Gauge and diffeomorphism invariance from quantum information principles

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Progress in algorithms and numerical tools for QCD (Orsay, 10 June 2026)

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with **C. Núñez, M. Asorey, J.I. Latorre & A. Cervera-Lierta**

Motivation & introduction

What are the ultimate principles underlying the structure of Nature?
Is it a Lagrangian? Is it a Hamiltonian? Is it a symmetry? …

It from bit: All things physical are information-theoretic in origin (Wheeler, '89).

Since everything follows quantum rules… **It from qubit?**

$$\mathcal{H}\,|\psi\rangle = E\,|\psi\rangle$$

Motivation & introduction

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Since everything follows quantum rules… **It from qubit?**

Fields, symmetries, interactions…
Predictive dynamics

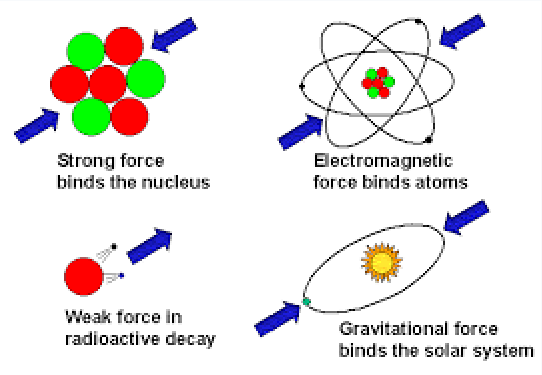
$$\mathcal{H}|\psi\rangle = E|\psi\rangle$$

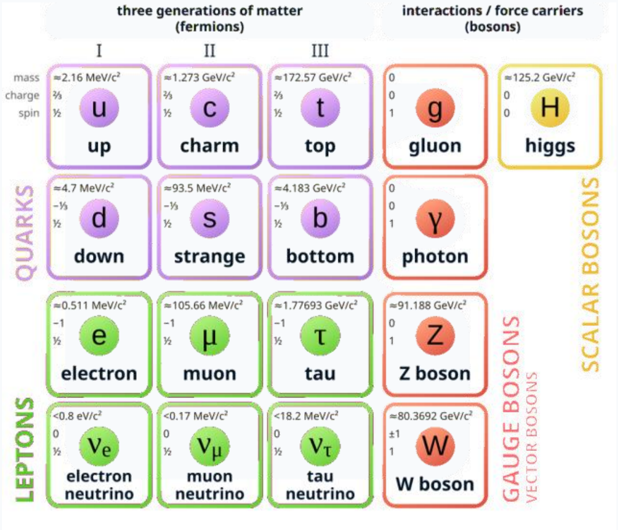
Entanglement, non-locality, purity…
State properties

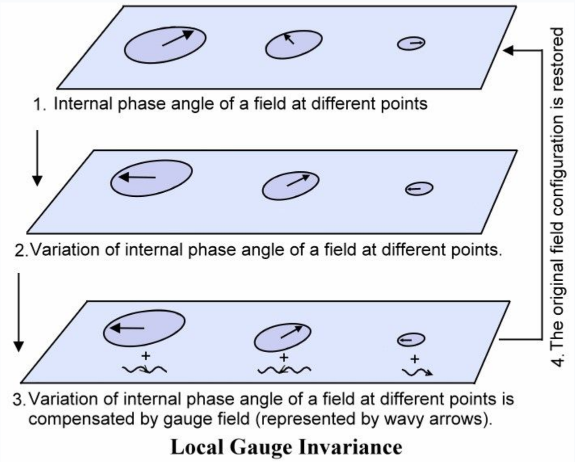
Motivation & introduction

Perhaps quantum information (QI) does constrain fundamental interactions?

Fundamental interactions ⟷ Standard Model of particle physics ⟷ Gauge Theory







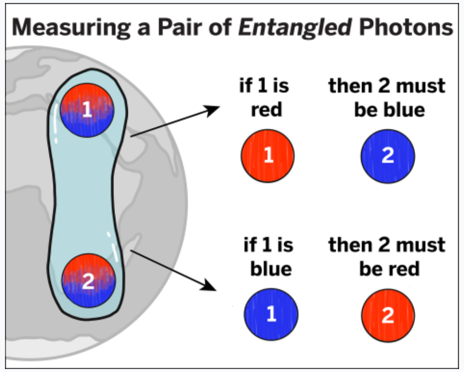
Motivation & introduction

Perhaps Quantum Information (QI) does constrain fundamental interactions?

Fundamental interactions ⟷ Standard Model of particle physics ⟷ Gauge Theory

⟷

Quantum Information?



Can QI tools lead us to rediscover gauge invariance in interactions?

Motivation & introduction

What if QI quantities are the underlying principle in fundamental interactions?

To take seriously this idea…

Which Quantum Infomation observables do we choose?

Which interaction processes do we pick?

Since the landscape is huge, we consider a minimal and simple approach:

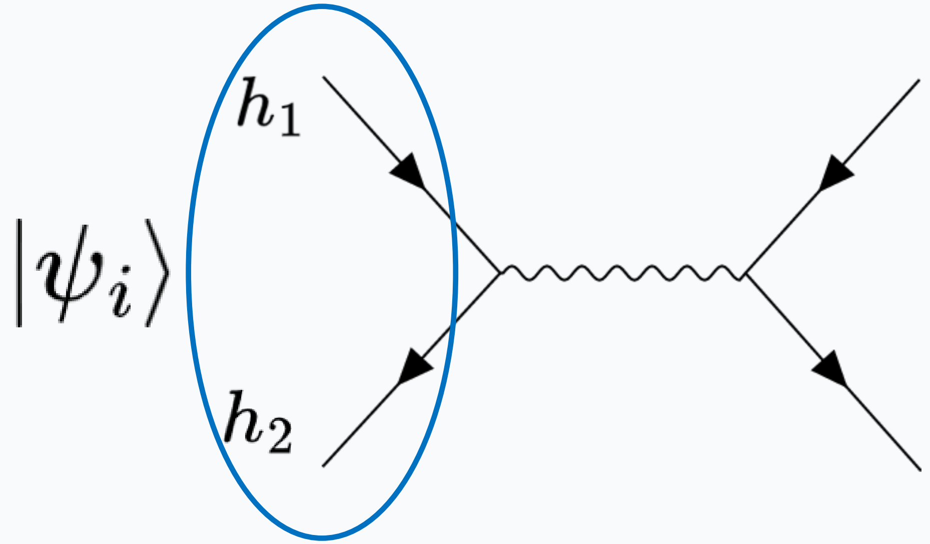
TWO QUBIT SYSTEM

Particle scattering as a 2-qubit system

Consider a tree-level scattering of 2 particles with 2 d.o.f. each (helicities in HE regime)

$$|\psi_i\rangle = |h_1 h_2\rangle$$

$$h_1, h_2 = \{L, R\}$$



$$|\psi_f\rangle \propto \mathcal{M}_{\psi_i \to RR}|RR\rangle + \mathcal{M}_{\psi_i \to RL}|RL\rangle + \mathcal{M}_{\psi_i \to LR}|LR\rangle + \mathcal{M}_{\psi_i \to LL}|LL\rangle$$

Now we can ask our questions in this specific framework!

