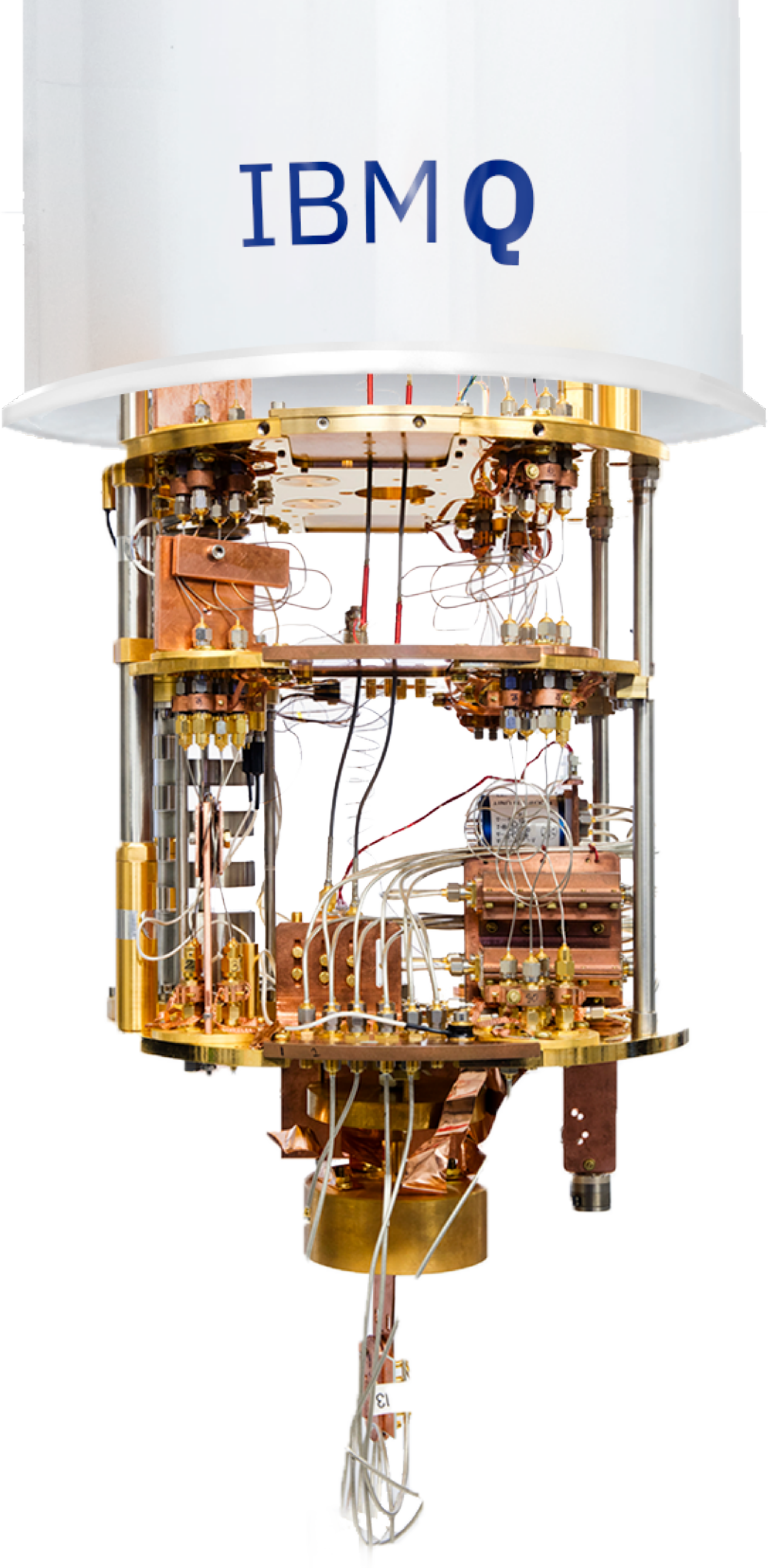
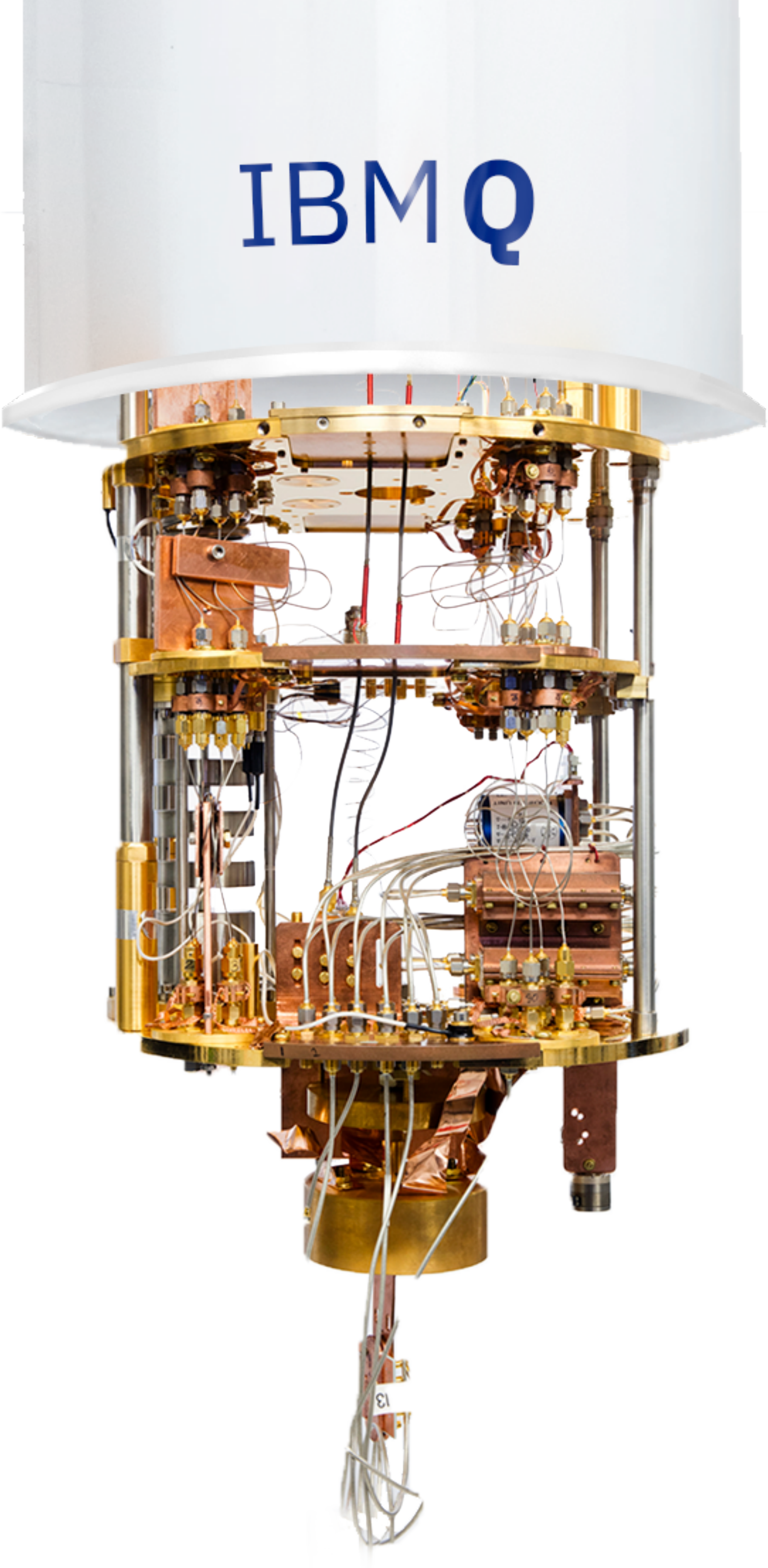


Imperial College
London

Collider Events on a Quantum Computer

Simon Williams

First Lund Jet Plane Institute
5th July 2023



Imperial College London

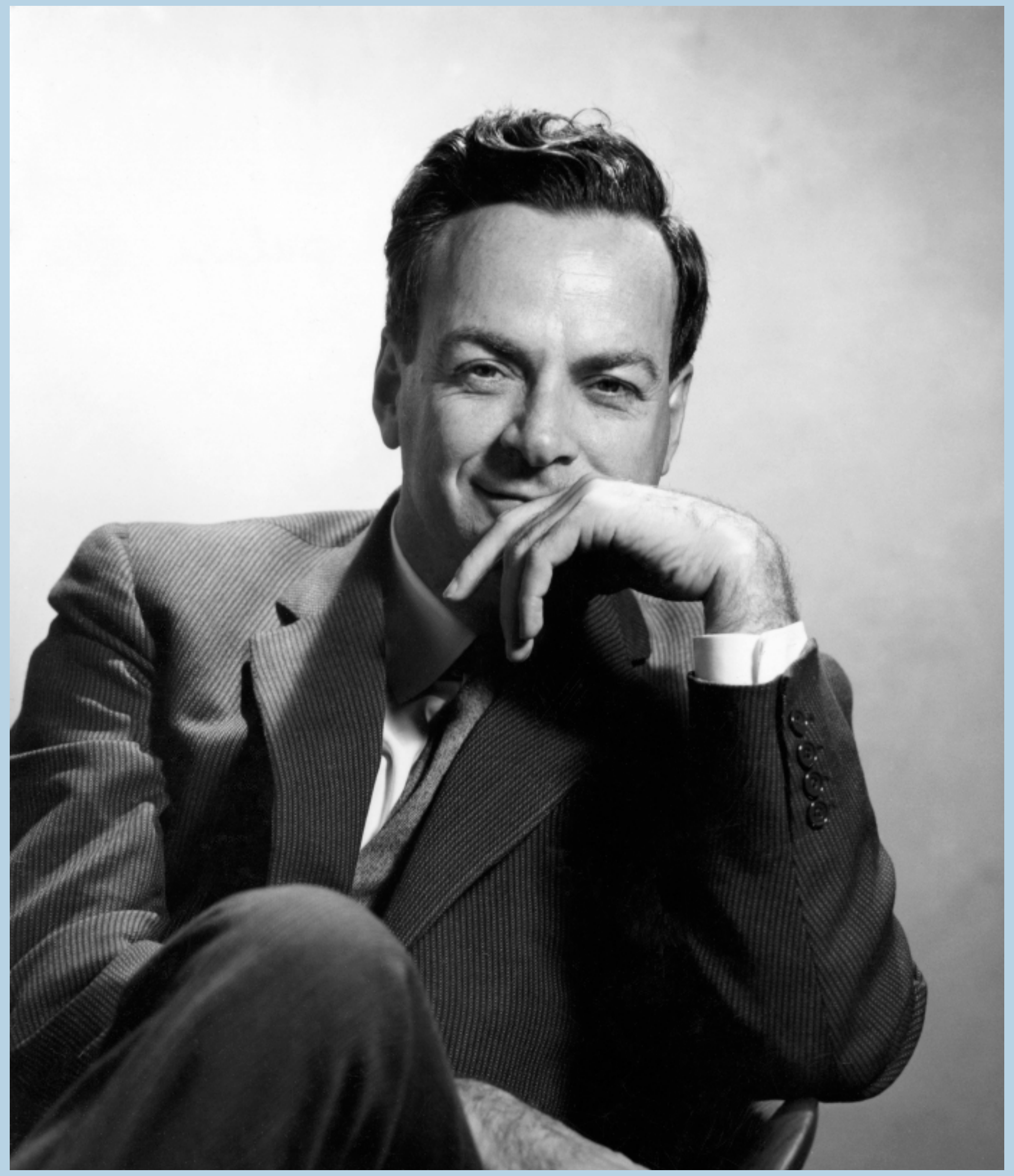
- Quantum Computing - The Power of the Qubit
- Why are we interested in High Energy Physics?
- The Parton Shower
    - Discretising QCD
- Collider Events on a Quantum Computer

G. Gustafson, S. Prestel, M. Spannowsky and S. Williams, Collider Events on a Quantum Computer, JHEP 11 (2022) 035

LUND UNIVERSITY

IP3

Quantum Computing - The Power of the Qubit!

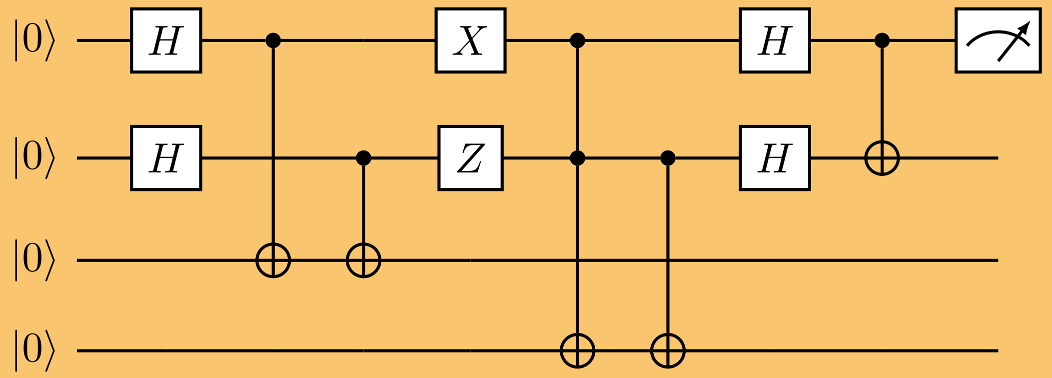


"Nature is quantum [...] so if you want to simulate it, you need a quantum computer"

- Richard Feynman (1982)

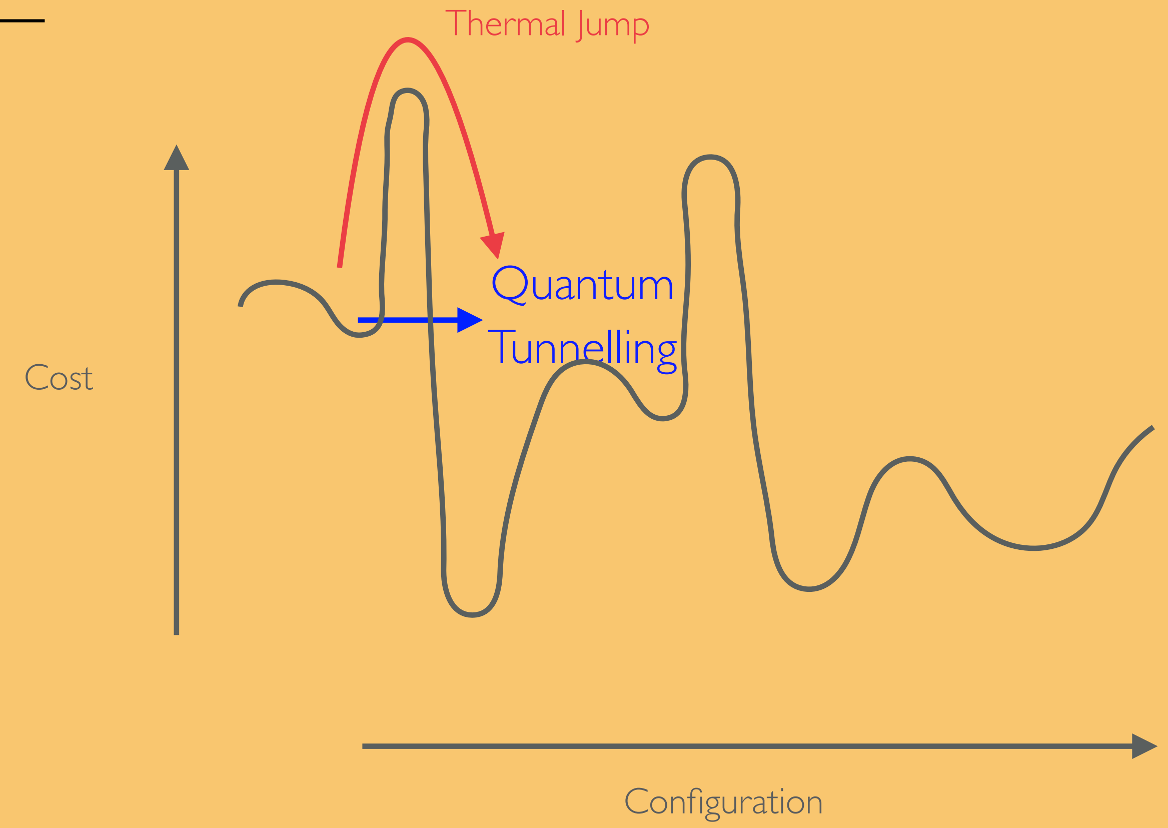
Quantum Computing has had a lot of successes since - most recently with Shor and Deutsch winning the **Breakthrough Prize** and the **2022 Nobel Prize** going to Quantum Information

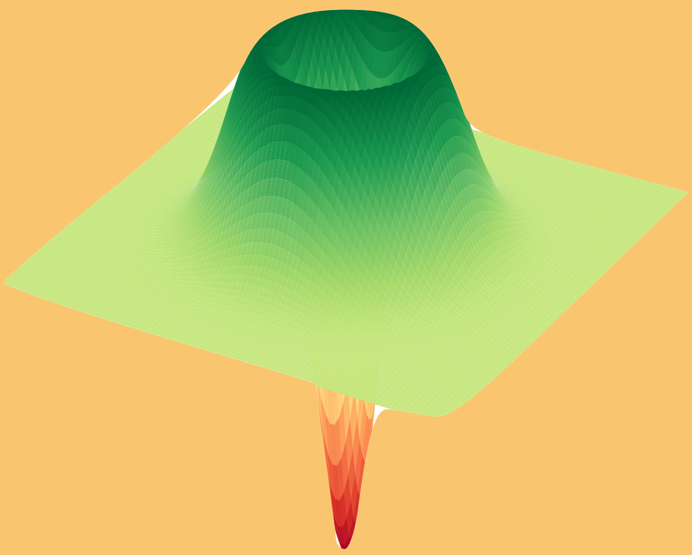
Types of Quantum Device:



Superconductor Quantum Computing

Quantum Annealing

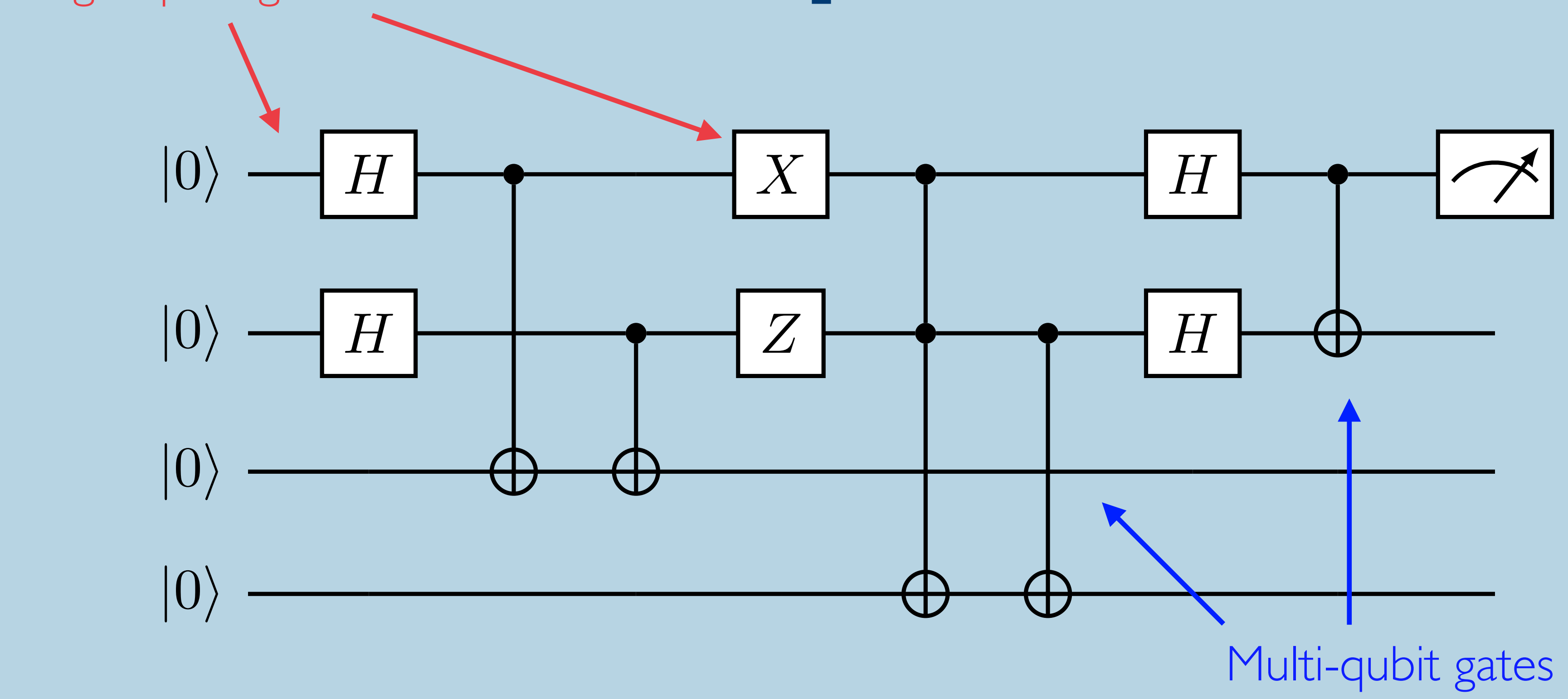




Photonic Devices

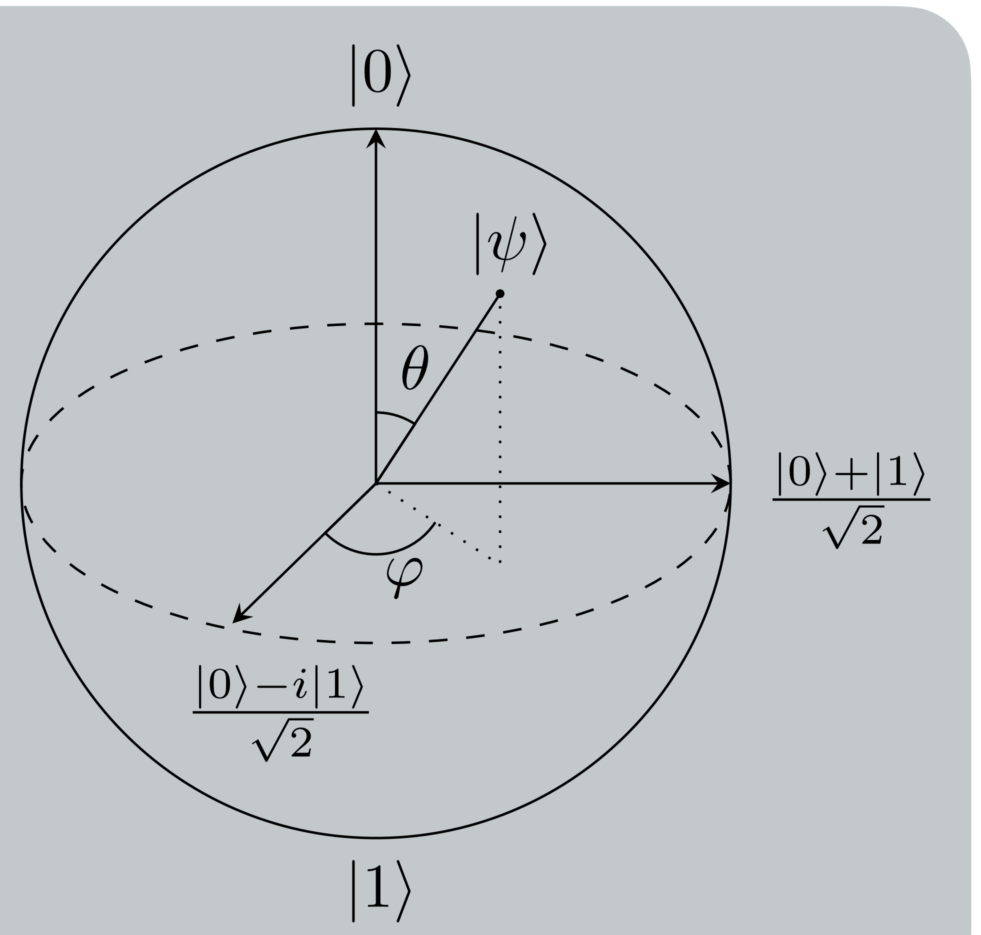
Types of Quantum Computing Devices

Superconductor QCs



Qubit model:

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



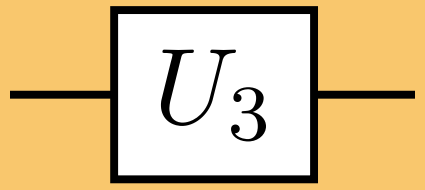
Advantages:

- Highly controllable qubits
- Universal computation

Disadvantages:

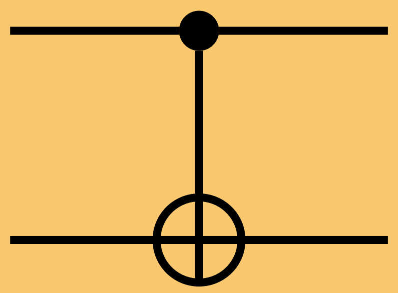
- Small number of qubits, not very fault tolerant

Single qubit gates:



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

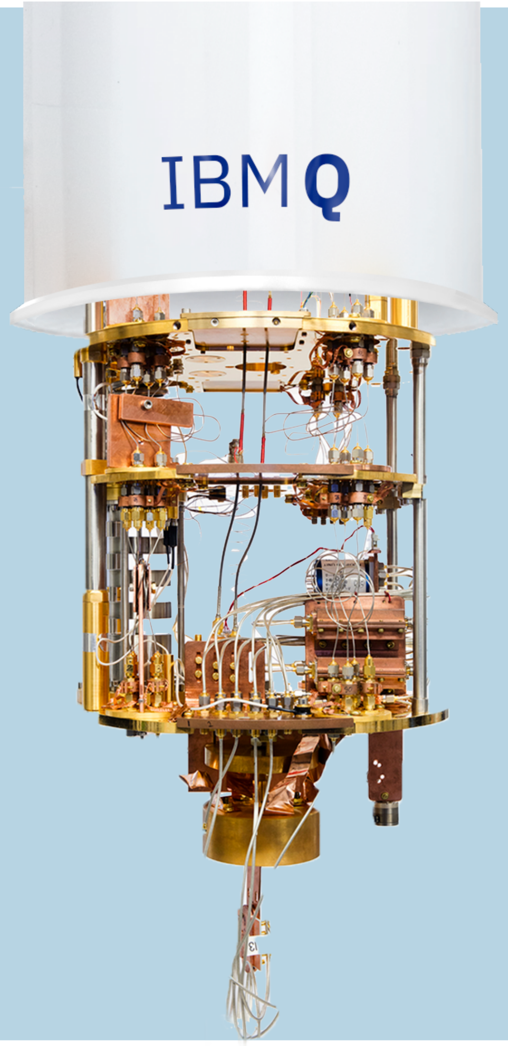
Multi-qubit gates:



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

Noisy Intermediate-Scale Quantum Devices

NISQ devices:



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

Transpilation:

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

Quantum errors:

Mutliqubit qubit gates: CNOT gates have higher associated errors than single qubit gates.

