Optical Emulation of Higher-Order Correlation Functions

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The Question

Can ordinary laser pulses reproduce selected correlation patterns of light detections associated with quantum light?

Quantum Light

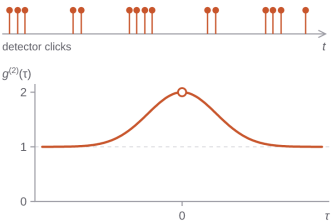
All light has a quantum description. Here, **nonclassical light** means statistics beyond a classical fluctuating-field description.

Classical field description possible · $g^{(2)}(0) \geq 1$

Nonclassical · $g^{(2)}(0) < 1$

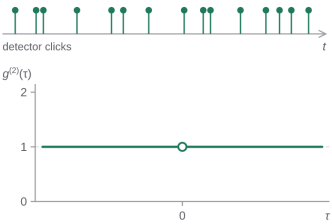
Bunched detections
e.g. thermal / chaotic light

$g^{(2)}(0) = 2$



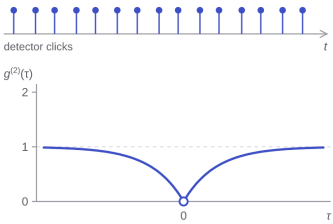
Poisson photon counts
e.g. coherent laser light

$g^{(2)}(0) = 1$



Exactly one photon
e.g. single-photon emitter

$g^{(2)}(0) = 0$



What are correlations?

For two detector responses separated by a delay τ,

$$g_{12}^{(2)}(\tau) = \frac{\mathbb{E}[D_1(t)D_2(t+\tau)]}{\mathbb{E}[D_1(t)]\,\mathbb{E}[D_2(t+\tau)]}.$$

Numerator: average product of responses separated by some time lag τ. Denominator: baseline expected under independence.

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Higher orders: measure more detections together.

$$g^{(m)}(t_1, \ldots, t_m) = \frac{\mathbb{E}\left[\prod_{i=1}^{m} D_i(t_i)\right]}{\prod_{i=1}^{m} \mathbb{E}[D_i(t_i)]}.$$

Independence implies $g^{(m)} = 1$. The converse does not necessarily hold. If $g^{(m)} > 1$, enhanced joint responses (bunching) are implied; if $g^{(m)} < 1$, suppression is implied.
The correlation described here is distinct from Pearson correlation.

Why study correlations?

Average brightness does not determine how detections occur together.

- **Characterize a source:** Determine whether the source produces thermal, coherent, or quantum light.
- **Measure time scales:** Study how correlations change with delay to reveal memory or recovery dynamics.
- **Determine spatial structure:** Compare signals at separated detectors to estimate a source's physical properties.

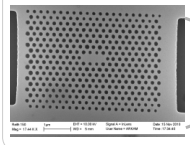
Historical example: Hanbury Brown and Twiss used intensity correlations to measure the angular diameter of Sirius (1956).

Next: what can three or four detector responses reveal beyond pairs?

When is higher-order important?

- Characterize rare multiphoton events.
- Distinguish models consistent with lower-order measurements.
- Test multi-detector measurement and its time-delay structure.

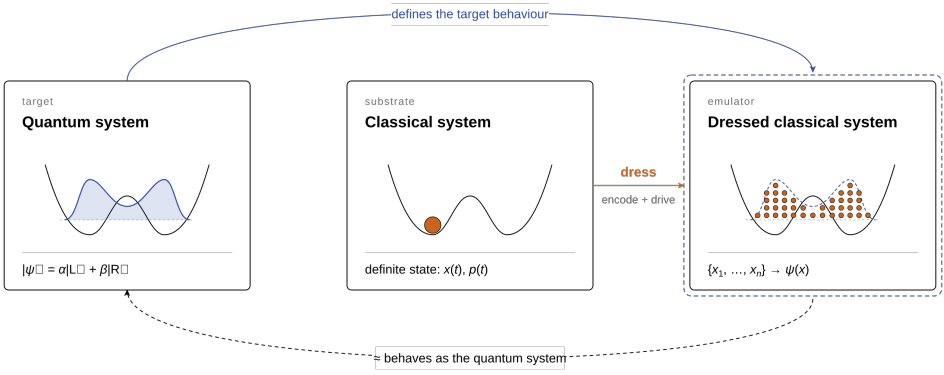
Cost: multiple channels, timing alignment, long stable acquisition.



