Maximal Entanglement in a Quantum Computer

Alba Cervera-Lierta
Fermilab
July 15th 2021

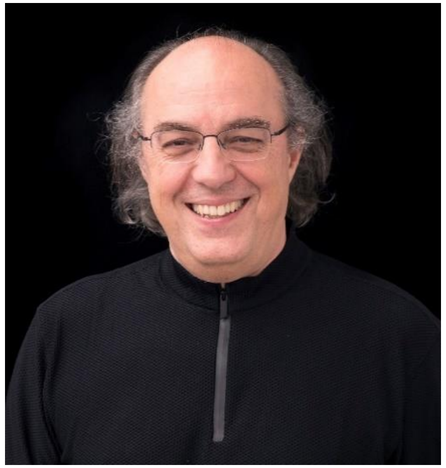
the matter lab

Outlook

1. Motivation: Maximal Entanglement as a principle
2. A hard test for a Quantum Computer
3. Beyond qubits: high-dimensional maximal entanglement
4. Outlook

Maximal Entanglement in Particle Physics

José Ignacio Latorre



Juan Rojo

Luca Rottoli

Maximal Entanglement in High-Energy Physics

A. Cervera-Lierta, J. I. Latorre, J. Rojo and L. Rottoli, SciPost Phys. **3**, 036 (2017).

Quantifying entanglement

Focus

Two-particle scattering processes at tree level
Entanglement of helicity degrees of freedom

$$|\psi\rangle_{final} = \alpha|00\rangle + \beta|01\rangle + \gamma|10\rangle + \delta|11\rangle$$

assuming $|0\rangle$, $|1\rangle$ helicity or polarization states.

$$|\alpha|^2 + |\beta|^2 + |\gamma|^2 + |\delta|^2 = 1$$

Figure of merit to quantify entanglement: concurrence

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

by construction, $0 \leq \Delta \leq 1$.

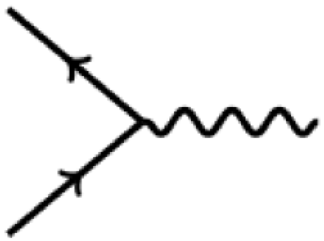
Question

Can a product state become entangled?

ACL, J. I. Latorre, J. Rojo and L. Rottoli, SciPost Phys. 3, 036 (2017).

MaxEnt generation in tree-level QED

The s-channel



$$j^{\mu}_{ss'} = e\bar{v}^{s'}(p')\gamma^{\mu}u^{s}(p)$$

Process: $e^+e^- \to \mu^+\mu^-$ at high energy

Incoming:

$$j^{\mu}_{RL} = 2ep_0\,(0, 1, i, 0)$$
$$j^{\mu}_{LR} = 2ep_0\,(0, 1, -i, 0)$$

Outgoing:

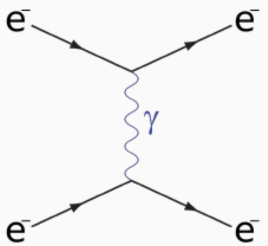
$$j^{\mu}_{RL} = 2ep_0\,(0, \cos\theta, i, -\sin\theta)$$
$$j^{\mu}_{LR} = 2ep_0\,(0, \cos\theta, -i, \sin\theta)$$

$$|RL\rangle \to (1+\cos\theta)|RL\rangle + (-1+\cos\theta)|LR\rangle$$

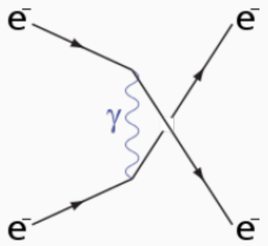
$$\theta = \pi/2 \to \Delta = 1$$

Indistinguishability

Process: $e^-e^- \to e^-e^-$ at high energy



t channel



u channel

$$\mathcal{M}(|RL\rangle \to |RL\rangle) = -2e^2\frac{u}{t}$$
$$\mathcal{M}(|RL\rangle \to |LR\rangle) = 0$$

$$\mathcal{M}(|RL\rangle \to |RL\rangle) = 0$$
$$\mathcal{M}(|RL\rangle \to |LR\rangle) = -2e^2\frac{t}{u}$$

$$|RL\rangle \to \frac{u}{t}|RL\rangle - \frac{t}{u}|LR\rangle$$

$$t = u\ (\theta = \pi/2) \to \Delta = 1$$

ACL, J. I. Latorre, J. Rojo and L. Rottoli, SciPost Phys. 3, 036 (2017).

It from bit

QED interaction can generate maximal entanglement in almost all processes and at different energy regimes.

Is this a property of nature interactions?

Could a symmetry emerge from a Maximum Entanglement Principle?

It from bit philosophy by J. A. Wheeler

*"All things physical are information-theoretic in origin"**

MaxEnt conjecture

Nature is such that maximally entangled states exist

*J. A. Wheeler, Proceedings III International Symposium on Foundations of Quantum Mechanics, Tokyo, 345-368 (1989)

Test: QED coupling

QED lagrangian at three-level (high-energy limit, $m = 0$)

	free fermions		free photons		interaction term
$\mathcal{L} =$	$i\bar{\psi}\gamma^\mu\partial_\mu\psi$	$+$	$\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$	$+$	$-eA_\mu\bar{\psi}G^\mu\psi$
	Dirac eq.		Maxwell eq.		

G^μ: 4×4 arbitrary matrices

Gauge invariance imposes $G^\mu = \gamma^\mu$

What are the couplings G^μ that generate maximal entanglement?

$$G^\mu = a^\mu \mathbb{I} + a^{\mu\nu}\gamma_\nu + ia^{\mu 5}\gamma^5 + a^{\mu\nu 5}\gamma^5\gamma_\nu + a^{\mu\nu\rho}[\gamma_\nu, \gamma_\rho]$$

Imposing P, C, T conservation →

$$G^\mu = a^{\mu\nu}\gamma^\nu \qquad a_{\mu\nu} \in \mathbb{R} \qquad a_{0i} = a_{i0} = 0$$

$$\mathcal{M}_{|initial\rangle \to |final\rangle} = f(\theta, a_{\mu\nu})$$

Constrain G^μ imposing MaxEnt in **ALL** tree level processes

$$\max_{a_{\mu\nu}} \{\Delta_{Bhabha}, \Delta_{Compton}, \Delta_{pair\ \ annhilation}, \Delta_{Moller}, \cdots\}$$

ACL, J. I. Latorre, J. Rojo and L. Rottoli, SciPost Phys. 3, 036 (2017).

Final solution: QED

Considering all tree level 2-particles processes (Bhabha, Moller, Compton, pair annihilation, ...)

$$(G^0, G^1, G^2, G^3) = \begin{cases} \left.\begin{array}{l} (\pm\gamma^0, \gamma^1, \gamma^2, \gamma^3) \\ (\pm\gamma^0, -\gamma^1, -\gamma^2, -\gamma^3) \end{array}\right\} \text{QED} \\ \\ \left.\begin{array}{l} (\pm\gamma^0, -\gamma^1, \gamma^2, \gamma^3) \\ (\pm\gamma^0, \gamma^1, -\gamma^2, -\gamma^3) \end{array}\right\} ? \end{cases}$$

All two-level processes are blind to the signs $\begin{array}{c} \gamma^i \to -\gamma^i \\ e \to -e \end{array}$

$-\gamma^1$ solution:

→ No rotational invariance!
→ Leads to a non-conservation of current
→ Could be discarded at higher orders or appealing to rotational symmetry?