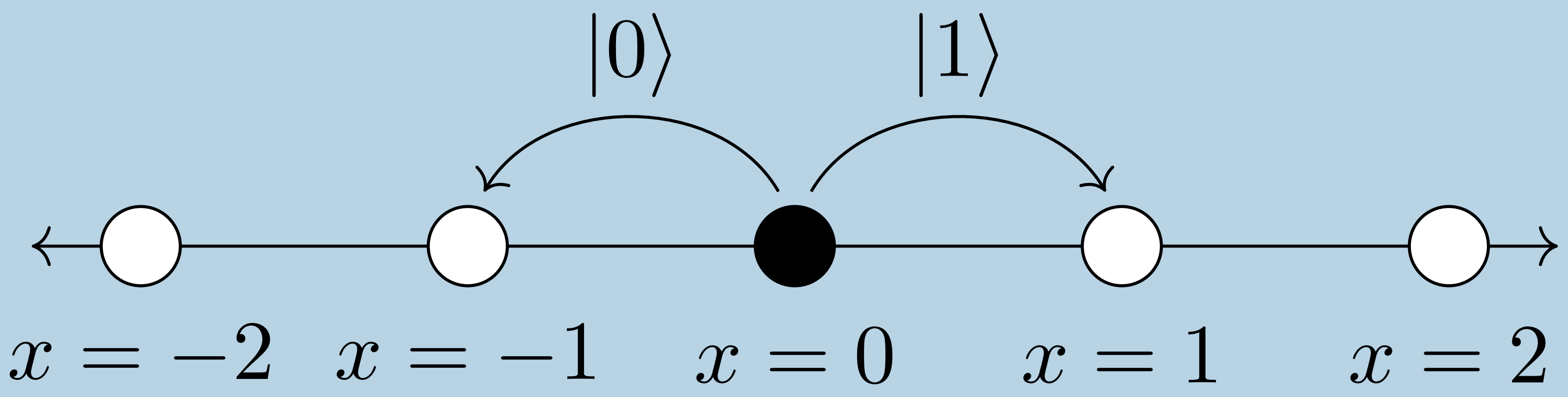
SWAP errors: SWAP operations require 3 CNOT gates

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

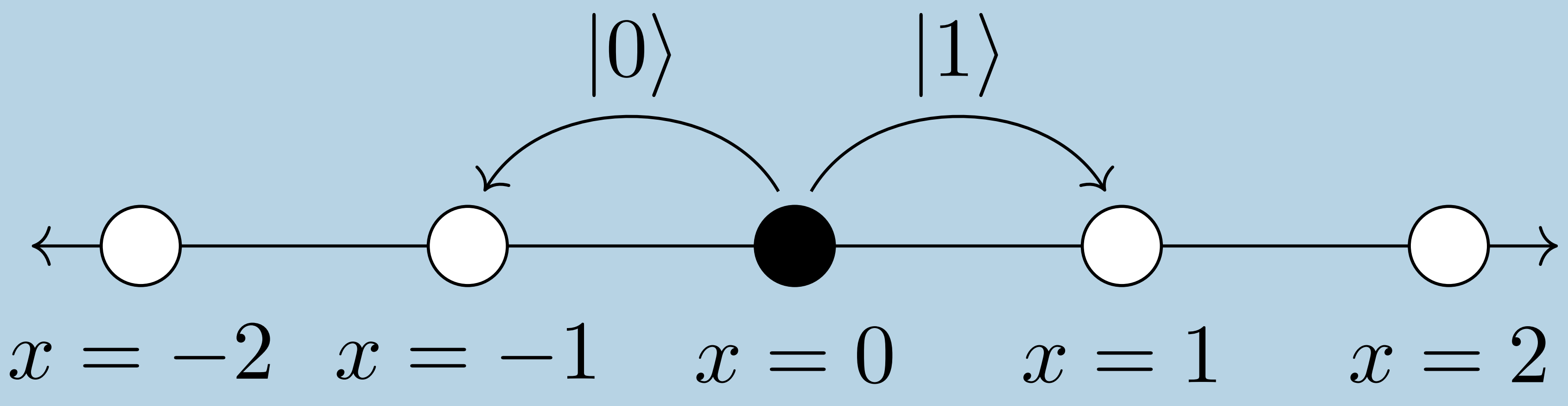
Circuit depth! - Compact circuits needed!

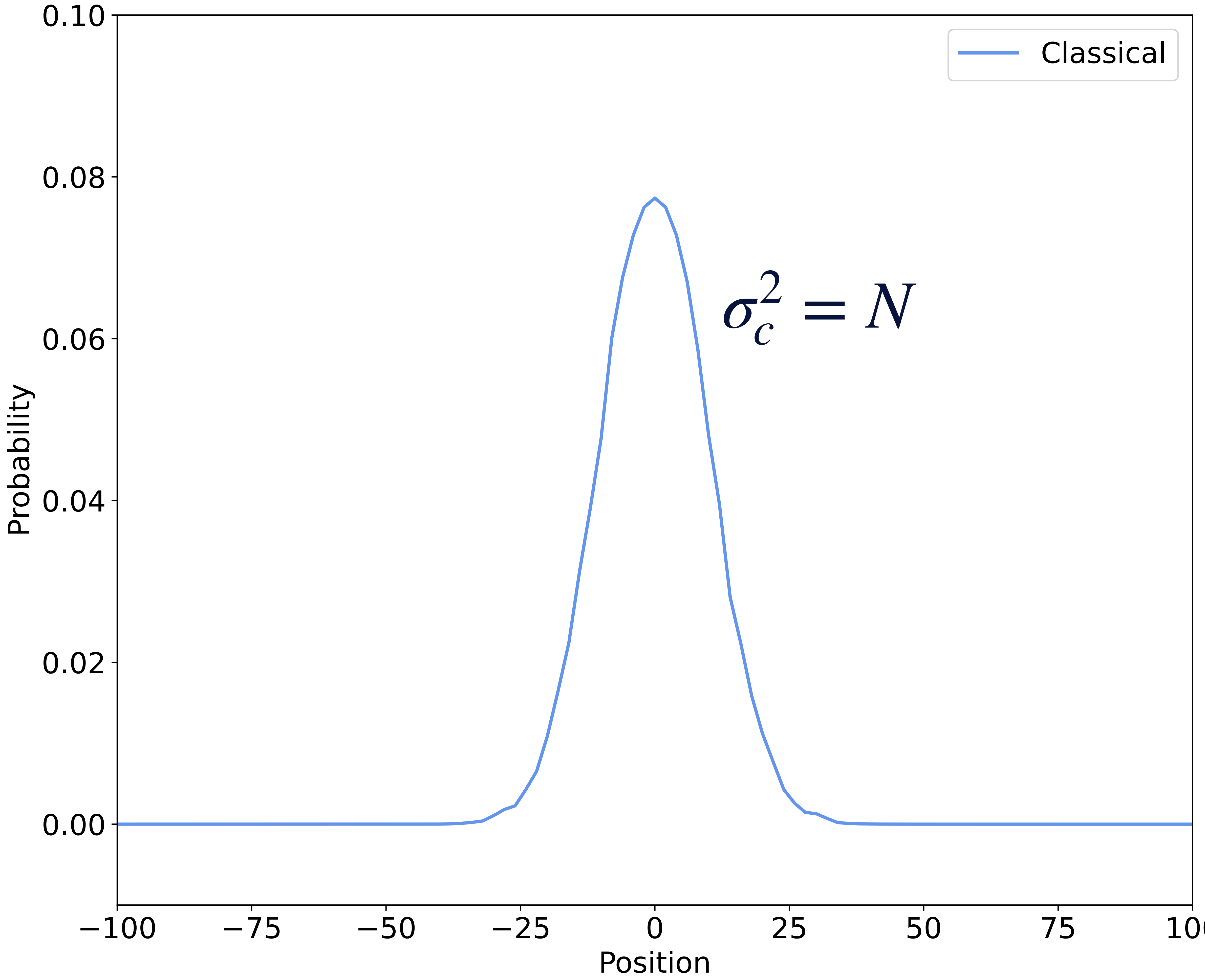
Classical Random Walk

Classical Random Walk

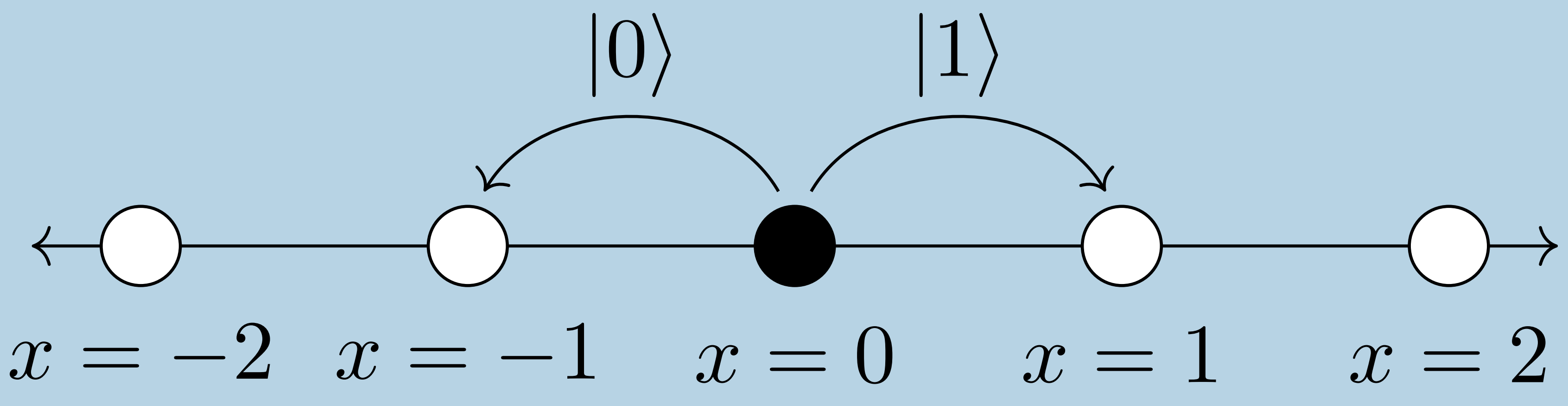


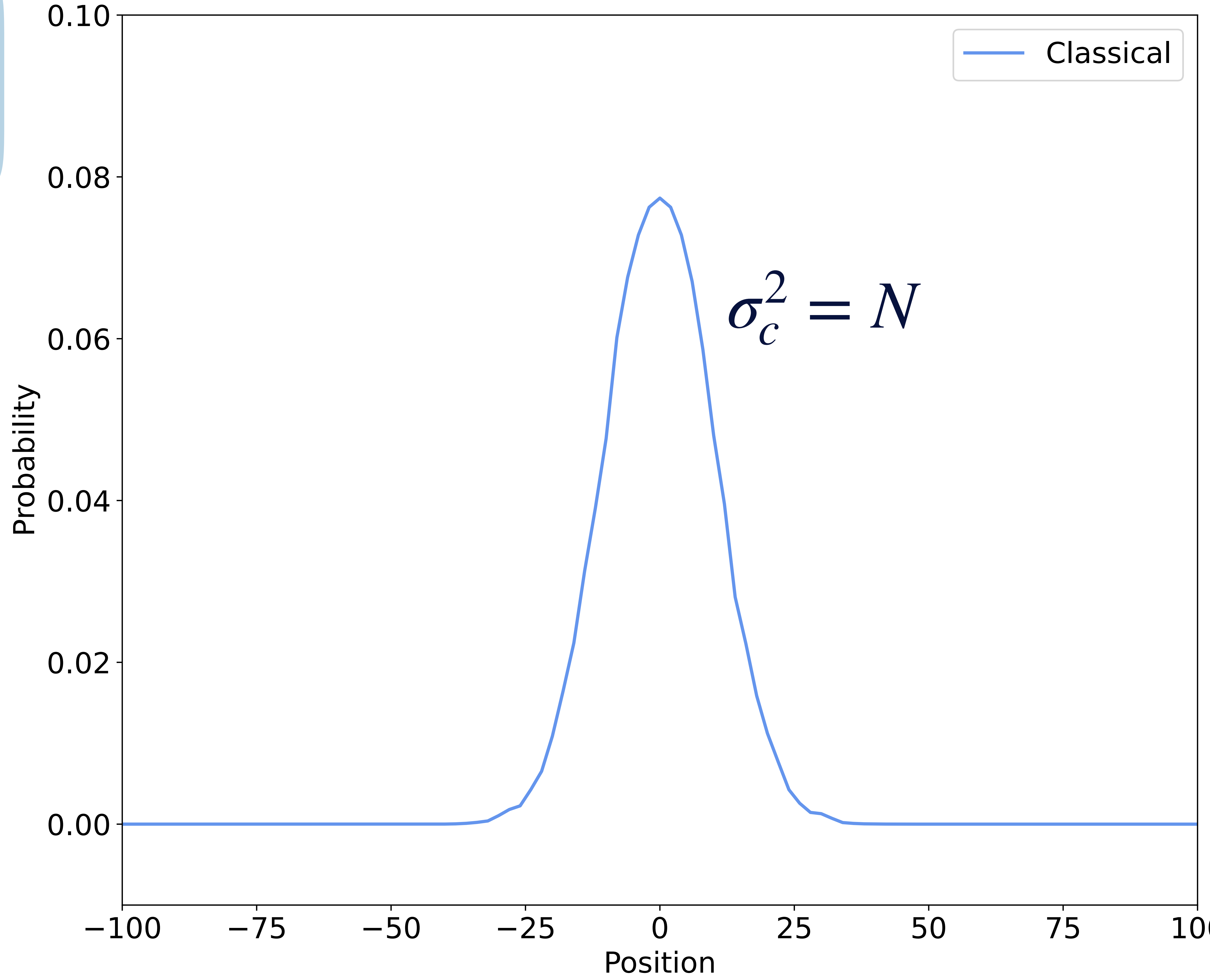
Classical Random Walk



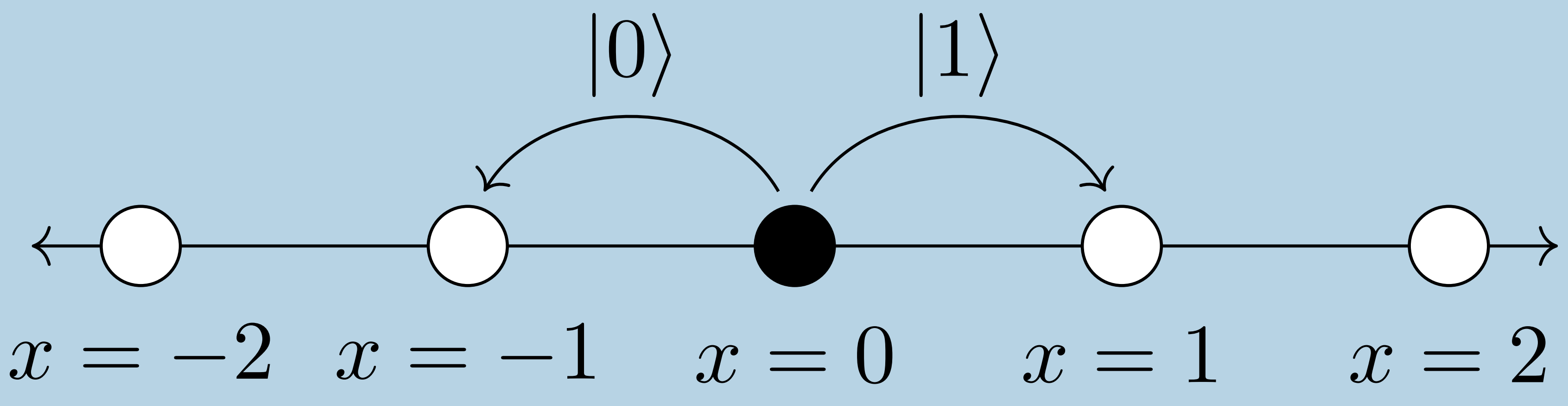


The Quantum Walk

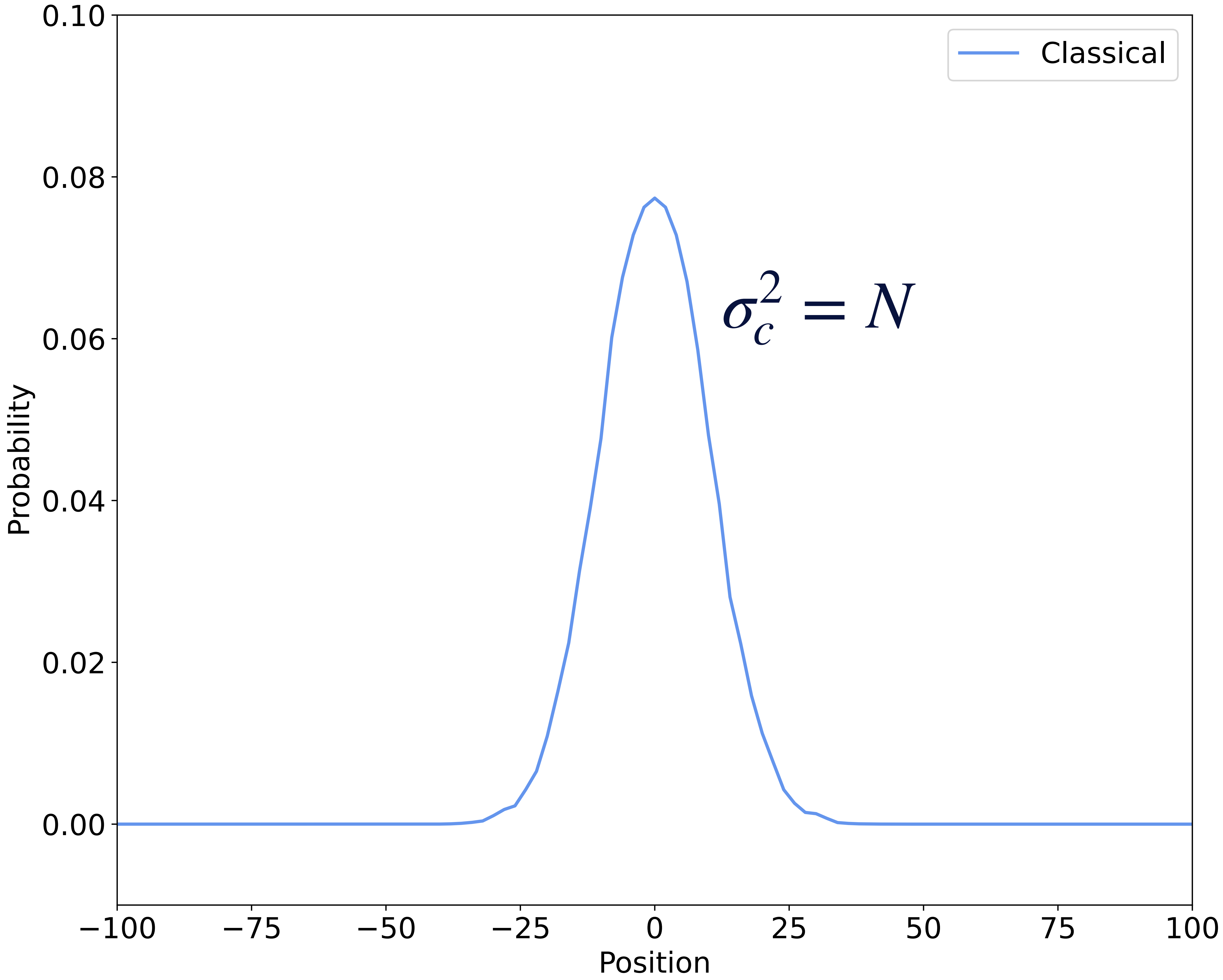




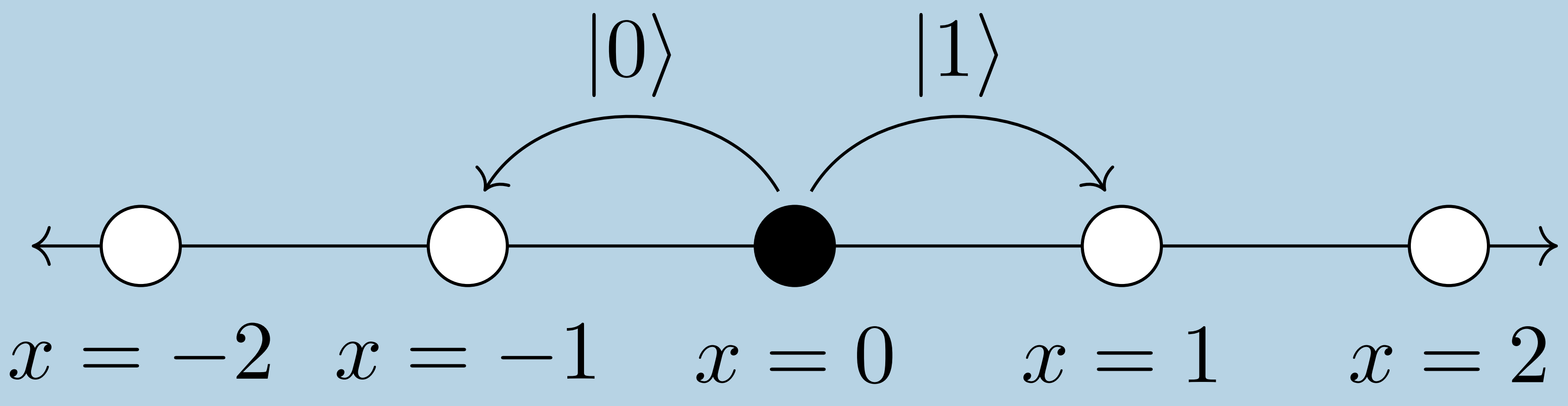
The Quantum Walk



$$\left.\begin{aligned}\mathscr{H}_P &= \{\,|i\rangle : i \in \mathbb{Z}\} \\ \mathscr{H}_C &= \{\,|0\rangle, |1\rangle\}\end{aligned}\right\} \mathscr{H} = \mathscr{H}_C \otimes \mathscr{H}_P$$



