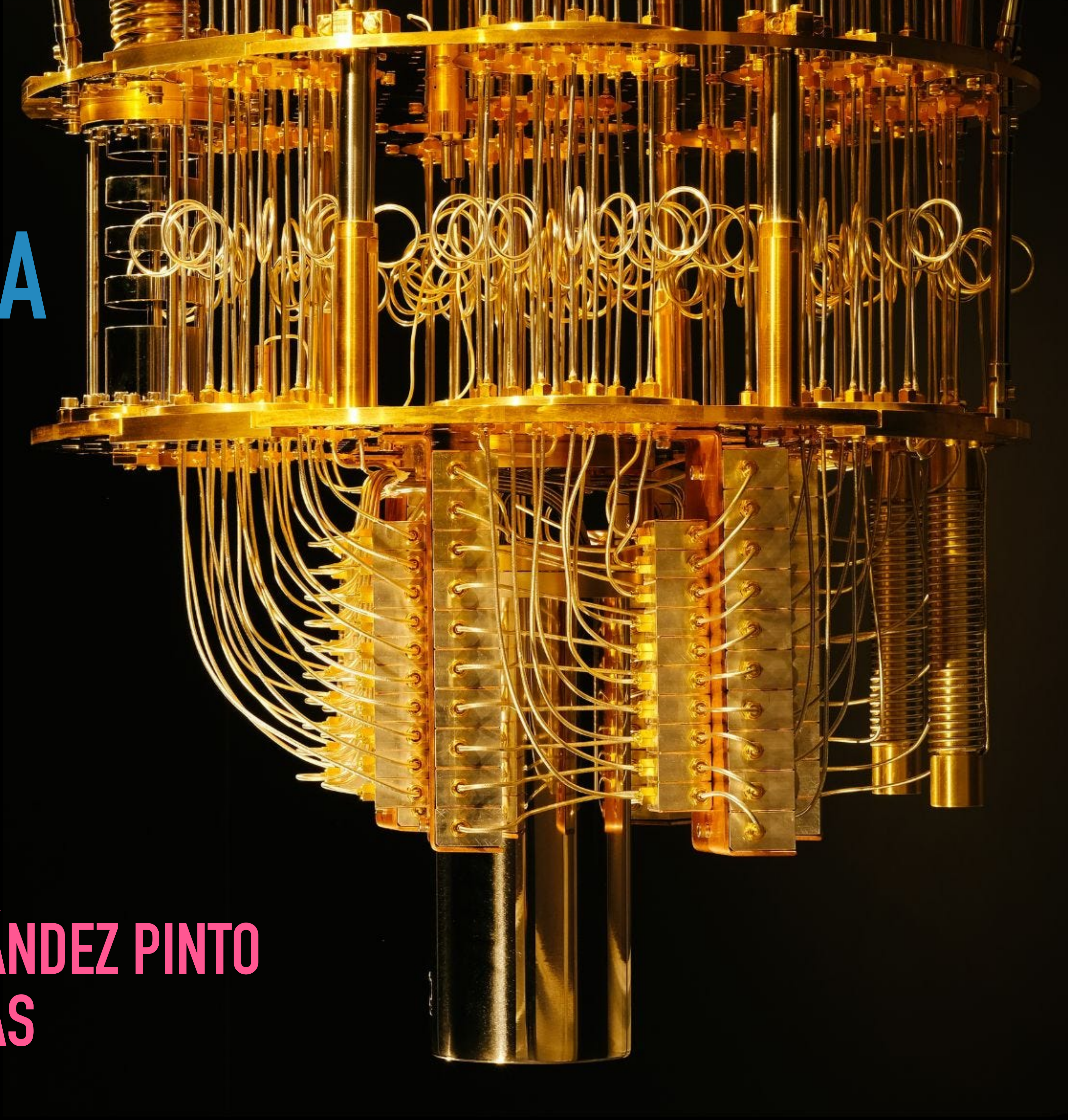
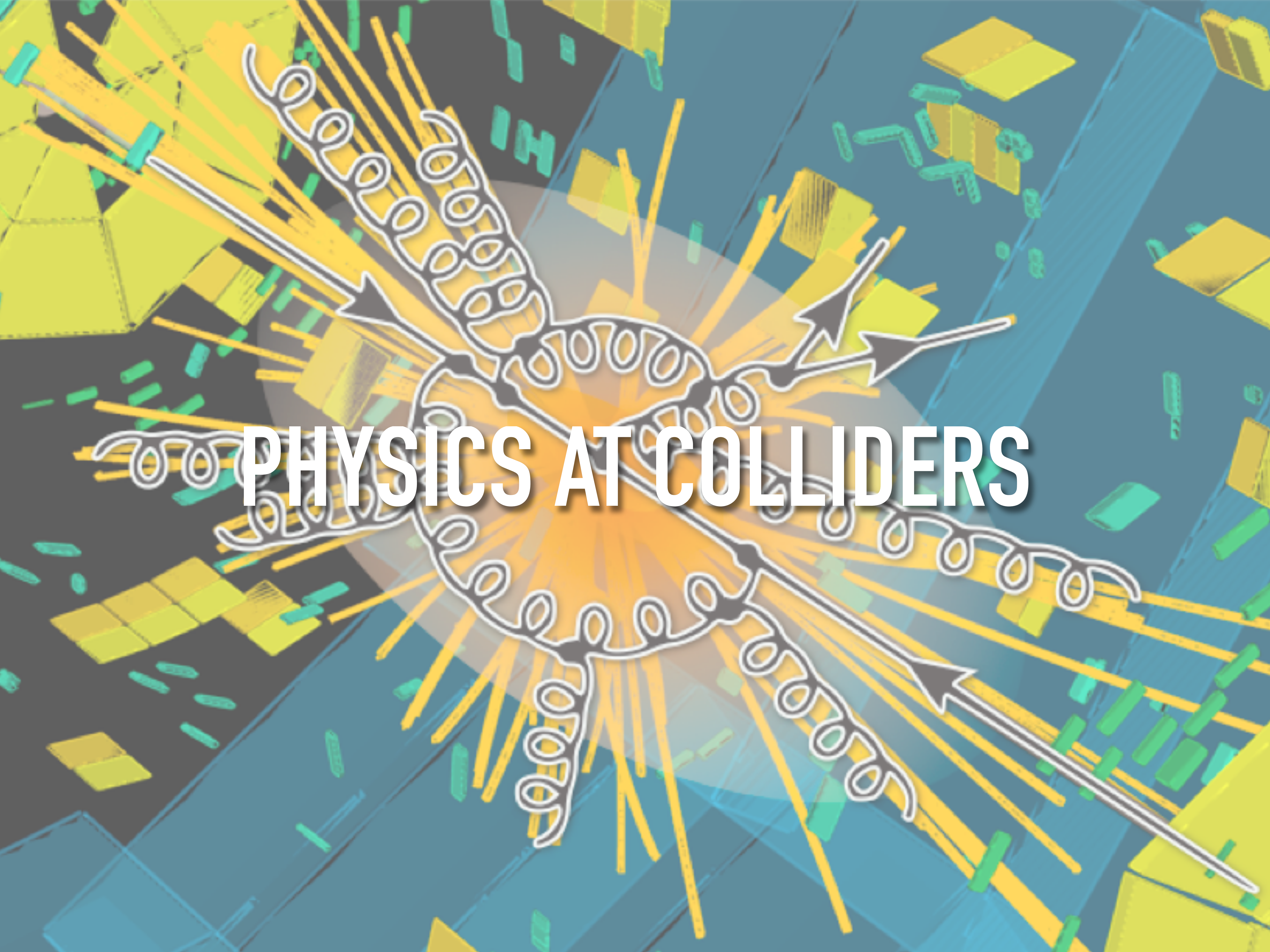
MAPPING CAUSAL CONFIGURATIONS VIA GRAPH-THEORETIC QUANTUM AUTOMATION



ROGER JOSÉ HERNÁNDEZ PINTO
FCFM-UAS

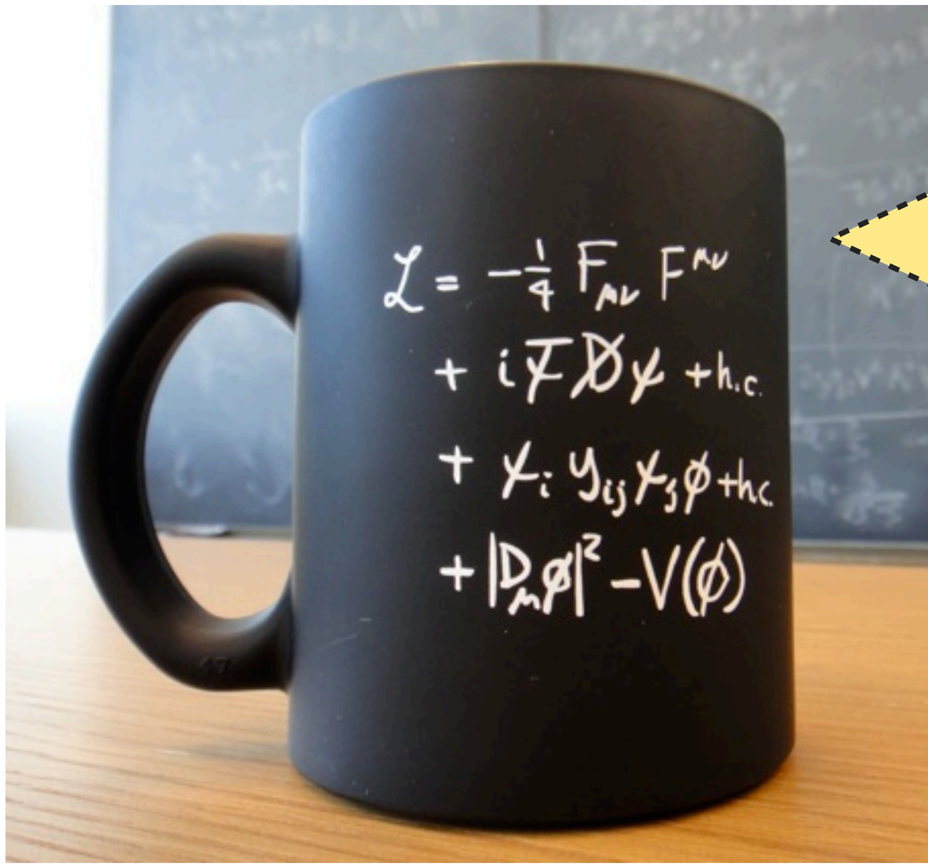
NEW TRENDS IN QFT, AMPLITUDES AND GRAVITY
CIIEC & BUAP- APR. 16, 2026

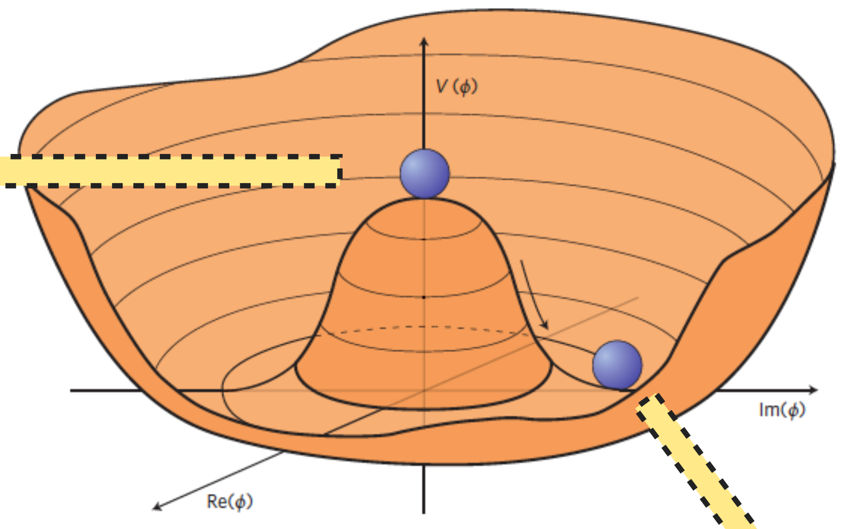

PHYSICS AT COLLIDERS

INTRODUCTION

- The description of fundamental interactions rely on unitary and local quantum field theories.
- Experimental observables are achieving such high precision that accurate theoretical predictions are vital for understanding the fundamental nature of particles.
- Accurate theoretical predictions in high-energy physics necessitate the treatment of multi-loop and multi-leg scattering amplitudes.
- Multi-loop scattering amplitudes, which describe the quantum fluctuations in high-energy scattering processes, are the main bottleneck.
- New ideas are necessary to find precision predictions—from handling singularities in the integrands to finding efficient numerical methods for Monte Carlo codes.

THE STANDARD MODEL LAGRANGIAN





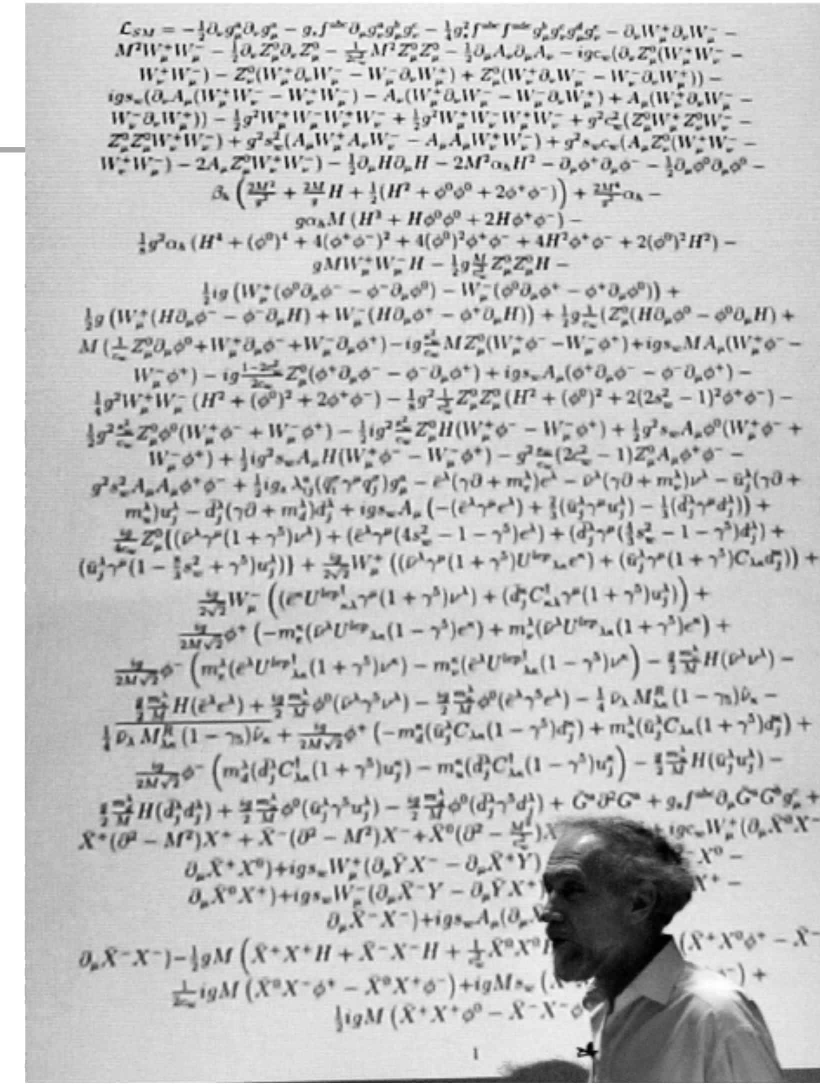
- SM Gauge Group: $SU(3)_c \times SU(2)_L \times U(1)_Y$
- Particles:
  - Fermions: $Q(\mathbf{3}, \mathbf{2}, y_q)$, $U(\mathbf{3}, \mathbf{1}, y_u)$, $D(\mathbf{3}, \mathbf{1}, y_d)$, $L(\mathbf{1}, \mathbf{2}, y_l)$, $E(\mathbf{1}, \mathbf{1}, y_e)$
  - Higgs field: $H(\mathbf{1}, \mathbf{2}, y_h)$
- Spontaneous symmetry breaking

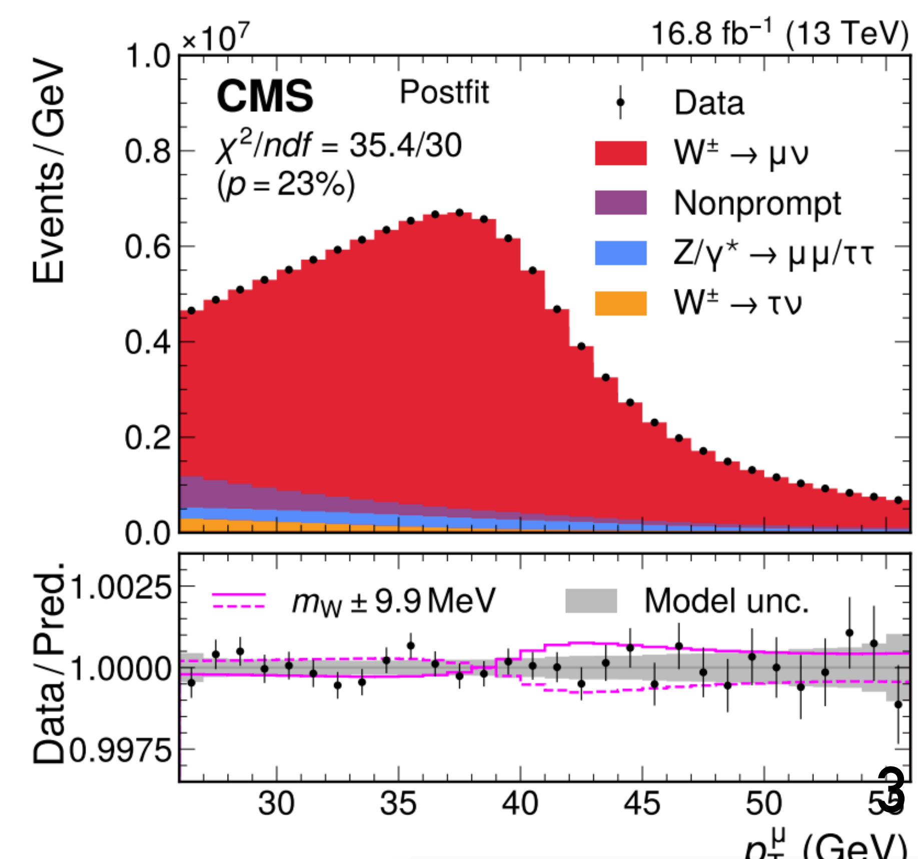
PARTICLE PHYSICS PHENOMENOLOGY

- Write your preferable model,
- Find the corresponding Feynman rules,
- Compute observables with experimental cuts at the highest possible accuracy (by means of Feynman rules):

$$\frac{d\sigma^{N^nLO}}{dp_T d\eta d\phi}$$

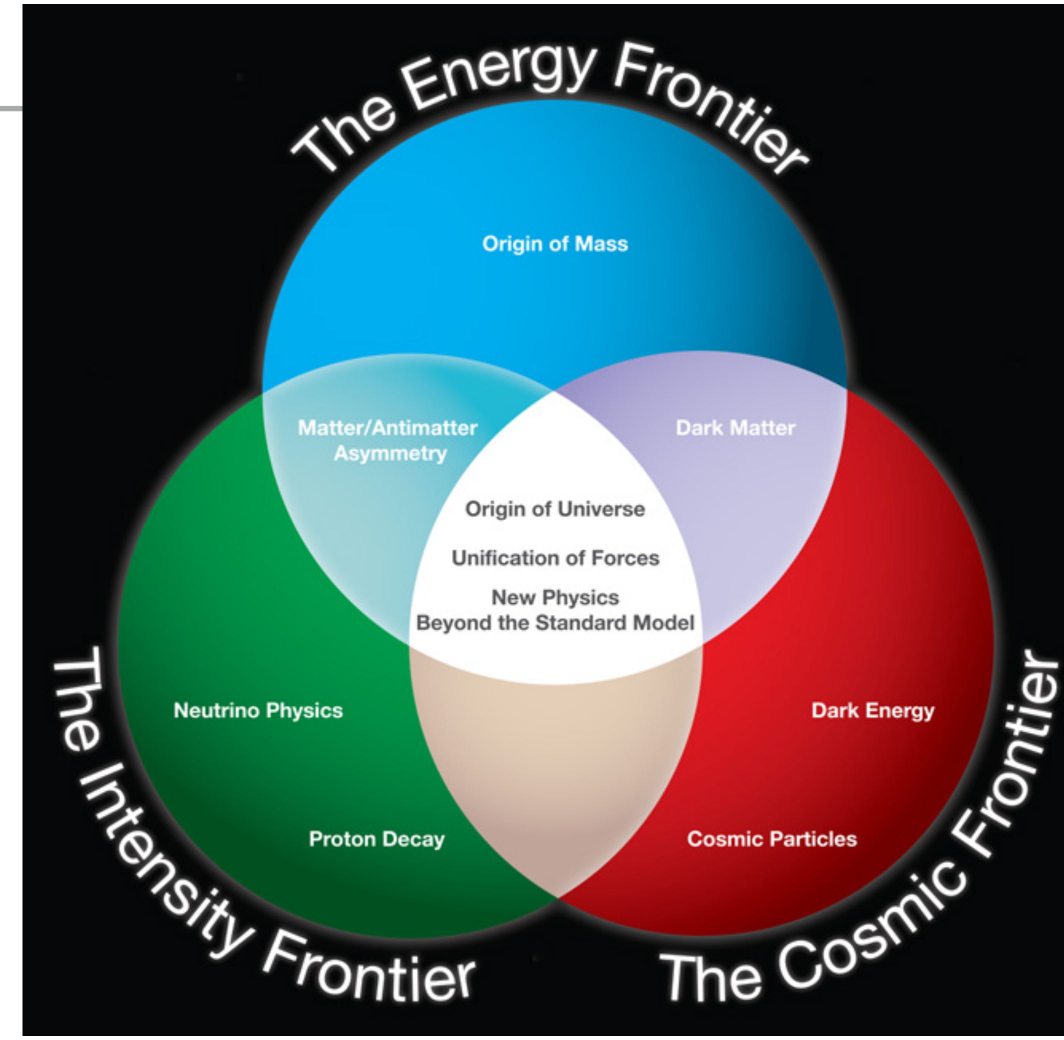
- Analyze the resulting distributions, are they compatible with experimental results ?

