Title: Verification of quantum simulations and indistinguishability of photons

Speakers: Barbara Kraus

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Verification of quantum computing and simulation & indistinguishability of photons

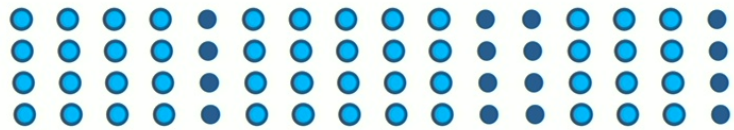
B. Kraus

School of Natural Science,
Technical University of Munich
Germany

Waterloo-Munich Joint Workshop

VERIFICATION OF QUANTUM DEVICES

NOW & NEAR FUTURE: MEDIUM SIZE/LARGE SYSTEMS

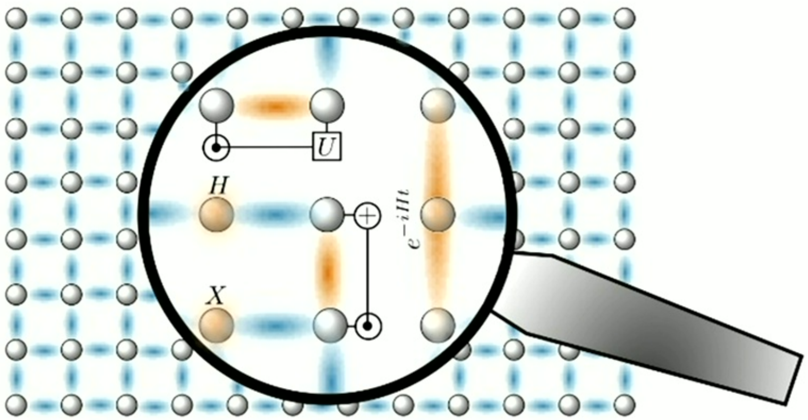


$\mathcal{H} = 2^n$

HOW?
Use device for e.g. q. computing/ q. simulation

How can we verify it?

VERIFYING QUANTUM COMPUTATION/SIMULATION



WHAT DO WE ACTUALLY WANT TO VERIFY? CORRECT OUTPUT STATE, OR CORRECT OUTPUT FOR LOCAL OBSERVABLES,...?

DEPENDS STRONGLY ON THE TASK AND ON WHO POSSESSES THE Q. DEVICE

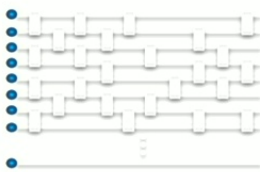
QUANTUM VERIFICATION

Solve a problem, e.g.
In NP: factorize 25

AQT

Easy to check classically

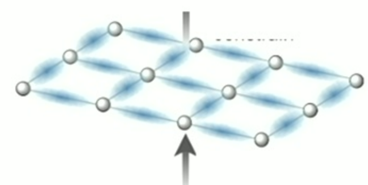
Solve a problem, e.g.
Is output of



0 or 1 $(p_1 = || \langle 1|U|0\rangle^{\otimes n} ||^2 \geq \frac{2}{3})$
(in BQP)

Output:
0

Q. simulation



$$H = \sum_m c_m S_m = \boldsymbol{c} \cdot \boldsymbol{S}$$

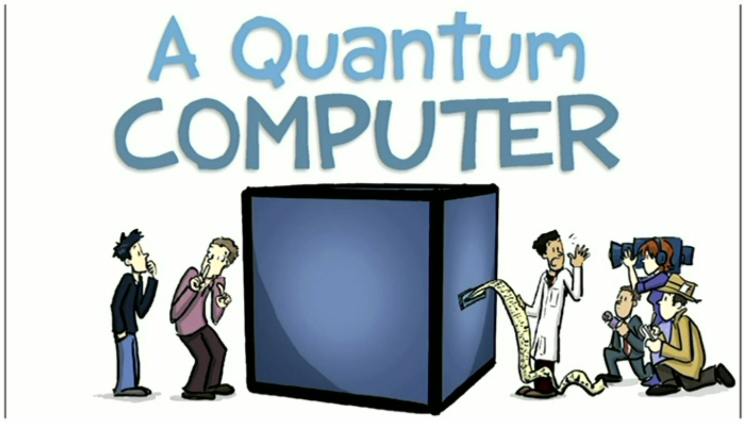
How should we check?
How should we check q. advantage?

QUANTUM VERIFICATION

HAVING ACCESS TO THE DEVICE

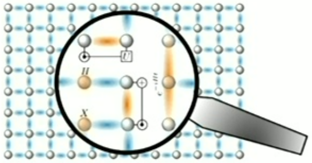
⇒ Run tests, obtain error model, estimate error,
⇒ improve device, confidence that works

CLOUD COMPUTATION
(NO ACCESS /UNTRUSTED DEVICE)



Why?
will not all possess Q laptop
⇒ Q. cloud computer

OUTLINE



GAINING CONFIDENCE ABOUT THE PERFORMANCE OF Q. DEVICES

J. Carrasco, M. Langer, A. Neven, BK Physical Review Research 2024, See also poster by M. Langer

Hamiltonian and Liouvillian learning in weakly-dissipative quantum many-body systems

T. Olsacher, T. Kraft, CH. Kokail, B.K., P. Zoller (arXiv `24)

Indistinguishability of identical bosons from a quantum information theory perspective

