Quantum computing approaches in particle physics

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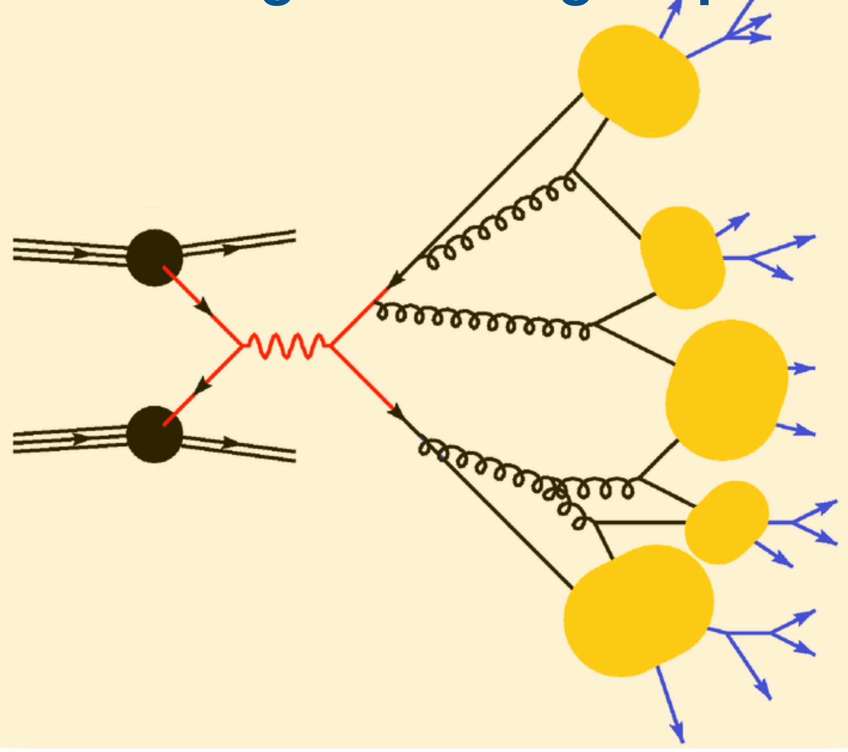
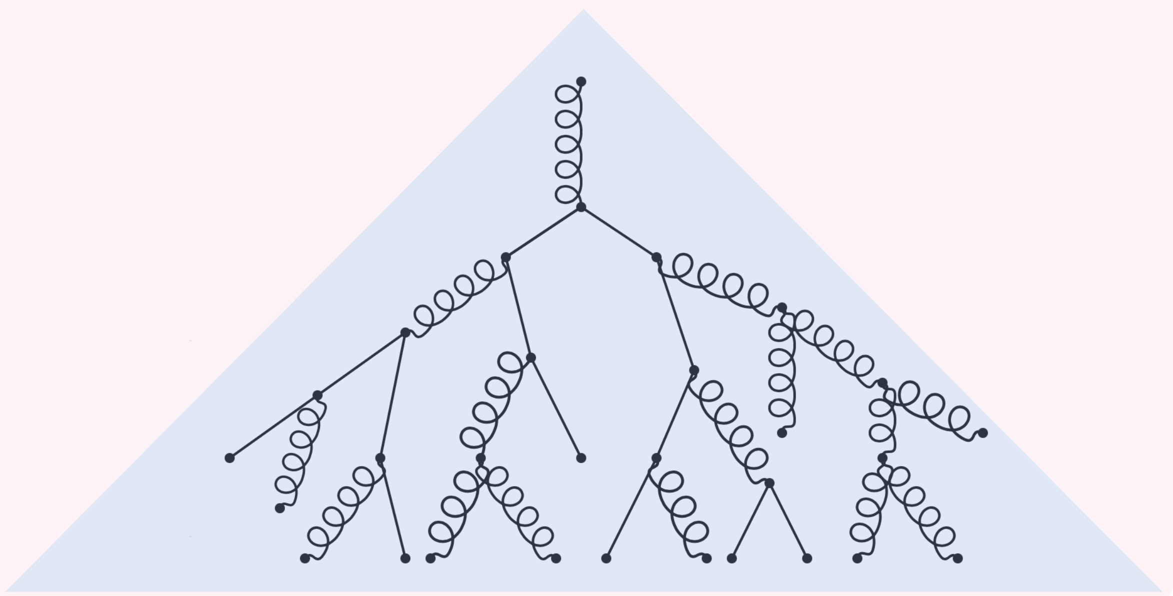
Quantum computing in HEP