Which Quantum Information observables do we choose?

ENTANGLEMENT: The global state of the system is not separable as two independent subsystems, stronger correlations than in classical physics.

CM: Well-defined individual properties, “what state is each object in?”. **Information IS in the parts**.
QM: NOT well-defined individual properties, ONLY globally, “How much of the information about the whole system exists only in the relationships between its parts?”. **Information is in the RELATIONSHIP between the parts.**

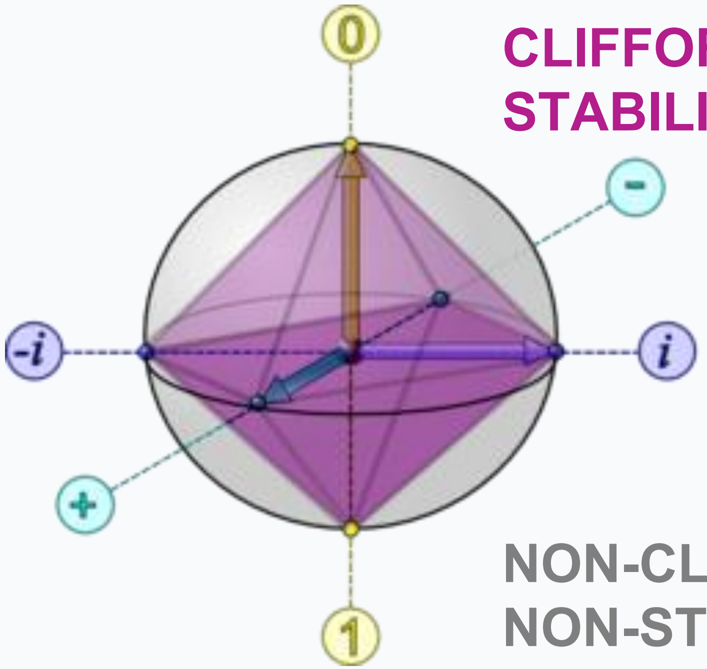
Concurrence as entanglement measure:

$$|\psi\rangle = \alpha|RR\rangle + \beta|RL\rangle + \gamma|LR\rangle + \delta|LL\rangle$$

$$\Delta = 2|\alpha\delta - \beta\gamma| \qquad 0 \leq \Delta \leq 1$$

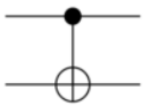
Which Quantum Information observables do we choose?

MAGIC RESOURCE: Measures universal quantum computation (Gottesman–Knill theorem of non-stabilizers). Clifford can be efficiently simulated classically, non-Clifford don’t.



CLIFFORD
STABILIZERS

NON-CLIFFORD
NON-STABILIZERS

Hadamard (H)	$\boxed{\mathbf{H}}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\ 1 & -1\end{bmatrix}$
Phase (S, P)	$\boxed{\mathbf{S}}$	$\begin{bmatrix}1 & 0\\ 0 & i\end{bmatrix}$
Controlled Not (CNOT, CX)		$\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & 0 & 1\\ 0 & 0 & 1 & 0\end{bmatrix}$
$\pi/8$ (T)	$\boxed{\mathbf{T}}$	$\begin{bmatrix}1 & 0\\ 0 & e^{i\pi/4}\end{bmatrix}$

Which Quantum Information observables do we choose?

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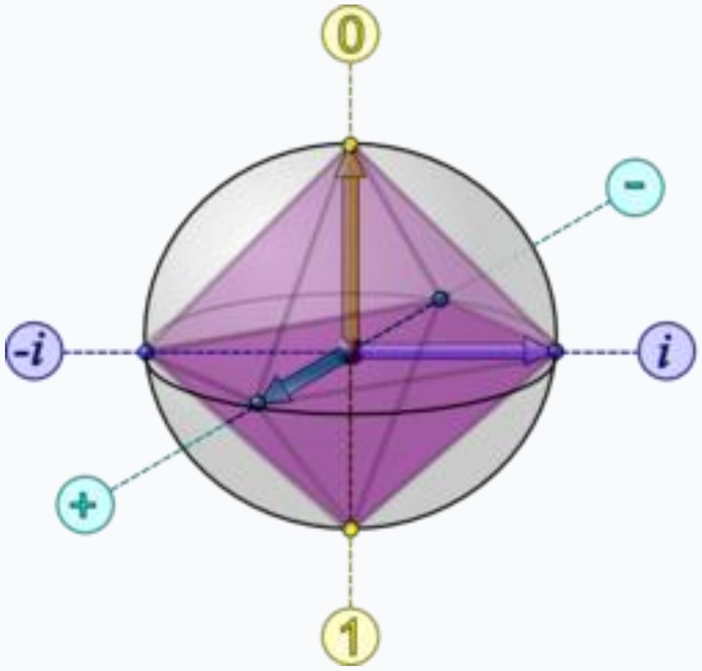


ALREADY EASY IN A CLASSICAL COMPUTER

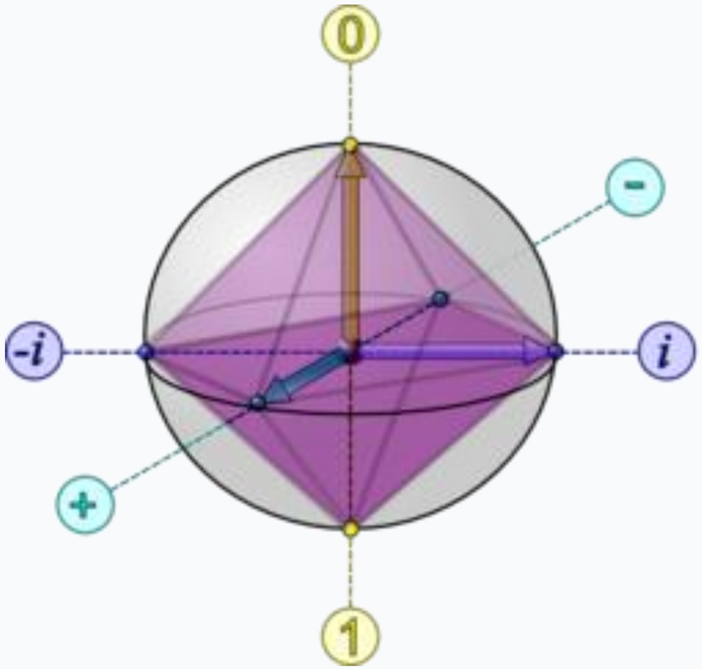
Hadamard (H)	$\boxed{\mathrm{H}}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\ 1 & -1\end{bmatrix}$
Phase (S, P)	$\boxed{\mathrm{S}}$	$\begin{bmatrix}1 & 0\\ 0 & i\end{bmatrix}$
Controlled Not (CNOT, CX)		$\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & 0 & 1\\ 0 & 0 & 1 & 0\end{bmatrix}$

GENUINE QUANTUM COMPUTATION ADVANTAGE

$\pi/8$ (T)	$\boxed{\mathrm{T}}$	$\begin{bmatrix}1 & 0\\ 0 & e^{i\pi/4}\end{bmatrix}$

Which Quantum Information observables do we choose?

