Quantum Algorithms for Event Generators at High-Energy Colliders

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Quantum Information Science in High Energy Nuclear Physics

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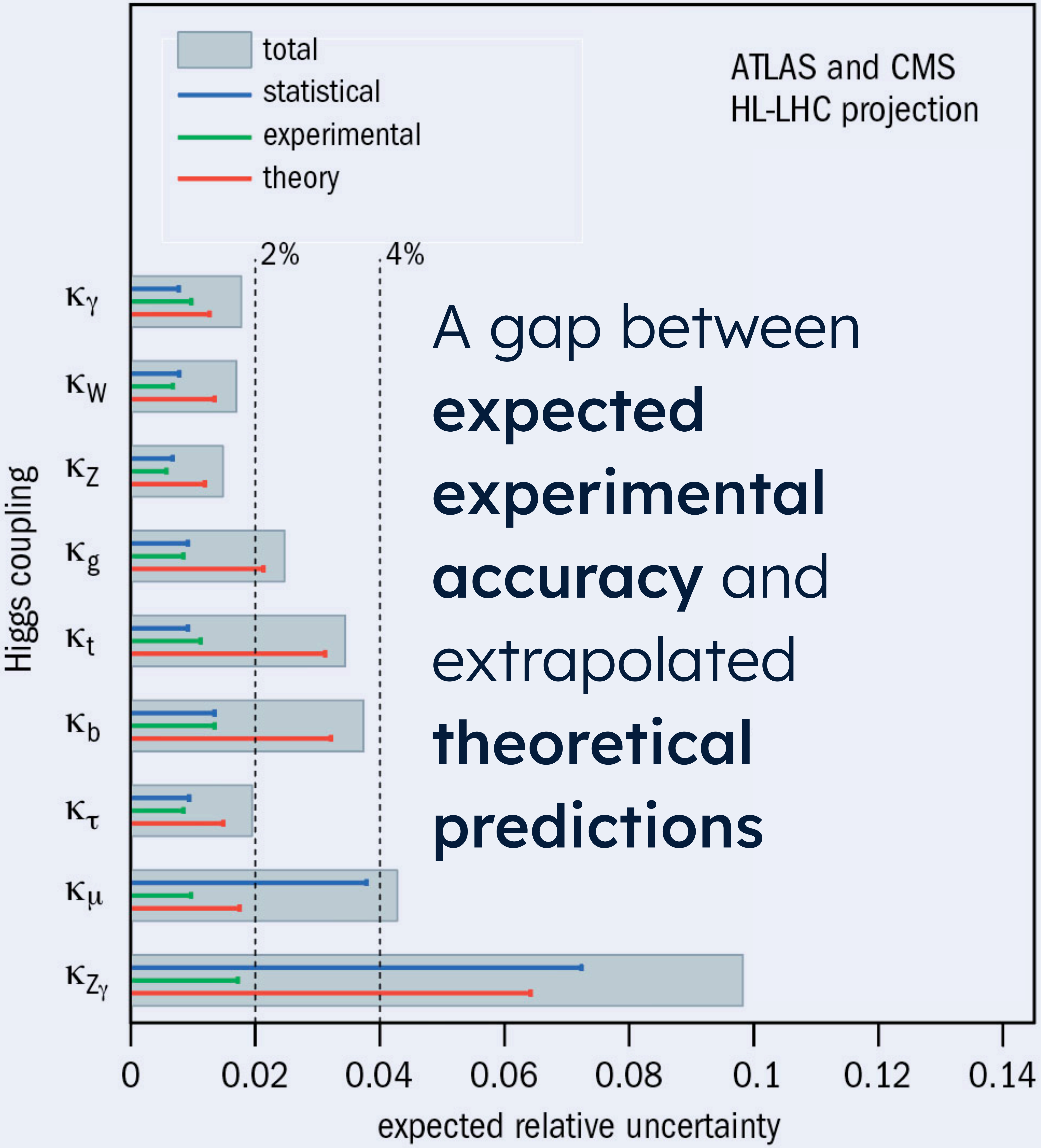
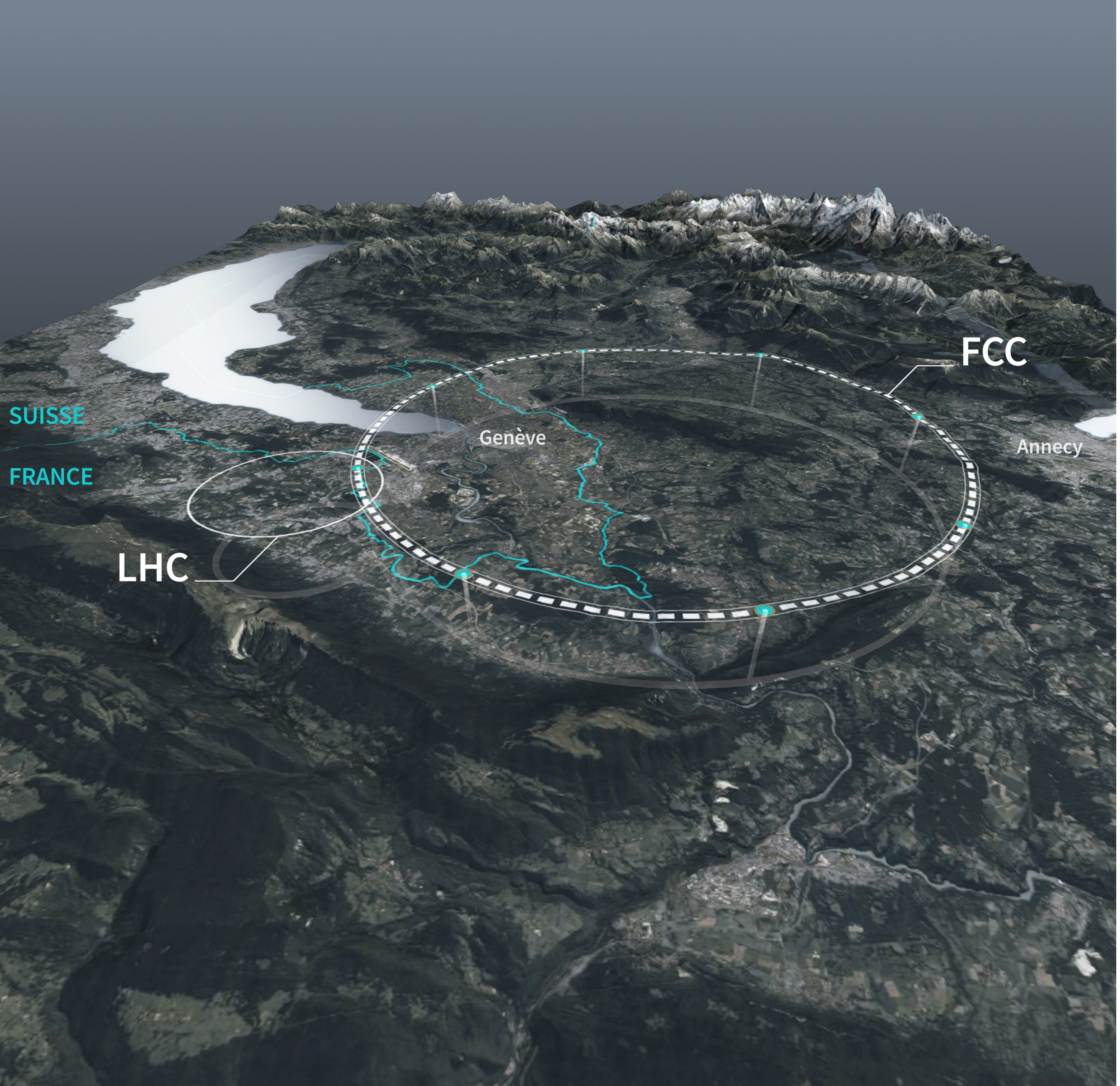
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
Cofinanciado por la Unión Europea
AGENCIA ESTATAL DE INVESTIGACIÓN
PID2023-14622NB-I00 EUR2025-164820

Motivation

credit: CERN Courier



A gap between **expected experimental accuracy** and extrapolated **theoretical predictions**



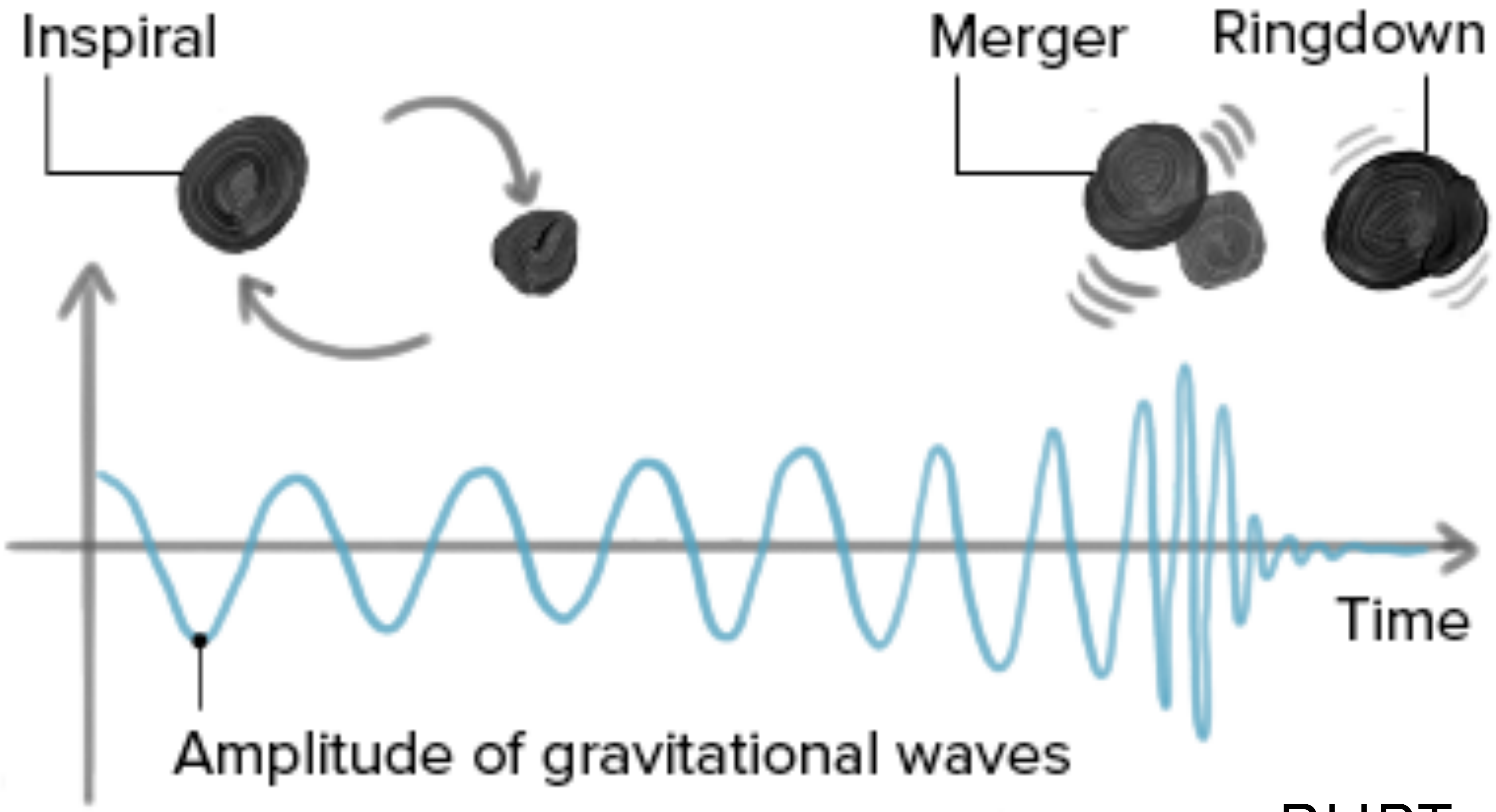
Theoretical challenges ahead

e.g. theoretical work needed to enable *extraction* of EWPO from measurements (additional work needed for making predictions)

Quantity	Current precision	FCC-ee stat. (syst.) precision	Required theory input	Theory status as of today	Needed theory improvement†
m_Z (MeV)	2.0	0.004 (0.1)	non-resonant $e^+e^- \to f\bar{f}$, initial-state radiation (ISR)	NLO, ISR logarithms up to 6th order	NNLO for $e^+e^- \to f\bar{f}$
Γ_Z (MeV)	2.3	0.004 (0.012)			
$\sin^2\theta^{\ell}_{\rm eff}$	1.6×10^{-4}	$1.2\ (1.2) \times 10^{-6}$			
m_W (MeV)	9.9	0.18 (0.16)	lineshape of $e^+e^- \to WW$ near threshold	NLO ($e^+e^- \to 4f$ or EFT framework)	NNLO for $e^+e^- \to WW$, $W \to f\bar{f}'$ in EFT setup
HZZ coupling	–*	0.1%	cross section for $e^+e^- \to ZH$	NLO EW plus partial NNLO QCD/EW	full NNLO EW
$m_{\rm top}$ (MeV)	290	4.2 (4.9)	threshold scan $e^+e^- \to t\bar{t}$	N^3LO QCD, NNLO EW, resummations up to NNLL, $\mathcal{O}$(30 MeV) scale uncert.	Matching fixed orders with resummations, merging with MC, α_S (input)

† The necessary theory calculations mentioned are a minimum baseline; additional partial higher-order contributions may also be required.
* No absolute value for the HZZ coupling can be extracted from the LHC data without additional assumptions.

[from FSR and Freitas *et al.* arXiv:1906.05379] credit: RIKEN



BHPT

perturbative expansions

numerical relativity

- LVK detects systems with $m_1/m_2 < 30$
- ET will detect $m_1/m_2 = \mathcal{O}(1000)$
- LISA with $m_1/m_2 = \mathcal{O}(10^4)$

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

High-energy colliders are **quantum machines**

QM ⊂ QFT

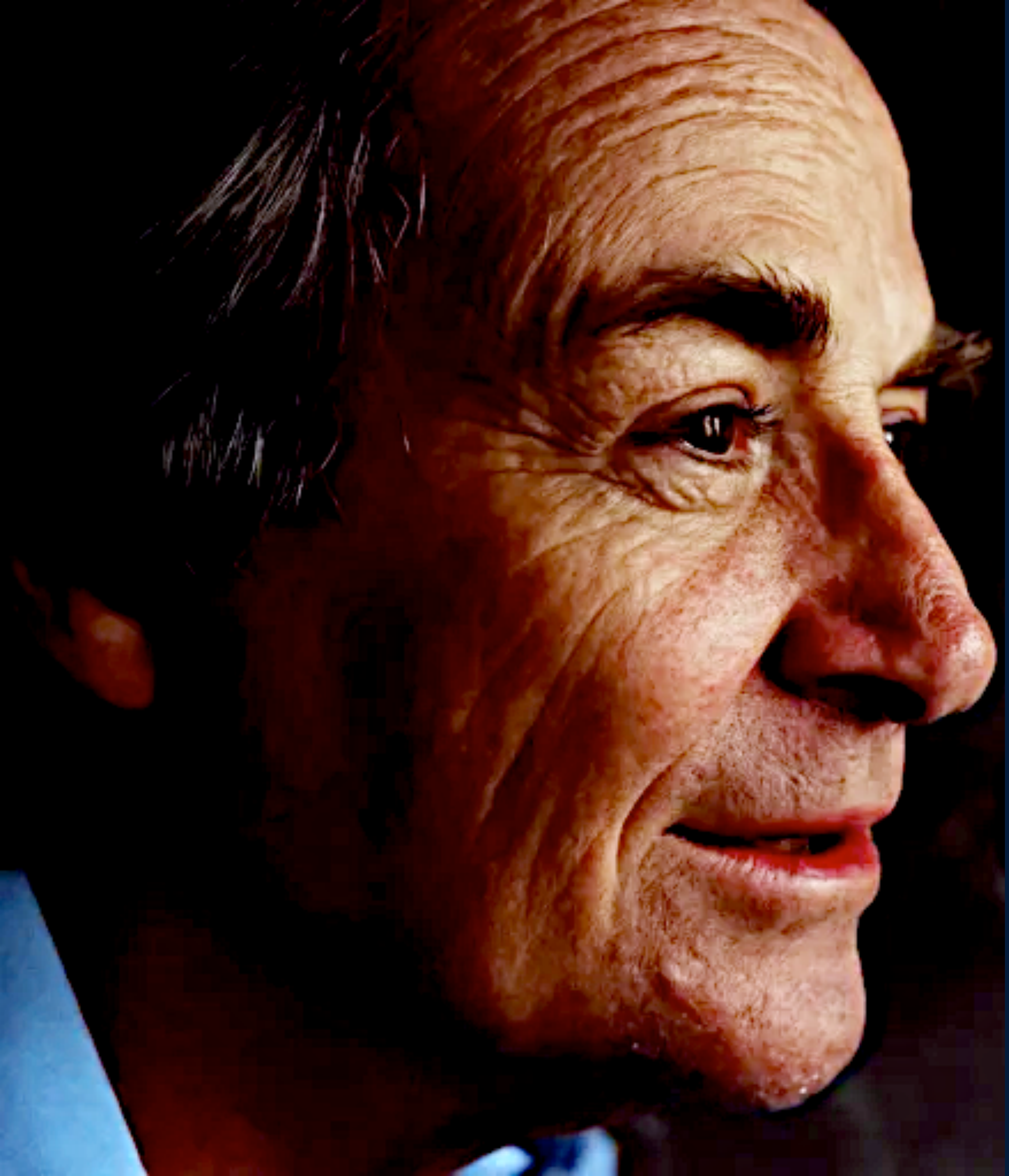
High-energy colliders
are **quantum machines**
QM ⊂ QFT
The LHC is the
Largest Quantum Machine
CMS
LHC
[Large Hadron Collider]
ALICE
ATLAS
© CERN

High-energy colliders
are **quantum machines**
QM ⊂ QFT

The LHC is the
Largest Quantum Machine

CERN is where **the Bell inequalities were born***

* 1964 *On the Einstein-Podolsky-Rosen Paradox*, published as U. Wisconsin but On leave of absence from SLAC and CERN

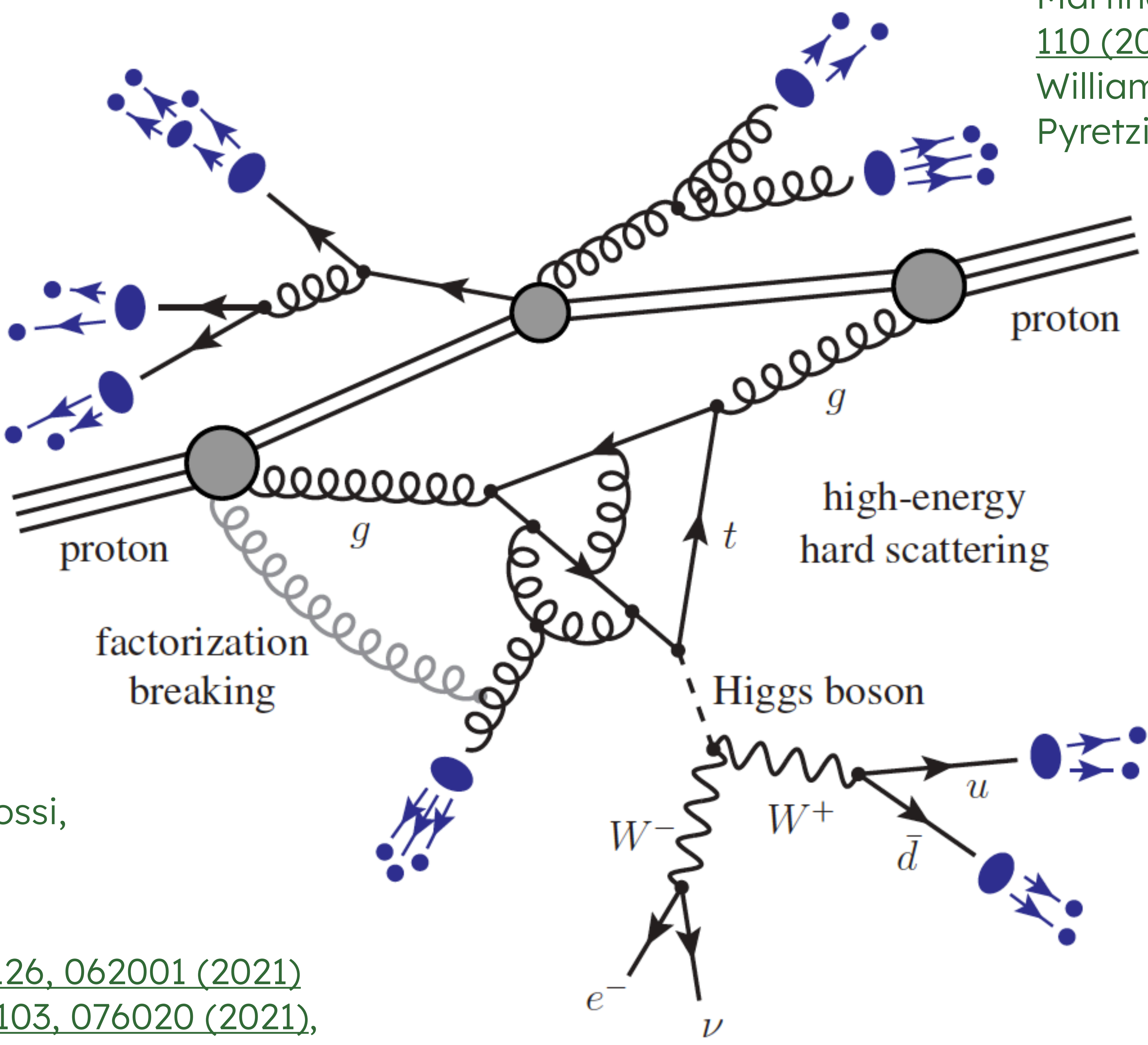


Nature isn’t classical, dammit, and if you want to make a simulation of nature, you better make it quantum

- Richard P. Feynman

Quantum at colliders

- track reconstruction:
  Mangano et al., PRD 105, 076012 (2022)
  Schwägerl, Issever, Jansen, Khoo, Kühn, Tüysüz, Weber, 2303.13249
  Duckett, Facini, Jastrzebski, Malik, Scanlon, Rettie, PRD 109, 052002 (2024)
  Nicotra, Lucio, de Vries, Merk, Driessens, Westra, Dibenedetto, Cámpora, JINST 18, P11028 (2023)
  Chiotopoulos, Nicotra, Scriven, Driessens, Merk, Schütz, de Vries, Winands, 2601.07766
- parton densities:
  Pérez-Salinas, Cruz-Martínez, Alhajri, Carrazza, PRD 103, 034027 (2021)
- fragmentation functions:
  Martínez de Lejarza, Wu, Kyriienko, GR, Grossi, Nat.Comm.Phys. 8, 448 (2025)
- parton showers:
  Bauer, de Jong, Nachman, Provasoli, PRL 126, 062001 (2021)
  Bepari, Malik, Spannowsky, Williams, PRD 103, 076020 (2021), PRD 106, 056002 (2022)
- quantum machine learning:
  Guan, Perdue, Pesah, Schuld, Terashi, Vallecorsa, Vlimant, MLST 2, 011003 (2021)
  Wu et al., JPG 48, 125003 (2021)
  Felser, Trenti, Sestini, Gianelle, Zuliani, Lucchesi, Montangero, npjQI 7, 111 (2021)



- Quantum integration and sampling:
  Herbert, Q6, 823 (2022)
  Agliardi, Grossi, Pellen, Prati, PLB 832, 137228 (2022)
  Cruz-Martínez, Robbiati, Carrazza, QST 9 (2024) 035053
  Martínez de Lejarza, Cieri, Grossi, Vallecorsa, GR, PRD 110 (2024) 074031, QST 10 (2025) 025026
  Williams, Pellen, QST 10 (2025) 045017
  Pyretzidis, Martínez de Lejarza, GR, 2506.19965
- tree-level helicity and/or color amplitudes:
  Bepari, Malik, Spannowsky, Williams, PRD 103, 076020 (2021)
  Chawdhry,.Pellen, Williams, 2507.07194
  Bashore, Moretti, Vitos, 2507.14252
  Haddad, Xu, Croft, Halimeh, Grossi, 2602.21311
- multiloop scattering amplitudes:
  Ramírez, Rentería, GR, Sborlini, Vale Silva, JHEP 2205, 100 (2022)
  Clemente, Crippa, Jansen, Ramírez, Rentería, GR, Sborlini, Vale Silva, PRD 108, 096035 (2023)
  Ochoa, Uribe, Ramírez, GR, 2508.04019
- jets in a medium:
  Barata, Du, Li, Qian, Salgado, PRD 106, 074013 (2022)
  Barata, Salgado, EPJC 81, 862 (2021)
- jet clustering:
  Wei, Naik, Harrow, Thaler, PRD 101, 094015 (2020)
  Pires, Bargassa, Seixas, Omar, 2101.05618
  Pires, Omar, Seixas, 2012.14514
  Martinez de Lejarza, Cieri, GR, PRD 106, 036021 (2022)

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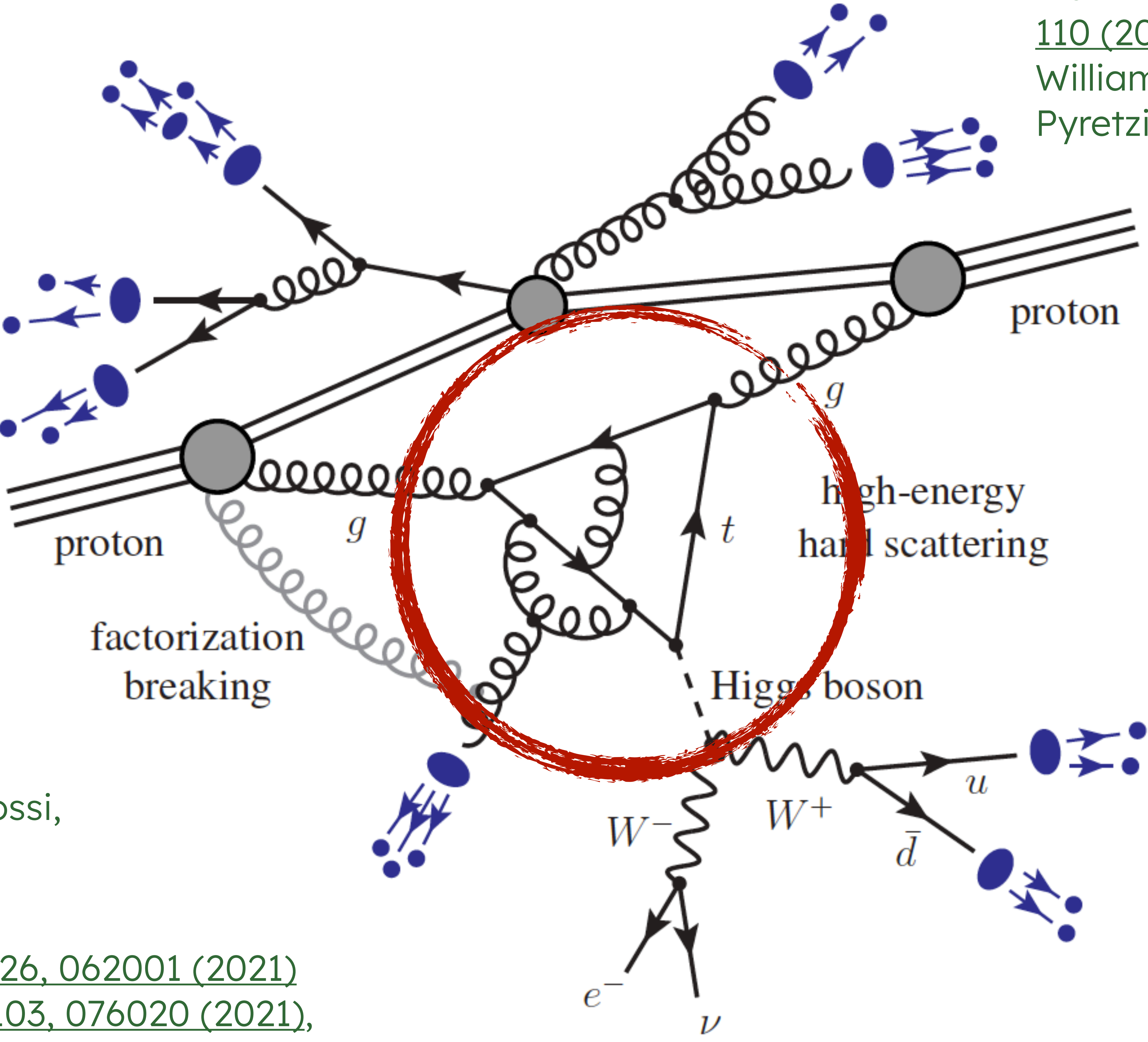

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The complexity under the hood

Why do we need Quantum Integration / Sampling?

