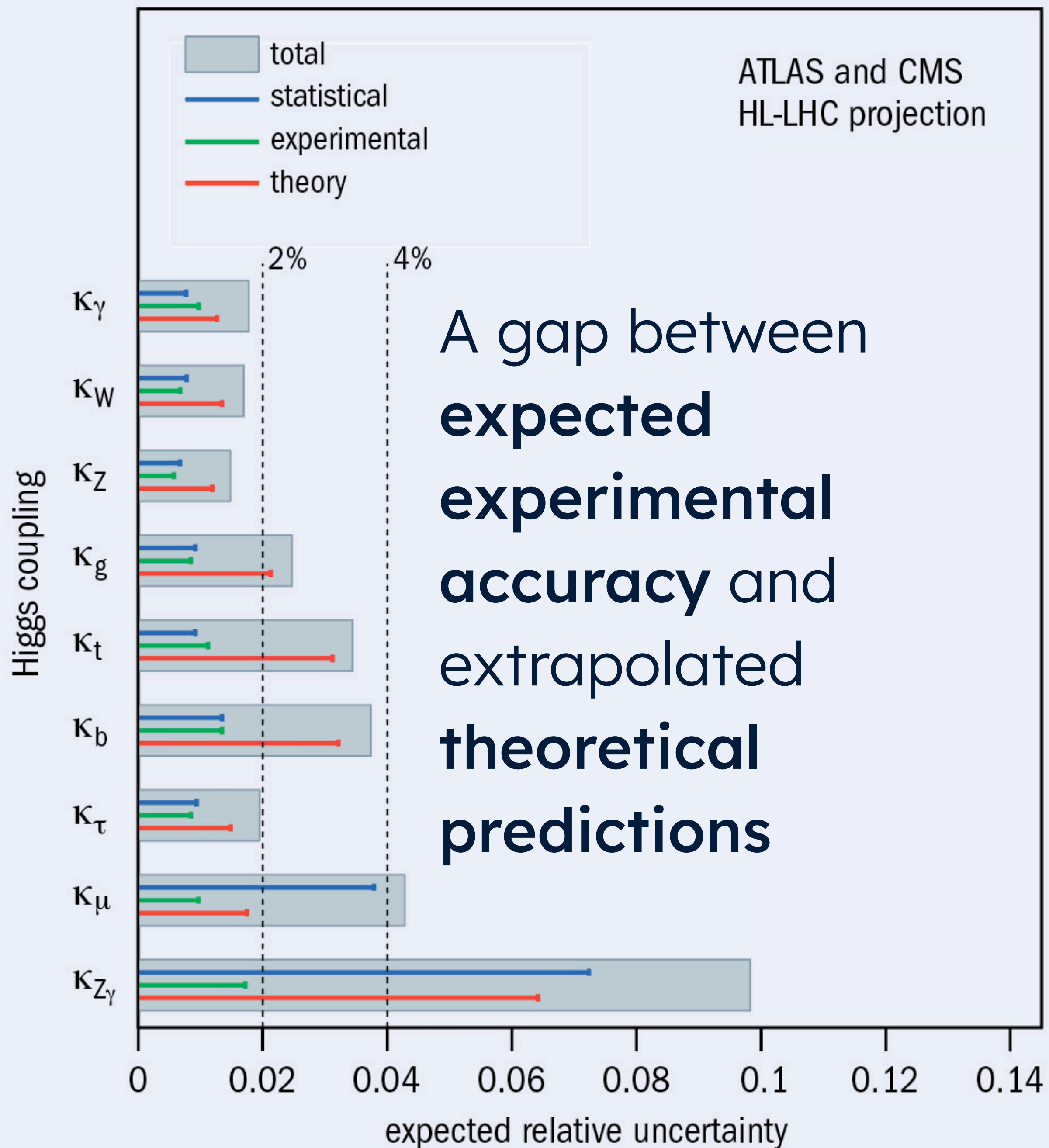


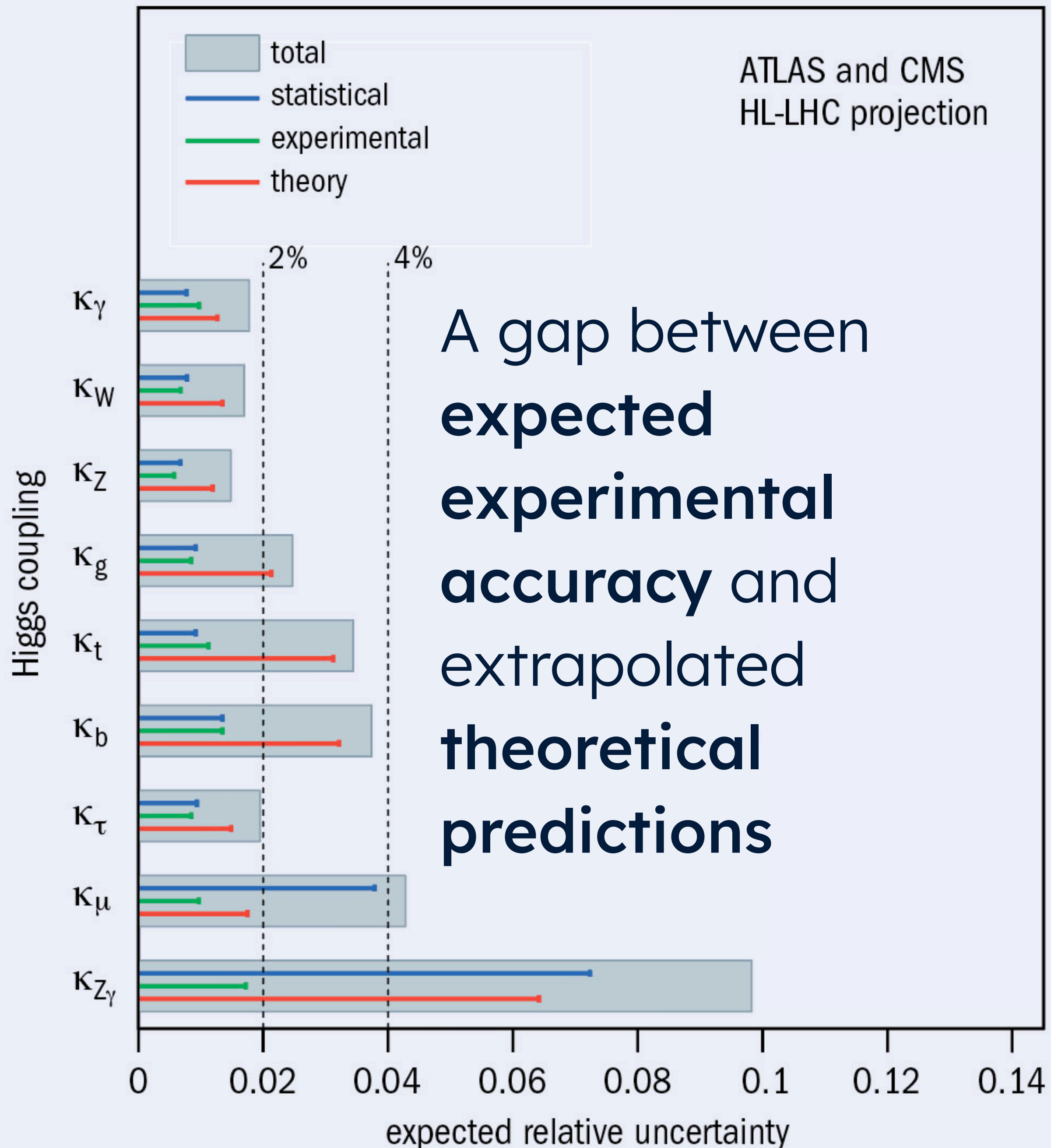
Closing the precision gap with Quantum Algorithms

Germán RODRIGO

Quantum Computing for High-Energy
Physics (**QC4HEP**)
München, Feb 26–27, 2026

Motivation

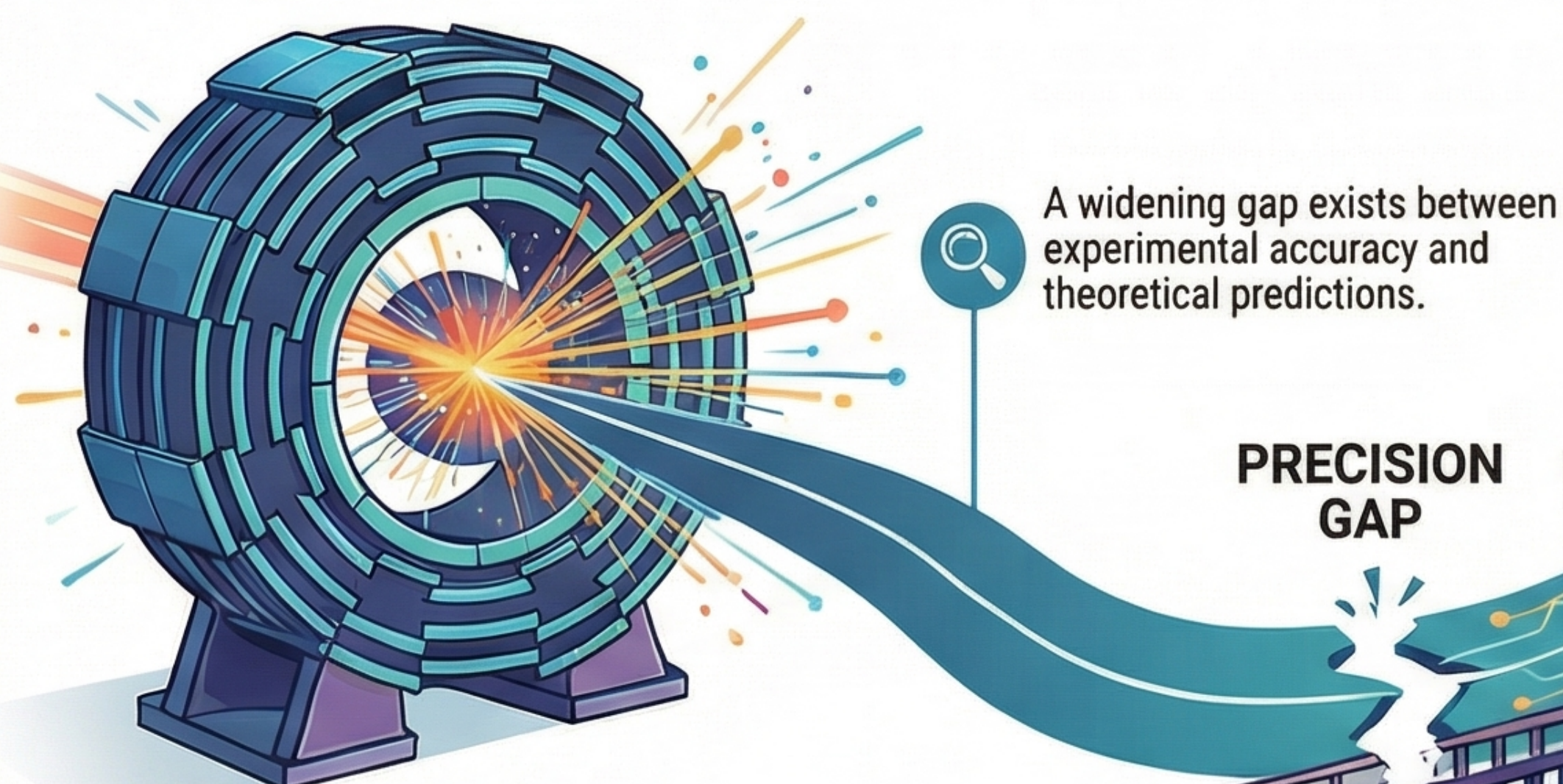




An imperative need to advance **theoretical predictions** for high-energy colliders beyond the current state of the art, to match precision measurements and unlock future discoveries

