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Simon Williams

Milan Joint Phenomenology Seminars - 23rd January

Simulating high energy collision events on a Quantum Computer

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- 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, [arXiv:2207.10694](https://arxiv.org/abs/2207.10694)

Quantum Computing - The Power of the Qubit! *g*

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

Types of Quantum Device: *p H U |*0i *H* $|0\rangle$ *H* **H** \longrightarrow *H H* $|0\rangle$ *H H* Z *H* H $|0\rangle$ $|0\rangle$ Thermal Jump Gate Quantum Computing

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

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*n Count |*0i

*e Emission |*0i

*h History |*0i

Configuration

Quantum

*p*1 . . . Quantum Annealing

Photonic Devices

Cost **Tunnelling**

Types of Quantum Computing Devices

Quantum Annealing Photonic Quantum Devices

Type of gate quantum computing, manipulating photon states

Advantages:

- Continuous variable devices
- Only weak interactions with environment

Disadvantages:

- All states must be Gaussian

Advantages:

- Well suited to optimisation problems

Disadvantages:

- Uncontrollable, noisy devices
- Not universal devices

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Types of Quantum Computing Devices *g p H U*

*p*0

- .
.
. .
. . - Highly controllable qubits
- Universal computation

- Small number of qubits, not very fault tolerant

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*e Emission |*0i **Disadvantages:**

Advantages:

Single qubit gates:

Multi-qubit gates:

 $CNOT|00\rangle \rightarrow |00\rangle, CNOT|10\rangle \rightarrow |11\rangle,$ $\text{CNOT} |01\rangle \rightarrow |01\rangle, \text{CNOT} |11\rangle \rightarrow |10\rangle$

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Simon Williams - s.williams | 9@imperial.ac.uk 6 Milan - 23/1/23 which is applied iteratively to represent the number of steps. For a quantum walk of *N*

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which is applied iteratively to represent the number of steps. For a quantum walk of *N*

wavefunction to recover the classical case of the walker being in either the *x* = 1 or *x* = 1 Unitary Transformation:

 $U = S\cdot(C \otimes I)$ o.00

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$$
H(- | 1 \rangle) = \frac{1}{\sqrt{2}} (| 0 \rangle - | 1 \rangle)
$$

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Initialising the coin in the −|1⟩ state

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$$

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Initialising the coin in the −|1⟩ state

Initialising the coin in the $-|1\rangle$ state

$$
H(- | 1 \rangle) = \frac{1}{\sqrt{2}} (| 0 \rangle - | 1 \rangle)
$$

Removing the asymmetry:

\n
$$
|c\rangle = \frac{1}{\sqrt{2}}(|0\rangle - i|1\rangle)
$$

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2

Initialising the coin in the $-|1\rangle$ state

$$
H(- | 1 \rangle) = \frac{1}{\sqrt{2}} (| 0 \rangle - | 1 \rangle)
$$

Left moving part $(|c\rangle = |0\rangle)$ propagates in **real** amplitudes. Right moving part $(|c\rangle = |1\rangle)$ propagates in **imaginary amplitudes**.

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Removing the asymmetry:

$$
|c\rangle = \frac{1}{\sqrt{2}}(|0\rangle - i|1\rangle)
$$

Quantum Walks with Memory

Figure 1

Advantages:

- Arbitrary dynamics
- Classical dynamics in unitary evolution

Disadvantages:

- Tight conditions on quantum advantage

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Qubit model:

Augment system further by adding an additional memory space

 $\mathscr{H} = \mathscr{H}_P \otimes \mathscr{H}_C \otimes \mathscr{H}_M$

Quantum Parton Showers:

Quantum Walks with memory have proven to be very useful for quantum parton showers.

Phys.Rev.D 106 (2022) 5, 056002

Speed up via Quantum Walks

Quantum Walks have long be conjectured to achieved at least **quadratic speed up**

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

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

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

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CMS Experiment at the LHC, CERN Data recorded: 2021-Oct-19 13:01:24.690432 GMT
Run / Event / LS: 345881 / 17244 / 734

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CMS Experimer

CMS Experiment at the LHC, CERN

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Data recorded: Data recorded: 2016-Oct-11 10:44:24.059904 GMT
Run / Event / LS: 282842 / 47118579 / 25

Parton Density Functions

[Phys. Rev. D 103, 034027](https://journals.aps.org/prd/abstract/10.1103/PhysRevD.103.034027)