→ QED is an isolated maximum: all deformations around QED produce lower entanglement

Weak interactions

Weak neutral current

$$J_\mu^{NC} = \bar{u}_f \gamma_\mu \left(g_V^f - \gamma^5 g_A^f \right) u_f$$

$$g_A^f = T_3^f/2 \qquad g_V^f = T_3^f/2 - Q_f \sin^2\theta_w$$

For electrons: $T_3^\ell = -1/2,\ Q_\ell = -1.$

Experimentally, $\sin^2\theta_w \simeq 0.23$

Guessing

- MaxEnt might be achievable on a line in the plane $\theta - \theta_w$
- Non-trivial tests: Bhabha (Z/γ interference)
- Special case, no kinematics: Z decay

ACL, J. I. Latorre, J. Rojo and L. Rottoli, SciPost Phys. 3, 036 (2017).

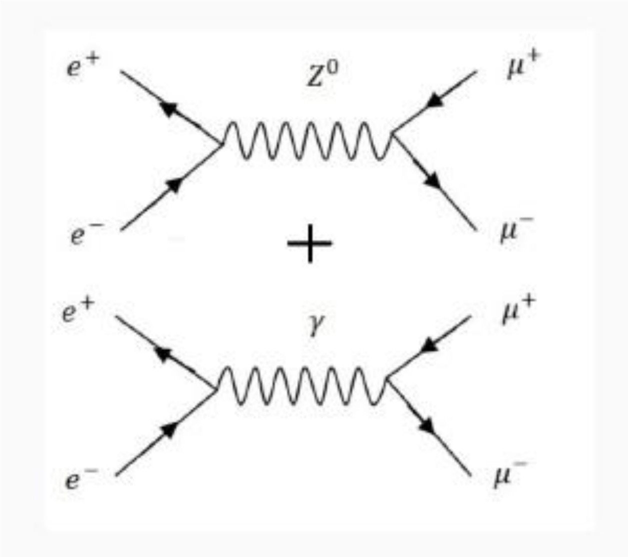
$e^-e^+ \rightarrow \mu^-\mu^+$ Z/γ interference

Photon contribution add terms to both RL and LR, which are independent of $sin^2\theta_w$

$$\mathcal{M} \sim \left(\mathcal{M}_Z^{RL}(\theta,\theta_w) + \mathcal{M}_\gamma^{RL}(\theta)\right)|RL\rangle + \left(\mathcal{M}_Z^{Lr}(\theta,\theta_w) + \mathcal{M}_\gamma^{LR}(\theta)\right)|LR\rangle$$

$$\Delta_{RL} = \frac{4\sin^2\theta}{6\cos\theta + 5(1+\cos^2\theta)} \quad \Delta_{RL} = 1 \rightarrow \quad \theta = \arccos\left(-\frac{1}{3}\right)$$

$$\Delta_{LR} = \frac{\sin^2\theta\sin^2\theta_w}{c^4 + 4s^4\sin^4\theta_w} \quad \Delta_{LR} = 1 \rightarrow \quad \theta_w = \arcsin\left(\frac{1}{\sqrt{2}}\cot(\theta/2)\right)$$



Imposing MaxEnt at the same COM angle

$$\theta = \arccos\left(-\frac{1}{3}\right), \quad \sin^2\theta_w = \frac{1}{4}$$

ACL, J. I. Latorre, J. Rojo and L. Rottoli, SciPost Phys. 3, 036 (2017).

Summary

Maximal entanglement:

- Discards classical physics by principle predictive
- Consistent with QED, which is an isolated solution
- MaxEnt is found in every channel where it was possible

Consequences: Can we use it as a tool to estimate the value of SM free parameters?

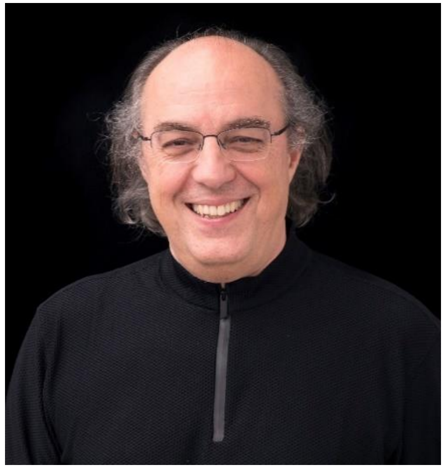
- Weak interactions: MaxEnt in tree-level weak interactions predict $sin^2\theta_w = 0.25$.

Some Open Questions:

- Relax C, P and T to CPT symmetry?
- Other interaction theories: QCD, chiral, gravity, …
- Other degrees of freedom: position/momenta space, flavor, color, …
- Multipartite entanglement?
- Higher-order terms?

Hard tests for Quantum Computers

José Ignacio Latorre

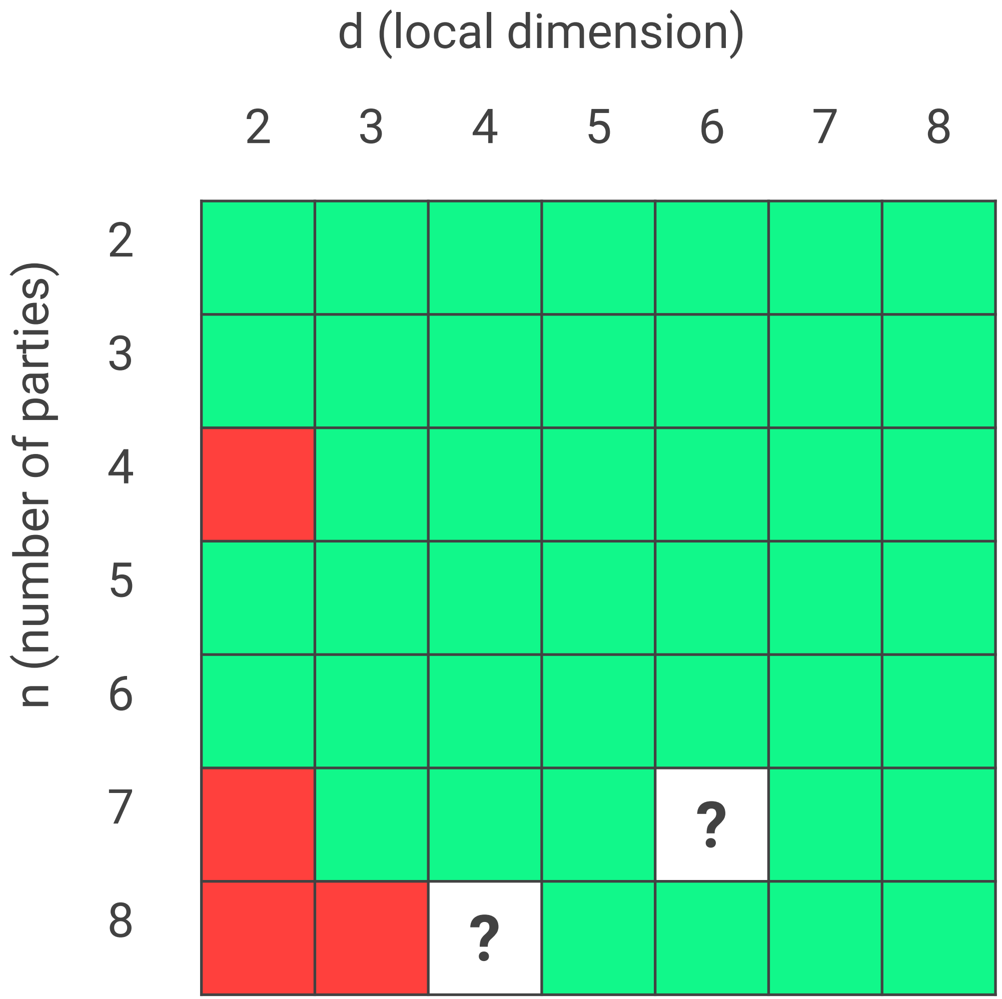


Dardo Goyeneche

Quantum Circuits for maximally entangled states

A. Cervera-Lierta, J. I. Latorre, D. Goyeneche
Physical Review A **100** (2), 022342 (2019).

Absolutely Maximally Entangled (AME) states



Absolutely Maximally Entangled (AME) states)

Pure states that are maximally entangled in all their bipartitions.

