$$\hat{a}^{+}|n\rangle = \sqrt{n+1}|n+1\rangle \ ; \ \hat{a}|n\rangle = \sqrt{n}|n-1\rangle$$

Boson subtraction and addition

Due to the symmetrical nature, the probability of a transition in which a photon is created into (subtracted from) state x is proportional to the number of bosons originally in state x.

$$\hat{a}^{+}|n\rangle = \sqrt{n+1}|n+1\rangle \; ; \; \hat{a}|n\rangle = \sqrt{n}|n-1\rangle$$

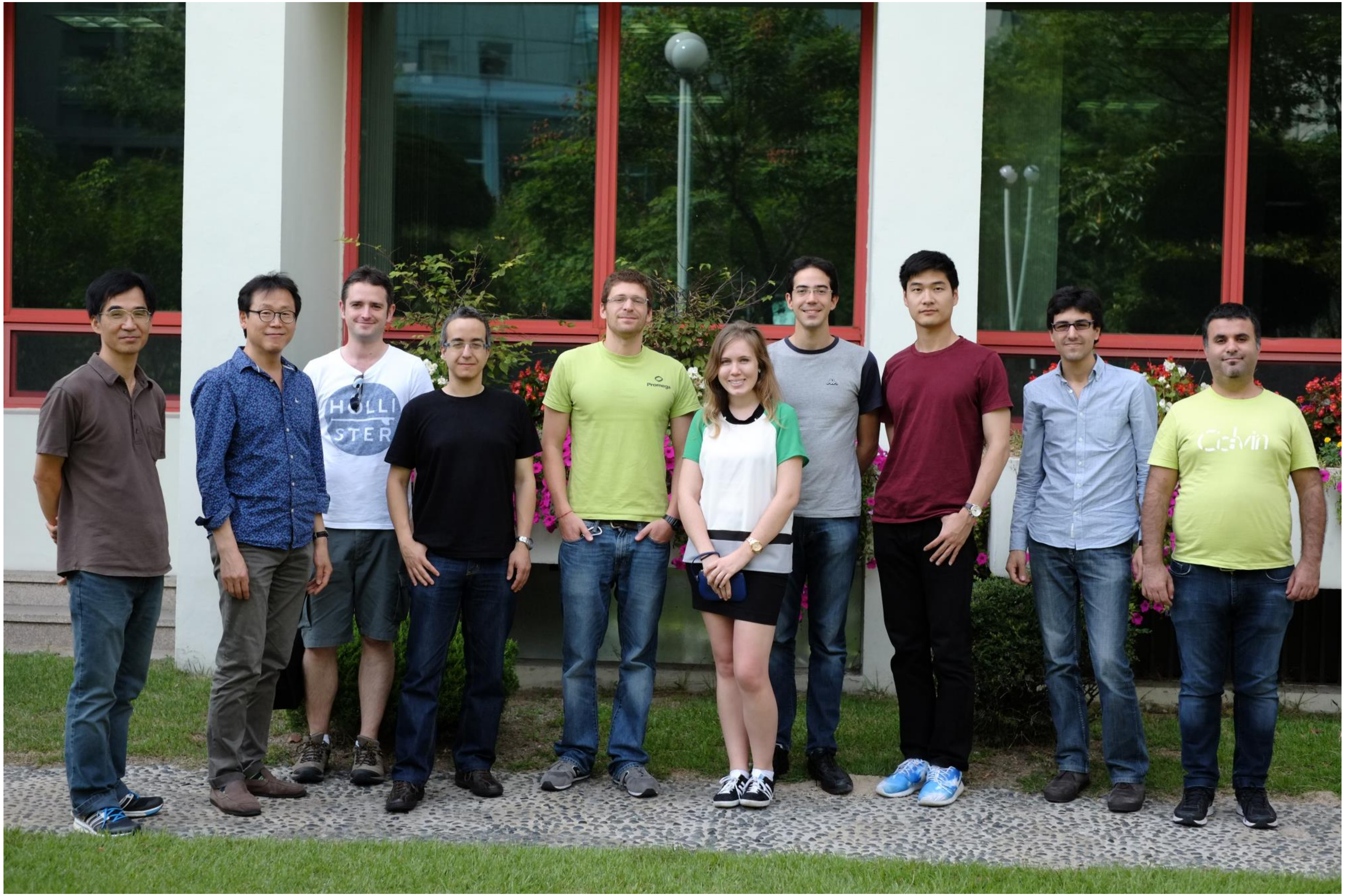
This provides a connection to a harmonic oscillator