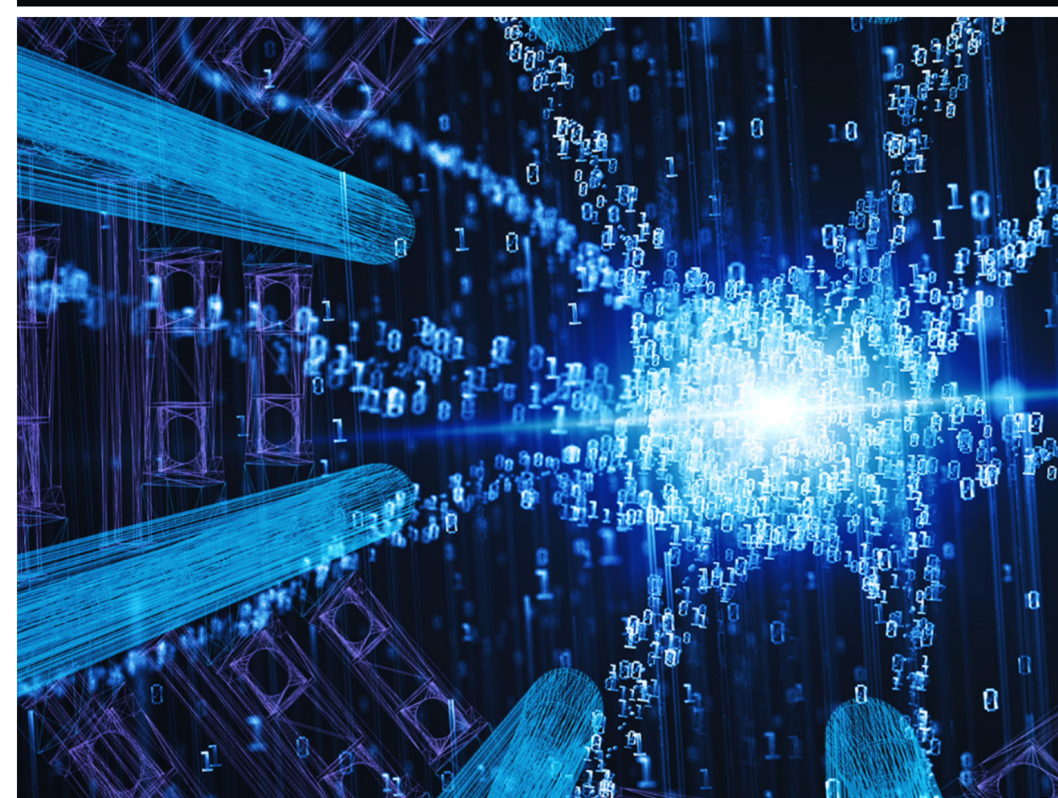


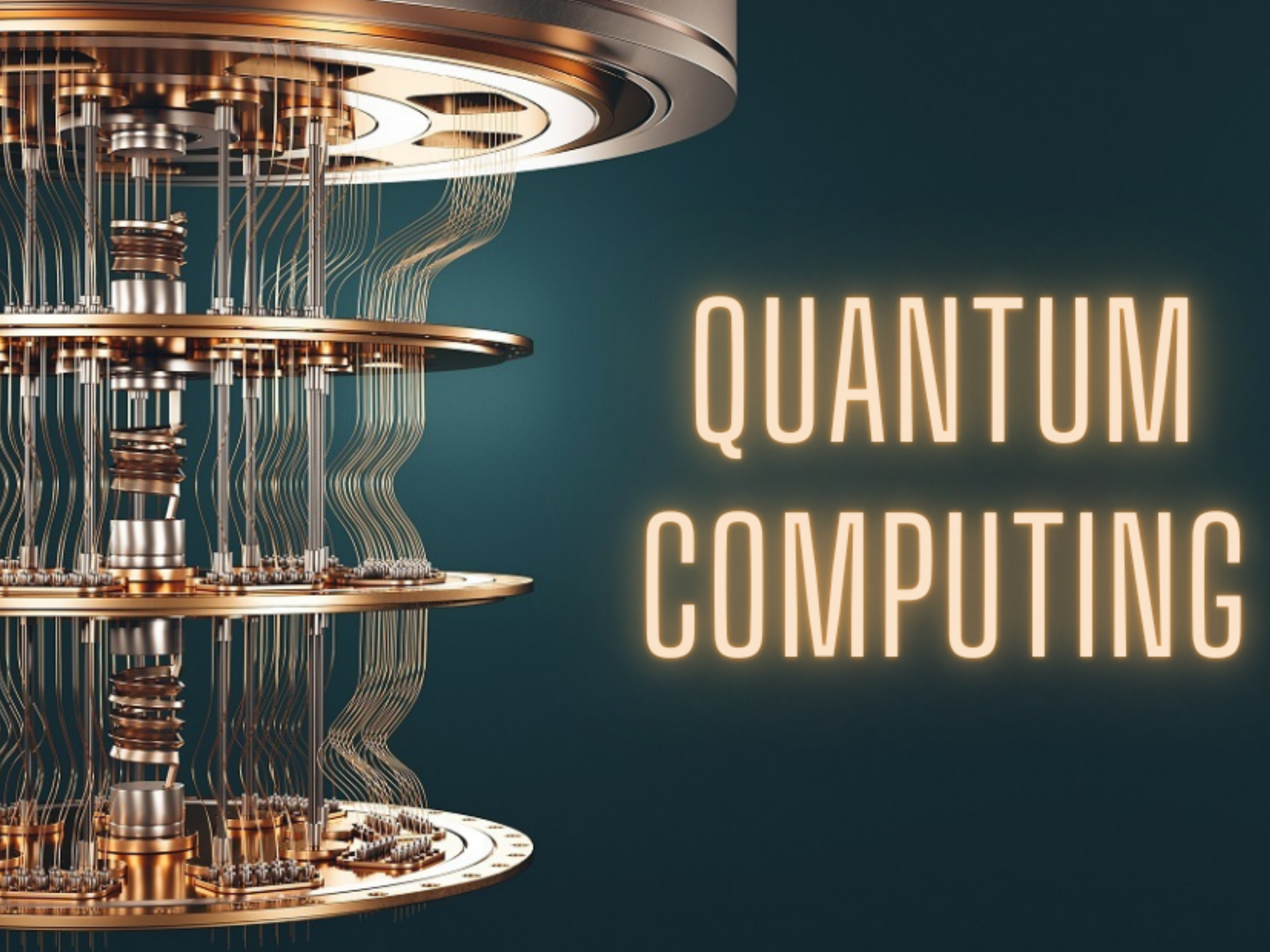


FUNDAMENTAL PHYSICS FRONTIERS

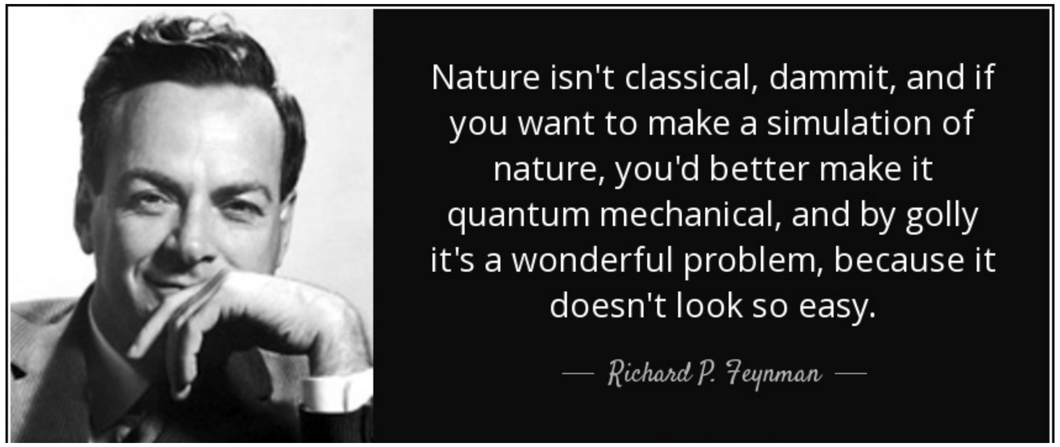
- Precision frontier: Measure particle properties with sensitive tools or high statistics,
- Energy frontier: Explore sub-atomic world with accelerators (LHC currently)
- Cosmic frontier: Explore the cosmos to test fundamental physics laws,
- Computational frontier: New tools are coming, use them all (or at least try them) !



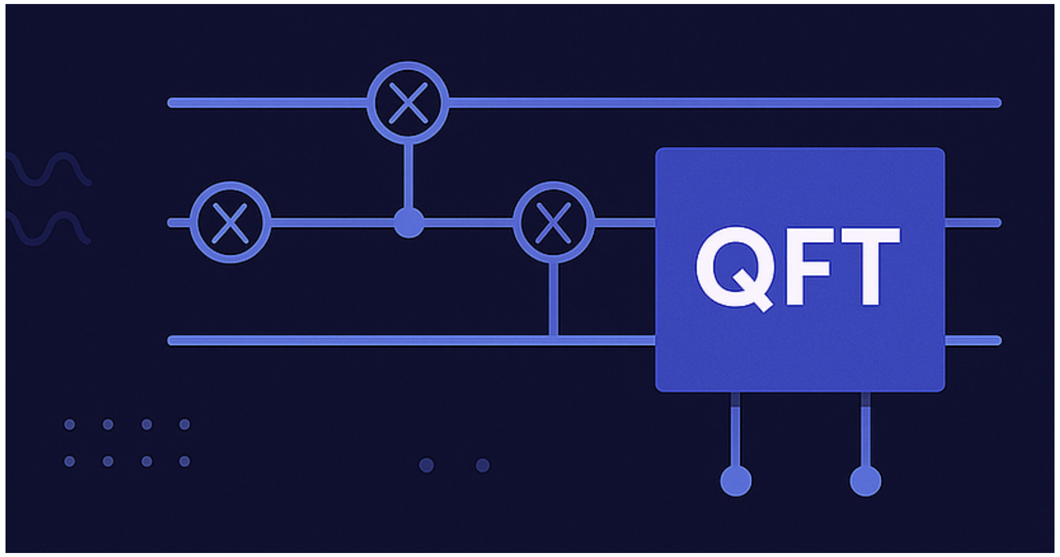



QUANTUM
COMPUTING

QUANTUM COMPUTING



- Apart from a potential seed-up, a different way of doing complex calculations.
- Quantum computers are expected to use less energy.
- QFT is quantum in essence.
- We need to think our problems as quantum systems, but… how ??



QUANTUM ALGORITHMS

- Quantum algorithms are well suited to solve those problems for which the quantum mechanic principles can be exploited:

    ✓ Superposition

$$|\psi\rangle = a_0 |0\rangle + a_1 |1\rangle$$

    ✓ Entanglement

$$|\psi_1 \psi_2\rangle = a_{00} |00\rangle + a_{01} |01\rangle + a_{10} |10\rangle + a_{11} |11\rangle$$

- Good for problems scaling exponentially or superpolinomially: i) Database querying, ii) Factoring integers into prime, iii) Combinatorial optimization, etc.

QUANTUM – HEP

- Monte Carlo integration:

Herbert, Q6, 823 (2022)
Agliardi, Grossi, Pellen, Prati, PLB 832, 137228 (2022)
Martínez de Lejarza, Grossi, Cieri, GR, 2305.01686

- Tree-level helicity amplitudes:

PBepari, Malik, Spannowsky, Williams, PRD103, 076020 (2021)

- Track reconstruction

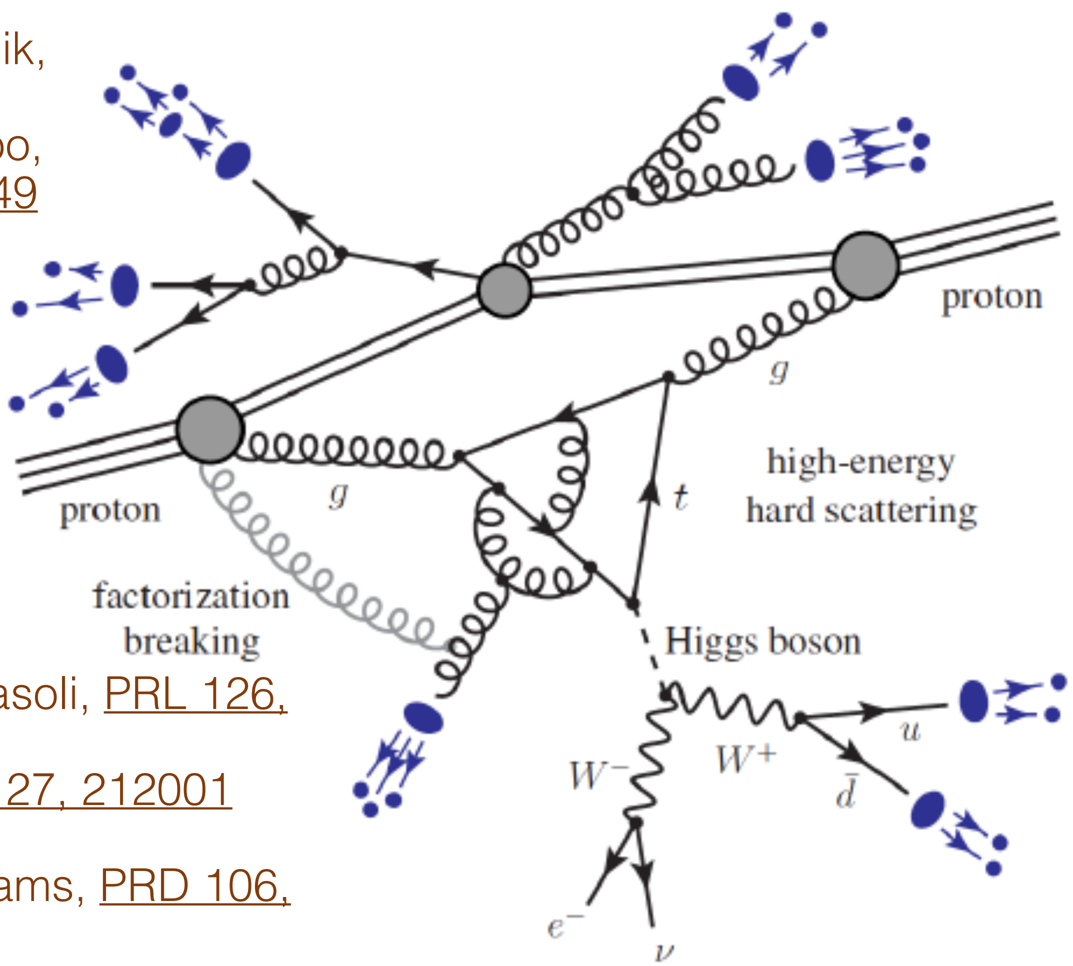
Mangano et al., PRD 105, 076012 (2022)
Duckett, Facini, Jastrzebski, Malik, Scanlon, Rettie, 2212.07279
Schwägerl, Issever, Jansen, Khoo, Kühn, Tüysüz, Weber, 2303.13249

- Parton densities:

Pérez-Salinas, Cruz-Martinez, Alhajri and Carrazza, PRD 103 (2021) 034027

- Parton showers:

Bauer, de Jong, Nachman, Provasoli, PRL 126, 062001 (2021)
Bauer, Freytsis, Nachman, PRL 127, 212001 (2021)
Bepari, Malik, Spannowsky, Williams, PRD 106, 056002 (2022)



- Multiloop scattering amplitudes

Ramírez, Rentería, GR, Sborlini, Vale Silva, JHEP 2205, 100 (2022)
Clemente, Crippa, Jansen, Ramírez, Rentería, GR, Sborlini, Vale Silva, 2210.13240
Ochoa-Oregon, Uribe Ramirez, Hernandez Pinto, Ramirez Uribe, Rodrigo, 2508.04019

- Jets in a medium

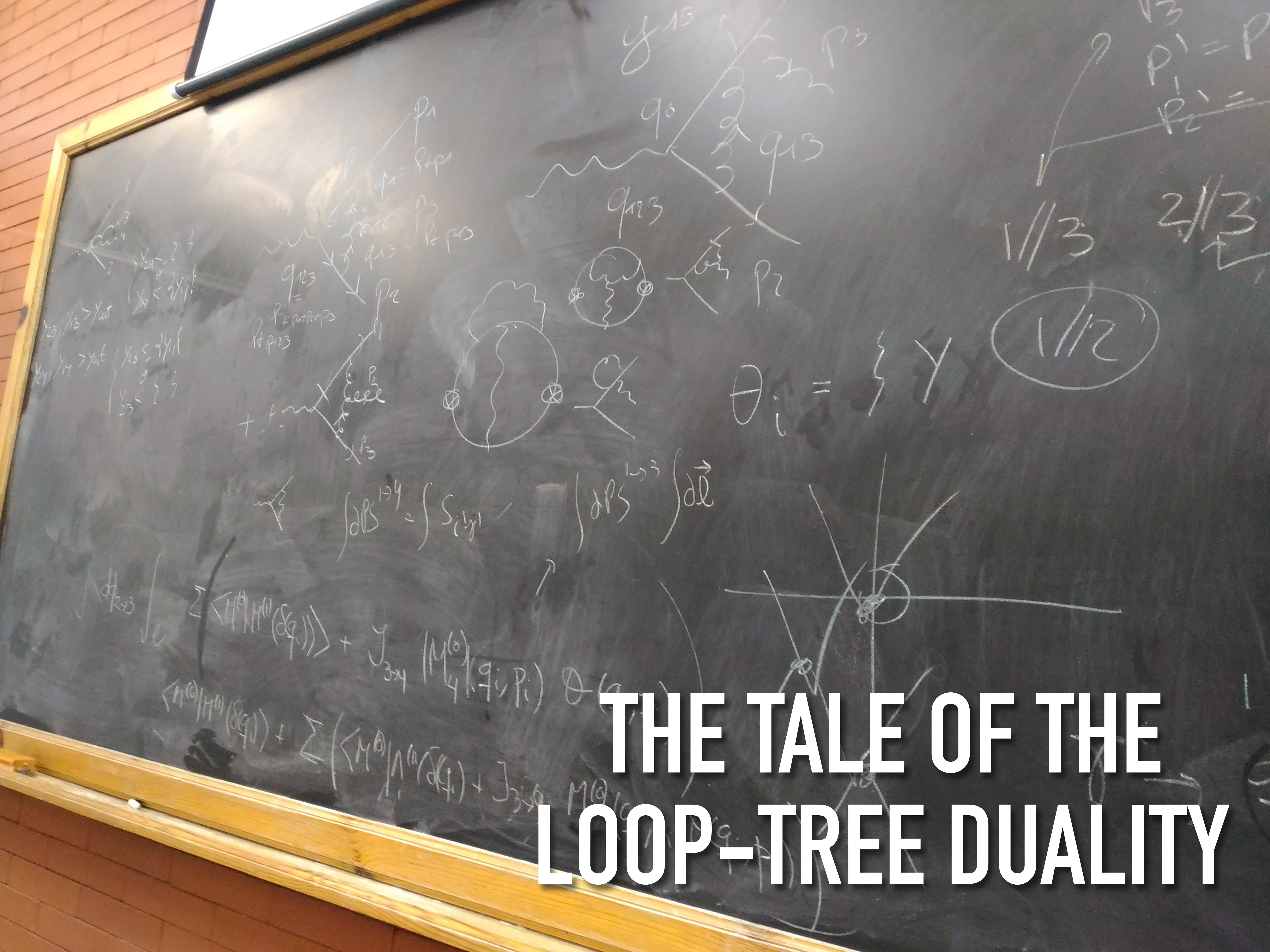
Barata, Du, Li, Qian, Salgado, PRD 106, 074013 (2022)
Barata, Salgado, EPJC 81, 862 (2021)

- 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)

- 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)



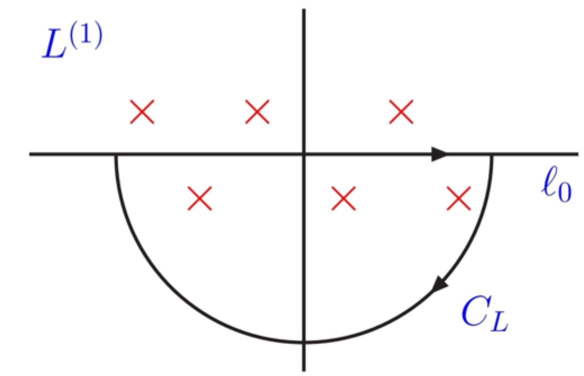
THE TALE OF THE LOOP-TREE DUALITY

LOOP-TREE DUALITY

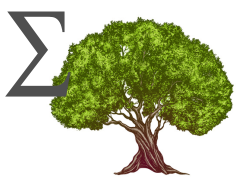
Catani, Gleisberg, Krauss, Rodrigo and Winter, *JHEP* **09** (2008) 065

Novel methodology aiming for a more suitable treatment of singularities in QFT

$$\int_\ell \mathcal{N}(\ell) \prod_{i=1}^{n} G_F(q_i)$$



$$\int_{C_L} \prod_{i=1}^{n} G_F(q_i) = -2\pi i \sum \mathrm{Res}\left(\prod_{i=1}^{n} G_F(q_i),\ \mathrm{Im}\,(\eta \bullet q_i) < 0 \right) = \sum$$



$$\left[\left(q_{i,0} - q_{i,0}^{(+)} \right) \left(q_{i,0} + q_{i,0}^{(+)} \right) \right]^{-1}$$