For a given n and d AMEs existence is an open problem in quantum information theory

F. Huber and N. Wyderka, “Table of AME states", http://www.tp.nt.uni-siegen.de/+fhuber/ame.html

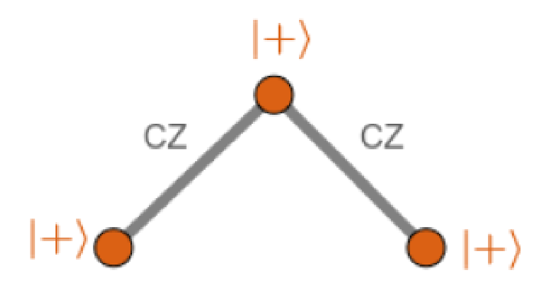
Graph states

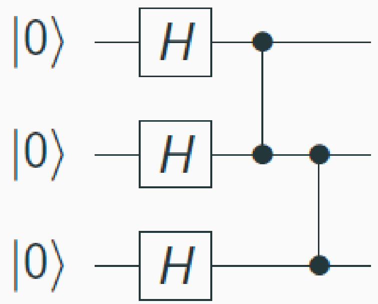
Those states that can be represented and constructed with a graph following the rules:

- Each vertex corresponds to a state in the superposition state $|+\rangle = H|0\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$
- Each edge corresponds to a Controlled-Z operation

Some AME states are also graph states.

Example: GHZ state



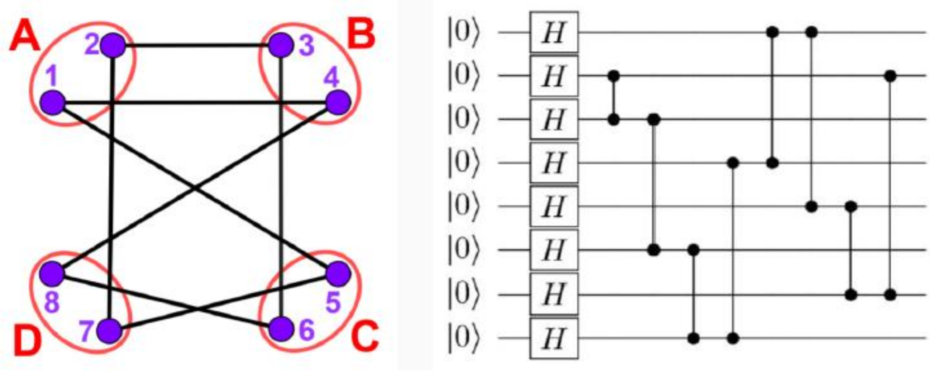


$$\frac{1}{2\sqrt{2}}(|000\rangle + |001\rangle + |010\rangle - |011\rangle$$
$$|100\rangle + |101\rangle - |110\rangle + |111\rangle)$$

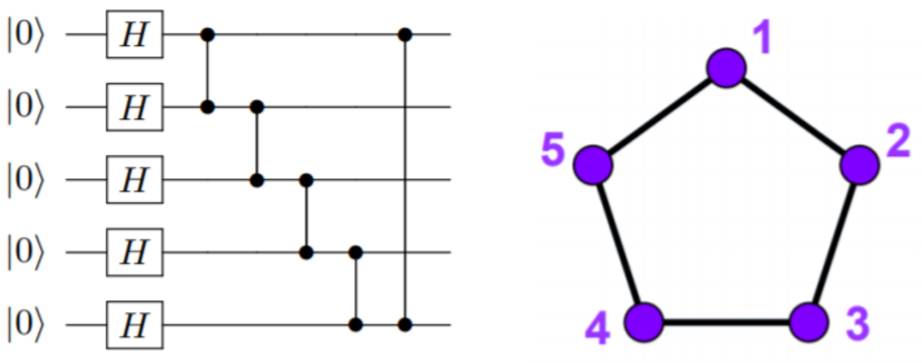
ACL, J. I. Latorre, D. Goyeneche, Phys. Revi. A 100 (2), 022342 (2019).

Quantum circuits for AME states

AME(4,4) state

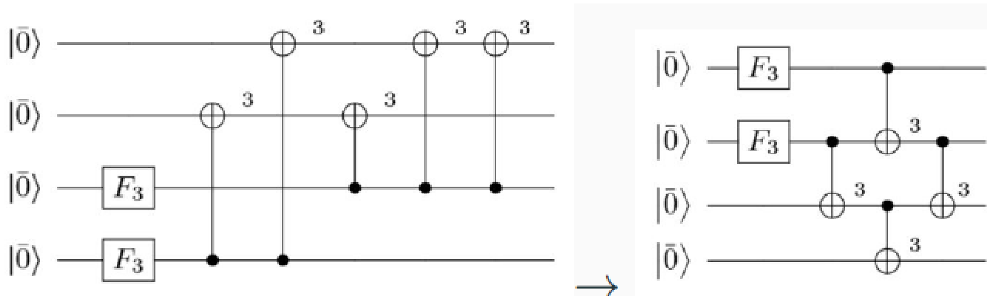


AME(5,2) state

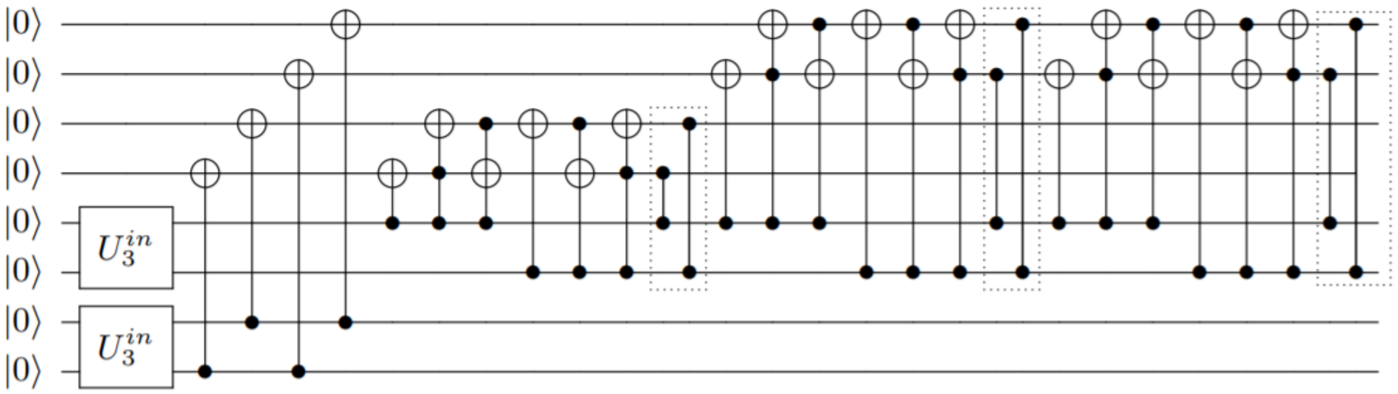


AME(4,3) state simulated with qubits

Qutrit circuit



Qubit circuit



Summary

We present a set of shallow quantum circuits which use standard native gates to generate Absolutely Maximally Entangled states.

We run these circuits in a real quantum computer (Rigetti and IBM) and we did not reproduce the state's basis elements probability amplitudes.

Slightly entangled states can be simulated efficiently with a classical computer (tensor networks).