Calculating scattering amplitudes



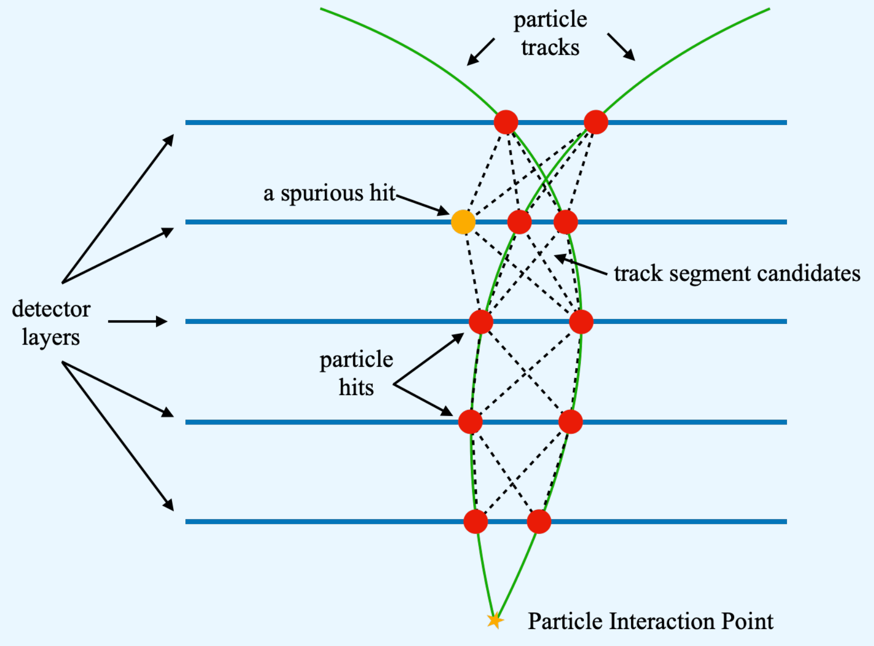
Simulating parton shower



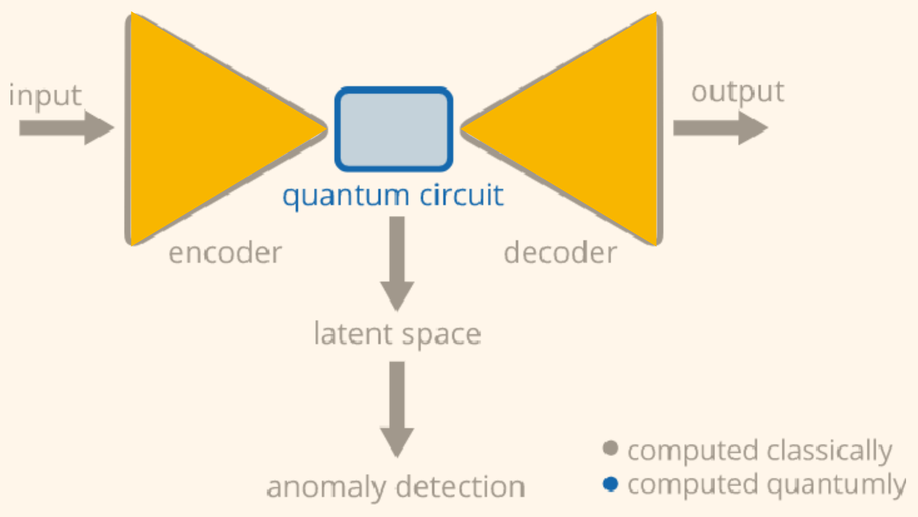
Quantum computing approaches

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

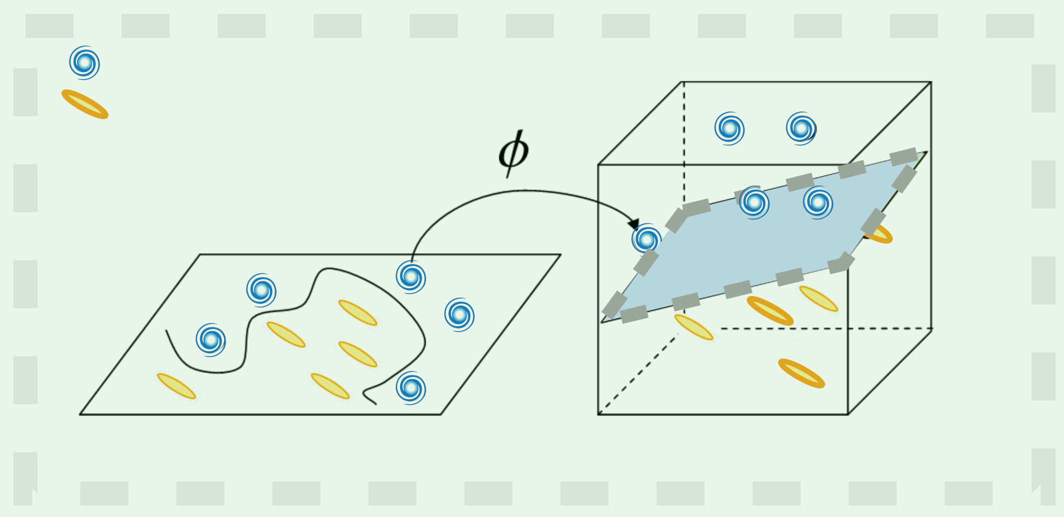
Reconstructing particle tracks



New physics search

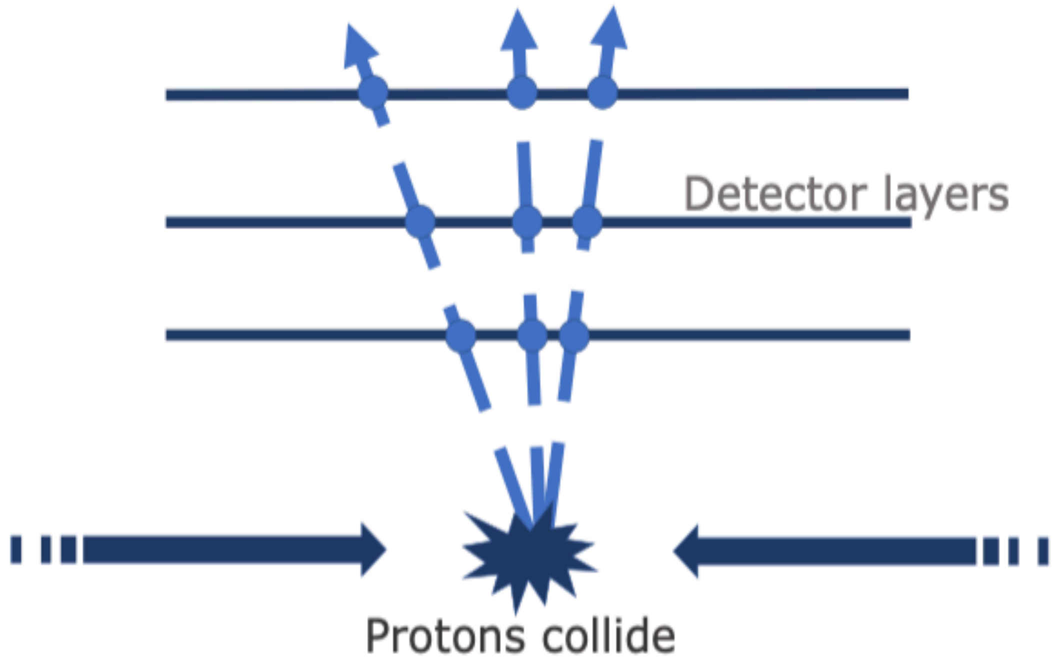


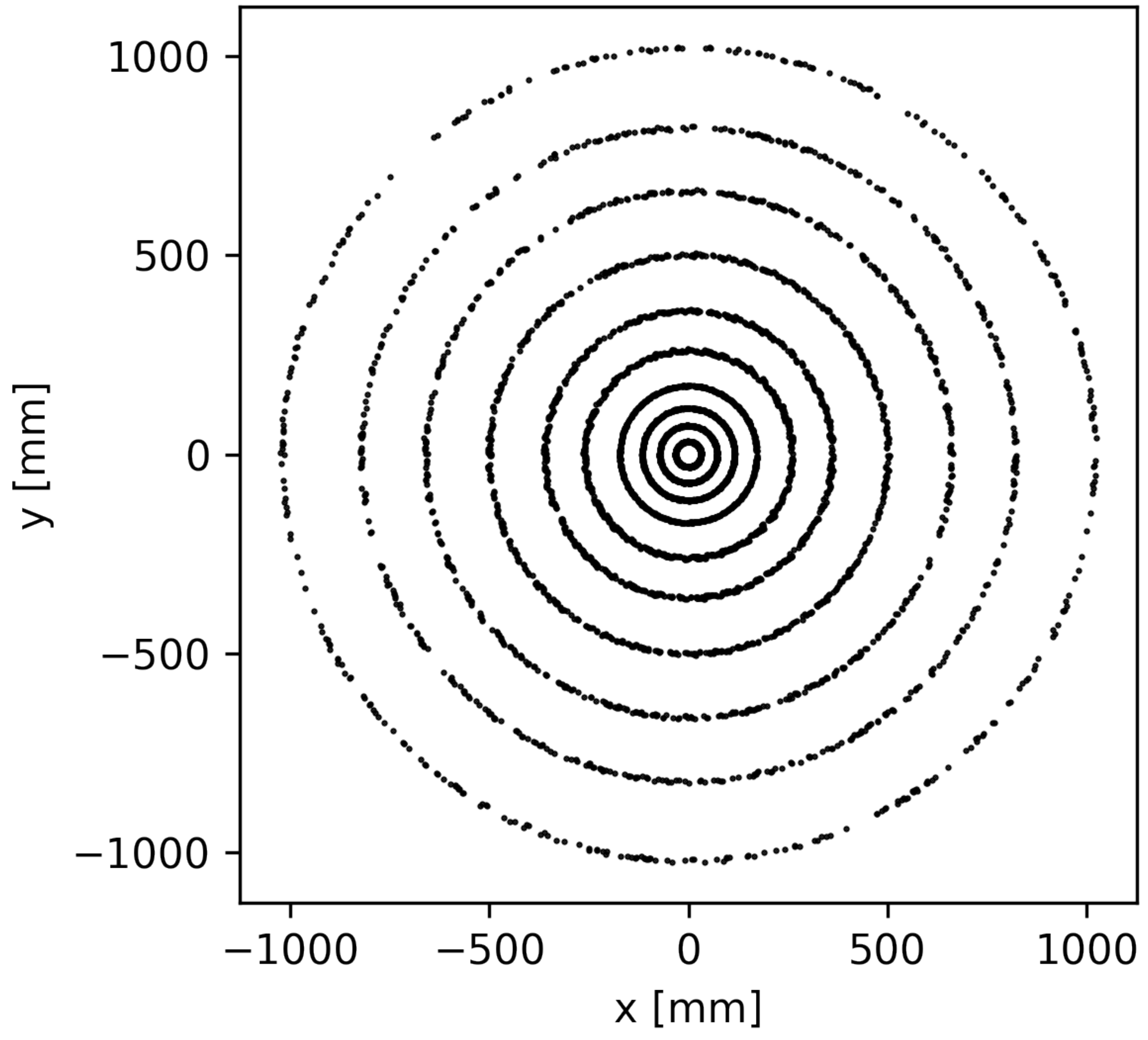
Classifying galaxies

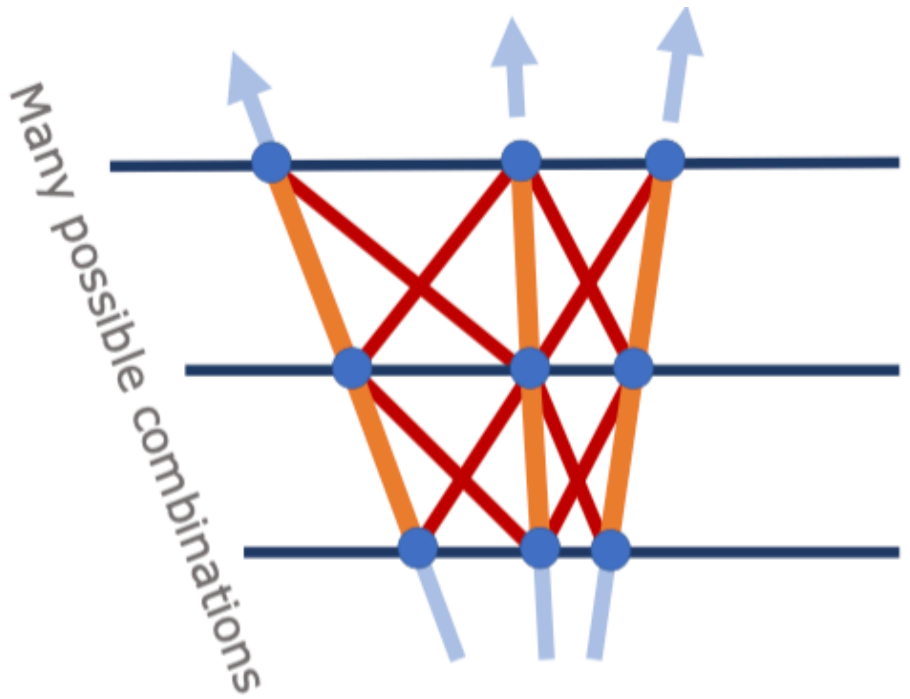


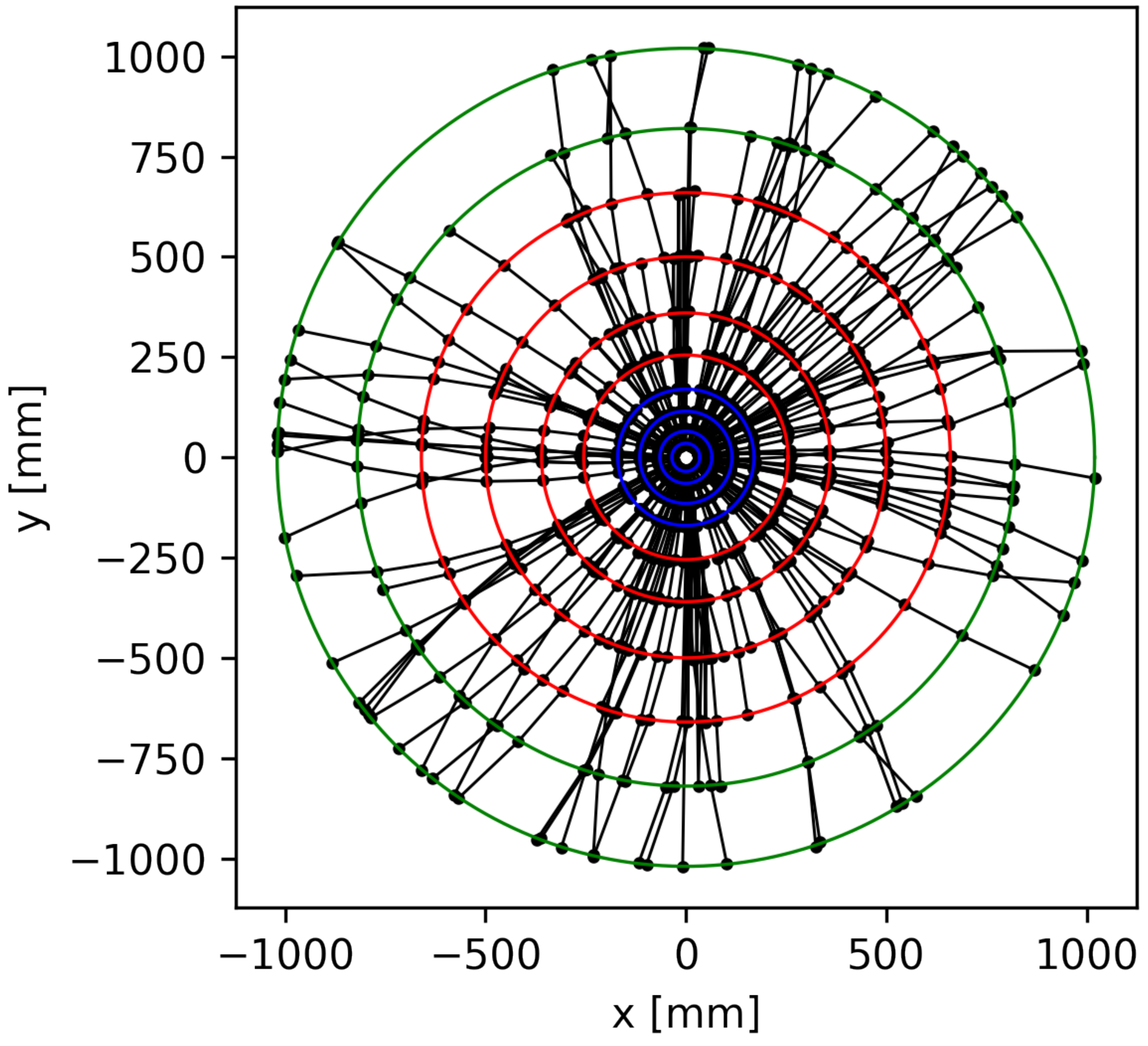
Quantum machine learning

arXiv:2212.07279









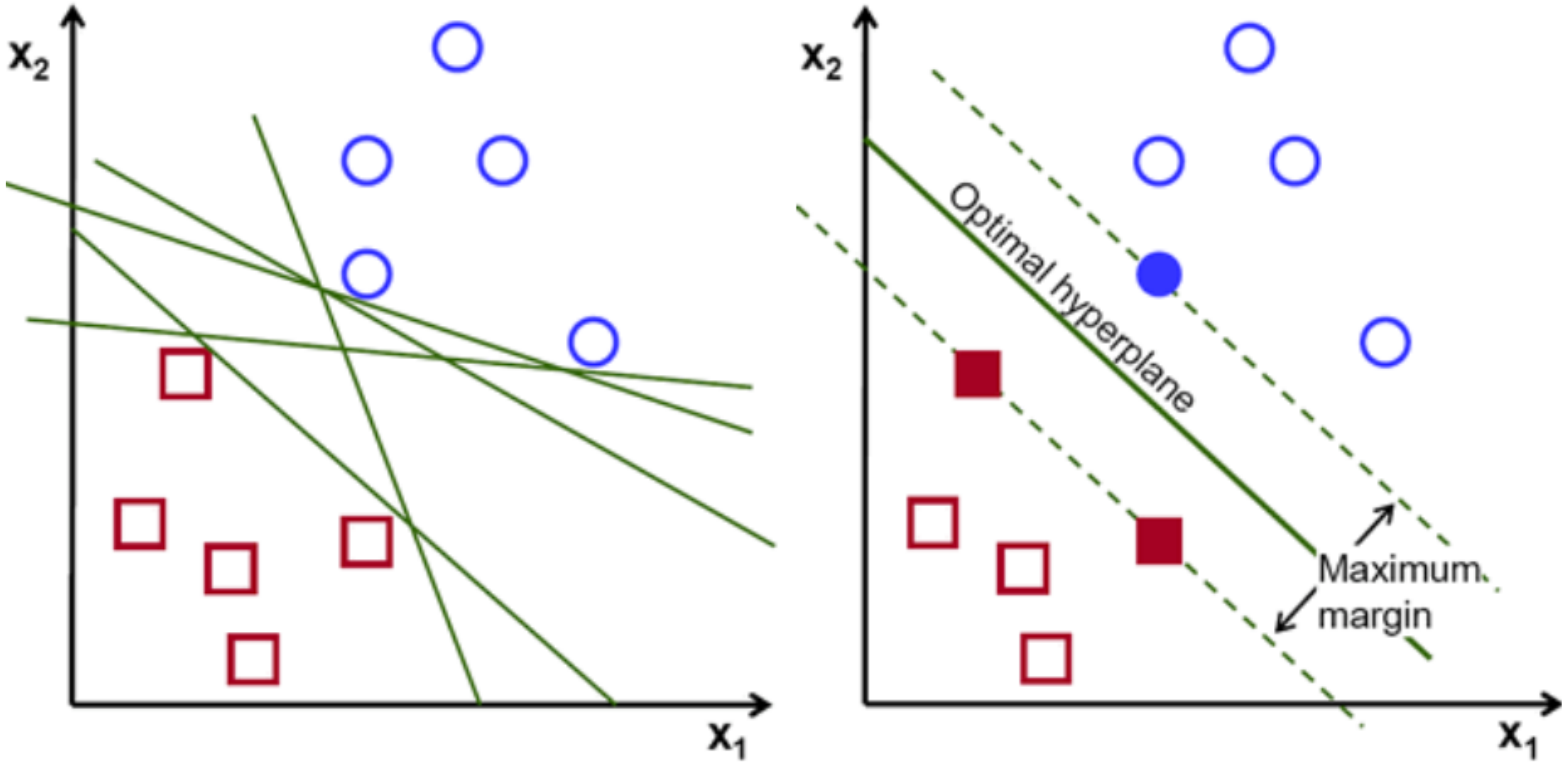
100,000 hits in detector

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



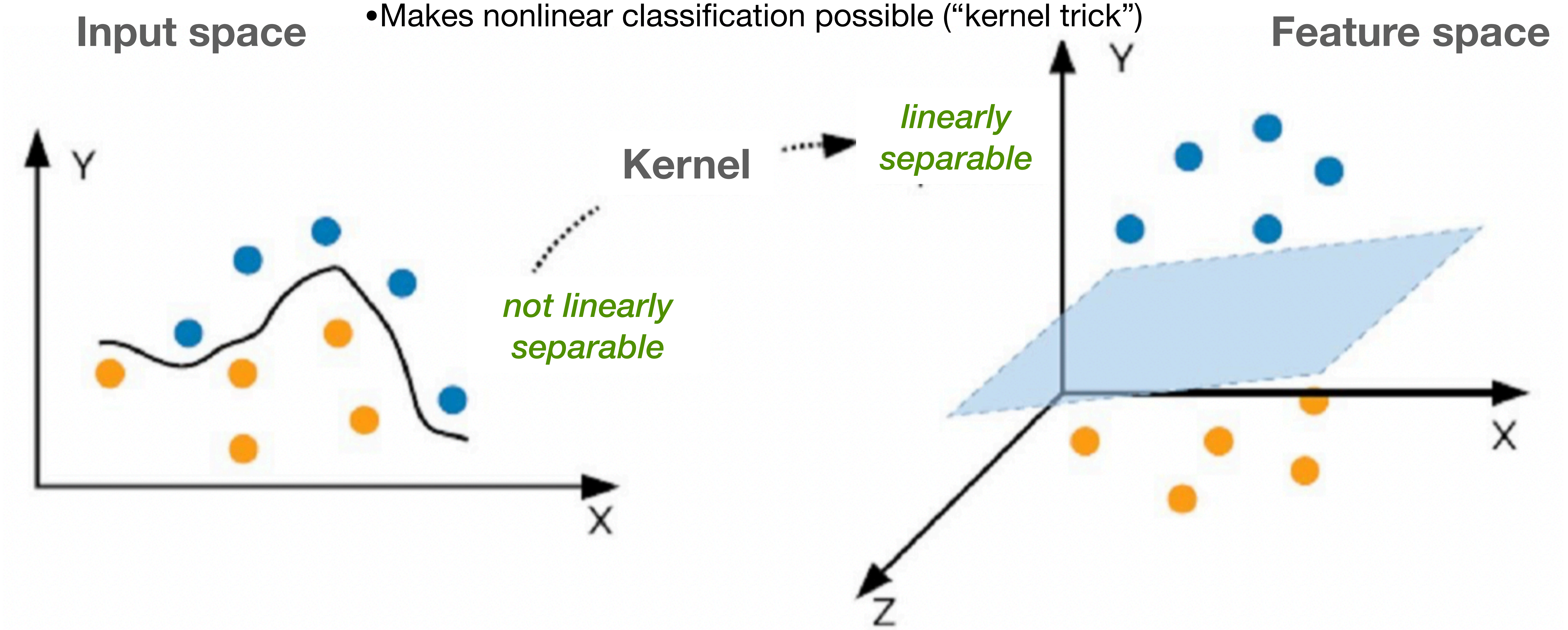
Support Vector Machine (SVM):

- 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")

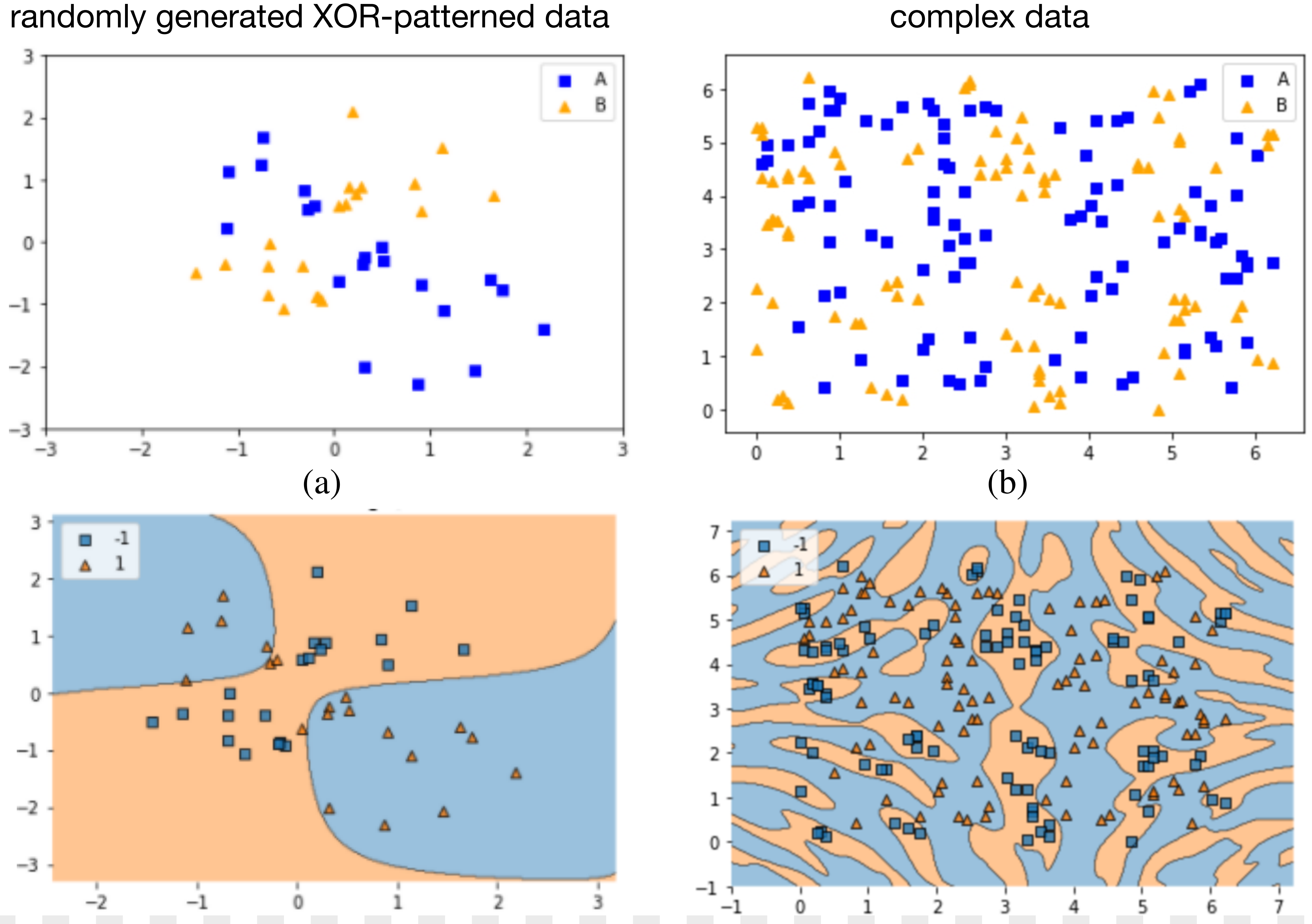


Support vector machine with quantum kernel

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



(a) (b)

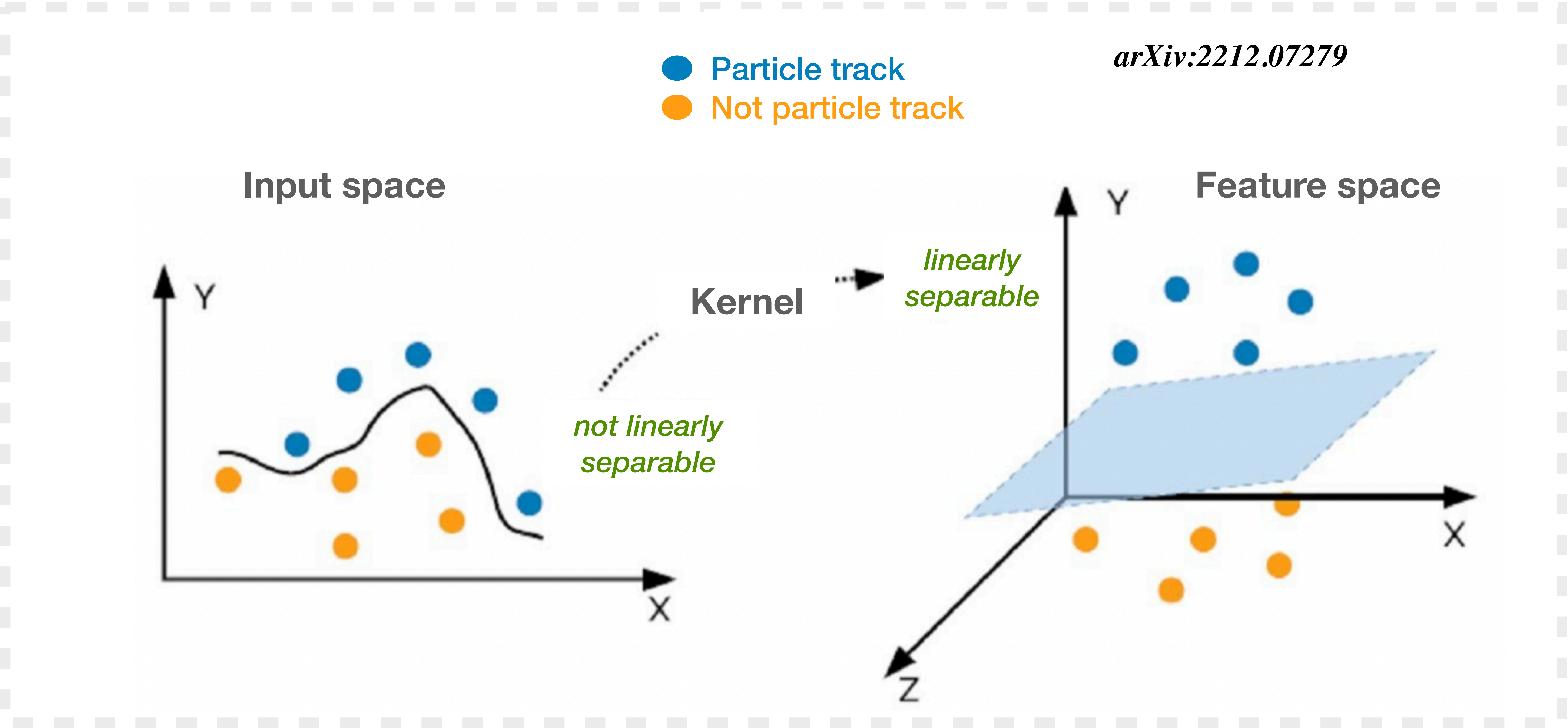
(c) (d)

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

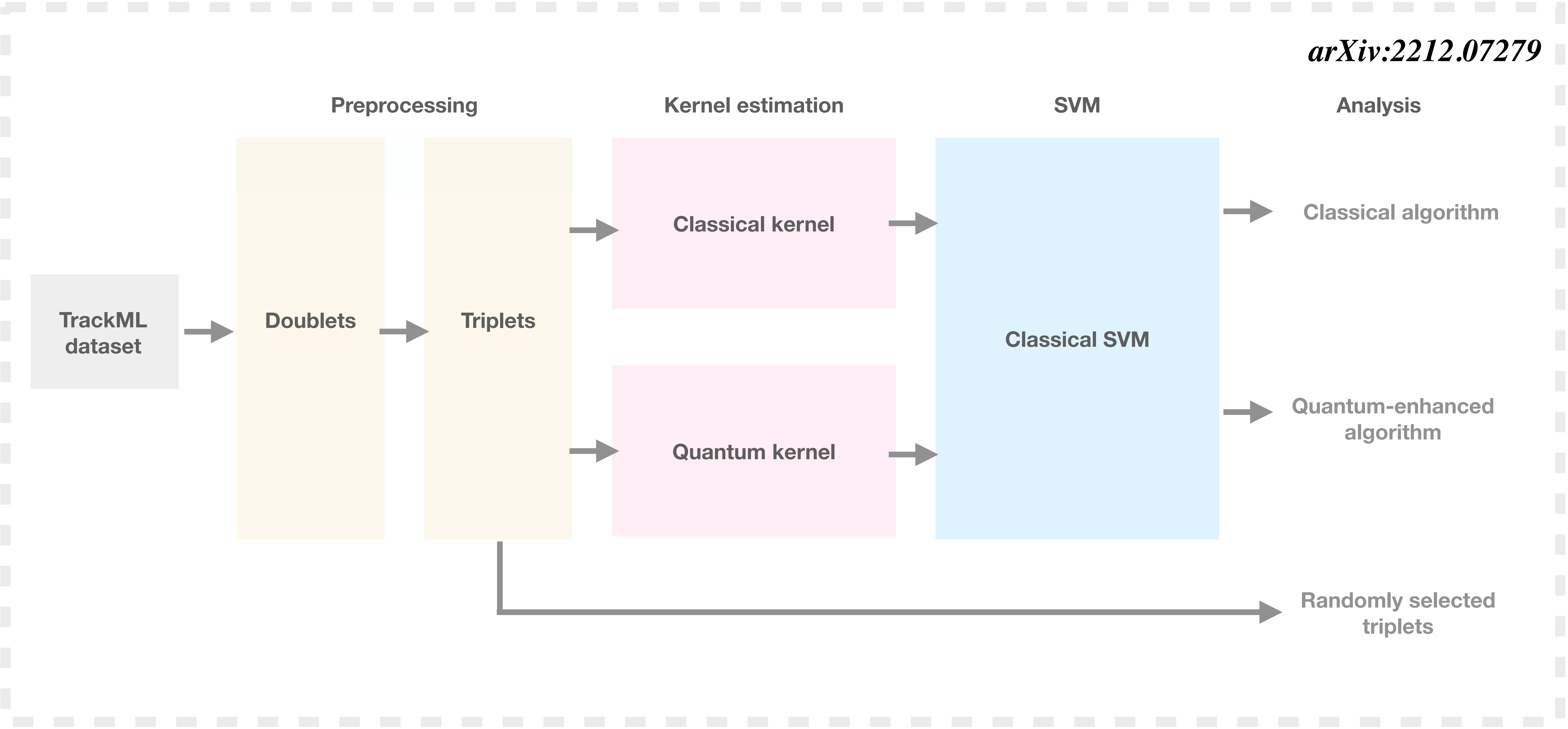
Reformulate as a classification task: Does a track segment (set of 3 consecutive hits) belong to a particle?



Support vector machine with quantum kernel

Quantum machine learning

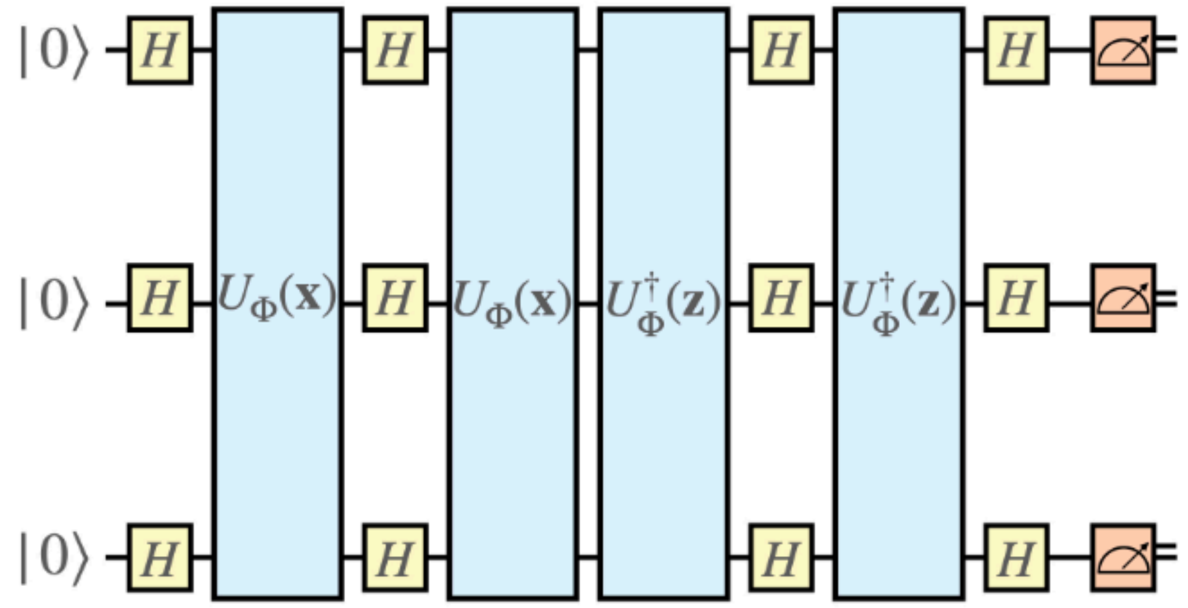
Reformulate as a classification task: Does a track segment (set of 3 consecutive hits) belong to a particle?



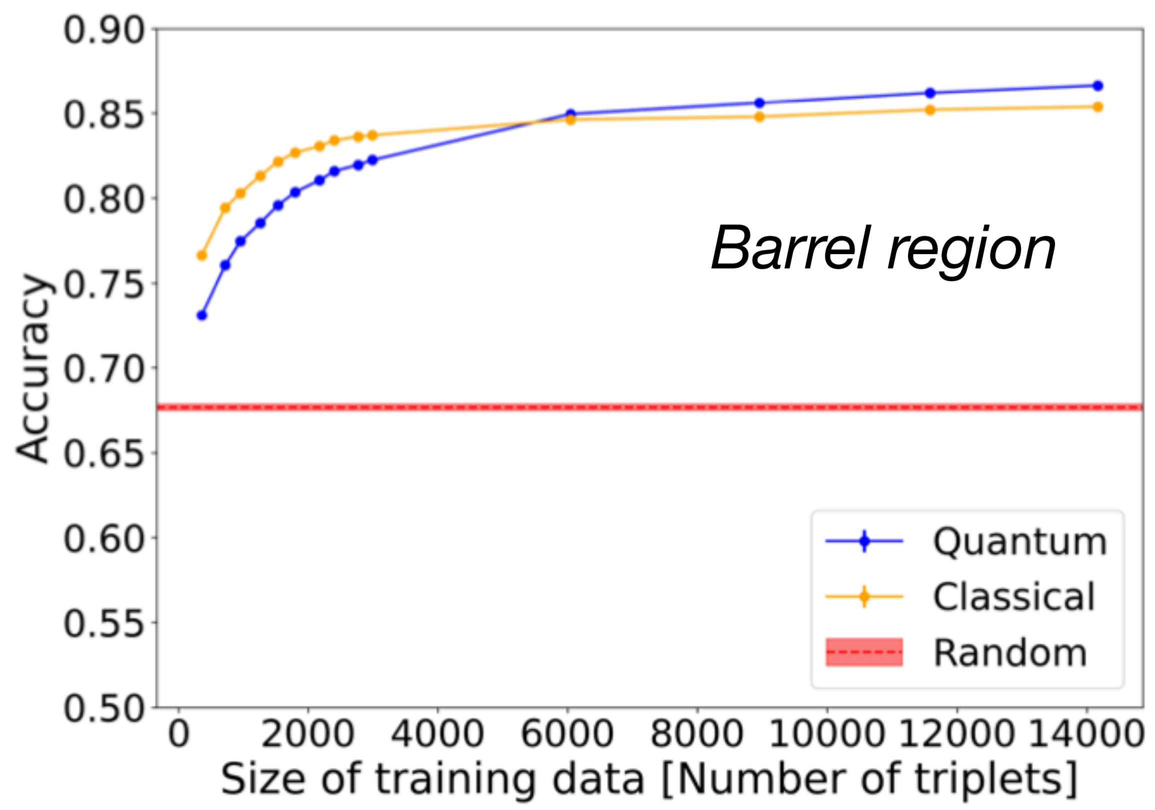
Quantum machine learning

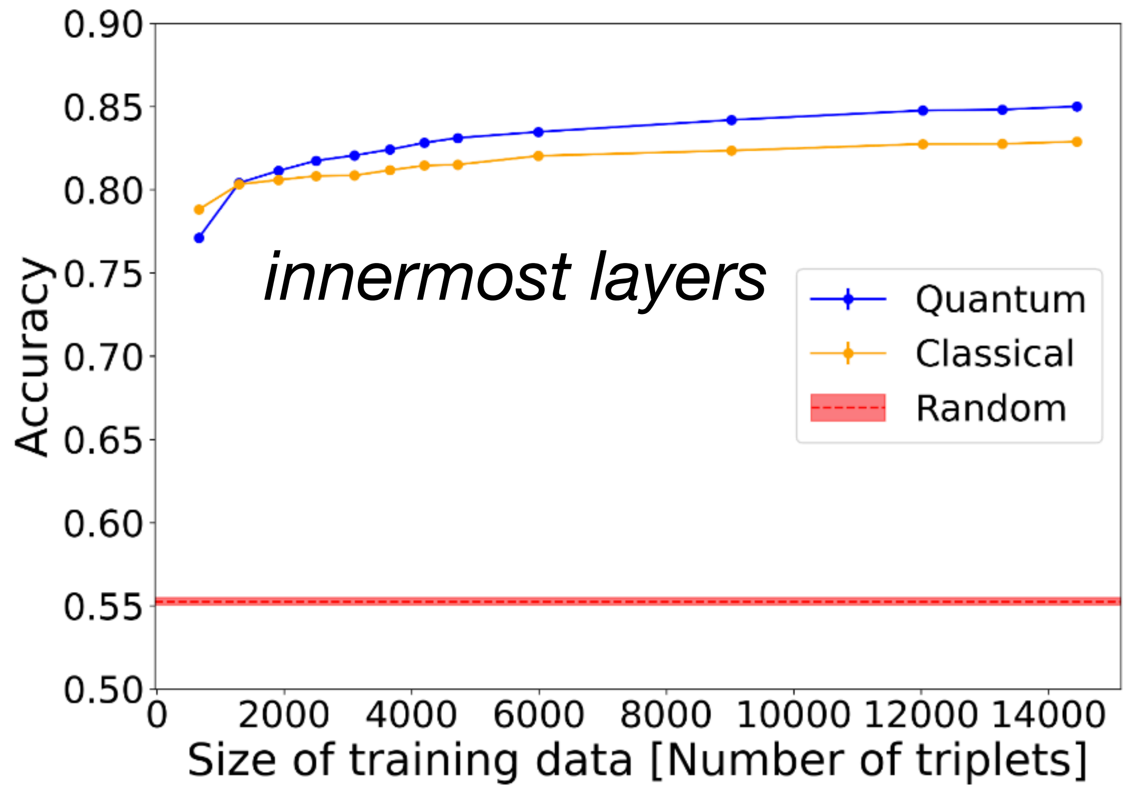
Reformulate as a classification task: Does a track segment (set of 3 consecutive hits) belong to a particle?

