A Magical Determination of the Weak Mixing Angle in the Standard Model

Based on 2502.17550, 2503.03098 & 2509.18251 with Qiaofeng Liu and Ian Low

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Quantum scattering

- Our current theoretical framework for describing microscopic particle scattering: Quantum Field Theory
- The final state of particle scattering naturally contains much "quantumness"

Entanglement $\propto$ Elastic Cross Section

$$\mathcal{E}^{\mathrm{f}}_{n,\mathrm{T/R}} \doteq \frac{n}{n-1} I_0 \, \sigma_{\mathrm{el}}$$

Low, **ZY**, 2405.08056, 2410.22414.

- Universal; valid to all loop orders
- Possible interpretation: An **area law**
  IR (black hole) $\leftrightarrow$ UV (microscopic particle scattering)

Property or principle?

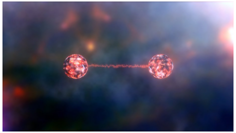
In recent years, it has been discovered that maximal or minimal entanglement leads to unique theories

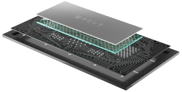
- Maximal entanglement → QED

  Cervera-Lierta, Latorre, Rojo, Rottoli; Fedida, Serafini; ...

- Minimal entanglement → classical BH scattering, strong interactions, flavor structures in SM, BSM theories...

  Beane, Kaplan, Klco, Savage; Aoude, Chung, Huang, Machado, Tam; Low, Mehen; Liu, Low, Mehen; Carena, Low, Wagner, Xiao; Thaler, Trifinopoulos; Núñez, Cervera-Lierta, Latorre...

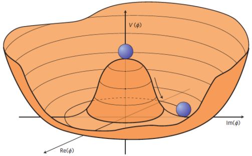




Quantum Information properties of particle scattering

? ↕

Underlying principles of QFT, e.g. symmetry



Quantum superiority

Entanglement is not enough to guarantee the advantage of quantum computing

- Gottesman-Knill theorem: Classical algorithms can efficiently simulate **stabilizer states** going through quantum circuit consisting of **Clifford gates**
- Clifford gates: Hadamard gate H and phase gate S for a single qubit; the CNOT gate for two qubits

"**Magic**" or non-stabilizerness: Quantifying the quantum advantage over classical algorithms

- Measure: Stabilizer Rényi entropy (SRE)

Leone, Oliviero, Hamma, *Phys.Rev.Lett.* 128 (2022) 5, 050402

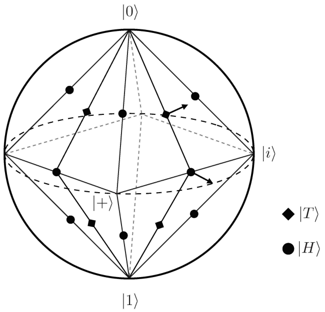
Exploration in the context of particle scattering:
nuclear physics, collider physics, neutrino physics...

Robin, Savage, 2024; White, White, 2024; Chernyshev, Robin, Savage, 2024...

Stabilizer states and magic

Stabilizer states: 0 magic

- For a single qubit:
  The 6 Pauli states



Credit: García-Álvarez, Ferraro, Ferrini, 1911.12346

- For 2 qubits: 60 states

The α-SRE:

$$M_\alpha(|\psi\rangle) = \frac{1}{1-\alpha} \ln \sum_{\mathcal{O}\in\mathcal{W}(d)} \frac{1}{d} |\langle\psi|\mathcal{O}|\psi\rangle|^{2\alpha}.$$

M_α quantifies, in a specific sense, the "distance" of a state to the stabilizer states

- $M_2(|T\rangle) = \ln(3/2)$

Maximal magic for 2-qubit

What is the maximal SRE for a 2-qubit system?

- Previous bound: $\ln(5/2) \approx 0.916$. It is known that the 2-qubit system cannot saturate the bound

Cuffaro, Fuchs, 2412.21083

- Our new bound: $\ln(16/7) \approx 0.827$

Liu, Low, **ZY**, 2502.17550

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Quantum Science and Technology

PAPER

Maximal magic for two-qubit states

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Maximal magic for 2-qubit

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Cuffaro, Fuchs, 2412.21083

- Our new bound: $\ln(16/7) \approx 0.827$

Liu, Low, **ZY**, 2502.17550

- States that saturate this bound: fiducial states for Weyl-Heisenberg mutually unbiased bases

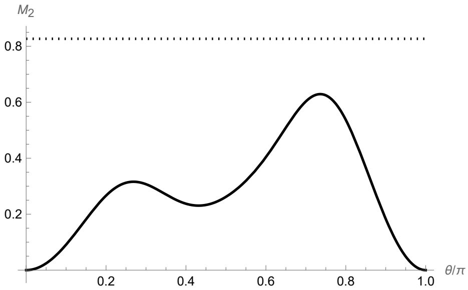
Feng, Luo, *Commun. Theor. Phys.* 77 (2025) 1, 015102

  - They contain a certain amount of entanglement

Magic in QED

Consider $2 \to 2$ scatterings of fermions in QED, and treat the spins of the two fermions as two qubits. How much magic can be generated?