Quantum Computing for Particle Physics: Closing the Precision Gap

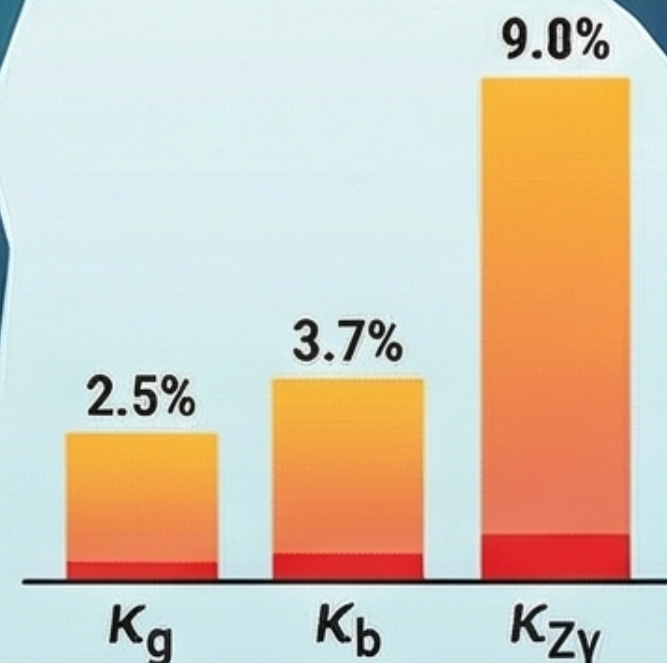
THE PRECISION PROBLEM



QUANTUM ALGORITHMS AS THE SOLUTION

PRECISION GAP

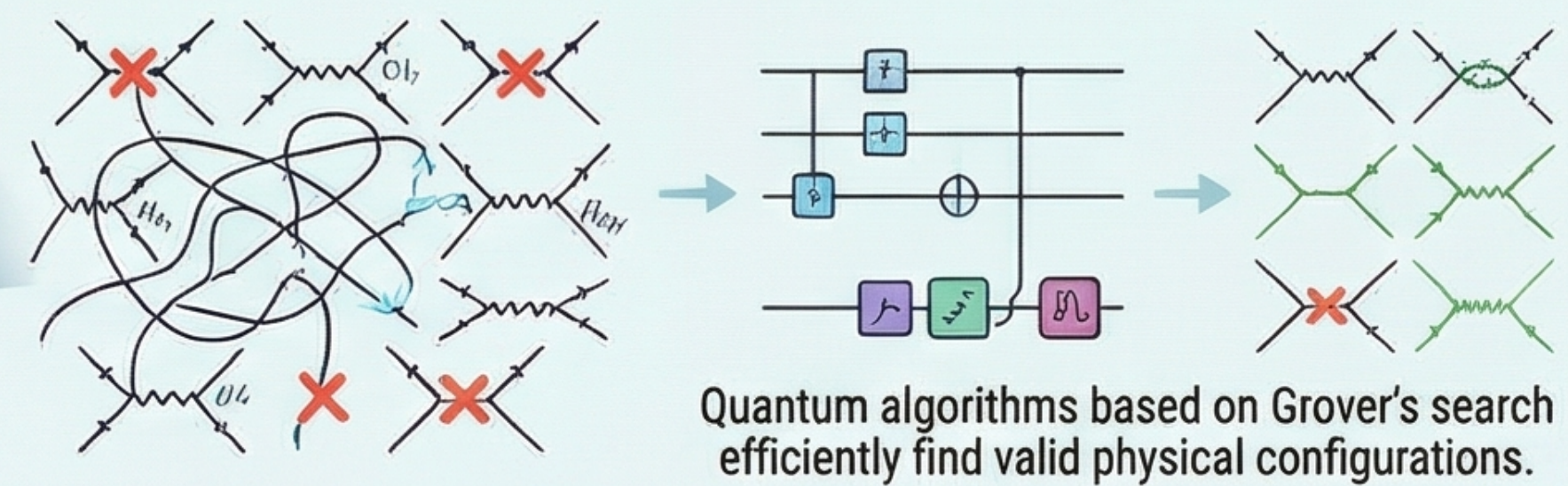
Higgs Coupling Uncertainty



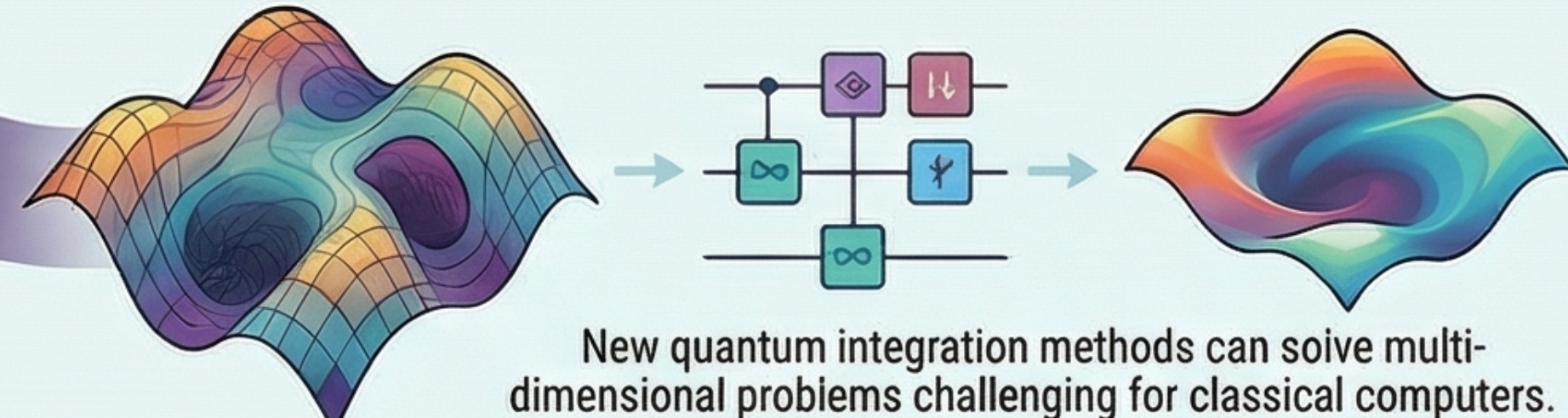
For many Higgs boson interactions, theoretical errors are the largest source of uncertainty.

NOVEL SOLUTIONS

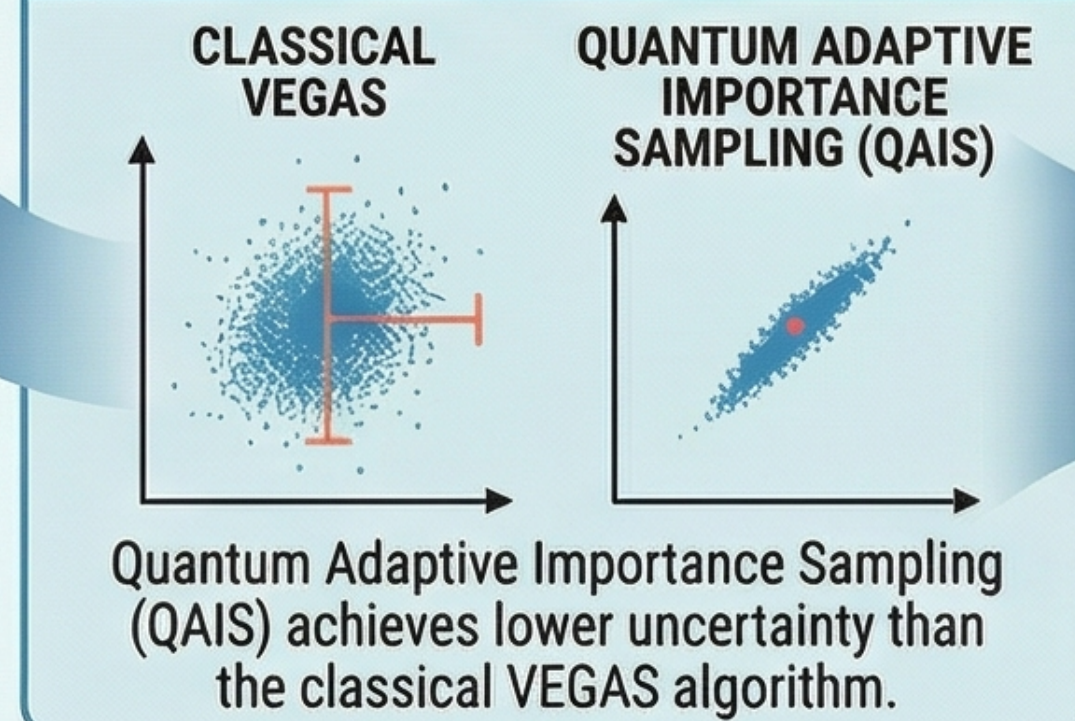
Challenge 1: Ensuring Causality in Calculations



Challenge 2: Calculating Complex Integrals



COMPARISON



Unlocking Discoveries

We need more powerful calculation methods to unlock future discoveries from collider data.

The complexity under the hood

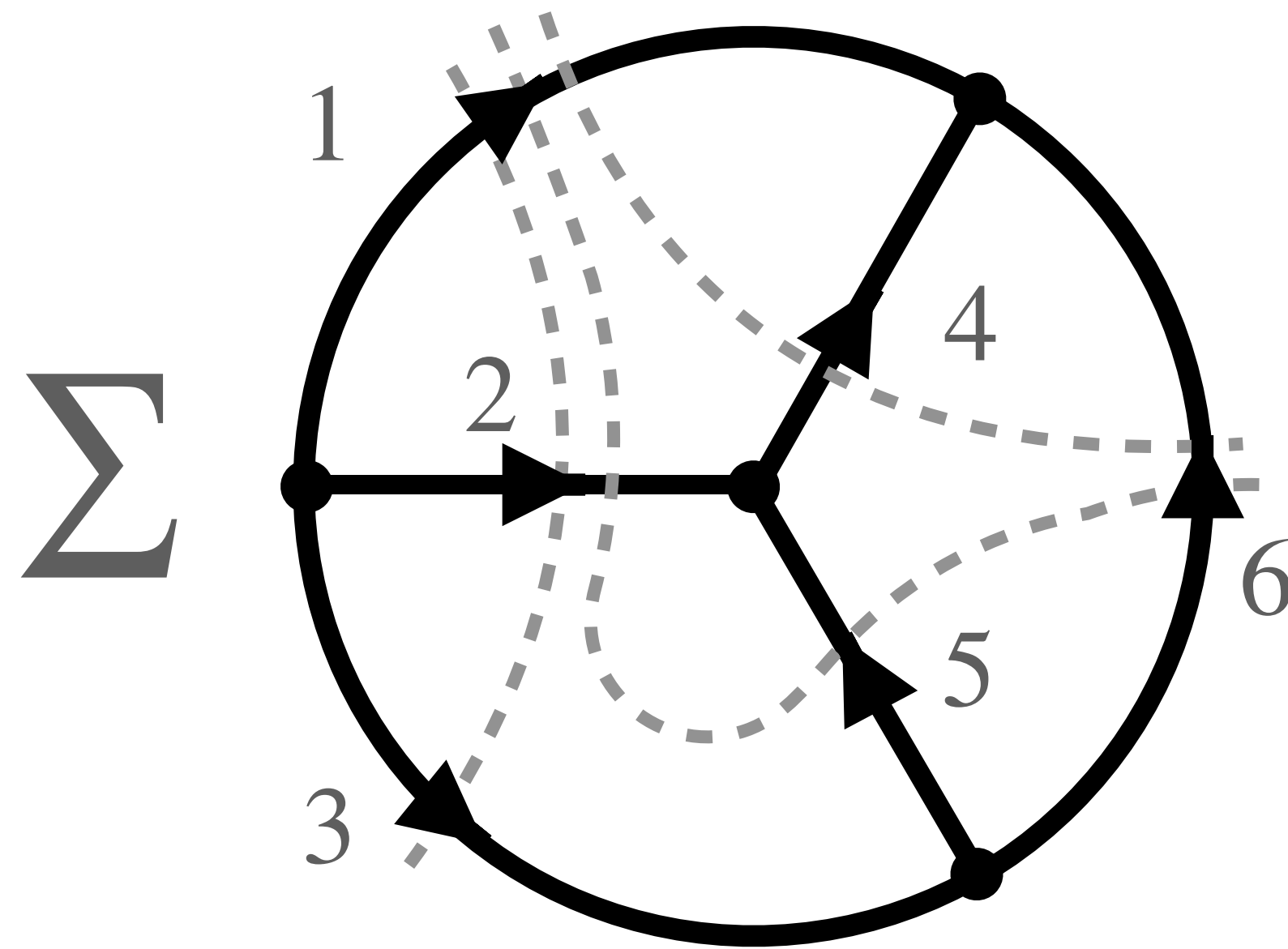
Why do we need Quantum Integration / Sampling?

- The accuracy of theoretical predictions relies on properly considering **loop quantum fluctuations** - particles momentarily appearing /disappearing in the vacuum - at high perturbative orders.
- Each loop adds dimensions to the loop integral
- Each radiated particle contributes with extra dimensions to the phase-space
- Complexity grows exponentially with dimensionality
- Quantum is the most natural approach for **sampling = event generation**

The Loop-Tree Duality LTD: vacuum amplitudes

the Euclidean space of the
loop three-momenta

on-shell energies



$$\mathcal{A}_D^{(\Lambda)} \sim \prod \frac{1}{\lambda_{i_1 i_2 \dots i_n}} \quad \mathcal{A}^{(\Lambda)} = \int_{\vec{\ell}_1 \dots \vec{\ell}_\Lambda} \mathcal{A}_D^{(\Lambda)}$$

$$\lambda_{i_1 i_2 \dots i_n} = \sum q_{i_s,0}^{(+)} = \sum \sqrt{\mathbf{q}_{i_s}^2 + m_{i_s}^2 - i0}$$

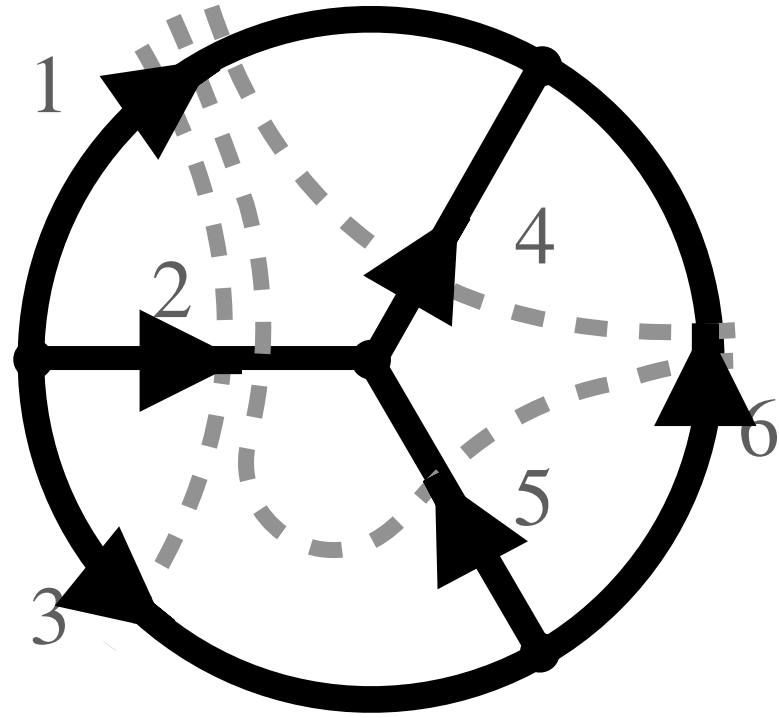
States with external particles are
generated from residues (cuts) over
causal propagators $1/\lambda_{i_1 i_2 \dots i_n}$ involving
both initial and final-state particles