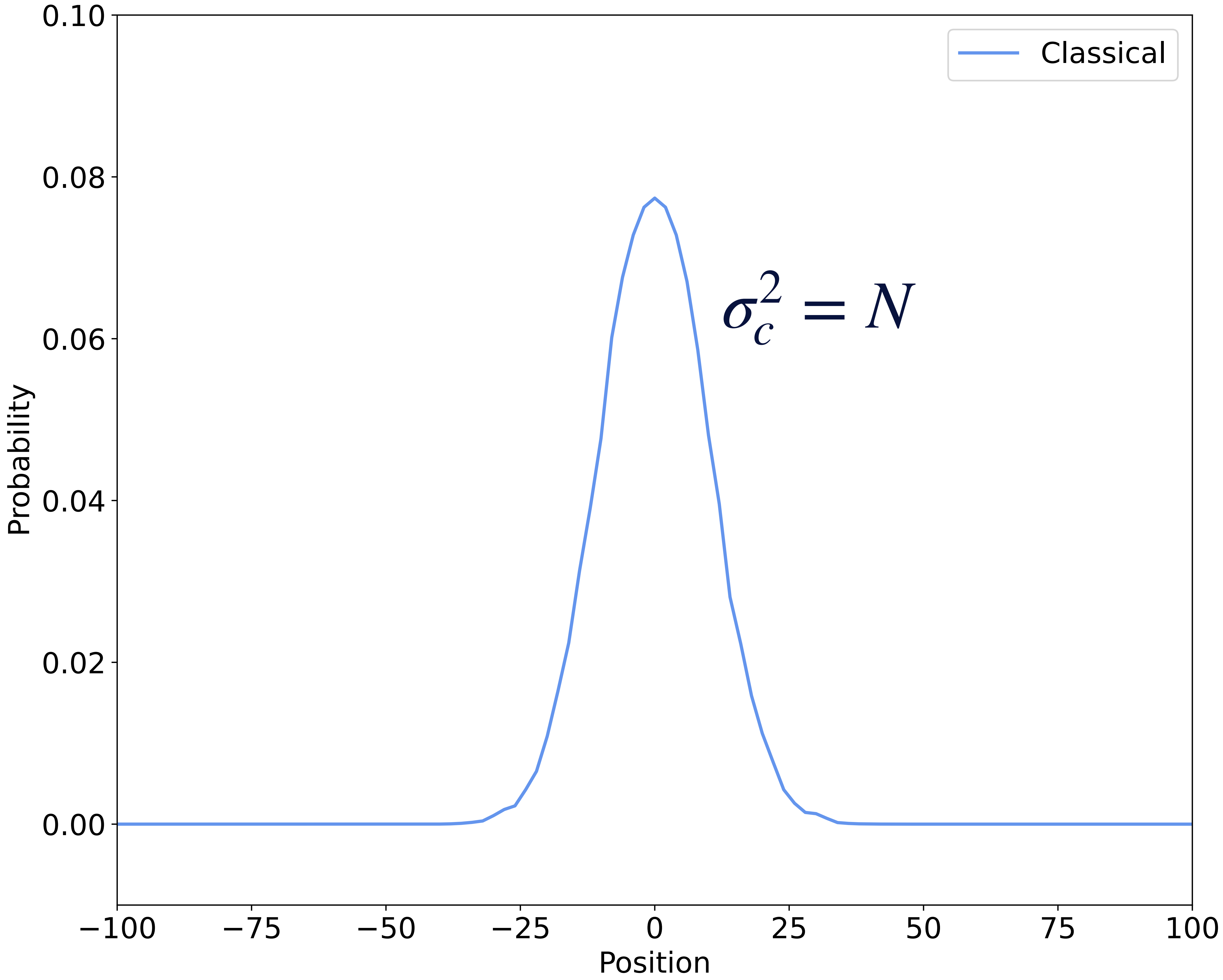
The Quantum Walk



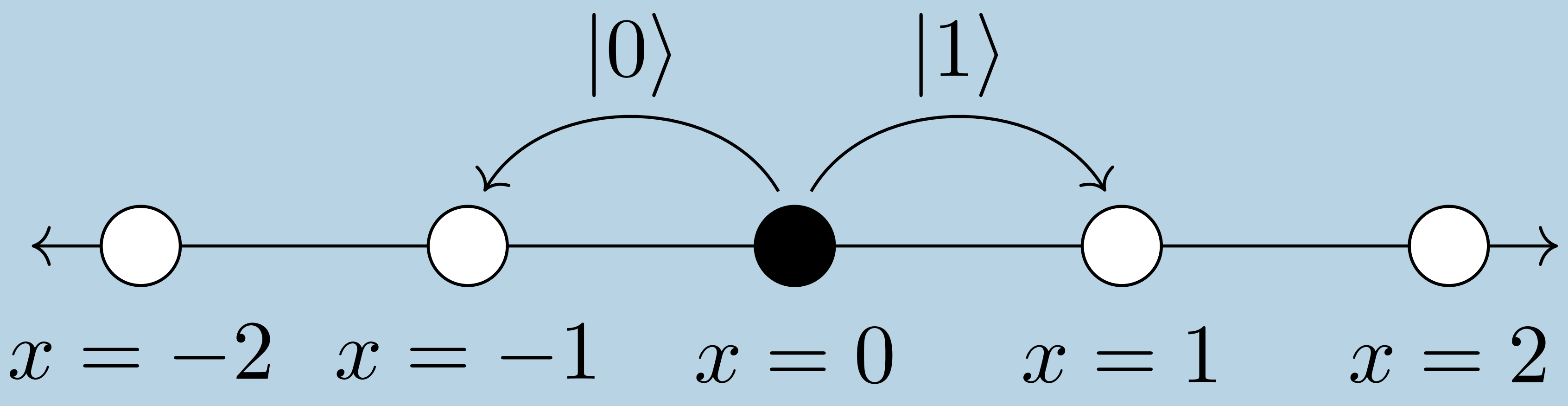
$$\left.\begin{array}{l}\mathcal{H}_P = \{\,|i\rangle : i \in \mathbb{Z}\} \\ \mathcal{H}_C = \{\,|0\rangle, |1\rangle\}\end{array}\right\} \mathcal{H} = \mathcal{H}_C \otimes \mathcal{H}_P$$

Unitary Transformation:

$$U = S\cdot(C \otimes I)$$



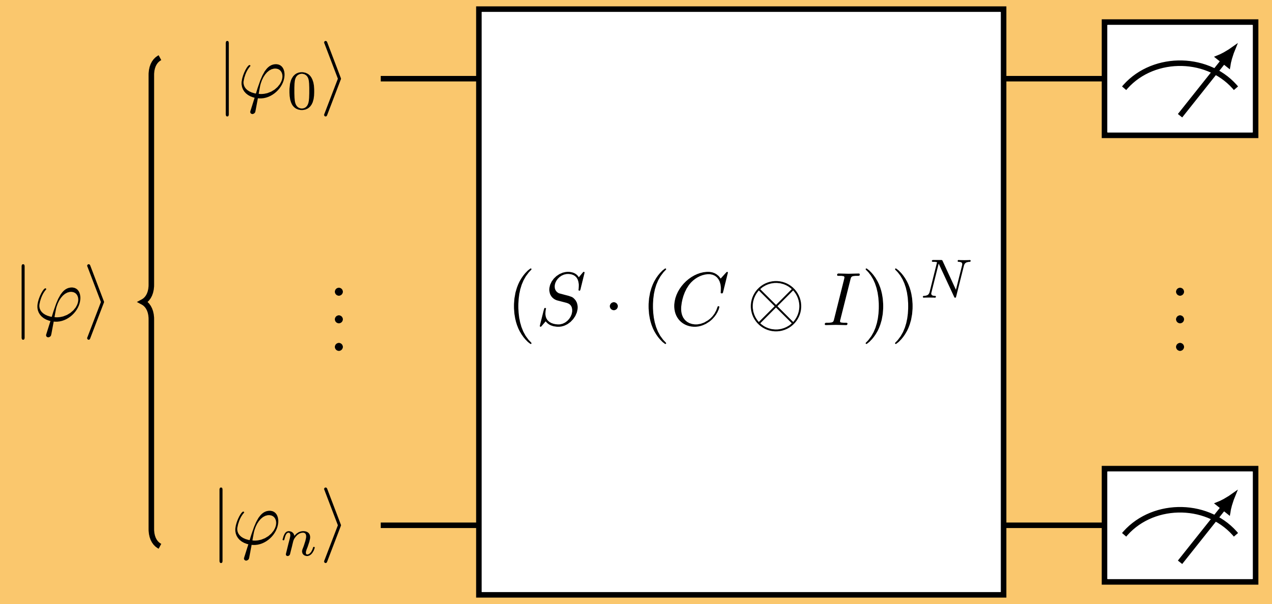
The Quantum Walk

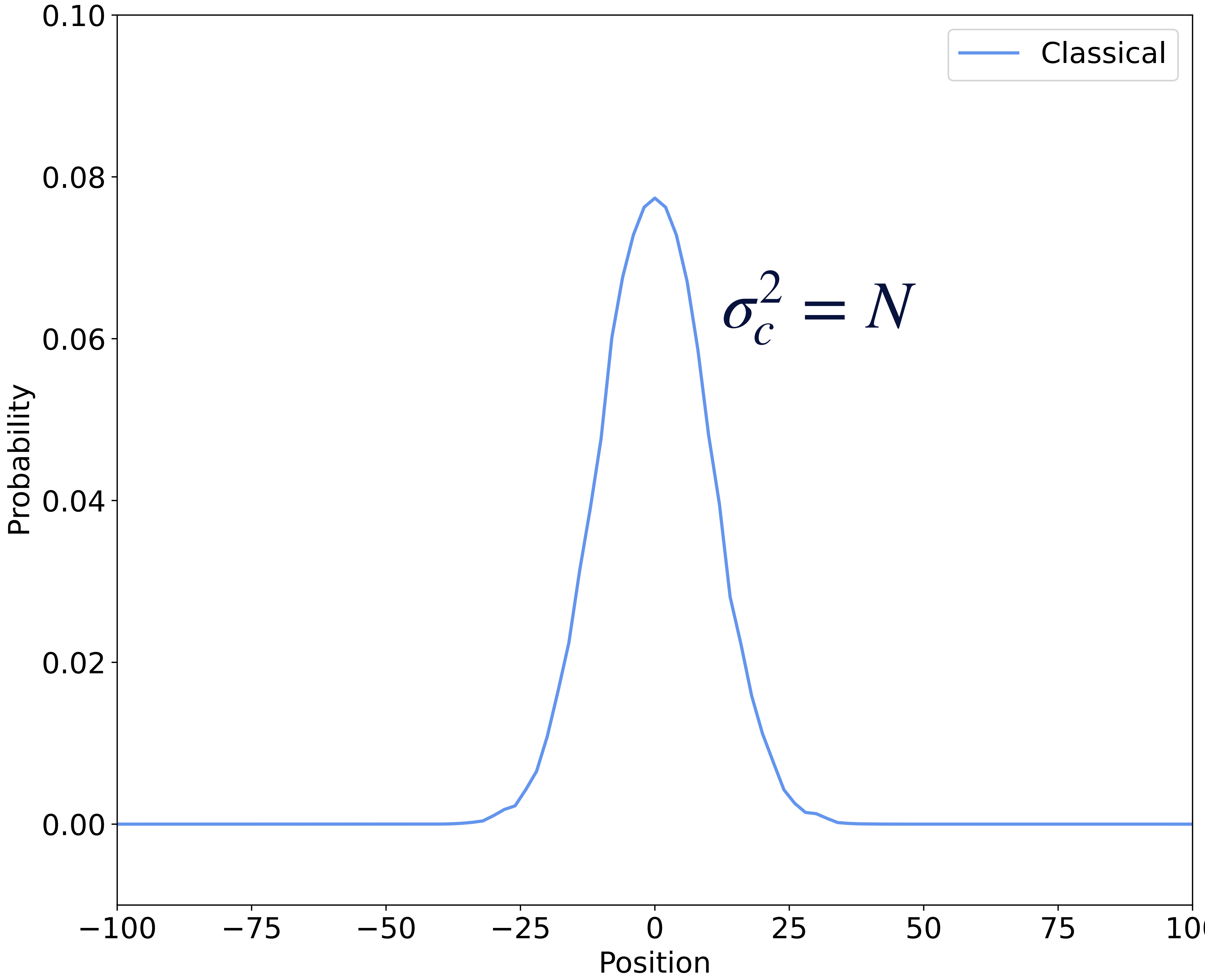


$$\left.\begin{array}{l}\mathscr{H}_P = \{\,|i\rangle : i \in \mathbb{Z}\} \\ \mathscr{H}_C = \{\,|0\rangle, |1\rangle\}\end{array}\right\} \mathscr{H} = \mathscr{H}_C \otimes \mathscr{H}_P$$

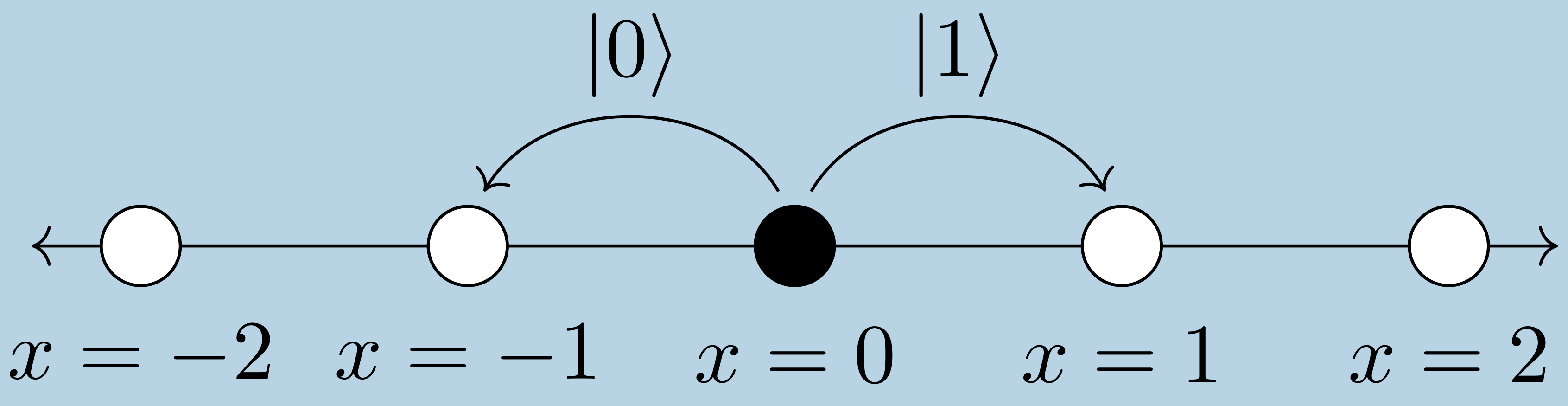
Unitary Transformation:

$$U = S\cdot(C \otimes I)$$





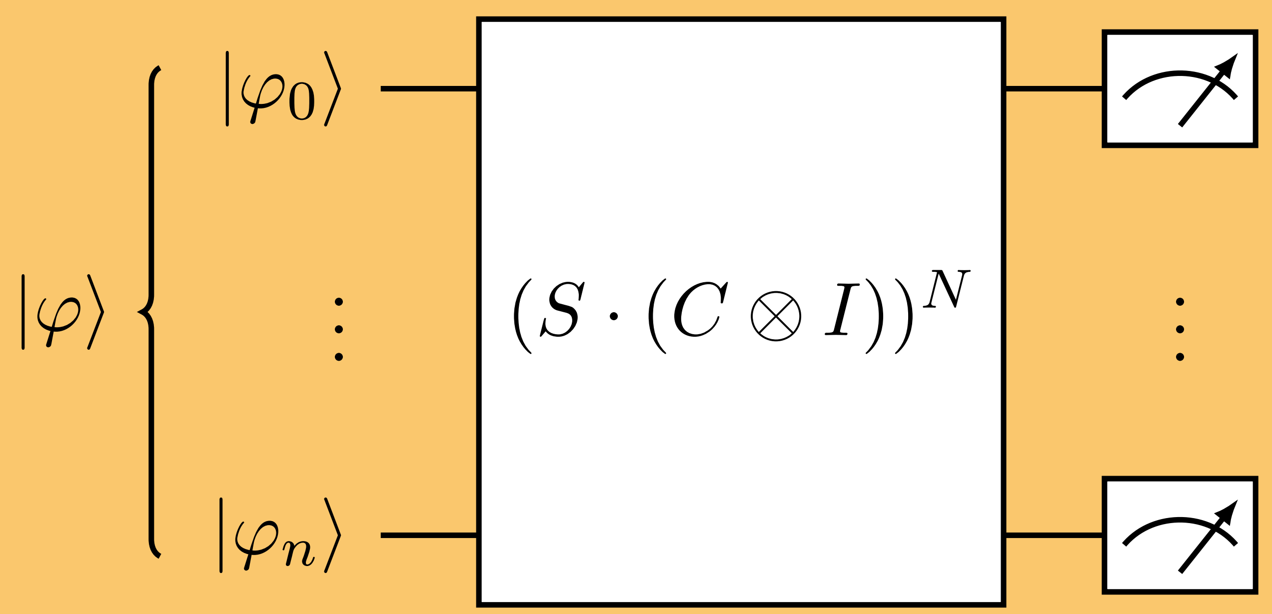
The Quantum Walk

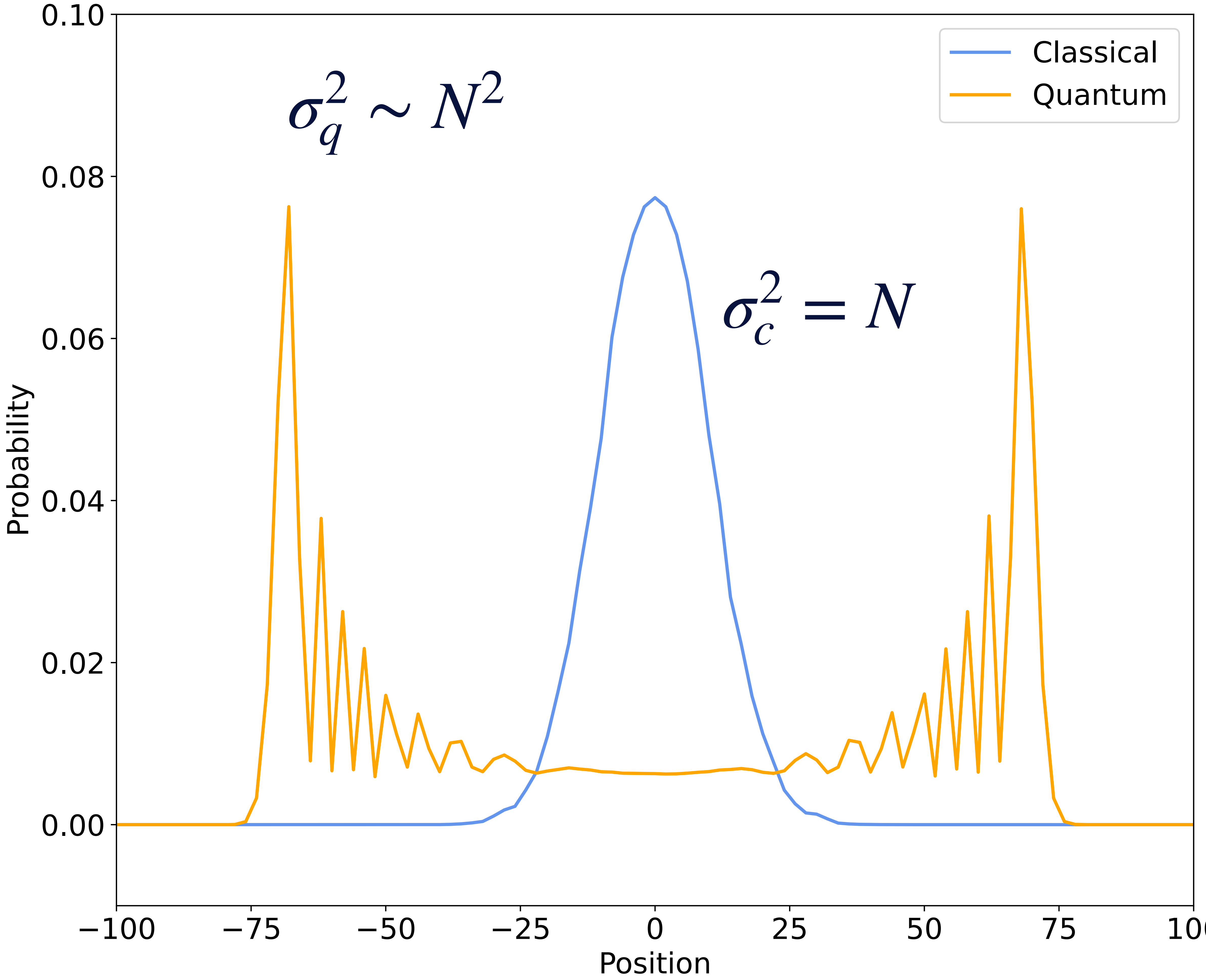


$$\left.\begin{array}{l}\mathscr{H}_P = \{\,|i\rangle : i \in \mathbb{Z}\} \\ \mathscr{H}_C = \{\,|0\rangle, |1\rangle\}\end{array}\right\} \mathscr{H} = \mathscr{H}_C \otimes \mathscr{H}_P$$

Unitary Transformation:

$$U = S\cdot(C \otimes I)$$





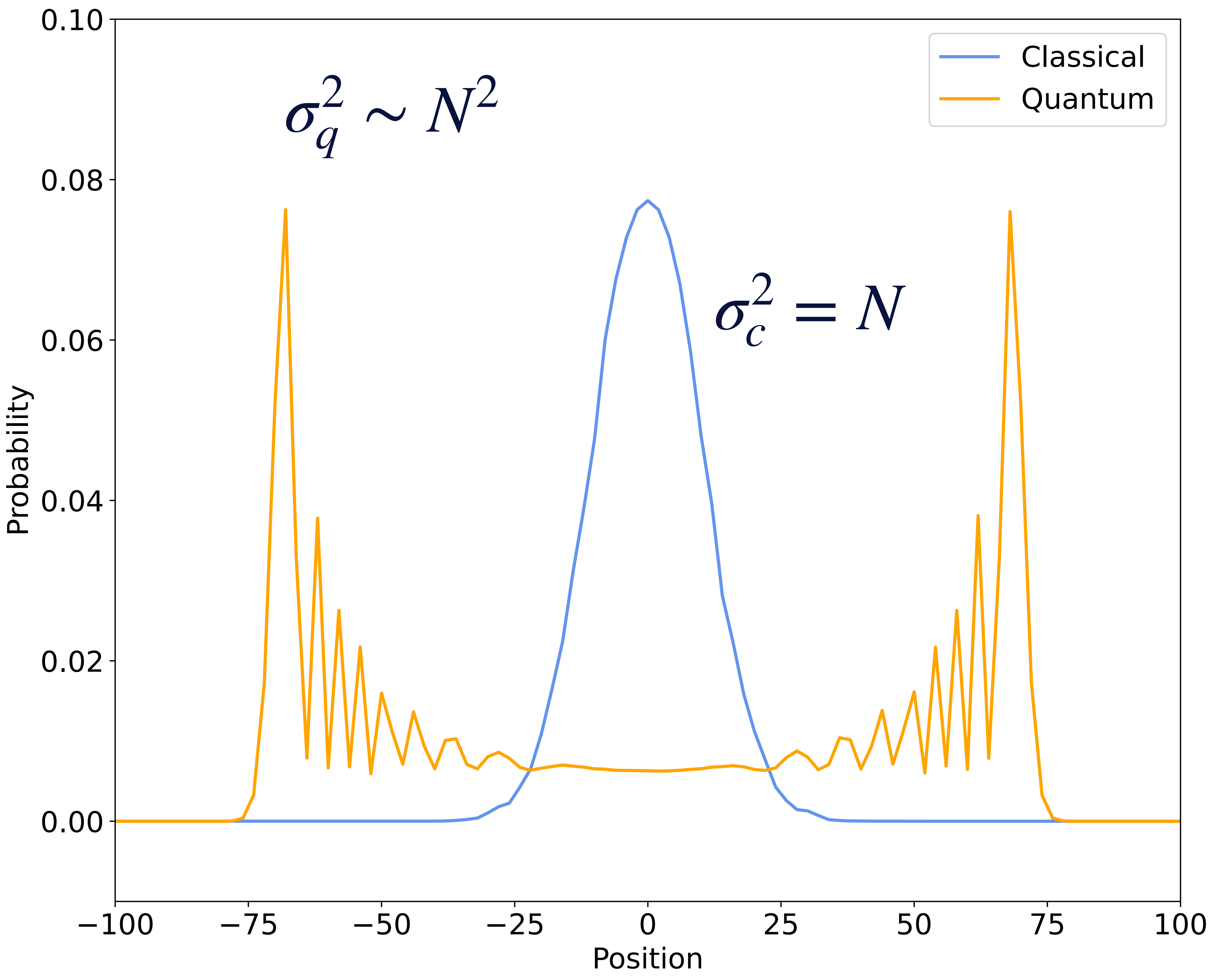
Speed up via Quantum Walks

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

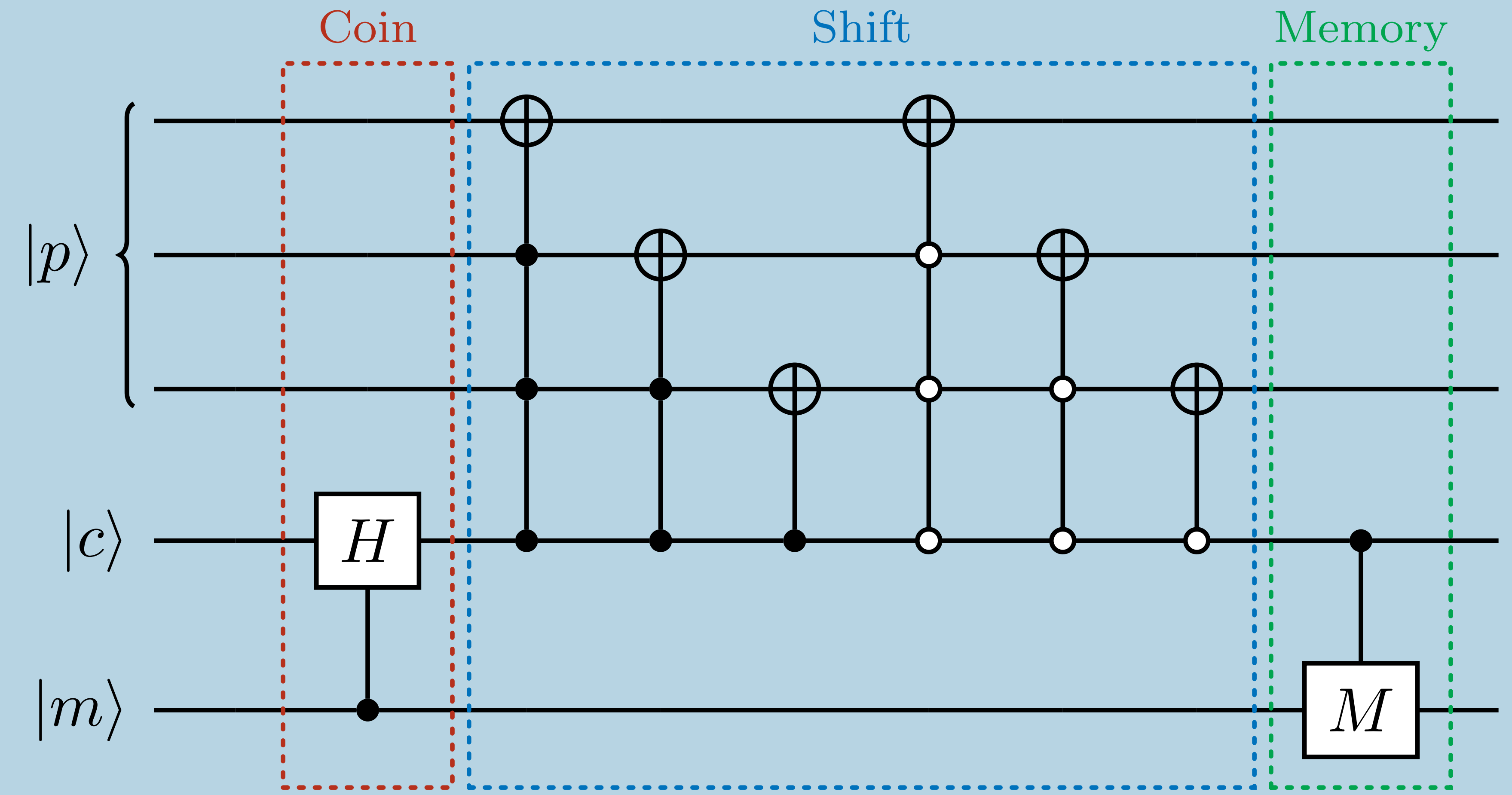
Szegedy Quantum Walks have been proven to achieve quadratic speed up for **Markov Chain Monte Carlo**

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



Qubit model:

Augment system further by adding an additional memory space

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

Advantages:

- Arbitrary dynamics
- Classical dynamics in unitary evolution

Disadvantages:

- Tight conditions on quantum advantage

Quantum Parton Showers:

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

K. Bepari, S. Malik, M. Spannowsky and SW, Phys. Rev. D 106 (2022) 5, 056002

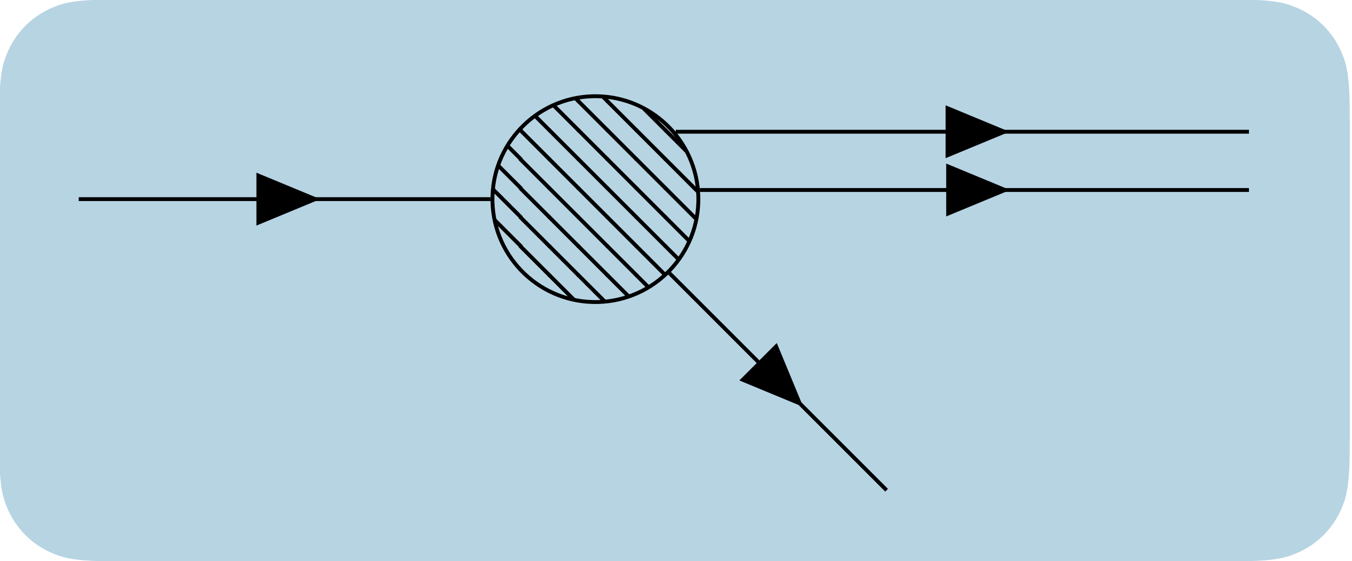
The Power of the Qubit! - Why are we interested in HEP?