Example 1: $e^- \mu^- \to e^- \mu^-$, high energy limit

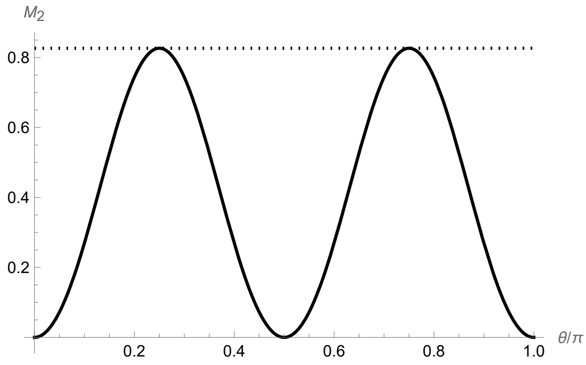


- Initial state: $(|\uparrow\uparrow\rangle + i|\uparrow\downarrow\rangle)/\sqrt{2}$
- $\max M_2 \approx 0.629$

Liu, Low, **ZY**, 2503.03098

Largest magic in QED

Example 2: $\mu^-\mu^+ \to e^-e^+$, low energy limit



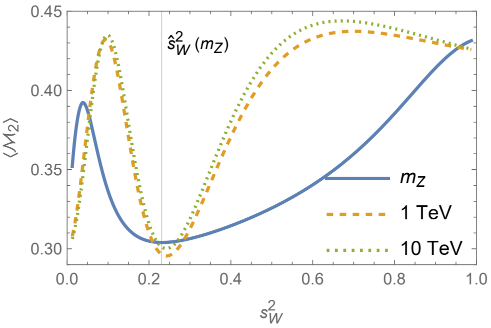
- Initial state: $(|\uparrow\uparrow\rangle + i|\uparrow\downarrow\rangle)/\sqrt{2}$
- The bound of $\ln 16/7$ is saturated in the $m_e/m_\mu \to 0$ limit

Liu, Low, **ZY**, 2503.03098

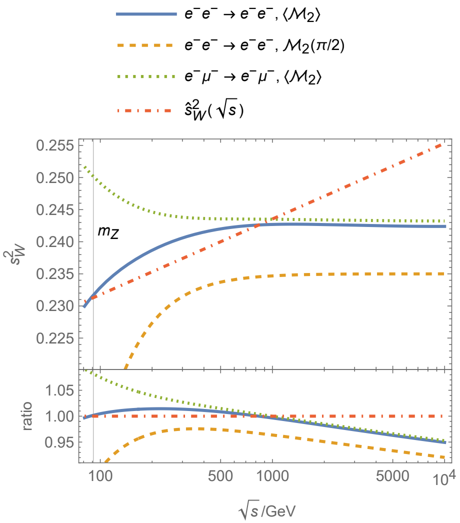
Magic in electroweak processes

Consider $2 \to 2$ lepton scattering, and treat θ_W as a free parameter:
The Standard Model tends to **minimize** average magic

Liu, Low, **ZY**, 2509.18251



$e^- e^- \to e^- e^-$



Outlook

- New concepts in QI are worth investigating
  - The maximal magic in more complicated systems? The effects of choosing different measures of magic? The basis dependence of magic?
- We should go beyond isolated observations and systematically investigate the QI properties of final states generated by particle scattering
  - What about the magic in the QCD sector?
  - What happens at loop level? Need to consider decoherence effects due to soft emissions
- We need to explain the reason behind the observed relations between the special QI properties and the features of QFT

Thank you!

Backup Slides

A universal relation

For AB $\to$ anything, select the elastic final state AB and consider the entanglement between A and B

$$\mathcal{E}^{\mathsf{f}}_{n,\mathsf{T/R}} \doteq \frac{n}{n-1} I_0 \, \sigma_{\mathsf{el}}$$

Low, **ZY**, 2405.08056, 2410.22414

- $\mathcal{E}^{\mathsf{f}}_{n,\mathsf{T/R}}$ is the nth Tsallis or Rényi entropy
- The result is of the leading order in the **plane wave limit**, i.e. for initial state **wave packets** approaching momentum eigenstates
  - Realizing concretely an expansion of $\delta_{\mathsf{p}}/|\vec{k}|$
- σ_{el} is the **total elastic cross section**; **non-perturbative** in coupling strength for any theory with at least 2 degrees of freedom
- I_0 is theory independent; size given by the inverse of the transverse **area** for the initial wave packets in the position space: $I_0 \sim 1/A$

Clifford gates

- Consider a single qubit: $|\psi\rangle = c_1|0\rangle + c_2|1\rangle \to (c_1, c_2)$

$$H = \frac{1}{2}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}, \quad S = \begin{bmatrix} 1 & 0 \\ 0 & i \end{bmatrix}$$

- Consider 2 qubits: $|\psi\rangle = c_1|00\rangle + c_2|01\rangle + c_3|10\rangle + c_4|11\rangle \to (c_1, c_2, c_3, c_4)$

$$\mathsf{CNOT}_{12} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

- Clifford gates + the T gate $\to$ universal quantum computing

$$T = \begin{bmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{bmatrix}$$