◎ $q_i = \ell + k_i$

◎ $\pm q_{i,0}^{(+)} = \pm \sqrt{\mathbf{q}_i^2 + m_i^2 - \imath 0}$

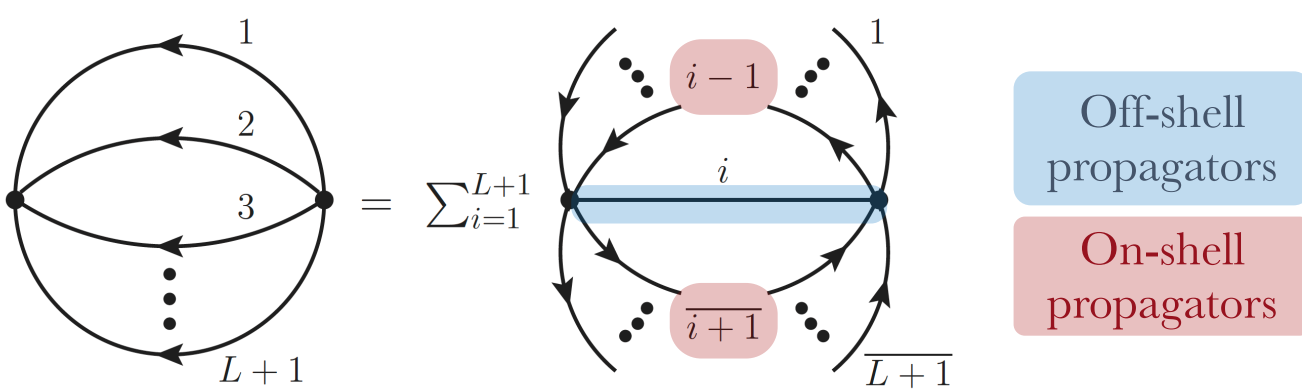
Two on-shell states

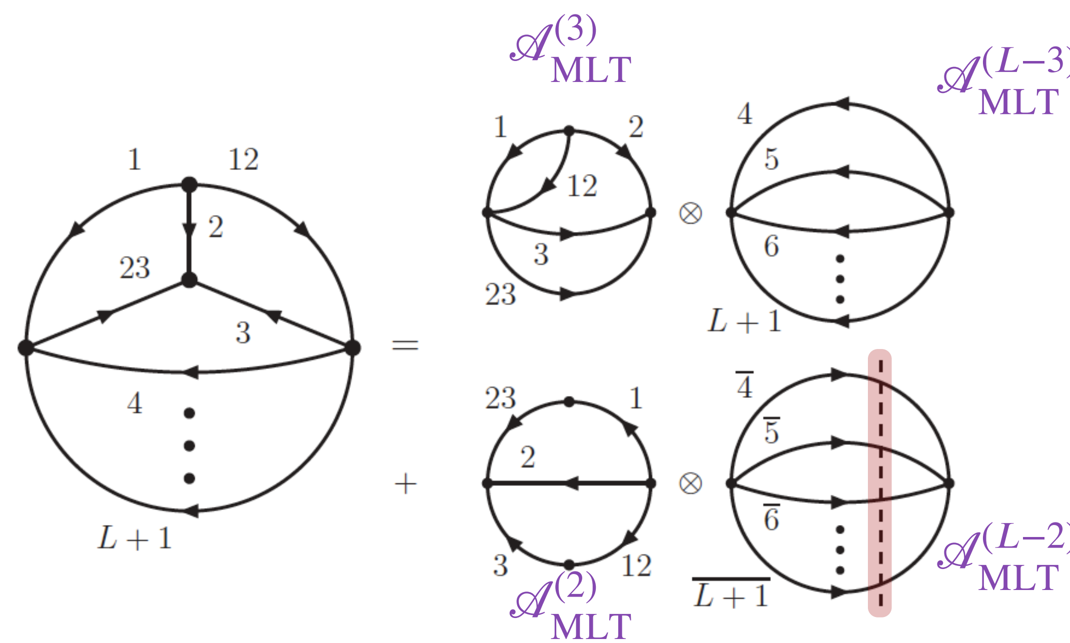
JHEP **10** (2010) 073 | *JHEP* **03** (2013) 025 | *JHEP* **11** (2014) 014 | *JHEP* **02** (2016) 044
arXiv: 1509.07167 | *JHEP* **08** (2016) 160 | *JHEP* **10** (2016) 162 | *EPJC* **77** (2017) 274
JHEP **12** (2017) 122 | *EPJC* **78** (2018) 231 | *EPJC* **78** (2018) 231 | *JHEP* **02** (2019) 143
JHEP 12 (2019) 163 | *EPJC* **81** (2021) 320 | *JHEP* **06** (2021) 089 | *PRD* **105** (2022) 016012

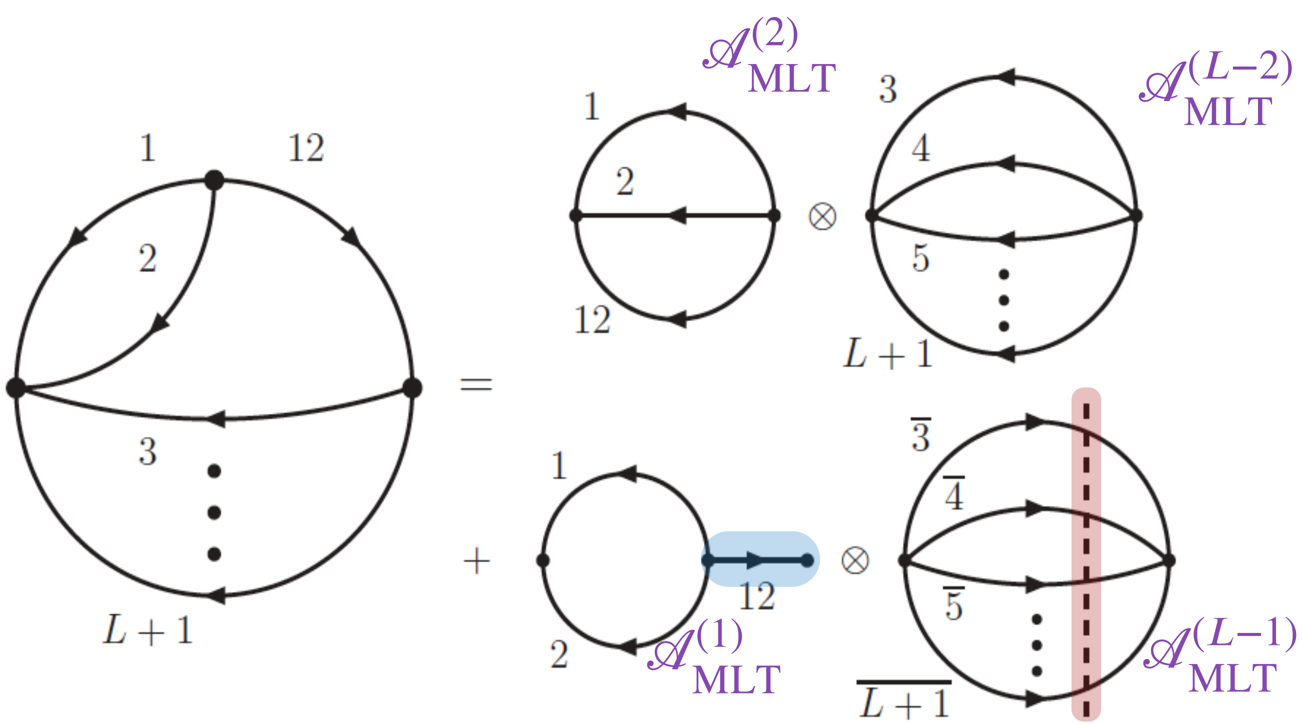
LTD AT ALL ORDERS

Aguilera, Driencourt, Hernández, Plenter, Ramírez, Rodrigo, Sborlini, Torres, Tracz, *PRL* 124 (2020) no.21, 211602.

LTD was firstly used to open any loop amplitude into tree level ones

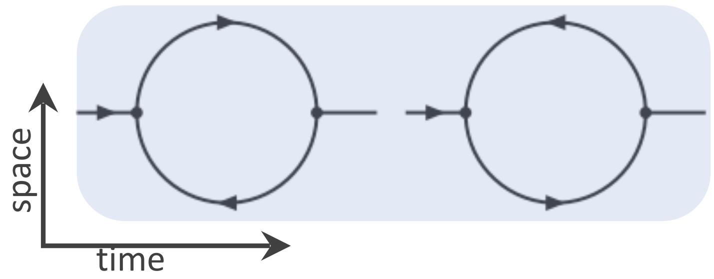






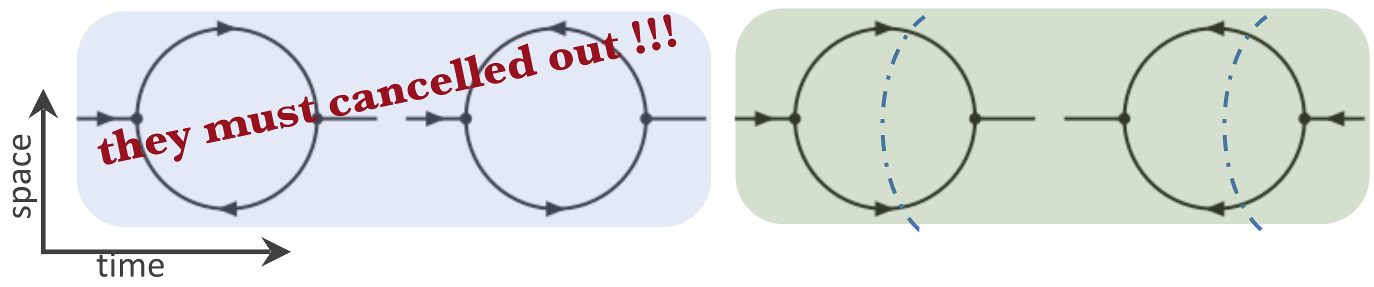
- The LTD representation is written in terms of nested residues
- Factorized convolution in terms of simpler subtopologies.

CANCELATION OF NON-CAUSAL CONFIGURATIONS



- ◎ The emmited particle returning to the initial point generates **non-physical singularities**.
- ◎ Directed cyclic graph are **not allowed**.

CANCELATION OF NON-CAUSAL CONFIGURATIONS

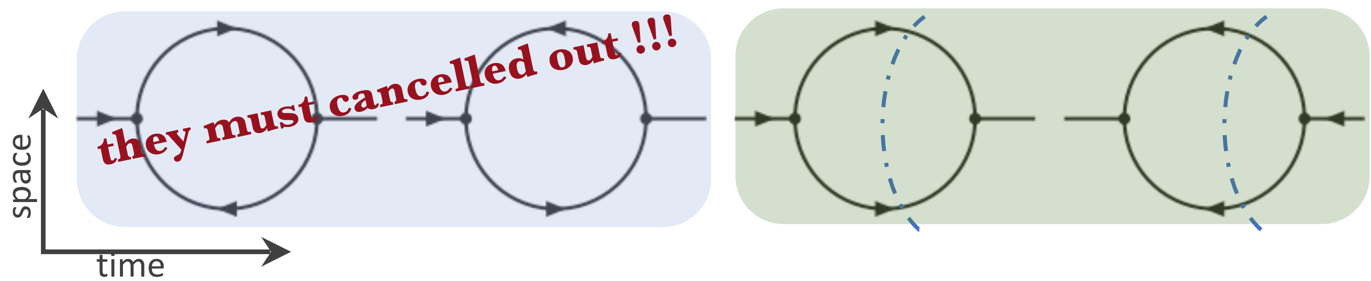


◎ The emmited particle returning to the initial point generates **non-physical singularities**.

◎ Directed cyclic graph are **not allowed**.

◎A causal singularity arises when the particles are set on shell.

CANCELATION OF NON-CAUSAL CONFIGURATIONS



◎ The emmited particle returning to the initial point generates **non-physical singularities**.

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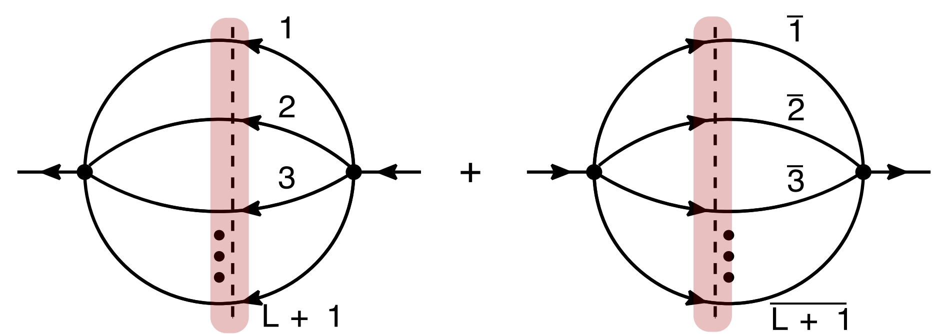
Causal Maximal Loop Topology

$$\mathcal{A}^{(L)}_{MLT}(1,\dots,L+1) = \int_{\vec{\ell}_{1},\dots,\vec{\ell}_{L}} \frac{1}{x_{L+1}}\left(\frac{1}{\lambda^{+}_{L+1}}+\frac{1}{\lambda^{-}_{L+1}}\right) =$$



$$x_{L+1} = \prod_{i=1}^{L+1} 2q_{i,0}^{(+)} \qquad \lambda^{\pm}_{L+1} = \sum_{i=1}^{L+1} q_{i,0}^{(+)} \pm k_{L+1,0}$$

external momentum

and $\int_{\vec{\ell}_s} \equiv -\mu^{4-d}\int \frac{d^{d-1}\ell_s}{(2\pi)^{d-1}}$

◎ Manifestly free of unphysical singularities and the same expression regardless the number of loops

◎ Causal singularities occur when either λ^{+}_{L+1} or λ^{-}_{L+1} vanishes, depending on the sign of $k_{L+1,0}$.

CAUSALITY WITH AN EXTRA VERTEX

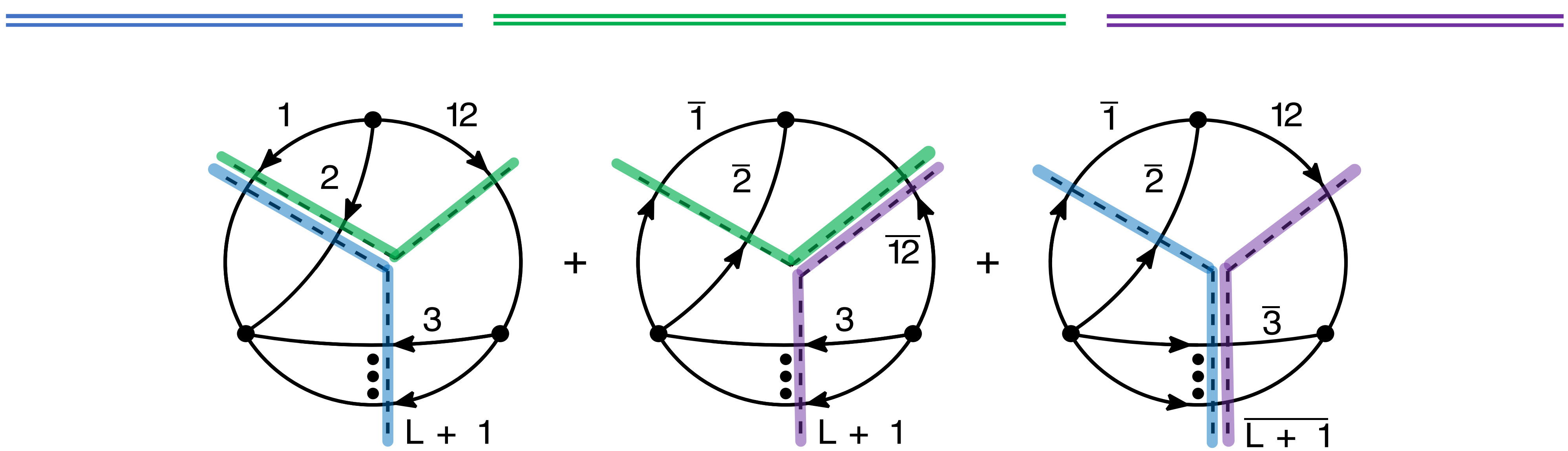
LTD causal representation is given in terms of products of causal propagators interpreted as **entangled thresholds**

Aguilera, Hernández, Rodrigo, Sborlini, Torres, *JHEP* 01, 069 (2021).

Causal Next-to-Maximal Loop Topology

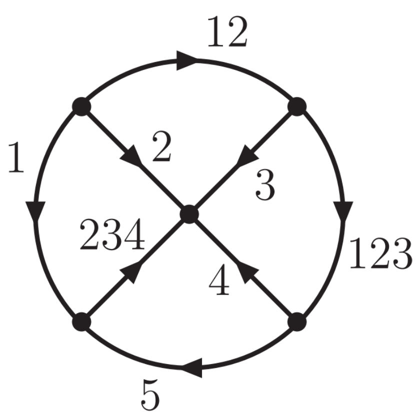
$$\mathscr{A}^{(L)}_{\mathrm{NMLT}}(1,\dots,L+1,12) = \int_{\vec{\ell}_1,..,\vec{\ell}_L} \frac{1}{x_{L+2}} \left[\frac{1}{\lambda_1^+ \lambda_2^-} + \frac{1}{\lambda_2^+ \lambda_3^-} + \frac{1}{\lambda_1^+ \lambda_3^-} + \left(\lambda_i^+ \leftrightarrow \lambda_i^-\right) \right]$$

$$\lambda_1^\pm = \sum_{i=1}^{L+1} q_{i,0}^{(+)} \pm k_{L+1,0} \qquad \lambda_2^\pm = q_{1,0}^{(+)} + q_{2,0}^{(+)} + q_{L+2,0}^{(+)} \pm k_{12,0} \qquad \lambda_3^\pm = \sum_{i=3}^{L+2} q_{i,0}^{(+)} \pm k_{3(L+2),0}$$

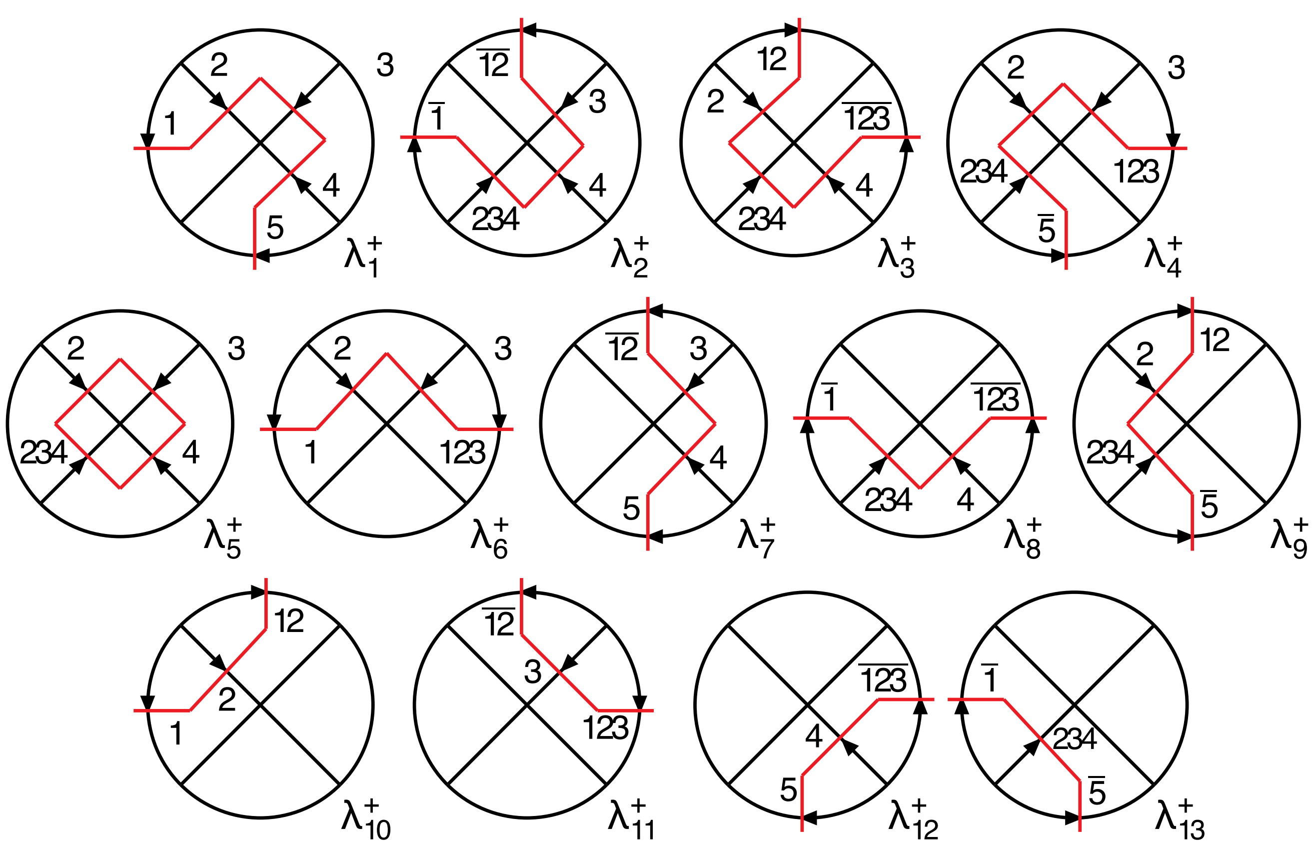


N3MLT CAUSAL REPRESENTATION

Ramírez, Hernández, Rodrigo, Sborlini, and Torres, *JHEP* 04, 129 (2021).