MAGIC RESOURCE: There is not a universal measure, we will choose SRE



STABILIZERS

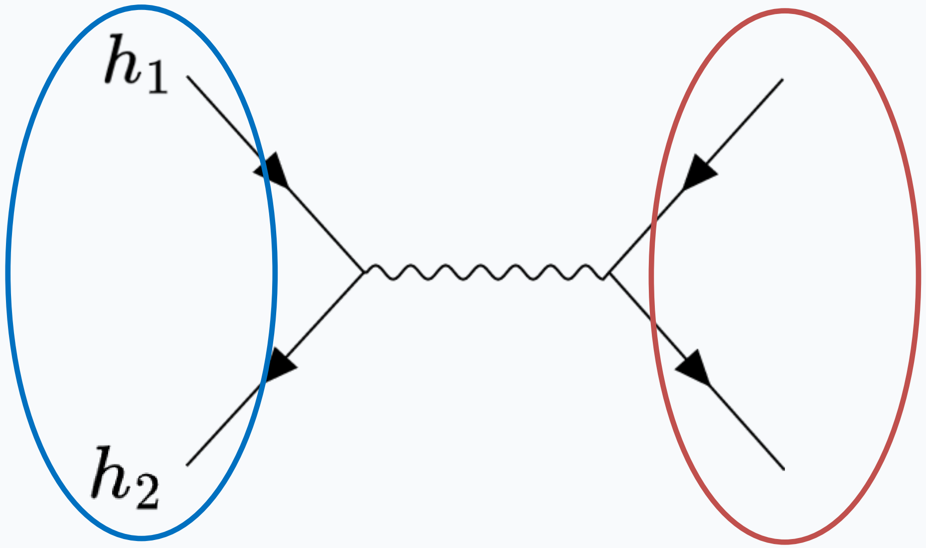
NON-STABILIZERS

$$M_\alpha\left(|\psi\rangle\right) = \frac{1}{1-\alpha}\log\left(\frac{1}{4}\sum_{P\in\mathcal{P}_n} |\langle\psi|P|\psi\rangle|^{2\alpha}\right)$$

where $\mathcal{P}_n$ is the $n-$qubit family of Pauli string operators, which for the $n=2$ is $P_2 = P_i \otimes P_j, \quad P_i, P_j \in \{\mathbb{1}, \sigma_x, \sigma_y, \sigma_z\}$, such that a Pauli or 2×2 identity matrix acts on each individual qubit. Then, for 2-qubits we have 16 different Pauli string operators. We will use the second order SRE, i.e. M_2.

Recipe for computing entanglement and magic in a 2-qubit system

$|\psi_i\rangle$



After summing over all possible outcomes

$|\psi_f\rangle$

$$|\psi_f\rangle \propto \mathcal{M}_{\psi_i \to RR}|RR\rangle + \mathcal{M}_{\psi_i \to RL}|RL\rangle + \mathcal{M}_{\psi_i \to LR}|LR\rangle + \mathcal{M}_{\psi_i \to LL}|LL\rangle$$

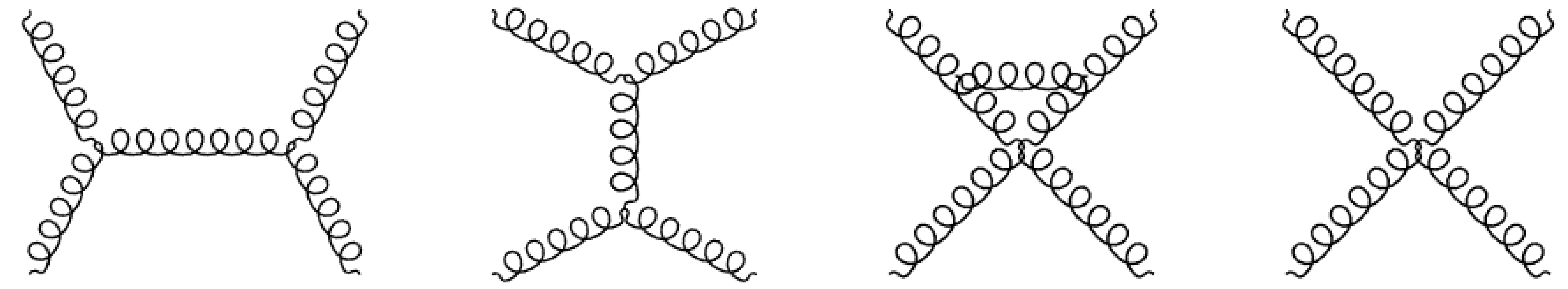
For this final scattering state we compute entanglement and magic:

$$\Delta = 2|\alpha\delta - \beta\gamma|$$

$$M_\alpha\left(|\psi\rangle\right) = \frac{1}{1-\alpha}\log\left(\frac{1}{4}\sum_{P\in\mathcal{P}_n}|\langle\psi|P|\psi\rangle|^{2\alpha}\right)$$

Which interaction processes do we pick?

QCD:

