

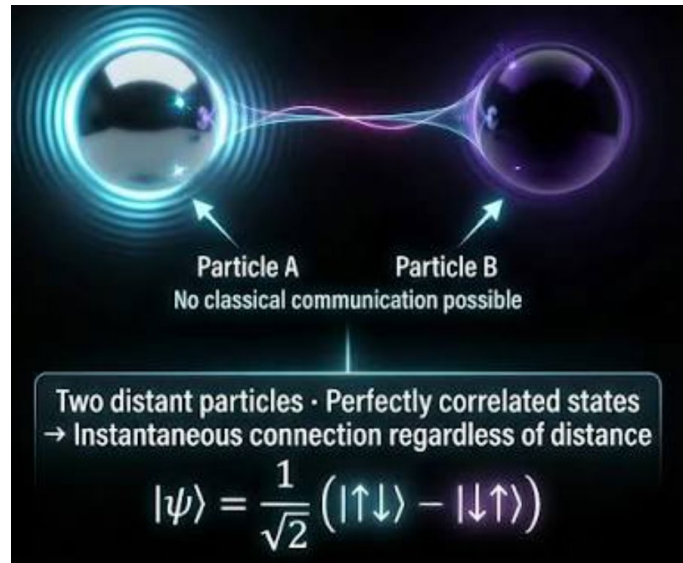
A Collider as a Quantum Computer

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Based on arXiv:2605.06907, in collaboration with Ji-Chong Yang

Entanglement in particle physics



- Entanglement, decoherence, and Bell inequalities in meson systems ($K^0\bar{K}^0$, $B^0\bar{B}^0$)
- Quantumness in neutrino oscillations (entanglement, Leggett–Garg inequalities, quantum correlations)
- Entanglement in scattering processes — talks at this workshop
 - W/H processes at the LHC — Lailin Xu et al.
 - Entanglement and Bell nonlocality at lepton colliders — Tianjun Li et al.
 - Quantum tomography of top quarks — Keping Xie et al.
 - Spin tomography with missing neutrinos — Jia Liu et al.

Entanglement generation in QED processes

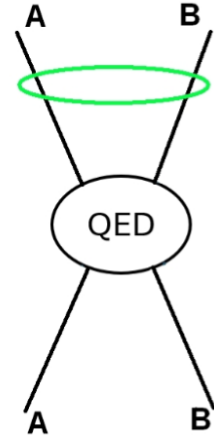
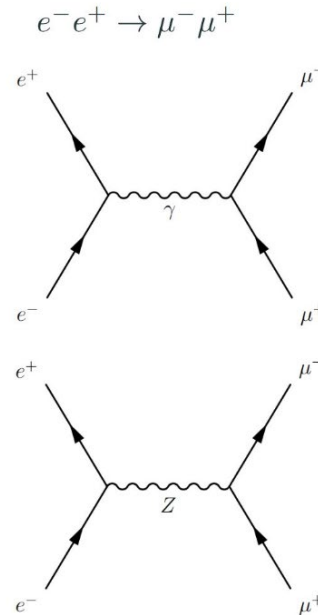
Processes

$$e^-e^- \rightarrow e^-e^-, \quad e^-e^+ \rightarrow \mu^-\mu^+, \quad e^-e^+ \rightarrow \gamma\gamma$$

$$e^-e^+ \rightarrow e^-e^+, \quad e^-\mu^- \rightarrow e^-\mu^-, \quad e^-\gamma \rightarrow e^-\gamma$$

What was learned?

- Helicity entanglement is a generic feature of many tree-level QED scattering processes.
- The amount of entanglement is controlled by kinematics and initial-state preparation.



Initial and final helicity states:

$$|i\rangle = |R\rangle_A \otimes |L\rangle_B$$

$$|f\rangle = \sum_{r,s=R,L} \mathcal{M}(RL;rs) |r\rangle_A |s\rangle_B$$

*A. Cervera-Lierta et al., SciPost Phys. (2017); S. Fedida, A. Serafini, Phys. Rev. D (2023).

*J.B. Araujo et al., Phys. Rev. D (2019).

M. B., G. Lambiase and B. Micciola, Phys. Rev. D (2024).

From Quantum Entanglement to Quantum Computation

➤ Quantum Computer

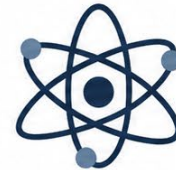
- A computer that uses laws of quantum mechanics to perform massively parallel computing through superposition, entanglement, and decoherence.

➤ Classical Computer

- A computer that uses voltages flowing through circuits and gates, which can be controlled and manipulated entirely by classical mechanics.

- Quantum entanglement is at the heart of the disparity between classical and quantum physics:
entanglement is a primary feature of quantum mechanics lacking in classical mechanics.

Quantum Algorithms



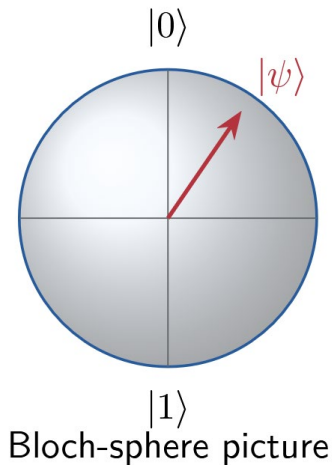
Factoring	Search	Simulation
Shor	Grover	Quantum systems
exponential speedup over known classical algorithms	quadratic query speedup	natural target for quantum processors

For some problems, the best quantum algorithms have lower asymptotic complexity than the best known classical approaches.