- The accuracy of theoretical predictions at colliders 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 (9 independent integration variables for $2 \to 2$ at NNLO in a hadron collider)
- Quantum is the most natural approach for **sampling** $\equiv$ **event generation**

A Feynman propagator is a sort of qubit

- A Feynman propagator describes a **quantum superposition** of propagation in both directions

$$G_F(q_i) = \frac{1}{q_i^2 - m_i^2 + \imath 0} \equiv \frac{1}{\sqrt{2}} \left(|0\rangle + |1\rangle \right)$$

- A Feynman diagram is a superposition of 2^n states

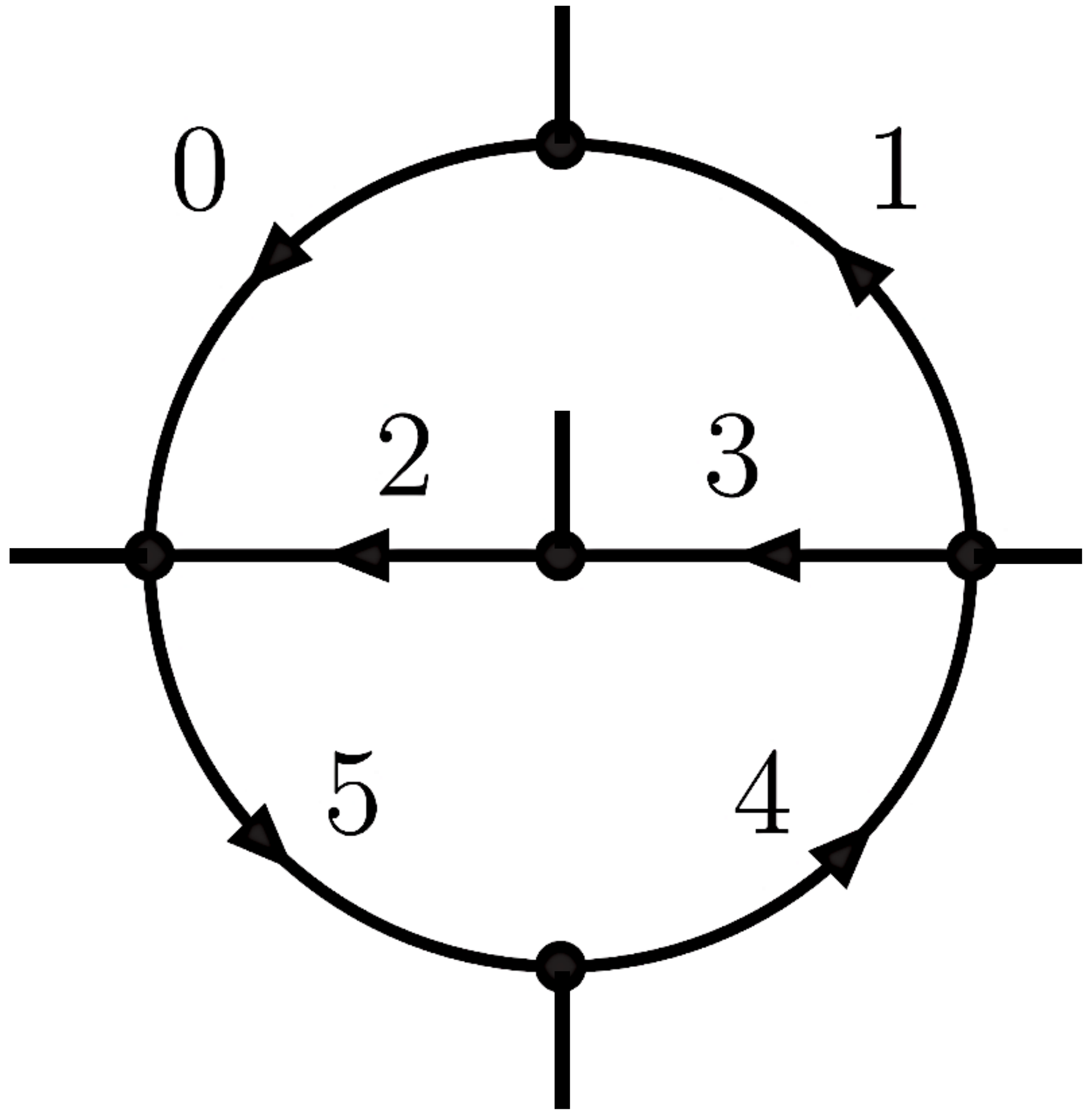
A Feynman propagator is a sort of qubit

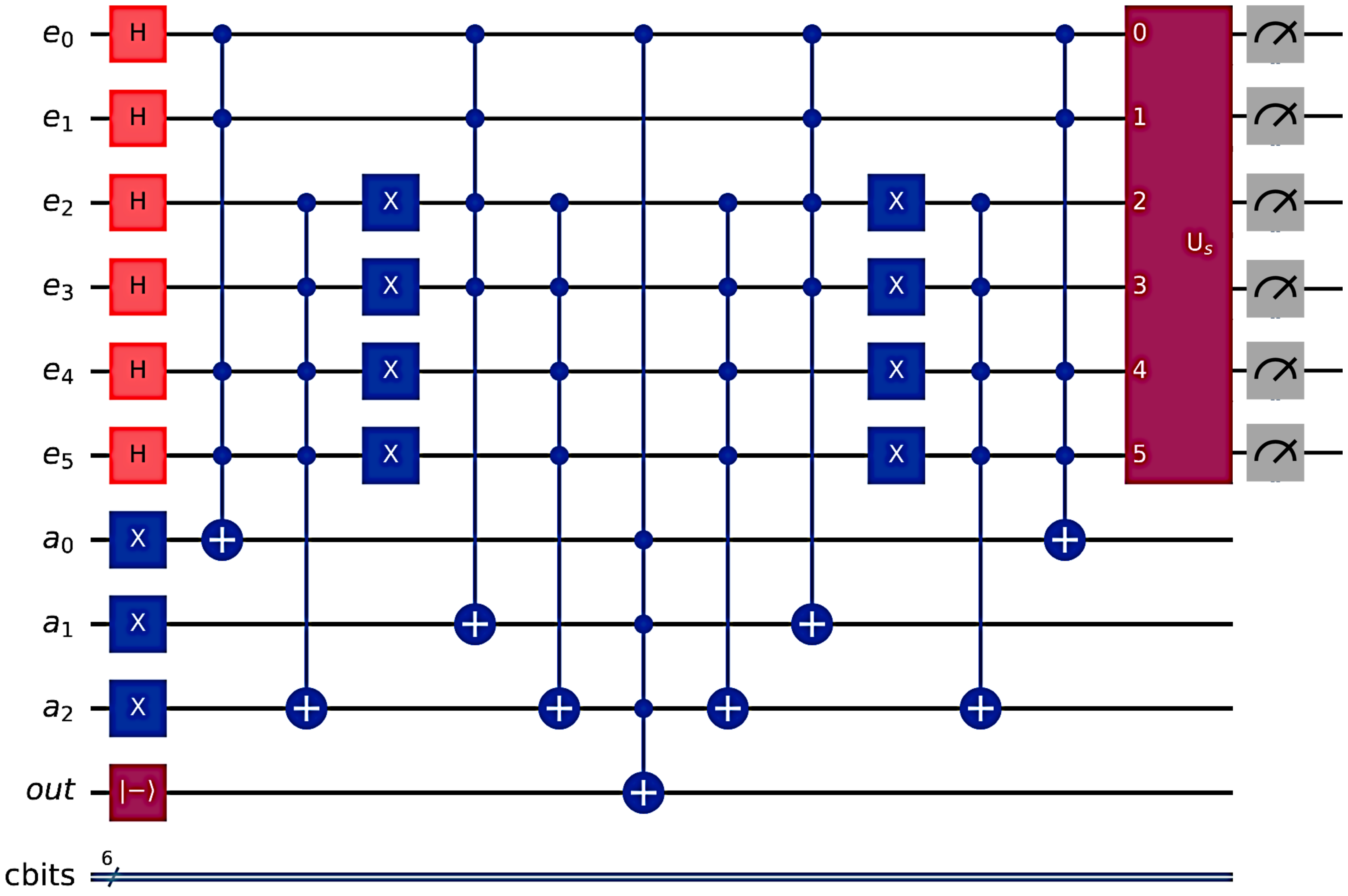
- A Feynman propagator describes a **quantum superposition** of propagation in both directions

$$G_{\rm F}(q_i) = \frac{1}{q_i^2 - m_i^2 + \imath 0} \equiv \frac{1}{\sqrt{2}}\left(|0\rangle + |1\rangle \right)$$

- A Feynman diagram is a superposition of 2^n states
- If a particle (momentum flow) returns to the point of emission: it travels back in time and thus **breaks causality ≡ cyclic configurations are nonphysical**
- Causal configurations of Feynman diagrams are **Directed Acyclic Graphs (DAG)** in graph theory

Oracle design: a two-loop topology with 6 edges





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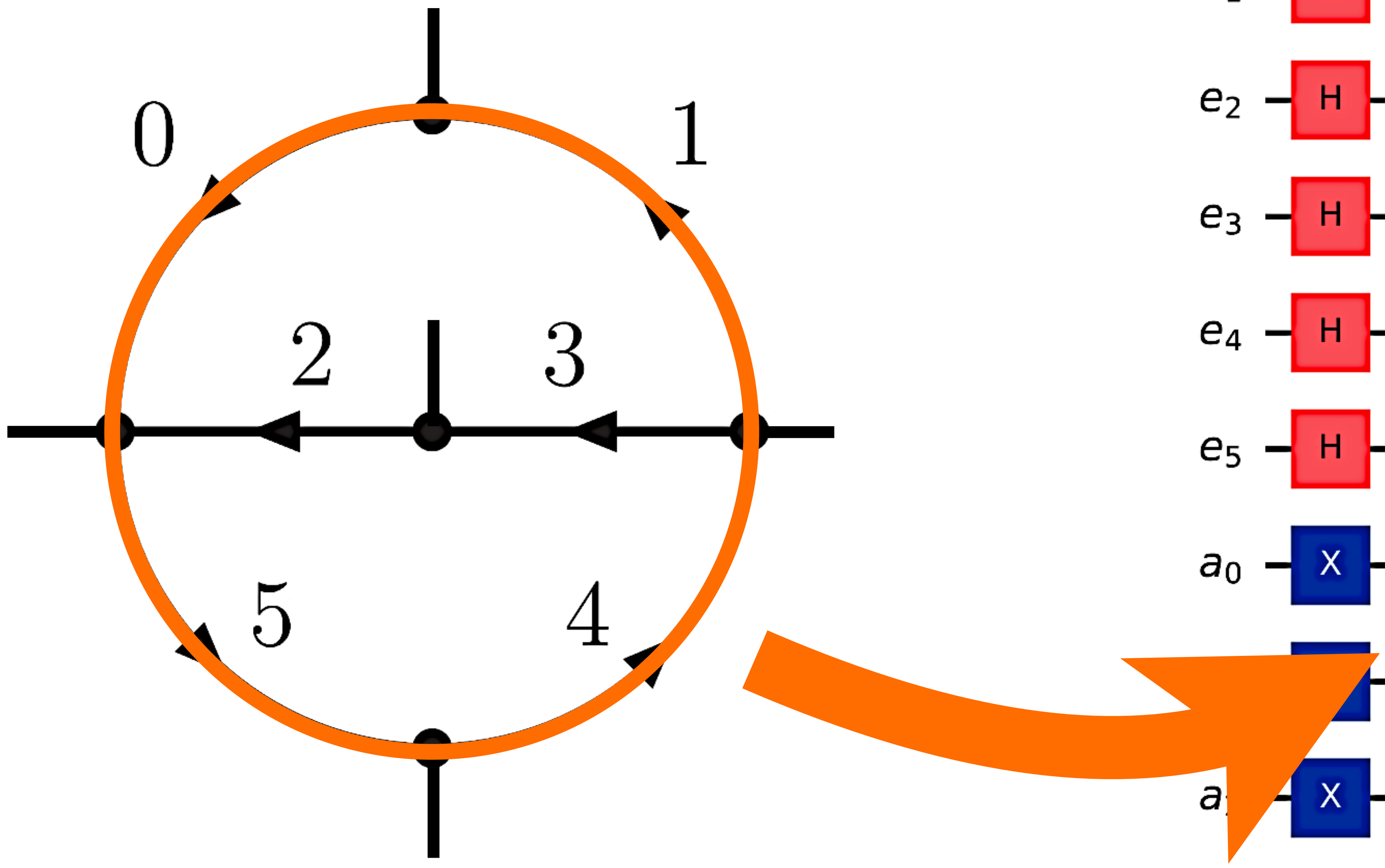

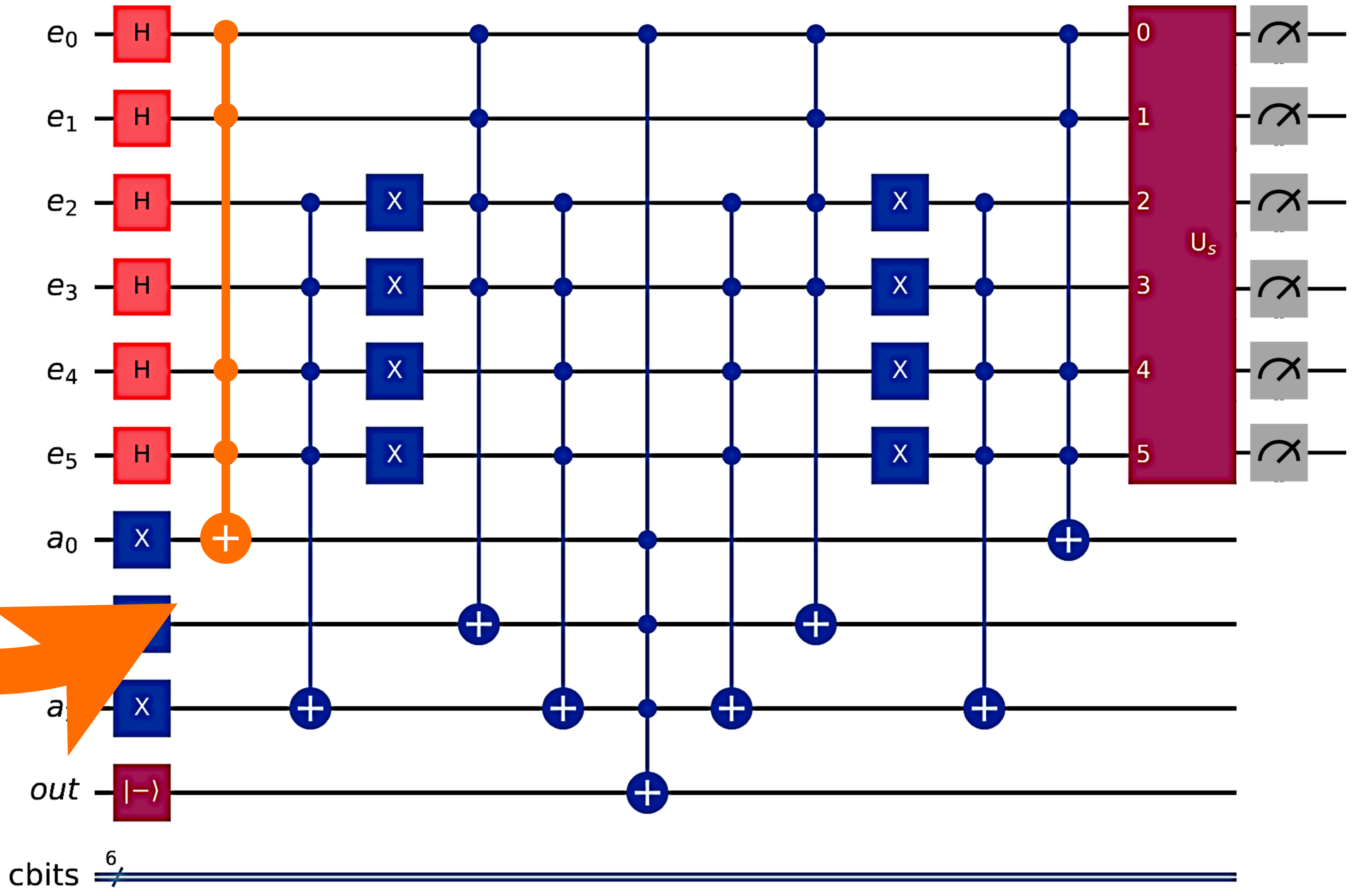

- Each loop cycle is mapped to a multi-controlled **Toffoli** gate

[Ramírez, Rentería, GR, 2404.03544]

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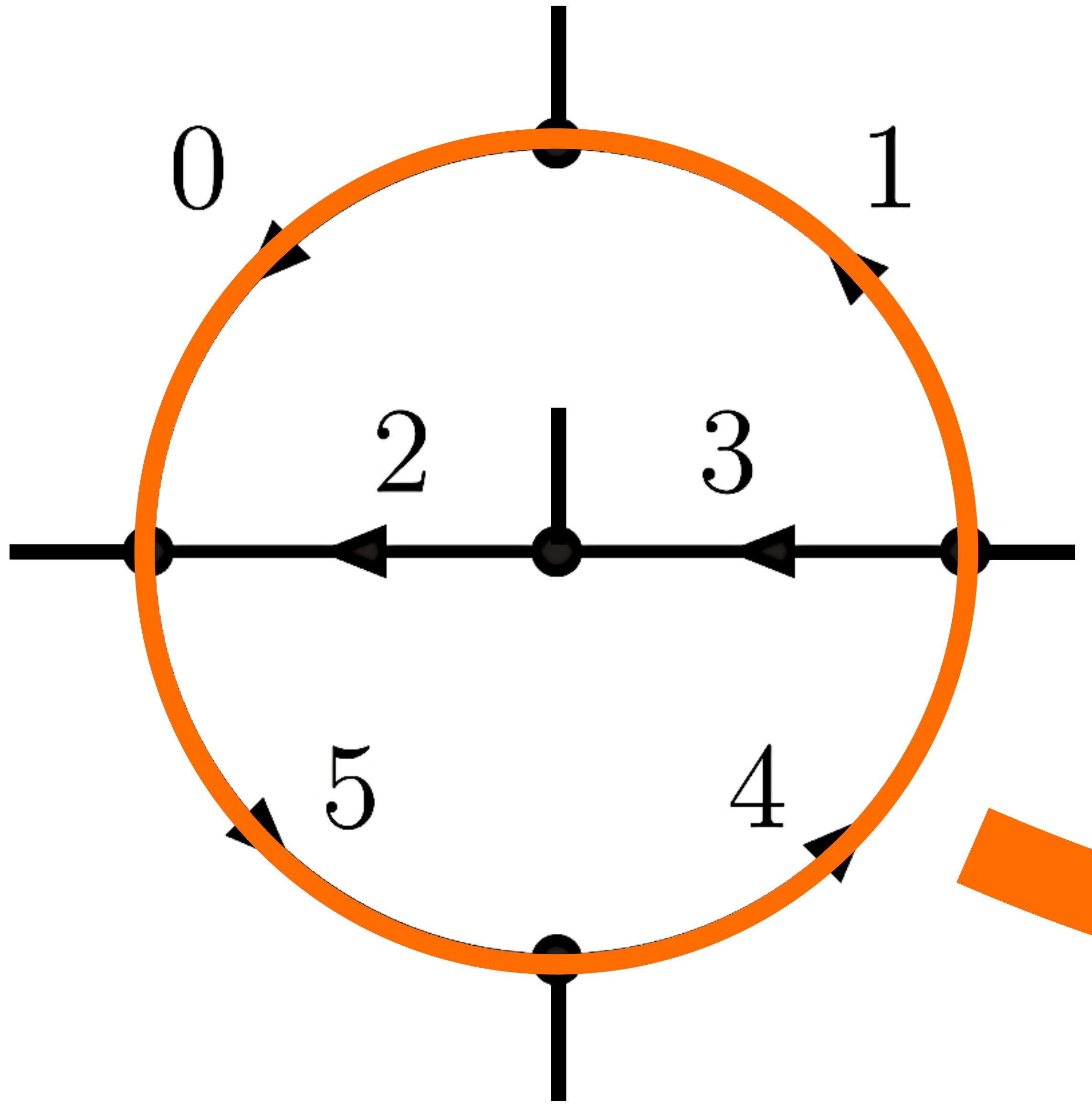
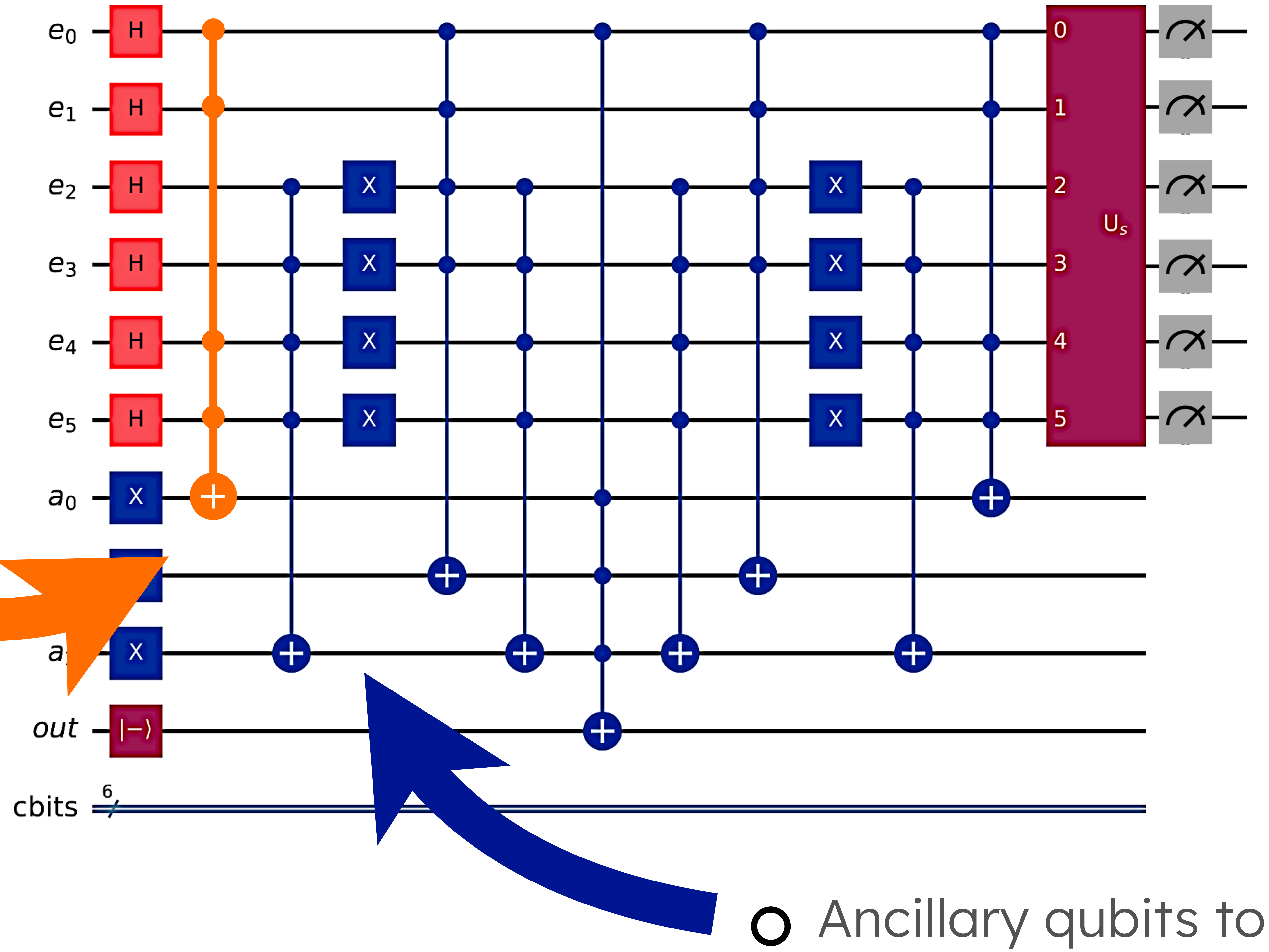


