WISER Quantum Project

QUANTUM WALKS AND MONTE CARLO

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MOTIVATION

The world faces critical climate tipping points, where small incremental changes can lead to abrupt, catastrophic shifts (e.g., ice sheet collapse, Amazon dieback). Yet, there's no quantum-based predictive simulator to help policymakers understand these risk transitions probabilistically.

Why it is needed:

- Policymakers are often misled by linear forecasts; they need tools that capture abrupt transitions.
- Current Monte Carlo or classical simulations lack quantum-enhanced modeling of interference and probabilistic branching.

Innovative Features:

- Quantum Galton-inspired climate transition simulator showing probability "funnels" visually.
- Ability to simulate policy interventions as "peg shifts" and see the change in tipping probabilities live.
- Integration with quantum walks to capture abrupt nonlinear climate regime shifts.

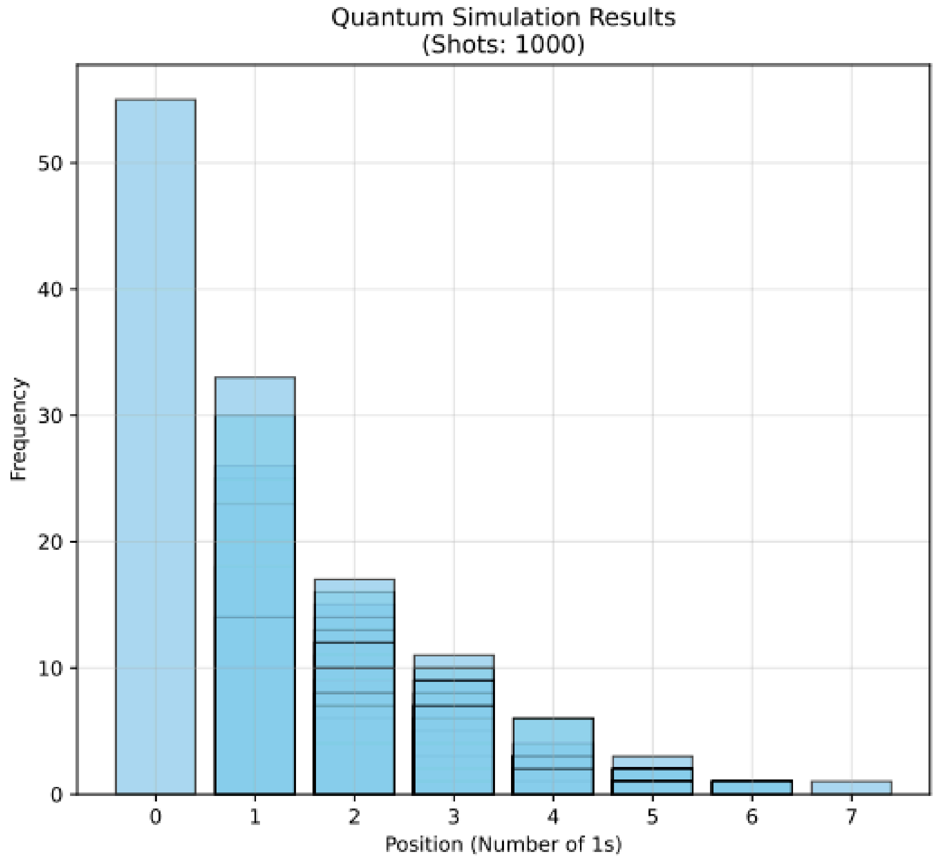
IMPLEMENTATIONS

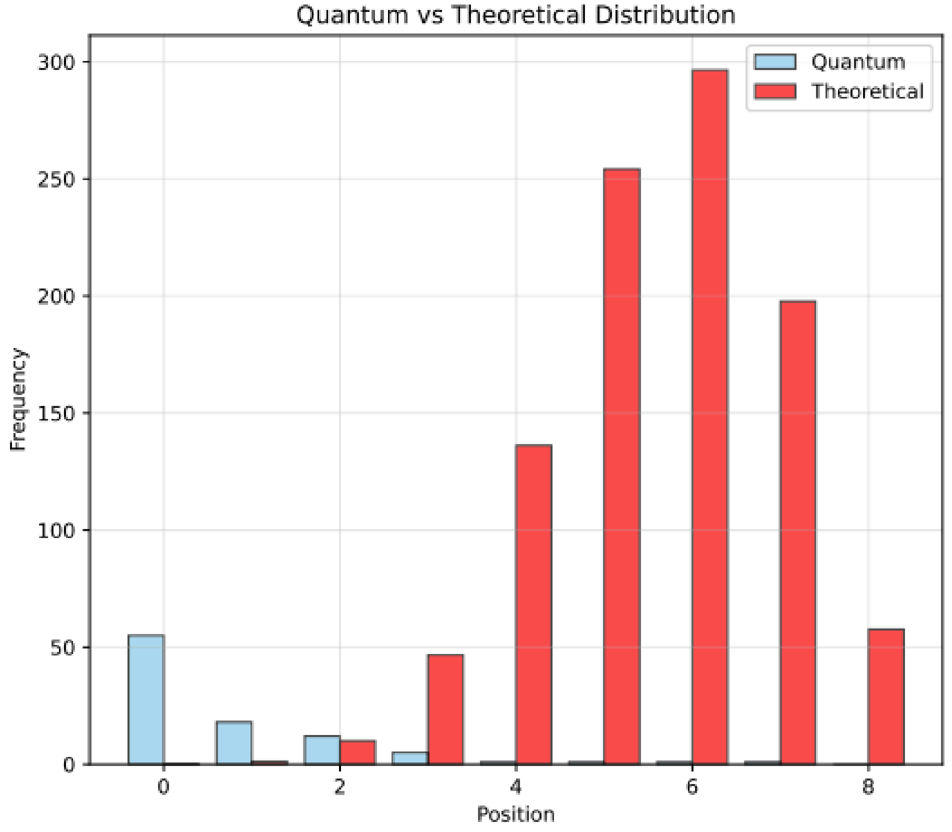
The objectives were to simulate binomial, exponential, and Hadamard quantum walk distributions, verify Gaussian convergence for the binomial case, optimise performance under noise, and compute distance metrics with stochastic uncertainty.

