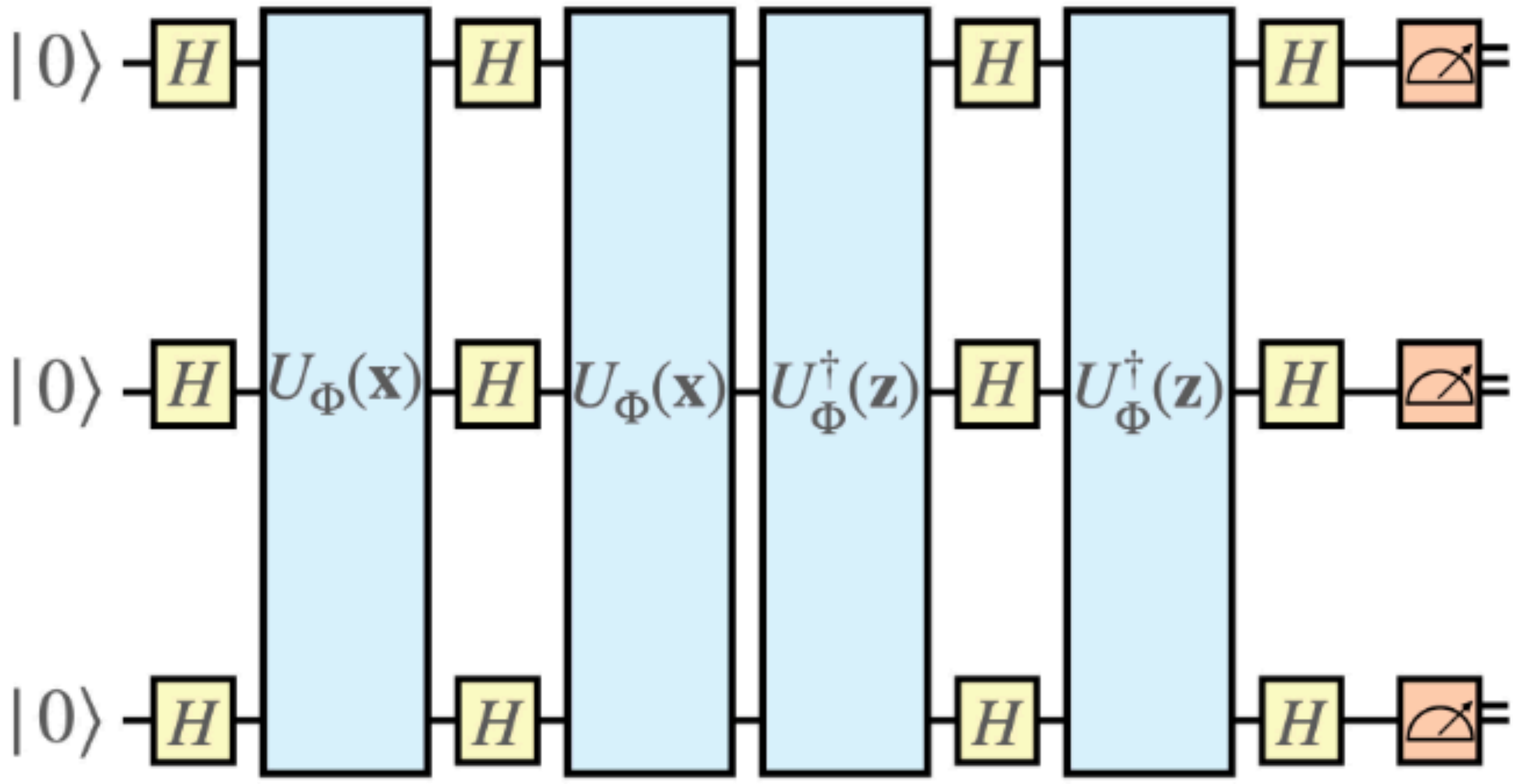
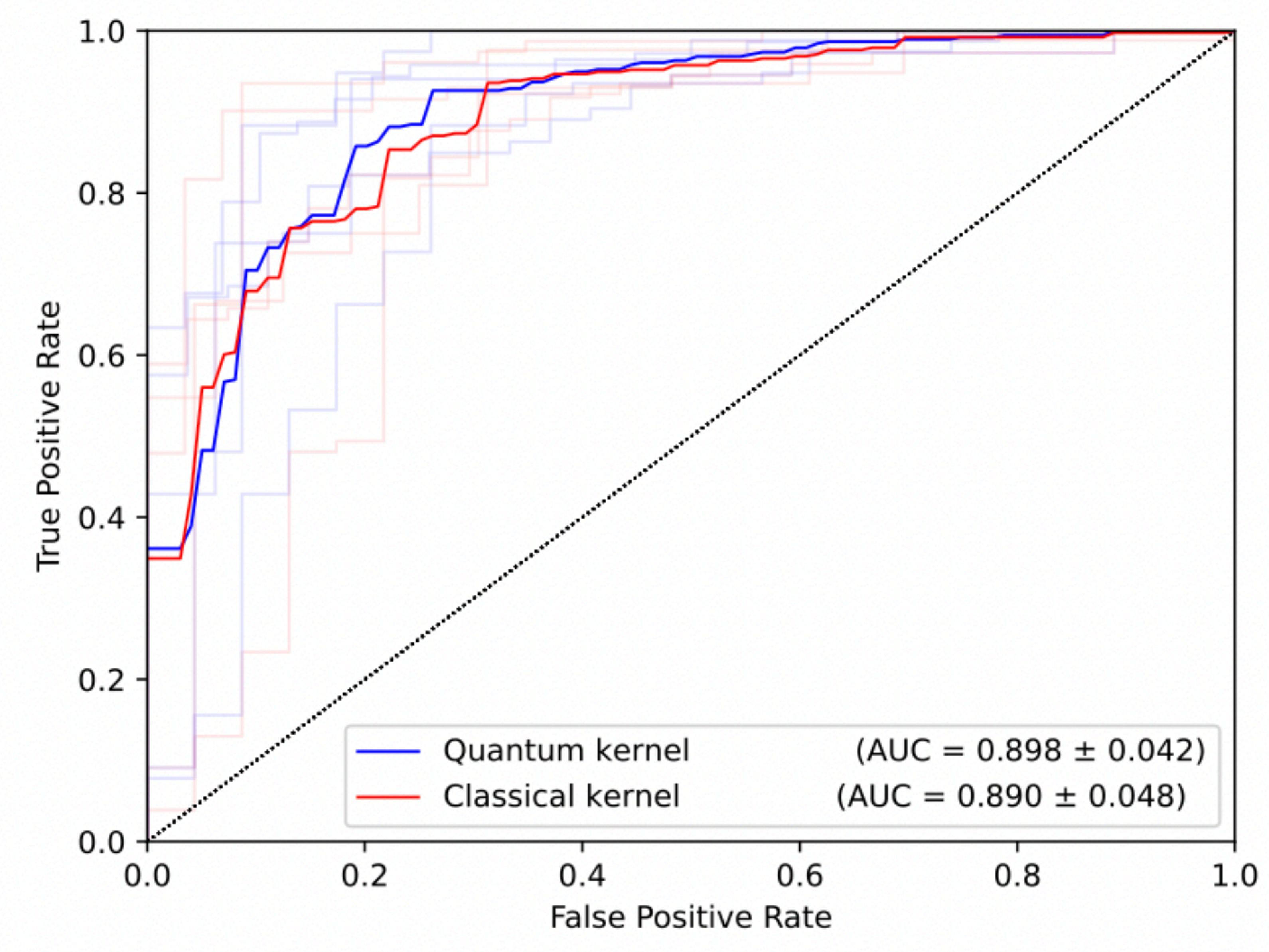


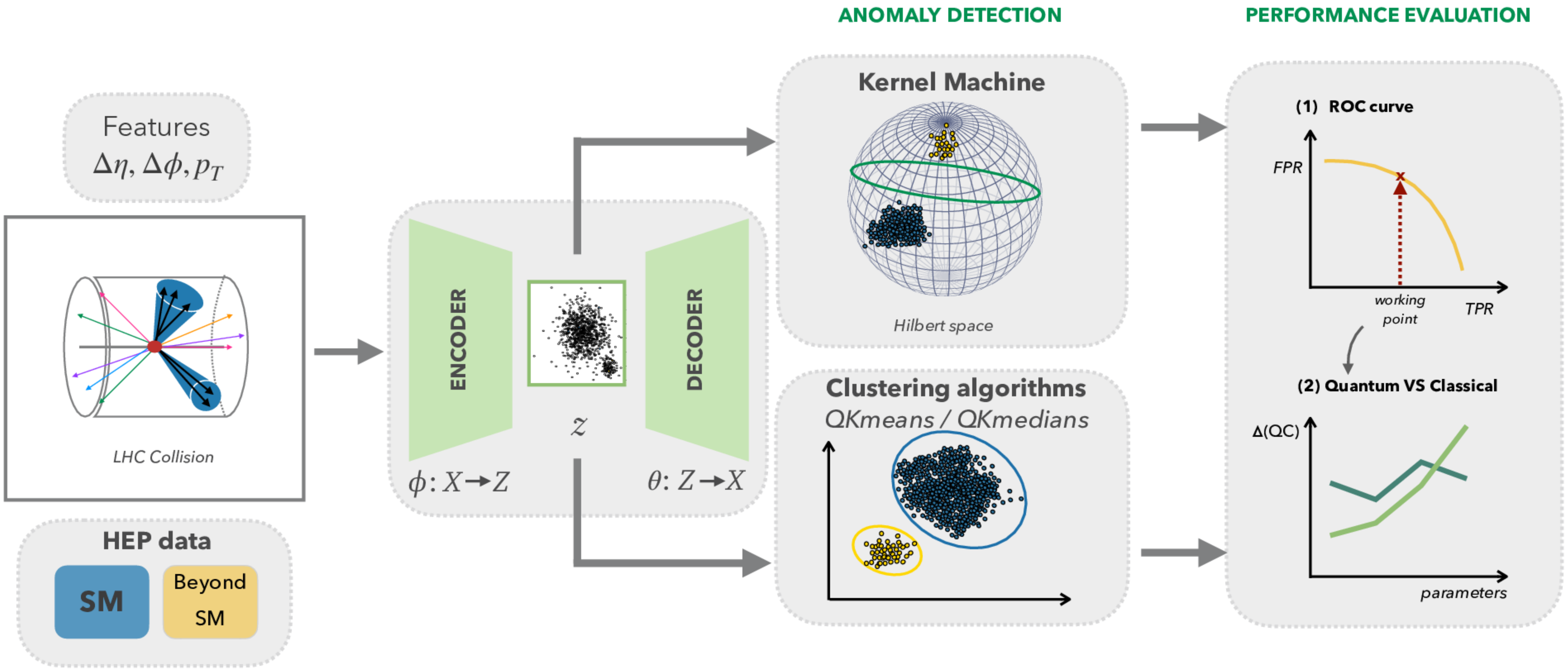




Almost the same algorithm used for classification in one area can be used in another - techniques in quantum computing (as in other areas like AI/machine learning) are cross-disciplinary

# Quantum anomaly detection

arXiv:2301.10780

- Increased interest in looking for new physics in a model-agnostic way
- Unsupervised machine learning approach used as anomaly-detection methods
- Train on Standard Model processes and detect outliers that may have new physics origins
- Search for new exotic particles decaying to jet pairs

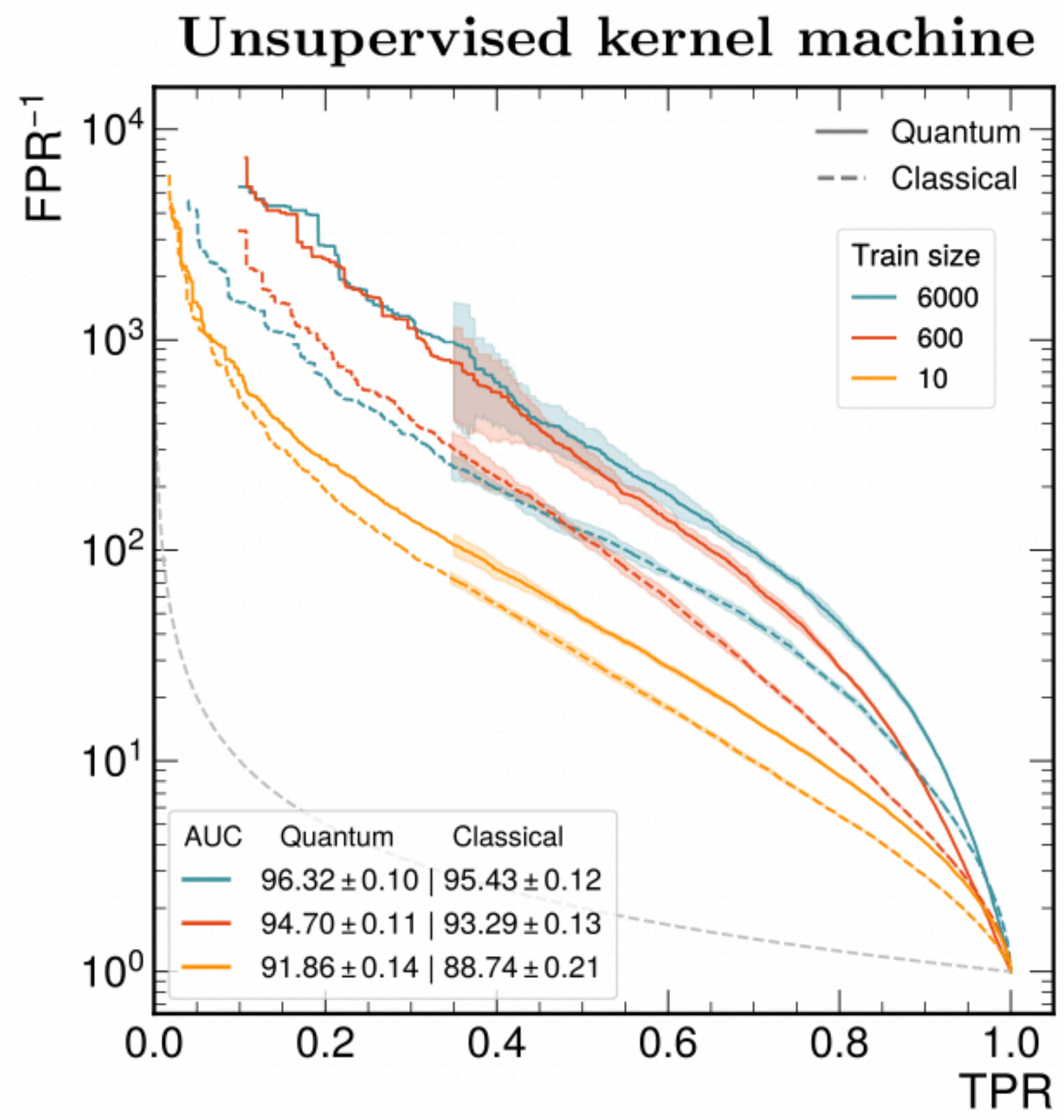


# Quantum anomaly detection

arXiv:2301.10780

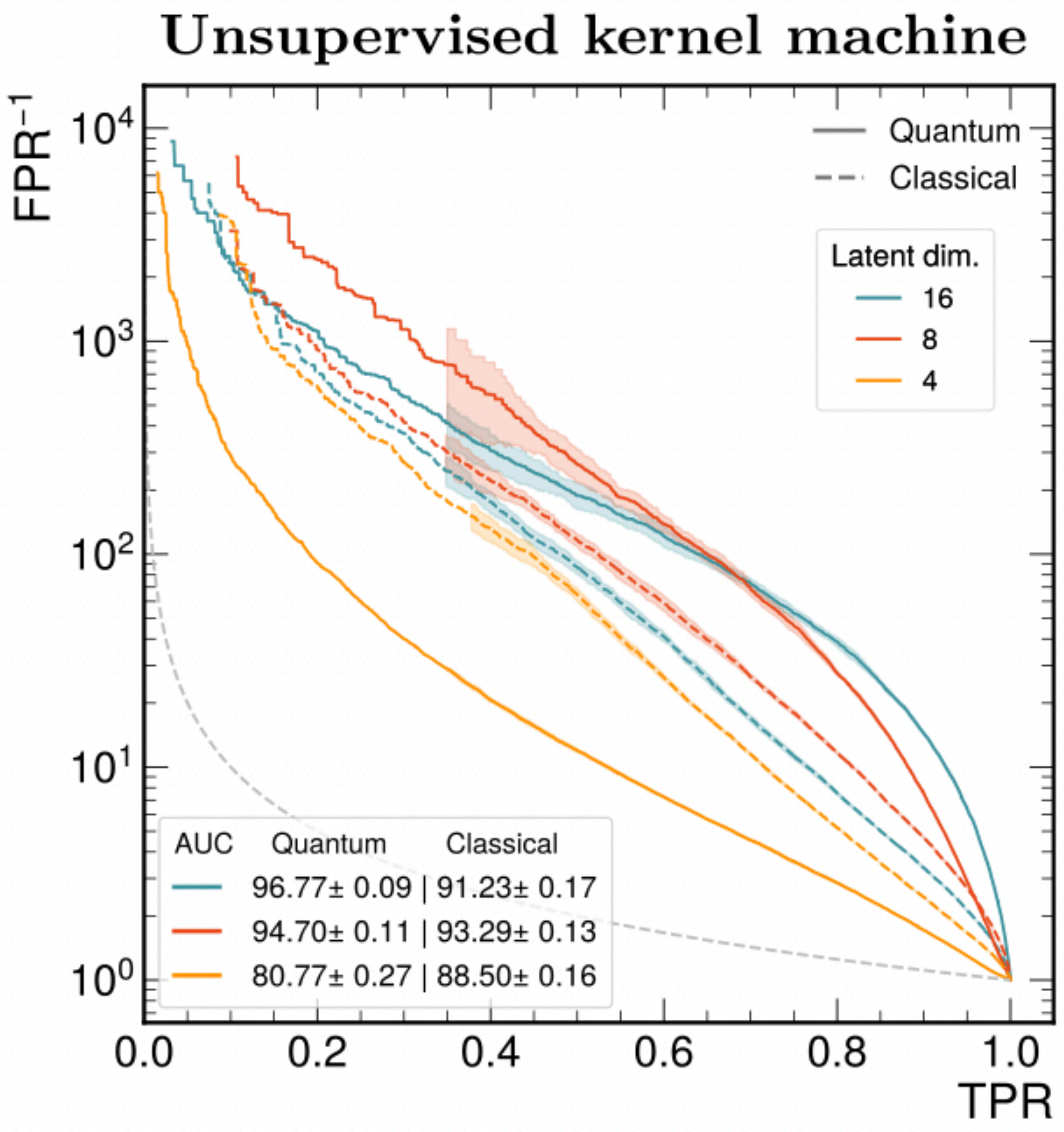
- Narrow Randall-Sundrum gravitons decaying to two W -bosons
- Scalar boson A decaying to a Higgs and Z boson, A—>HZ—>ZZZ
- Broad Randall-Sundrum gravitons decaying to two W -bosons

number of training samples




Large training size = better performance

latent space dimension




For quantum, best performance for latent dimension > 4

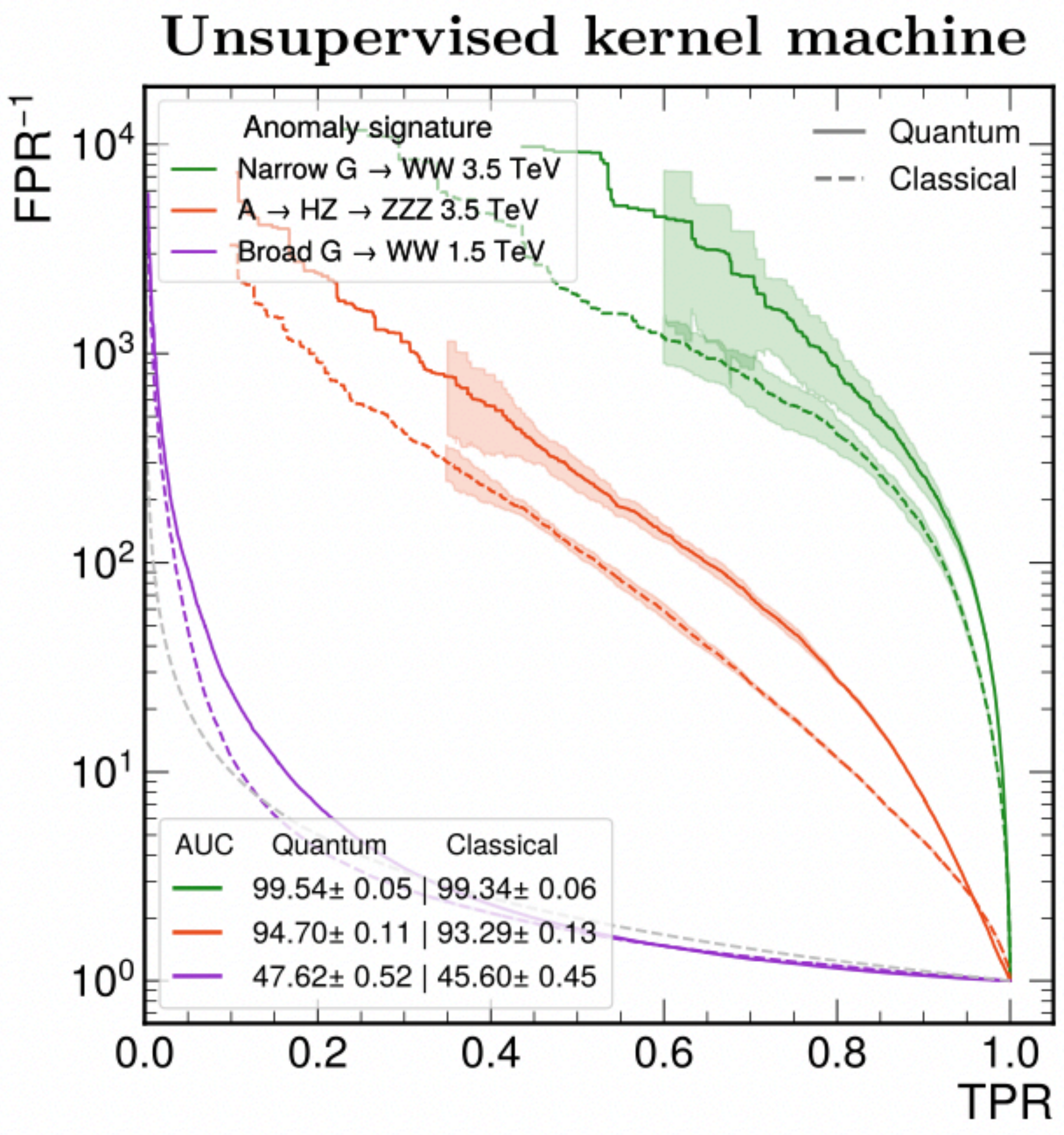
latent dimension = 8

training size = 600

Narrow graviton

Scalar boson A

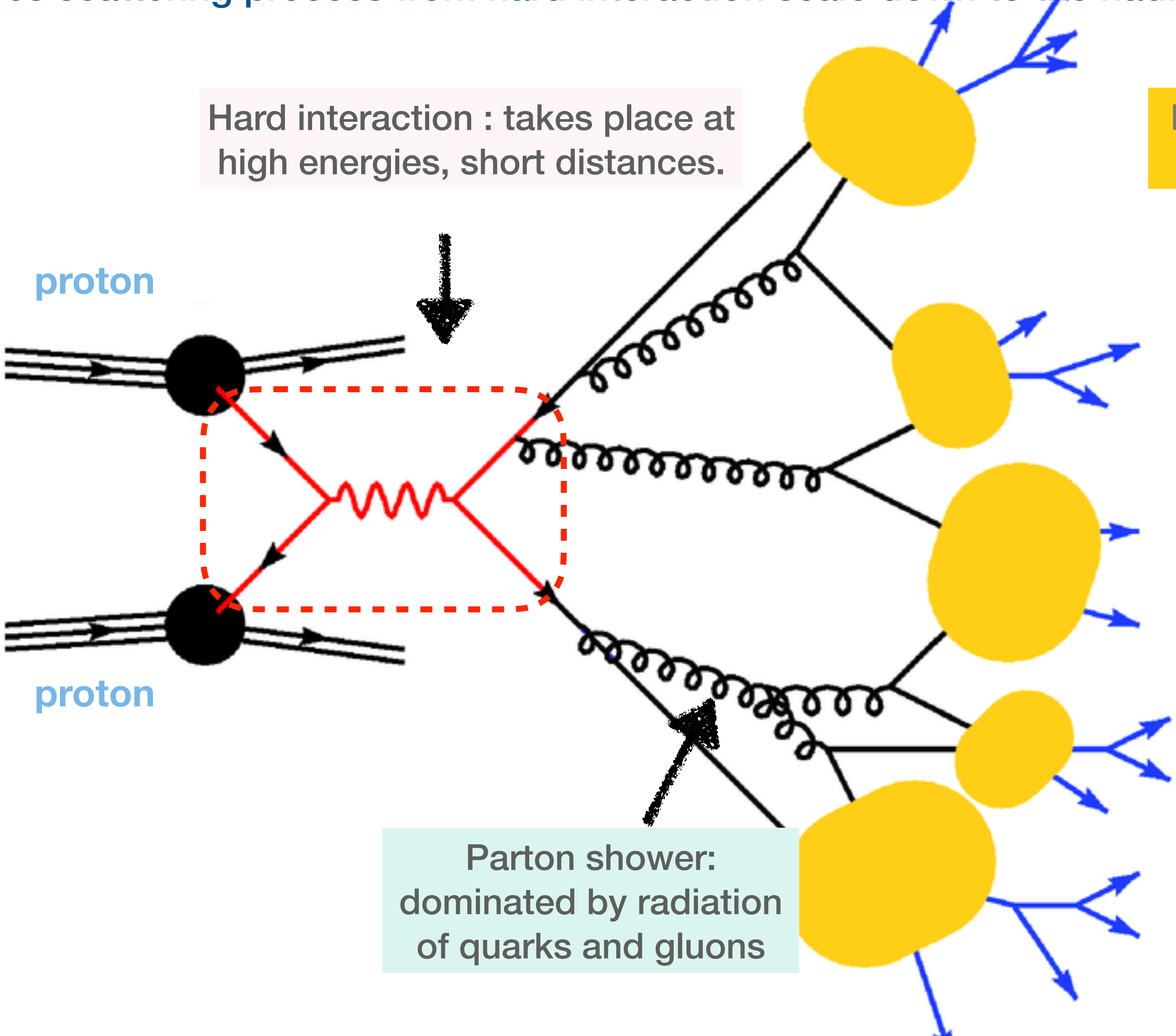
Broad graviton




Outperforms classical

# Parton Shower

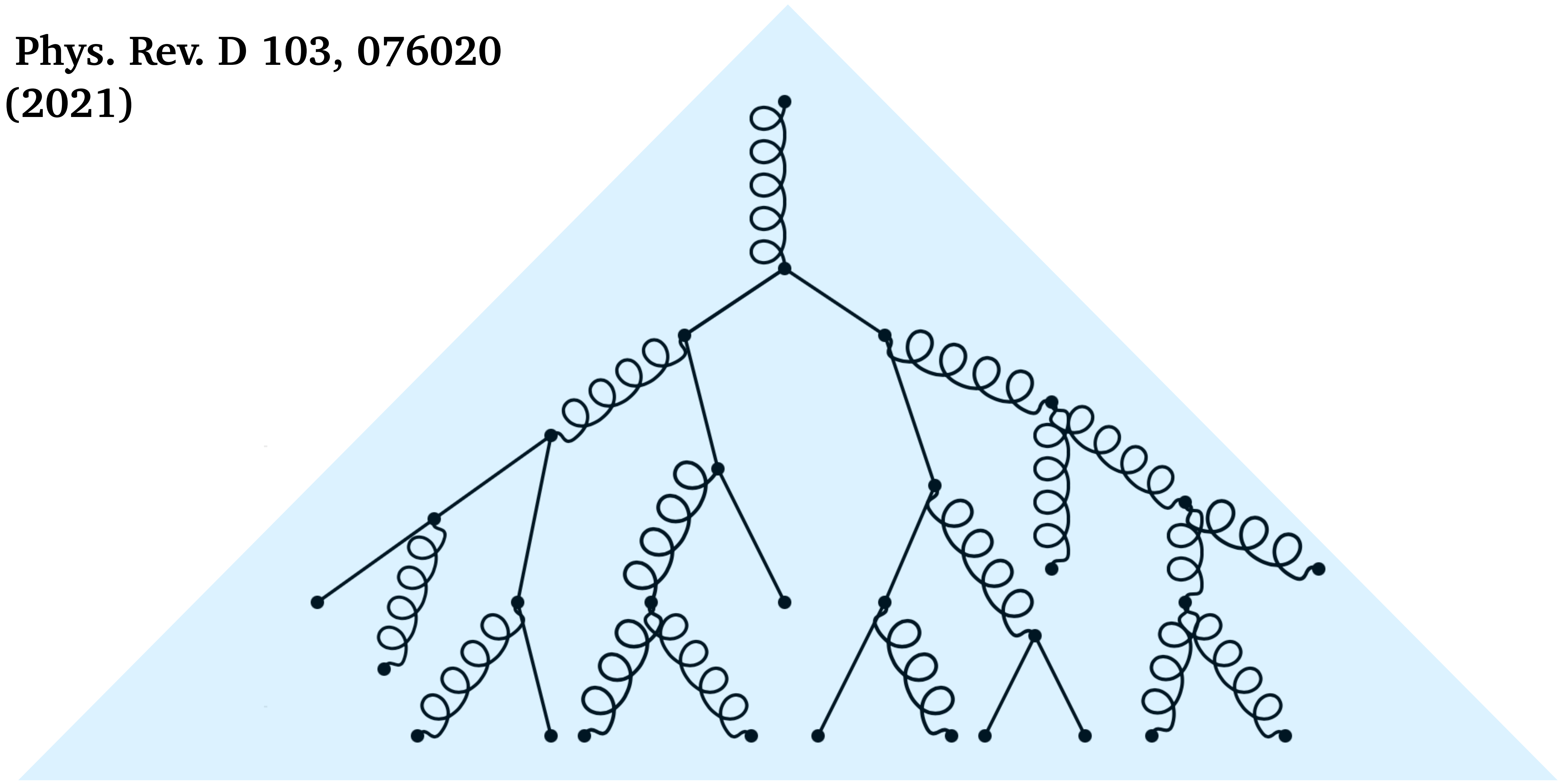
- After the hard interaction, next step in simulating an event at LHC is the parton shower
- Parton shower evolves scattering process from hard interaction scale down to the hadronisation scale



# Simulating parton shower

## Parton shower

Phys. Rev. D 103, 076020 (2021)

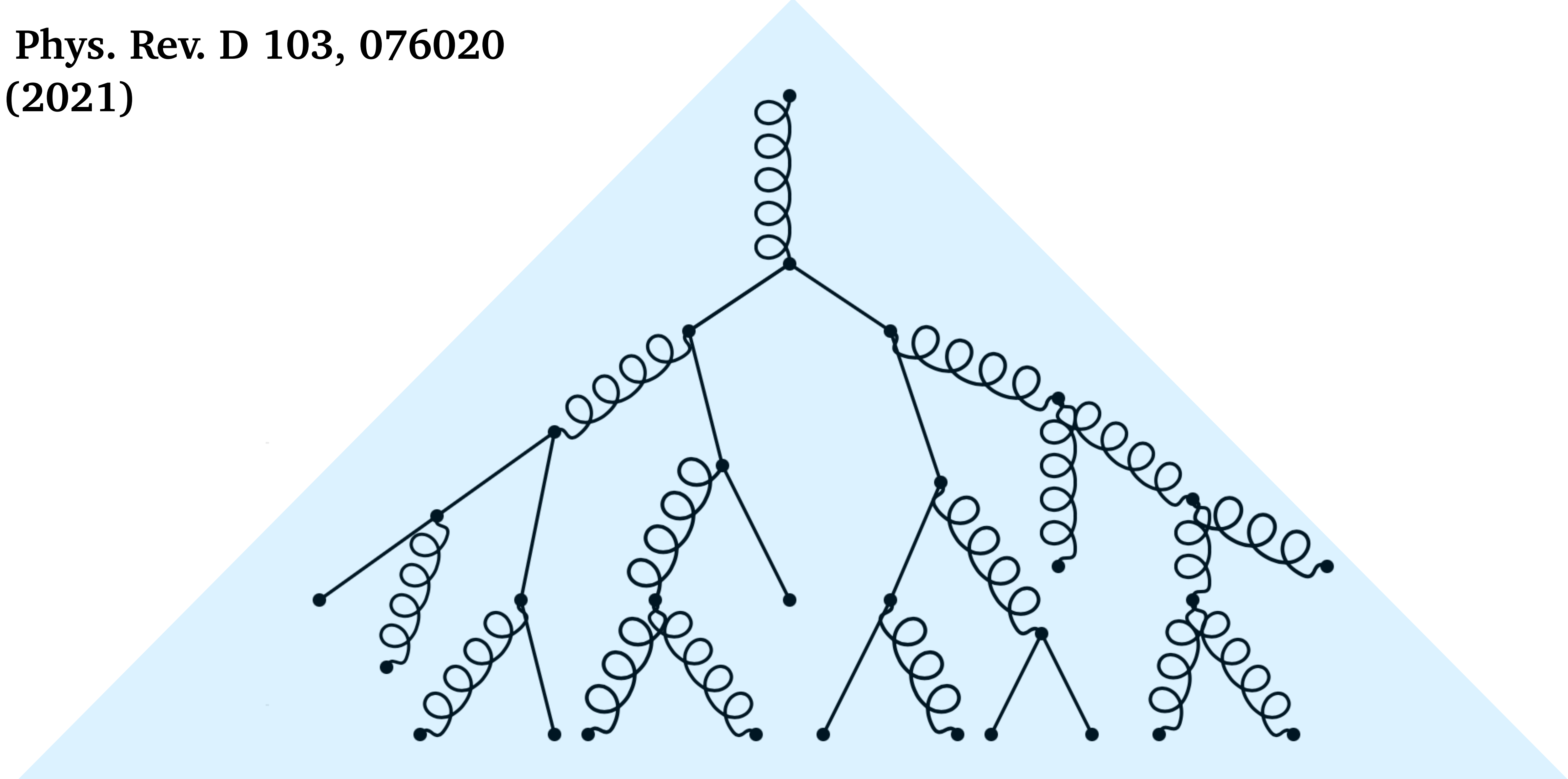


- Classical methods manually track individual shower histories and store in physical memory
- Quantum computing algorithm calculates all possible shower histories simultaneously
- Simulate 2-step parton shower with 31 qubits