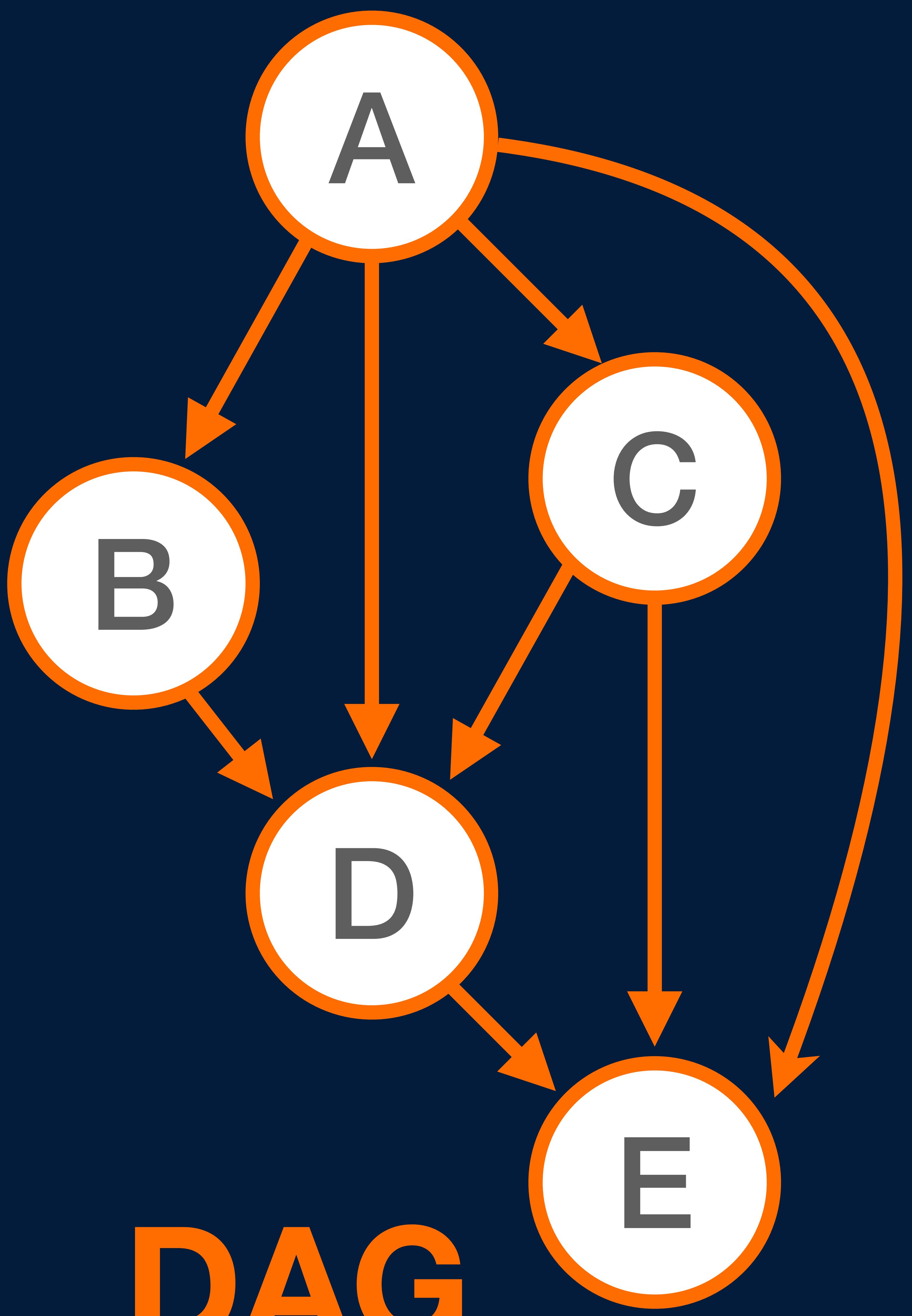


- Each loop cycle is mapped to a multi-controlled **Toffoli** gate

[Ramírez, Rentería, GR, 2404.03544]

- Ancillary qubits to store loop clauses

Oracle design by leveraging graph-theory principles



DAG

Directed Acyclic Graph

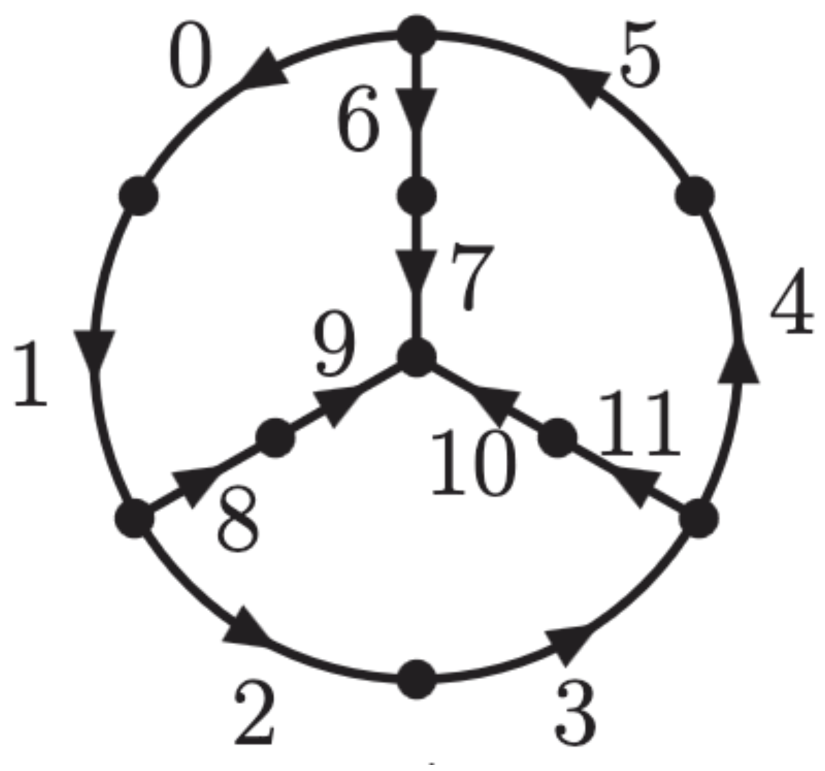
A clique, also known as a complete subgraph, is a subset of vertices from a specific graph in which each pair of vertices is directly connected by an edge

Minimum Clique Partition (MCP): minimum number of cliques that generate a graph

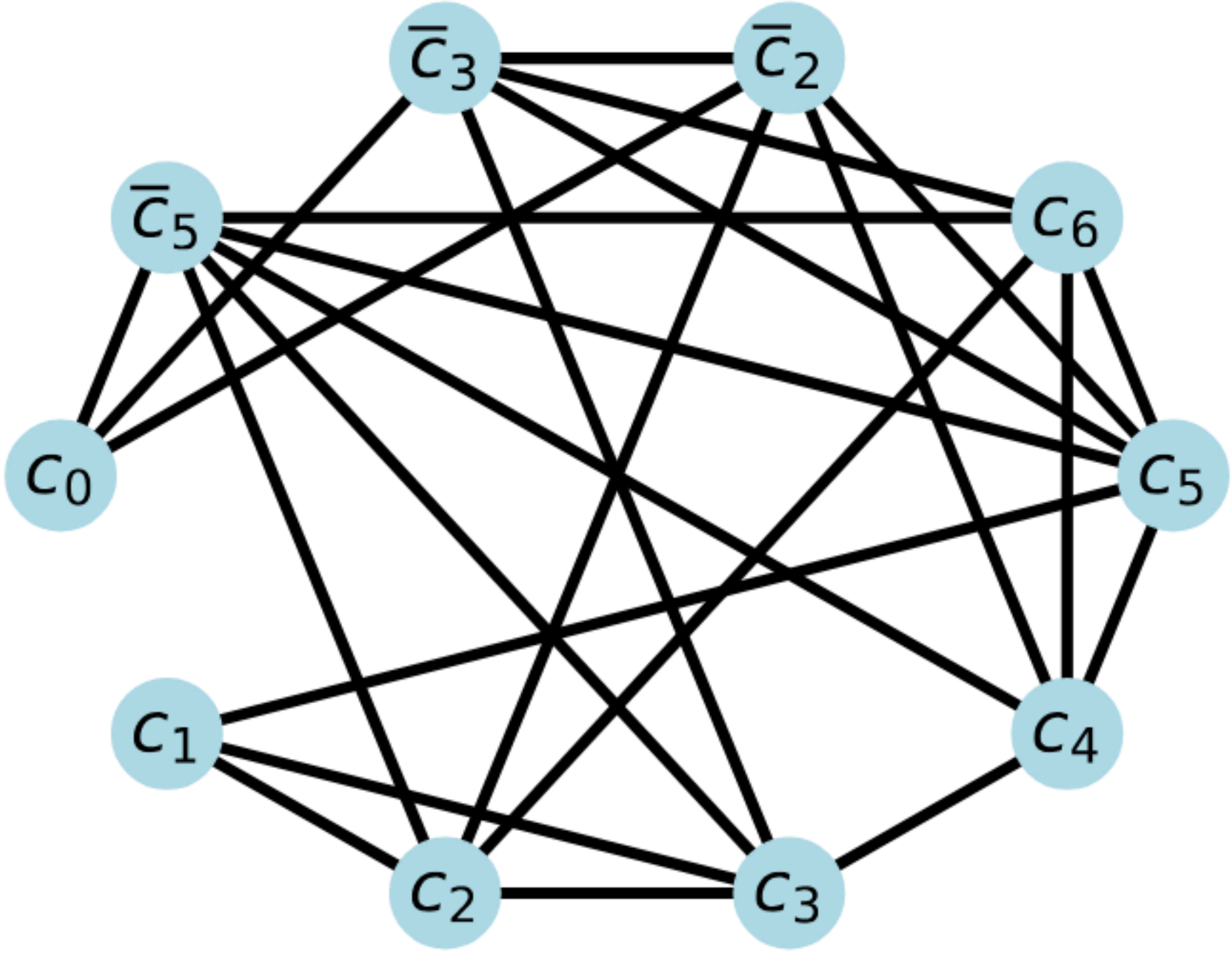
- optimise the number of ancillary qubits used to encoding the loop clauses based on the principle of **"Mutually Exclusive Clauses (MECs)"**, i.e. clauses that cannot be satisfied simultaneously: $c_i \wedge c_j = 0$
- The information on MECs can be stored in a single ancillary qubit because $c_i \vee c_j = c_i \veebar c_j$

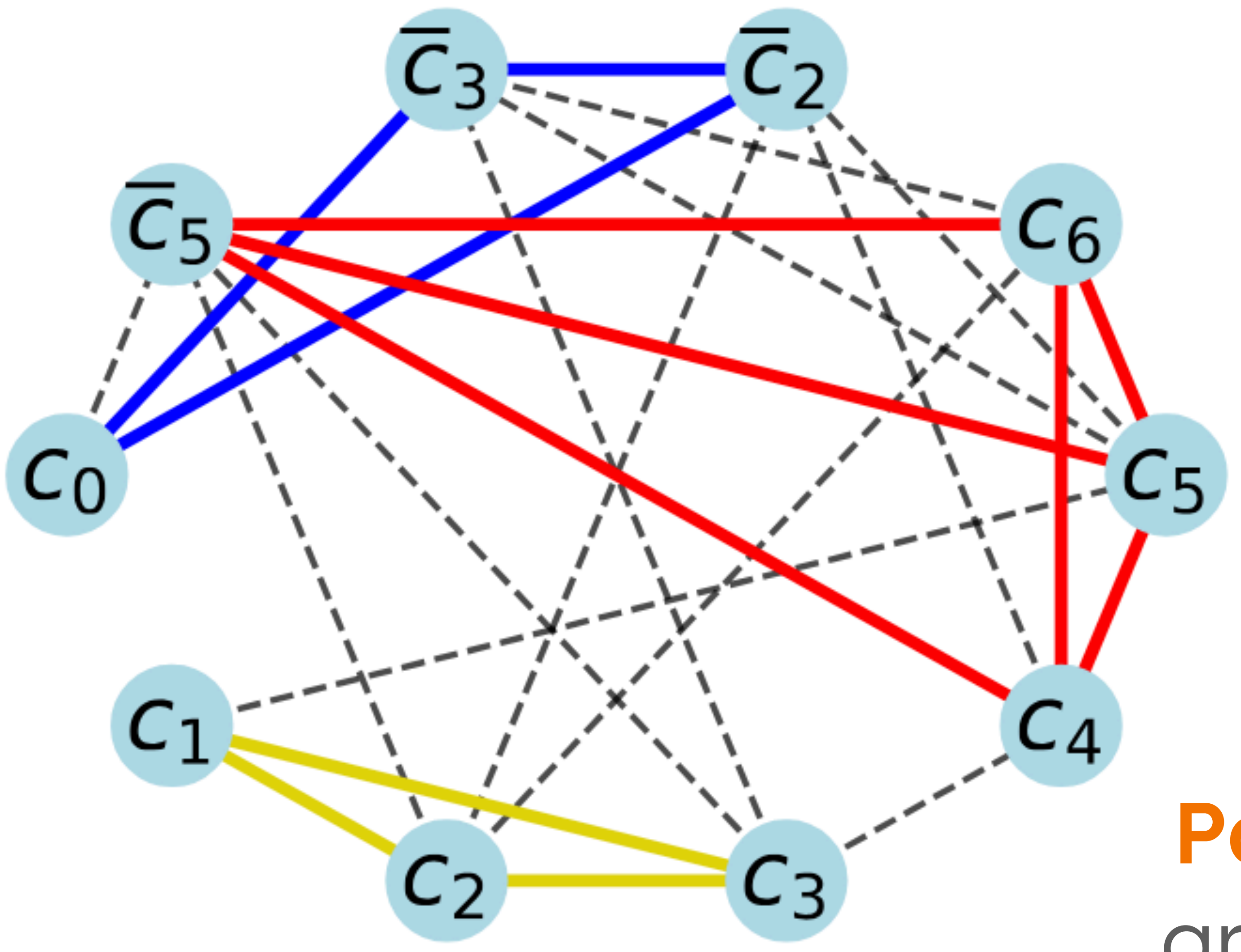
MCA: Ochoa, Uribe, Hernández, Ramírez, GR, Nat.Comm.Phys. 2508.04019

A three-loop topology with 12 edges



Graph representing the adjacency matrix of **Mutually Exclusive Clauses** (MECs)





Minimum Clique Partition (MCP) of the graph representing the MEC adjacency matrix

- A first algorithm to identify MCP of the adjacency matrix

  MAUXc$^{(3,12)} = \{\{c_4, c_5, \bar{c}_5, c_6\}, \{c_0, \bar{c}_2, \bar{c}_3\}, \{c_1, c_2, c_3\}\}$

mutually exclusive sets of clauses
(3 ancillary qubits instead of 7)

- A second algorithm to determine the optimal order in which the gates (Toffoli+XNOT) are applied, it impacts the quantum depth

  OMUTc$^{(3,12)} = \{\{c_0\}, \{c_1, c_4, \bar{c}_3\}, \{c_2, c_5\}, \{c_3, c_6, \bar{c}_2\}, \{\bar{c}_5\}\}$

MCA: Ochoa, Uribe, Hernández, Ramírez, GR, Nat.Comm.Phys. 2508.04019

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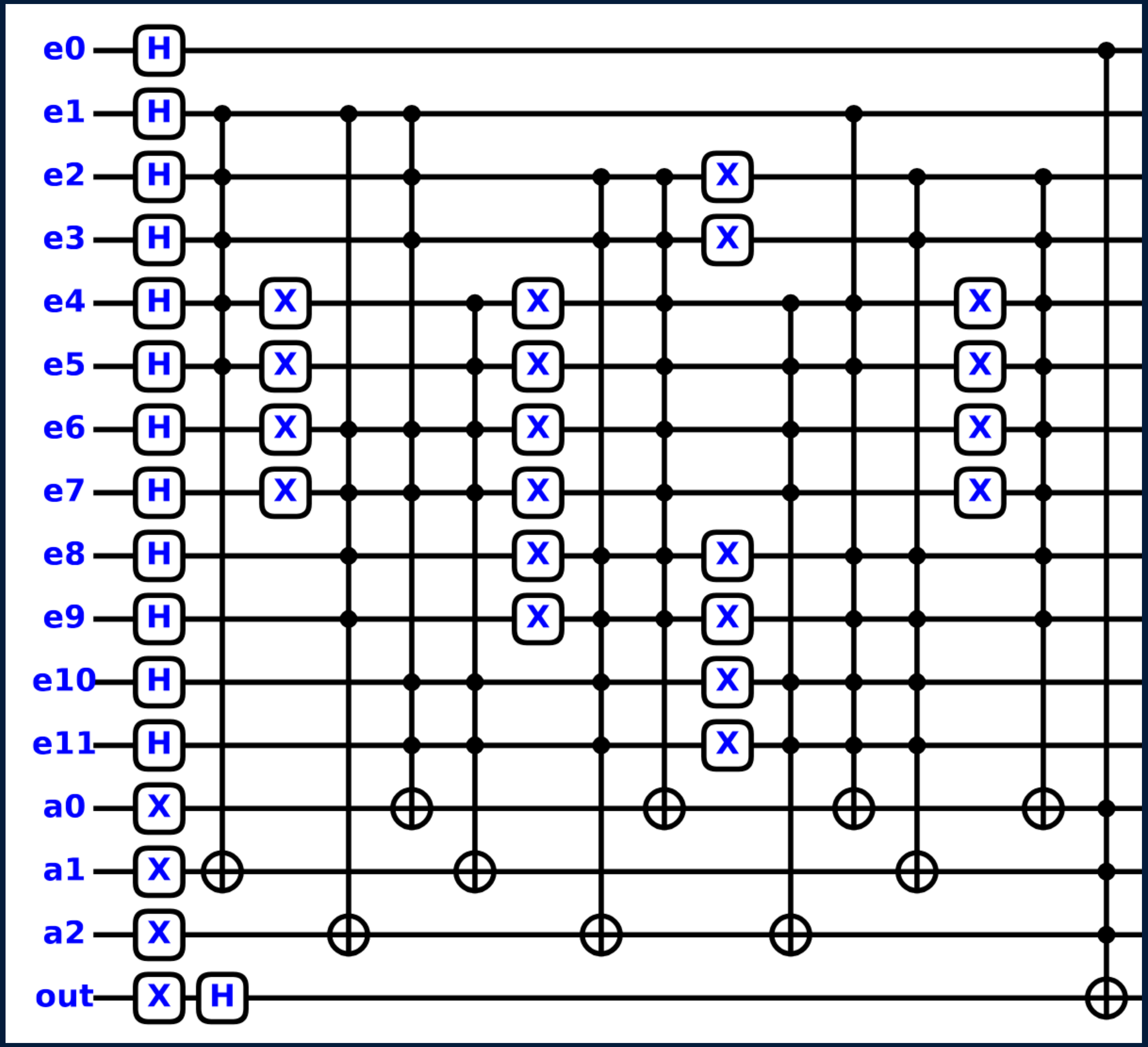
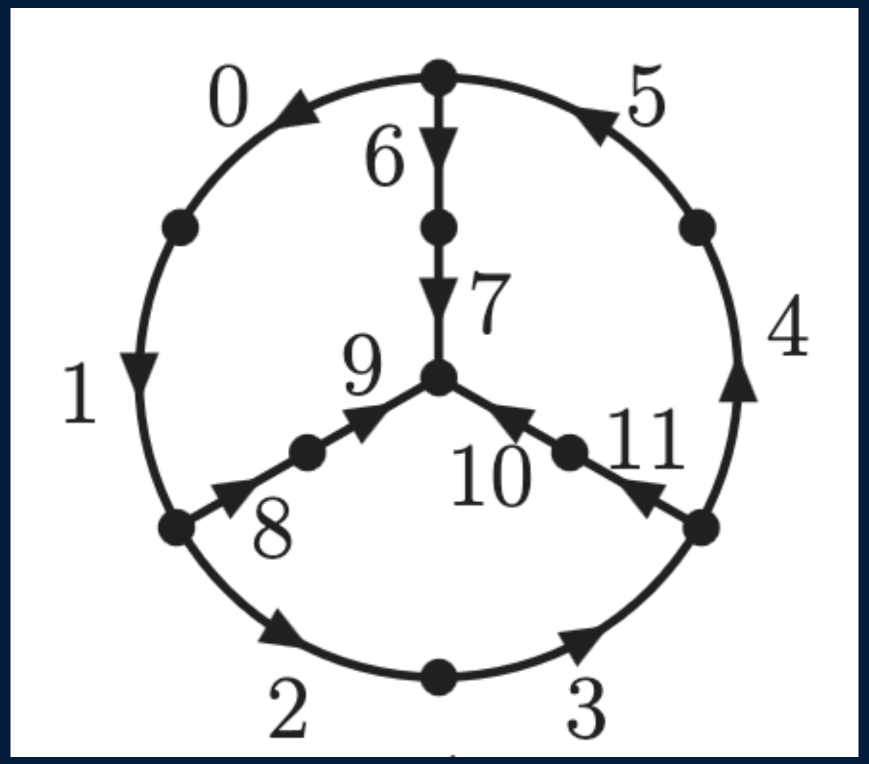
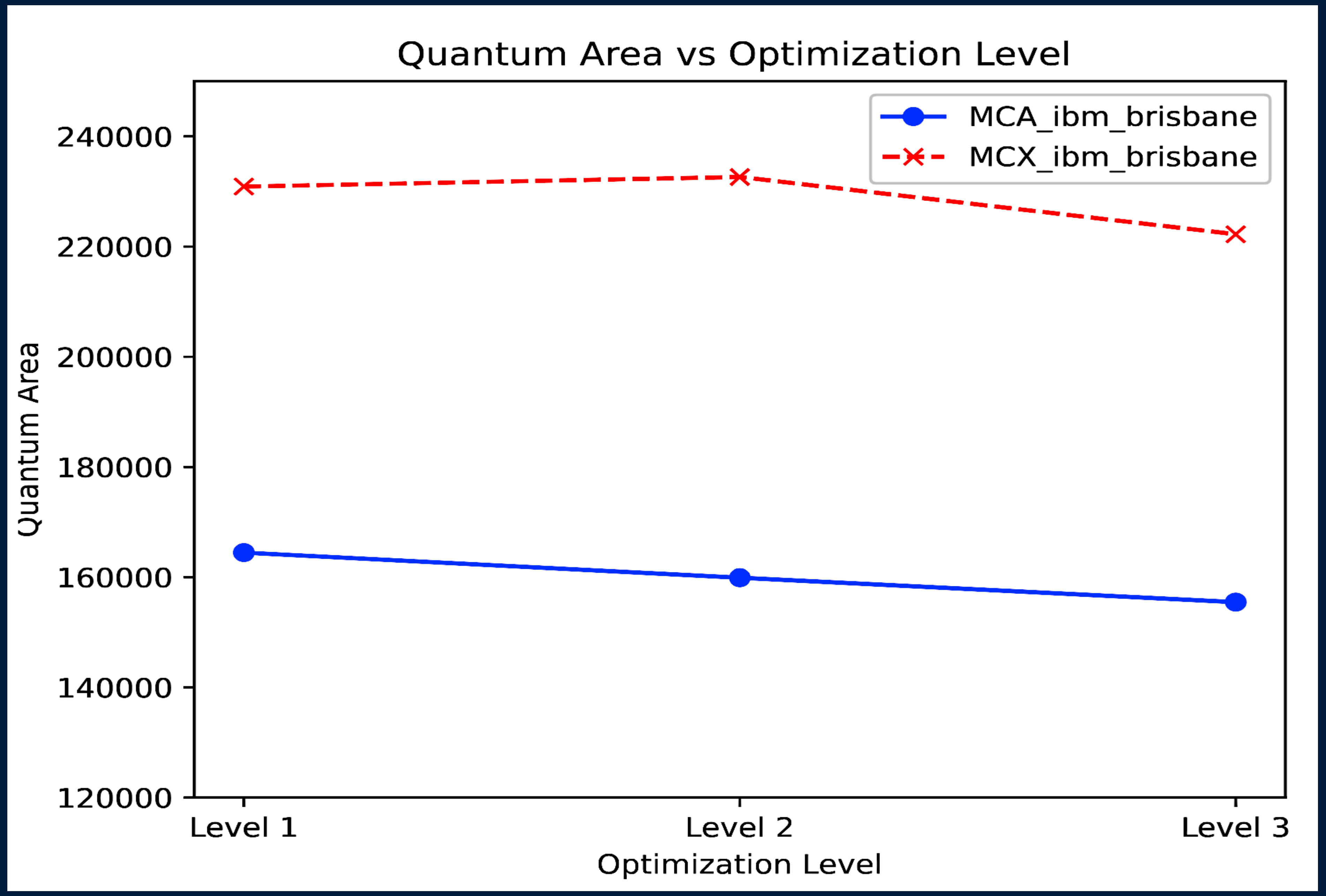
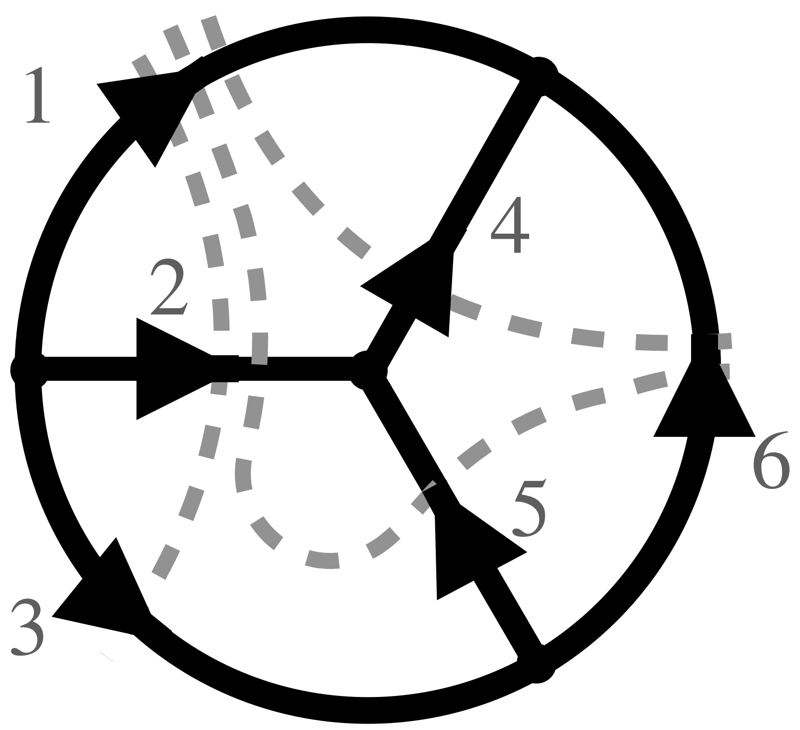