A quantum-dot cavity: measure its multiphoton output. Rundquist et al. (2014), Fig. 1(a), SEM crop.

What is Emulation?

Use a simpler, controllable system to reproduce select measurements of another system.



What is Emulation?

Previous optical examples:

- **B92 and six-state quantum key distribution:** emulate state preparation and measurement protocols.[1,2]
- **Quantum state tomography and Bell-test emulation:** reconstruct states and analyze polarization correlations.[3]

[1] Gandelman, Maslennikov and Rozenman, *Photonics* **12**, 220 (2025). B92 protocol.

[2] Gandelman and Rozenman, *Eur. Phys. J. Spec. Top.* **235**, 2967–2975 (2026). Six-state protocol.

[3] Arbel et al., *Results in Optics* **21**, 100847 (2025). Quantum state tomography and Bell-test emulation.

The question

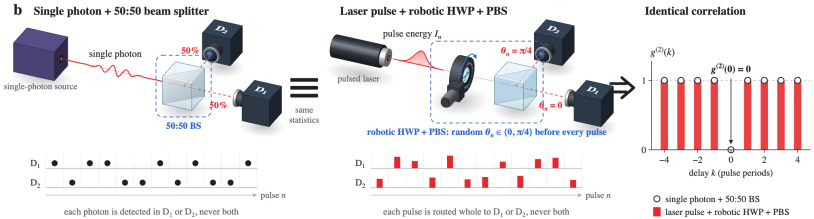
Research Question

Can an optical apparatus with random routing reproduce expected correlation measurements of higher orders?

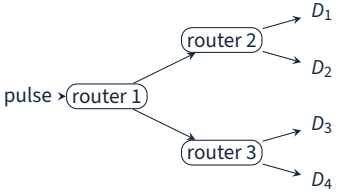
The Goal

Create an apparatus that emulates coincidence-exclusion patterns in third- and fourth-order correlations, providing an accessible platform for further experimentation on and teaching of higher-order correlations.

The optics implement a random choice



- We use pulsed lasers, half-wave plates, and polarizing beam splitters.
- Half-wave plate rotates the polarization; polarizing beam splitter separates the two orthogonal ones.



Three routers, four detectors.

A probabilistic routing model

$$D_{i,n} = I_n \chi_{i,n}, \qquad \chi_{i,n} \in \{0, 1\}, \qquad \sum_{i=1}^{4} \chi_{i,n} = 1.$$

I_n: pulse energy. $\chi_{i,n}$: indicator that pulse n reaches detector i.

$$\boxed{\chi_{i,n}\chi_{j,n} = 0 \quad (i \neq j)}$$

- Destination probabilities $q_i > 0$, fixed across pulses.
- Routing choices independent across pulses and of pulse energies.
- Pulse energies i.i.d., with finite positive mean μ.

The detector indicators within one pulse are mutually exclusive.

What do we expect to see?