ISNFQC18, Kolkata, India

Nonclassicalities in multiphoton interference

Luca Rigovacca, Carlo Di Franco and Myungshik Kim

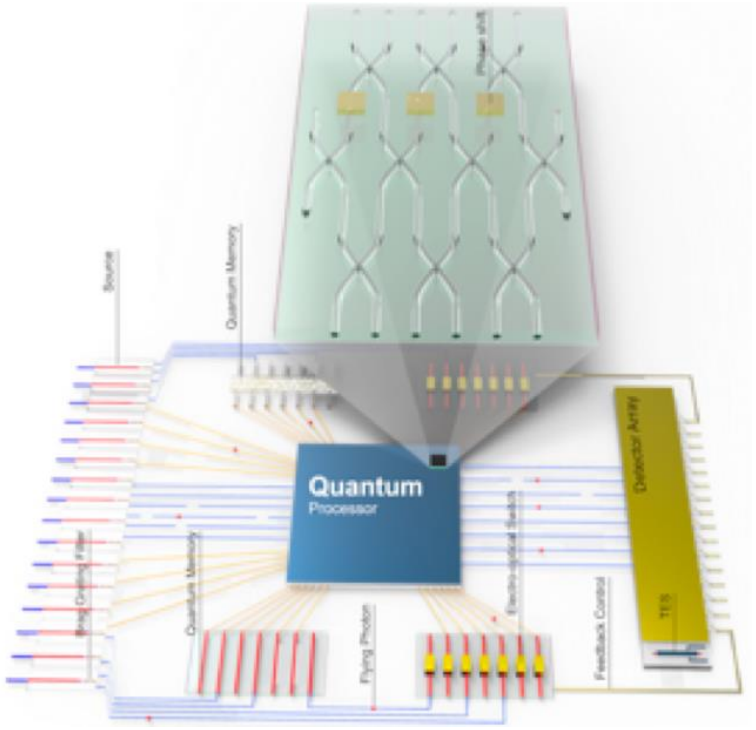
Imperial College London



SCIENTIA IMPERII DECUS ET TUTAMEN

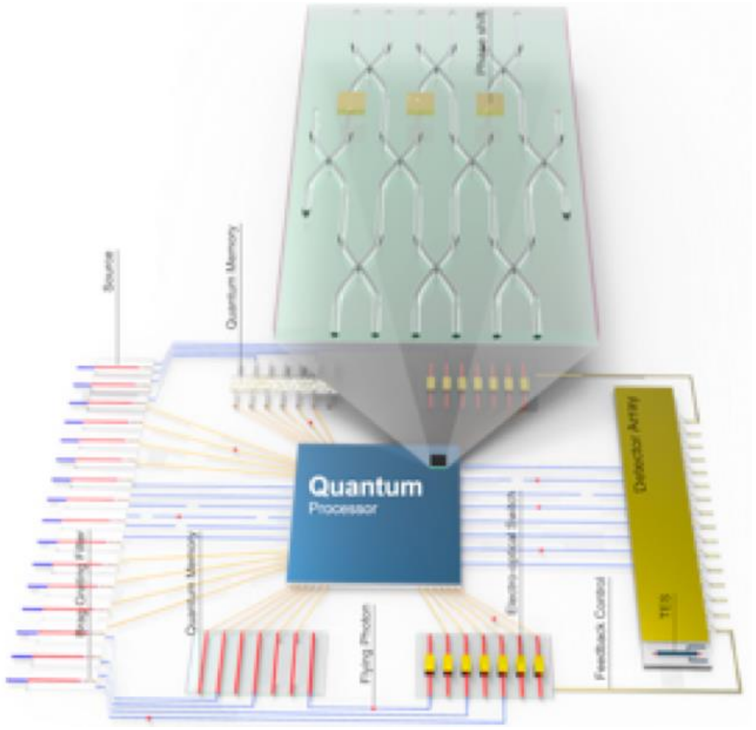
Motivation

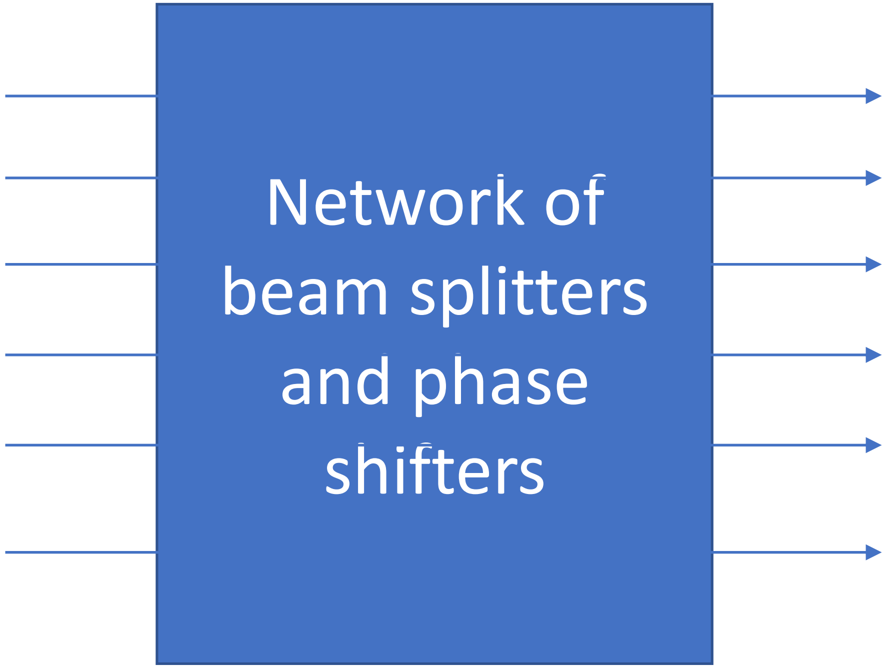
- Linear photonic quantum computation/simulation



Motivation

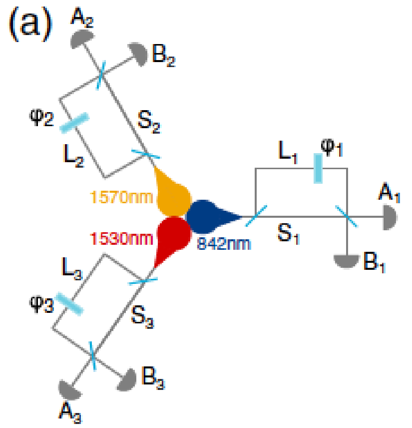
- Nonclassical features of multiphoton interference