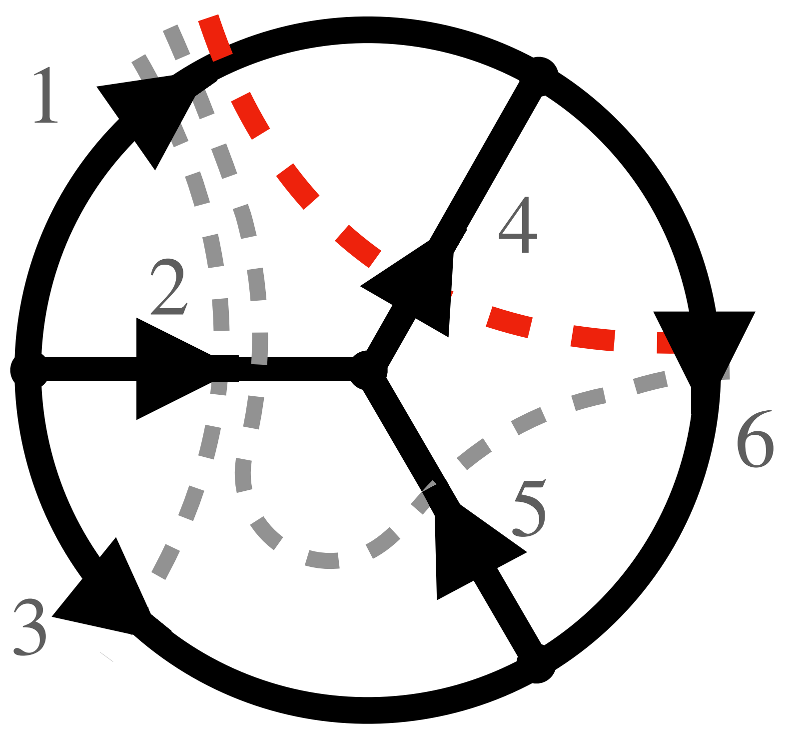
- quantum area = #qubits × quantum depth
- transpiled quantum depth ≫ quantum circuit
- transpiled #qubits > theoretical qubits



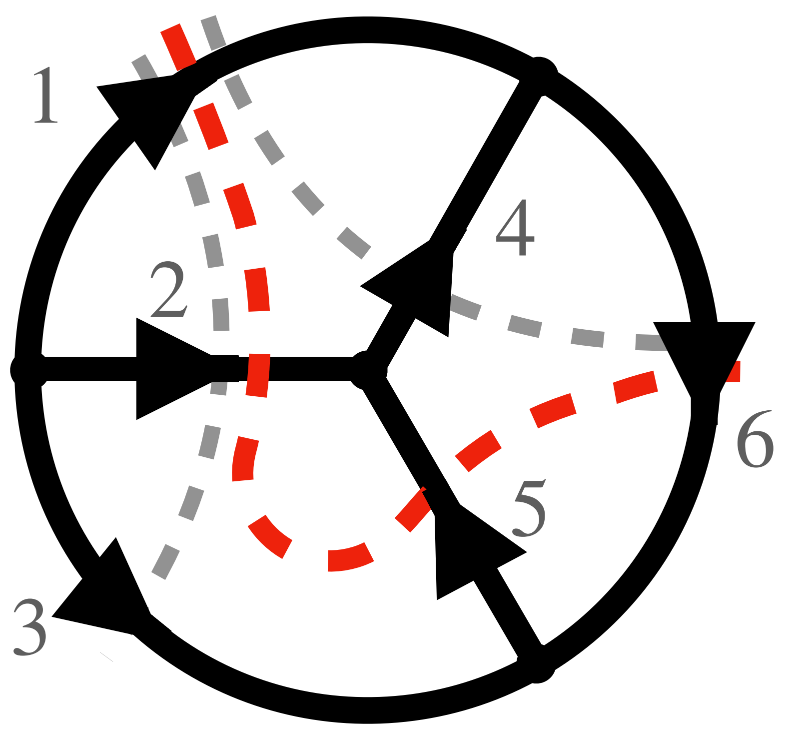
The Loop-Tree Duality LTD: vacuum amplitudes



$$\mathscr{A}_{\rm D}^{(\Lambda)} \sim \frac{1}{\lambda_{123}\lambda_{1256}\lambda_{146}}$$



$$\text{Res}\left(\mathscr{A}_{\rm D}^{(\Lambda)}, \lambda_{146}\right) \sim \frac{1}{\lambda_{123}\lambda_{25\bar{4}}}$$



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

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

Energy conservation

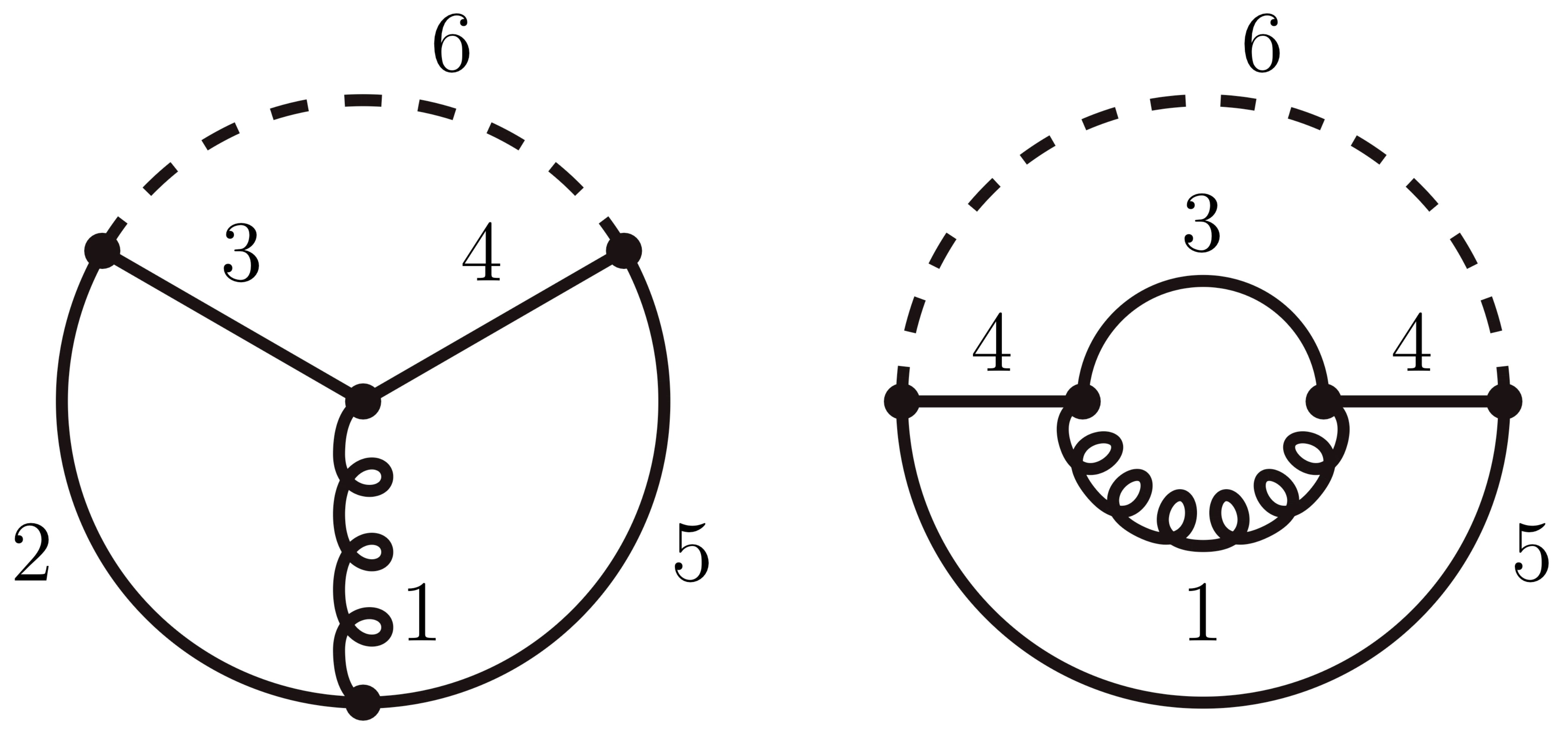
$$\lambda_{i_1 i_2 \cdots i_n} = \sum q_{i_s,0}^{(+)} = \sum \sqrt{\boldsymbol{q}_{i_s}^2 + m_{i_s}^2 - \imath 0}$$

On-shell energies

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

G. RODRIGO

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

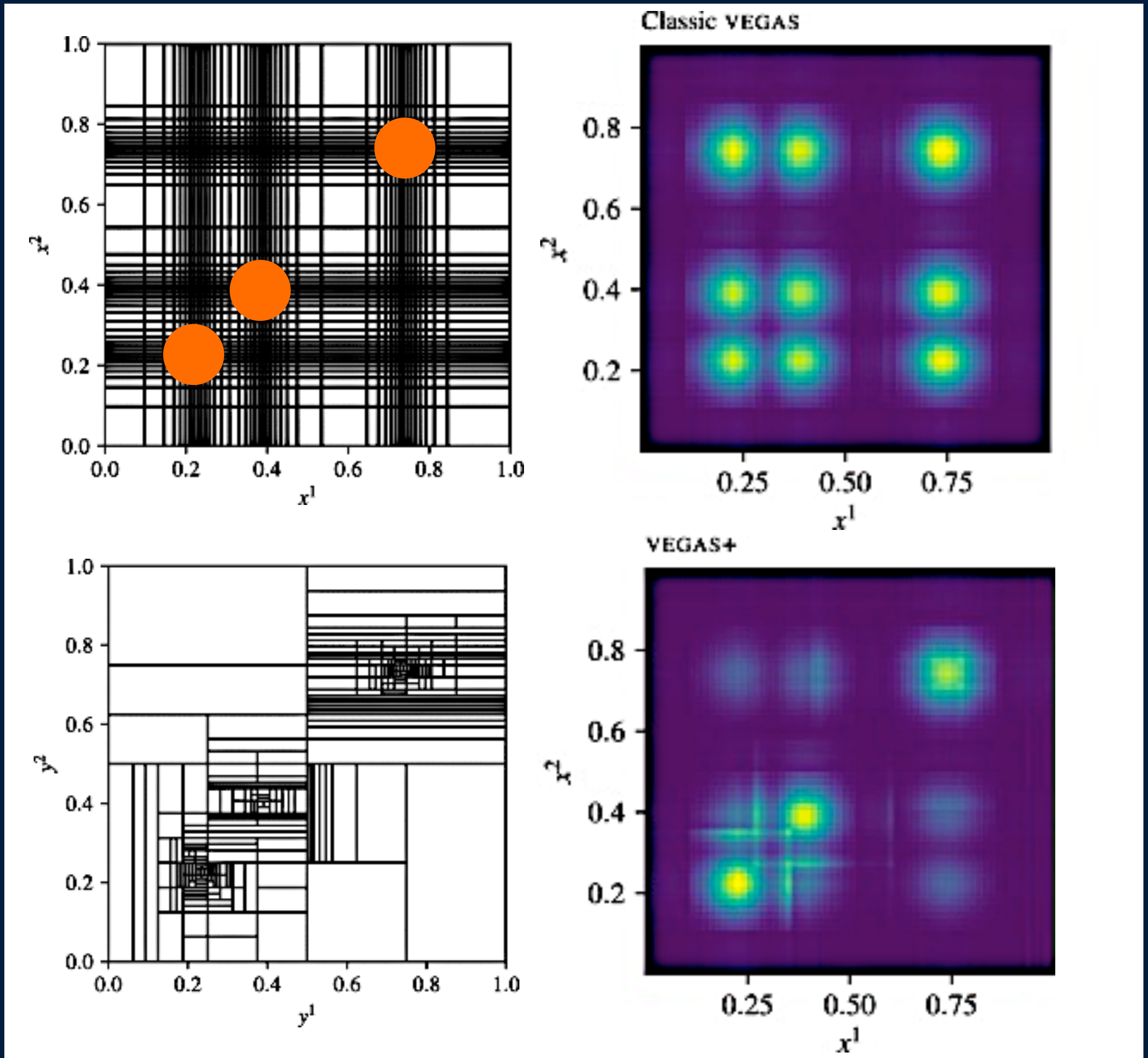


Vacuum amplitudes and time-like causal unitary in the loop-tree duality, LTD Collaboration, JHEP 01 (2025) 103 [2404.05492]

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

Lepage, J. Comput. Phys. 27 (1978) 192
Lepage, J. Comput. Phys. 439 (2021) 110386

Adaptive Importance Sampling



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

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

- 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: $(N_g)^d \to d \cdot N_g$
- Makes the grid tractable in a classical computer but generates **phantom peaks**

Pyretzidis, Martínez de Lejarza, GR, Nat.Comm.Phys. 2506.19965

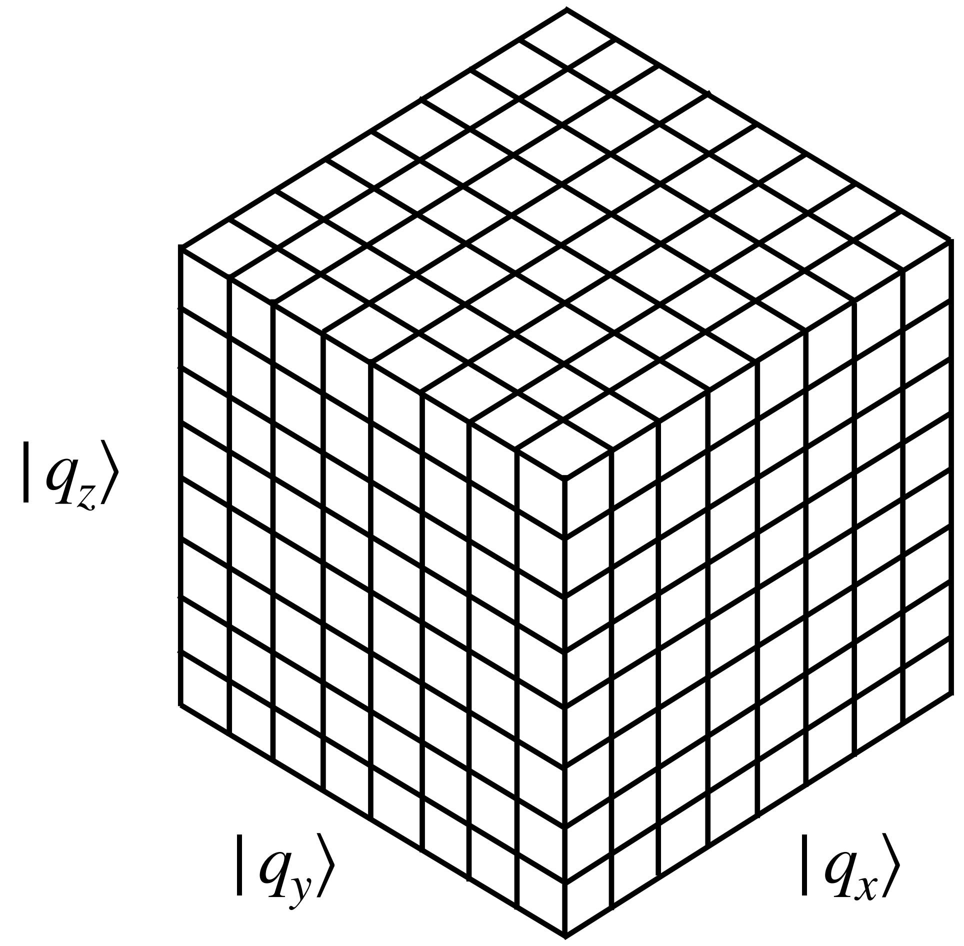
QAIS - Quantum Adaptive Importance Sampling

- **QAIS:** 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

Pyretzidis, Martínez de Lejarza, GR, Nat.Comm.Phys. 2506.19965

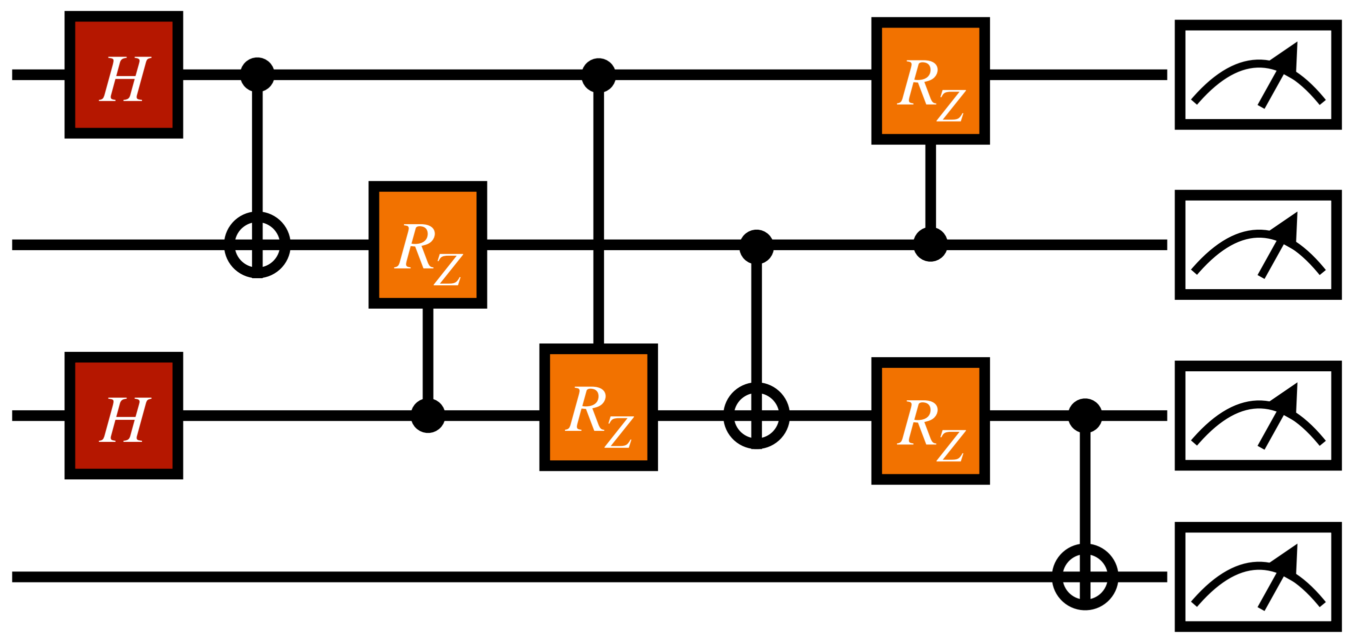
Quantum Adaptive Importance Sampling (QAIS)

Stage 1 Encoding



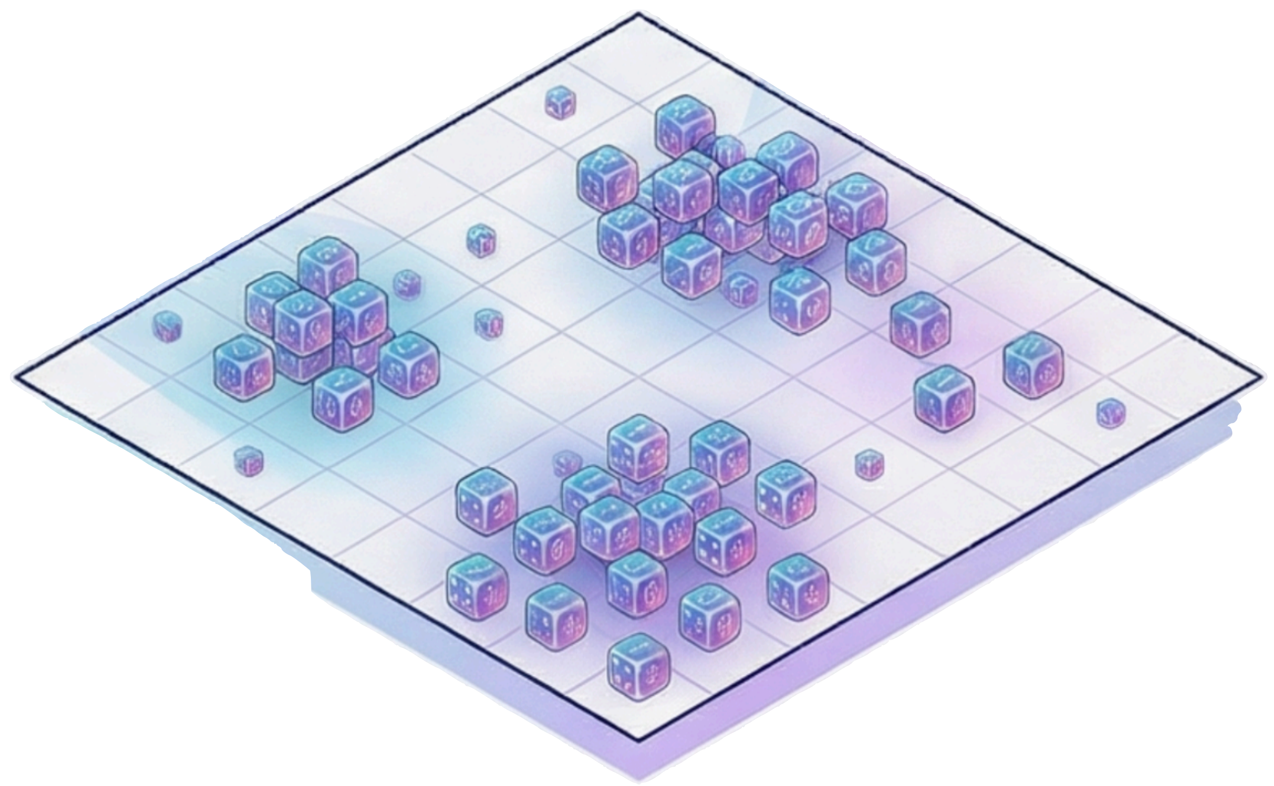
The d-dimensional integration domain is **discretized and mapped into an n-qubit Hilbert space**. Each of the 2^n computational basis state corresponds to a specific grid cell.

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 Integral Estimation

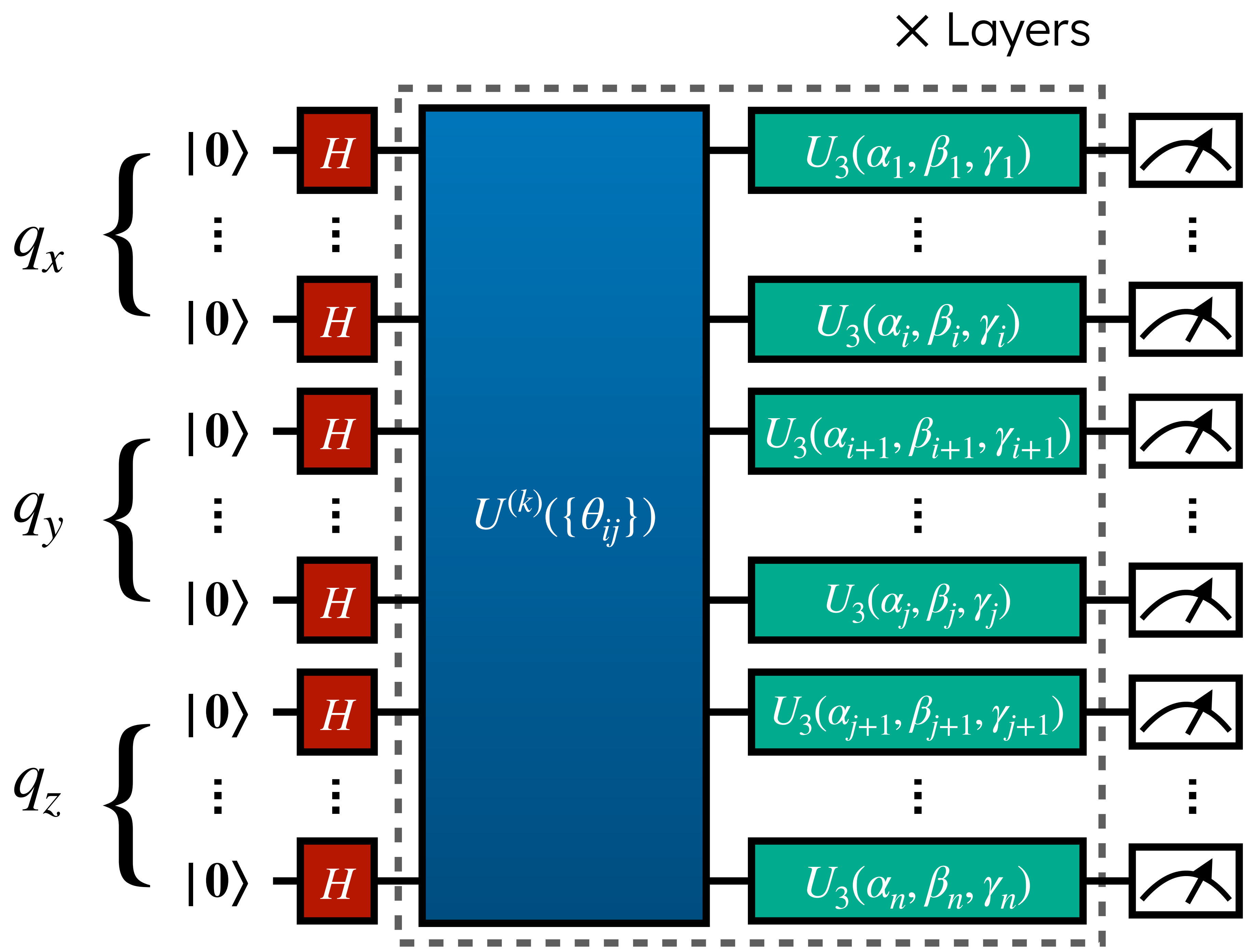


Measurements are performed on the optimized PQC. The **frequency of outcomes determines the number of samples (N_j)** allocated to each grid cell. A dedicated statistical framework, adjusted for quantum measurements is used to calculate the integral estimate and its variance.