Quantum Algorithm Zoo: <https://quantumalgorithmzoo.org/>

More Quantum Algorithms

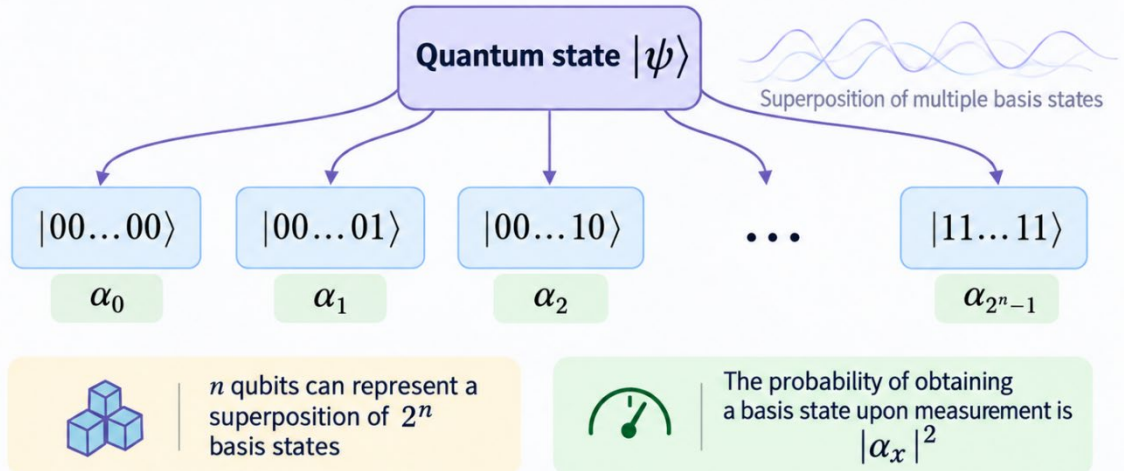
Basics of Quantum Computers: Quantum Bit



n -Qubit Quantum State

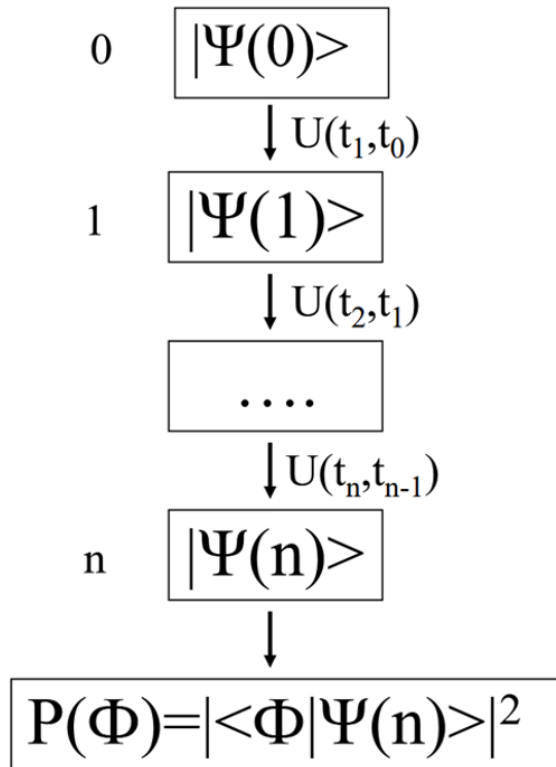
$$|\psi\rangle = \sum_{x=0}^{2^n-1} \alpha_x |x\rangle$$

Here x denotes an n -bit computational basis state, and α_x is the corresponding complex amplitude



Quantum computing encodes information in quantum amplitudes and phases, then uses interference to amplify desired outcomes.

Unitary Transformation as Quantum Computing



PREPARATION:

The initial preparation of the state defines a wave function at time $t_0=0$.

STATE EVOLUTION:

Evolved by a sequence of unitary operations

....

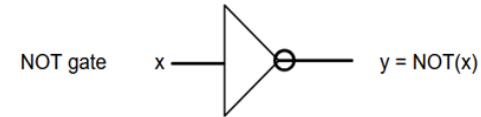
MEASUREMENT:

Quantum measurement is projective.

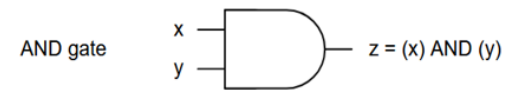
Collapsed by measurement of the state

Quantum vs. Classic Gates

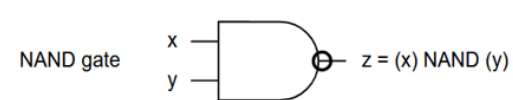
Operator	Gate(s)	Matrix
Pauli-X (X)	 	$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$
Pauli-Y (Y)		$\begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$
Pauli-Z (Z)		$\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$
Hadamard (H)		$\frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$
Phase (S, P)		$\begin{bmatrix} 1 & 0 \\ 0 & i \end{bmatrix}$
$\pi/8$ (T)		$\begin{bmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{bmatrix}$
Controlled Not (CNOT, CX)		$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$
Controlled Z (CZ)		$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}$
SWAP	 	$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$
Toffoli (CCNOT, CCX, TOFF)		$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$