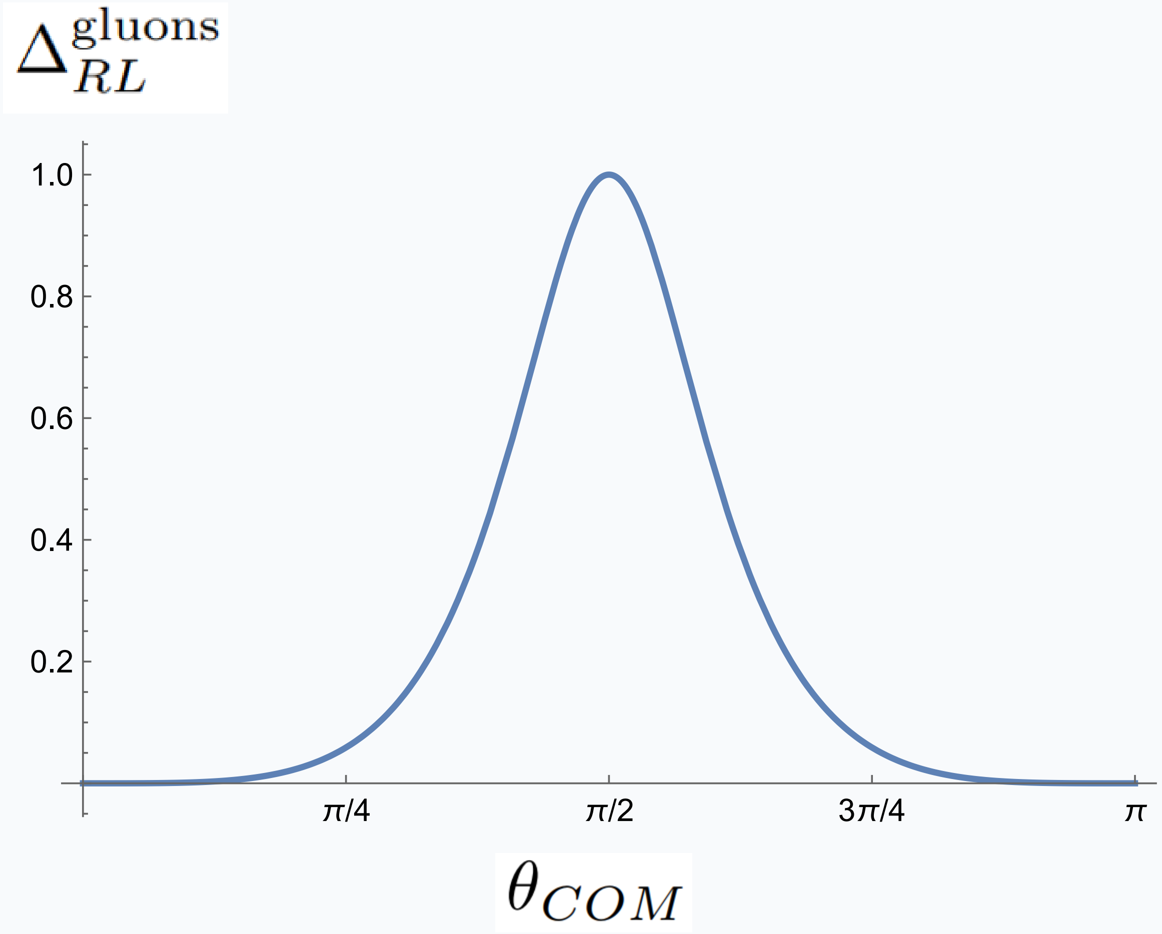


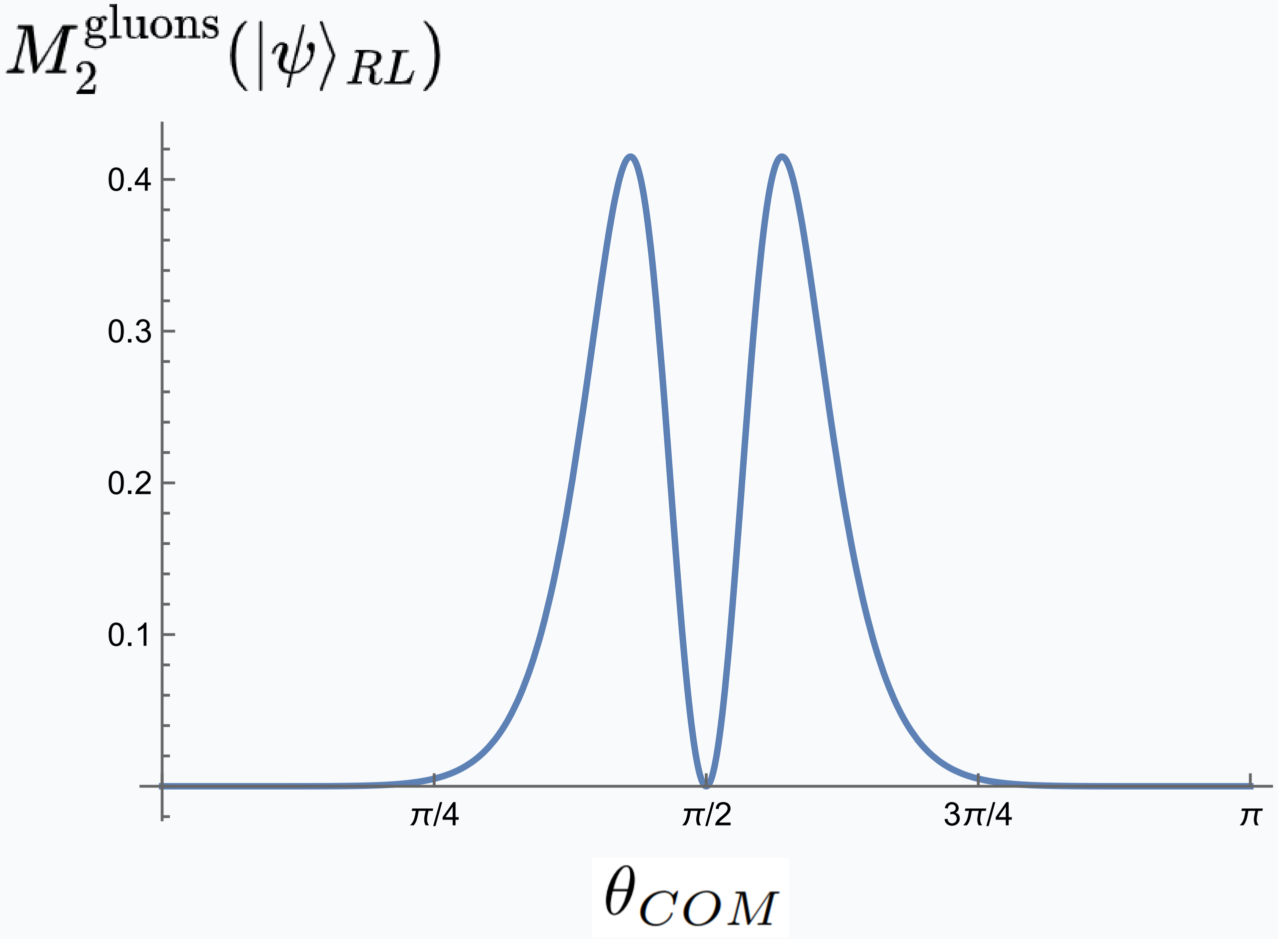
$$\mathcal{M} = \mathcal{M}_s + \mathcal{M}_t + \mathcal{M}_u + \mathcal{M}_4$$

$$\Delta_{RL}^{\text{gluons}} = \frac{2t^2u^2}{t^4 + u^4}$$

$$M_2(|\psi\rangle_{RL}) = -\log\left(\frac{t^{16} + 14t^8u^8 + u^{16}}{(t^4+u^4)^4}\right)$$

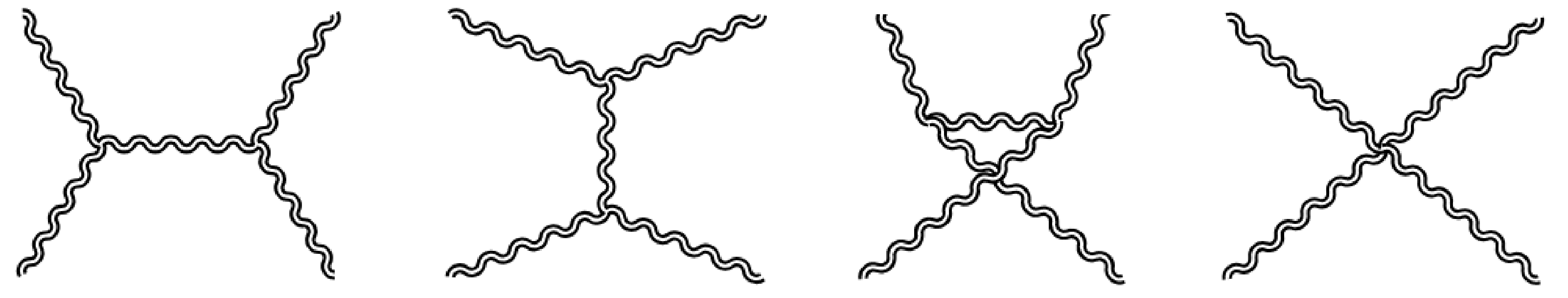
Entanglement and magic in QCD





Which interaction processes do we pick?