Quantum circuit to compute kernel



arXiv:2212.07279



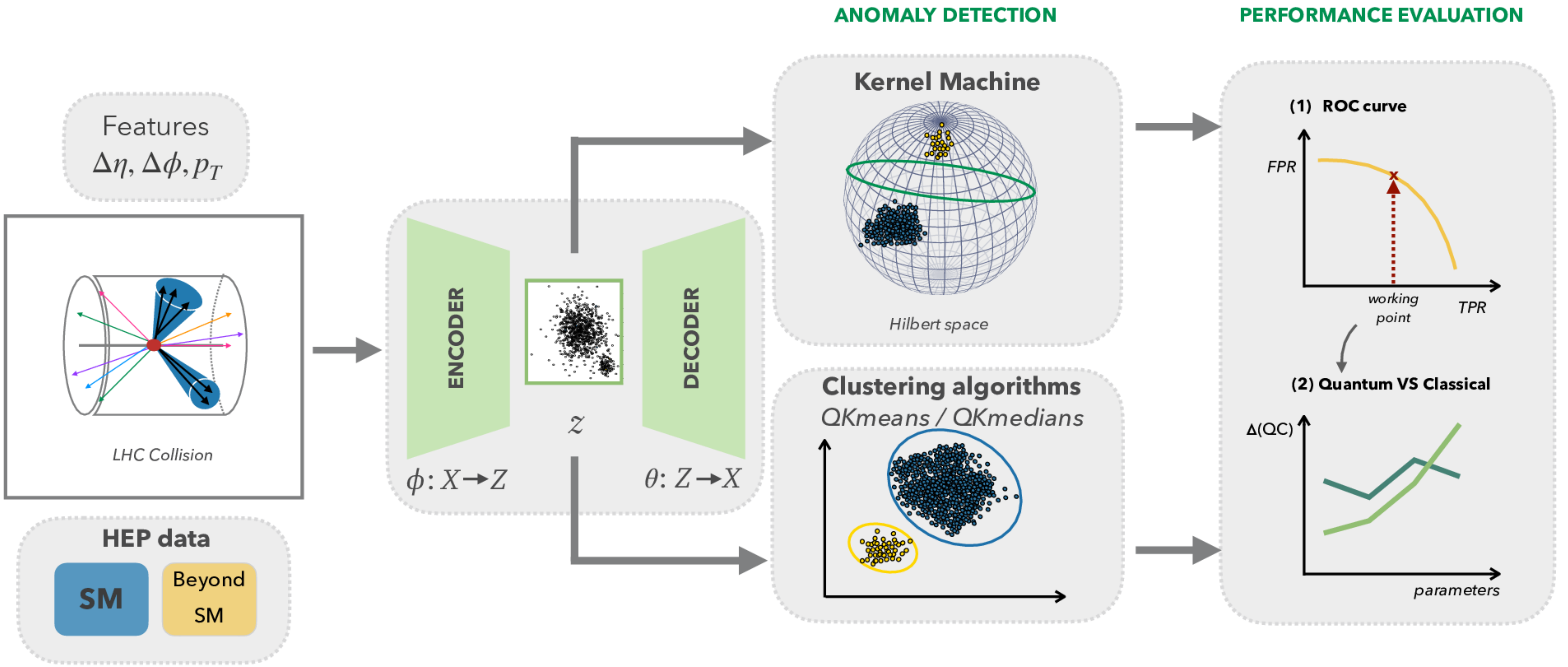


Support vector machine with quantum kernel

Quantum anomaly detection

- 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

arXiv:2301.10780

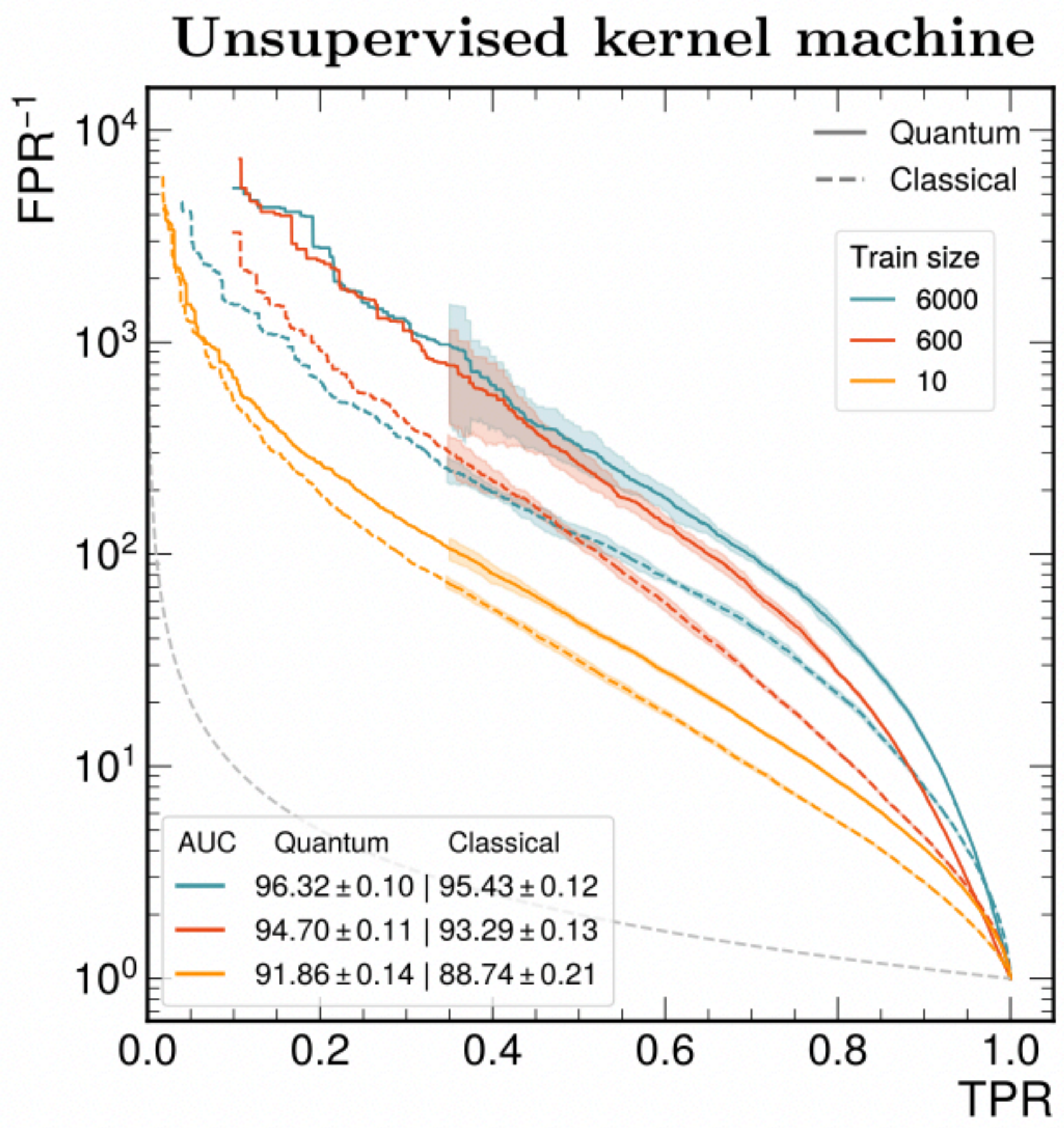


Quantum anomaly detection

arXiv:2301.10780

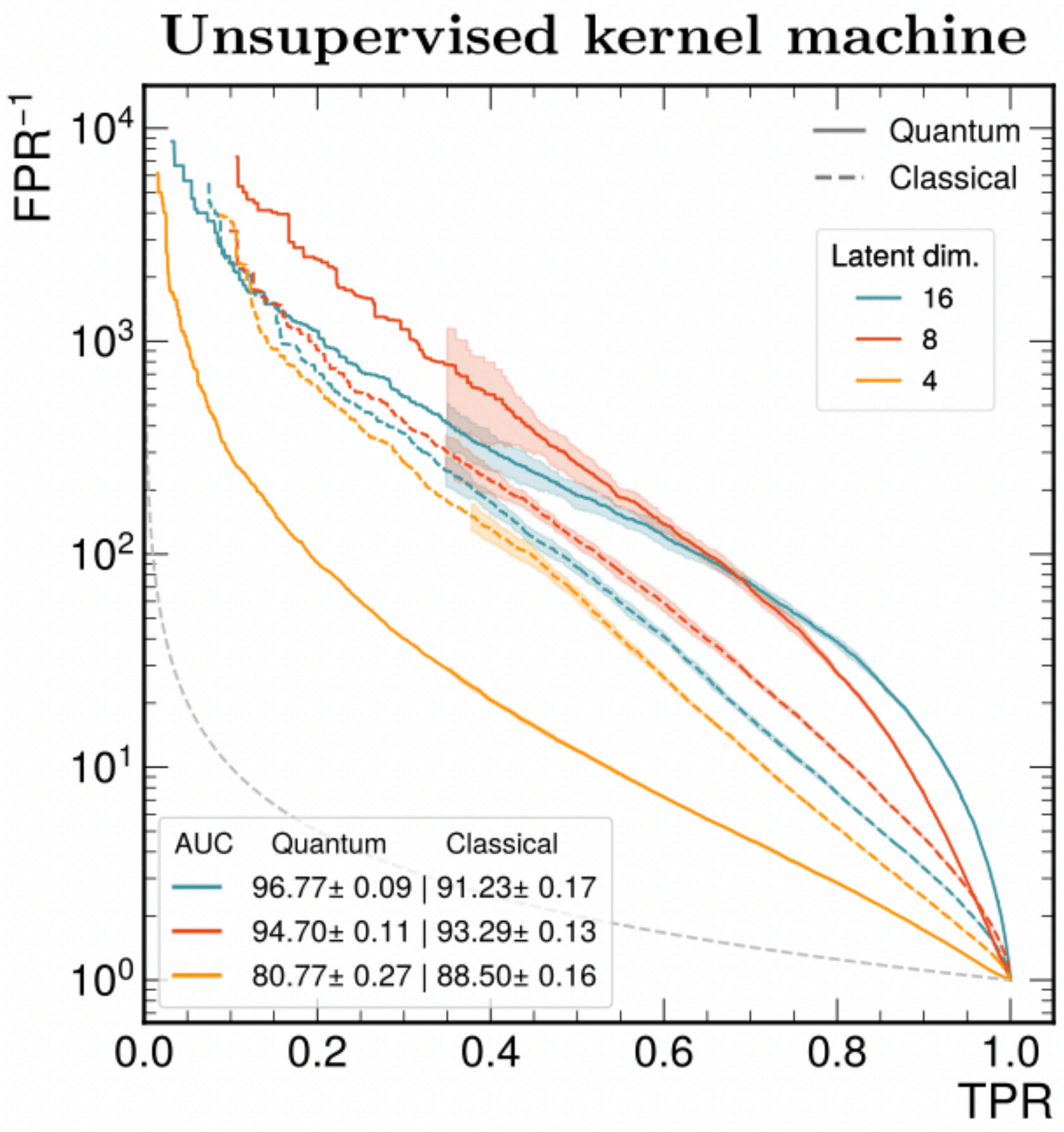
- Narrow Randall-Sundrum gravitons decaying to two W -bosons
- Scalar boson A decaying to a Higgs and Z boson, A—>HZ—>ZZZ
- Broad Randall-Sundrum gravitons decaying to two W -bosons

number of training samples



Large training size = better performance

latent space dimension



For quantum, best performance for latent dimension > 4

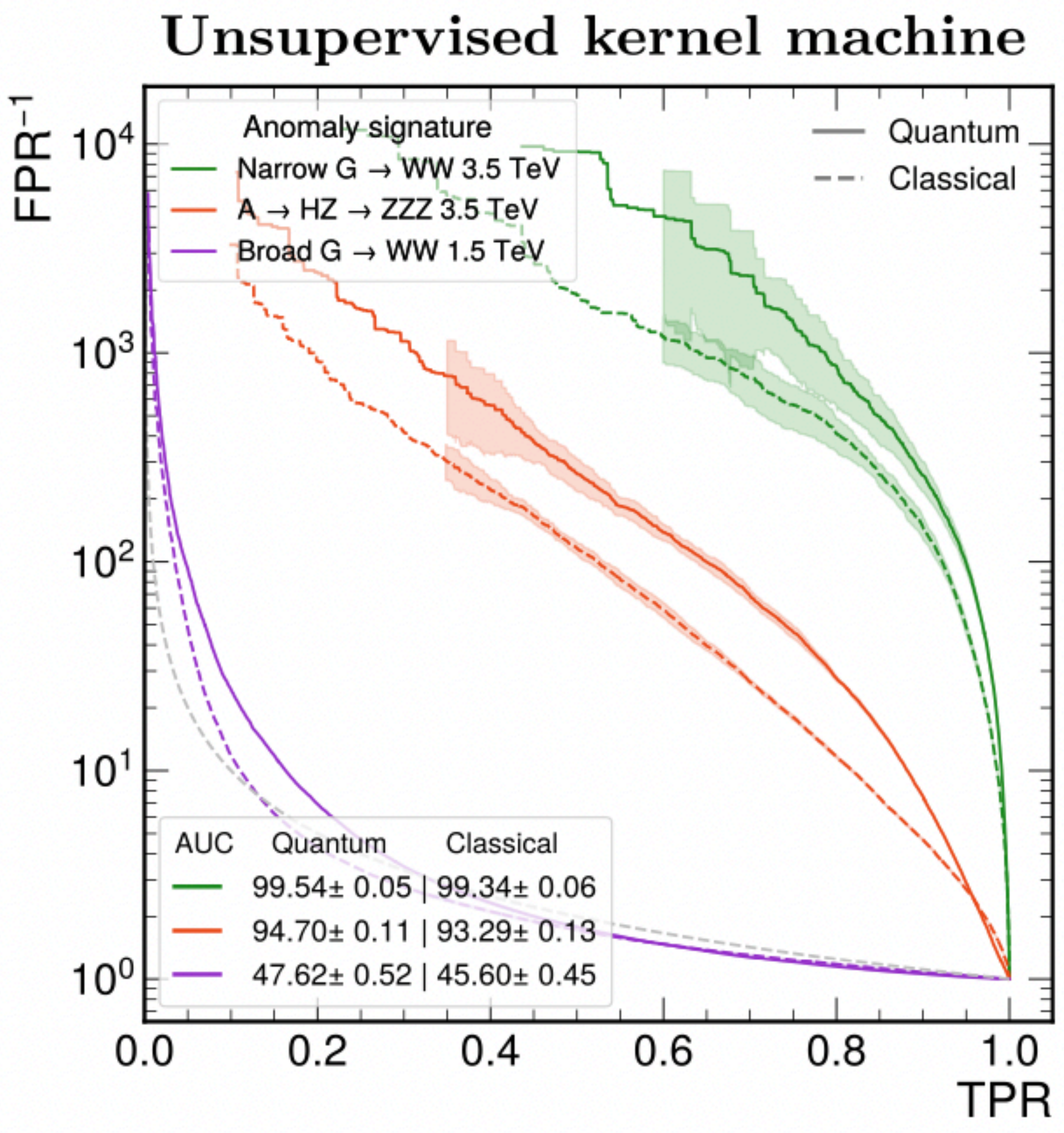
latent dimension = 8

training size = 600

Narrow graviton

Scalar boson A

Broad graviton

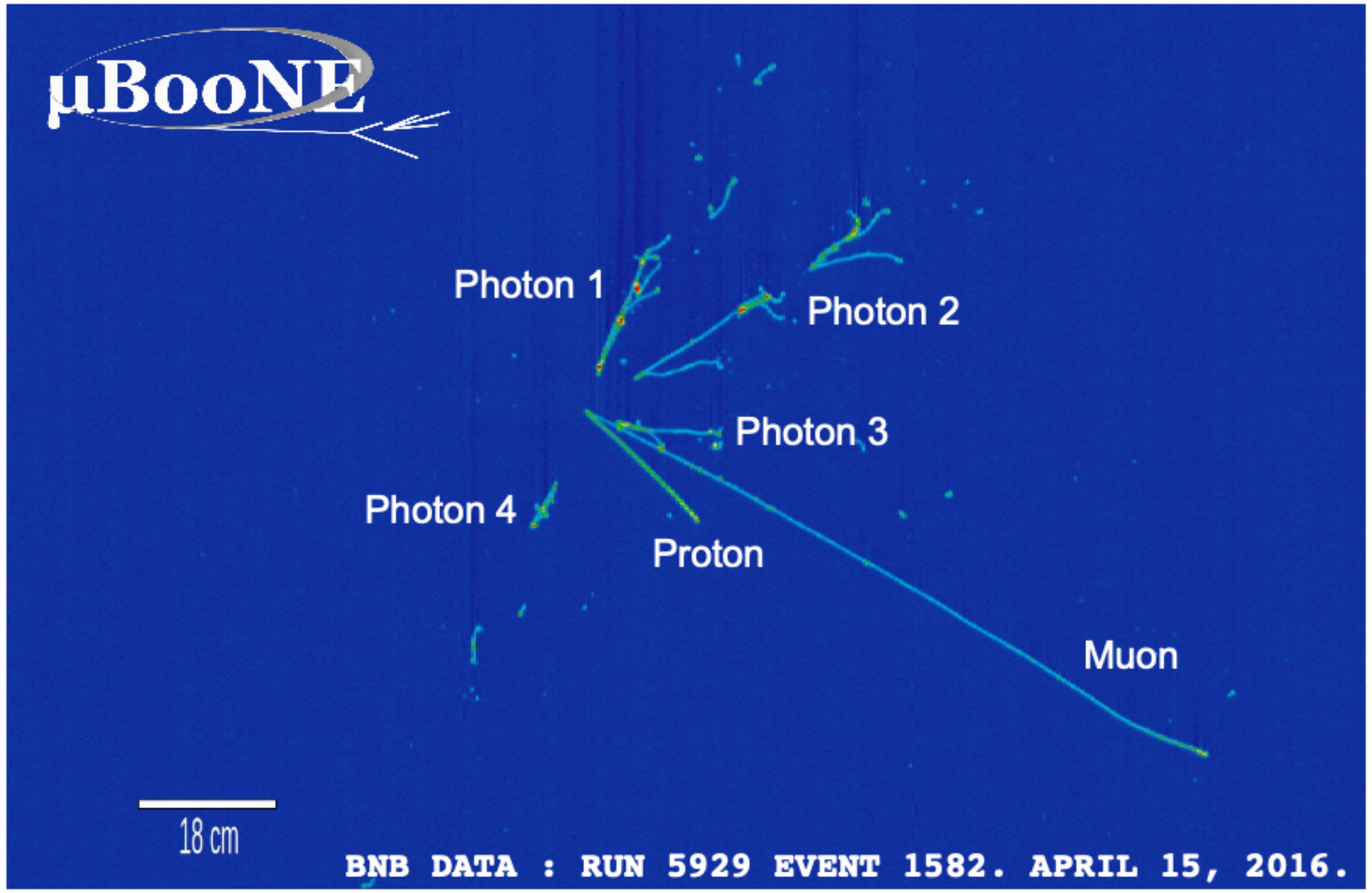


Outperforms classical

Quantum Machine Learning for LArTPC Topology Classification

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

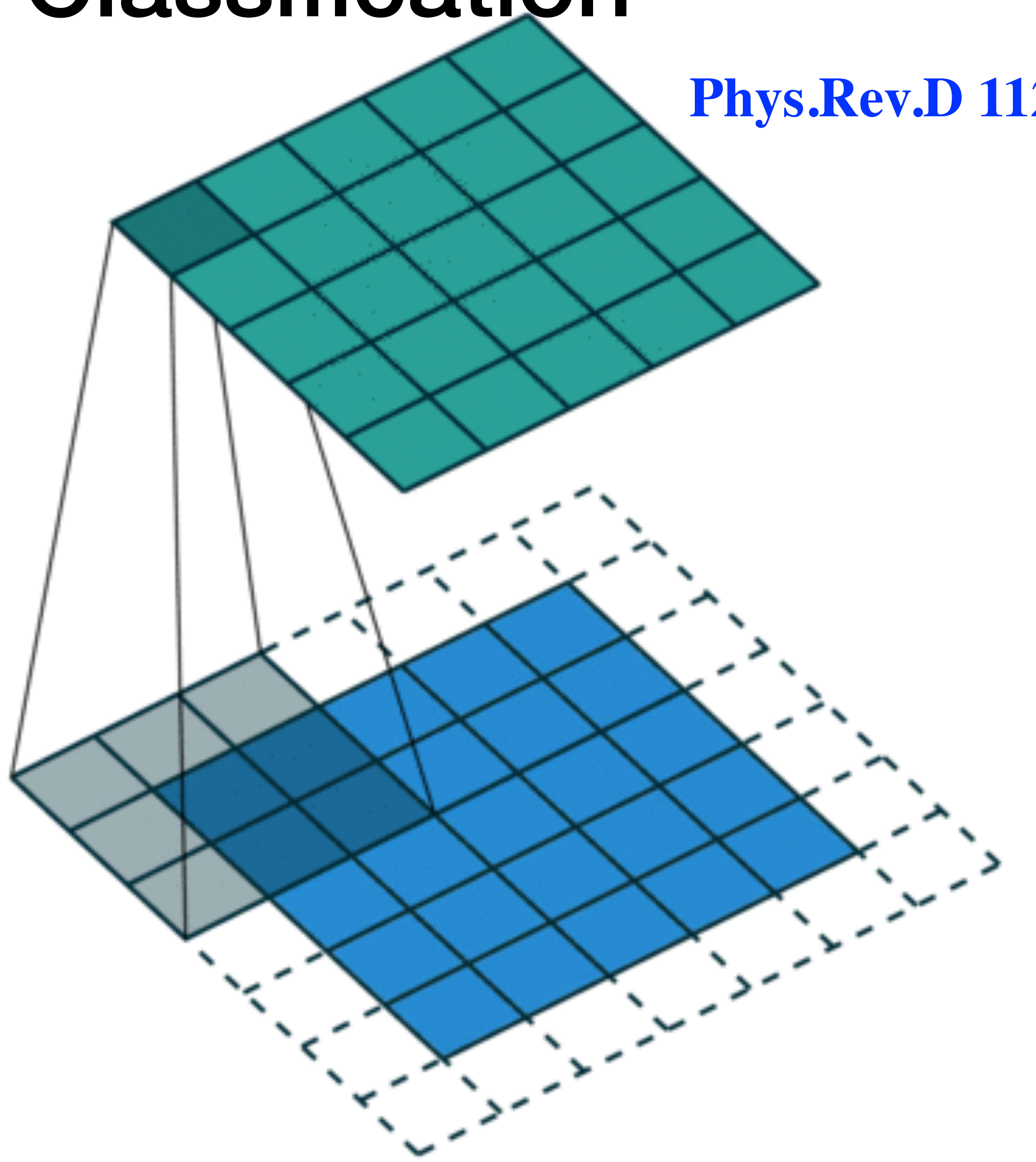
- Classify track-like vs shower-like topologies in Liquid Argon Time Projection Chambers (LArTPCs).
- Improves neutrino event reconstruction in experiments such as MicroBooNE and DUNE.
- Apply quantum machine learning (QML) methods — quanvolutional neural networks (QNNs) — to classify event topologies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