# Simulating parton shower

## Parton shower

Phys. Rev. D 103, 076020 (2021)



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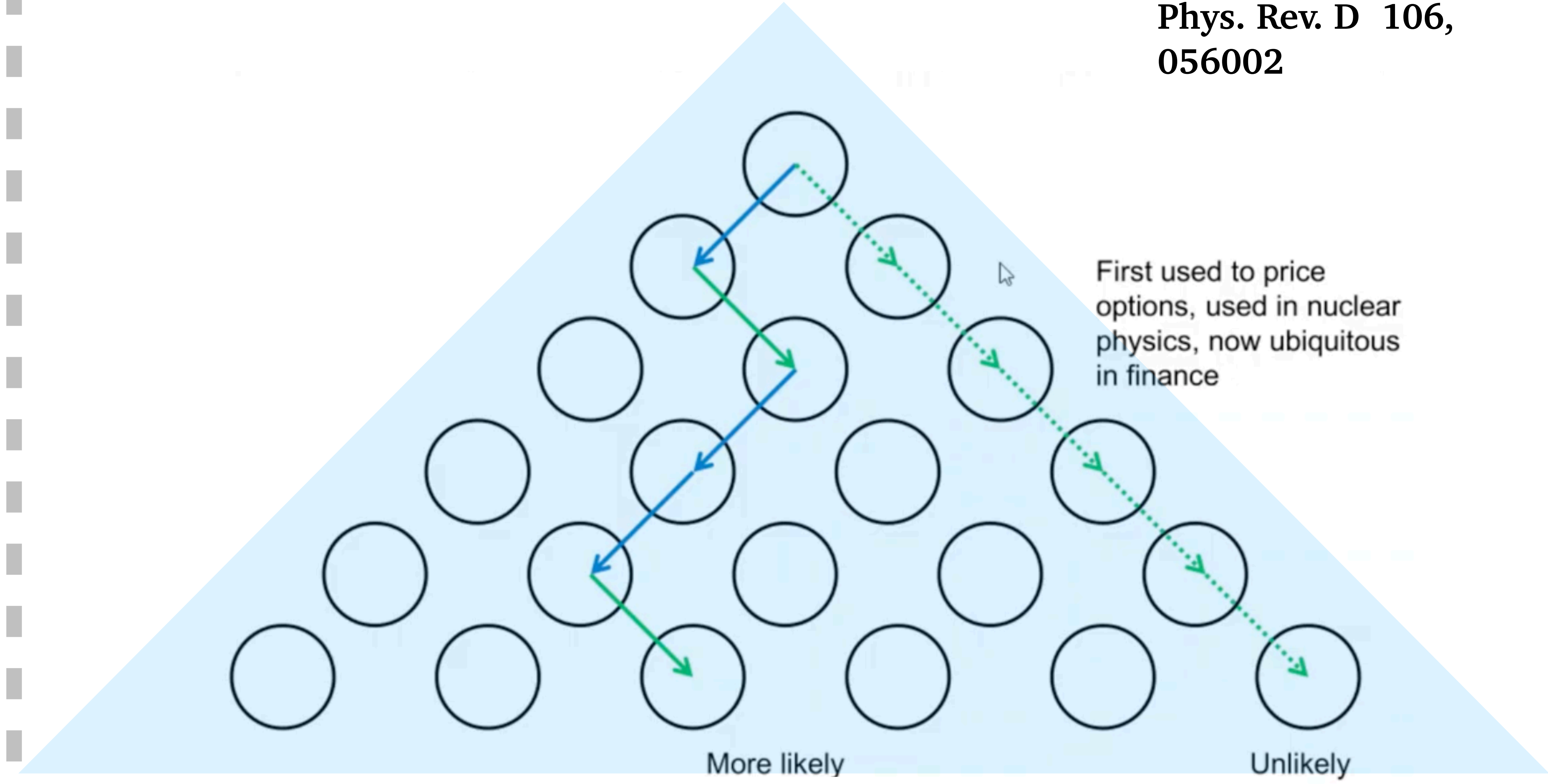
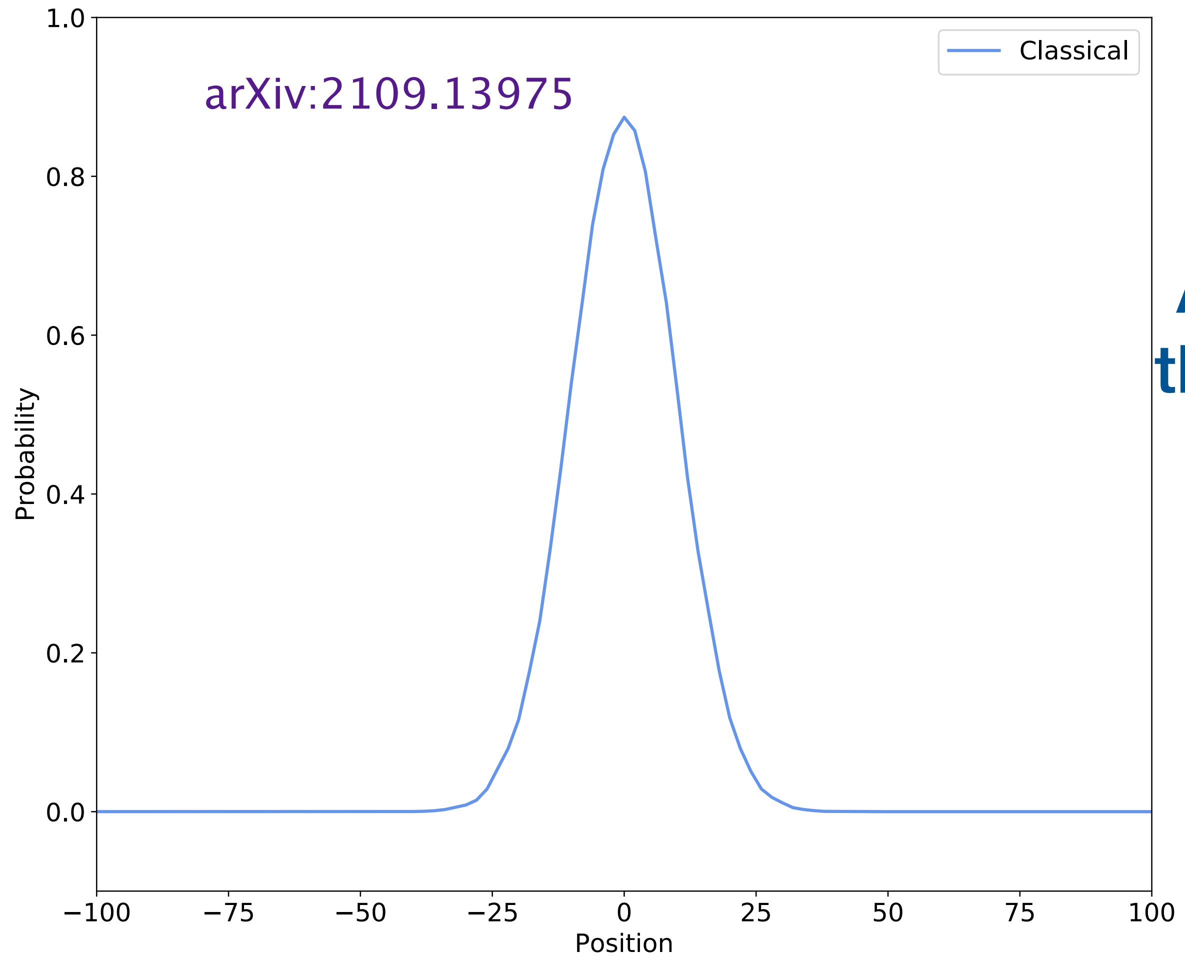
## Classical walk

Phys. Rev. D 106, 056002




First used to price options, used in nuclear physics, now ubiquitous in finance

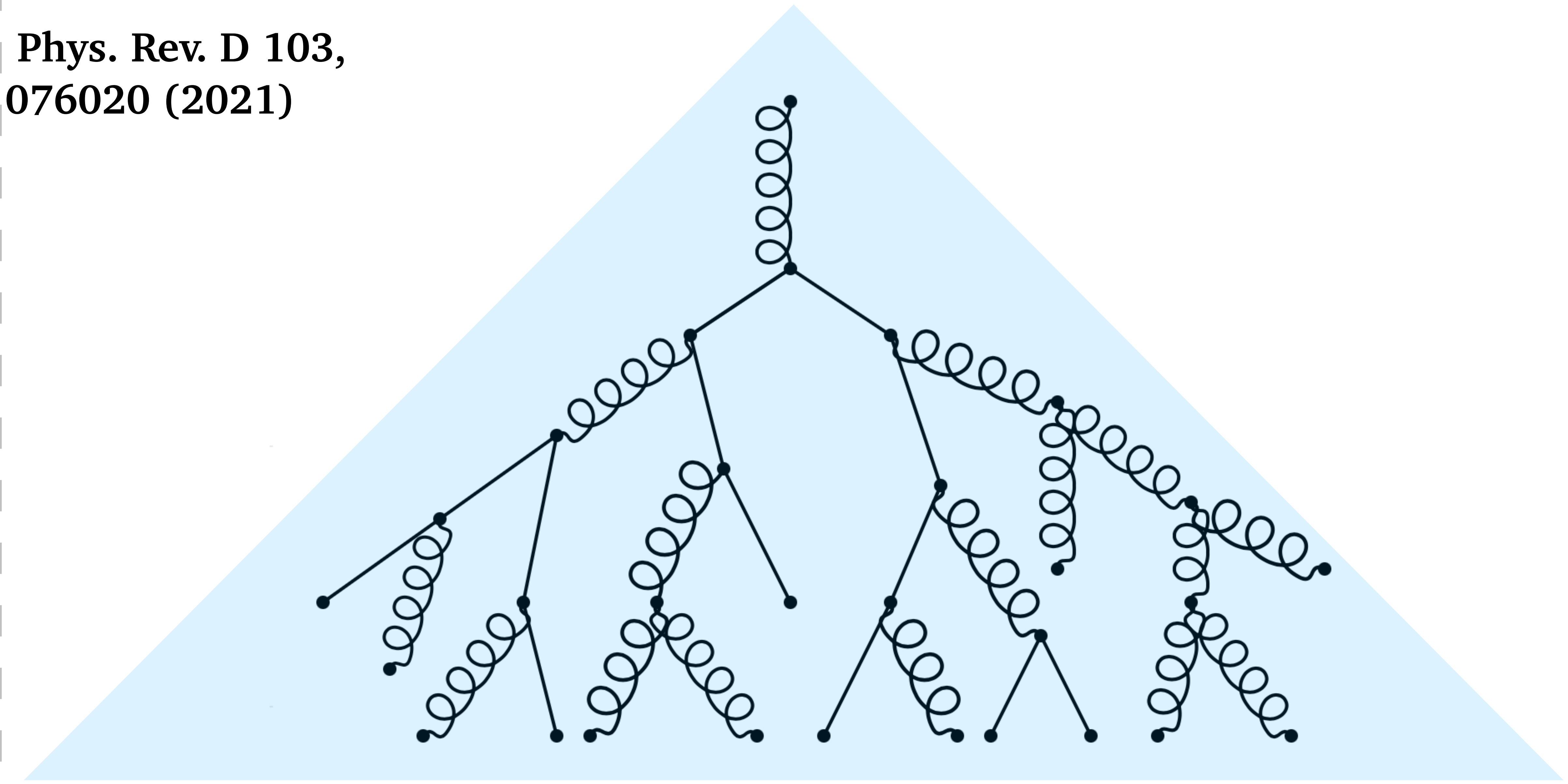



Average distance of the walker from initial position = $\sqrt{t}$

# Simulating parton shower

## Parton shower

Phys. Rev. D 103, 076020 (2021)



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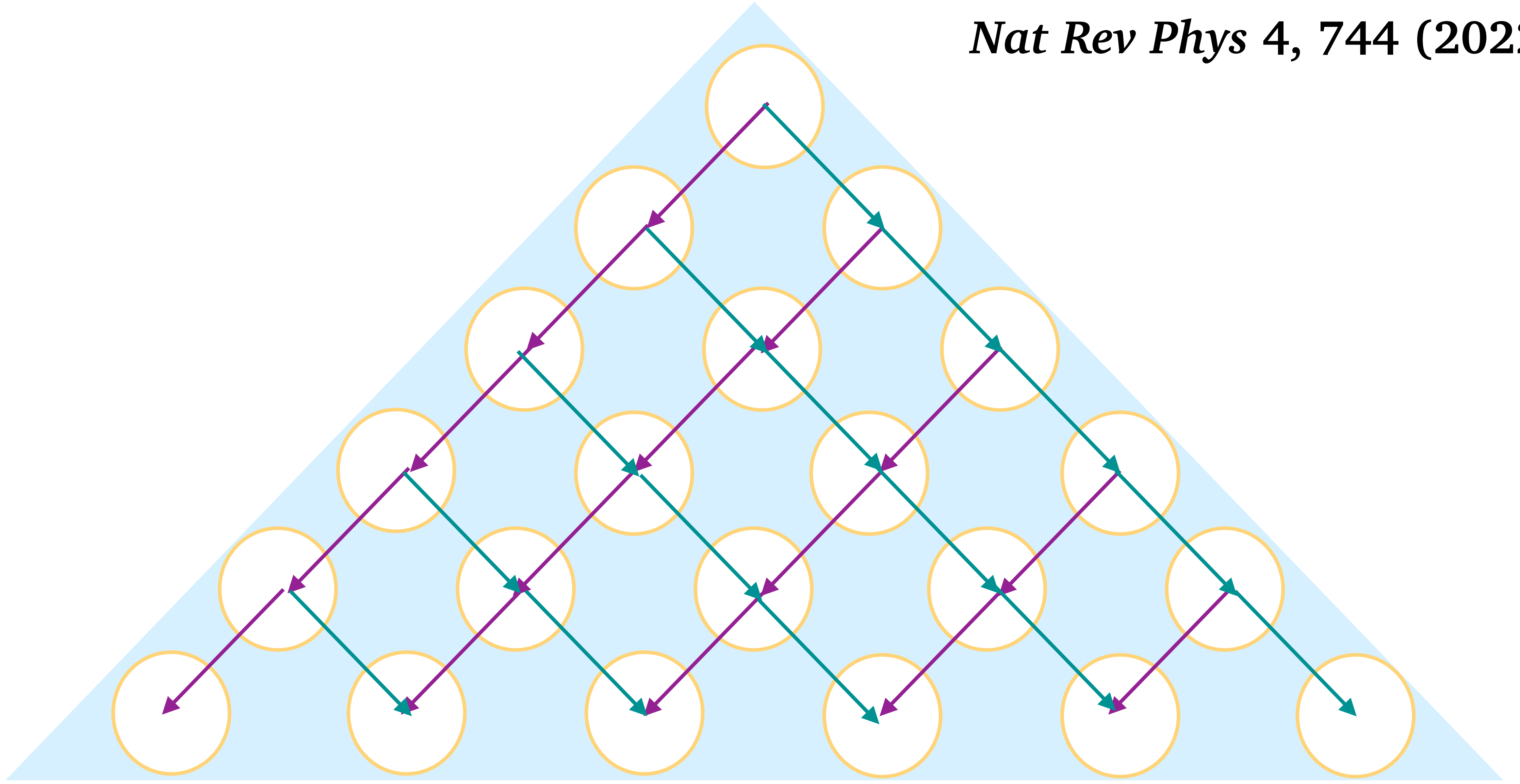
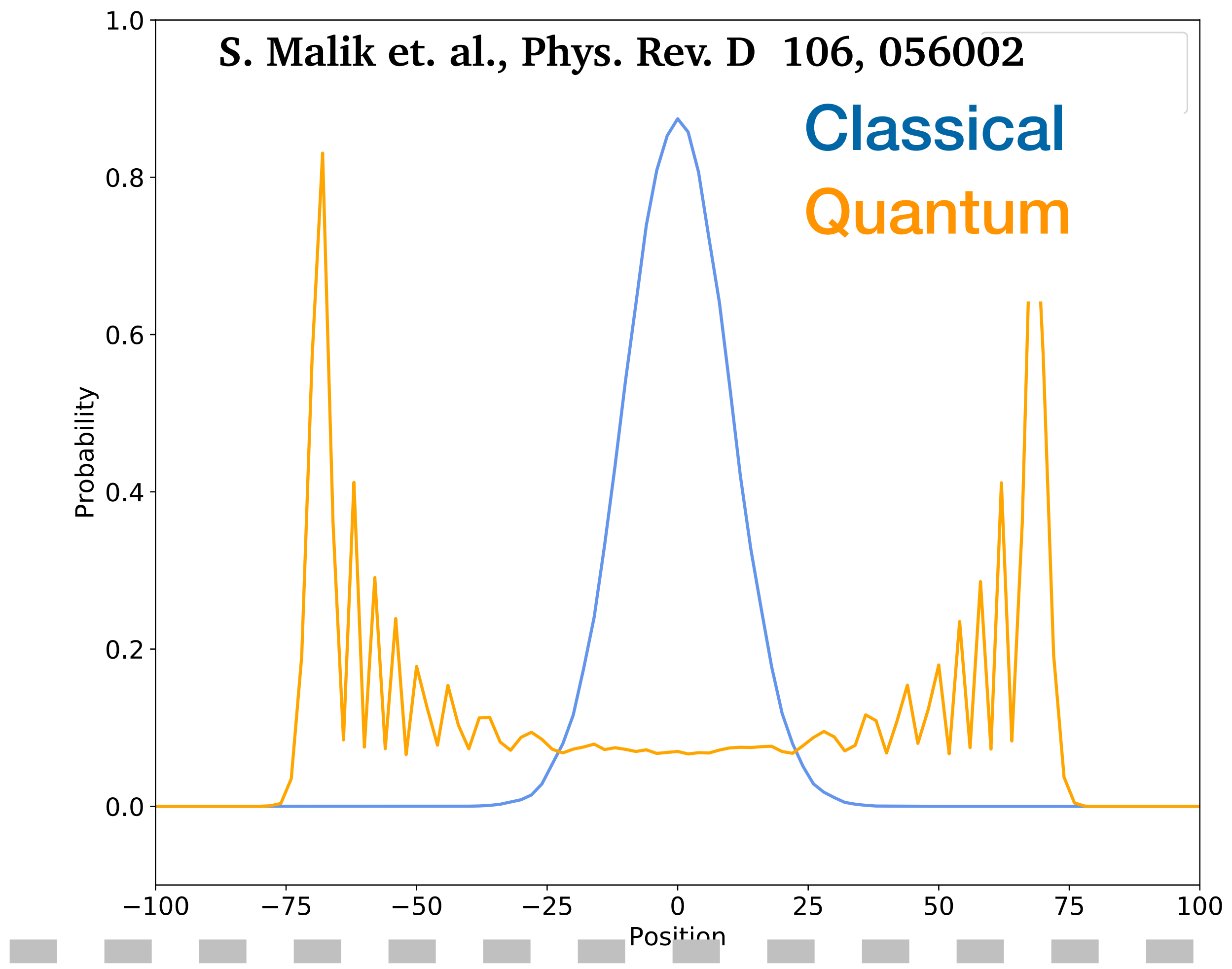
## Quantum walk

*Nat Rev Phys* 4, 744 (2022)



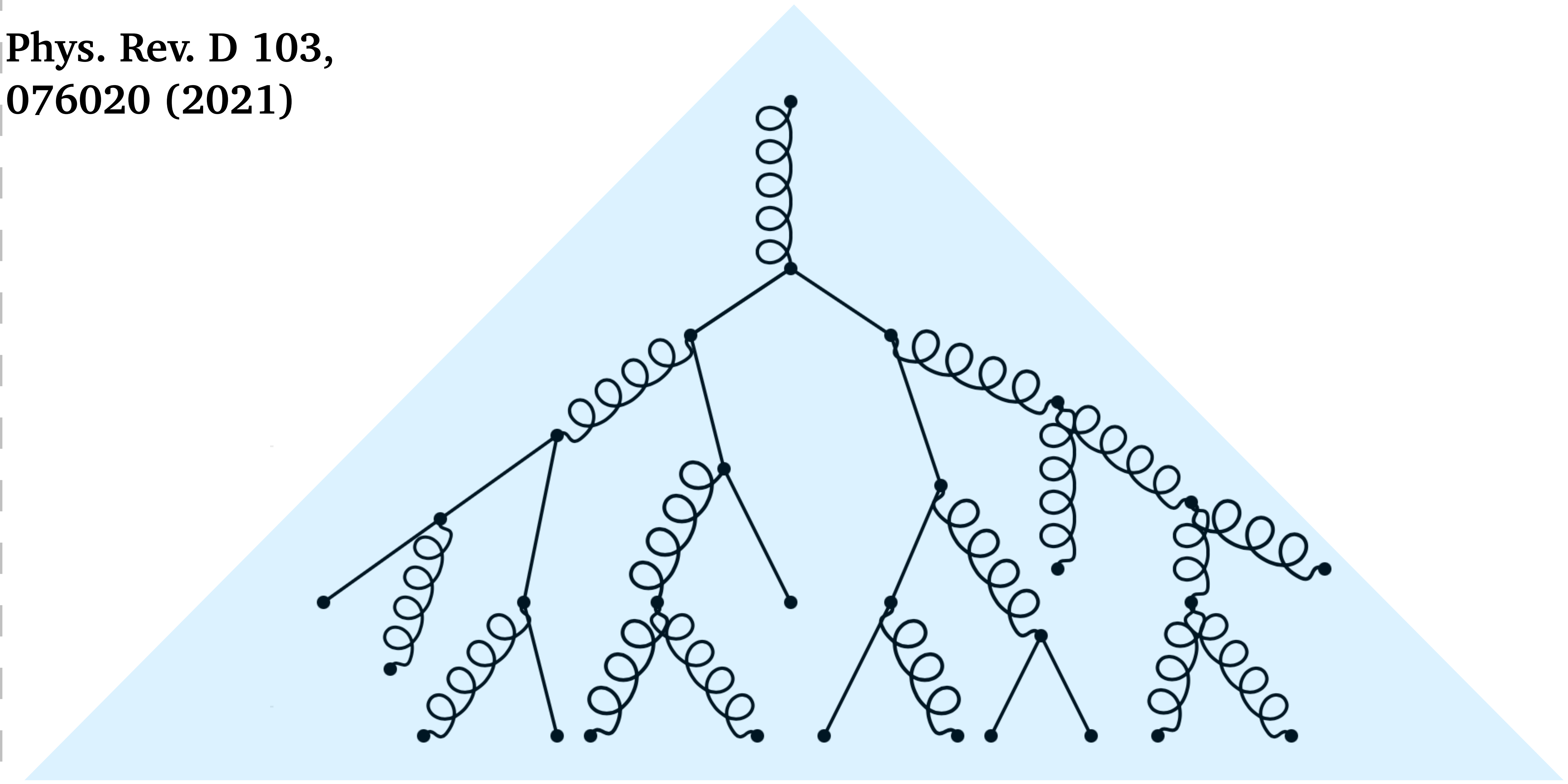



Quantum walker quadratically faster than classical walker

# Simulating parton shower

## Parton shower

Phys. Rev. D 103, 076020 (2021)



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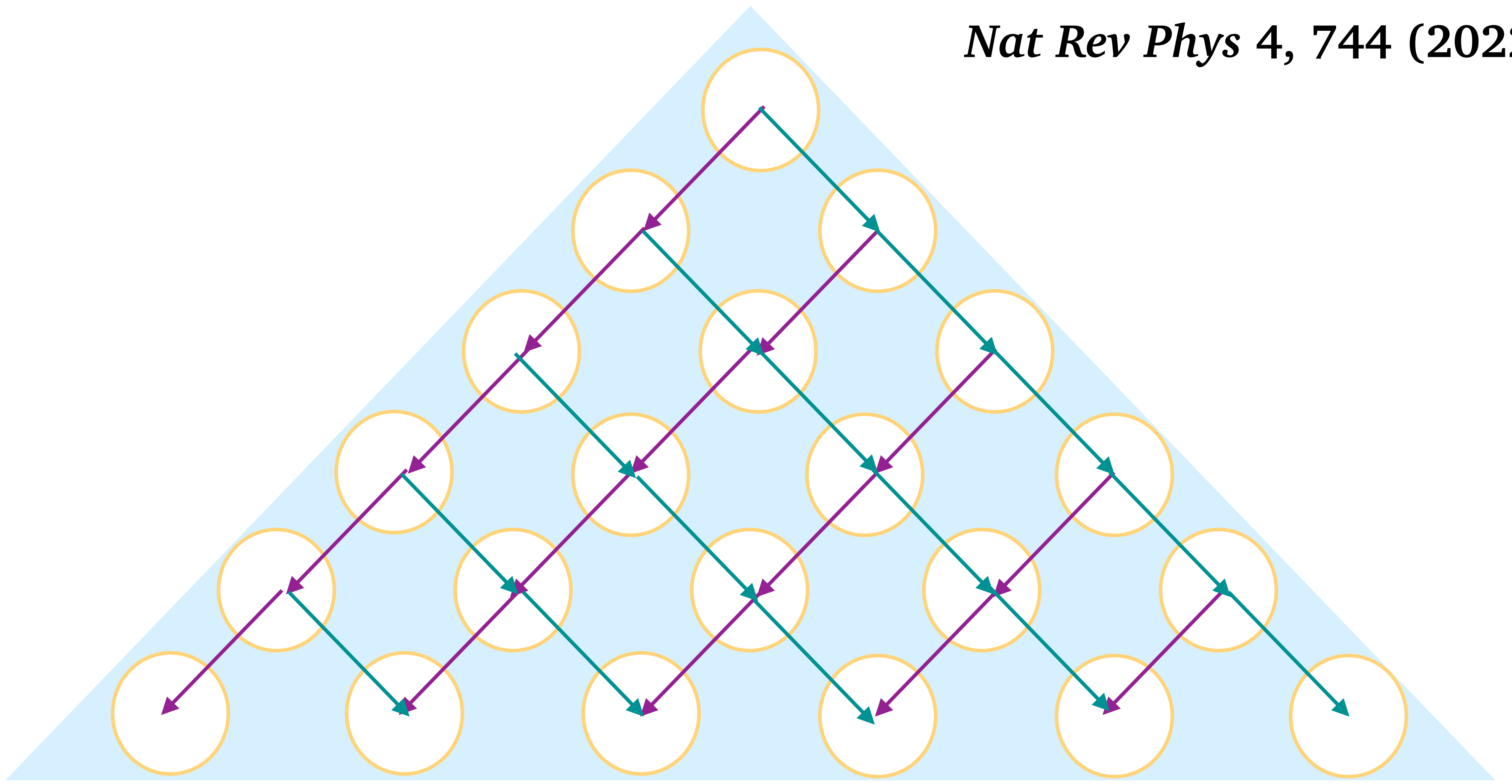
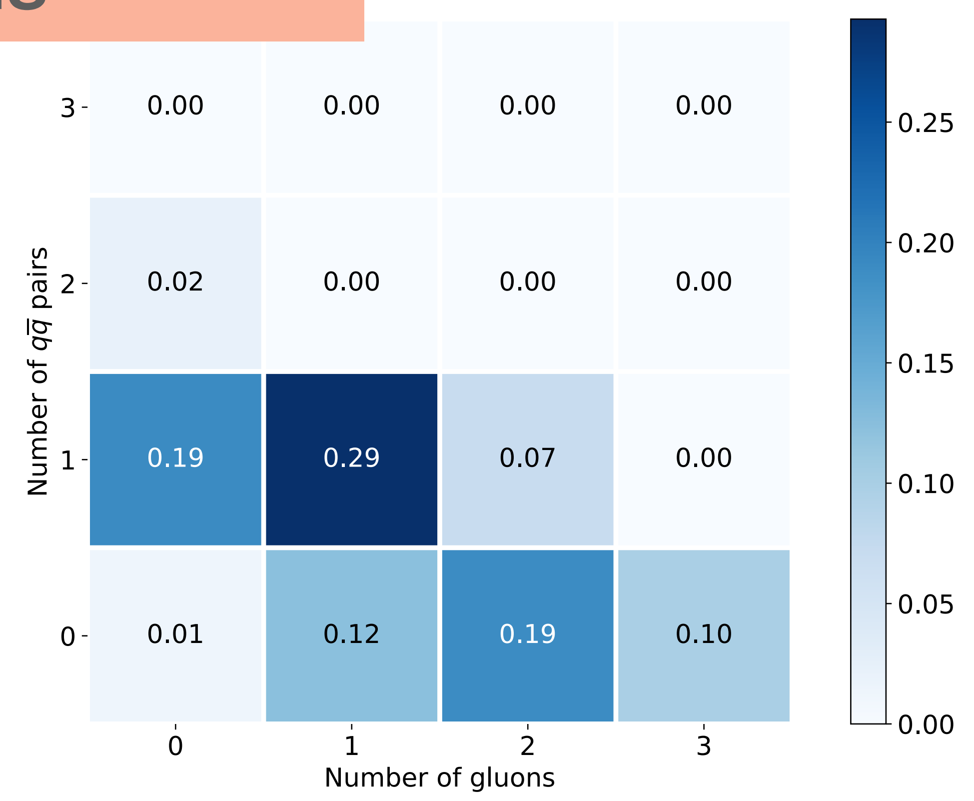