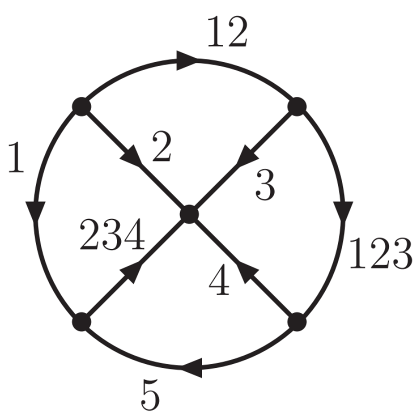


$$= \int_{\vec{\ell}_1,\dots,\vec{\ell}_L} \frac{1}{x_{L+4}} \sum_{\sigma} \frac{\mathcal{N}_{\sigma(i_1,\dots,i_4)}\left(\left\{q^{(+)}_{s,0},\ k_{j,0}\right\}\right)}{\lambda_{\sigma(i_1)}\lambda_{\sigma(i_2)}\lambda_{\sigma(i_3)}\lambda_{\sigma(i_4)}}$$



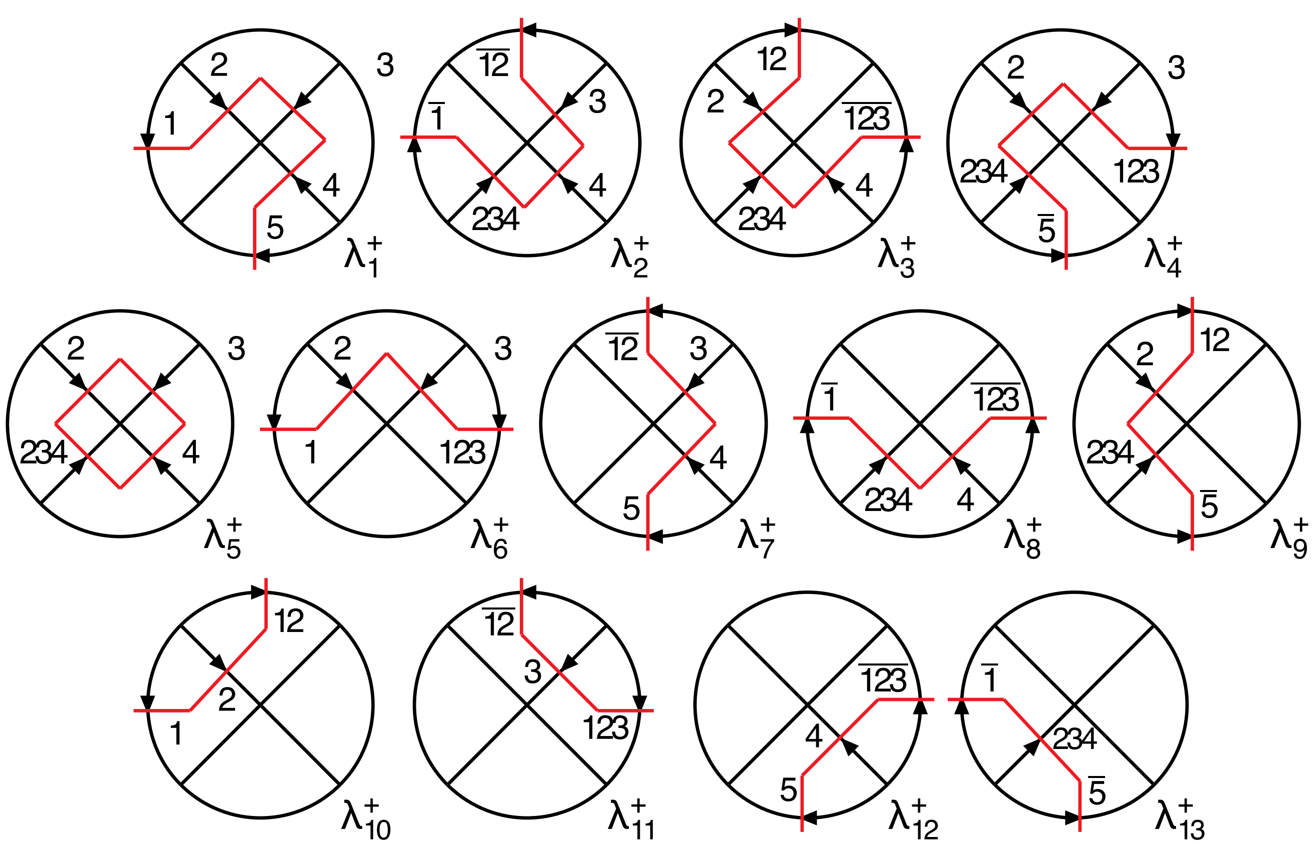
N3MLT CAUSAL REPRESENTATION

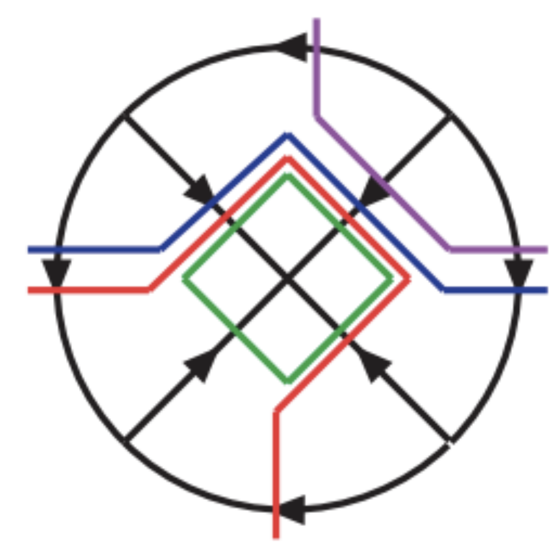
Ramírez, Hernández, Rodrigo, Sborlini, and Torres, *JHEP* 04, 129 (2021).

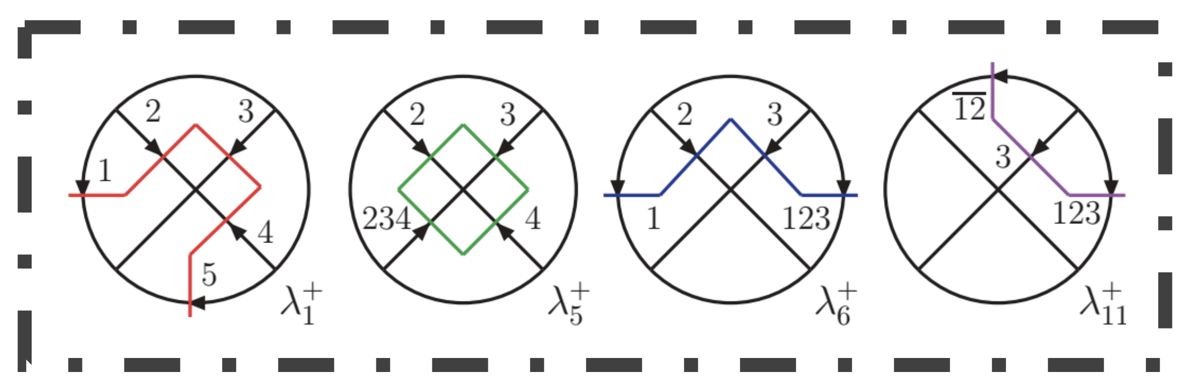


$$= \int_{\vec{\ell}_1,\dots,\vec{\ell}_L} \frac{1}{x_{L+4}} \sum_\sigma \frac{\mathcal{N}_{\sigma(i_1,\dots,i_4)}\left(\left\{q_{s,0}^{(+)},\ k_{j,0}\right\}\right)}{\lambda_{\sigma(i_1)}\lambda_{\sigma(i_2)}\lambda_{\sigma(i_3)}\lambda_{\sigma(i_4)}}$$

Compatibility among
26 thresholds



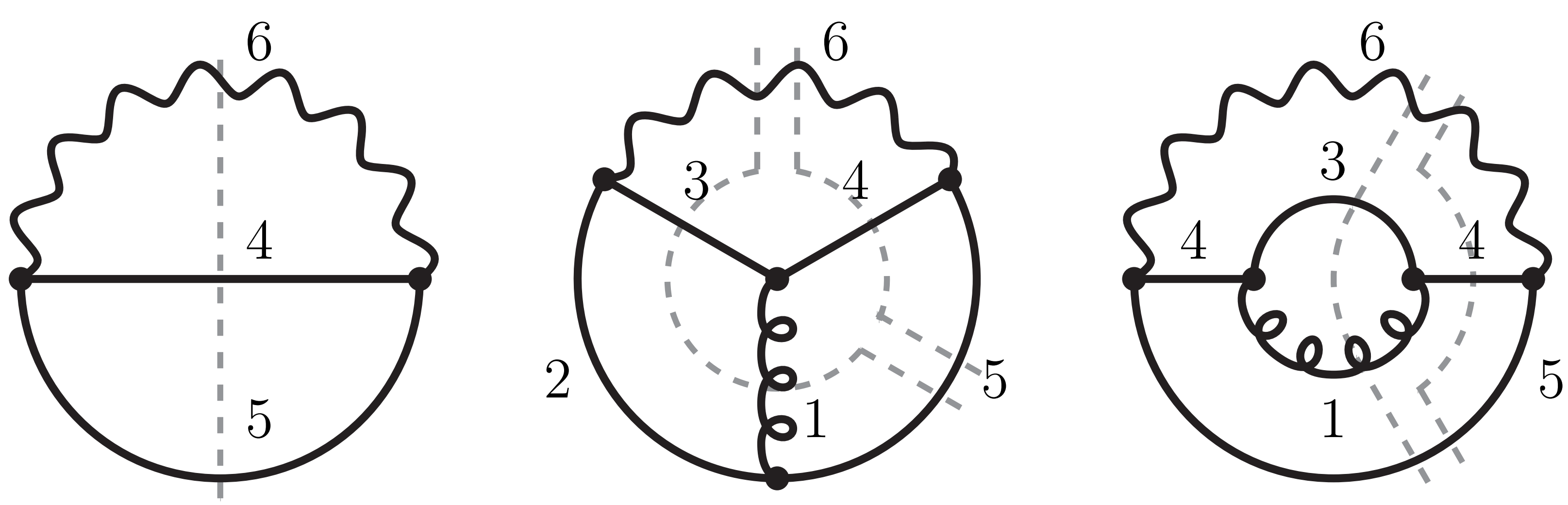




CAUSAL CROSS-SECTIONS

Ramírez-Uribe et al. JHEP 01 (2025) 103

- Causal integrands can be used to build physical observables.
- From MLT, NMLT topologies, it was possible to reproduce the well-known $f \to q\bar{q}$, with $f \in \{\gamma^*, H\}$ at NLO in QCD.
- Starting from vacuum amplitudes,



and the ***selection*** of causal amplitudes and the correct mapping of variables to cancel out physical singularities, lead to a perfect agreement with respect to classical DREG results.

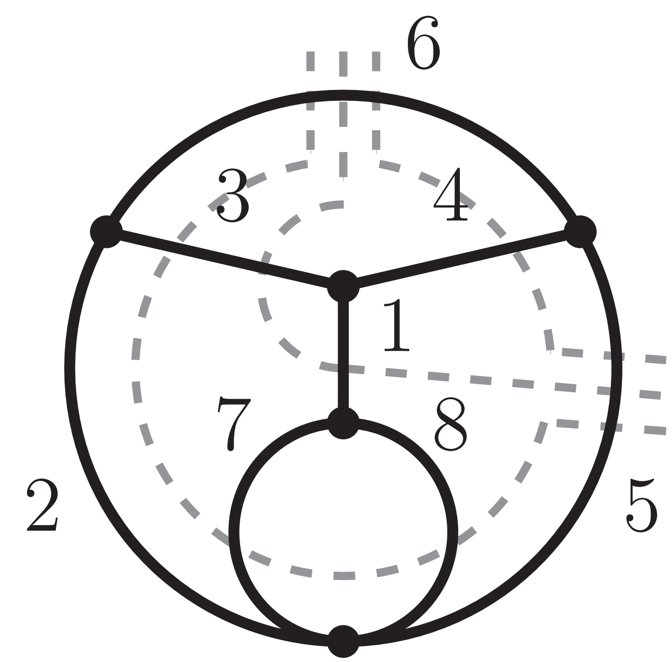
Ramírez-Uribe et al. JHEP 01 (2025) 103

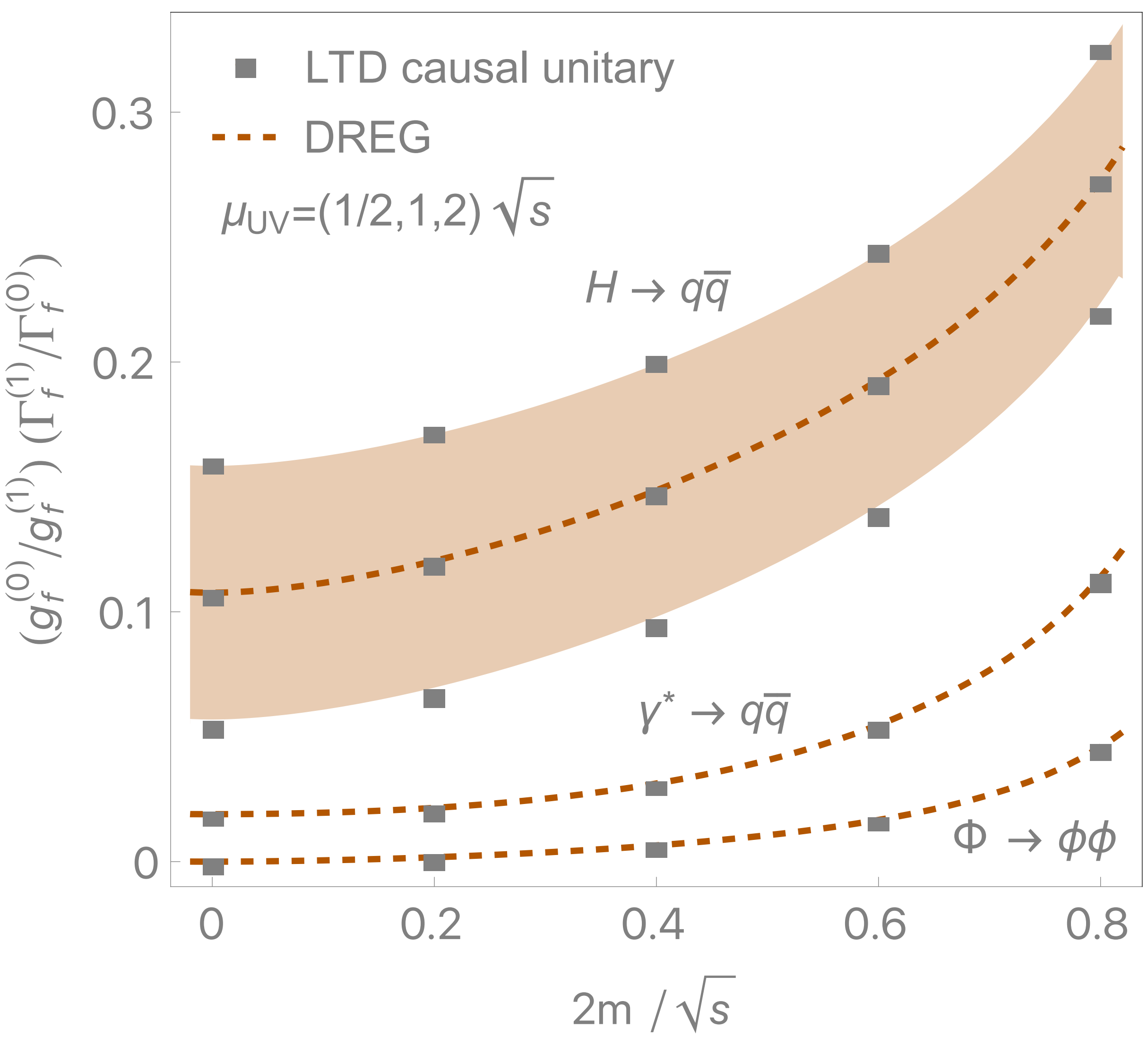
CAUSAL CROSS-SECTIONS

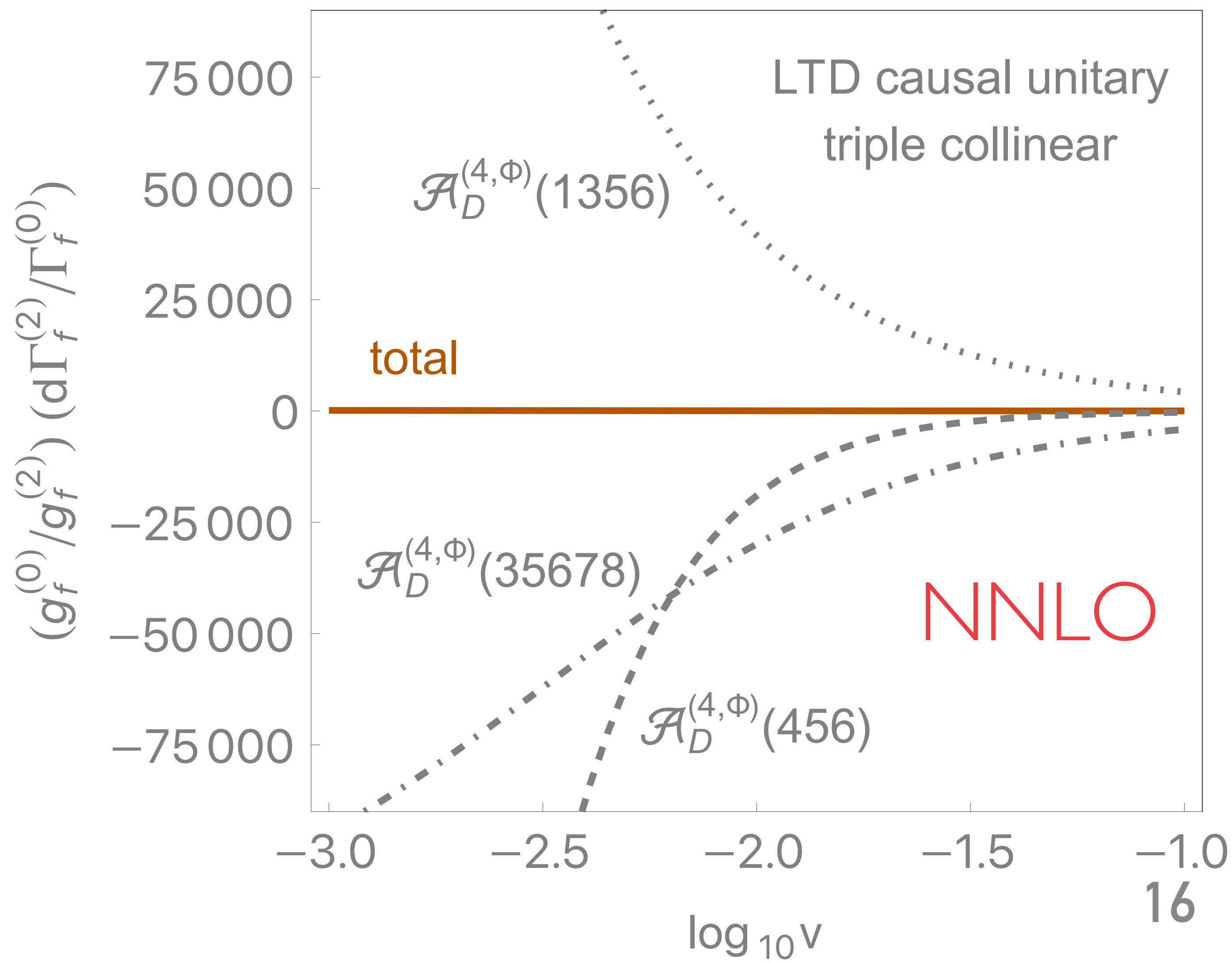
- We present also the numerical evaluation for the heavy scalar decay into light scalars.

$\Phi \to \phi\phi$

NNLO







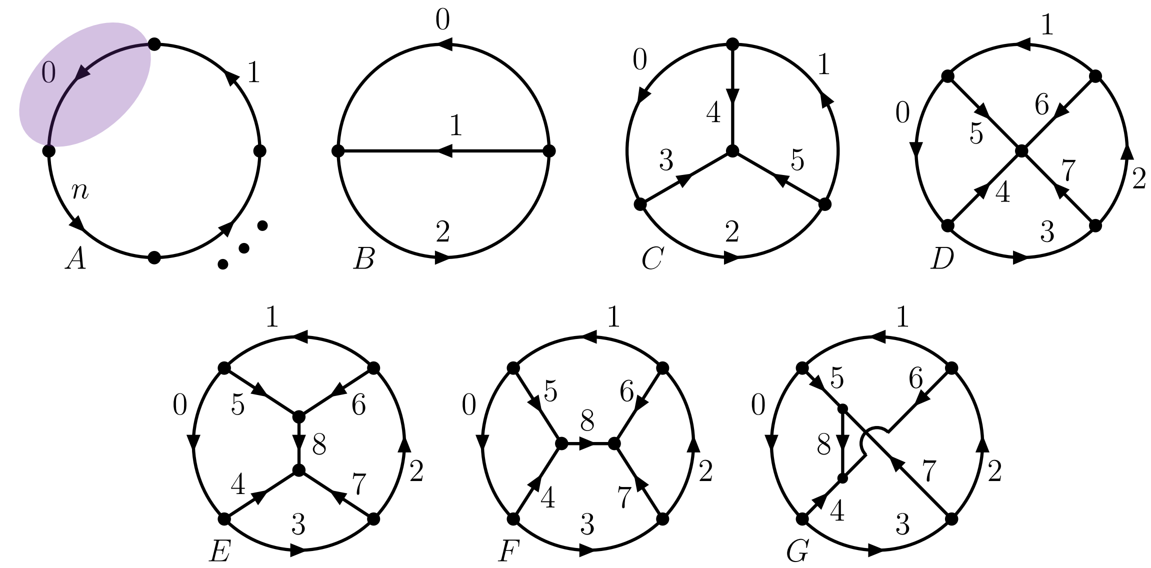

QUANTUM QUERYING
OF CAUSALITY

QUANTUM QUERYING OF CAUSAL GRAPHS

Representative multiloop topologies.