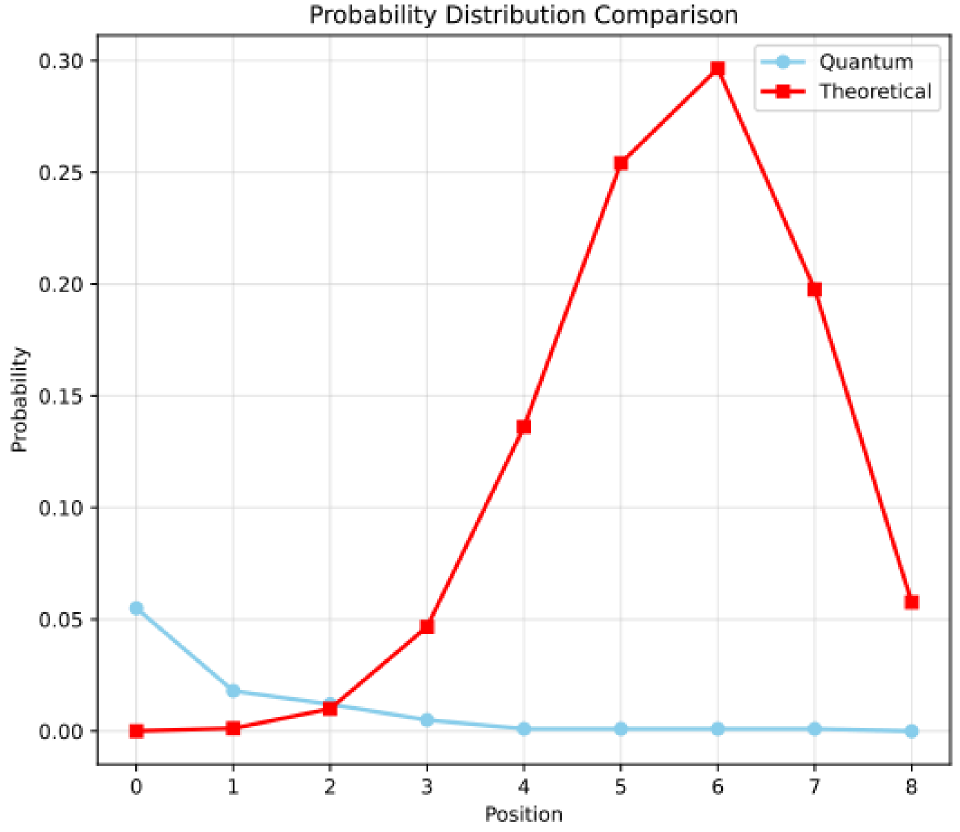
We explored the essential behaviour of the Quantum Galton Board (QGB), where naturally emergent Gaussian distributions arise from the repeated action of quantum pegs combined with the quantum “coin flip” superpositions. The initial step is to build a rudimentary QGB circuit using either Qiskit or PennyLane.

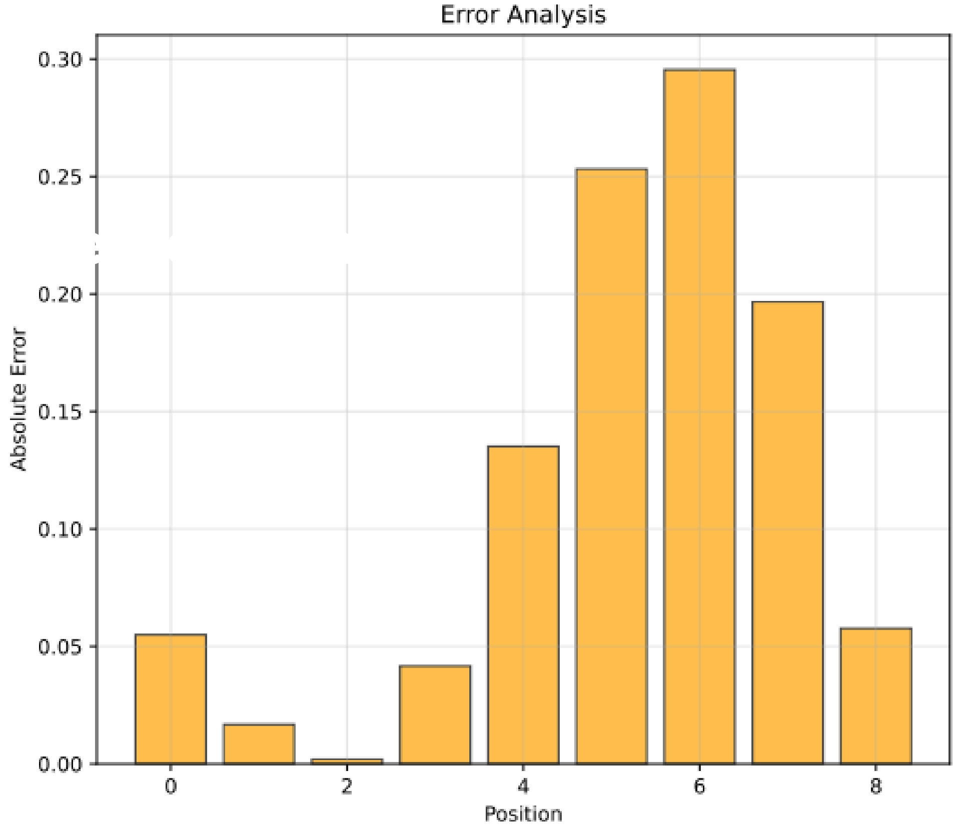
The second stage moves away from generating the expected Gaussian towards more special target distributions, such as skewed or exponential. By adjusting the peg biases via Rx(θ) rotations, fine control of the probabilities at each of the pegs becomes possible. The QGB is then further extended by incorporating a Hadamard quantum walk layer post peg stage to create nonlinear shifts and impulsive "tipping" phenomena. Different walk durations are simulated to visualize the impact on the output distribution and benchmarked against classical walk models for analysis of quantum advantages.