M. Englbrecht, T. Kraft, Ch. Dittel, A. Buchleitner, G. Giedke, BK, PRL'23

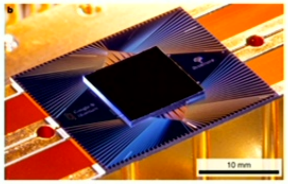
QUANTUM VERIFICATION HAVING ACCESS

Check that single qubit and 2-qubit gates can be implemented with high fidelity
$\Rightarrow$ Enough?
$\Rightarrow$ Crosstalking, drifts,...
$\Rightarrow$ Depends on output

$\Rightarrow$ Run tests, obtain error model, estimate error,
$\Rightarrow$ improve device

VERIFICATION OF Q. COMPUTATION/ SIMULATION OF DEVICE WITH DIRECT ACCESS TO IT

NISQ devices



Tracing: ✗
Check that leads to correct outcome for those computations which we can verify ✓
e.g. simulation on small input, simplified q. circuits

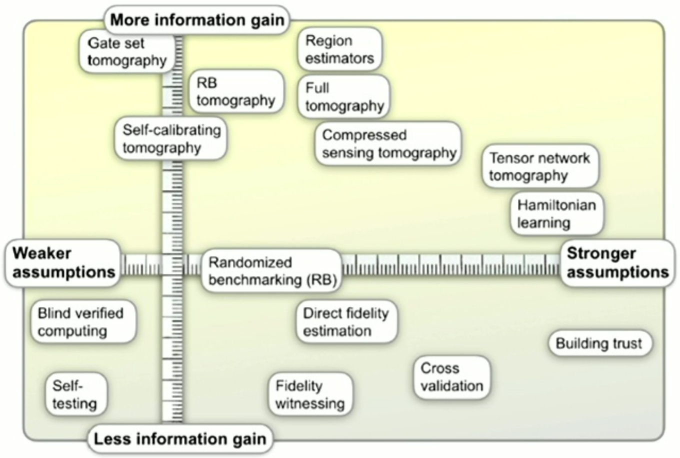
There are errors!

Might not be enough to check whether output it correct or not, need to estimate the error

single & two-qubit gates, use cl. simulable q. circuits to validate error model
need to be able to compare to correct/ predicted outcome

VERIFICATION OF Q. DEVICE WITH DIRECT ACCESS TO IT

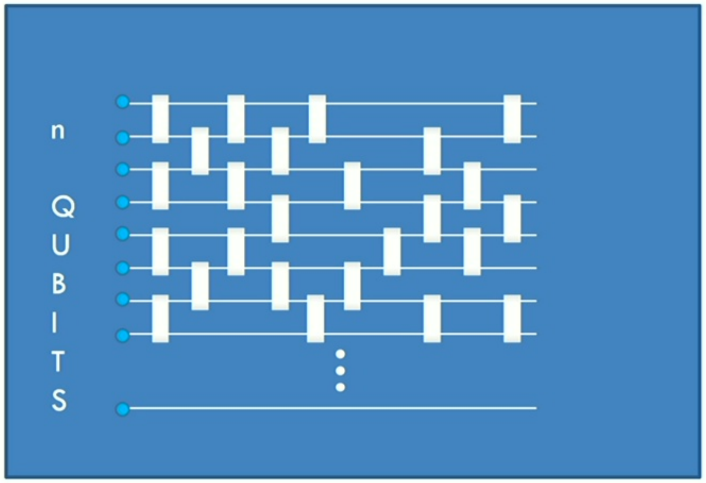
Review: e.g J. Eisert, D. Hangleiter, N. Walk, I. Roth,
D. Markham, R. Parekh, U. Chabaud, E. Kashefi (2019)



Test gate set, ...
Averaged error

Different approach: Given Circuit, what is the error?

Given Circuit C



Ideal: $C|0\rangle^{\otimes n}$
Errors: ρ_{out}

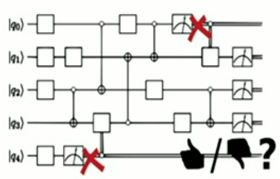
How can we estimate the error? How can we gain confidence in the realization of C up to a certain error? ρ_{out}?

J. Carrasco, M. Langer, A. Neven, BK (2023)

Universal versus efficiently simulable circuits

Some circuits can be simulated efficiently
adding additional resources ⇒ universal

→ Use for verification (of arbitrary q. computation)



simulable vs universal QC

Match gates

2-qubit gates fulfilling algebraic constraint

n.n. Match gate circuits: cl. efficiently simulable

J. Carrasco, M. Langer, A. Neven, BK (2023)

Clifford circuits:

R. Jozsa and S. Strelchuk (arXiv: 1705.02817 (2017))
S. Ferracin, T. Kapourniotis, and A. Datta, New. J. Phys. 21, 113038 (2019),...

UNIVERSAL VERSUS EFFICIENTLY SIMULABLE CIRCUITS

Main idea:

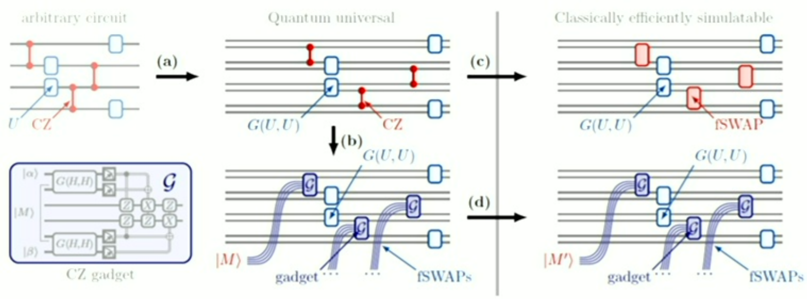
Some circuits can be simulated cl. efficiently adding additional resources ⇒ universal } ⇒ Use for verification (of arbitrary q. computation)