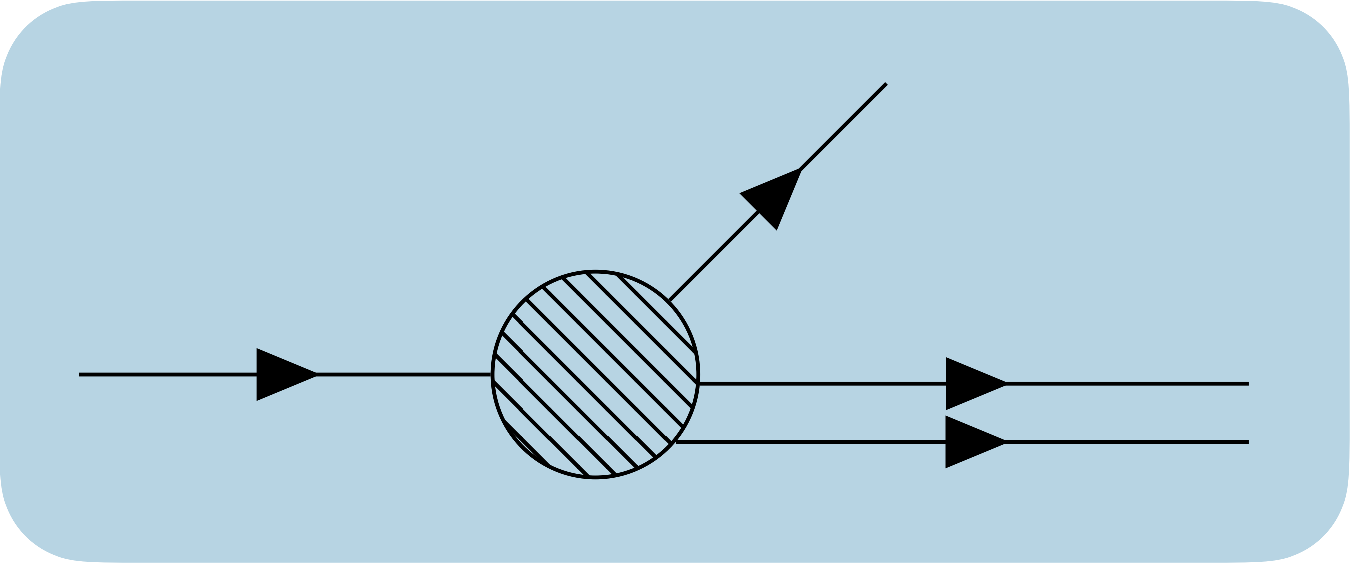

CMS
CMS Experiment at the LHC, CERN
Data recorded: 2021-Oct-19 13:01:24.690432 GMT
Run / Event / LS: 345881 / 17244 / 734


CMS Experiment at the LHC, CERN
Data recorded: 2016-Oct-11 10:44:24.059904 GMT
Run / Event / LS: 282842 / 47118579 / 25

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

Parton Density Functions

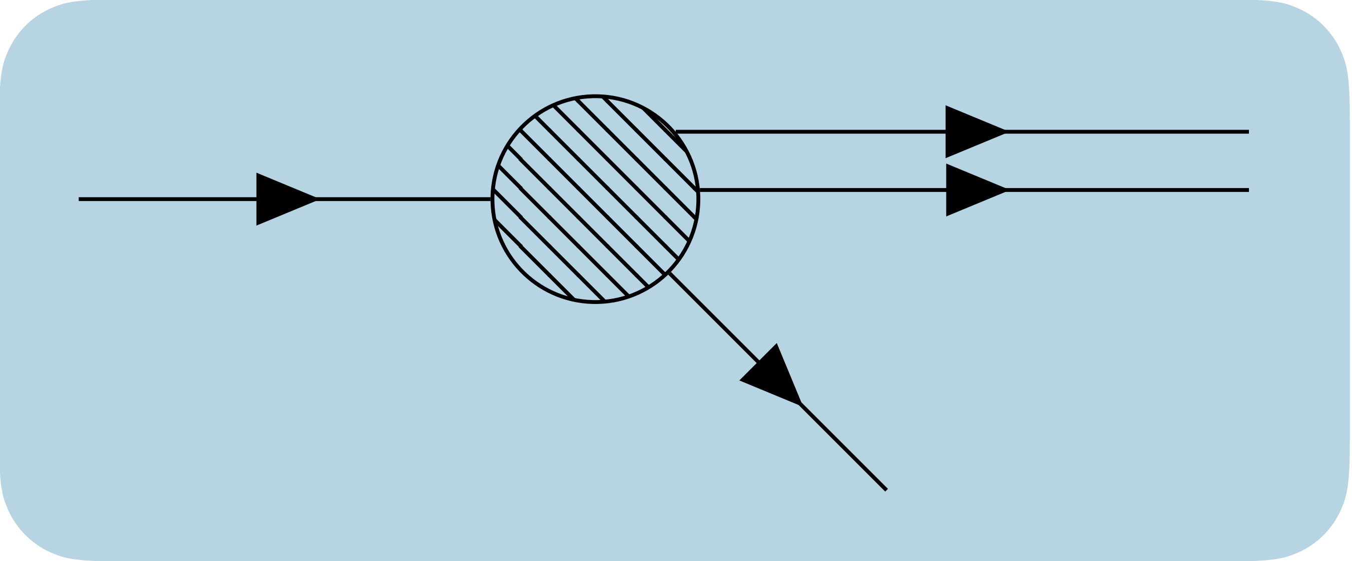




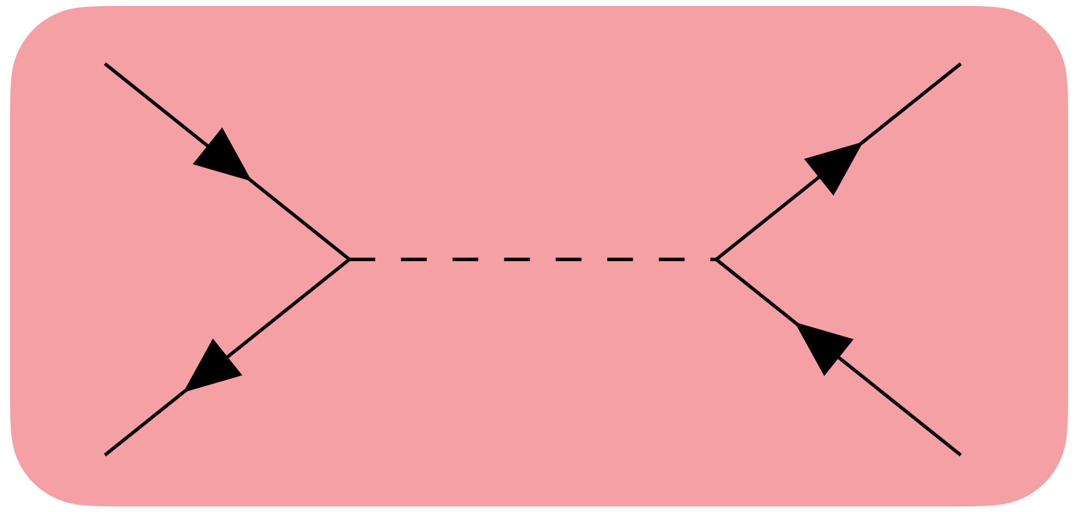
Phys. Rev. D 103, 034027

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

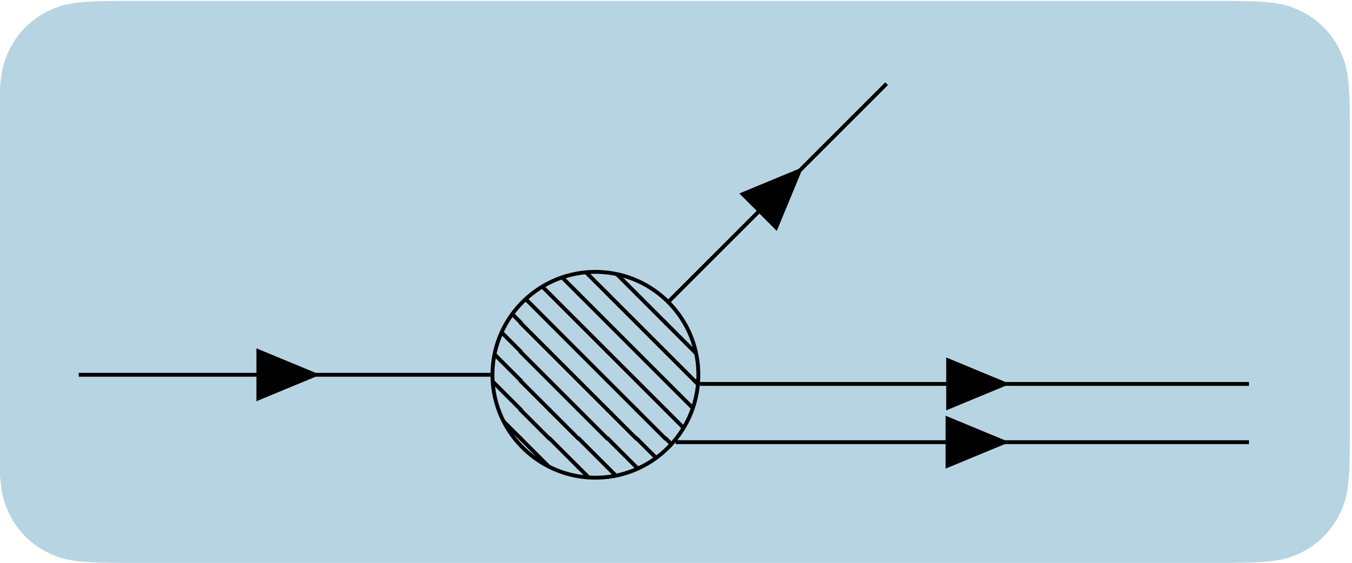
Parton Density Functions



Hard Process



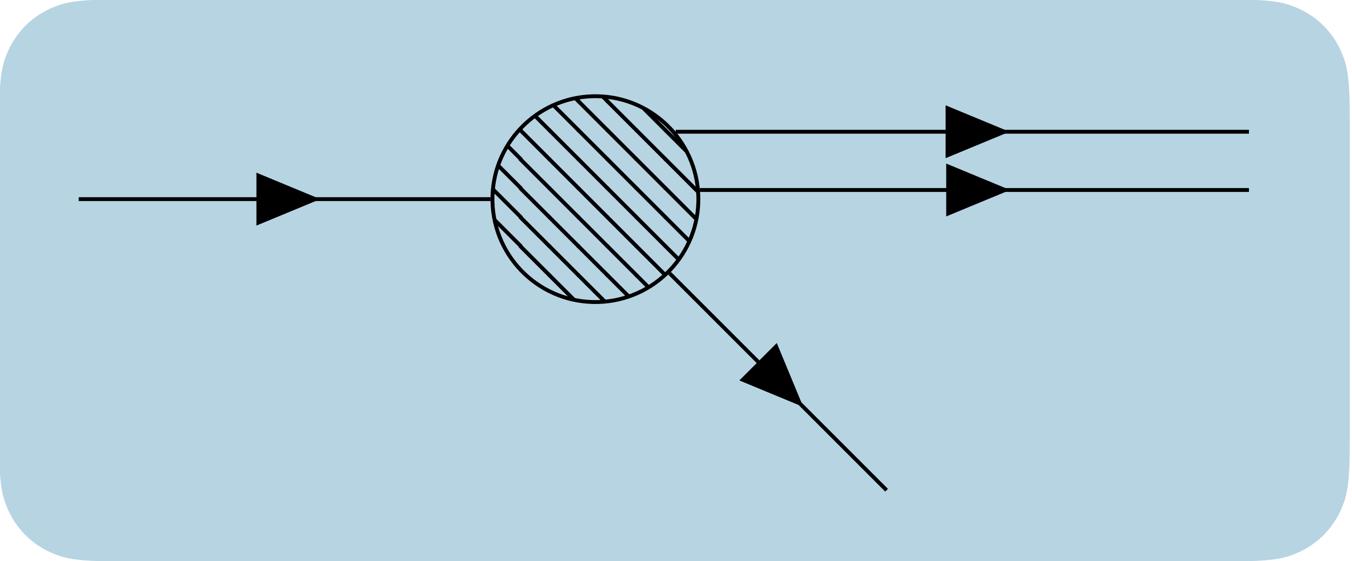
[Phys. Rev. D 103, 076020]



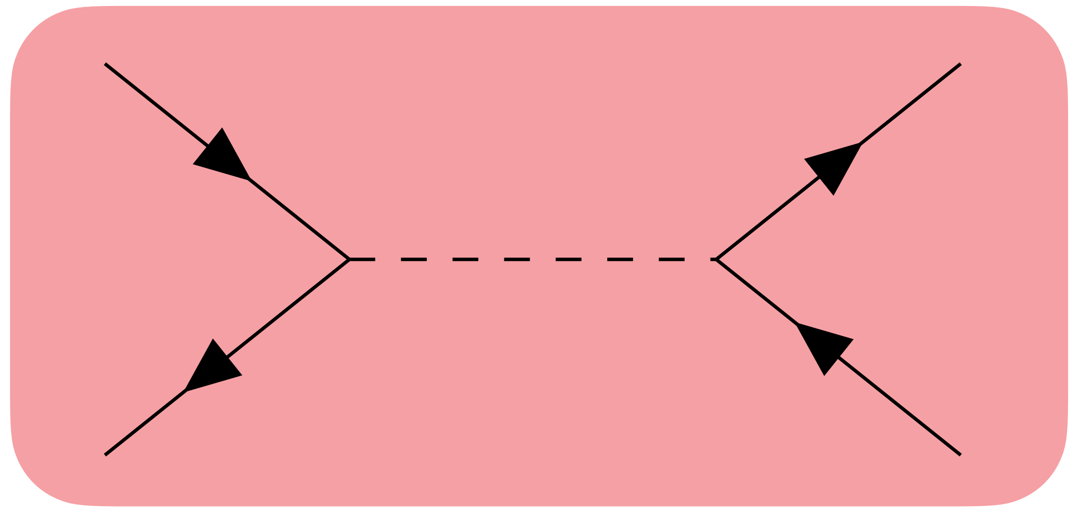
[Phys. Rev. D 103, 034027]