Hard but necessary test for Quantum Computers

Quantum Computers must be able to generate and hold highly entangled states (otherwise, everything will be efficient in a classical simulator)

Beyond qubits: high-dimensional maximal entanglement

Mario Krenn

Alán Aspuru-Guzik

Alexey Galda

Experimental high-dimensional Greenberger-Horne-Zeilinger entanglement with superconducting transmon qutrits

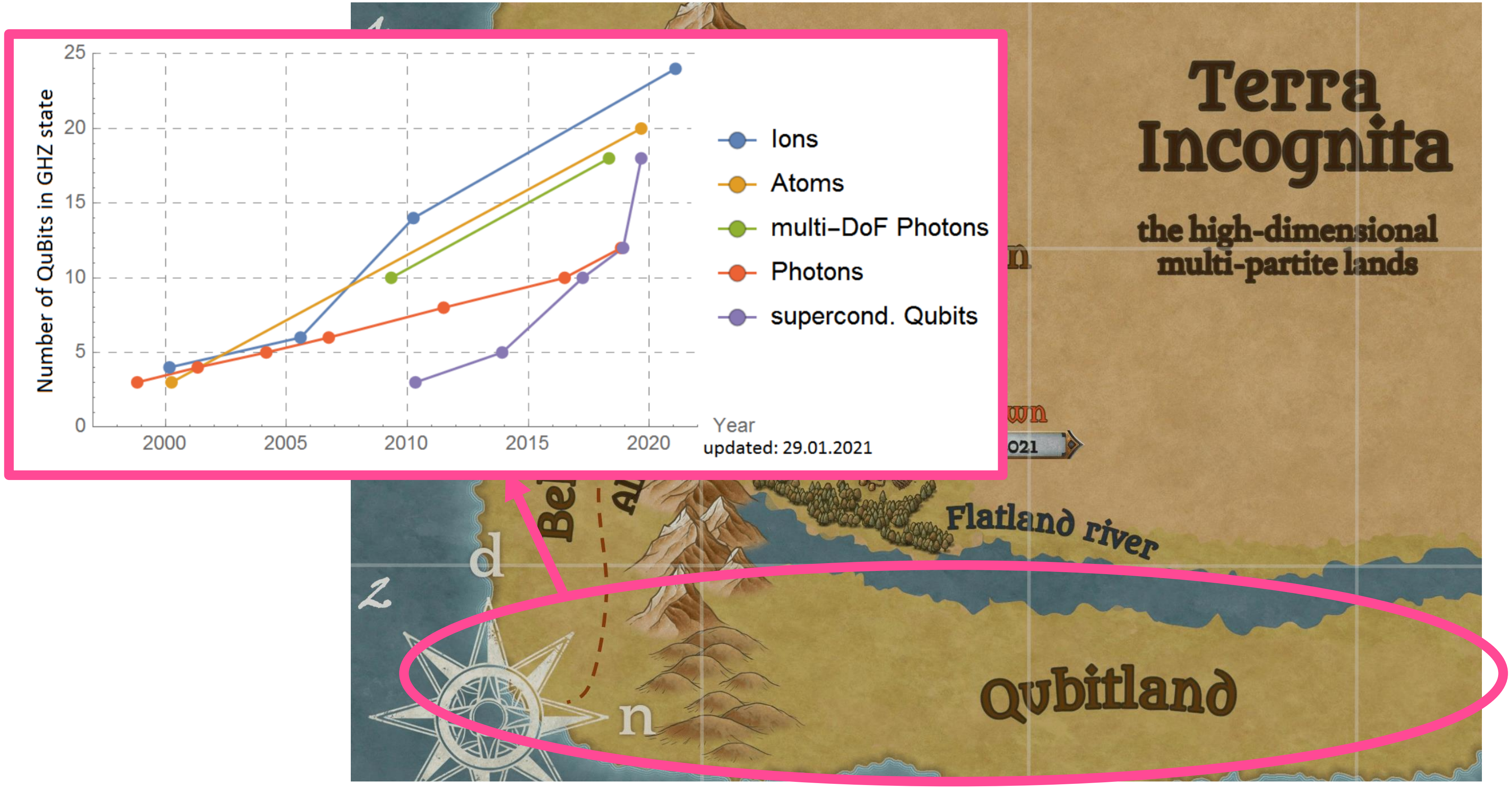
A. Cervera-Lierta, M. Krenn, A. Aspuru-Guzik, A. Galda, arXiv:2104.05627 [quant-ph] (2021).

Entangland

Local dimension d

Number of parties n

Entangland: qubitland



References:

https://mariokrenn.wordpress.com/
2021/01/29/reference-list-for-records-in-large-entanglement-generation-number-of-qubits-in-ghz-states/

Entangland: high-dimensional regions

Generation and confirmation of a (100 × 100)-dimensional entangled quantum system
Mario Krenn et. al., PNAS **111** (17) 6243-6247 (2014)

Experimental Greenberger–Horne–Zeilinger entanglement beyond qubits
Manuel Erhard et. al., Nature Photonics **12**, pages759–764 (2018)

Experimental creation of multi-photon high-dimensional layered quantum states
Xiao-Min Hu et. al., npj Quantum Information **6**, 88 (2020)

GHZ plain

d= 3

$n = 3$

The Greenberger-Horne-Zeilinger state:

$$|GHZ\rangle = \frac{1}{\sqrt{d}}\sum_{k=0}^{d-1}|kkk\rangle$$

For qubits ($d = 2$)

$$|GHZ\rangle = \frac{1}{\sqrt{2}}(|000\rangle + |111\rangle)$$

For qutrits ($d = 3$)

$$|GHZ\rangle = \frac{1}{\sqrt{3}}(|000\rangle + |111\rangle + |222\rangle)$$

Applications of High-dimensional physics

What are the physics in the GHZ plain?

- Quantum foundations: non-locality tests (GHZ contradictions)
    - Qubits: theory 1990 [1], experiment 2000 [2]
    - Qudits: theory 2014 [3], experiment ???
- Quantum Error Correction [4]
- Quantum Computation [5]
- Quantum Simulation: spin>1/2 systems

[1] D. M. Greenberger, A. Horne, A. Zeilinger, American Journal of Physics **58**, 1131 (1990).

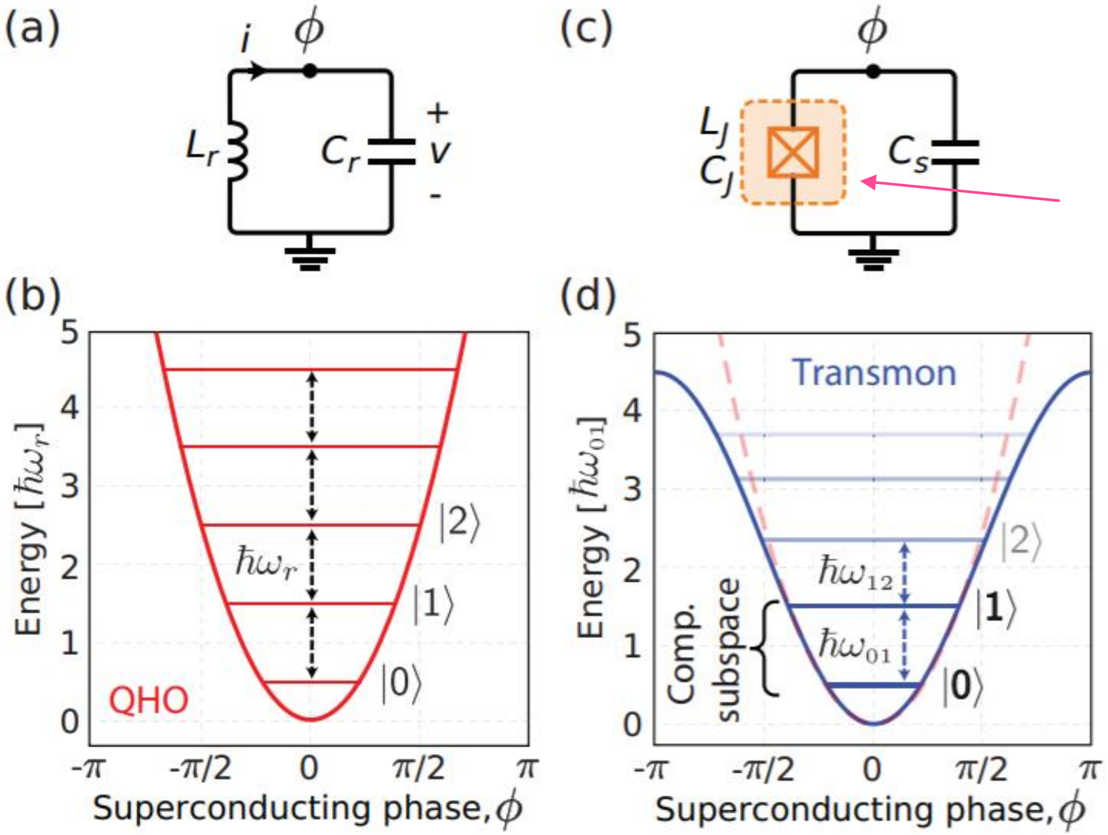
[2] J-W Pan, D. Bouwmeester, M. Daniell, H. Weinfurter, A. Zeilinger, Nature **403**, 515–519 (2000).