Two possible on-shell states

quantum sates $|1\rangle$ and $|0\rangle$



Causal representation is closely related to **graph theory**:

causal configurations are **directed acyclic graphs**

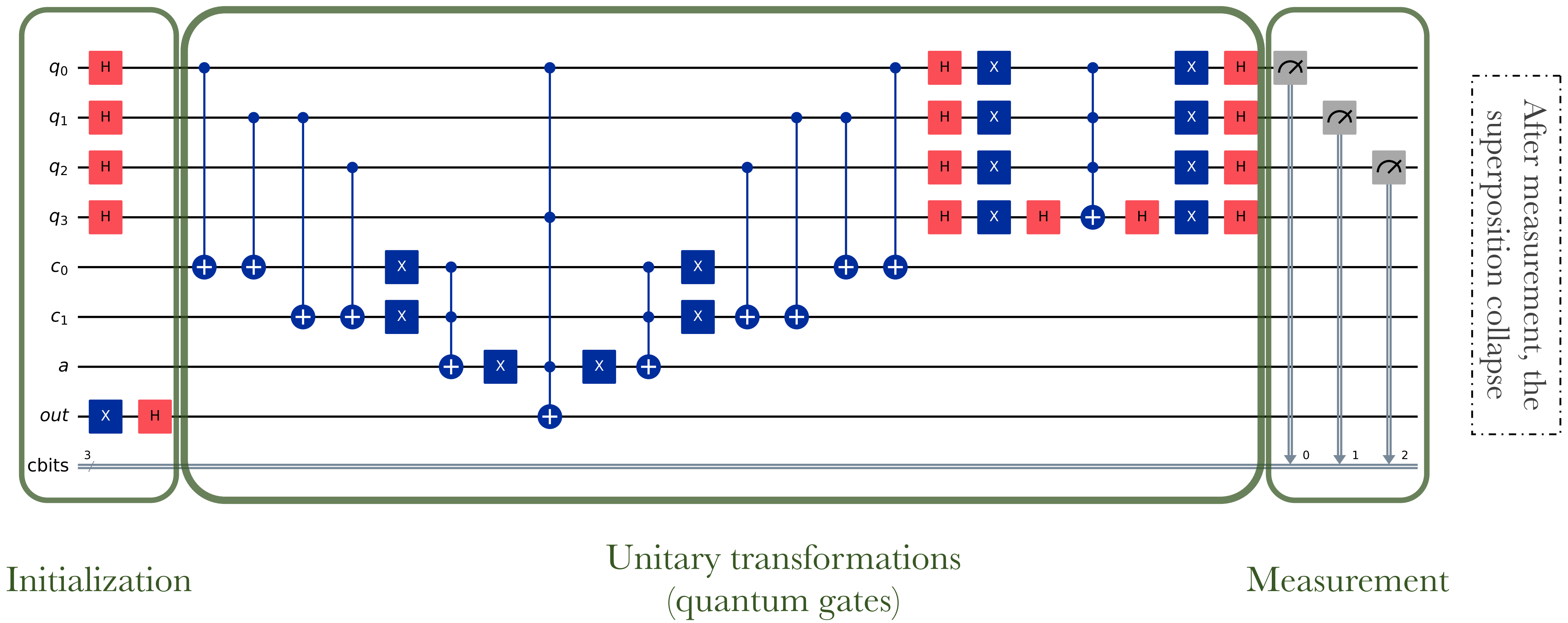
Grover's algorithm
Amplitud amplification

Variational quantum eigensolver
Minimization of a Hamiltonian

Ramírez, Rentería, Rodrigo, Sborlini, and Vale, *JHEP* 05, 100 (2022)
Clemente, Crippa, Jansen, Ramírez, Rentería, GR, Sborlini, Vale, 2210.13240

QUANTUM CIRCUITS

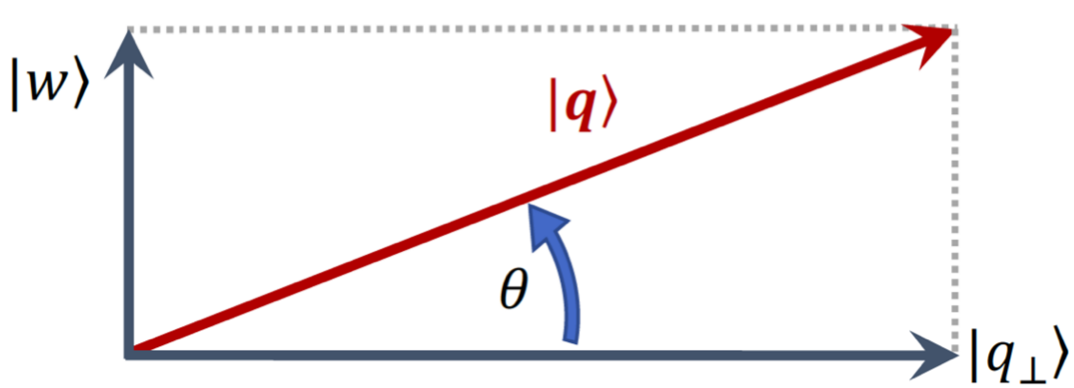
- The problem is clear, search for all causal configurations, DAG, and then make all causal flows compatible.
- How you do it in a quantum computer ?



GROVER'S QUANTUM ALGORITHM

Having n propagators generates $N = 2^n$ possible configurations

1) Superposition
2) Oracle
3) Diffusion



1) Superposition

$$|q\rangle = \begin{cases} \frac{1}{\sqrt{N}} \sum |x\rangle \\ \cos\theta\,|q_\perp\rangle + \sin\theta\,|w\rangle \end{cases}$$

Mixing angle

Winning state **encodes causal states**

Orthogonal state

$$|w\rangle = \frac{1}{\sqrt{r}} \sum_{x \in w} |x\rangle$$

$$|q_\perp\rangle = \frac{1}{\sqrt{N-r}} \sum_{x \notin w} |x\rangle$$

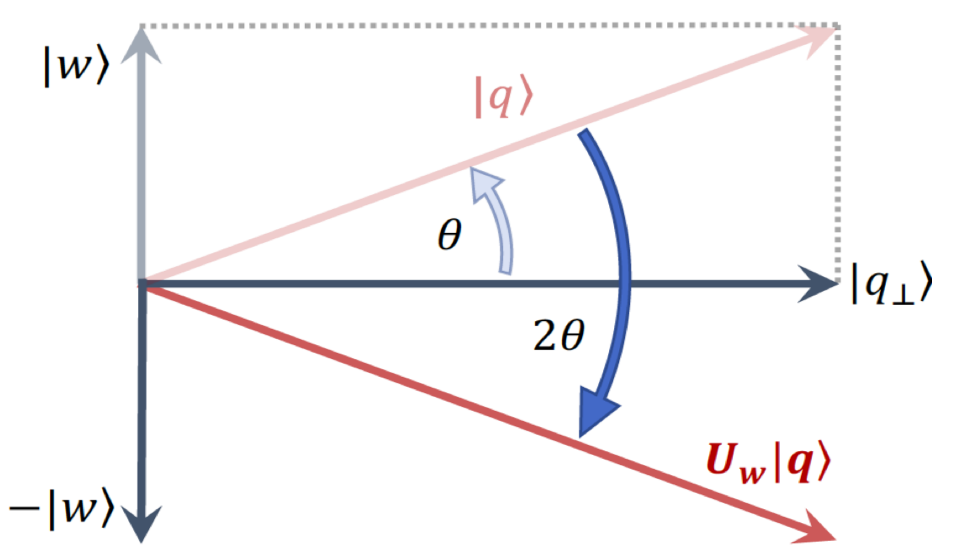
$$\theta = \arcsin\sqrt{r/N}$$

GROVER'S QUANTUM ALGORITHM

2) Oracle operator $\left(U_w = \boldsymbol{I} - 2|w\rangle\langle w|\right)$

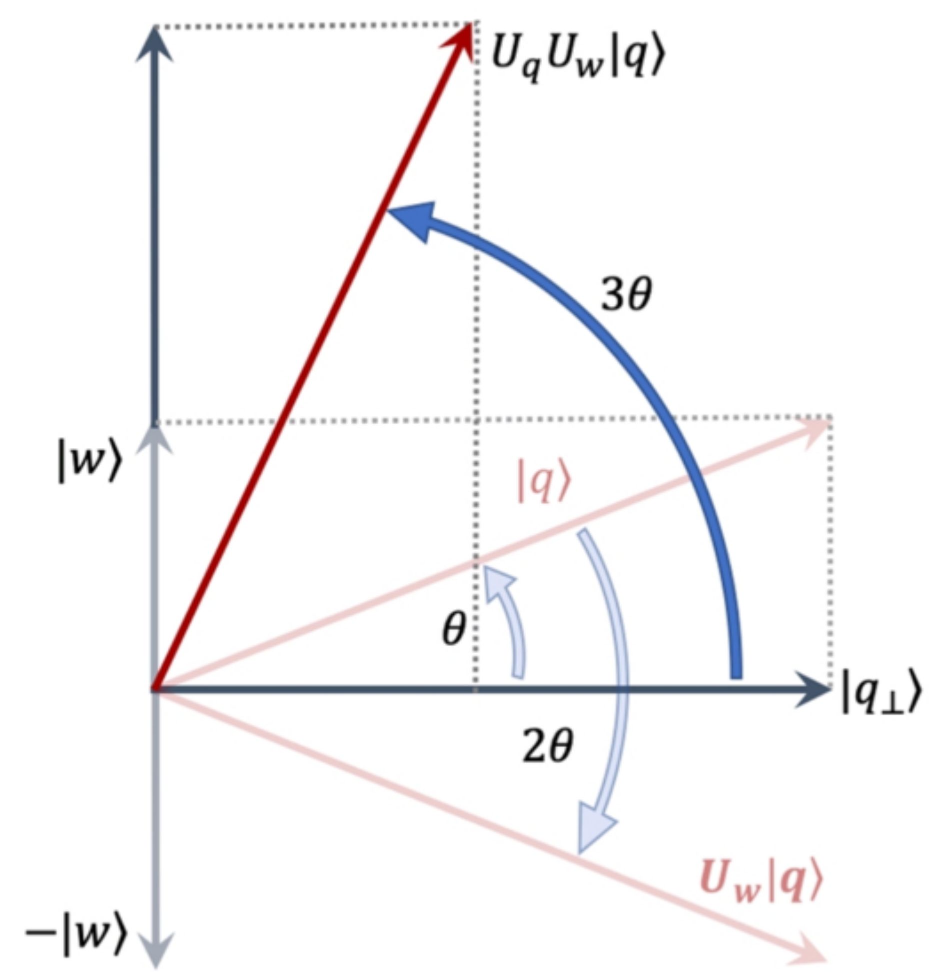
$$U_w|x\rangle = \begin{cases} -|x\rangle & if\ x \in w \\ |x\rangle & if\ x \notin w \end{cases}$$

Flips the state $|x\rangle$ if $x \in |w\rangle$ and leaves it unchanged otherwise.



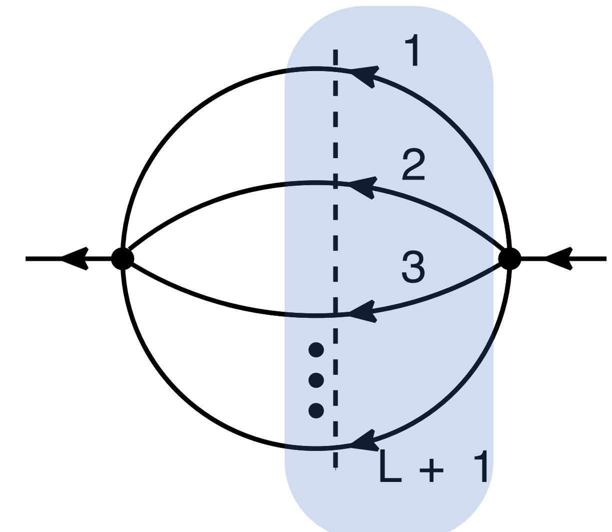
3) Diffusion operator $\left(U_q = 2|q\rangle\langle q| - \boldsymbol{I}\right)$

Performs a reflection around the initial state $|q\rangle$

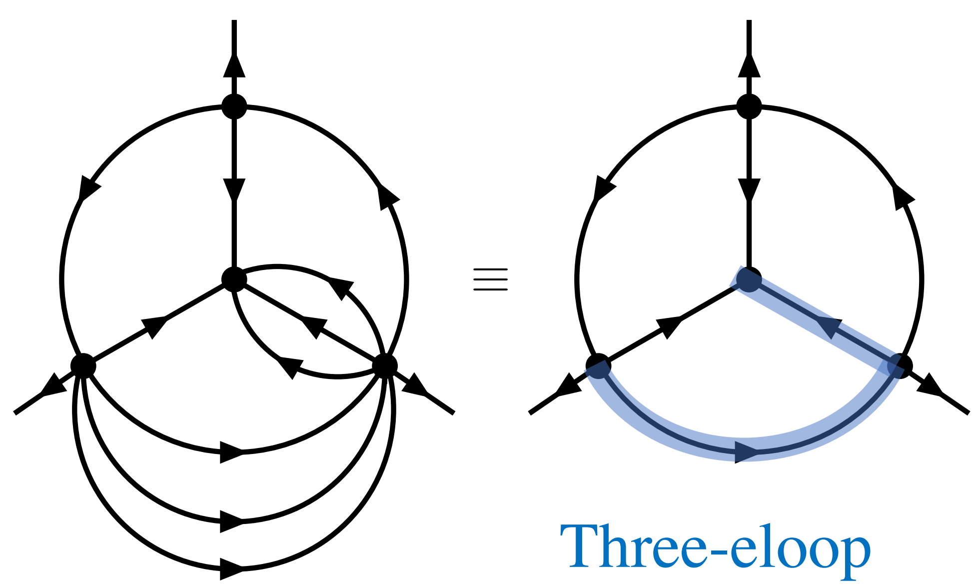


THE GENERAL GRAPH ELEMENTS – ELOOPS

Causality requires the momentum flow of all the propagators, connecting two vertices, to be aligned in the same direction.



Dual causal representation can be described by relying on reduced Feynman graphs built from vertices and edges.



Edges are defined as the union of an arbitrary number of propagators connecting two interaction vertices.

QUANTUM CIRCUIT

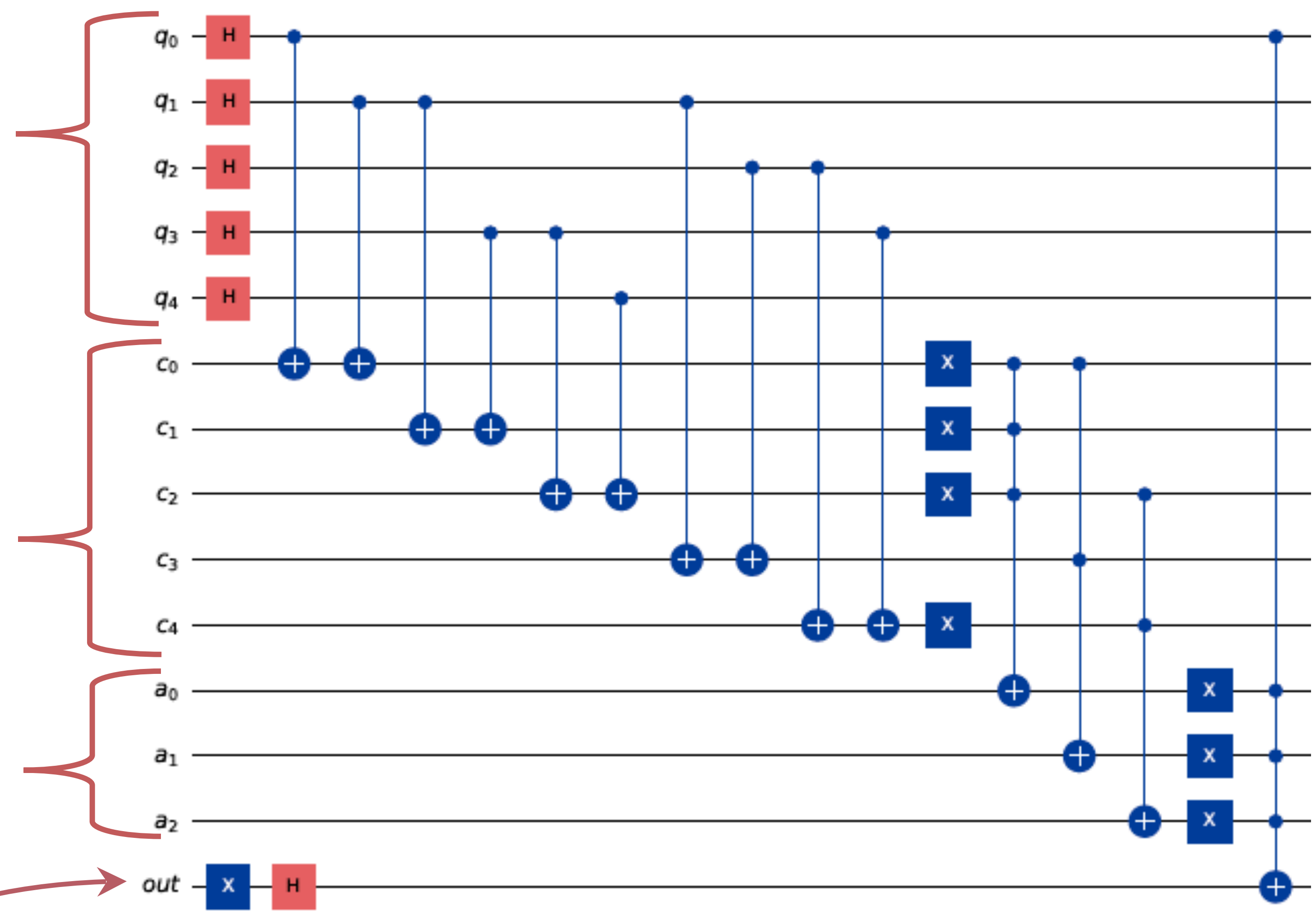
Each topology requires a certain number of qubits, divided in four main groups,

$|q\rangle$ Encodes the state of the edges.

$|c\rangle$ Stores binary clauses that probe if two adjacent edges are oriented in the same direction.

$$c_{ij} \equiv \left(q_i = q_j\right) \qquad \bar{c}_{ij} \equiv \left(q_i \neq q_j\right)$$

$|a\rangle$ Stores the eloop clauses probing if all the qubits in each subloop form a cyclic circuit.



$|out\rangle$ Oracle's marker

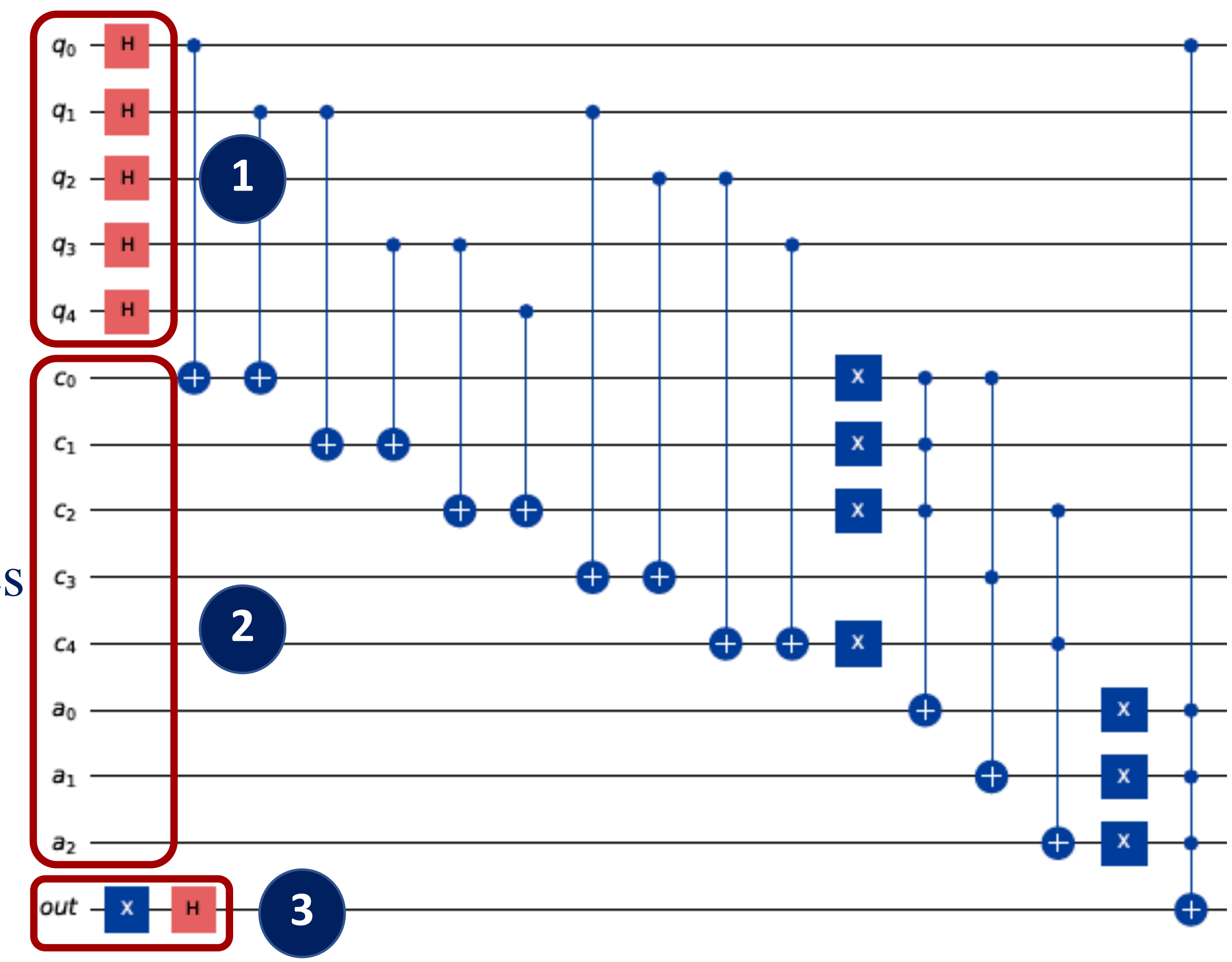
INITIALIZATION

In our case, we shall use the qubits to build the possibilities of energy modes, the combination for DAG, and the amplification of the probability.