G. RODRIGO

Pyretzidis, Martínez de Lejarza, GR, Nat.Comm.Phys. 2506.19965

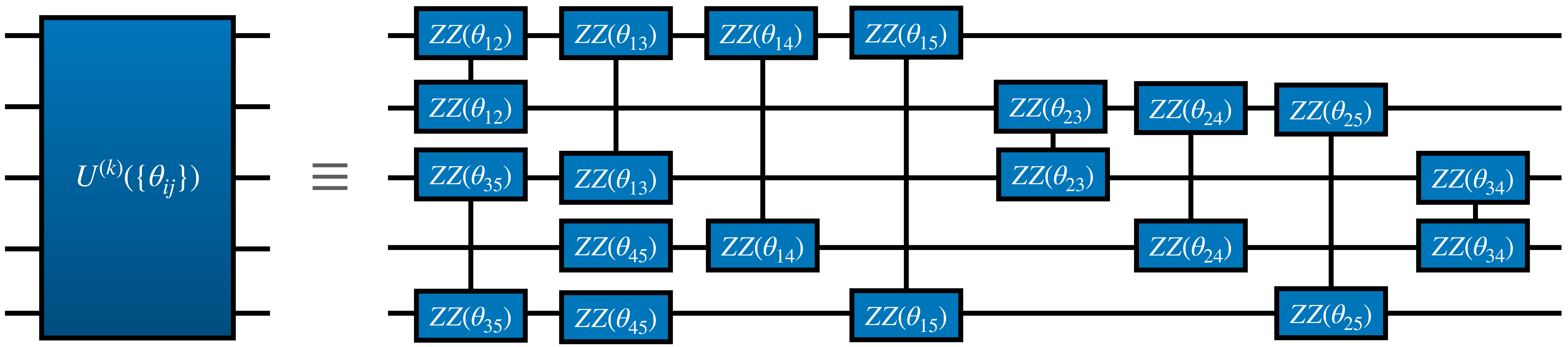
Parametrized Quantum Circuit



- **all-to-all connectivity** approach with two-qubit gates and single qubit gates
- Performs much better than Hardware Efficient Ansatz (HEA)
- Cost function: discretised version of Kullback-Leibler (KL) divergence

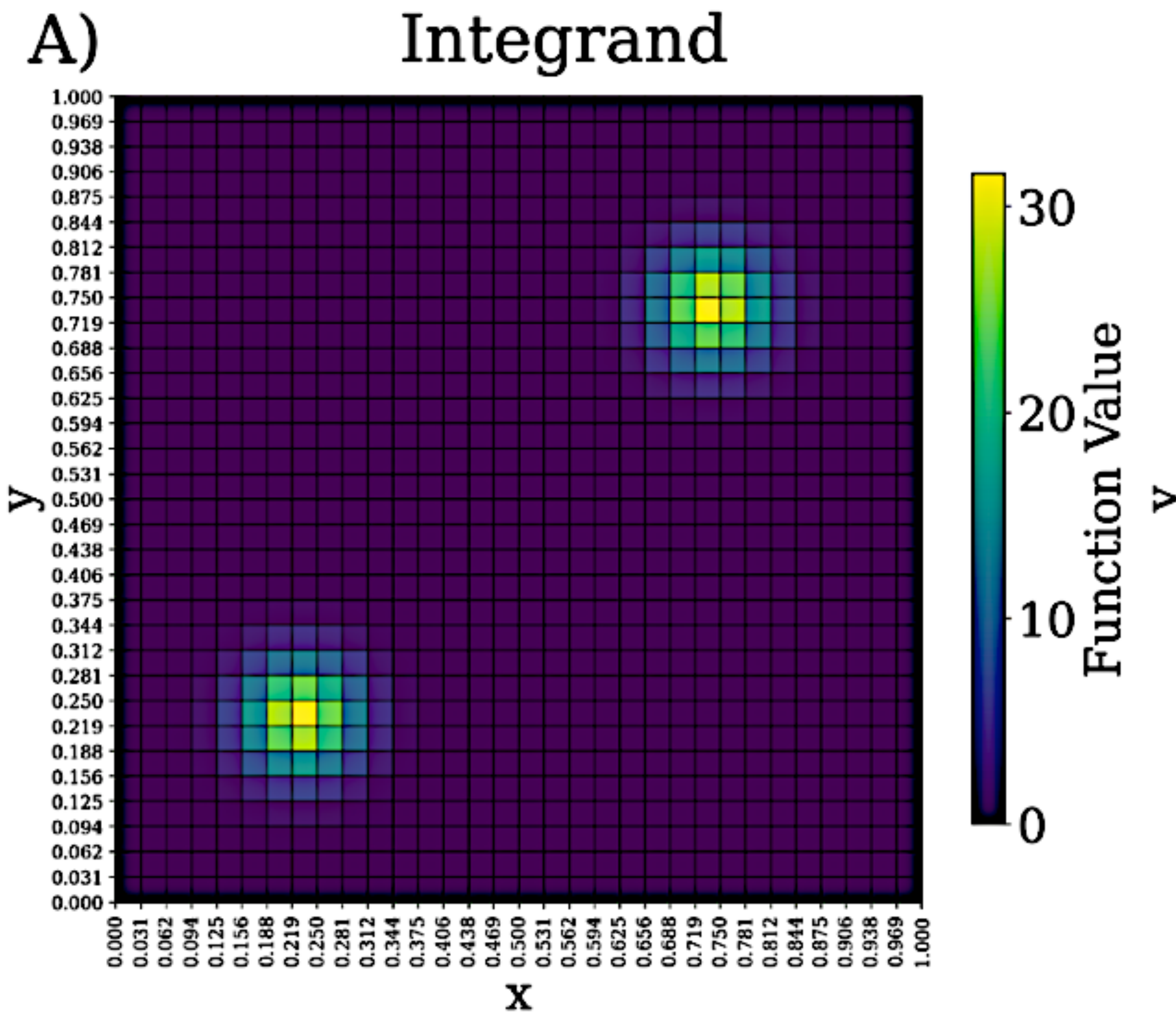
$$D_{\mathrm{KL}}(P\|Q) = \sum_{i=1}^{M} P(\Omega^{(i)}) \log\left(\frac{P(\Omega^{(i)})}{Q(\Omega^{(i)})}\right)$$

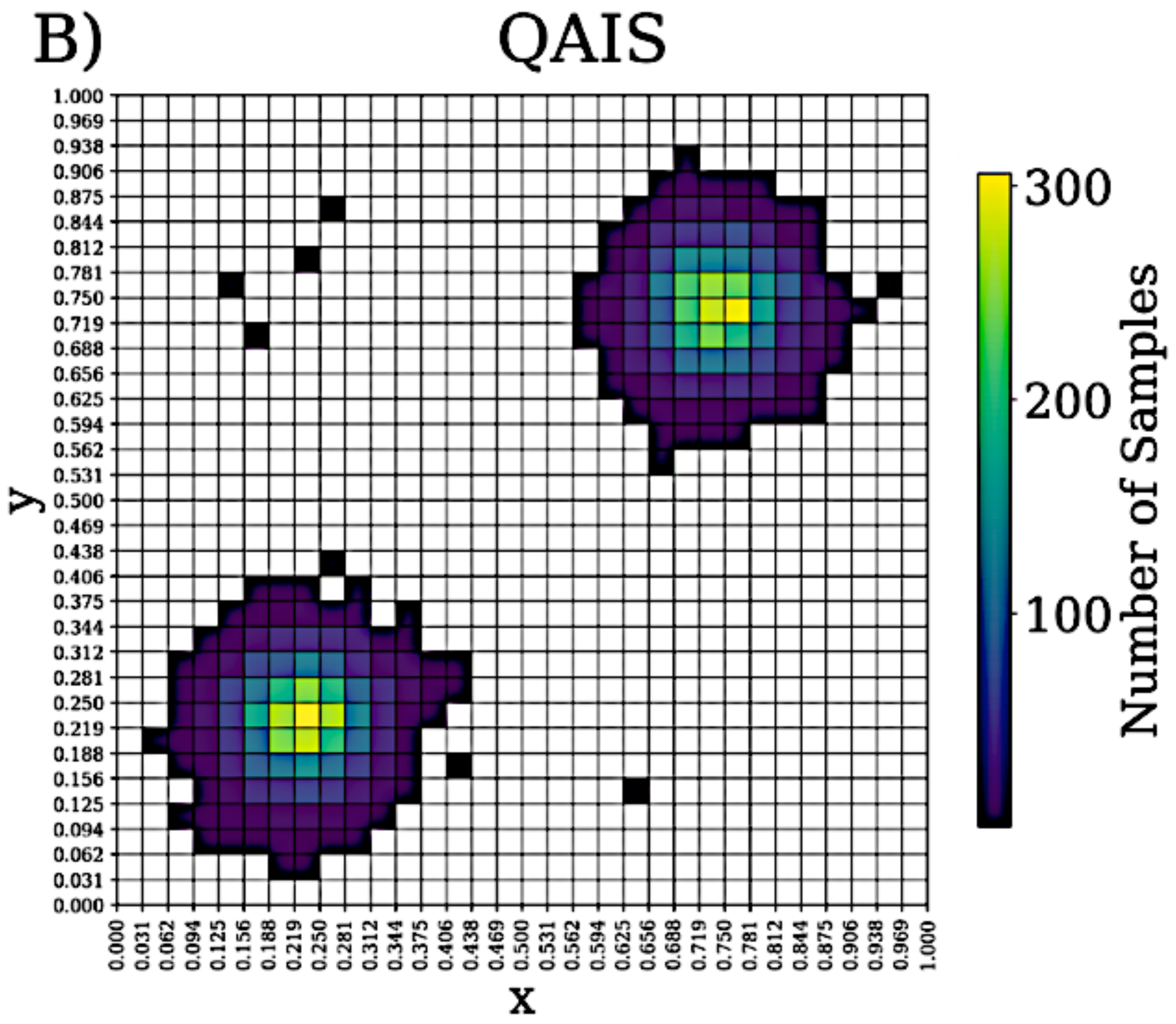
- COBYLA optimizer
- With respect to **Classical Machine Learning** (e.g. Normalizing Flows [Gao, Isaacson, Krause ….], Madnis [Plehn, Maltoni …]), far fewer parameters while better capturing correlations

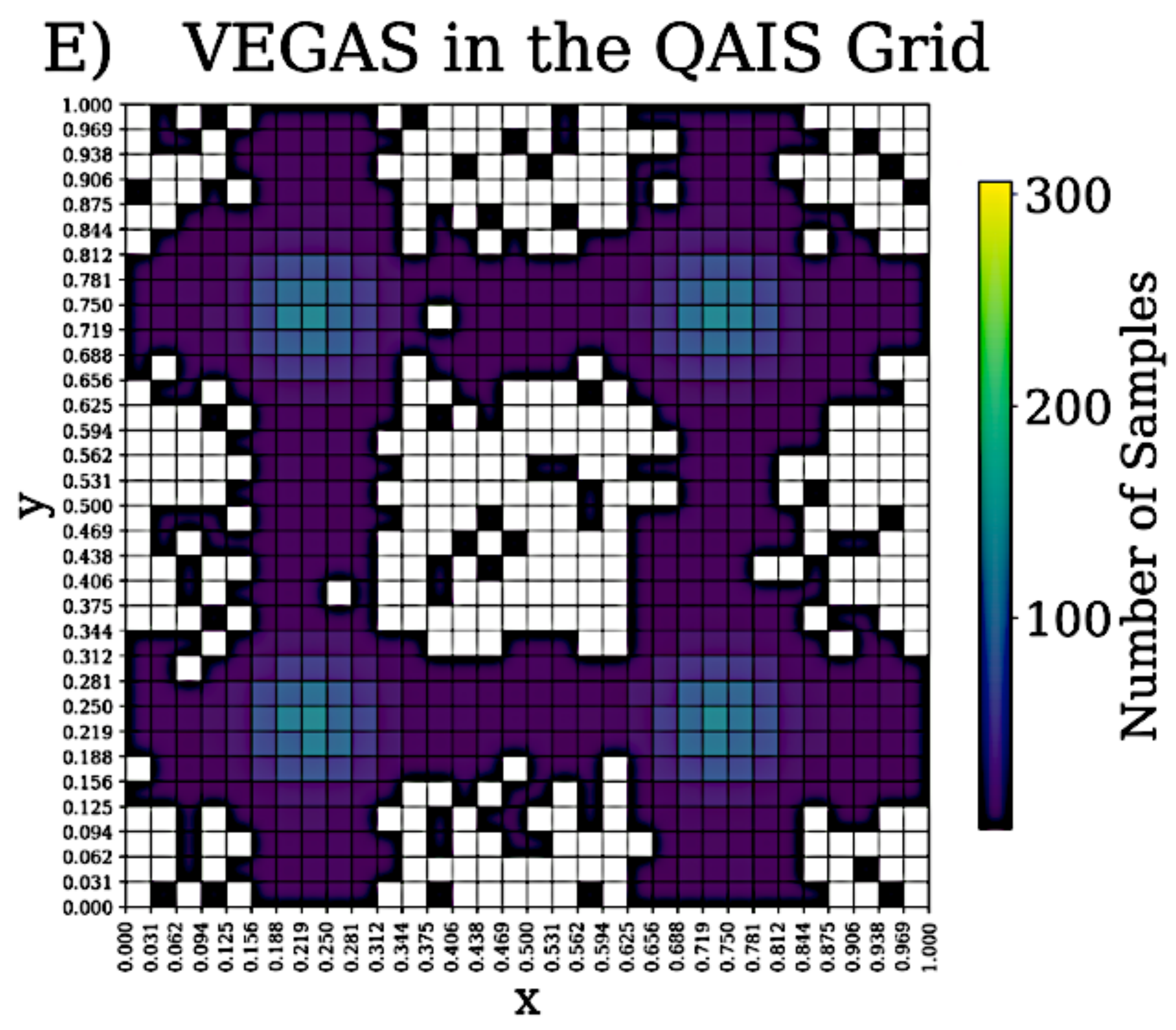


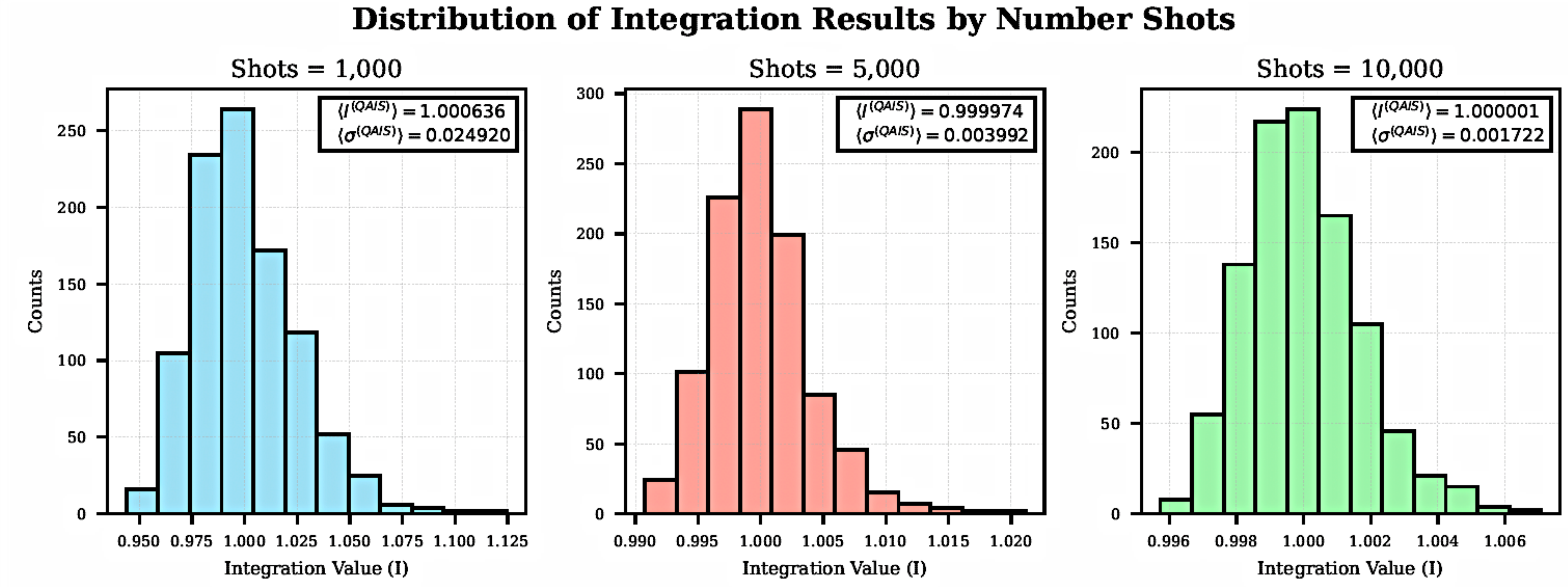
Pyretzidis, Martínez de Lejarza, GR, Nat.Comm.Phys. 2506.19965

Absence of phantom peaks





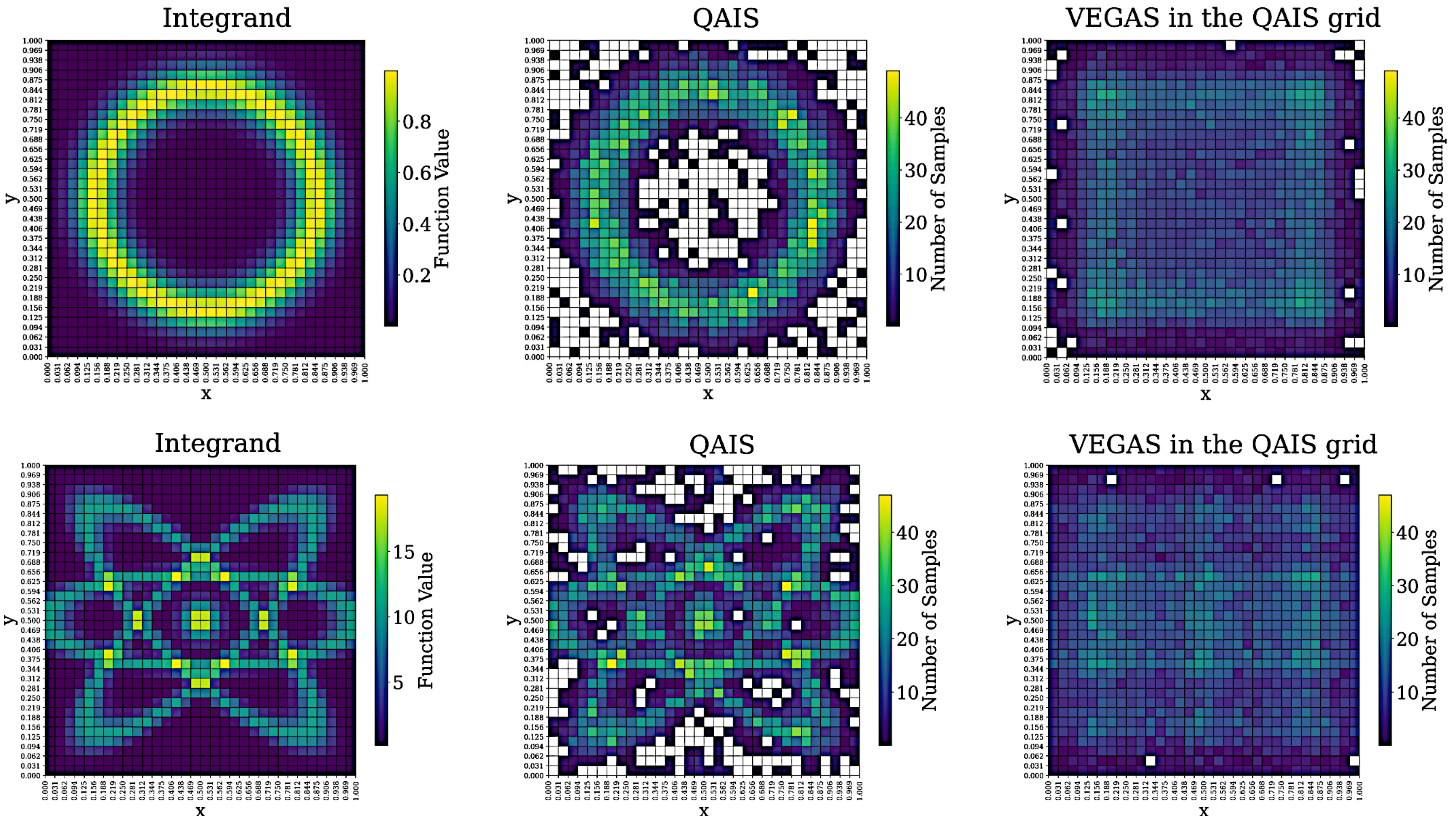




- Integral normalised to one
- 1000 independent runs with the same PDF as a function of the number of shots
- Includes a Tiling module to reduce bias from unobserved cells

CHALLENGING FOR VEGAS

Pyretzidis, Martínez de Lejarza, GR, Nat.Comm.Phys. 2506.19965



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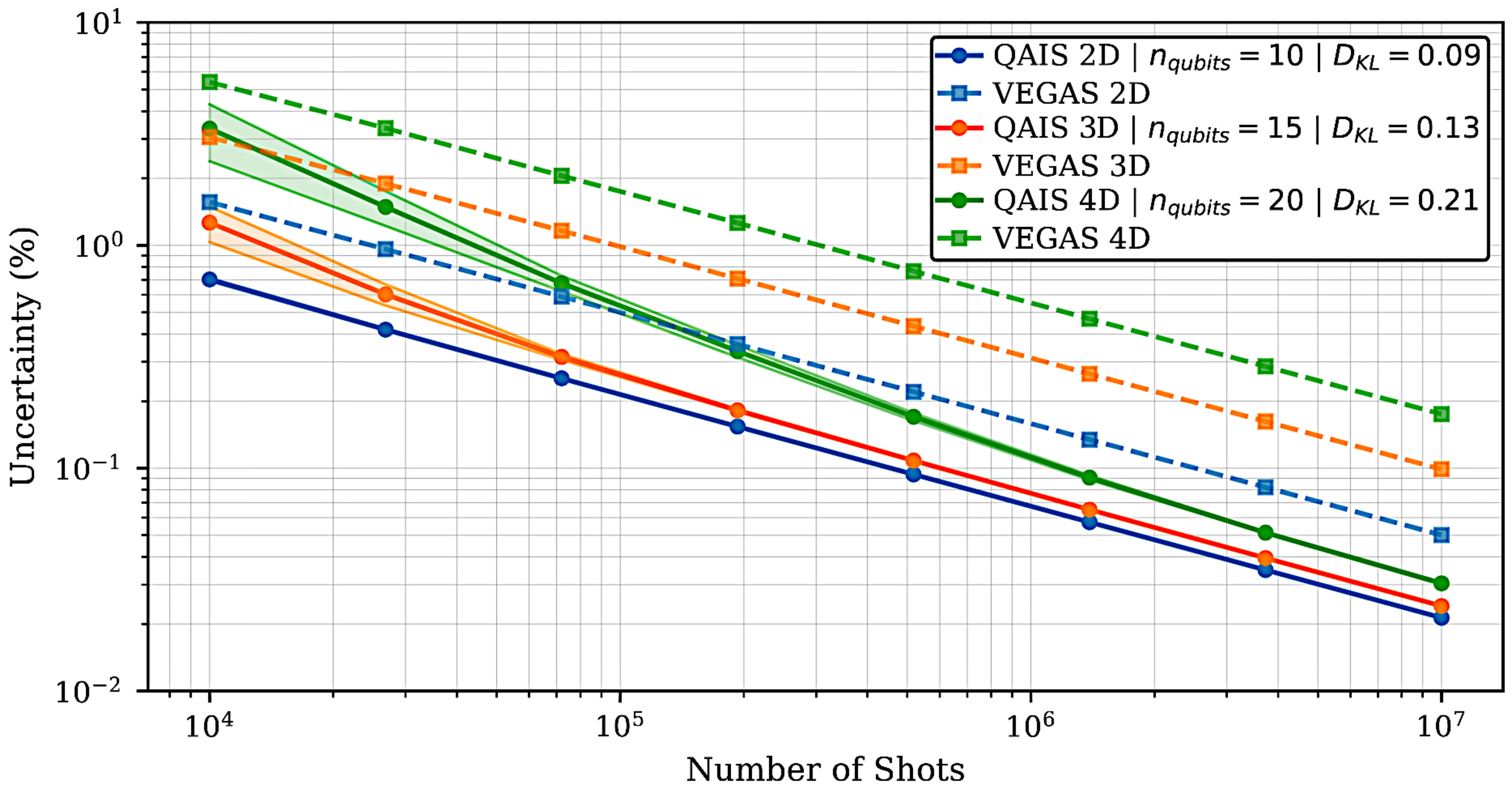
Cross-dimensional

Comparison

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



One-loop pentagon

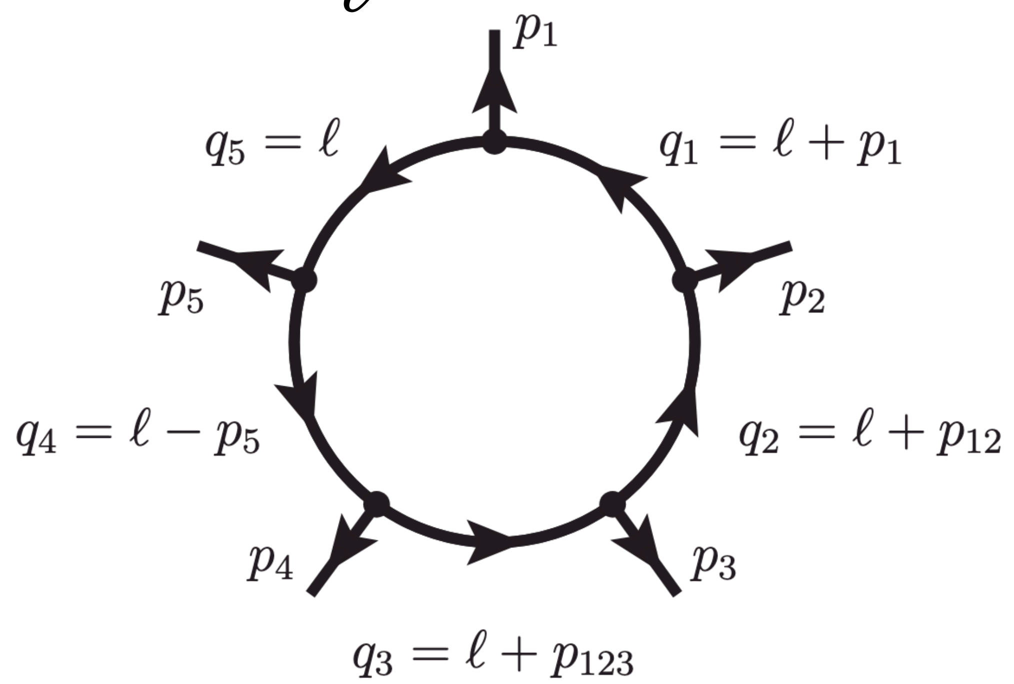
in the Loop-Tree Duality (LTD)