x	y
0	1
1	0



x	y	z
0	0	0
0	1	0
1	0	0
1	1	1



x	y	z
0	0	1
0	1	1
1	0	1
1	1	0



x	y	z
0	0	0
0	1	1
1	0	1
1	1	1



x	y	z
0	0	1
0	1	0
1	0	0
1	1	0

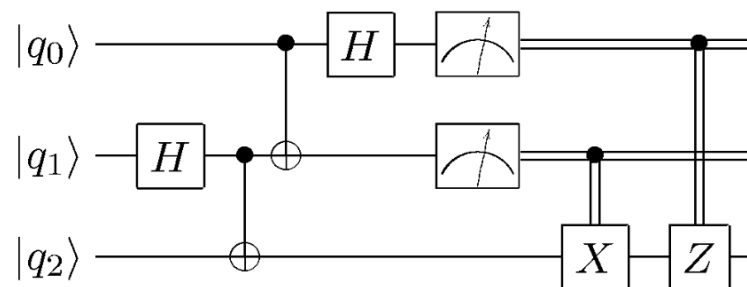
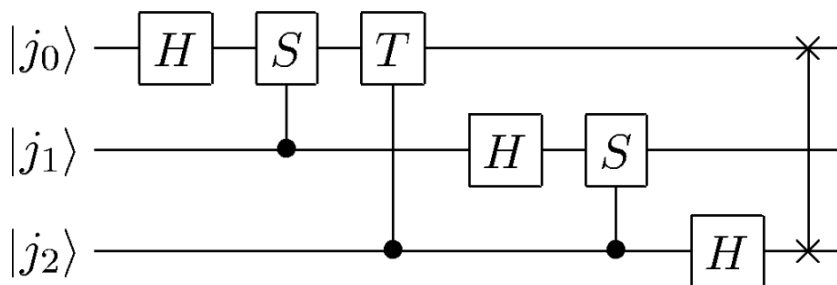
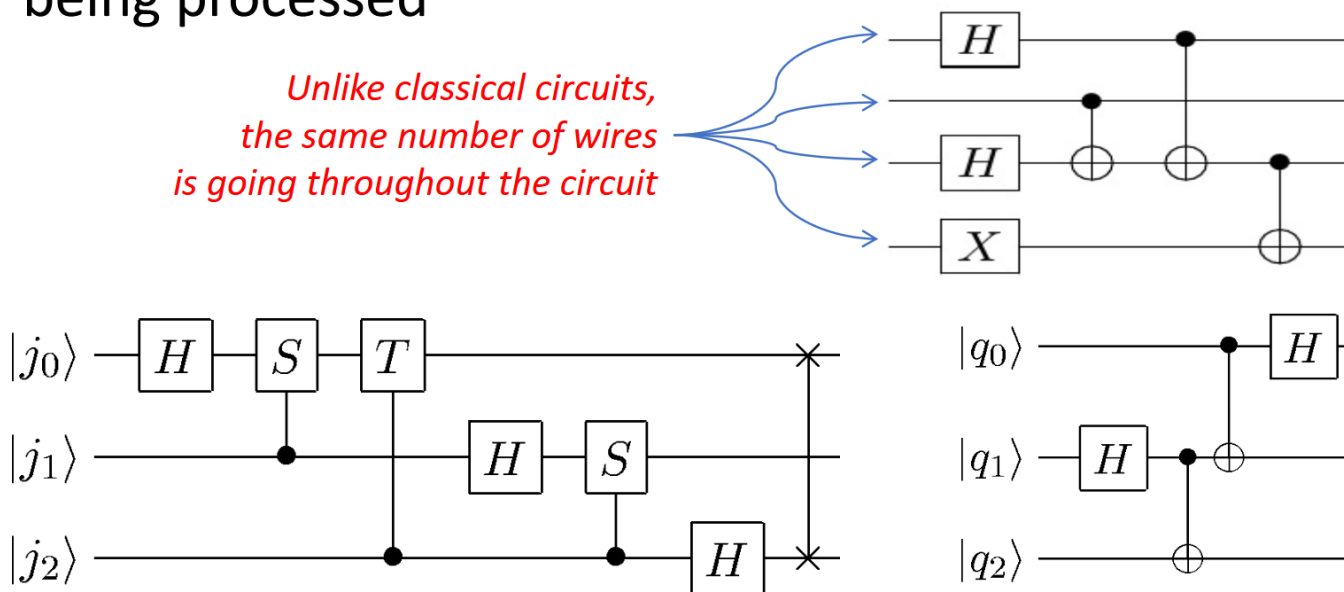


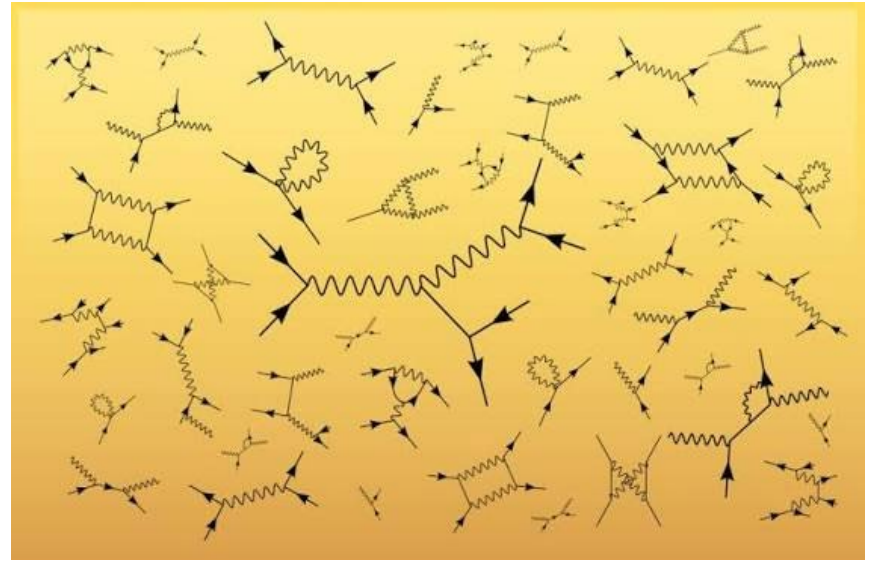
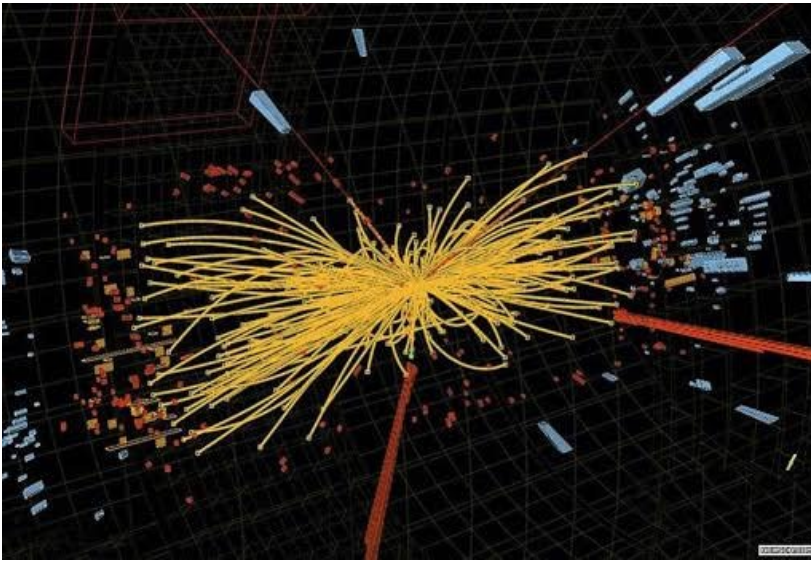
x	y	z
0	0	0
0	1	1
1	0	1
1	1	0

Quantum Circuit

- A quantum circuit is a model for quantum computation in which a computation is a **sequence** of **quantum gates** with n -qubit register linked by “wires”
- The circuit has fixed “width” corresponding to the number of qubits being processed

*Unlike classical circuits,
the same number of wires
is going throughout the circuit*





Can particle colliders be used for quantum computing?

