Collider Events on a Quantum Computer

Simon Williams

First Lund Jet Plane Institute
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Imperial College London

- Quantum Computing - The Power of the Qubit
- Why are we interested in High Energy Physics?
- The Parton Shower
  - Discretising QCD
- Collider Events on a Quantum Computer

G. Gustafson, S. Prestel, M. Spannowsky and S. Williams, Collider Events on a Quantum Computer, JHEP 11 (2022) 035
Quantum Computing - The Power of the Qubit!

“Nature is quantum […] so if you want to simulate it, you need a quantum computer”
- Richard Feynman (1982)

Quantum Computing has had a lot of successes since - most recently with Shor and Deutsch winning the Breakthrough Prize and the 2022 Nobel Prize going to Quantum Information.
Types of Quantum Computing Devices

**Superconductor QCs**

- Single qubit gates: $H$, $X$, $Z$, $H$
- Multi-qubit gates: $U_3$, CNOT

**Advantages:**
- Highly controllable qubits
- Universal computation

**Disadvantages:**
- Small number of qubits, not very fault tolerant

**Qubit model:**

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

**Single qubit gates:**

- $U_3 |0\rangle \rightarrow \cos \frac{\theta}{2} |0\rangle + e^{i\phi} \sin \frac{\theta}{2} |1\rangle$

**Multi-qubit gates:**

- CNOT $|00\rangle \rightarrow |00\rangle$, CNOT $|10\rangle \rightarrow |11\rangle$
- CNOT $|01\rangle \rightarrow |01\rangle$, CNOT $|11\rangle \rightarrow |10\rangle$
Noisy Intermediate-Scale Quantum Devices

**NISQ devices:**

No continuous quantum error correction, prone to large noise effects from environment.

**Quantum errors:**

**Multiqubit qubit gates:** CNOT gates have higher associated errors than single qubit gates.

**SWAP errors:** SWAP operations require 3 CNOT gates.

**T1 times:** The time it takes for an excited qubit to decay back to the ground state.

**Circuit depth!** - Compact circuits needed!

**Transpilation:**

Loading the circuit onto the backend, transpilation can be used to optimise the circuit: *qubit and coupling mapping, noise models, etc.*
Classical Random Walk
Classical Random Walk

Figure 1: One dimensional walker at position $x = 0$ can move either left or right depending on the outcome of the coin flip, $|0\rangle$ and $|1\rangle$ respectively.

Hadamard space. The shift operation is then performed, moving the walker into a superposition of the position states, $x = 1$ and $x = 1$. A measurement after the step collapses the wavefunction to recover the classical case of the walker being in either the $x = 1$ or $x = 1$ position.

The Hadamard coin used here is a balanced unitary coin operation $\dagger$ and therefore the coin and shift operations can be defined as a single unitary transformation to the initial qubit state, $U = S \cdot (C \cdot I)$, (2.3)

which is applied iteratively to represent the number of steps. For a quantum walk of $N$ steps, the propagation of the walker is described by the transformation $U_N$. An example of running an $N = 100$ step one dimensional, linear random walk for both the classical case and the quantum case is shown in Figure 2.

The classical case, shown in Figure 2a, has been achieved by measuring the coin qubit at each step, removing the superposition from the system. As expected, the classical walk yields a Gaussian distribution of positions centred about the initial position of the particle, with the variance $\sigma^2 = N$.

In stark contrast to the classical case, Figure 2b shows the probability distribution of the quantum random walk. It is clear to see the quantum interference between the intermediate steps of the walk process in the distribution. It can be shown $^1$ that the variance of the quantum random walk process goes as $\sigma^2 \ll N^2$. This is a remarkable attribute of the quantum random walker, which propagates quadratically faster through the graph than the classical walker. The average distance of the walker from the initial position is $\langle x \rangle = \sqrt{N}$ and $\ll N$ for the classical and quantum walks respectively.

