The Quantum Magic of Standard Model Parameters

Based on 2509.18251 and 2610.11121 with Qiaofeng Liu and Ian Low

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Oct 25, 2026

@ The 2026 International Workshop

on the High-Energy Circular Electron-Positron Collider, Shanghai

Quantum scattering

- Our framework for microscopic particle scattering: Quantum Field Theory (QFT)
- The final state of a scattering process naturally carries a lot of "quantumness"

For example: **entanglement** $\propto$ **cross section**

Low, **ZY**, 2405.08056, 2410.22414

See also Aoude, Elor, Remmen, Sumensari, 2402.16956; Zheng, Gu, 2610.10704

QI features: Property or principle?

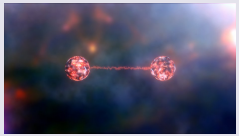
In recent years, maximal or minimal entanglement has been found to single out unique theories

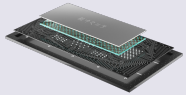
- Maximal entanglement $\rightarrow$ QED

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

- Minimal entanglement $\rightarrow$ classical BH scattering, strong interactions, flavor structures in the 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; ...

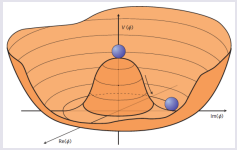




Quantum information properties of particle scattering

? $\updownarrow$

Underlying principles of QFT, e.g. symmetry



Quantum advantage

Entanglement alone is **not** enough to guarantee a quantum computational advantage

- Gottesman–Knill theorem: classical algorithms can efficiently simulate **stabilizer states** evolving through quantum circuits made of **Clifford gates**
- Clifford gates: the Hadamard gate H, the phase gate S, and the CNOT gate
  - Universal quantum computing: Clifford gates + the T gate

For a single qubit:

$$H = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}, \quad S = \begin{bmatrix} 1 & 0 \\ 0 & i \end{bmatrix},$$
$$T = \begin{bmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{bmatrix}$$

For 2 qubits:

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

Quantum magic

Magic, or non-stabilizerness: quantifies the quantum advantage over classical algorithms

- A computable measure: the stabilizer Rényi entropy (SRE)

Leone, Oliviero, Hamma, 2106.12587

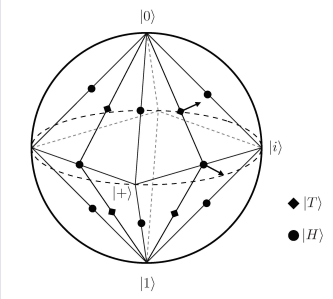
Explored in the context of particle scattering:
nuclear physics, collider physics, neutrino physics, ...

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

Stabilizer states and magic

Stabilizer states: zero magic

- For a single qubit: the 6 Pauli states



Credit: García-Álvarez, Ferraro, Ferrini, 1911.12346

- For 2 qubits: 60 states, with zero or maximal entanglement

The α-SRE:

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

where $\mathcal{W}(d)$ is the Weyl–Heisenberg (WH) group

- For a single qubit: $\mathcal{W}(2) = \{\mathbf{1}, \sigma_x, \sigma_y, \sigma_z\}$
- For n-qubit systems: $\mathcal{W}(2)^{\otimes n}$

No optimization over states needed!

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

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

Maximal magic for 2 qubits

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

- $M_2 \leq \ln(16/7) \approx 0.827$

  Liu, Low, **ZY**, 2502.17550

- States saturating this bound: fiducial states for Weyl–Heisenberg mutually unbiased bases

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

  - They are partially entangled: concurrence $1/2$ or $1/\sqrt{2}$



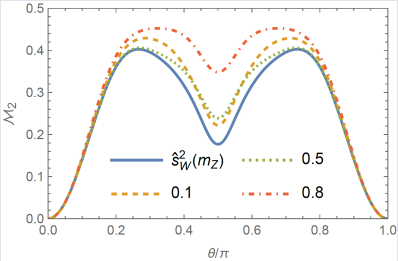
Magic in electroweak processes

Consider $e^-e^- \to e^-e^-$ and treat the spins of the two fermions as two qubits

- Treat θ_W as a free parameter

Average over the 60 stabilizer initial states...

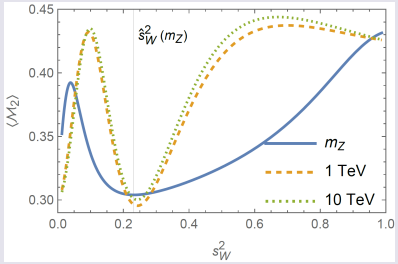
$$\mathcal{M}_2(\theta) \equiv \frac{1}{60}\sum_{i=1}^{60} M_2(|\psi_s\rangle_i, \theta)$$



(for $\sqrt{s} = m_Z$)

...as well as over the scattering angle

$$\langle \mathcal{M}_2 \rangle \equiv \int \frac{d\Omega}{4\pi} \mathcal{M}_2(\theta)$$