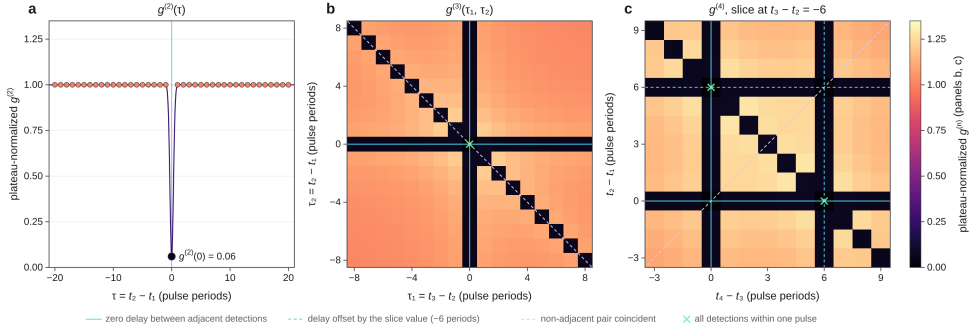
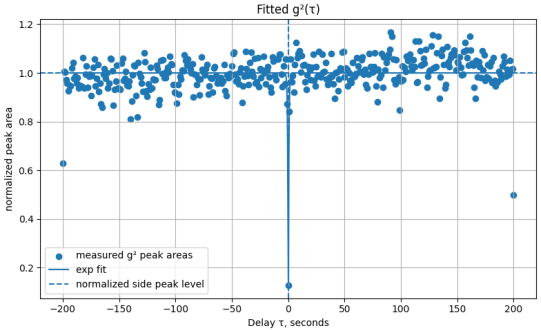


Figure: (a) Expected second-order correlation function; (b) Expected third-order correlation function; (c) Expected fourth-order correlation function

Second order: suppression between two outputs



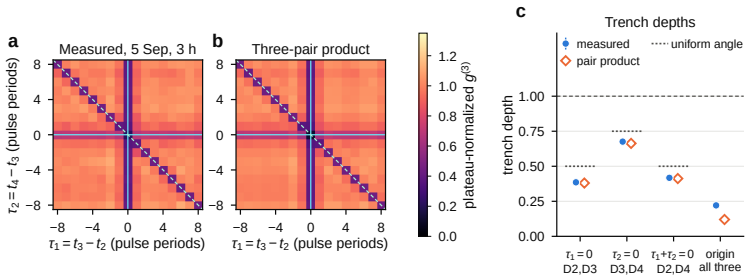
500-second run

Timing jitter: $\delta = 333$ ms.

Suppression near zero delay; fitted minimum approximately 0.125.

A routed pulse favors one output. This cross-correlation dip does not certify nonclassical light.

The three-detector case checks the same argument



$$(n, n+\tau_1, n+\tau_1+\tau_2): \quad \tau_1 = 0, \quad \tau_2 = 0, \quad \tau_1 + \tau_2 = 0.$$

Three suppressed lines; pair-product Pearson $r = 0.997$; 9817 valid pulses.
Origin (all three responses from one pulse): measured 0.22 vs. pair-product 0.12—a joint third moment is not a product of pair moments.

A short proof of the five-line pattern

Fix $t_4 - t_1 = T = 6$ pulse periods: a 2D slice of a three-delay function. Use $x = t_4 - t_3$, $y = t_2 - t_1$, with pulse indices $(s_1, s_2, s_3, s_4) = (n,\ n + y,\ n + T - x,\ n + T)$,

$$G(x, y) = \frac{\mathbb{E}[\prod_{i=1}^{4} D_{i,s_i}]}{\mu^4 \prod_{i=1}^{4} q_i}.$$

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Repeated index: $s_i = s_j$ implies $\chi_{i,s_i}\chi_{j,s_j} = 0$, so $G = 0$.

Distinct indices: independence gives $\mathbb{E}[\prod_i D_{i,s_i}] = \mu^4 \prod_i q_i$, so $G = 1$.