Parton shower = quantum walk in 2 dimensions

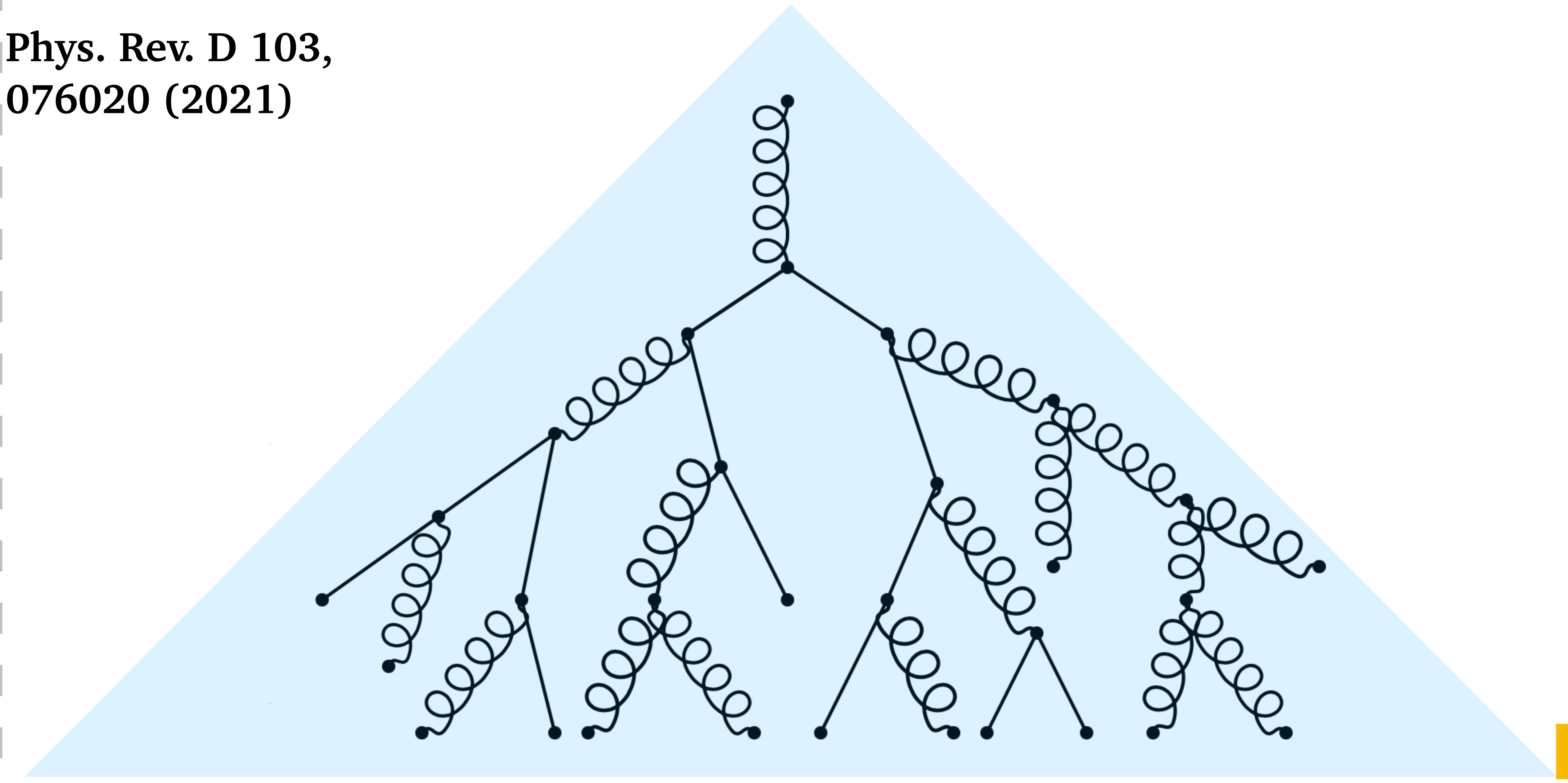
Novel approach, simulate 31-step parton shower using 16 qubits



# Simulating parton shower

## Parton shower

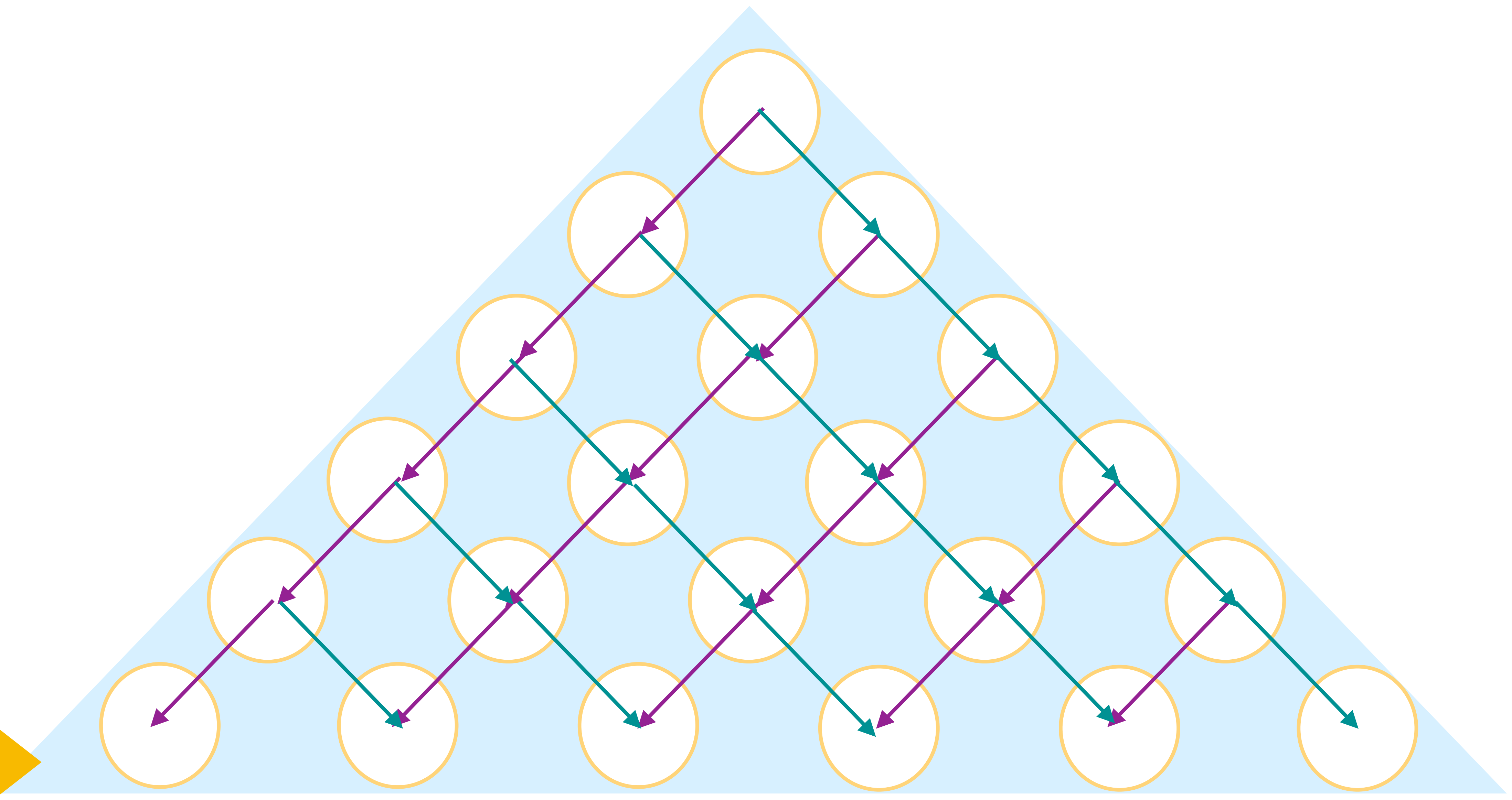
Phys. Rev. D 103, 076020 (2021)



'Translational approach'

- Quantum computing algorithm calculates all possible shower histories simultaneously
- Simulate 2-step parton shower with 31 qubits

## Quantum walk



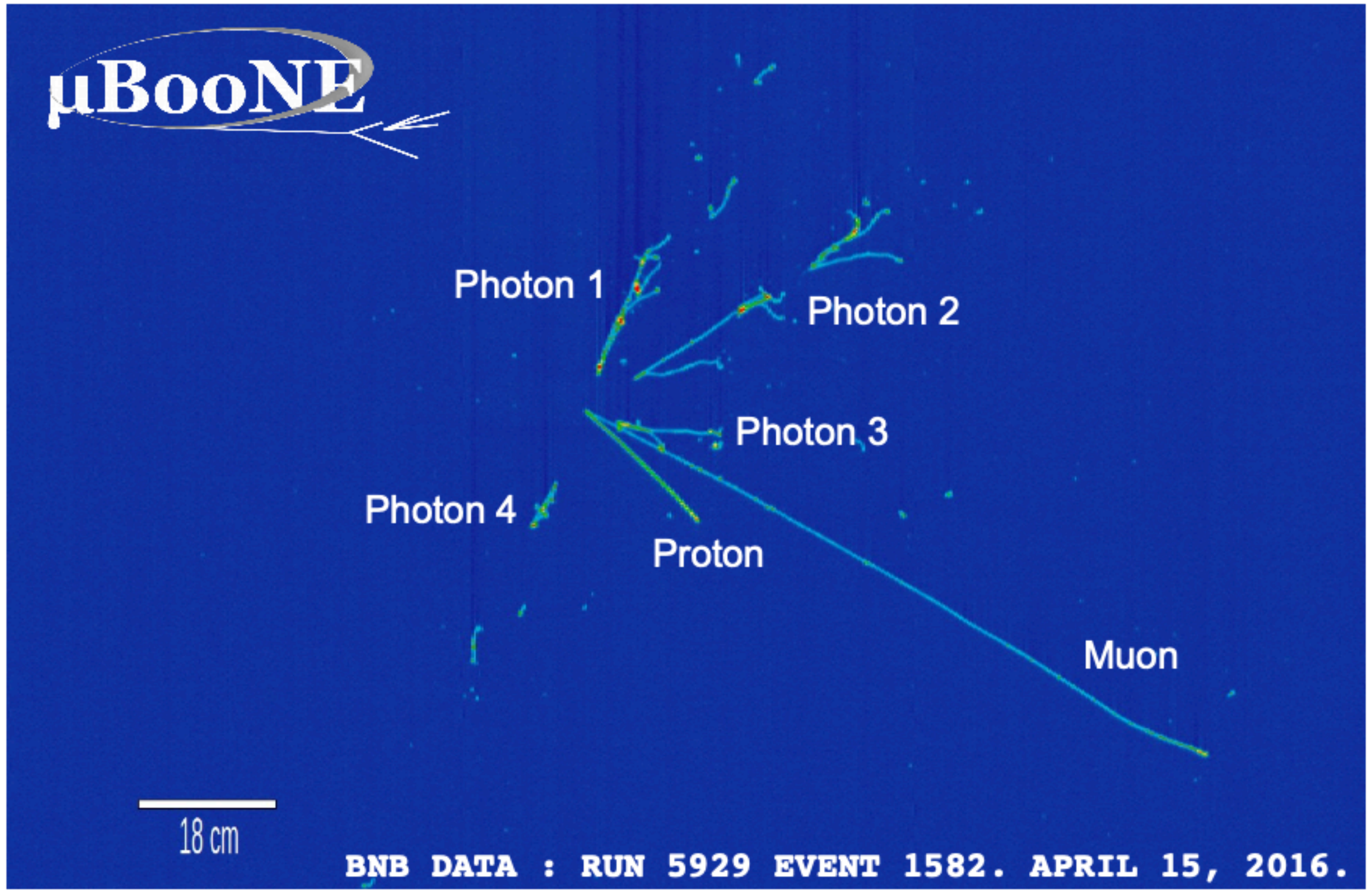
'Quantum-centric approach'

Quantum walk approach, simulate 31-step parton shower using 16 qubits

# Quantum Machine Learning for LArTPC Topology Classification

Phys.Rev.D 112 (2025) 9, 092006

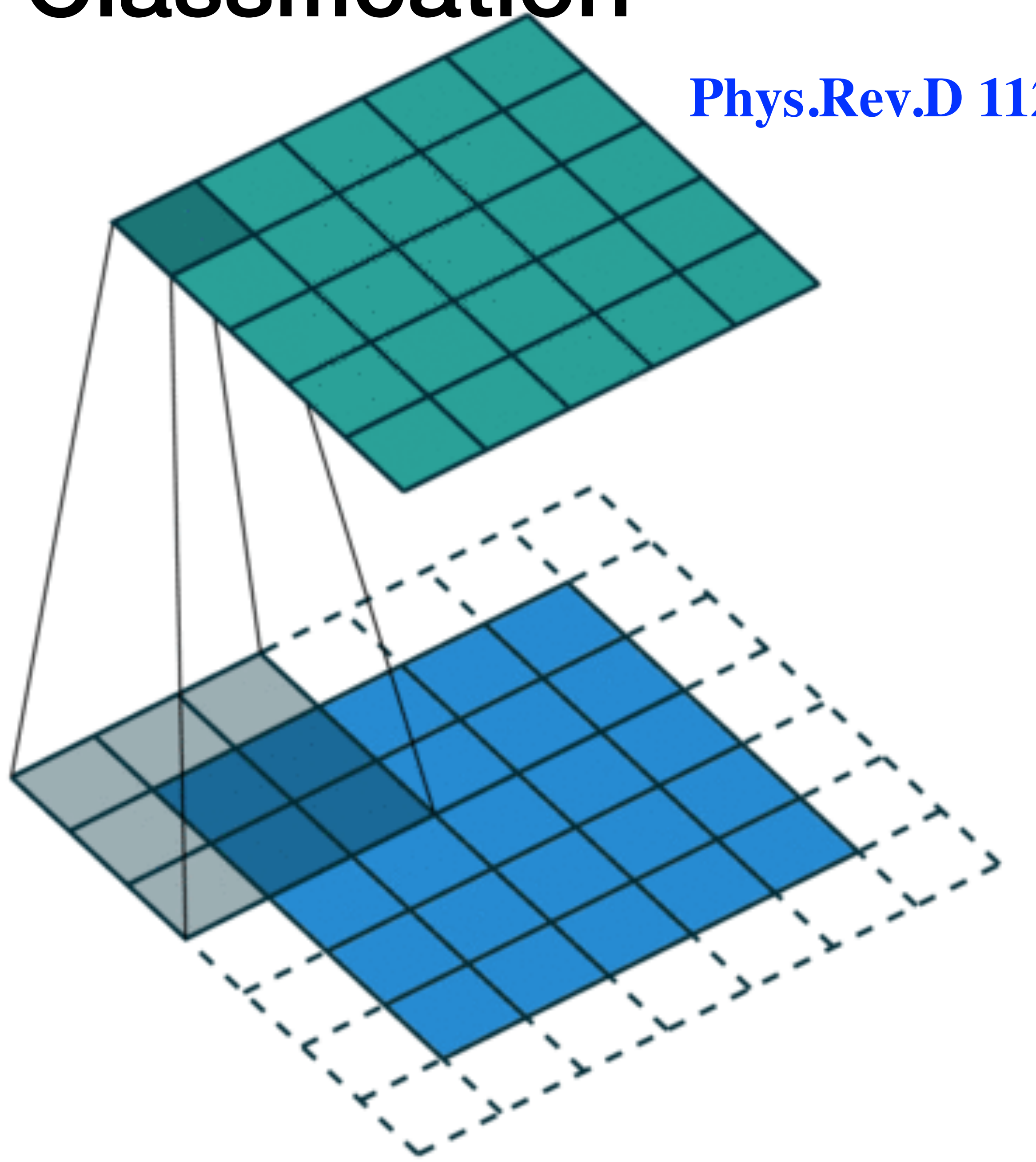
- Classify track-like vs shower-like topologies in Liquid Argon Time Projection Chambers (LArTPCs).
- Improves neutrino event reconstruction in experiments such as MicroBooNE and DUNE.
- Apply quantum machine learning (QML) methods —quanvolutional neural networks (QNNs) — to classify event topologies using detector hit data.
- Dataset: Simulated MicroBooNE and synthetic datasets with variable opening angles.



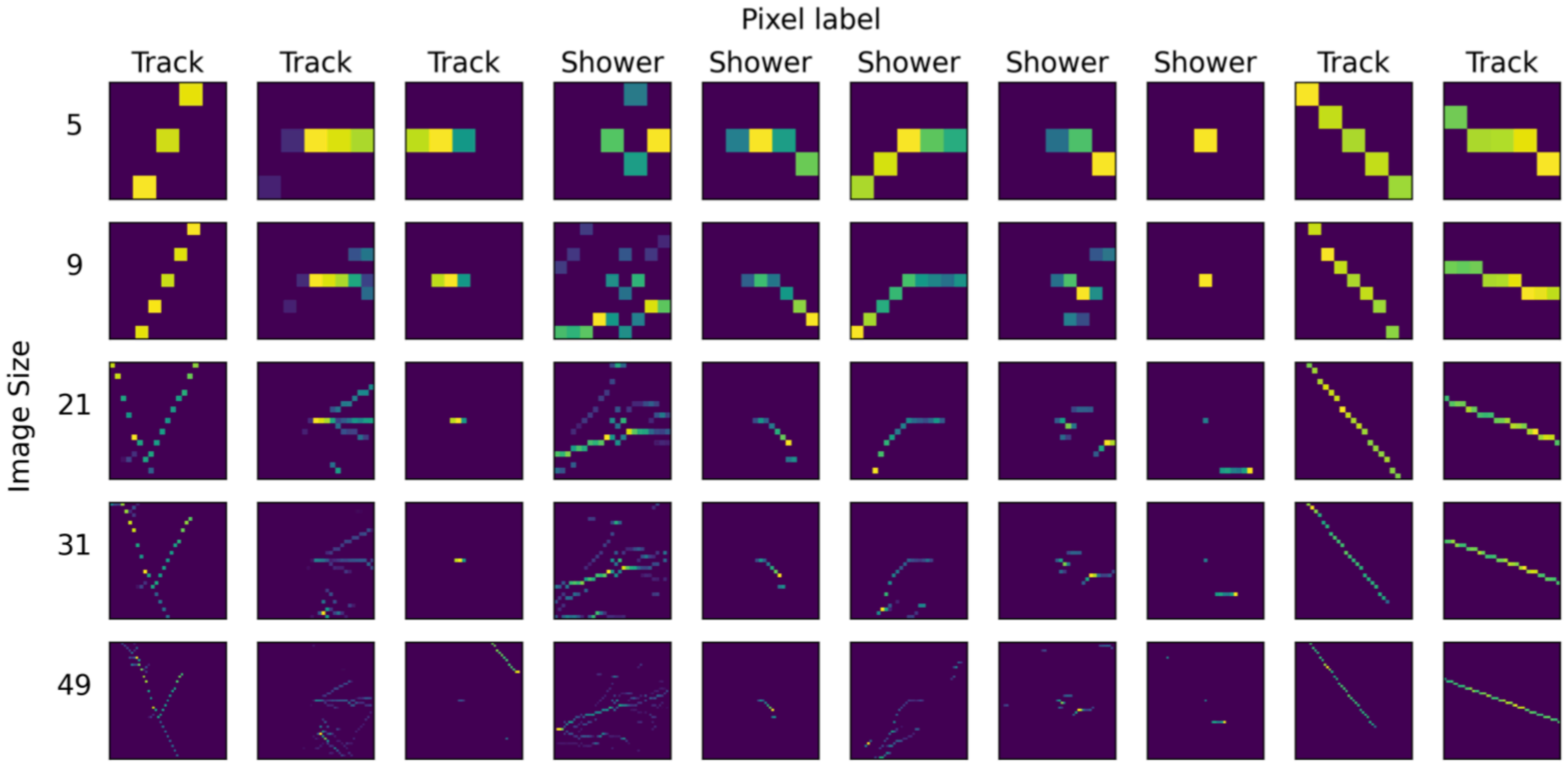

*Neutrino interaction event in a LArTPC from MicroBooNE. 6 particles from the interaction vertex: 2 track-like (muon and proton) and 4 shower-like (photons)*

# Quantum Machine Learning for LArTPC Topology Classification

Phys.Rev.D 112 (2025) 9, 092006



- Classical CNNs use convolutional filters to slide across images for local feature extraction.
- Quanvolutional Neural Networks (QNNs) replace these classical filters with **small quantum circuits**.
- Each **image patch** (e.g 2x2 pixels) is encoded into qubits, applies unitary transformations, and outputs measured features.
- These features then fed into a **classical classifier** (also test a fully quantum invariant model)
- **Rotational symmetry** added, so rotating the input by 90 degrees gives equivalent outputs



# Results

Phys.Rev.D 112 (2025) 9, 092006

- Quantum models outperform classical CNNs with similar parameter counts.

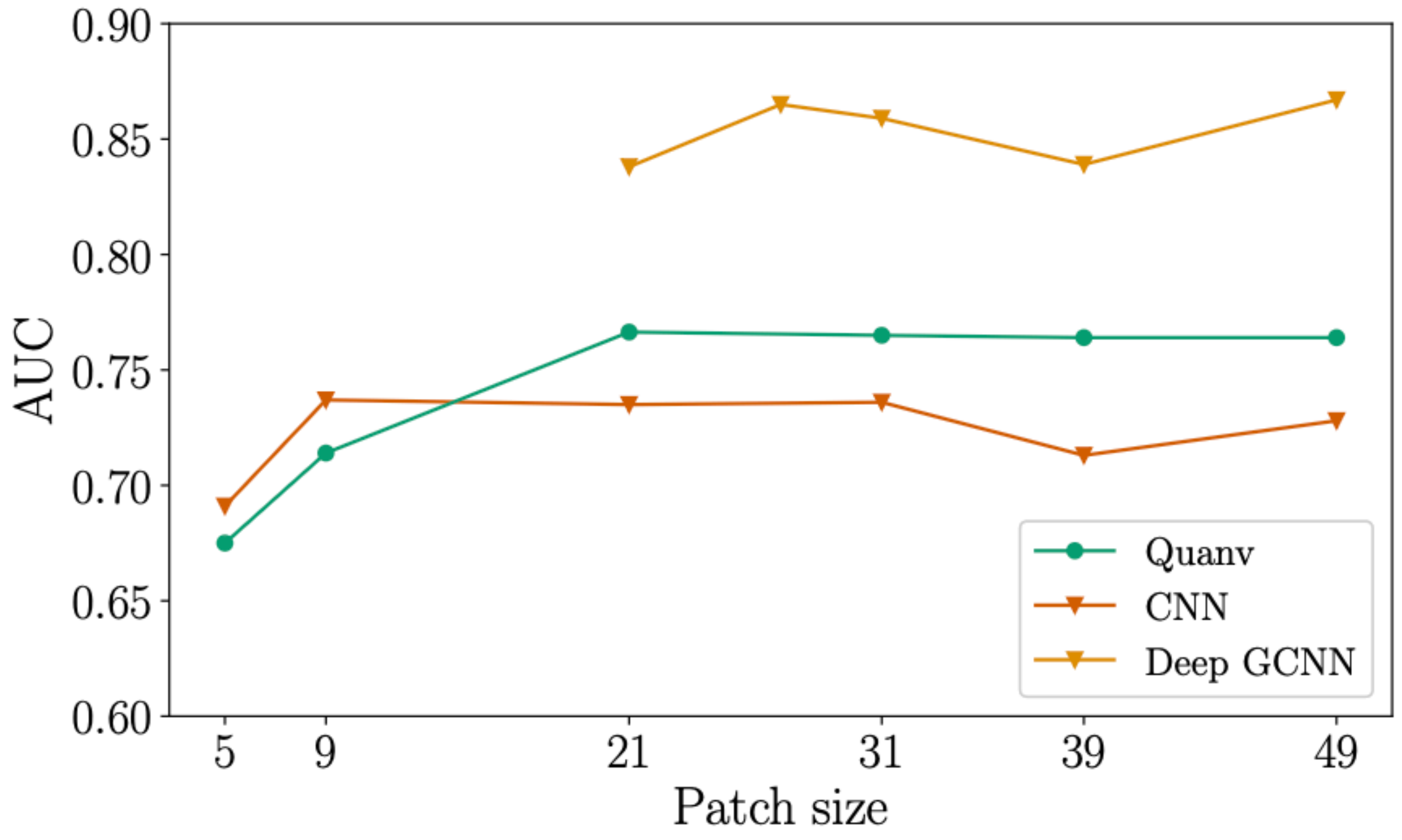
- Deep classical models (100× parameters) still perform best overall.

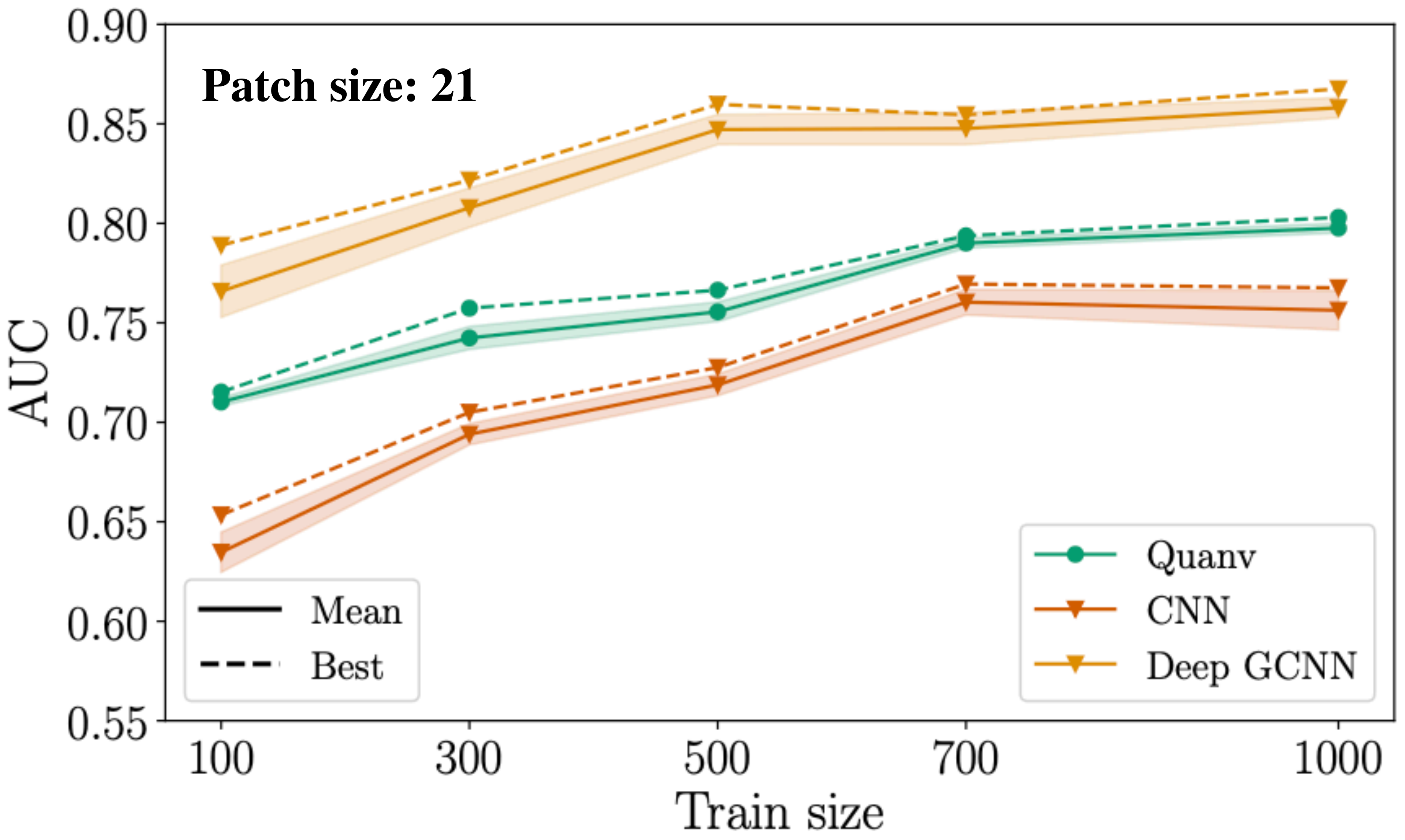
- Quantum models generalize better with limited data

- Adding symmetry gives minor gains but no clear advantage.

- Future work: Separating shower-like deposits from different particles, integrating hybrid models into DUNE's reconstruction pipeline.

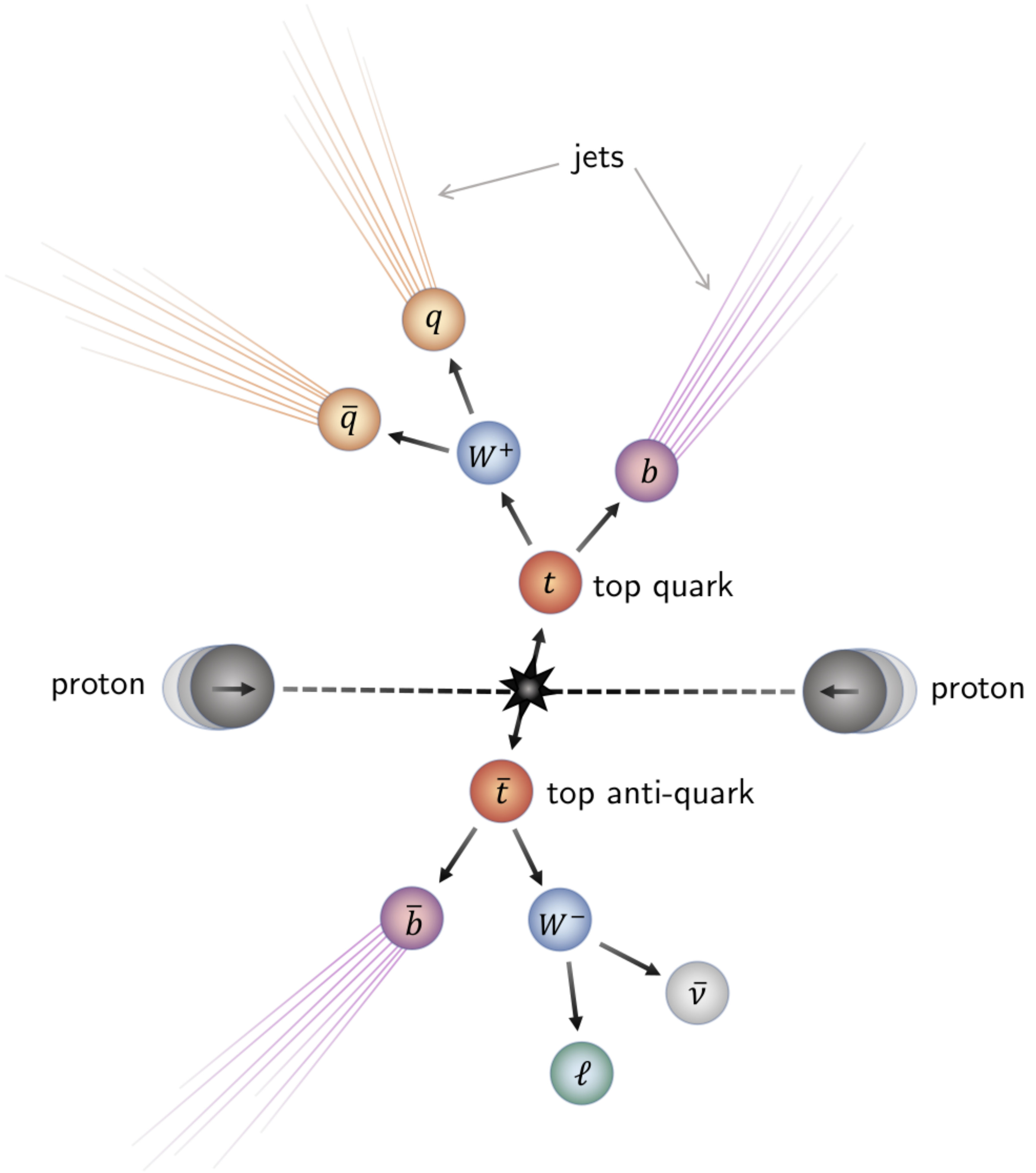
**Learning capability of various models**



# Testing Bell Inequalities at the LHC with Top-Quark Pairs

Can we use other high-energy processes to test quantum foundations in new ways?




Phys. Rev. Lett. 127, 161801 (2021)

Use pairs of top quarks produced in pp collisions at LHC to probe quantum entanglement at high energies not explored so far.

The top–antitop system forms a natural two-qubit state:

- Top quark spin = 1/2 → behaves like a qubit.

- Top decays before hadronization → spin info measurable.

Spin correlations of the top and antitop quark are measurable through their decay products

Reconstruct the spin entanglement of top–antitop pairs at from decay products using a density-matrix approach, extract the correlation matrix, and compute its eigenvalues.

By constructing a single observable from eigenvalues derived from the spin-correlation matrix can test a Bell-inequality violation.