Construct circuits which are:

(i) classically efficiently simulable not only without, but also with errors

(ii) very similar to the original (universal) computation

CL. EFFICIENTLY SIMULABLE Q. CIRCUIT

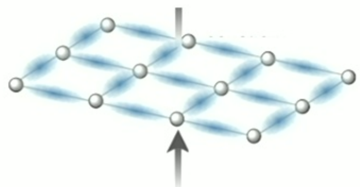


(i) classically efficiently simulable
(weak simulation, M. Hebenstreit, R. Jozsa, BK, S. Strelchuk, PRA 2020)
(ii) very similar to the original (universal) computation
in (d) exactly same circuit applied to slightly different input state
(iii) Errors can be included using weak simulation &
randomized compiling (J. J. Wallman, J. Emerson, PRA (2016))
⇒ cl. simulate output including errors

See poster

Marc Langer

Quantum Simulation

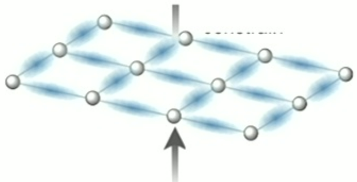


$$H = \sum_m c_m S_m = \boldsymbol{c} \cdot \boldsymbol{S}$$

How can we make sure that the evolution is due to some specific H?

Having access to the device

Hamiltonian learning



$$H = \sum_m c_m S_m = \boldsymbol{c} \cdot \boldsymbol{S}$$

"Learning a local Hamiltonian from local measurements" E. Bairey, I. Arad, N. H. Lindner, PRL (2019),
"Hamiltonian tomography via quantum quench " Z. Li, L. Zou, and T. H. Hsieh, PRL (2020),...

X.-L. Qi and D. Ranard, Quantum 3, 159 (2019)
E. Bairey, C. Guo, D. Poletti, N. H. Lindner, and I. Arad, New J. Phys. 22, 032001 (2020)
D. Stilck França, L. A. Markovich, V. V. Dobrovitski, A. H. Werner, J. Borregaard (2022),..

Learning Hamiltonian and Liouvillian in weakly-dissipative quantum many-body systems

T. Olsacher, T. Kraft, Ch. Kokail, B.K., P. Zoller (arXiv '24)

Hamiltonian learning

Assumption: unitary evolution $|\Psi(0)\rangle \rightarrow |\Psi(t)\rangle = \mathrm{e}^{-iHt}|\Psi(0)\rangle$

$$\mathrm{H} = \sum_{i=1}^{m} c_i^H h_i$$ h_i traceless hermitian operators, e.g. Pauli operators

AIM: determine c_i^H

Main idea: e.g. energy conservation $\langle H\rangle_0 - \langle H\rangle_T = 0$ with $\langle H\rangle_t = \langle\Psi(t)|H|\Psi(t)\rangle$

Ansatz for H: $\mathrm{A(c)} = \sum_{i=1}^{n} c_i h_i$, for some choice of subset of operators

$$\{|\Psi_i(0)\rangle \rightarrow |\Psi_i(t)\rangle = \mathrm{e}^{-iHt}|\Psi_i(0)\rangle, i = 1,2, \dots p\}$$

$$M_{i,j} = \langle\Psi_i(0)|\mathrm{h_j}|\Psi_\mathrm{i}(0)\rangle - \langle\Psi_\mathrm{i}(t)|\mathrm{h}_j|\Psi_\mathrm{i}(t)\rangle$$

Measure $M_{i,j} \Rightarrow$ Solve $\mathrm{M}\vec{c} = 0 \Rightarrow$ subspace commuting with H

Z. Li, L. Zou, and T. H. Hsieh, Hamiltonian tomography via quantum quench, PRL 124, 160502 (2020).
E. Bairey, I. Arad, N. H. Lindner, Learning a local Hamiltonian from local measurements, PRL (2019),...

Hamiltonian & Liouvillian learning in weakly-dissipative quantum many-body systems

Assumption: evolution governed by master equation

$$\frac{d}{dt}\rho = -i[H,\rho] + \frac{1}{2}\sum_k \gamma_k([l_k\rho, l_k^t] + [l_k, \rho l_k^t]) \equiv L(\rho)$$

l_k Lindblad operators
$\gamma_k > 0$ rates
Weak dissipation: $\gamma_k \ll ||H||$

e.g. $\mathrm{H} = \sum_{i=1}^{N-1} J_{i,i+1}^{z}\,\sigma_i^z \sigma_{i+1}^z + \cdots$ $\quad l_k \in \{\sigma_-, \sigma_+, \sigma_x\}$ $\quad \gamma_k \ll ||H||$

For $\gamma_k = 0 \rightarrow$ H-learning
*For $\gamma_k > 0 \rightarrow$ **small perturbation** to energy conservation*

Aim: determine H and (if possible) $\{\gamma_k, l_k\}$

T. Olsacher, T. Kraft, CH. Kokail, B.K., P. Zoller (arXiv '24)

Hamiltonian & Liouvillian learning (weak dissipation)

Ansatz: for H: $\mathrm{A(c)} = \sum c_i h_i$, for dissipation: $\{d_k, a_k\}_k$

Aim: determine $\mathrm{c^H}$ and (if possible) $\{\gamma_k, l_k\}_k$

Ehrenfest's theorem: $$\frac{d}{dt}\langle O\rangle = \langle i[O,H]\rangle + \frac{1}{2}\sum_k \gamma_k(\langle l_k^t[O,l_k] + [l_k^t,O]l_k\rangle)$$