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Hadronisation

HAMMANNAMY

Parton Density Functions

Parton Shower

Hadronisation

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Hard Process

[Phys. Rev. D 103, 076020](https://journals.aps.org/prd/abstract/10.1103/PhysRevD.103.076020)

[Phys. Rev. D 106, 056002](https://journals.aps.org/prd/abstract/10.1103/PhysRevD.106.056002)

Parton Shower

[Phys. Rev. Lett. 126, 062001](https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.126.062001)

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[JHEP 11 \(2022\) 035](https://arxiv.org/abs/2207.10694)

The Parton Shower

Collinear mode:

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$$
k \frac{\overrightarrow{P}}{\overrightarrow{j}} \qquad p_i = zP, \quad p_j = (1 - z)P
$$

Soft mode: $p_i \approx 0$ $k \longrightarrow j$ *i*

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

q

g

q Successive decay steps factorise into independent quasi-classical steps

Interference effects only allow for partial factorisation

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

g This interpretation allows for straightforward interference patterns and momentum conservation

The Parton Shower - The Veto Algorithm

dP (*q*(*p*I)¯*q*(*p*K) ! *q*(*pi*)*g*(*p^j*)¯*q*(*pk*)) '

*s*IK

dP (*q*(*p*I)¯*q*(*p*K) ! *q*(*pi*)*g*(*p^j*)¯*q*(*pk*)) '

 $2s_{\rm IK}$

dsij

*s*IK

=

*s*IK

dsjk

*s*IK

^C ↵*^s*

2⇡

2

*k*2

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

ξ and *t* as **continuous** algorithm treat the phase space variables

The choice of the variables ξ and t is known as the **phase space parameterisation**

 $\mathcal{F}_n(\Phi_n, t_n, t_c; O) = \Delta(t_n, t_c) O(\Phi_n)$ $+$ Z *tn tc* $dt d\xi$ $d\phi$ 2π $C\frac{\alpha_s}{2}$

 2π

Master Equation

ي
م≛ا

 2π $2s_{ik}(t,\xi)$ $s_{ij}(t,\xi)s_{jk}(t,\xi)$ $\Delta(t_n,t)\mathcal{F}_n(\Phi_{n+1},t,t_c;O)$

Non-Emission Probability

PS : ! *[|]*1i(cos² ✓*|*00ⁱ + sin² ✓*|*01i)*/*

sijsjk

Inclusive Decay Probability Current interpretations of the veto

 $\frac{1}{\sqrt{2}}$ $d\mathcal{P}$ $(q(p_1)\bar{q}(p_K) \rightarrow q(p_i)g(p_j)\bar{q}(p_k)) \simeq$ ds_{ij} *s*IK ds_{jk} *s*IK $C\frac{\alpha_s}{2}$

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Collider Events on a Quantum Computer

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^cHigh 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_algiers* 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.

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 $\overline{4}$

$$
= \frac{1}{2} \ln \left(\frac{s_{ij}}{s_{jk}} \right)
$$

 $\frac{C\alpha_s}{\pi}d\kappa dy$ $d\kappa dy$

which lead which leads to which leads to the inclusive probability: $F(x) = \int_{0}^{x} f(x) dx$ *tn*

> $\frac{4}{\sqrt{2}}$ Due to the colour charge of emitted gluons, the rapidity span for subsequent dipole decays is increased. This is interpreted as **"folding out"**

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Discrete QCD - Abstracting the Parton Shower Method T implementation on intermediate-step Λ intermediate-scale Λ The first abstracting the i antonibility of the independent the $\Sigma_{\text{measured}} \cap \cap \Gamma$ and intermediate-scale Γ The first abstraction to consider is removing the independent treatment of decay prob- T_{max} Λ leads and intermediate-scale Λ The first abstraction to consider is removing the independent treatment of decay prob-*L*

I. Parameterise phase space in terms of gluon transverse momentum and rapidity: parametrisation in terms of the gluon terms of the gluon in terms of the gluon terms of the gluon stransverse momentum, and the gluon terms of the gluon terms of the gluon stransverse momentum, and the gluon stransverse mo *dP* (*q*(*p*I)¯*q*(*p*K) ! *q*(*pi*)*g*(*p^j*)¯*q*(*pk*)) ' dity: \overline{r}