# Testing Bell Inequalities at the LHC with Top-Quark Pairs

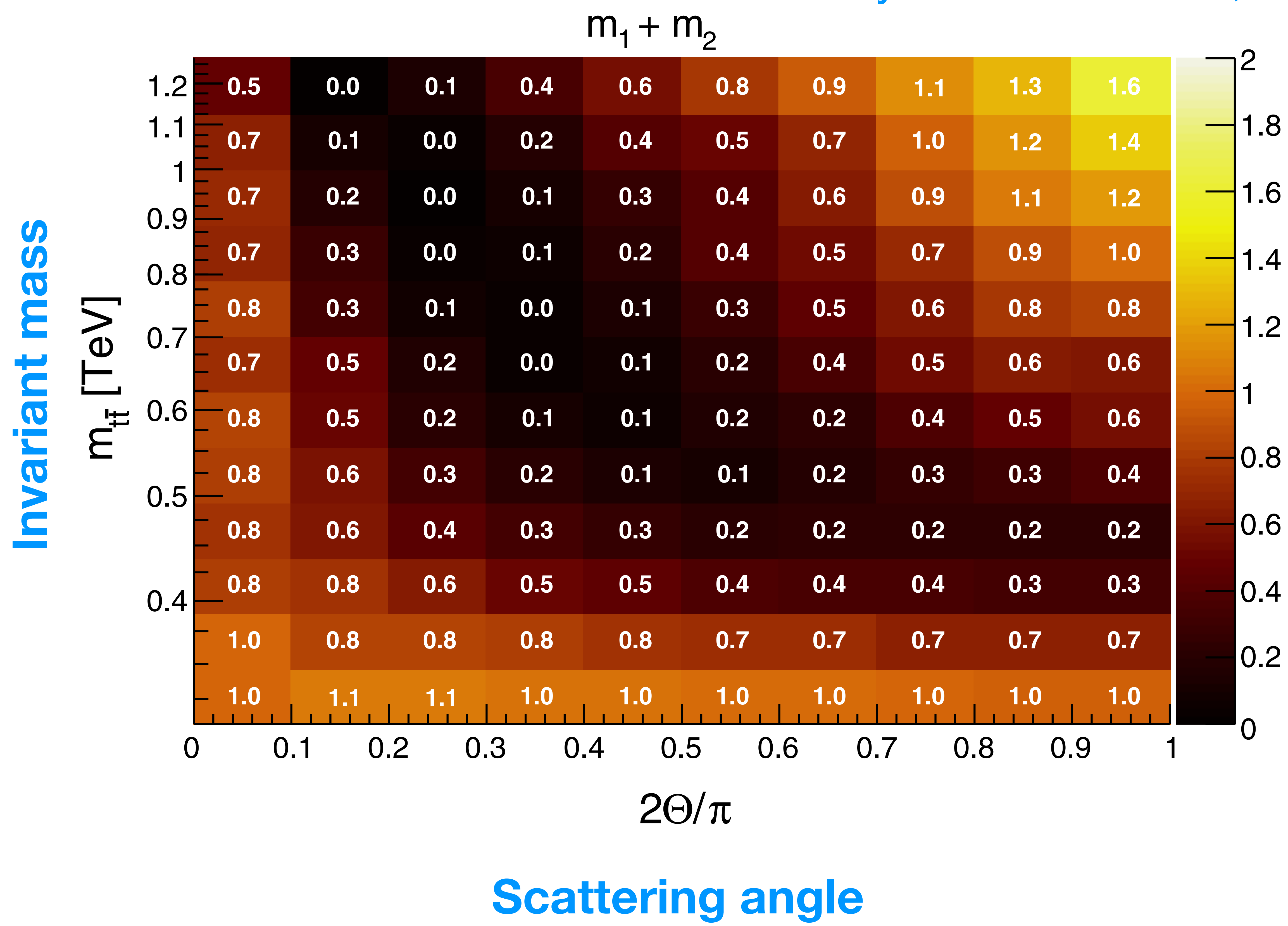
Phys. Rev. Lett. 127, 161801 (2021)

Two regions show m1 +m2 >1:

1. Near threshold

2. High-energy region:

Of the two, only the high-energy region shows a clean, strong Bell violation.



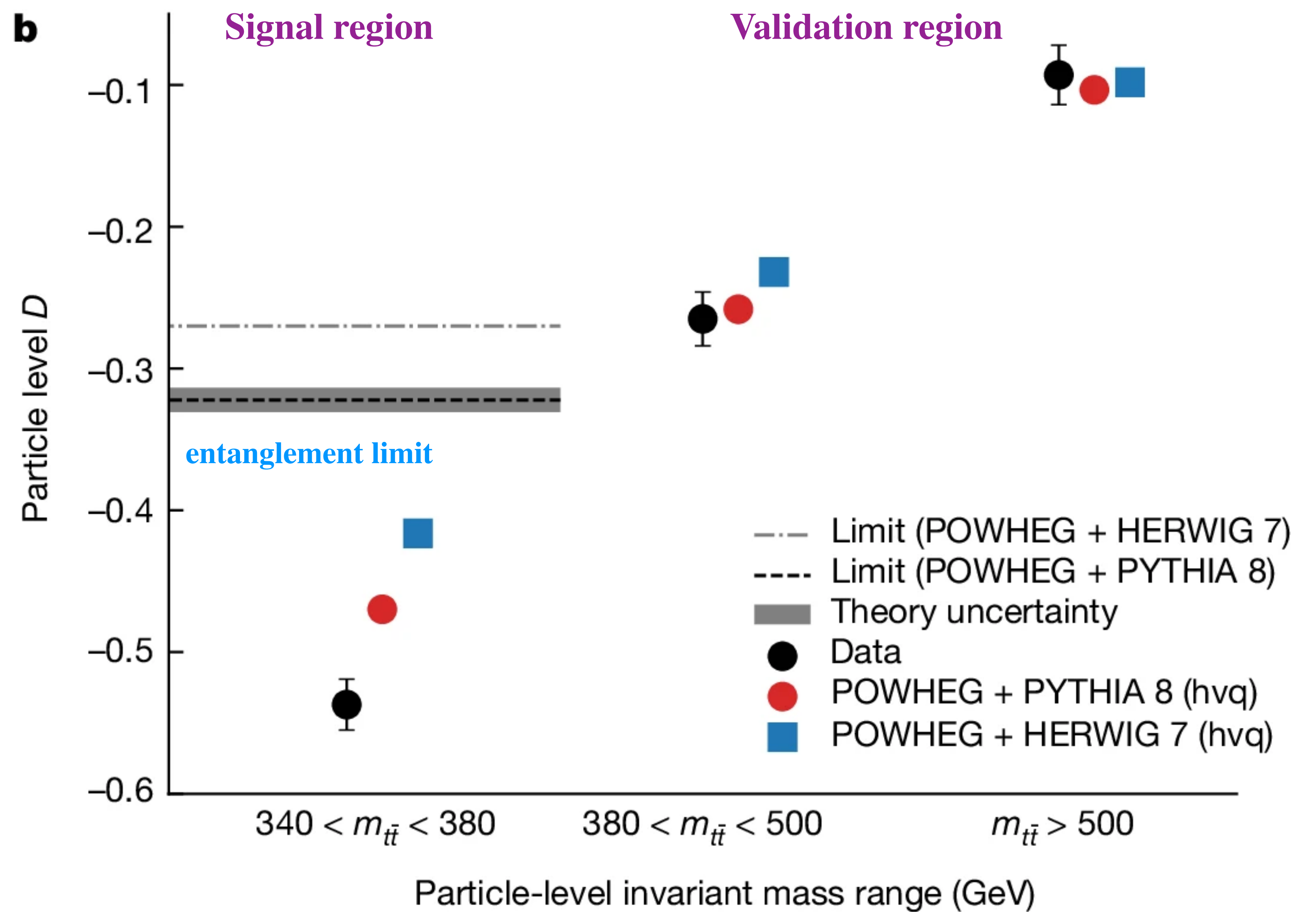

The most robust and unambiguous Bell inequality violation happens at high energies and forward angles, where both production mechanisms (gg and q̄q) align to produce maximally entangled spin states of the top–antitop pair.

With existing LHC Run II data, can achieve ~98% confidence level (C.L.), and with LHC Run III data up to ~99.99% C.L (4σ significance)

# ATLAS & CMS probe entanglement

Nature 633 (2024) 542

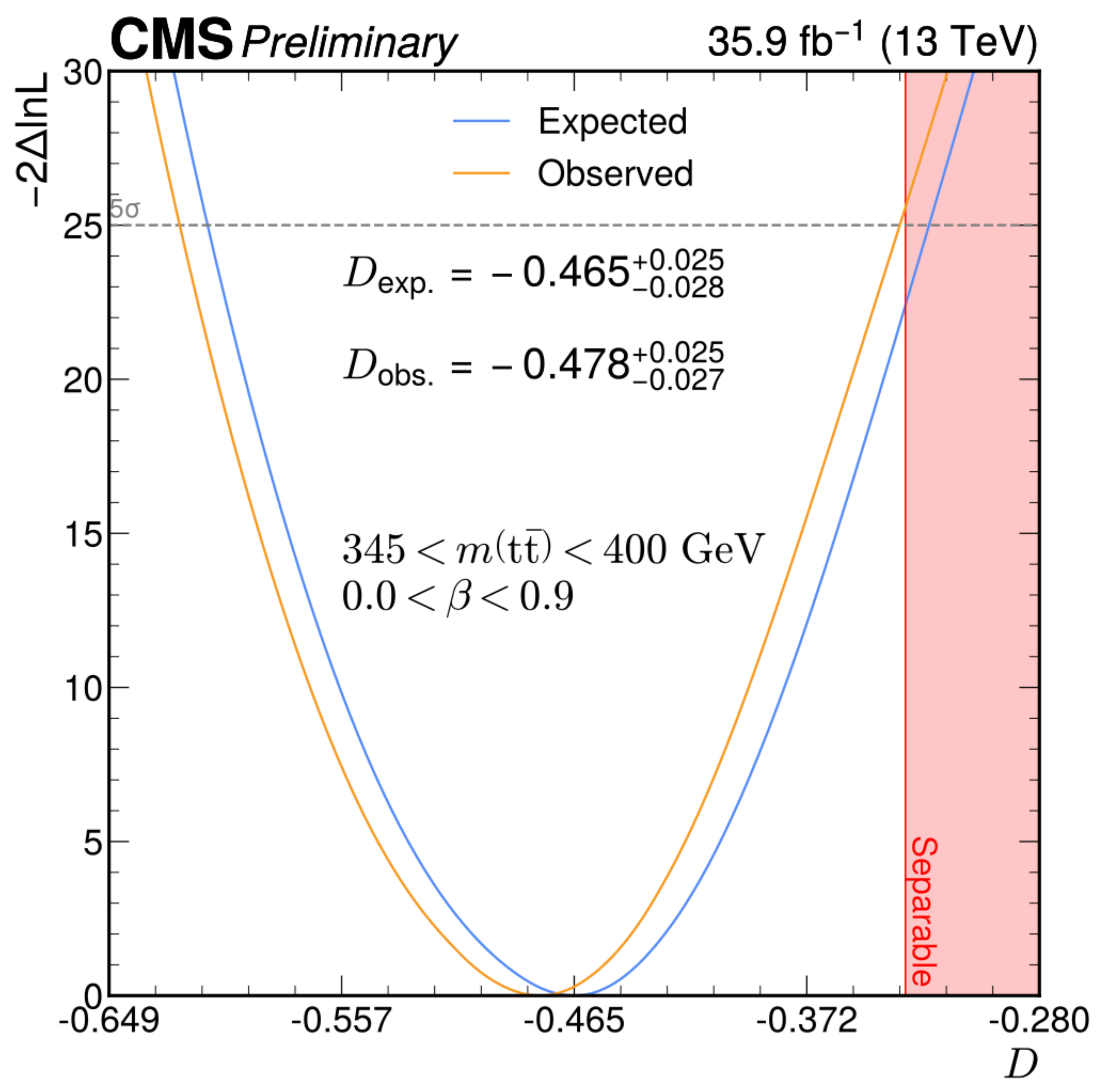
## ATLAS




- Use particle colliders as a laboratory to study quantum information and foundational problems in quantum mechanics
- Data from 13TeV ATLAS experiment during 2015–2018 — integrated luminosity of 140fb–1
- Entanglement variable D=−0.537±0.002 (stat.)±0.019 (syst.)
- More than five standard deviations from a scenario without entanglement
- First observation of entanglement in a quark–antiquark pair

## CMS

CMS PAS TOP-23-001




- Measure entanglement of top quark pairs using the spin correlation variable D as entanglement proxy.
- Events with two oppositely charged leptons.
- Binned profile likelihood fit of D from the distribution of cos ϕ in the most sensitive kinematic phase space of 345 < m(tt) < 400 GeV and 0.0 < β < 0.9.
- Entanglement proxy D itself is measured by a negative log-likelihood scan
- Expected (observed) significance of 4.7 (5.1) s.d —> observation of top quark entanglement

# Discussions

arXiv:2507.15949v1 [hep-ph] 21 Jul 2025

BONN-TH-2025-22, IPPP/25/48

## Colliders are Testing neither Locality via Bell's Inequality nor Entanglement versus Non-Entanglement

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Abstract: Recently there has been an increased interest in possible tests of locality via Bell's inequality or tests of entanglement at colliders, in particular at the LHC. These have involved various physical processes, such as $t\bar{t}$, or $\tau^+\tau^-$ production, or the decay of a Higgs boson to 2 vector bosons $H \to VV^*$. We argue that *none* of these proposals constitute a test of locality via Bell's inequality or a test of quantum entanglement versus non-entanglement. In all cases what is measured are the momenta of the final state particles. Using the construction proposed by Kasday (1971) in a different context, and adapted to collider scenarios by Abel, Dittmar, and Dreiner (1992), it is straightforward to construct a local hidden variable theory (LHVT) which exactly reproduces the data. This construction is only possible as the final state momenta all commute. This LHVT satisfies Bell's inequality and is by construction *not* entangled. Thus a test of locality via Bell's inequality or a test of entanglement versus non-entanglement is inherently *not* possible.

arXiv:2508.10979v2 [hep-ph] 28 Oct 2025

## Addressing Local Realism through Bell Tests at Colliders

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(Dated: October 30, 2025)

Abstract

One of the most notable aspects of quantum systems is that their components can exhibit correlations much stronger than those allowed by classical physics. Two examples of quantum correlations are quantum entanglement and Bell nonlocality, but generally there is a hierarchy of many types of quantum correlations. Among these correlations, Bell nonlocality holds a special place because it plays a dual role in distinguishing theories where local realism is a valid description. A Bell test, which is a test of local realism, typically needs to be augmented with assumptions to address possible loopholes in the experimental setup. In this work, we study Bell tests in experiments in which the detector reports the correct outcome with a specified probability. This mirrors the situation at high-energy colliders, where particle spins are not measured directly but inferred from the angular distributions of their decay products. We show that, in this setup, a test of local realism is not possible. Quantum correlations, however, are still present, measurable, and informative in high-energy colliders. These correlations are the building blocks of the interesting, developing quantum information science program at high-energy colliders. The measurements of entanglement by the ATLAS and CMS experiments are the first steps in this initiative.

# Quantum Information Concepts at the LHC

10.1103/PhysRevD.110.116016

- Two key phenomena of superposition and entanglement that distinguish quantum from classical computers
- Presence of entanglement in certain well-known quantum algorithms allows for an exponential speed-up relative to classical computing
- But, entanglement by itself not sufficient to provide an advantage over classical algorithms
- For any number of qubits, there are a certain number of ‘stabilizer’ states, which include some maximally entangled configurations. The Gottesman-Knill theorem states that quantum circuits involving stabilizer states only can be efficiently simulated using a classical computer
- For quantum advantage, need something else - ‘magic’
- Quantum computation introduces 'magic states' — quantum states that enable computational advantage over classical algorithms.
- Does nature produce 'magic' states at high energies?

PHYSICAL REVIEW D **110,** 116016 (2024)

**Magic states of top quarks**

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(Received 15 July 2024; accepted 20 November 2024; published 18 December 2024)

Recent years have seen an increasing body of work examining how quantum entanglement can be measured at high energy particle physics experiments, thereby complementing traditional table-top experiments. This raises the question of whether more concepts from quantum computation can be examined at colliders, and we here consider the property of *magic*, which distinguishes those quantum states which lead to a genuine computational advantage over classical states when used in algorithms. We examine top-antitop pair production at the LHC, showing that nature chooses to produce magic tops, where the amount of magic varies with the kinematics of the final state. We compare results for individual partonic channels and at proton level, showing that averaging over final states typically increases magic. This is in contrast to entanglement measures, such as the concurrence, which typically decrease. Also, while some entanglement measures (e.g., the concurrence) have a nonzero threshold for entanglement, there is no such nonzero threshold for magic. Our results create new links between the quantum information and particle physics literatures, providing practical insights for further study.

DOI: 10.1103/PhysRevD.110.116016

# “Magic Tops” at the LHC — Results & Implications

10.1103/PhysRevD.110.116016

- Magic analyzed as function of top velocity β and scattering angle z = cosθ.

• Nature produces 'magic' tops across most of phase space

• Zero-magic regions correspond to stabilizer states at special kinematic limits (maximal/minimal entanglement).

• Combining channels or angular averaging increases magic (mixing destroys stabilizer purity)

• Maximal entanglement ≠ maximal magic — magic measures computational potential, not correlation

Future directions:

- Use magic as a new observable to probe physics beyond the Standard Model.

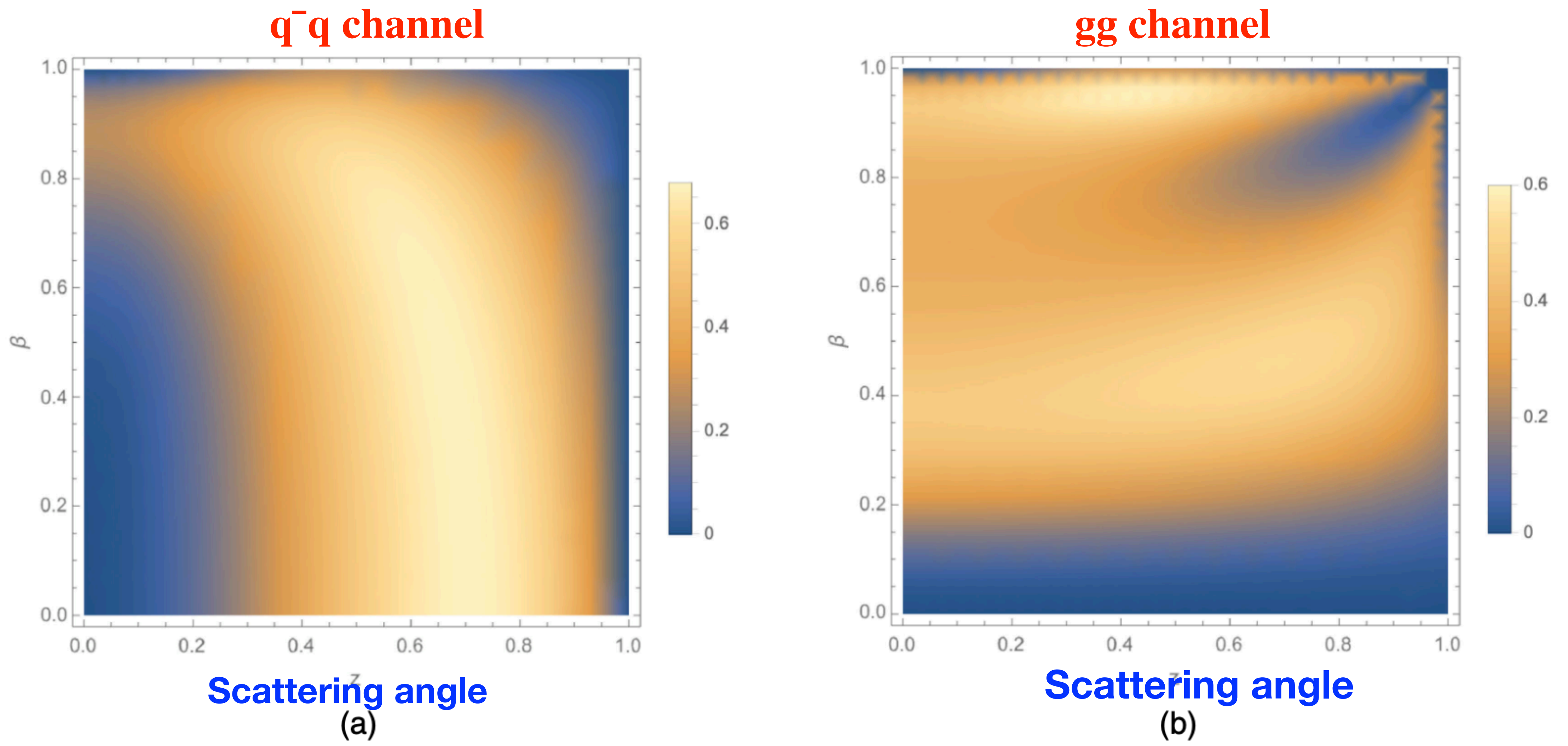



FIG. 3. The magic of a mixed top-antitop final state in (a) the $q\bar{q}$ channel and (b) the $gg$ channel.

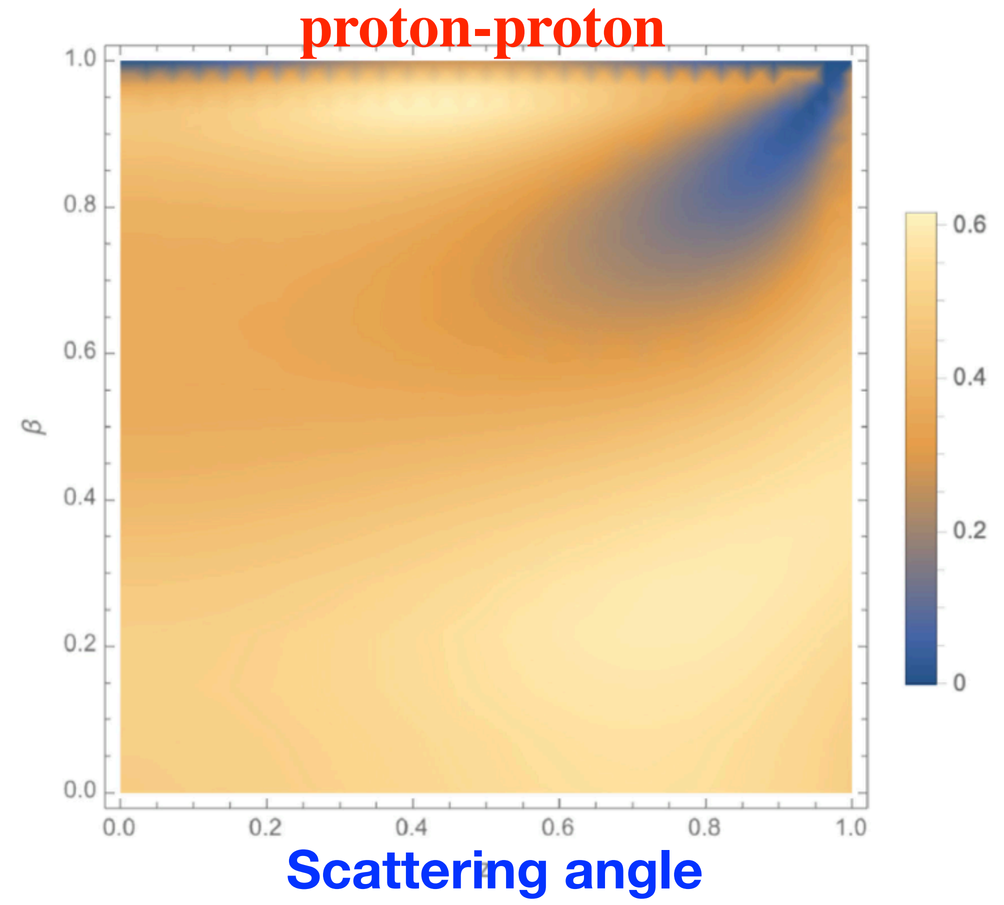



FIG. 4. The magic of a mixed top-antitop final state, for a proton-proton initial state.

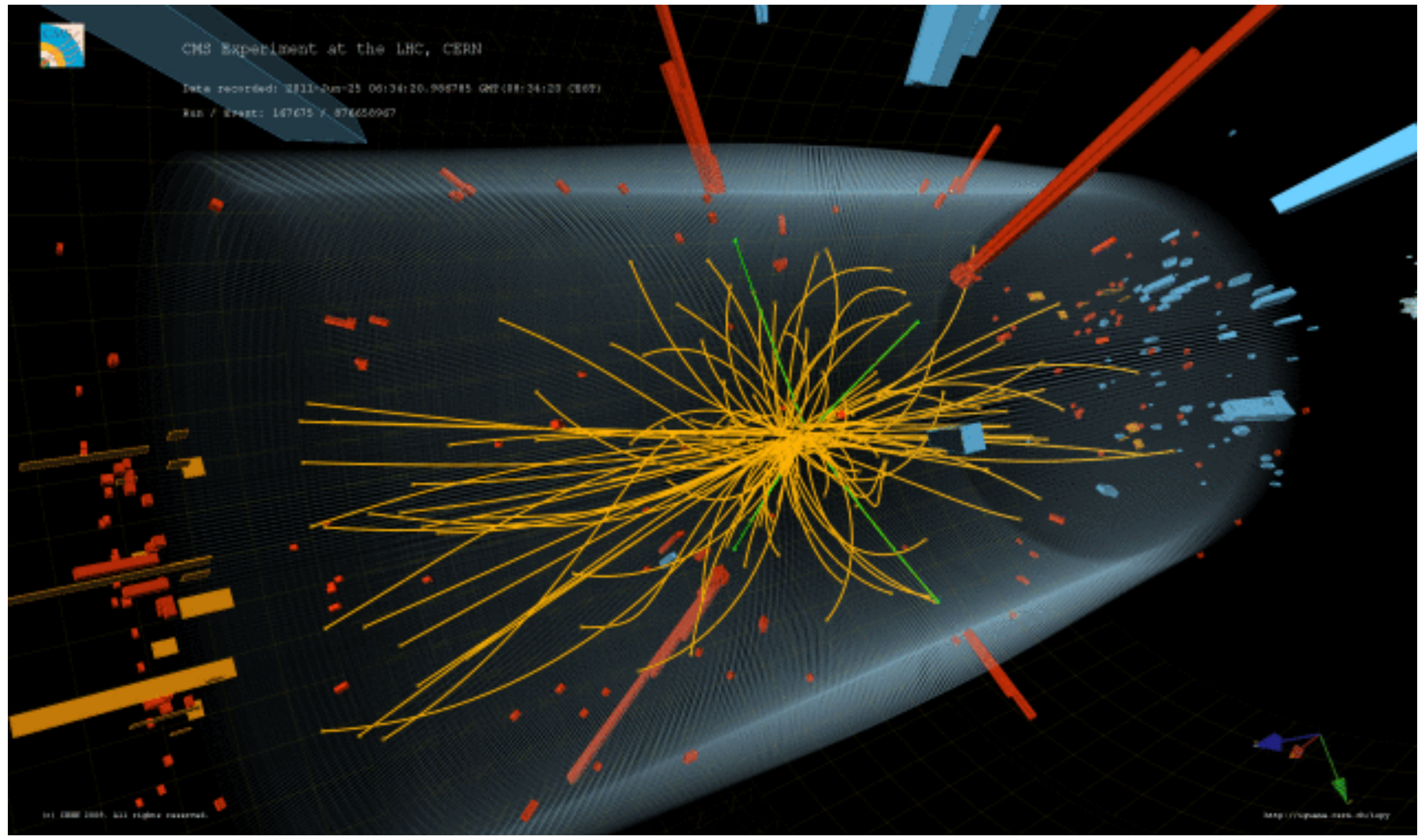
# Summary

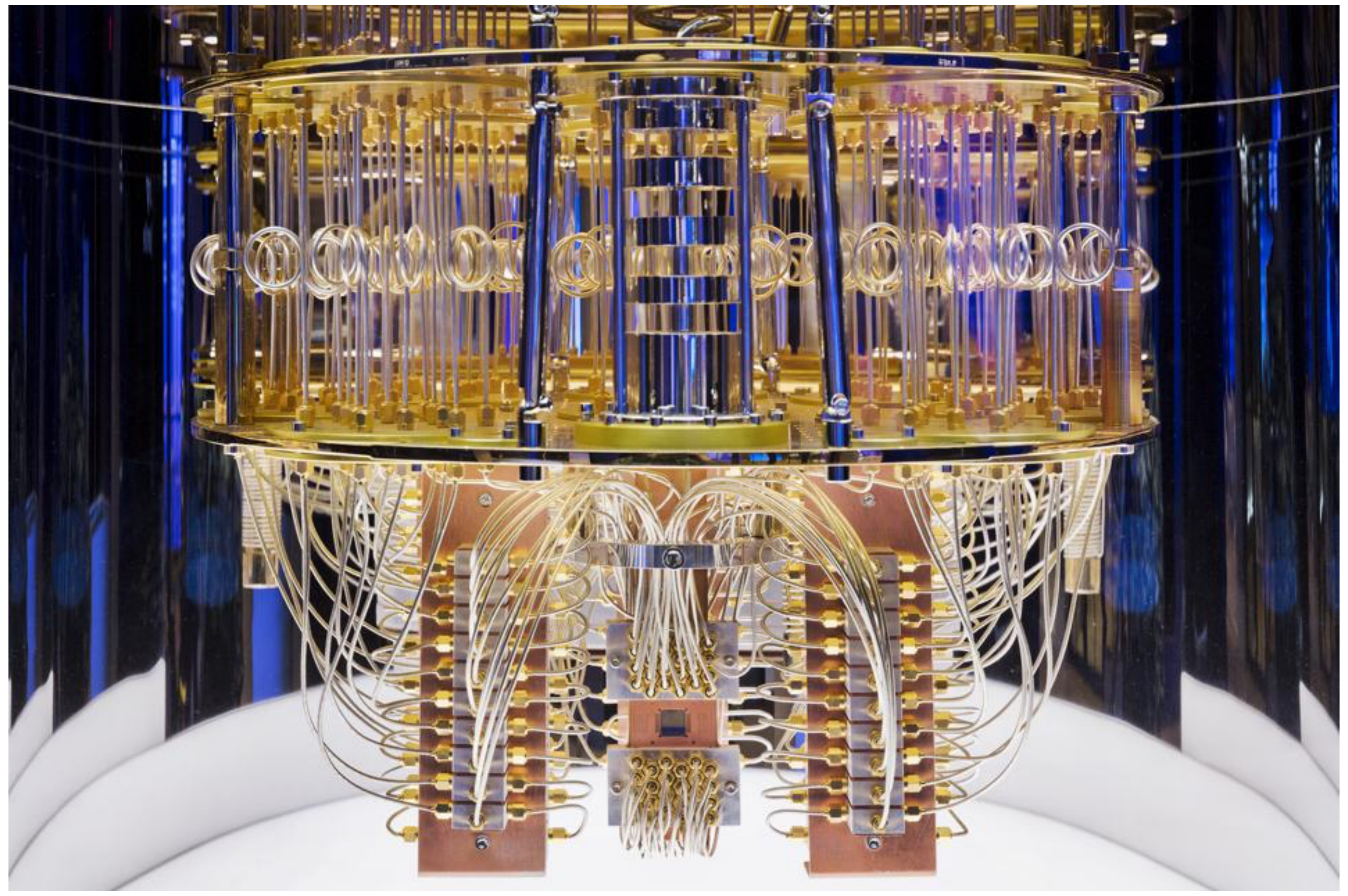
- Quantum computing is an emergent and rapidly developing field with potential applications in variety of different areas

- Solutions to some of the most challenging problems in particle physics may well be at the intersection of these two fields

- Current machines are excellent test beds for demonstrating proof-of-principle studies

- Interesting bidirectional exchange between quantum computing/information and particle physics

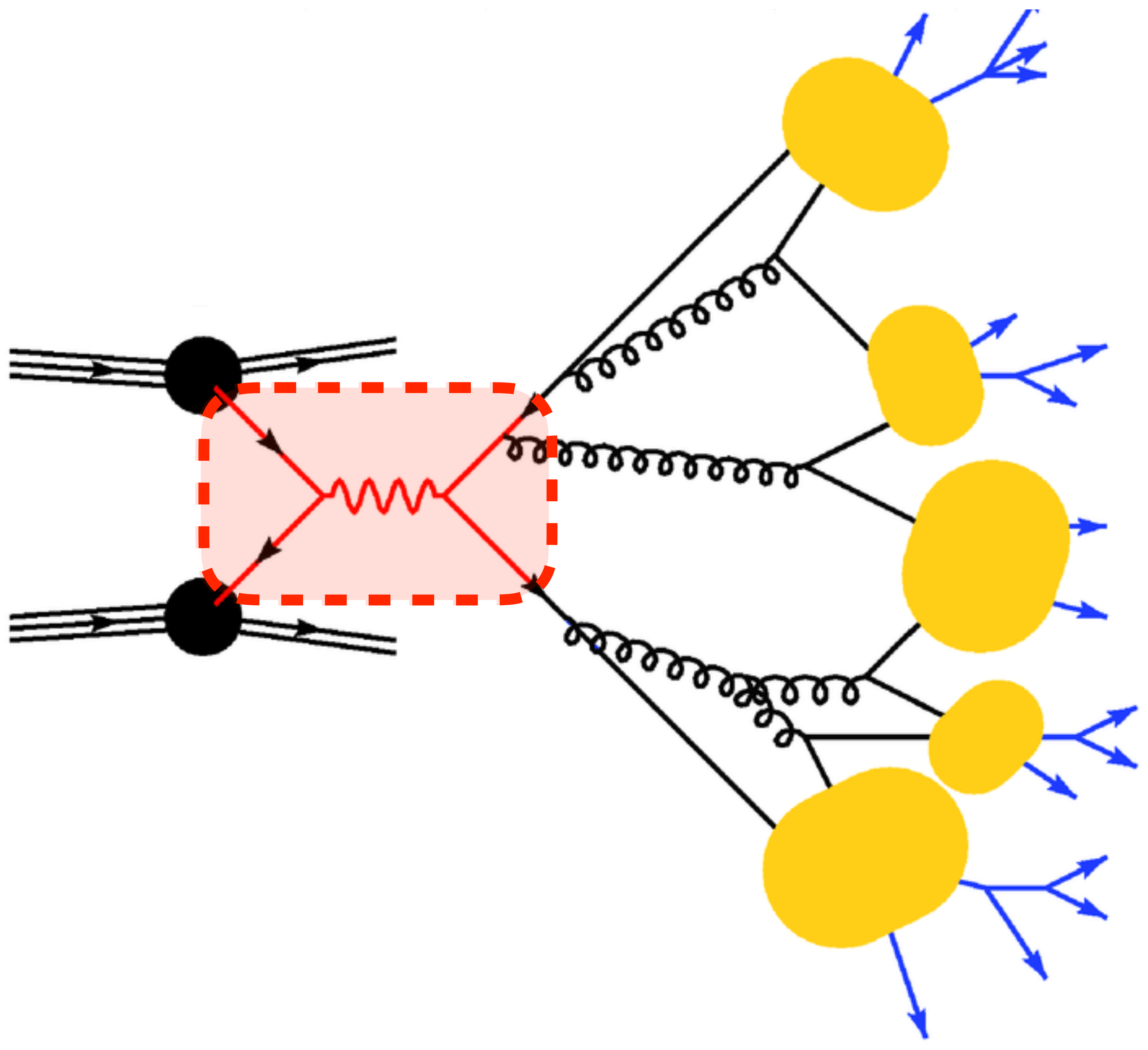


# BACKUP

# Scattering amplitudes

- Scattering amplitudes - essential for calculating predictions for collider experiments.
- At LHC, collisions dominated by QCD processes, which carry large theoretical uncertainty due to limited knowledge of higher order terms in perturbative QCD
- Improving accuracy of theoretical predictions of cross-sections means computing loop amplitudes and tree level amplitudes of higher multiplicities.