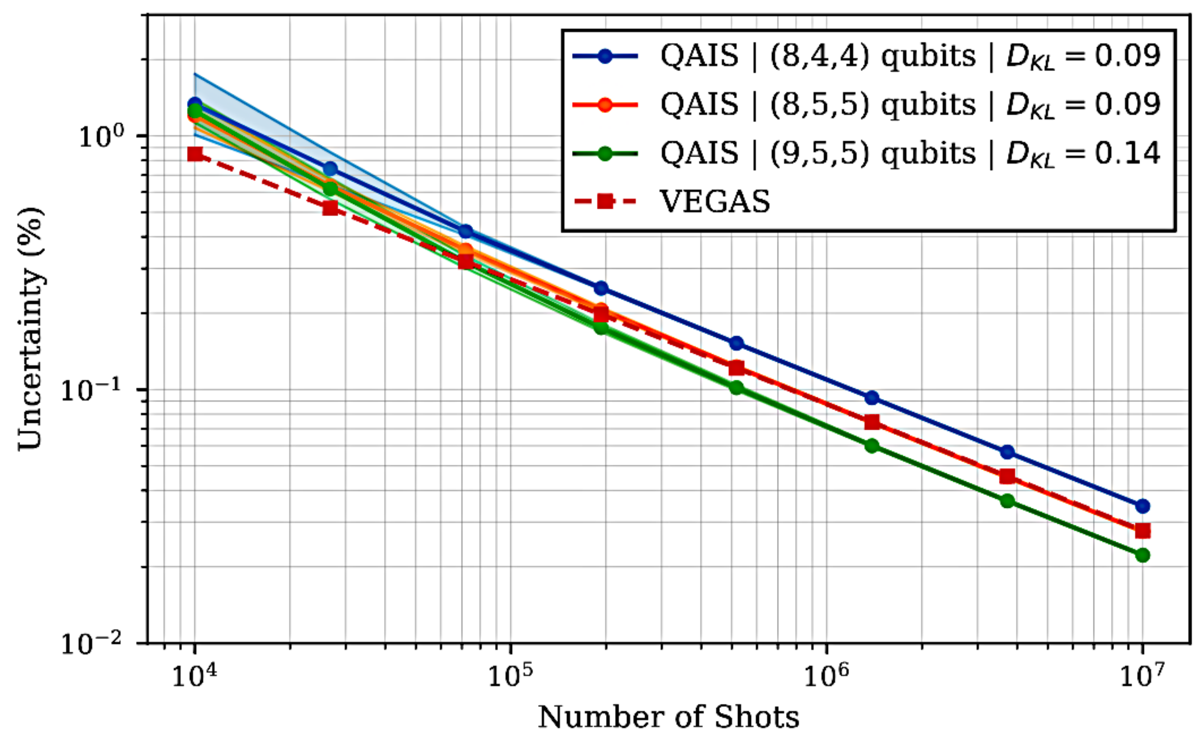
$$\mathcal{A}_5^{(1)} = \int_\ell \prod G_F(q_i) \to \int_{\vec{\ell}} \mathcal{A}_D^{(1)}$$

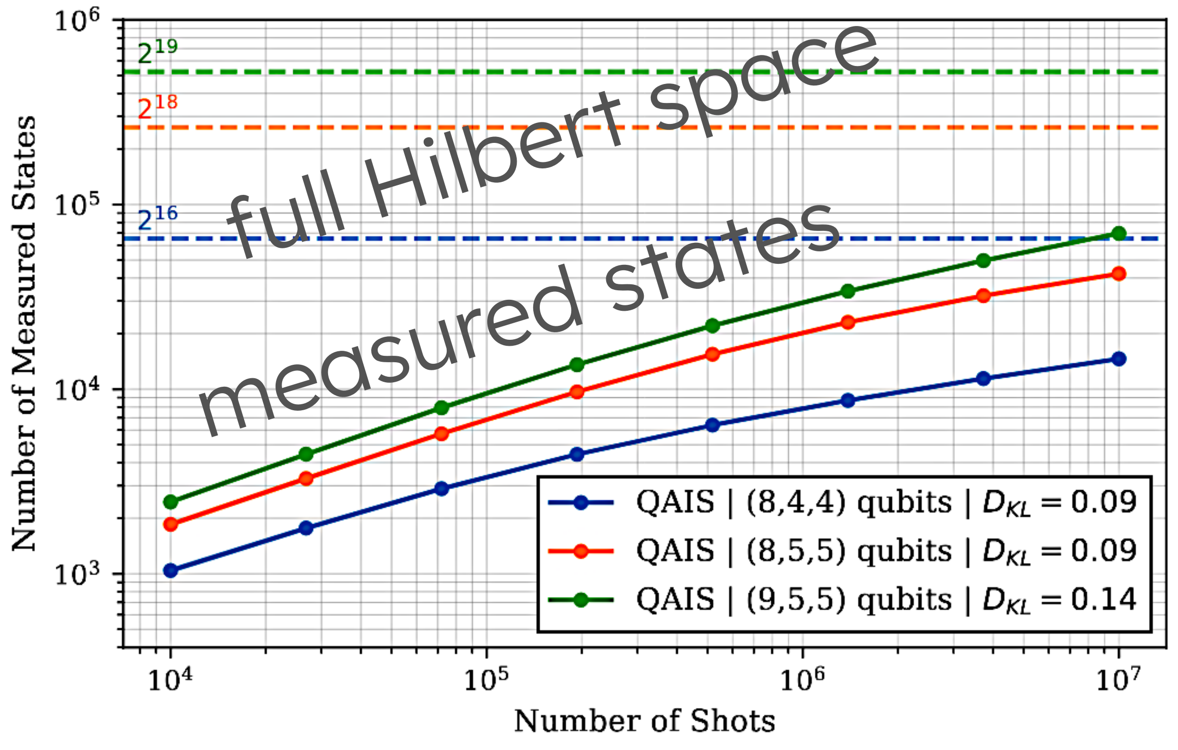
$$\lambda_i^\pm = q_{i,0}^{(+)} + q_{i+1,0}^{(+)} \pm p_{i,0}$$

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

$$j = i+1 \quad q_{i,0}^{(+)} = \sqrt{\vec{\mathbf{q}}_i^{\,2} + m_i^2 - \imath 0}$$

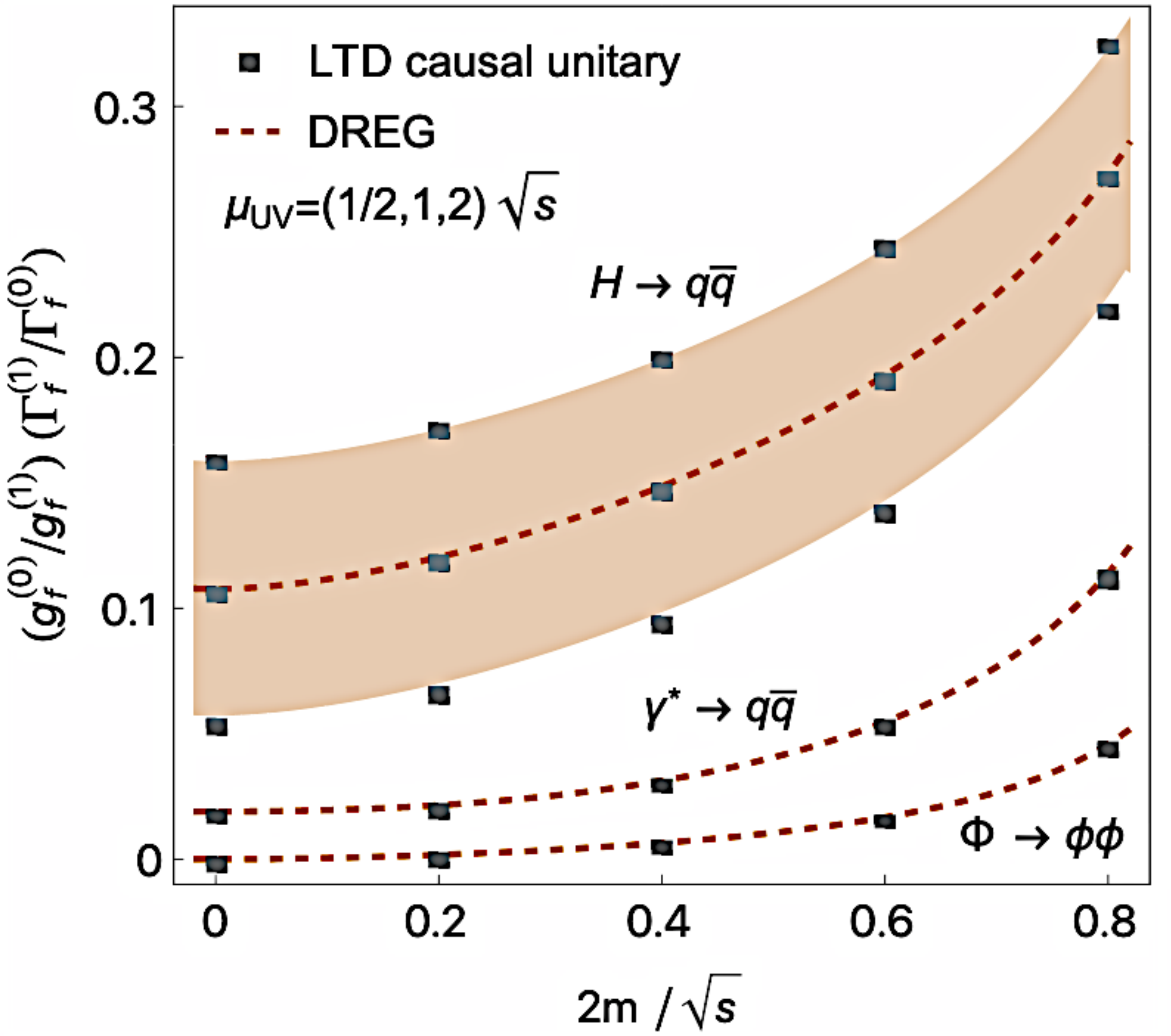


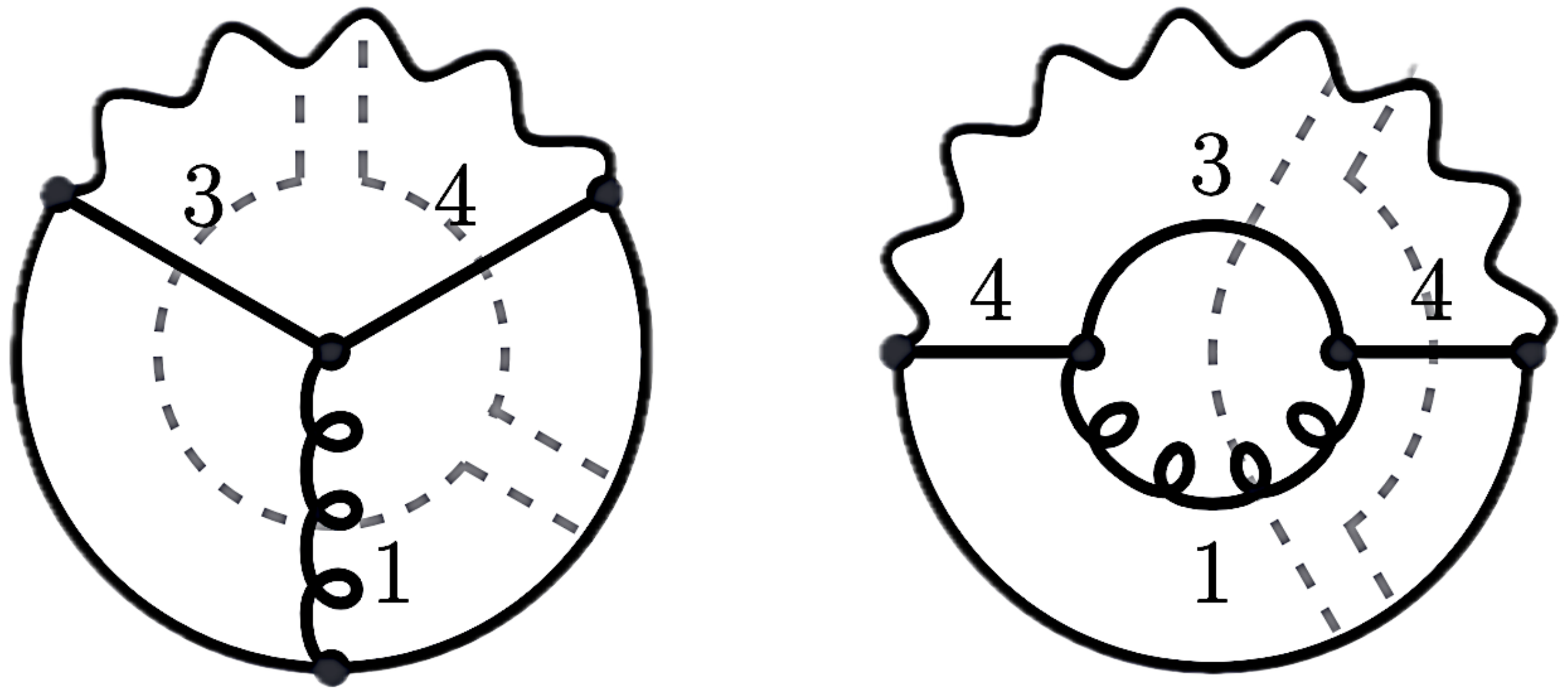




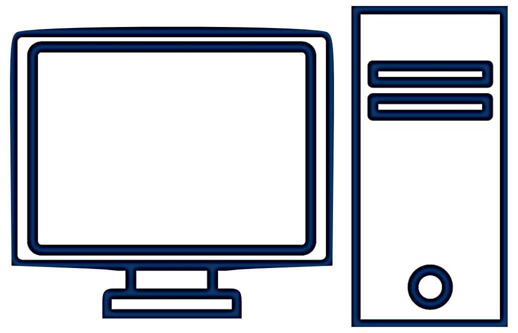
- uncertainty bands from 100 independent runs with the same PDF

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



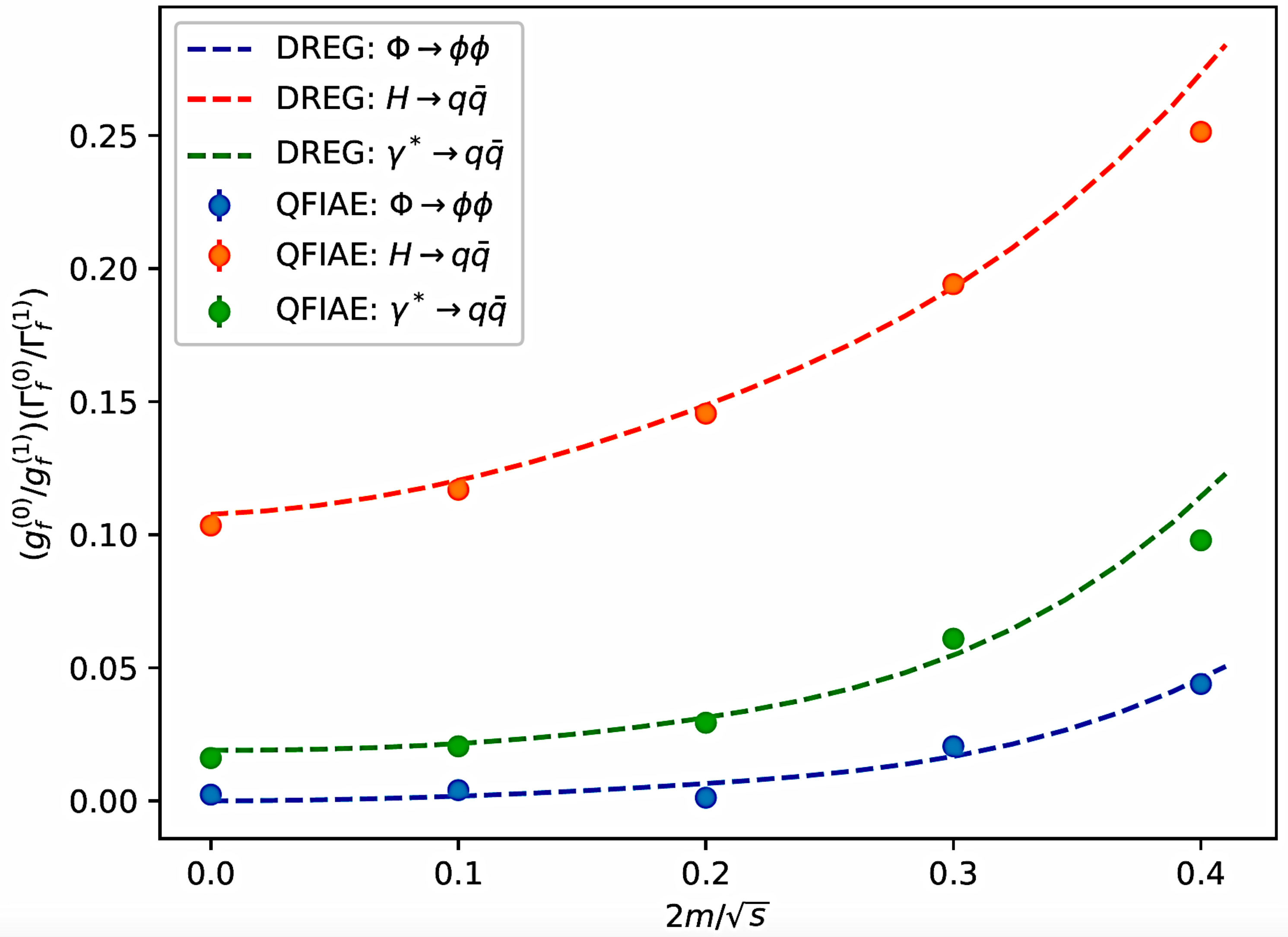


Quantum integration of decay rates at second order in perturbation theory
J.J. Martínez de Lejarza, D.F. Rentería Estrada, M. Grossi, GR, Quantum Sci.Technol. 10 (2025) 2, 025026 [2409.12236]

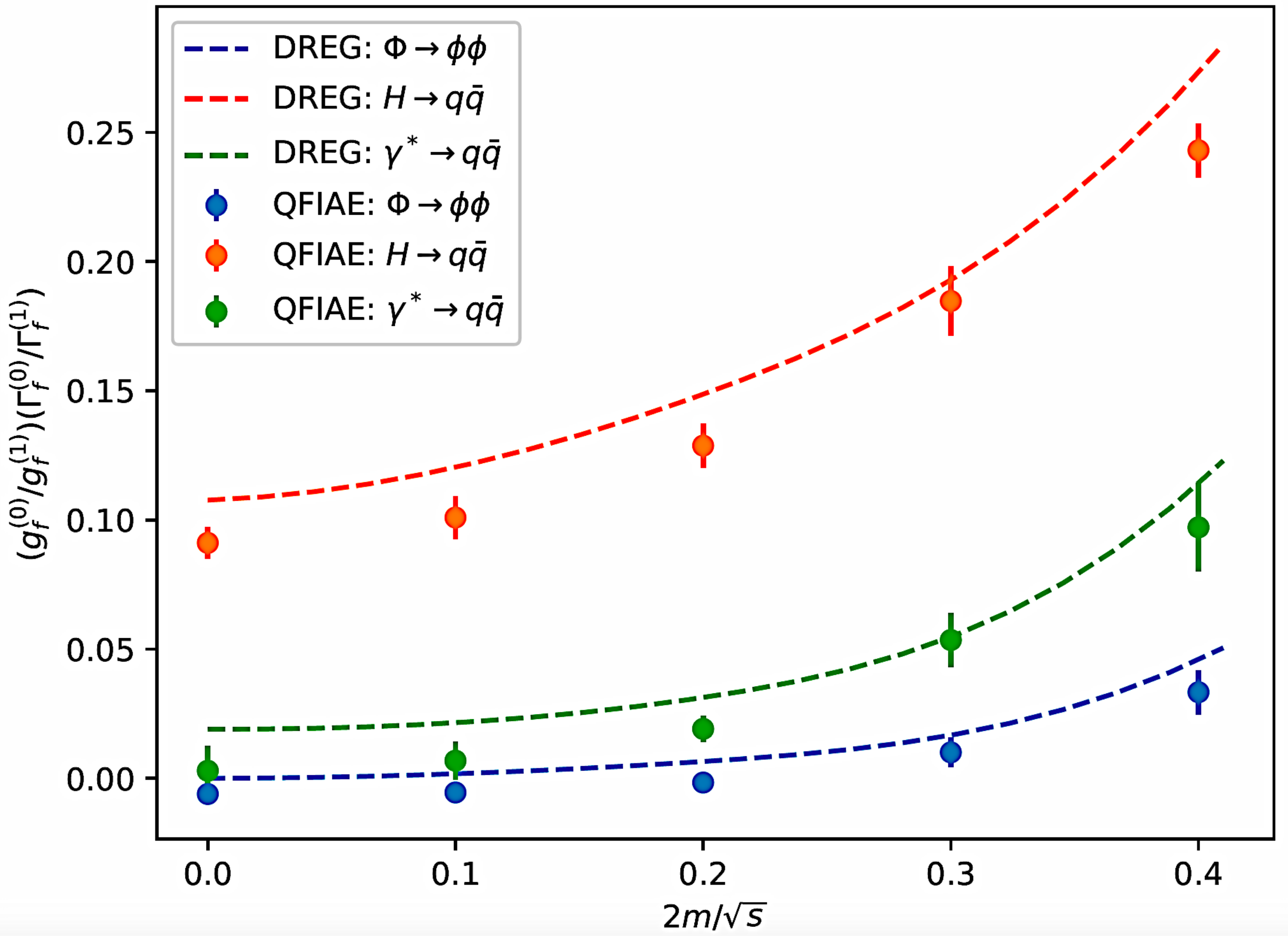


- Classical Monte Carlo

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

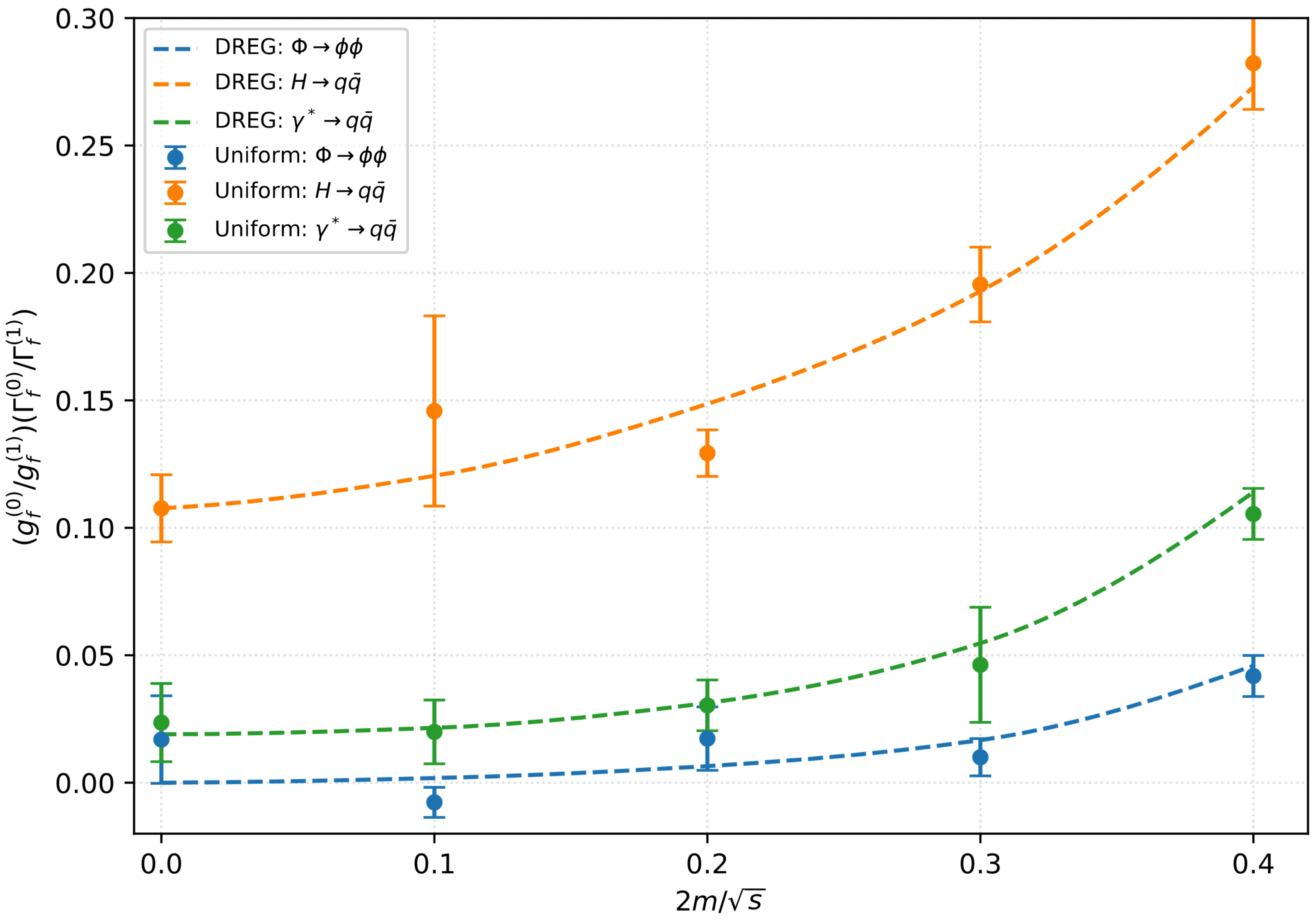


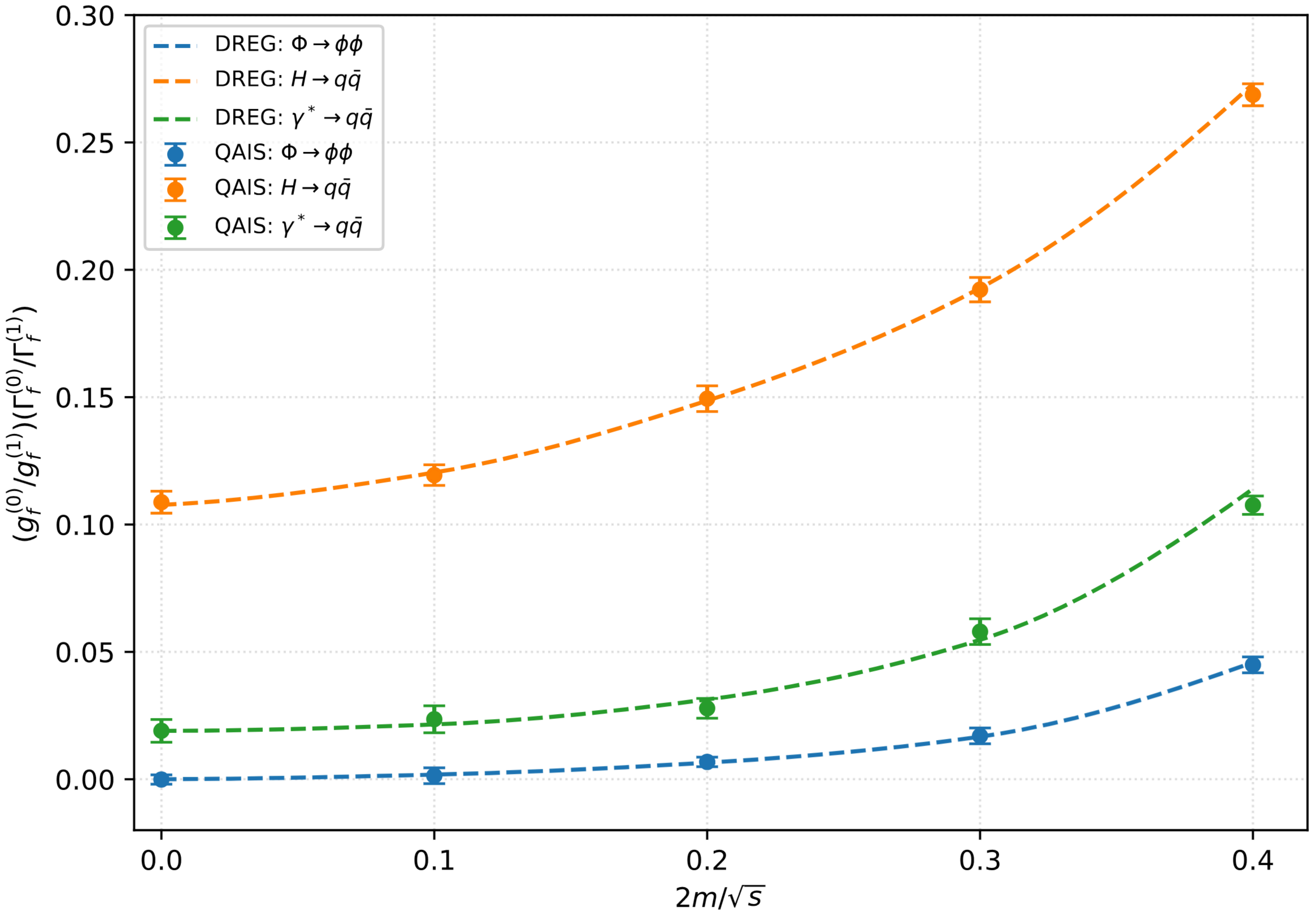
- Quantum simulator



- Partially in quantum hardware

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





- With only 50.000 shots per point

Bepari, Malik, Spannowsky, Williams, PRD 103, 076020 (2021)
Chawdhry, Pellen, Williams, 2507.07194
Bashore, Moretti, Vitos, 2507.14252
Haddad, Xu, Croft, Halimeh, Grossi, 2602.21311