For $\mathrm{O = H} \Rightarrow$

$$-\langle H\rangle_0 + \langle H\rangle_T = \frac{1}{2}\sum_k \gamma_k \int_0^T \langle l_k^t[H,l_k] + [l_k^t,H]l_k\rangle_t \, dt$$ for any state (pure and mixed)

Hamiltonian & Liouvillian learning (weak dissipation)

Inserting Ansatz: for H: $A(c) = \sum c_i h_i$, for dissipation: $\{d_k, a_k\}_k$

$$\Rightarrow \qquad [M_H + M_D(\vec{d})]\vec{c} = 0$$

$$M_H = (M)_{ij} = \langle h_j \rangle_{i,0} - \langle h_j \rangle_{i,T}$$

$$M_D(d) = \sum_k d_k M^{(k)} \qquad [M^{(k)}]_{ij} = \int_0^T \langle a_k^t [h_j, a_k] + [a_k^t, h_j] a_k \rangle_{\Psi_i(t)} \, dt$$

$$(c^{rec}, d^{rec}) = \underset{(c,d):\, ||c|| = 1,\, d_k \geq 0}{\arg\min} ||[\widetilde{M}_H + \widetilde{M}_D(d)]\, c||$$

Taking errors into account

Solve by finding d^{rec} which leads to smallest singular value, λ_1
c^{rec} is right eigenvector to this singular value

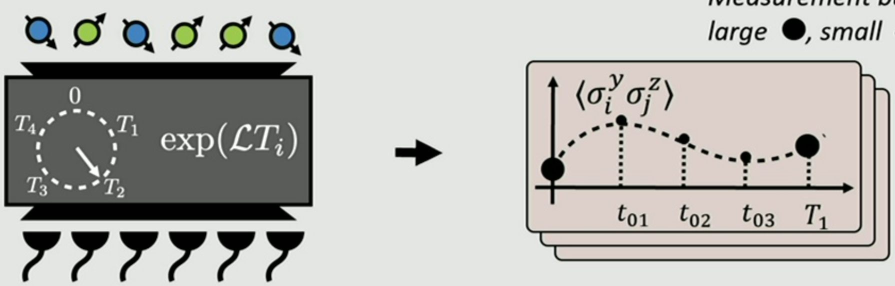
Measurements for Hamiltonian & Liouvillian learning

Aim: measure elements of constraint matrix $-\langle H\rangle_0 + \langle H\rangle_T = \frac{1}{2}\sum_k \gamma_k \int_0^T \left\langle l_k^t[H, l_k] + [l_k^t, H]l_k \right\rangle_t dt$

We consider simple quench experiments (with product states and product measurements):

Measurement budget:
large ●, small •

1. Prepare product state.
2. Apply $\mathcal{L}$ for time t.
3. Measure product basis, e.g., in the **Pauli basis.**



$$\langle X\rangle_t = \mathrm{tr}[X \exp\{(\mathcal{L}_H + \mathcal{L}_D)t\}\varrho(0)]$$

Typically, many of these can be measured in parallel!

AIM: experimentally feasible
⇒ small number of measurements (10^6)

T. Olsacher, T. Kraft, Ch. Kokail, B. Kraus, P. Zoller, arXiv '24

How to assess the ansatz

$$(c^{rec}, d^{rec}) = \underset{(c,d):\,||c||=1,\, d_k \geq 0}{\arg\min} ||[\widetilde{M}_H + \widetilde{M}_D(d)]\, c|| \;\Rightarrow d^{rec}, c^{rec}$$

λ_1, λ_2 *smallest singular values of* $\widetilde{M}_H + \widetilde{M}_D(d)$

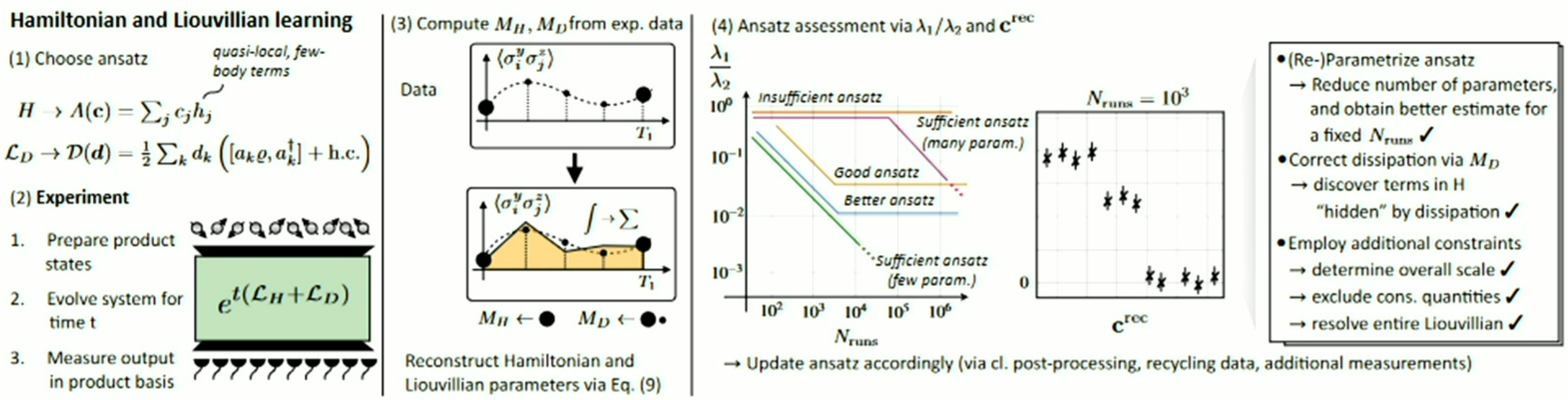
2 types of errors: (1) **finite** # of measurements $\rightarrow$ shot-noise (statistical errors): $M_H + M_D \rightarrow \widetilde{M}_H + \widetilde{M}_D$

