

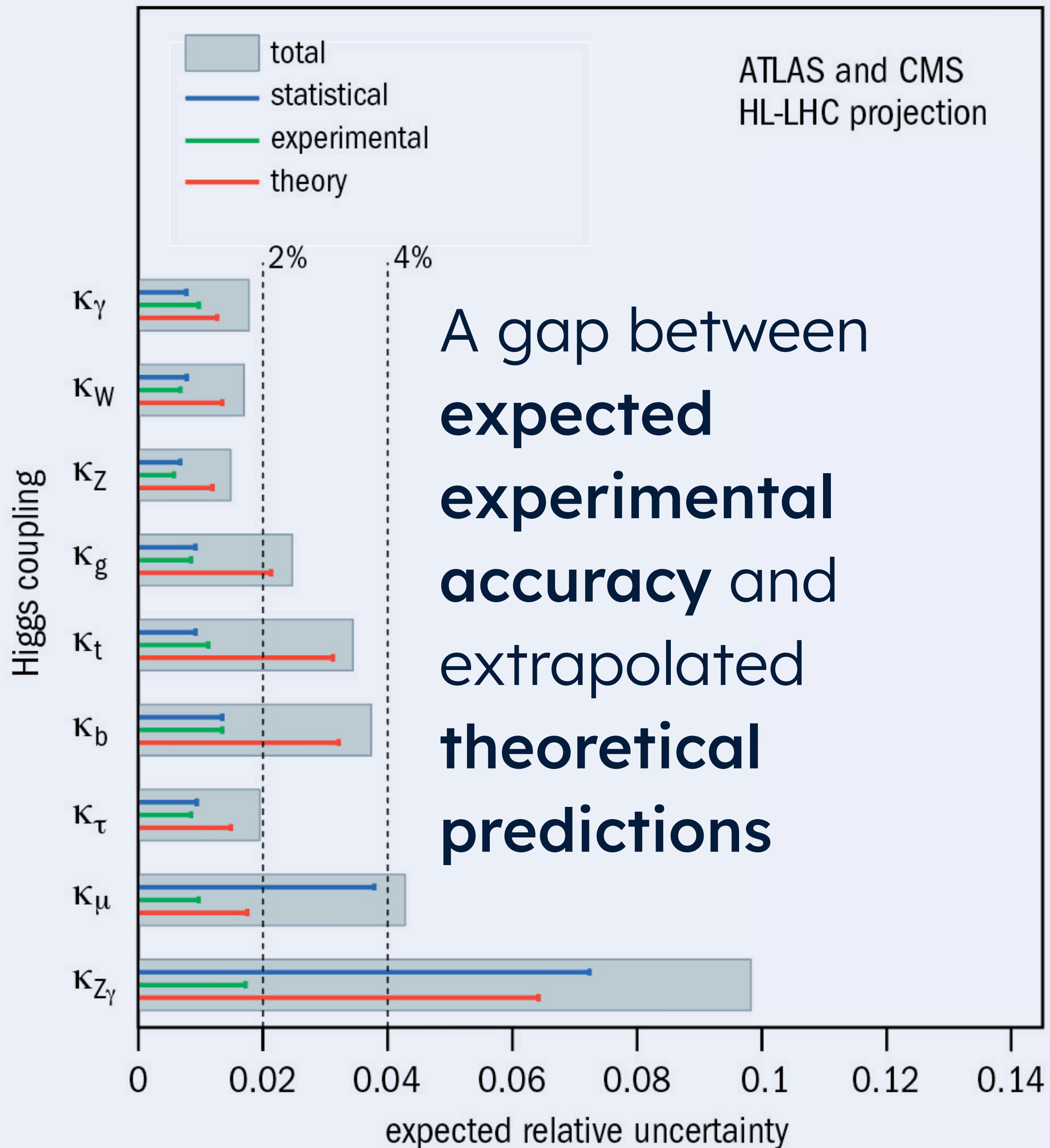
Theoretical predictions for colliders at high perturbative orders

Germán RODRIGO

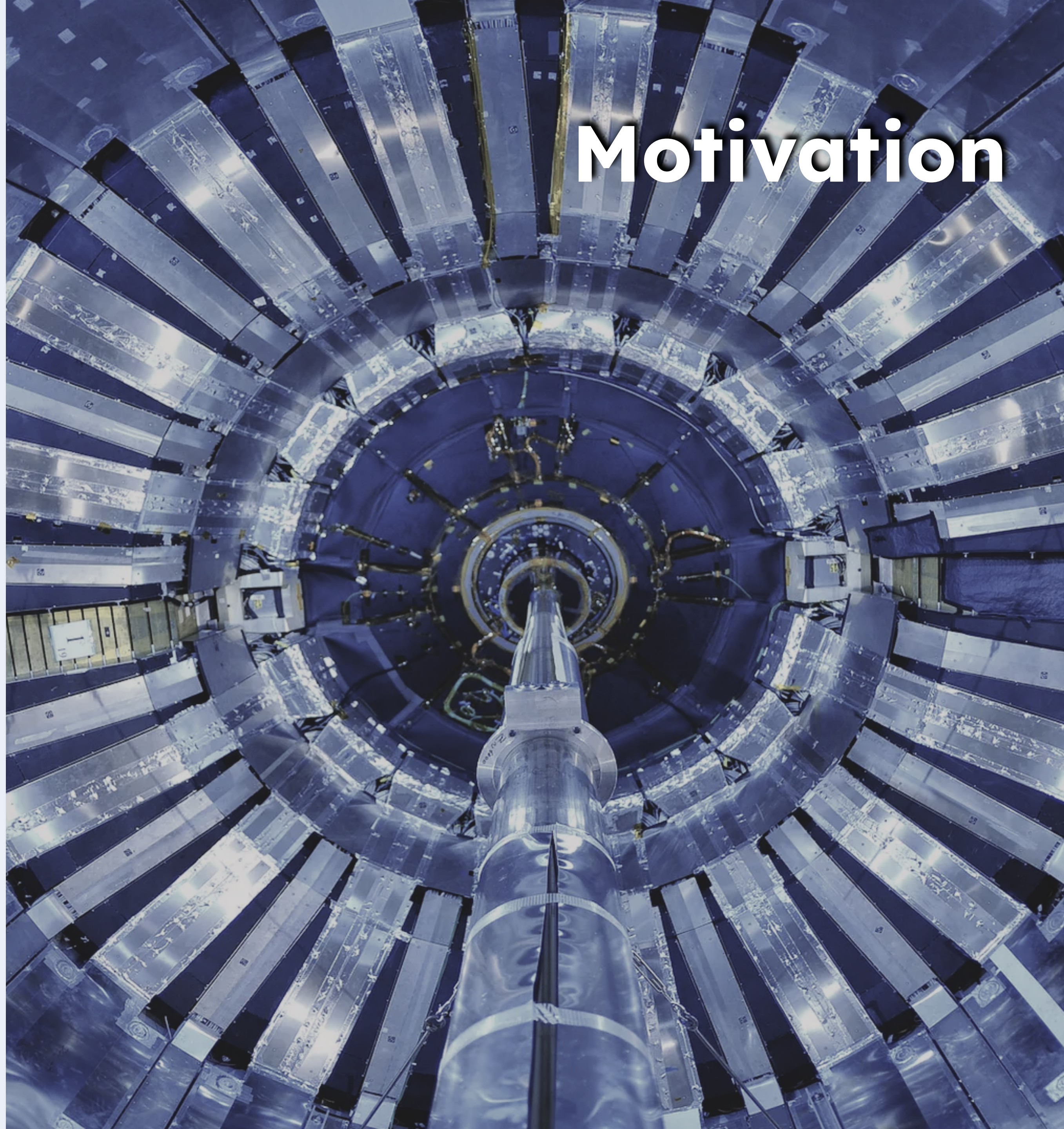
QuantHEP 2026

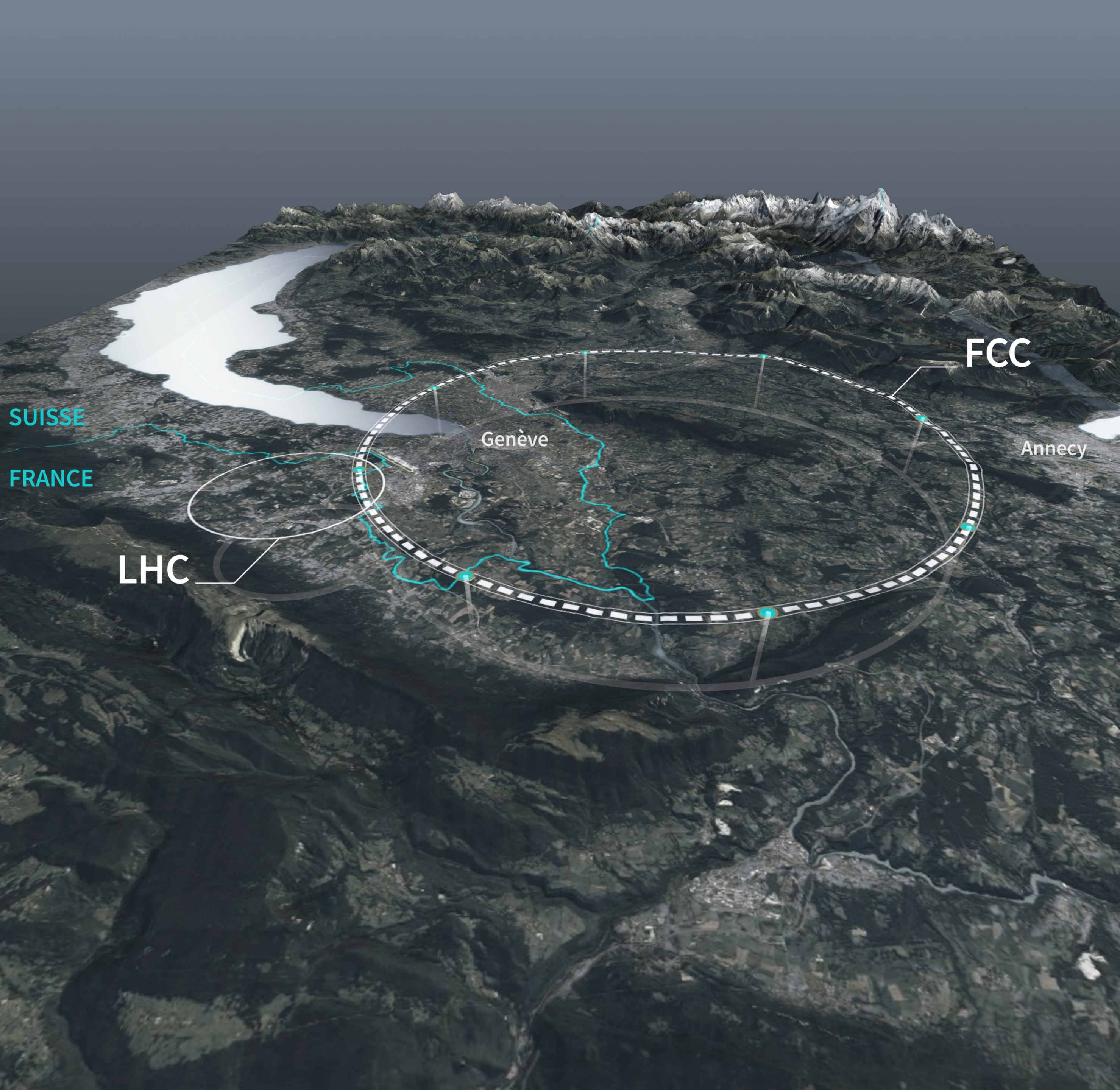
London 13-16 July 2026





Motivation





Theoretical challenges ahead

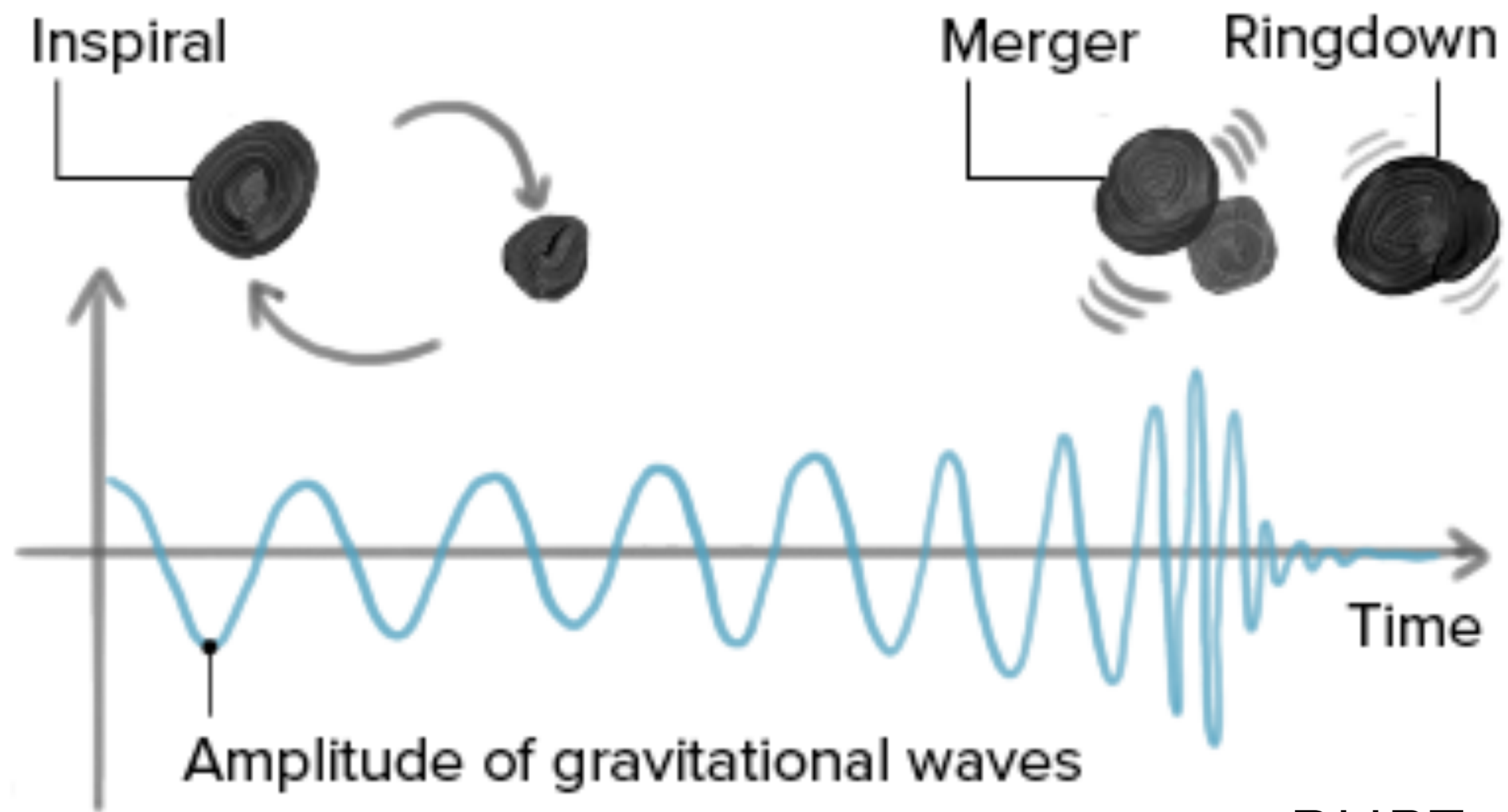
e.g. theoretical work needed to enable *extraction* of EWPO from measurements (additional work needed for making predictions)

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 $e^+e^- \rightarrow f\bar{f}$, initial-state radiation (ISR)	NLO, ISR logarithms up to 6 th order	NNLO for $e^+e^- \rightarrow f\bar{f}$
Γ_Z (MeV)	2.3	0.004 (0.012)			
$\sin^2 \theta_{\text{eff}}^\ell$	1.6×10^{-4}	$1.2 (1.2) \times 10^{-6}$			
m_W (MeV)	9.9	0.18 (0.16)	lineshape of $e^+e^- \rightarrow WW$ near threshold	NLO ($e^+e^- \rightarrow 4f$ or EFT framework)	NNLO for $e^+e^- \rightarrow WW$, $W \rightarrow f\bar{f}'$ in EFT setup
HZZ coupling	– *	0.1%	cross section for $e^+e^- \rightarrow ZH$	NLO EW plus partial NNLO QCD/EW	full NNLO EW
m_{top} (MeV)	290	4.2 (4.9)	threshold scan $e^+e^- \rightarrow t\bar{t}$	N ³ LO QCD, NNLO EW, resummations up to NNLL, $\mathcal{O}(30 \text{ MeV})$ 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



perturbative
expansions

BHPT
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

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 \(2023\)](#)

Okawa et al. [CSBS 8 \(2024\)](#)

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 \(2021\)](#)

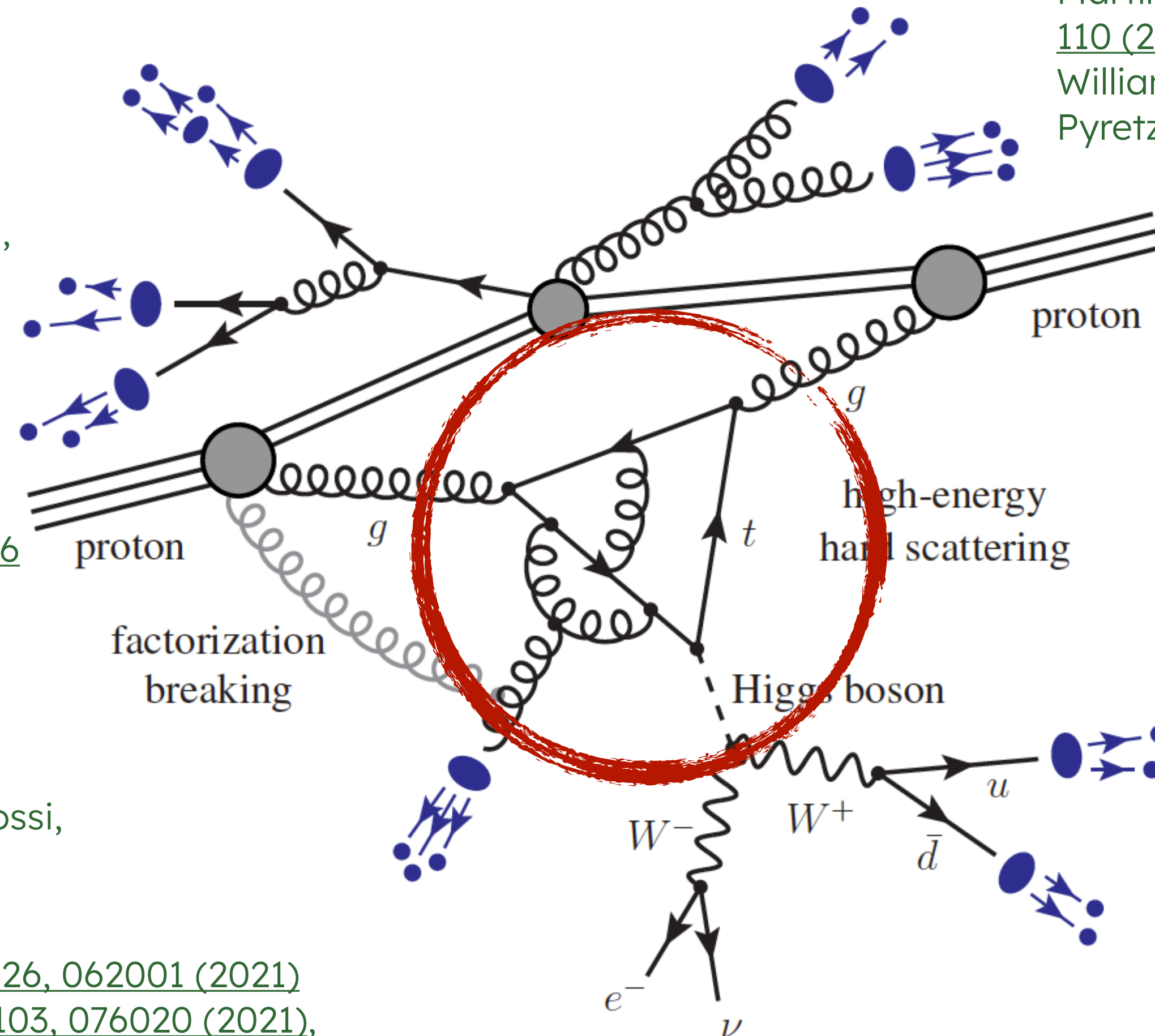
Bepari, Malik, Spannowsky, Williams, [PRD 103, 076020 \(2021\)](#), [PRD 106, 056002 \(2022\)](#)

○ 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, [NCP \(2026\)](#)

○ 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 et al. [PRD 108, 096035 \(2023\)](#)

Ochoa, Uribe, Hernández, Ramírez, GR, [NCP \(2026\)](#)

○ 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, Omar, Seixas, [PLB843 \(2023\) 138000](#)

Martínez de Lejarza, Cieri, GR, [PRD 106, 036021 \(2022\)](#)

Okawa et al. [PLB 864 \(2025\) 139393](#)

The complexity under the hood

Why Quantum

- 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.
- Scattering amplitudes contain all kinds of singularities: IR, UV and threshold
- 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 $2 \rightarrow 2$ 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

$$G_F(q_i) = \frac{1}{q_i^2 - m_i^2 + i0} \equiv \frac{1}{\sqrt{2}} (|0\rangle + |1\rangle)$$

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

A Feynman propagator is a sort of qubit

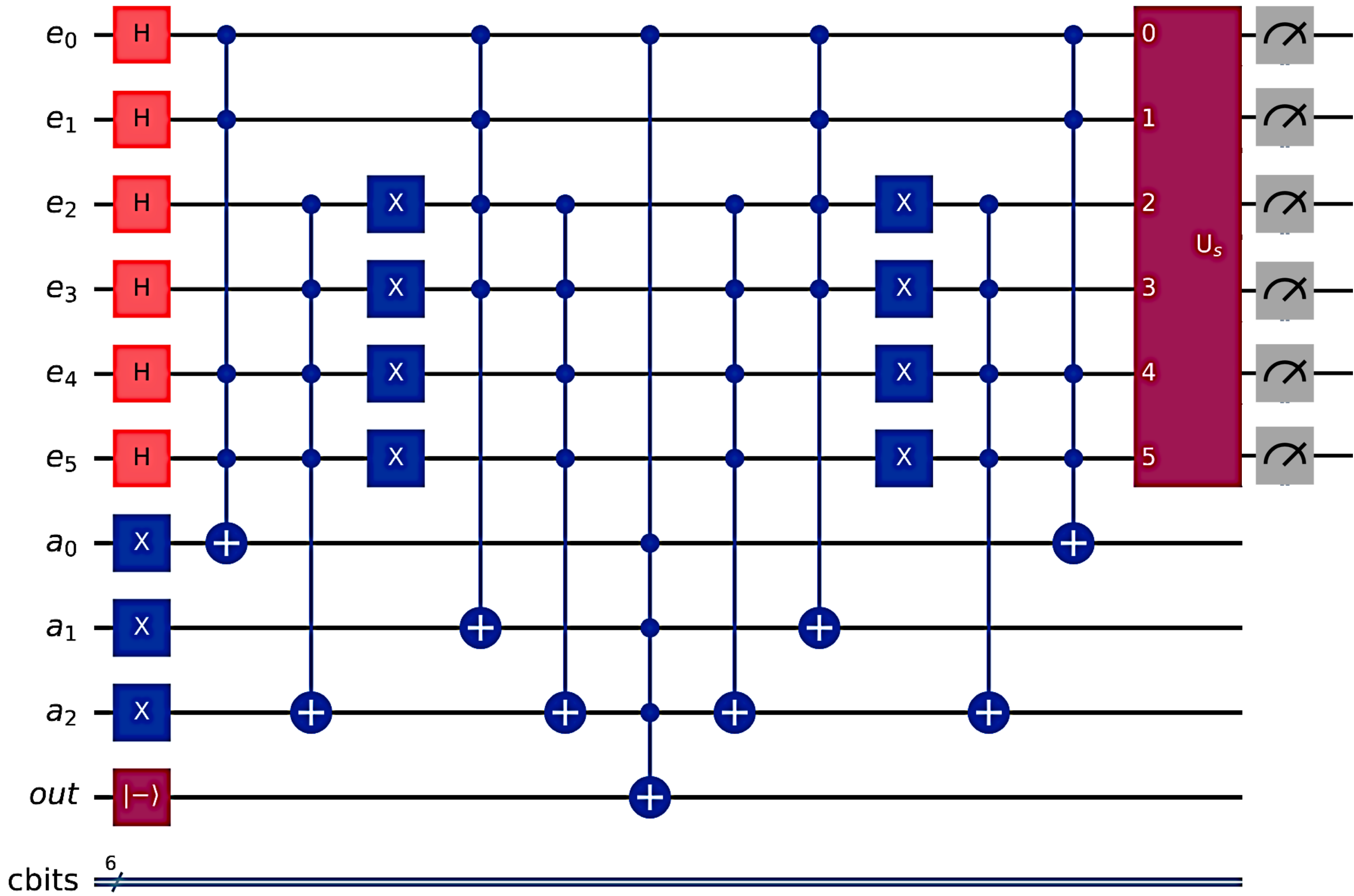
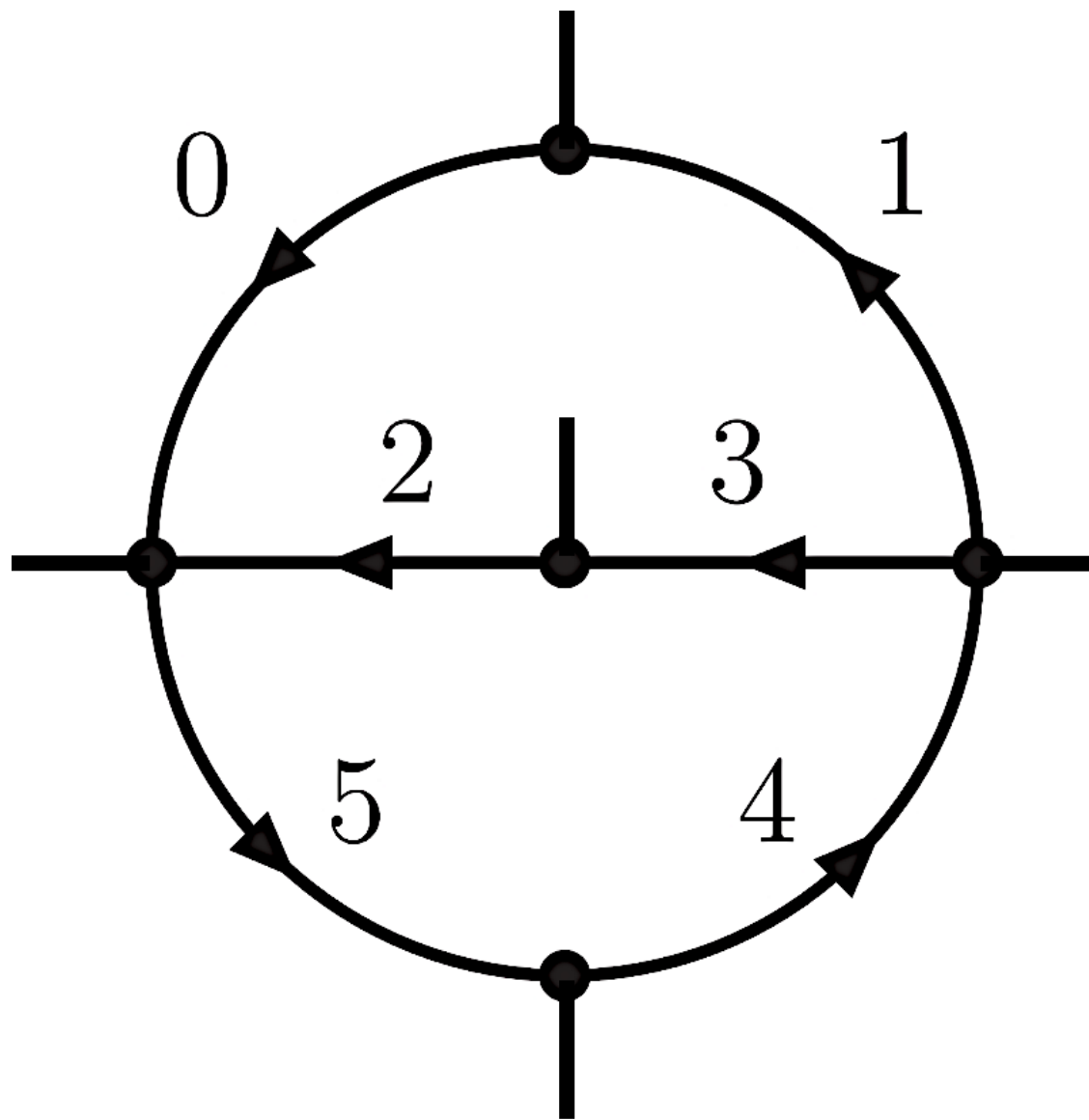