Major hardware platforms for quantum computing

- Superconducting qubits
- Trapped ions
- Neutral atoms / Rydberg atoms
- Photonic quantum computing
- Semiconductor quantum dots / spin qubits

Finite Helicity Space inside an Infinite Quantum Field Theory

The apparent obstacle

Quantum field theory and the full S -matrix act on infinite-dimensional asymptotic Hilbert spaces.

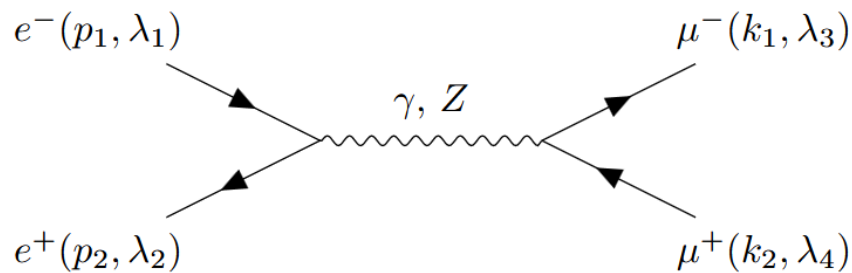
The finite computational space

After fixing particle content and kinematics, the remaining internal degrees of freedom form a finite helicity space:

$$T(x) : \mathcal{H}_{\text{in}}^{\text{hel}} \longrightarrow \mathcal{H}_{\text{out}}^{\text{hel}}.$$

For $e^+e^- \rightarrow \mu^+\mu^-$: $(R, L) \times (R, L)$ gives a two-qubit helicity register.

$e^+e^- \rightarrow \mu^+\mu^-$: the concrete example



$$|0\rangle \equiv |R\rangle, \quad |1\rangle \equiv |L\rangle$$

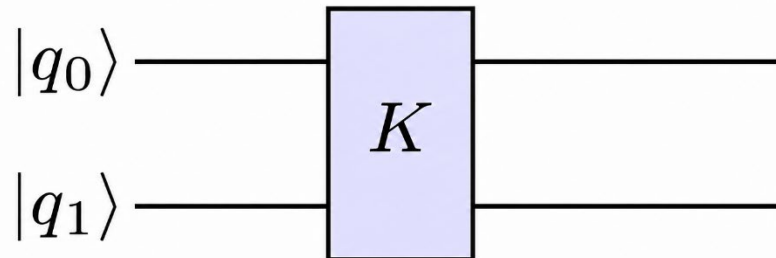
- Each lepton helicity is a two-level degree of freedom.
- At fixed energy and scattering angle, the amplitudes form a finite matrix.
- That matrix is the object to be encoded as a circuit.

basis: (RR, RL, LR, LL)

Helicity Transition Matrix

basis: (RR, RL, LR, LL)

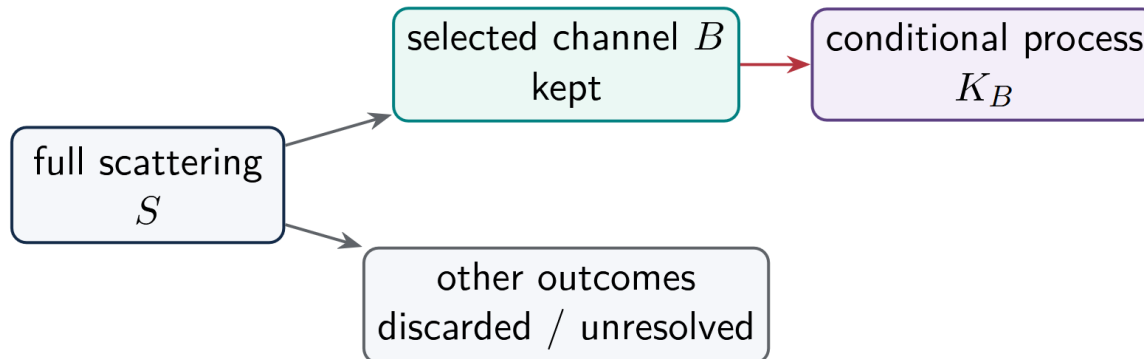
$$K = \begin{pmatrix} \mathcal{M}_{RR \rightarrow RR} & \mathcal{M}_{RR \rightarrow RL} & \mathcal{M}_{RR \rightarrow LR} & \mathcal{M}_{RR \rightarrow LL} \\ \mathcal{M}_{RL \rightarrow RR} & \mathcal{M}_{RL \rightarrow RL} & \mathcal{M}_{RL \rightarrow LR} & \mathcal{M}_{RL \rightarrow LL} \\ \mathcal{M}_{LR \rightarrow RR} & \mathcal{M}_{LR \rightarrow RL} & \mathcal{M}_{LR \rightarrow LR} & \mathcal{M}_{LR \rightarrow LL} \\ \mathcal{M}_{LL \rightarrow RR} & \mathcal{M}_{LL \rightarrow RL} & \mathcal{M}_{LL \rightarrow LR} & \mathcal{M}_{LL \rightarrow LL} \end{pmatrix}.$$