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

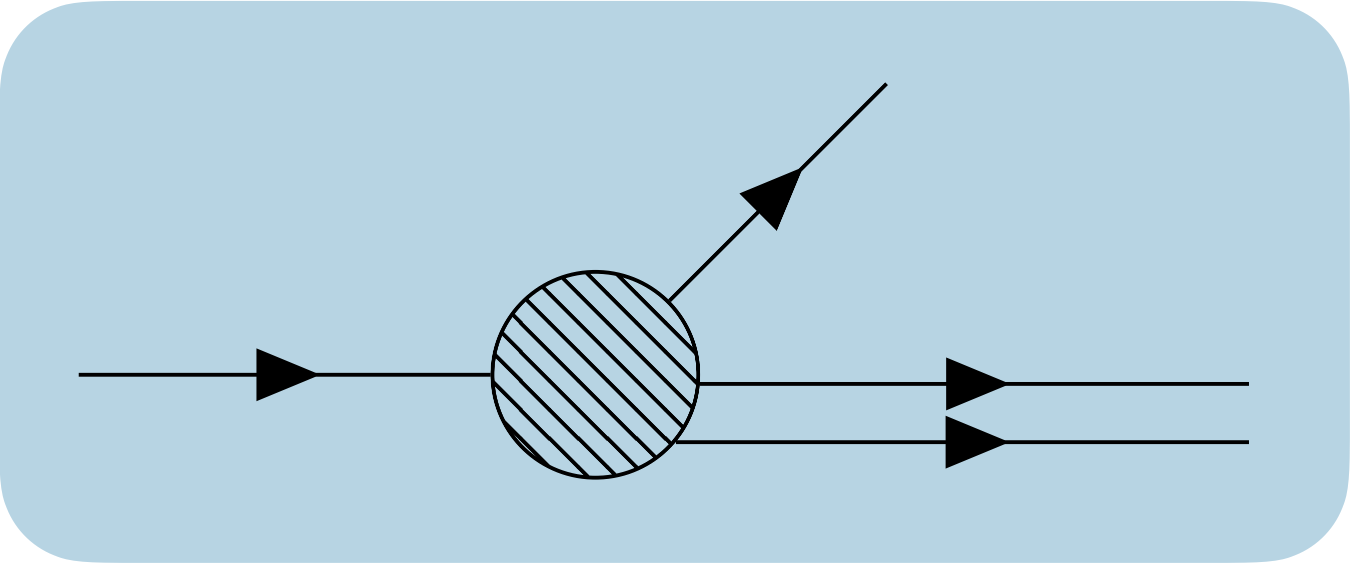
Parton Density Functions



Hard Process

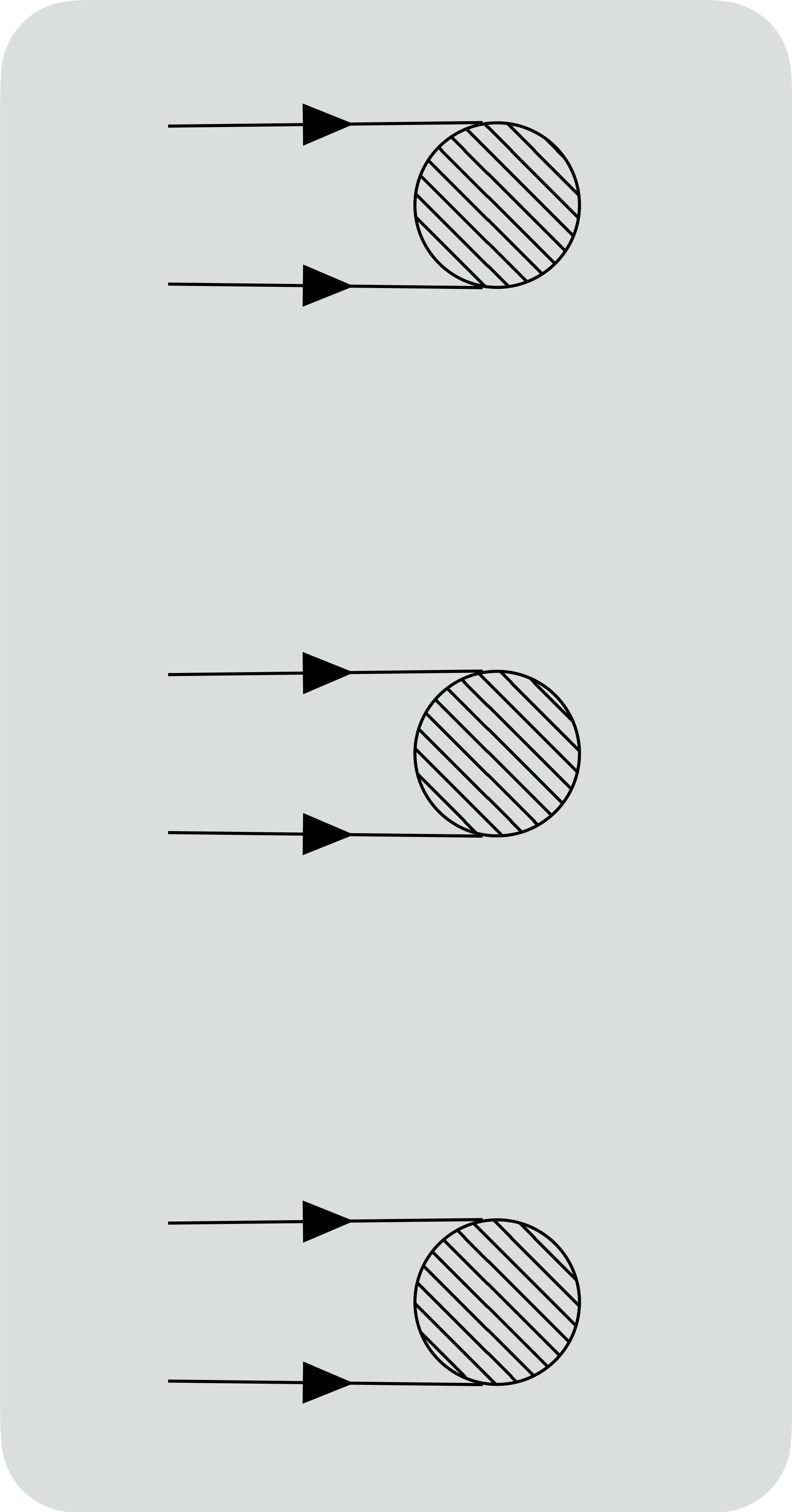


Phys. Rev. D 103, 076020



Phys. Rev. D 103, 034027

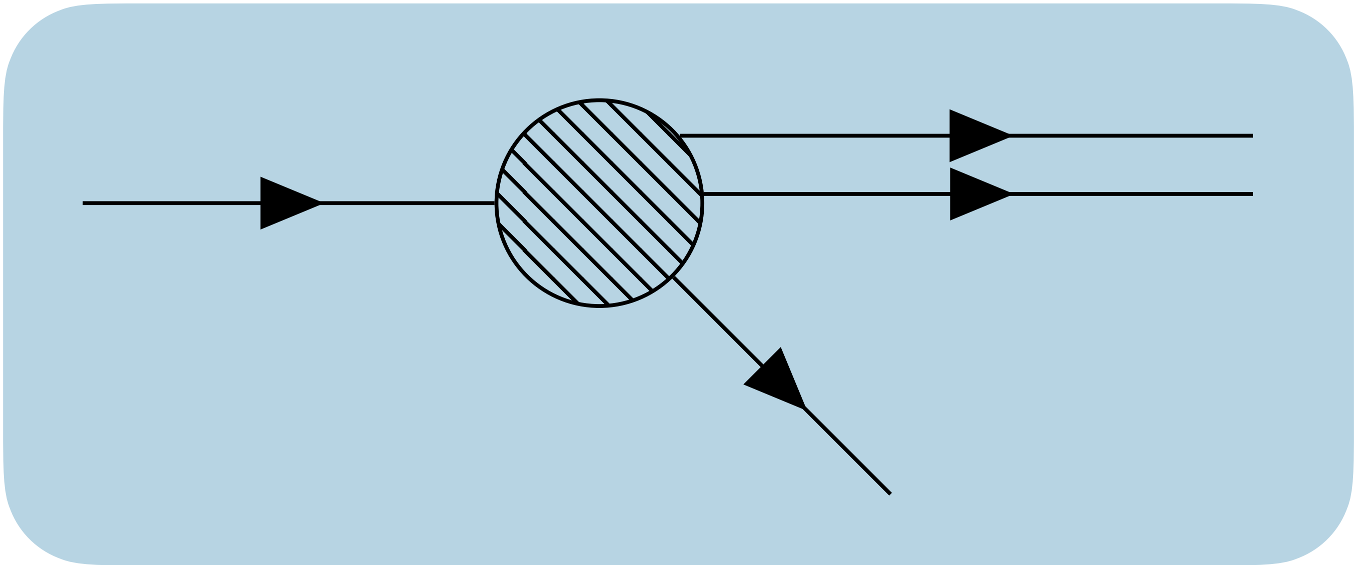
Hadronisation



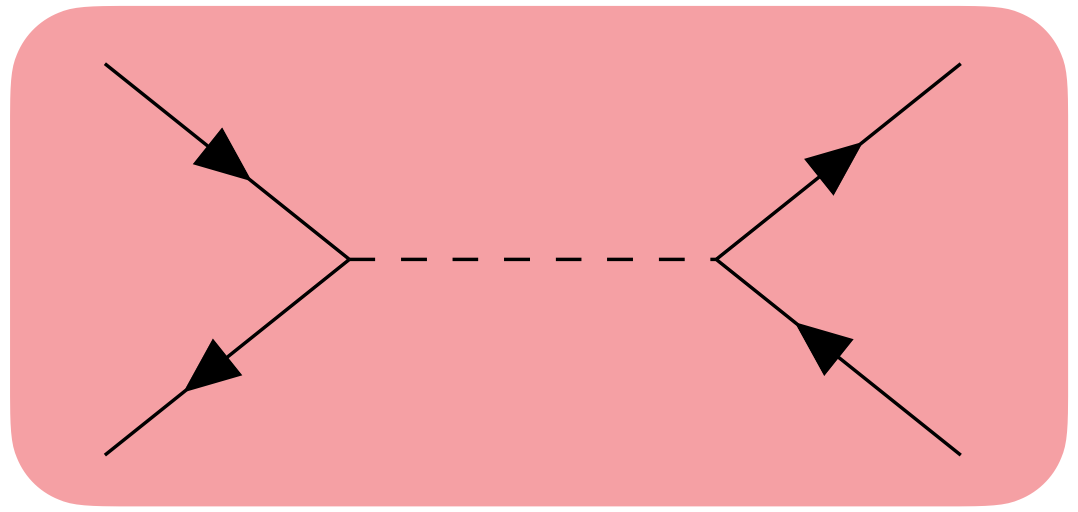
JHEP 11 (2022) 035

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

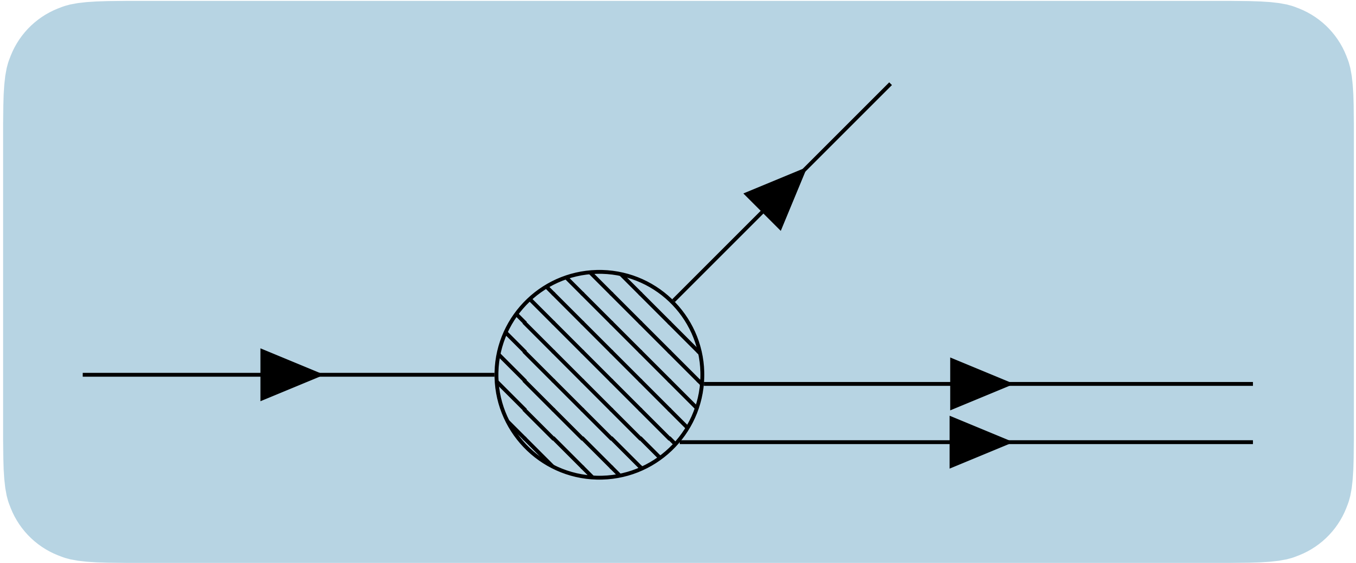
Parton Density Functions



Hard Process



[Phys. Rev. D 103, 076020]

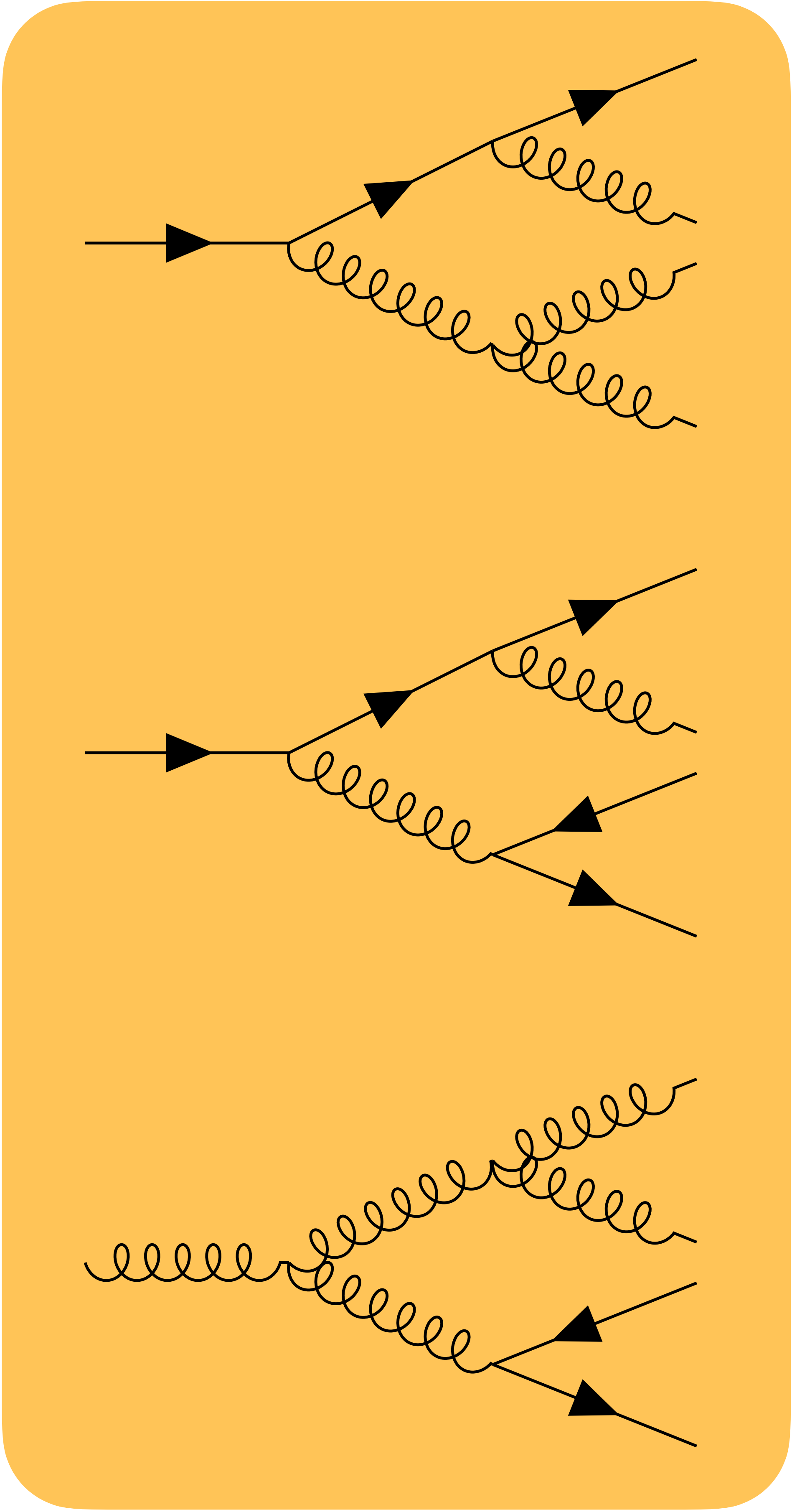


[Phys. Rev. D 106, 056002]

[Phys. Rev. D 103, 034027]

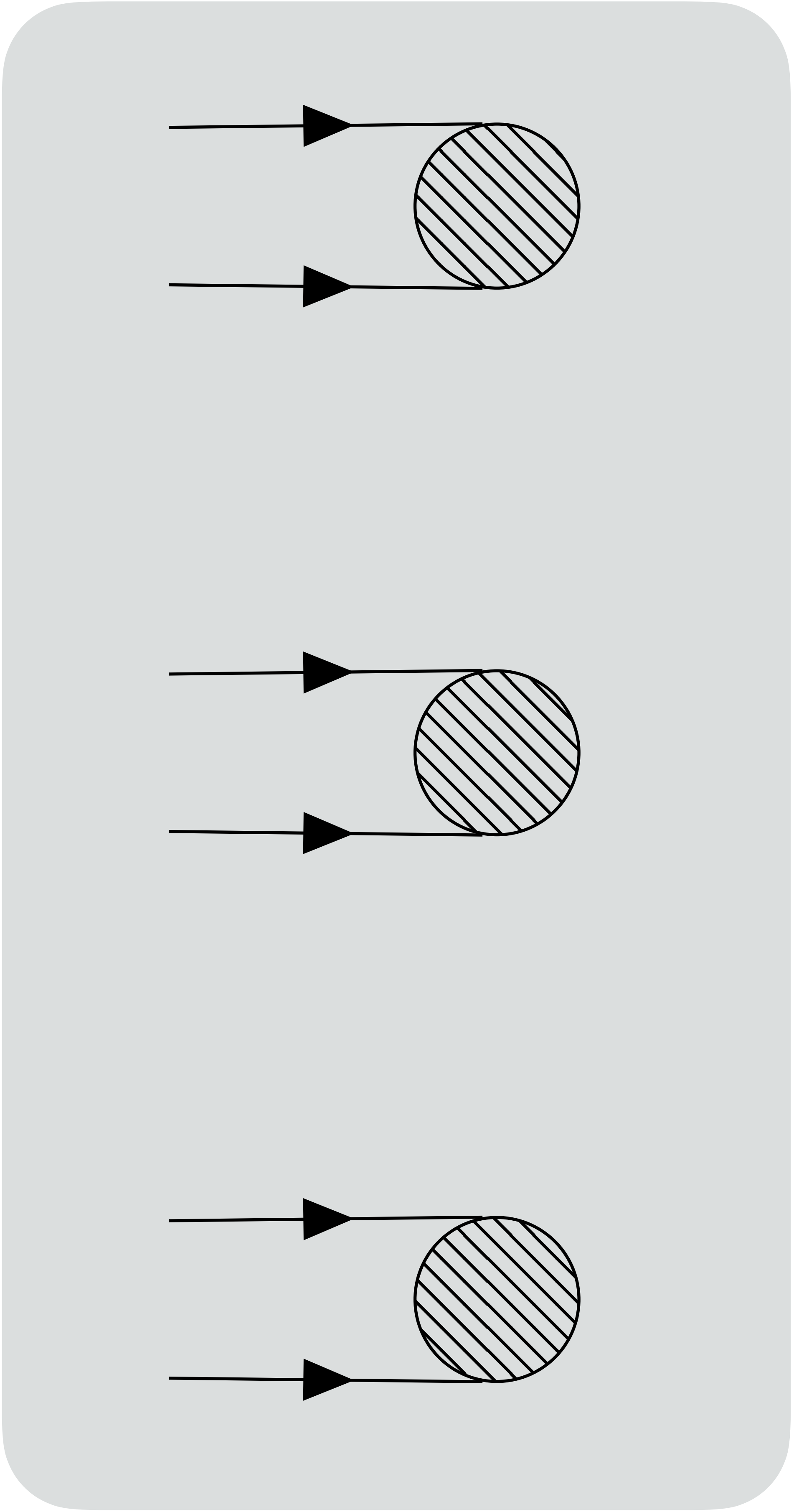
[Phys. Rev. Lett. 126, 062001]

Parton Shower



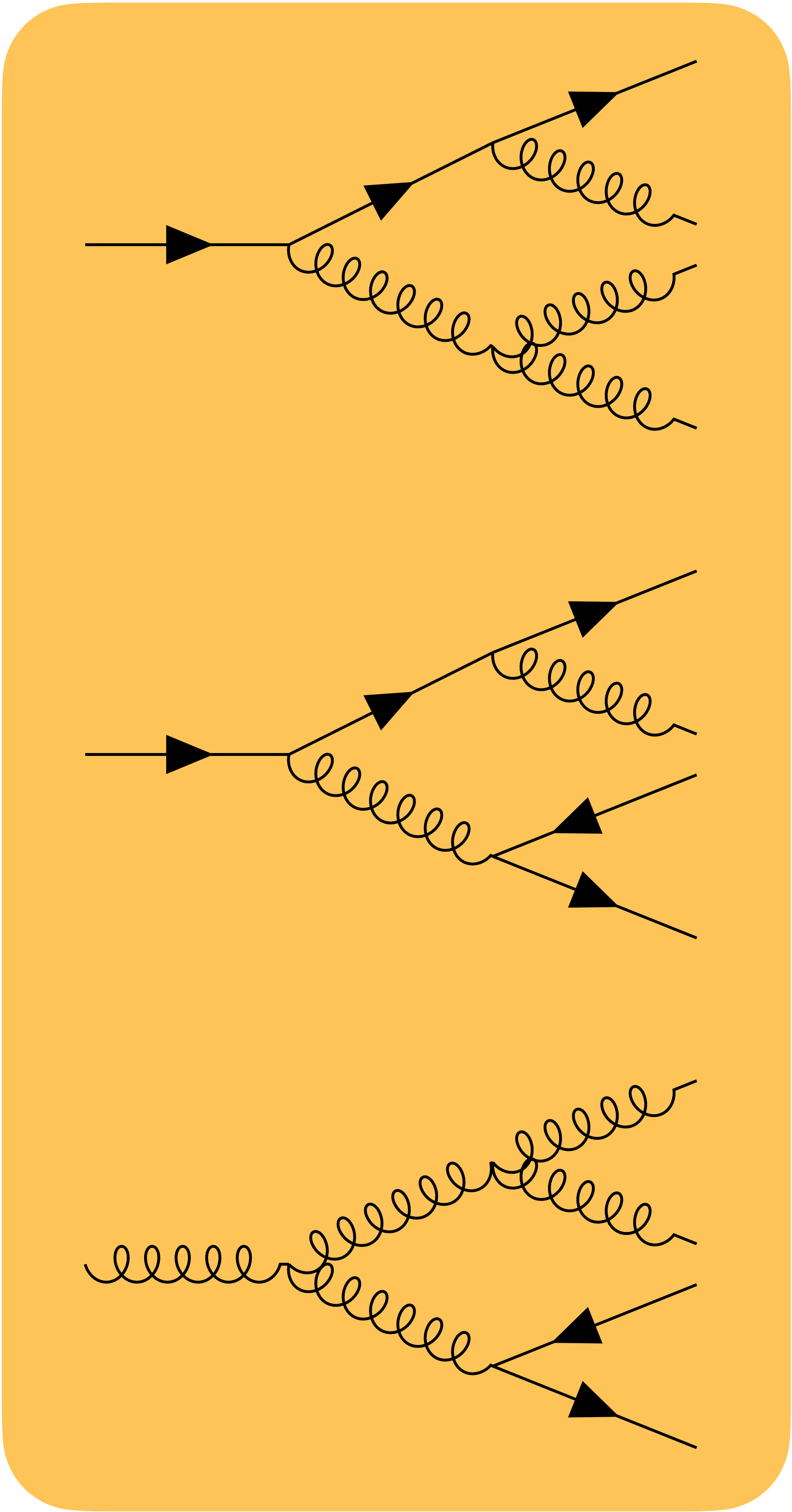
[JHEP 11 (2022) 035]

Hadronisation

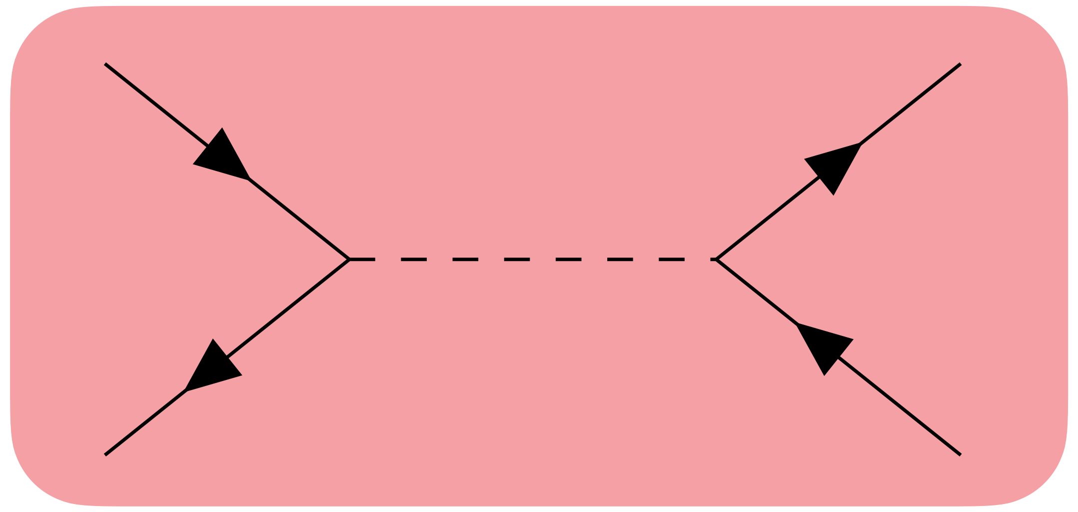


The Power of the Qubit! - Why are we interested in HEP?

Parton Shower



Hard Process



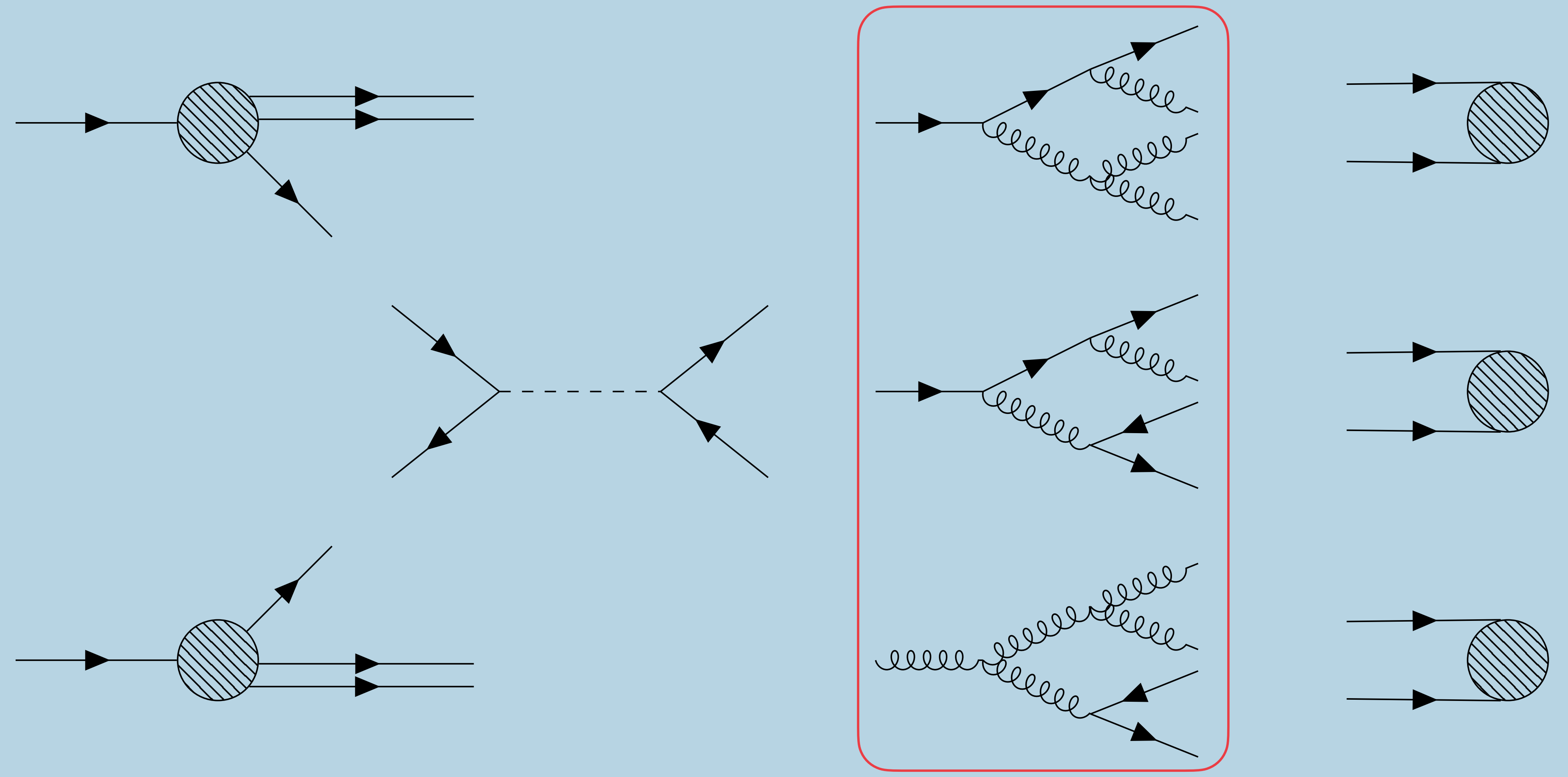
Phys. Rev. D 103, 076020

Phys. Rev. D 106, 056002

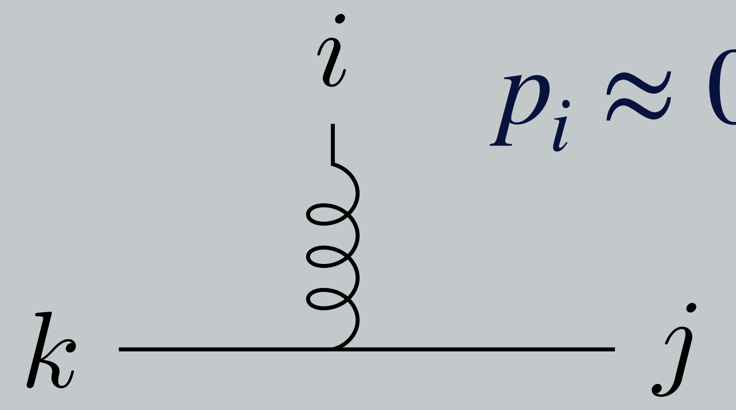
Phys. Rev. Lett. 126, 062001

JHEP 11 (2022) 035

The Parton Shower



Soft mode:

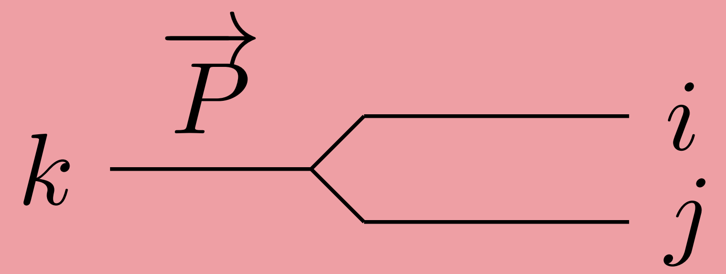


$p_i \approx 0$

Interference effects only allow for partial factorisation

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

Collinear mode:



$p_i = zP, \quad p_j = (1-z)P$

Successive decay steps factorise into independent quasi-classical steps

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 ξ and t is known as the **phase space parameterisation**

Non-Emission Probability

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

Master Equation

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

Inclusive Decay Probability

$$d\mathcal{P}\left(q(p_{\mathrm{I}})\bar{q}(p_{\mathrm{K}}) \to q(p_i) g(p_j) \bar{q}(p_k)\right) \simeq \frac{ds_{ij}}{s_{\mathrm{IK}}} \frac{ds_{jk}}{s_{\mathrm{IK}}} C \frac{\alpha_s}{2\pi} \frac{2 s_{\mathrm{IK}}}{s_{ij} s_{jk}}$$

Current interpretations of the veto algorithm treat the phase space variables ξ and t as **continuous**

Collider Events on a Quantum Computer

Gösta Gustafson,[a] **Stefan Prestel,**[a] **Michael Spannowsky,**[b] **Simon Williams**[c]

[a] *Department of Astronomy and Theoretical Physics, Lund University, S-223 62 Lund, Sweden*

[b] *Institute for Particle Physics Phenomenology, Department of Physics, Durham University, Durham DH1 3LE, U.K.*

[c] *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_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.