- A Feynman propagator describes a **quantum superposition** of propagation in both directions

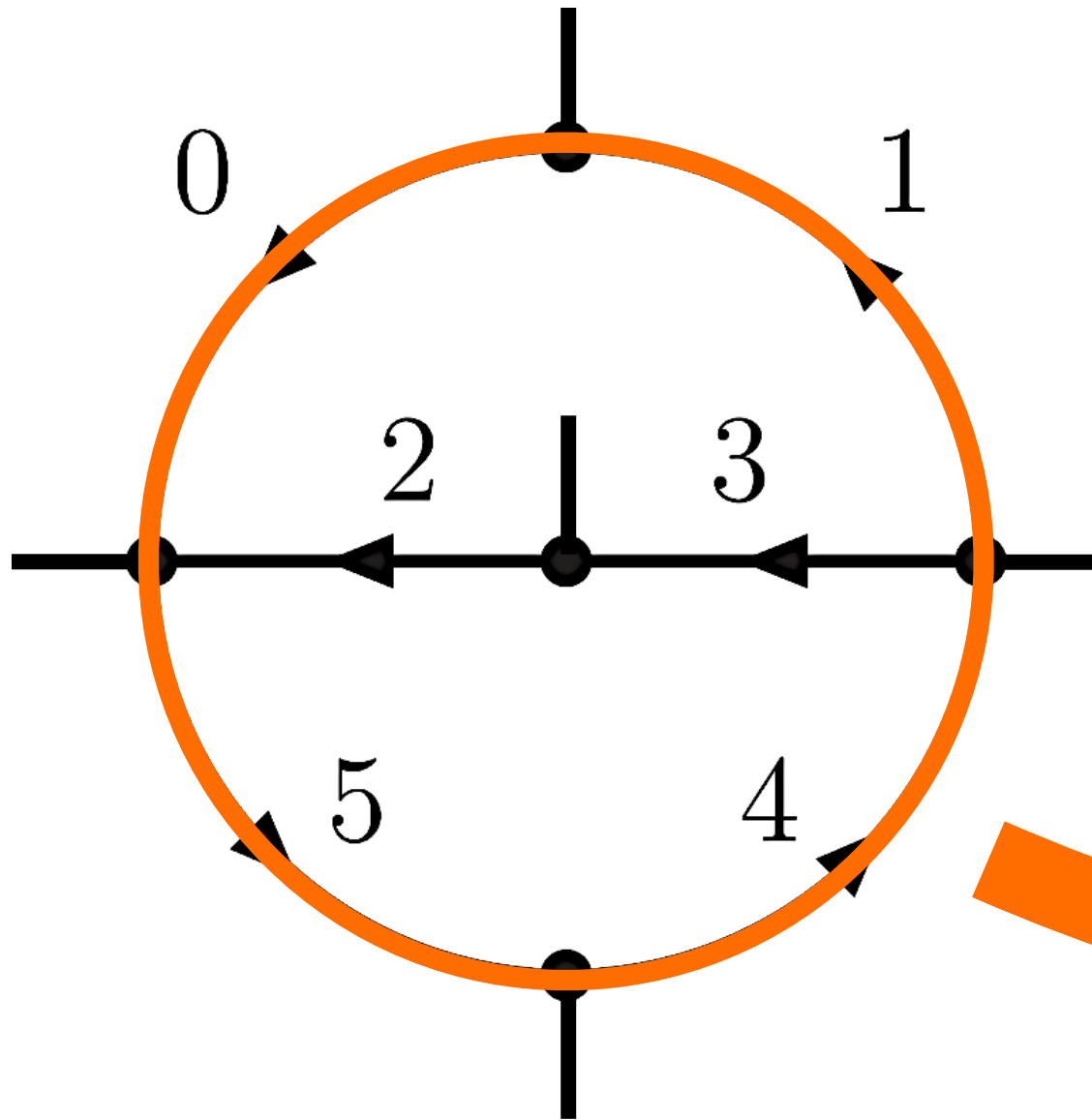
$$G_F(q_i) = \frac{1}{q_i^2 - m_i^2 + i0} \equiv \frac{1}{\sqrt{2}} (|0\rangle + |1\rangle)$$

- 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 $\equiv$ cyclic configurations are nonphysical**
- Causal configurations of Feynman diagrams are **Directed Acyclic Graphs (DAG)** in graph theory

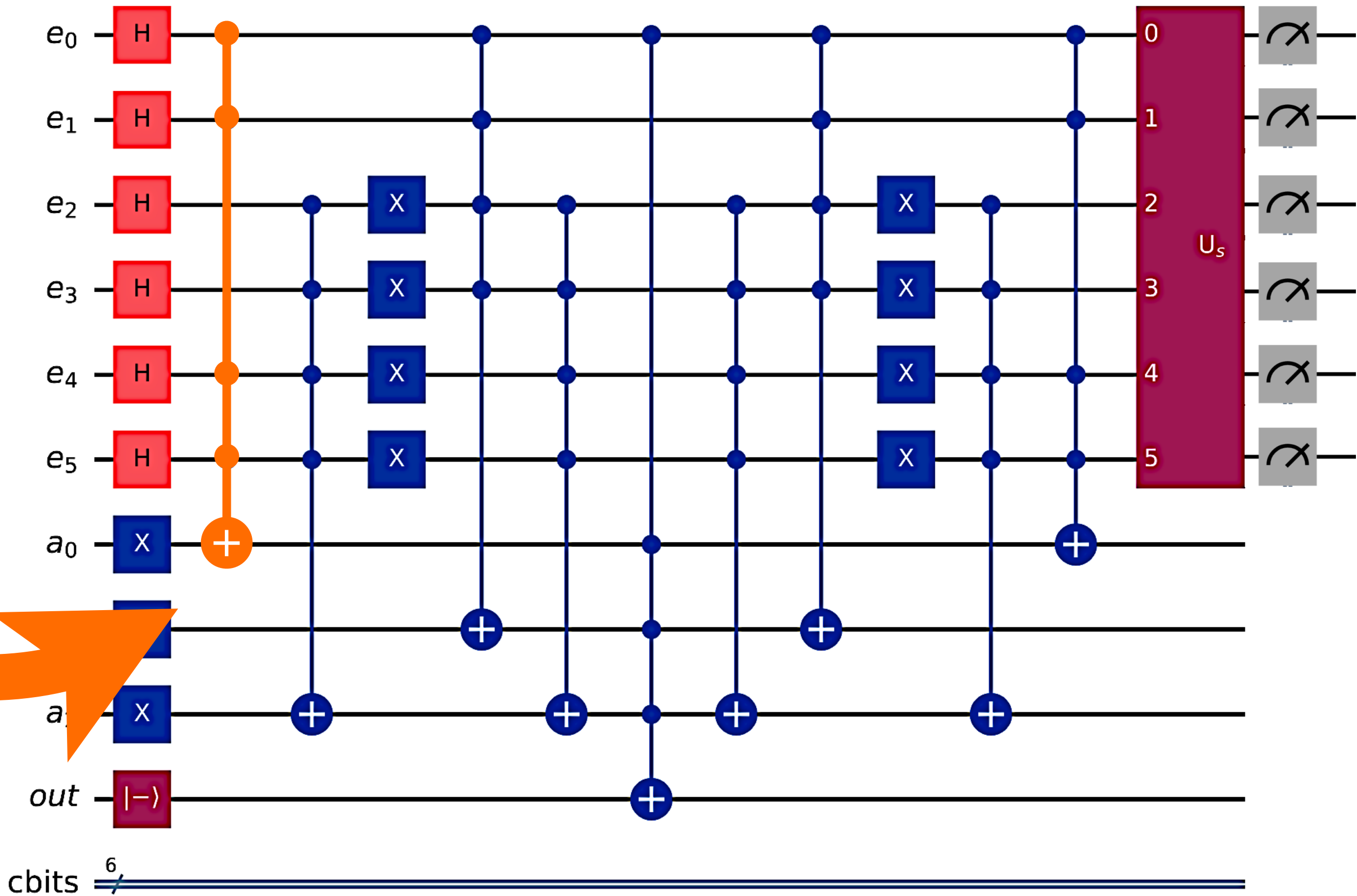
Oracle design: a two-loop topology with 6 edges



Oracle design: a two-loop topology with 6 edges

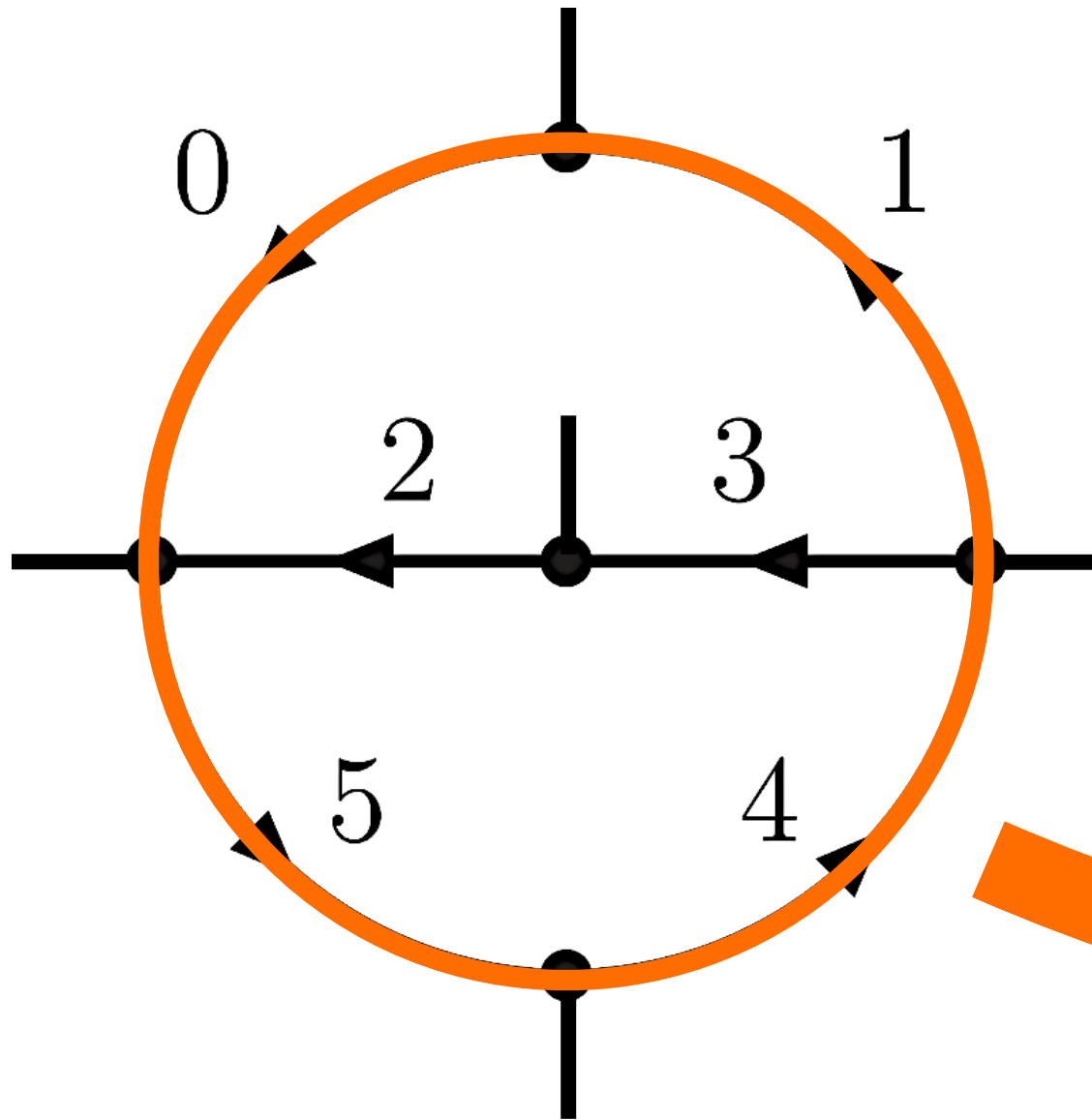


- Each loop cycle is mapped to a multi-controlled Toffoli gate



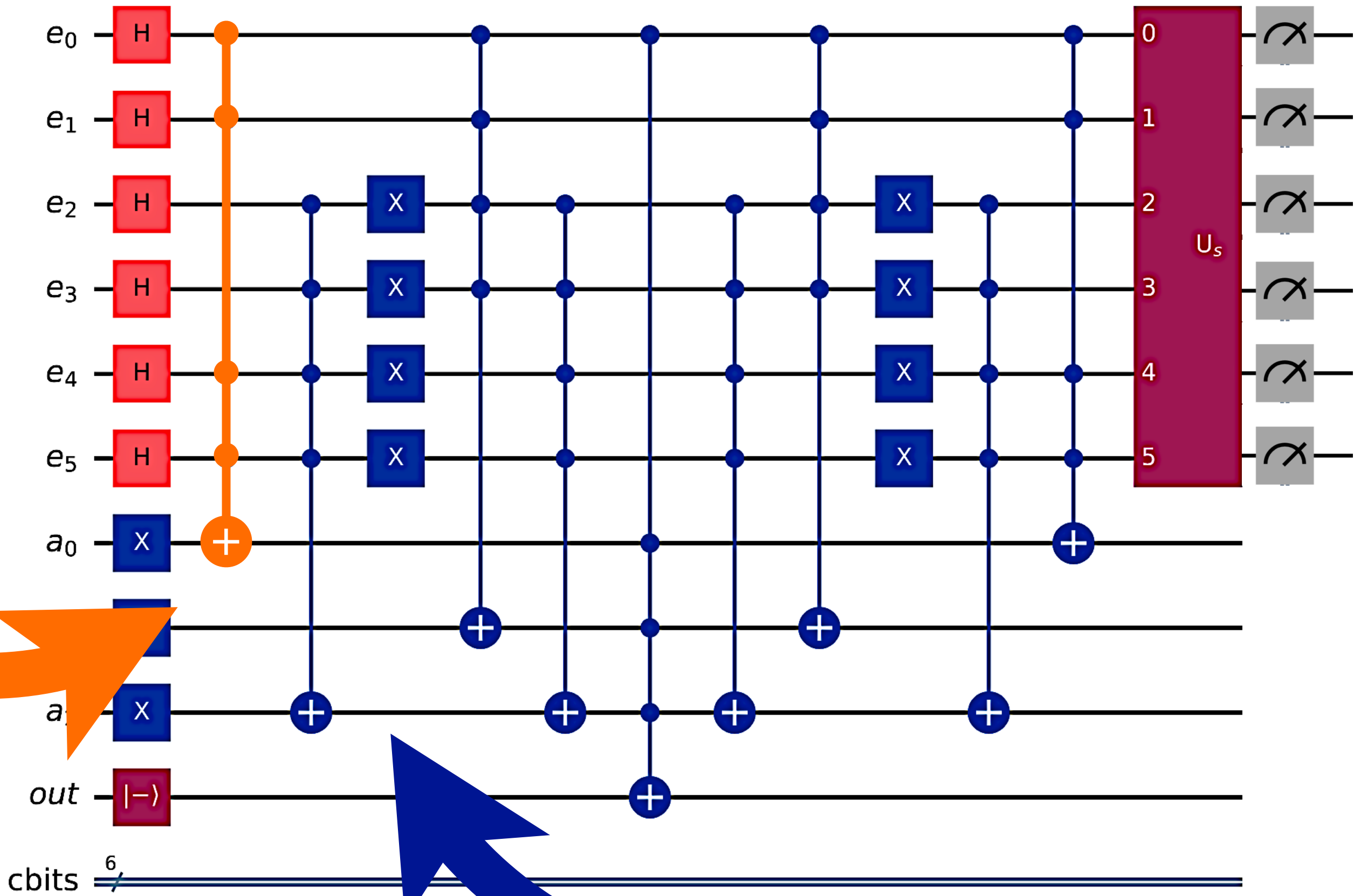
[Ramírez, Rentería, GR, 2404.03544]

Oracle design: a two-loop topology with 6 edges

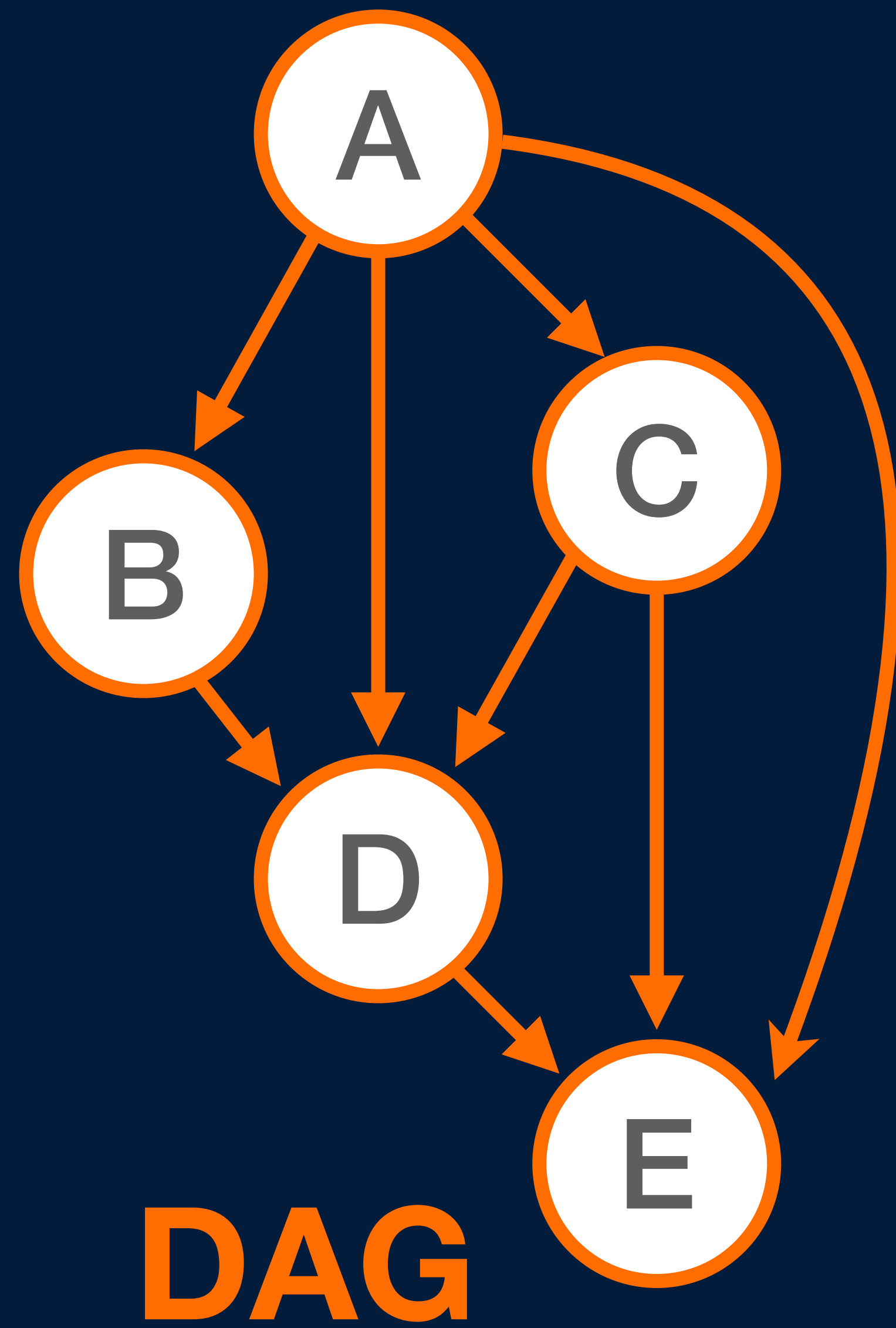


- Each loop cycle is mapped to a multi-controlled Toffoli gate

[Ramírez, Rentería, GR, [2404.03544](#)]