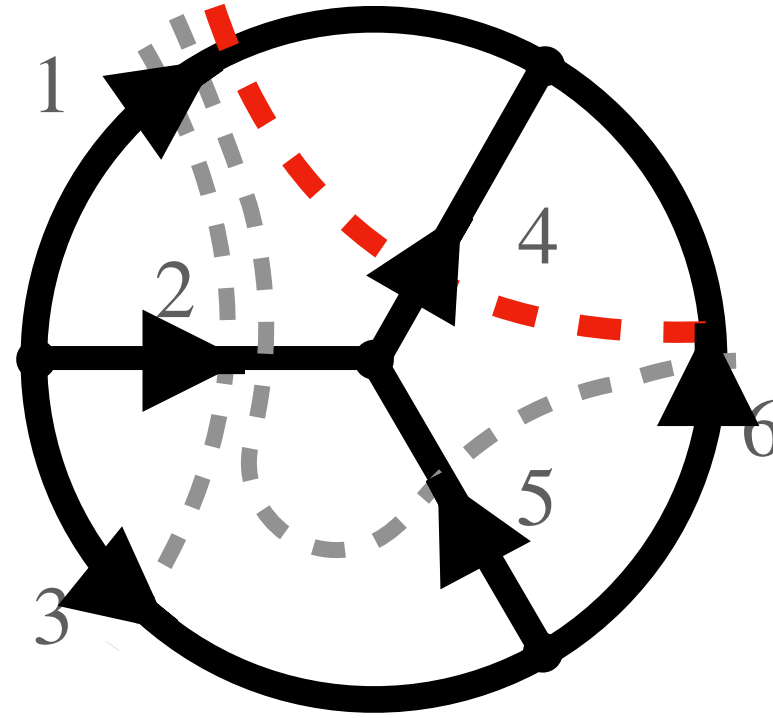
Vacuum amplitudes are **intrinsically IR finite and threshold free**: local cancellation of singularities
between phase-space residues, hence **no artificial
separation** between loops and trees, and $d = 4$

S. Ramírez Uribe, P.K. Dhani, G.F.R. Sborlini, GR,
"Rewording theoretical predictions at colliders
with vacuum amplitudes," [PRL133, 211901 \(2024\)](#)

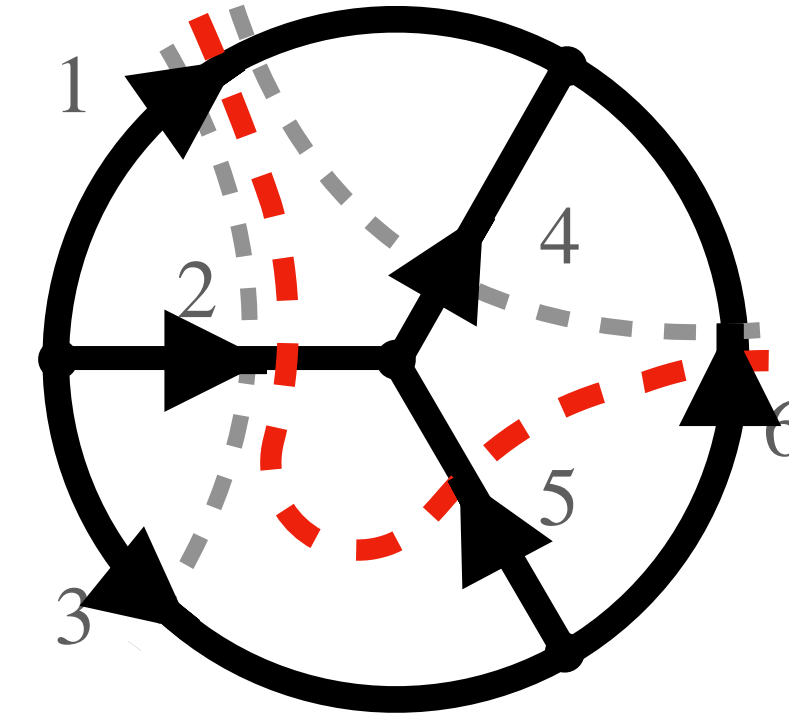
The Loop-Tree Duality LTD: vacuum amplitudes



$$\mathcal{A}_D^{(\Lambda)} \sim \frac{1}{\lambda_{123}\lambda_{1256}\lambda_{146}}$$



$$\text{Res} \left(\mathcal{A}_D^{(\Lambda)}, \lambda_{146} \right) \sim \frac{1}{\lambda_{123}\lambda_{25\bar{4}}}$$



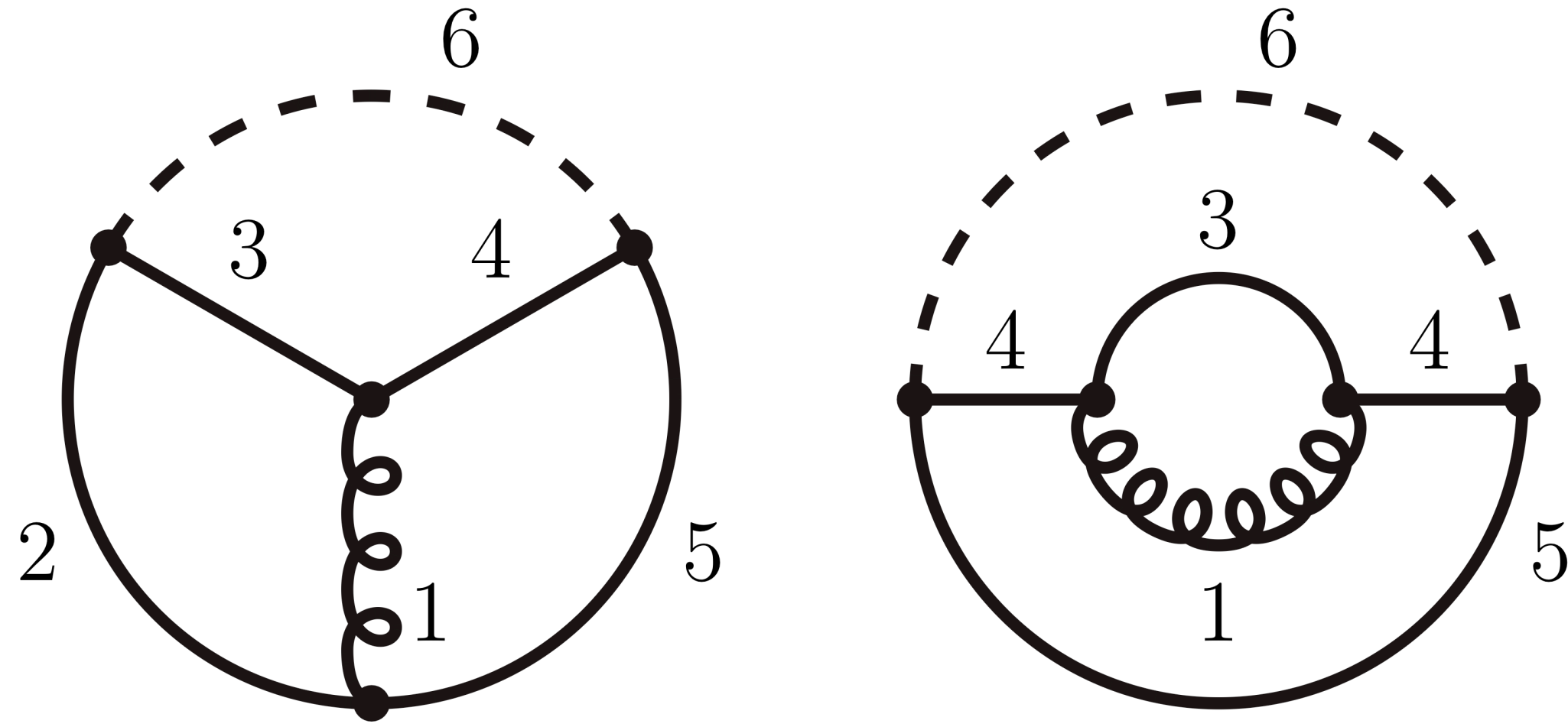
$$\text{Res} \left(\mathcal{A}_D^{(\Lambda)}, \lambda_{1256} \right) \sim \frac{-1}{\lambda_{123}\lambda_{25\bar{4}}}$$

$$d\Gamma_{N^k\text{LO}} \sim \int_{\vec{\ell}_1 \dots \vec{\ell}_{\Lambda-1}} \sum \text{Res} \left(\mathcal{A}_D^{(\Lambda,R)}, \lambda_{i_1 i_2 \dots i_n a} \right) \delta \left(\lambda_{i_1 i_2 \dots i_n} - \lambda_a \right)$$

$$\lambda_{i_1 i_2 \dots i_n} = \sum q_{i_s,0}^{(+)} = \sum \sqrt{q_{i_s}^2 + m_{i_s}^2 - i0}$$

S. Ramírez Uribe, P.K. Dhani, G.F.R. Sborlini, GR,
*"Rewording theoretical predictions at colliders
 with vacuum amplitudes,"* [PRL133, 211901 \(2024\)](#)

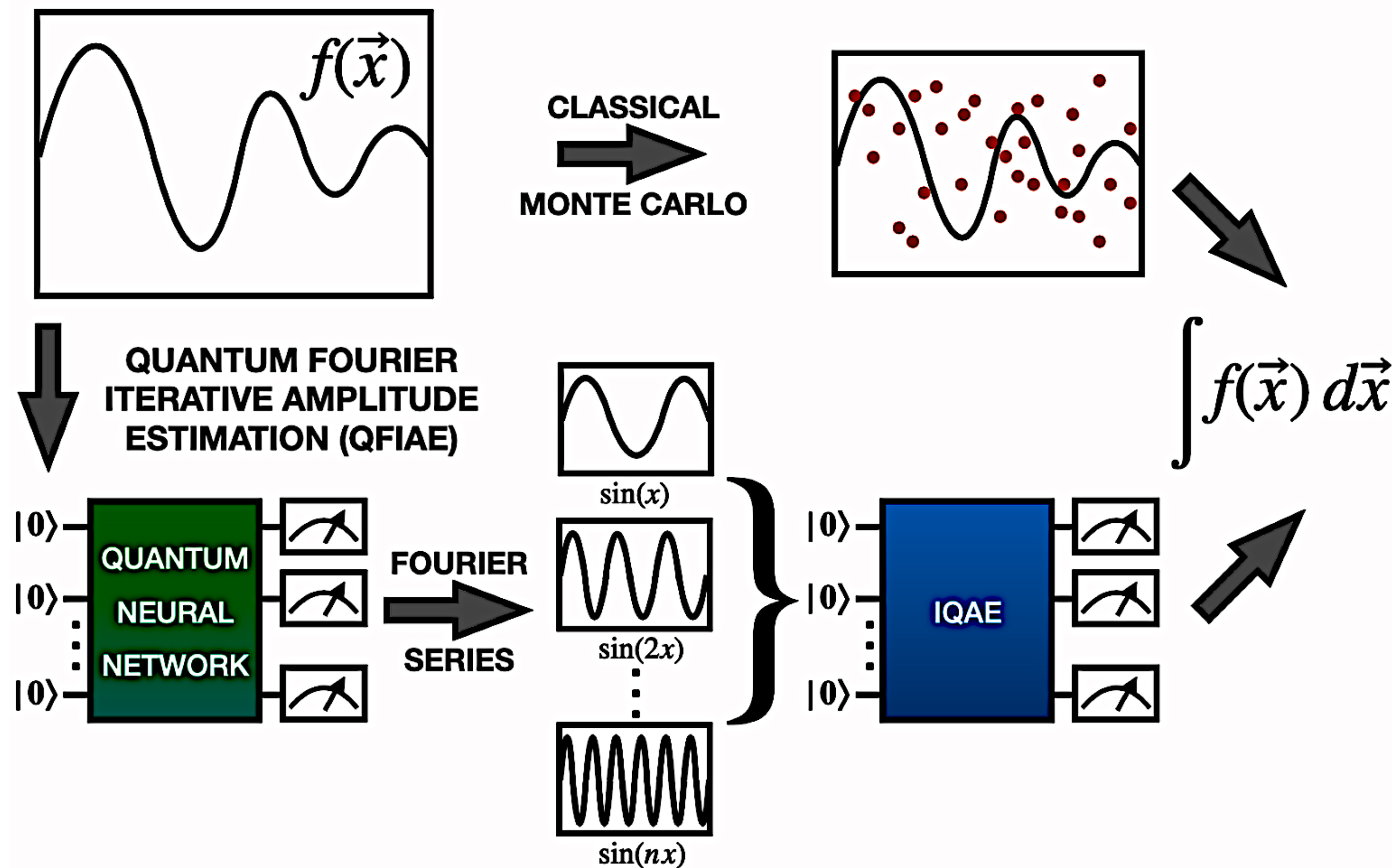
Three-loop vacuum amplitude for Higgs + $q\bar{q}g$



Vacuum amplitudes and time-like causal unitarity in the loop-tree duality, LTD
Collaboration, [JHEP 01 \(2025\) 103 \[2404.05492\]](#)