Edges

Binary and eloop clauses

Grover's marker



1 Superposition
$|q\rangle = H^{\bigotimes n}|0\rangle$

2 $|c\rangle$ and $|a\rangle$ are set to $|0\rangle$

3 The Grover's marker
$$|out\rangle = \frac{|0\rangle - |1\rangle}{\sqrt{2}} \equiv |-\rangle$$

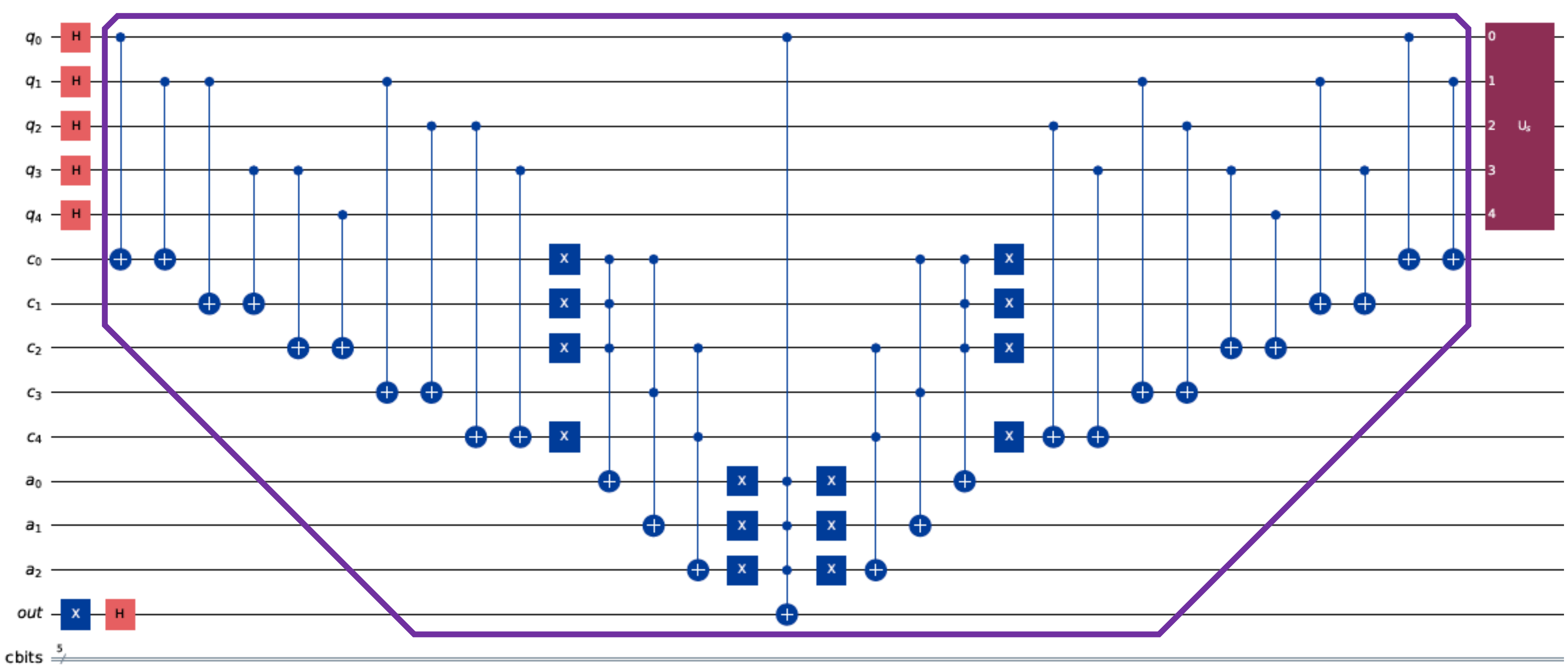
ORACLE OPERATOR

The oracle operator is, in general, the mirror of the original querying confirguration

$$U_w|q\rangle|c\rangle|a\rangle|out\rangle = |q\rangle|c\rangle|a\rangle\left|out \otimes f(a, q_0)\right\rangle$$

$$|out \otimes 0\rangle \quad |out\rangle$$

$$|out \otimes 1\rangle = -|out\rangle$$



BINARY CLAUSES

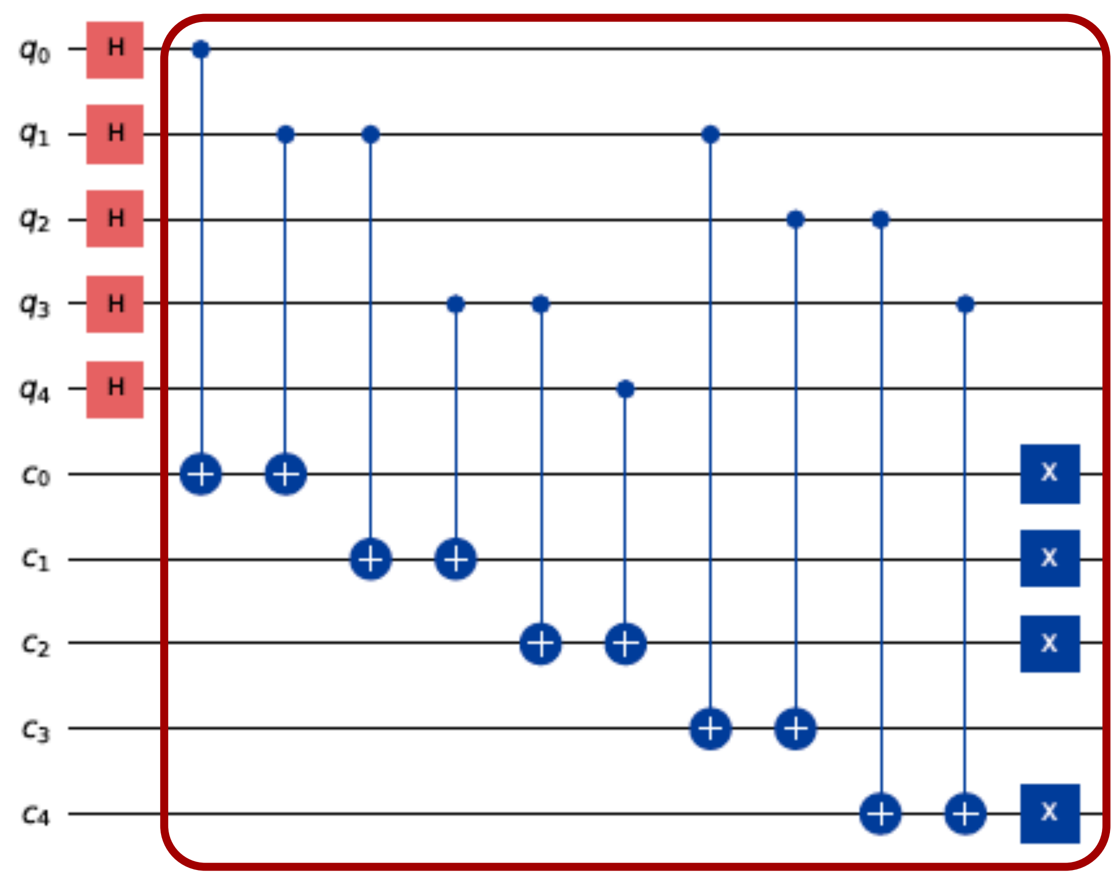
As an example of the methodology applied to cLTD, consider the two eloops 5 edges topology

$$\bar{c}_{ij} \equiv \left(q_i \neq q_j\right)$$

Two CNOT gates

$$c_{ij} \equiv \left(q_i = q_j\right)$$

Two CNOT gates and extra XNOT gate



$c_{01} \equiv \left(q_0 = q_1\right)$

$c_{13} \equiv \left(q_1 = q_3\right)$

$c_{34} \equiv \left(q_3 = q_4\right)$

$\bar{c}_{12} \equiv \left(q_1 \neq q_2\right)$

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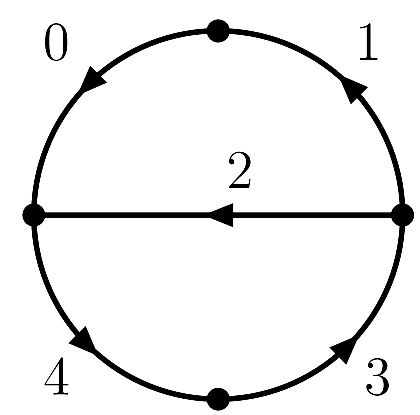

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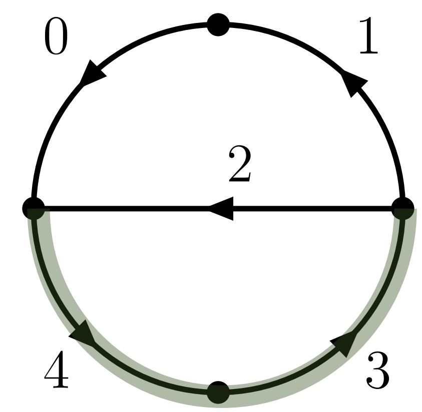

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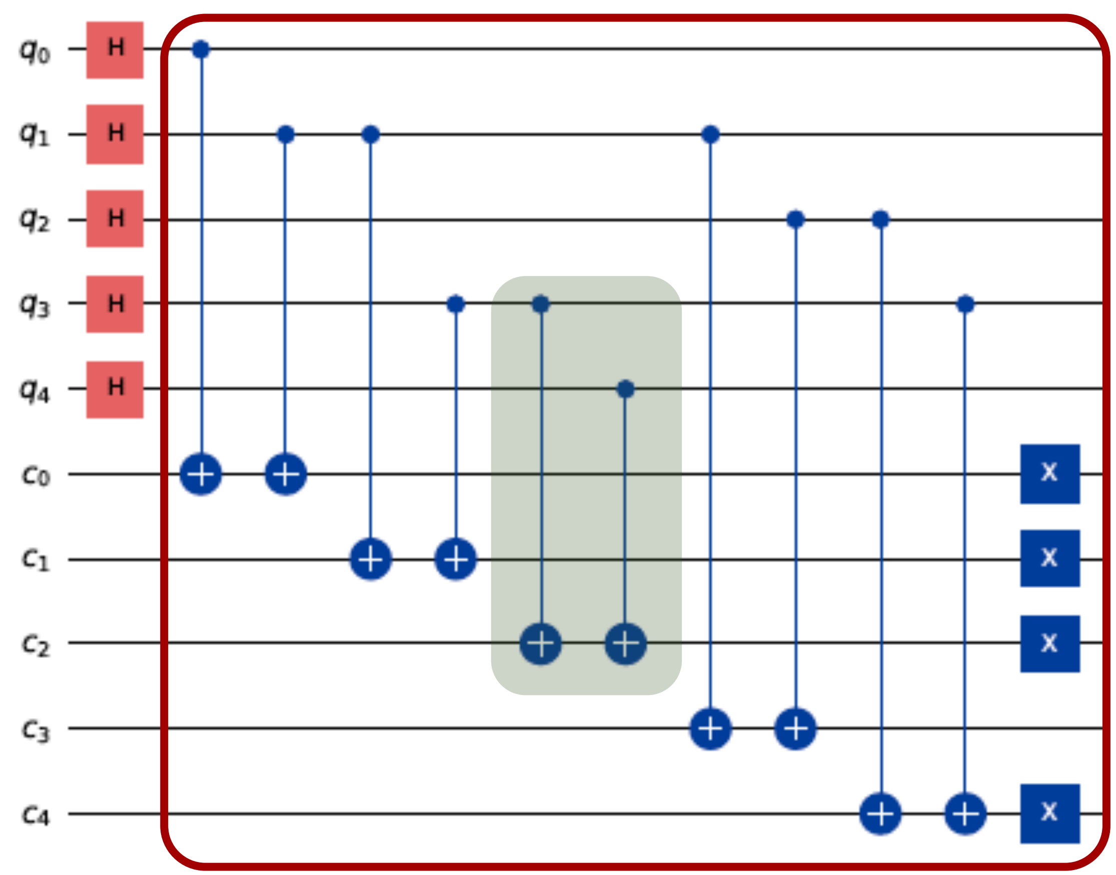

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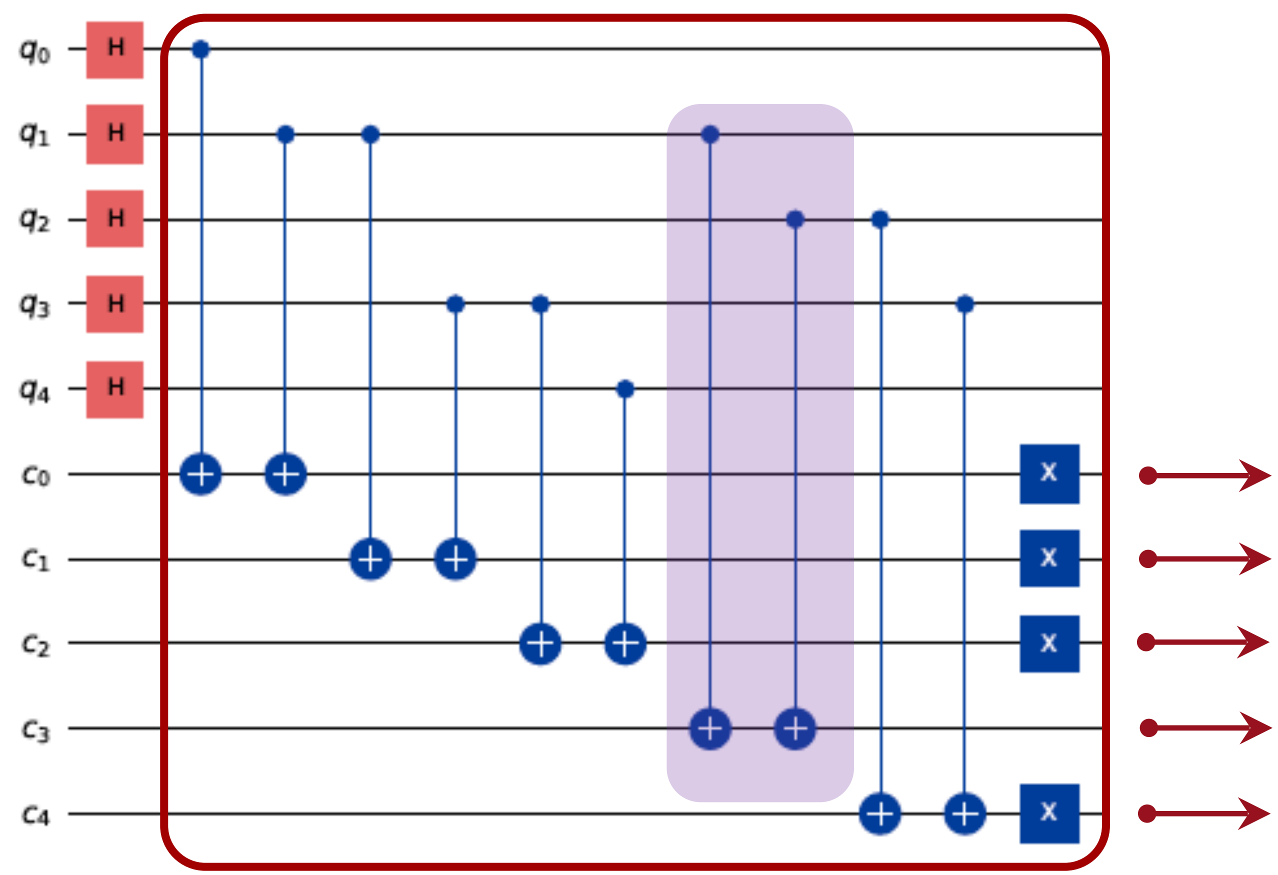

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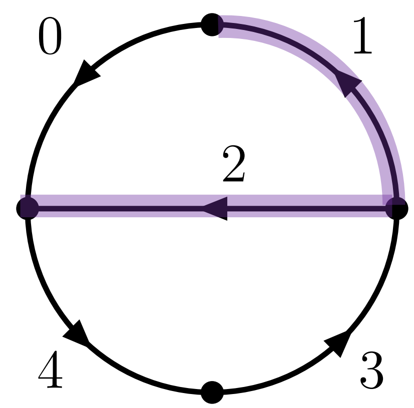

CAUSALITY IN BOTH DIRECTIONS

There is no need to compute all causal flows, since the reversed flow is also causal.

Eloop clauses

$$a_0 = \neg\left(c_{01} \wedge c_{13} \wedge c_{34}\right)$$
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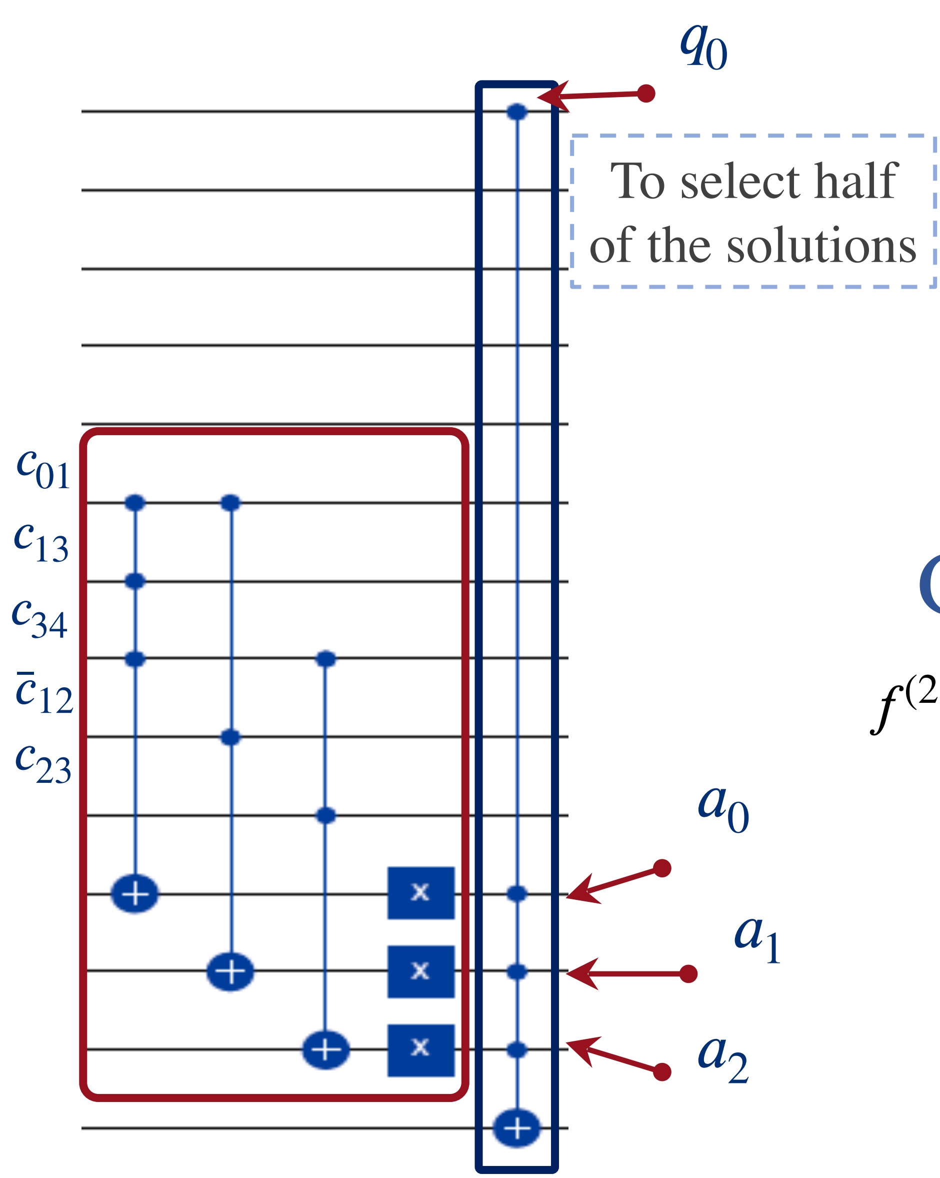

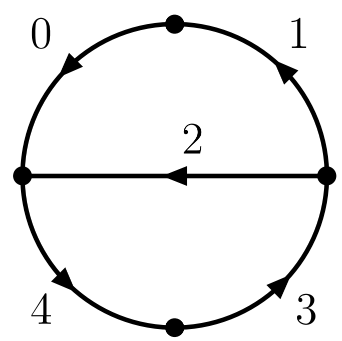

Grover's marker

$$f^{(2)}(a, q) = \left(a_0 \wedge a_1 \wedge a_2\right) \wedge q_0$$

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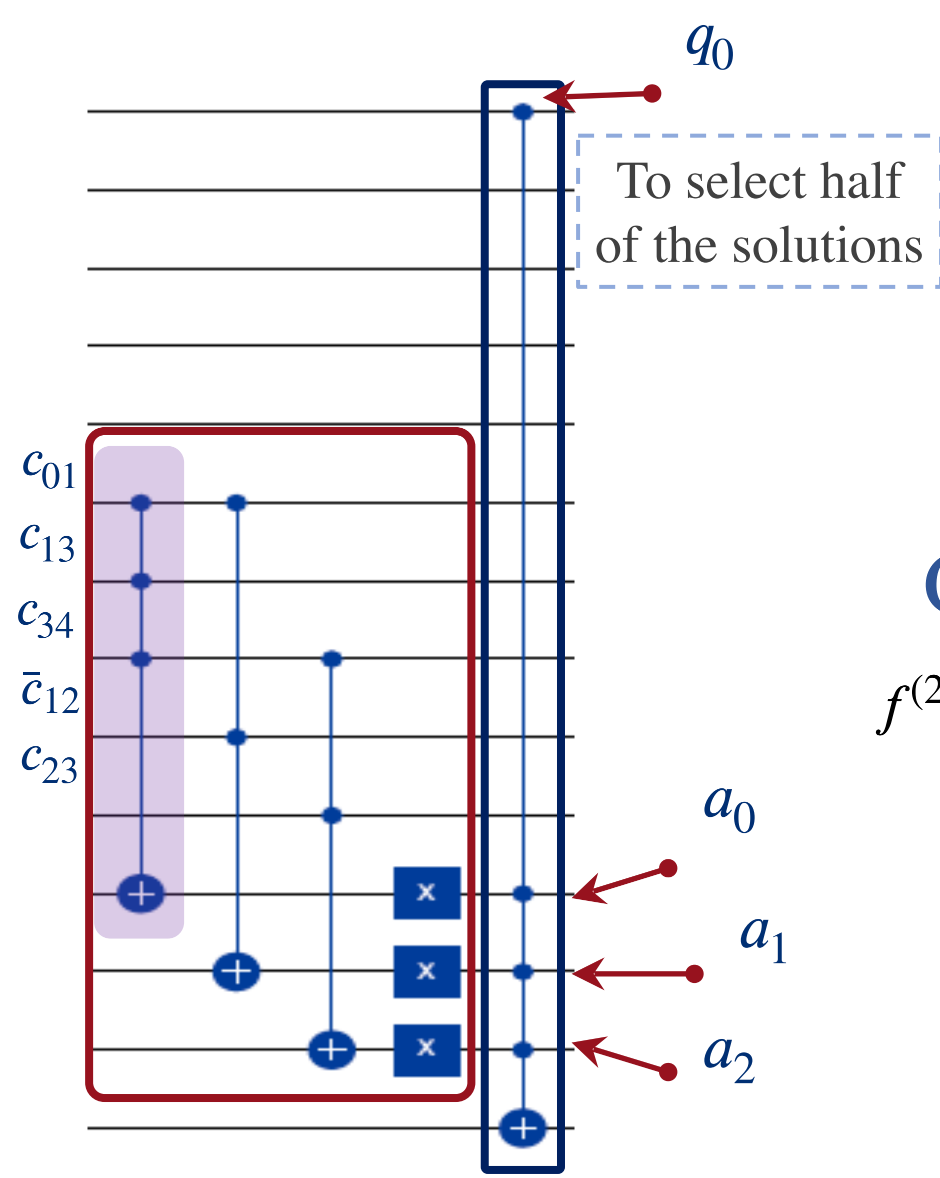