- Ancillary qubits to store loop clauses



DAG

Directed Acyclic Graph

Oracle design by leveraging graph-theory principles

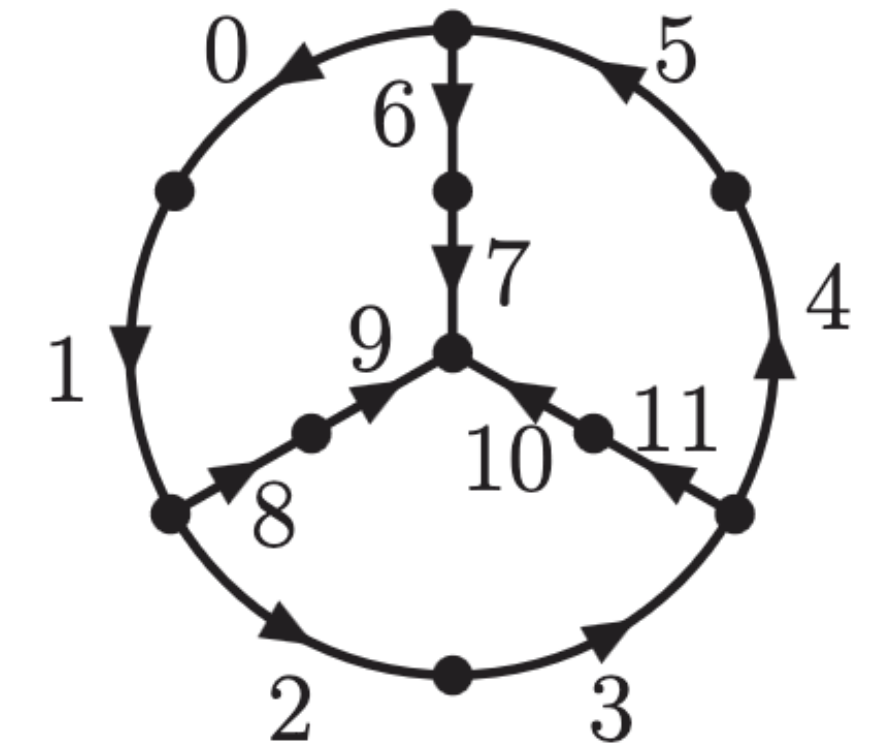
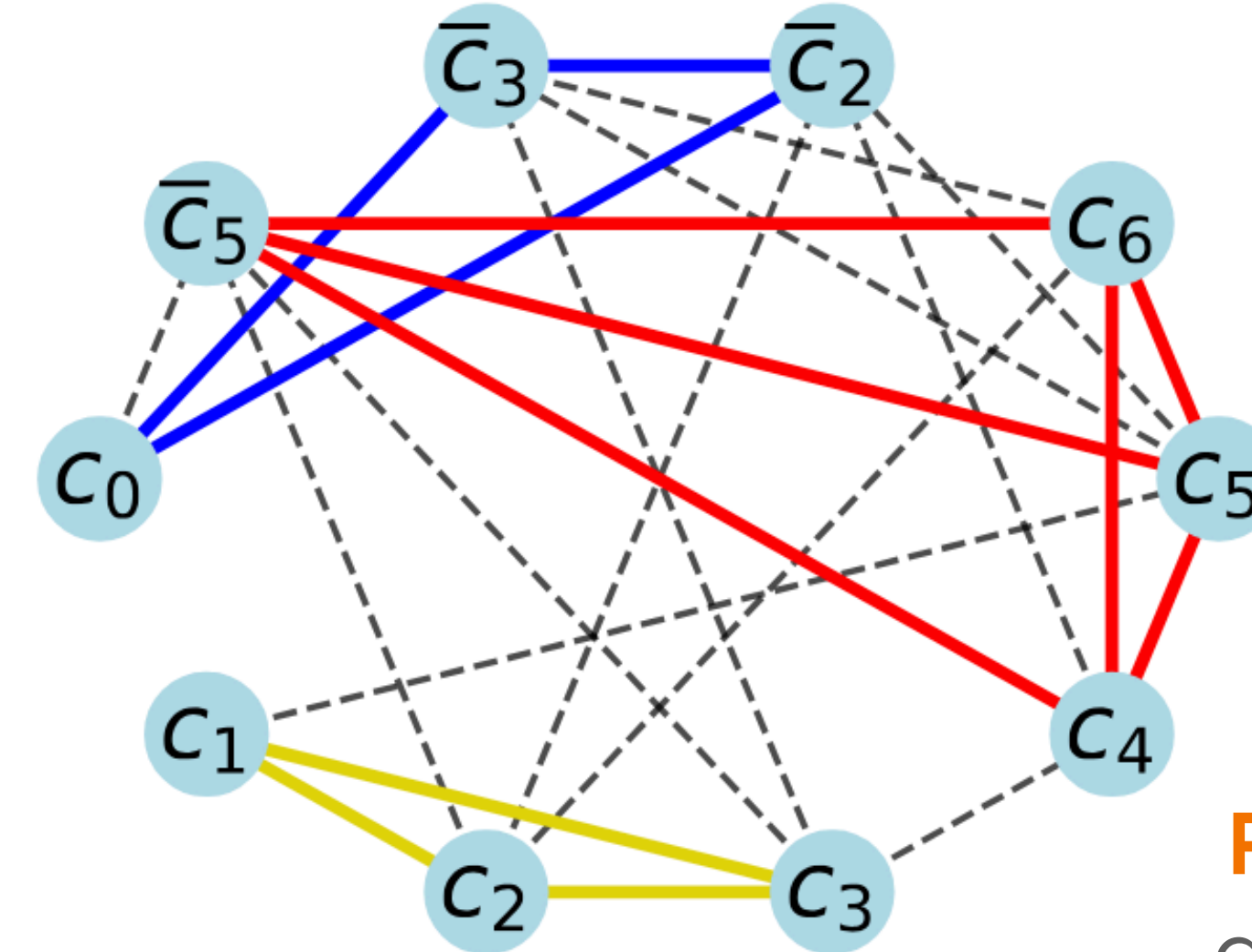
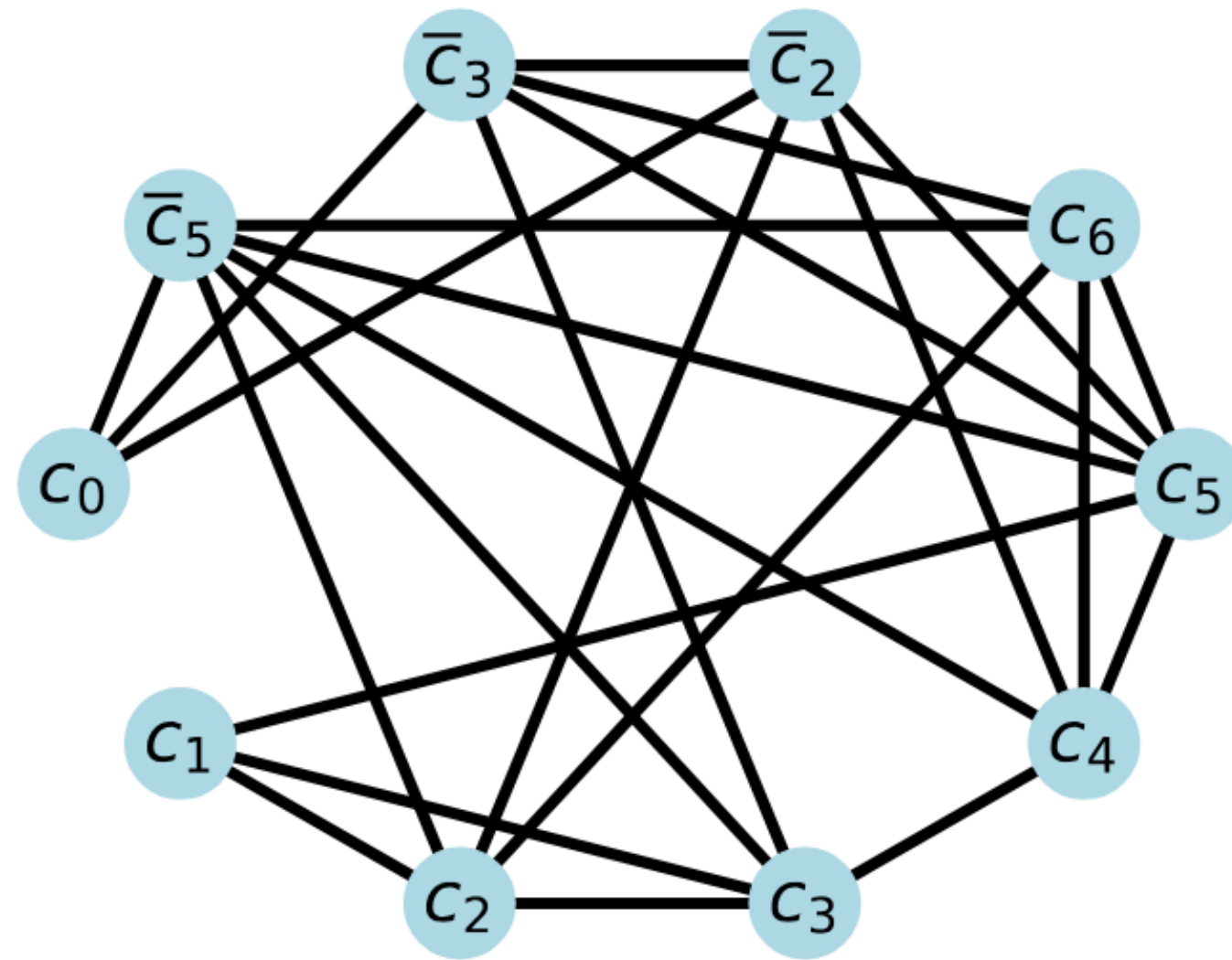
A **clique**, also known as a **complete subgraph**, is a subset of vertices from a specific graph in which each pair of vertices is directly connected by an edge

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 $c_i \vee c_j = c_i \underline{\vee} c_j$

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

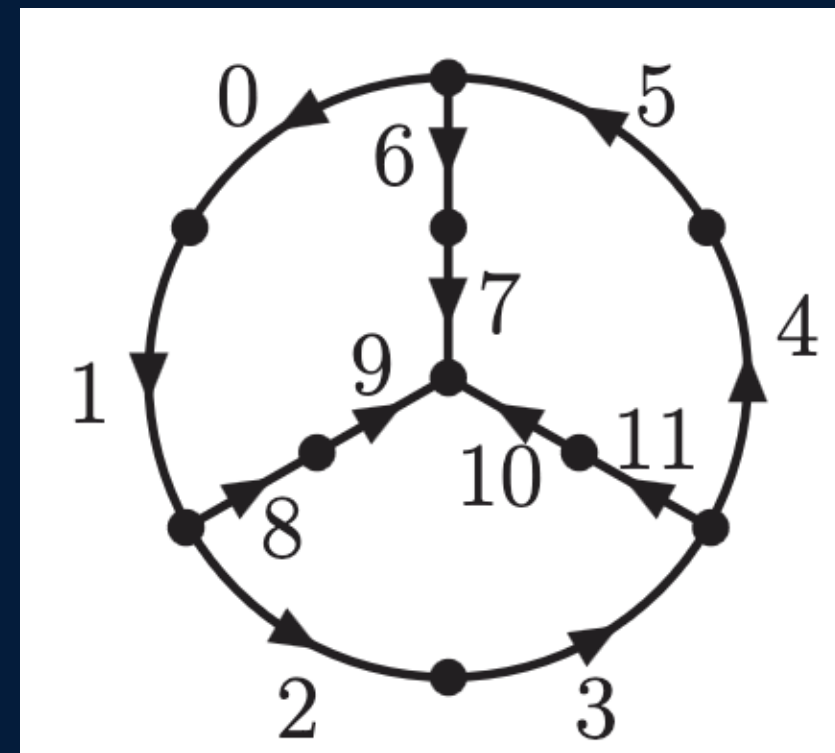
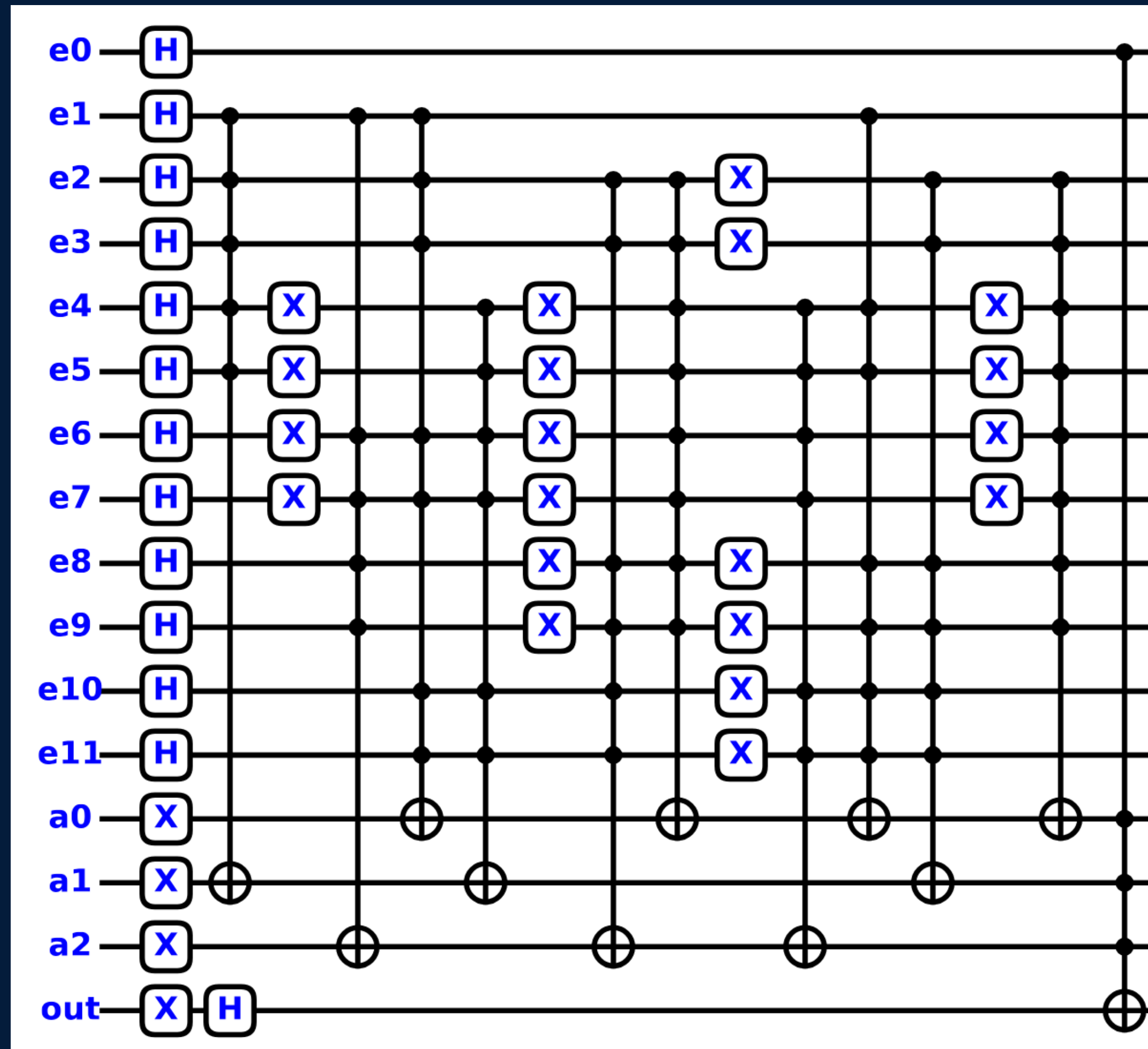
- A first algorithm to identify MCP of the adjacency matrix

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

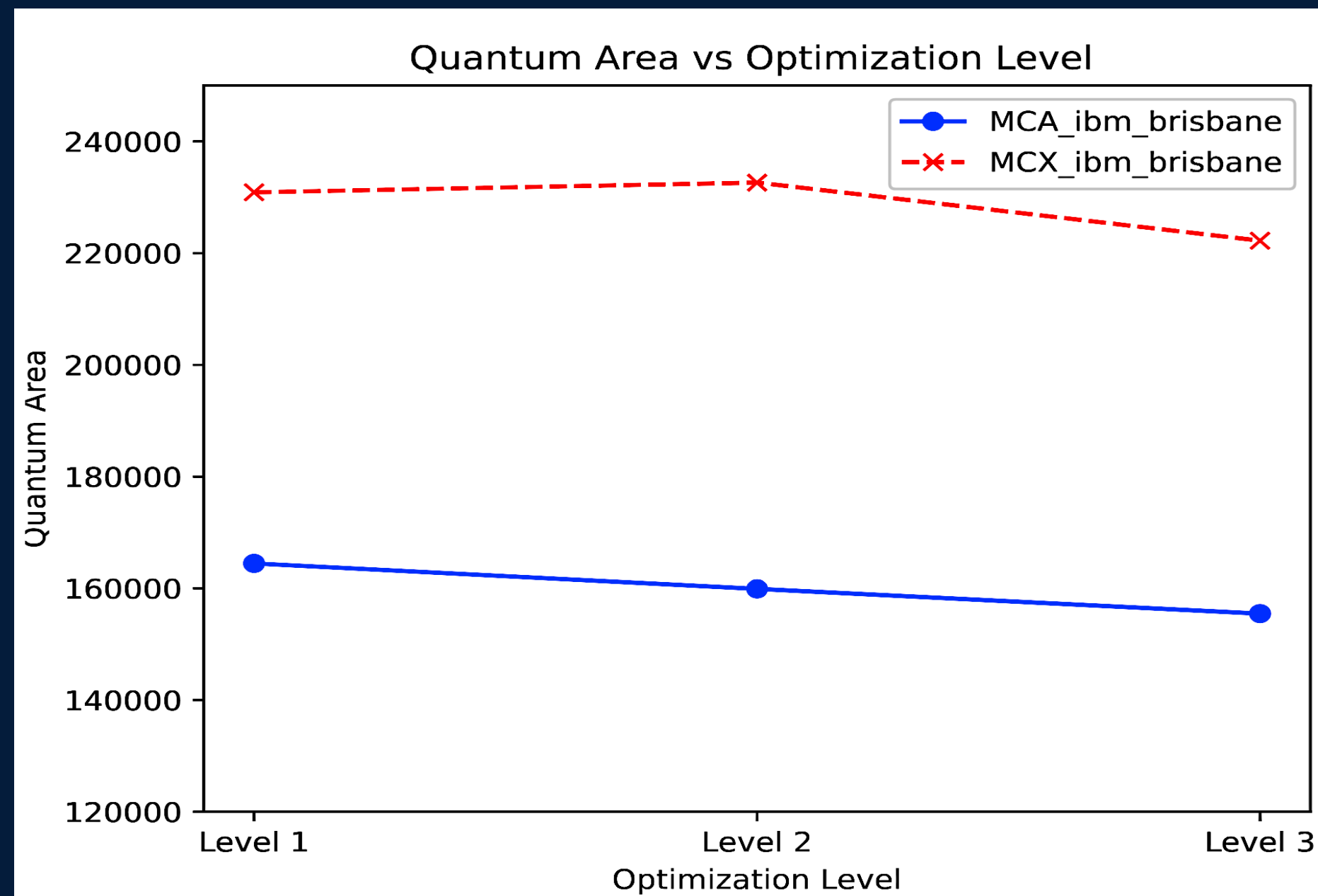
mutually exclusive sets of clauses
(3 ancillary qubits instead of 7)
- A second algorithm to determine the optimal order in which the gates (Toffoli+XNOT) are applied, it impacts the quantum depth

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

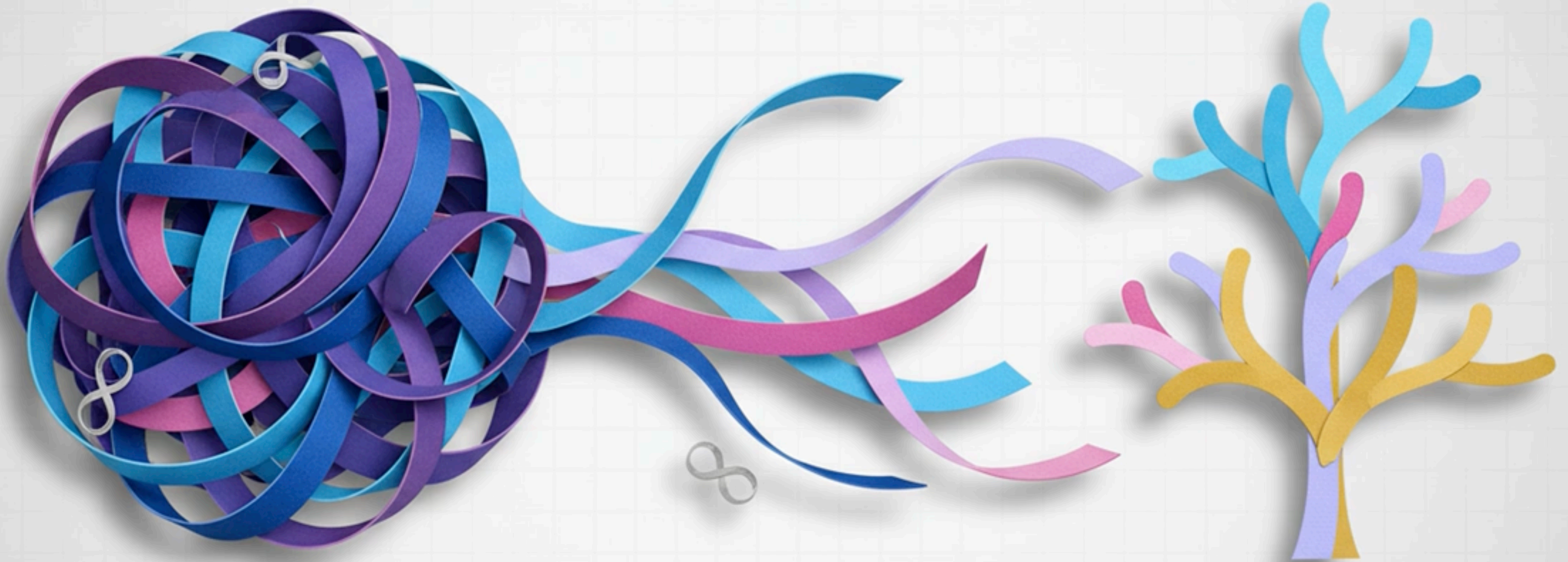
A three-loop topology with 12 edges



- quantum area = #qubits $\times$ quantum depth
- transpiled quantum depth $\gg$ quantum circuit
- transpiled #qubits $>$ theoretical qubits

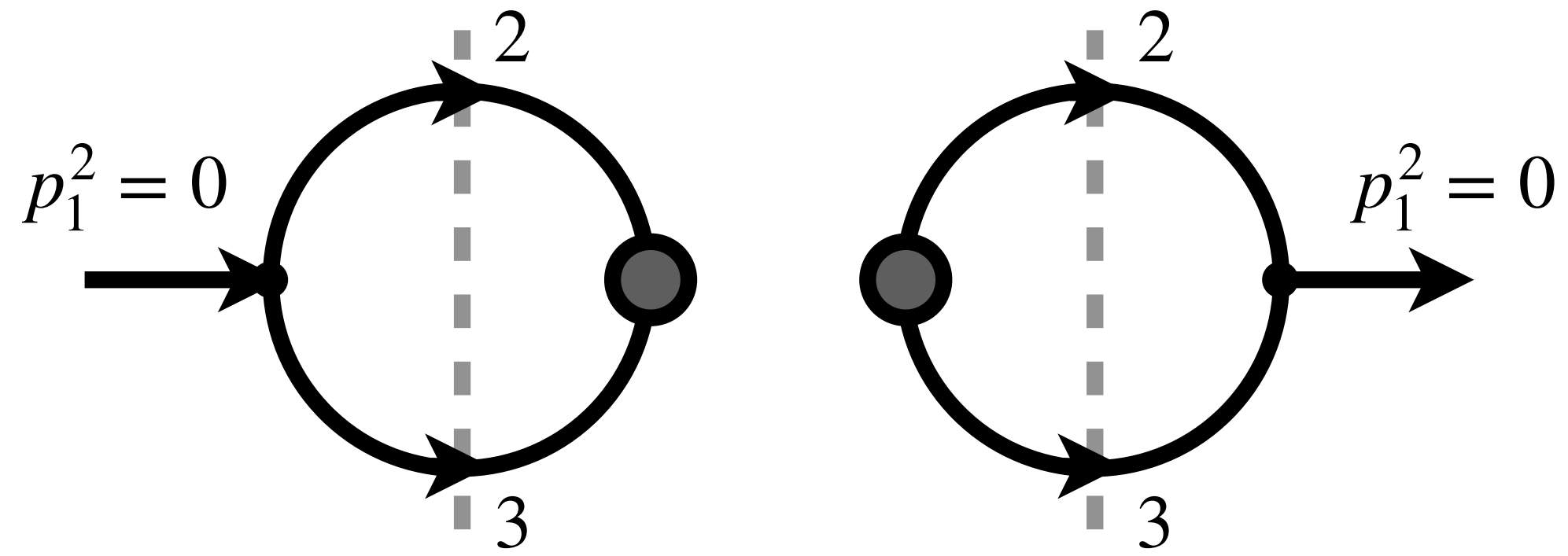


Loop-Tree Duality (LTD)



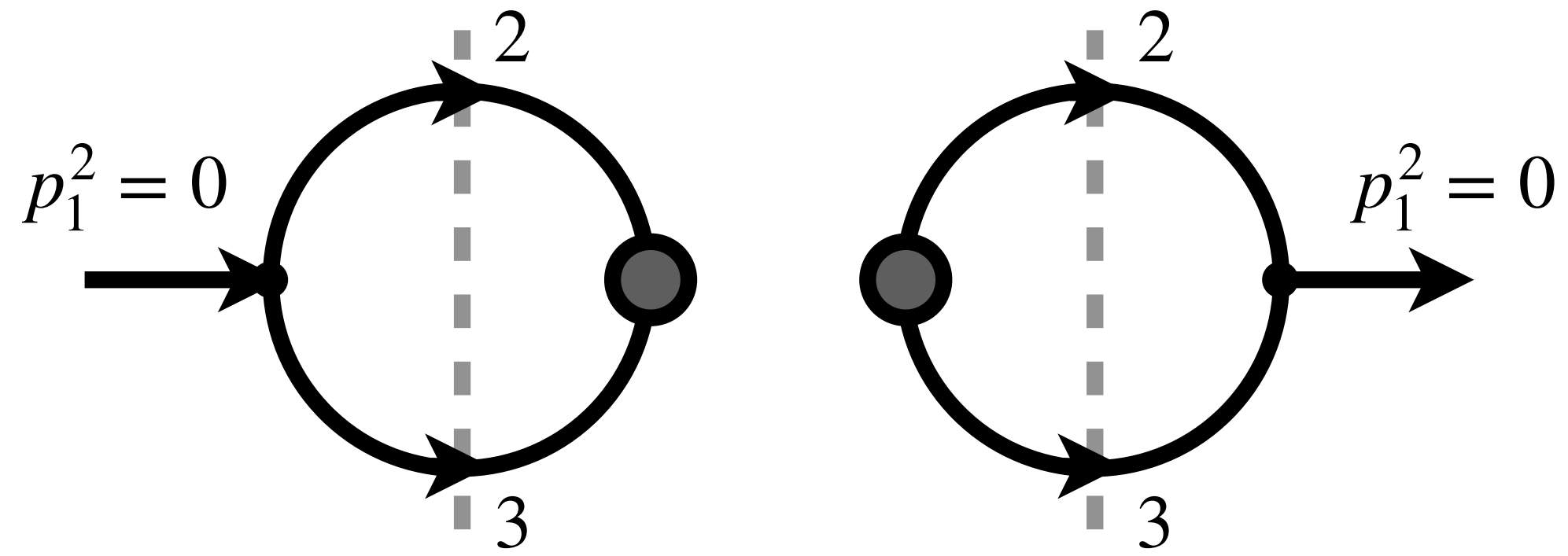
P.K. Dhani, K. Pyretzidis, N.S. Ramírez Uribe, J. Ríos, G.F.R. Sborlini, S. Tiwari, GR,
"A Systematic Approach to Finite Multiloop Feynman Integrals,"
2603.18691