[3] J. Lawrence, Phys. Rev. A **89**, (2014).

[4] E. T. Campbell, Phys. Rev. Lett. **113**, 230501 (2014).

[5] P. Gokhale, J. M Baker, C. Duckering, N. C Brown, K. R Brown, F. T Chong, Proceedings of the 46th International Symposium on Computer Architecture, 554–566 (2019).

Superconducting transmon ~~qubits~~ qudits



Non-linear inductance
(Josephson Junction)

Quantum Harmonic Oscillator

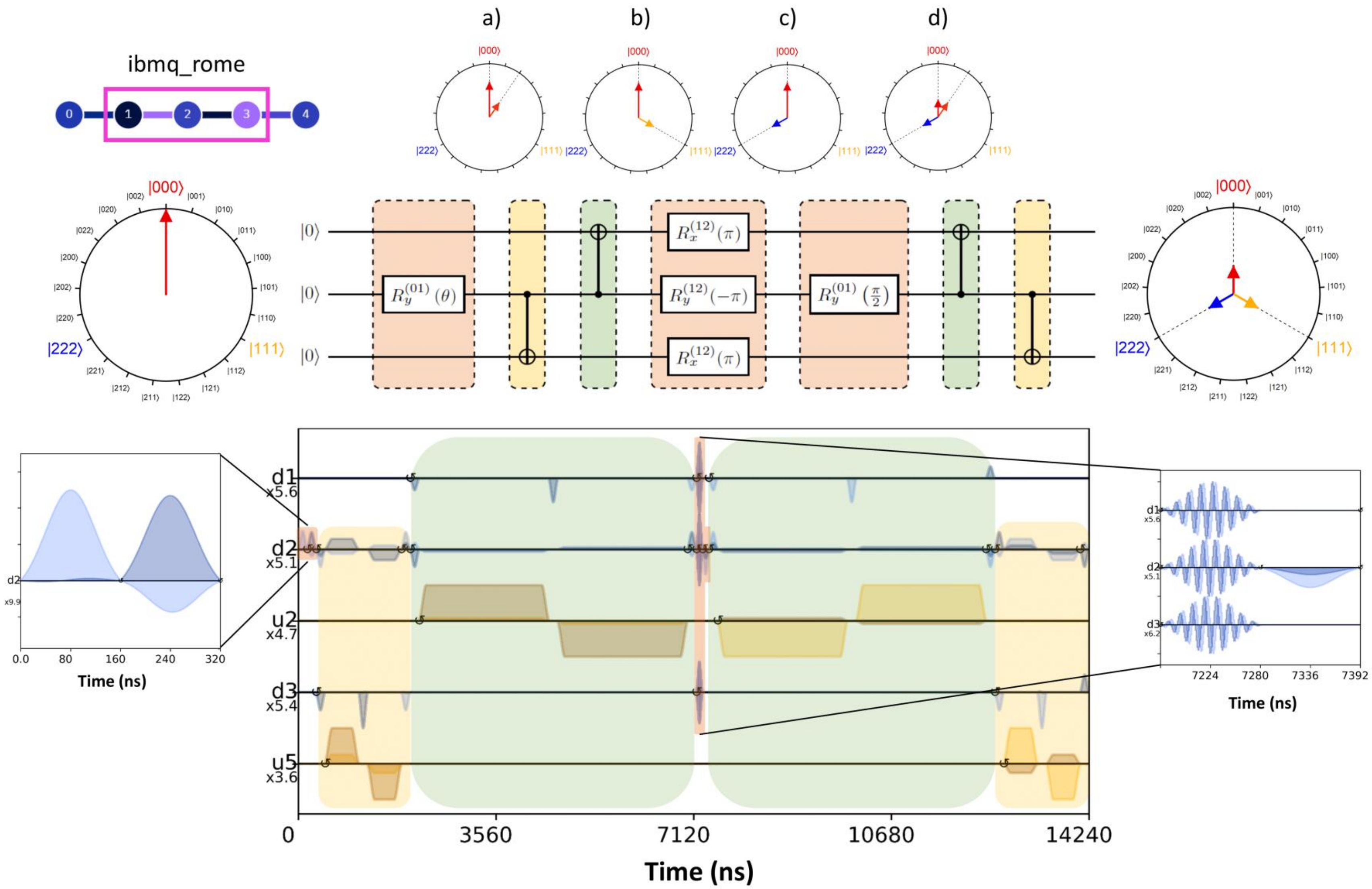
Quantum anharmonic Oscillator

Transmons contain more than two energy levels.

By finding the proper frequency transitions we can address and manipulate high-dimensional states.

Philip Krantz et. al., Applied Physics Reviews 6, 021318 (2019)

Pulse Schedule and circuit



A. Cervera-Lierta, M. Krenn, A. Aspuru-Guzik, A. Galda, arXiv:2104.05627 [quant-ph]

Detecting entanglement

$$\mathrm{Tr}\left(\rho|GHZ\rangle\langle GHZ|\right)$$

$$F_{exp} = \frac{1}{3}\left(\sum_{i=0}^{2}\langle iii|\rho|iii\rangle + 2\sum_{\substack{i,j=0\\ i<j}}^{2}\mathrm{Re}\langle iii|\rho|jjj\rangle\right)$$

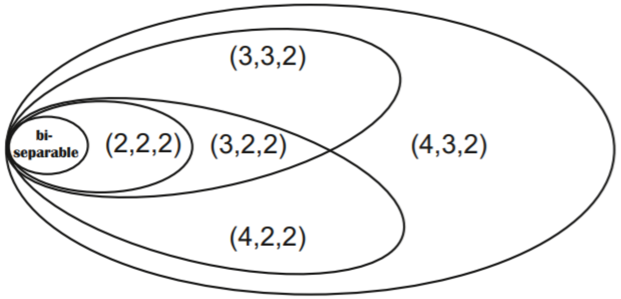
$$\langle 000|\rho|111\rangle,\ \langle 000|\rho|222\rangle \text{ and } \langle 111|\rho|222\rangle$$

$$\mathrm{Re}\left(\langle ijk|\rho|lmn\rangle\right) = \frac{1}{8}\Big(\langle\sigma_x^{(il)}\sigma_x^{(jm)}\sigma_x^{(kn)}\rangle - \langle\sigma_y^{(il)}\sigma_y^{(jm)}\sigma_x^{(kn)}\rangle - \langle\sigma_y^{(il)}\sigma_x^{(jm)}\sigma_y^{(kn)}\rangle - \langle\sigma_x^{(il)}\sigma_y^{(jm)}\sigma_y^{(kn)}\rangle\Big)$$

$$\mathrm{Im}\left(\langle ijk|\rho|lmn\rangle\right) = \frac{1}{8}\Big(\langle\sigma_y^{(il)}\sigma_y^{(jm)}\sigma_y^{(kn)}\rangle - \langle\sigma_x^{(il)}\sigma_x^{(jm)}\sigma_y^{(kn)}\rangle - \langle\sigma_x^{(il)}\sigma_y^{(jm)}\sigma_x^{(kn)}\rangle - \langle\sigma_y^{(il)}\sigma_x^{(jm)}\sigma_x^{(kn)}\rangle\Big)$$

We have to project into the $\sigma_{x,y}^{(ij)}$ basis to compute these expectation values.