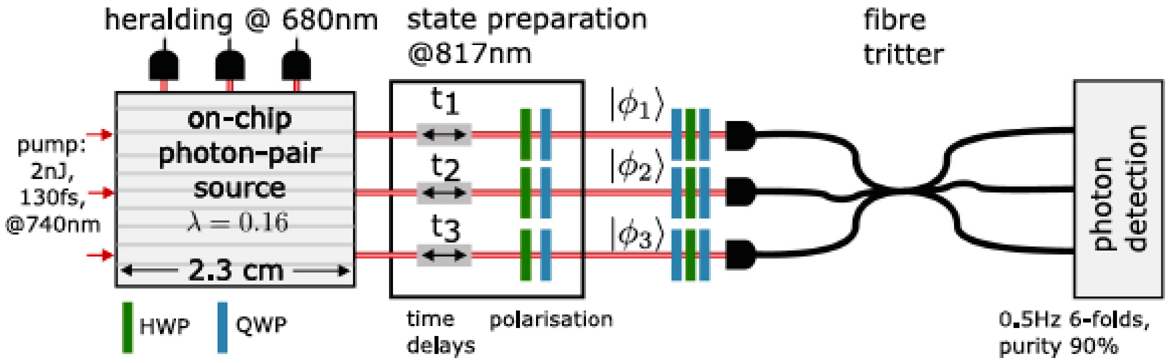


Flow of the talk

- Recent experiments of three photon interference



S. Agne *et al.* PRL 118, 153602 (17)



A. J. Messen *et al*, PRL 118, 153603 (17)

-- Remarks on nonclassicalities

- Generalisation of Hong-Ou-Mandel interferometer – Nonclassical criteria

Franson interferometer

VOLUME 62, NUMBER 19 PHYSICAL REVIEW LETTERS 8 MAY 1989

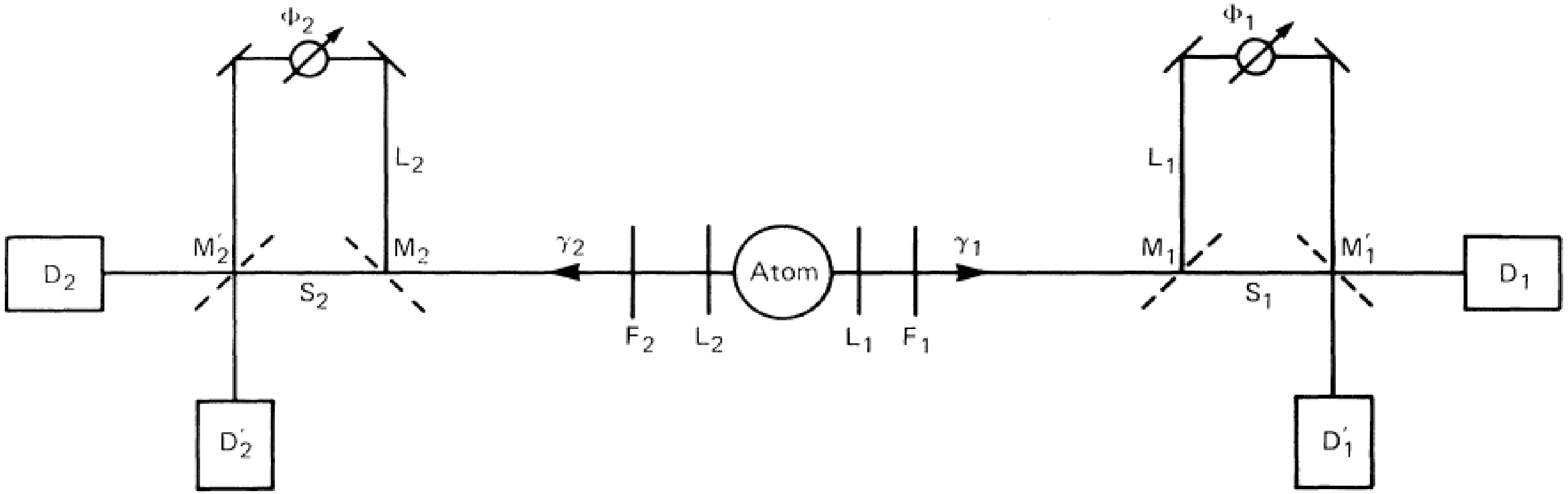
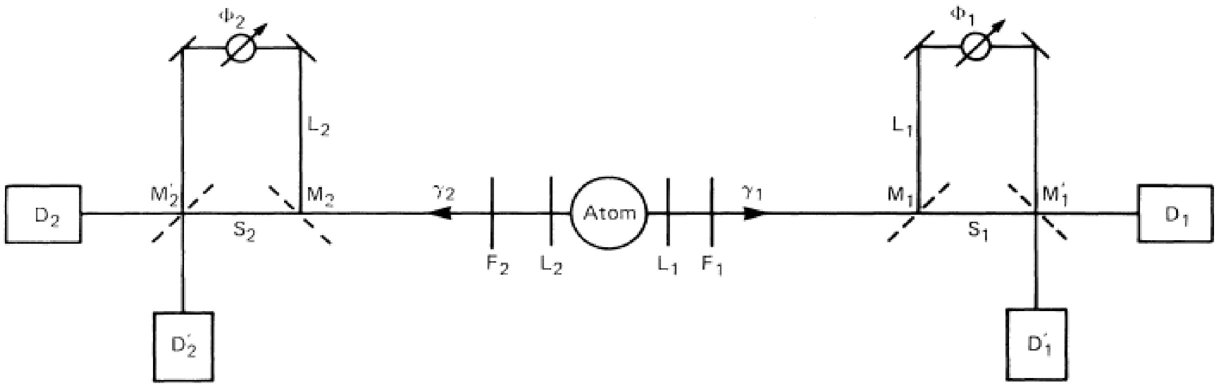


FIG. 2. Photon coincidence measurements including interference between the amplitudes along the shorter paths, S_1 and S_2, and the longer paths, L_1 and L_2.