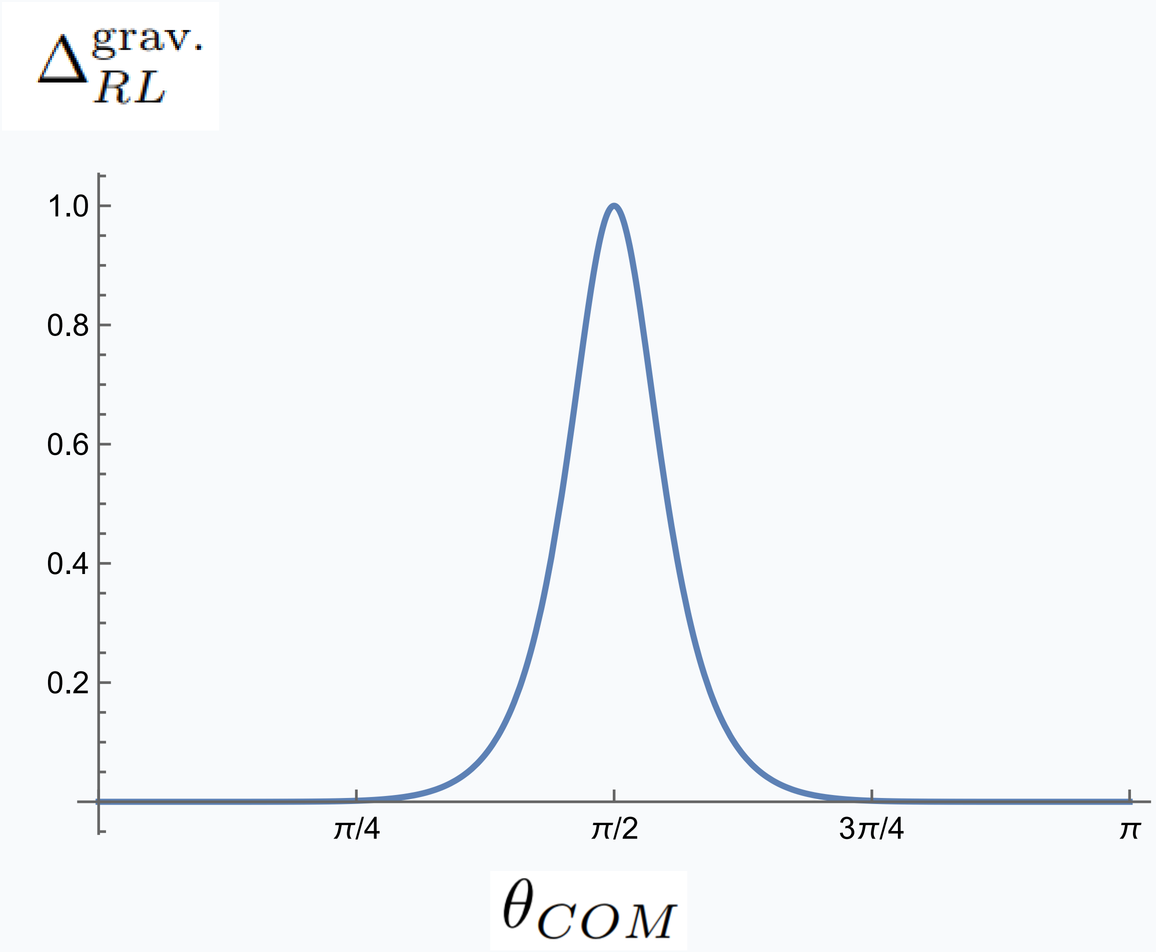
Gravity:

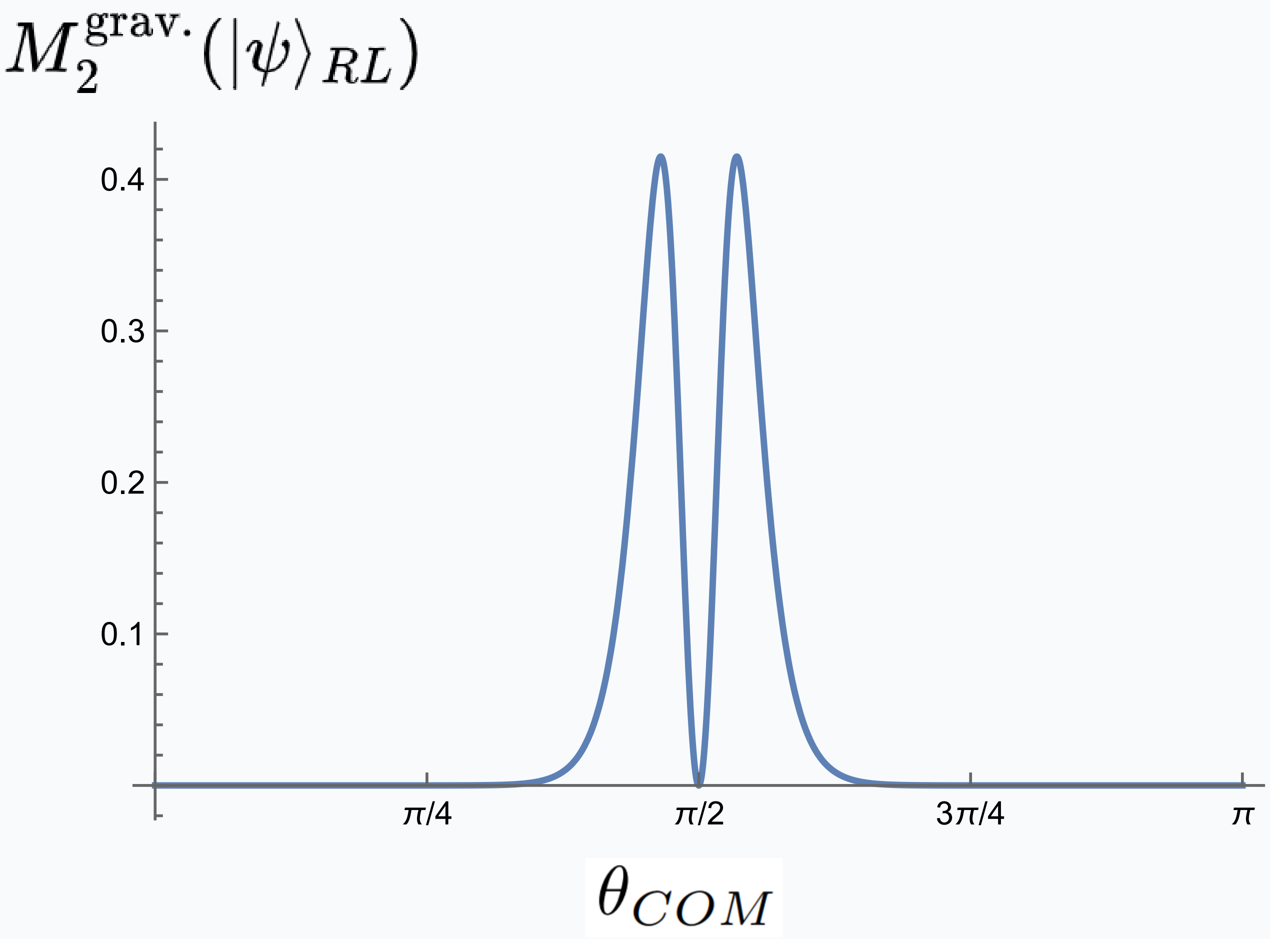


$$\Delta_{RL}^{\text{grav.}} = \frac{2t^4u^4}{t^8 + u^8}$$

$$M_2(|\psi\rangle_{RL}) = -\log\left(\frac{t^{32} + 14t^{16}u^{16} + u^{32}}{(t^8 + u^8)^4}\right)$$