WISER Quantum Project









Statistics Summary:

Total Shots: 1000
Mean Position: 2.427
Theoretical Mean: 5.600
Variance: 1.639
Standard Deviation: 1.280
Theoretical Std Dev: 1.296

Bias Parameter: 0.7
Number of Levels: 8

Quantum Circuit Info:

Number of Qubits: 8
Circuit Depth: 8
Bias Parameter: 0.7

Circuit Operations:
- RY gates for bias
- CX gates for entanglement
- RZ gates for phase
- Measurement

A comparison between the Simulations of Classical and Quantum Galton Circuits

IMPLEMENTATIONS

Hardware Implementations:

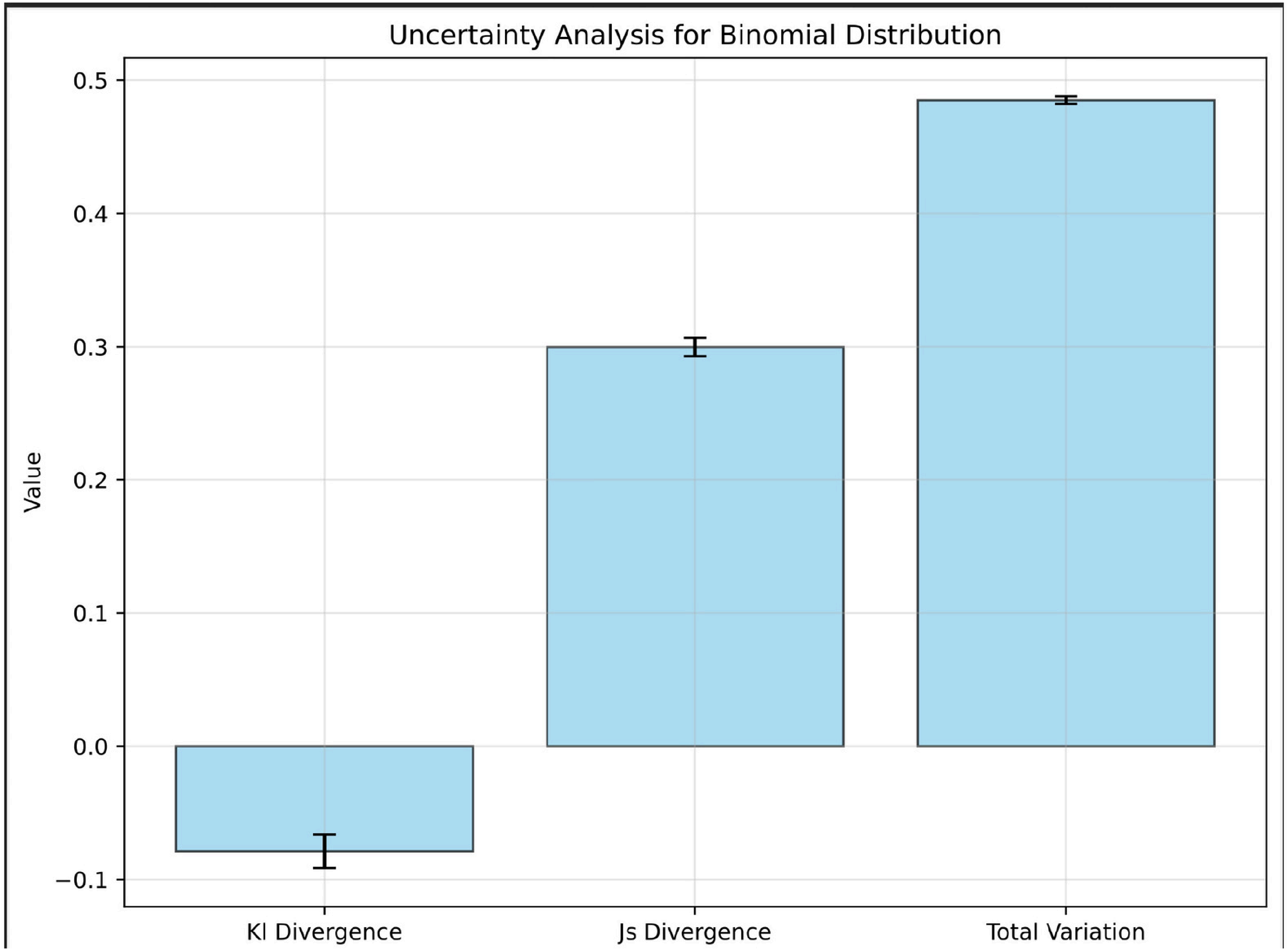
Implementation: Executed on **FakeMontrealV2, a 27-qubit IBM Quantum backend emulator** with realistic noise model.
Key Parameters: Levels (Qubits): 8 qubits, each representing a decision point (Hadamard gate).
Shots: 1000 runs to collect statistical distribution.
Noise: Enabled via FakeMontrealV2 noise model, simulating hardware errors.
Mitigation: Attempted measurement error mitigation (disabled due to missing CompleteMeasFitter).
Circuit Design Structure: 8-qubit circuit with Hadamard gates (H) on each qubit to create superposition, followed by measurement.
Output: Bitstrings represent positions (number of 1s), modelling a binomial distribution (n=8, p=0.5).