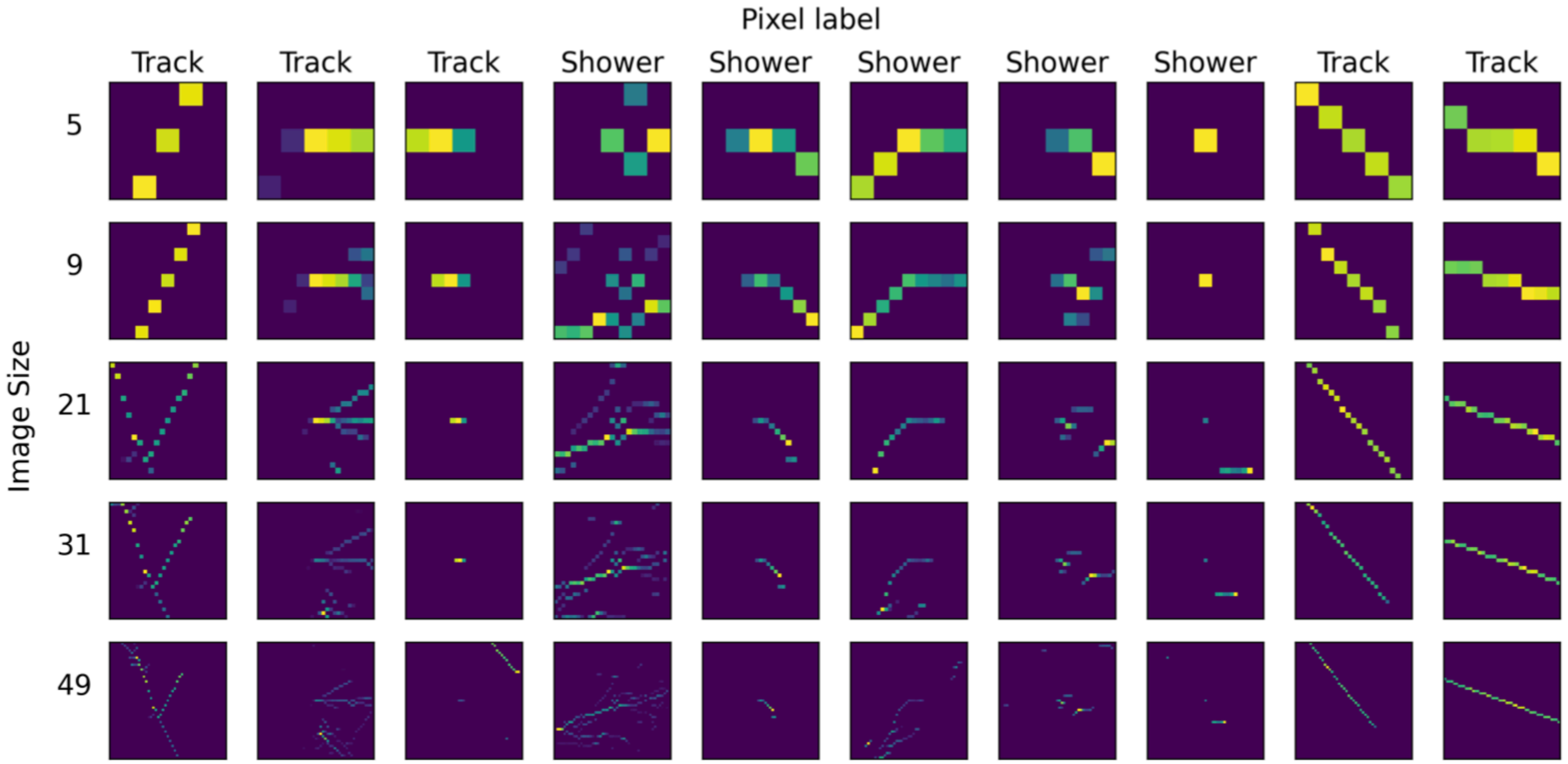
Neutrino interaction event in a LArTPC from MicroBooNE. 6 particles from the interaction vertex: 2 track-like (muon and proton) and 4 shower-like (photons)

Quantum Machine Learning for LArTPC Topology Classification

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

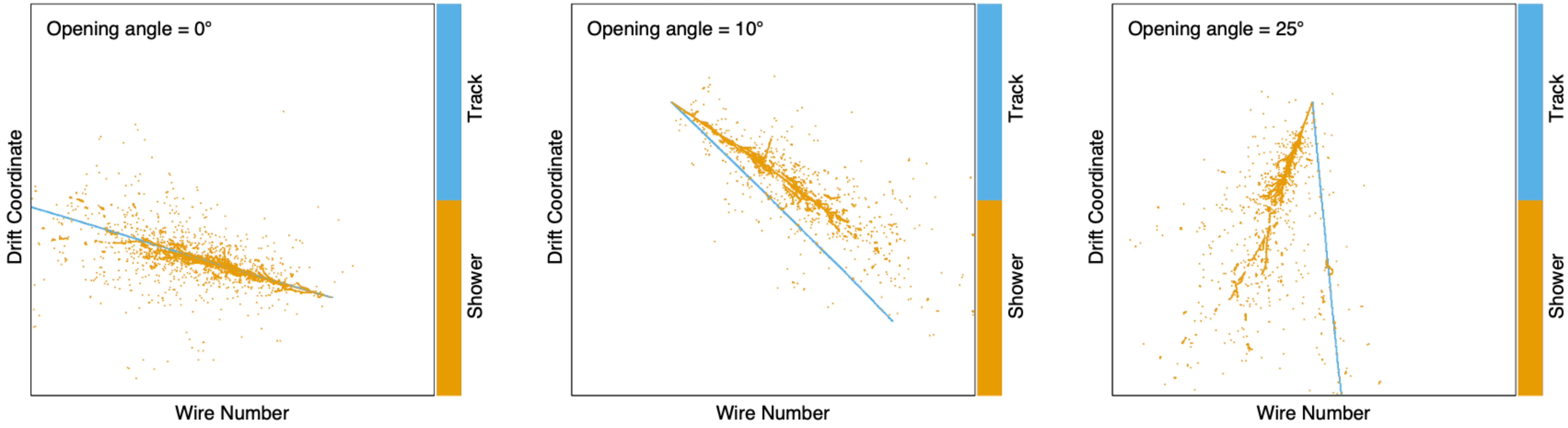


- Classical CNNs use convolutional filters to slide across images for local feature extraction.
- Quanvolutional Neural Networks (QNNs) replace these classical filters with **small quantum circuits**.
- Each **image patch** (e.g 2x2 pixels) is encoded into qubits, applies unitary transformations, and 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

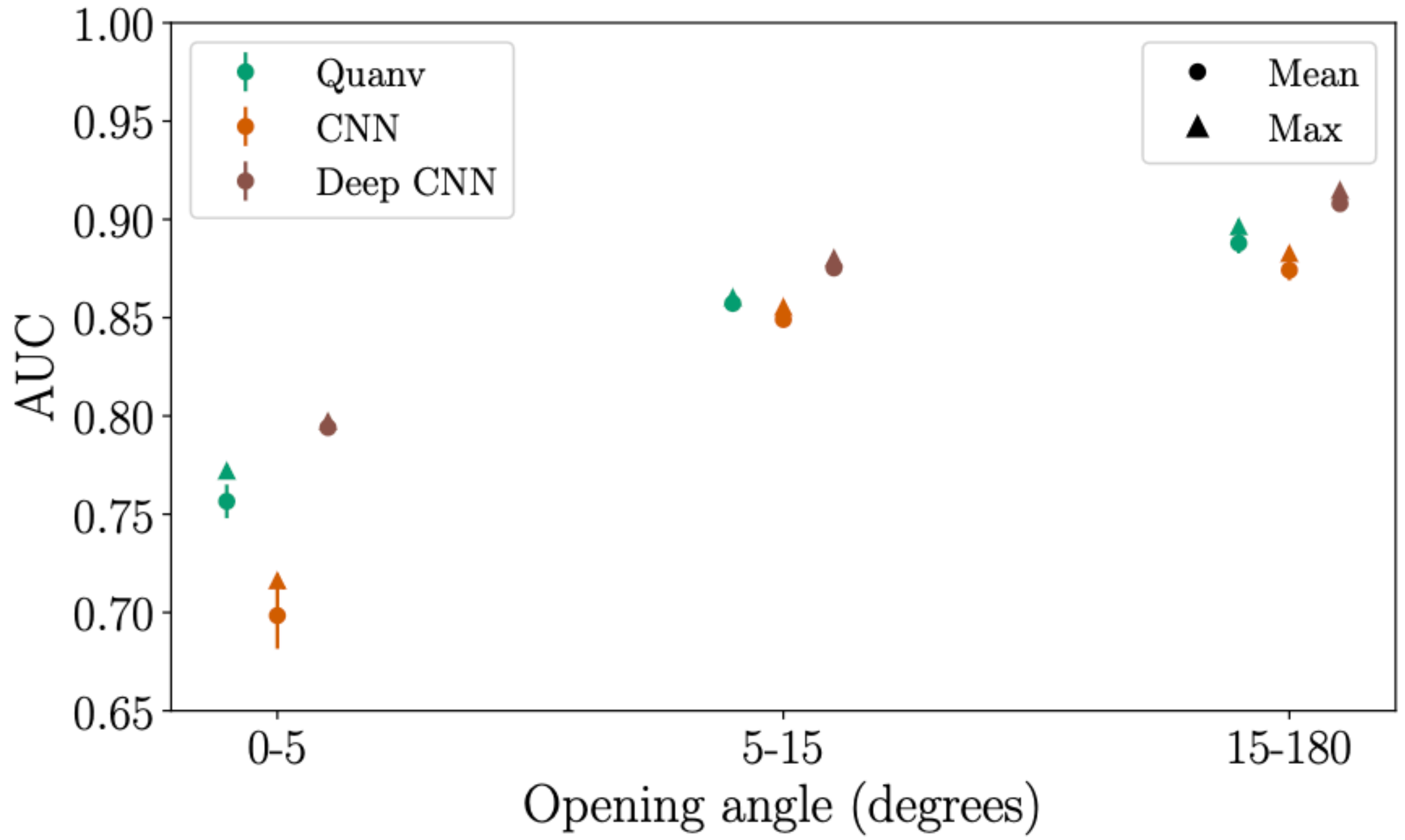


Quantum Machine Learning for LArTPC Topology Classification

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



- **Easy**: 15° – 180° (widely separated particles)
- **Medium**: 5° – 15° (moderate overlap)
- **Hard**: 0° – 5° (significant overlap and the most complex topology)



Results

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

- Quantum models outperform classical CNNs with similar parameter counts.

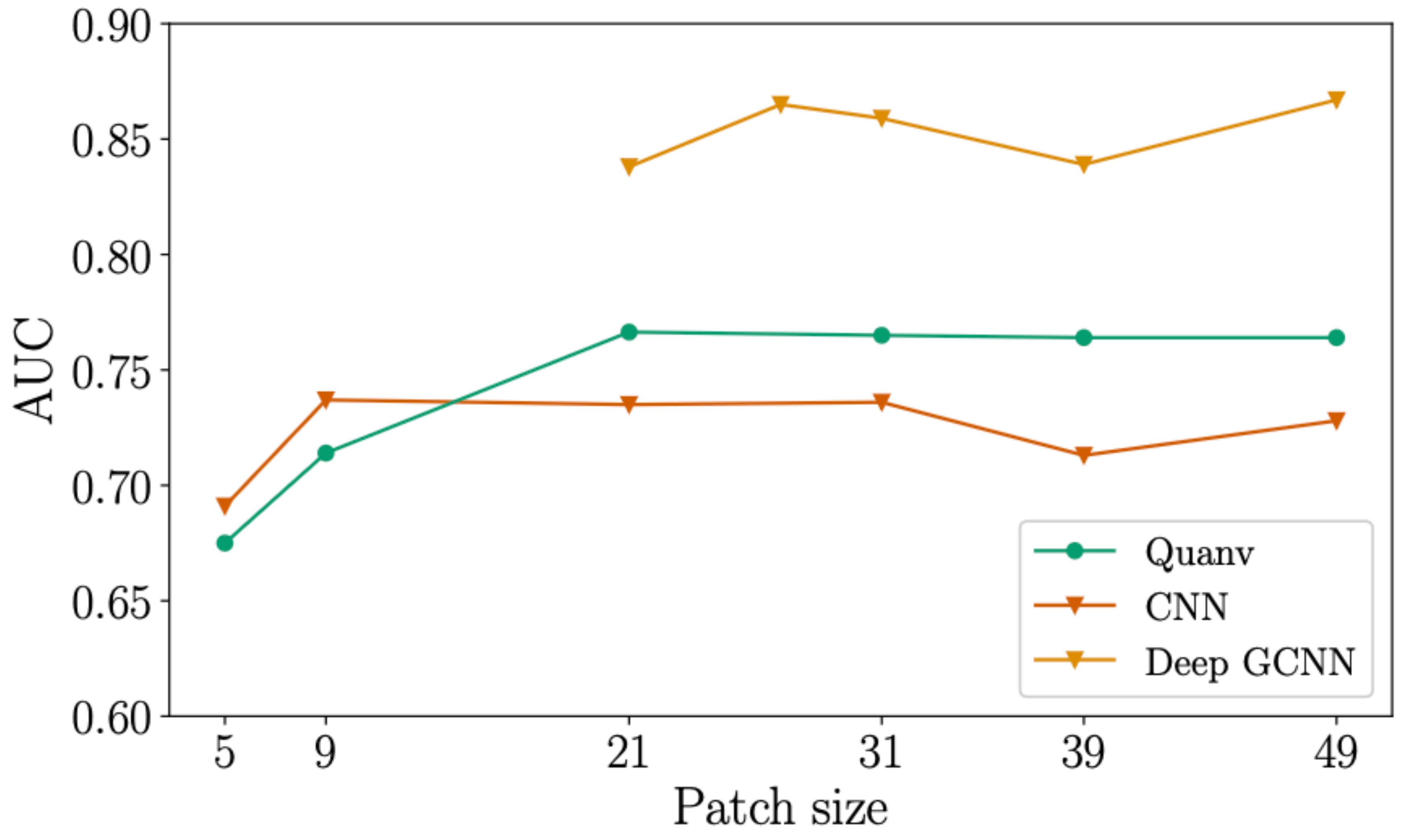
- Deep classical models (100× parameters) still perform best overall.

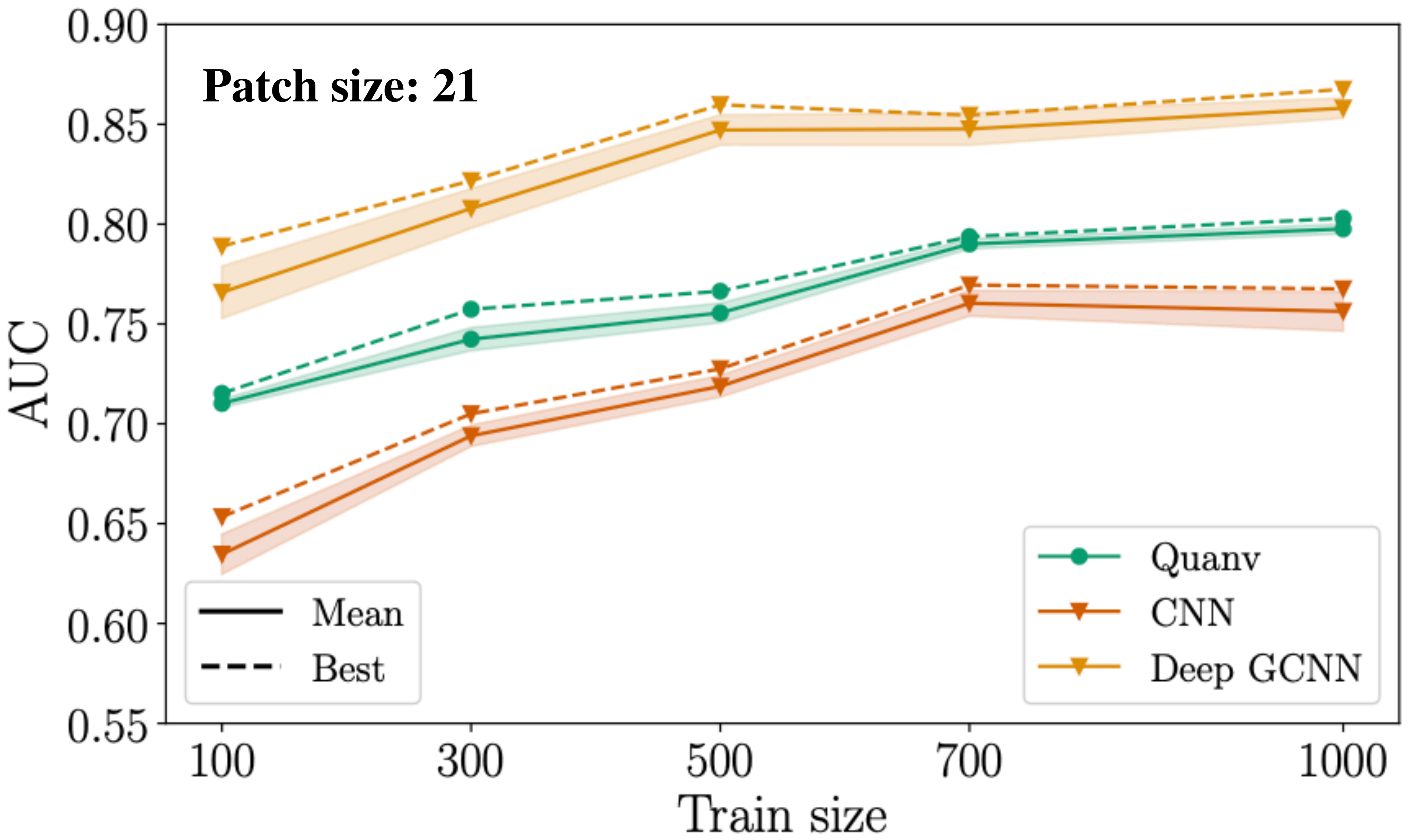
- Quantum models generalize better with limited data

- 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

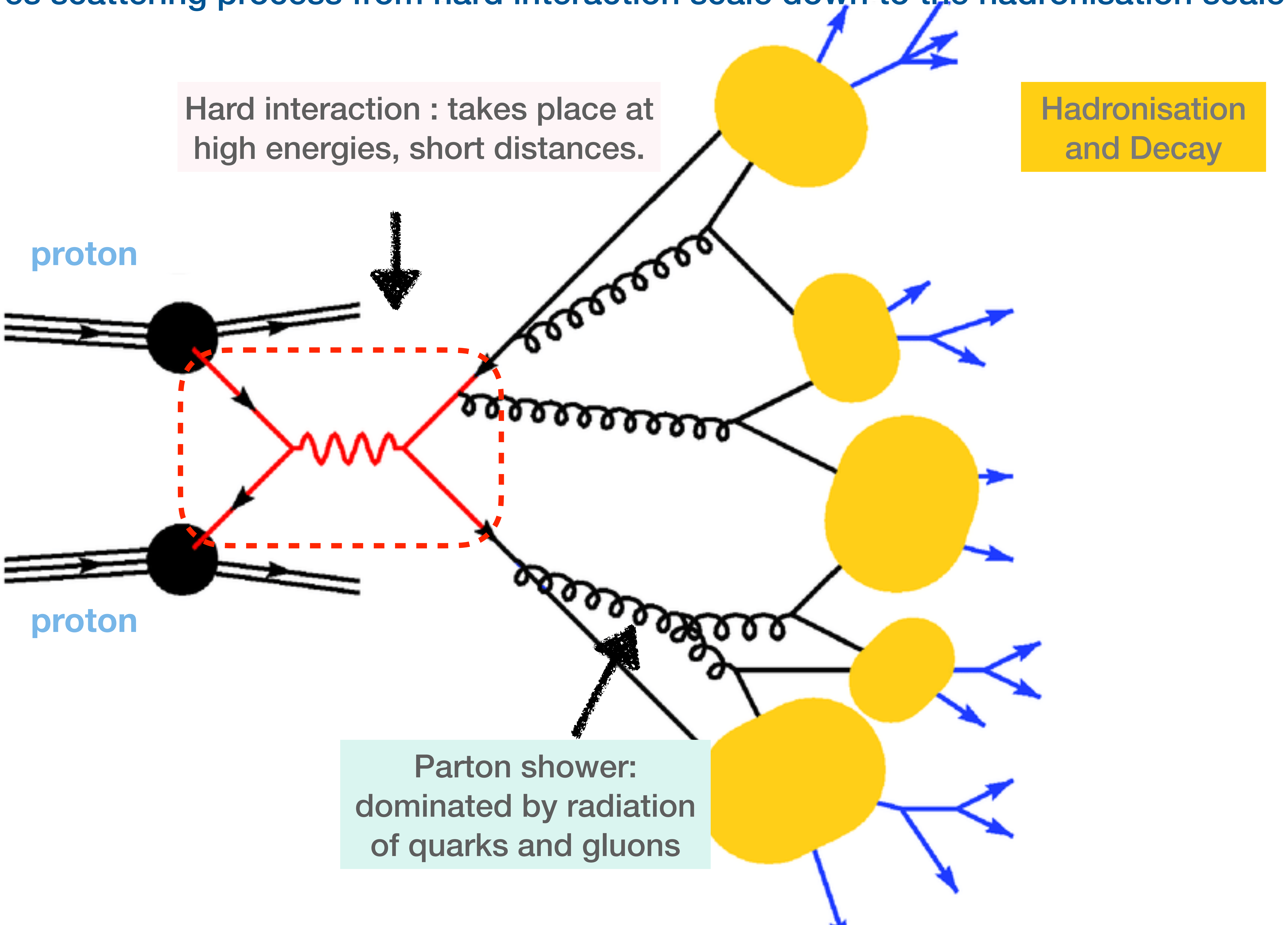




Parton Shower

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

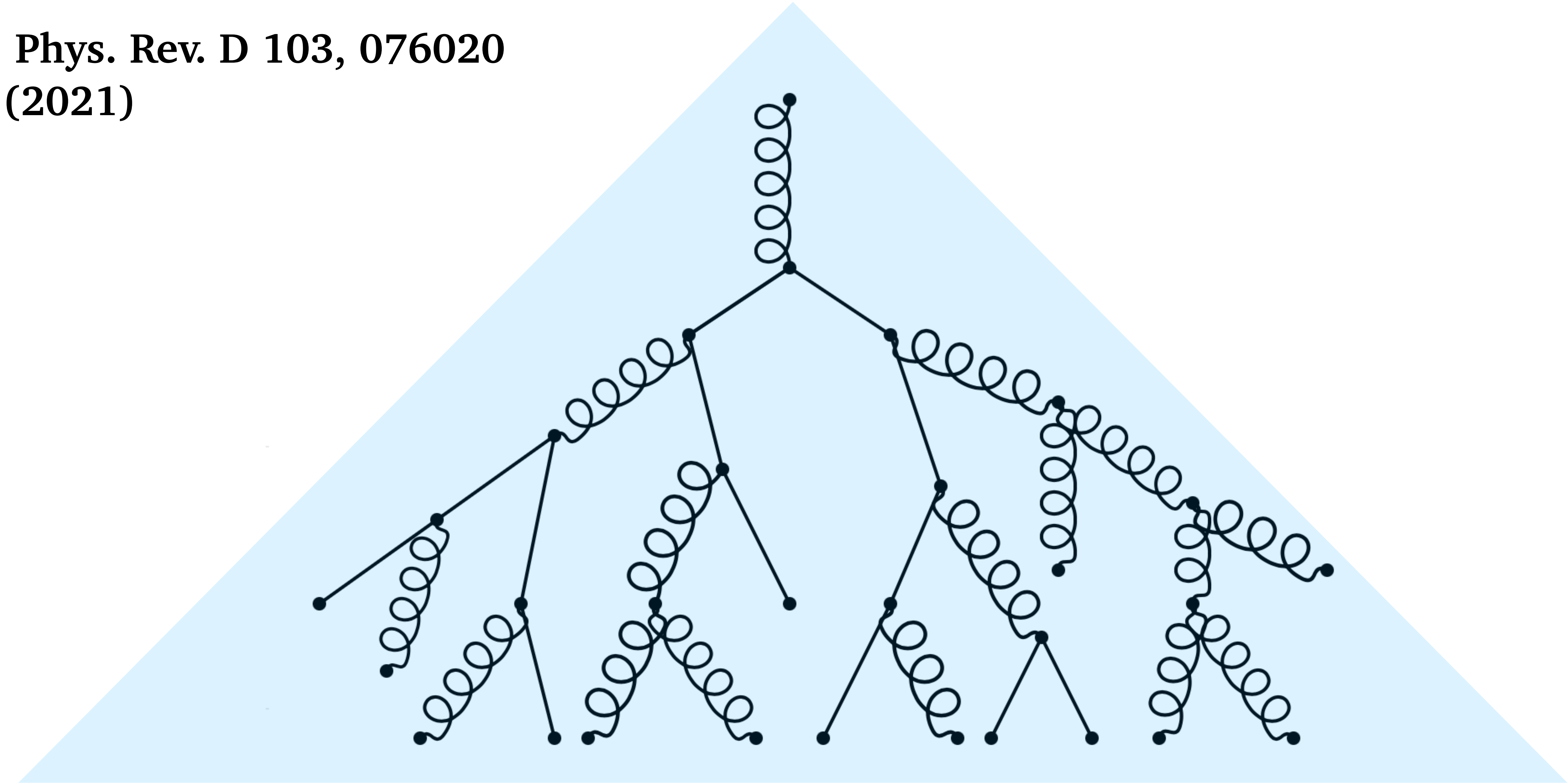
- Parton shower evolves scattering process from hard interaction scale down to the hadronisation scale