What is the maximal fidelity achievable by a state with Schmidt Rank (3,3,2)?



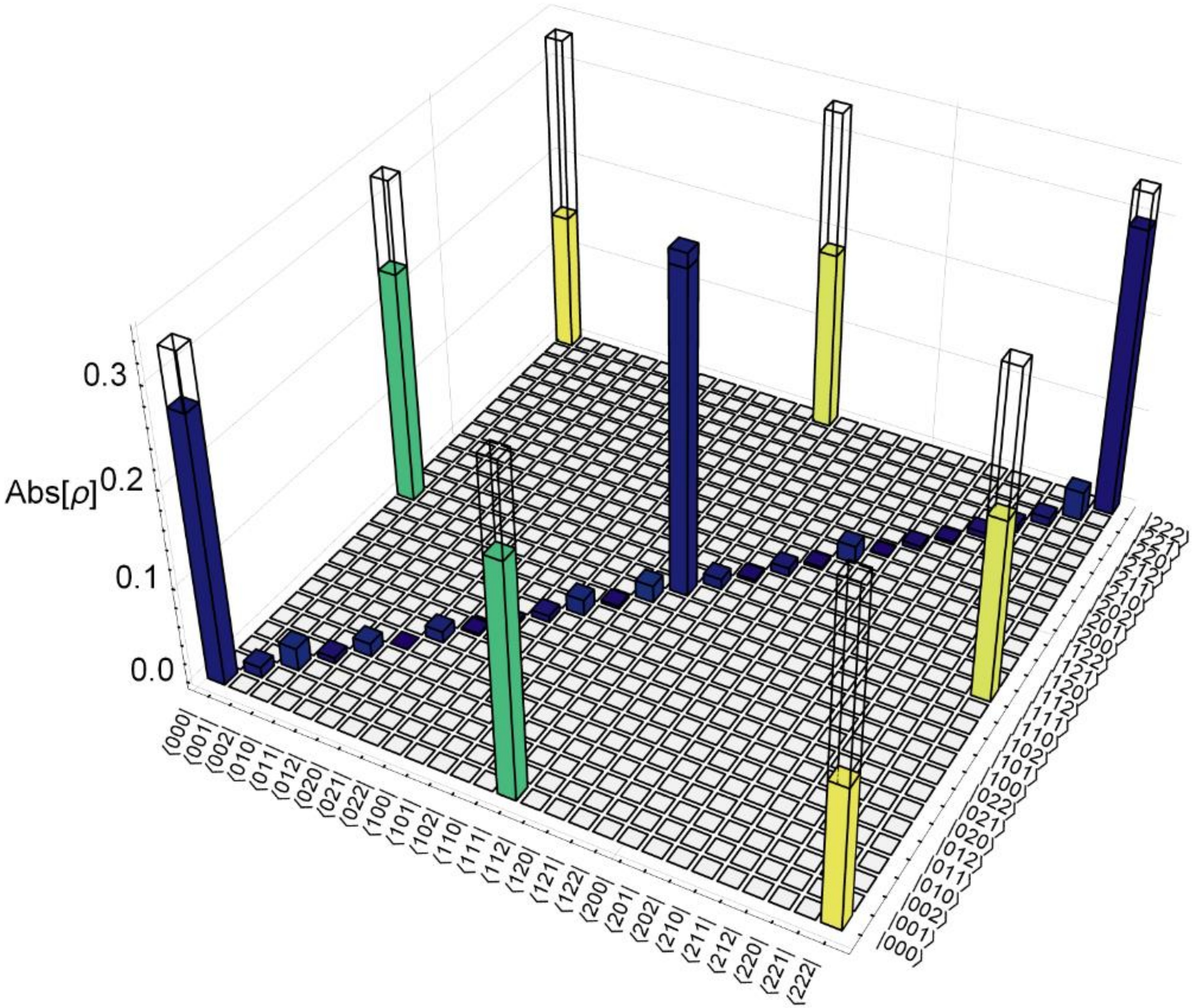
$$F_{max} = \max_{\sigma\in(3,3,2)} \mathrm{Tr}\left(\sigma|GHZ\rangle\langle GHZ|\right) = \frac{2}{3}$$

If we measure a fidelity > 66%, we have a genuine 3-dimensional 3-partite entangled state.

M. Huber, J. I. de Vicente, Phys. Rev. Lett. **110**, 030501 (2013)

A. Cervera-Lierta, M. Krenn, A. Aspuru-Guzik, A. Galda, arXiv:2104.05627 [quant-ph]

Results



$$F_{raw} = 0.69 \pm 0.01$$

$$F_{mit} = 0.76 \pm 0.01$$

Rome [4,3,2] transmons

Summary

This is the **first** experiment that generates the a high-dimensional multi-partite state with superconducting circuits.

This is the **first** experiment that generates a high-dimensional multi-partite state with a non-photonic platform.

The photonic experiment took **weeks**, ours took **seconds**.

This opens the path to explore high-dimensional physics out of reach for other physical platforms.

This experiment was carried out in the cloud!

A. Cervera-Lierta, M. Krenn, A. Aspuru-Guzik, A. Galda, arXiv:2104.05627 [quant-ph]

Outlook

- Nature is able to generate maximal entangled states (Bell inequalities are violated, classical physics can not describe quantum mechanics). Is this fact a principle?

- To harness the power of quantum computers, we need to understand and control entanglement. Low entanglement phenomena can be simulated efficiently with classical tools.

- Why get stuck in the flatland? High-dimensional quantum physics is an unexplored world full of new phenomena and applications.

- We are developing a tool (programmable quantum computers) that can theoretically generate these entangled states.

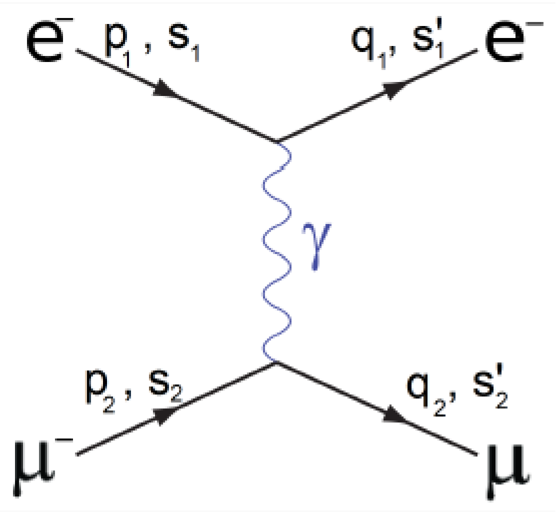
    - We need tests to benchmark their performance and that help us to seek for improvements!