Singular Value Decomposition of K matrix

$$S^\dagger S = I$$

Experiments always select outcomes



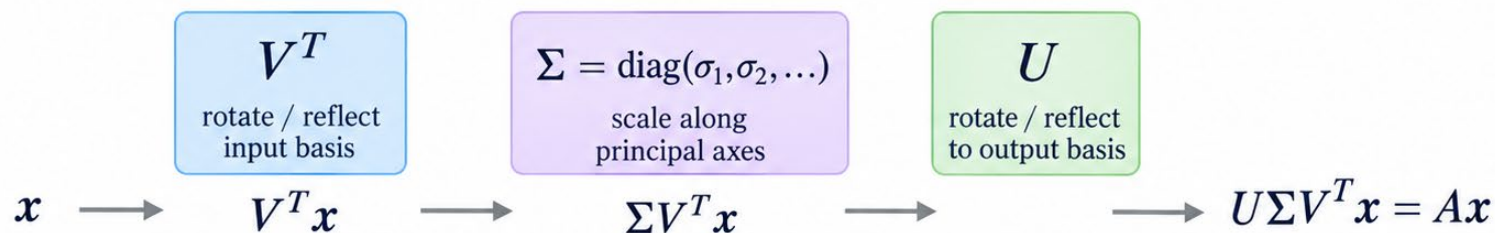
$$K_B = P_B S P_{\text{in}}$$

Singular Value Decomposition (SVD)

Any matrix can be decomposed into rotations/reflections and scaling.

$$A = U \Sigma V^T$$

(for complex matrices, use $V^\dagger$ instead of V^T)



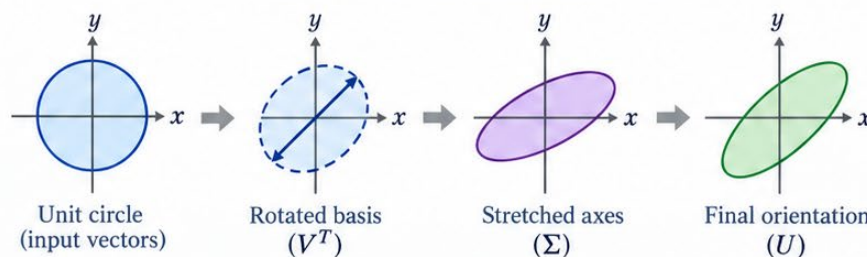
Example (2×2 matrix)

$$A = \begin{bmatrix} 3 & 1 \\ 1 & 3 \end{bmatrix} = U \Sigma V^T$$

$$U = V = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

$$\Sigma = \begin{bmatrix} 4 & 0 \\ 0 & 2 \end{bmatrix}$$

Geometric illustration

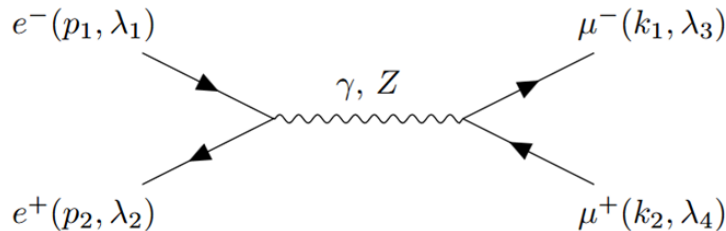


circle $\rightarrow$ rotated basis $\rightarrow$ stretched axes $\rightarrow$ final orientation

SVD reveals the principal directions and scaling strengths of a linear transformation.

Singular Value Decomposition of K matrix

$$i\mathcal{M} = \bar{v}(p_2, \lambda_2)(ie\gamma^\mu)u(p_1, \lambda_1) \frac{-ig_{\mu\nu}}{q^2} \bar{u}(k_1, \lambda_3)(ie\gamma^\nu)v(k_2, \lambda_4) \\ + \bar{v}(p_2, \lambda_2) \left(i\frac{g}{c_W} \gamma^\mu (g_L P_L + g_R P_R) \right) u(p_1, \lambda_1) \frac{-ig_{\mu\nu}}{q^2 - m_Z^2} \bar{u}(k_1, \lambda_3) \left(i\frac{g}{c_W} \gamma^\nu (g_L P_L + g_R P_R) \right) v(k_2, \lambda_4)$$



$$K = \begin{pmatrix} \mathcal{M}_{RR \rightarrow RR} & \mathcal{M}_{RR \rightarrow RL} & \mathcal{M}_{RR \rightarrow LR} & \mathcal{M}_{RR \rightarrow LL} \\ \mathcal{M}_{RL \rightarrow RR} & \mathcal{M}_{RL \rightarrow RL} & \mathcal{M}_{RL \rightarrow LR} & \mathcal{M}_{RL \rightarrow LL} \\ \mathcal{M}_{LR \rightarrow RR} & \mathcal{M}_{LR \rightarrow RL} & \mathcal{M}_{LR \rightarrow LR} & \mathcal{M}_{LR \rightarrow LL} \\ \mathcal{M}_{LL \rightarrow RR} & \mathcal{M}_{LL \rightarrow RL} & \mathcal{M}_{LL \rightarrow LR} & \mathcal{M}_{LL \rightarrow LL} \end{pmatrix}.$$

SVD: factor the conditional process into three operations

$$K = U \Sigma V^\dagger$$

Singular Value Decomposition of K matrix

$$K = U \Sigma V^\dagger$$

The expression of $V^\dagger$ is given by

$$V^\dagger = \begin{pmatrix} v_{11} & v_{12} & v_{13} & v_{14} \\ v_{21} & v_{22} & v_{23} & v_{24} \\ v_{31} & v_{32} & v_{33} & v_{34} \\ v_{41} & v_{42} & v_{43} & v_{44} \end{pmatrix}, \quad (\text{B7})$$

with $v_{11} = v_{14} = v_{21} = v_{24} = v_{31} = v_{32} = v_{33} = v_{42} = v_{43} = v_{44} = 0$, $v_{34} = v_{41} = 1$ and

$$v_{12} = \frac{\cos^2\left(\frac{\theta}{2}\right) \csc^2(\theta) ((a-d) \cos(\theta) + a - d - k)}{b \sqrt{\frac{\csc^4\left(\frac{\theta}{2}\right) ((d-a) \cos(\theta) - a + d + k)^2}{16b^2} + 1}}, \quad (\text{B8})$$