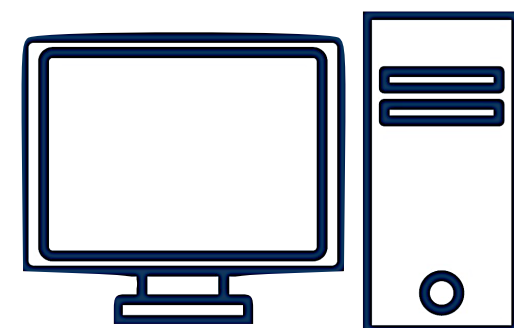
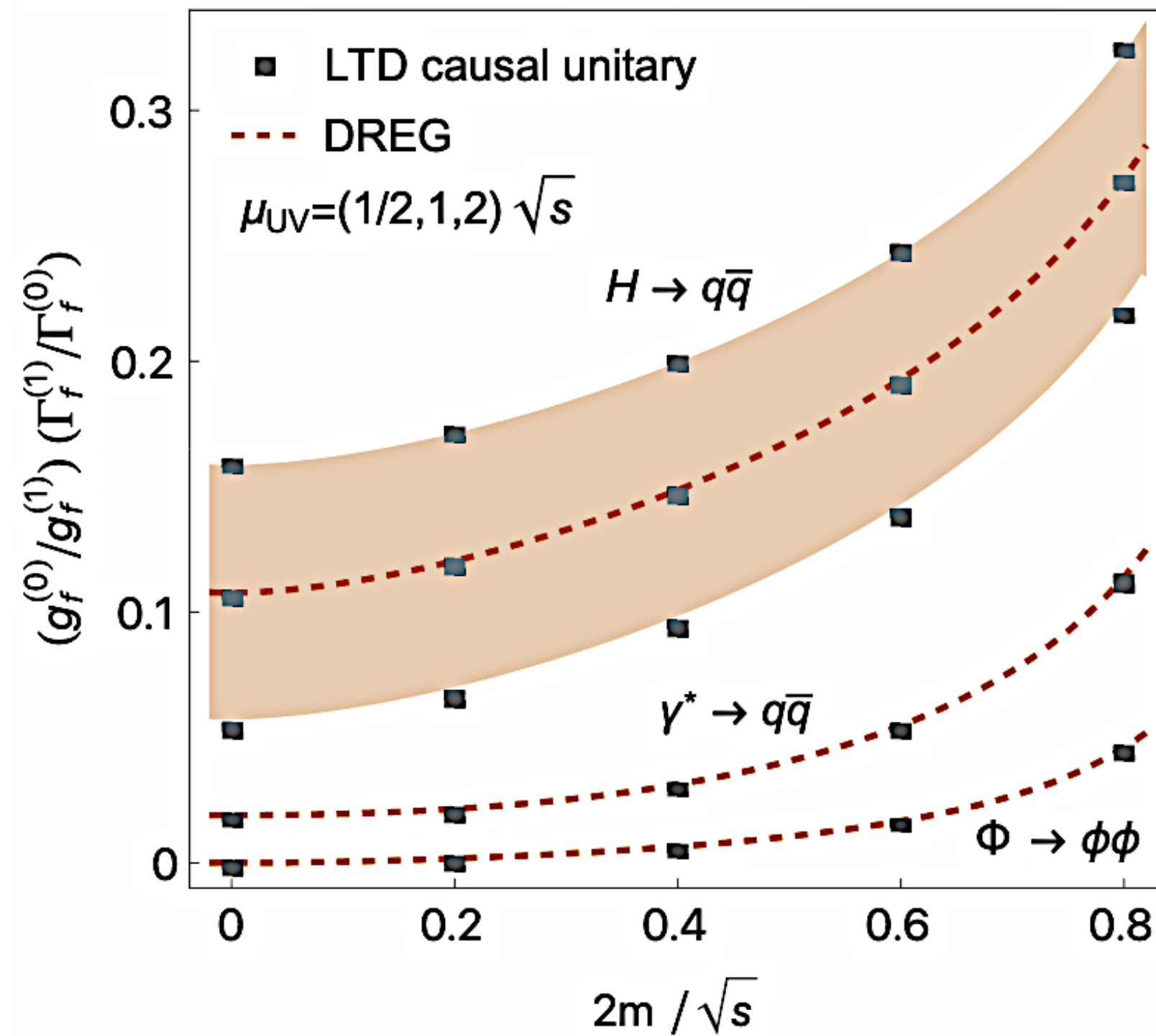
$$\begin{aligned}
 \mathcal{A}_D^{(3)}(Hq\bar{q}g) = & \frac{4g_H^{(3)}}{x_{123456}} \left\{ \lambda_6^4 (1 + \beta^2) \beta^2 \right. \\
 & \times \left[\left(\frac{1}{\lambda_{134}} + \frac{1}{\lambda_{456}} \right) \left(\frac{1}{\lambda_{125}} + \frac{1}{\lambda_{236}} \right) \frac{1}{2\lambda_{1356}} + \frac{1}{\lambda_{134}\lambda_{456}\lambda_{2345}} \right] \\
 & + \frac{\lambda_2}{\lambda_4} \left[\frac{\lambda_6^2 \beta^2}{\lambda_{456}} \left((d-2)\lambda_{1\bar{3}} \left(\frac{1}{\lambda_4} + \frac{1}{\lambda_{456}} \right) - \frac{2m^2}{\lambda_{456}} \left(\frac{1}{\lambda_{134}} + \frac{1}{\lambda_{1356}} \right) \right) \right. \\
 & \left. - \frac{2m^2}{\lambda_{134}} \left(\frac{\lambda_6^2 \beta^2}{\lambda_{134}} \left(\frac{1}{\lambda_{456}} + \frac{1}{\lambda_{1356}} \right) + 2\lambda_{5\bar{6}} \left(\frac{1}{\lambda_4} + \frac{1}{\lambda_{134}} \right) \right) \right] \\
 & + \lambda_1 \lambda_6^2 \left(\frac{1}{2\lambda_{236}} + \frac{1}{\lambda_{2345}} \right) \frac{(d-2)\beta^2 - 2}{\lambda_{456}} \\
 & + \lambda_2 \left[\left(\left(2\lambda_6^2 \beta^2 \left(2 - \frac{m^2}{\lambda_4^2} \right) - (d-2)\lambda_{236}\lambda_{\bar{2}36} \right) \right. \right. \\
 & \times \left(\frac{1}{\lambda_{134}} + \frac{1}{\lambda_{456}} \right) + 2(d-2)\lambda_4 \left. \right) \frac{1}{\lambda_{1356}} \\
 & + \left(2\lambda_6^2 \beta^2 \left(2 - \frac{m^2}{\lambda_4^2} \right) - (d-2)\lambda_{2\bar{3}6}\lambda_{\bar{2}\bar{3}6} \right) \frac{1}{\lambda_{134}\lambda_{456}} \\
 & \left. + \frac{(d-2)\lambda_{1\bar{3}}\lambda_{5\bar{6}}}{\lambda_4^2} \right] \\
 & - 2\lambda_6 \left[\left(\frac{1}{2\lambda_{125}} + \frac{1}{\lambda_{2345}} \right) \frac{2\lambda_6^2 - 6m^2 + \lambda_{456}\lambda_{45\bar{6}}}{\lambda_{134}} \right. \\
 & \left. - \frac{2\lambda_4\lambda_5}{\lambda_{134}\lambda_{125}} \right] + (d-4) \left[\frac{\lambda_6\lambda_{25} - 2\lambda_2\lambda_5}{\lambda_{134}} - \frac{\lambda_1\lambda_6}{\lambda_{2345}} \right] \left. \right\} \\
 & + (2 \leftrightarrow 3, 4 \leftrightarrow 5) + (2 \leftrightarrow 4, 3 \leftrightarrow 5) + (2 \leftrightarrow 5, 3 \leftrightarrow 4) , \tag{34}
 \end{aligned}$$

Quantum Fourier Iterative Amplitude Estimation (QFIAE)



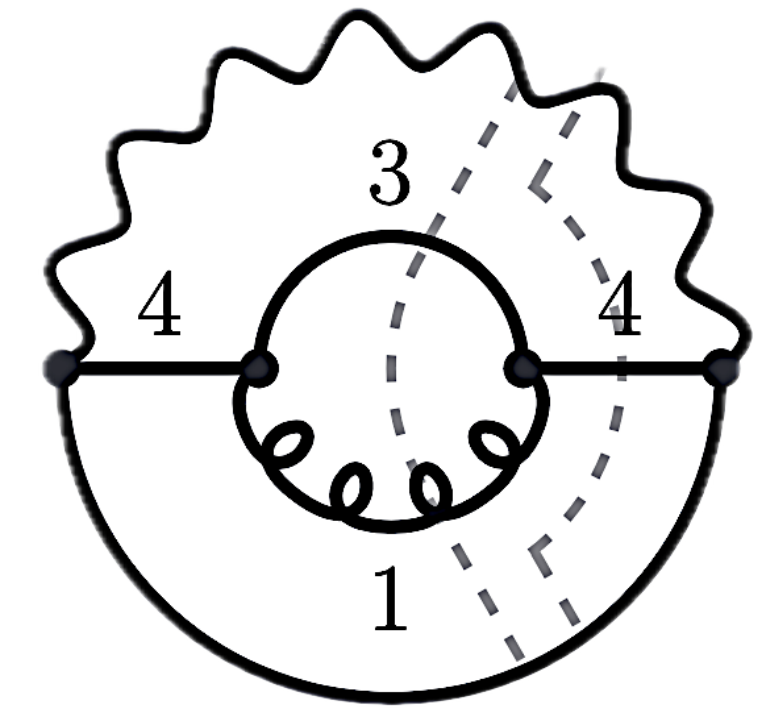
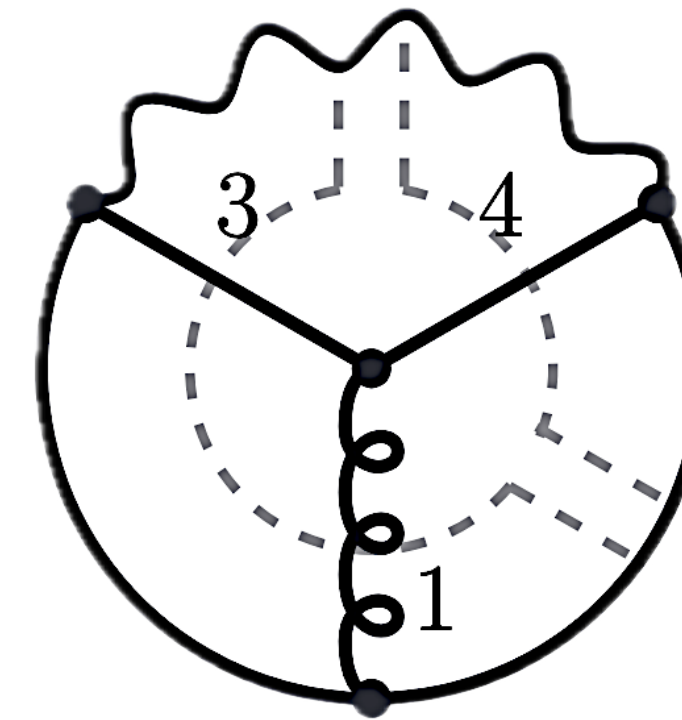
- Integration of multidimensional functions
- Quantum Machine Learning + Grover's amplification
- Fourier series using a **Quantum Neural Network (QNN)**
- Integrates each trigonometric component using **Iterative Quantum Amplitude Estimation (IQAE)** [Grinko, Gacon, Zoufal, Woerner, npj QI 7, 52 (2021)], a variant of Grover's algorithm

Decay rate of Higgs boson / photon / toy-scalar at NLO



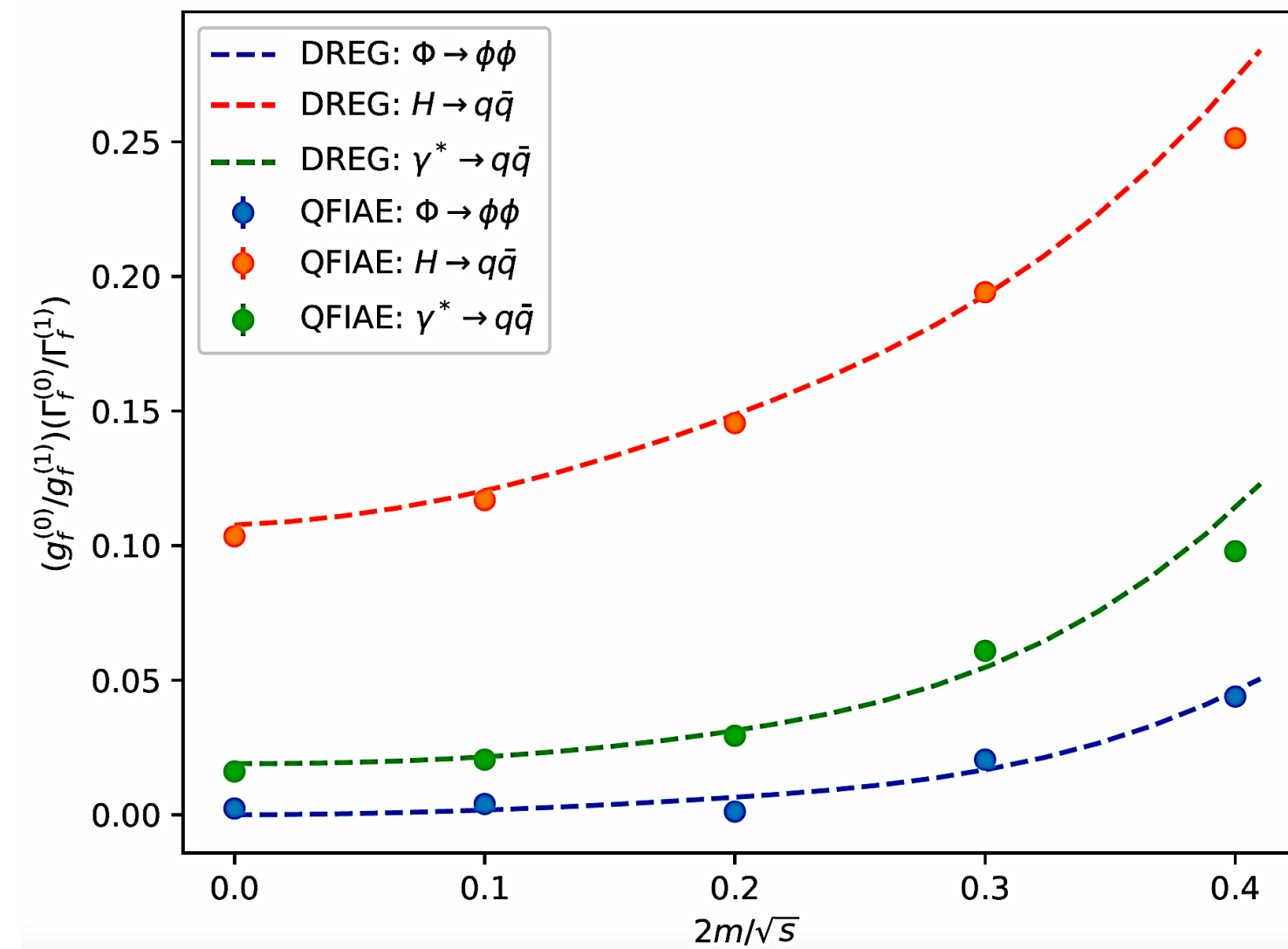
○ Classical Monte Carlo

Vacuum amplitudes and time-like causal unitary in the loop-tree duality, LTD
Collaboration, [JHEP 01 \(2025\) 103 \[2404.05492\]](#)