- Conventional method of computing an unpolarised cross section involves squaring the amplitude at the beginning and then summing analytically over all possible helicity states using trace techniques
- For complex processes, this approach is not very feasible. For N feynman diagrams for an amplitude, there are $N^2$ terms in the square of the amplitude

# Spinor helicity formalism

- Tool for calculating scattering amplitudes much more efficiently than conventional approach. Greatly simplifies the calculation of scattering amplitudes for complex processes.

Compute amplitudes of fixed helicity setup which has the advantage:

  - For massless particles, chirality and helicity coincide. Chirality is preserved by gauge interactions, hence helicity is also conserved. Helicity basis an optimal one for massless fermions.

  - Different helicity configurations do not interfere. Full amplitude obtained by summing the squares of all possible helicity amplitudes. $\sum_{\text{helicity}} |M_n|^2,$

- Using recursion relations such as BCFW, it is possible to calculate multi-gluon scattering amplitudes which would be prohibitive using traditional methods

# Equivalence between spinors and qubits

Helicity amplitude calculations based on manipulation of helicity **spinors**

Helicity spinors for massless states can be expressed as :

$$|p\rangle^{\dot{a}} = \sqrt{2E}\begin{pmatrix}\cos\frac{\theta}{2}\\ \sin\frac{\theta}{2}e^{i\phi}\end{pmatrix}$$

**Qubits** can be represented on a Bloch sphere as a linear superposition of orthonormal basis states $|0\rangle$ and $|1\rangle$ as:

$$|\psi\rangle = \cos\frac{\theta}{2}|0\rangle + e^{i\varphi}\sin\frac{\theta}{2}|1\rangle = \begin{pmatrix}\cos\frac{\theta}{2}\\ \sin\frac{\theta}{2}e^{i\phi}\end{pmatrix}$$

**Equivalence between spinors and qubits**

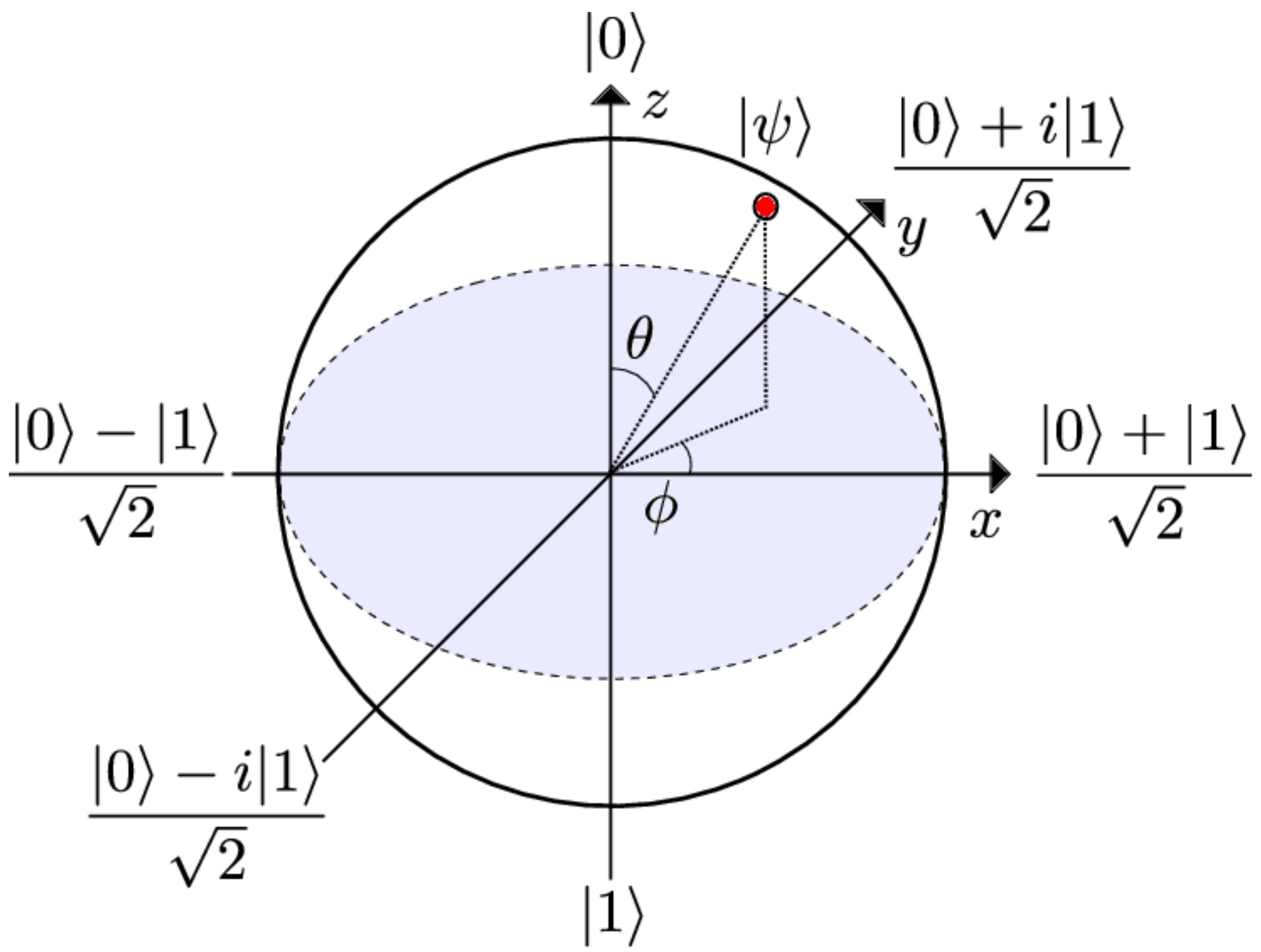
$$|p\rangle^{\dot{a}} = \sqrt{2E}\begin{pmatrix}\cos\frac{\theta}{2}\\ \sin\frac{\theta}{2}e^{i\phi}\end{pmatrix} \longrightarrow |\psi\rangle = \begin{pmatrix}\cos\frac{\theta}{2}\\ \sin\frac{\theta}{2}e^{i\phi}\end{pmatrix}$$

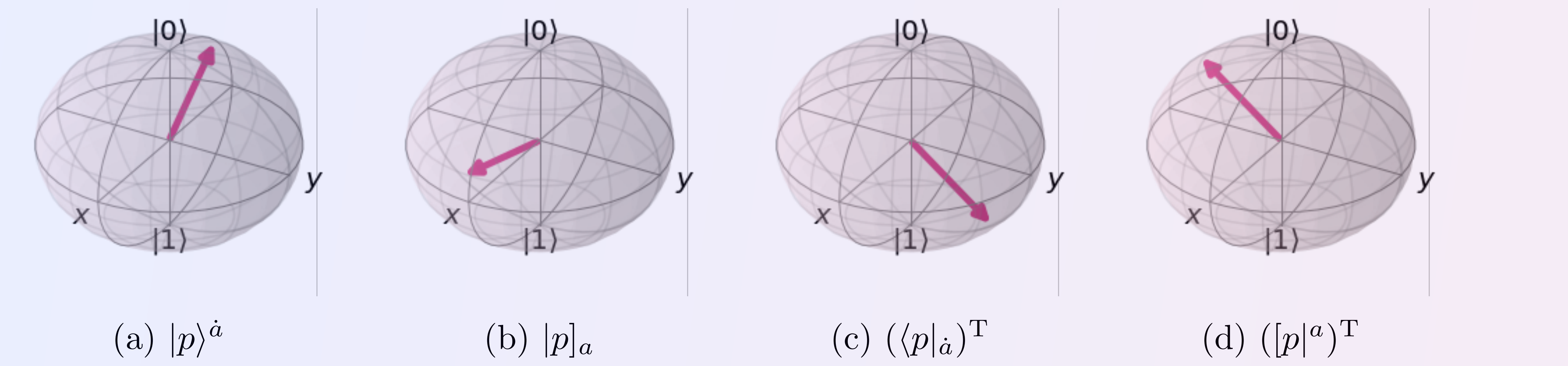
Spinors naturally live in the same representation space as qubits, thus helicity spinors can be represented as qubits

# Equivalence between spinors and qubits

Calculation of helicity amplitudes follows same structure as a quantum computing algorithm; quantum operators act
transform it into a state that can be measured

- Encode operators acting on spinors as a series of unitary transformations in the quantum circuit
- These unitary operations are applied to qubits to calculate helicity amplitude



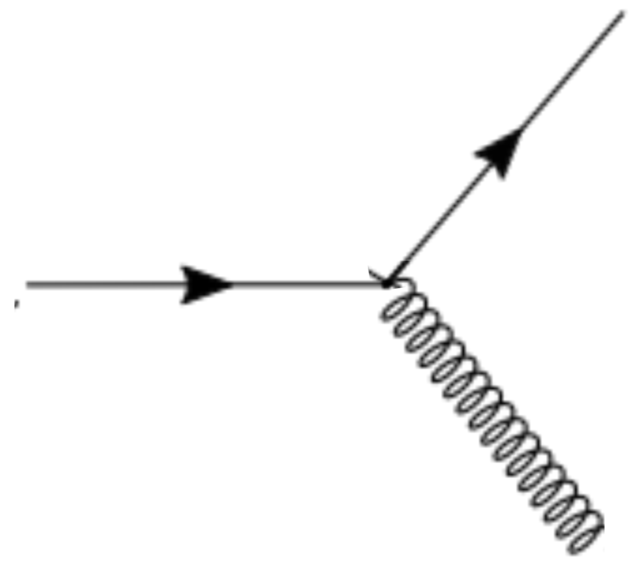




Visualisation of helicity spinors

# 1→2 helicity amplitude calculation

A simple application of the helicity amplitude approach is the calculation of a 1→2 process

$$\mathcal{M}_{gq\bar{q}} = \langle p_f|\bar{\sigma}_\mu|p_{\bar{f}}]\epsilon^\mu_\pm,$$



- Gluon polarisation vectors given by :

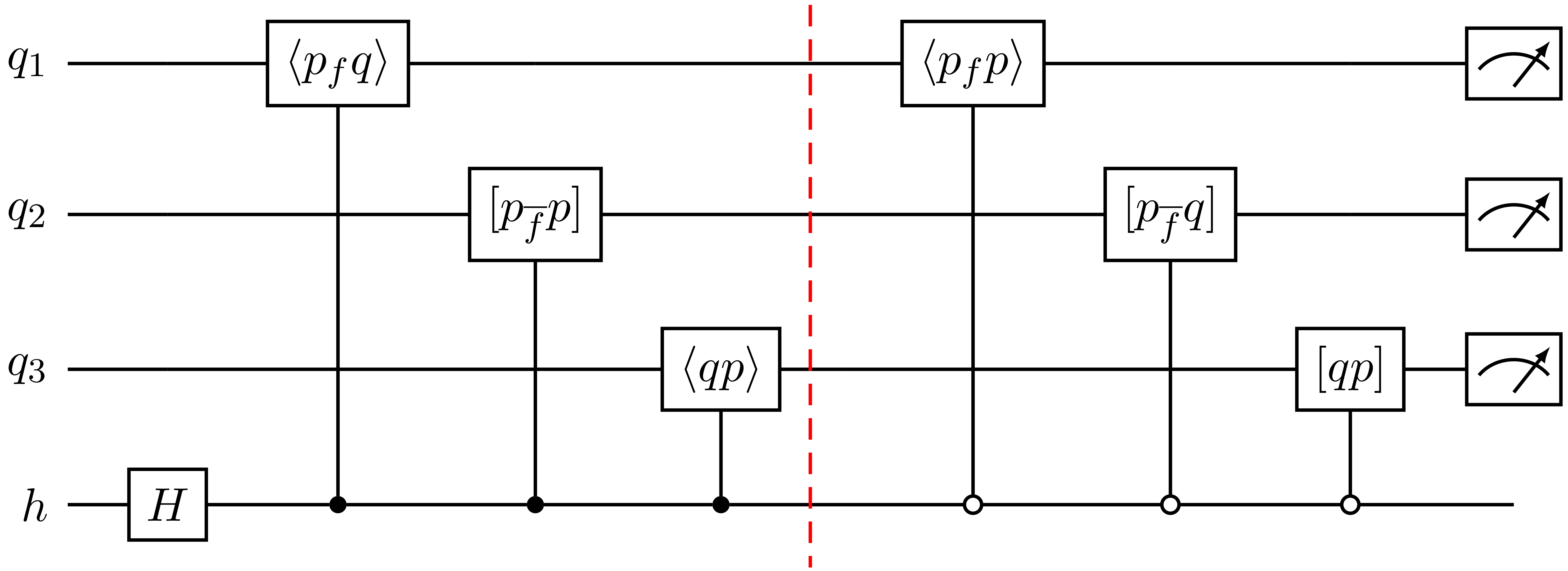
$$\epsilon^\mu_+ = -\frac{\langle q|\bar{\sigma}^\mu|p]}{\sqrt{2}\langle qp\rangle}, \qquad \epsilon^\mu_- = -\frac{\langle p|\bar{\sigma}^\mu|q]}{\sqrt{2}[qp]}.$$

- Can create circuit where each 4-vector calculated individually on 4 qubits - but this will require many qubits and large circuit depth.
- Instead, simplify amplitude using Fierz identity (hence reduce qubits from 10 → 4)

$$\boxed{\mathcal{M}_+ = -\sqrt{2}\frac{\langle p_f q\rangle[p_{\bar{f}}p]}{\langle qp\rangle}, \qquad \mathcal{M}_- = -\sqrt{2}\frac{\langle p_f p\rangle[p_{\bar{f}}q]}{[qp]}.}$$

# 1→2 helicity amplitude circuit

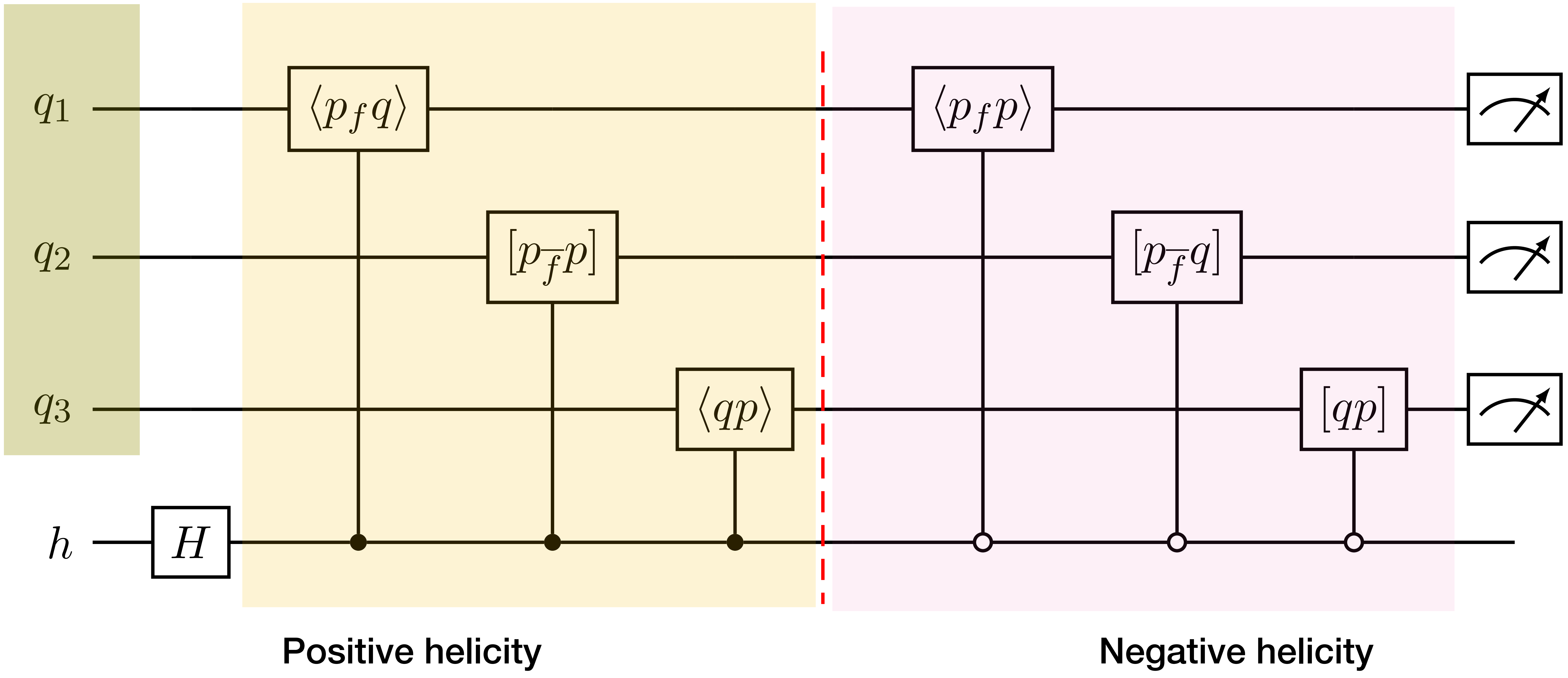
$$\mathcal{M}_+ = -\sqrt{2}\frac{\langle p_f q\rangle [p_{\bar{f}} p]}{\langle qp\rangle}, \qquad \mathcal{M}_- = -\sqrt{2}\frac{\langle p_f p\rangle [p_{\bar{f}} q]}{[qp]}.$$



# 1→2 helicity amplitude circuit

$$\mathcal{M}_+ = -\sqrt{2}\frac{\langle p_f q\rangle [p_{\bar{f}} p]}{\langle qp\rangle}, \qquad \mathcal{M}_- = -\sqrt{2}\frac{\langle p_f p\rangle [p_{\bar{f}} q]}{[qp]}.$$

qubits calculate the 3 scalar products for each helicity amplitude



# 1→2 helicity amplitude circuit

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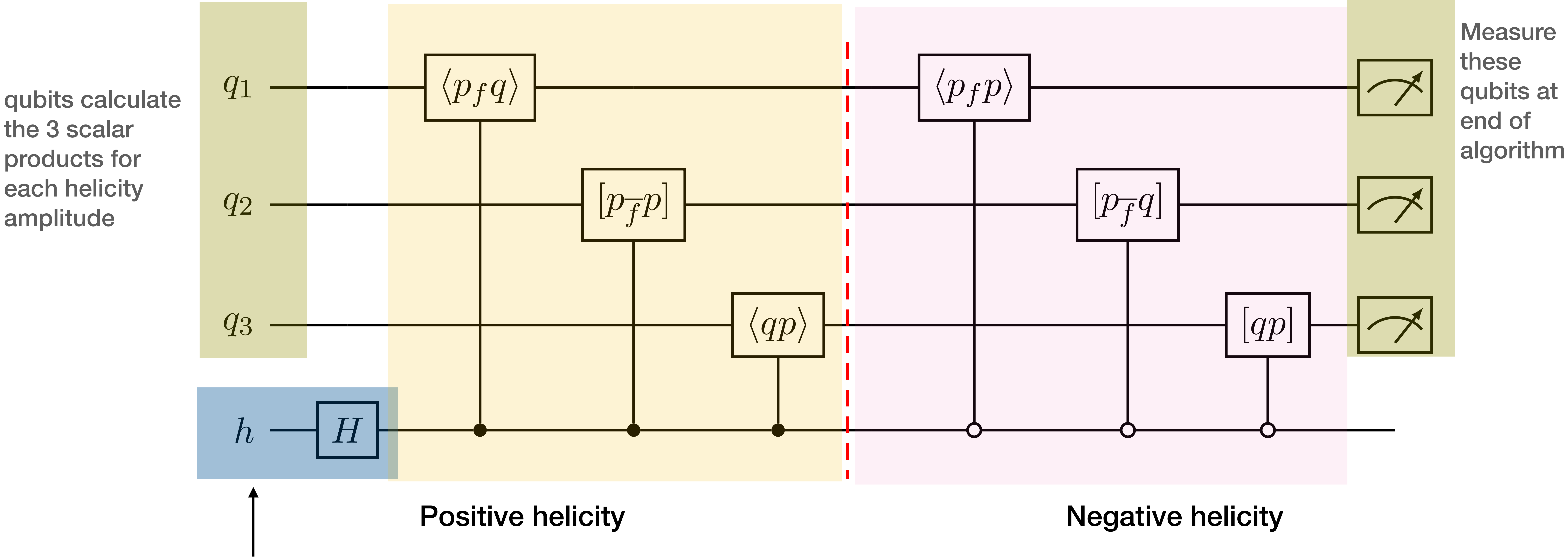



- Helicity register controls the helicity of each particle. Using a Hadamard gate, we introduce a superposition between the helicity states $|+\rangle = |1\rangle$ and $|-\rangle = |0\rangle$
- Hence, calculate the helicity of each particle involved simultaneously!

# 1→2 helicity amplitude calculation

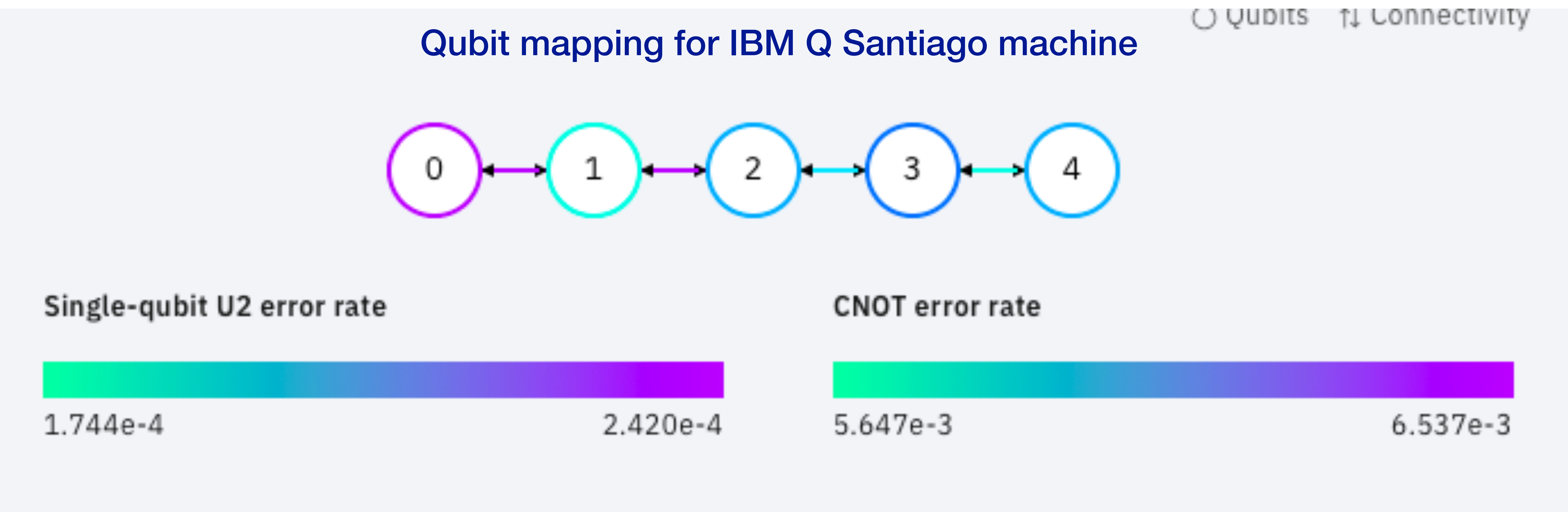
Run algorithm on:
- IBM Q 32-qubit simulator (10,000 shots) without noise profile
- IBM Q 5-qubit Santiago quantum computer (819,200 shots)

# 1→2 helicity amplitude calculation

Run algorithm on:

- IBM Q 32-qubit simulator (10,000 shots) without noise profile
- IBM Q 5-qubit Santiago quantum computer (819,200 shots)

Qubit mapping for IBM Q Santiago machine



# 1→2 helicity amplitude calculation

Run algorithm on:
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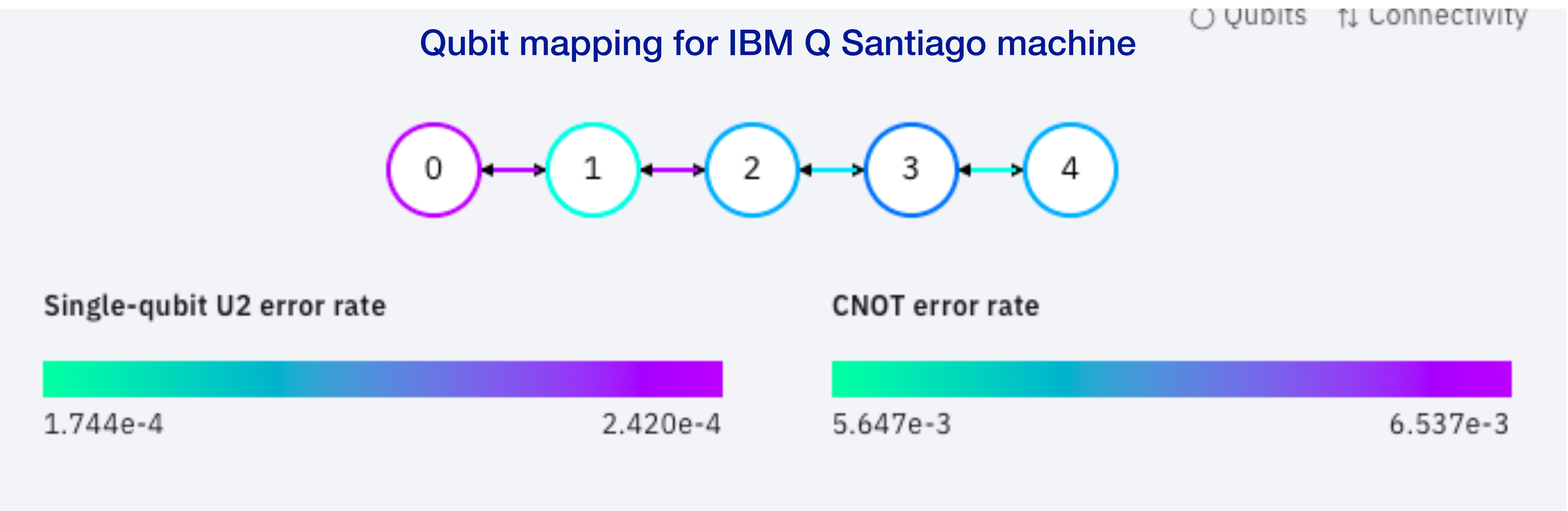
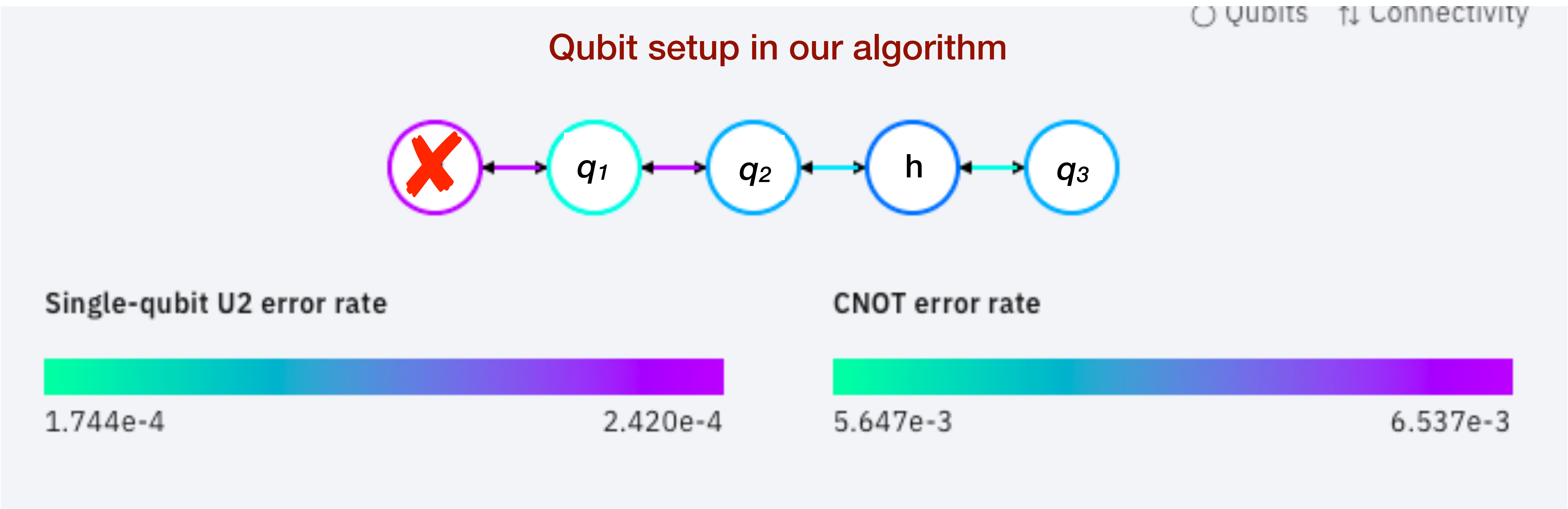
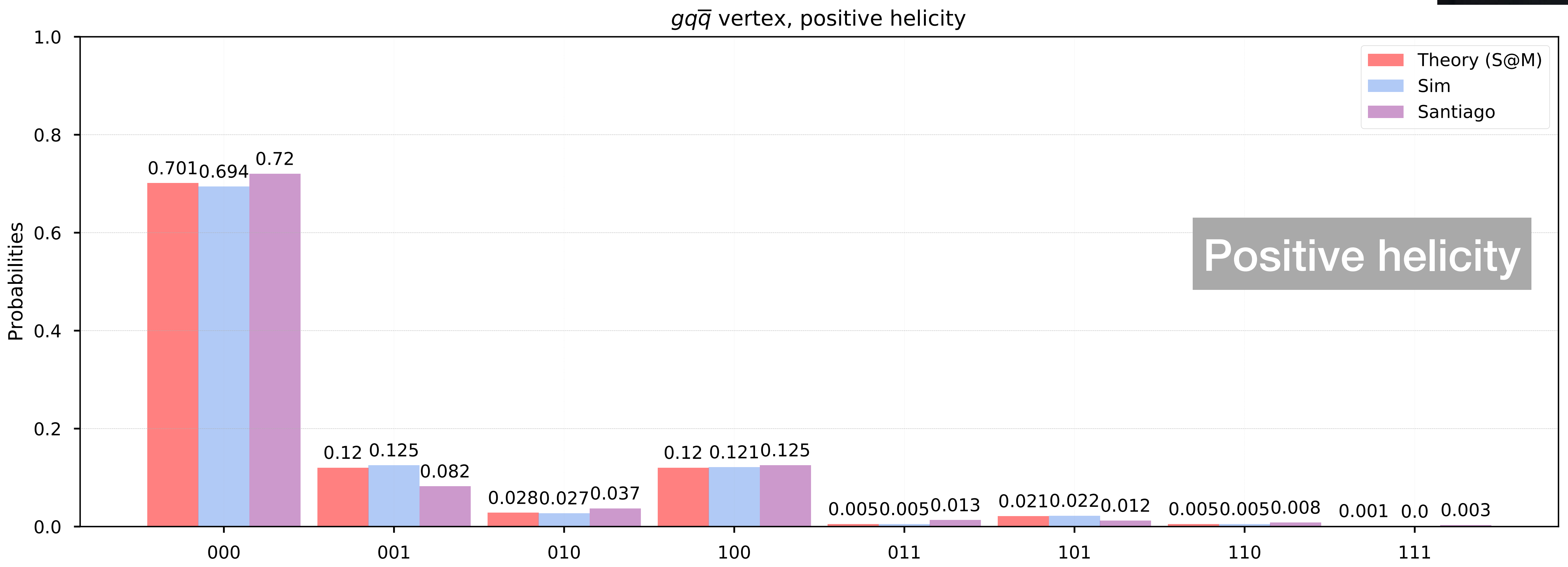