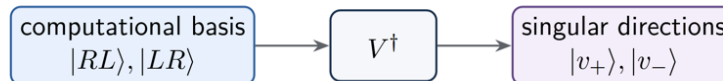
$$v_{13} = \frac{1}{\sqrt{\frac{\csc^4\left(\frac{\theta}{2}\right) ((d-a) \cos(\theta) - a + d + k)^2}{16b^2} + 1}}, \quad (\text{B9})$$

$$v_{22} = \frac{\cos^2\left(\frac{\theta}{2}\right) \csc^2(\theta) ((a-d) \cos(\theta) + a - d + k)}{b \sqrt{\frac{\csc^4\left(\frac{\theta}{2}\right) ((a-d) \cos(\theta) + a - d + k)^2}{16b^2} + 1}}, \quad (\text{B10})$$

$$v_{23} = \frac{1}{\sqrt{\frac{\csc^4\left(\frac{\theta}{2}\right) ((a-d) \cos(\theta) + a - d + k)^2}{16b^2} + 1}}. \quad (\text{B11})$$

$V^\dagger$: find the natural incoming helicity modes

$$|\psi\rangle = c_+ |v_+\rangle + c_- |v_-\rangle$$



$$a = \left(\frac{4\mu^2 g_R^2}{4\mu^2 - 1} \sec^2 \theta_W + \sin^2 \theta_W \right), \quad (11)$$

$$b = \left(\frac{4\mu^2 g_R g_L}{4\mu^2 - 1} \sec^2 \theta_W + \sin^2 \theta_W \right), \quad (12)$$

$$d = \left(\frac{4\mu^2 g_L^2}{4\mu^2 - 1} \sec^2 \theta_W + \sin^2 \theta_W \right), \quad (13)$$

in which θ_W is the Weinberg angle, and g_L and g_R denote the left and right handed couplings of the leptons to the Z boson. In the above expressions, we have defined a dimensionless parameter $\mu \equiv |\vec{p}|/m_Z$, where $\vec{p}$ is the 3-momentum of the incoming electron.

$$k = \sqrt{2 \cos \theta [(a - d)^2 - 4b^2] + \frac{1}{2} [\cos(2\theta) + 3] [(a - d)^2 + 4b^2]}.$$

Singular Value Decomposition of K matrix

$$K = U\Sigma V^\dagger$$

The expression of Σ is given by

$$\Sigma = \begin{pmatrix} \sigma_+ & 0 & 0 & 0 \\ 0 & \sigma_- & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}, \quad (\text{B12})$$

with

$$\sigma_+ = \frac{1}{4} \sqrt{8(a^2 + d^2) \cos^4\left(\frac{\theta}{2}\right) + 2\sqrt{2} \sqrt{(a+d)^2 \cos^4\left(\frac{\theta}{2}\right) - (4(-4b^2 + (a-d)^2) \cos(\theta) + (4b^2 + (a-d)^2)(3 + \cos(2\theta))) + 16b^2 \sin\left(\frac{\theta}{2}\right)^4}}, \quad (\text{B13})$$

$$\sigma_- = \frac{1}{4} \sqrt{8(a^2 + d^2) \cos^4\left(\frac{\theta}{2}\right) - 2\sqrt{2} \sqrt{(a+d)^2 \cos^4\left(\frac{\theta}{2}\right) - (4(-4b^2 + (a-d)^2) \cos(\theta) + (4b^2 + (a-d)^2)(3 + \cos(2\theta))) + 16b^2 \sin\left(\frac{\theta}{2}\right)^4}}. \quad (\text{B14})$$

Singular values in Σ : conditional transmission amplitudes

$$\Sigma = \text{diag}(\sigma_+, \sigma_-), \quad p_B(\psi) = \sum_i \sigma_i^2 |\langle v_i | \psi \rangle|^2$$

Singular Value Decomposition of K matrix

$$K = U\Sigma V^\dagger$$

The expression of U is given by

$$U = \begin{pmatrix} u_{11} & u_{12} & u_{13} & u_{14} \\ u_{21} & u_{22} & u_{23} & u_{24} \\ u_{31} & u_{32} & u_{33} & u_{34} \\ u_{41} & u_{42} & u_{43} & u_{44} \end{pmatrix}, \quad (\text{B1})$$

with $u_{11} = u_{12} = u_{13} = u_{23} = u_{24} = u_{33} = u_{34} = u_{41} = u_{42} = u_{44} = 0$, $u_{14} = u_{43} = 1$ and

$$u_{21} = \frac{4(\cos(\theta)(a^2 - ad + 2b^2) + a \csc^2(\frac{\theta}{2})(-2a + 2d + k) + a(3a - 3d - k) - 2b^2)}{\sqrt{\csc^4(\frac{\theta}{2})(\cos(\theta)(4a^2 - 2a(2d + k) - 8b^2) + \cos(2\theta)(a^2 - ad + 2b^2) + a(3a - 3d - 2k) + 6b^2)^2 + 16b^2((a + d)\cos(\theta) + a + d - k)^2}}, \quad (\text{B2})$$

$$u_{22} = \frac{4\left(\cos(\theta)(a^2 - ad + 2b^2) + \frac{a(\cos(\theta)(3a - 3d + k) + a - d + k)}{\cos(\theta) - 1} - 2b^2\right)}{\sqrt{\csc^4(\frac{\theta}{2})(\cos(2\theta)(a^2 - ad + 2b^2) + 2\cos(\theta)(a(2a - 2d + k) - 4b^2) + a(3a - 3d + 2k) + 6b^2)^2 + 16b^2((a + d)\cos(\theta) + a + d + k)^2}}, \quad (\text{B3})$$

$$u_{31} = -\frac{4b((a + d)\cos(\theta) + a + d - k)}{\sqrt{\csc^4(\frac{\theta}{2})(\cos(\theta)(4a^2 - 2a(2d + k) - 8b^2) + \cos(2\theta)(a^2 - ad + 2b^2) + a(3a - 3d - 2k) + 6b^2)^2 + 16b^2((a + d)\cos(\theta) + a + d - k)^2}}, \quad (\text{B4})$$