Collinear

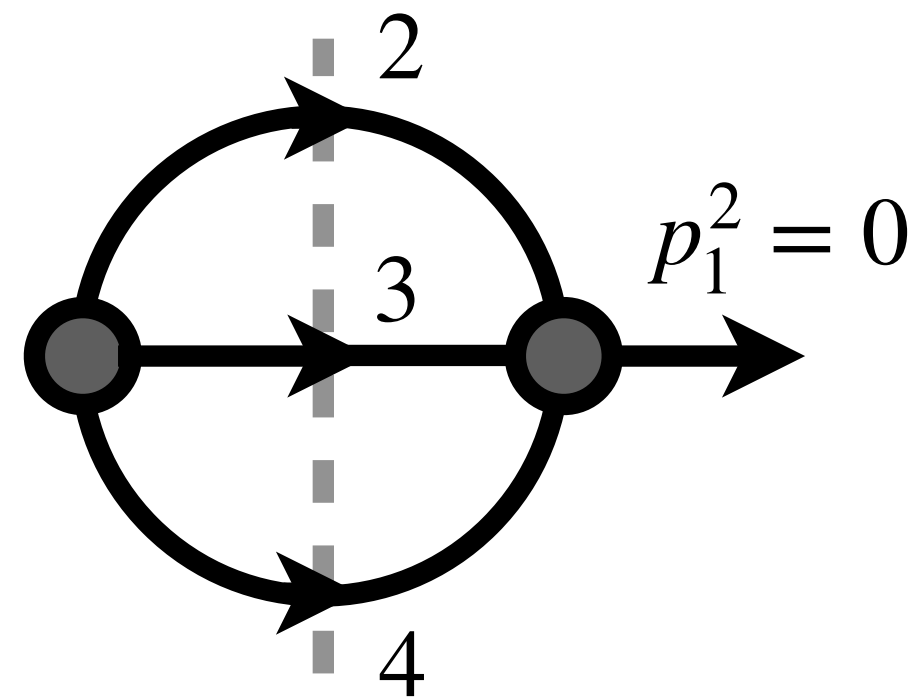


○ Double collinear: $\lambda_{32;\bar{1}}^{-1} = \mathcal{O}(k_{\perp}^{-2})$

Collinear

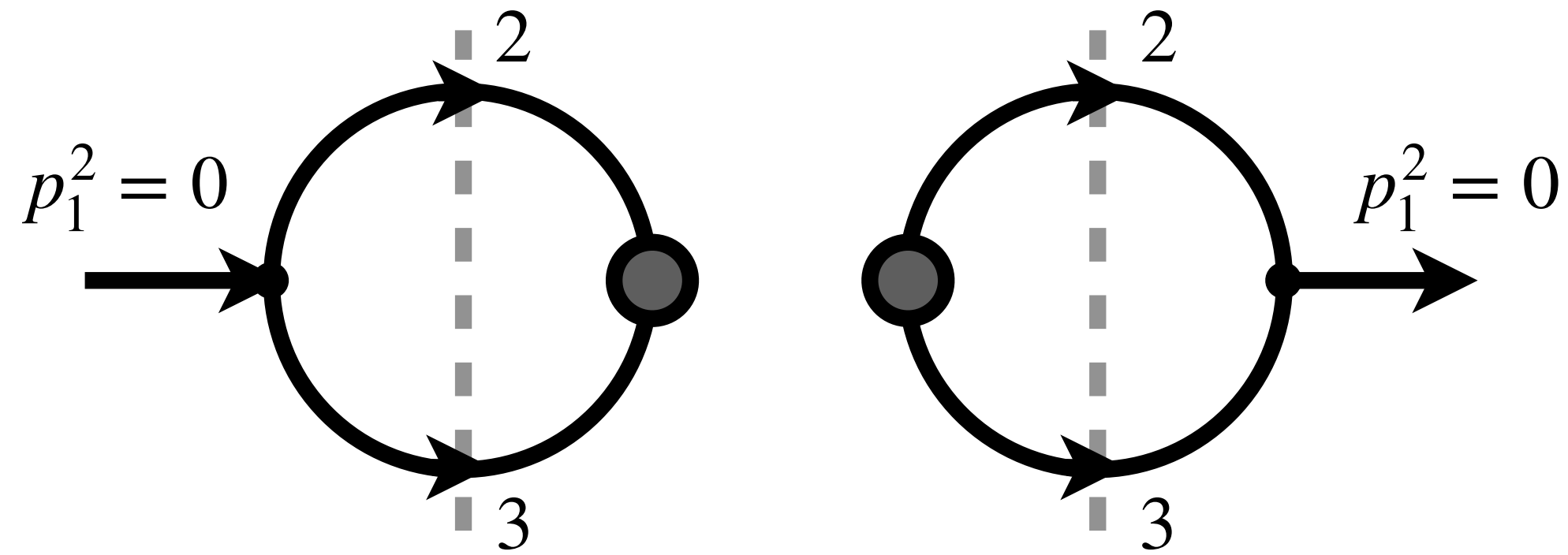


○ Double collinear: $\lambda_{32;\bar{1}}^{-1} = \mathcal{O}(k_{\perp}^{-2})$

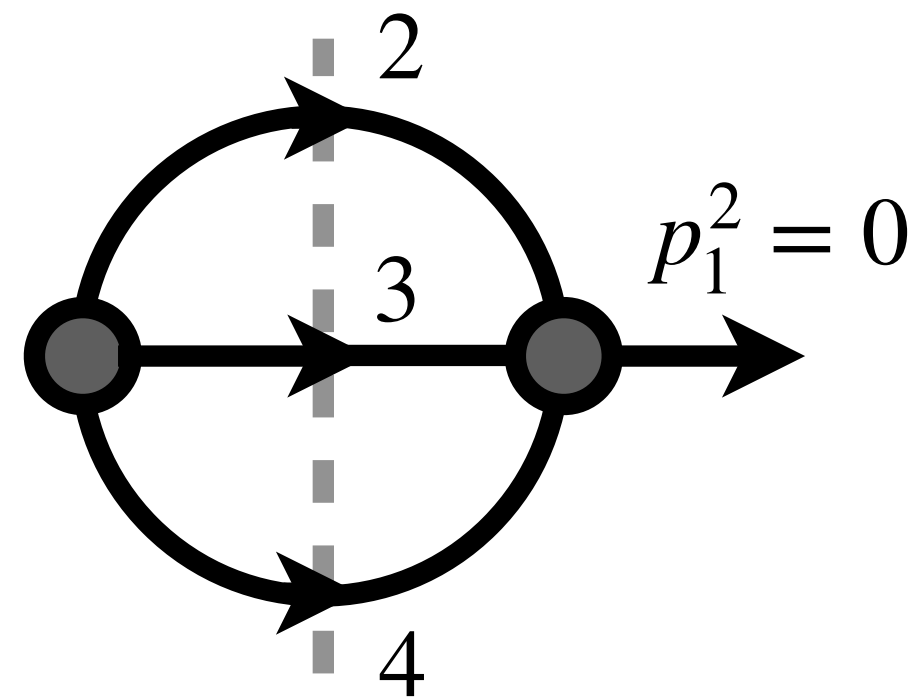


○ Triple collinear: $\lambda_{432;\bar{1}}^{-1} = \mathcal{O}(k_{\perp}^{-2})$

Collinear

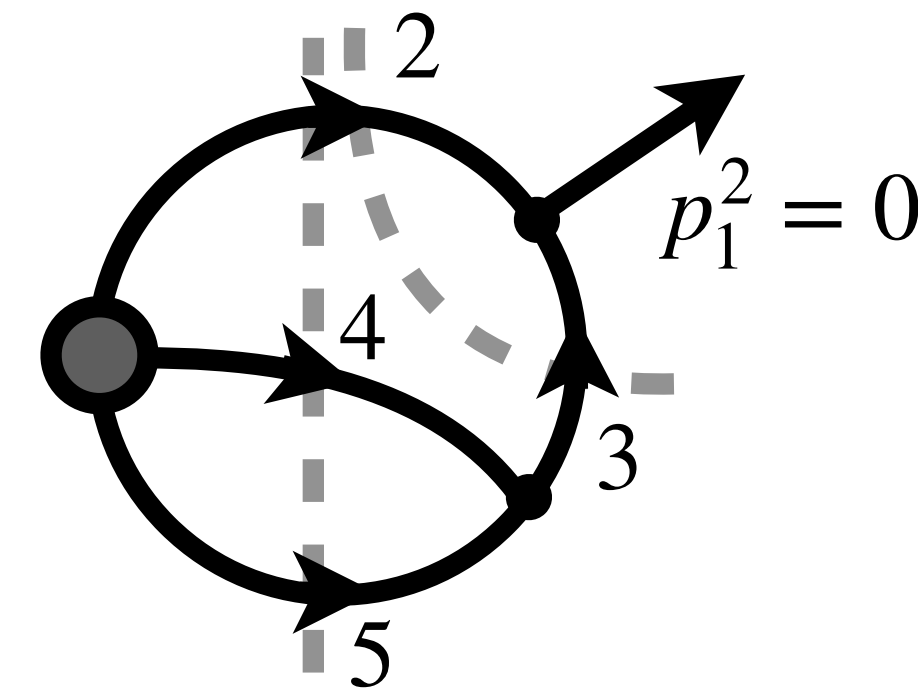


○ Double collinear: $\lambda_{32;\bar{1}}^{-1} = \mathcal{O}(k_{\perp}^{-2})$



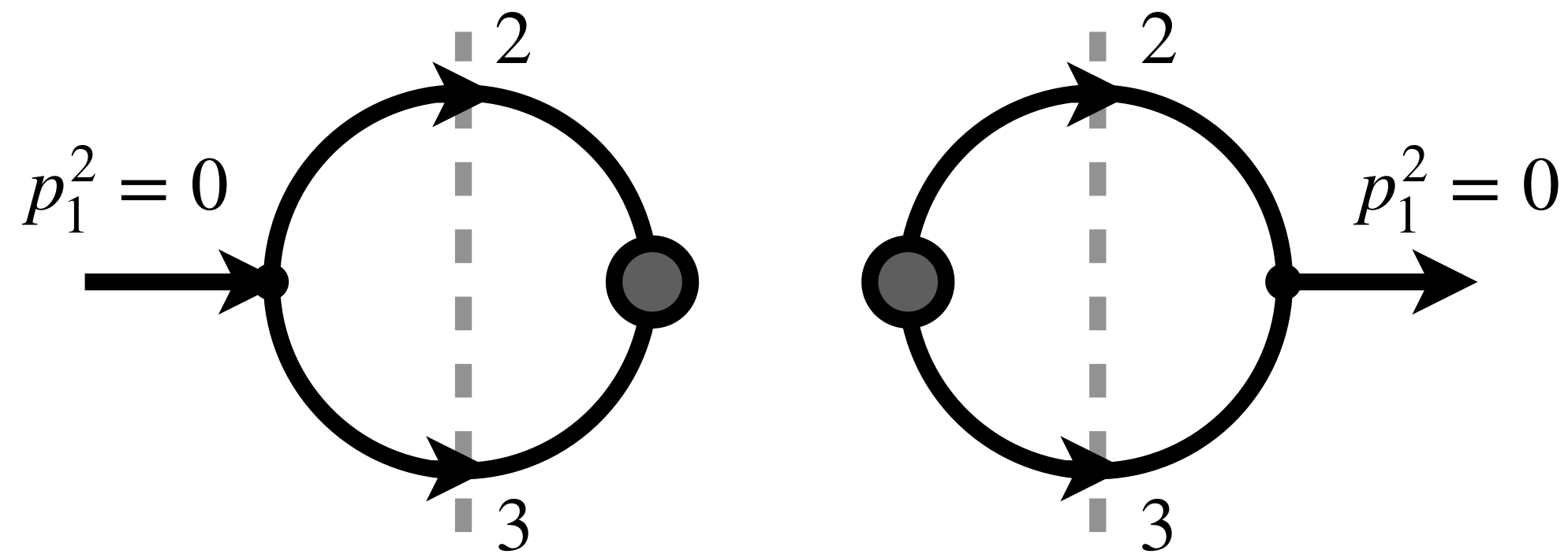
○ Triple collinear: $\lambda_{432;\bar{1}}^{-1} = \mathcal{O}(k_{\perp}^{-2})$

Overlapping Collinear

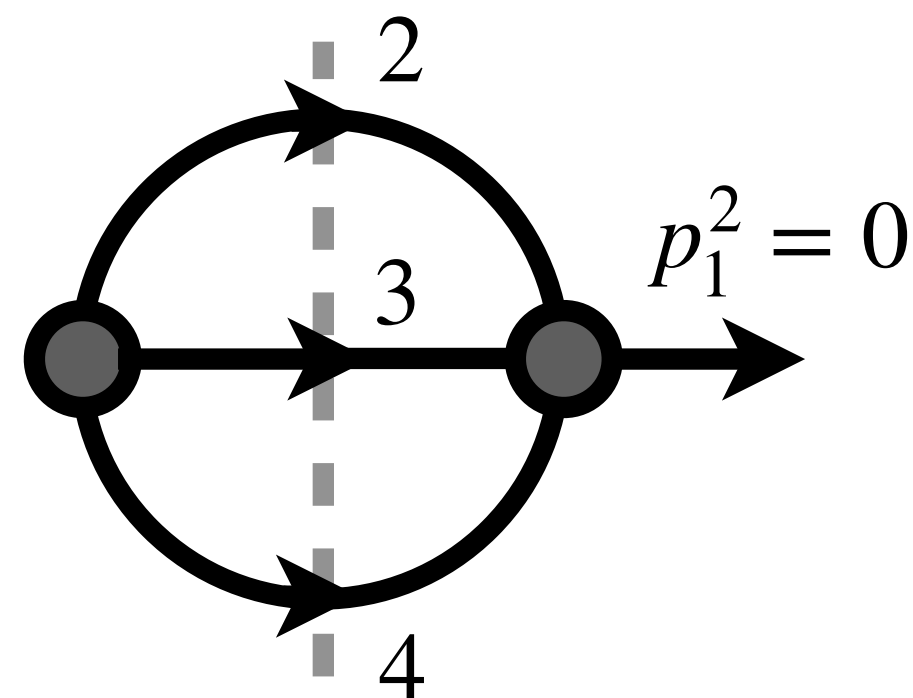


○ Double and triple collinear
 $\lambda_{32;\bar{1}}^{-1} \lambda_{542;\bar{1}}^{-1} = \mathcal{O}(k_{\perp}^{-4})$

Collinear

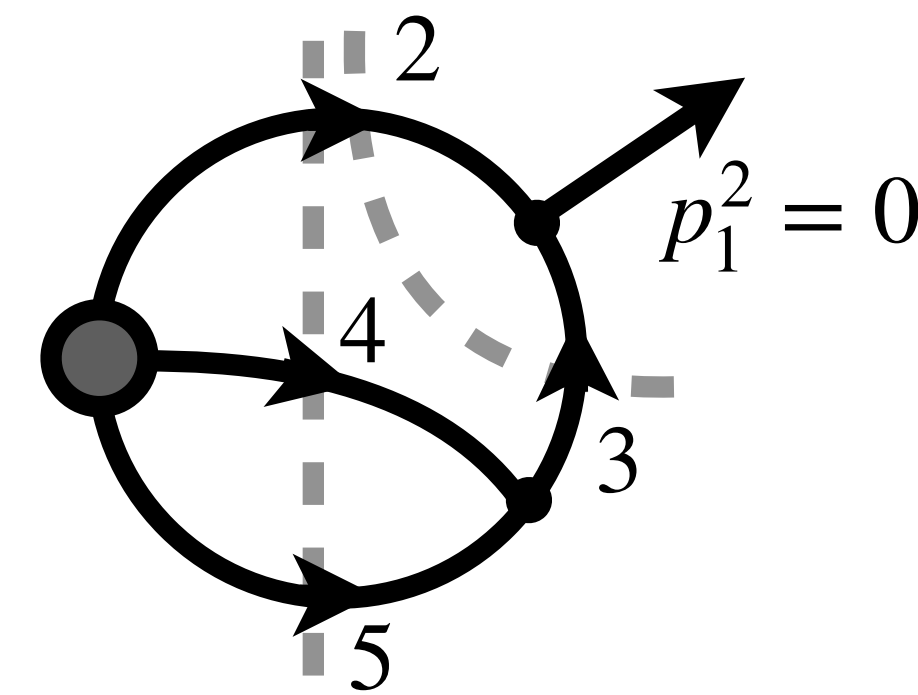


- Double collinear: $\lambda_{32;\bar{1}}^{-1} = \mathcal{O}(k_{\perp}^{-2})$



- Triple collinear: $\lambda_{432;\bar{1}}^{-1} = \mathcal{O}(k_{\perp}^{-2})$

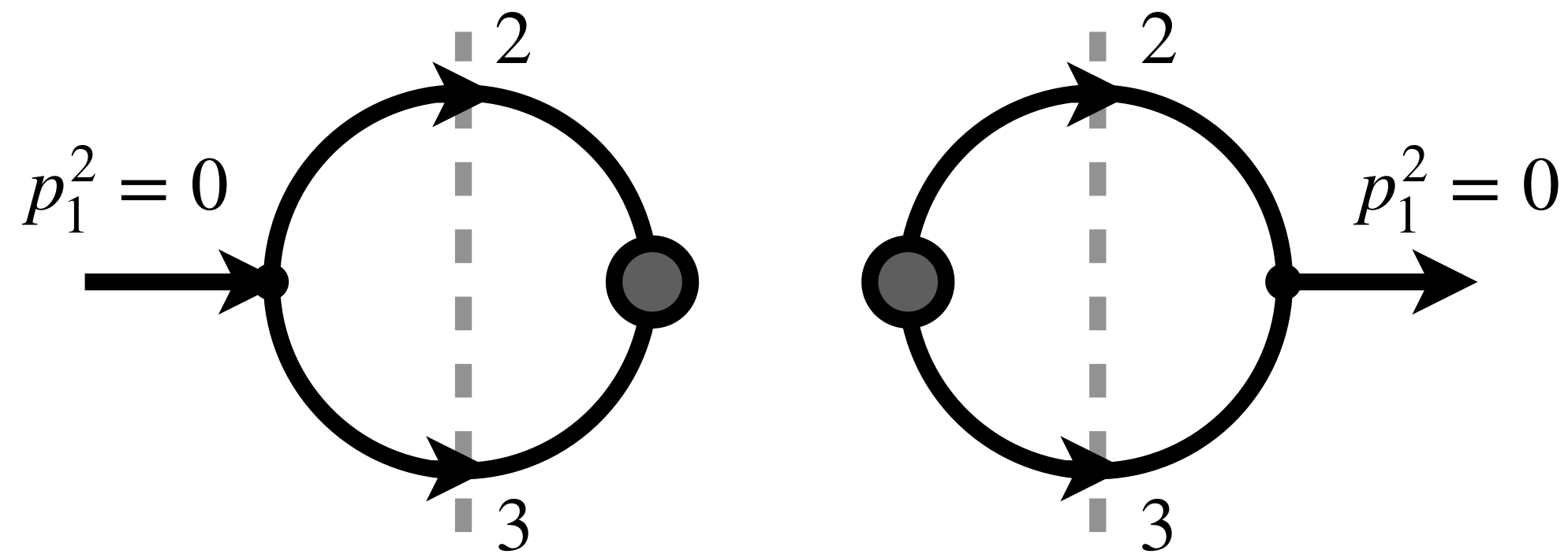
Overlapping Collinear



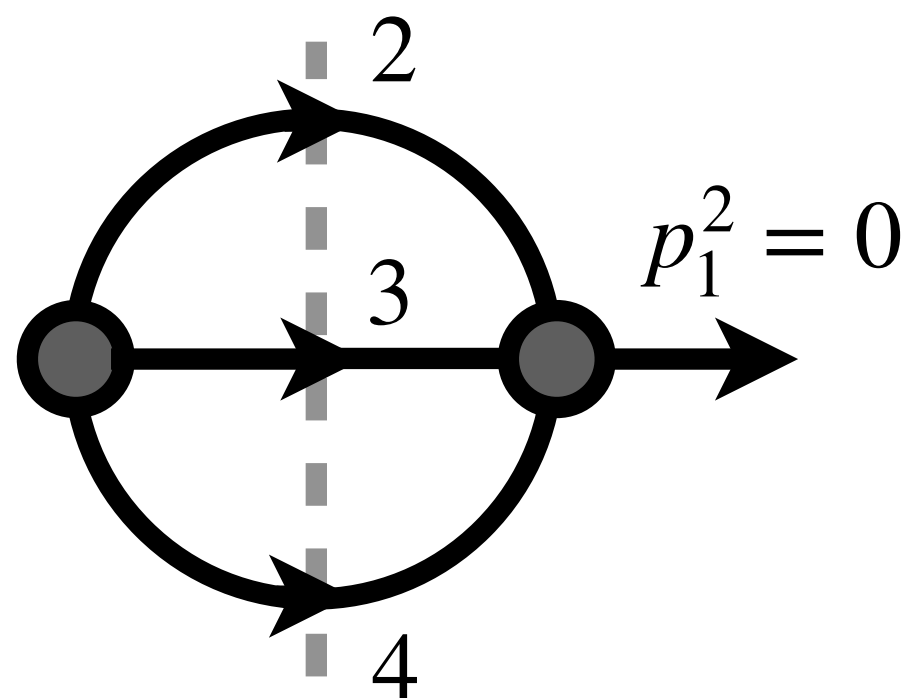
- Double and triple collinear
 $\lambda_{32;\bar{1}}^{-1} \lambda_{542;\bar{1}}^{-1} = \mathcal{O}(k_{\perp}^{-4})$

quasicollinear ($m_i \neq 0$) and threshold ($p_1 \rightarrow p_i \pm p_j$)

Collinear

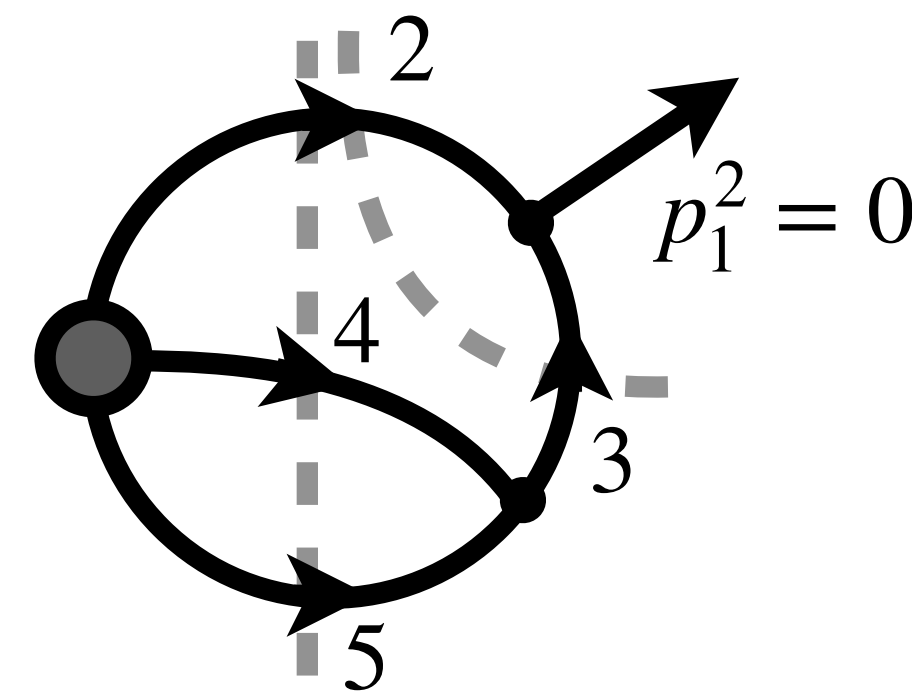


○ Double collinear: $\lambda_{32;\bar{1}}^{-1} = \mathcal{O}(k_{\perp}^{-2})$



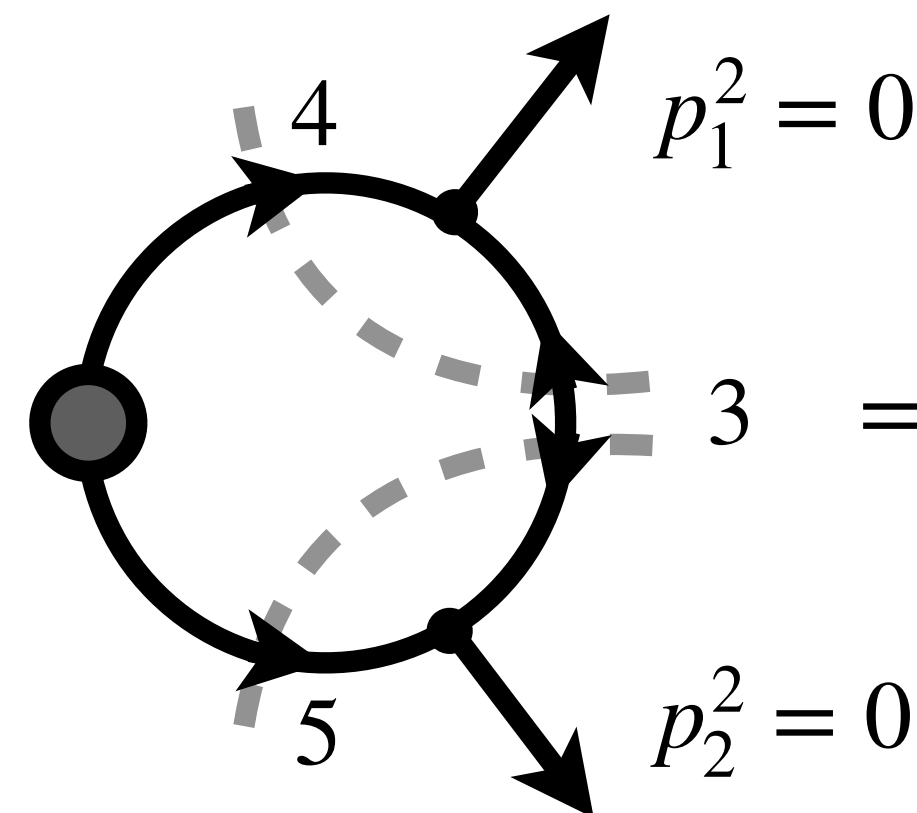
○ Triple collinear: $\lambda_{432;\bar{1}}^{-1} = \mathcal{O}(k_{\perp}^{-2})$