Source emits time-correlated photons

$$\int dt\hat{a}^\dagger(t)\hat{b}^\dagger(t)|00\rangle_{ab}$$

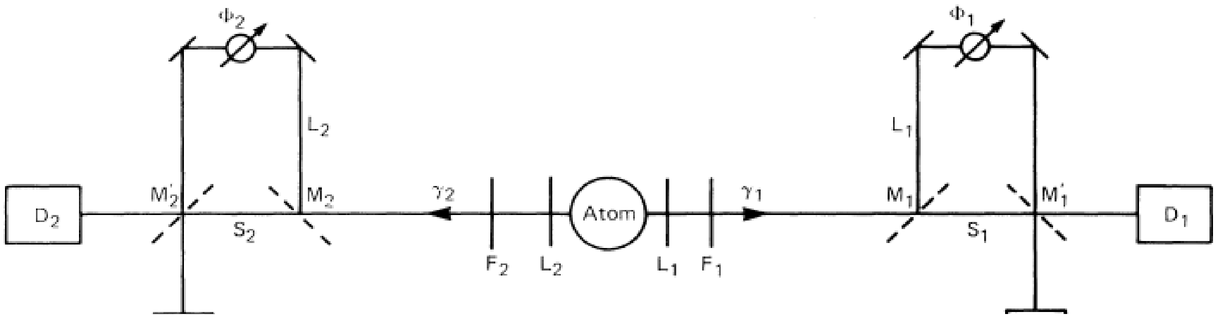


At the output ports

$$\frac{1}{4}\int dt \quad \left[\hat{a}^\dagger(t) - \hat{c}^\dagger(t) + e^{i\phi_1}(\hat{c}^\dagger(t-\Delta) + \hat{a}^\dagger(t-\Delta))\right]$$

$$\left[\hat{b}^\dagger(t) - \hat{d}^\dagger(t) + e^{i\phi_2}(\hat{d}^\dagger(t-\Delta) + \hat{b}^\dagger(t-\Delta))\right]|0\rangle$$

At the output ports (if there is no



$$\frac{1}{4}\int dtdt' \left[\hat{a}^\dagger(t) - \hat{c}^\dagger(t) + e^{i\phi_1}(\hat{c}^\dagger(t-\Delta) + \hat{a}^\dagger(t-\Delta))\right]$$

$$\left[\hat{b}^\dagger(t') - \hat{d}^\dagger(t') + e^{i\phi_2}(\hat{d}^\dagger(t'-\Delta) + \hat{b}^\dagger(t'-\Delta))\right]|0\rangle$$

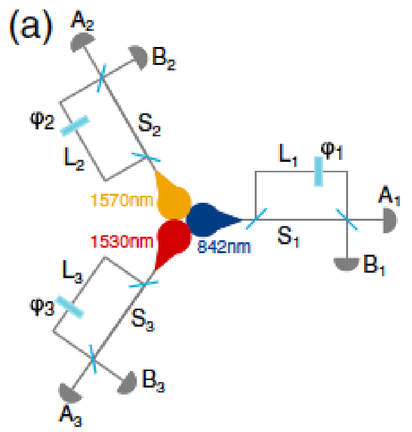
Coincident detection probability at the detectors D_1 and D_2