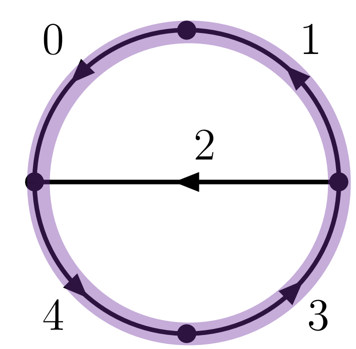

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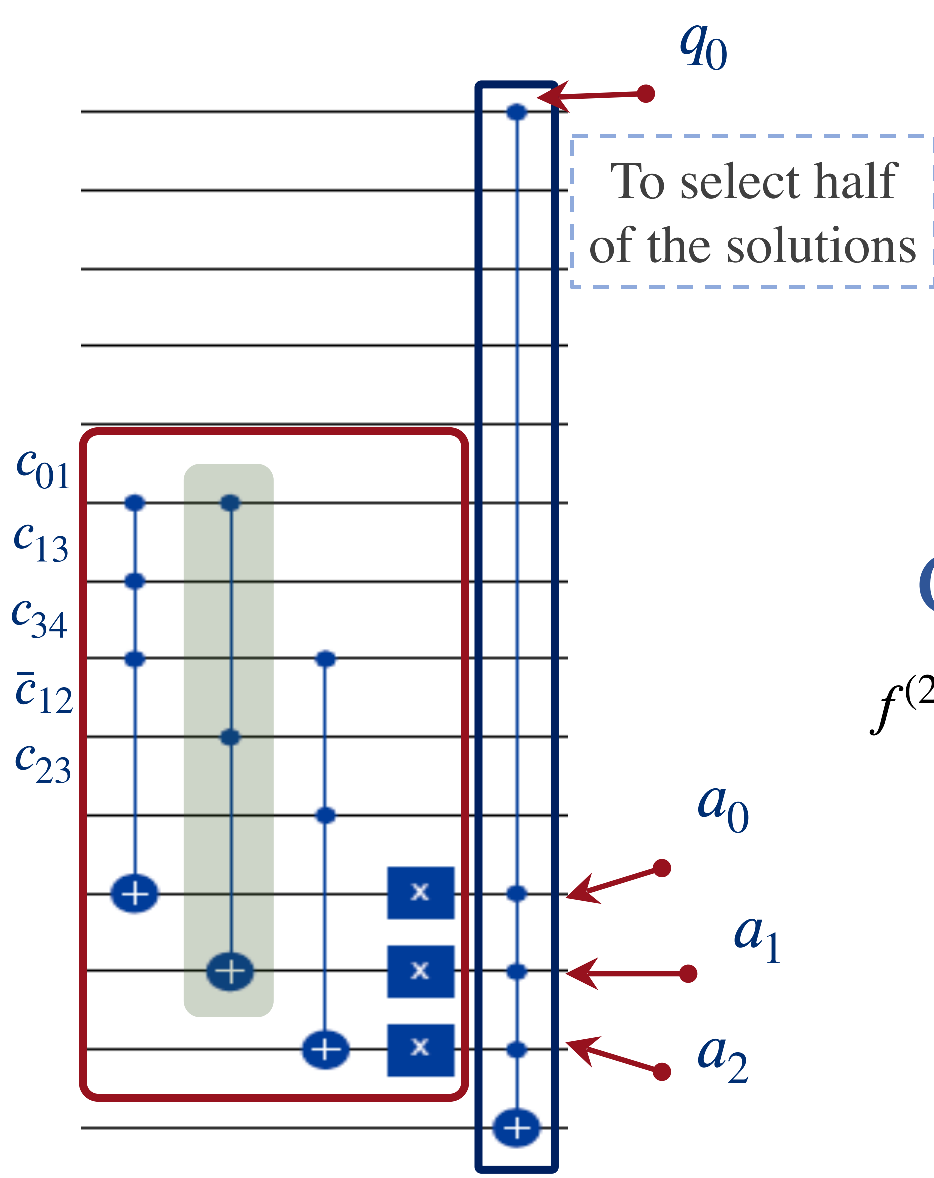

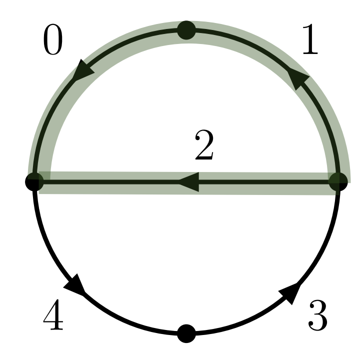

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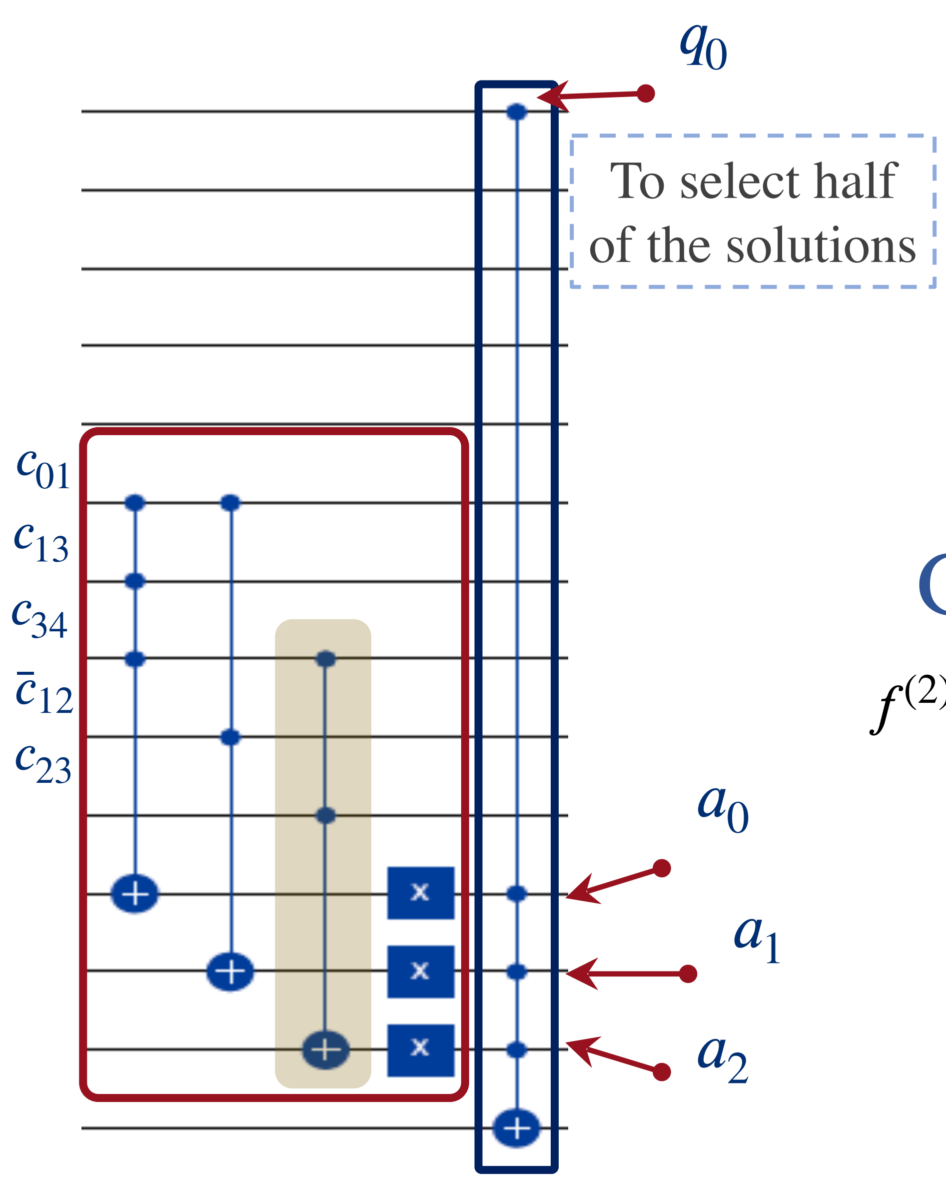

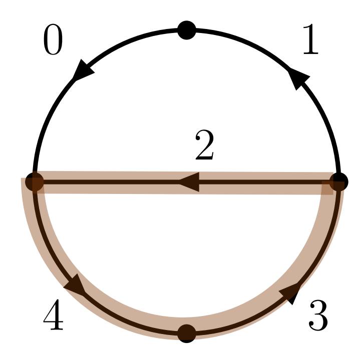

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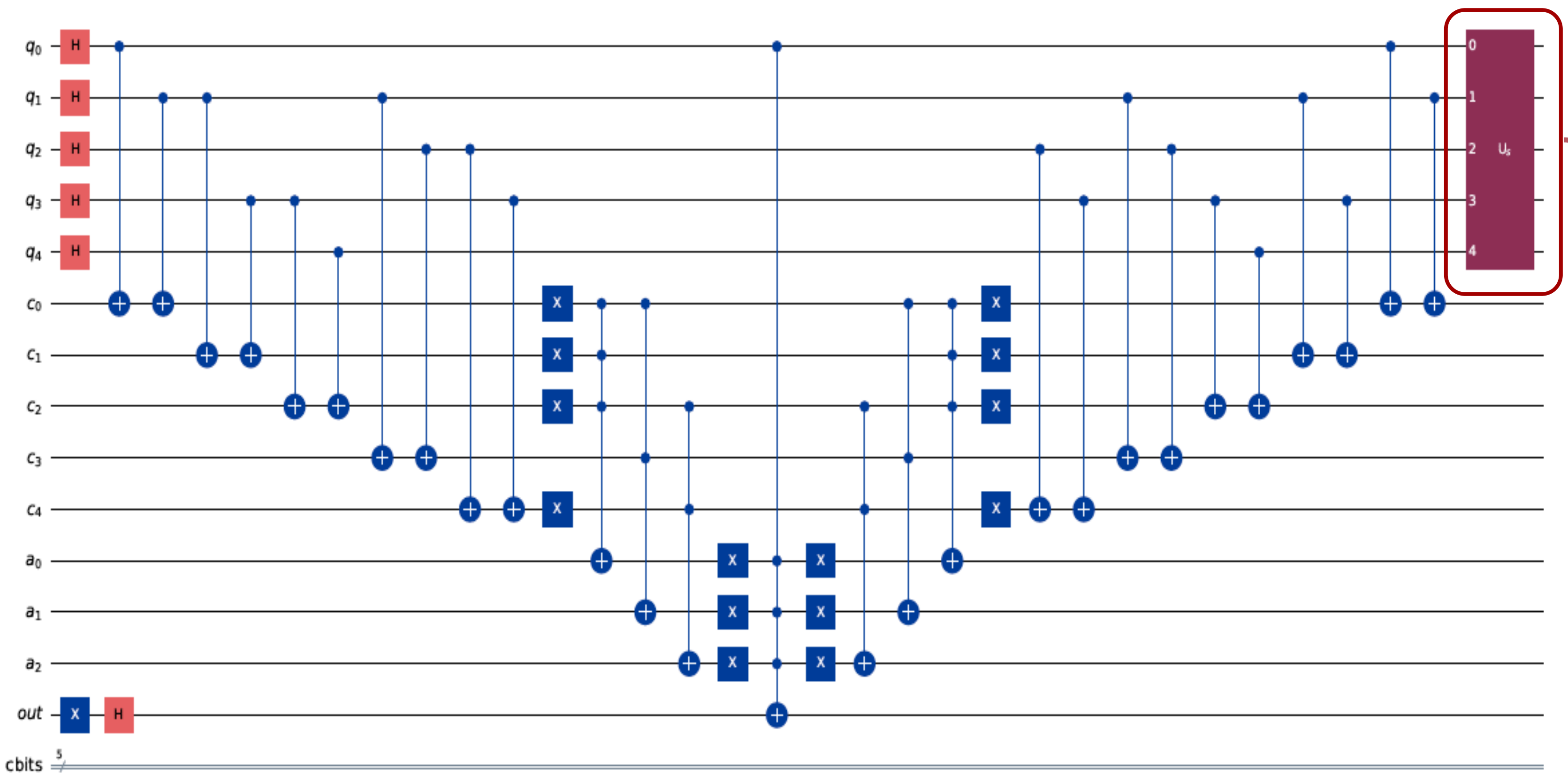
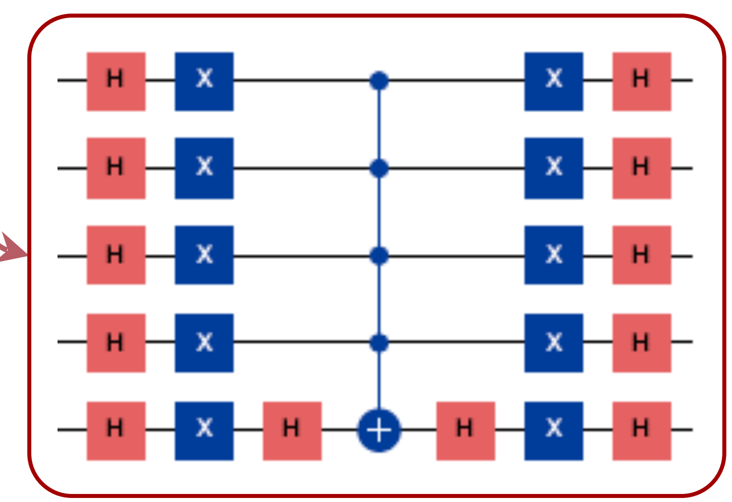
DIFUSSION OPERATOR

The diffusion operator is already given in a open source from IBM, Qiskit

There are other open source codes as Pennylane that are used nowadays too



Difusser U_q



From IBM Qiskit

GENERALIZATION TO AN ARBITRARY NUMBER OF EDGES

The upper and lower limit in the number of qubits needed to analise loop topologies of up to four eloops.

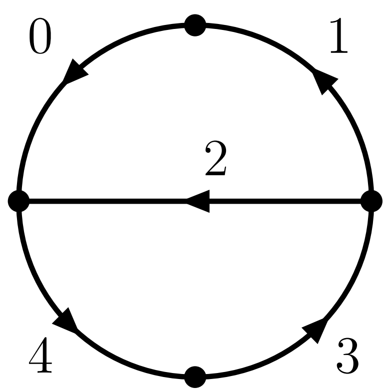
In a real machine, we do not have access to an infinite number of qubits.

Depending on your problem, a quantum computer will be able to solve it or not.

eloops (edges per set)	$\vert q\rangle$	$\vert c\rangle$	$\vert a\rangle$	Total	
one (n)	$n+1$	$n-1$	1	$2n+2$	8
two (n_0, n_1, n_2)	n	n	3	$2n+4$	14
three $(n_0, \ldots, n_5)$	n	$n+(2 \text{ to } 3)$	4 to 7	$2n+(7 \text{ to } 11)$	19
four$^{(\mathrm{N^3MLT})}$ $(n_0, \ldots, n_7)$	n	$n+(3 \text{ to } 6)$	5 to 13	$2n+(9 \text{ to } 20)$	25
four$^{(t,s)}$ $(n_0, \ldots, n_8)$	n	$n+(4 \text{ to } 7)$	5 to 13	$2n+(10 \text{ to } 21)$	28
four$^{(u)}$ $(n_0, \ldots, n_8)$	n	$n+(5 \text{ to } 8)$	9 to 13	$2n+(15 \text{ to } 22)$	33

Qiskit allows you to run simulations of up to 32 qubits for free.

RESULTS FOR TWO ELOOPS WITH FIVE EDGES



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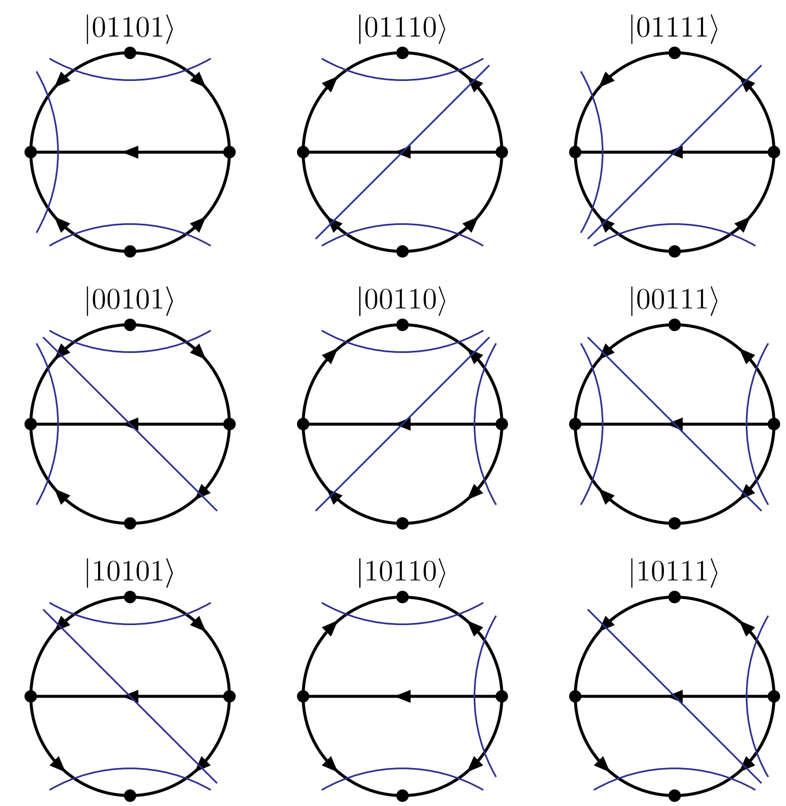
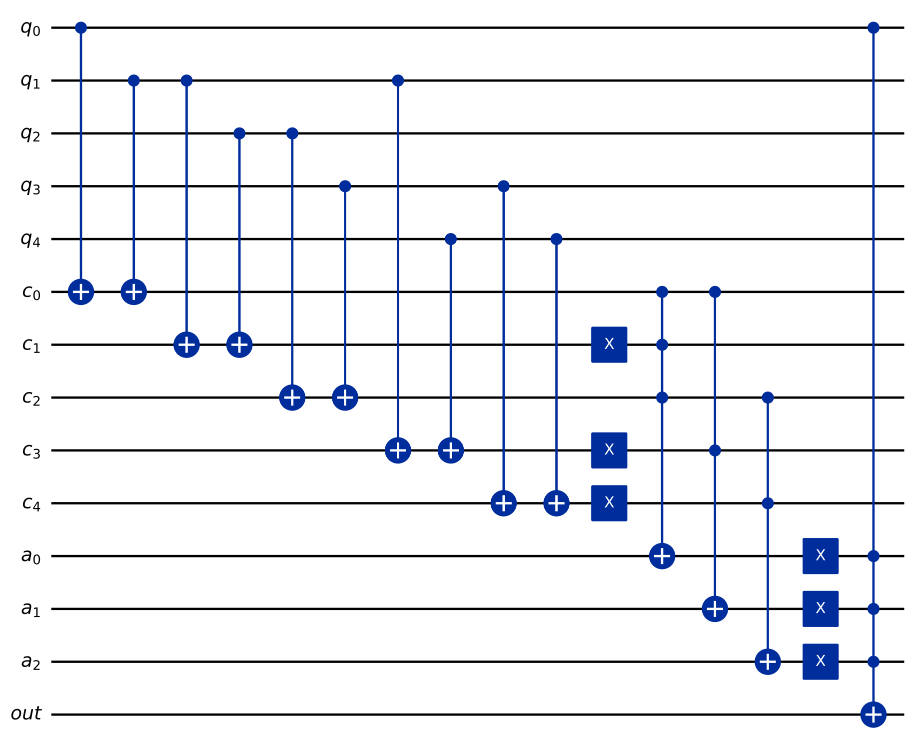
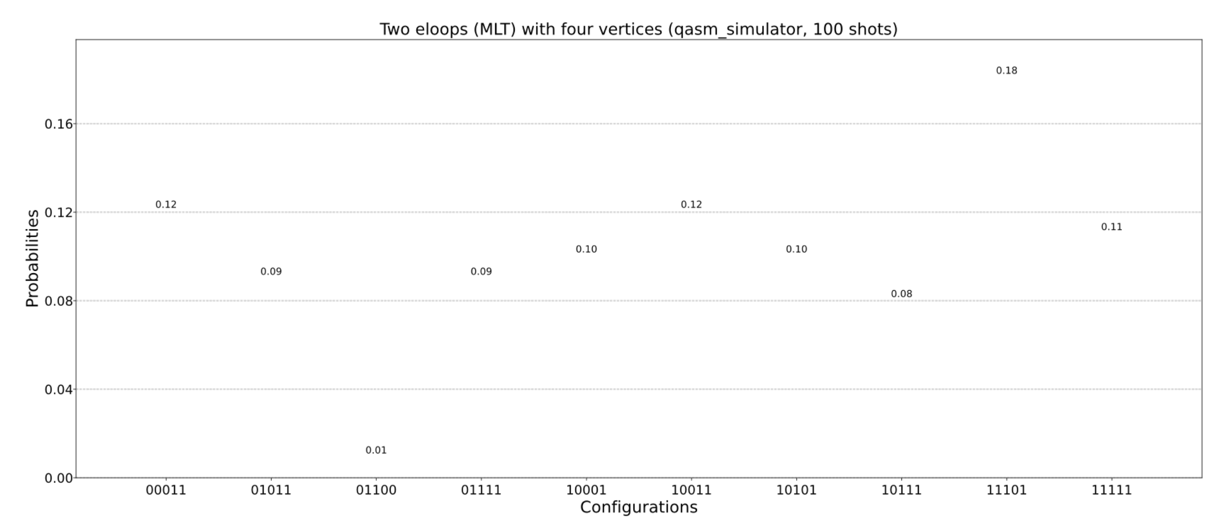
$$f^{(2)}(a, q) = (a_0 \wedge a_1 \wedge a_2) \wedge q_2$$