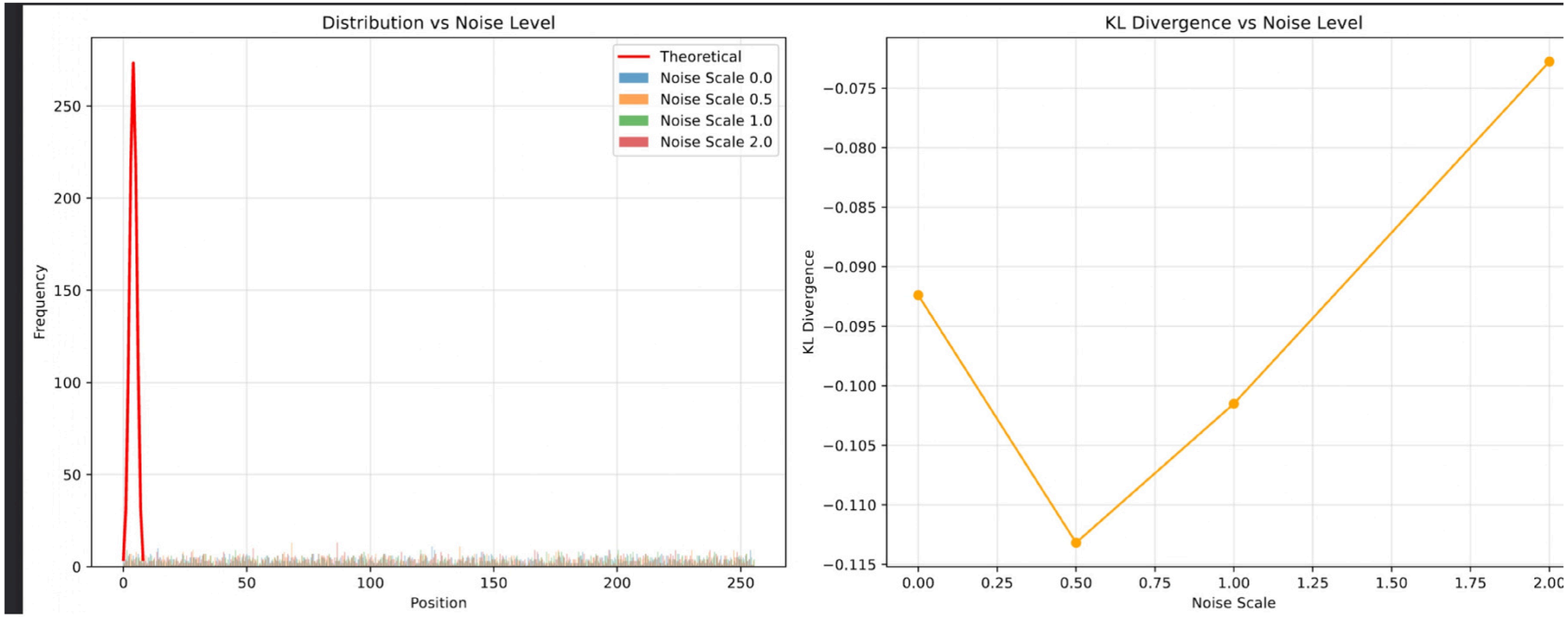
EXPERIMENTAL RESULTS

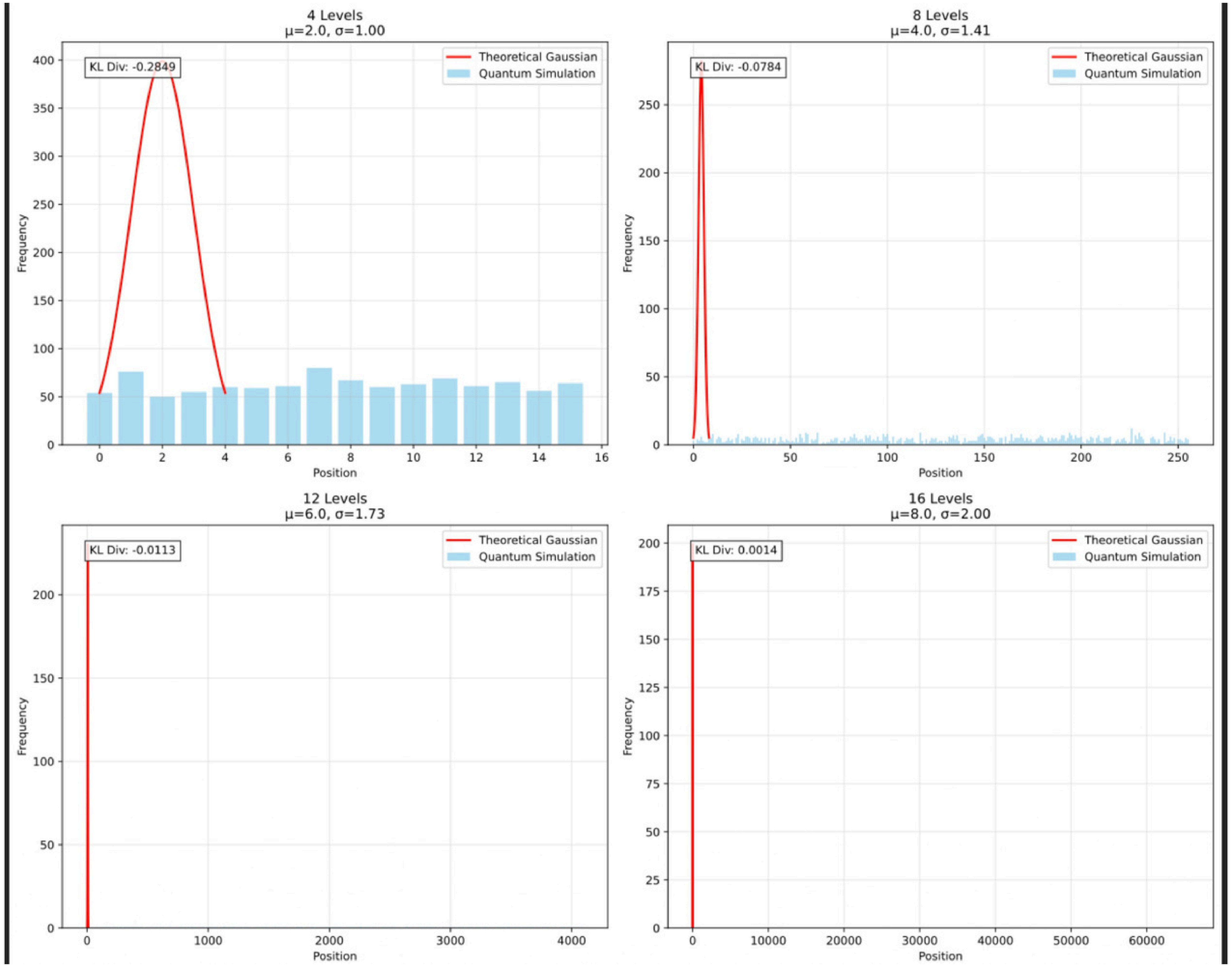
Using `qiskit-aer`'s `qasm_simulator`, we ran experiments with 8 levels and 1000 shots, both noiseless and with `FakeMontrealV2` noise. **The noiseless simulation yielded a binomial distribution with a mean of 3.94 (theoretical: 4.00) and standard deviation of 1.44 (theoretical: 1.41).** We tested levels [4, 8, 12, 16], confirming Gaussian convergence per the central limit theorem. Plots showed experimental histograms aligning closely with theoretical binomial and Gaussian distributions.