$$\frac{1}{4}(1+\cos\phi_1)(1+\cos\phi_2)$$

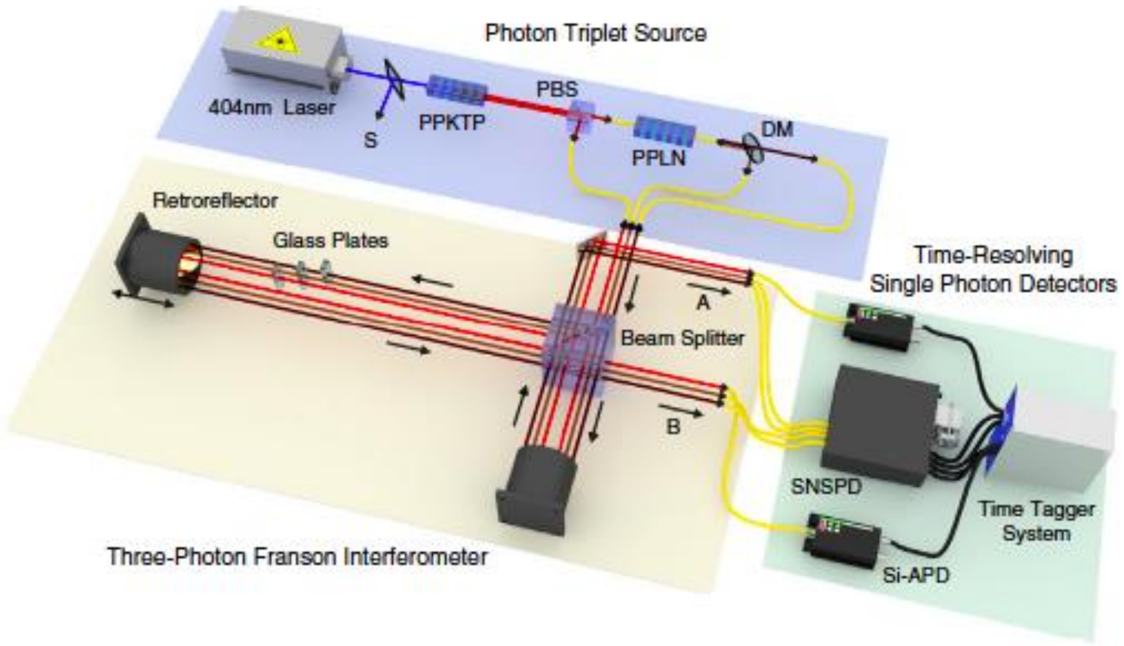
$$\frac{1}{2}(1+\cos(\phi_1+\phi_2))$$

Agne *et al* from Innsbruck

PRL 11

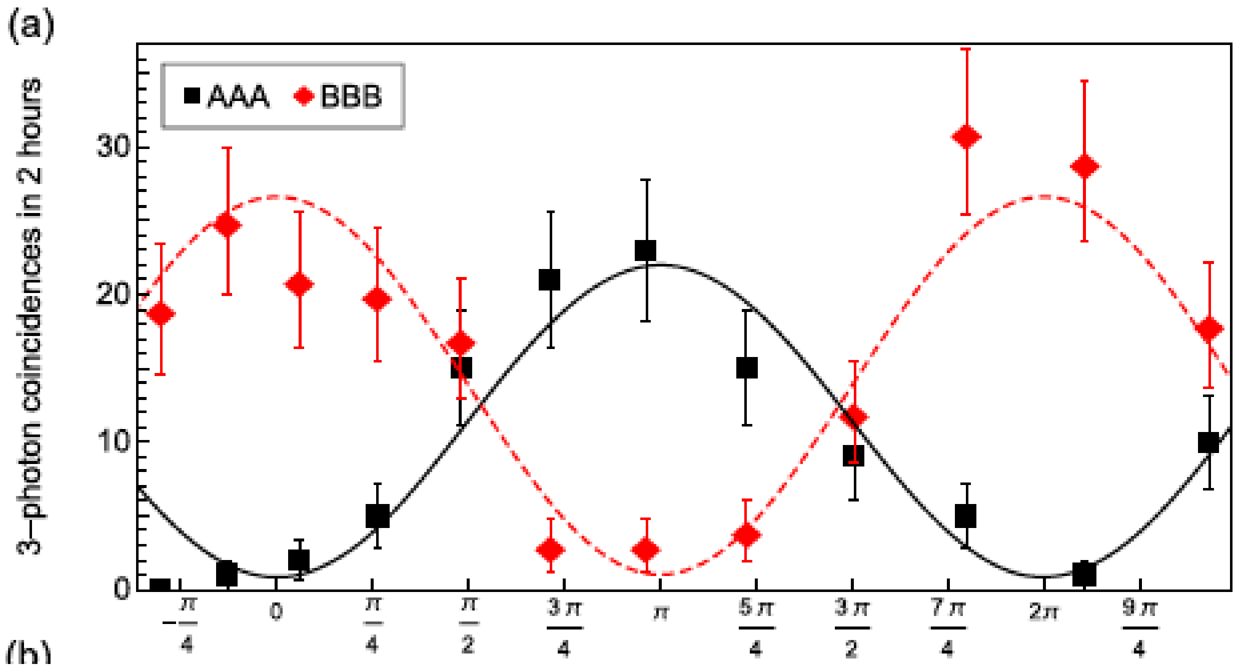


- Extended the Franson interferometer to three-correla



S. Agne *et al.* PRL 118, 153602 (17)

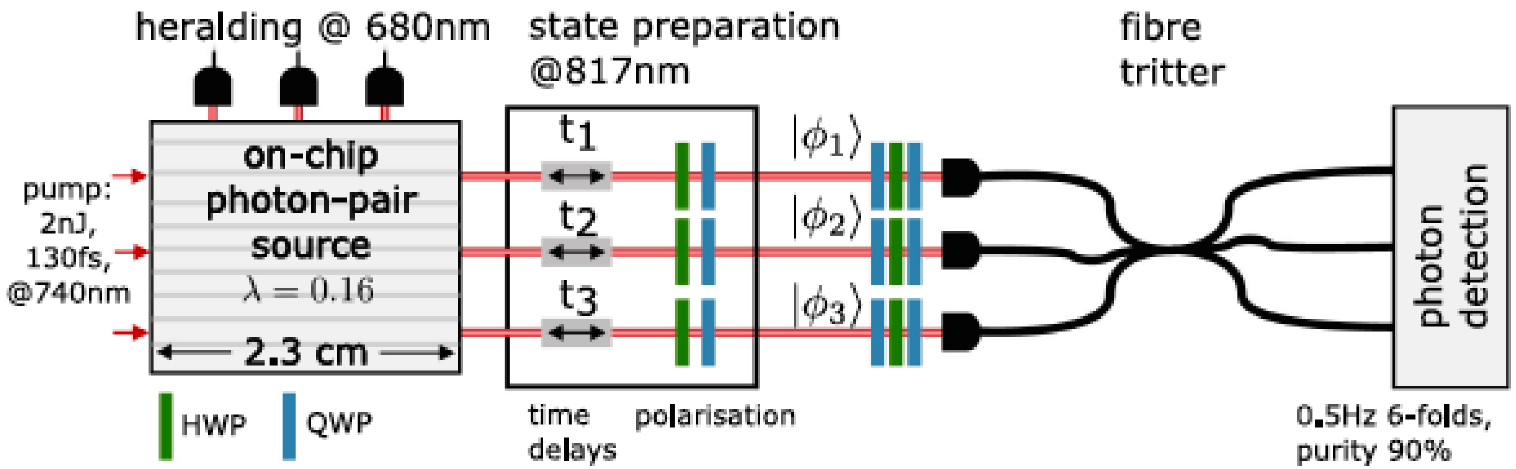