Backup slides

Unconstrained Mott scattering

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

$$\begin{aligned}
\mathcal{M}_{|RL\rangle \to |RR\rangle} &= 0 \\
\mathcal{M}_{|RL\rangle \to |RL\rangle} &= f(a) \\
\mathcal{M}_{|RL\rangle \to |LR\rangle} &= 0 \\
\mathcal{M}_{|RL\rangle \to |LL\rangle} &= 0
\end{aligned}$$



No entanglement can be generated!
No constraints emerge from this process

Unconstrained e^-e^+ annihilation to muons

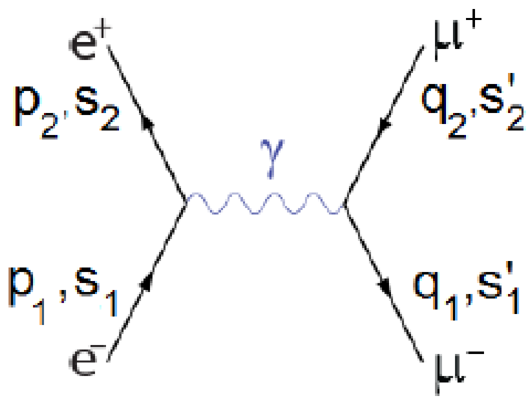
$$e^- e^+ \to \mu^- \mu^+$$

Amplitudes quadratic in a's:

$$\begin{aligned}
\mathcal{M}_{|RL\rangle\to|RL\rangle} &= \left(-a_{i2}^2 - a_{i1}^2\cos\theta + a_{i1}a_{i3}\sin\theta\right) + i\left(a_{i1}a_{i2}(1-\cos\theta) + a_{i2}a_{i3}\sin\theta\right)\\
\mathcal{M}_{|RL\rangle\to|LR\rangle} &= \left(-a_{i2}^2 + a_{i1}^2\cos\theta - a_{i1}a_{i3}\sin\theta\right) + i\left(a_{i1}a_{i2}(1+\cos\theta) - a_{i2}a_{i3}\sin\theta\right)\\
\mathcal{M}_{|RL\rangle\to|RR\rangle} &= \mathcal{M}_{|RL\rangle\to|LL\rangle} = 0
\end{aligned}$$

Arbitrary angle dependent solutions are discarded by other processes

MaxEnt	$\theta = \pi/2$ $\Delta = 1$	$\Longrightarrow$	$A = aa^T \geq 0$ $A_{22}A_{13} - A_{12}A_{23} = 0$
QED	$a_{ij} = \begin{cases} 0 \ \forall i \neq j \\ 1 \ \forall i = j \end{cases}$	$\Longrightarrow$	$A_{ij} = \begin{cases} 0 \ \forall i \neq j \\ 1 \ \forall i = j \end{cases}$



Z decay to leptons

$$m \ll M_Z,\ g_R = (g_V - g_A)/2 \text{ and } g_L = (g_V + g_A)/2$$

Longitudinal polarization:

$$\left.\begin{aligned} \mathcal{M}_{|0\rangle\to|RL\rangle} &= g_R M_Z \sin\theta \\ \mathcal{M}_{|0\rangle\to|LR\rangle} &= g_L M_Z \sin\theta \end{aligned}\right\} \Delta_0 = \frac{2|g_L g_R|}{g_L^2 + g_R^2}$$

$$\Delta_0 = 1 \text{ if } |g_L| = |g_R| \Rightarrow g_A = 0 \text{ or } g_V = 0.$$

$$g_A = T_3/2 \neq 0 \Rightarrow g_V = 0 \Rightarrow \sin^2\theta_w = \frac{T_3}{2Q} \xrightarrow{\text{for charged leptons}} \sin^2\theta_w = 1/4.$$

Z decay to leptons

$m \ll M_Z$, $g_R = (g_V - g_A)/2$ and $g_L = (g_V + g_A)/2$

Circular polatization

$$\mathcal{M}_{|R\rangle\to|RL\rangle} = g_R M_Z \sqrt{2}\sin^2(\theta/2) \qquad \mathcal{M}_{|L\rangle\to|RL\rangle} = g_R M_Z \sqrt{2}\cos^2(\theta/2)$$
$$\mathcal{M}_{|R\rangle\to|LR\rangle} = -g_L M_Z \sqrt{2}\cos^2(\theta/2) \qquad \mathcal{M}_{|L\rangle\to|LR\rangle} = -g_L M_Z \sqrt{2}\sin^2(\theta/2)$$

$$\Delta_{\frac{R}{L}} = \frac{2|g_L g_R|\sin^2\theta}{|2(g_L^2 - g_R^2)\cos\theta \pm (g_L^2 + g_R^2)(1+\cos^2\theta)|}$$

$$\Delta_{\frac{R}{L}} = 1 \text{ if } \begin{cases} \frac{g_R}{g_L} = \pm\cot^2(\theta/2) \\ \frac{g_R}{g_L} = \pm\tan^2(\theta/2) \end{cases}$$

Assuming g_R and g_L are independent of the initial polatization:

$$\frac{g_R}{g_L} = \pm 1 \Rightarrow |g_L| = |g_R|$$

$$\Rightarrow g_V = 0 \Rightarrow \sin^2\theta_w = 1/4$$

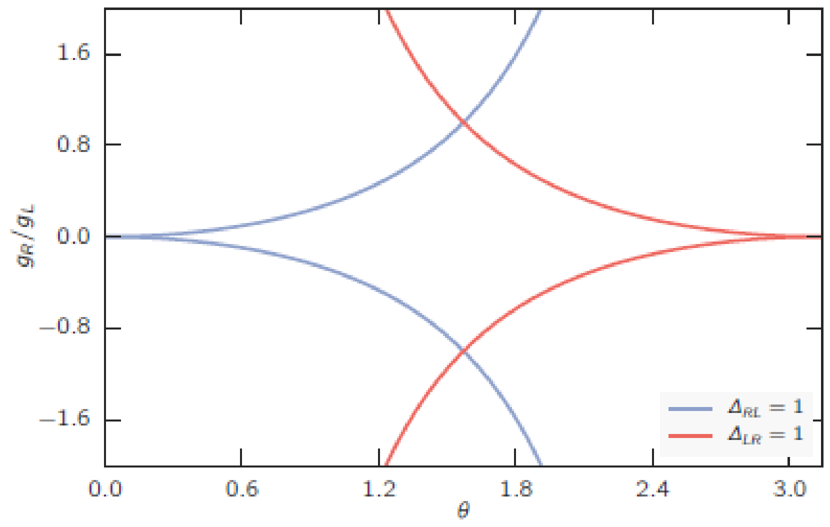
$e^-e^+ \to \mu^-\mu^+$ Z mediated

$m \ll M_Z,$

$$\mathcal{M}_{RL} \sim (1+\cos\theta)g_R^2 \; |RL\rangle + (-1+\cos\theta)g_R g_L \; |LR\rangle$$
$$\mathcal{M}_{LR} \sim (-1+\cos\theta)g_R g_L \; |RL\rangle + (1+\cos\theta)g_L^2 \; |LR\rangle$$

$$\Delta_{RL} \sim \frac{\sin^2\theta |g_L g_R|}{2\left(s^4 g_L^2 + c^4 g_R^2\right)} \qquad \Delta_{LR} \sim \frac{\sin^2\theta |g_L g_R|}{2\left(c^4 g_L^2 + s^4 g_R^2\right)}$$

$c = \mathrm{co}$



Imposing maximal entanglement at the same COM angle:

$$s^2 g_L \pm c^2 g_R = 0 \to \Delta_{RL} = 1$$
$$c^2 g_L \pm s^2 g_R = 0 \to \Delta_{LR} = 1$$

$$\theta = \frac{\pi}{2}, \; \sin^2\theta_w = \frac{1}{4}$$

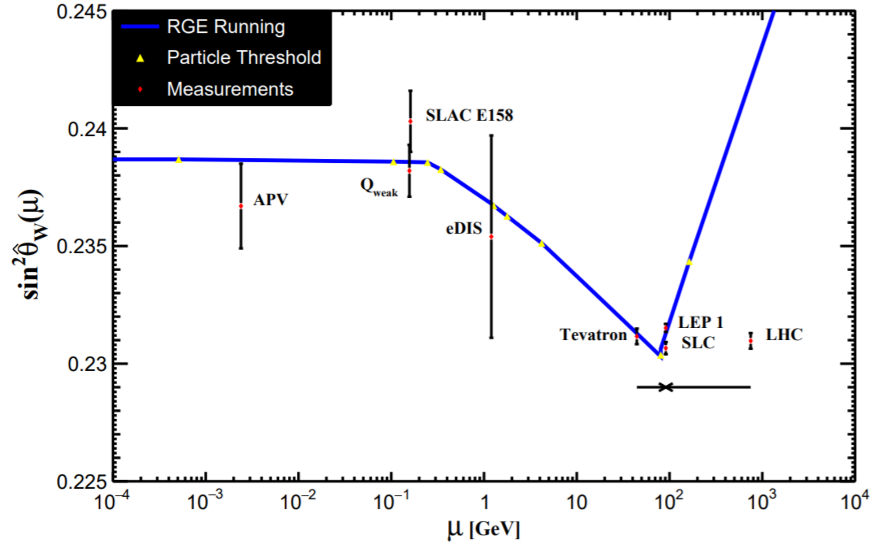
Next steps

→ Multipartite entanglement? (e.g. ortopositronium decay)

→ Higher orders in perturbation theory

  → Renormalization scheme?
  → IR divergences ?