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

ability and momentum-space integration by absorbing the non-uniform probability density density density density α

plane, as illustrated by the left-hand panel of Fig. 1. Due to the colour charge of an emitted

$$
d\mathcal{P}(q(p_{\rm I})\bar{q}(p_{\rm K})\to q(p_i)g(p_j)\bar{q}(p_k))\simeq=\frac{C\alpha_s}{\pi}d\kappa dy
$$

where ν^2 where $\kappa = \ln\left(\frac{1}{\Lambda^2}\right)$ and Λ is an arbitrary mass scale where κ^2 is an arbitrary mass scale. With this phase space parameters κ^2 where $\kappa = m(\sqrt{2})$ and *I* is an arbitral y mass scale $\kappa = \ln\left(\frac{k_{\perp}^2}{\epsilon}\right)$ and Λ is an arbitrary mass scale parameters in the phase space parameter of Λ dipole decays are constrained to a triangular region of height *L* = ln(*s*IK*/*⇤2) in the (*y,*)- $\kappa = \ln\left(\frac{k_{\perp}^2}{\Lambda^2}\right)$ Λ^2 \setminus where $\kappa = \ln\left(\frac{n_+}{\Lambda^2}\right)$ and Λ is an arbitrary mass scale

[⊥]*/*Λ²)

y **triangle external to positive** *y* act coherently $\| \psi \|$ i.e. $\|$ $\frac{1}{2}$ $\frac{1}{2}$ generative gluons at the centre of discrete the phase-space triangle. **triangleris within** oy_g **act conerently** $|_{\{u\}}|_{\{k\}}|_{\{v\}}$ as one effective gluon and the particles of 2*y*^{*g*}. Thus, we may model the parton shower by the particle particle in the particle particle in the particle in the particle particle in the particle in the particle in the **Gluons within** δ ^{*y*g} act coherently

These realisations for the basis of the basis of the basis of the basis of \mathcal{A} . The "Discrete \mathcal{A} " of \mathcal{A}

Simon Williams - s.williams | 9@imperial.ac.uk 16 Milan - 23/1/23 Eq. 2.2) shows that the exclusive rate for finding an e↵ective gluon in a fixed *y*-bin takes Each rapidity slice can be treated independently of any other slice. Inserting Eq. 2.7 $\frac{16}{16}$ of the excluding term in the second term in the second term in the second term in the shower master equation, $\frac{16}{16}$

may write

Each rapidity slice can be treated independently of any other slice. Inserting Eq. 2.7

Interpreting the running coupling renormalisation group as a as gain-loss equation means that gluons within a rapidity range *y^g* act coherently as one \blacksquare toss equation: as in Fig. 1. Thus, the rapidity rapidity range of each triangular rapidity rapidity rapidity rapi Interpreting the running coupling renormalisation group as a gainas gain-loss equation means that gluons within a rapidity range *y^g* act coherently as one "e illustrated by 1 in Fig. 1. Thus, the rapidity range of each triangular range of each triangular range of e
Thus, the rapidity range of each triangular range of each triangular range of each triangular range of each tr loss equation:

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Discrete QCD - Abstracting the Parton Shower Method Uiscrete ()(I) - Abstracting the Parton $\mathcal{L}_{\mathcal{A}}$ the e $\mathcal{L}_{\mathcal{A}}$ Diccroto OCD Abetracting the Parton Sh Examining the e↵ect of a transverse-momentum-dependent running coupling – as sup-@ Y $\overline{}$ \mathcal{A} *max*

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Δερατική στ *L* **2.** Neglect $g \rightarrow q\overline{q}$ splittings and examine transversemomentum-dependent running coupling ↵*s*(*k*² bendent running o ϵ nd dent running coup

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

leads to the inclusive probability

$$
d\mathcal{P}\left(q(p_1)\bar{q}(p_K) \to q(p_i)g(p_j)\bar{q}(p_k)\right) \simeq = \frac{d\kappa}{\kappa} \frac{dy}{\delta y_g} \quad \text{with}
$$

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Δερατική στ *L* **2.** Neglect $g \rightarrow q\overline{q}$ splittings and examine transversemomentum-dependent running coupling ↵*s*(*k*² bendent running o ϵ nd dent running coup

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

leads to the inclusive probability

$$
d\mathcal{P}\left(q(p_1)\bar{q}(p_K) \to q(p_i)g(p_j)\bar{q}(p_k)\right) \simeq = \frac{d\kappa}{\kappa} \frac{dy}{\delta y_g} \quad \text{with} \quad \delta
$$