Red={A1A2A3, A1B2B3, B1A2B3, B1B2A3}



$$P = \frac{1}{2}[1 \mp \cos(\phi_1 + \phi_2 + \phi_3))$$

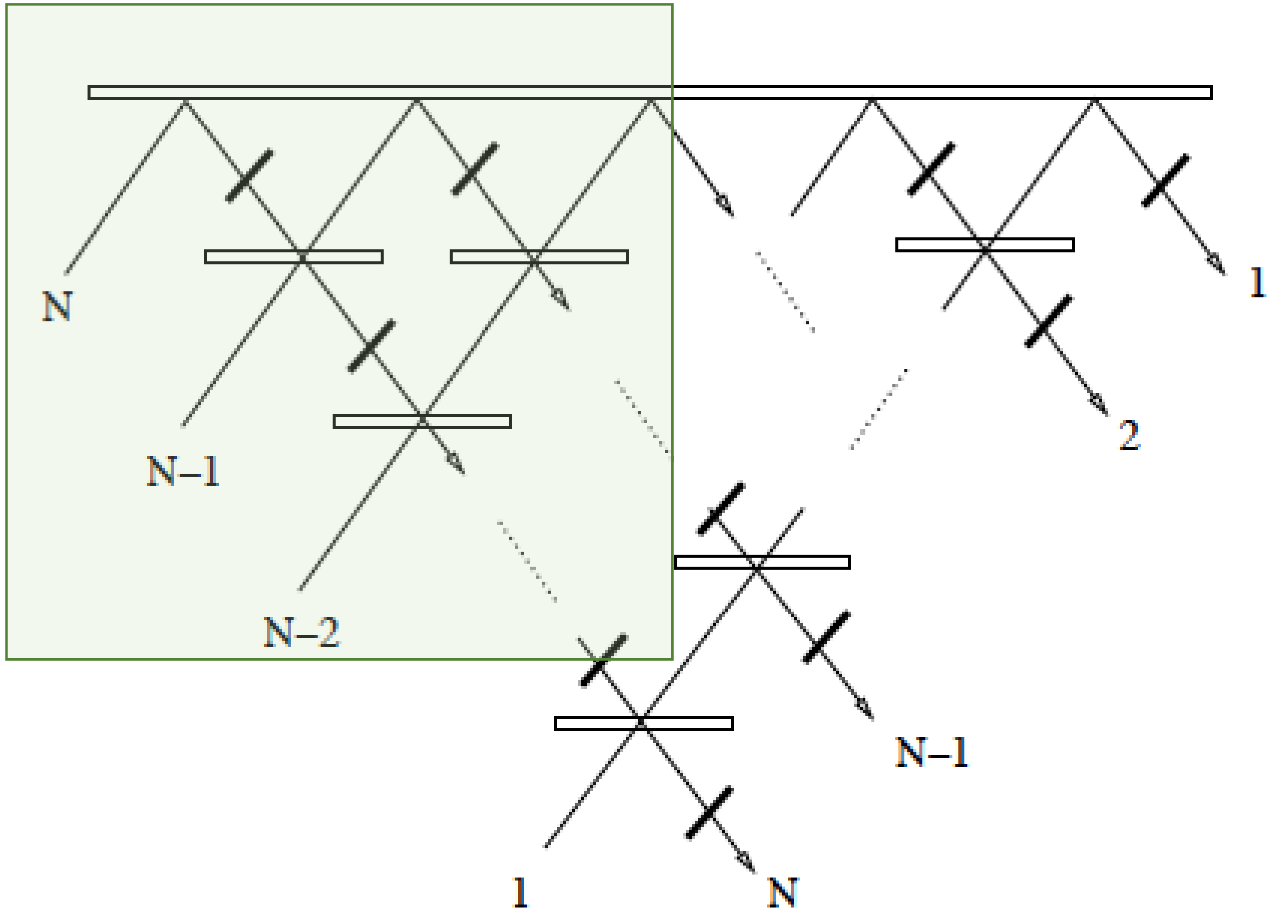
Experiment 2: Menssen *et al*

PRL 118, 153603 (2017)



$$\hat{U}_{\text{tritter}} = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 1 & 1 \\ 1 & e^{4\pi i/3} & e^{2\pi i/3} \\ 1 & e^{2\pi i/3} & e^{4\pi i/3} \end{pmatrix}$$