Overlapping Collinear

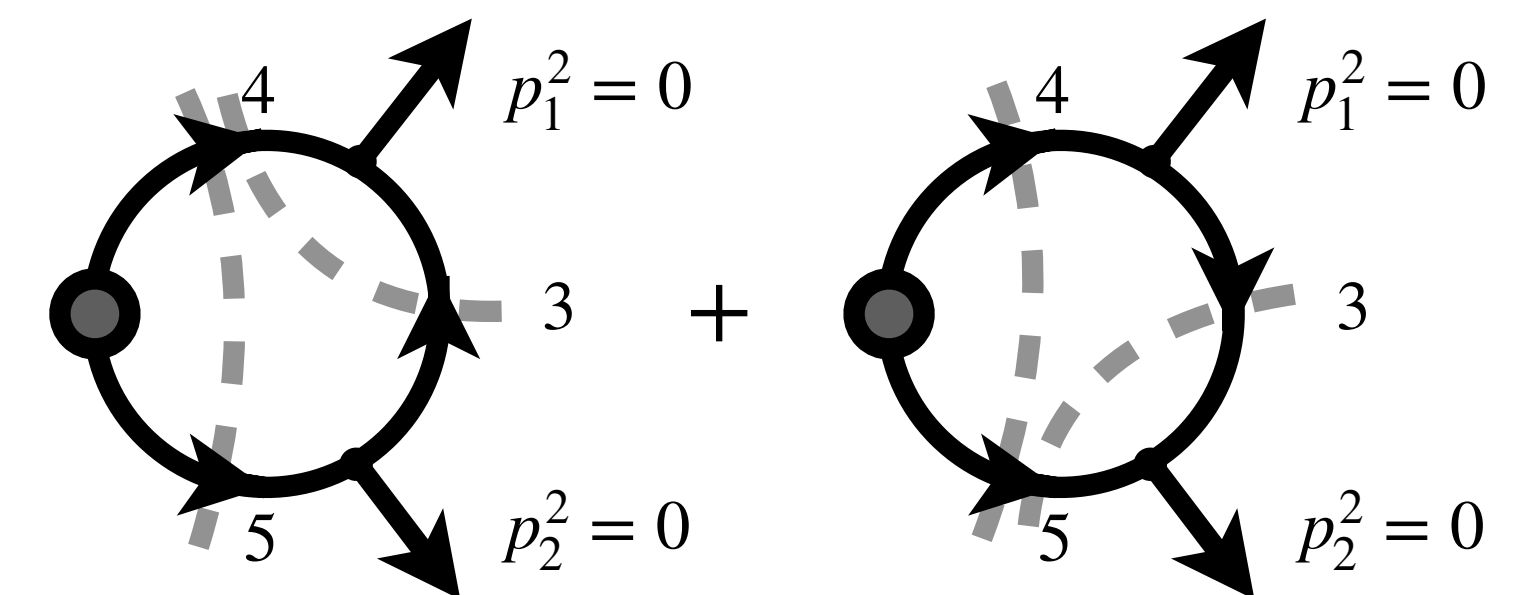


○ Double and triple collinear
 $\lambda_{32;\bar{1}}^{-1} \lambda_{542;\bar{1}}^{-1} = \mathcal{O}(k_{\perp}^{-4})$

Soft

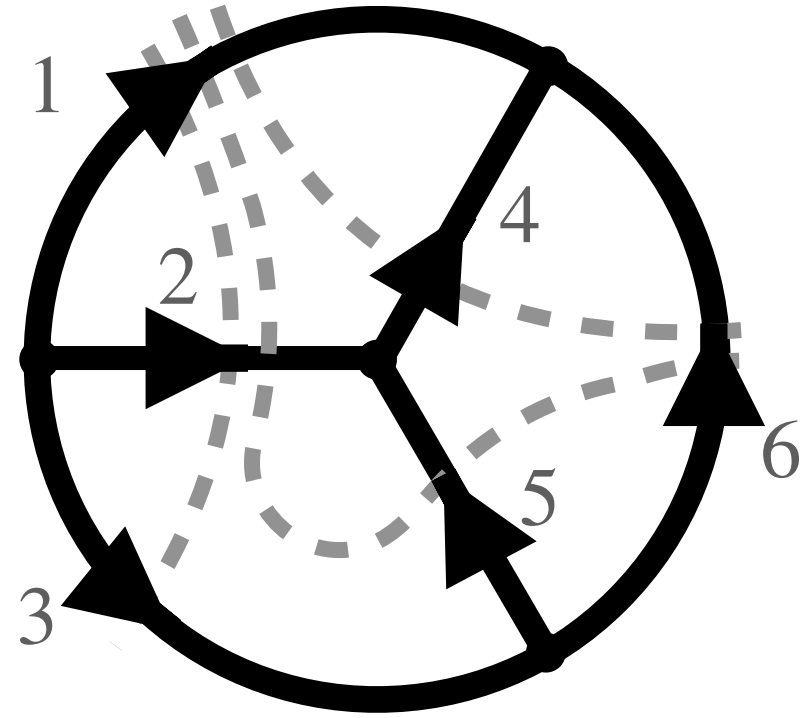


○ Soft: $\left(x_3 \lambda_{45;\bar{1}2} (\lambda_{43;\bar{1}} + \lambda_{53;\bar{2}}) \right)^{-1} d^3 \mathbf{q}_3 \quad \lambda_3 \rightarrow 0$

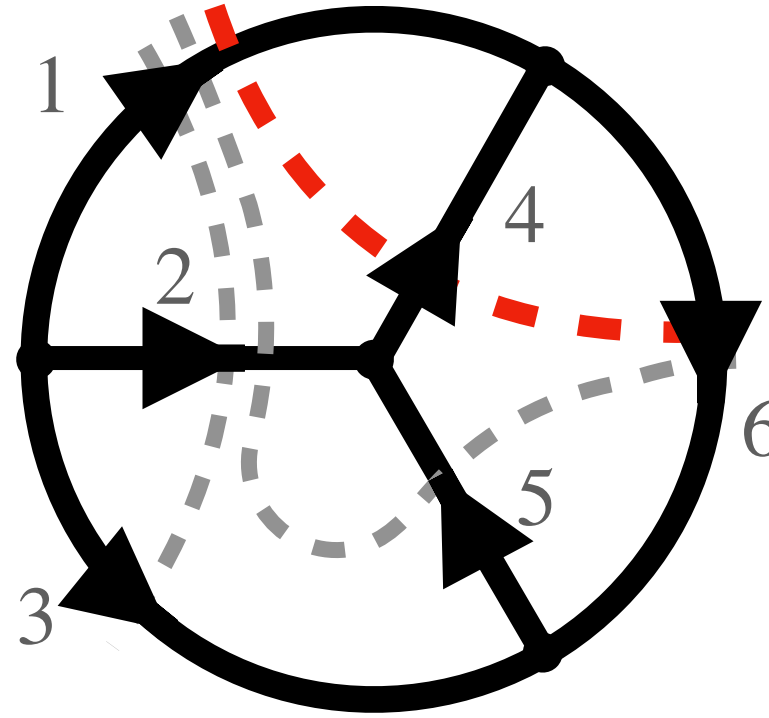


quasicollinear ($m_i \neq 0$) and threshold ($p_1 \rightarrow p_i \pm p_j$)

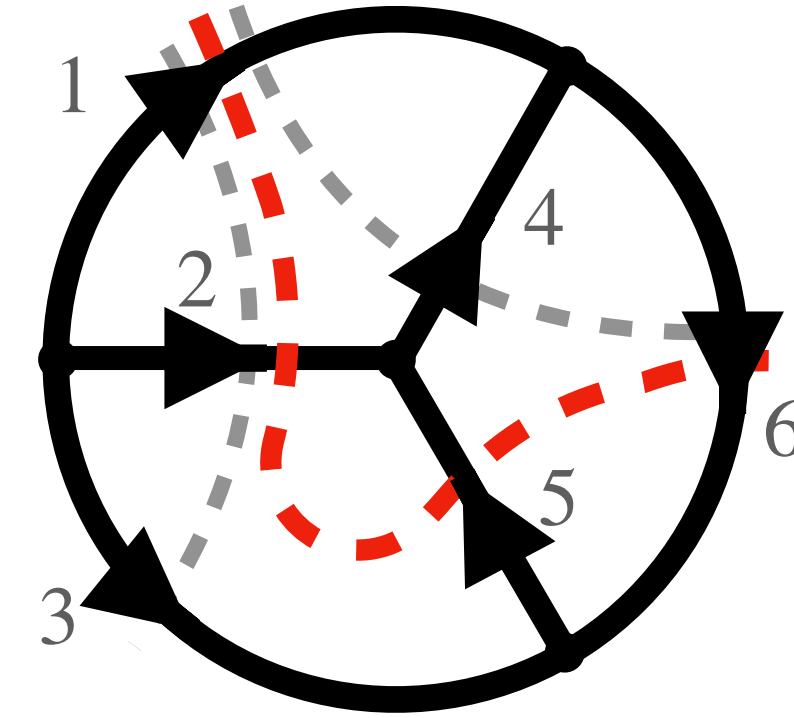
The Loop-Tree Duality LTD: vacuum amplitudes



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



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



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

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

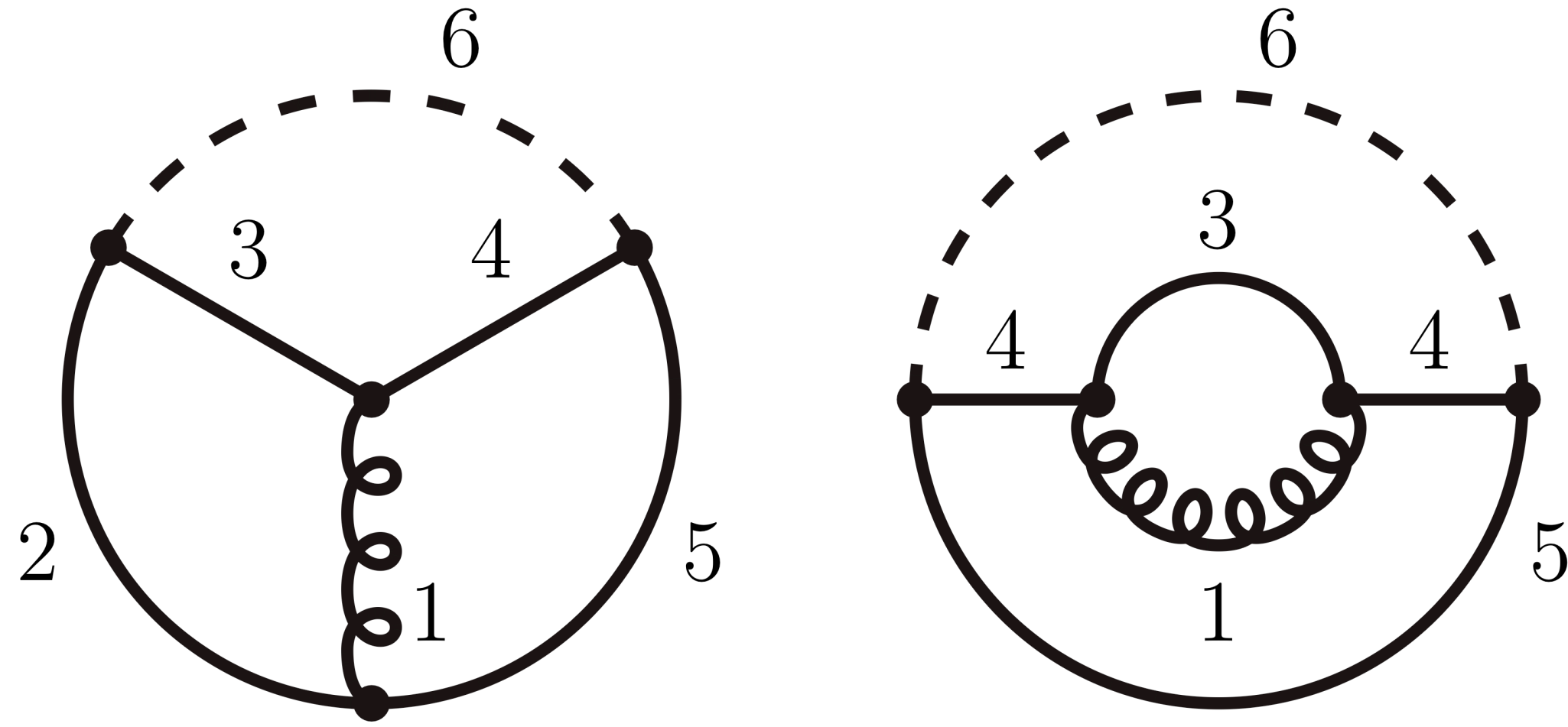
**Simultaneous integration
of loops and phase-space**

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

On-shell energies

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

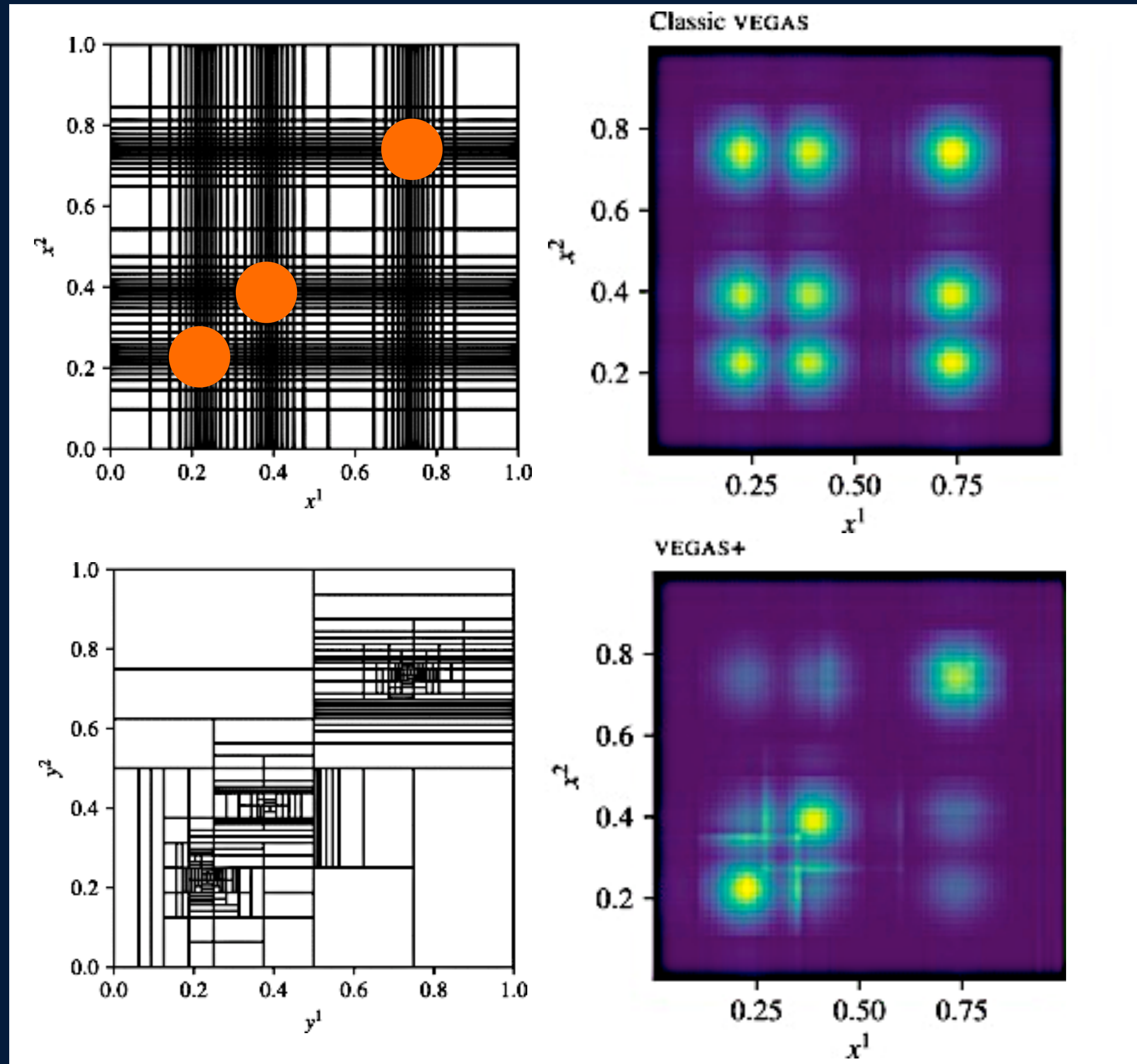
Three-loop vacuum amplitude for Higgs + $q\bar{q}g$



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. \\
 & - \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) \left. \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}} \\
 & + \frac{(d-2)\lambda_{1\bar{3}}\lambda_{5\bar{6}}}{\lambda_4^2} \left. \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. \\
 & - \frac{2\lambda_4\lambda_5}{\lambda_{134}\lambda_{125}} \left. \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}$$

Adaptive Importance Sampling



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

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

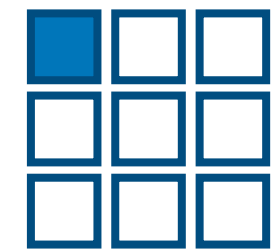
- Adapts a **grid** to concentrate samples in regions of high variance
- **The size of the grid grows** exponentially with dimensionality
- **A separable grid:** each dimension divided into intervals of varying widths independently
DoF: $(N_g)^d \rightarrow d \cdot N_g$
- Makes the grid tractable in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

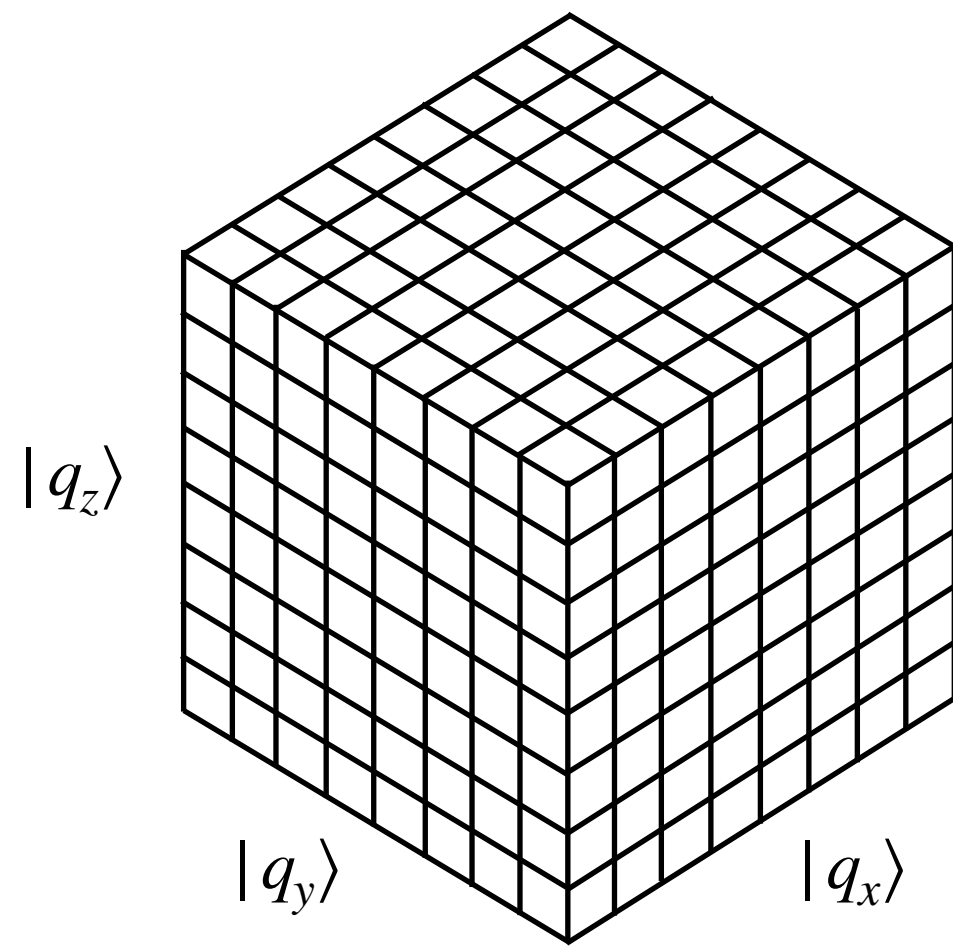
QAIS - Quantum Adaptive Importance Sampling

- **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

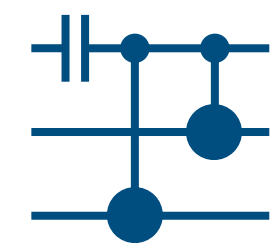


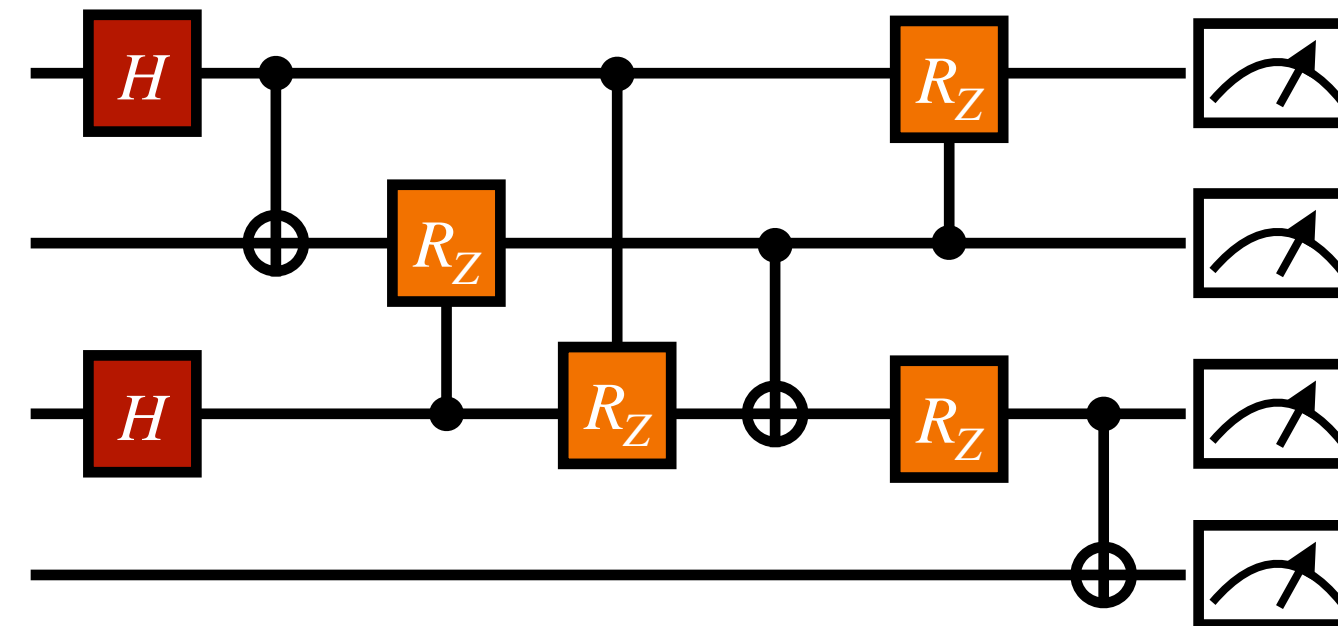
Quantum Adaptive Importance Sampling (QAIS)

 Stage 1
Encoding



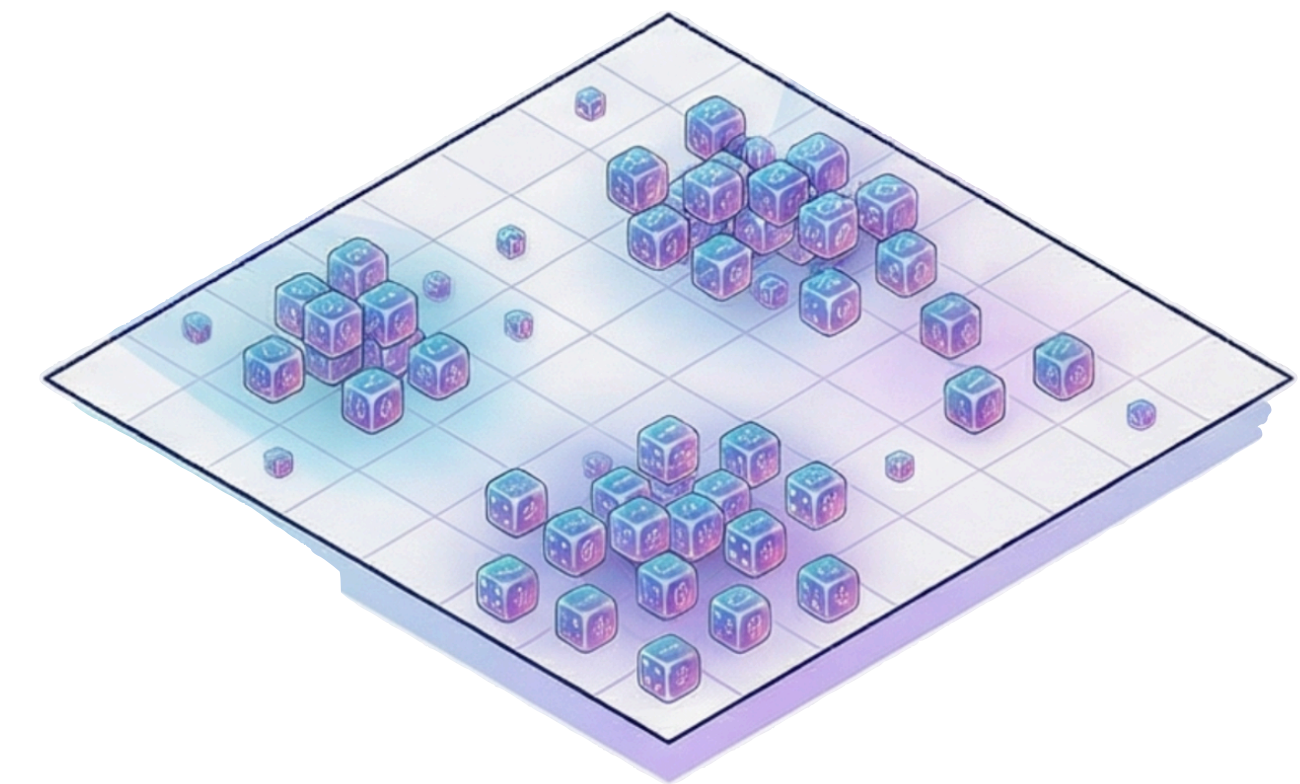
The d -dimensional integration domain is **discretized and mapped into an n -qubit Hilbert space**. Each of the 2^n computational basis state corresponds to a specific grid cell.