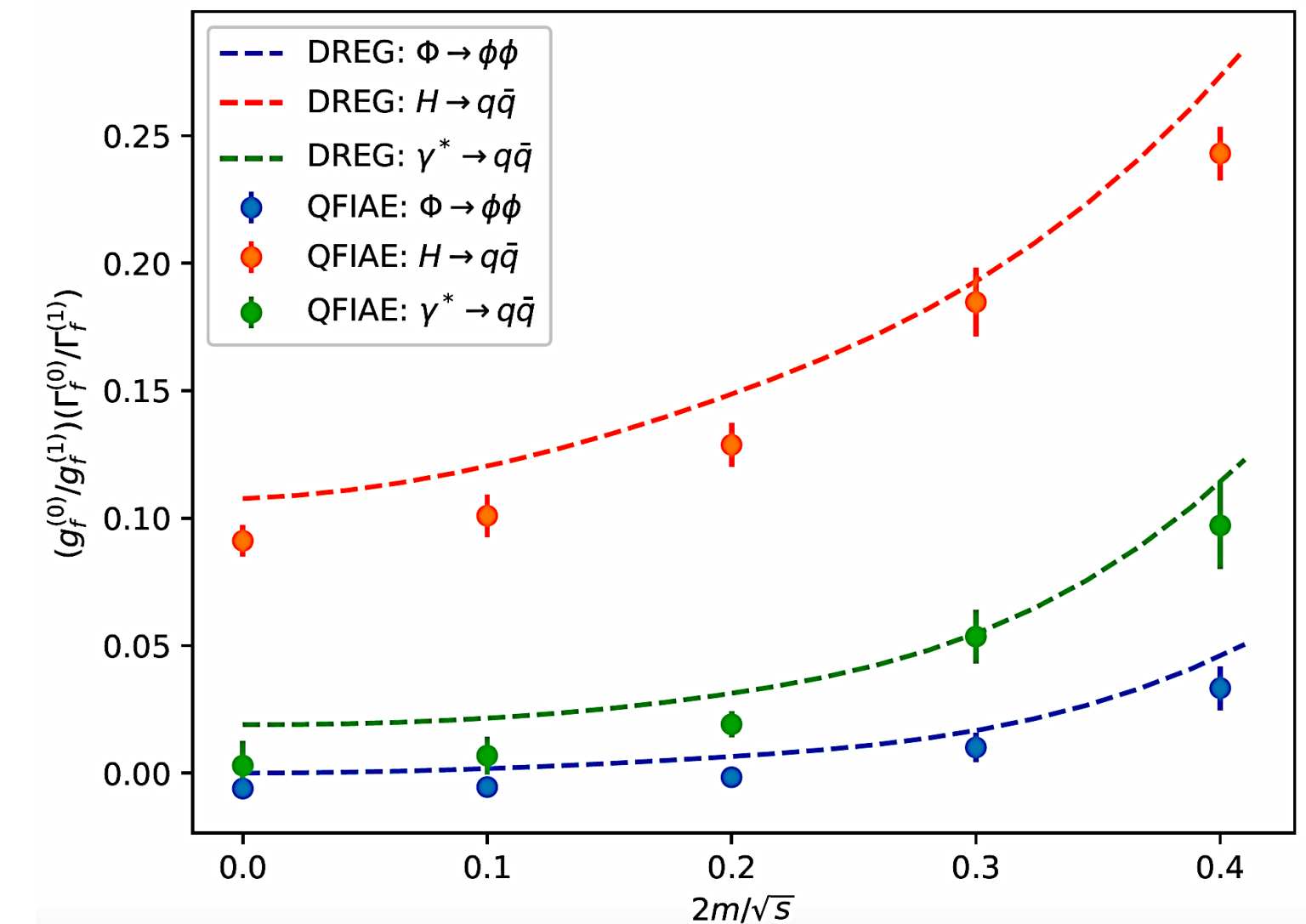


Quantum integration of decay rates at second order in perturbation theory

J.J. Martínez de Lejarza, D.F. Rentería Estrada, M. Grossi, GR, [Quantum Sci.Technol. 10 \(2025\) 2, 025026 \[2409.12236\]](#)

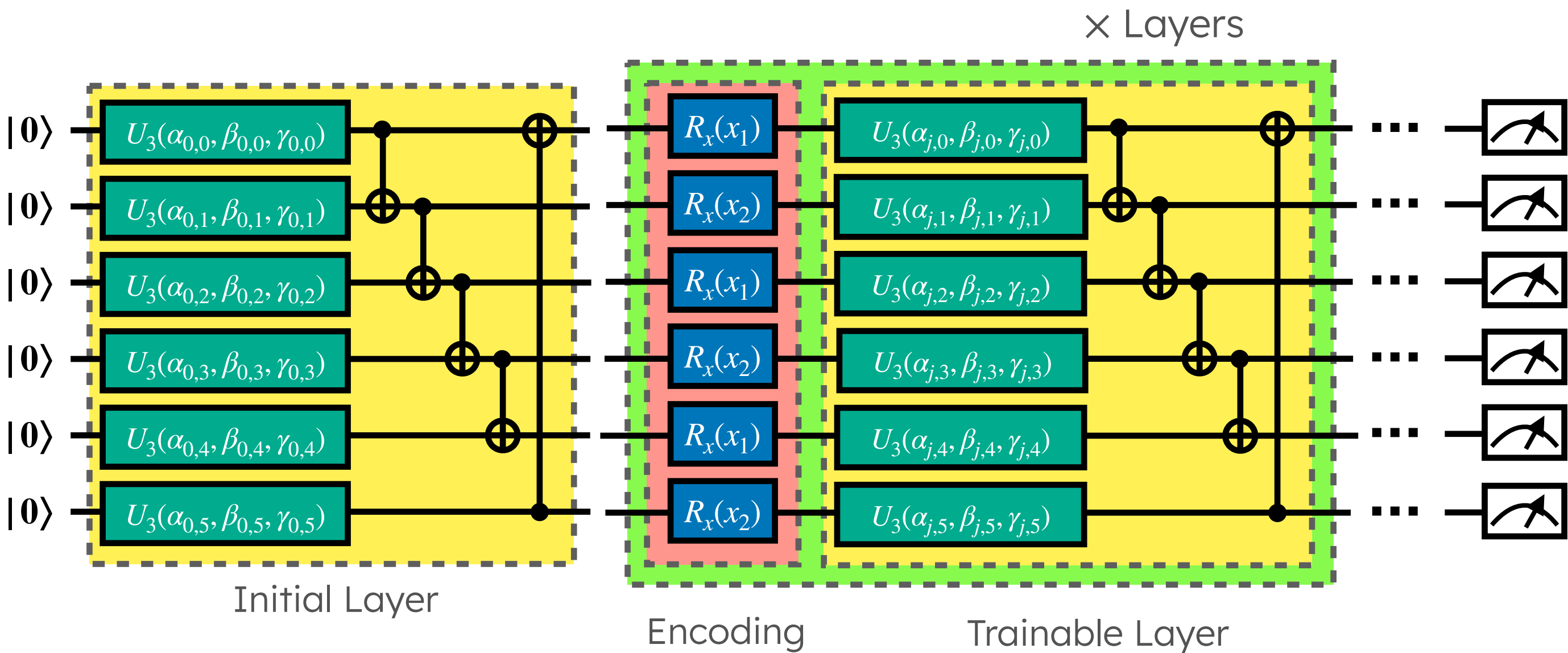


○ Quantum simulator



○ Partially in quantum hardware

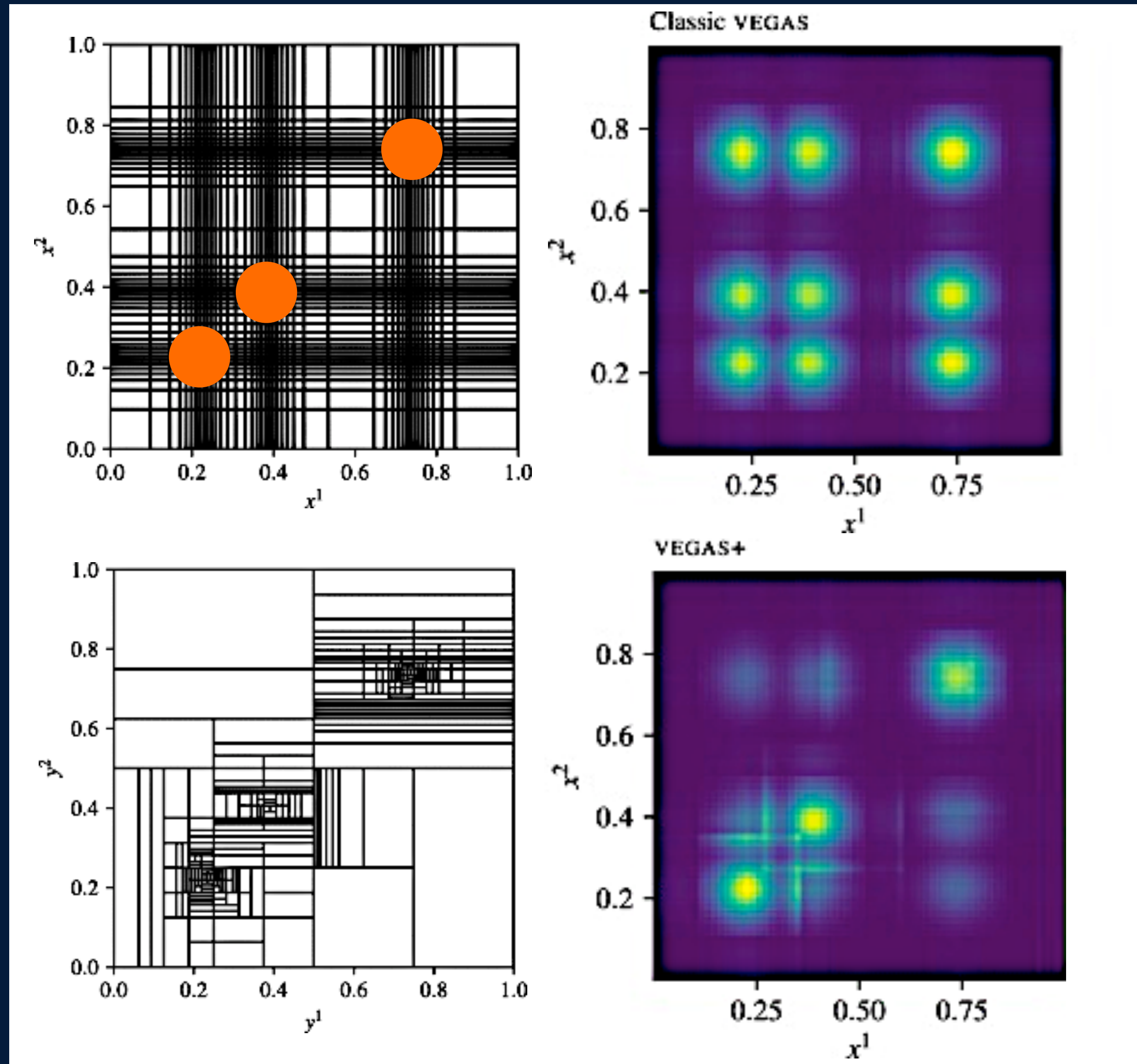
Technical details



Decay	$2m/\sqrt{s}$	Hardware	Simulator	DREG
$\Phi \rightarrow \phi\phi(\phi)$	0.0	−0.0061(28)	0.0023(5)	0.0000
	0.1	−0.0055(31)	0.0040(6)	0.0018
	0.2	−0.0016(30)	0.0011(6)	0.0065
	0.3	0.0101(56)	0.0205(11)	0.0167
	0.4	0.0333(85)	0.0439(15)	0.0459
$H \rightarrow q\bar{q}(g)$	0.0	0.0911(61)	0.1034(13)	0.1077
	0.1	0.1009(83)	0.1169(14)	0.1204
	0.2	0.1288(85)	0.1455(14)	0.1486
	0.3	0.1847(135)	0.1941(20)	0.1928
	0.4	0.2431(104)	0.2513(30)	0.2730
$\gamma^* \rightarrow q\bar{q}(g)$	0.0	0.0029(96)	0.0161(14)	0.0190
	0.1	0.0068(74)	0.0205(13)	0.0215
	0.2	0.0191(50)	0.0293(13)	0.0313
	0.3	0.0535(103)	0.0609(20)	0.0547
	0.4	0.0971(171)	0.0979(30)	0.1140