Decomposition of a beam tritter

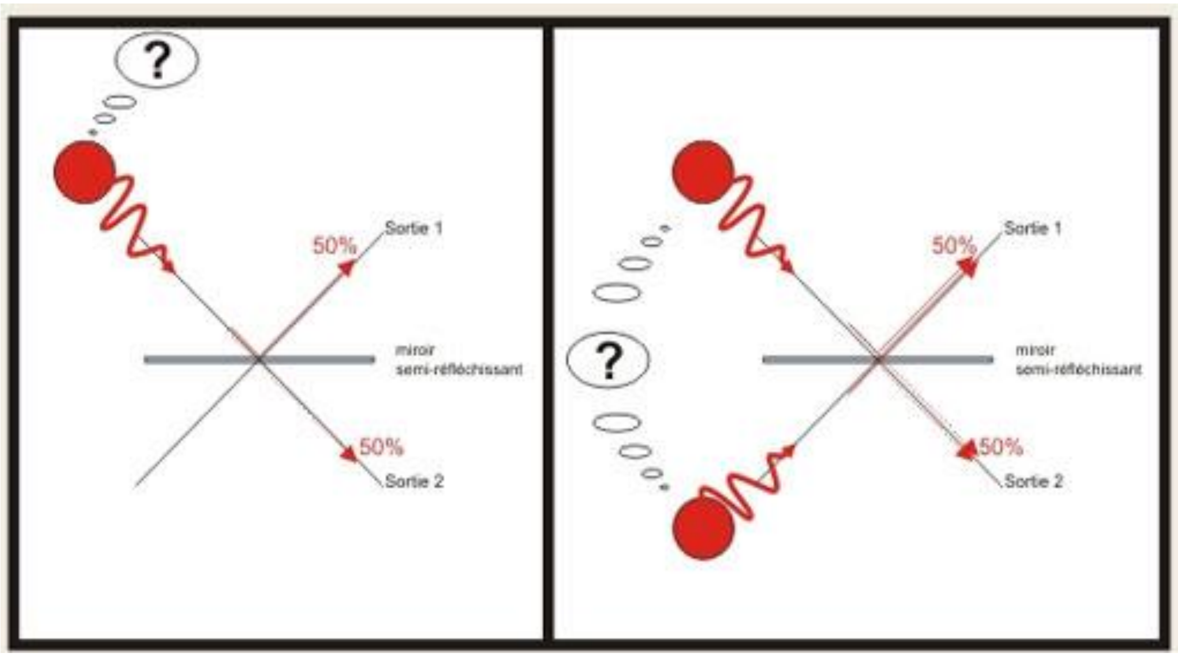


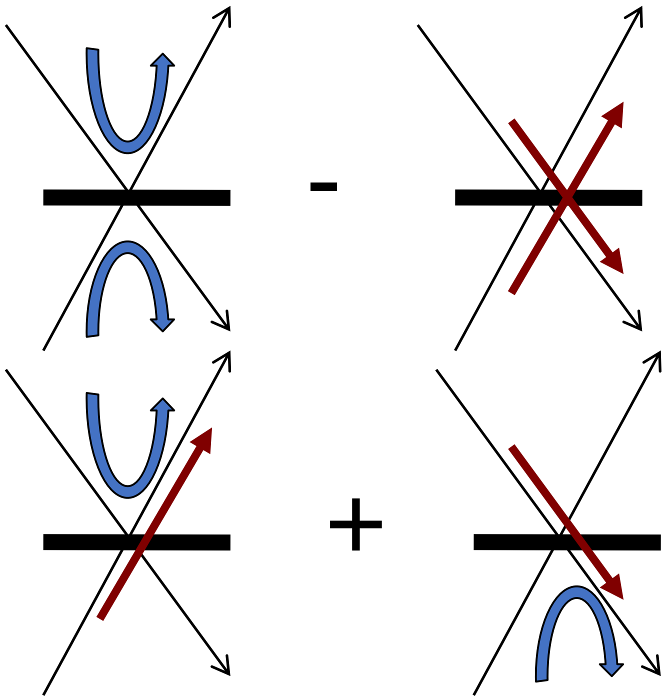
Generalised Hong-Ou-Mandel experiments with bosons and fermions
Lim and Beige, New J. Phys 7, 155 (2005)

Nonclassical properties

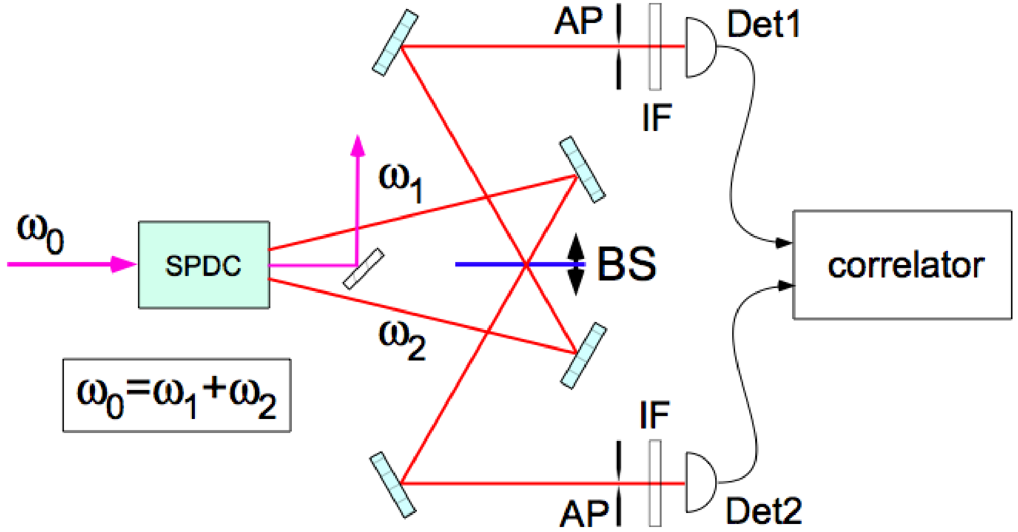
- Q: How do we detect input not classical by measuring output intensities after their interference?
- Let us consider the Hong-Ou-Mandel interferometer