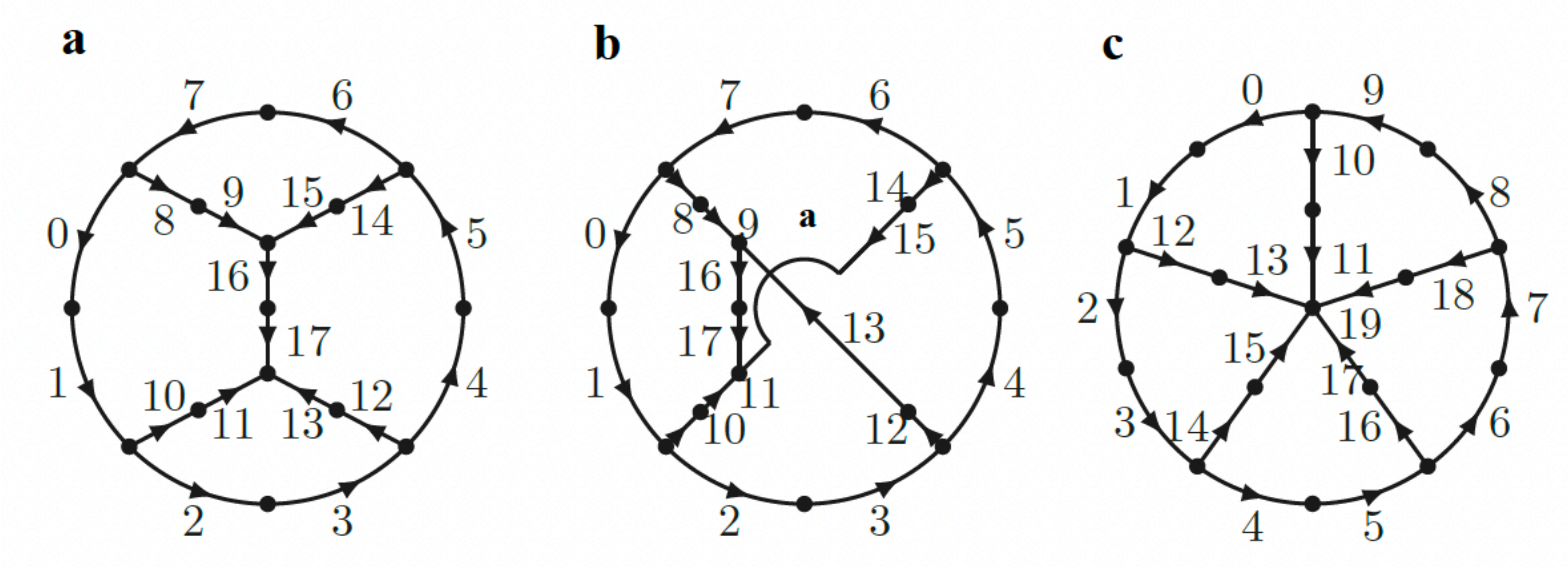


Can we reduce the number of qubits ? What about quantum efficiency?

QUANTUM PROBLEMS

In more complex topologies, the algorithm presented before, so-called MCX, **reaches the limit of current quantum simulators faster**.

It would be interesting to find all causal structures of,



the so-called t- and u-channels and the five-loops diagram with an effective five-point interaction vertex.

Issue: Even if we are able to write a quantum circuit in the best possible scenario, we still need to reduce the quantum noise since every step increases it.

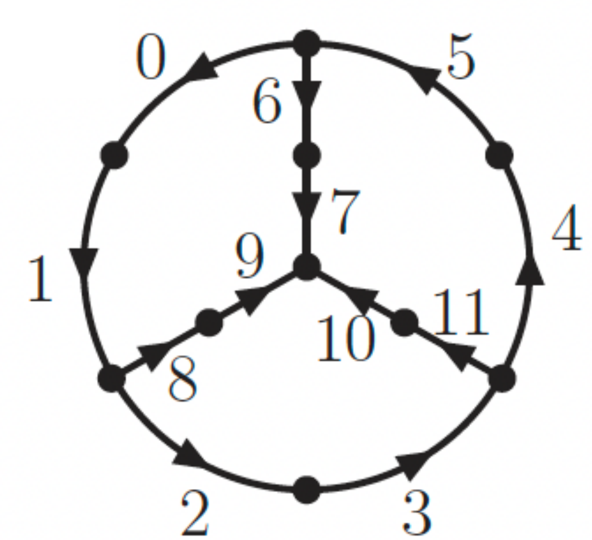
THE MCP PROBLEM IN GRAPH THEORY

Idea: Some selection criteria might be overweighted and should be reduced, from all sides

— The minimum clique partition problem —

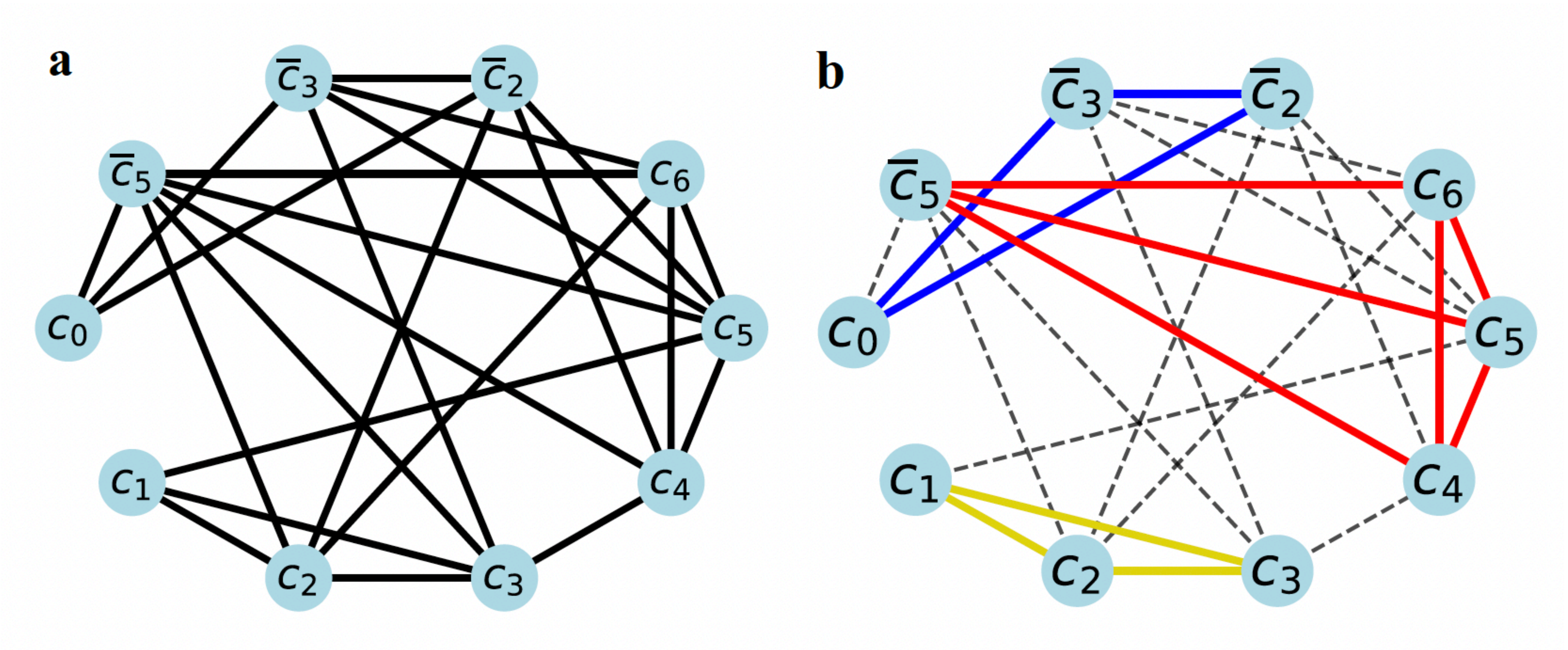
The Minimum Clique Partition (MCP) problem consists of partitioning the vertex set of a graph into the minimum number of disjoint cliques, such that each vertex belongs to exactly one clique.

To show the method, let us consider the vacuum amplitude with 10 clauses



REDUCING CLIQUES

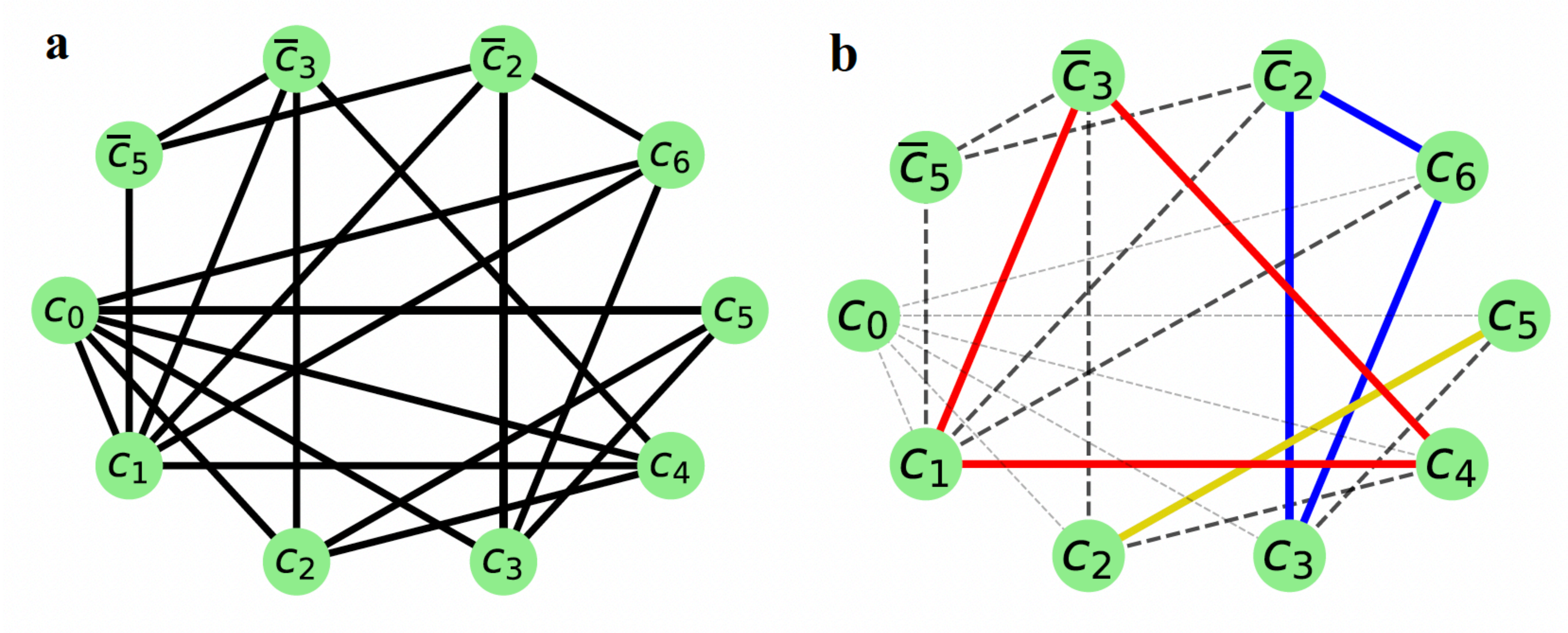
We developed an algorithm to find the adjacency matrix of Mutually Exclusive Clauses, then we find the Mutual Auxiliary clauses (cliques).



In this example, we need three qubits to store each clique.

REDUCING QUANTUM NOISE

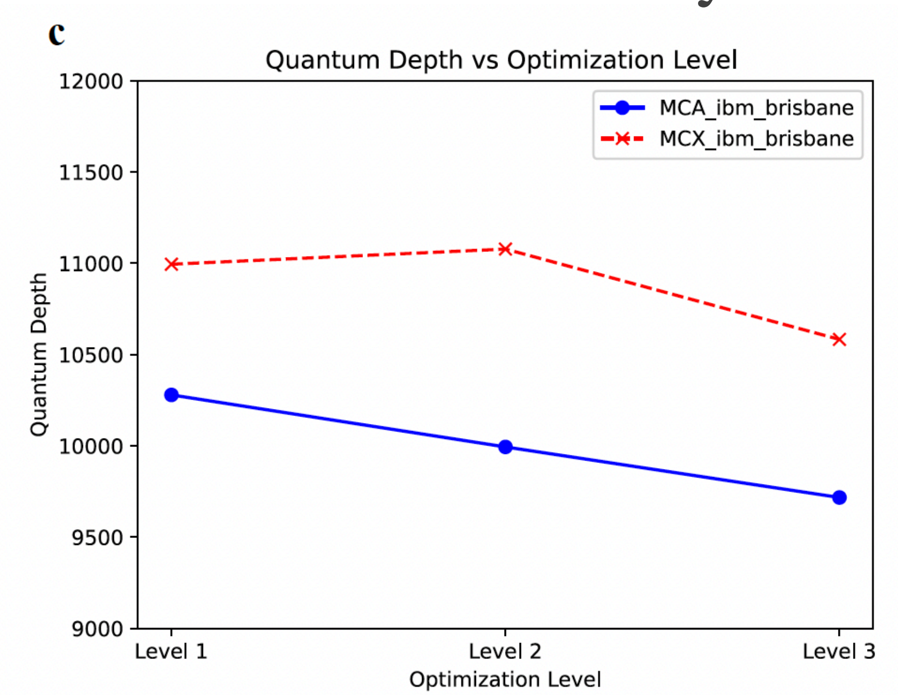
Then, we implemented an algorithm to reduce the quantum depth by defining an optimal order of the gates.

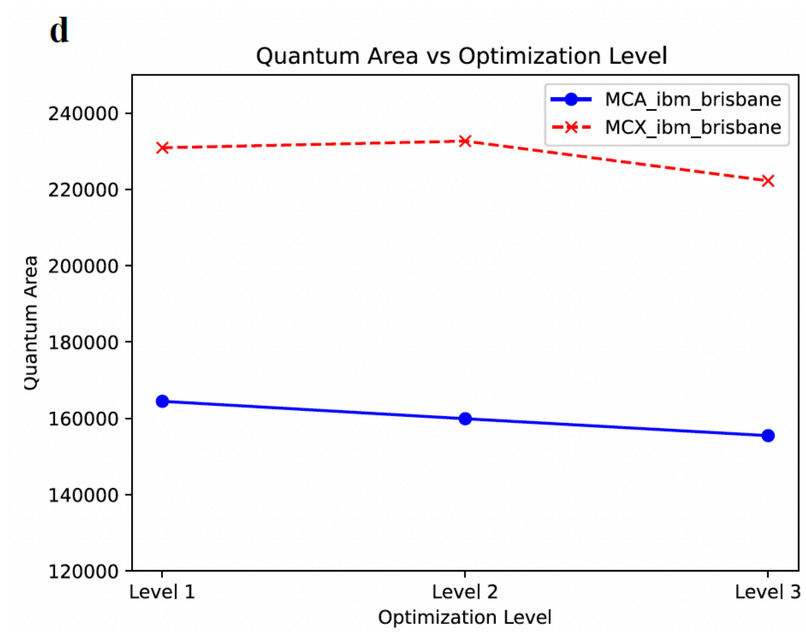


All quantum gates must be placed correctly in order to reduce the quantum noise.

RESULTS WITH MCA

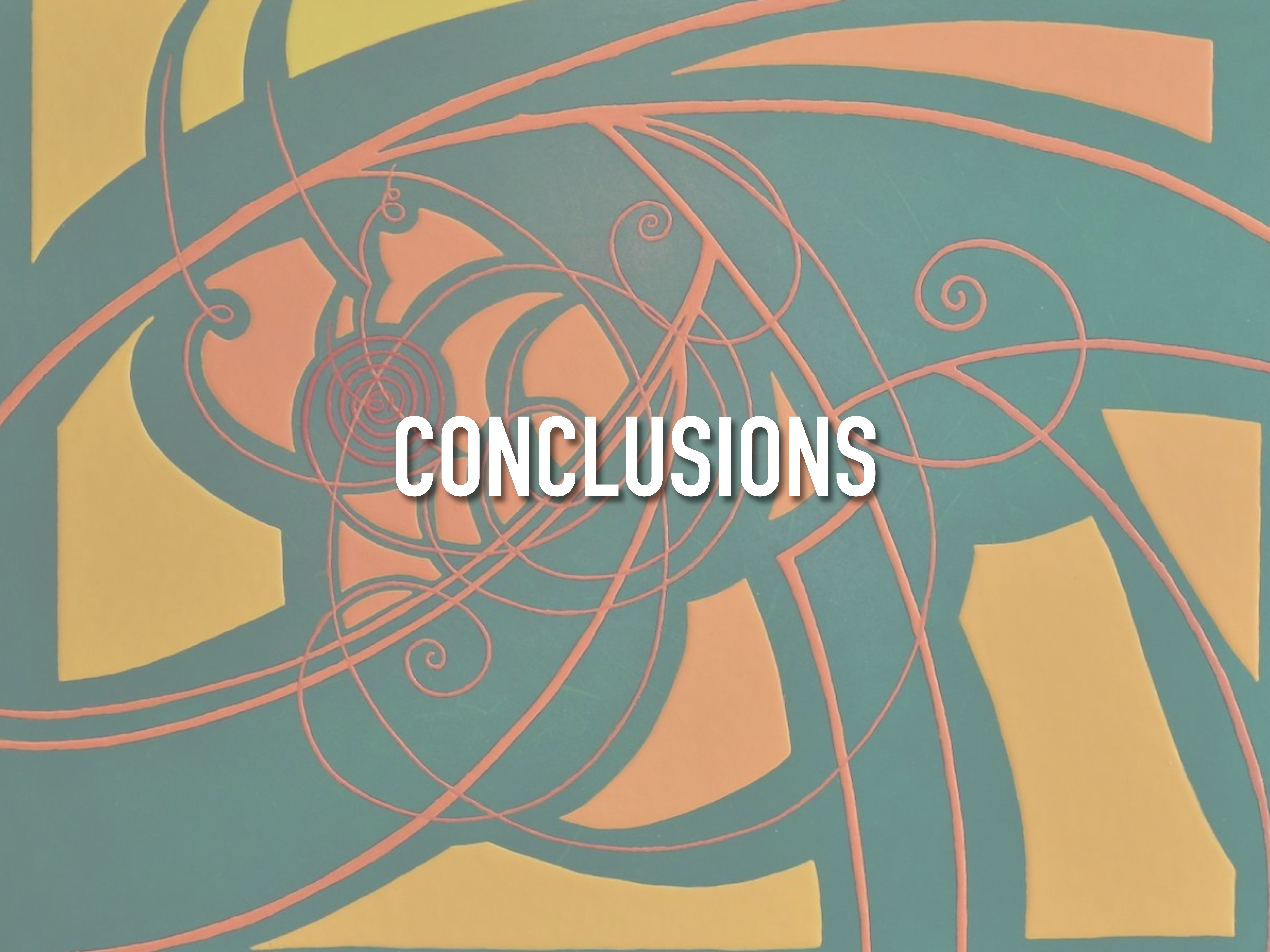
Quantum noise can be analyzed with the quantum depth and quantum area





Additionally, we reach topologies that the MCX algorithm couldn't.

eloops (edges)	$\vert e\rangle$	$\vert a\rangle$	Total Qubits	Quantum Depth	Total states
three (9)	9	2 | 4	12 | 14	15 | 17	512
three (12)	12	3 | 7	16 | 21	23 | 31	8192
four$^{(c)}$ (12)	12	4 | 5	17 | 18	15 | 15	4096
four$^{(c)}$ (16)	$16+1$	6 | 13	24 | 31	39 | 45	131072
four$^{(t)}$ (18)	$18+1$	6 | 13	26 | 33	39	262144
four$^{(u)}$ (18)	$18+1$	7 | 15	27 | 35	49	262144
five$^{(c)}$ (20)	$20+1$	9 | 21	31 | 43	57	1048576


CONCLUSIONS

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- Collider phenomenology is reaching the scientific frontiers very fast.
- The tools from QFT are applied to several other fundamental physics problems.
- In HEP, the technological limitations are pushing scientist around the world to tackle the recent and upcoming bottlenecks.
- A deep understanding of the mathematical structure of the amplitudes, which are compared with experimental data, is required.
- Quantum computing is opening a new paths towards the computational frontier.
- New ideas are very welcome !


THANK YOU !