Simulating parton shower

Parton shower

Phys. Rev. D 103, 076020 (2021)

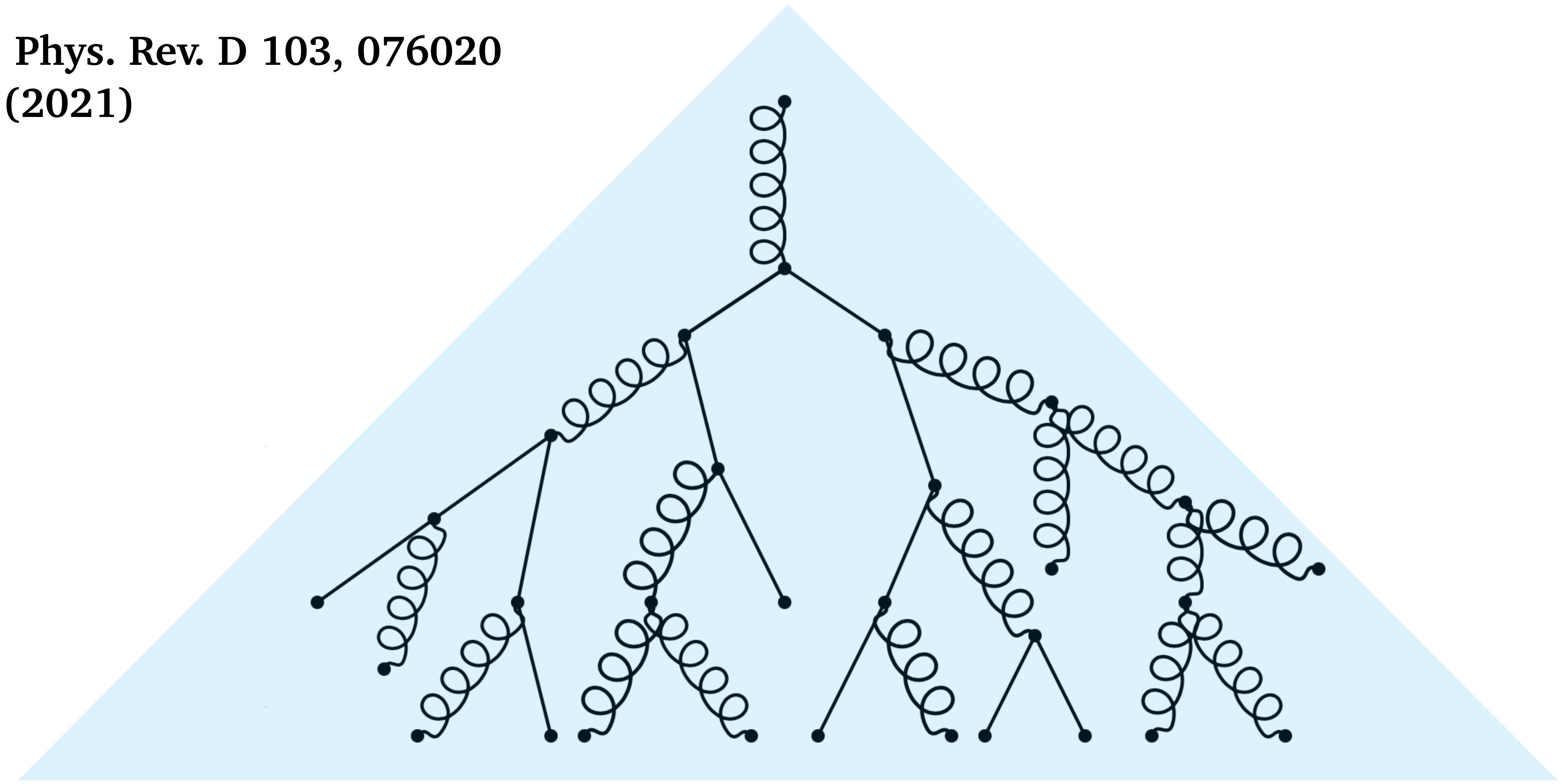


- Classical methods manually track individual shower histories and store in physical memory
- Quantum computing algorithm calculates all possible shower histories simultaneously
- Simulate 2-step parton shower with 31 qubits

Simulating parton shower

Parton shower

Phys. Rev. D 103, 076020 (2021)



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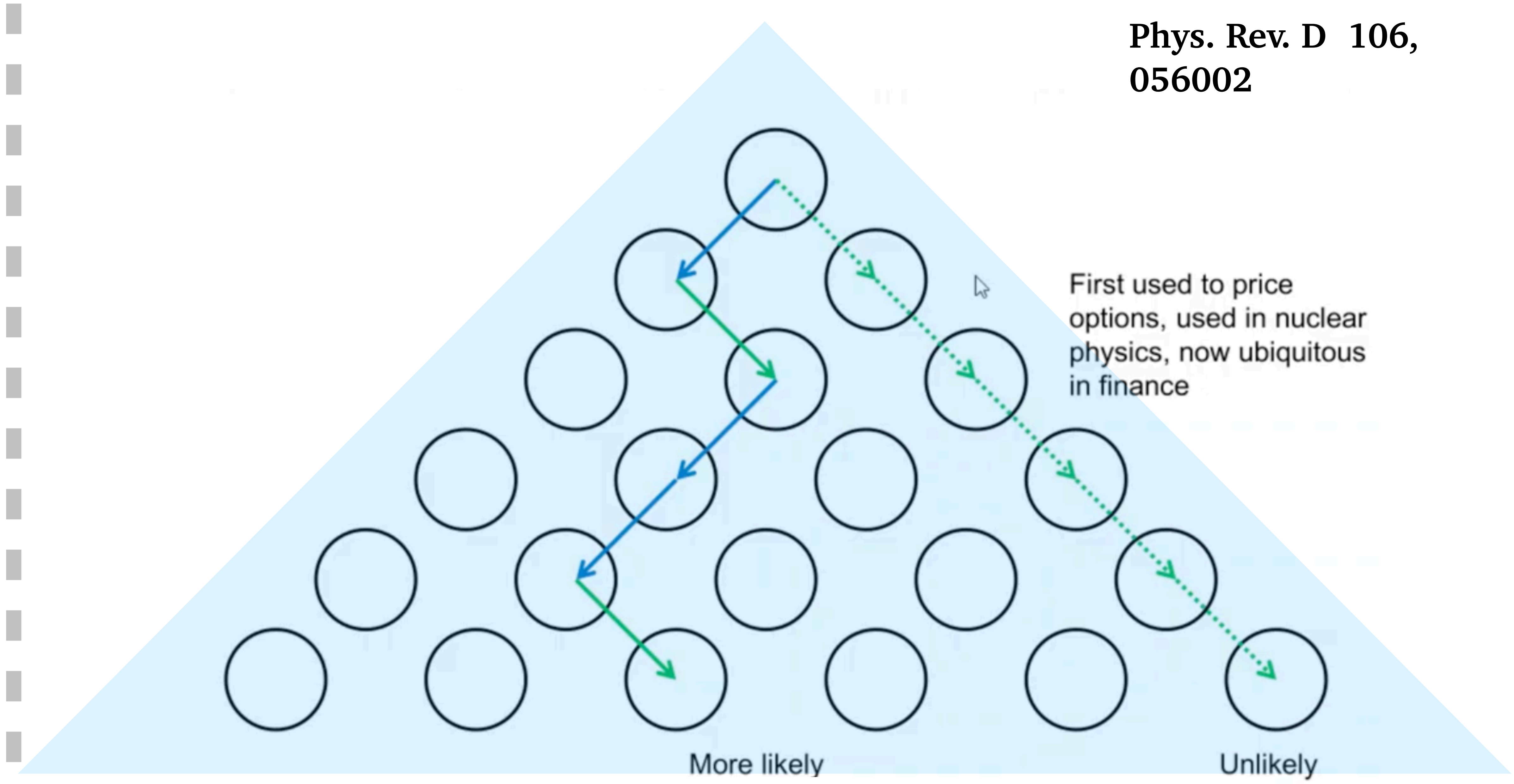
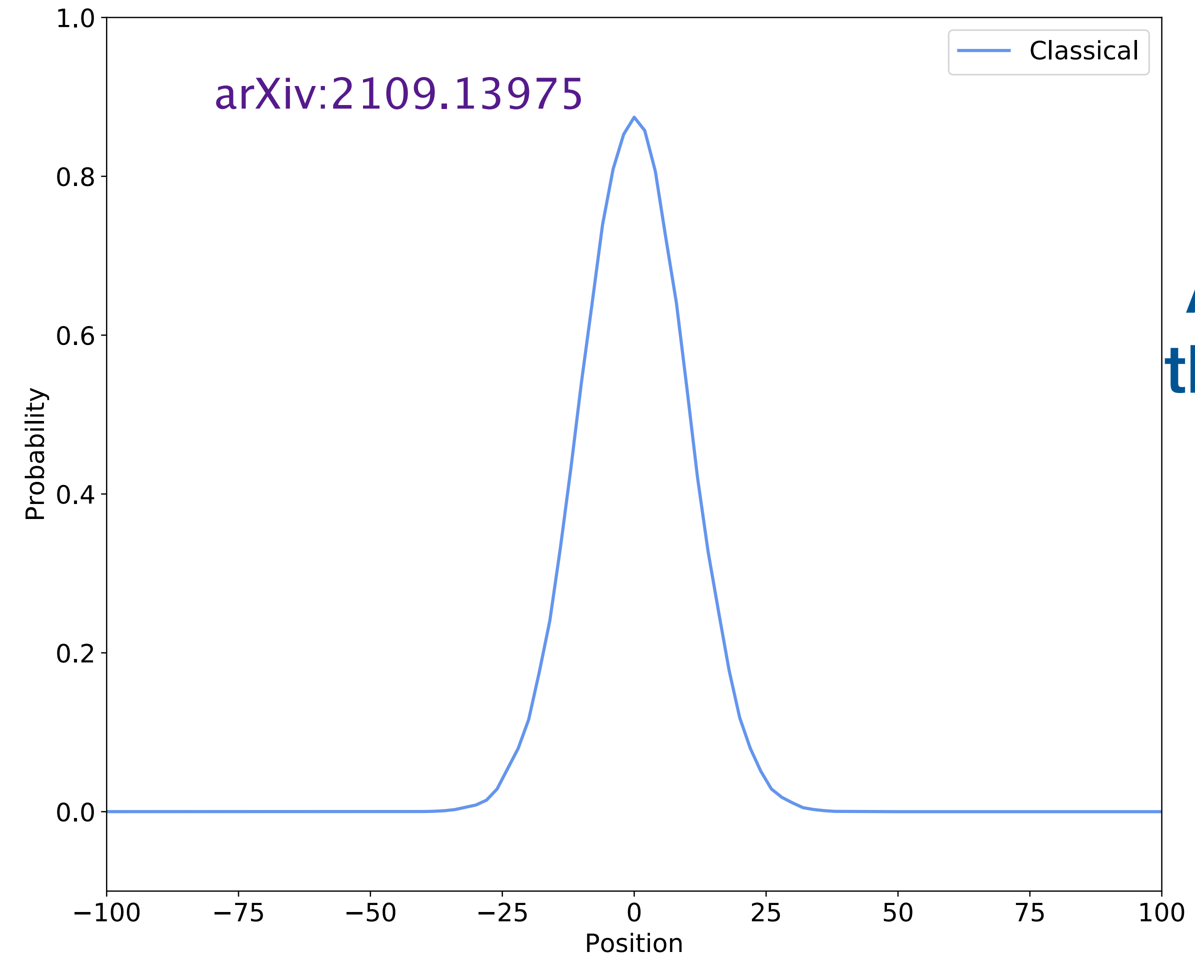
Classical walk

Phys. Rev. D 106, 056002



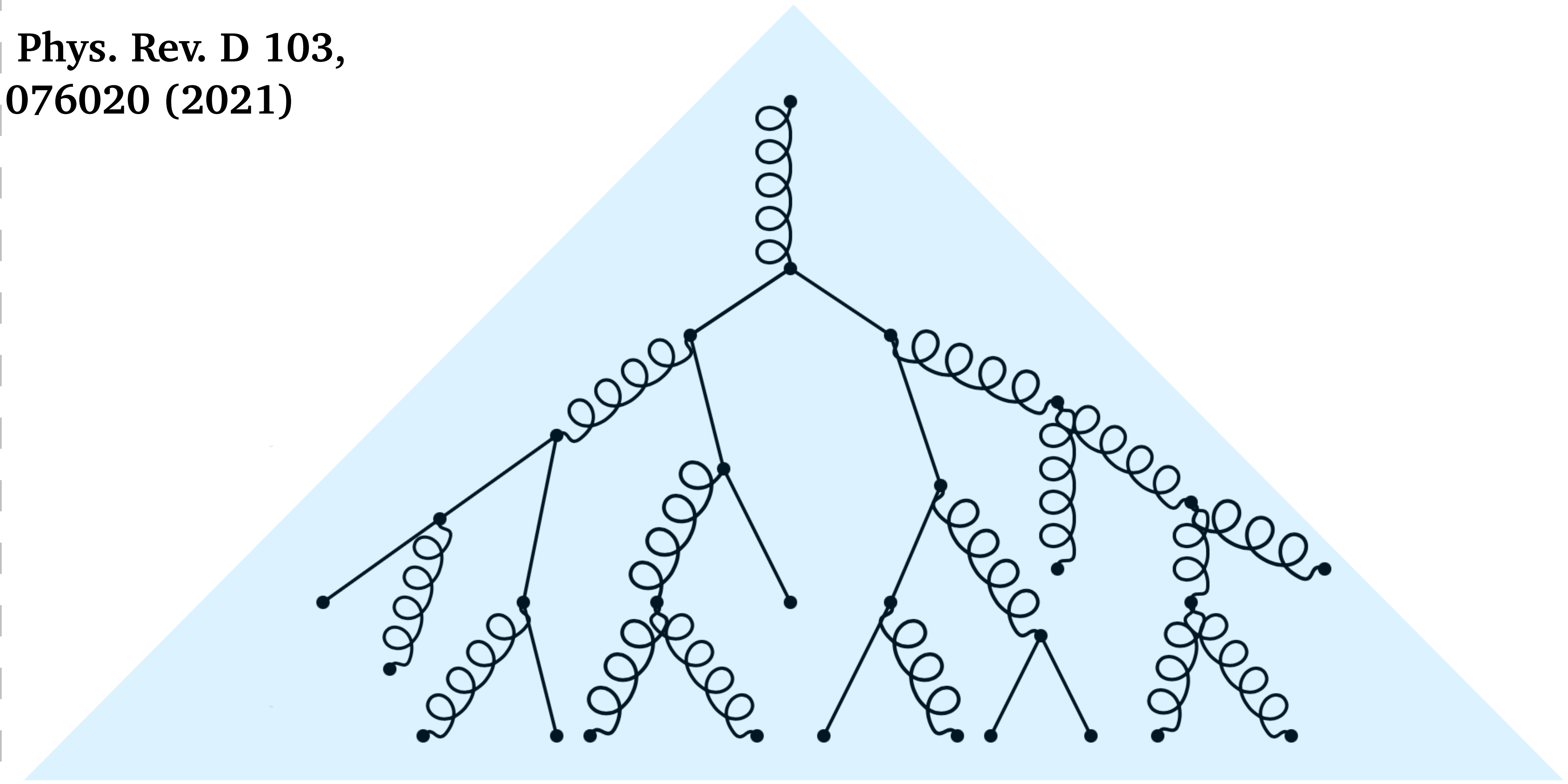


Average distance of the walker from initial position = $\sqrt{t}$

Simulating parton shower

Parton shower

Phys. Rev. D 103, 076020 (2021)



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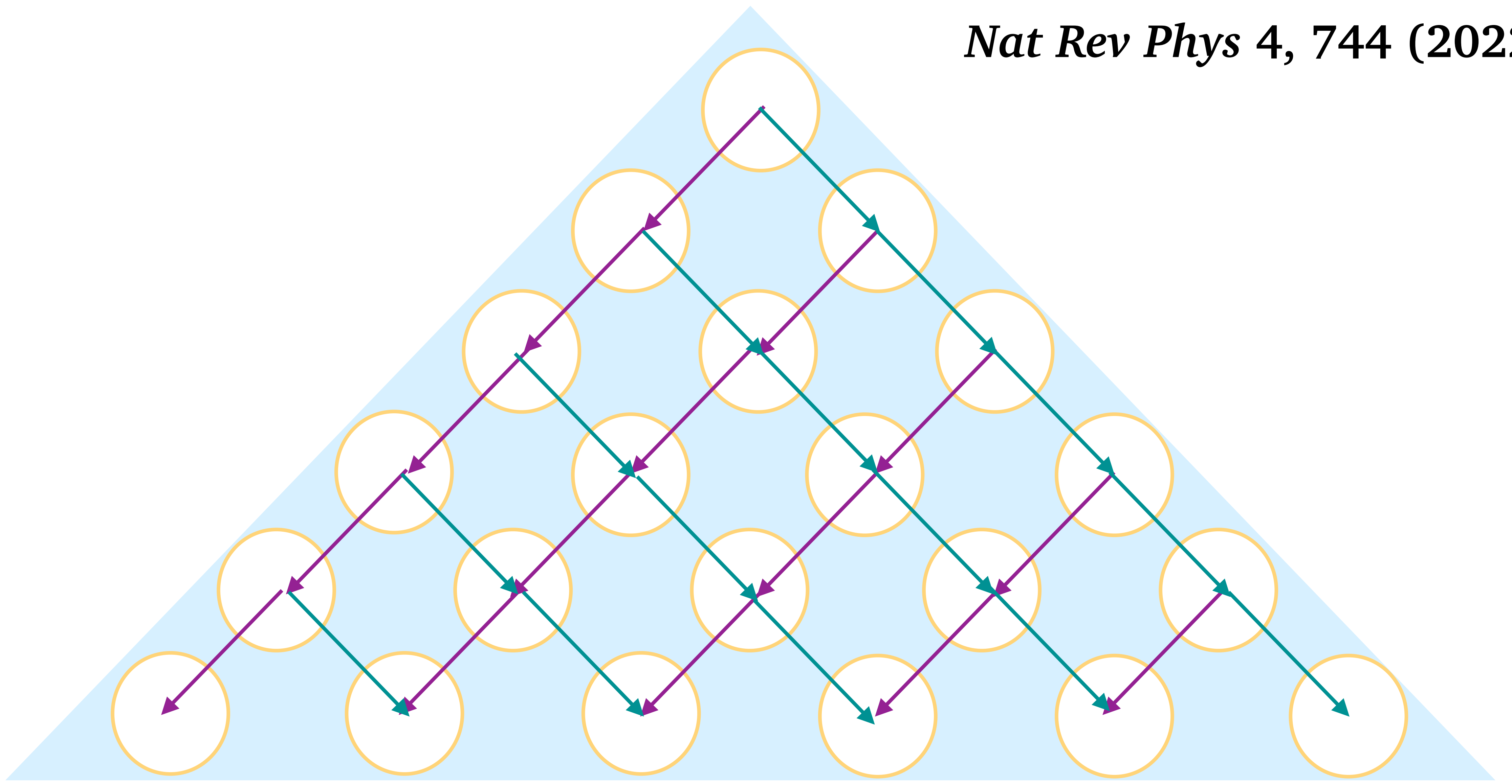
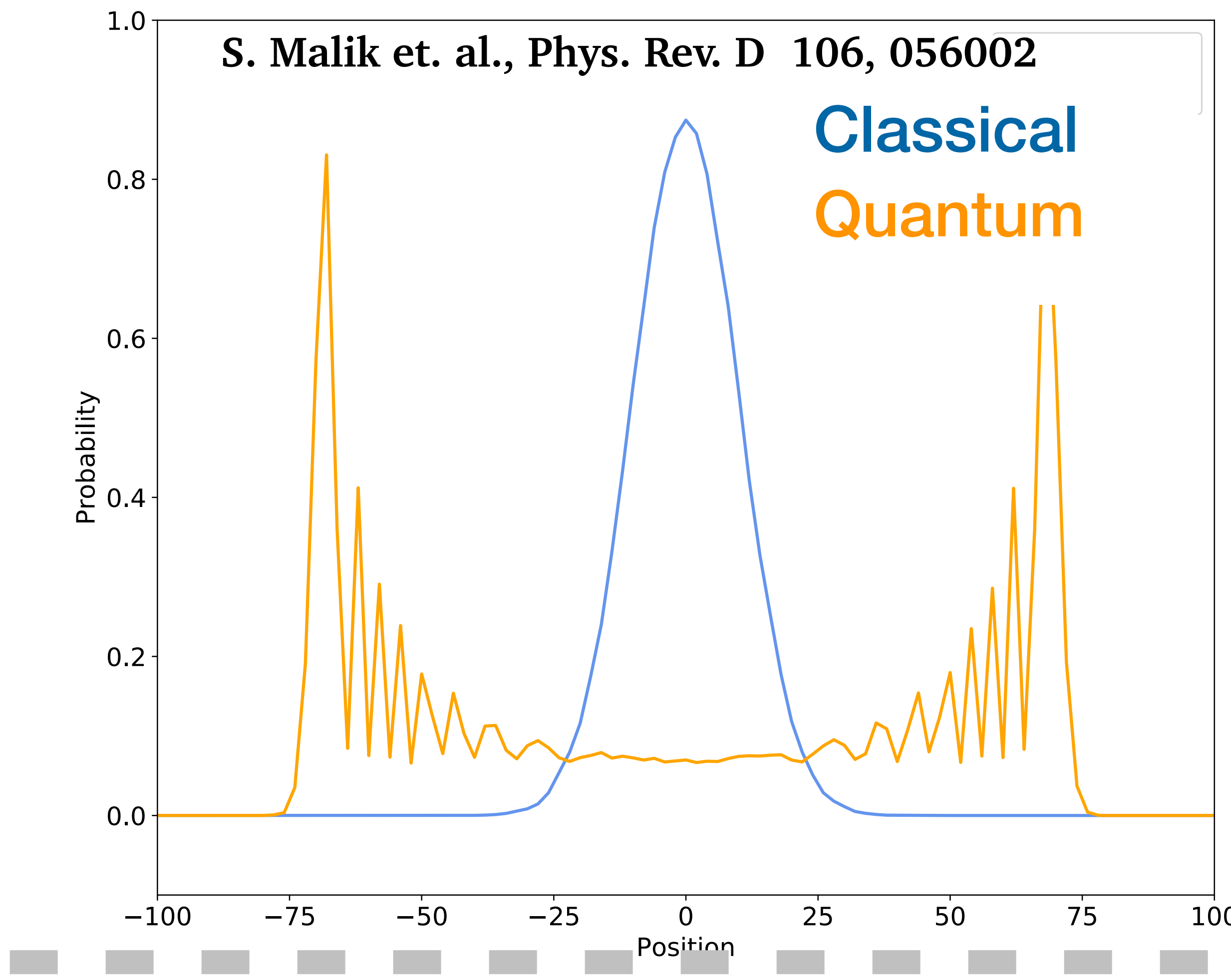
Quantum walk