- **PennyLane** to construct and train the QNN (6-qubit Ansatz), 20 layers
- IQAE module implemented with **Qibo** on quantum simulators, and with **Qiskit** on a real hardware (5 qubits), executed on the 27-qubit IBMQ superconducting device ibmq_mumbai
- **error mitigation**: pulse-efficient transpilation, error suppression Dynamical Decoupling (DD) within the circuit execution and error mitigation Zero Noise Extrapolation (ZNE) to the output

Adaptive Importance Sampling



$$\int_{\Omega} f(x) dx \equiv \int_{[0,1]^d} J(y) f(x(y)) dy$$

$$I_{MC}^{(VEGAS)} = \frac{1}{N} \sum_{i=1}^N J(y_i) f(x(y_i))$$

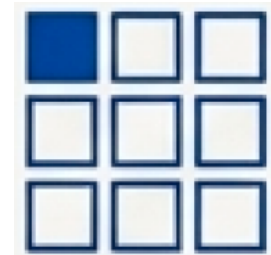
- Adapts a **grid** to concentrate samples in regions of high variance
- **The size of the grid grows** exponentially with dimensionality
- **A separable grid**: each dimension divided into intervals of varying widths independently
DoF: $(N_g)^d \rightarrow d \cdot N_g$
- Makes the grid tractable in a classical computer but generates **phantom peaks**

QAIS - Quantum Adaptive Importance Sampling

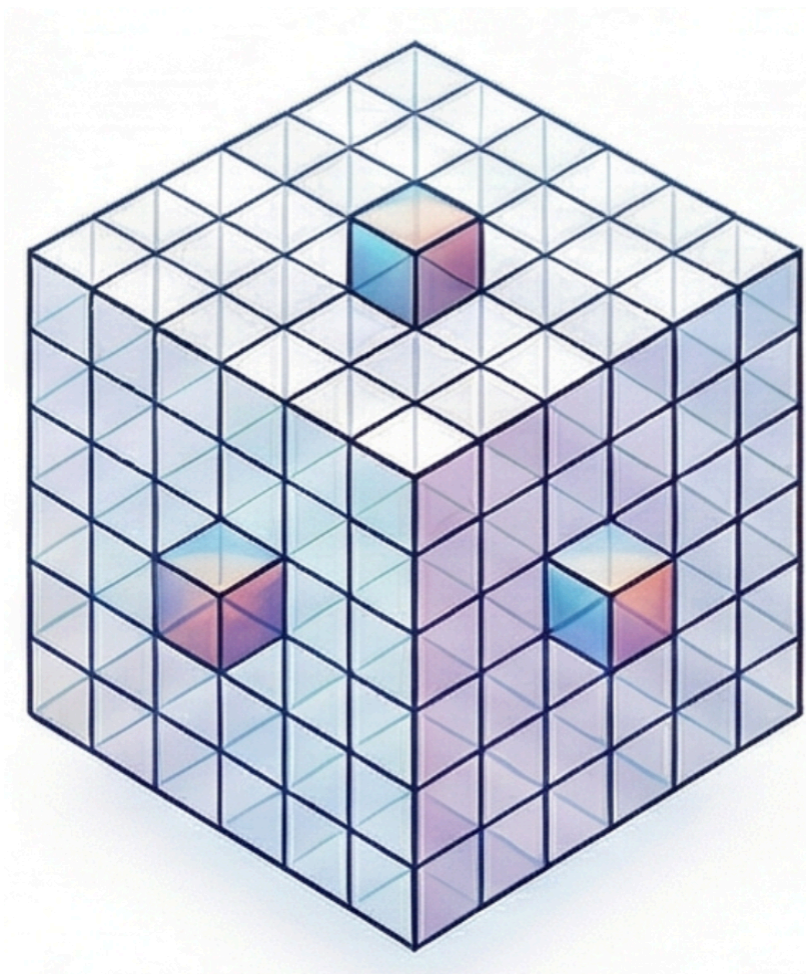
- Leverage a **Parametrized Quantum Circuit (PQC)** to construct a Probability Density Function (PDF) that accurately approximates the target function
- Reduce the number of function evaluations by **efficiently allocating samples** in the integration domain



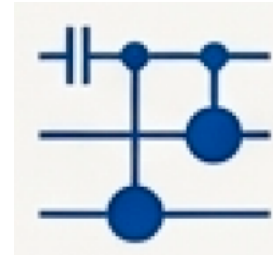
Quantum Adaptive Importance Sampling (QAIS)



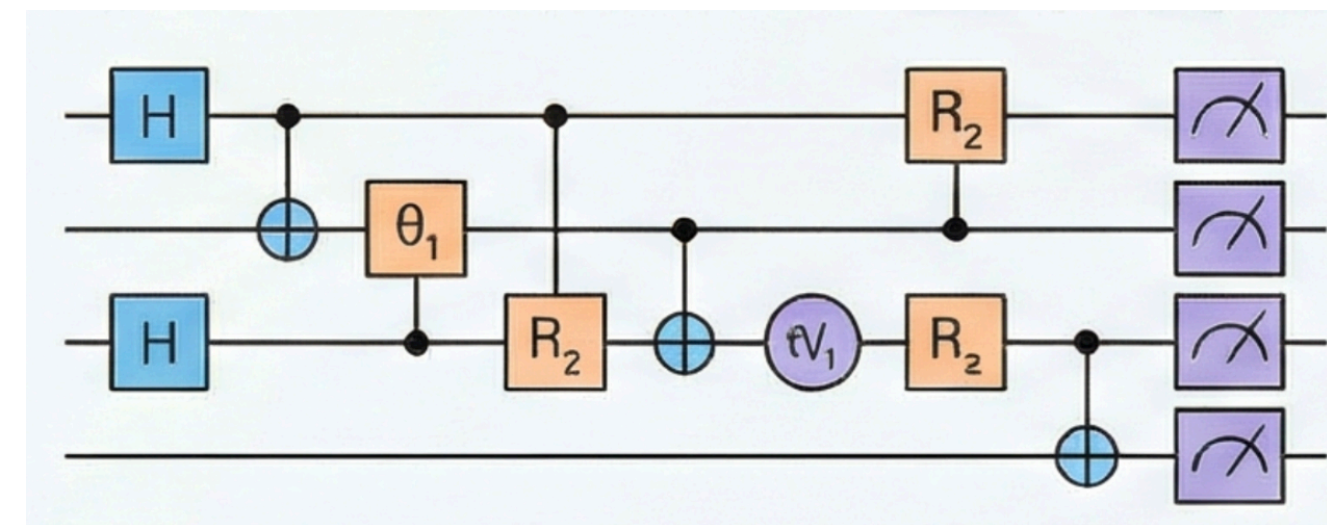
Stage 1
Encoding



The d -dimensional integration domain is **discretized and mapped into an n -qubit Hilbert space**. Each of the 2^n computational basis state corresponds to a specific grid cell.



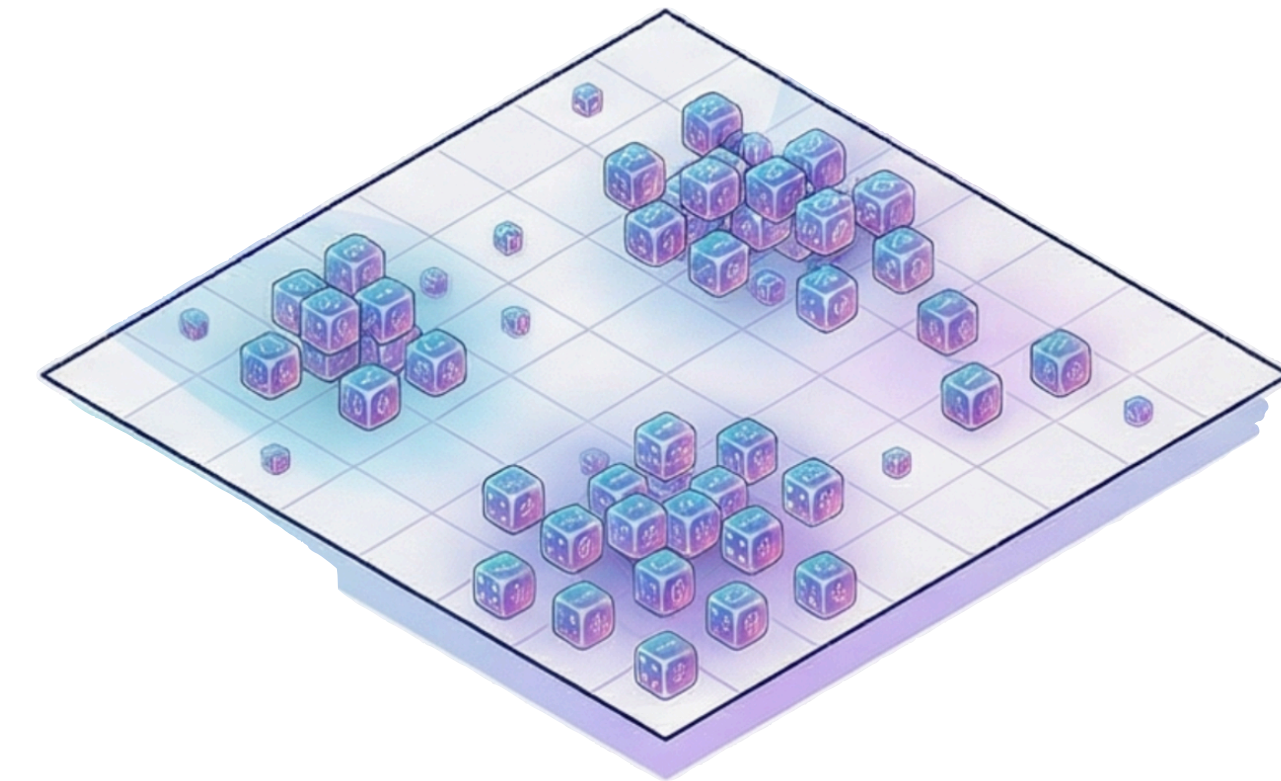
Stage 2
State Preparation



A PQC is trained (e.g. as a Quantum Circuit Born Machine) to generate a quantum state $|\psi\rangle$. The training objective is to make the measurement probabilities $|\langle j | \psi \rangle|^2$ **match the structure of the target integrand $f(\mathbf{x})$** . This shapes the proposal PDF



Stage 3
Integrand Estimation



Measurements are performed on the optimized PQC. The **frequency of outcomes determines the number of samples (N_j)** allocated to each grid cell. A dedicated statistical framework, adjusted for quantum measurements is used to calculate the integral estimate and its variance.