Entanglement and magic in general relativity



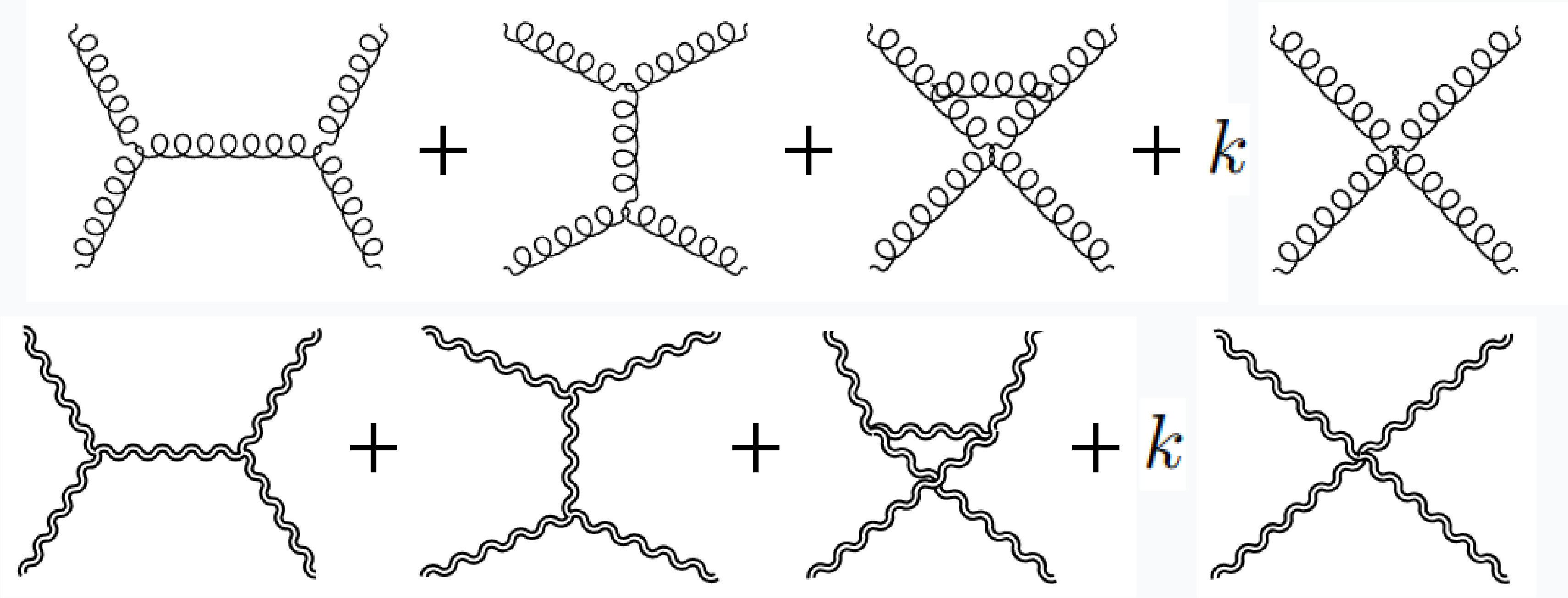


Probing gauge invariance from QI constraints

What can these QI quantities reveal about fundamental interactions?

We deform gauge invariance with a free parameter:

$$\mathcal{M} = \mathcal{M}_s + \mathcal{M}_t + \mathcal{M}_u + k\mathcal{M}_4$$



Probing gauge invariance from entanglement in QCD & GR

MaxEnt Principle?