3 Quantum walk as a parton shower simulation

The quantum walk mechanism provides a natural framework for the simulation of parton showers.

3.1 Theoretical outline of shower algorithm

We present a discrete QCD, collinear parton shower using the quantum walk framework. Similarly to the parton shower algorithms presented in References $^3$, $^4$, the algorithm $^\dagger$ Strictly speaking, the Hadamard coin introduces a bias to the quantum walk through the phase on the coin qubit. This is discussed in detail in $^11$ and references therein. Here we remove this bias by using a symmetric initial state.

$^-$
Classical Random Walk

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The Hadamard coin used here is a balanced unitary coin operation and therefore the coin and shift operations can be defined as a single unitary transformation to the initial qubit state, $U = S \cdot (C \oplus I)$, which is applied iteratively to represent the number of steps. For a quantum walk of $N$ steps, the propagation of the walker is described by the transformation $U_N$.

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In stark contrast to the classical case, Figure 2b shows the probability distribution of the quantum random walk. It is clear to see the quantum interference between the intermediate steps of the walk process in the distribution. It can be shown \cite{11,14} that the variance of the quantum random walk process goes as $\sigma_q^2 \sim N^2$. This is a remarkable attribute of the quantum random walker, which propagates quadratically faster through the graph than the classical walker. The average distance of the walker from the initial position is $\langle x \rangle = \sqrt{N}$ and $\sim N$ for the classical and quantum walks respectively.

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The Quantum Walk

$\sigma^2 = N$

Figure 1: One dimensional walker at position $x = 0$ can move either left or right depending on the outcome of the coin flip, $|0\rangle$ and $|1\rangle$ respectively. H-space. The shift operation is then performed, moving the walker into a superposition of the position states, $x = 1$ and $x = 1$. A measurement after the step collapses the wavefunction to recover the classical case of the walker being in either the $x = 1$ or $x = 1$ position.

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The Quantum Walk

\[ \sigma^2_c = N \]

\[ \mathcal{H}_P = \{ |i\rangle : i \in \mathbb{Z} \} \]
\[ \mathcal{H}_C = \{ |0\rangle, |1\rangle \} \]
\[ \mathcal{H} = \mathcal{H}_C \otimes \mathcal{H}_P \]

Figure 1: One dimensional walker at position \( x = 0 \) can move either left or right depending on the outcome of the coin flip, \( |0\rangle \) and \( |1\rangle \) respectively.

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The Quantum Walk

\[ |0\rangle \quad |1\rangle \]

\[ x = -2 \quad x = -1 \quad x = 0 \quad x = 1 \quad x = 2 \]

\[ \mathcal{H}_P = \{ |i\rangle : i \in \mathbb{Z} \} \]
\[ \mathcal{H}_C = \{ |0\rangle, |1\rangle \} \]
\[ \mathcal{H} = \mathcal{H}_C \otimes \mathcal{H}_P \]

Unitary Transformation:
\[ U = S \cdot (C \otimes I) \]

\[ \sigma_c^2 = N \]
The Quantum Walk

\[ \sigma_c^2 = N \]

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The Quantum Walk

\[\sigma_q^2 \sim N^2\]
\[\sigma_c^2 = N\]

Unitary Transformation:
\[U = S \cdot (C \otimes I)\]

**Figure 1**: One dimensional walker at position \(x = 0\) can move either left or right depending on the outcome of the coin flip, \(|i\rangle\) and \(|'i\rangle\) respectively. The shift operation is then performed, moving the walker into a superposition of the position states, \(x = 1\) and \(x = 2\). A measurement after the step collapses the wavefunction to recover the classical case of the walker being in either the \(x = 1\) or \(x = 1\) position.

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Speed up via Quantum Walks

Quantum Walks have long been conjectured to achieve at least **quadratic speed up**.

Szegedy Quantum Walks have been proven to achieve quadratic speed up for **Markov Chain Monte Carlo**.