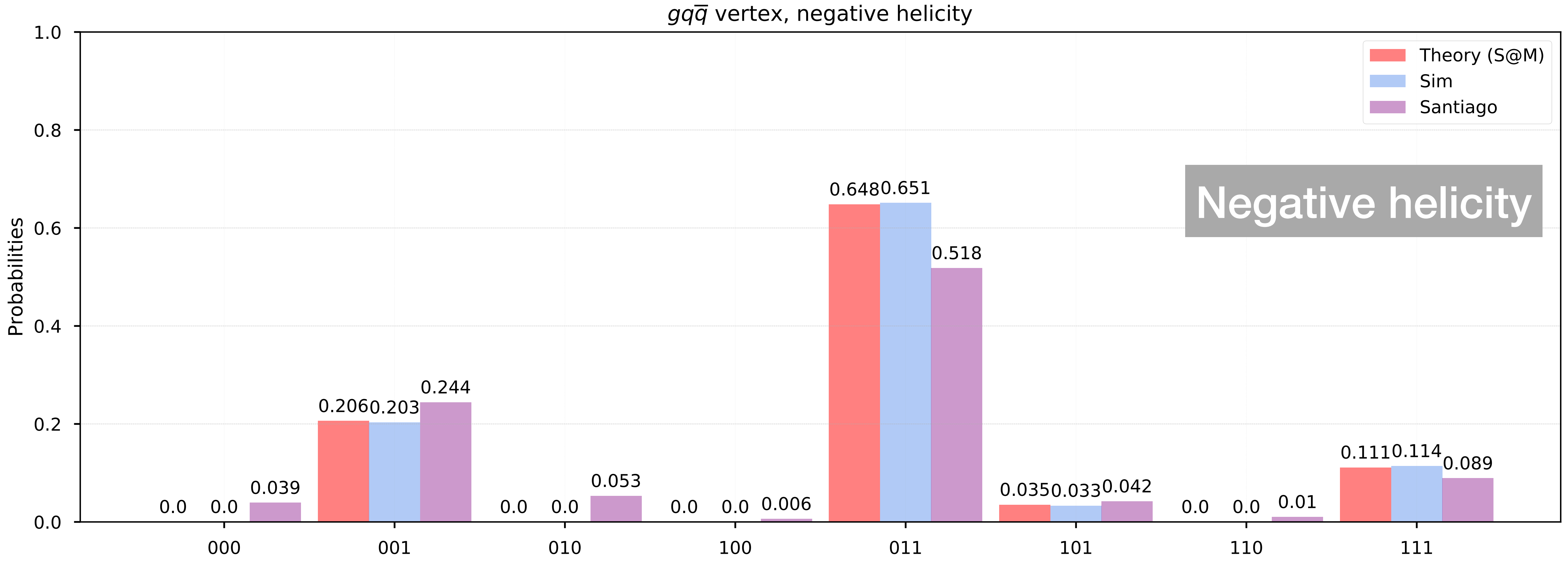




Optimal qubit setup to reduce CNOT errors and limit the number of SWAP operations

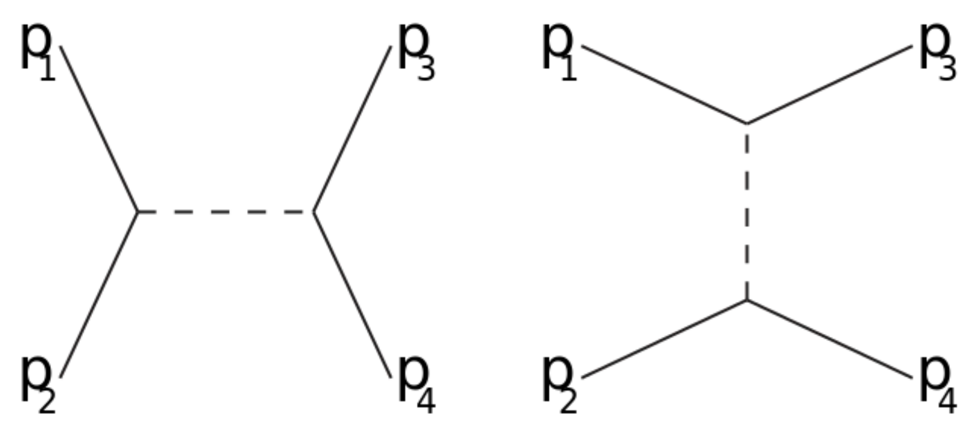
# 1→2 helicity amplitude calculation

Run algorithm on:
- IBM Q 32-qubit simulator (10,000 shots) without noise profile
- IBM Q 5-qubit Santiago quantum computer (819,200 shots)
- Compare with theoretical calculation

Extending from the 1 → 2 process, we consider the 2 → 2 scattering case of $q\bar{q} \rightarrow q\bar{q}$




s-channel t-channel

Amplitudes for the s and t-channel:

$$\mathcal{M}_{s(+-+-)} = -\langle 2|\bar{\sigma}^{\mu}|1]\frac{1}{s_{12}}[3|\sigma_{\mu}|4\rangle, \qquad \mathcal{M}_{s(+--+)} = -\langle 2|\bar{\sigma}^{\mu}|1]\frac{1}{s_{12}}\langle 3|\bar{\sigma}_{\mu}|4]$$

$$\mathcal{M}_{t(++--)} = -\langle 3|\bar{\sigma}^{\mu}|1]\frac{1}{s_{13}}[2|\sigma_{\mu}|4\rangle, \qquad \mathcal{M}_{t(+--+)} = -\langle 3|\bar{\sigma}^{\mu}|1]\frac{1}{s_{13}}\langle 2|\bar{\sigma}_{\mu}|4]$$

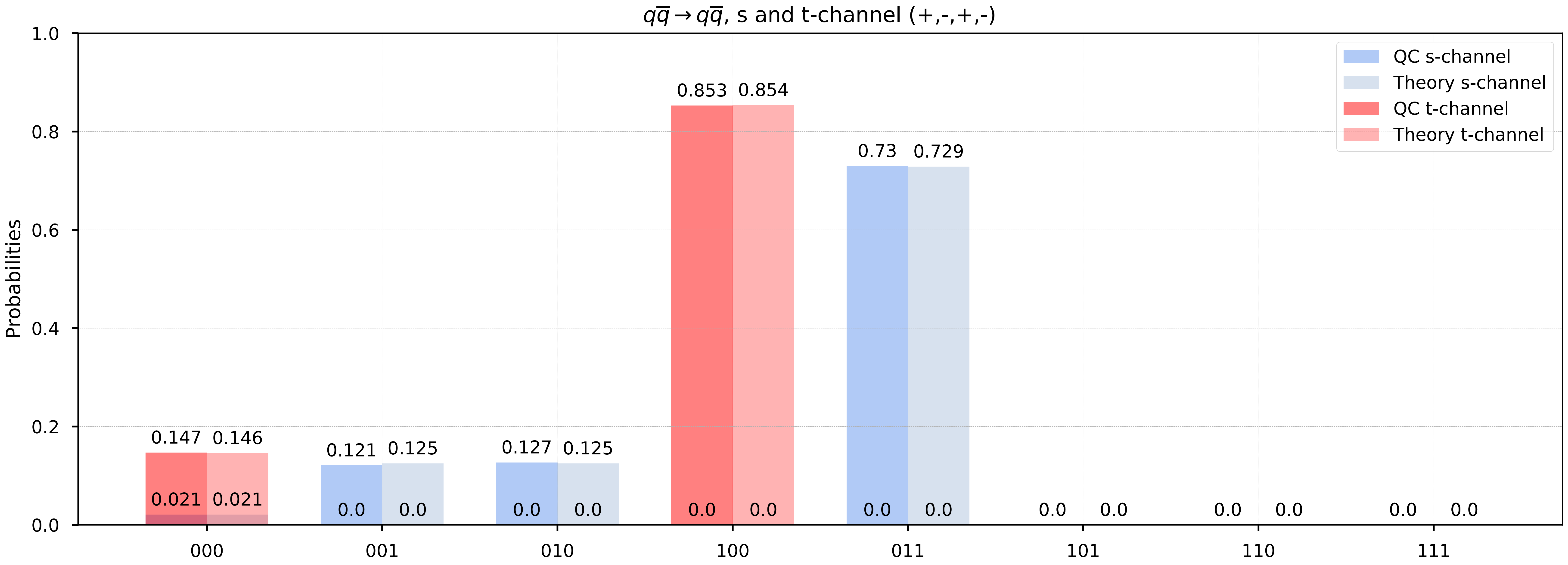
Again using the Fiery identity, can simplify these to (reduce # of qubits needed from 17 to 12) :

$$\mathcal{M}_{t_{(++--)}} = 2\frac{\langle 34\rangle[21]}{\langle 13\rangle[31]}, \qquad \mathcal{M}_{t_{(+--+)}} = 2\frac{\langle 32\rangle[41]}{\langle 13\rangle[31]}.$$

$$\mathcal{M}_{s_{(+-+-)}} = 2\frac{\langle 24\rangle[31]}{\langle 12\rangle[21]}, \qquad \mathcal{M}_{s_{(+--+)}} = 2\frac{\langle 23\rangle[41]}{\langle 12\rangle[21]}$$

# 2→2 helicity amplitude calculation

**Run algorithm on:**
- **IBM Q 32-qubit simulator (10,000 shots)**
- **Compare with theoretical calculation**




- Algorithm calculates the positive and negative helicity of each particle involved AND the s and t-channels simultaneously!

# 2→n helicity amplitude calculation

- Proposed algorithm can be generalised to calculating helicity amplitudes for multi-particle final states.

- Using BCFW recursion formula, scattering amplitudes for massless partons can be reduced to combination of scalar products between helicity spinors

e.g. Parke-Taylor formula for 2→n gluon scattering process

$$\mathcal{A}_n[1^+ \cdots i^- \cdots j^- \cdots n^+] = (-g_s)^{n-2} \frac{\langle ij \rangle^4}{\langle 12 \rangle \langle 23 \rangle \cdots \langle n1 \rangle}.$$

- The number of calculation qubits and helicity qubits needed in the algorithm both scale linearly with the number of final state particles.

- Each scalar product requires two spinor operations, the circuit depth scales linearly with number of scalar products.

# Parton shower

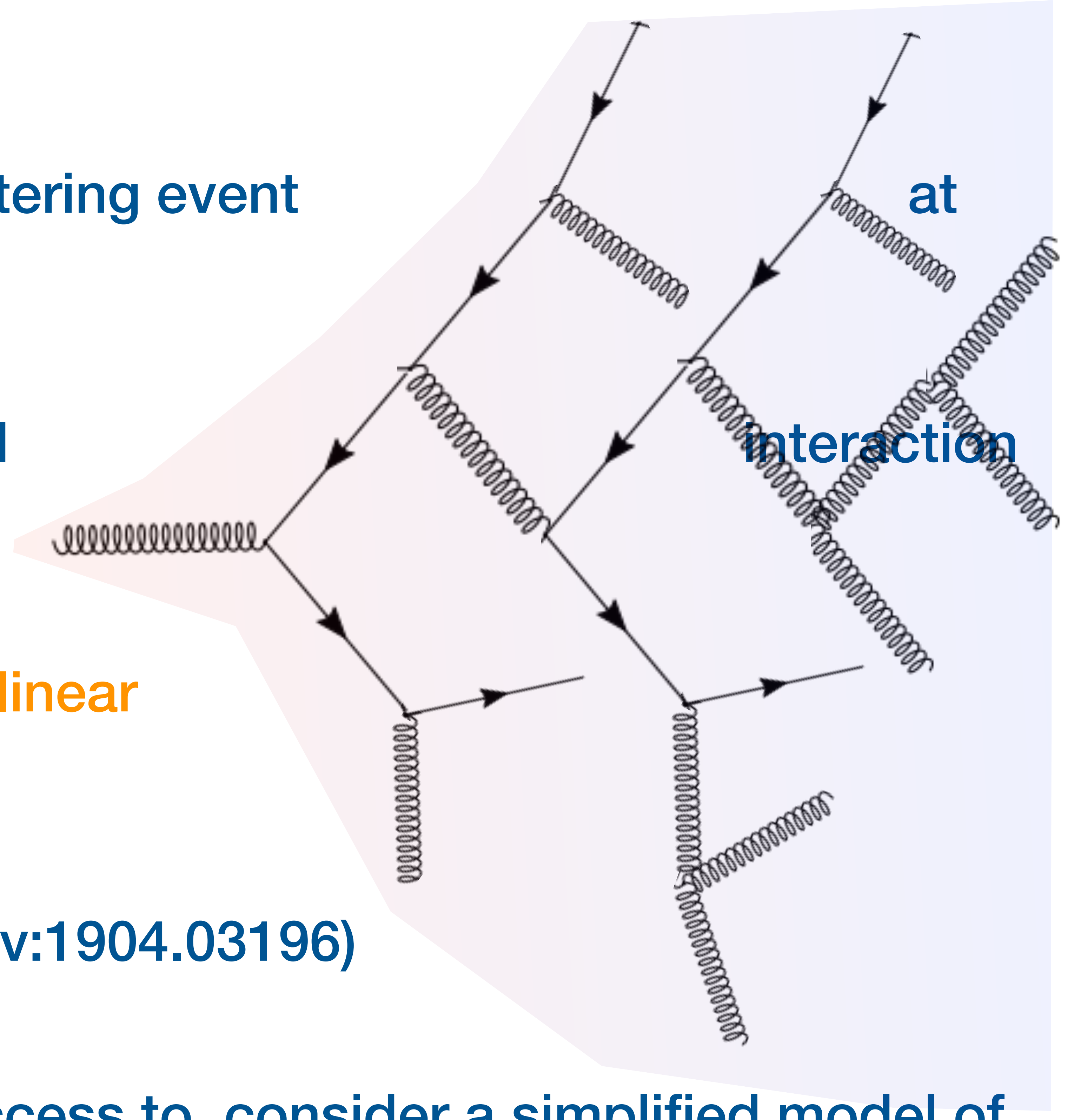
- After the hard interaction, the next step in simulating a scattering event at LHC is the parton shower

- Parton shower evolves the scattering process from the hard interaction scale down to the hadronisation scale

- Propose a quantum computing algorithm that simulates collinear emission in a 2-step parton shower

- This algorithm builds on previous work by Bauer et. al. (arXiv:1904.03196)

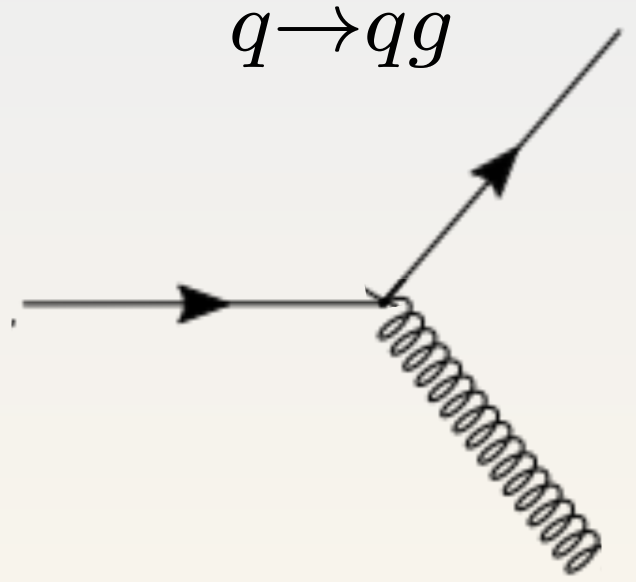
- To comply with capability of quantum computers we had access to, consider a simplified model of the parton shower consisting of only one flavour of quark



# Parton shower

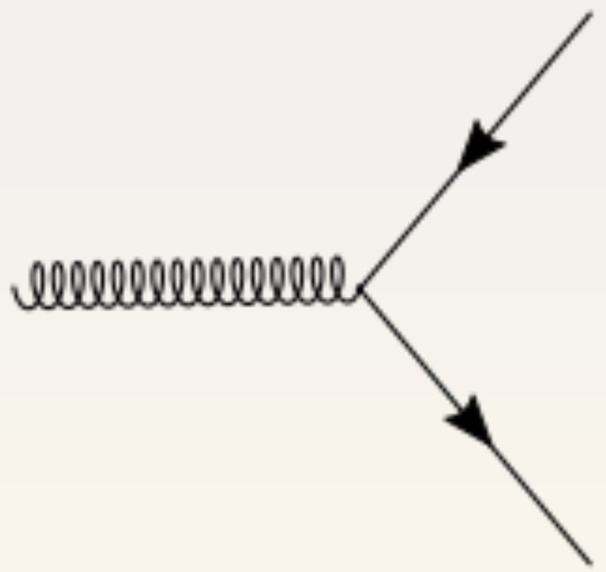
- Collinear emission occurs when a parton splits into two massless particles which have parallel 4-momenta
- The total momentum, P, of the parton is distributed between the particles as: $p_i = zP, \quad p_j = (1-z)P$
- Emission probabilities are calculated using collinear splitting functions, which at LO are given by:

$q \to qg$



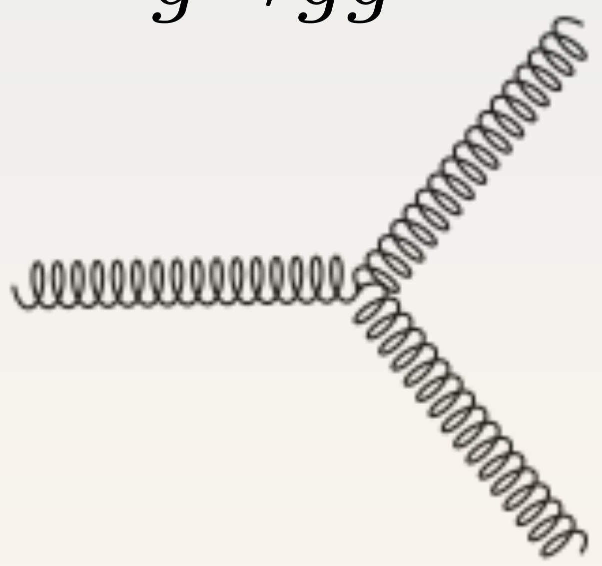
$$P_{q\to qg}(z) = C_F \frac{1+(1-z)^2}{z},$$

$g \to q\bar{q}$



$$P_{g\to q\bar{q}}(z) = n_f T_R (z^2 + (1-z)^2),$$

$g \to gg$



$$P_{g\to gg}(z) = C_A \left[2\frac{1-z}{z} + z(1-z)\right]$$

Non-emission probability calculated using Sudakov factors

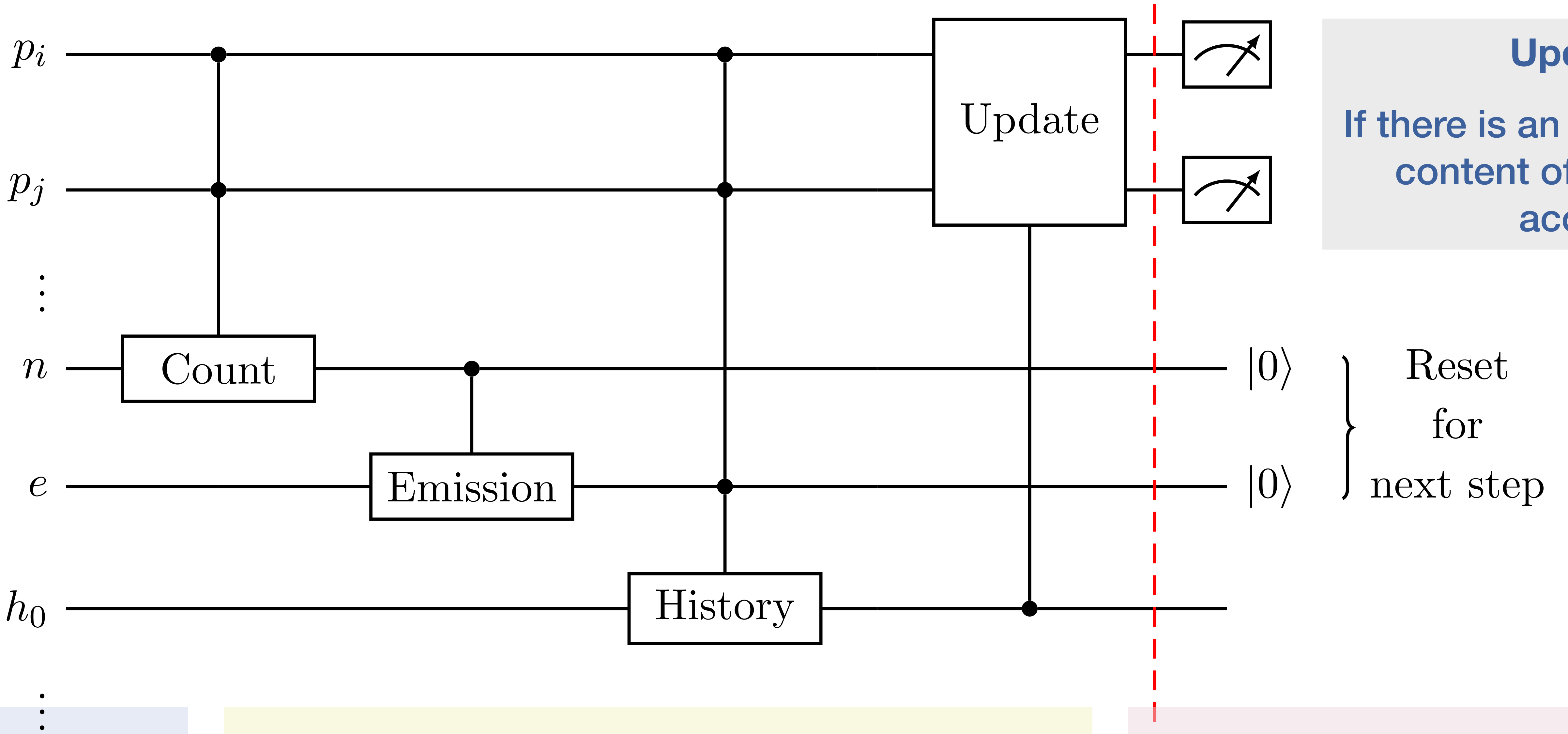
$$\Delta_{i,k}(z_1, z_2) = \exp\left[-\alpha_s^2 \int_{z_1}^{z_2} P_k(z')dz'\right],$$

Probability of a splitting is given by,

$$\mathrm{Prob}_{k\to ij} = \left(1 - \Delta_k\right) \times P_{k\to ij}(z).$$

# Circuit for parton shower algorithm

- Circuit comprises of particle registers, emission registers, and history registers and uses a total of 31 qubits

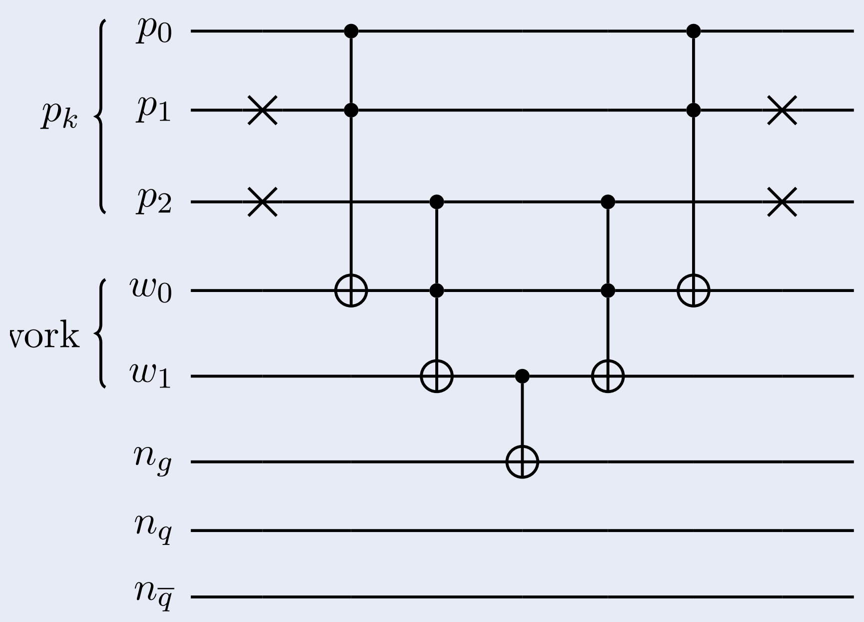



**Update gate**

If there is an emission, changes content of particle counts accordingly

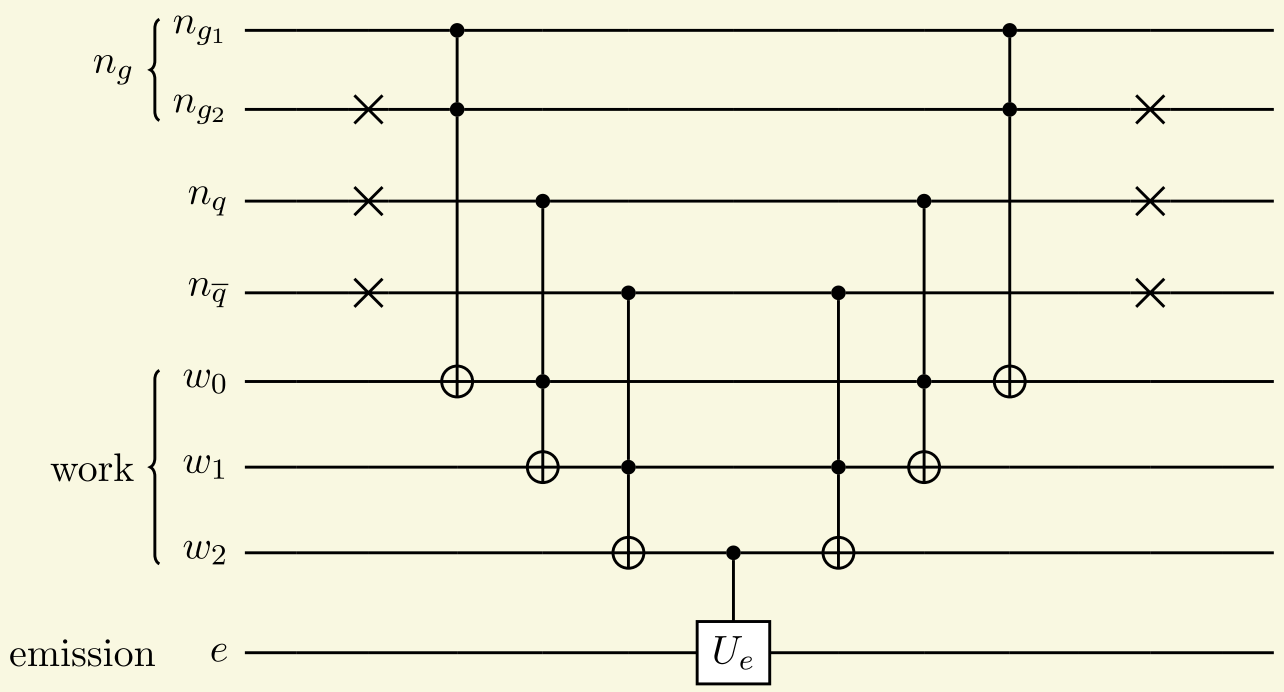
## Count gate

Uses series of NOT, CNOT and Toffoli (CCNOT) gates to count number of each type of particle



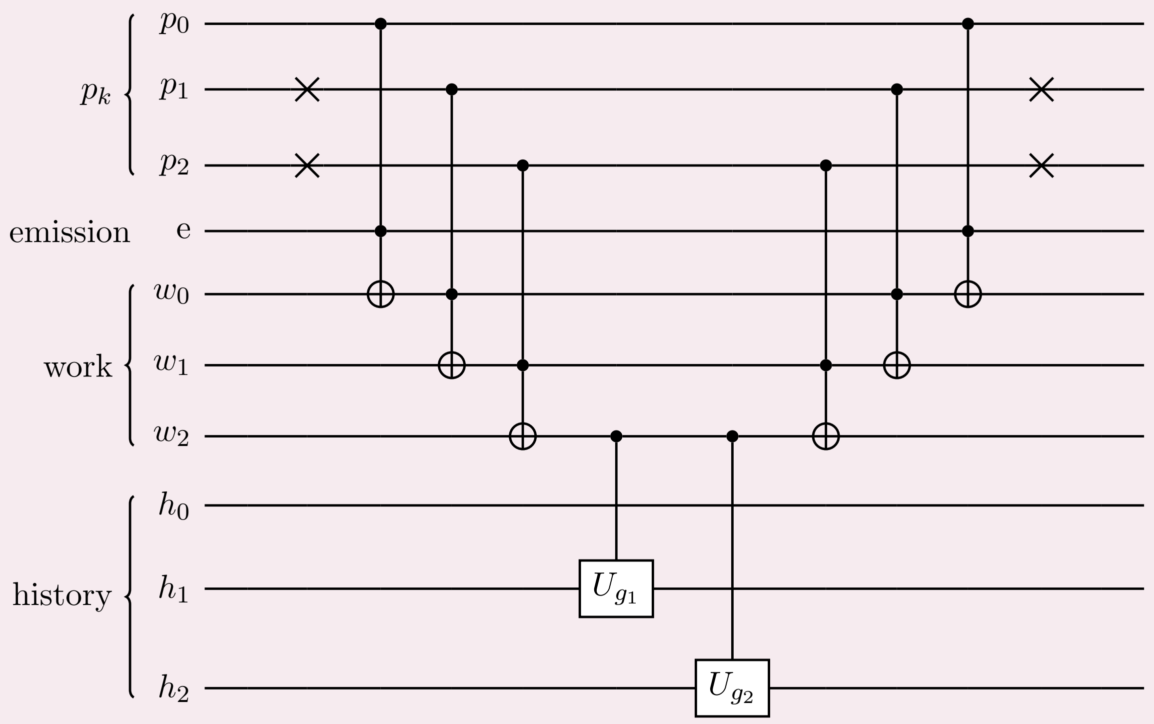

## Emission gate

Implements the Sudakov factors using a rotation, which changes the state of the emission gate to $|1\rangle$ if emission, $|0\rangle$ if not.