Nat Rev Phys 4, 744 (2022)



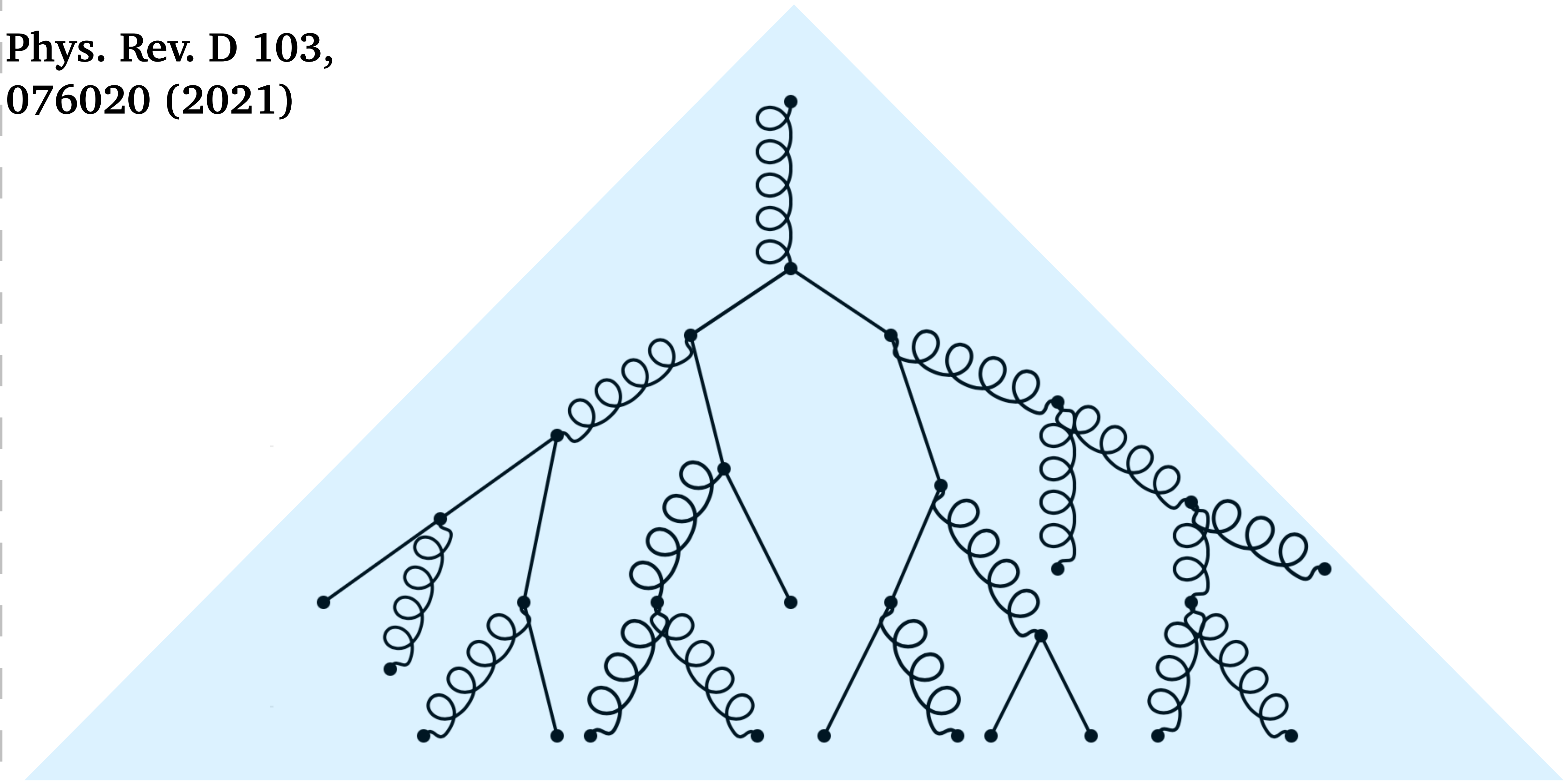


Quantum walker quadratically faster than classical walker

Simulating parton shower

Parton shower

Phys. Rev. D 103, 076020 (2021)



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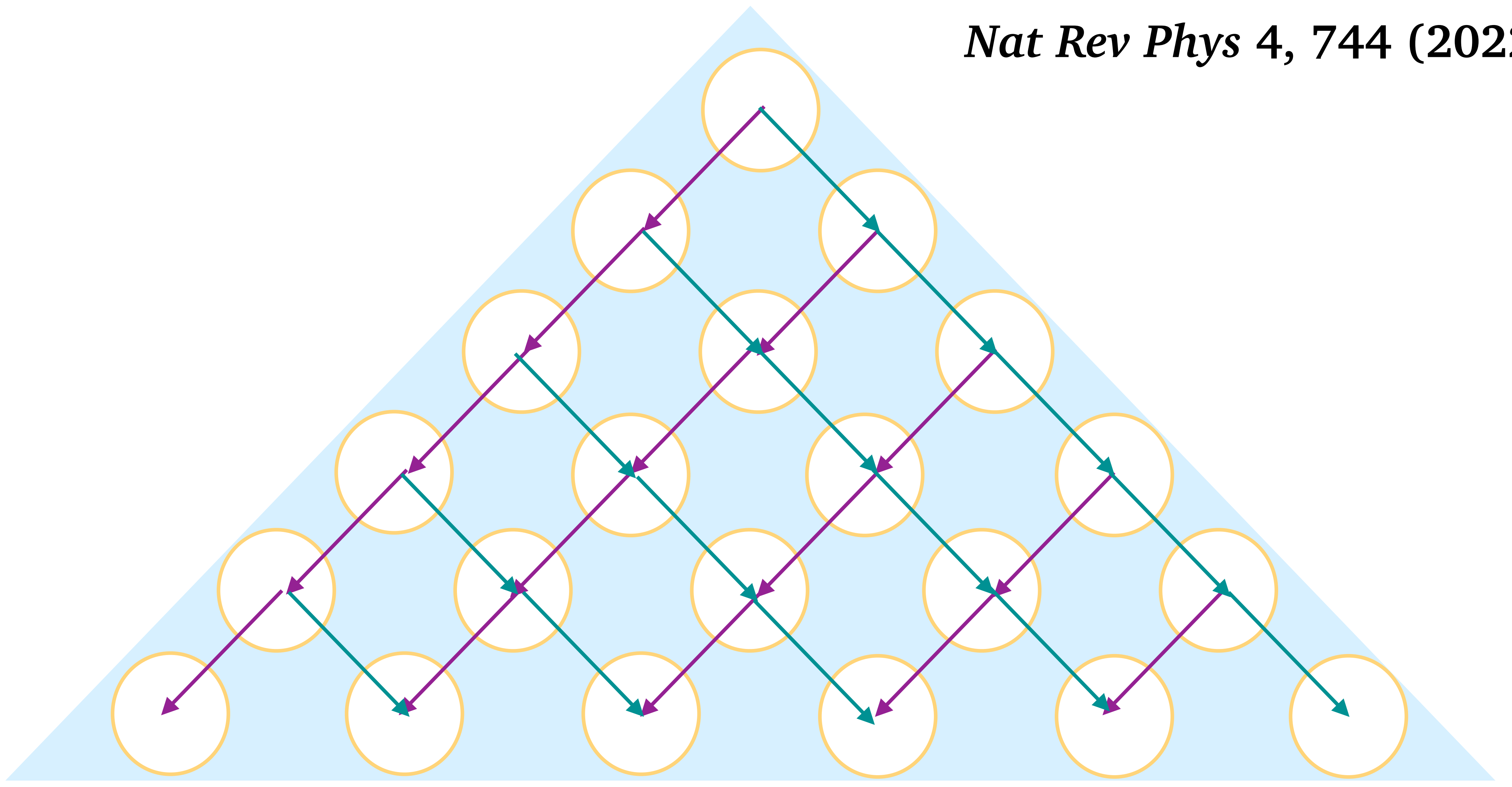
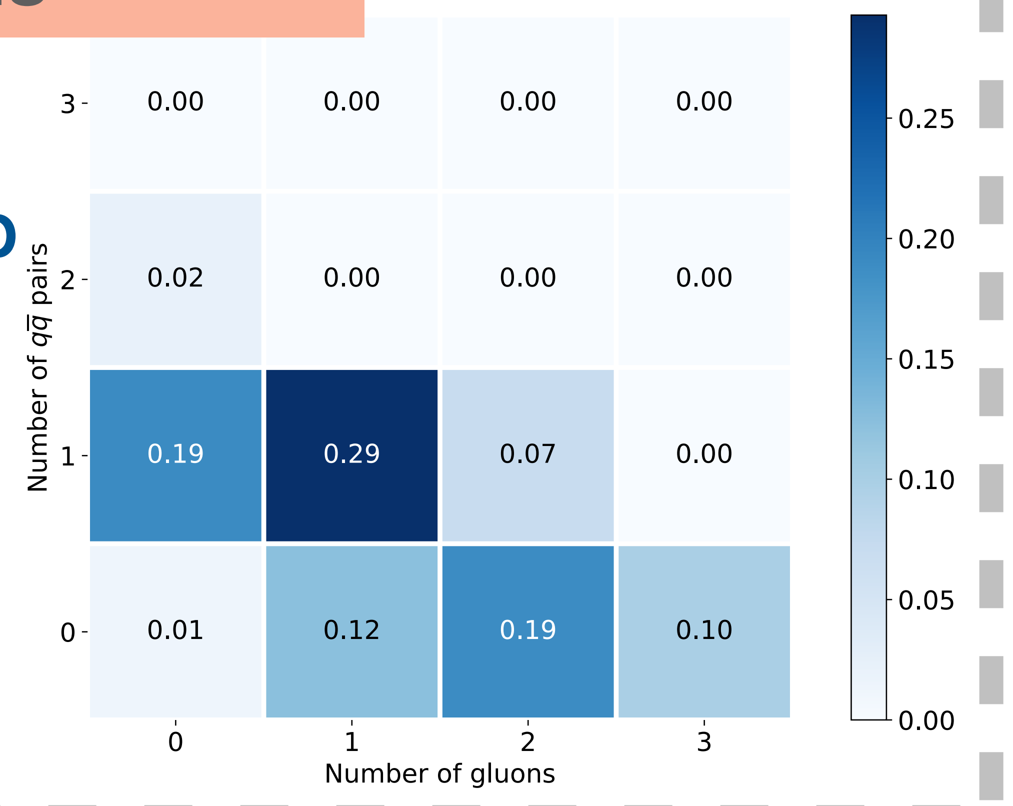
Quantum walk

Nat Rev Phys 4, 744 (2022)



Parton shower = quantum walk in 2 dimensions

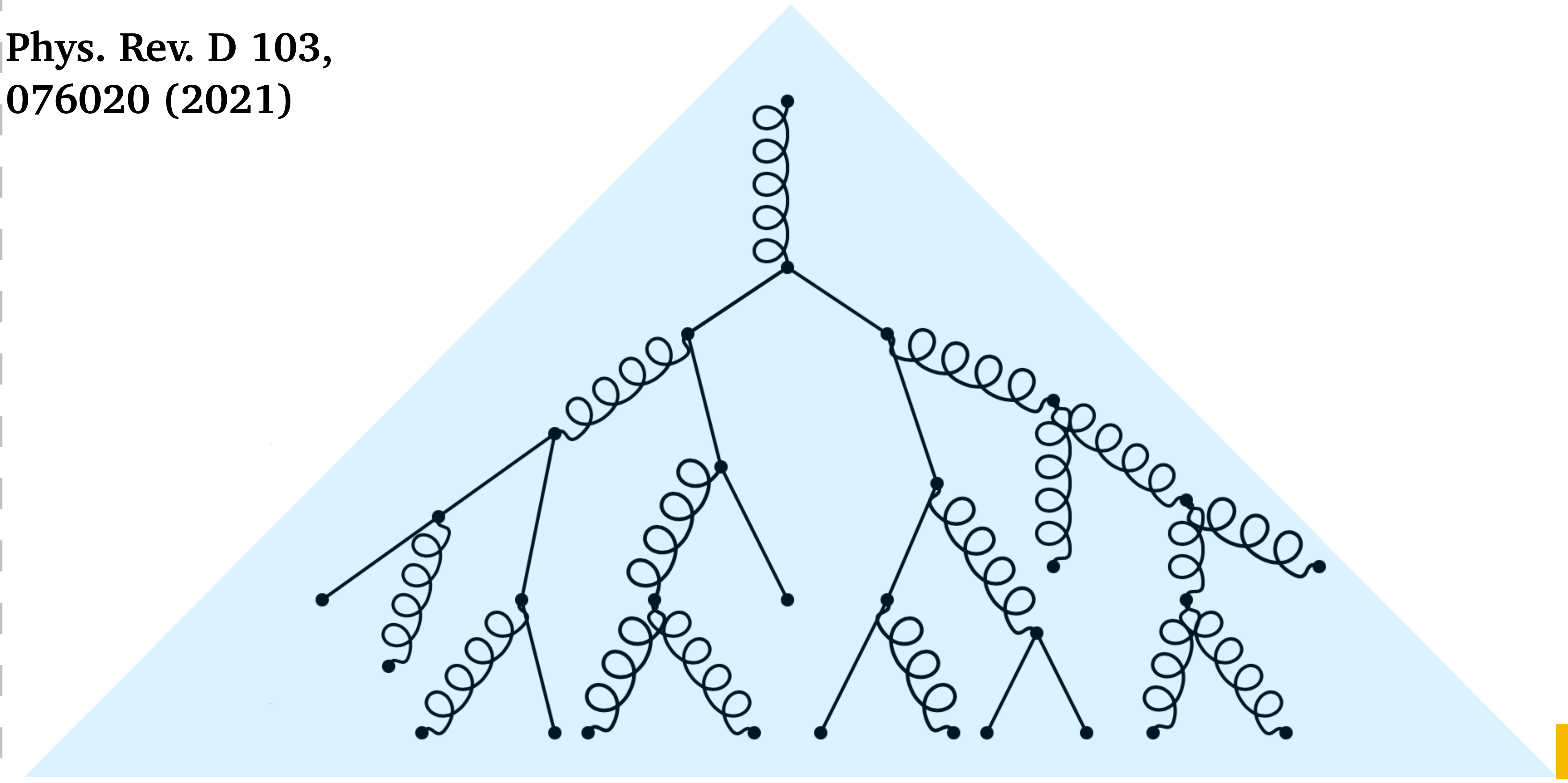
With this approach, simulate 31-step parton shower using 16 qubits



Simulating parton shower

Parton shower

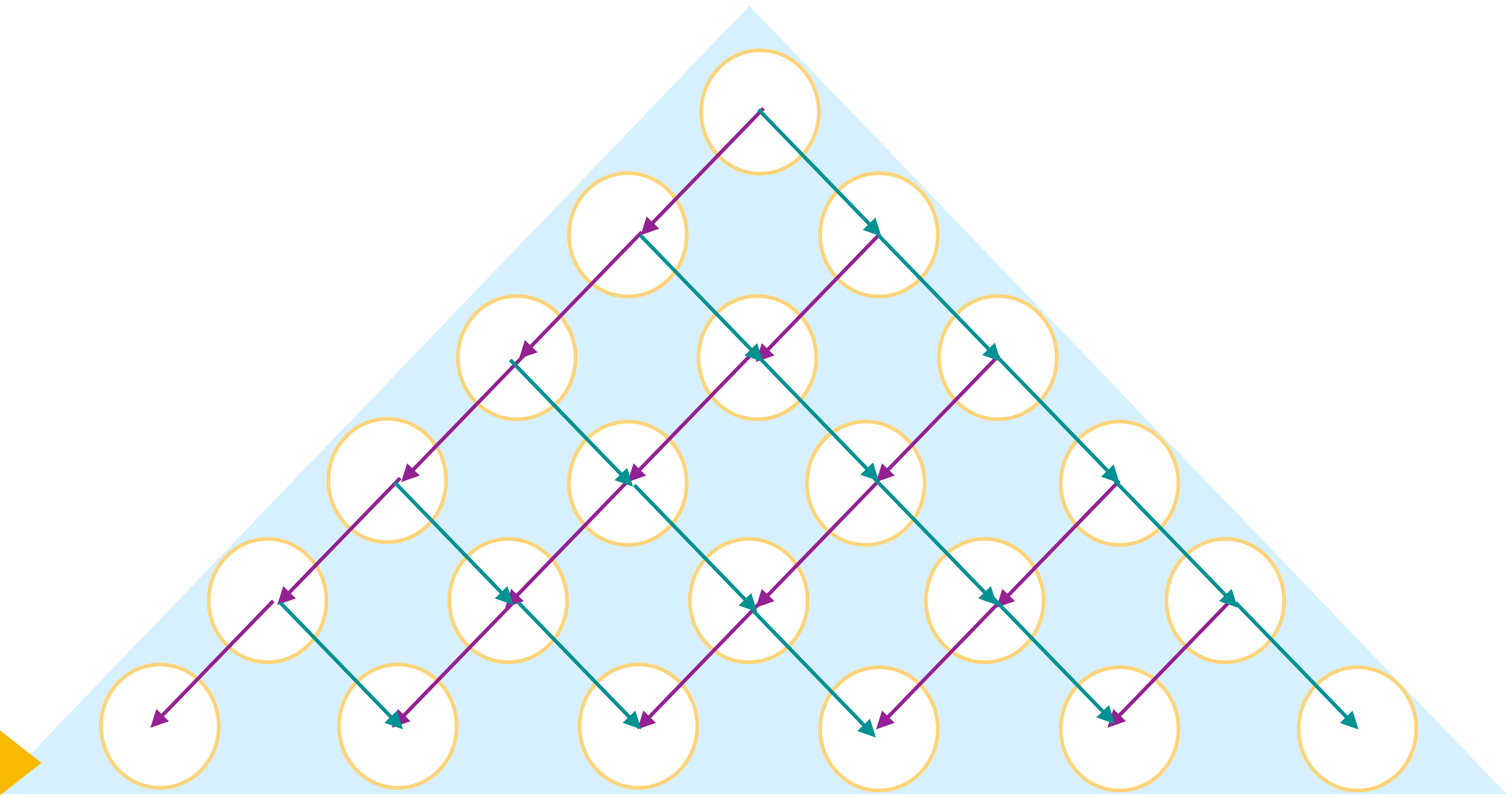
Phys. Rev. D 103, 076020 (2021)



'Translational approach'

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

Quantum walk

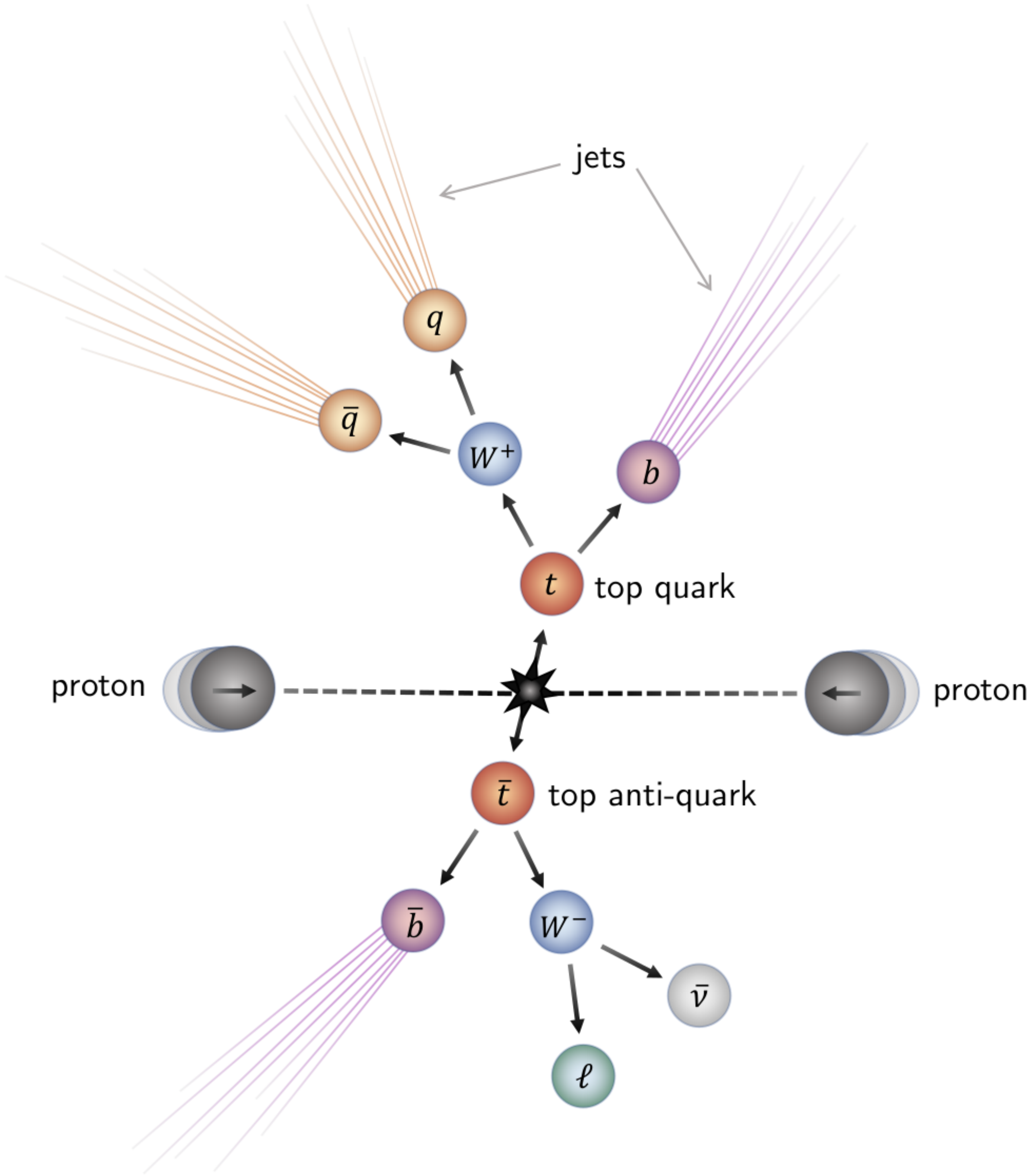


'Quantum-centric approach'

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

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)