Building on B. Andersson, G. Gustafson and J. Samuelsson, Nucl. Phys. B 463 (1996) 217

Discrete QCD - Abstracting the Parton Shower Method

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

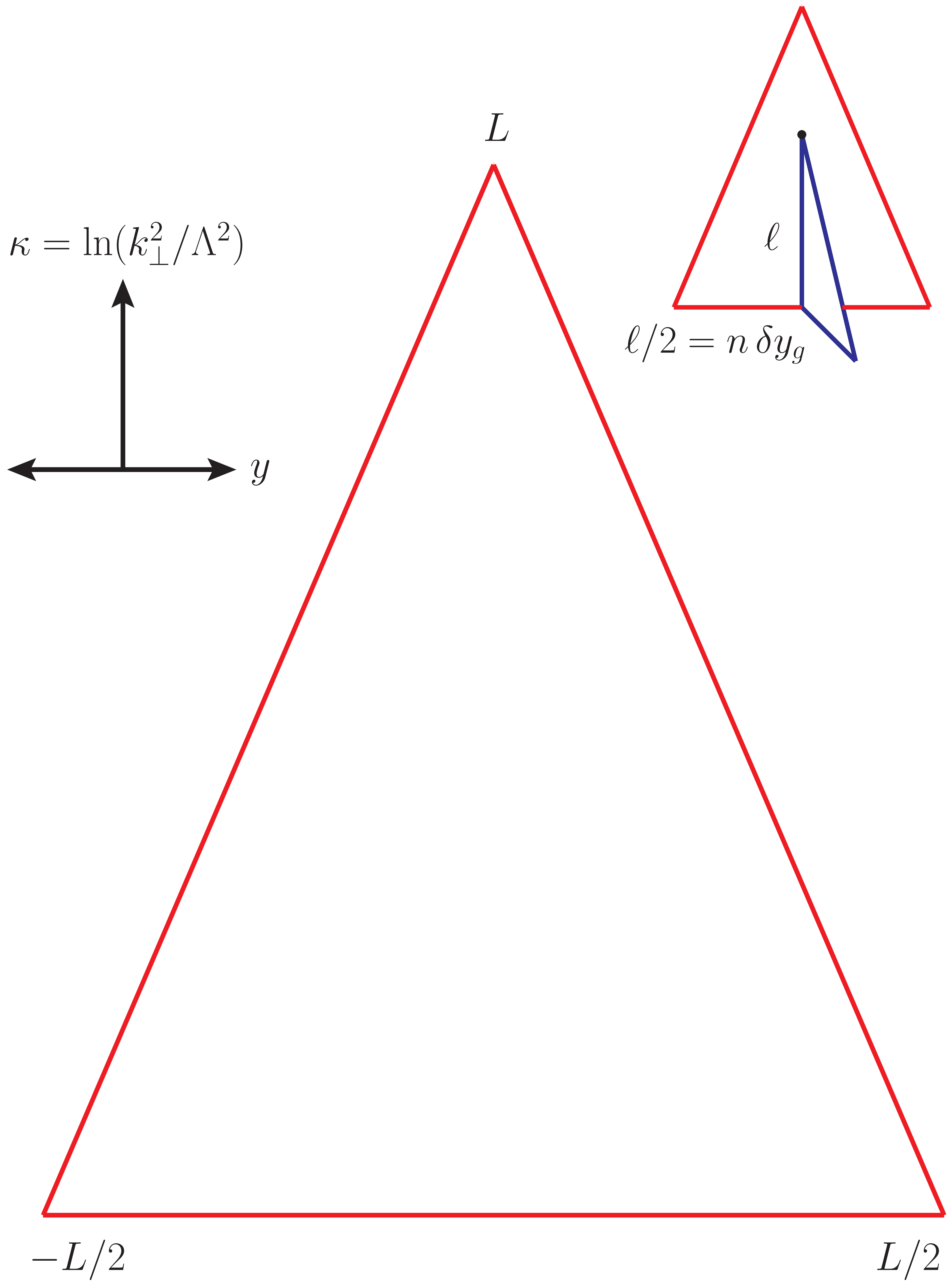
$$k_\perp^2 = \frac{s_{ij}s_{jk}}{s_{\mathrm{IK}}} \qquad \text{and} \qquad y = \frac{1}{2}\ln\left(\frac{s_{ij}}{s_{jk}}\right)$$

which leads to the inclusive probability:

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

where $\kappa = \ln\left(\frac{k_\perp^2}{\Lambda^2}\right)$ and $\boldsymbol{\Lambda}$ 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 $g \to q\bar{q}$ splittings and examine transverse-momentum-dependent running coupling

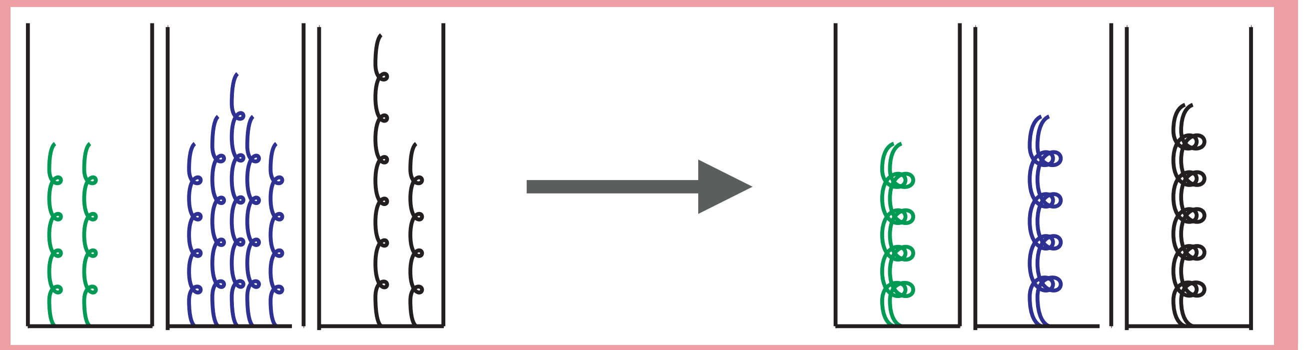
$$\alpha_s(k_\perp^2) = \frac{12\pi}{33 - 2n_f} \frac{1}{\ln(k_\perp^2/\Lambda_{\rm QCD}^2)}$$

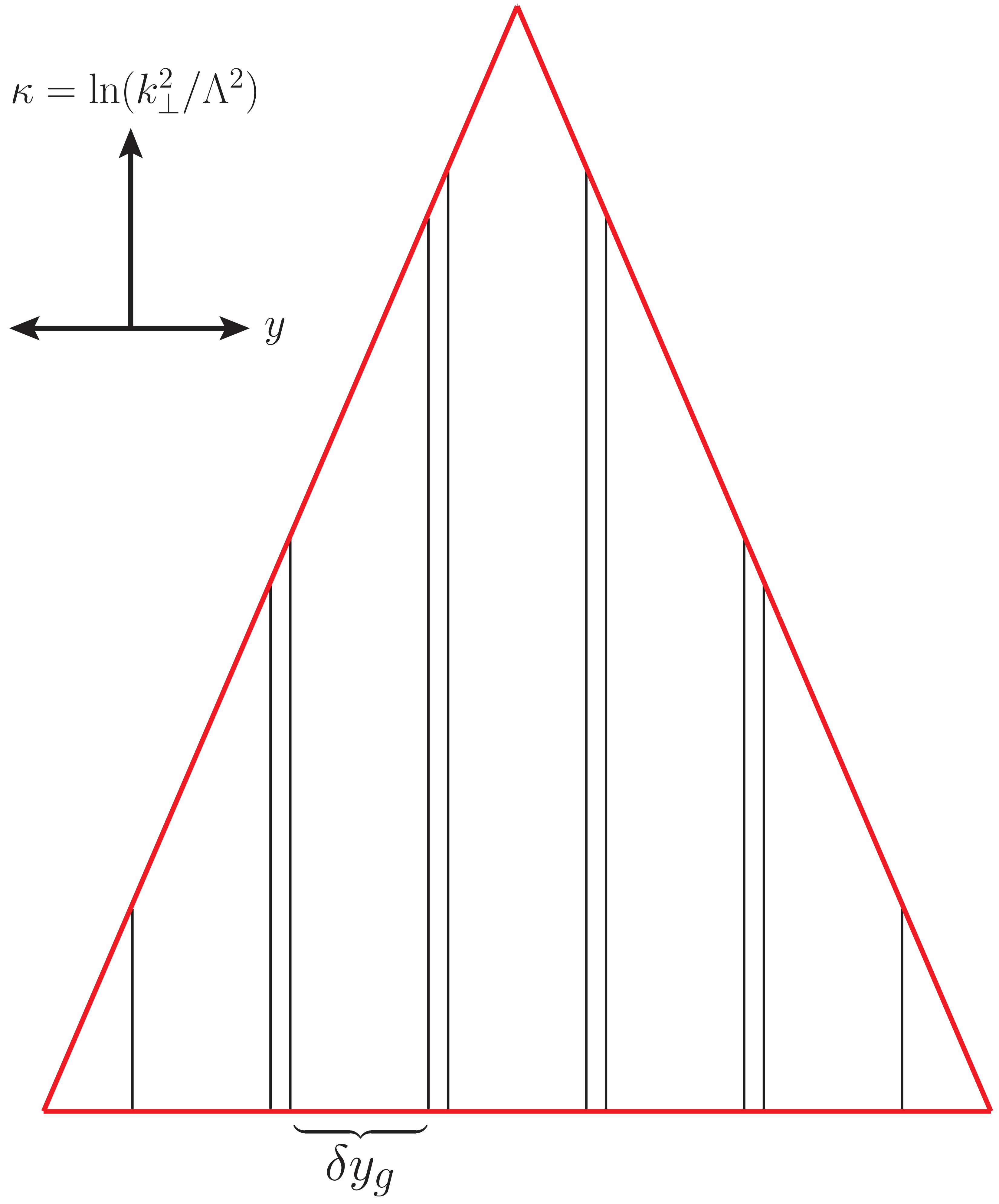
leads to the inclusive probability

$$d\mathcal{P}\left(q(p_{\rm I})\bar{q}(p_{\rm K}) \to q(p_i)g(p_j)\bar{q}(p_k)\right) \simeq= \frac{d\kappa}{\kappa}\frac{dy}{\delta y_g} \quad \text{with} \quad \delta y_g = \frac{11}{6}$$

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

Gluons within δy_g act coherently as one effective gluon





Discrete QCD - Abstracting the Parton Shower Method

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

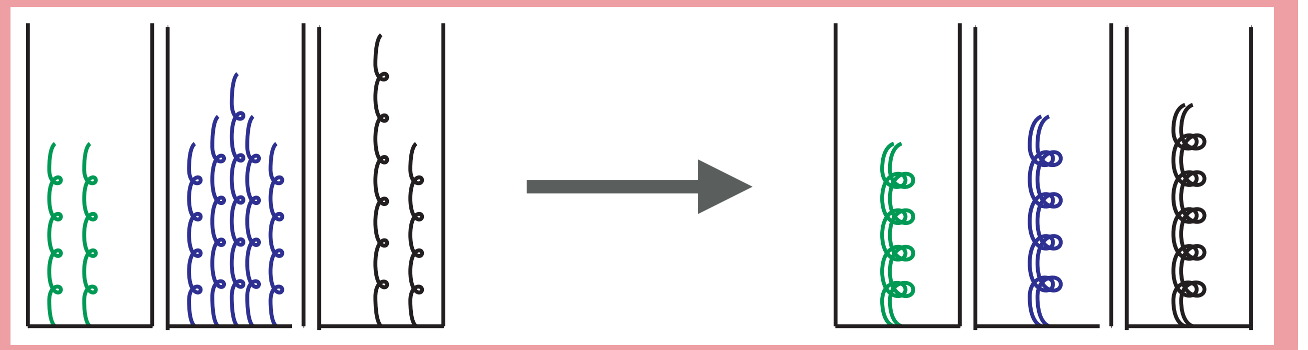
$$\alpha_s(k_\perp^2) = \frac{12\pi}{33 - 2n_f} \frac{1}{\boxed{\ln(k_\perp^2/\Lambda_{\mathrm{QCD}}^2)}} = \frac{\text{const.}}{\kappa}$$

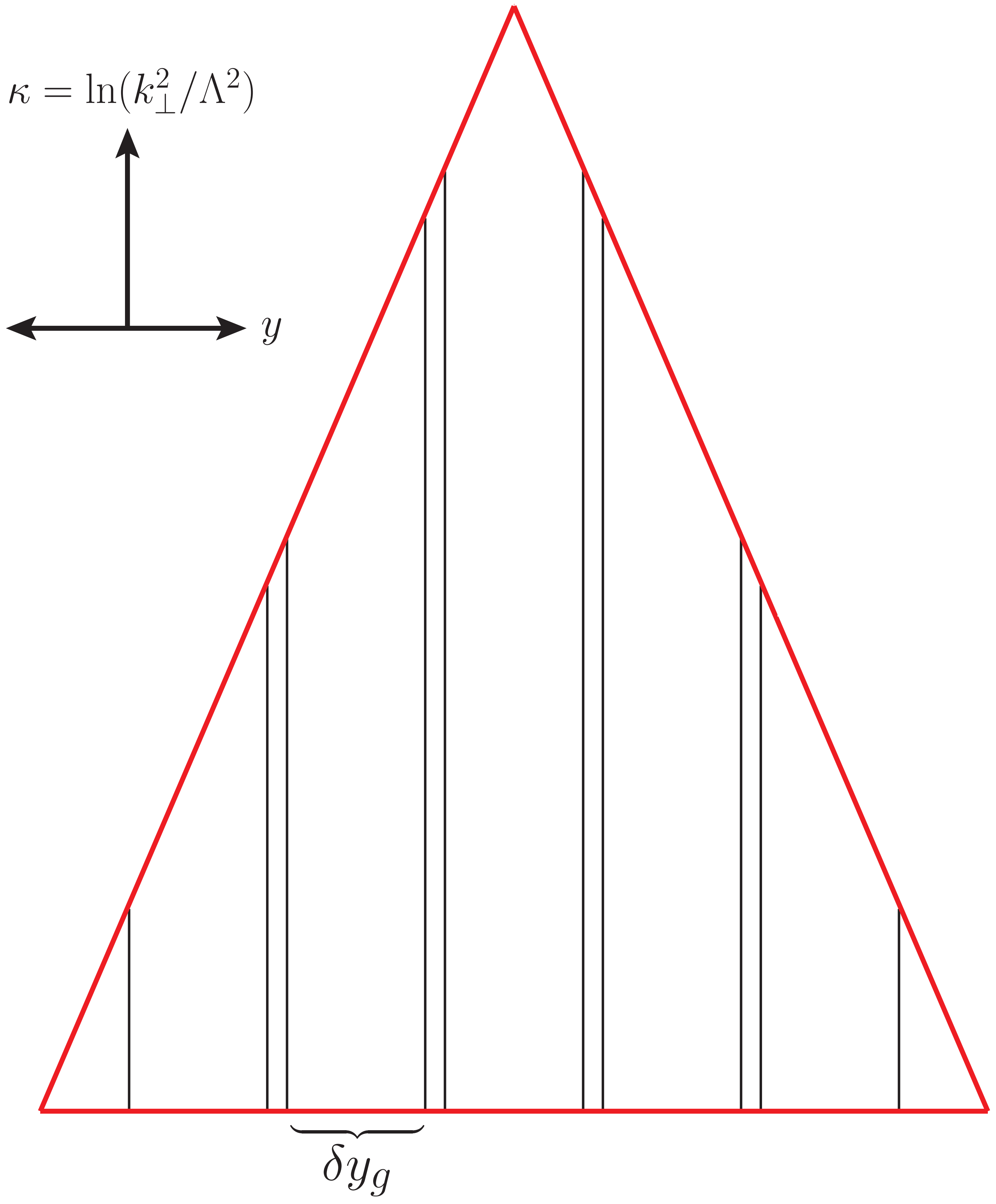
leads to the inclusive probability

$$d\mathcal{P}\left(q(p_\mathrm{I})\bar{q}(p_\mathrm{K}) \to q(p_i)g(p_j)\bar{q}(p_k)\right) \simeq= \frac{d\kappa}{\kappa}\frac{dy}{\delta y_g} \quad \text{with} \quad \delta y_g = \frac{11}{6}$$

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

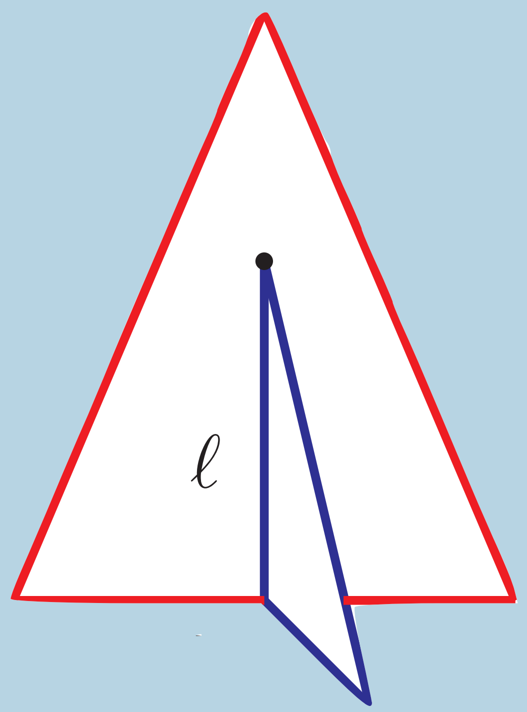
Gluons within δy_g act coherently as one effective gluon





Discrete QCD - Abstracting the Parton Shower Method

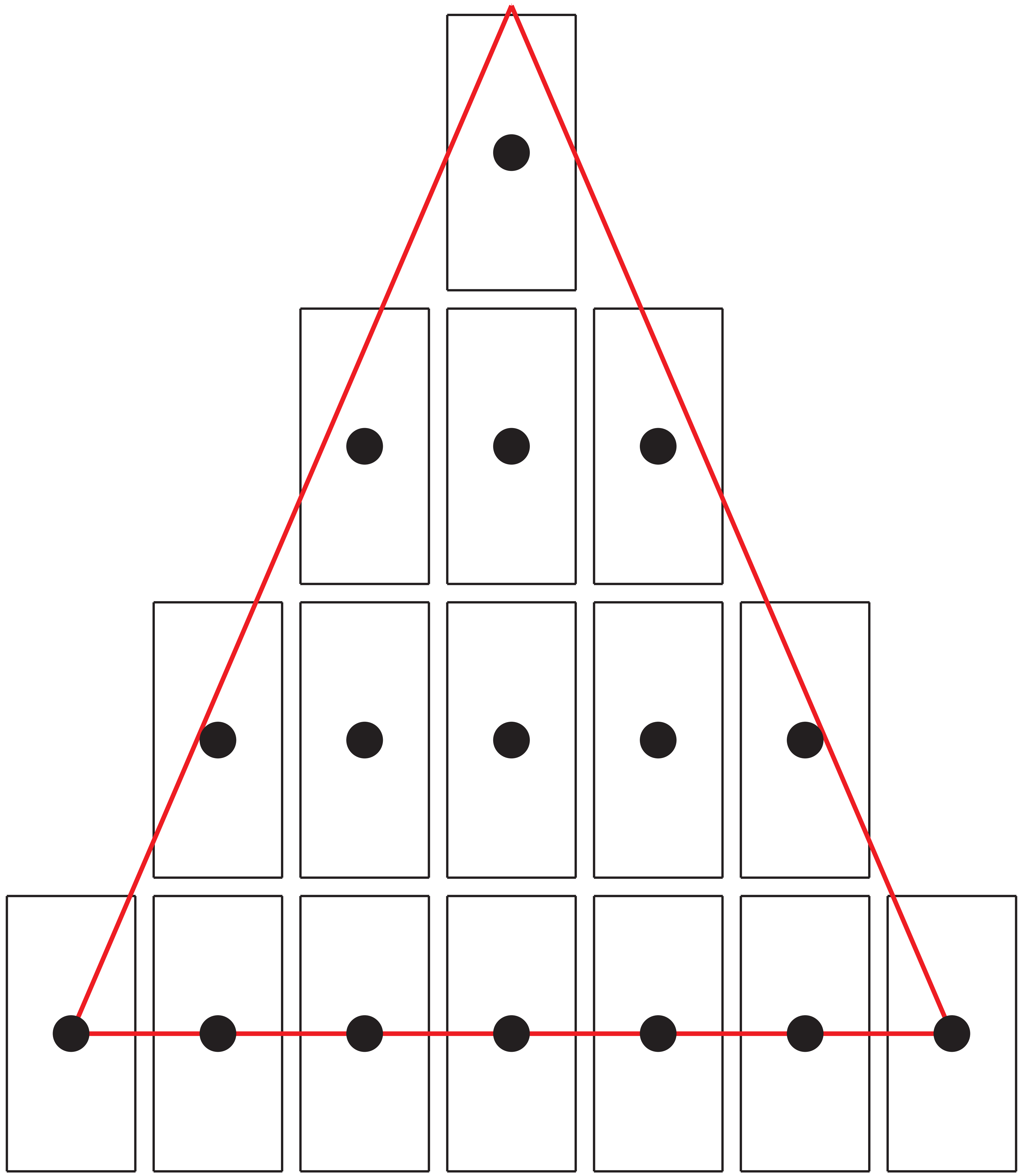
Folding out extends the baseline of the triangle to positive y by $\frac{l}{2}$, where l is the height at which to emit effective gluons



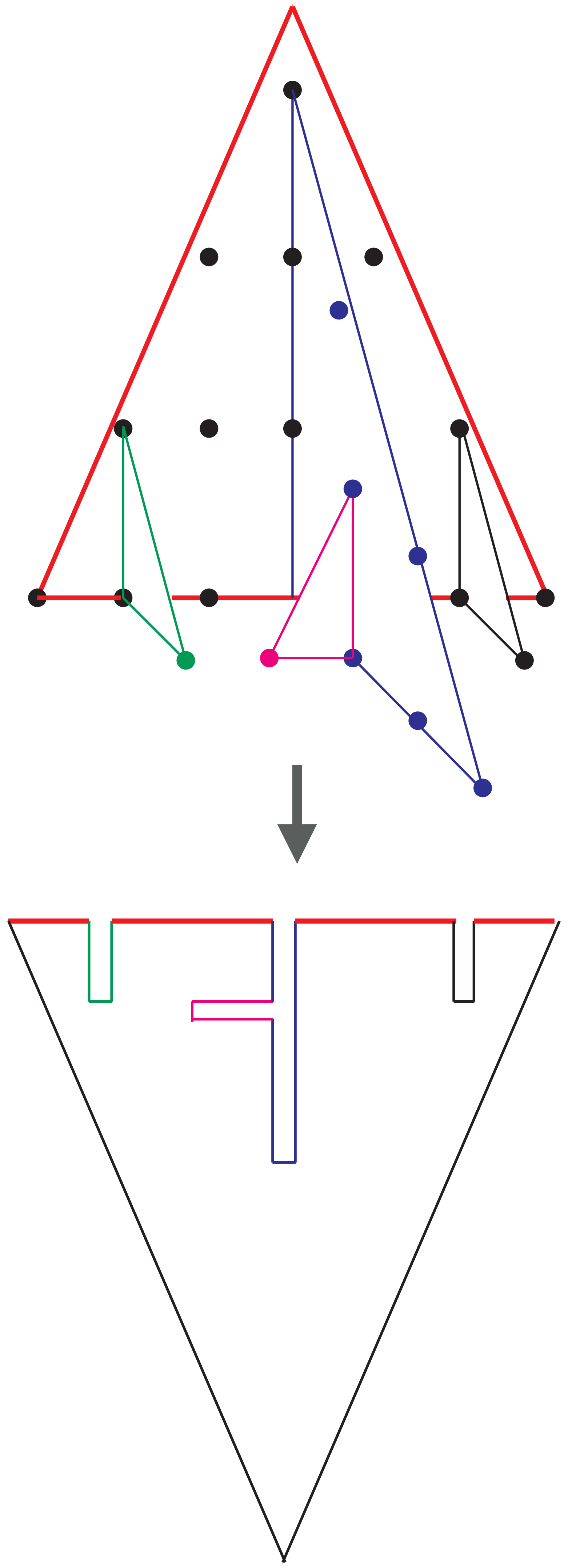
A consequence of folding is that the κ axis is quantised into multiples of $2\delta y_g$