 Stage 2
State Preparation



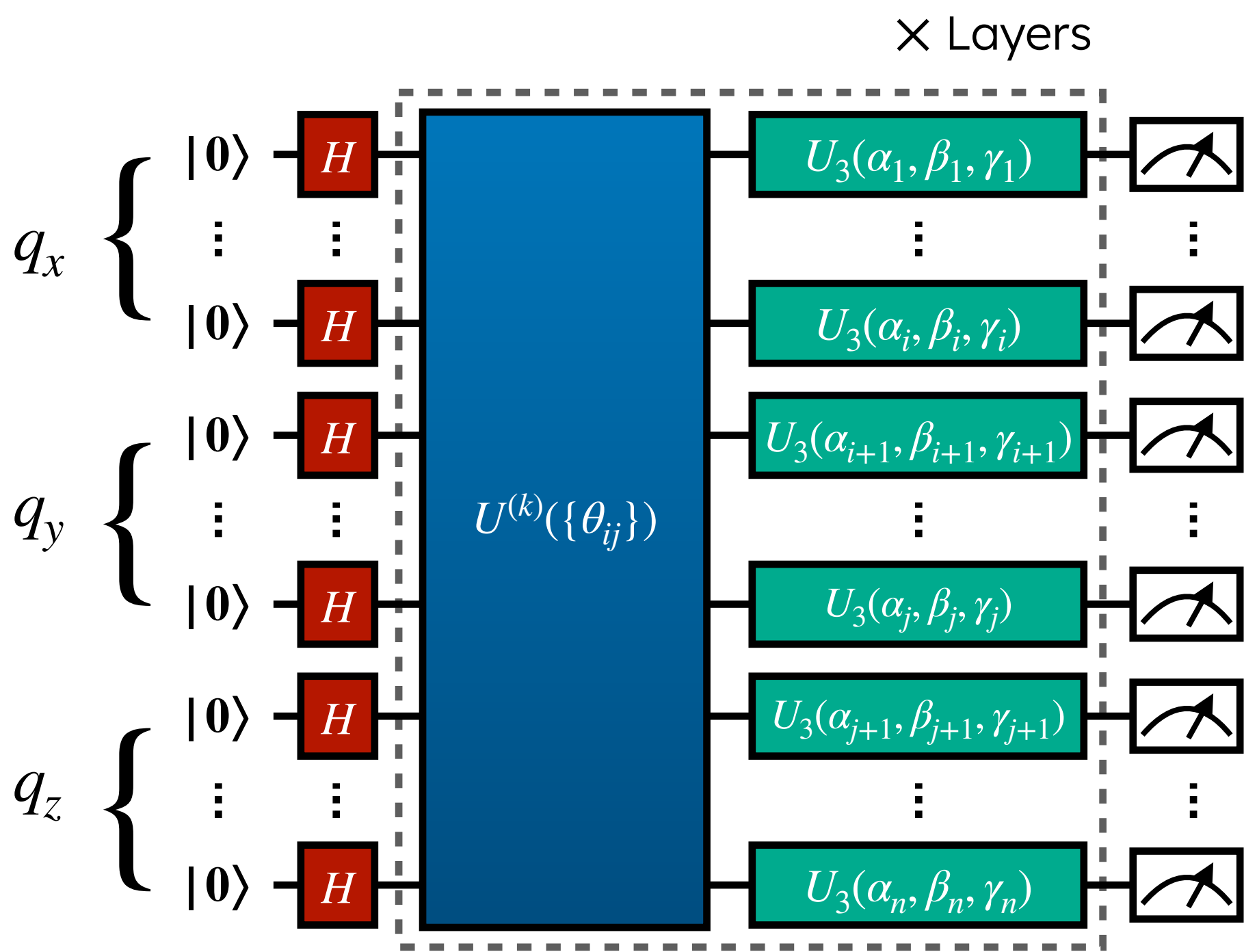
A PQC is trained (e.g. as a Quantum Circuit Born Machine) to generate a quantum state $|\psi\rangle$. The training objective is to make the measurement probabilities $|\langle j | \psi \rangle|^2$ **match the structure of the target integrand $f(\mathbf{x})$** . This shapes the proposal PDF

 Stage 3
Integral Estimation

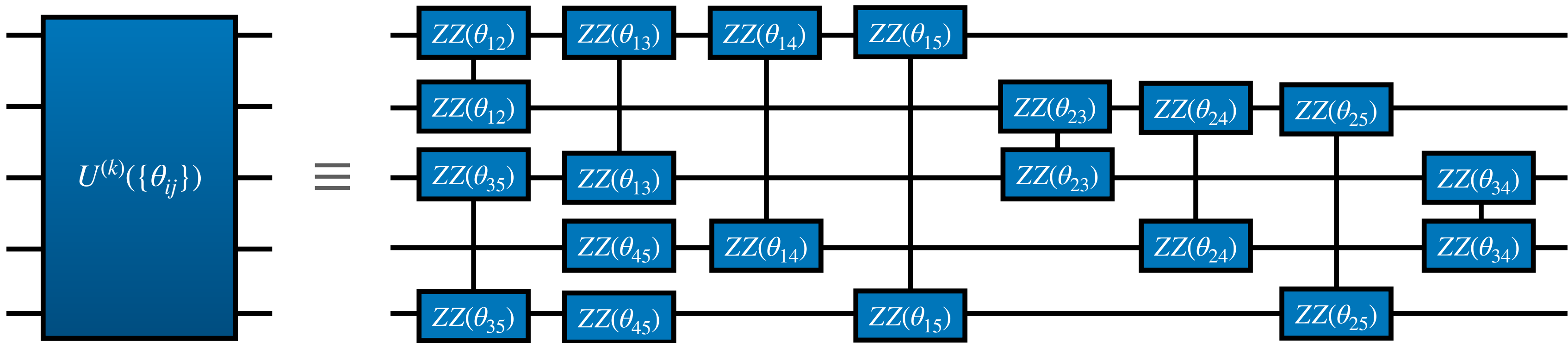


Measurements are performed on the optimized PQC. The **frequency of outcomes determines the number of samples (N_j)** allocated to each grid cell. A dedicated statistical framework, adjusted for quantum measurements is used to calculate the integral estimate and its variance.

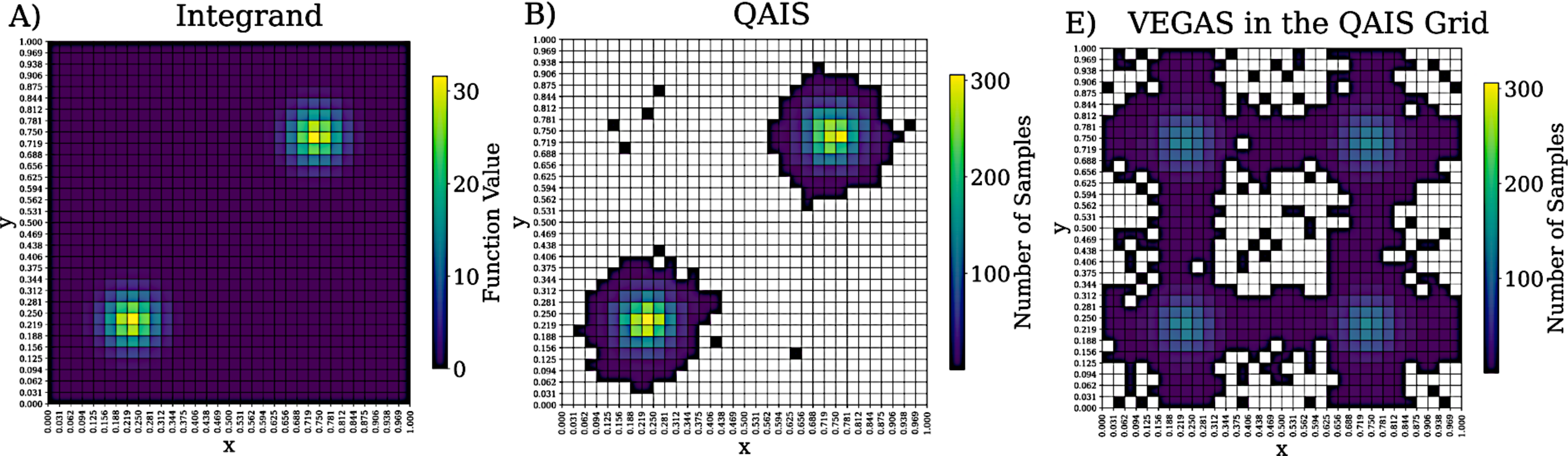
Parametrized Quantum Circuit



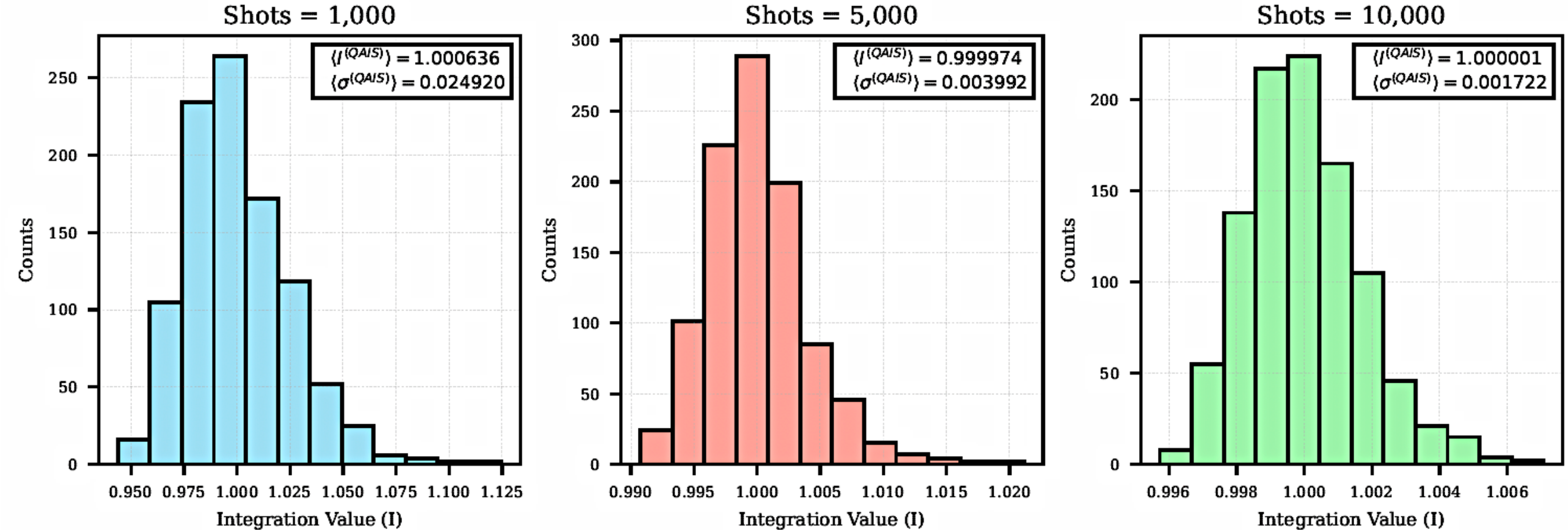
- **all-to-all connectivity** approach with two-qubit gates and single qubit gates
- Performs much better than Hardware Efficient Ansatz (HEA)
- Cost function: discretised version of Kullback-Leibler (KL) divergence
$$D_{\text{KL}}(P\|Q) = \sum_{i=1}^M P(\Omega^{(i)}) \log \left(\frac{P(\Omega^{(i)})}{Q(\Omega^{(i)})}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



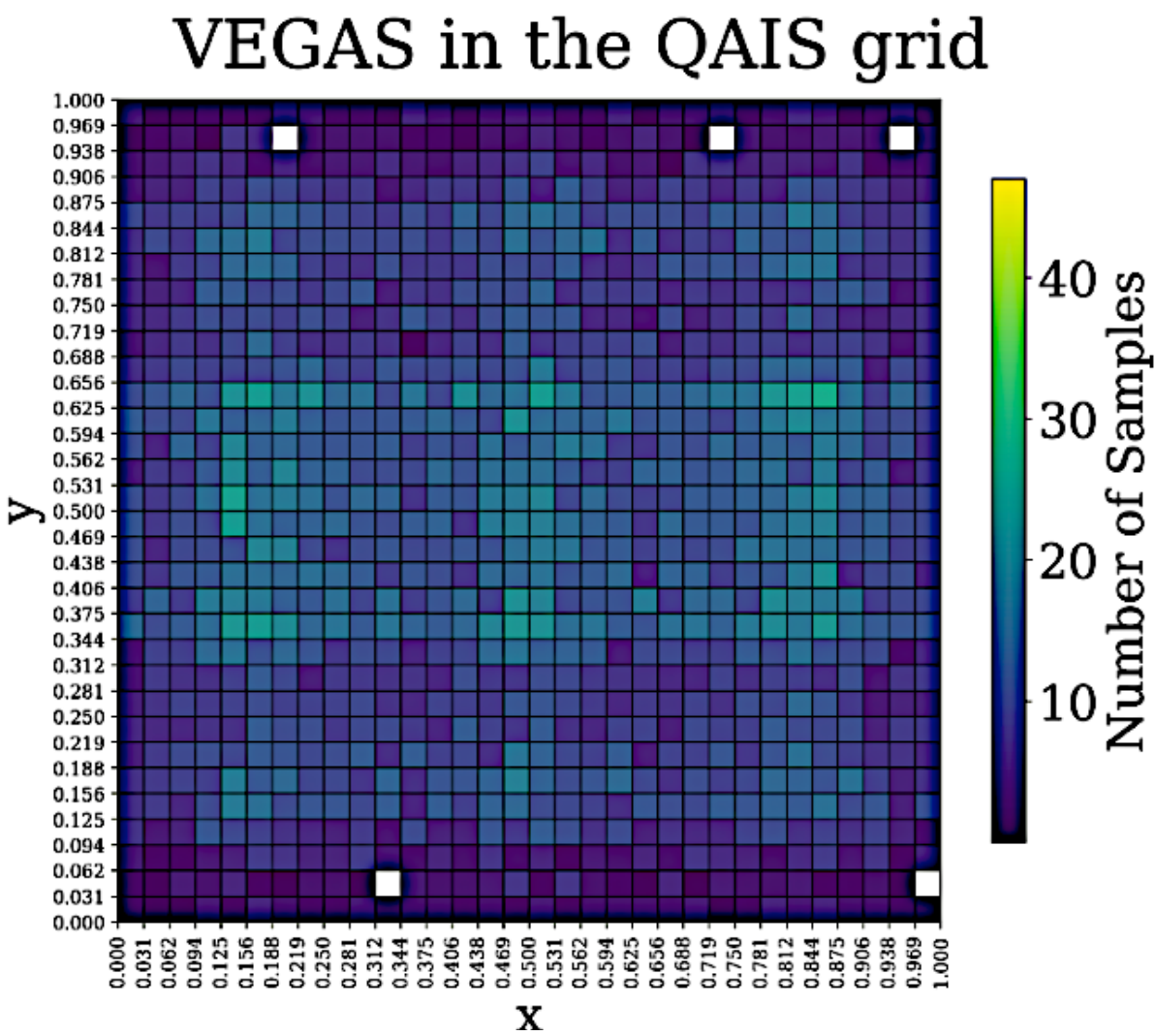
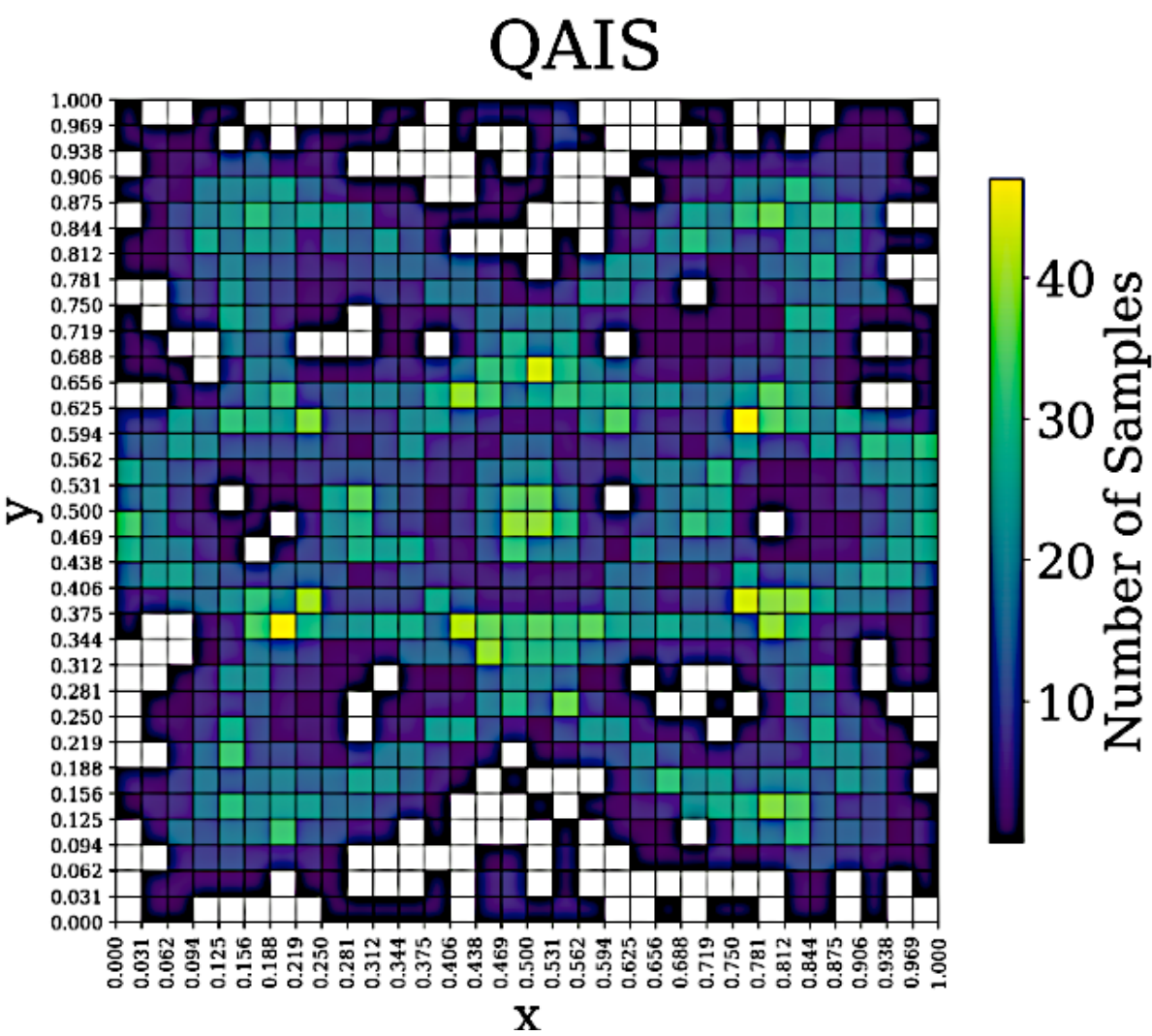
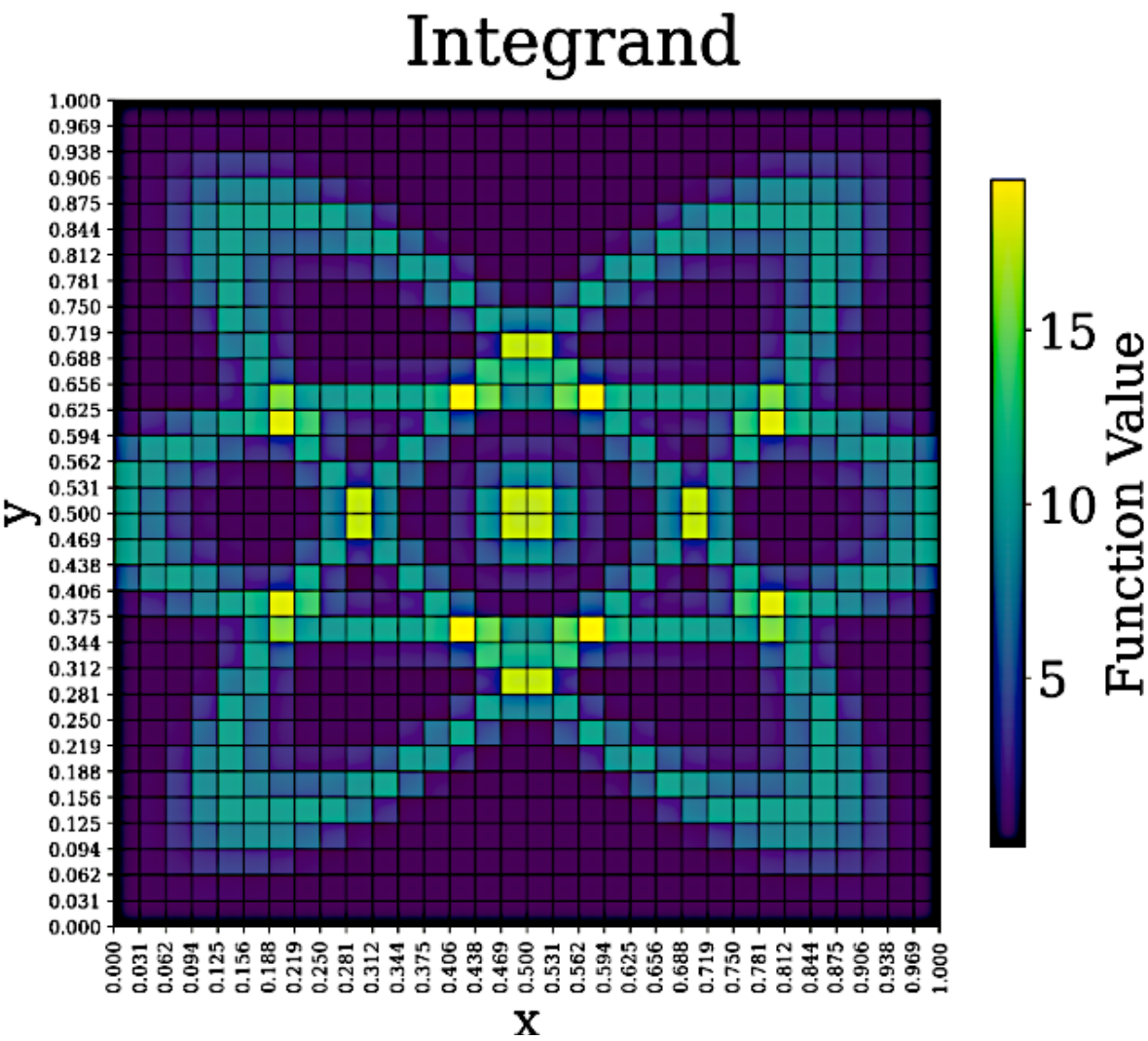
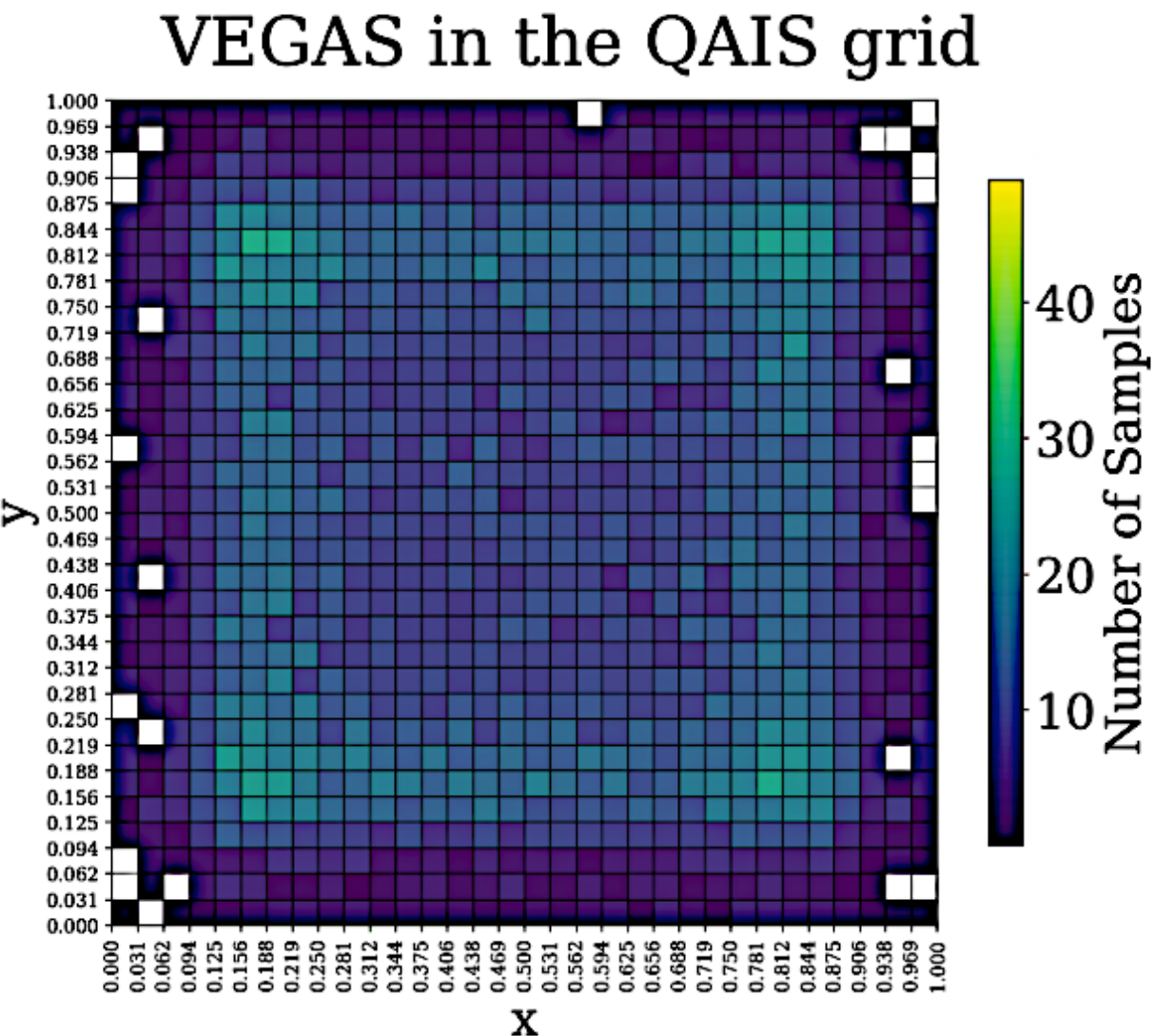
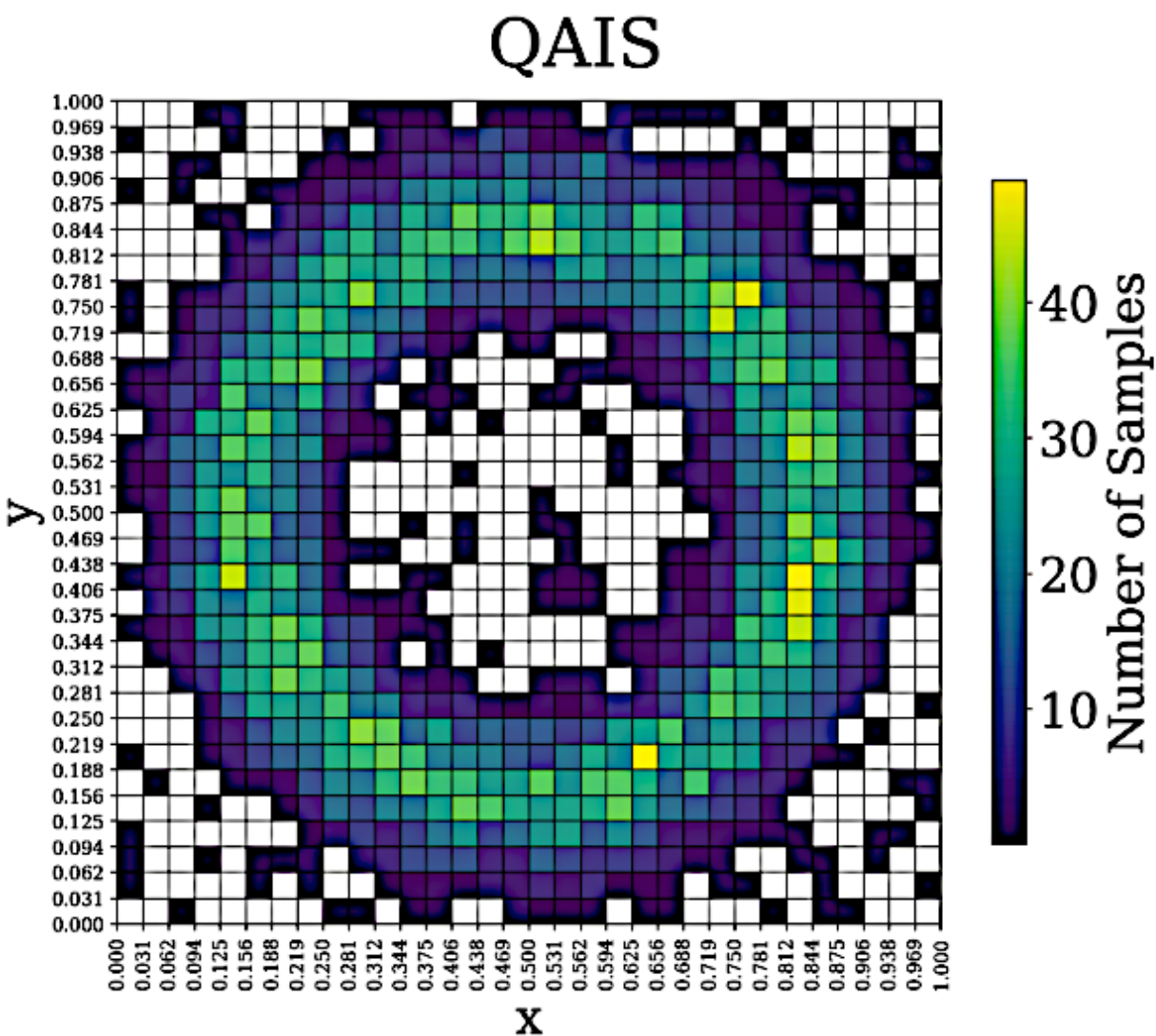
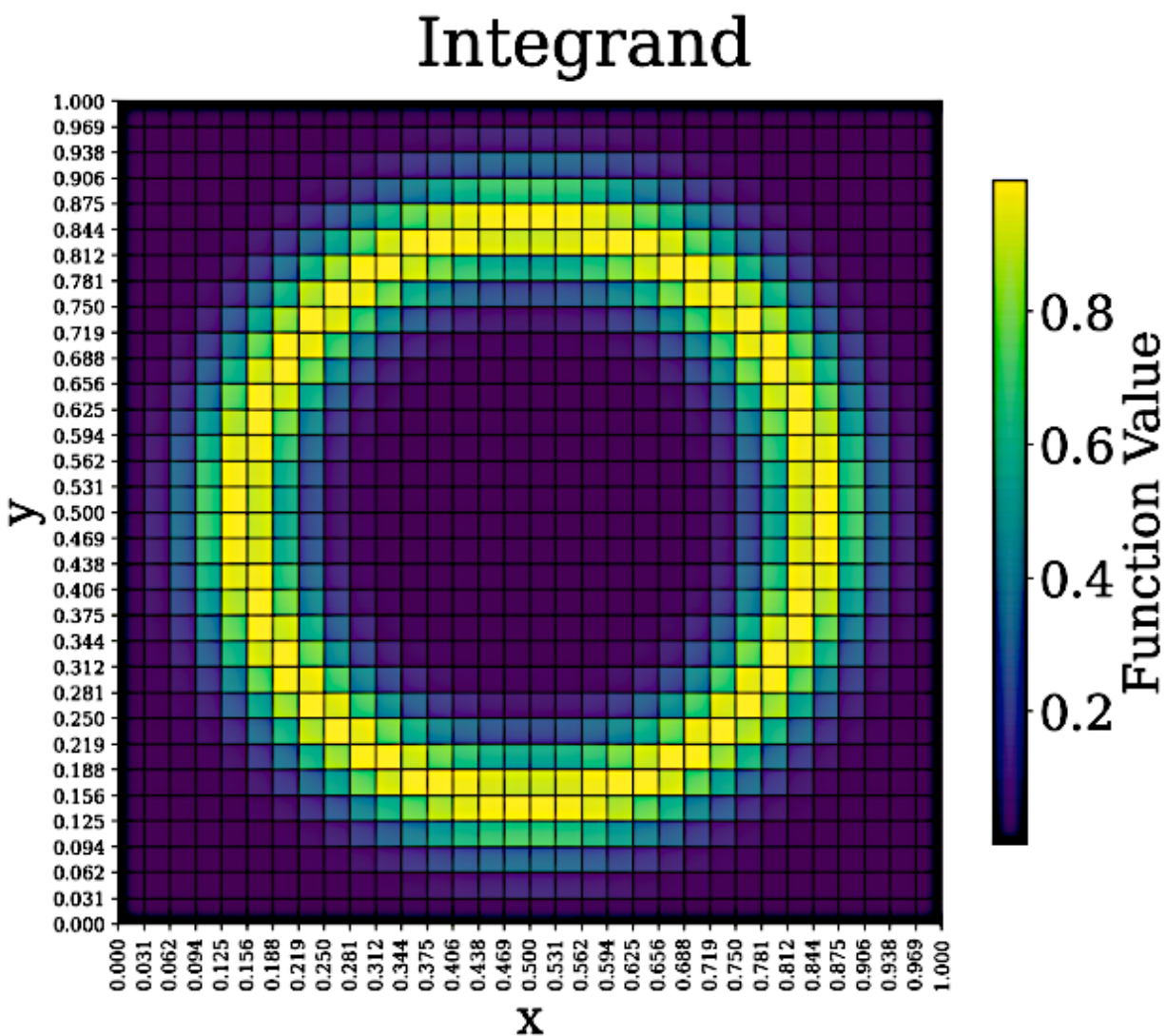
Absence of phantom peaks