This has been proven under the condition that the MCMC algorithm is **reversible and ergodic**.

Work is ongoing to prove this is true for all QWs, but latest upper limits are on par with classical RW.
Quantum Walks with Memory

### Advantages:
- Arbitrary dynamics
- Classical dynamics in unitary evolution

### Disadvantages:
- Tight conditions on quantum advantage

### Qubit model:
Augment system further by adding an additional memory space

\[ \mathcal{H} = \mathcal{H}_C \otimes \mathcal{H}_P \otimes \mathcal{H}_M \]

### Quantum Parton Showers:
Quantum Walks with memory have proven to be very useful for quantum parton showers.

The Power of the Qubit! - Why are we interested in HEP?
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Parton Density Functions

Phys. Rev. D 103, 034027
The Power of the Qubit! - Why are we interested in HEP?

Parton Density Functions

Hard Process

Phys. Rev. D 103, 034027

Phys. Rev. D 103, 076020
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Hadronisation

JHEP 11 (2022) 035
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Parton Density Functions

Phys. Rev. D 103, 076020
Phys. Rev. D 106, 056002
Parton Shower

Phys. Rev. Lett. 126, 062001

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Phys. Rev. D 103, 076020

Phys. Rev. D 106, 056002

Phys. Rev. Lett. 126, 062001

Parton Shower

JHEP 11 (2022) 035
The Parton Shower

**Collinear mode:**
\[ k \rightarrow \overrightarrow{P} \rightarrow i \rightarrow j \quad p_i = zP, \quad p_j = (1 - z)P \]

Successive decay steps factorise into independent quasi-classical steps

**Soft mode:**
\[ p_i \approx 0 \]

Interference effects only allow for partial factorisation

Leading contributions to the decay rate in the collinear limit are included in the soft limit

In this limit, the decay from high energy to low energy proceeds as a **colour-dipole cascade**.

This interpretation allows for straightforward interference patterns and momentum conservation
The Parton Shower - The Veto Algorithm

The choice of the variables \( \xi \) and \( t \) is known as the **phase space parameterisation**

\[
\mathcal{F}_n(\Phi_n, t_n, t_c; O) = \Delta(t_n, t_c) O(\Phi_n)
+ \int_{t_c}^{t_n} dt d\xi \frac{d\phi}{2\pi} C \frac{\alpha_s}{2\pi} \frac{s_{ik}(t, \xi)}{s_{ij}(t, \xi) s_{jk}(t, \xi)} \Delta(t_n, t) \mathcal{F}_n(\Phi_{n+1}, t, t_c; O)
\]

**Master Equation**

**Non-Emission Probability**

\[
\Delta(t_n, t) = \exp \left( - \int_{t}^{t_n} dt d\xi \frac{d\phi}{2\pi} C \frac{\alpha_s}{2\pi} \frac{2s_{ik}(t, \xi)}{s_{ij}(t, \xi) s_{jk}(t, \xi)} \right)
\]

**Inclusive Decay Probability**

\[
dP(q(p_1)\bar{q}(p_K) \rightarrow q(p_i) g(p_j) \bar{q}(p_k)) \approx \frac{ds_{ij} ds_{jk}}{s_{IK} s_{IK}} C \frac{\alpha_s}{2\pi} \frac{2s_{IK}}{s_{ij} s_{jk}}
\]

Current interpretations of the veto algorithm treat the phase space variables \( \xi \) and \( t \) as **continuous**

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Collider Events on a Quantum Computer

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Institute for Particle Physics Phenomenology, Department of Physics, Durham University, Durham DH1 3LE, U.K.
High Energy Physics Group, Blackett Laboratory, Imperial College, Prince Consort Road, London, SW7 2AZ, United Kingdom