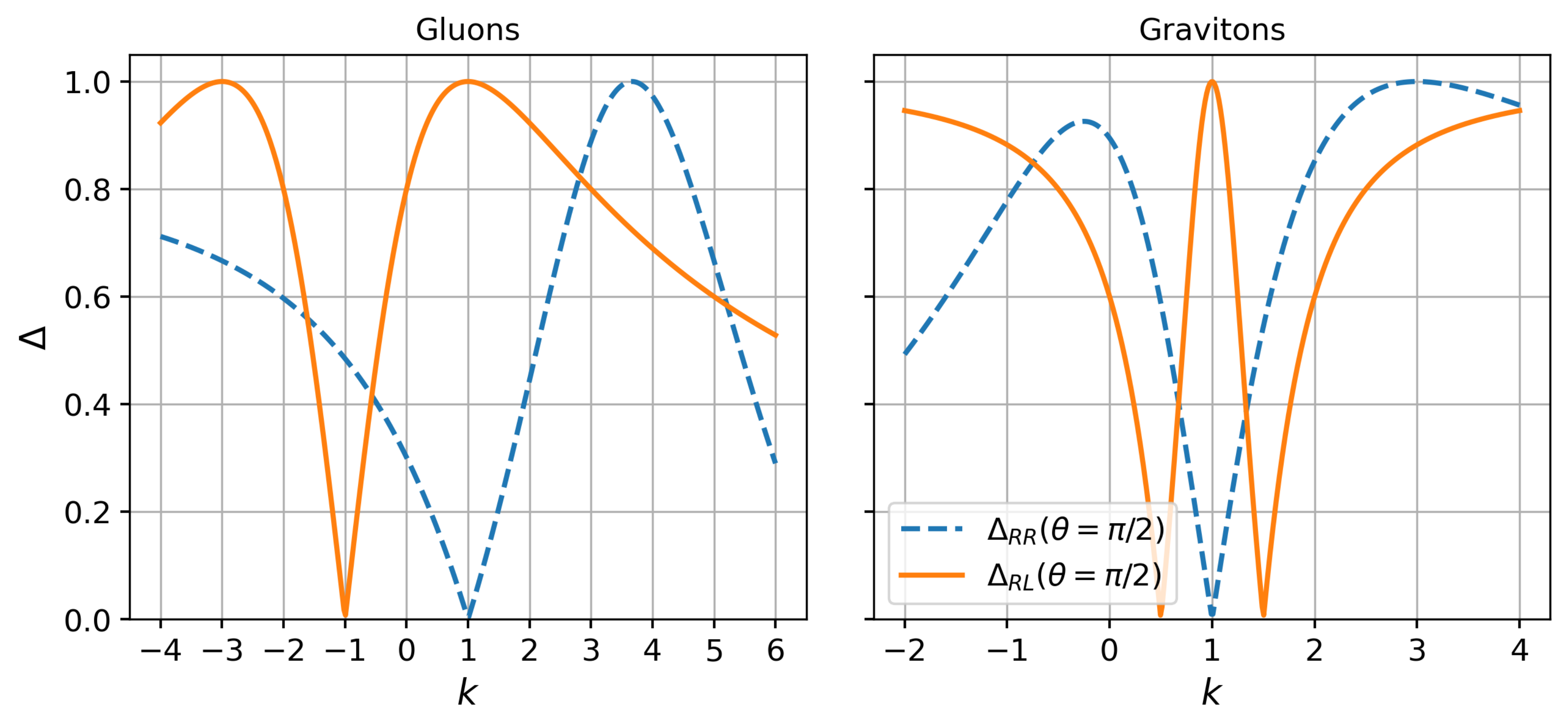
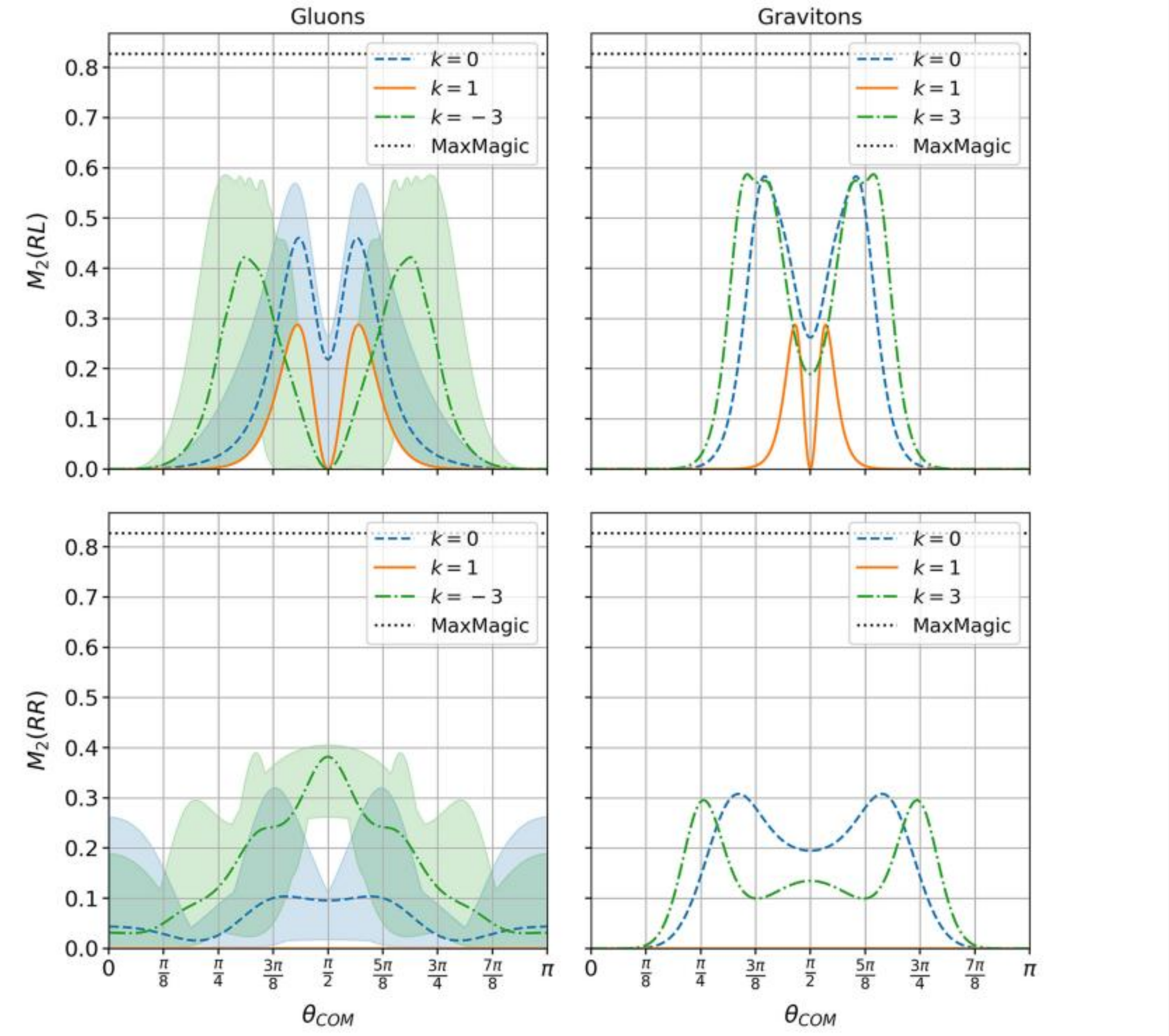


FIG. 1. Concurrence as a function of the four-vertex parameter k for initial polarizations RL and RR and COM angle $\theta_{\mathrm{COM}} = \pi/2$. The gauge-invariant solutions correspond to $k = 1$, where MaxEnt is achieved for initial RL polarization while RR generates a product state. Left: for QCD, MaxEnt is also obtained for two other unphysical solutions, $k = -3$ and $k = 11/3$, for an initial polarization of $|RR\rangle$. Right: in gravity, another nonphysical solution is obtained, $k = 3$, for an initial polarization of $|RR\rangle$.

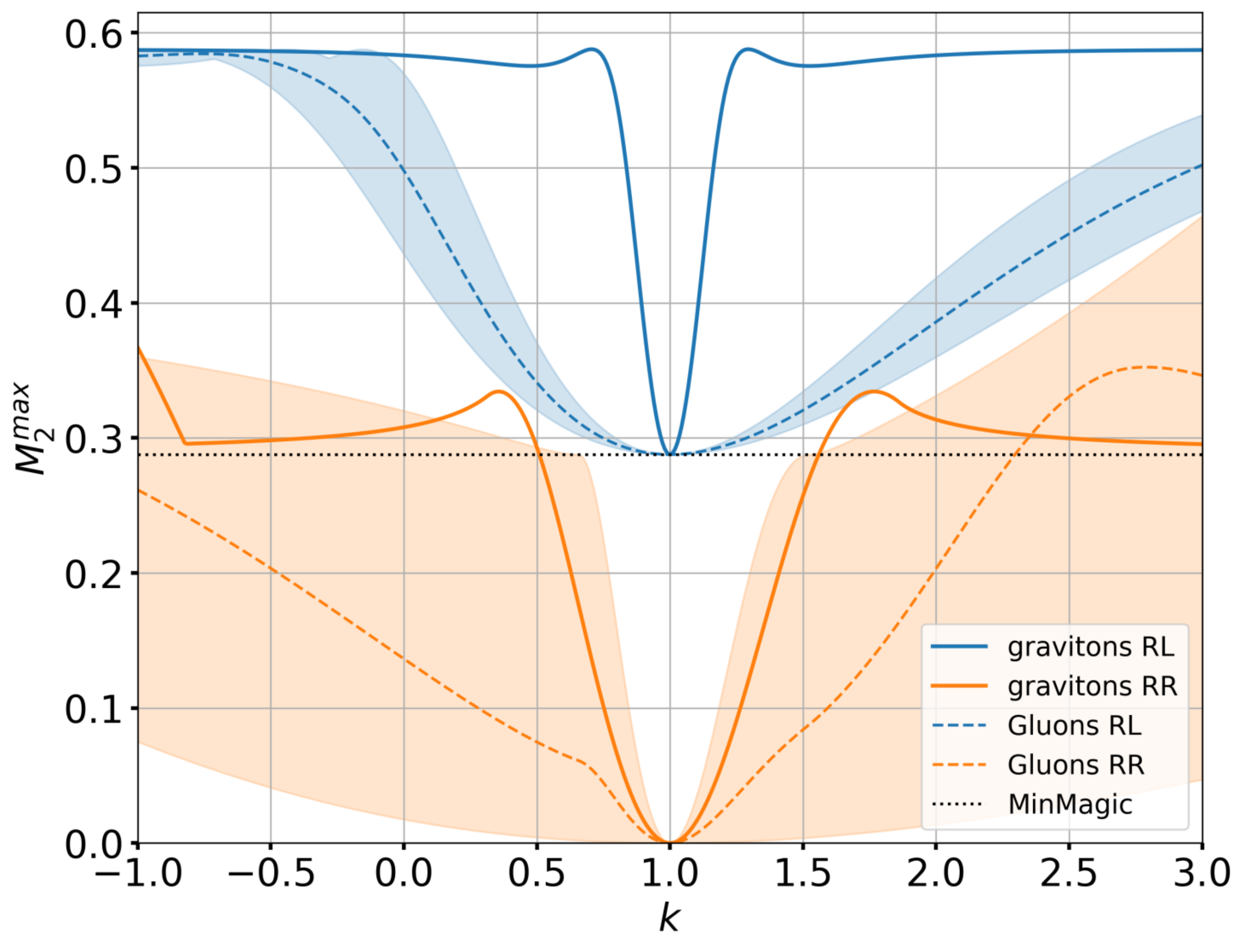
Probing gauge invariance from magic in QCD & GR