Discrete QCD - Abstracting the Parton Shower Method

Folding out extends the baseline of the triangle to positive y by $\frac{1}{2}$, where l is the height at which to emit effective gluons *l* 2 *l* $\overline{2}$, where \overline{l} is t \overline{a} height at wh 。
)
)

isequence of folding is that the κ axis is quantised into \blacksquare A consequence of folding is that the *κ* axis is quantised into multiples of $2\delta y_g$ $\frac{1}{2}$ sin in *sin III*
1111 - Sin 2 III + sin 2 III + sin 2 II + si
1111 - Sin 2 II + sin 2 II +

−*L/*2 *L/*2

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

−*L/*2 *L/*2

$$
\frac{d\kappa}{\kappa} \exp\left(-\int\limits_{\kappa}^{\kappa_{max}} \frac{d\bar{\kappa}}{\bar{\kappa}}\right) = \frac{d\kappa}{\kappa_{max}}
$$

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cR(✓) : *|*100i ! *|*1i(cos ✓*|*0i + sin ✓*|*1i)*|*0i

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Discrete QCD as a Quantum Walk

 Γ is schematic of the quantum circuit for one slice in the fold. For each slice in the algorithm is splitted in the algorithm is splitted in the fold. For each slice in the algorithm is splitted in the algorithm is spl

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

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Discrete QCD - Grove Structures

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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 *κ* 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 $I\!K$, read off the values s_{ij} , s_{jk} and s_{IK} from the grove
-

This has been done using the ibm_cloud 27 qubit device ibm_algiers, with 20,000 shots on the device. A comparison with a like-for-like classical parton shower algorithm has been made.

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3. Generate a uniformly distributed azimuthal decay angle ϕ , and then employ momentum mapping (here we have used [Phys. Rev. D 85, 014013 \(2012\), 1108.6172](https://journals.aps.org/prd/abstract/10.1103/PhysRevD.85.014013)) to produce post-branching momenta

Running on a Quantum Simulator

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y

Running on a Quantum Device - Streamlined Circuit Levice - Streamlined Circuit

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to increase the grove baseline, *S*, and e↵ective gluon position, *S*0

; (3) The memory operation, *M*, then

Figure 1: Schematic of the quantum circuit for one slice in the fold. For each slice, the algorithm is split into three distinct sections: (1) The coin operation, *C*, controls from the relevant walk memory to apply **116 gate operations 121 gate operations** along the base of the fold, *B*, and then controls from the coin outcome to shift the walker accordingly **(102 multi-qubit, 14 single qubit)** ¹ **15 qubits 10 qubits**

updates the memory register with the outcome of the outcome of the coin operation. This is the coin operation

21 gate operations (12 multi-qubit, 9 single qubit)

Running on a Quantum Device - Streamlined Circuit Γ the event of an emitted eller energy de new fold could produce further energy σ

1

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Coin operation constructs an equal superposition of *n* states on a coin register of *m* qubits:

$$
C|0\rangle^{\otimes m} = \frac{1}{\sqrt{n}}(|0\rangle + |1\rangle + \dots + |n-1\rangle)
$$

Discrete QCD as a Quantum Walk - Raw Grove Simulation

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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

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Better technology?

New technology could be the answer - will new qubit hardwares be more **fault tolerant?**

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The Future of Quantum Computing

A lot of emphasis on more qubits, but without fault tolerance, large qubit devices become **impractical**

Be better architects?

Realistic algorithms are already being created for NISQ devices. Efficient architectures allow for **practical algorithms** on NISQ devices.

IBM Roadmap

On track to deliver **1000 qubits by 2023**

Summary

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

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

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**

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Backup Slides

Simon Williams

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Collider Events on a Quantum Computer - Varying Λ

Varying values for the mass scale Λ . This leads to non-negligible uncertainties, however this is expected from a leading logarithm model.

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Collider Events on a Quantum Computer - Varying Λ

Varying values for the mass scale Λ . This leads to non-negligible uncertainties, however this is expected from a leading logarithm model.

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Collider Events on a Quantum Computer

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Collider Events on a Quantum Computer - Changing tune

Observables dominated by non-perturbative dynamics show mild dependence on the mass scale Λ , but are highly sensitive to changes in the tune.

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Collider Events on a Quantum Computer

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Looking to the Future of Quantum Computers

Scaling IBM Quantum technology

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