(2) Ansatz does not include H or Liouvillian (systematic errors)

systematic errors $\Rightarrow \lambda_1 > 0$ (even if ∞ many measurements)

$\frac{\lambda_1}{\lambda_2}$ plays important role in finding right strategy

Protocol for H & L learning (weak dissipation)



Use Ehrenfest Theorem to derive constraints on parameters of H (and dissipation)

Use $\frac{\lambda_1}{\lambda_2}$ to update the Ansatz: whenever plateau:

either reparameterize the Ansatz $\vec{c} \to G\vec{c}$ (e.g. to reduce # of parameters)

or focus on dominante terms

or include dissipation,...

Good ansatz: early shot-noise scaling, low plateau

H & L learning (weak dissipation)

$(c^{rec}, d^{rec}) = \arg\min ||[\widetilde{M}_H + \widetilde{M}_D(d)]\, c|| \Rightarrow$

without dissipation → lin. optimization;
with dissipation → nonlinear optimization

Learn H **without** learning the complete Liouvillian
Dissipation: does not need to be uniquely defined (e.g depends only on $d_1 + d_2$).

Learn H up to **overall scale** & possible **conserved quantities** of H.
Additional constraints → learning H and complete Liouvillian

Illustration

Example Longitudinal & transverse-field Ising model with dominant nearest neighbor & sub-dominant next-nearest neighbor interaction (small disorder).

$$\mathrm{H} = \sum_{i=1}^{N-1} J_{i,i+1}^{z}\, \sigma_i^z \sigma_{i+1}^z + \sum_{i=1}^{N-2} J_{i,i+2}^{z}\, \sigma_i^z \sigma_{i+2}^z + B_x \sum_{i=1}^{N} \sigma_i^x + B_z \sum_{i=1}^{N} \sigma_i^z$$

+ weak dissipation: $\gamma_k \ll ||H||$

Assumption (not required) : Know type of dissipation, but not the rates

Dissipation: spatially homogeneous: $\sigma_+, \sigma_-, \sigma_x$

For n=10 qubits

Goal: Learn operator structure of H and dissipation rates. Use only appx. 10^6 runs.

Illustration

plateau → extend ansatz

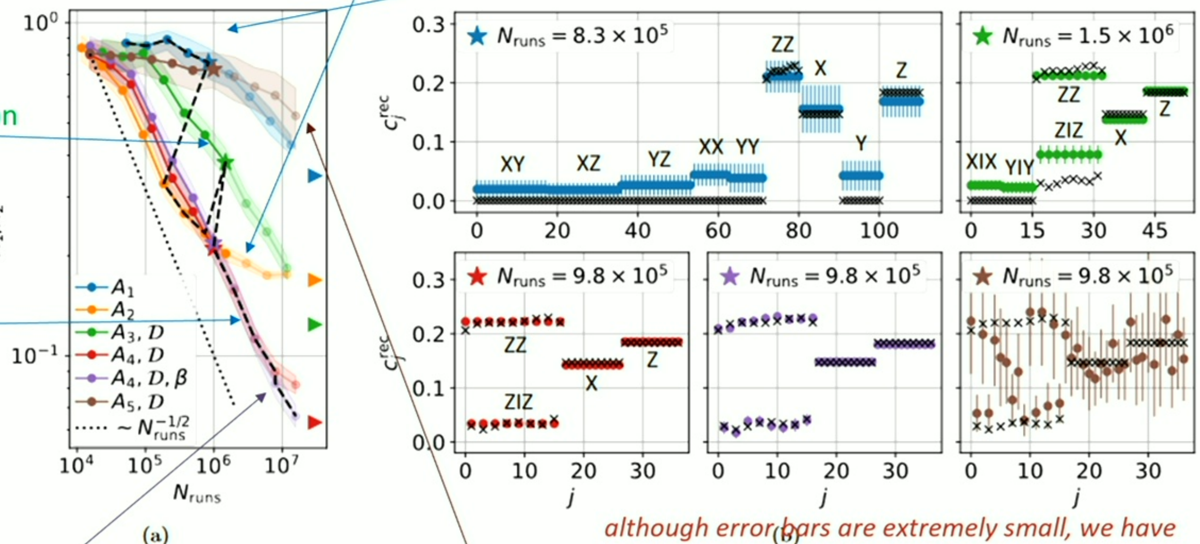
A2: $\frac{\lambda_1}{\lambda_2}$ much smaller/ plateau

A1: all n.n. & local terms identify 3 dominante terms

A3: after Including dissipation Can learn n.n.n. coefficients

A4: including Dominant nnn Term

keep Z1Z



A5: reparameterization

A6: naive approach (unparametrized ansatz of the form) $A_6 = A^{\rm free}_{\rm nnZZ} + A^{\rm free}_{\rm nnnZZ} + A^{\rm free}_{\rm X} + A^{\rm free}_{\rm Z}$

although error bars are extremely small, we have not yet reached a plateau. But, can search for solutions taking spatial disorder into account