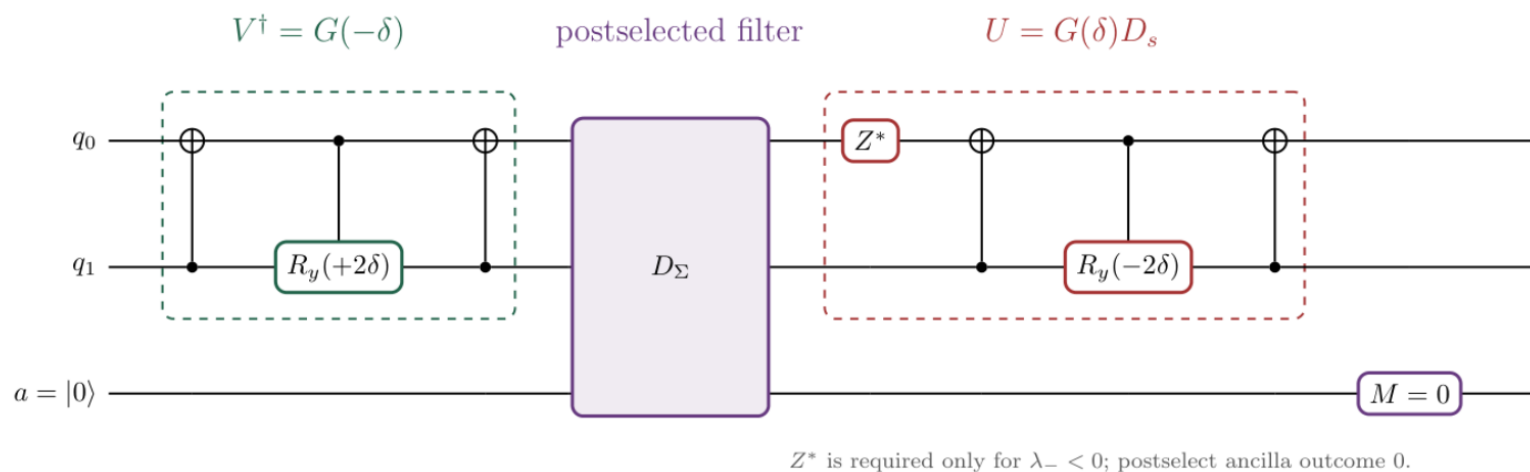
$$u_{32} = -\frac{4b(a + d + k + (a + d)\cos(\theta))}{\sqrt{16b^2(a + d + k + (a + d)\cos(\theta))^2 + (6b^2 + a(3a - 3d + 2k) + 2(-4b^2 + a(2a - 2d + k))\cos(\theta) + (a^2 + 2b^2 - ad)\cos(2\theta))^2 \csc^4(\frac{\theta}{2})}}. \quad (\text{B5})$$

U : map transmitted components to outgoing helicity states

$$K|v_i\rangle = \sigma_i|u_i\rangle$$



Circuit representation: $V^\dagger - D_\Sigma - U$



Left: incoming singular directions

Center: non-unitary filter $\hat{\Sigma}$

Right: outgoing rotation U

Circuit parameters vary with the scattering angle

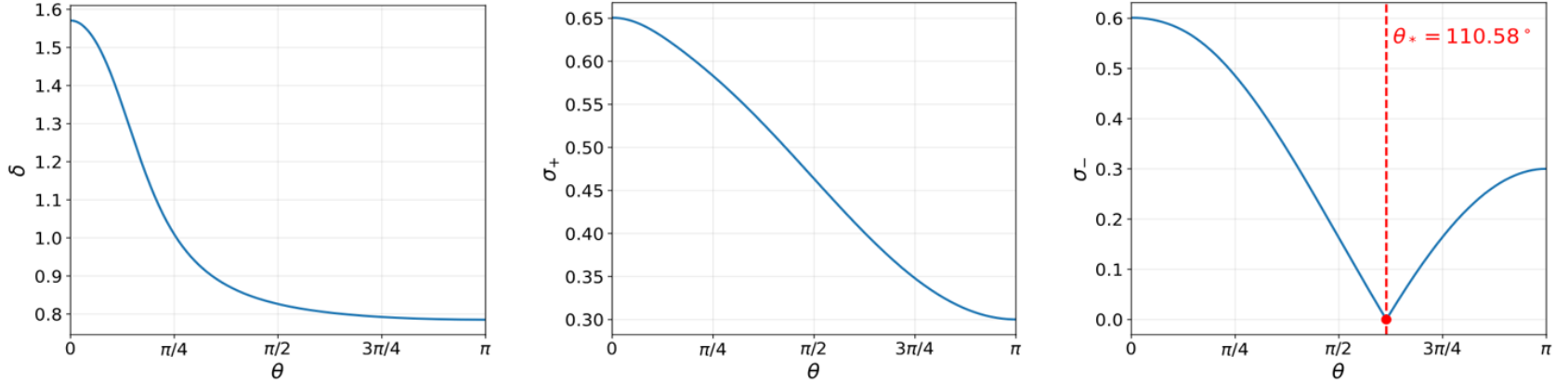


Figure 2: Dependence of the circuit parameters on the scattering angle θ . Left: the active-subspace rotation angle $\delta(\theta)$. Middle: the unnormalized singular value $\sigma_+(\theta)$. Right: the unnormalized singular value $\sigma_-(\theta)$; the marked point is $\theta_* = 110.58^\circ$, where the conditional amplitude becomes rank one. The singular values of the circuit contraction are $\hat{\sigma}_\pm = \sigma_\pm/\Lambda$ with the fixed scale in Eq. (9).

$$\cos \delta = \frac{1}{\sqrt{\frac{[(a-d) \cos \theta + a - d + k]^2 \left(\frac{\csc^4 \frac{\theta}{2} [(d-a) \cos \theta - a + d + k]^2}{16b^2} + 1 \right)}{[(d-a) \cos \theta - a + d + k]^2 \left(\frac{\csc^4 \frac{\theta}{2} [(a-d) \cos \theta + a - d + k]^2}{16b^2} + 1 \right)} + 1}},$$