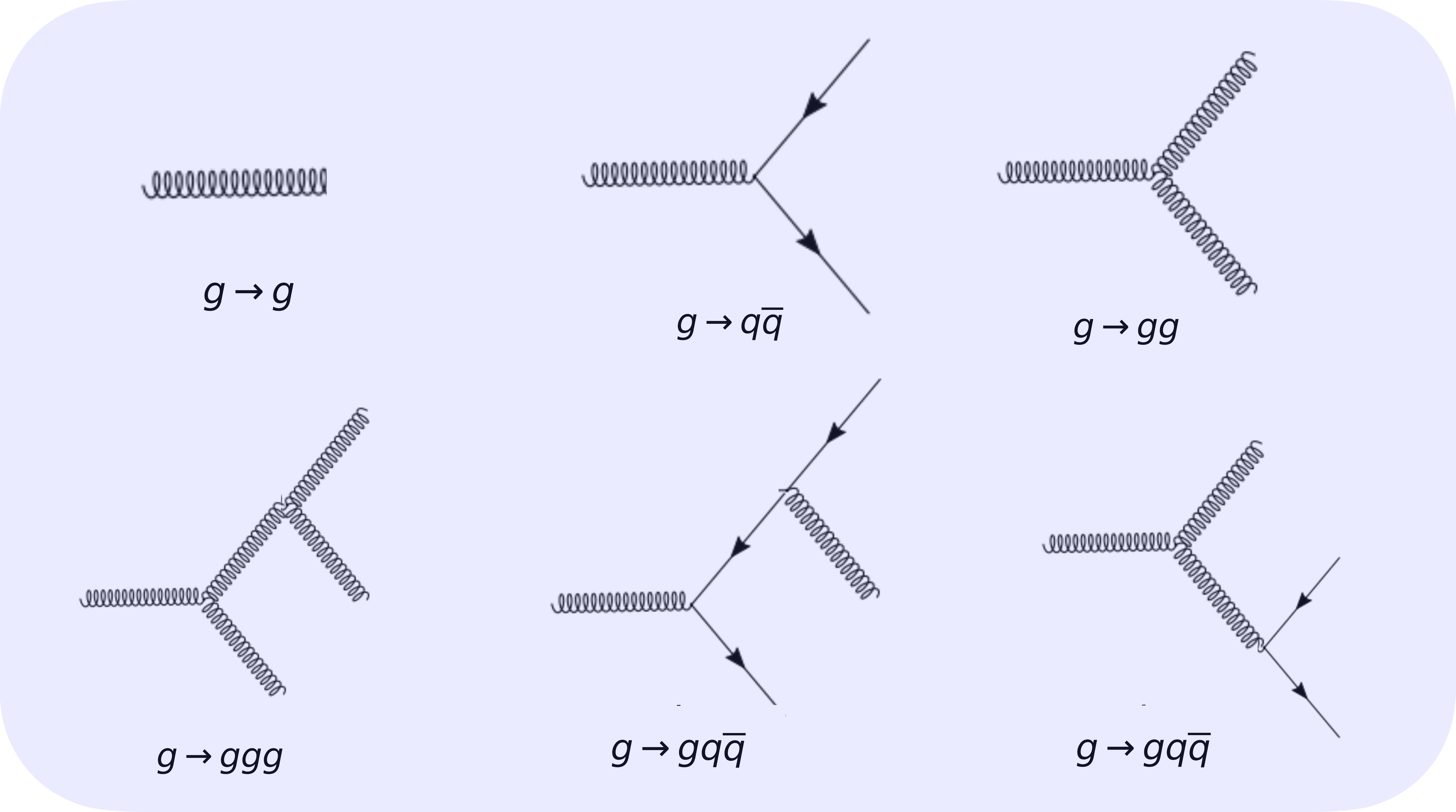



## History gate

Determines which emission has occurred



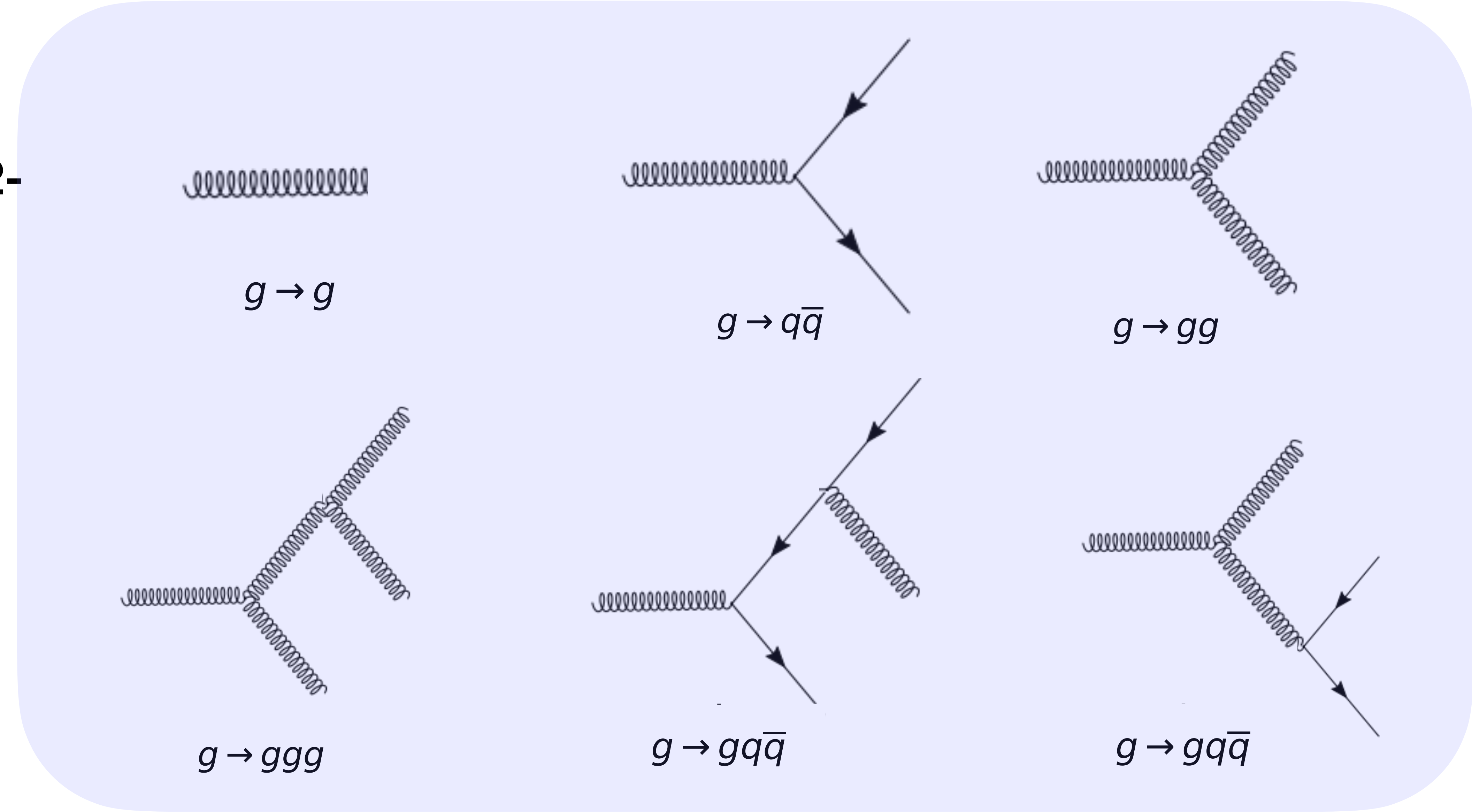
# 2-step parton shower: initial state a gluon

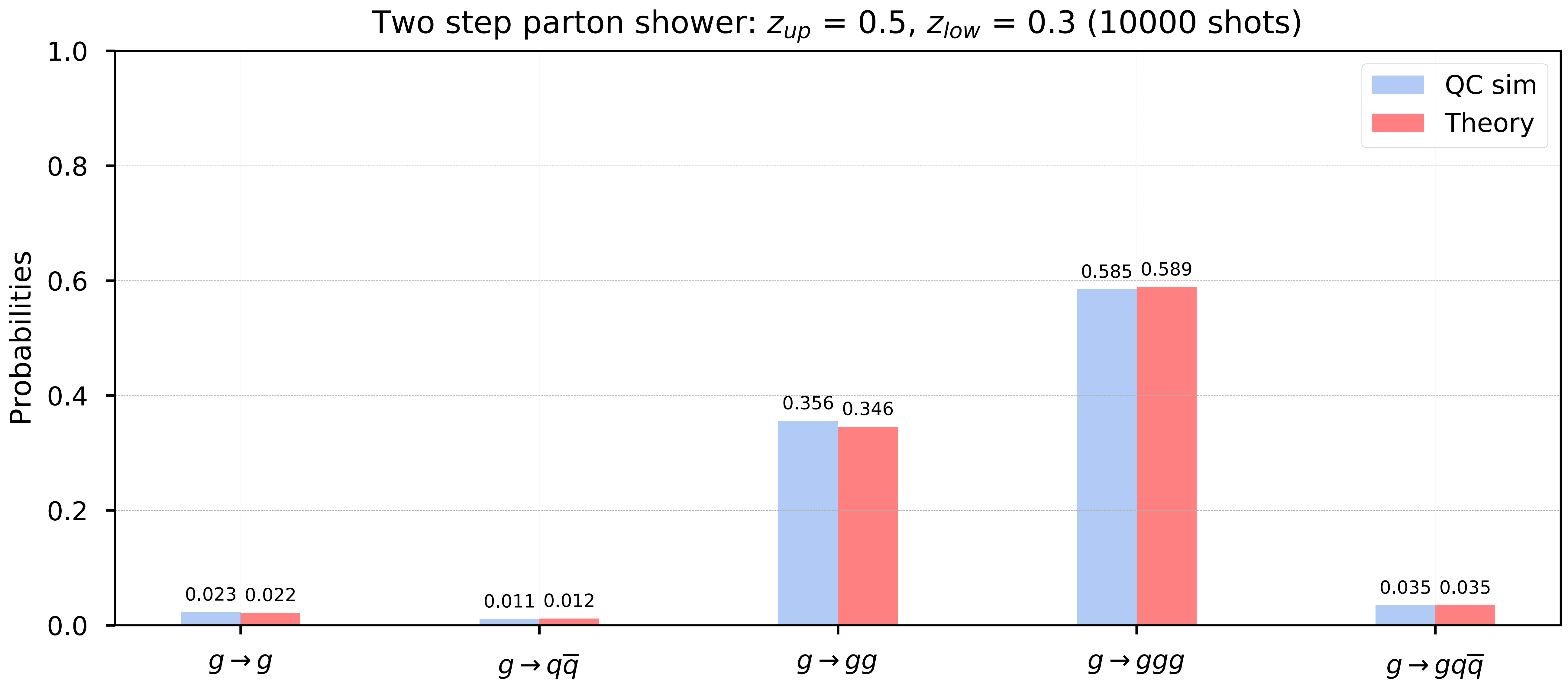



- Classical Monte Carlo methods need to manually keep track of individual shower histories, which must be stored on a physical memory device.
- Quantum computing algorithm constructs a wavefunction for the whole process and calculates all possible shower histories simultaneously!

# Results for parton shower algorithm

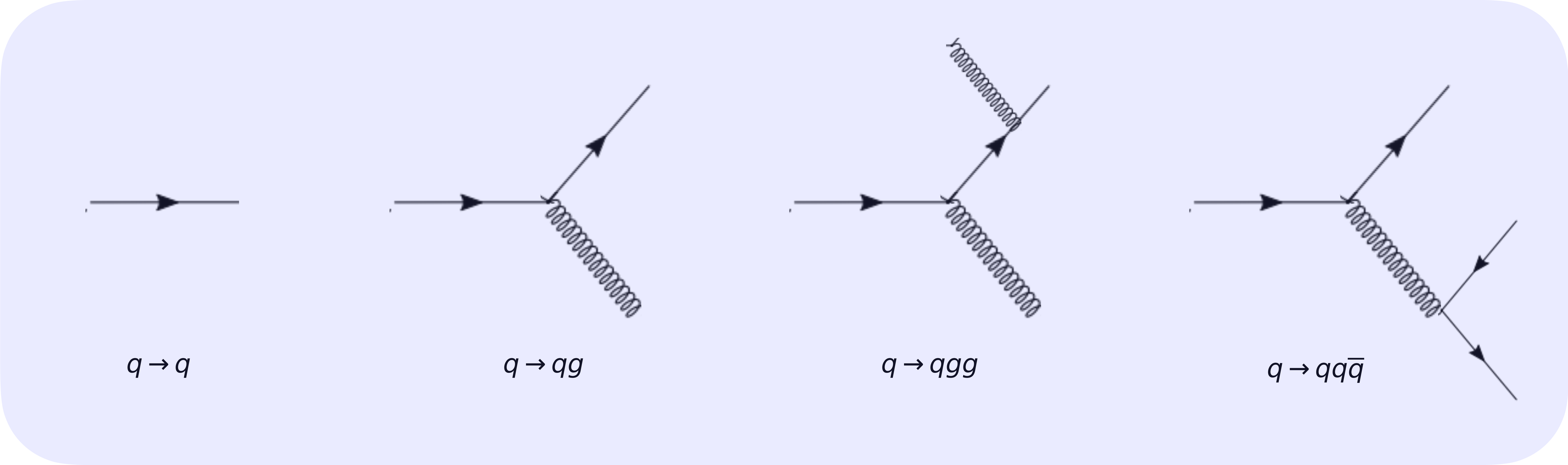
Run 10,000 shots on IBM Q 32-qubit Quantum Simulator

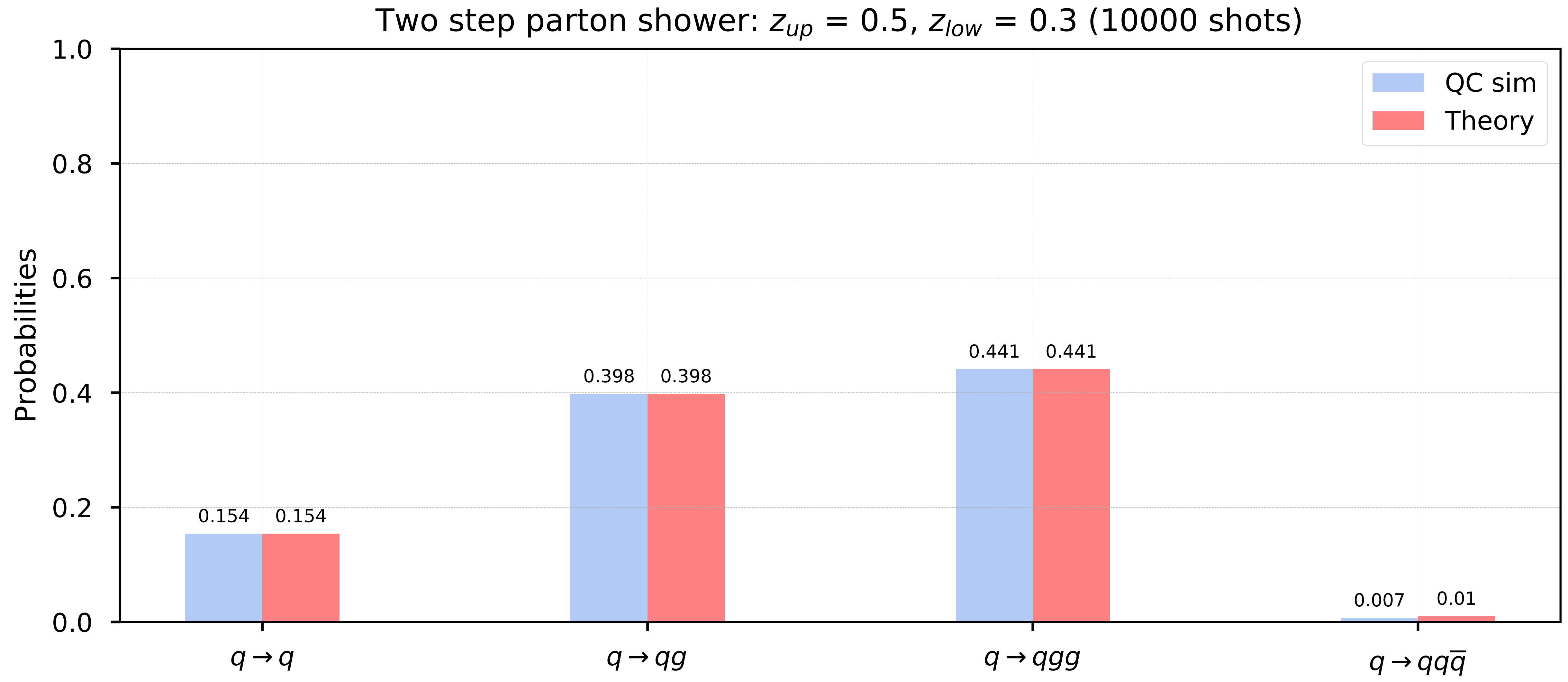



(a) Initial particle a gluon.

# Results for parton shower algorithm



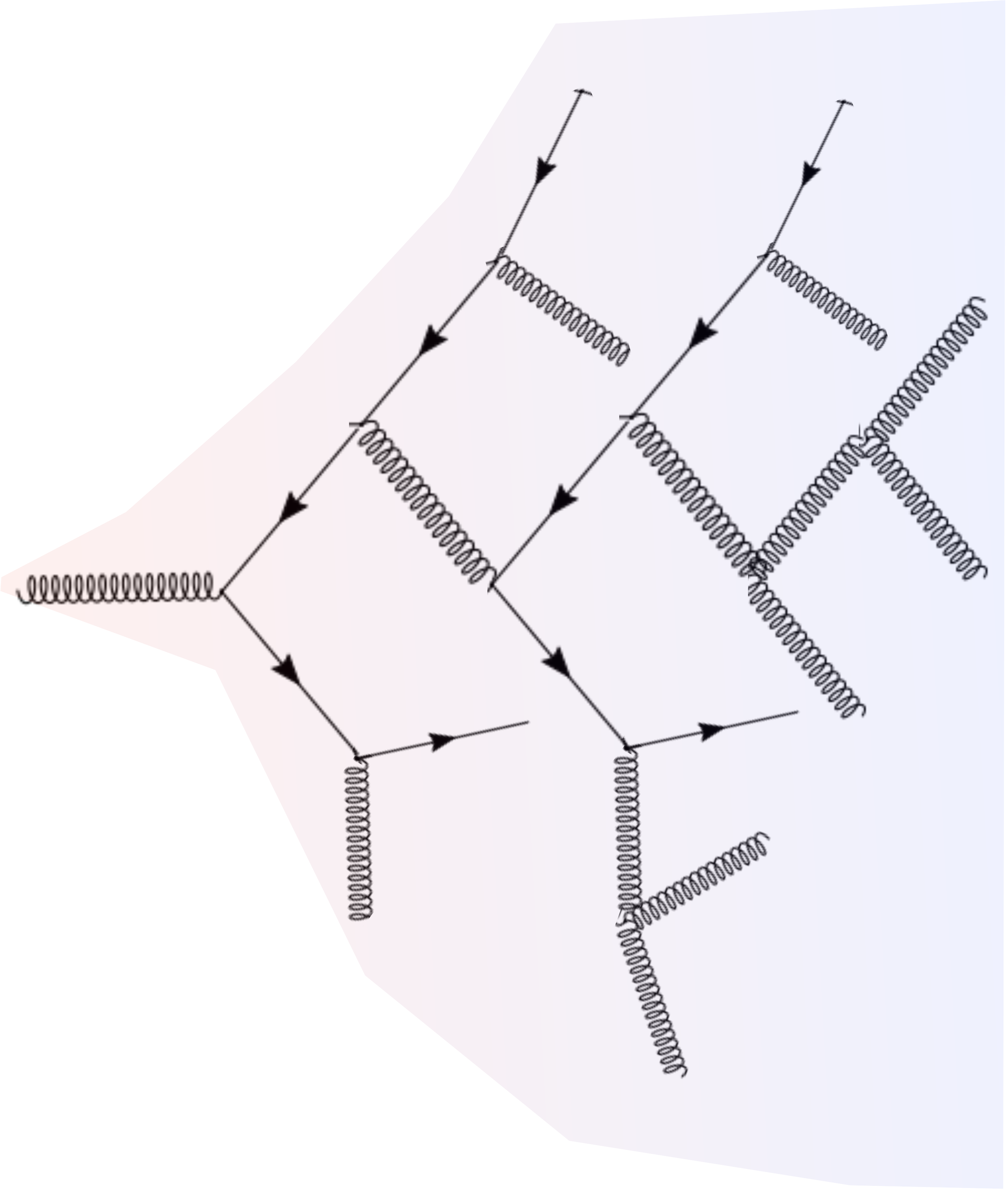

(b) Initial particle a quark.

# Summary of parton shower algorithm

- Algorithm builds on previous work by Bauer et. al. [1] by including a vector boson and boson splittings → significant changes in its implementation

- Can simulate both gluon and quark splittings, thus provides the foundations for developing a general parton shower algorithm

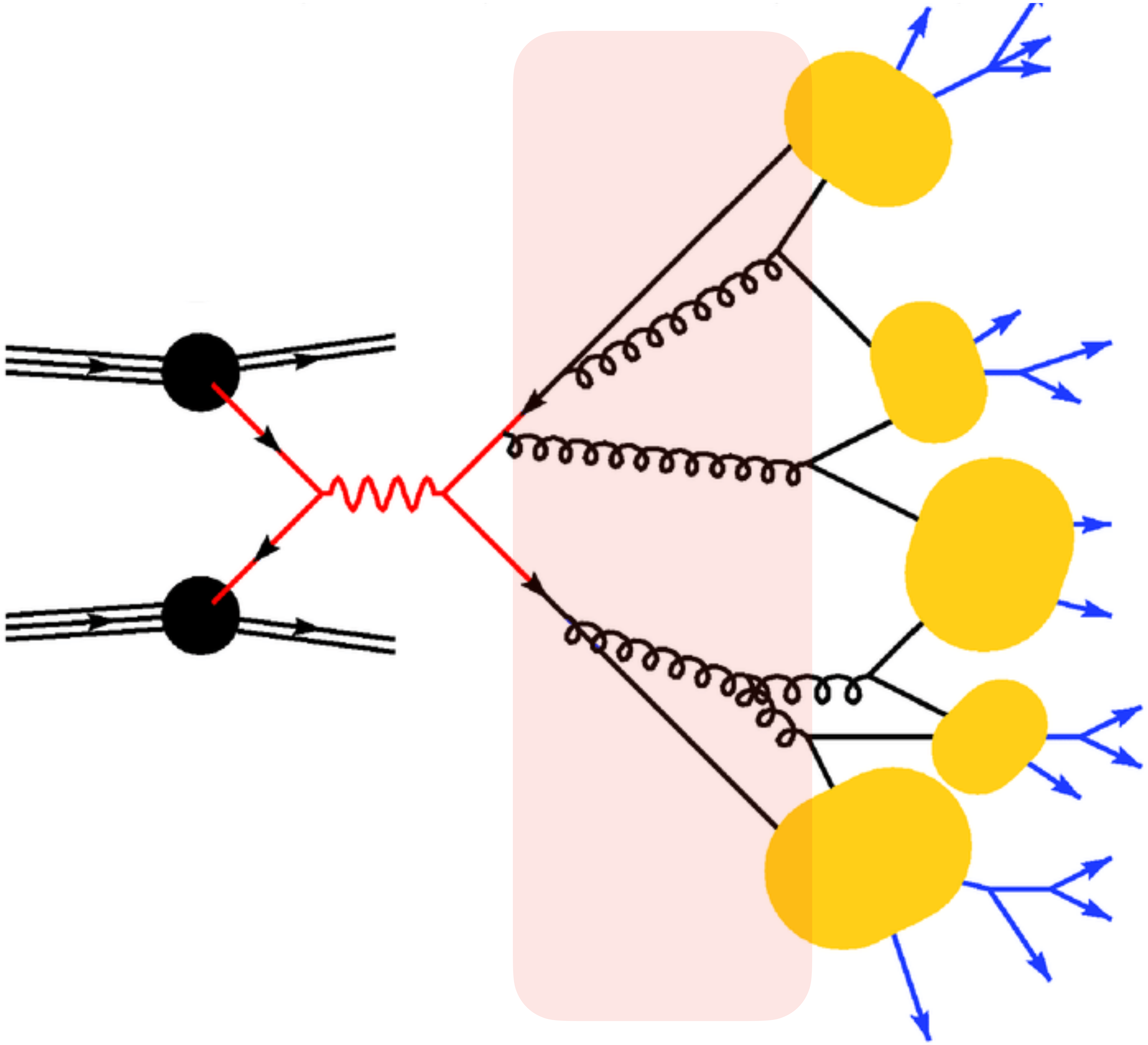
- With advancements in quantum technologies, algorithm can be extended to include all flavours of quarks without adding disproportionate computational complexity



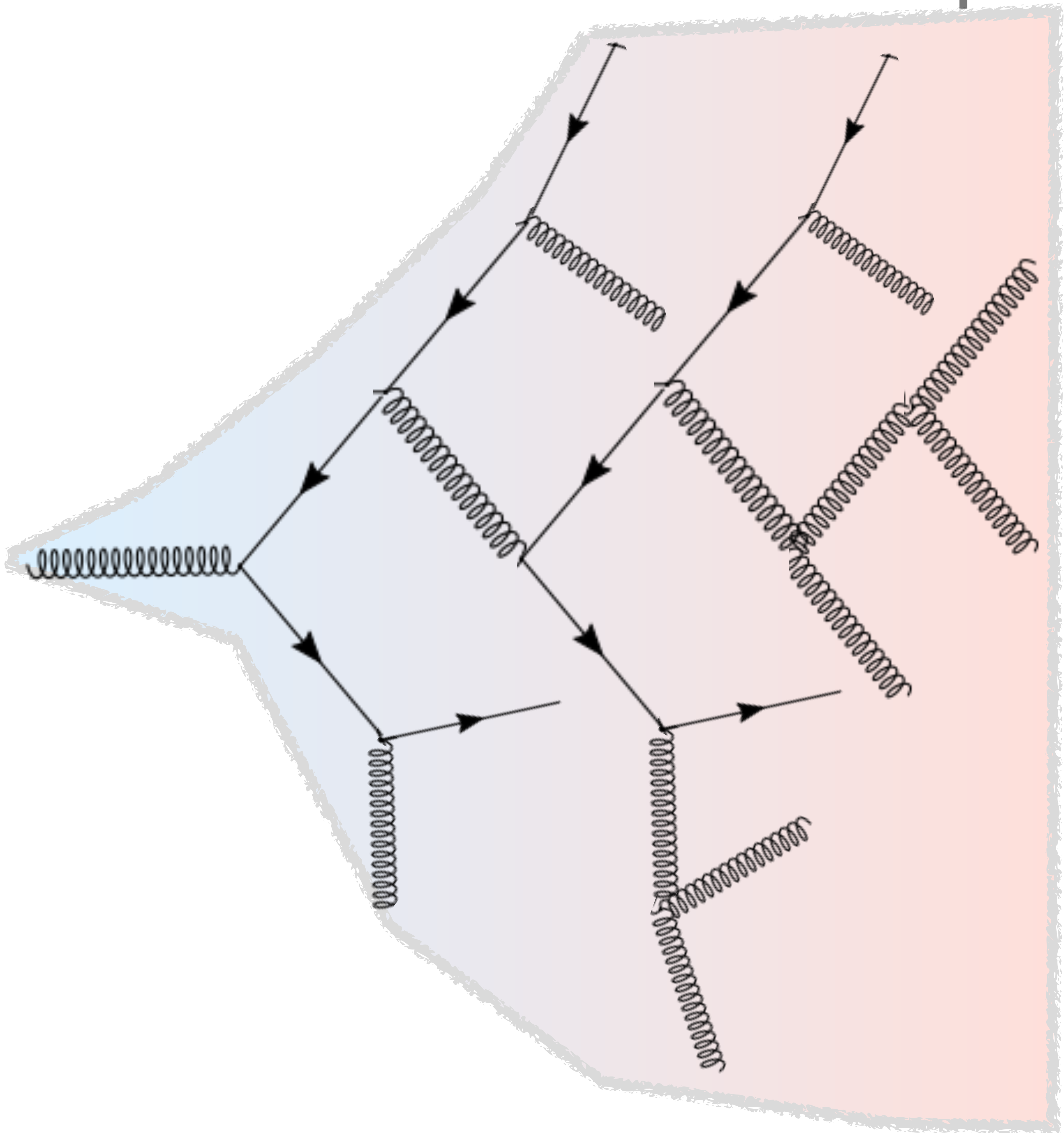
[1] : arXiv:1904.03196

# Parton shower

- After the hard interaction, next step in simulating an event at LHC is the parton shower
- Parton shower evolves scattering process from hard interaction scale down to the hadronisation scale



# Parton shower: classical vs quantum

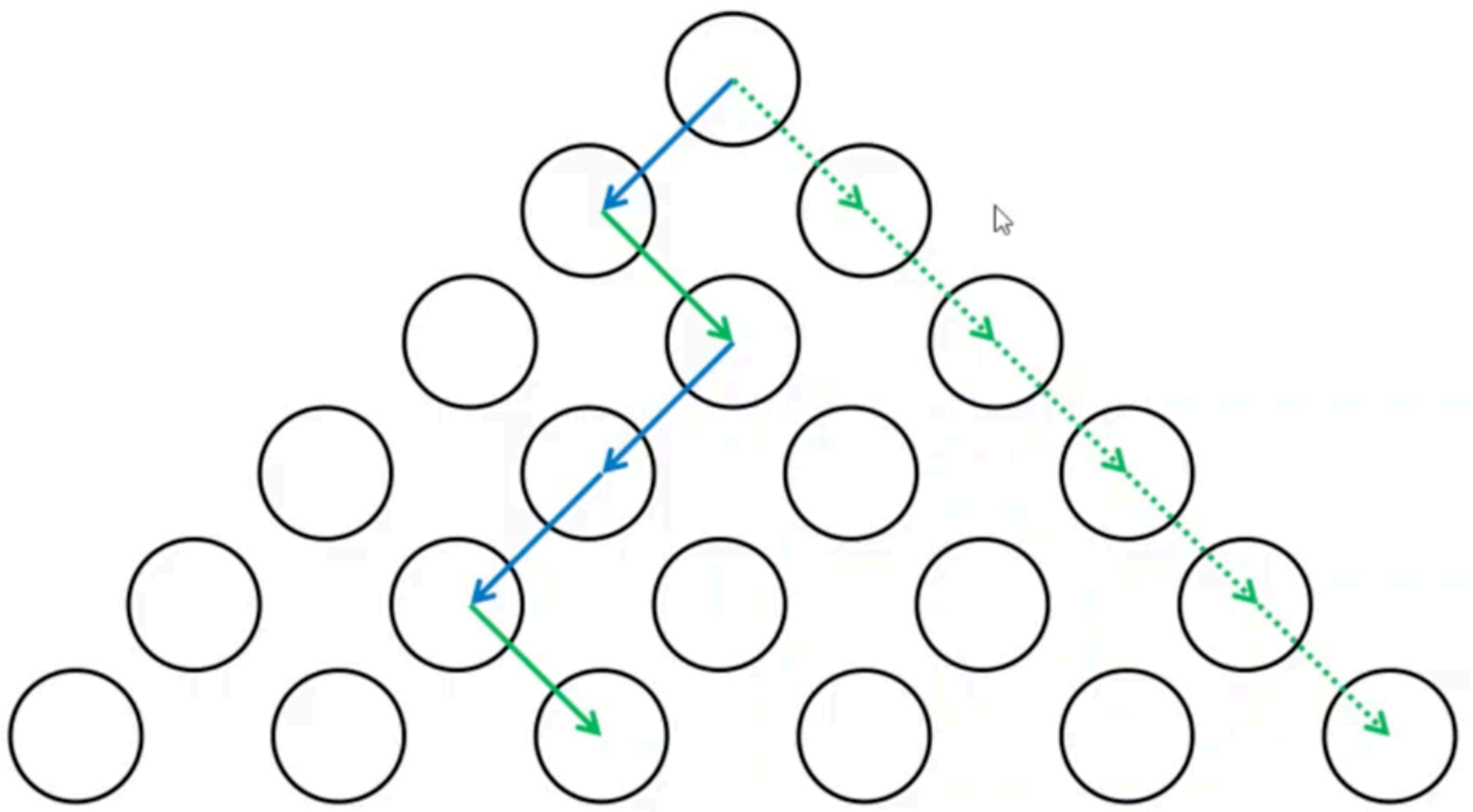


- Classical Monte Carlo methods need to manually keep track of individual shower histories, which must be stored on a physical memory device.
- Quantum computing algorithm constructs a wavefunction for the whole process and calculates all possible shower histories simultaneously!