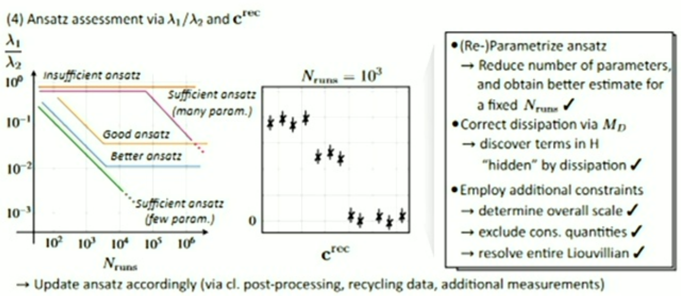
Matches behaviour of error

Conclusion and Outlook

Gaining confidence about realization of arbitrary q. circuit

Derive cl. efficiently simulable circuits, which are very similar to the original (encoded) circuit
Circuit can be weakly simulated including errors

H & L learning in presence of weak dissipation



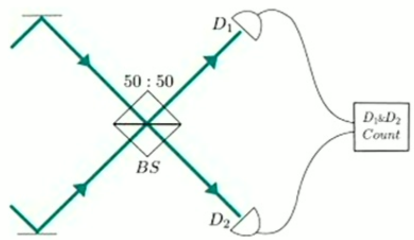
Outlook: experiment
combine with classical shadow techniques and other H-learning protocols

Indistinguishability of identical bosons

Consider N bosons: When are they indistinguishable? How can one measure indistinguishability?

e.g. 2 photons:

Hong–Ou–Mandel



If perfectly indistinguishable would always exit in the same mode

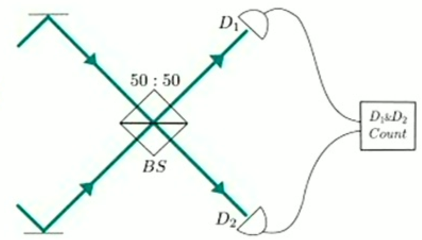
When are N photons indistinguishable?

Why do we care? Indistinguishability is a resource, e.g. boson sampling, quantum computing

Indistinguishability of identical particles (bosons)

How to define (in)distinguishability:

- E.g. Hong Ou mandel experiment ⇒ only partial info for N particles
- For states with fixed particle number **per external mode**:
  entanglement between external and internal DOF



⇒ **What about general states?**

How to quantify (in)distinguishability? E.g suppression laws, correlations between output of detectors, entanglement measures …

⇒ **Arbitrary states? How can we efficiently measure it experimentally?**

Dittel, C., Dufour, G., Walschaers, M., Weihs, G., Buchleitner, A., & Keil, R. (2018). *Physical review letters*, *120*(24), 240404.
Walschaers, M. (2020). *Journal of Physics B: Atomic, Molecular and Optical Physics*, *53*(4), 043001.
Dittel, C., Dufour, G., Weihs, G., & Buchleitner, A. (2021) *Physical Review X*, *11*(3), 031041.
Shchesnovich, V. S. *Physical Review A* 91.1 (2015): 013844.

Indistinguishability of identical bosons from a quantum information theory perspective

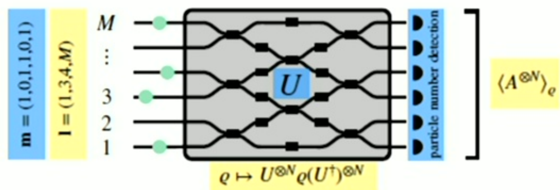
- Definition of (in)distinguishability for arbitrary states with fixed total particle number
- Measure of indistinguishability and its operational meaning
- Tight upper and lower bounds on measure (experiment)
- Simple characterization of perfectly distinguishable states (representation theory)
- Perfect distinguishability not preserved under convex combinations

M. Englbrecht, T. Kraft, Ch. Dittel, A. Buchleitner, G. Giedke, BK, PRL'23

Setting

Bosons: indistinguishable particles whose total state is symmetric

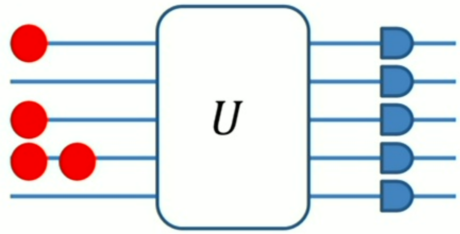
N bosons in M external modes of a passive linear interferometer + particle # measurement



Experiments: only a subset of degrees of freedom are accessible = external dofs.
indistinguishable particles become (partially) distinguishable

Inaccessible dofs (internal dofs): e.g. polarization, time of arrival,...

Indistinguishability depends on experimental setting



Single photon Hilbert space:

$$H_{ex} \otimes H_{int}$$

DOF which are exp. accessible, i.e are manipulated and measured

- Unresolved, e.g. polarization, time of arrival,…
- makes particles distinguishable

Only

$$\rho_{ex} = Tr_{in}(|\psi\rangle\langle\psi|)$$

is accessible ⇒ contains all the information about distinguishability

Dittel, C., Dufour, G., Weihs, G., & Buchleitner, A. (2021) *Physical Review X*, *11*(3), 031041.
Shchesnovich, V. S. *Physical Review A* 91.1 (2015): 013844.