Parametrized Quantum Circuit

q_x

$|0\rangle$

H

$\vdots$

$\vdots$

$\vdots$

$|0\rangle$

H

$\vdots$

$\vdots$

$\vdots$

q_y

$|0\rangle$

H

$\vdots$

$\vdots$

$\vdots$

$|0\rangle$

H

$\vdots$

$\vdots$

$\vdots$

q_z

$|0\rangle$

H

$\vdots$

$\vdots$

$\vdots$

$|0\rangle$

H

$U^{(k)}(\{\theta_{ij}\})$

$U_3(\alpha_1, \beta_1, \gamma_1)$

$\vdots$

$U_3(\alpha_i, \beta_i, \gamma_i)$

$\vdots$

$U_3(\alpha_{i+1}, \beta_{i+1}, \gamma_{i+1})$

$\vdots$

$U_3(\alpha_j, \beta_j, \gamma_j)$

$\vdots$

$U_3(\alpha_{j+1}, \beta_{j+1}, \gamma_{j+1})$

$\vdots$

$U_3(\alpha_n, \beta_n, \gamma_n)$

Measurement

$\vdots$

Measurement

$\vdots$

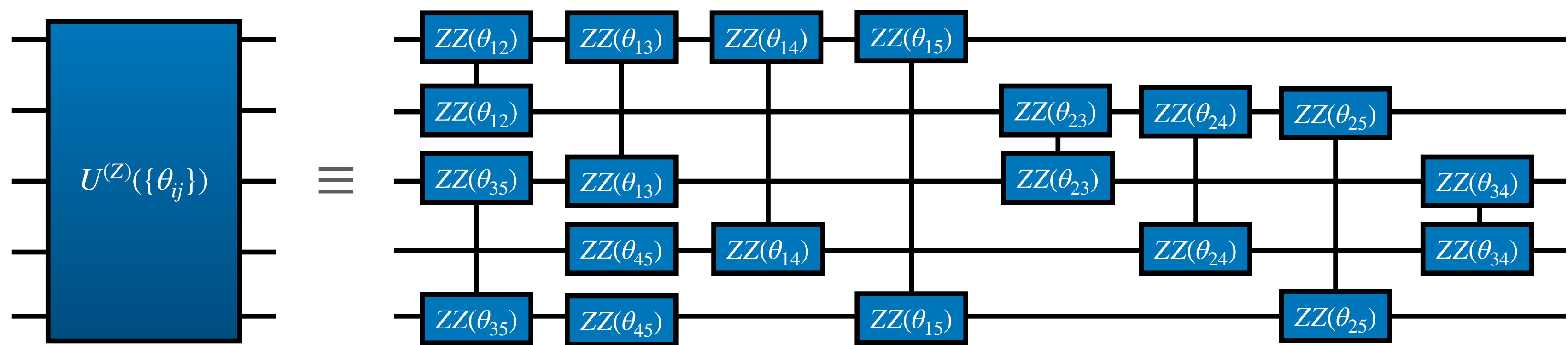
Measurement

$\vdots$

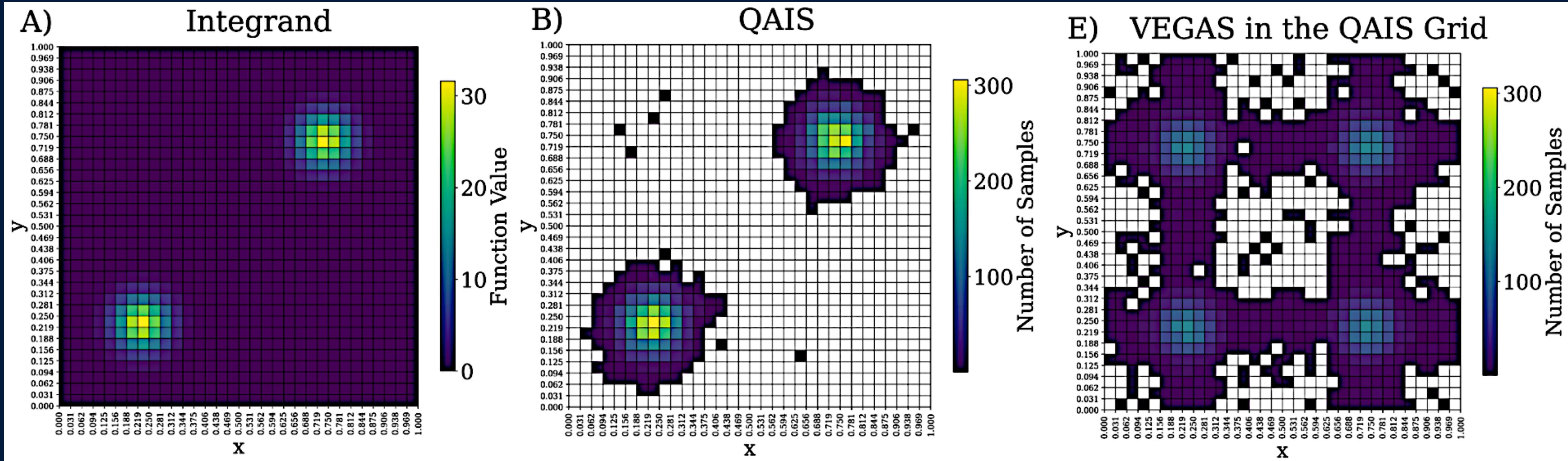
Measurement

$\times \text{ Layers}$

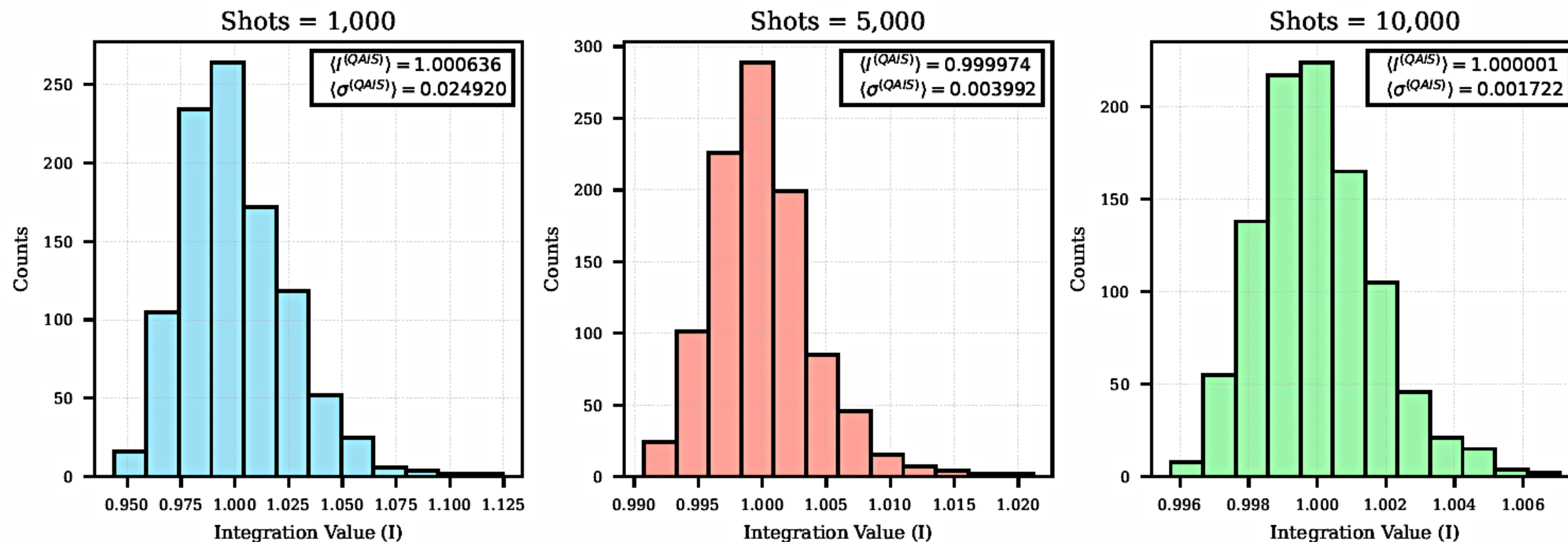
- $\bigcirc$ **all-to-all connectivity** approach with two-qubit gates and single qubit gates
- $\bigcirc$ Performs much better than Hardware Efficient Ansatz (HEA)
- $\bigcirc$ Cost function: discretised version of Kullback-Leibler (KL) divergence
$$D_{\text{KL}}(P\|Q) = \sum_{i=1}^M P(\Omega^{(i)}) \log \left(\frac{P(\Omega^{(i)})}{Q(\Omega^{(i)})} \right)$$
- $\bigcirc$ COBYLA optimizer



Absence of phantom peaks

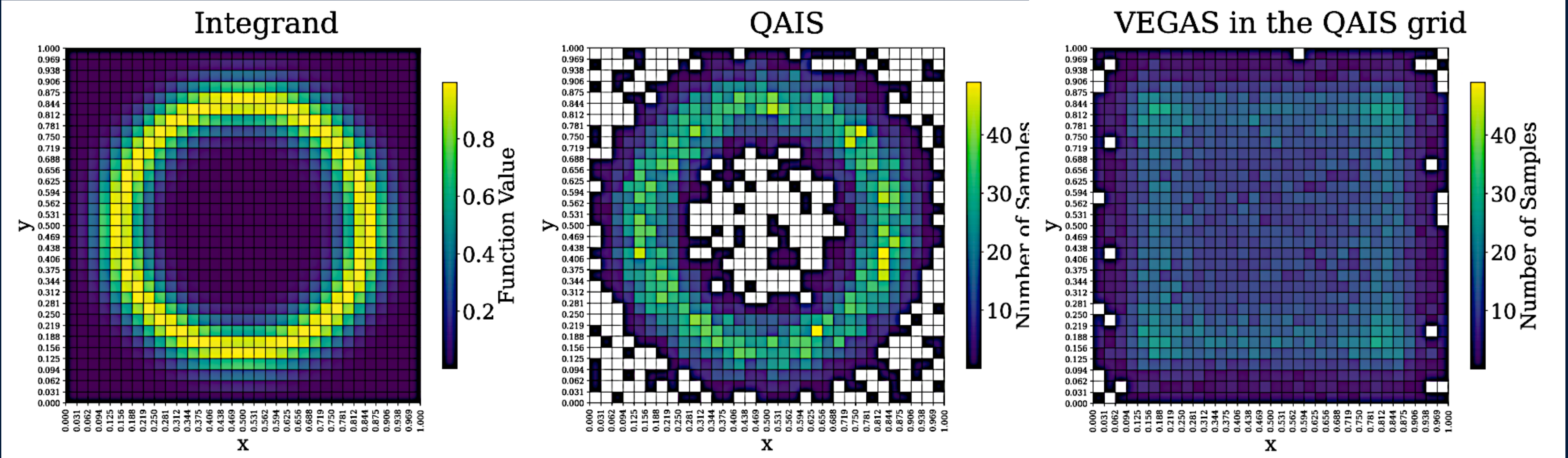


Distribution of Integration Results by Number Shots



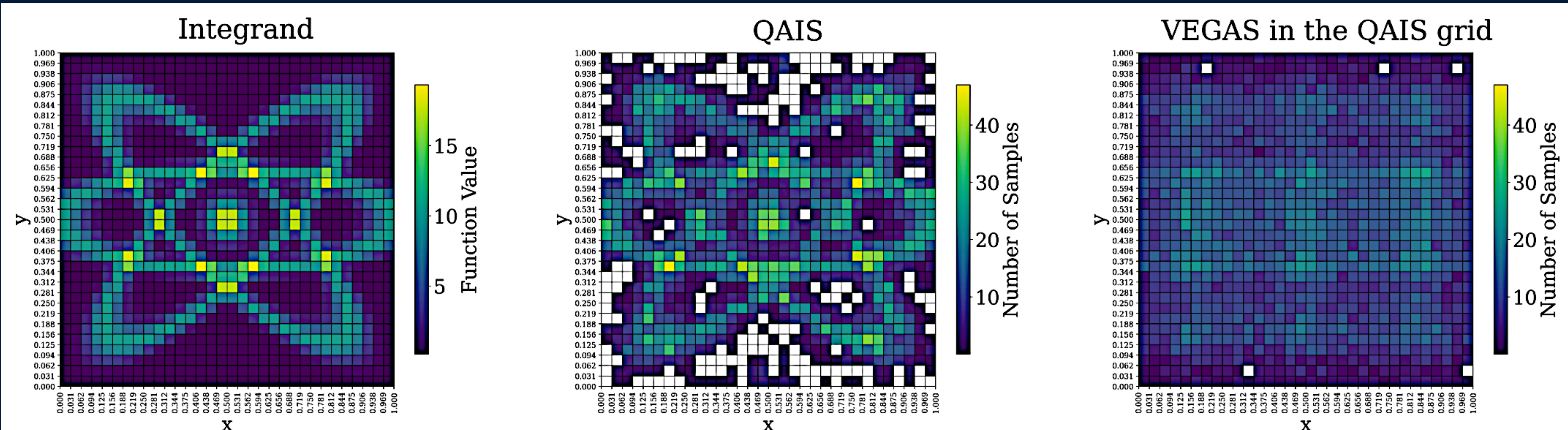
- Integral normalised to one
- 1000 independent runs with the same PDF as a function of the number of shots
- Includes a Tiling module to reduce bias from unobserved cells

A ring-shaped 2d function



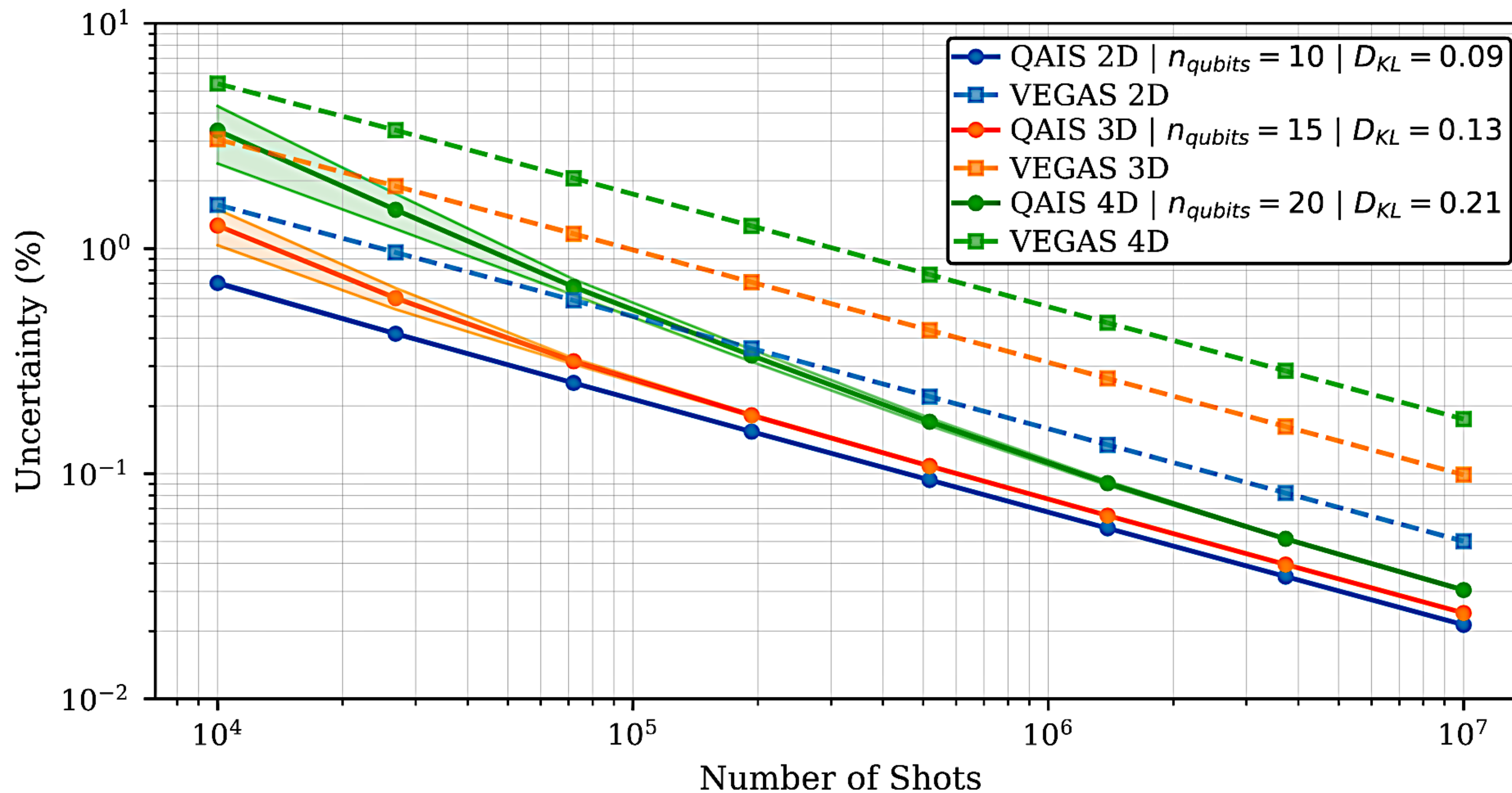
EVEN MORE CHALLENGING FOR VEGAS

An atom-shaped 2d function



Cross-dimensional Integration Comparison

$$\int_{[0,1]^d} f(\mathbf{x}) d\mathbf{x} = \int_{[0,1]^d} \left(\sum_{i=0}^2 e^{-50|\mathbf{x}-\mathbf{r}_i|} \right) d\mathbf{x}$$