→ Compute more processes: entanglement maximization over θ_w



Scheme	Notation	Value	Uncertainty
On-shell	s_W^2	0.22337	±0.00010
$\overline{\text{MS}}$	$\hat{s}_Z^2$	0.23121	±0.00004
$\overline{\text{MS}}$ND	$\hat{s}_{\text{ND}}^2$	0.23141	±0.00004
$\overline{\text{MS}}$	$\hat{s}_0^2$	0.23857	±0.00005
Effective angle	$\bar{s}_\ell^2$	0.23153	±0.00004

$$s_W^2 \equiv 1 - \frac{M_W^2}{M_Z^2} \qquad \hat{s}_Z^2 \equiv \sin^2\hat{\theta}_W(M_Z)$$

$$\sin^2\hat{\theta}_W(\mu) \equiv \frac{\hat{g}'^2(\mu)}{\hat{g}^2(\mu)+\hat{g}'^2(\mu)} \qquad \hat{s}_0^2 \equiv \sin^2\hat{\theta}_W(0)$$

$$\bar{s}_f^2 \equiv \sin^2\bar{\theta}_{Wf} \equiv \hat{\kappa}_f\hat{s}_Z^2 = \kappa_f s_W^2$$

Particle Data Group, Prog. Theor. Exp. Phys. 2020, 083C01 (2020).

ACL, J. I. Latorre, J. Rojo and L. Rottoli, SciPost Phys. 3, 036 (2017).

Open questions

- Relax C, P and T to CPT symmetry?

- Other interaction theories: QCD, chiral, gravity, …

    - QCD: no asymptotic states (confinement), what does it mean to have an entangled state?
    - CKM relation to mass rations?
    - Neutrino oscillations?
    - Gravity: Feynman rules for graviton interactions?

- Formulation in terms of probabilities and Bell inequalities?

- Other degrees of freedom instead of helicities and polarizations
    - Position/momenta space
    - Flavour
    - Color
    - …

Color in gluon-gluon scattering:
no extra information from maximal entanglement
(see arXiv:1906.12099 [quant-ph])

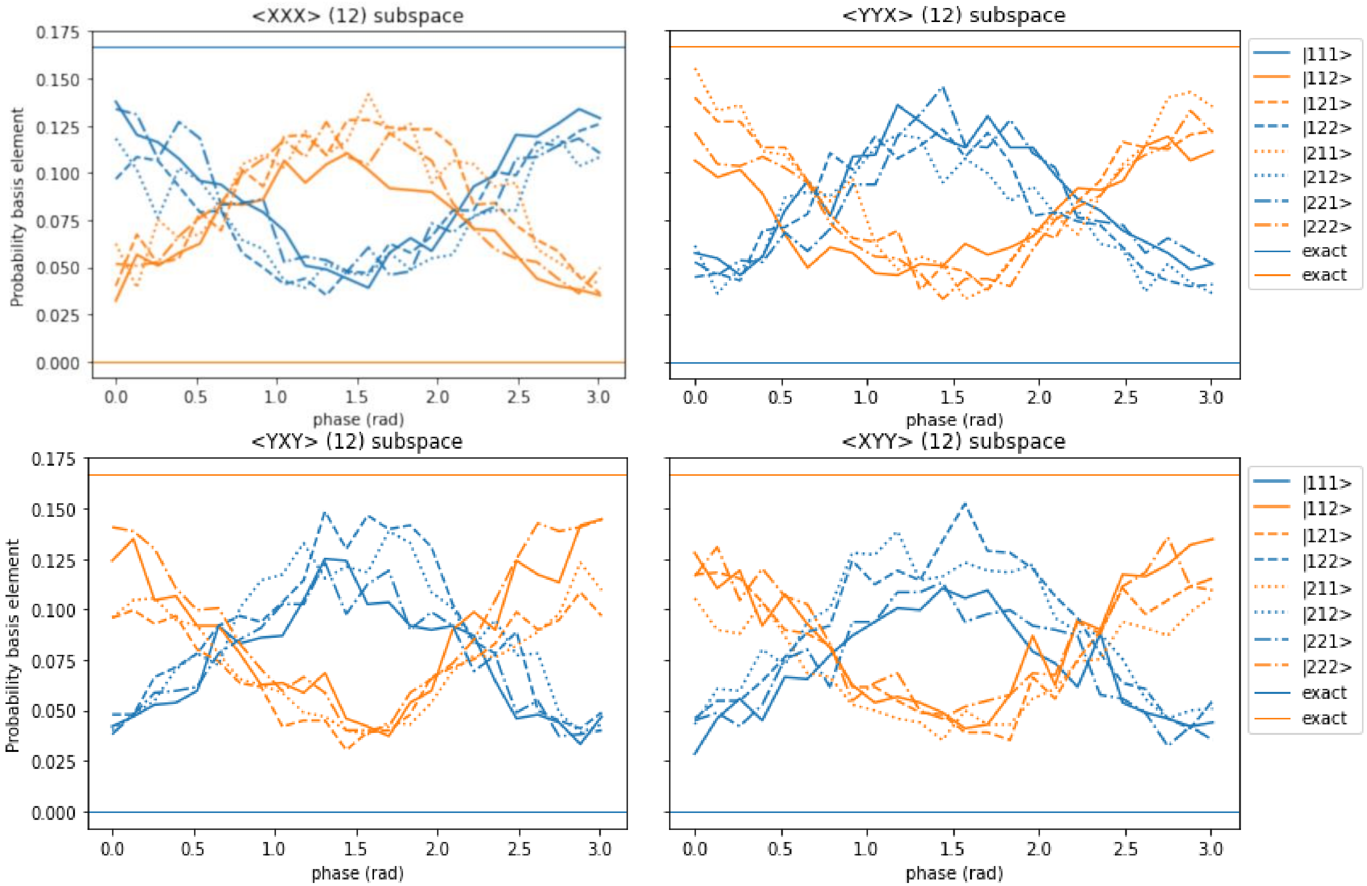
Tracking the phase

The relative phase introduced by the CNOT*

Other noisy phenomena (cross-talk, AC Stark shift, …): instead of applying $R_{x,y}^{12}$ gates, we apply R_{n}^{12} where n is a unit vector in the (x, y) plane.

To compensate this phase acumulation, we apply a phase gate on one of the qutrits and scan for different phases.

$$\mathrm{Re}\left(\langle ijk|\rho|lmn\rangle\right) = \frac{1}{8}\Big(\langle\sigma_x^{(il)}\sigma_x^{(jm)}\sigma_x^{(kn)}\rangle - \langle\sigma_y^{(il)}\sigma_y^{(jm)}\sigma_x^{(kn)}\rangle - \langle\sigma_y^{(il)}\sigma_x^{(jm)}\sigma_y^{(kn)}\rangle - \langle\sigma_x^{(il)}\sigma_y^{(jm)}\sigma_y^{(kn)}\rangle\Big)$$



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