Description of experiment

Bosons $\Rightarrow$ symmetric states

$$\pi \otimes \tilde{\pi}|\Psi\rangle_{ext,int} = |\Psi\rangle_{ext,int} \text{ for any permutation } \pi \in S_N$$

$\pi(\tilde{\pi})$ representation of a permutation π in the external (internal) Hilbert space

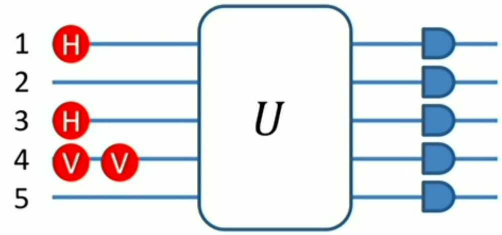
projector onto the N-particle symmetric subspace of $\mathrm{H_N}$: $\mathrm{P_{tot}^{(N)}} = \sum_{\pi\in S_N} \pi \otimes \tilde{\pi}$
And for ext Dof: $\mathrm{P^{(N)}} = \sum_{\pi\in S_N} \pi$

$$\Rightarrow \ \pi\rho_{ext}\pi^t = \rho_{ext}$$

Bosonic states:

$$Inv(\mathcal{H}) = \{\rho: \pi\rho\pi^t = \rho \ \forall\pi \in S_N, \rho \geq 0, tr(\rho) = 1\}$$

Example



$a^{\dagger}_{1,H} a^{\dagger}_{3,H} a^{\dagger}_{4,V} a^{\dagger}_{4,V} |vac\rangle = \sum_{\pi \in S_4} \pi \otimes \pi \ |1344\rangle |HHVV\rangle$

interferometer acts as $U \otimes U \otimes \ldots \otimes U = U^{\otimes 4}$

Example for 2 distinguishable particles:

$$|\psi\rangle \propto \sum_{\pi \in S_2} \pi \otimes \pi \ |12\rangle|12\rangle$$

$\rightarrow \rho_{ex} = |12\rangle\langle 12| + |21\rangle\langle 21|$

$H_{ex} = span\{|1\rangle, |2\rangle\}$

$H_{in} = span\{|1\rangle, |2\rangle\}$

Example for 2 indistinguishable particles:

$$|\psi\rangle \propto \sum_{\pi \in S_2} \pi \otimes \pi \ |12\rangle|11\rangle$$

$\rightarrow \rho_{ex} = (|12\rangle + |21\rangle)(\langle 12| + \langle 21|)$

Indistinguishable particles

DEF: Indistinguishable particles if externally, particles behave like bosons, i.e identical particles described by a state $\rho \in Inv(\mathcal{H})$ are called perfectly indistinguishable if

$$\pi_N \rho_{ext} = \rho_{ext}$$

REMARK: Does not make use of the internal d.o.f. (as they are inaccessible)
e.g., two bosons in the state

$|\Psi\rangle = |11\rangle_{ext} \otimes |11\rangle_{int}$ as well as

$|\Psi\rangle = |11\rangle_{ext} \otimes (|12\rangle + |21\rangle)_{int}$ are indistinguishable

As $\pi_N \rho_{ext} = \rho_{ext}$

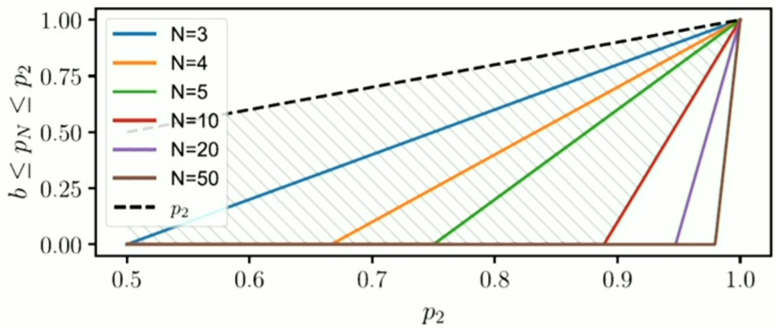
Quantifying indistinguishability

$$P_N = < P_N > = tr(P_N \rho_{ext})$$

- $P_N = 1$ perfectly indistinguishable (independent of internal states)
- Generalizes result for fixed mode occupations to arbitrary states
- Gives upper bound on trace distance to indistinguishable part of ρ_{ext}, i.e. $\mathrm{P_N} \rho_{ext} \mathrm{P_N}$

Bounds on quantifier of indistinguishability

Note if $P_2 = 1 \Rightarrow P_N = 1$
A large value of $P_2 \Rightarrow$ strong conditions on $\rho \in Inv(\mathcal{H}) \Rightarrow$ leads to good bounds on P_N:



$$b = \begin{cases} 0 \; if \; 0 \leq p_2 \leq (N-2/N-1) \\ p_2(N-1) - (N-2) \; else \end{cases}$$

$$b \leq p_N \leq p_2$$

Similar with p_k for any k ≥ 3.

p_2 can be measured efficiently ⇒ if N particles are sufficiently indistinguishable, this can be verified efficiently

$P^{(2)} \otimes id^{(N-2)}$ is linear combination of $\sim M^4$ operators of the form $A \otimes A \otimes id^{(N-2)}$, which can be measured efficiently (interferometer U, such that UAU† is diagonal).

Quantifying indistinguishability

$$P_N = < P_N > = tr(P_N \rho_{ext})$$

How can we measure P_N?

Other approaches to quantify indistinguishability (also P_N) rely on measuring probabilities that become exponentially small with N (e.g. (V. S. Shchesnovich, Phys. Rev. A 91, 063842 (2015)).

Here: tight bound via simple measurements via $P_2 = < P^{(2)} > = tr((P_2 \otimes Id^{(N-2)})\rho_{ext})$ measures how symmetric the two-particle reduced state is.