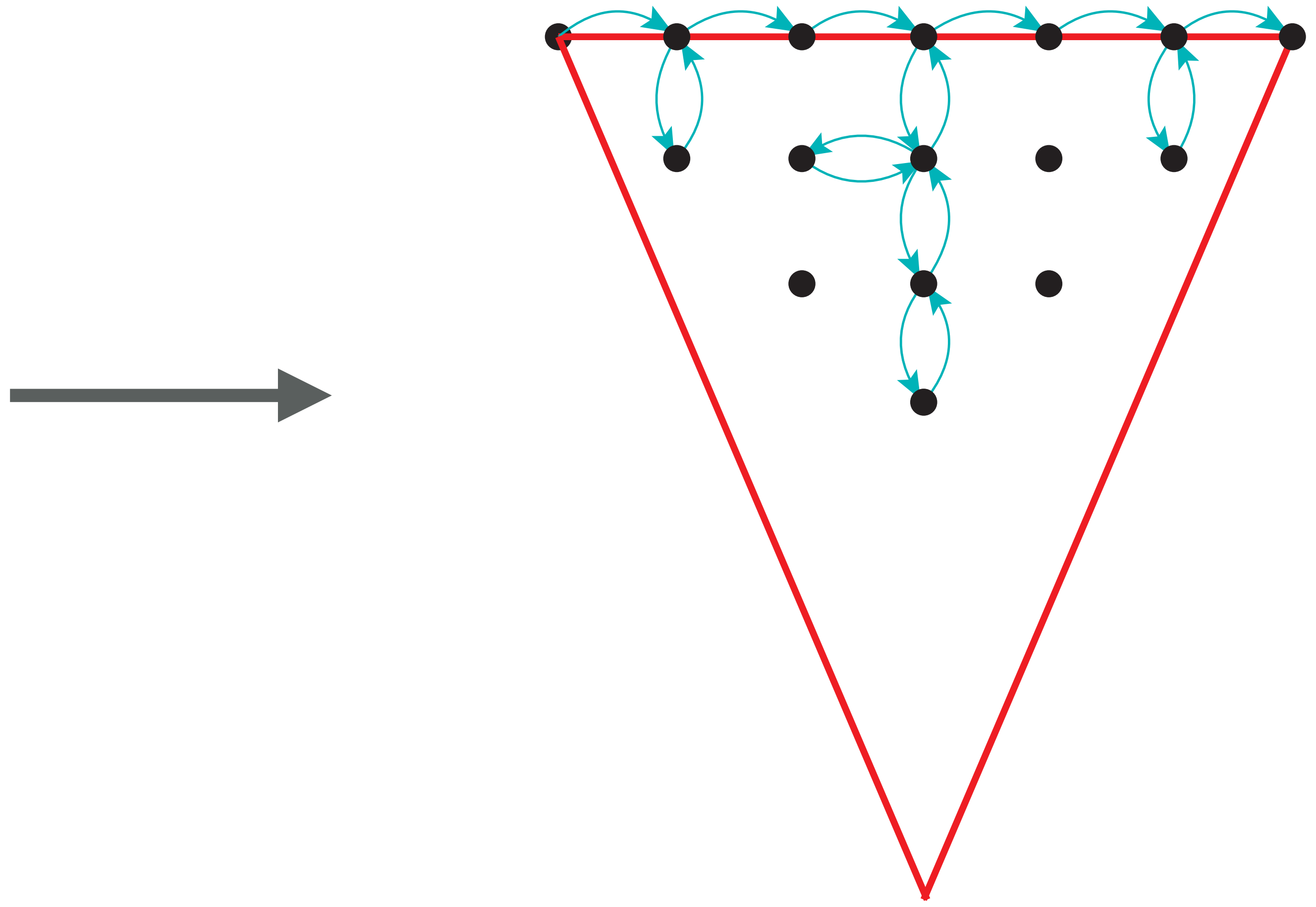
Each rapidity slice can be treated independently of any other slice. The exclusive rate probability takes the simple form:

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



Discrete QCD as a Quantum Walk

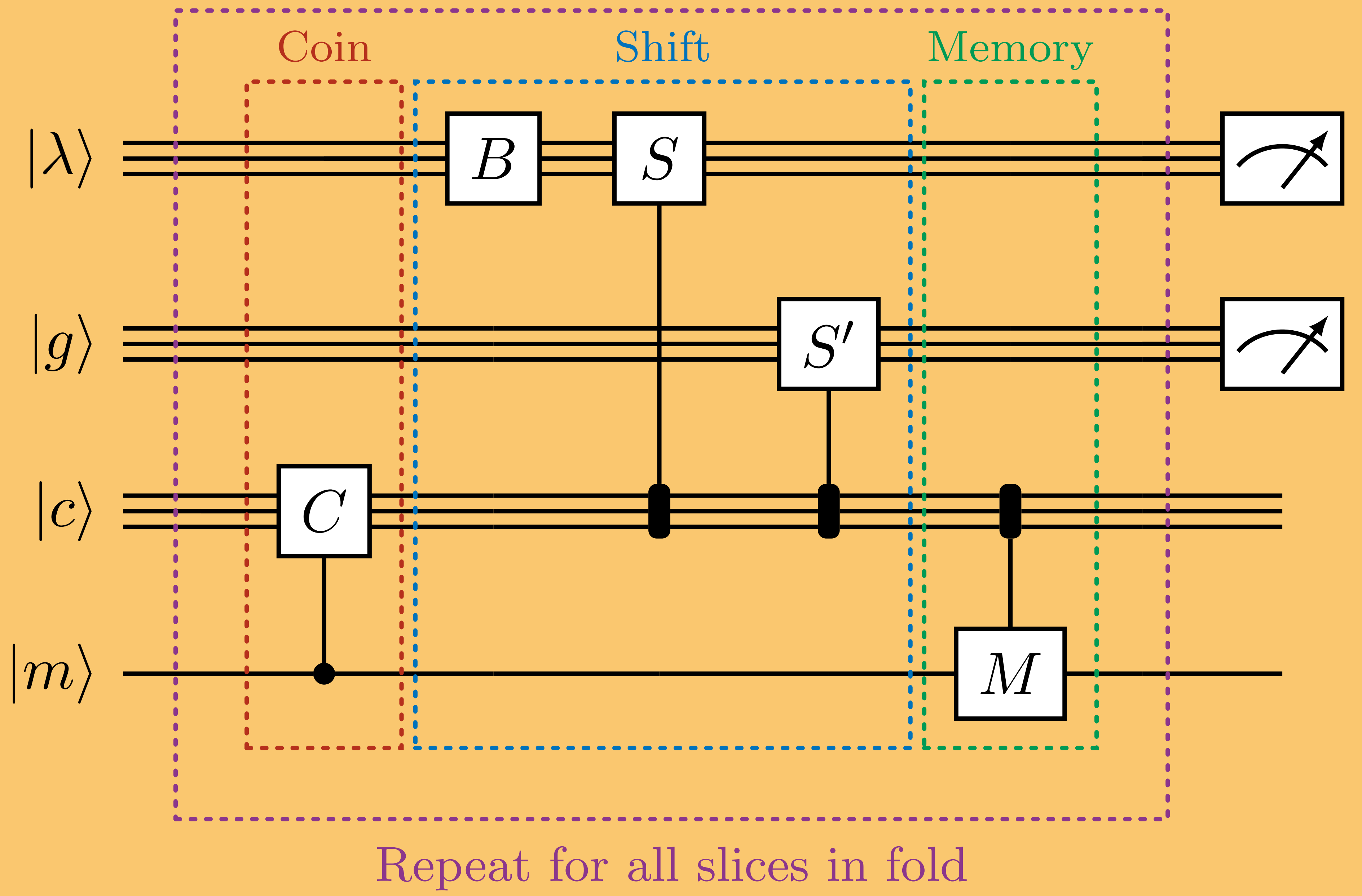




The **baseline** of the grove structure contains all kinematics information

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

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



Generating Scattering Events from Groves

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

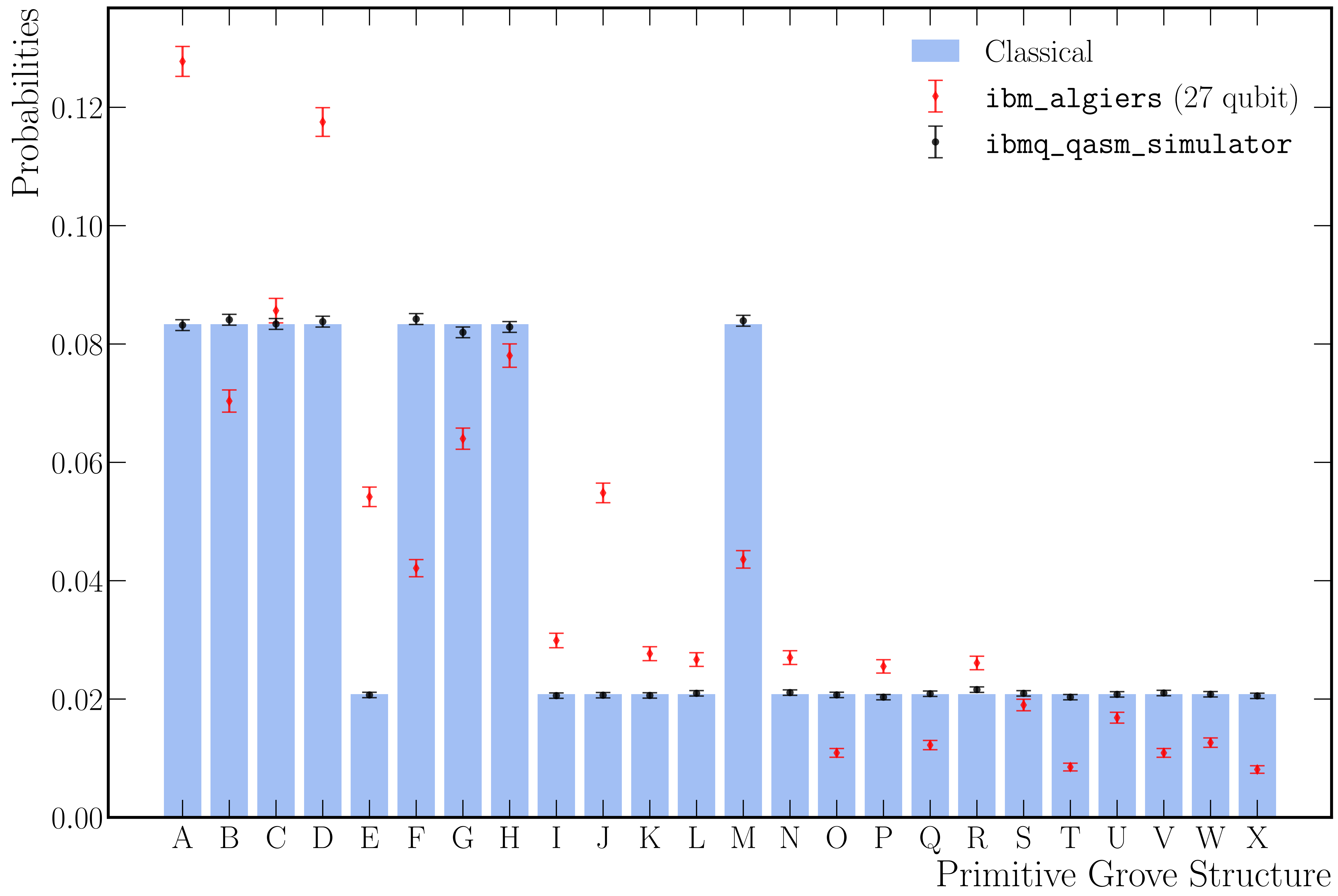
1. Create the highest κ effective gluons first (i.e. go from top to bottom in phase space)

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

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) 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.

Discrete QCD as a Quantum Walk - Raw Grove Simulation



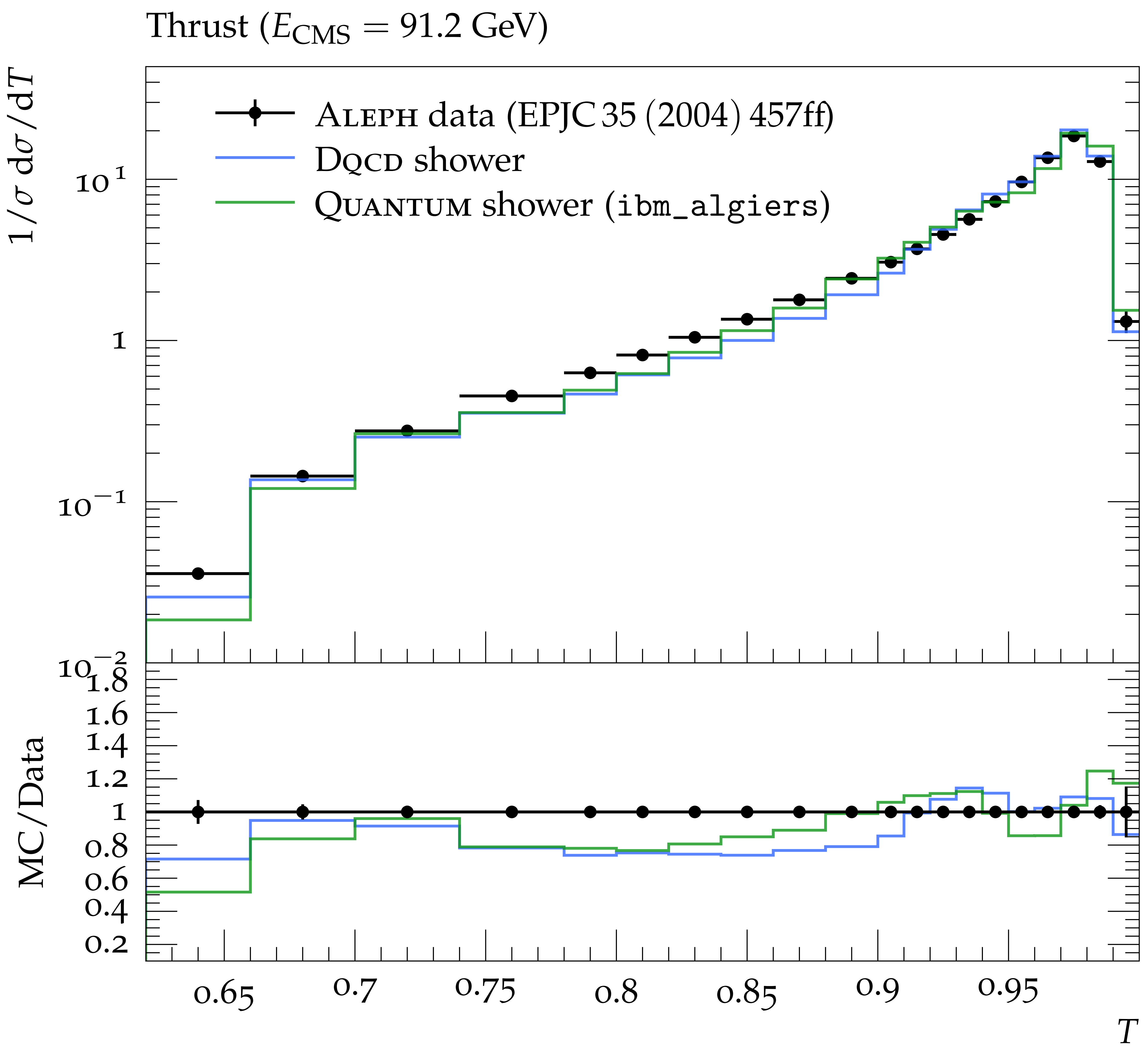
The algorithm has been run on the **IBM Falcon 5.11r chip**

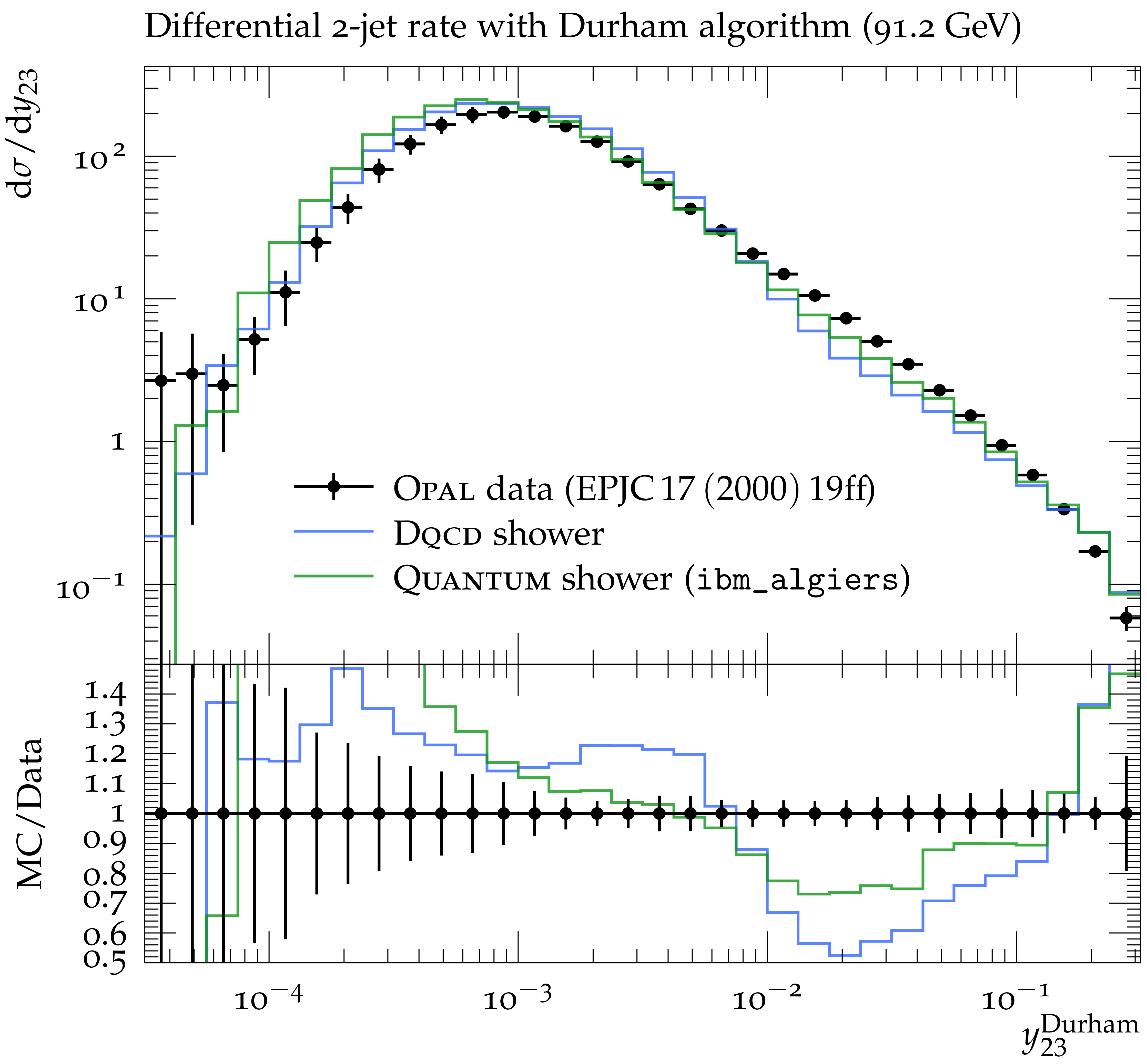
The figure shows the uncorrected performance of the **ibm_algiers** device compared to a simulator

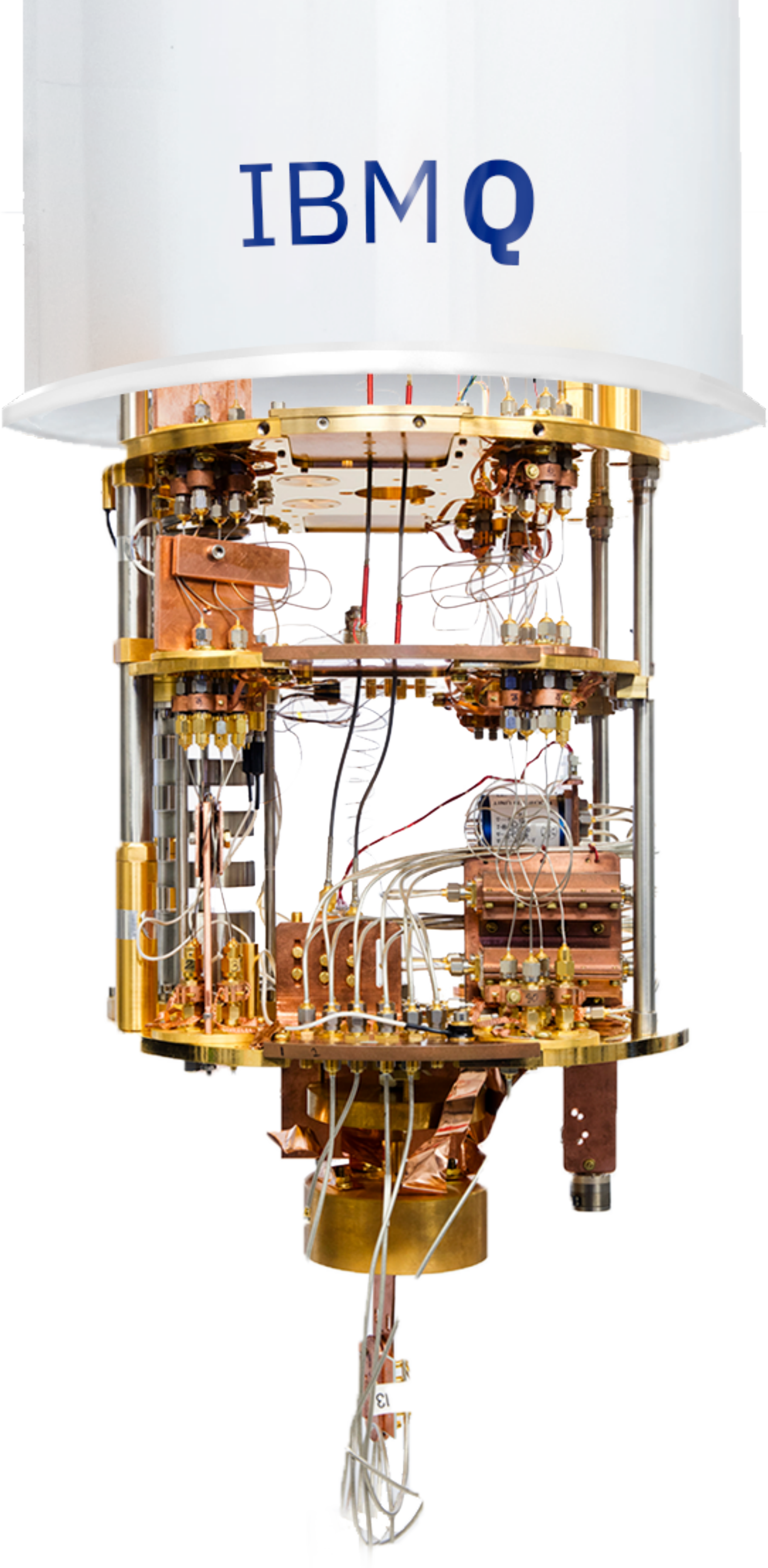
The 24 grove structures are generated for a $E_{CM} = 91.2$ GeV, corresponding to typical collisions at LEP.