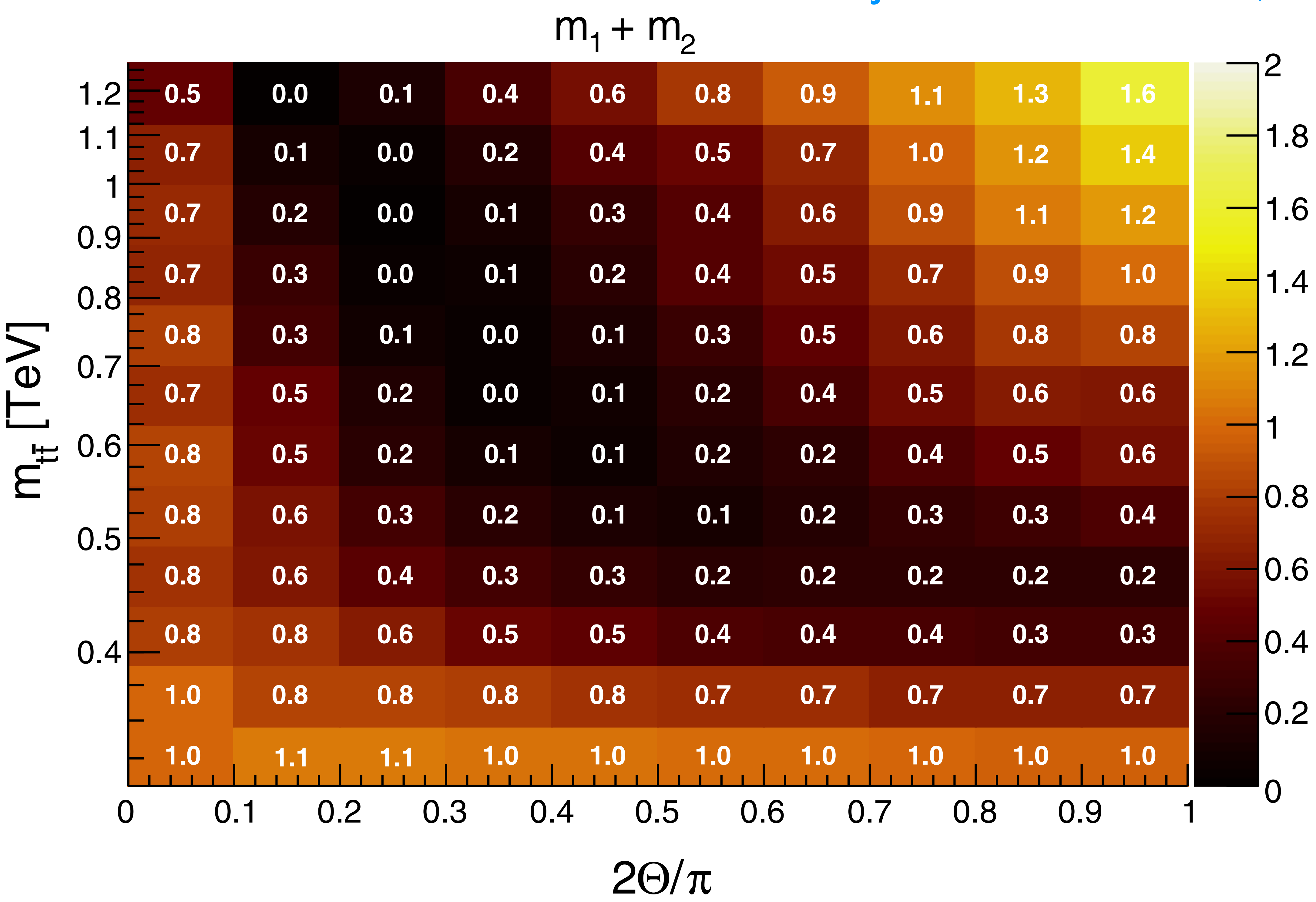
Two regions show m1 +m2 >1:

1. Near threshold

2. High-energy region:

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

Invariant mass



Scattering angle

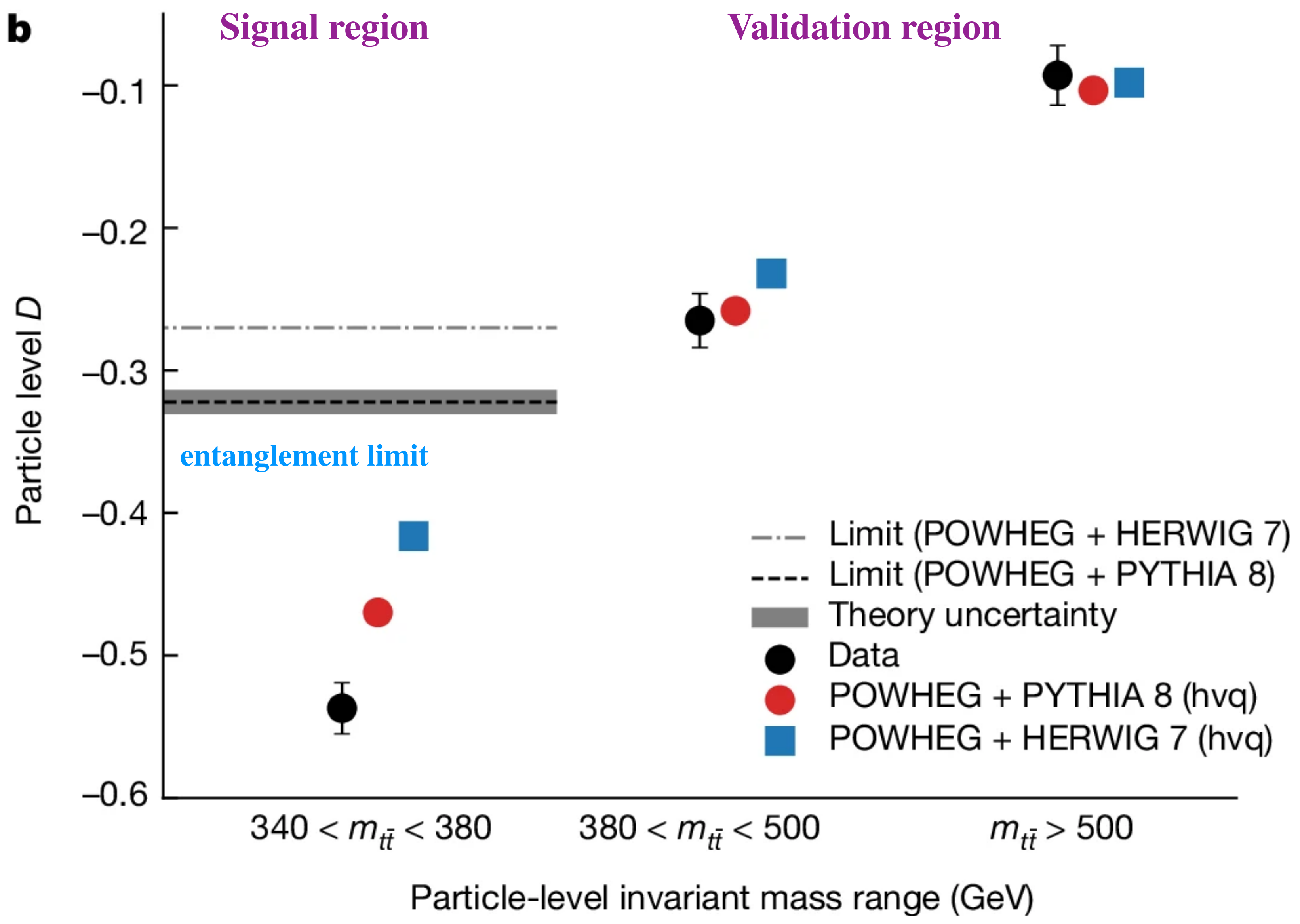
The most robust and unambiguous Bell inequality violation happens at high energies and forward angles, where both production mechanisms (gg and q̄q) align to produce maximally entangled spin states of the top–antitop pair.

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

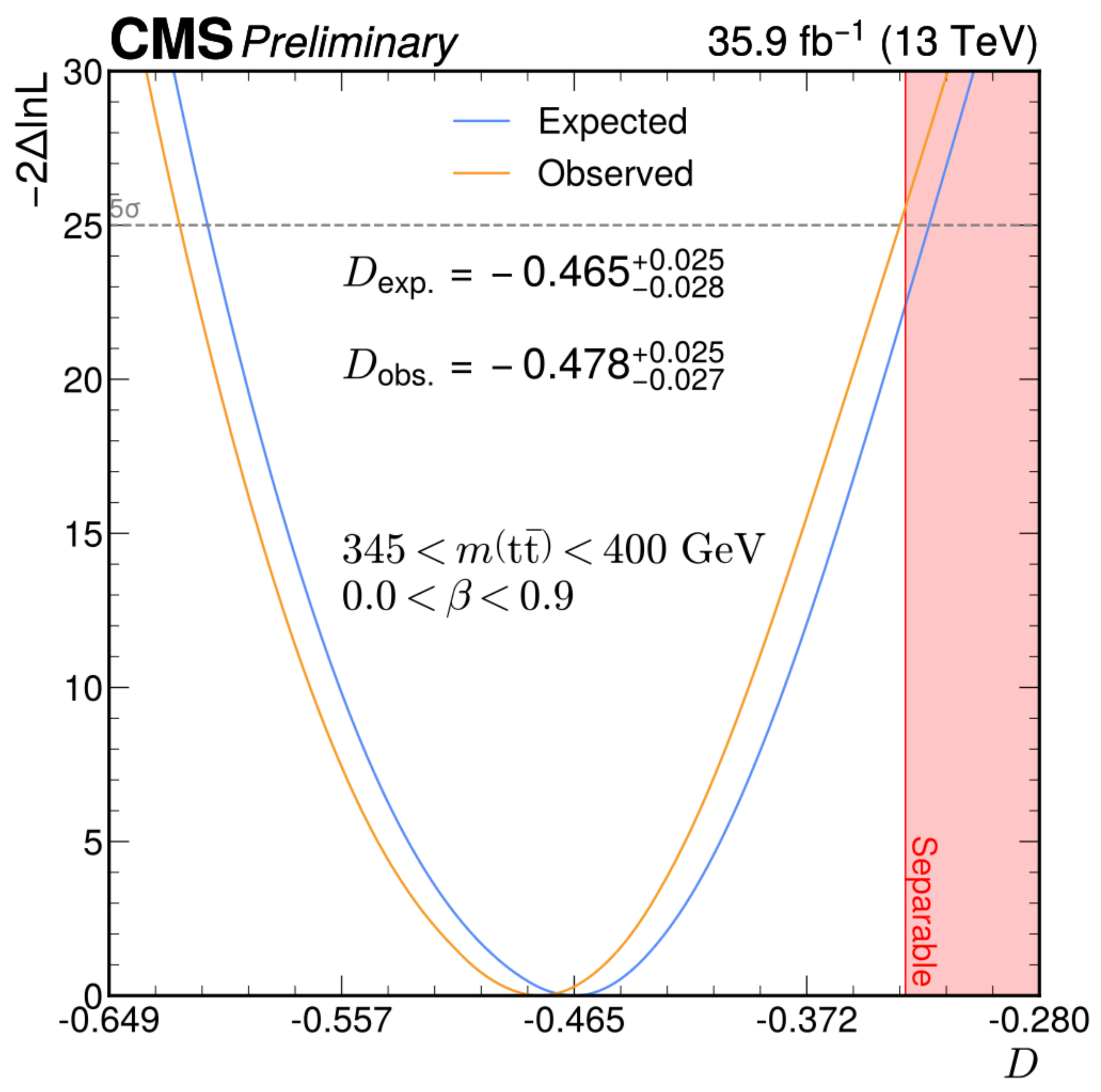
ATLAS



- 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

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

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

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

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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.

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Addressing Local Realism through Bell Tests at Colliders

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

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Department of Physics and Astronomy,
University of Pittsburgh, Pittsburgh, USA

(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

Future directions:

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

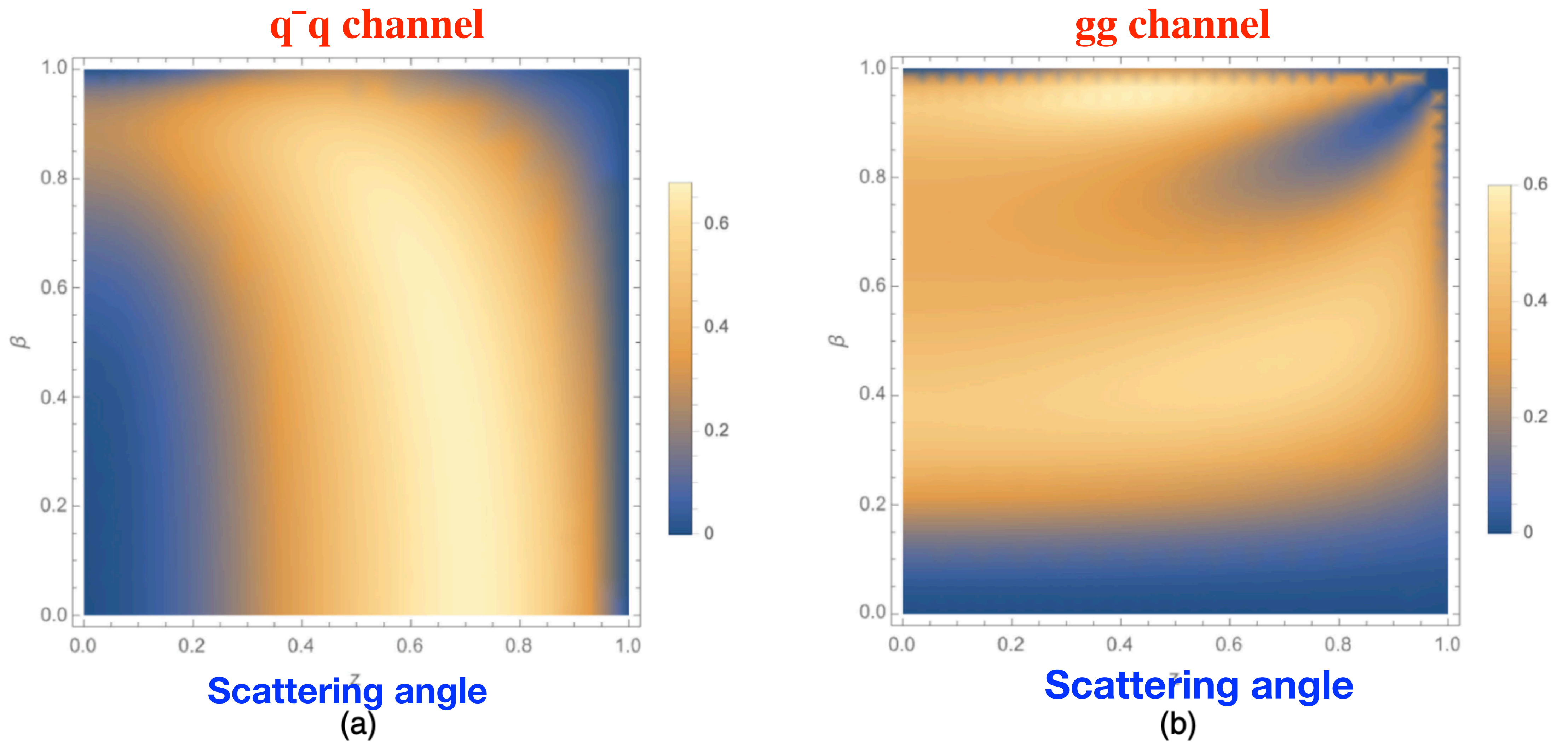


FIG. 3. The magic of a mixed top-antitop final state in (a) the $q\bar{q}$ channel and (b) the gg channel.

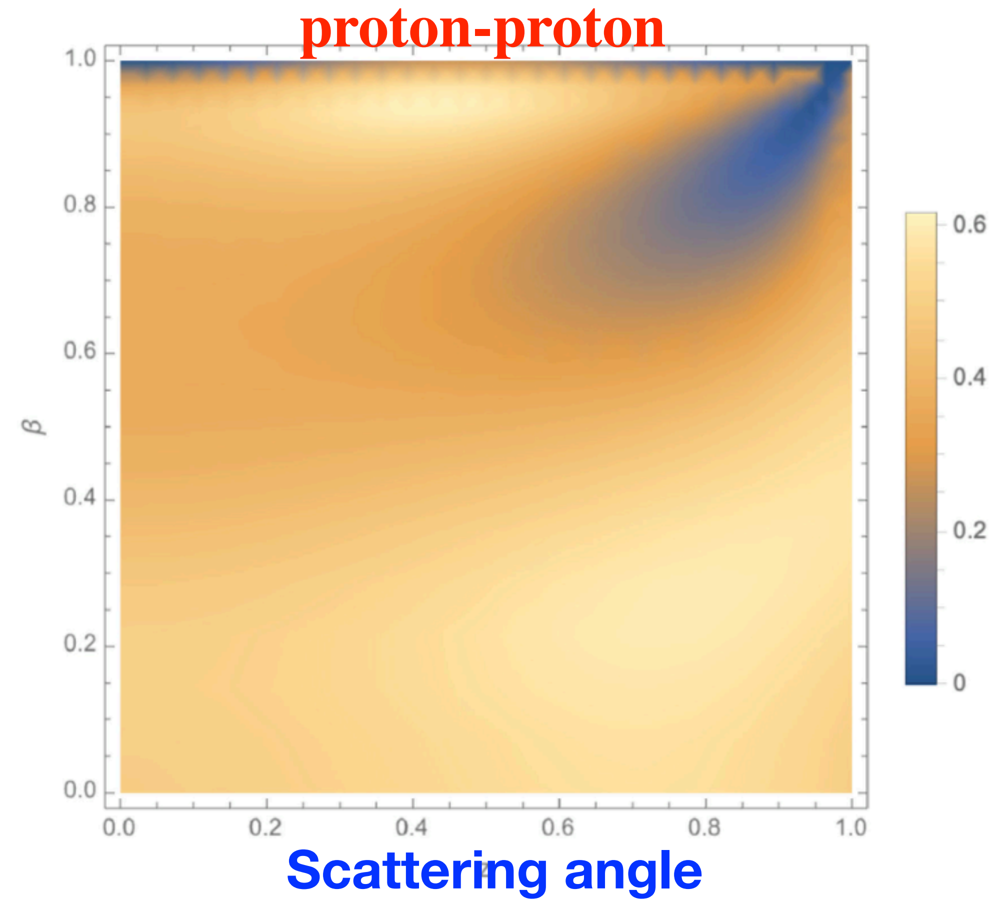


FIG. 4. The magic of a mixed top-antitop final state, for a proton-proton initial state.

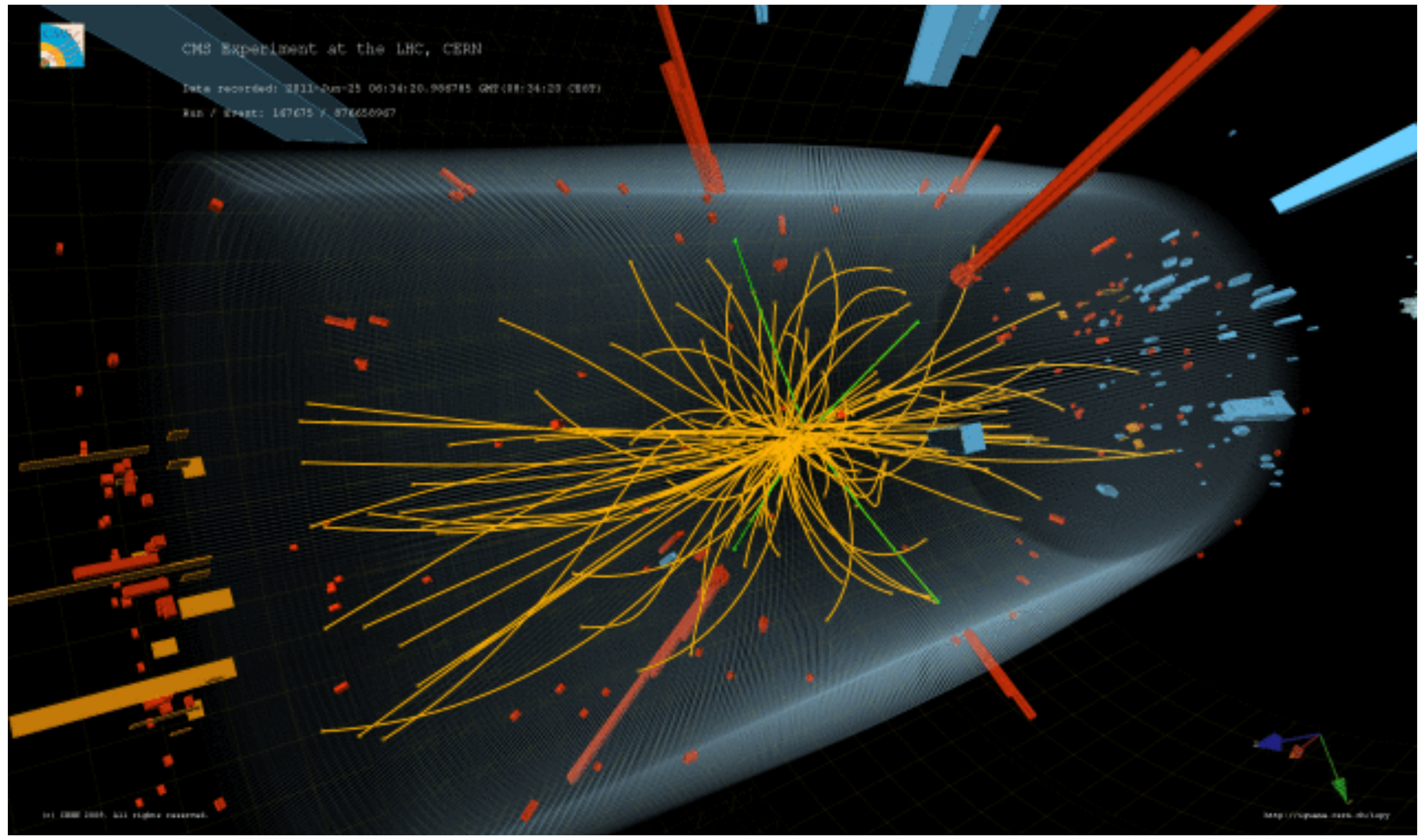
Summary

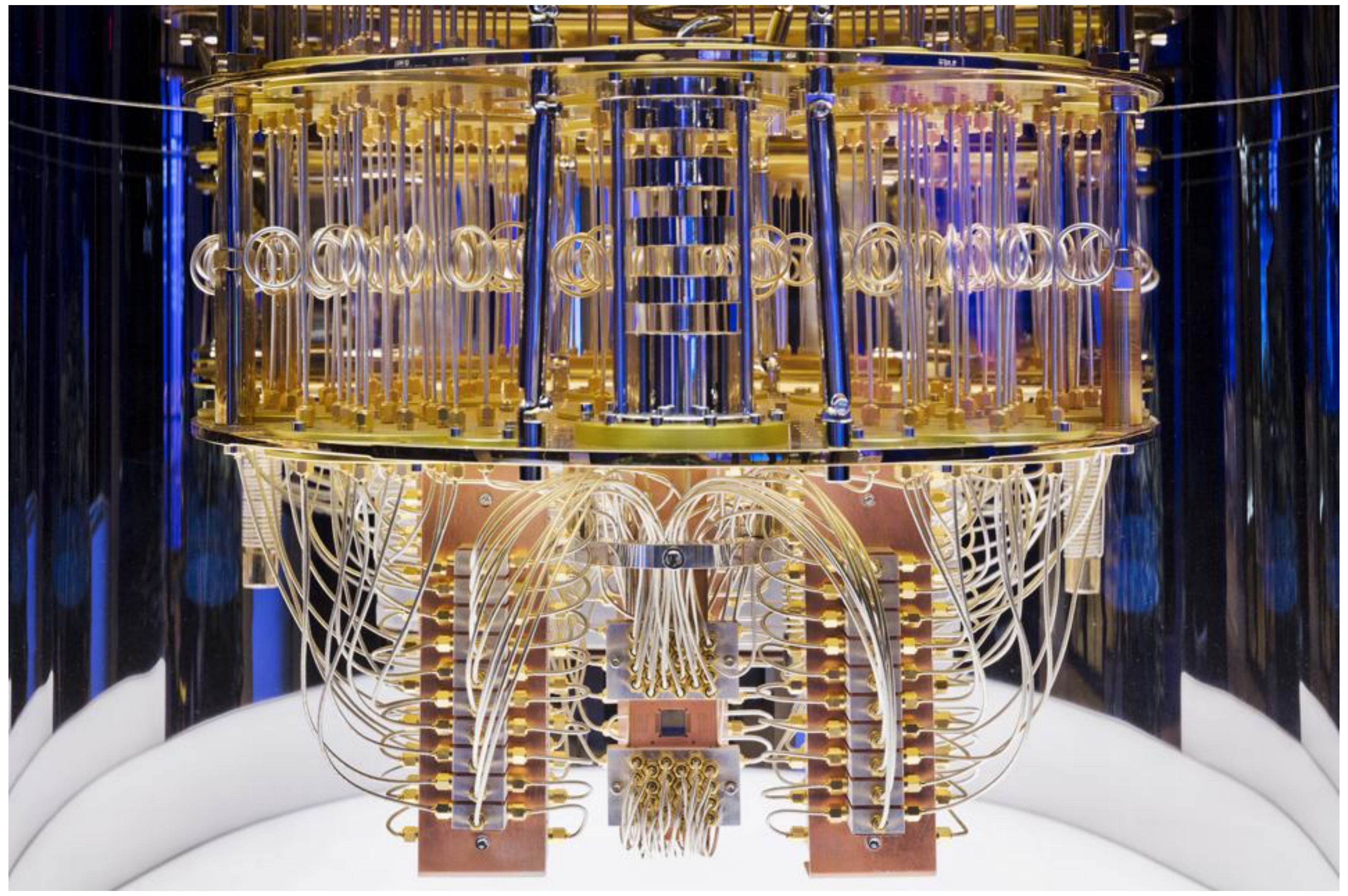
- Quantum machine learning finding various applications across particle physics: event classification, particle identification, clustering algorithms.