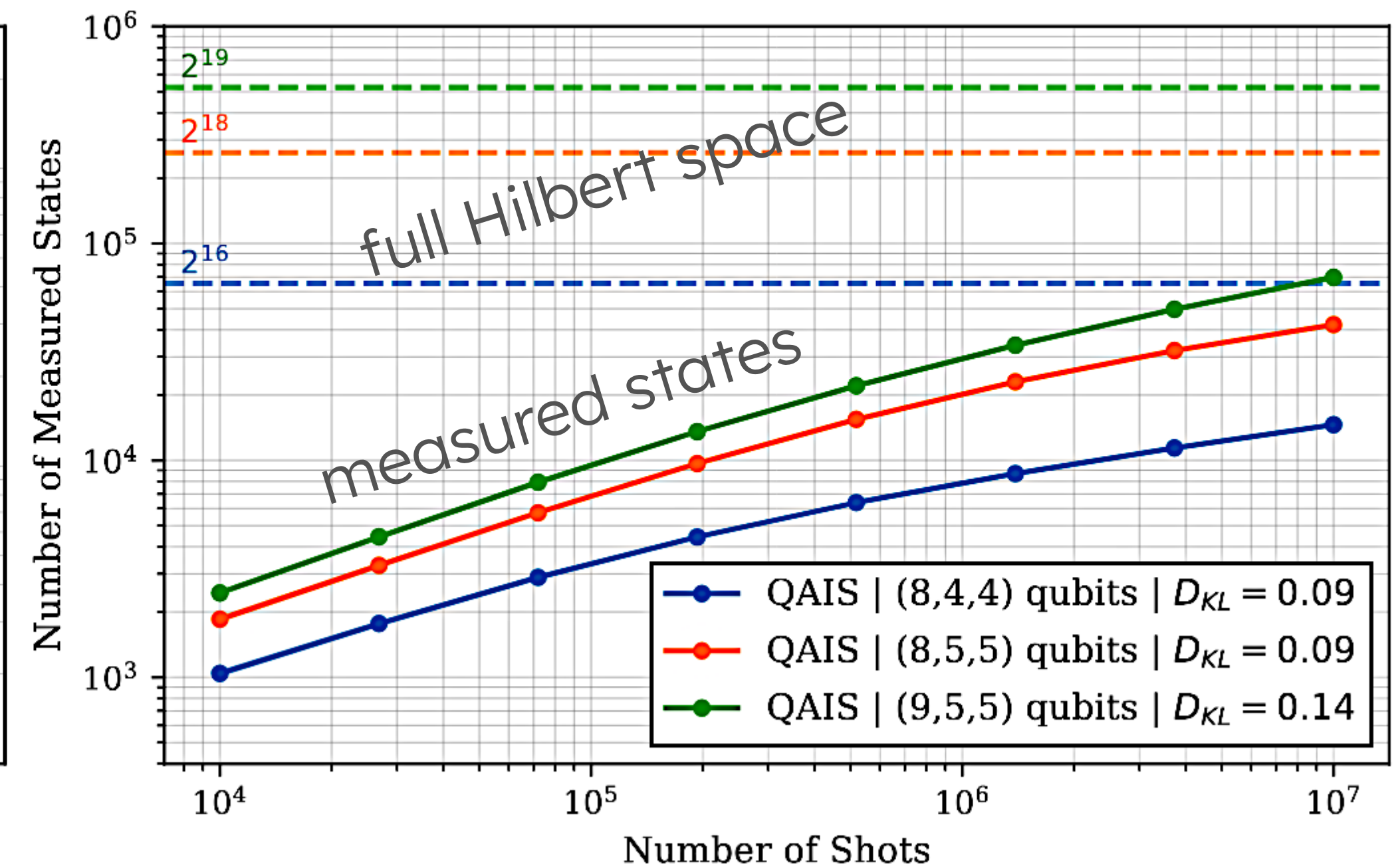
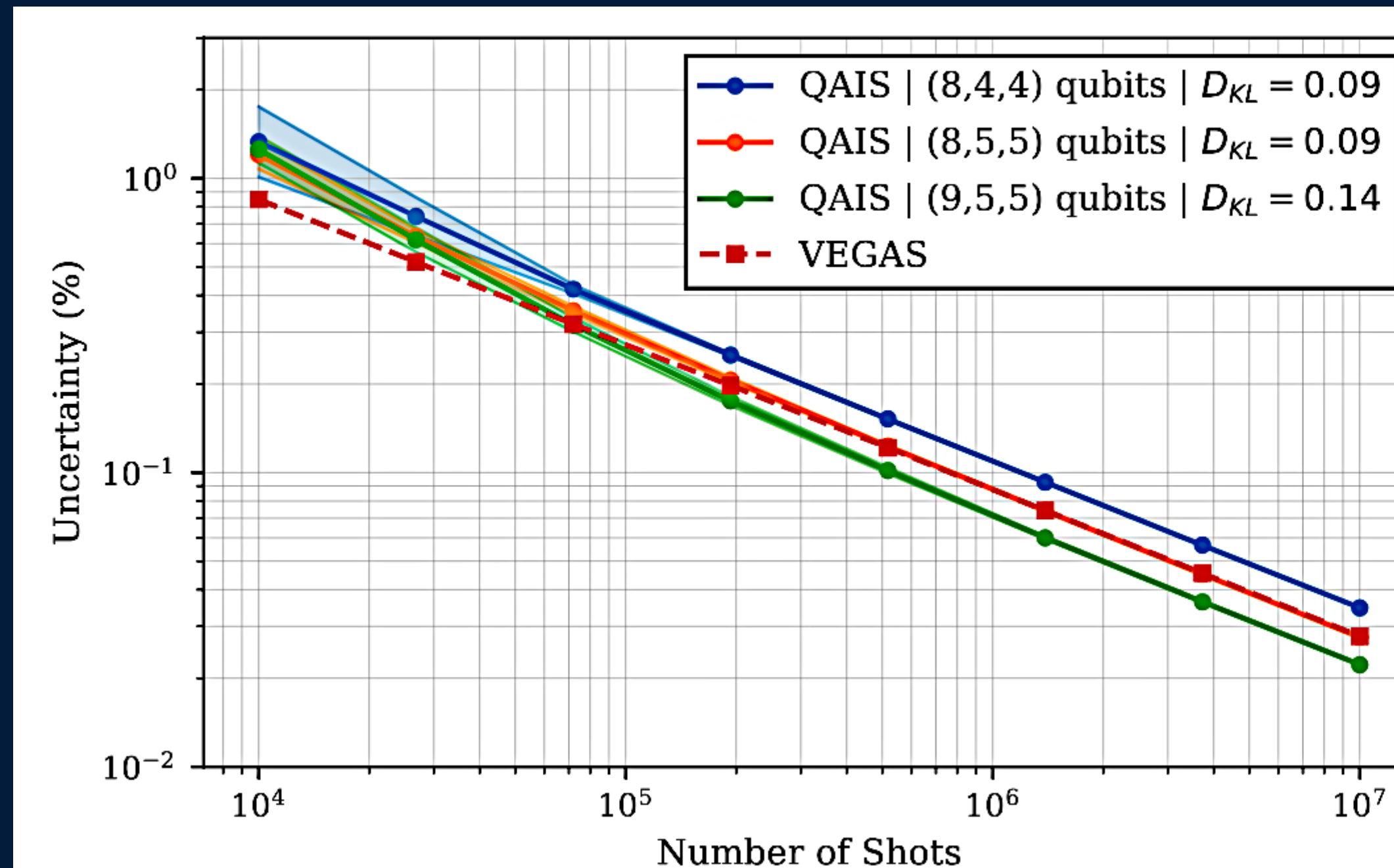
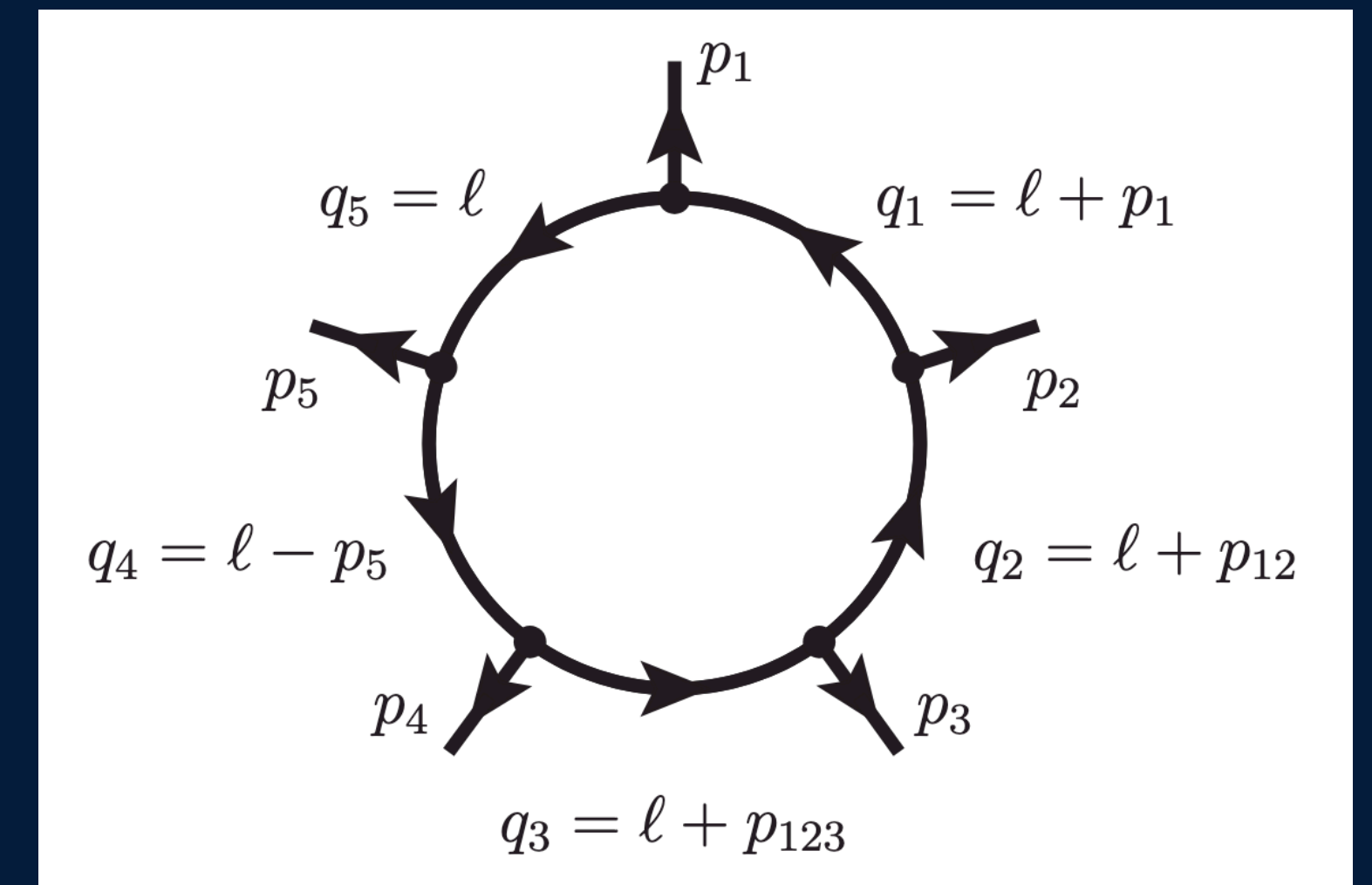


The one-loop pentagon

$$\mathcal{A}_5^{(1)} = \int_{\ell} \prod G_F(q_i) \rightarrow \int_{\vec{\ell}} \mathcal{A}_D^{(1)}$$

$$\lambda_i^{\pm} = q_{i,0}^{(+)} + q_{i+1,0}^{(+)} \pm p_{i,0}$$

$$\lambda_{ij}^{\pm} = q_{i,0}^{(+)} + q_{j+1,0}^{(+)} \pm (p_i + p_j)_0, \quad j = i + 1$$



○ uncertainty band from 100 independent runs with the same PDF

Conclusions

- High-energy colliders are **quantum machines** (with the LHC the largest quantum machine ever built), and so well suited for a Quantum Computing (QC) approach
- Accuracy of theoretical predictions hinges critically on efficiently integrating and sampling multidimensional functions, a challenge that **scales exponentially with dimensionality**: a clear QC use case also across multiple fields
- QFIAE, and in particular QAIS, efficiently boost quantum integration and sampling of multidimensional functions
- With respect to Classical Machine Learning (e.g. Normalizing Flows [Gao, Isaacson, Krause], Madnis [Plehn, Maltoni ...]), far fewer parameters while better capturing correlations
- My (long-term) dream: a **quantum event generator** with NNLO, ..., $N^k\text{LO} + N^k\text{LL}$ accuracy