Main source of error from CNOT errors from large amount of SWAPs

Collider Events on a Quantum Computer







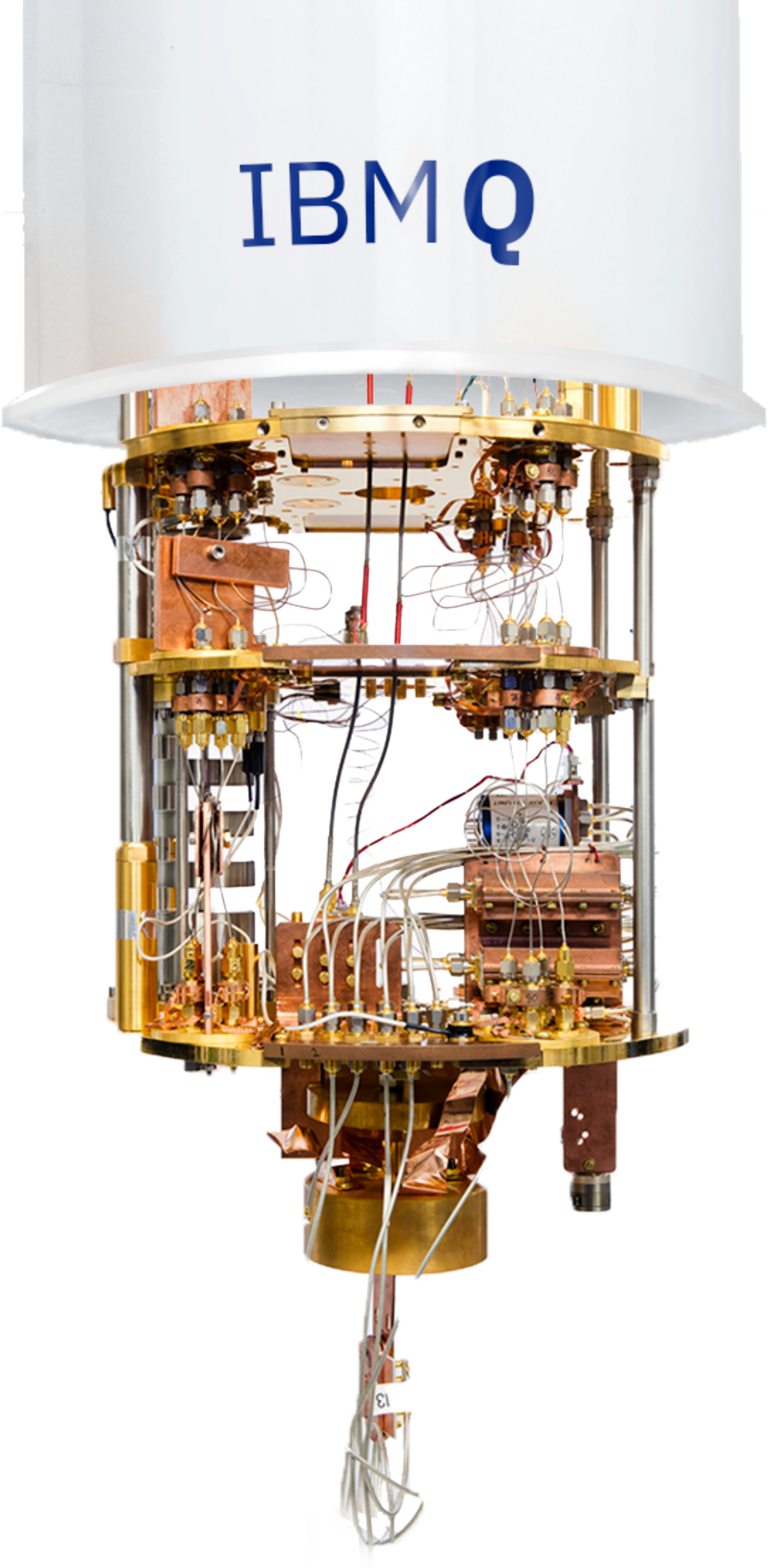
Summary

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

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**



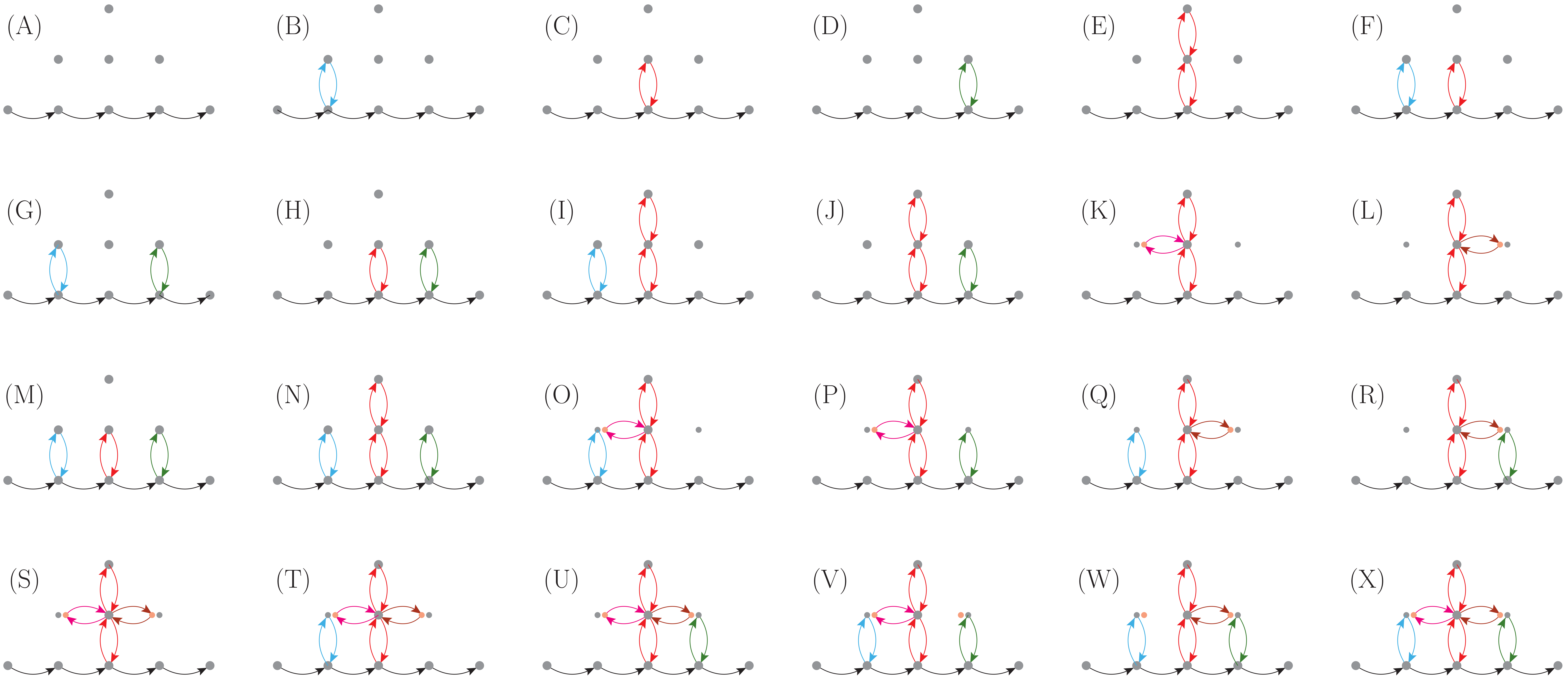
Imperial College
London

Backup Slides

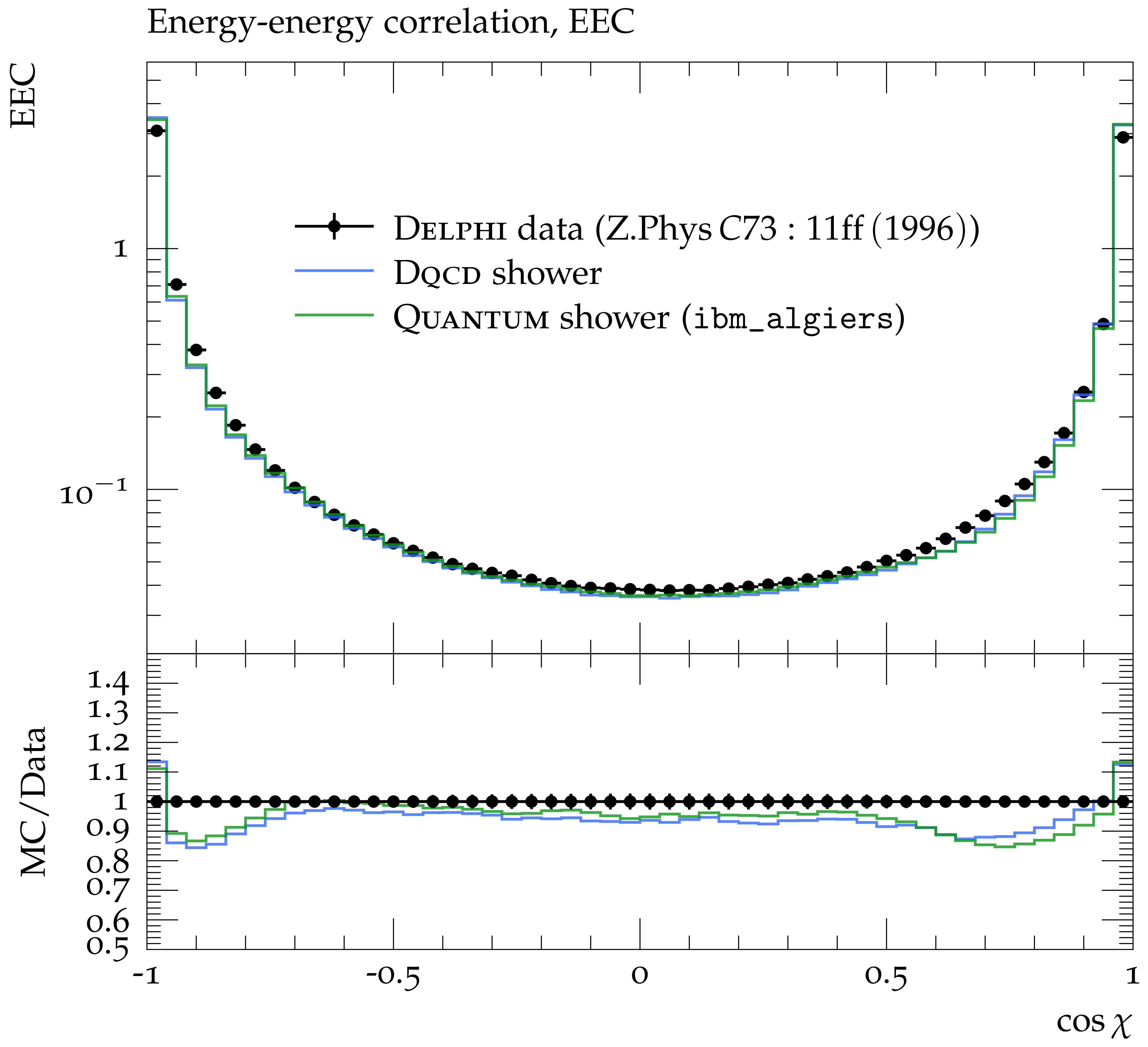
Simon Williams

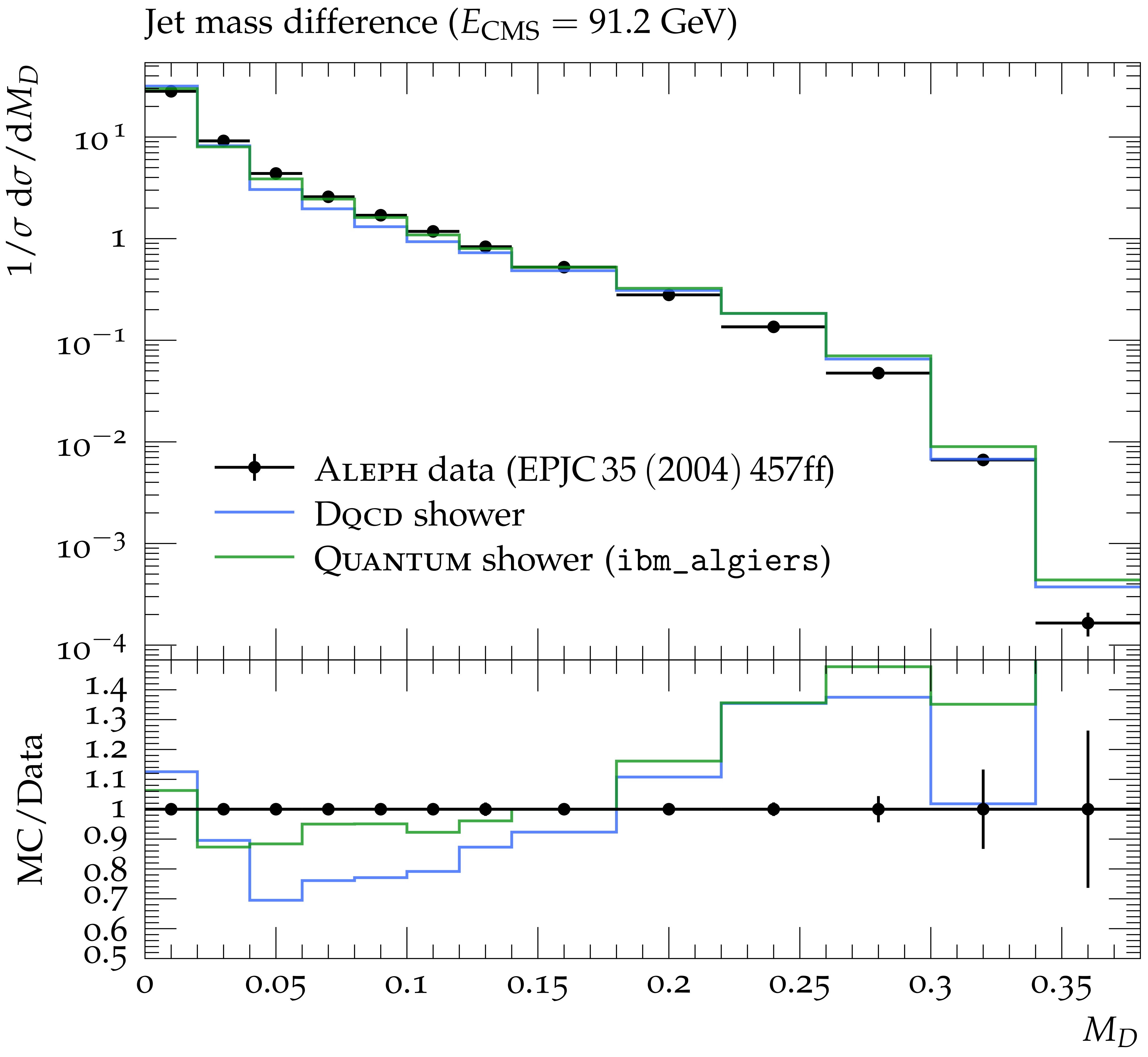
First Lund Jet Plane Institute
5th July 2023

Discrete QCD - Grove Structures

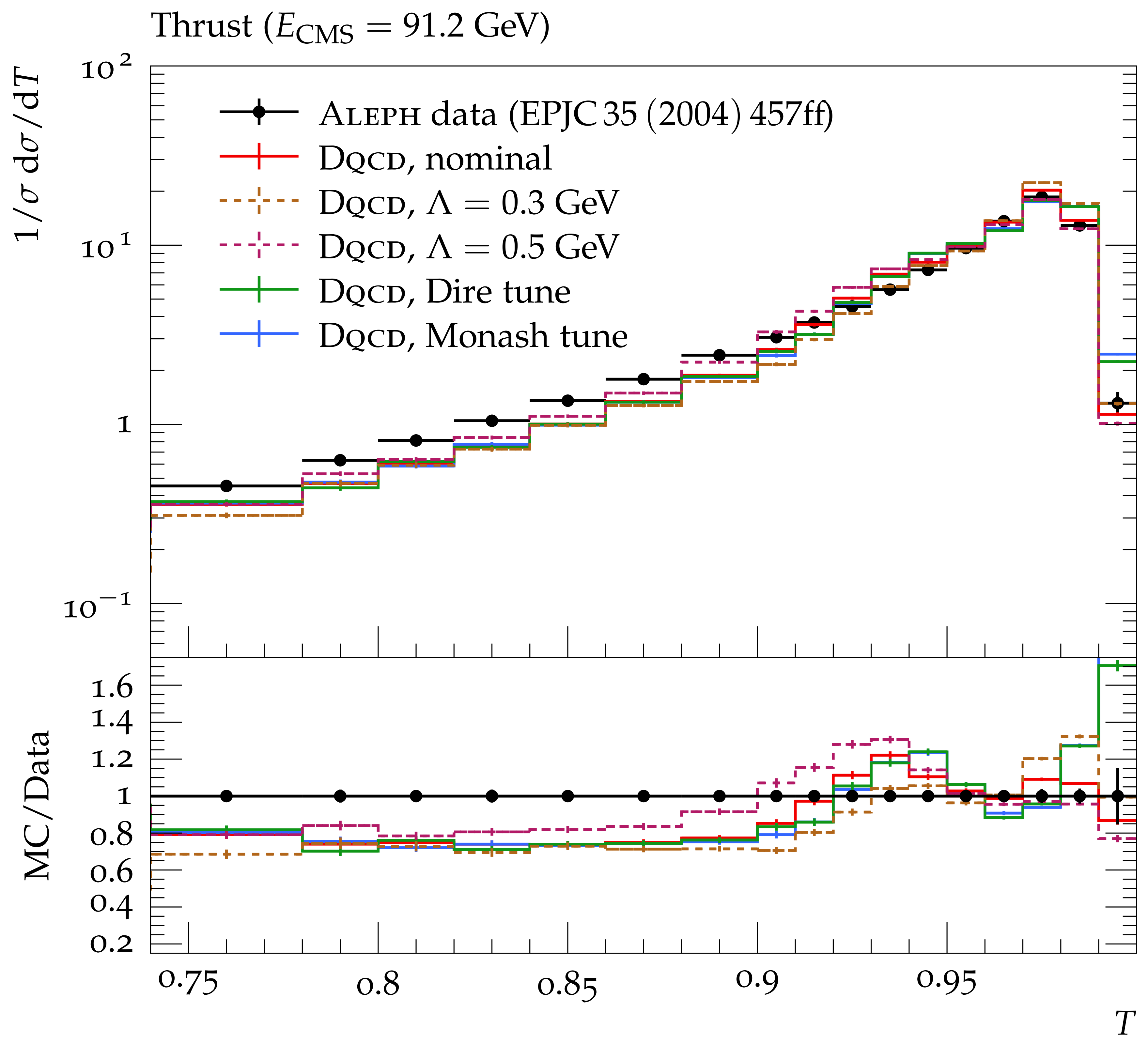


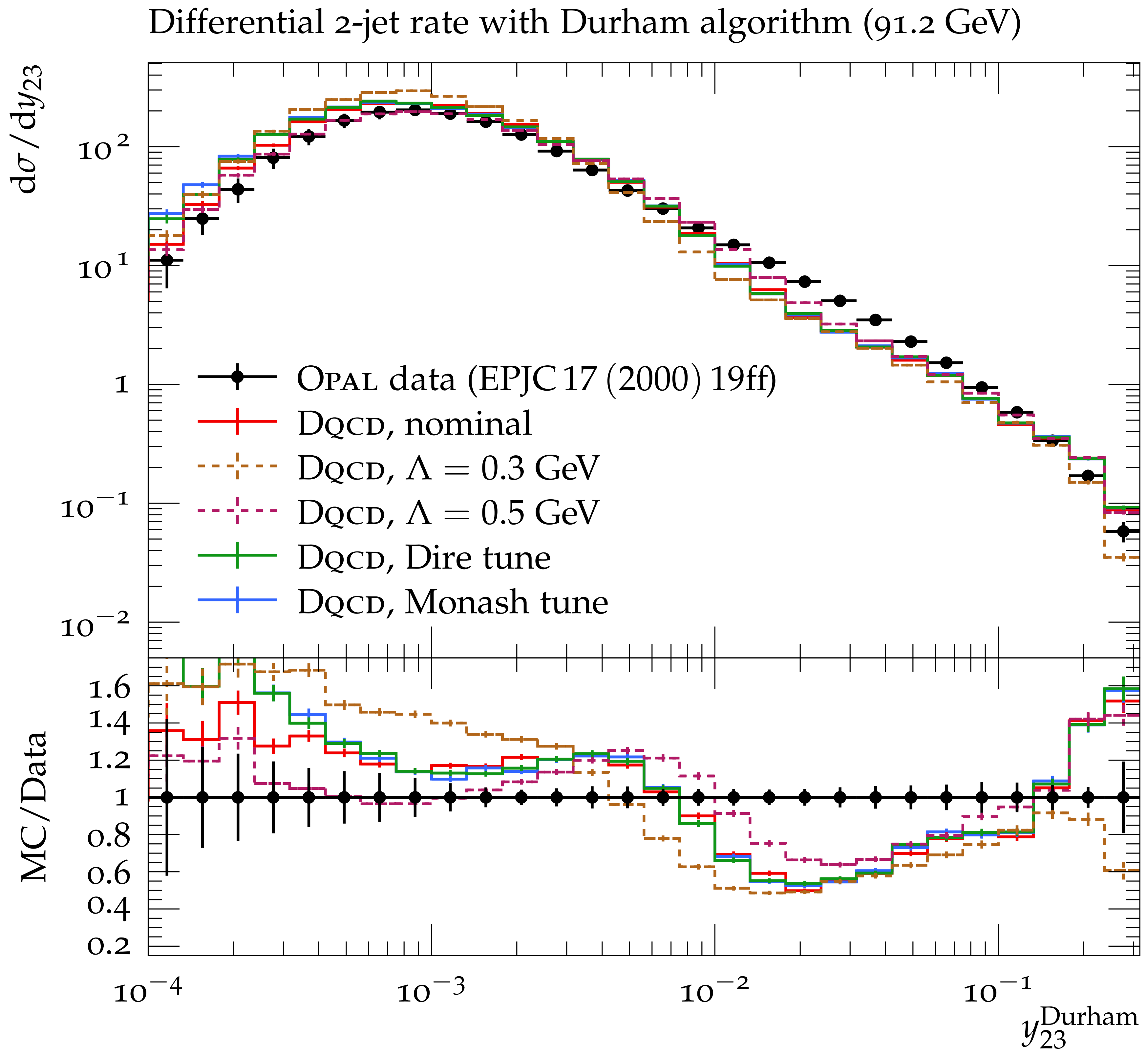
Collider Events on a Quantum Computer





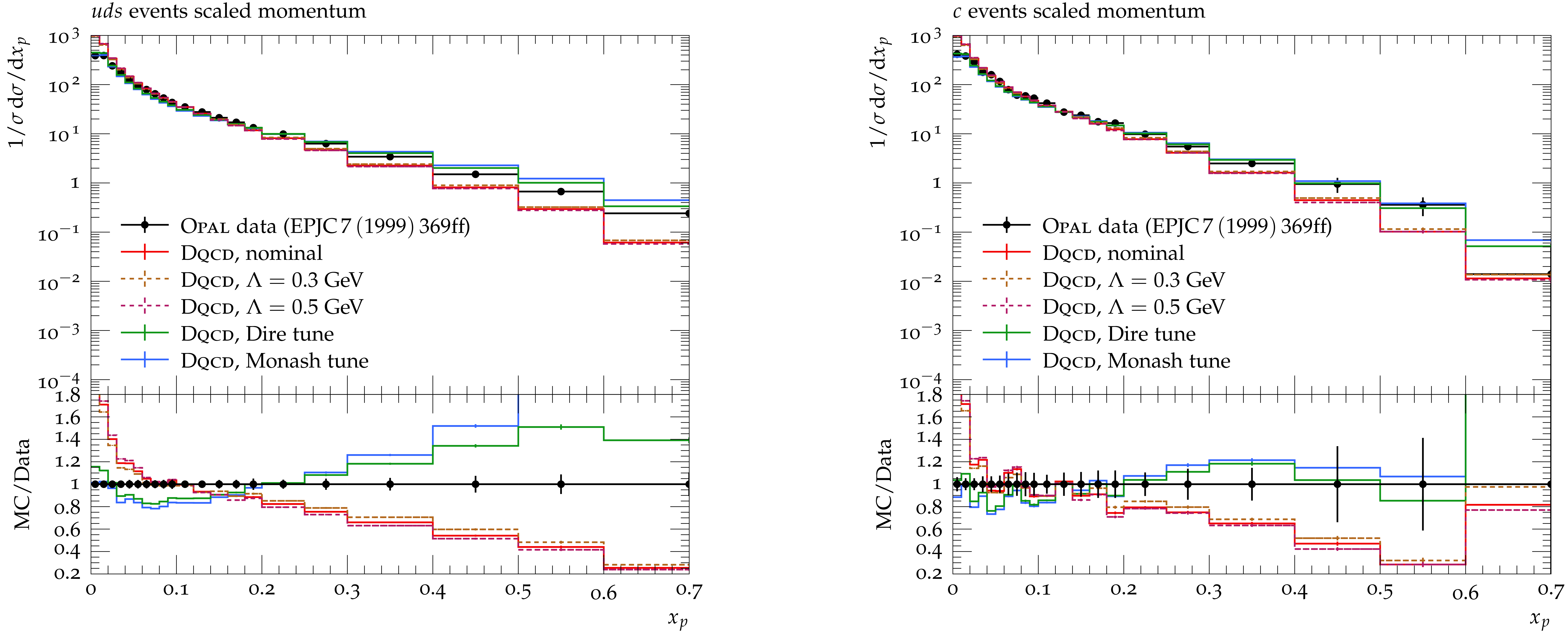
Collider Events on a Quantum Computer - Varying Λ





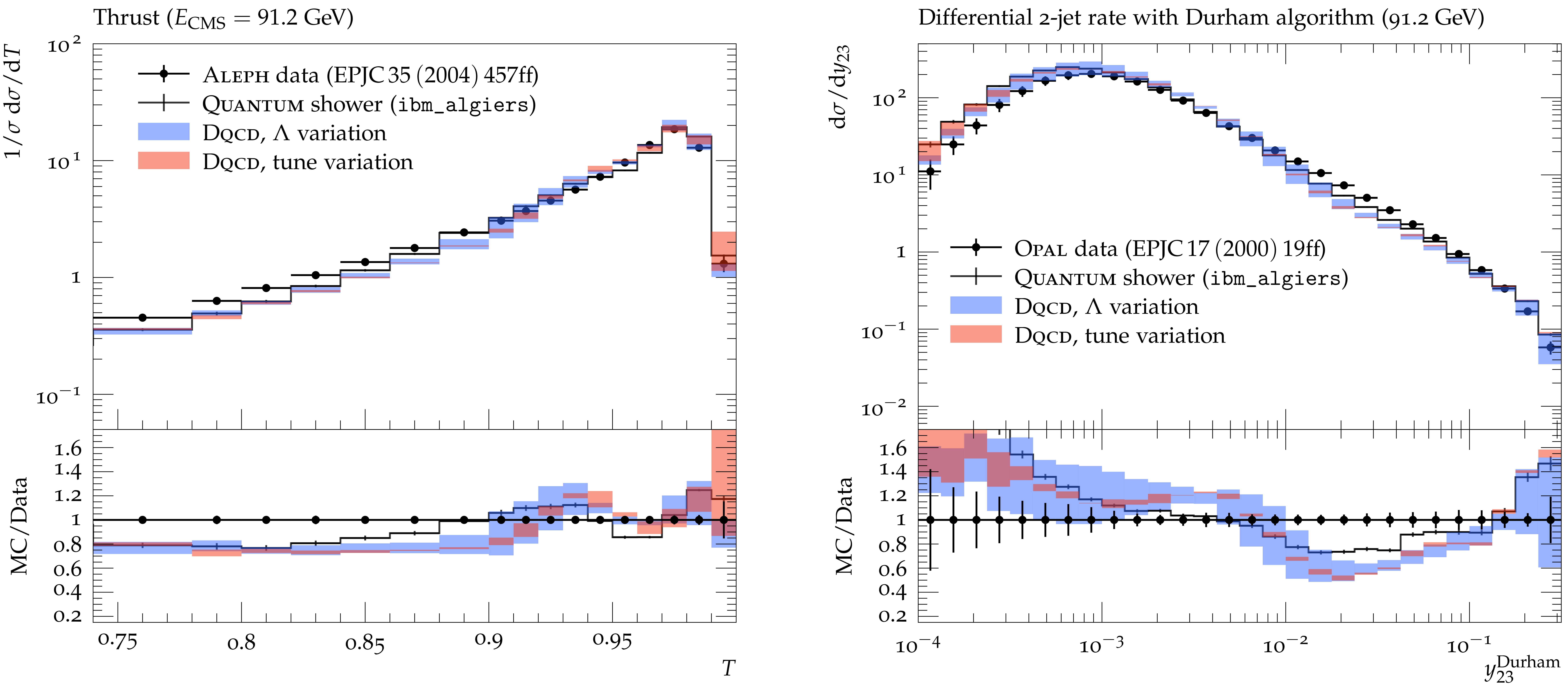
Varying values for the mass scale Λ. This leads to non-negligible uncertainties, however this is expected from a leading logarithm model.

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.

Collider Events on a Quantum Computer



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.

Collider Events on a Quantum Computer