Liu, Low, **ZY**, 2509.18251

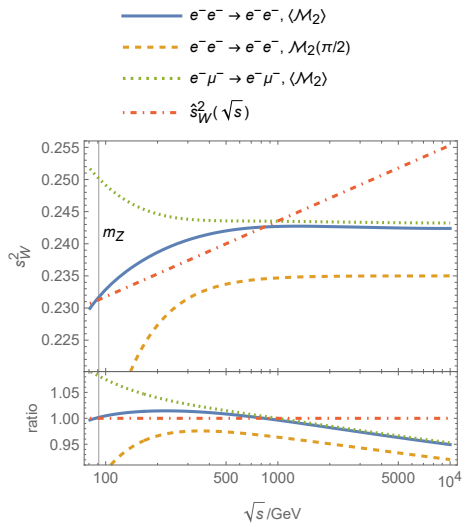
Magic for the weak mixing angle

The Standard Model value of s^2_W tends to **minimize** the average magic

Liu, Low, **ZY**, 2509.18251

For charged leptons,
$s^2_W = 1/4 \Rightarrow$ the Z coupling is purely axial

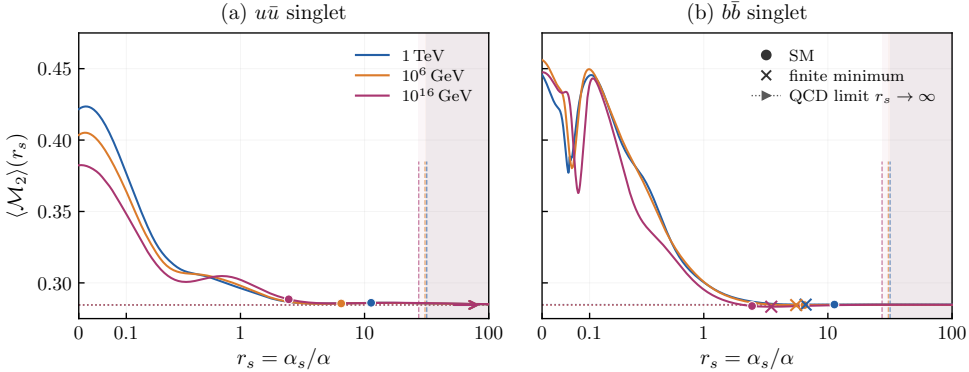
- $e^-e^- \to e^-e^-$: t and u channels
- $e^-\mu^- \to e^-\mu^-$: t channel only



Magic in QCD processes

Consider color-singlet $q\bar{q} \to q\bar{q}$, treating the two fermion spins as two qubits

- Treat α_s/α as a free parameter
- Light quarks: $\alpha_s > \alpha$ is preferred

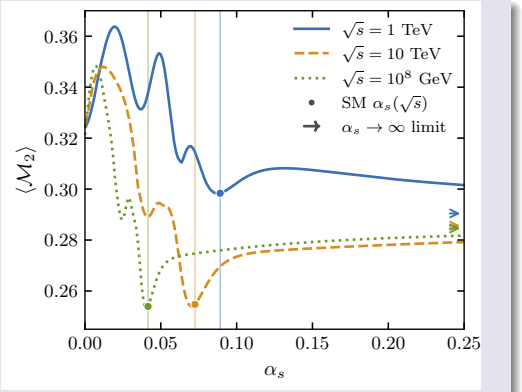


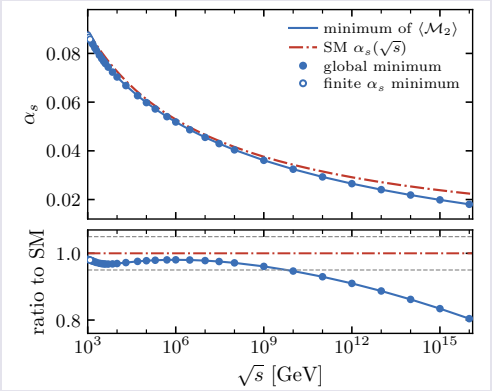
Liu, Low, **ZY**, 2610.11121

Magic for the strong coupling constant

$t\bar{t}$: the Standard Model value of α_s tends to **minimize** the average magic

Liu, Low, **ZY**, 2610.11121

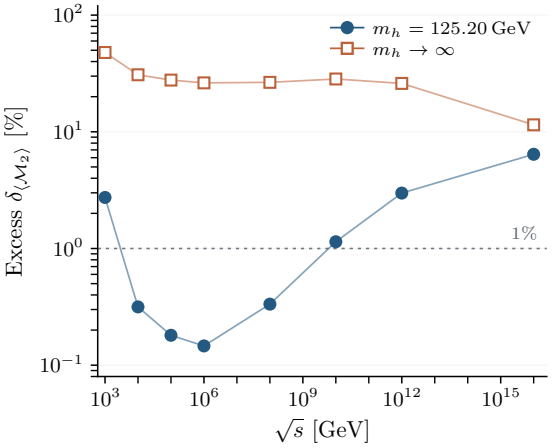




Magic for the Higgs sector?

- Higgs exchange is essential for the SM magic to lie close to the minimum
- Removing the Higgs exchange channel, i.e. taking $m_h \to \infty$, significantly worsens the agreement

Liu, Low, **ZY**, 2610.11121



Outlook

Implications: minimizing the resource for quantum computation as an underlying principle of fundamental physics?

- Why the SRE? Other measures of magic?

Shen, **ZY**, Zhang, *upcoming*

- The prescription for the quantum simulation, e.g. basis dependence?

Li, Low, Wang, **ZY**, 2608.19095

- Which processes determine which SM parameters? Quantitative predictions?
- The mechanism behind magic minimization?

Thank you!