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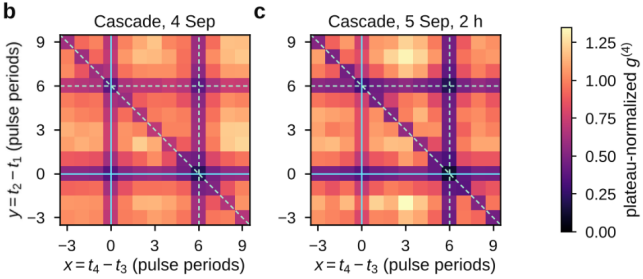
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$$\underbrace{s_1 = s_2}_{y=0} \quad \underbrace{s_3 = s_4}_{x=0} \quad \underbrace{s_1 = s_3}_{x=T} \quad \underbrace{s_2 = s_4}_{y=T} \quad \underbrace{s_2 = s_3}_{x+y=T} \quad \underbrace{s_1 = s_4}_{\text{never: } T>0}$$

Zero set: five lines in the (x, y) plane; value 1 elsewhere.
Zeros do not require balanced routing or a particular energy distribution. The off-line value uses independence across pulses.

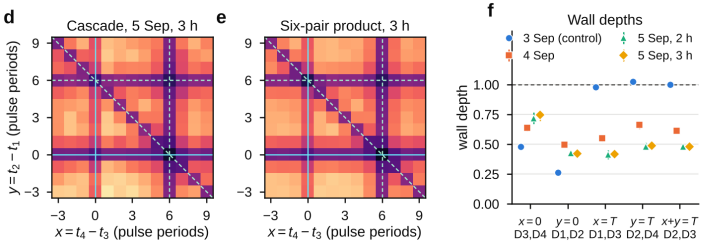
The predicted lines appear in the measured maps



- Five suppressed lines, reproduced in three runs on two days.
- Line means 0.41–0.75: imperfect routing gives partial suppression.

The measured geometry agrees with the routing model.

How much does a product of pair moments explain?

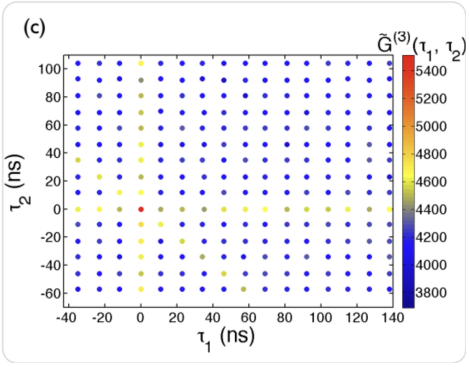


$G_{\text{pair}} = \prod_{i<j} g_{ij}^{(2)}(s_j - s_i)$; three-hour run: Pearson $r = 0.987$, RMSE 0.043.

- Memoryless model: distinct pulse indices split into independent groups; a group of ≤ 2 responses is fixed by pair moments.
- Three coincident times leave a third-order moment, which pairs do not determine.

Comparison with quantum-dot experiment

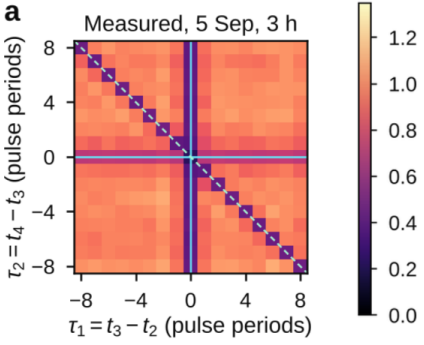
Quantum-dot–cavity experiment



Rundquist et al., Phys. Rev. A **90**, 023846 (2014), Fig. 2(c).

Third-order correlations in a bunching regime.

Classical optical emulator



This work: Third-order coincidence exclusion.

Measured three-detector correlation, 3-hour run.

What the model and experiment establish

- **Exclusivity** determines the predicted zero set.
- **Independence across pulses** gives a flat ideal background.
- **Imperfect routing** produces partial suppression in the data.

Emulation: a controllable test bed for estimators, background handling, calibration and teaching.

Classical routing produces this pattern; it does not certify quantum light. The present emulator does not reproduce emitter recovery dynamics or interference.

Next: faster switching and lower leakage (deeper walls, same positions); programmable memory (other source classes); fourth-order-only correlations, alongside a quantum processor.

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Thank you!

Acknowledgments

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- I would also like to thank the MIT PRIMES program for making this research opportunity and this conference possible.

Selected references

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