Abstract: High-quality simulated data is crucial for particle physics discoveries. Therefore, Parton shower algorithms are a major building block of the data synthesis in event generator programs. However, the core algorithms used to generate parton showers have barely changed since the 1980s. With quantum computers’ rapid and continuous development, dedicated algorithms are required to exploit the potential that quantum computers provide to address problems in high-energy physics. This paper presents a novel approach to synthesising parton showers using the Discrete QCD method. The algorithm benefits from an elegant quantum walk implementation which can be embedded into the classical toolchain. We use the ibm_aligers device to sample parton shower configurations and generate data that we compare against measurements taken at the ALEPH, DELPHI and OPAL experiments. This is the first time a Noisy Intermediate-Scale Quantum (NISQ) device has been used to simulate realistic high-energy particle collision events.

Parameterise phase space in terms of gluon transverse momentum and rapidity:

\[ k_\perp^2 = \frac{s_{ij}s_{jk}}{s_{IK}} \quad \text{and} \quad y = \frac{1}{2} \ln \left( \frac{s_{ij}}{s_{jk}} \right) \]

which leads to the inclusive probability:

\[ dP(q(p_i)\bar{q}(p_K) \rightarrow q(p_i)g(p_j)\bar{q}(p_k)) \simeq \frac{C\alpha_s}{\pi} d\kappa dy \]

where \( \kappa = \ln \left( \frac{k_\perp^2}{\Lambda^2} \right) \) and \( \Lambda \) is an arbitrary mass scale.

Due to the colour charge of emitted gluons, the rapidity span for subsequent dipole decays is increased. This is interpreted as “folding out”.

---

Discrete QCD - Abstracting the Parton Shower Method
2. Neglect $g \rightarrow q\bar{q}$ splittings and examine transverse-momentum-dependent running coupling

$$\alpha_s(k_\perp^2) = \frac{12\pi}{33 - 2n_f} \frac{1}{\ln(k_\perp^2/\Lambda_{QCD}^2)}$$

leads to the inclusive probability

$$dP(q(p_1)q(p_3) \rightarrow q(p_i)g(p_j)g(p_\ell)) \simeq \frac{d\kappa}{\kappa dy_g} \text{ with } \delta y_g = \frac{11}{6}$$

Interpreting the running coupling renormalisation group as a gain-loss equation:

**Gluons within $\delta y_g$ act coherently as one effective gluon**
Discrete QCD - Abstracting the Parton Shower Method

2. Neglect $g \rightarrow q\bar{q}$ splittings and examine transverse-momentum-dependent running coupling

$$\alpha_s(k_{-1}^2) = \frac{12\pi}{33 - 2n_f} \frac{1}{\ln(k_{-1}^2/\Lambda_{QCD}^2)} \text{ const.}$$

leads to the inclusive probability

$$dP(q(p_1)\bar{q}(p_2) \rightarrow q(p_4)g(p_j)\bar{q}(p_k)) \simeq \frac{d\kappa}{\kappa} \frac{dy}{\delta y_g} \quad \text{with} \quad \delta y_g = \frac{11}{6}$$

Interpreting the running coupling renormalisation group as a gain-loss equation:

Gluons within $\delta y_g$ act coherently as one effective gluon
Discrete QCD - Abstracting the Parton Shower Method

**Folding out** extends the baseline of the triangle to positive \( y \) by \( \frac{l}{2} \), where \( l \) is the height at which to emit effective gluons.

A consequence of folding is that the \( \kappa \) axis is quantised into multiples of \( 2\delta y_g \).

Each rapidity slice can be treated independently of any other slice. The exclusive rate probability takes the simple form:

\[
\frac{d\kappa}{\kappa} \exp \left( - \int_{\kappa}^{\kappa_{\text{max}}} \frac{d\kappa}{k} \right) = \frac{d\kappa}{\kappa_{\text{max}}}
\]
Discrete QCD as a Quantum Walk

The baseline of the grove structure contains all kinematics information.