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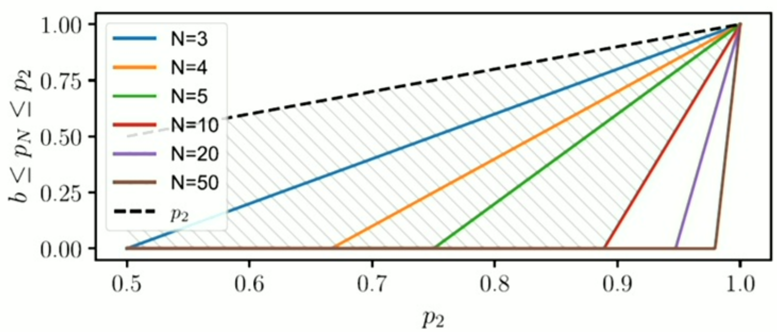

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Perfectly distinguishable particles

perfectly distinguishable particles if maximally violating indistinguishability condition, $\pi_N \rho_{ext} = \rho_{ext}$

Characterization of perfectly distinguishable states:
States whose eigenspaces are spanned (up to a permutationally invariant unitary) by computational basis vectors with distinct entries (e.g. $|1,2,3\rangle$) and their permutations (only possible if $\mathrm{M} \geq N$).

Example: the fixed mode occupation state $\rho = \sum_{\pi \in S_N} \pi |1, \dots, N\rangle\langle 1, \dots, N| \pi^t$ is perfectly distinguishable, also any state $\tilde{\rho} = U^{\otimes N} \rho \left(U^{\otimes N}\right)^t$

Conclusion and Outlook

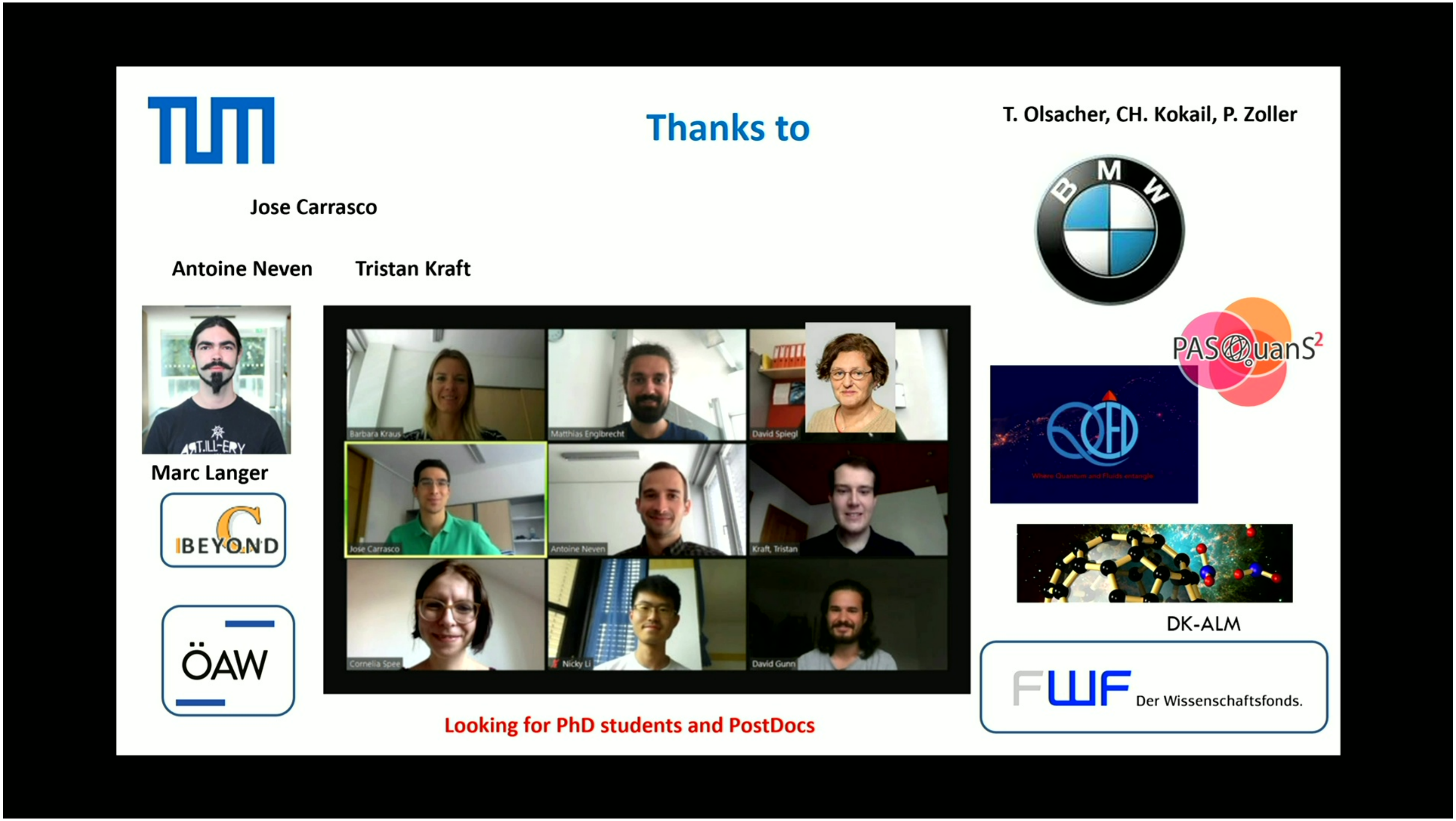
Gaining confidence about realization of arbitrary q. circuit

H & L learning in presence of weak dissipation

Indistinguishability of photons:

- Definition of (in)distinguishability for arbitrary states with fixed total particle number
- Measure of indistinguishability + bounds on measure (experiment)

Outlook: Using $P^{(k)}$ to learn more about indistinguishability; relation to entanglement/interference? How can we characterize the source producing the photons?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