It seems that the maximum magic generated in $k = 1$ is always minimal compared to any other k for all scattering angles…

MinMagic principle?

Probing gauge invariance from magic in QCD & GR



$$M_2^{\max} \equiv \max_{\theta_{\mathrm{COM}}} M_2(\theta_{\mathrm{COM}}, k)$$

We maximize magic with respect to the scattering angle for each k

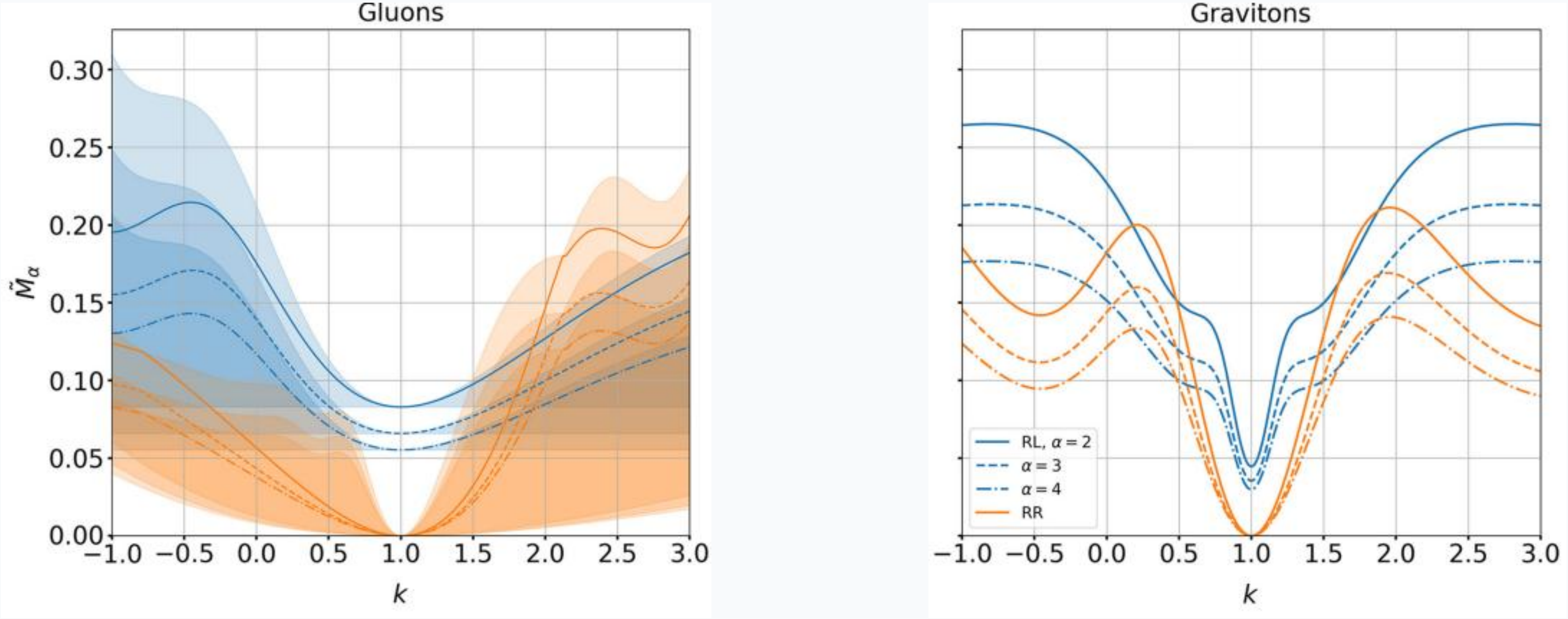
MinMagic principle selects $k = 1$

FIG. 3. Maximum M_2 achieved as a function of the four-vertex parameter k. The global minimum is obtained for $k = 1$, i.e., the gauge-invariant solution, and corresponds to $M_2 = \log(4/3)$ (MinMagic) for initial RL polarization, and zero for initial RR polarization.

Probing gauge invariance from magic in QCD & GR

The same conclusion holds for different α-SRE measures and also averaging over all angles instead of maximizing:

$$\tilde{M}_\alpha(k) \equiv \frac{1}{2}\int_{\theta_{\mathrm{COM}}} M_\alpha(k, \theta_{\mathrm{COM}}) \sin\theta_{\mathrm{COM}} d\theta_{\mathrm{COM}}$$



MinMagic principle selects $k = 1$

FIG. 4. Stabilizer Renyi entropies of degree $\alpha = 2, 3, 4$ for gluons and gravitons' final state scattering. The SRE are integrated over the COM angle. For gluons, the result depends on the color, so the plot shows the region between maximum and minimum values and the lines correspond to the median. As happened in Fig. 3, there is a single global minimum at $k = 1$, the gauge-invariant solution.

Conclusions

- QCD and gravity (also QED, see SciPost Phys. 20, 063 (2026)) generate entanglement when considering tree level scattering.

- MaxEnt (maximum quantum correlations) and MinMagic (close to classical simulability) as quantum information principles are able to recover gauge invariance when a deformation is considered in the 4-vertex interaction.

- **However:** SREs are good magic measures only for pure states, also different measures of magic remains an active topic of research. Other measures? Other interactions? More than 2 particle processes? Other deformations in the Lagrangian? Higher orders? Which other quantum information observables to impose?