Distribution of Integration Results by Number Shots

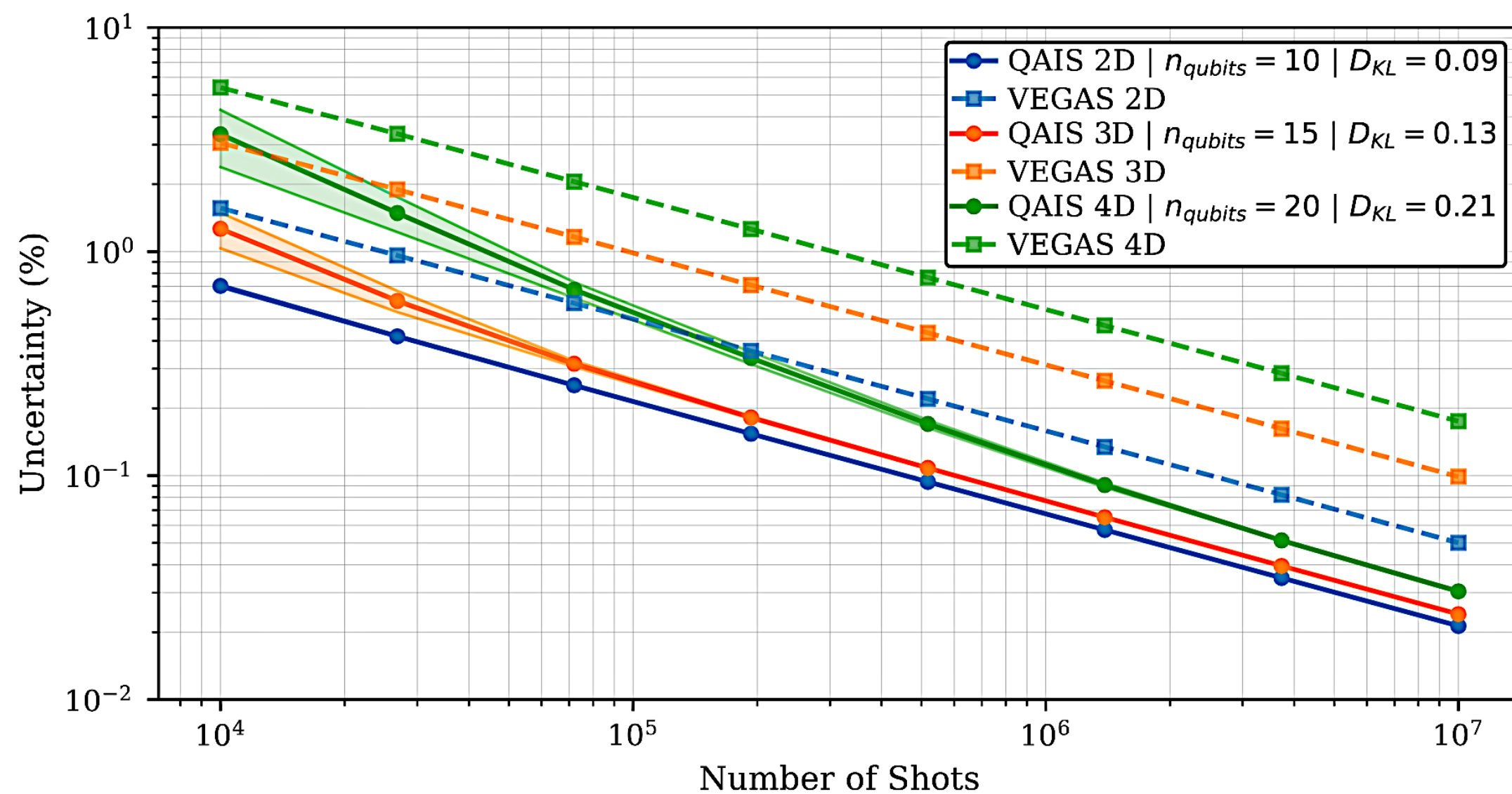


- Integral normalised to one
- 1000 independent runs with the same PDF as a function of the number of shots
- Includes a Tiling module to reduce bias from unobserved cells



Cross-dimensional Comparison

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



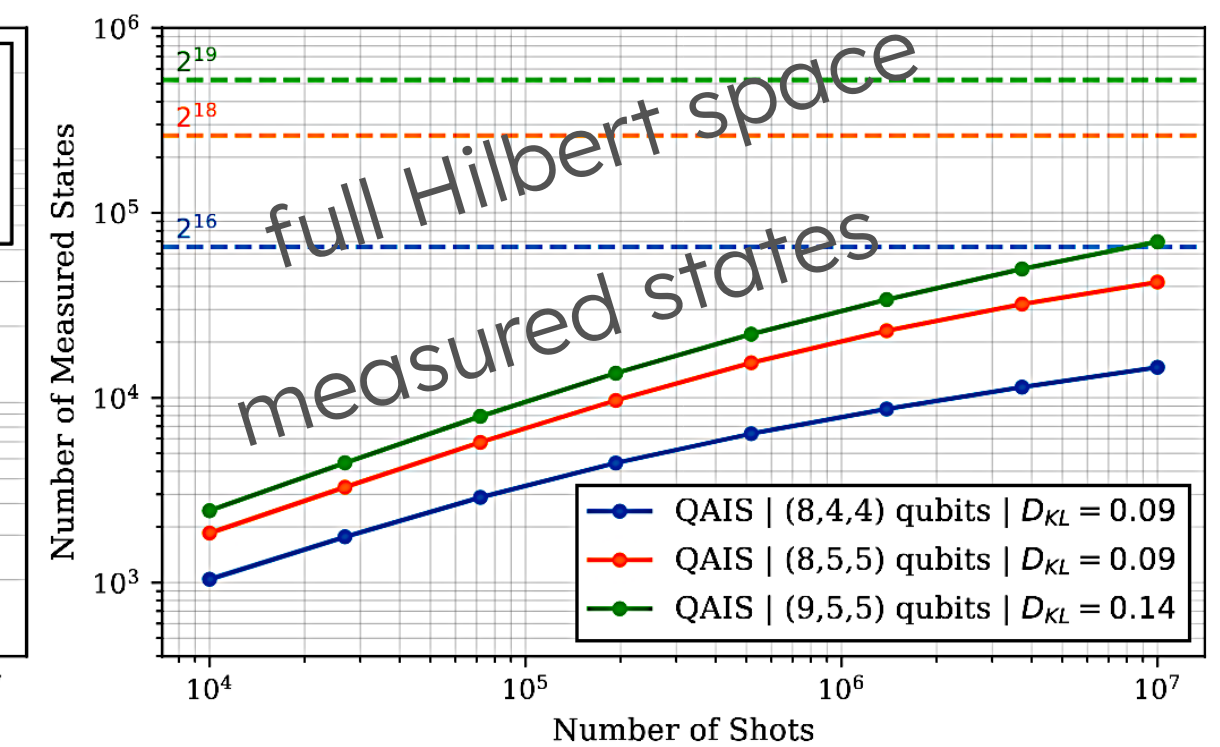
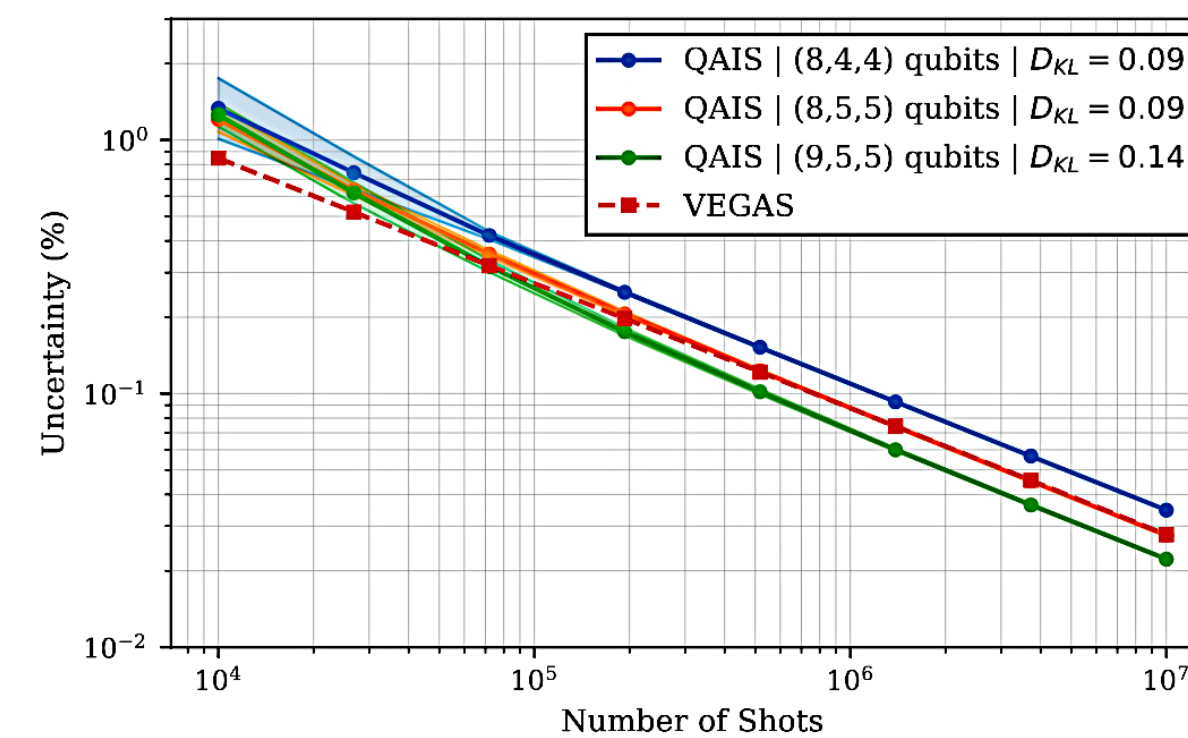
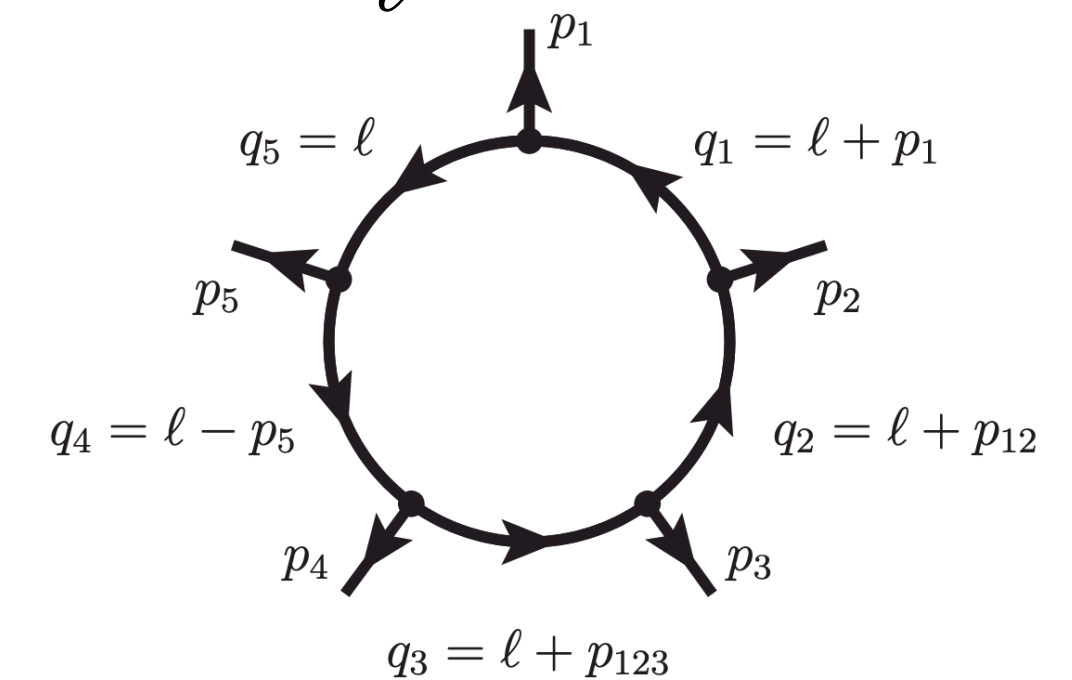
One-loop pentagon in the Loop-Tree Duality (LTD)

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

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

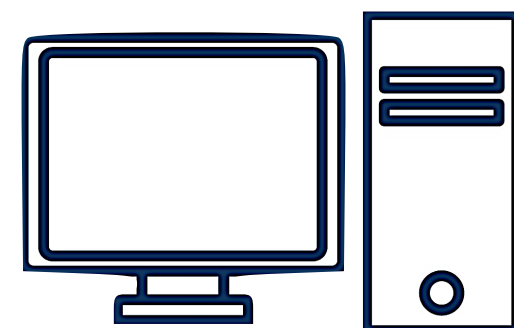
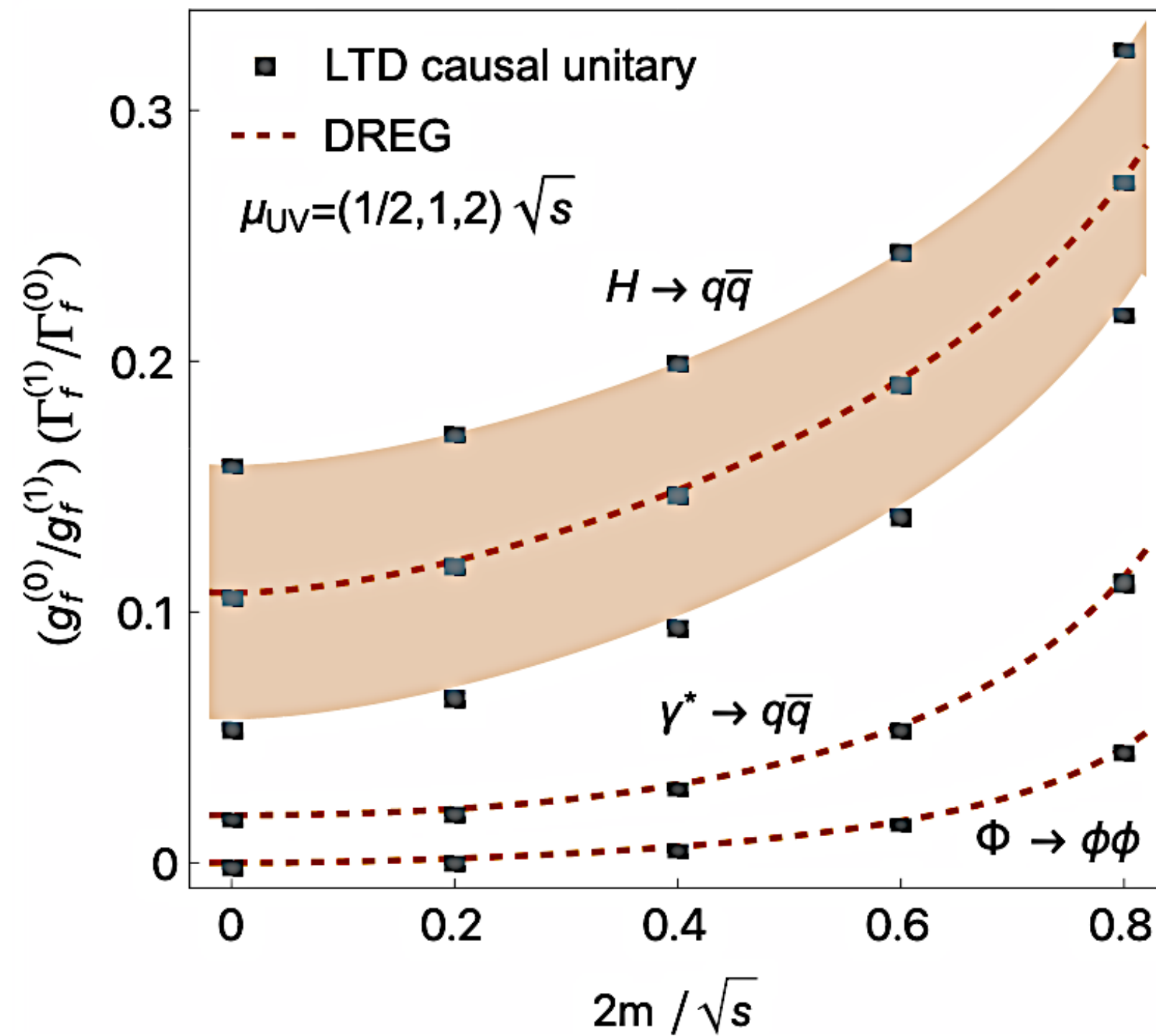
$$\lambda_{ij}^{\pm} = q_{i,0}^{(+)} + q_{j+1,0}^{(+)} \pm (p_i + p_j)_0$$

$$j = i + 1 \quad q_{i,0}^{(+)} = \sqrt{\vec{q}_i^2 + m_i^2 - i0}$$



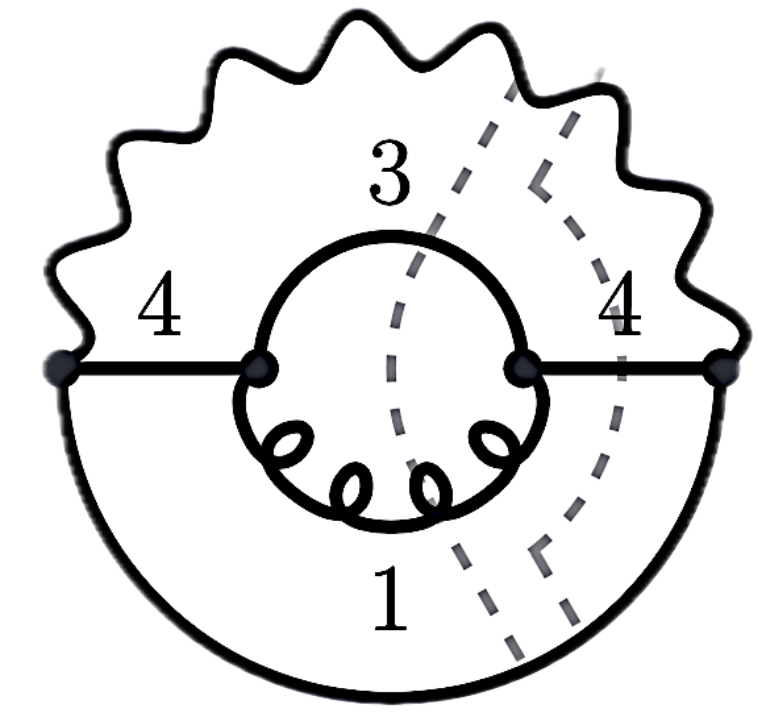
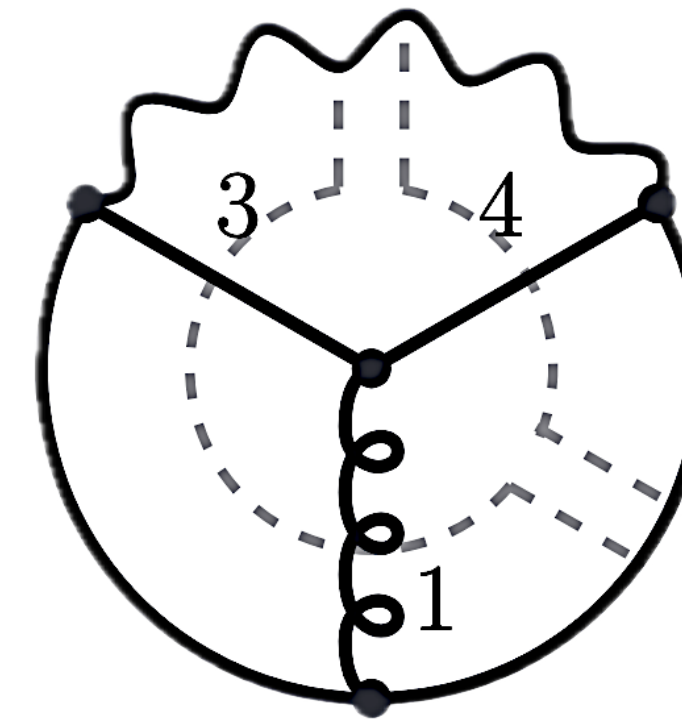
○ uncertainty bands from 100 independent runs with the same PDF