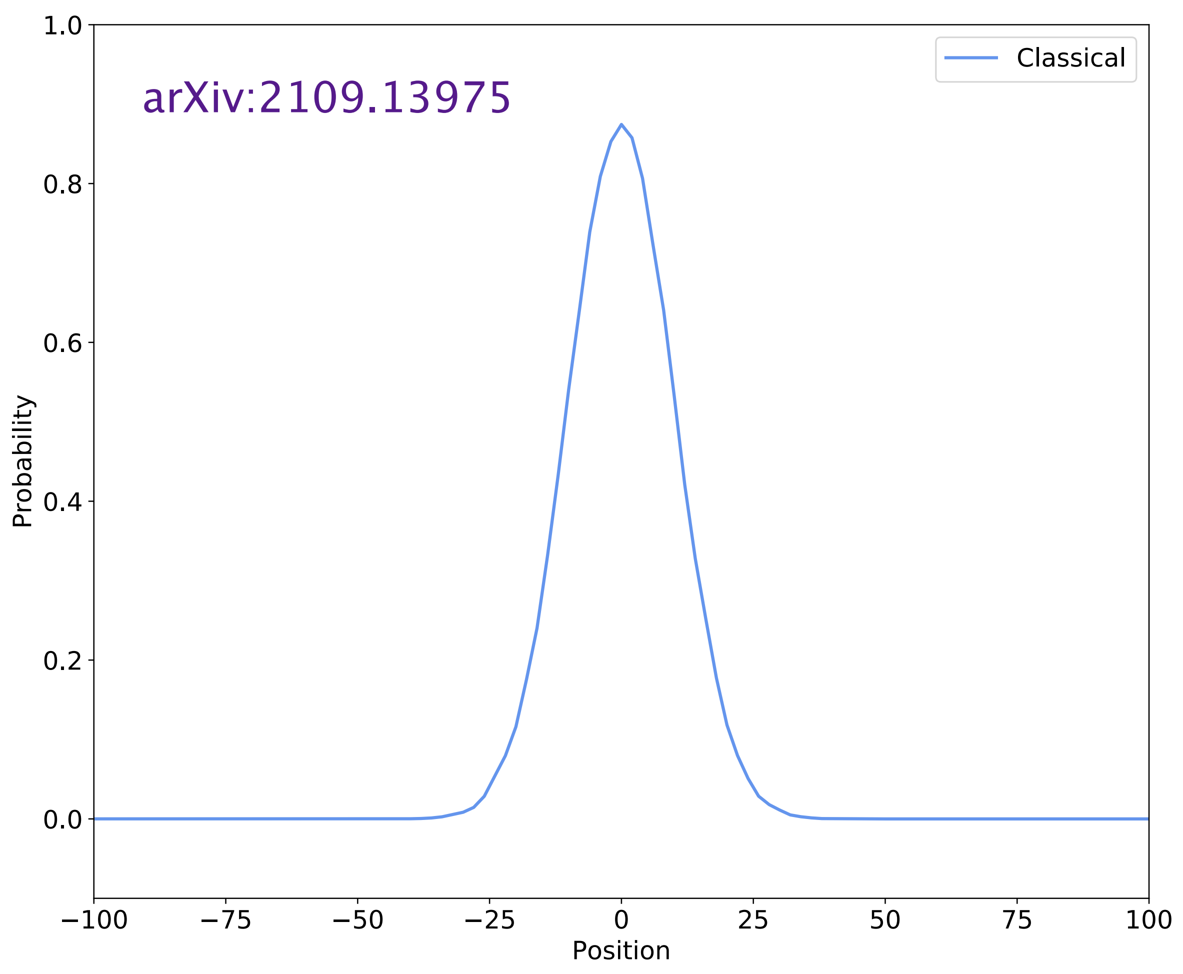
# Classical random walk

**Toss a coin at each step, move left or right**

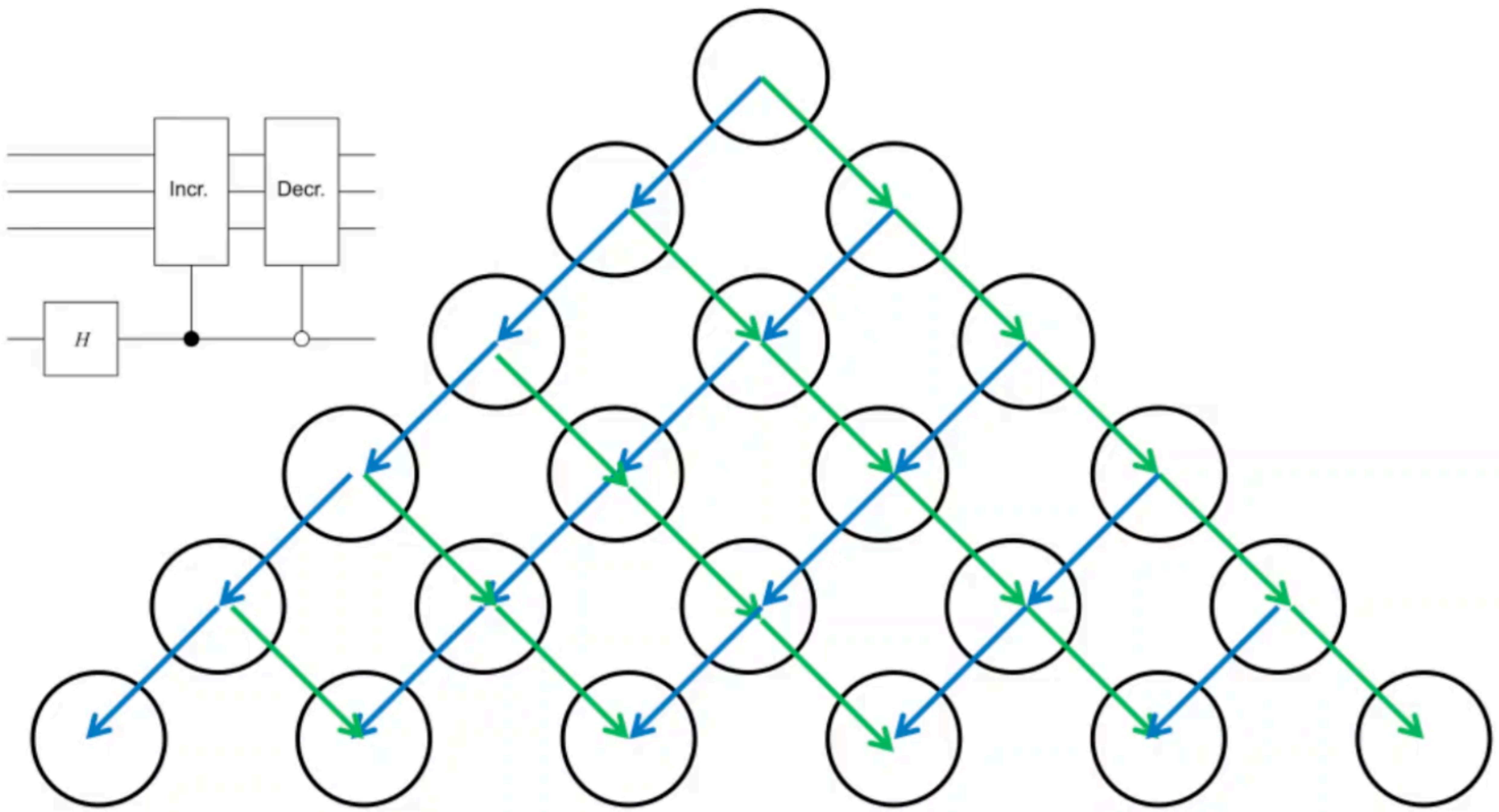
**Diagram taken from talk at QEF05**




Average distance of the walker from the initial position = $\sqrt{t}$

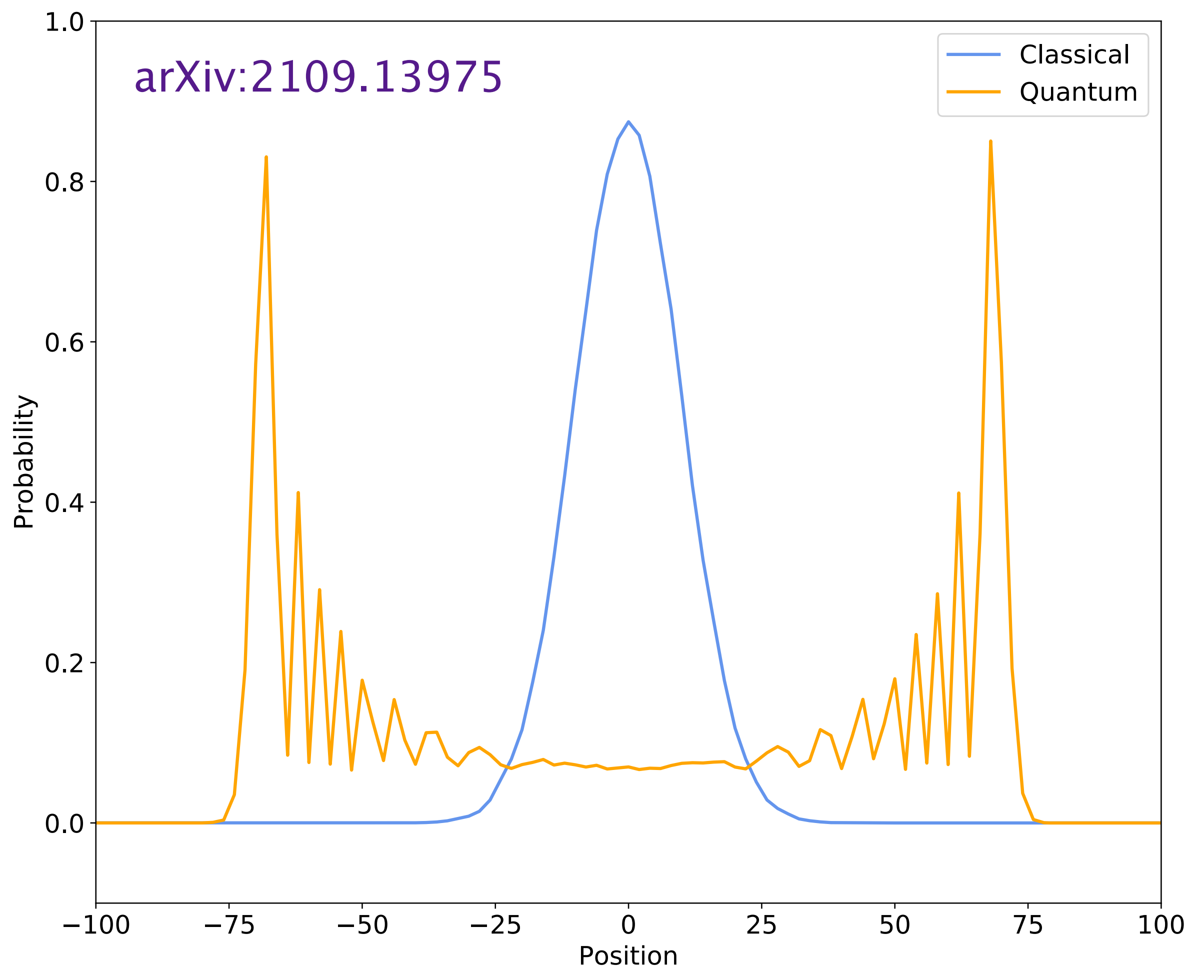


# Quantum Walk



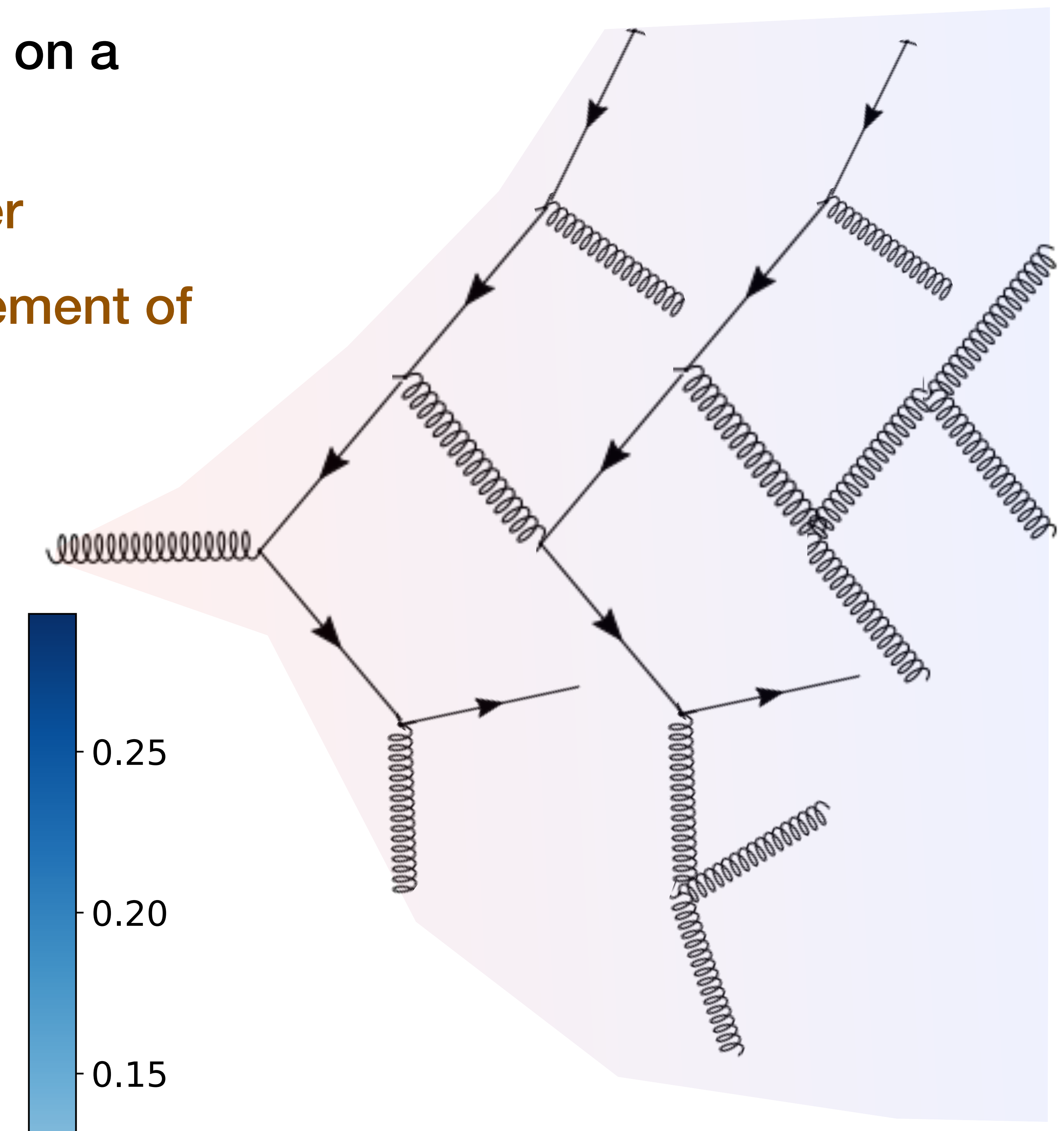

**Average distance of the walker from the initial position = t**

Quantum walker propagates quadratically faster than classical walker

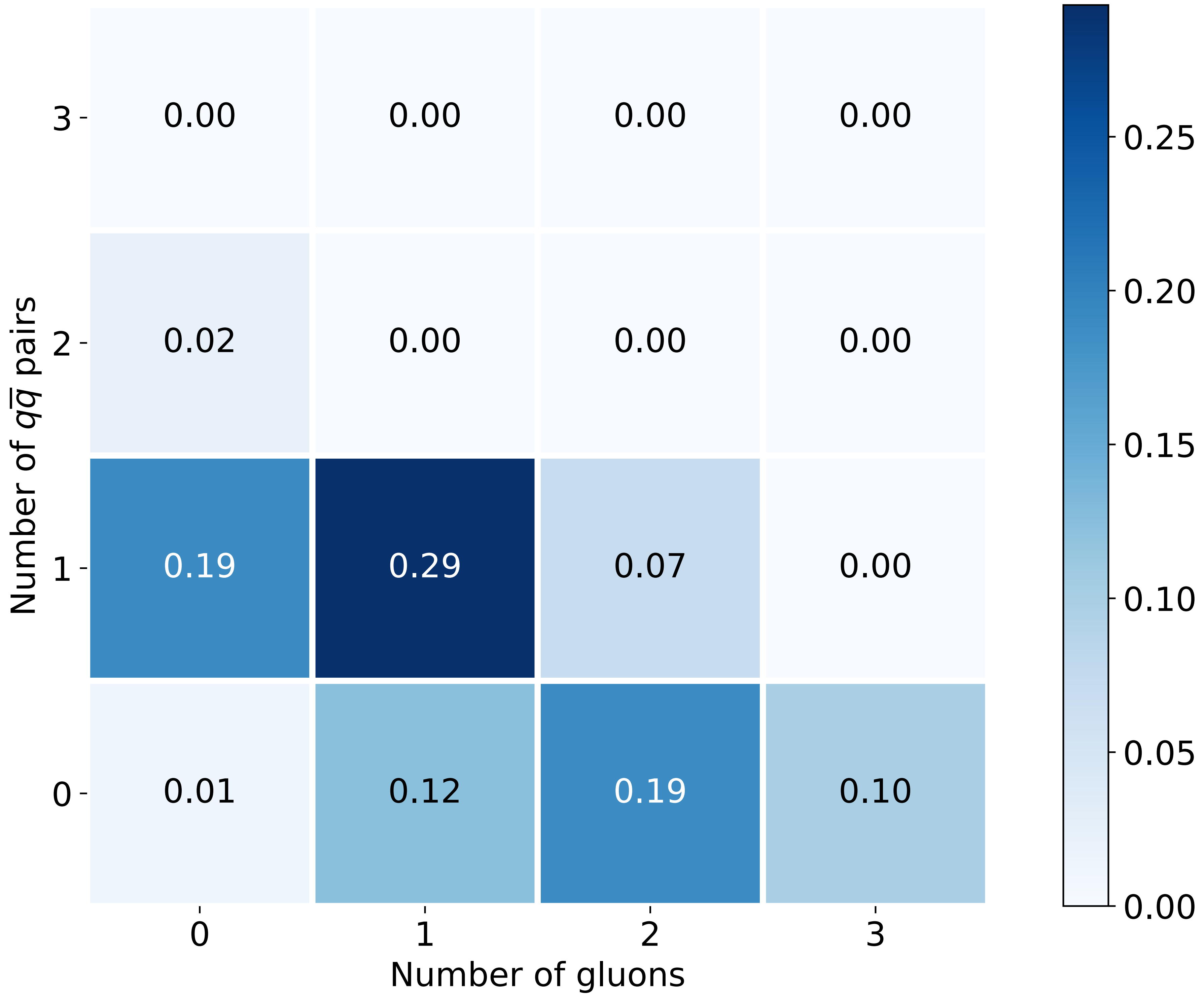


# Quantum walk approach to simulating parton showers

- A novel quantum walk approach to simulating parton showers on a quantum computer.
  - emission probabilities implemented as coin flip for walker
  - particle emissions to either gluons or quark pairs = movement of the walker in 2D



arXiv:2109.13975



# Quantum walk approach to simulating parton showers

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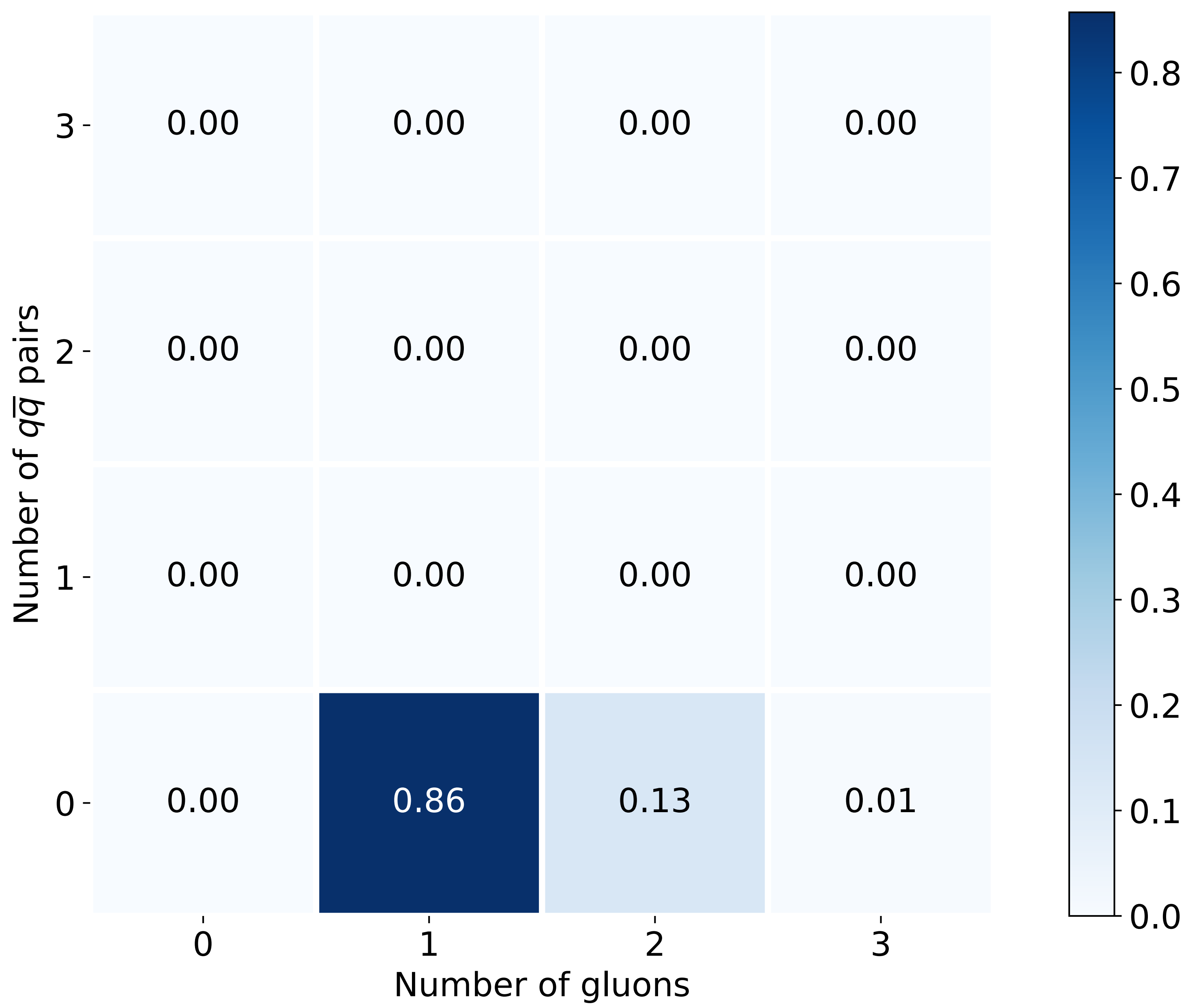
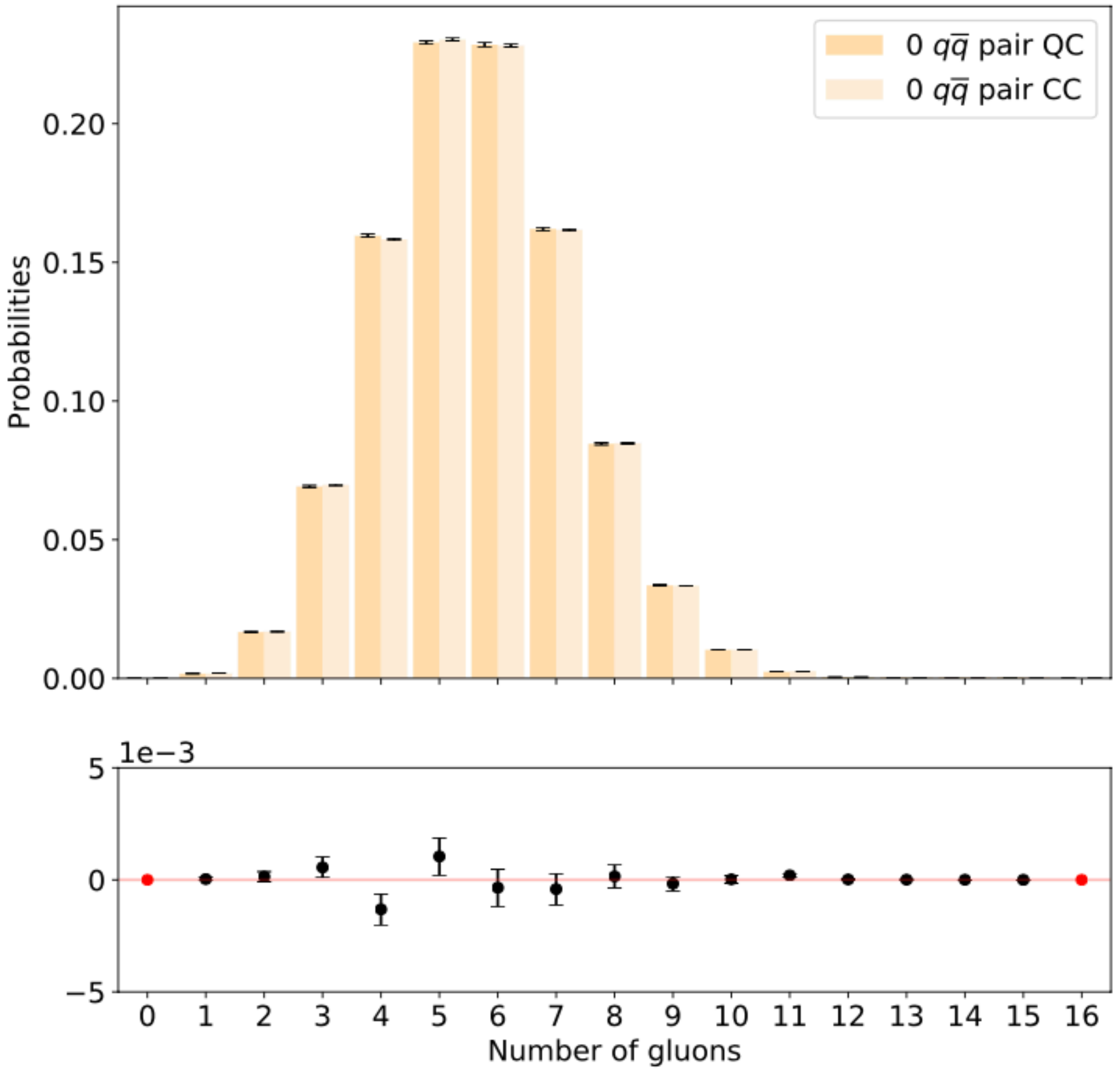
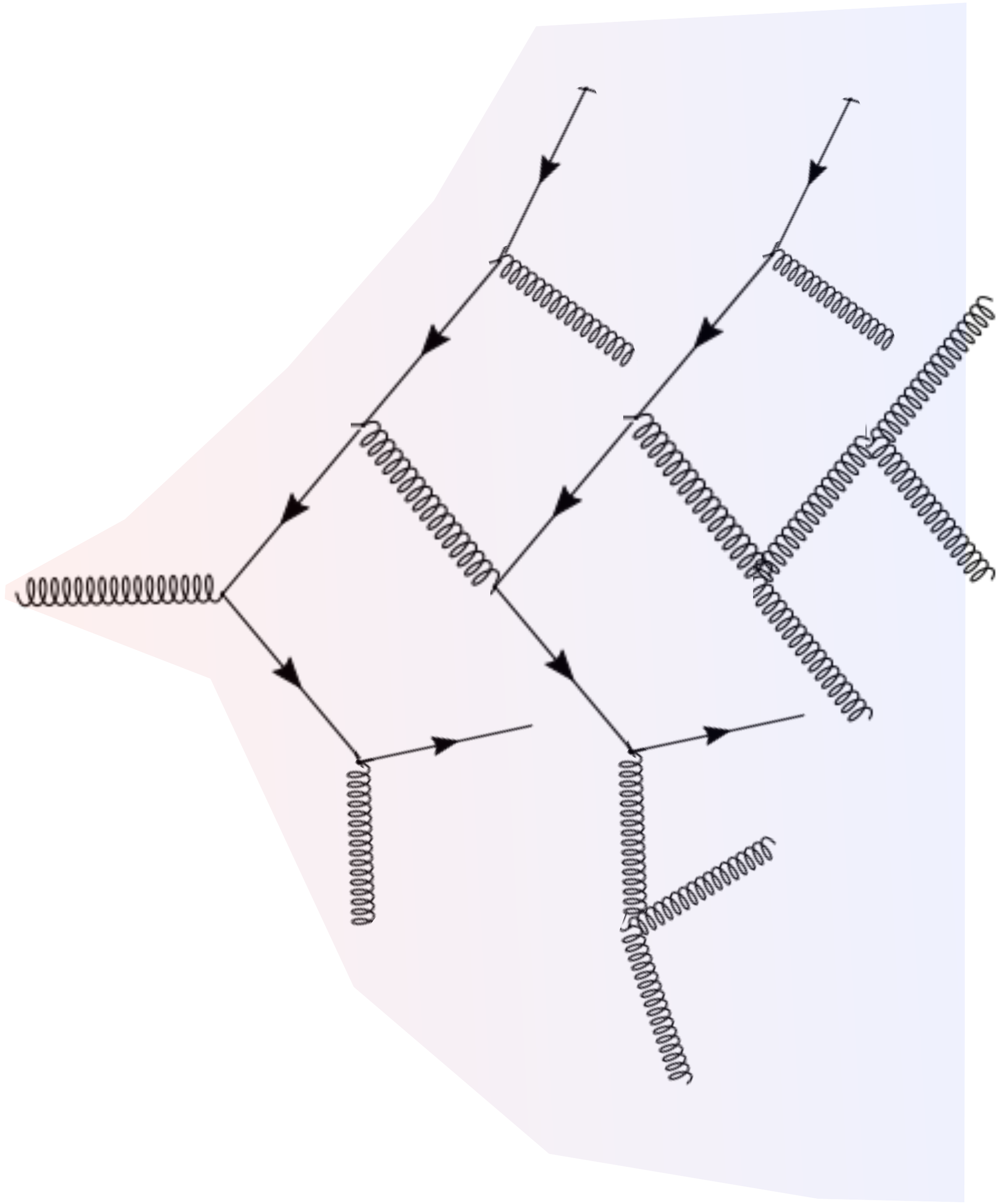
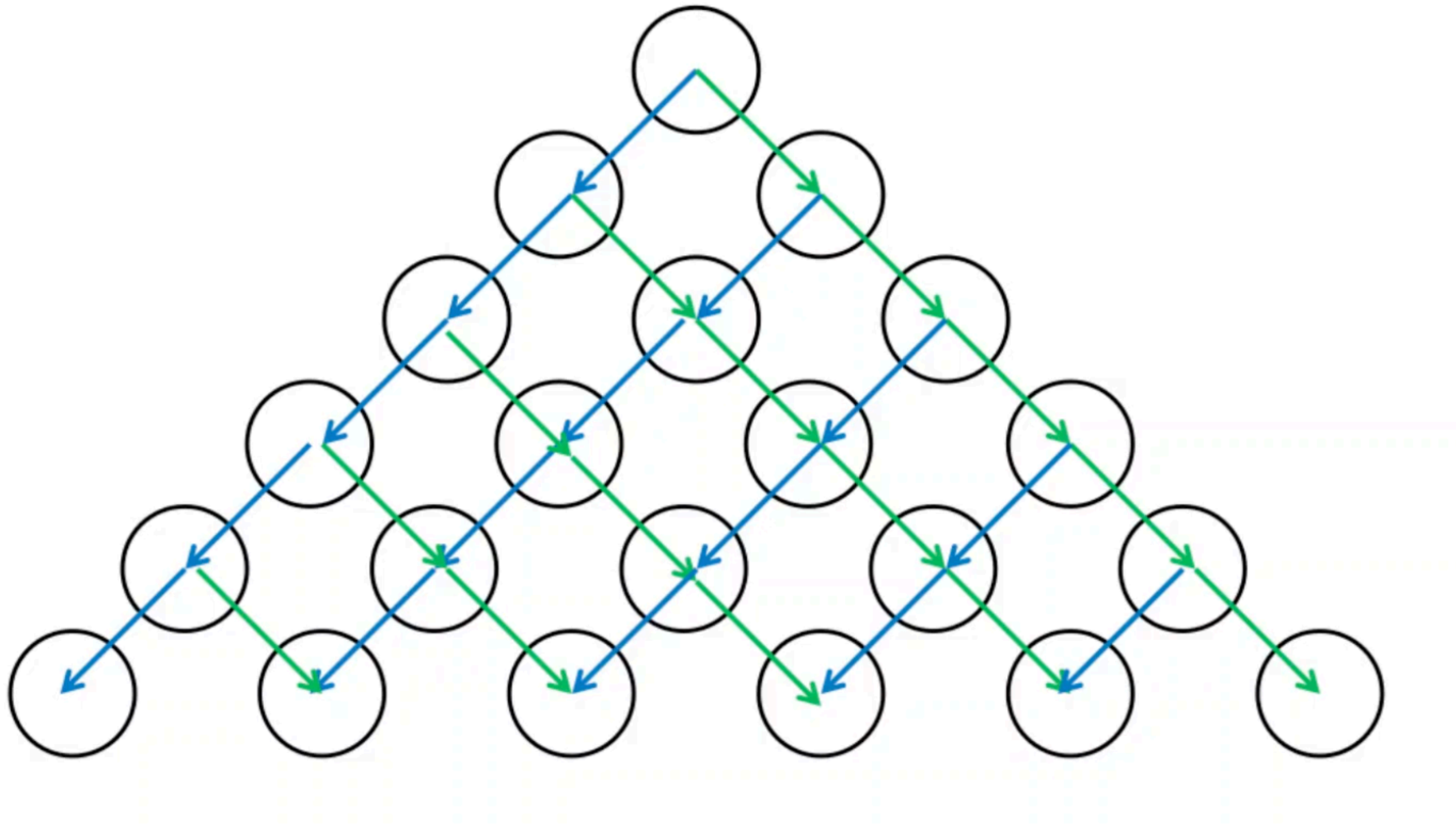



- Quantum walk paradigm thus offers a natural and much more efficient approach to simulating parton showers on quantum devices.
- Proposed algorithm dramatically increases the number of steps that can be simulated compared to previous quantum algorithms (2-step parton shower in previous algorithm)

# Evolution of parton shower algorithm






- Parton shower algorithm : quantum vs classical, quantum algorithm constructs a wavefunction for whole parton shower process, allowing simultaneous calculation of all shower histories. Simulate 2-step parton shower with 31 qubits in arXiv:2010.00046

- In arXiv:2109.13975, reframing the parton shower as a quantum walking 2-dimensions allowed us to simulate a 31-step parton shower with 16 qubits.