Helicity and Colour Interferences

- The Weyl spinors for a particle with three-momentum $\mathbf{p} = E(\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta)$

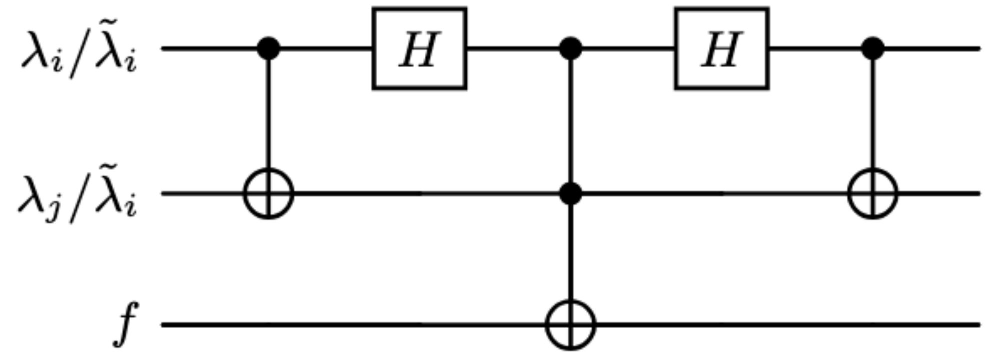
$$\lambda_\alpha = \sqrt{2E}\begin{pmatrix}\cos(\theta/2)\\ e^{\imath\phi}\sin(\theta/2)\end{pmatrix}, \qquad \tilde{\lambda}_{\dot\alpha} = \sqrt{2E}\begin{pmatrix}\cos(\theta/2)\\ e^{\imath\phi}\sin(\theta/2)\end{pmatrix}.$$

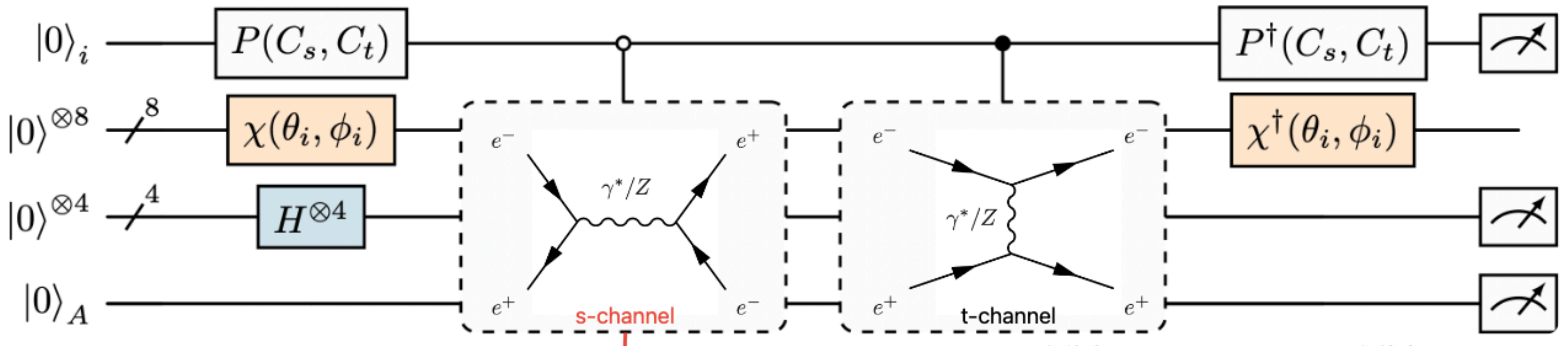
Their **angular** component naturally encoded as a qubit

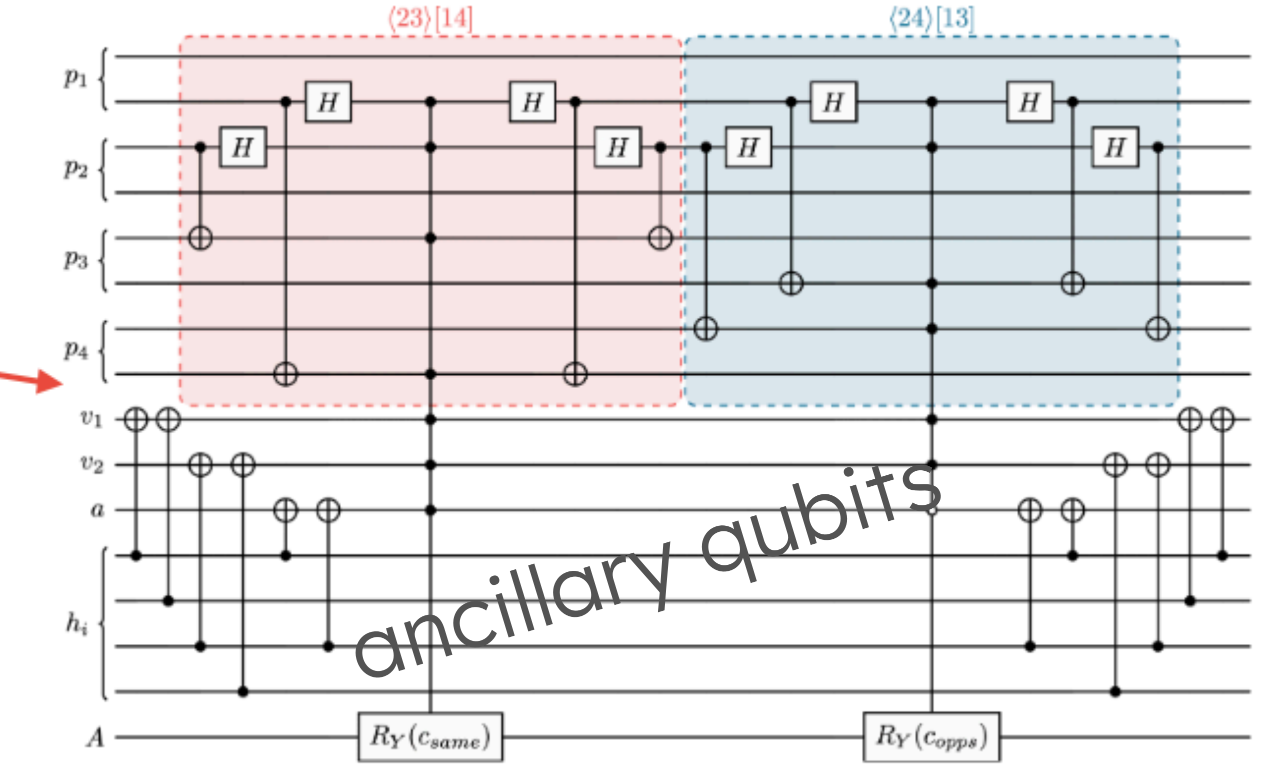
$$|\lambda_\alpha(\mathbf{p})\rangle = U_3(\theta,\phi,-\phi)\,|0\rangle = \cos(\theta/2)\,|0\rangle + e^{\imath\phi}\sin(\theta/2)\,|1\rangle$$

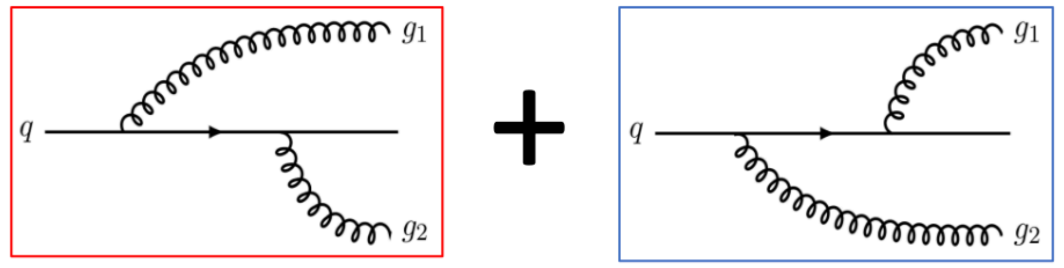
- Energy component added in a post-processing steep
- The bi-spinor products

$$\langle ij\rangle, [ij] \sim$$

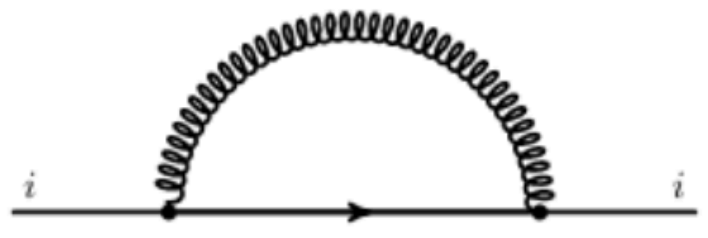


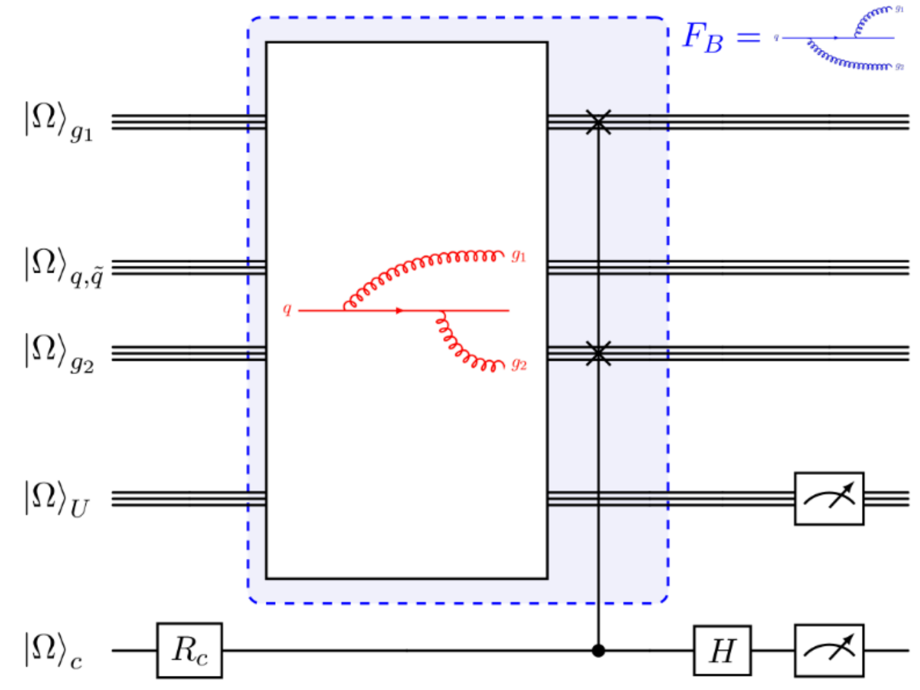






- Encoding the colour of a gluon: 3 qubits (2^3 states)
- Encoding a quark: 2 qubits by wasting one state

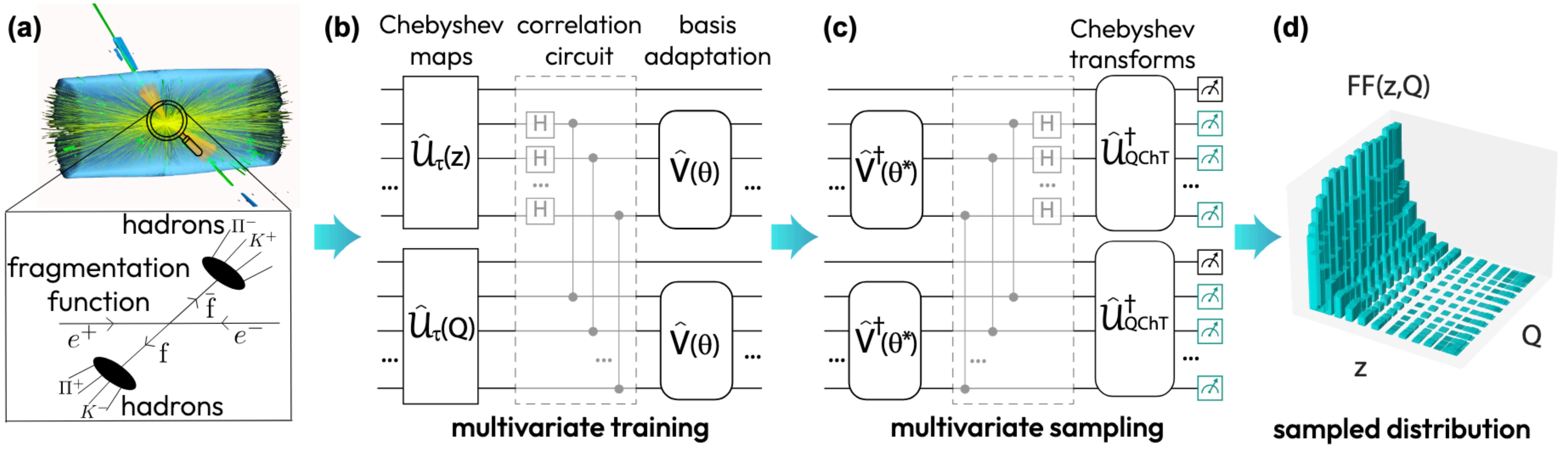
Diagram	Analytical	Numerical
	$C_F N = 4$	3.9988 ± 0.0012

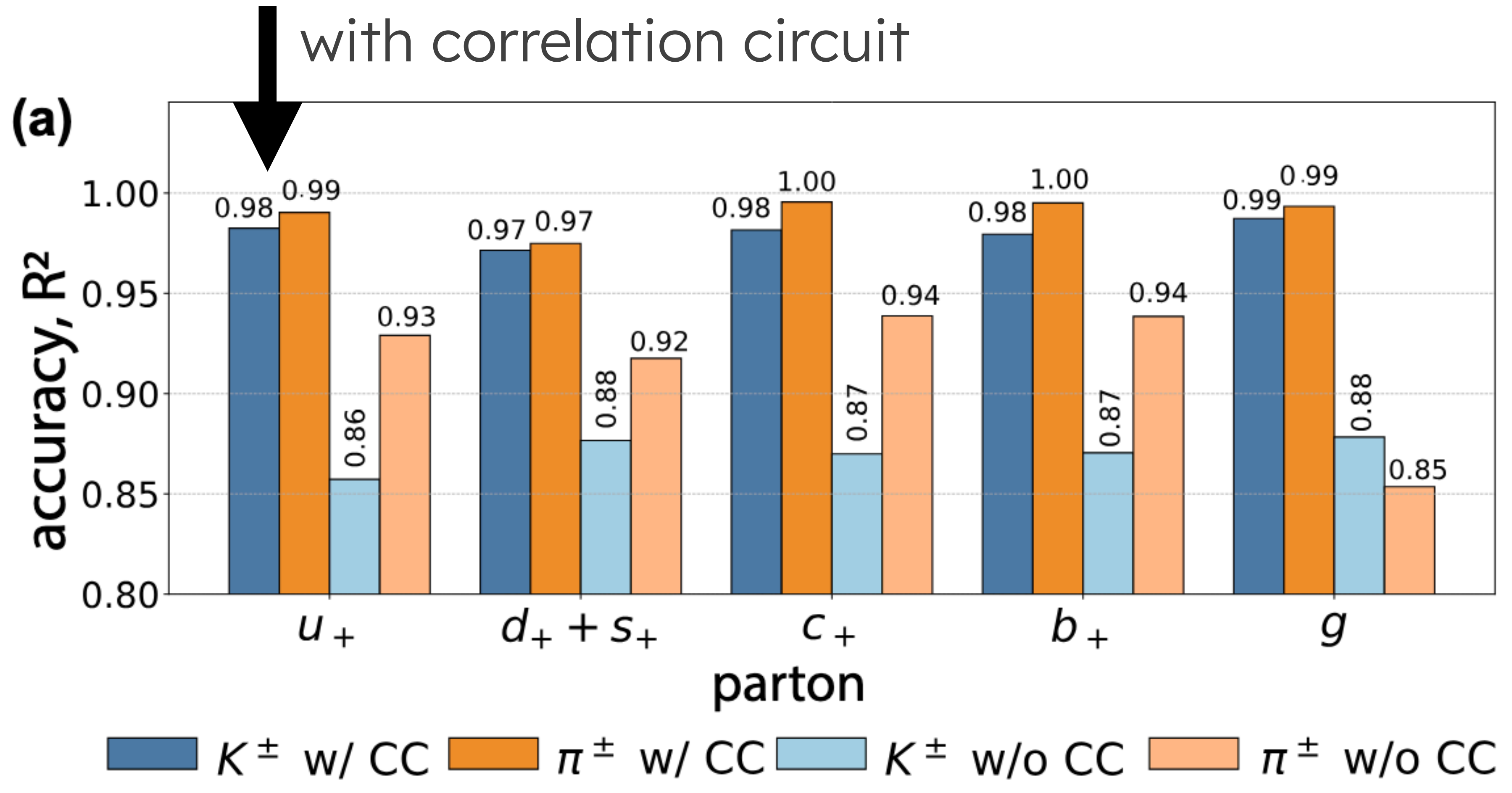


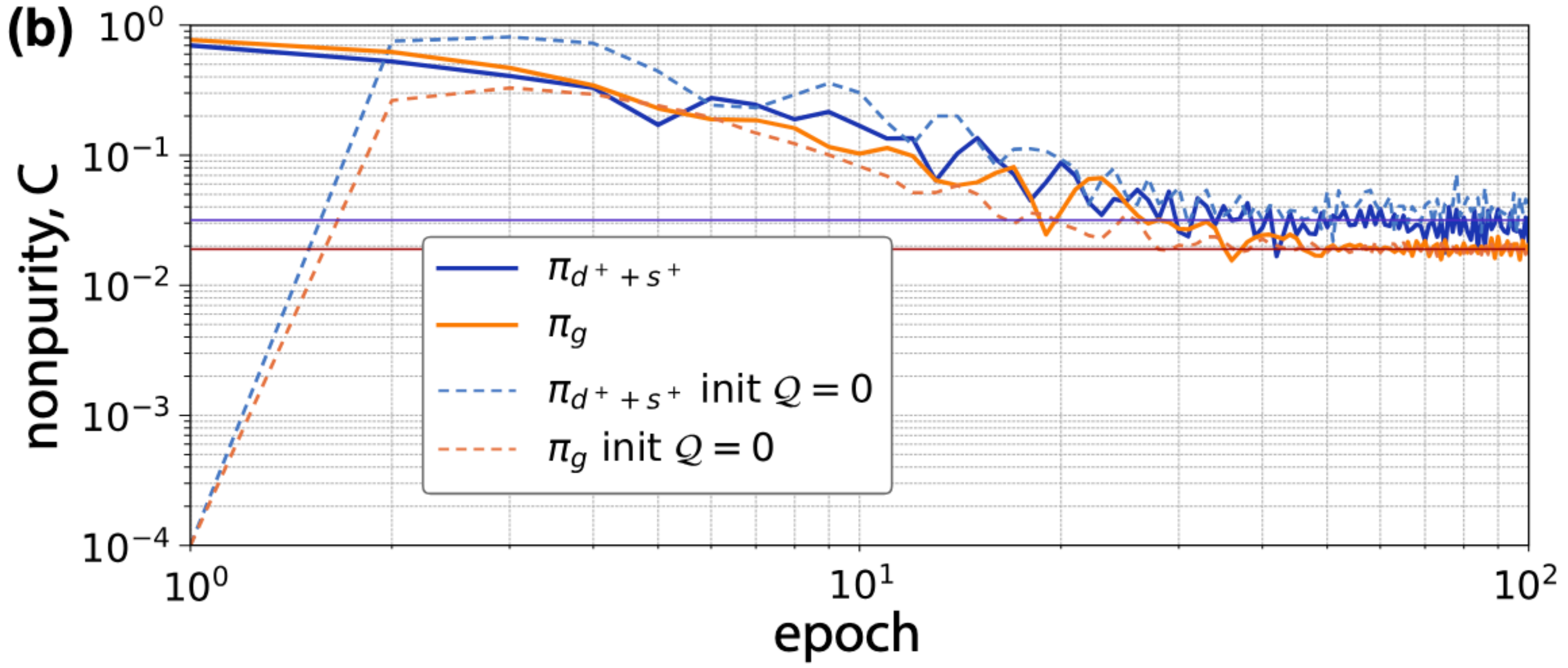
Analytic: 1/3 ≈ 0.333
Noiseless simulation: 0.330 +/- 0.015
Physical device (H1): 0.342 +/- 0.015

Martínez de Lejarza, Wu, Kyriienko, GR, Grossi, Nat.Comm.Phys. 8 (2025) 1, 448

Quantum Chebyshev Probabilistic Models (QCPM)