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



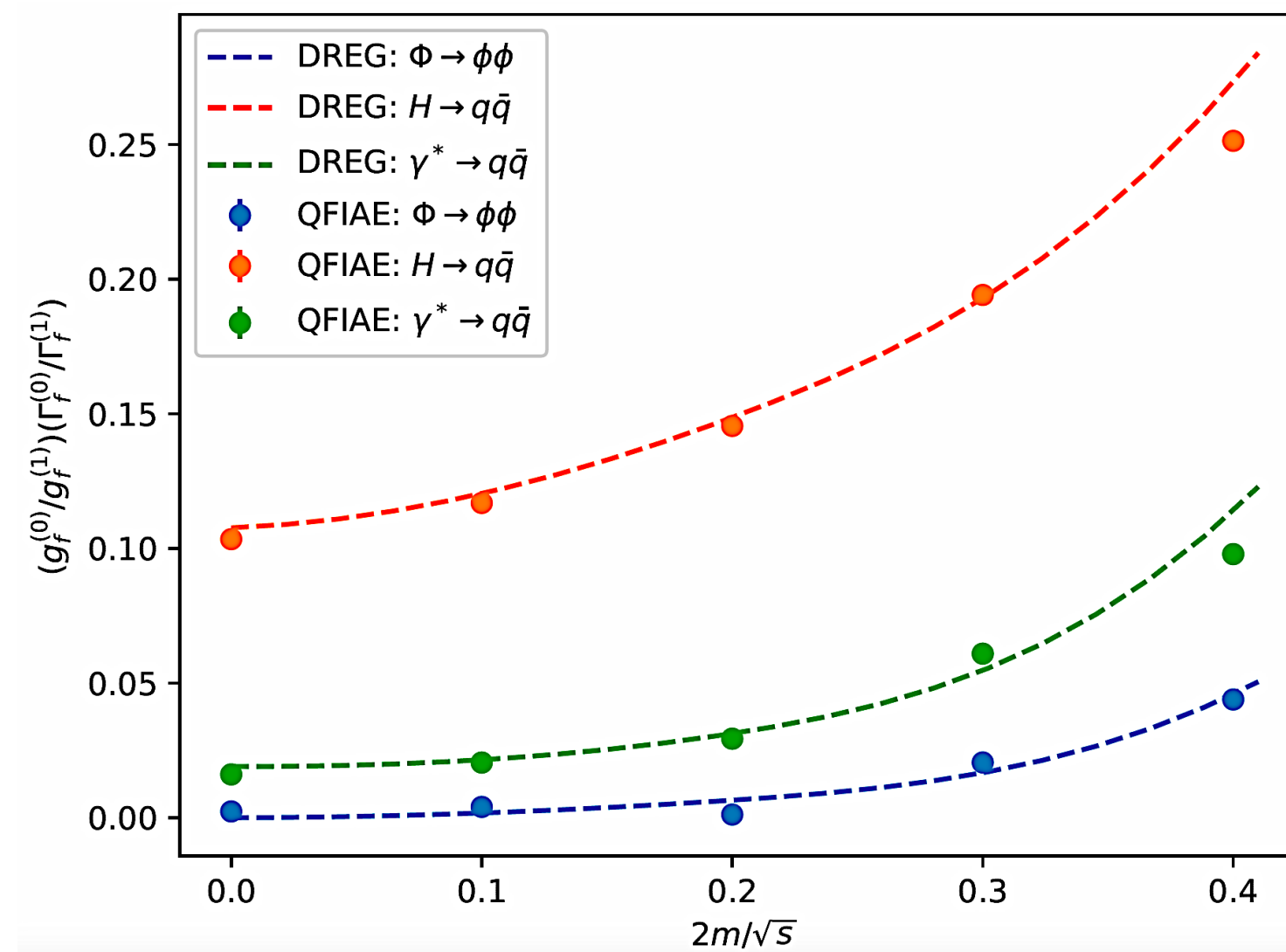
○ Classical Monte Carlo

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

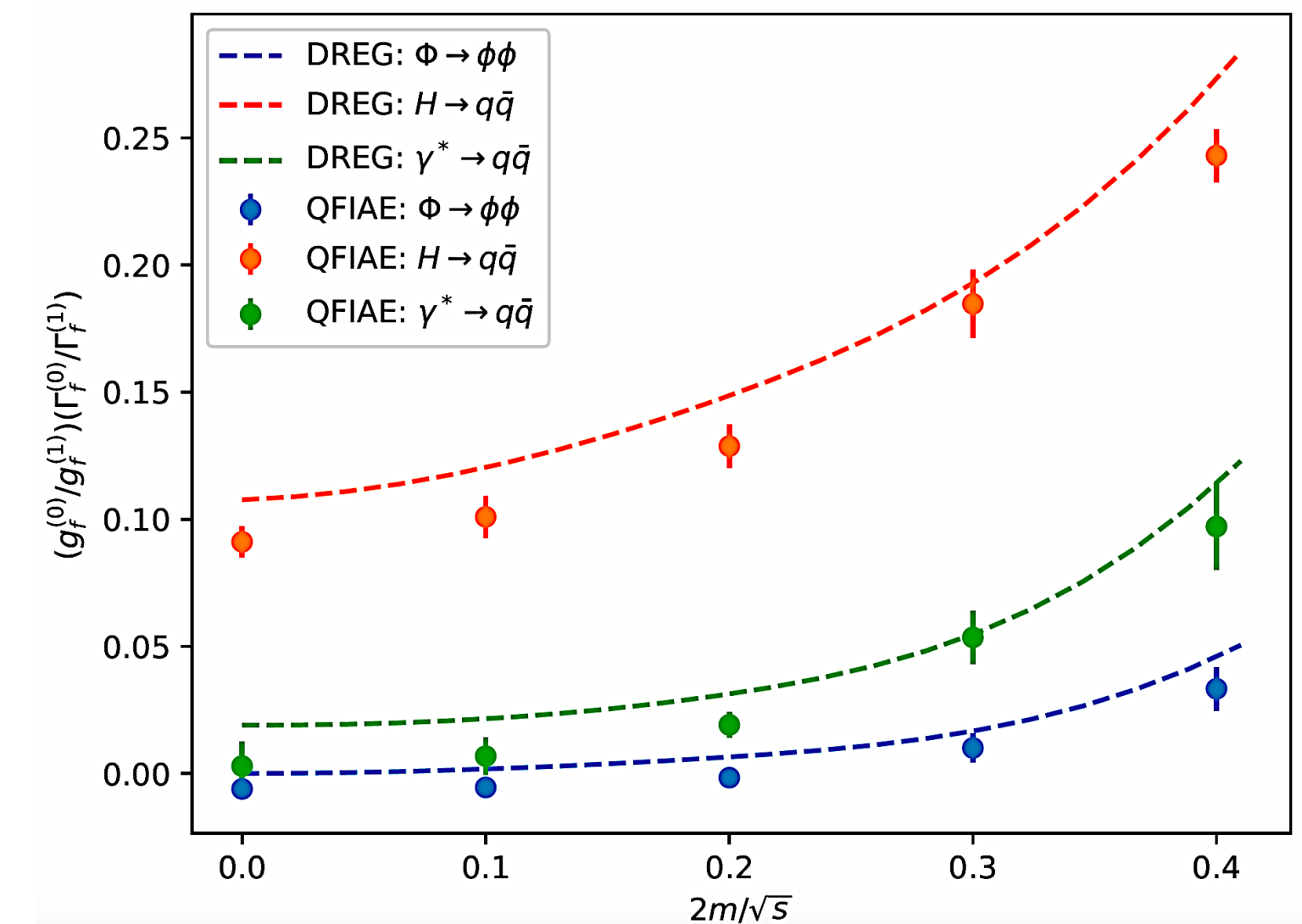


Quantum integration of decay rates at second order in perturbation theory

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



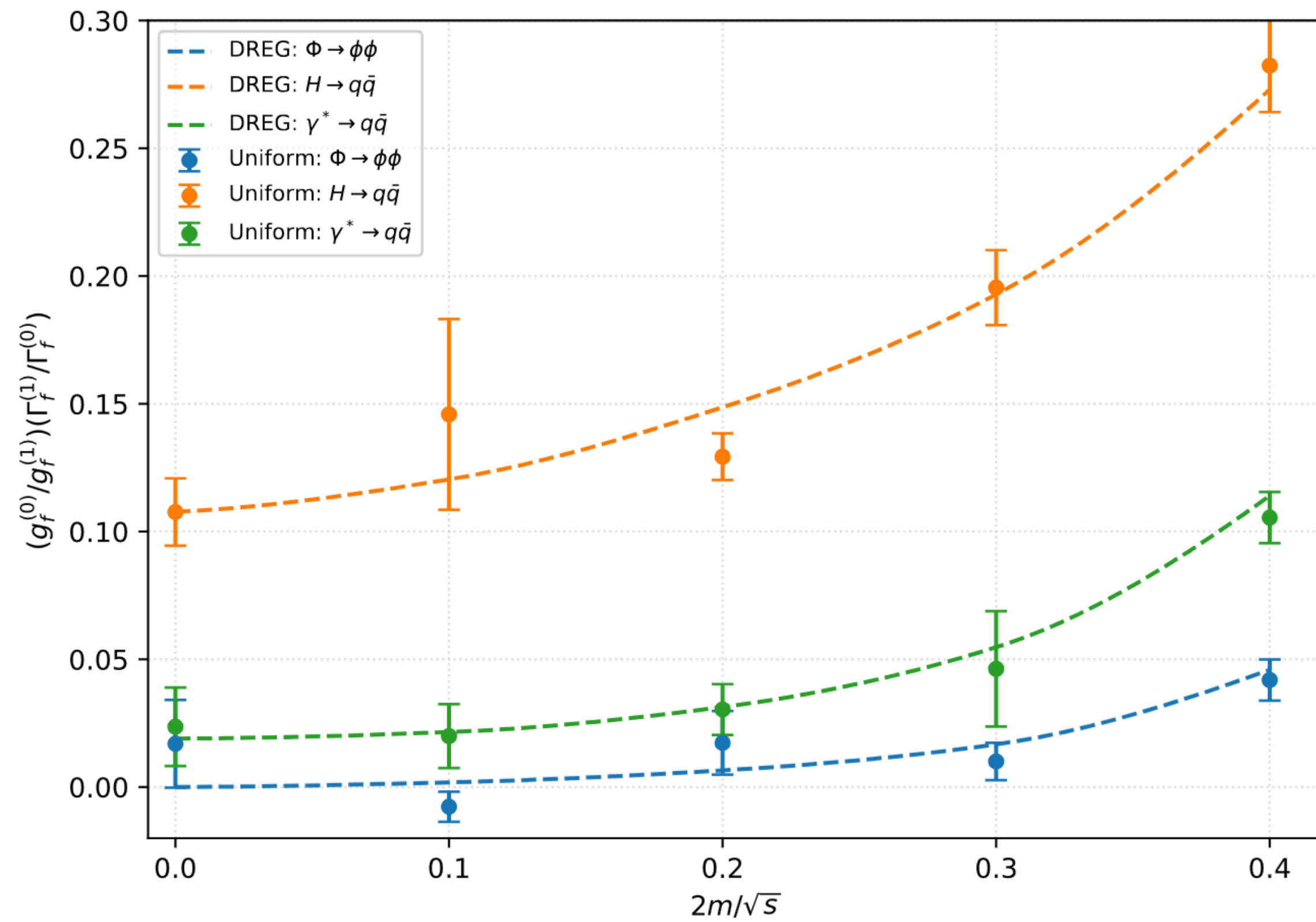
○ Quantum simulator



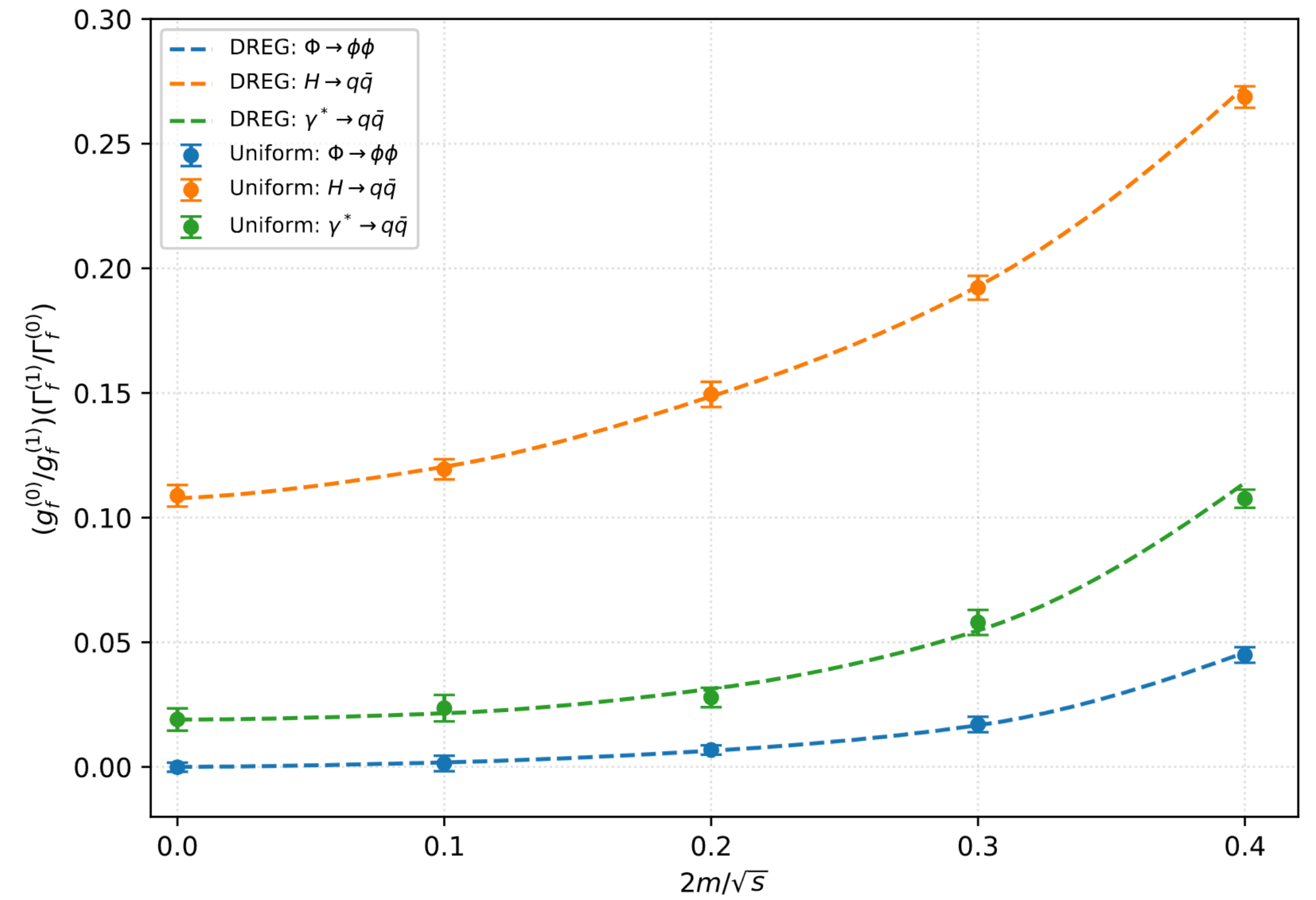
○ Partially in quantum hardware

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

Uniform PDF

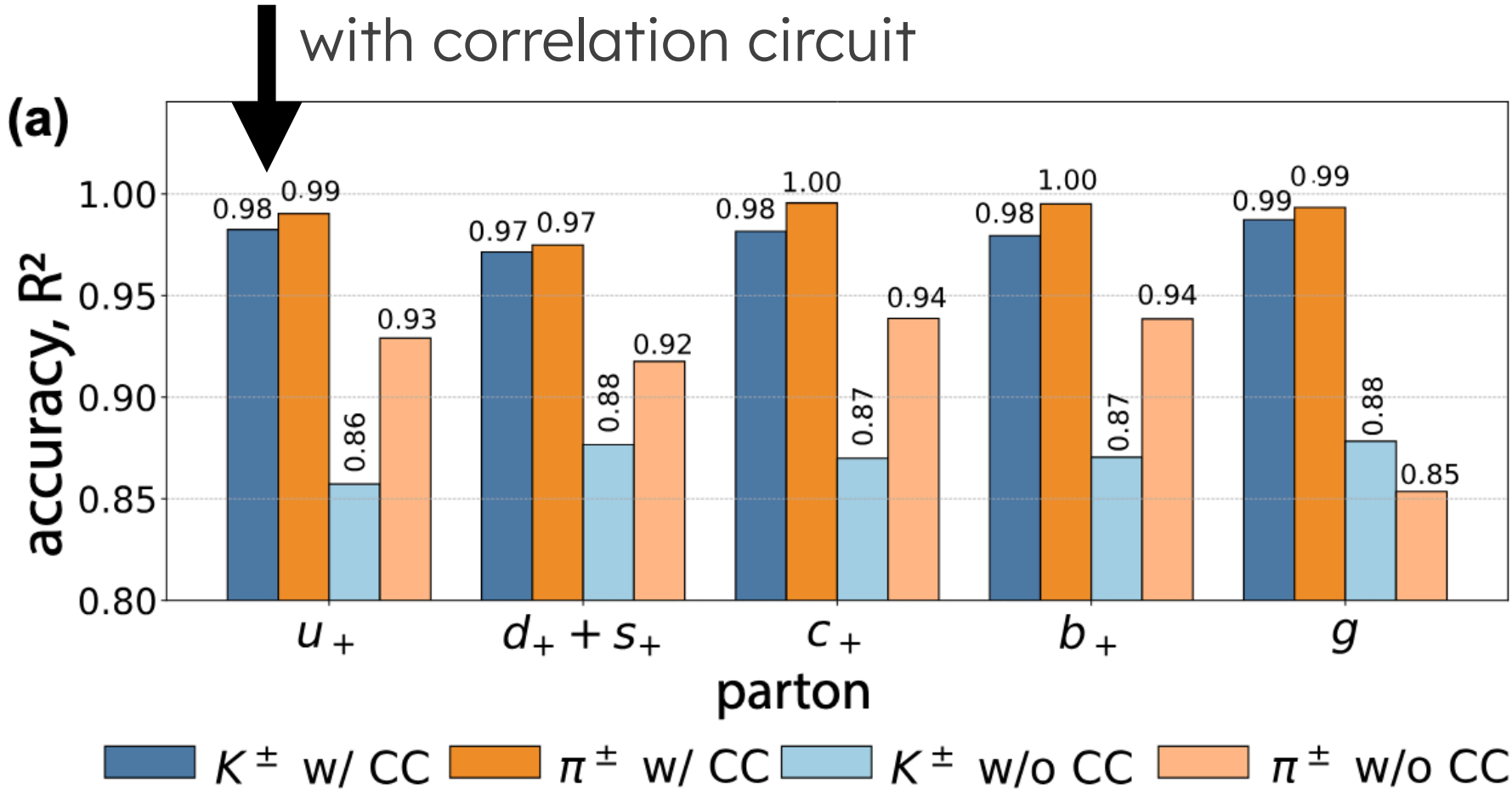
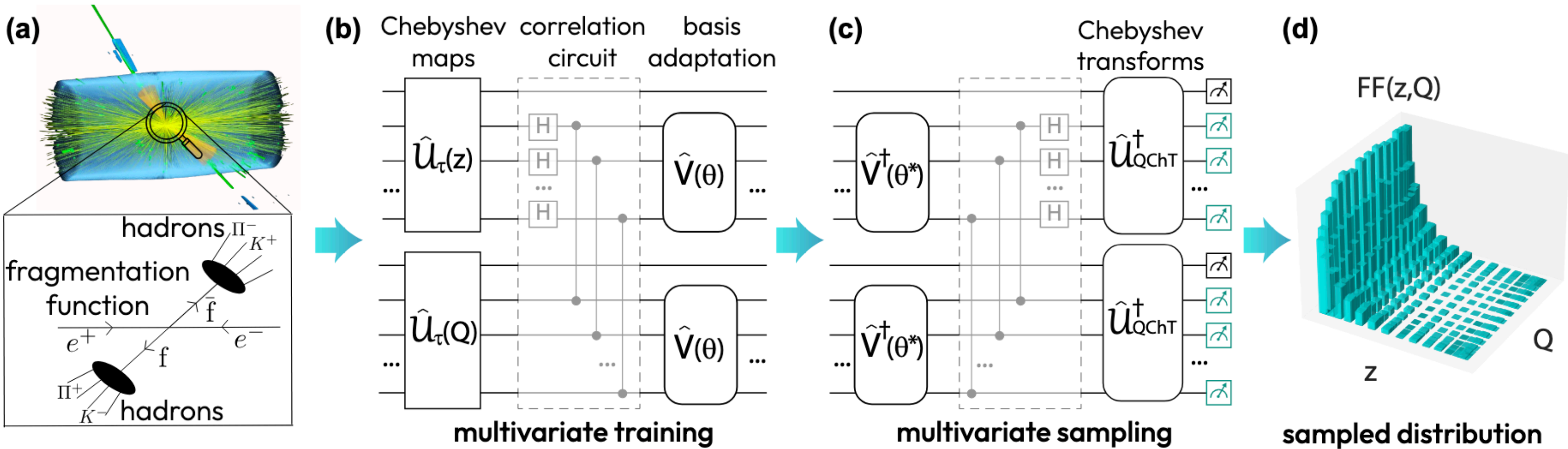


QAIS

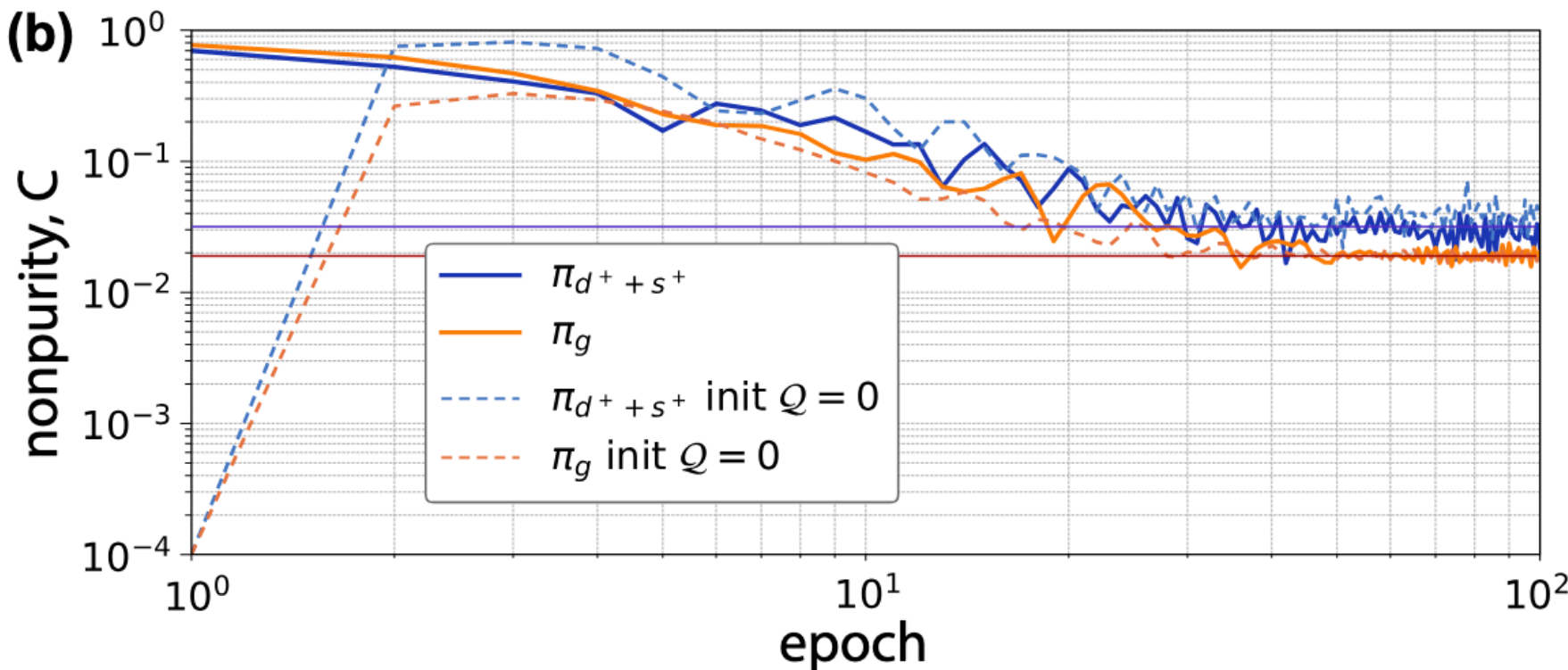


○ With only 50.000 shots per point

Quantum Chebyshev Probabilistic Models (QCPM)



○ QCPM with the correlation circuit consistently outperform those without



○ A lower non-purity ($C = |1 - \text{Tr}(\rho^2)|$) suggests a higher degree of entanglement, indicating strong correlations between z and Q

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 (fault tolerant) quantum computer becomes a reality
- My (long-term) dream: a **quantum event generator** with NNLO, ..., $N^k\text{LO} + N^k\text{LL}$ accuracy