For LEP data there are 24 unique grove structures for $\Lambda_{\text{QCD}} \in [0.1,1]$ GeV.

The Discrete-QCD dipole cascade can therefore be implemented as a simple Quantum Walk.

The baseline of the grove structure contains all kinematics information.

For LEP data there are 24 unique grove structures for $\Lambda_{\text{QCD}} \in [0.1,1]$ GeV.

The Discrete-QCD dipole cascade can therefore be implemented as a simple Quantum Walk.

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Generating Scattering Events from Groves

Once the grove structure has been selected, event data can be synthesised in the following steps using the baseline:

1. Create the highest $\kappa$ effective gluons first (i.e. go from top to bottom in phase space)

2. For each effective gluon $j$ that has been emitted from a dipole $IK$, read off the values $s_{ij}$, $s_{jk}$ and $s_{IK}$ from the grove

3. Generate a uniformly distributed azimuthal decay angle $\phi$, and then employ momentum mapping (here we have used Phys. Rev. D 85, 014013 (2012), 1108.6172) to produce post-branching momenta

The algorithm has been run on both the ibm_qasm_simulator and the ibm_algiers 27 qubit device. A like-for-like classical implementation has been used as a comparison.
The algorithm has been run on the IBM Falcon 5.11r chip.

The figure shows the uncorrected performance of the `ibm_algiers` device compared to a simulator.

The 24 grove structures are generated for a $E_{CM} = 91.2$ GeV, corresponding to typical collisions at LEP.

Main source of error from CNOT errors from large amount of SWAPs.
Collider Events on a Quantum Computer

Thrust ($E_{CMS} = 91.2$ GeV)

Differential 2-jet rate with Durham algorithm (91.2 GeV)

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ALEPH data (EPJC 35 (2004) 457ff)
DQCD shower
QUANTUM shower (ibm_algiers)
High Energy Physics is on the edge of a computational frontier, the High Luminosity Large Hadron Collider and FCC will provide unprecedented amounts of data.

Quantum Computing offers an impressive and powerful tool to combat computational bottlenecks, both for theoretical and experimental purposes.

The first realistic simulation of a high energy collision has been presented using a compact quantum walk implementation, allowing for the algorithm to be run on a NISQ device.

Future Work: A dedicated research effort is required to fully evaluate the potential of quantum computing applications in HEP.
Backup Slides

Simon Williams

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5th July 2023
Discrete QCD - Grove Structures

(A)  

(B)  

(C)  

(D)  

(E)  

(F)  

(G)  

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(J)  

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(S)  

(T)  

(U)  

(V)  

(W)  

(X)
Collider Events on a Quantum Computer

Energy-energy correlation, EEC

Jet mass difference ($E_{CMS} = 91.2$ GeV)
Collider Events on a Quantum Computer - Varying $\Lambda$

Varying values for the mass scale $\Lambda$. This leads to non-negligible uncertainties, however this is expected from a leading logarithm model.
Varying values for the mass scale $\Lambda$. This leads to non-negligible uncertainties, however this is expected from a leading logarithm model.
Collider Events on a Quantum Computer

Thrust ($E_{CMS} = 91.2$ GeV)

- ALEPH data (EPJC 35 (2004) 457ff)
- QUANTUM shower (ibm_algiers)
- DqCD, Λ variation
- DqCD, tune variation

Differential 2-jet rate with Durham algorithm (91.2 GeV)

- OPAL data (EPJC 17 (2000) 19ff)
- QUANTUM shower (ibm_algiers)
- DqCD, Λ variation
- DqCD, tune variation
Collider Events on a Quantum Computer - Changing tune

Observables dominated by non-perturbative dynamics show mild dependence on the mass scale $\Lambda$, but are highly sensitive to changes in the tune.
Collider Events on a Quantum Computer

\[ \kappa = \ln(k_s^2/\Lambda^2) \]

\[ \ell/2 = n \delta y_g \]