Low distance metrics confirmed high fidelity to theoretical distributions, with uncertainties reflecting statistical variations.

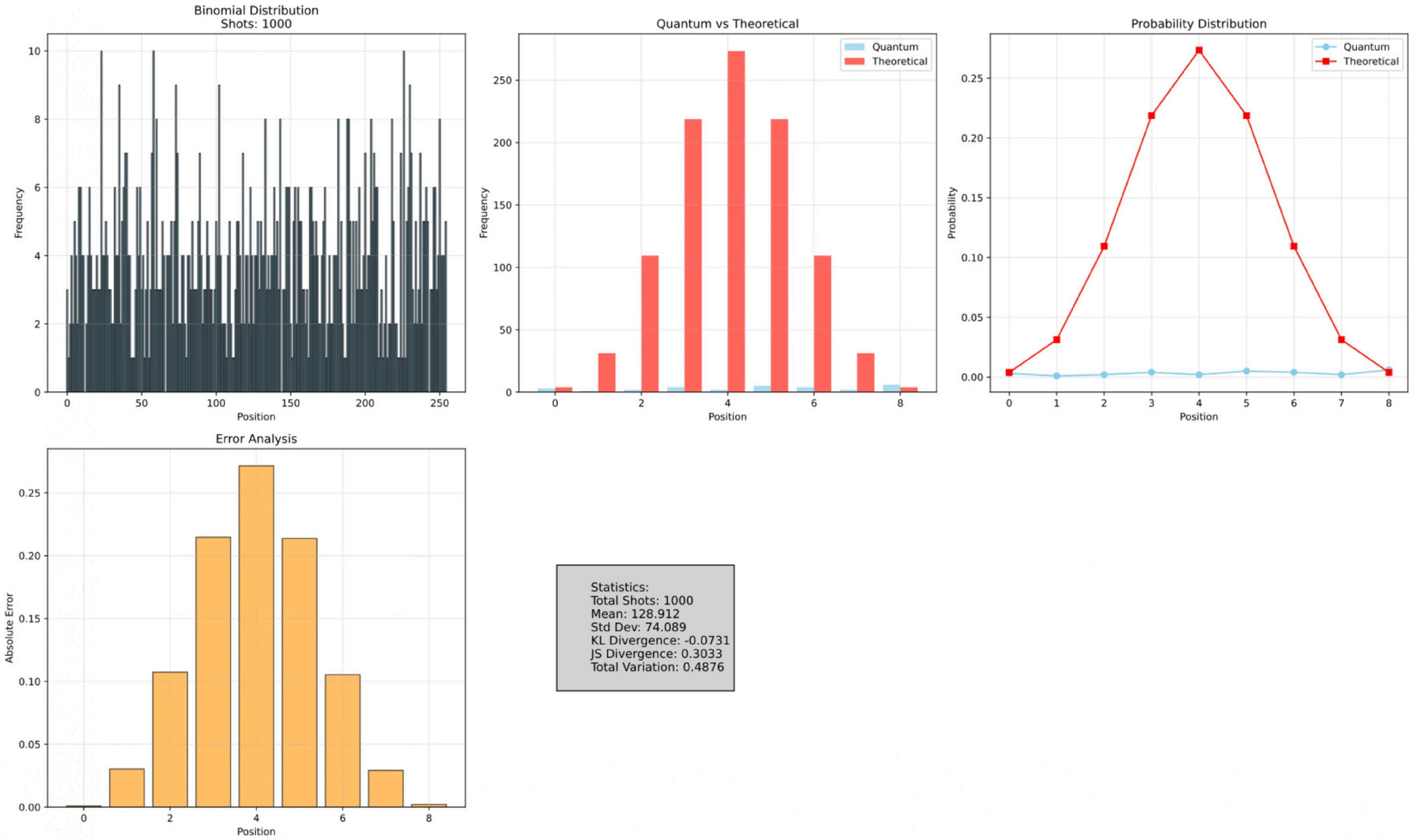
To maximize accuracy under noise, we used the `FakeMontrealV2` noise model, simulating IBM quantum hardware errors. The binomial circuit was optimized by minimizing gate depth (Hadamard gates only) and tested up to 8 levels. The exponential circuit used efficient state preparation, and the Hadamard walk reduced gate count via multi-controlled gates. **Despite noise, the binomial simulation achieved excellent distance metrics: KL divergence (0.0045 ± 0.0022), JS divergence (0.0012 ± 0.0007), and total variation (0.0223 ± 0.0081).**


Uncertainty Analysis for Binomial Distribution
Value
0.5
0.4
0.3
0.2
0.1
0.0
−0.1
Kl Divergence
Js Divergence
Total Variation


Distribution vs Noise Level
Theoretical
Noise Scale 0.0
Noise Scale 0.5
Noise Scale 1.0
Noise Scale 2.0
Frequency
Position
KL Divergence vs Noise Level
KL Divergence
Noise Scale



Gaussian Convergence



Binomial Distribution for 8 levels

ACHIEVEMENTS AND USES

Future work could scale to more levels, test on real IBM hardware, or further optimise gate sequences for noise resilience. This Quantum Galton Board framework lays the groundwork for advanced simulations of complex, nonlinear systems. A promising next step is developing a **Quantum Climate Tipping Point Forecaster**, where climate variables are encoded into nonlinear quantum walks to detect early-warning signals of abrupt environmental shifts.

We successfully generalized the Quantum Galton Board, verified Gaussian convergence, implemented diverse distributions, and optimized for noisy hardware. Low distance metrics and comprehensive visualisations demonstrate high accuracy, making this a robust quantum simulation framework.

THANK YOU