- Challenge is to match the right algorithm to the most effective use-case.

- Highlighted the difference between a translational versus quantum-centric approach to applying quantum techniques to HEP problems

- Interesting bidirectional exchange between quantum computing/information and particle physics, using LHC to test the foundations of quantum mechanics.

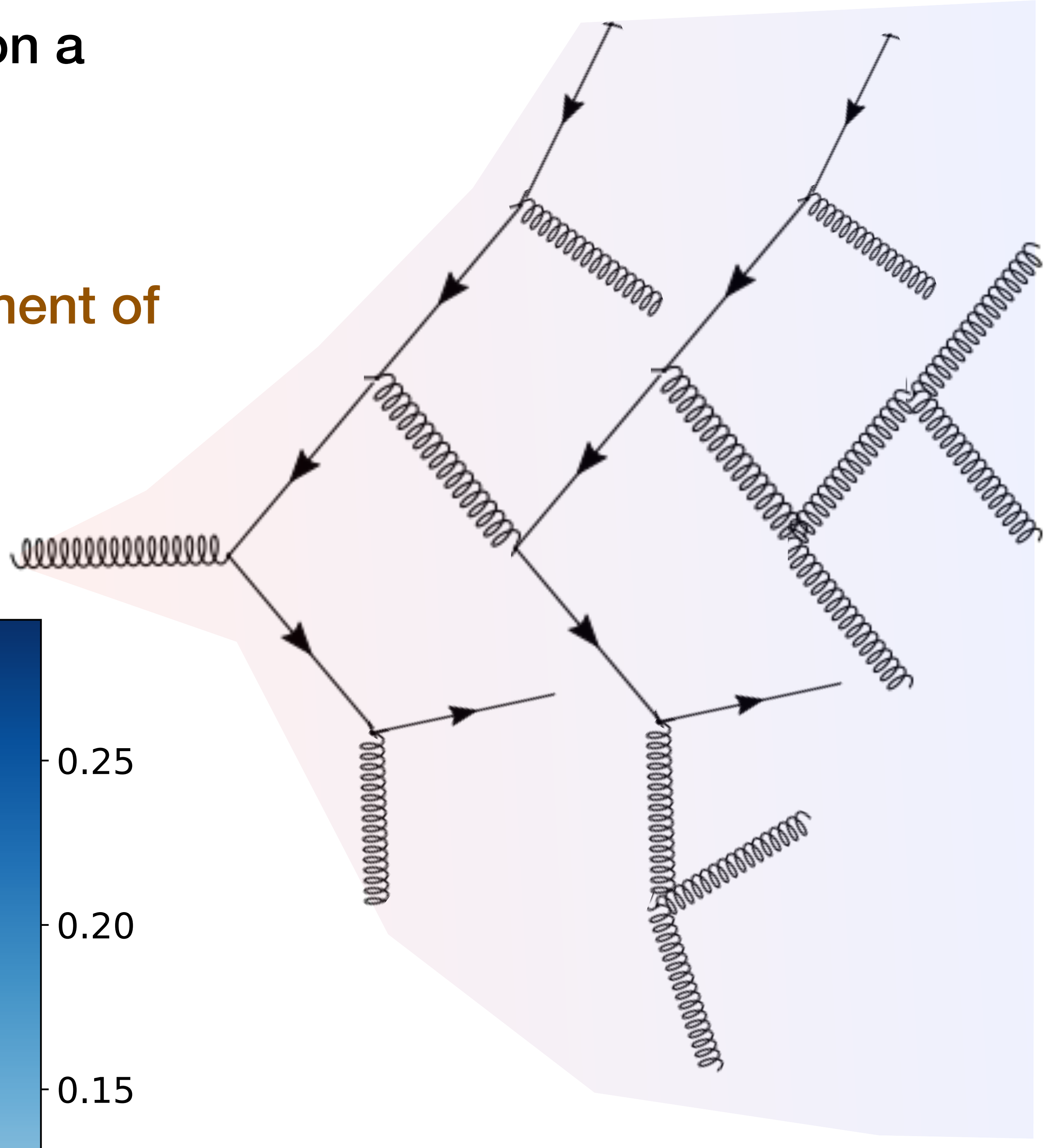




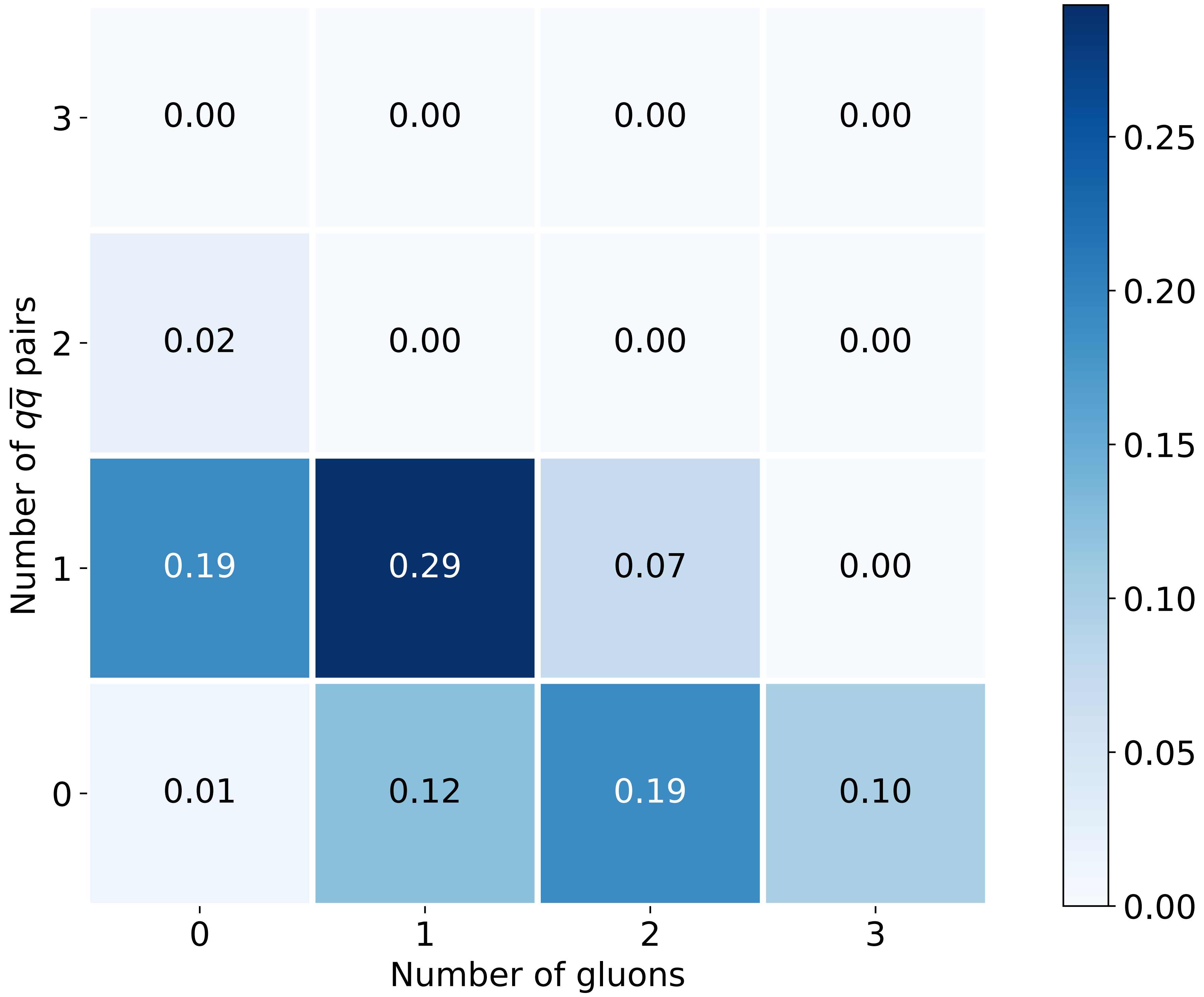
BACKUP

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

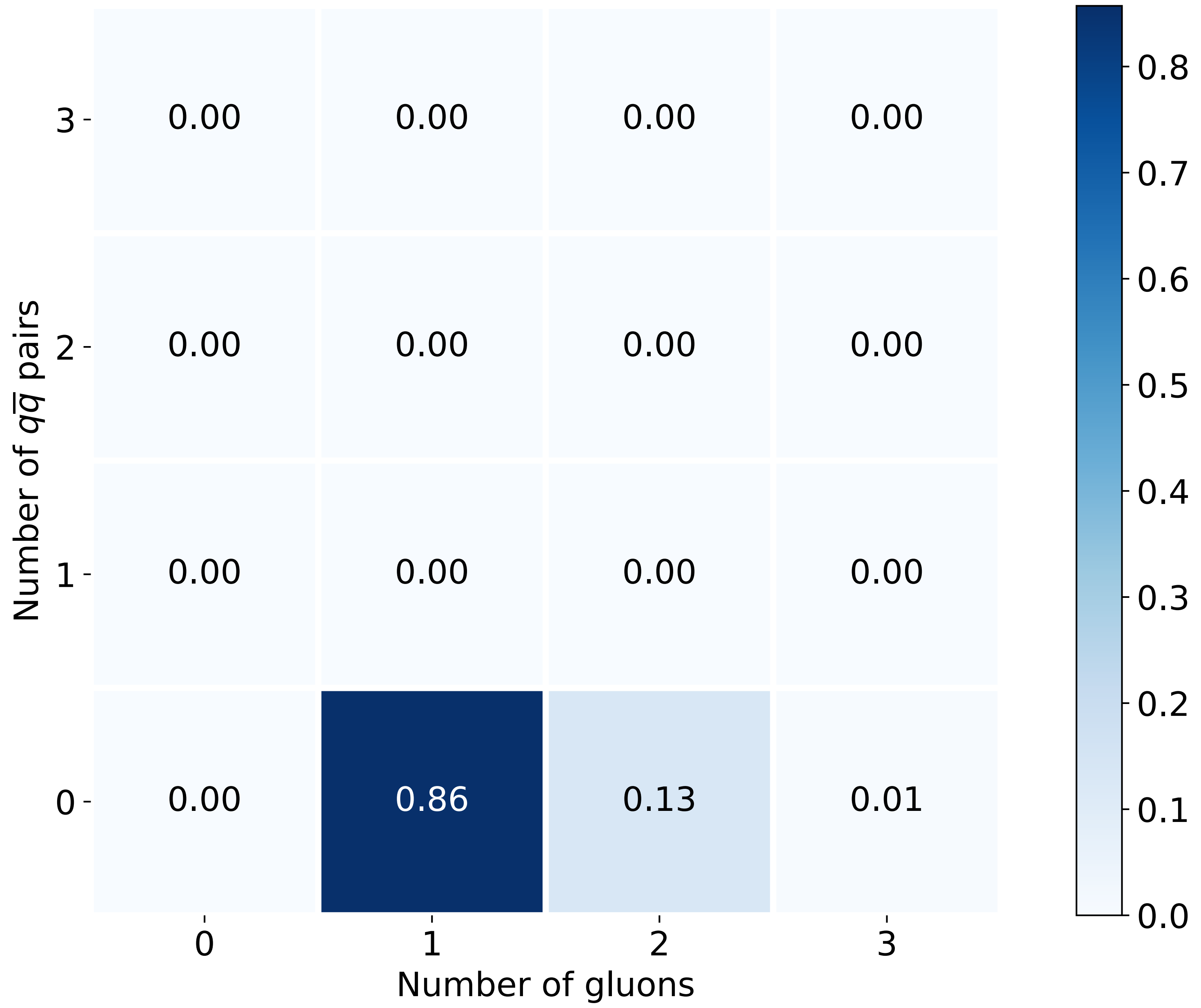


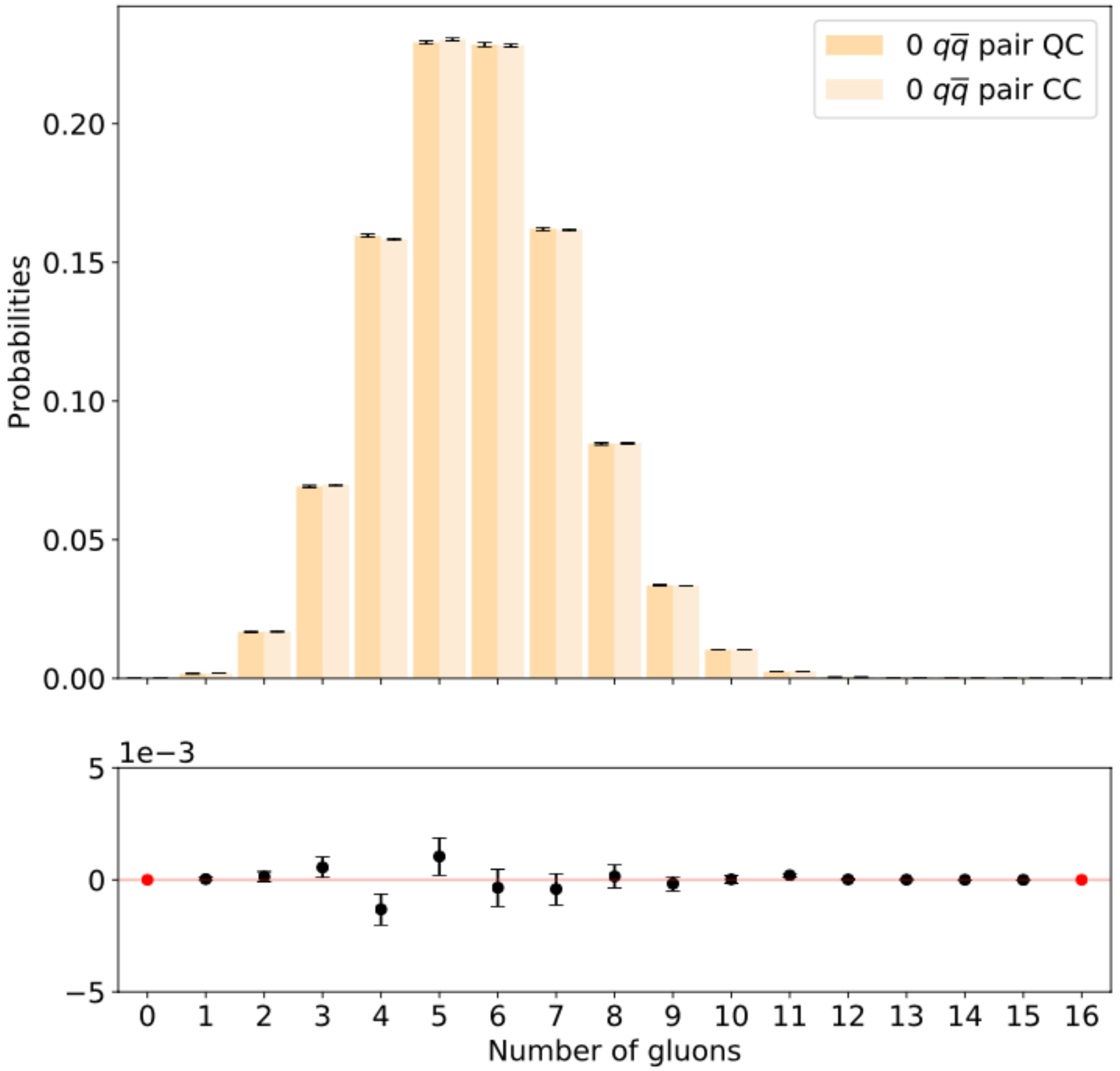
arXiv:2109.13975



Quantum walk approach to simulating parton showers

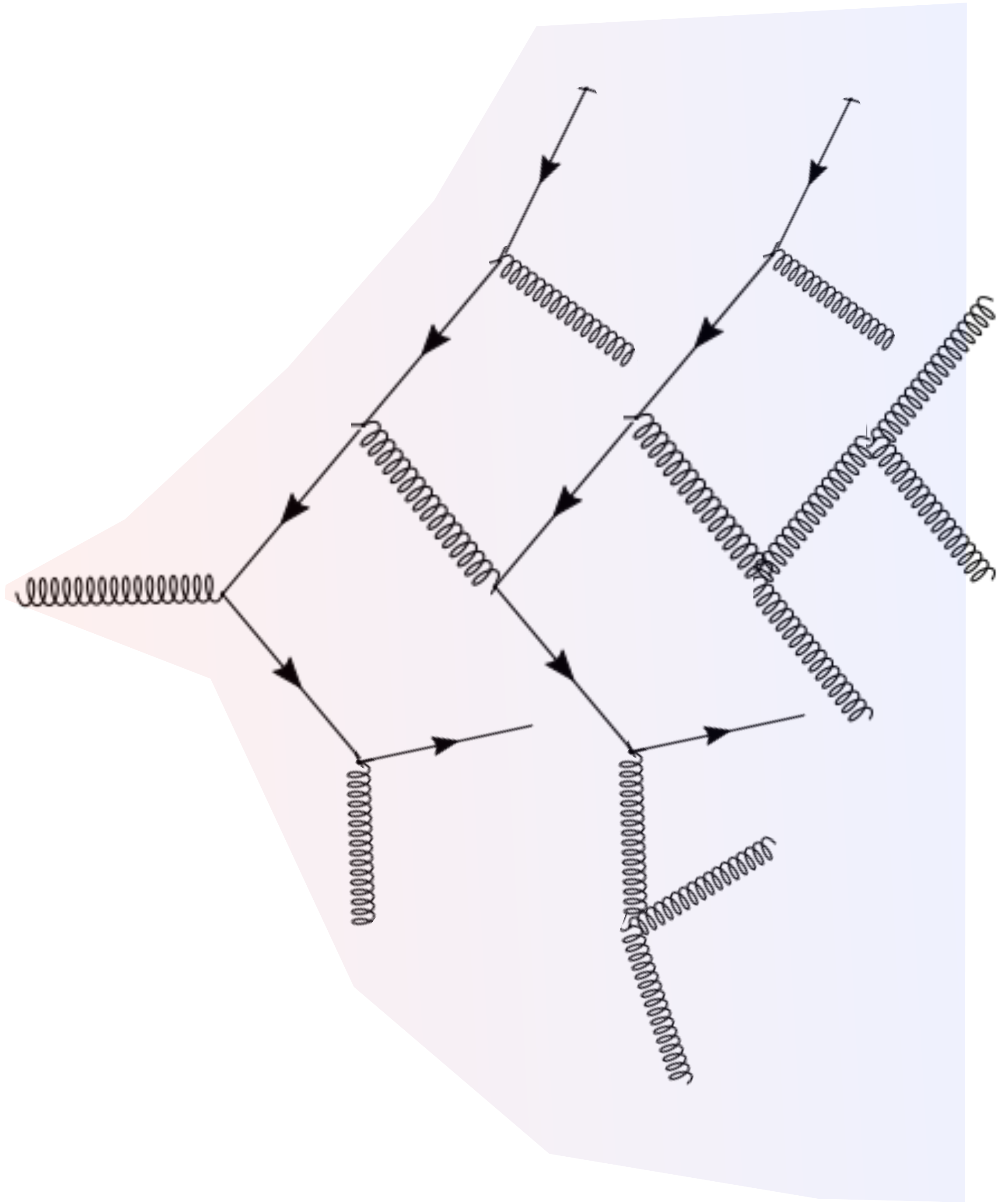
arXiv:2109.13975

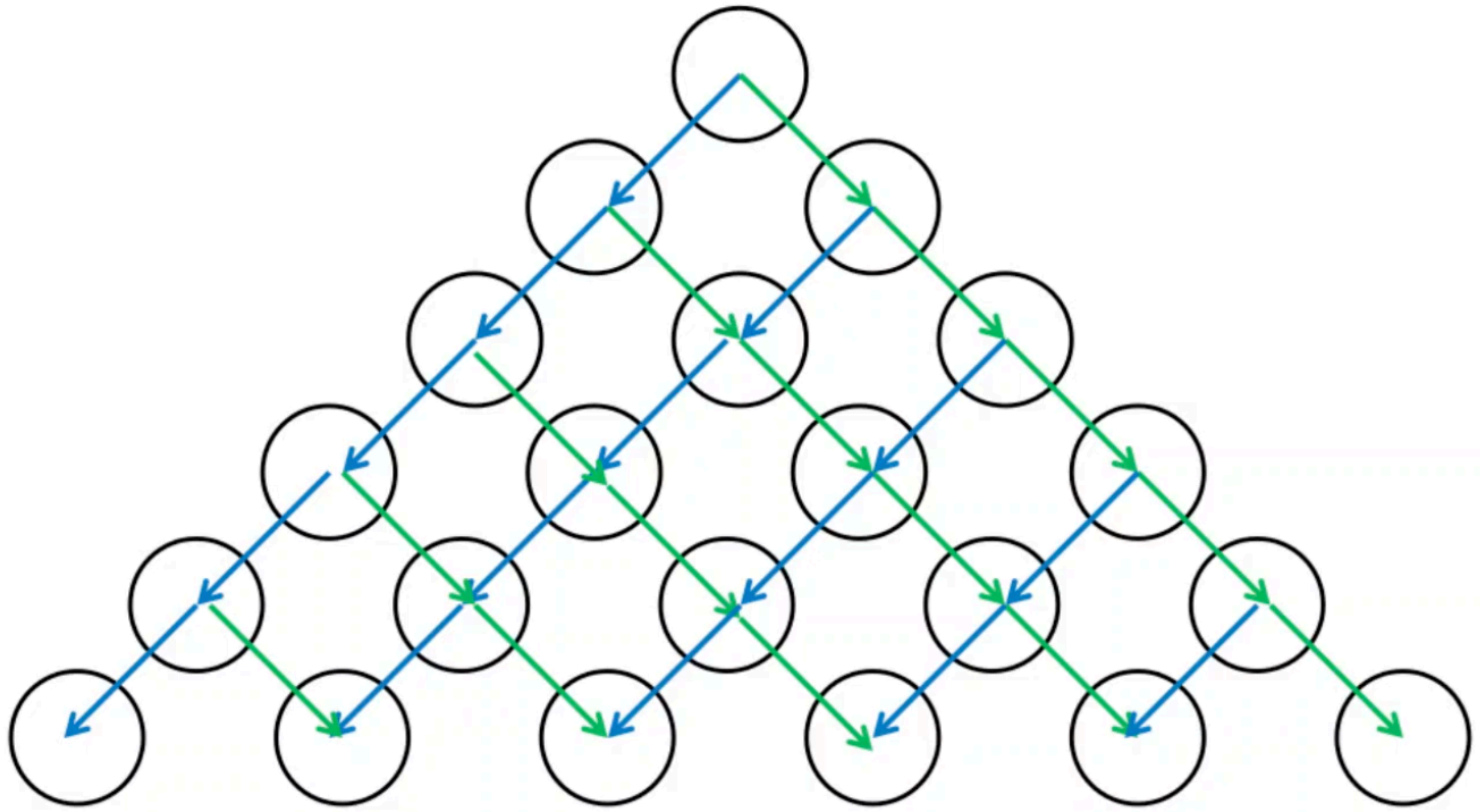




- Quantum walk paradigm thus offers a natural and much more efficient approach to simulating parton showers on quantum devices.
- Proposed algorithm dramatically increases the number of steps that can be simulated compared to previous quantum algorithms (2-step parton shower in previous algorithm)

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.