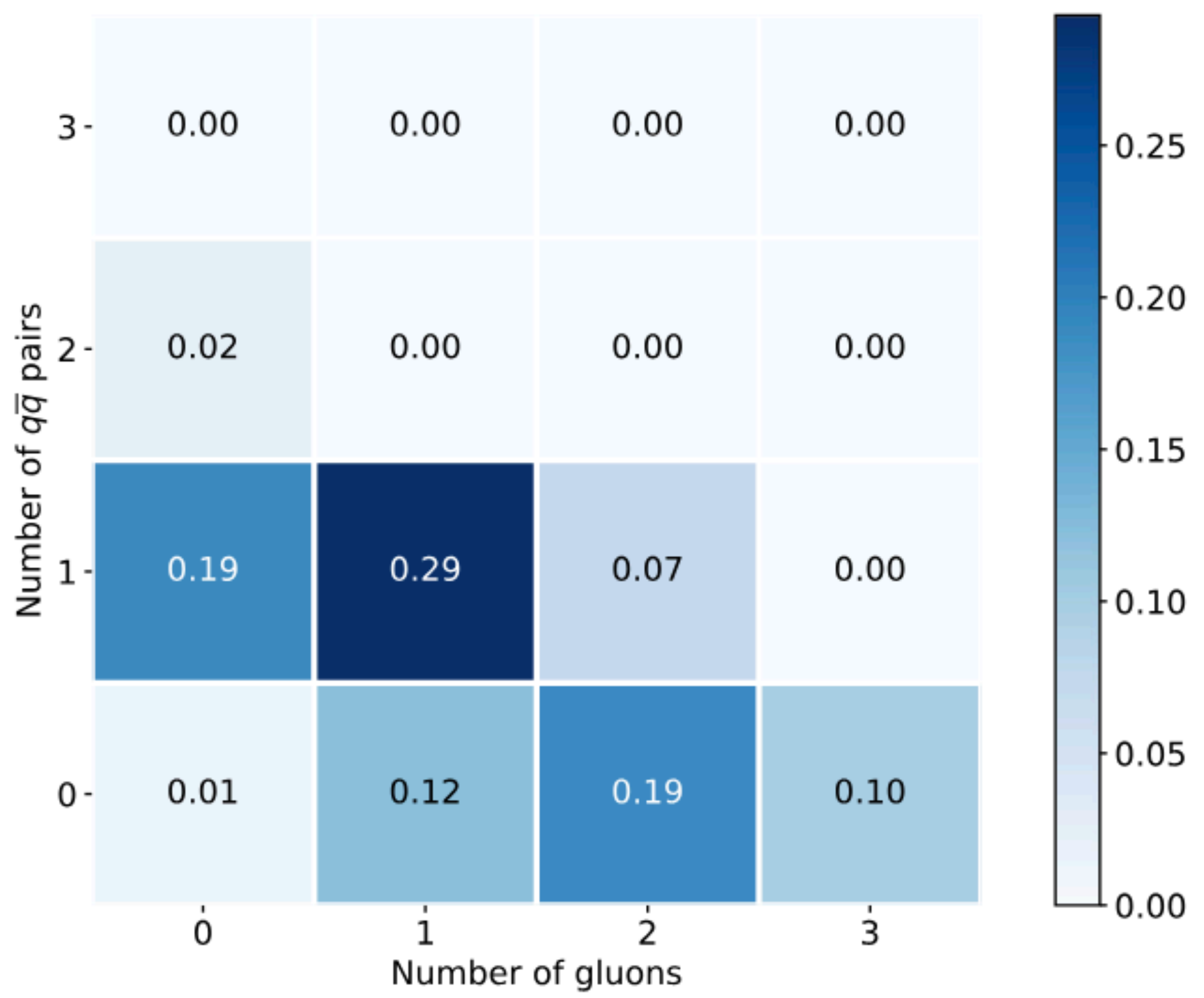


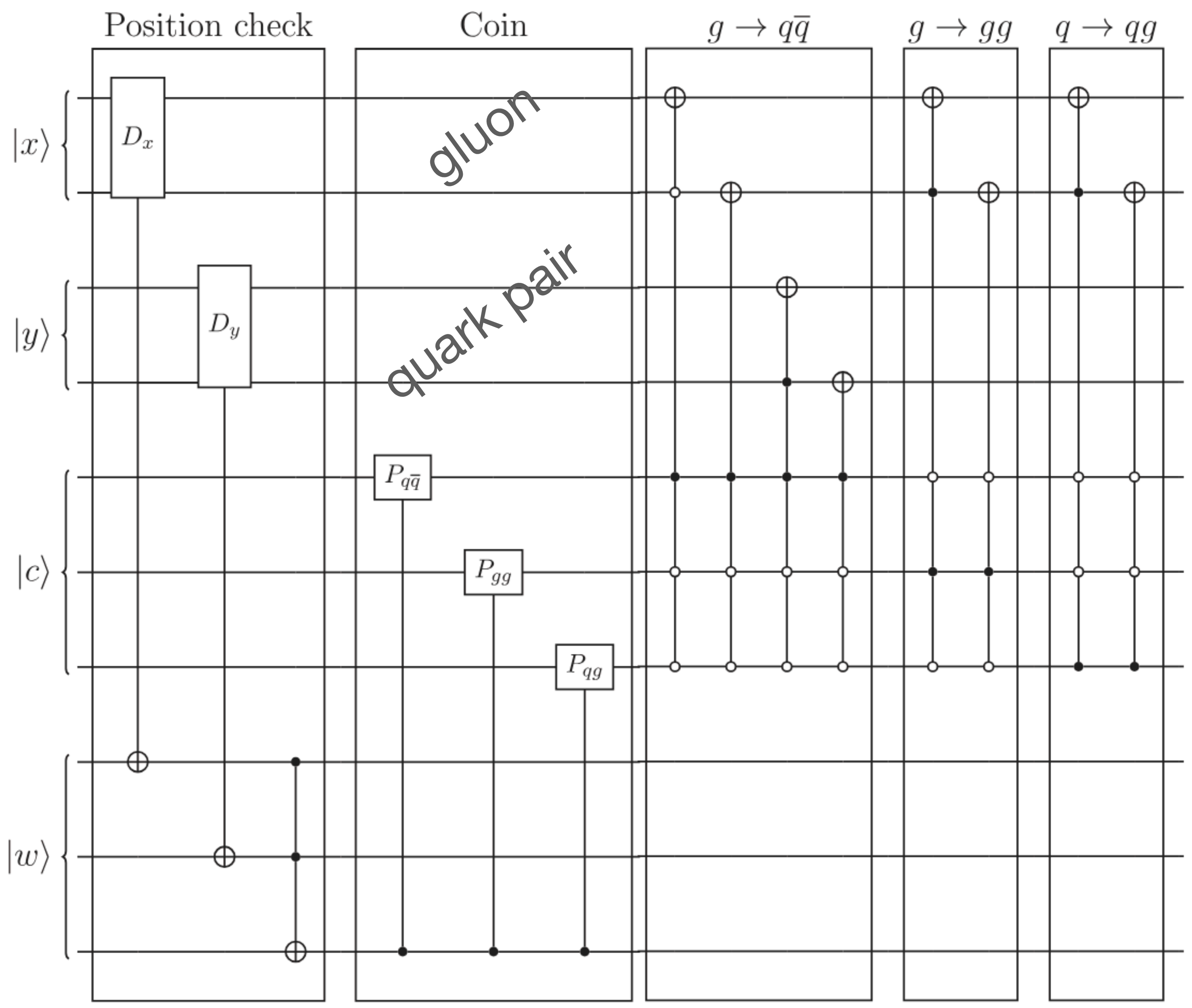
- QCPM with the correlation circuit consistently outperform those without
- A lower non-purity ($C = |1 - \mathrm{Tr}(\rho^2)|$) suggests a higher degree of entanglement, indicating strong correlations between z and Q

Bauer, de Jong, Nachman, Provasoli, PRL 126, 062001 (2021)
Bepari, Malik, Spannowsky, Williams, PRD 103, 076020 (2021), PRD 106, 056002 (2022)

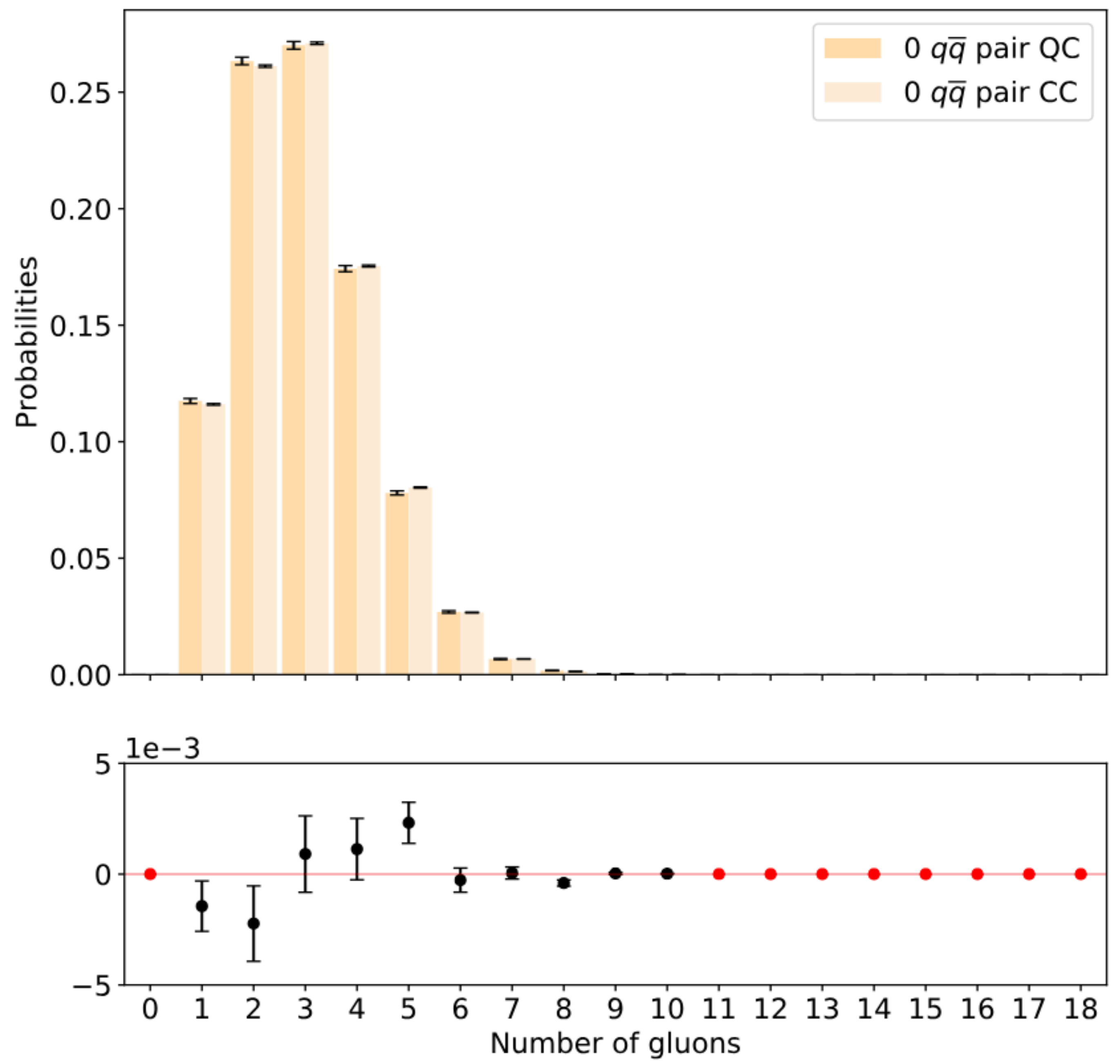
Parton Showers

- Involve a large number or particles: fast growing computational complexity
- **Quantumness is lost** in each step of the classical **Markov Chain Monte Carlo**: classical showers simulate radiation cascades sequentially, with no memory, i.e. they compute probabilities, not amplitudes, structurally neglecting complex interference patterns between different branching histories
- **Quantum walks** preserve interference cross-terms through the cascade $|A+B|^2 = |A|^2 + |B|^2 + 2\mathrm{Re}(A^*B)$
- The coin: a Hadamard gate $H = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$, all shower histories encoded in superposition
- Toy PS, e.g. kinematics missing, one quark flavor





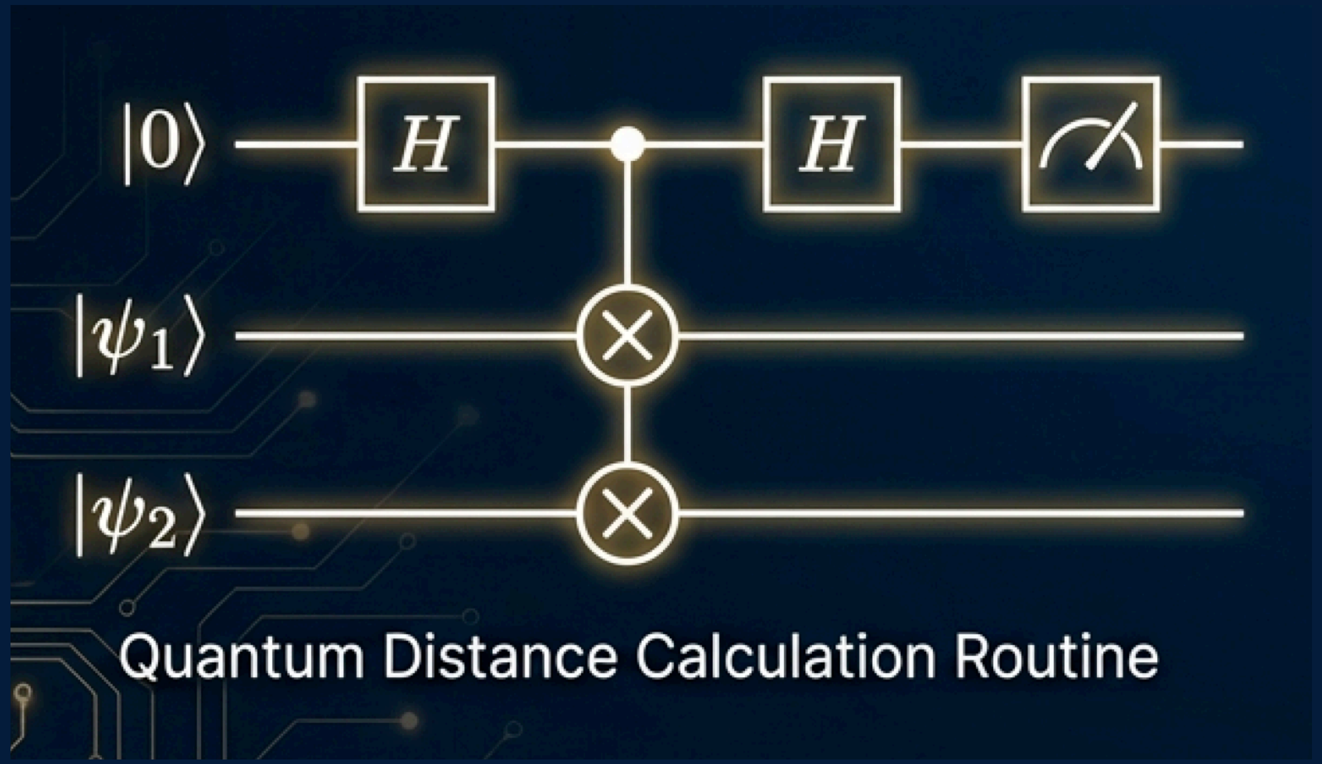
one quark flavor and a gluon



Martínez de Lejarza, Cieri, Rodrigo, PRD 106, 036021 (2022)

Jet clustering at the LHC

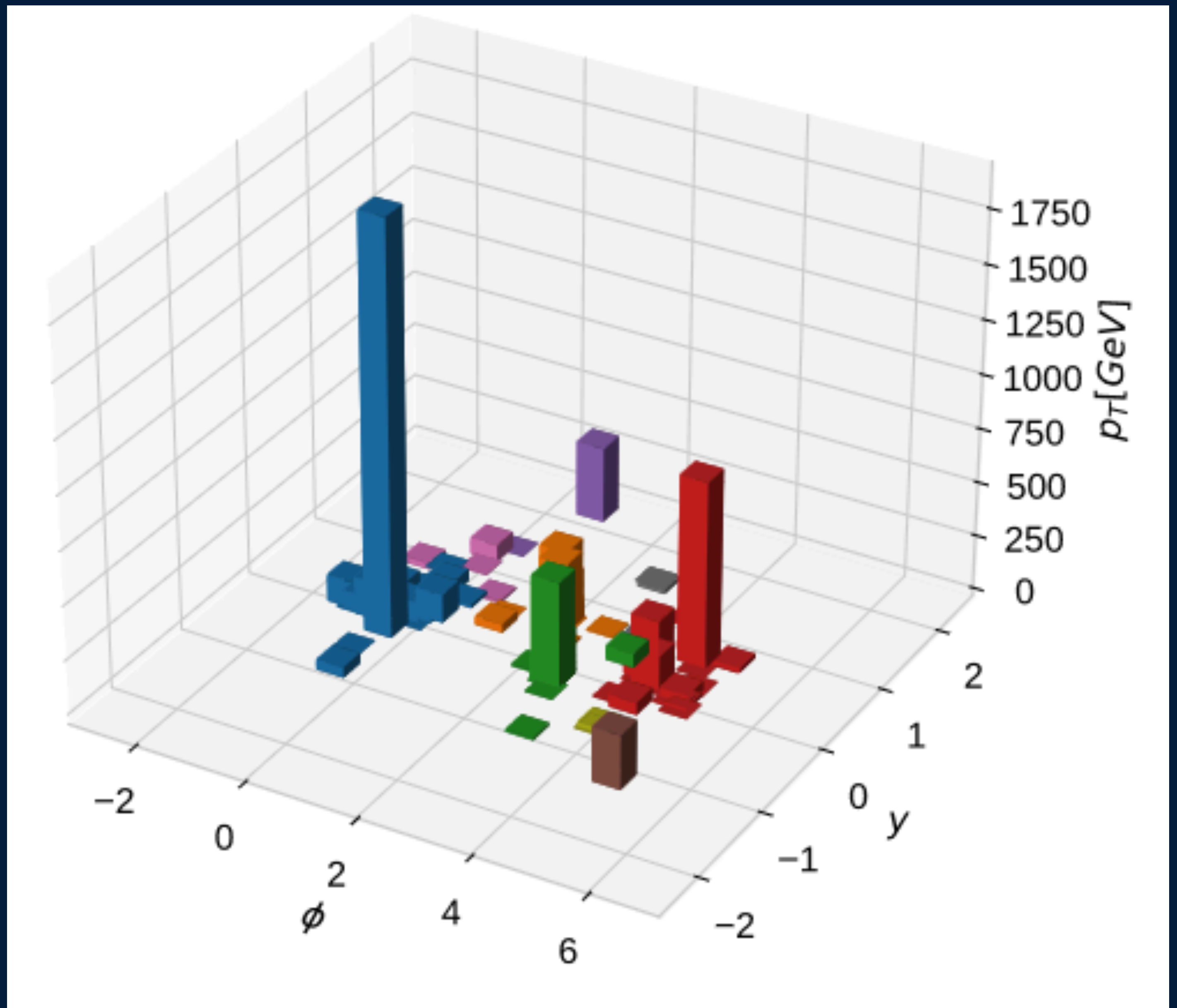
- Three clustering algorithms: K-means, Affinity Propagation, k_T-jet
- Hierarchical classical clustering (e.g. k_T-jet) requires to find the absolute minimum distance between all pairs of particles at each intermediate steep: very costly computationally
- Minimum distance in a quantum algorithm is probabilistic and less expensive: **clustering ordering relaxed**
- Bare **classical** anti-k_T has complexity $\mathcal{O}(N^3)$, reduced to $\mathcal{O}(N \log(N))$ by using geometrical nearest neighbour and optimization with Voronoi diagrams [Salam, Cacciari]
- Bare **quantum** version is $\mathcal{O}(N^2 \log(N))$ without any optimization



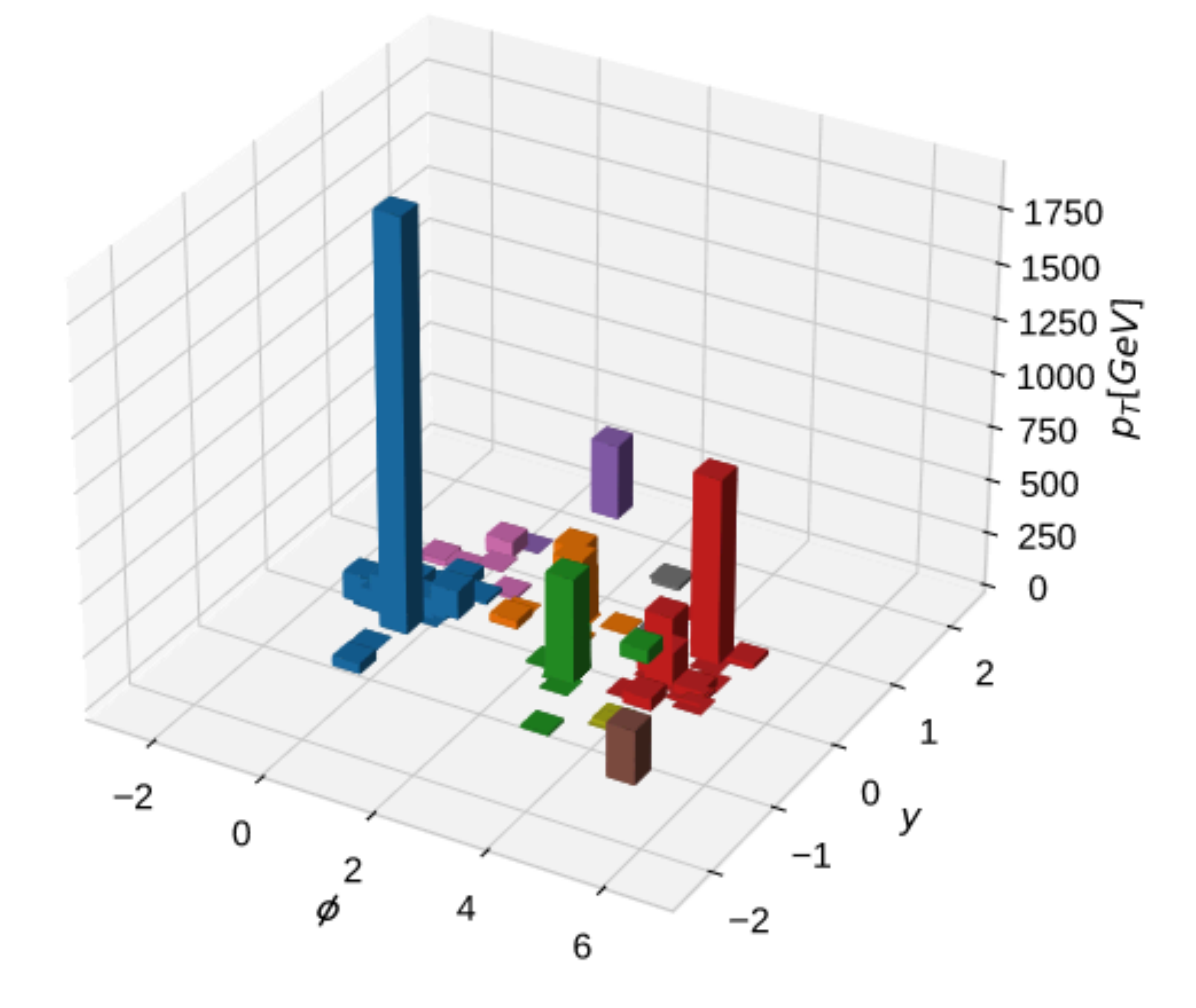
$$|\psi_1\rangle = \frac{1}{\sqrt{2}}(|0,x_i\rangle + |1,x_j\rangle)$$

$$|\psi_2\rangle = \frac{1}{\sqrt{|\mathbf{x}_i|^2 + |\mathbf{x}_j|^2}}(|\mathbf{x}_i||0\rangle + |\mathbf{x}_j||1\rangle)$$

$$d_E^{(Q)}(\mathbf{x}_i, \mathbf{x}_j) = \sqrt{2\left(|\mathbf{x}_i|^2 + |\mathbf{x}_j|^2\right)\left(2P_{\Psi_3}(|0\rangle) - 1\right)}$$



(a) Classical anti-k_T, $p = -1$, $R = 1$.



(b) Quantum anti-k_T, $p = -1$, $R = 1$, $\epsilon_c = 0.99$.

Conclusions

- High-energy colliders are **quantum machines** (with the LHC the largest quantum machine ever built, and the FCC the next quantum machine), and so well suited for a Quantum Computing (QC) approach
- Potential advantage for solving problems (or parts of problems) where computational complexity grows rapidly, or where correlations are relevant, i.e. where superposition, entanglement and interference can be exploited
- Today, classical methods still perform better, though leading vendors project **50–100 logical qubits** within ~5 years
- A number of potential applications in collider physics ready for scaling once a quantum computer becomes a reality
- My (long-term) dream: a **quantum event generator** with NNLO, …, $N^kLO + N^kLL$ accuracy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EN TECNOLOXÍAS CUÁNTICAS DA INFORMACIÓN QUE
PERMITA IMPULSAR A I+D+i en GALICIA
Apoiar a transición cara a unha economía dixital
Operación financiada pola Unión Europea, a través do
EUROPEO DE DESENVOLVEMENTO REXIONAL (FEDER),
da resposta da Unión á pandemia da COVID-19
Unha maneira de facer Europa
Qmio
CESGA
FUJITSU
OQC
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34
4 0 1 2 3

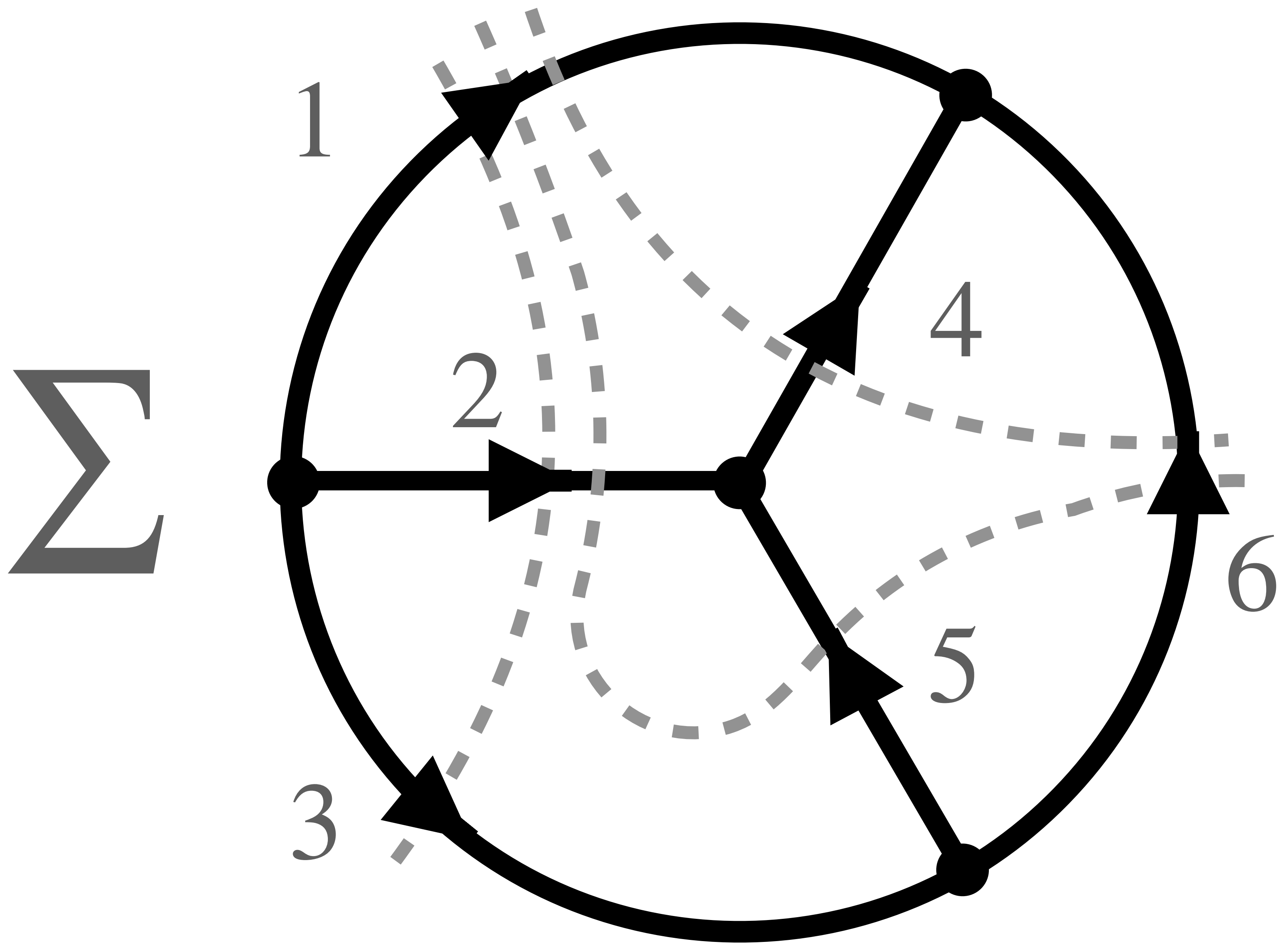
The Loop-Tree Duality LTD: vacuum amplitudes

the Euclidean space of the loop three-momenta

$$\mathscr{A}_{\rm D}^{(\Lambda)} \sim \prod \frac{1}{\lambda_{i_1 i_2 \cdots i_n}} \qquad \mathscr{A}^{(\Lambda)} = \int_{\vec{\ell}_1 \cdots \vec{\ell}_\Lambda} \mathscr{A}_{\rm D}^{(\Lambda)}$$

on-shell energies

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



States with external particles are generated from residues (cuts) over causal propagators $1/\lambda_{i_1 i_2 \cdots i_n}$ 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)