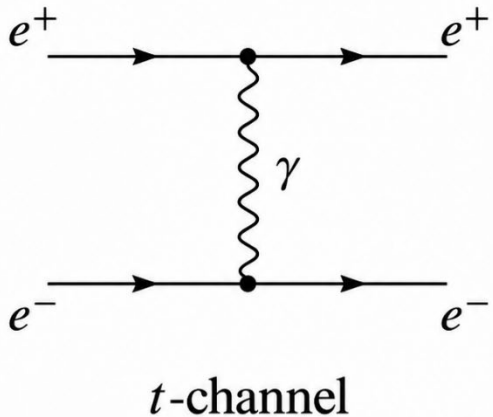
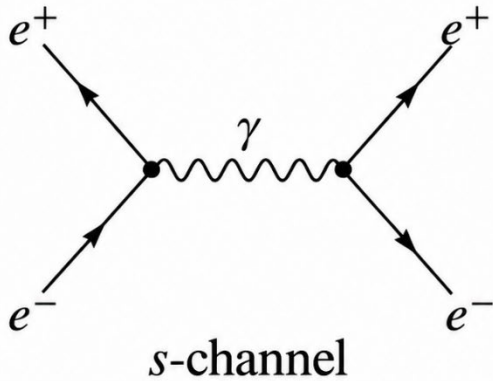
$$\sigma_+ = \frac{1}{4} \sqrt{8(a^2 + d^2) \cos^4 \left(\frac{\theta}{2} \right) + 2\sqrt{2} \sqrt{(a+d)^2 \cos^4 \left(\frac{\theta}{2} \right) - (4(-4b^2 + (a-d)^2) \cos(\theta) + (4b^2 + (a-d)^2)(3 + \cos(2\theta))) + 16b^2 \sin \left(\frac{\theta}{2} \right)^4}}, \quad (\text{B13})$$

$$\sigma_- = \frac{1}{4} \sqrt{8(a^2 + d^2) \cos^4 \left(\frac{\theta}{2} \right) - 2\sqrt{2} \sqrt{(a+d)^2 \cos^4 \left(\frac{\theta}{2} \right) - (4(-4b^2 + (a-d)^2) \cos(\theta) + (4b^2 + (a-d)^2)(3 + \cos(2\theta))) + 16b^2 \sin \left(\frac{\theta}{2} \right)^4}}. \quad (\text{B14})$$

Quantum circuit of Bhabha scattering

Bhabha Scattering

$$e^+ e^- \rightarrow e^+ e^-$$



$$T(\theta) = \begin{pmatrix} C(\theta) & 0 & 0 & 0 \\ 0 & A(\theta) & B(\theta) & 0 \\ 0 & B(\theta) & D(\theta) & 0 \\ 0 & 0 & 0 & C(\theta) \end{pmatrix},$$

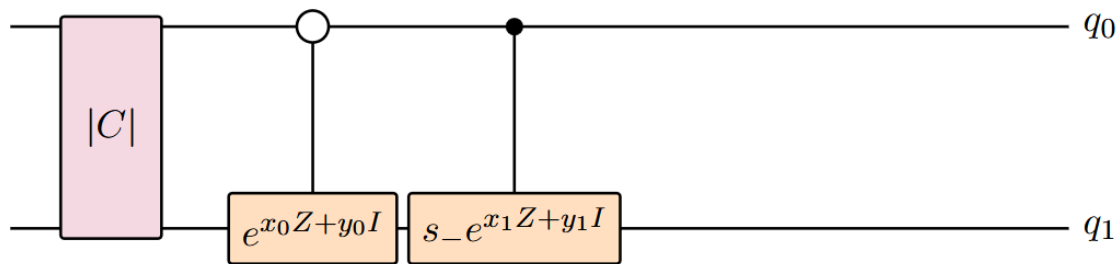
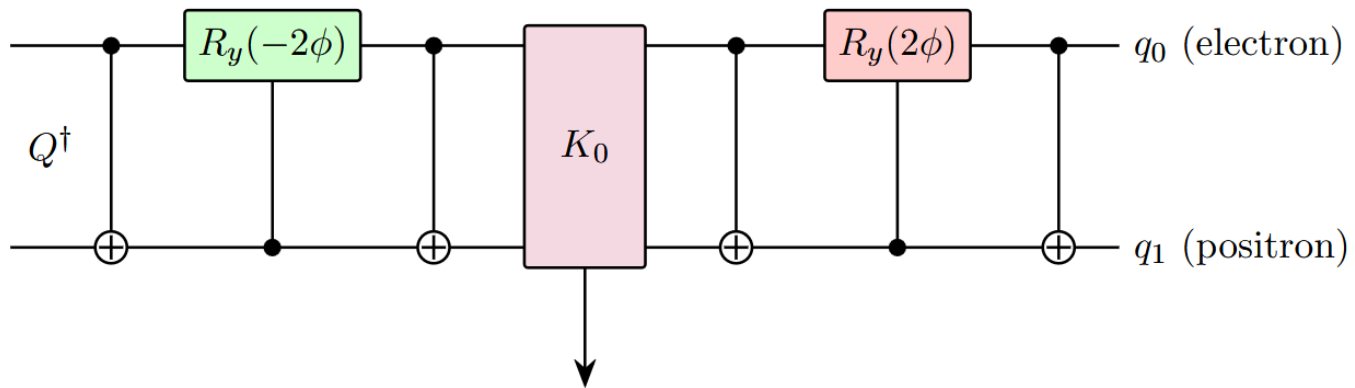
$$A(\theta) = 2u \left[\frac{1 + f_1(s)}{s} + \frac{1 + f_1(t)}{t} \right],$$

$$B(\theta) = -\frac{2t}{s} [1 + f_3(s)],$$

$$D(\theta) = 2u \left[\frac{1 + f_2(s)}{s} + \frac{1 + f_2(t)}{t} \right],$$

$$C(\theta) = -\frac{2s}{t} [1 + f_3(t)].$$

$$K = U\Sigma V^\dagger$$



Important caveat: this is not a universal programmable computer

What the collider provides

A physically fixed map whose parameters are determined by interactions and kinematics.

What a general computer requires

Programmable composition of gates, scalable registers, and controlled error correction.

“Collider as a quantum computer” is a process-level representation, not a claim of universal programmability.

Summary

- ▶ Collider scattering defines a finite-dimensional quantum map in helicity space.
- ▶ SVD reveals its operational structure and can be represented as quantum circuits
- ▶ Realizing a universal quantum computer and a programmable collider remains an open problem.

Thanks !