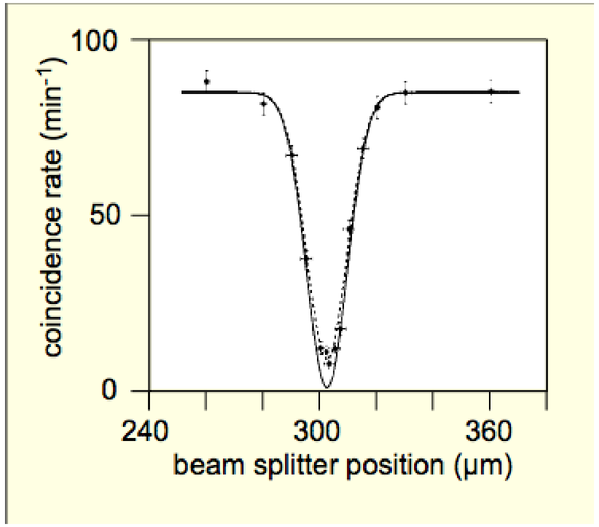
Two photons do interfere





Hong-Ou-Mandel experiment

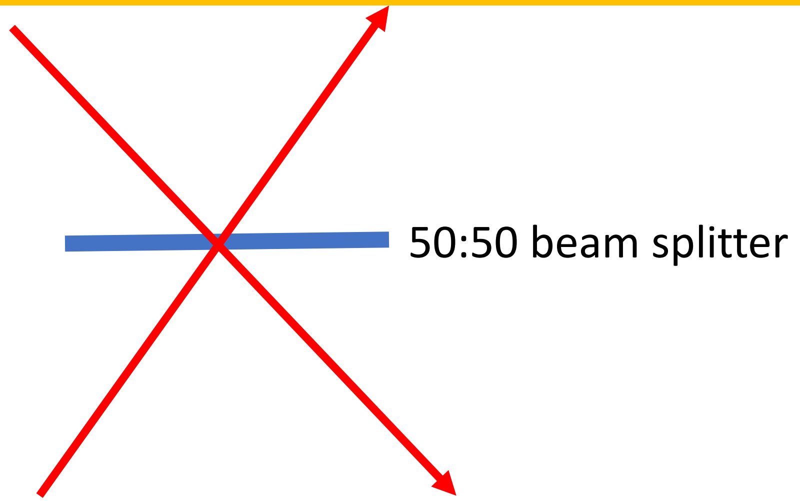


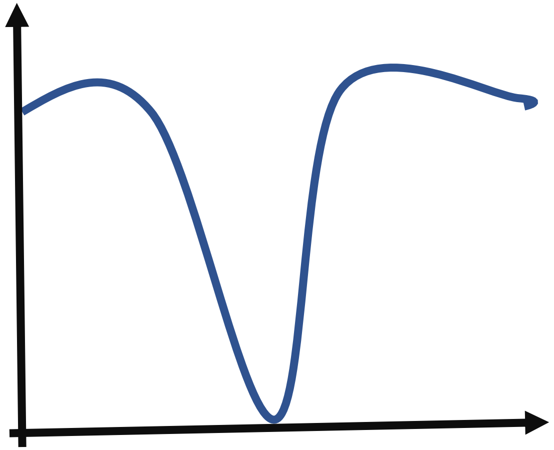


Hong et al., PRL

- Zero coincidence detection – Nonclassical effect
- 50% visibility is the classical limit
  - Where is this limit from?

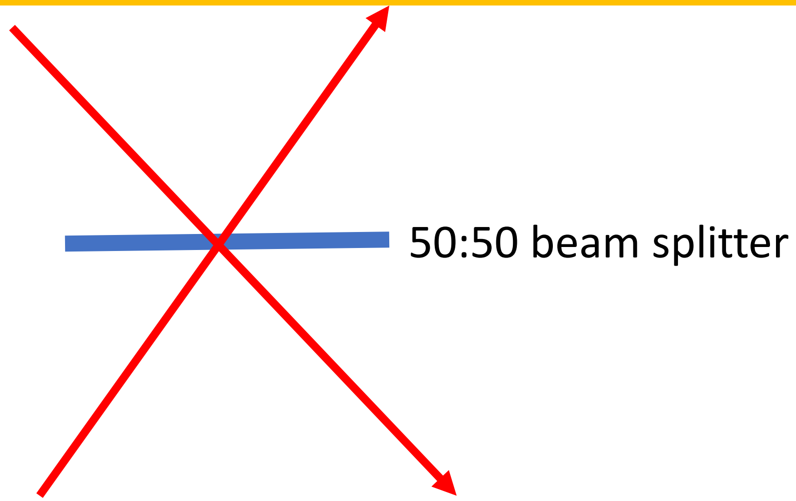
Hong-Ou-Mandel Interferometer

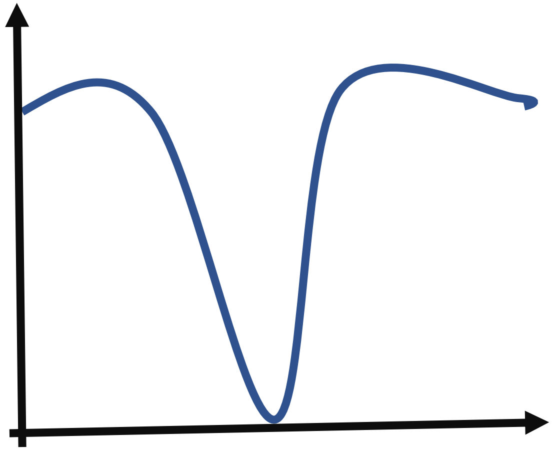




- Two coherent states of the same amplitudes interfere
- One output port will be empty
- Coincident detection rate is zero

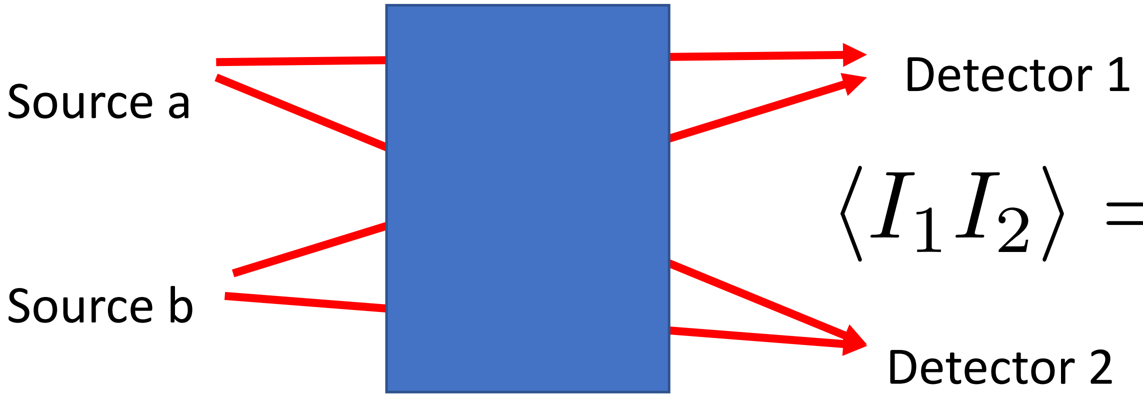
Hong-Ou-Mandel Interferometer





- Assumption 1: Two input fields have random phases <E>=0
- How about each input is from {E, -E} then <E>=0: Coincident detection rate is zero
- Assumption 2: $<E_1E_2>=0$

Hanbury Brown and Twiss Interferometer



$$\langle I_1 I_2\rangle = \langle (I_a + I_b)^2\rangle + 2\langle I_a I_b\rangle \cos\phi$$

$$\langle : \hat{I}_a^2 : \rangle \to \langle \hat{n}_a(\hat{n}_a - 1)\rangle$$

Visibility

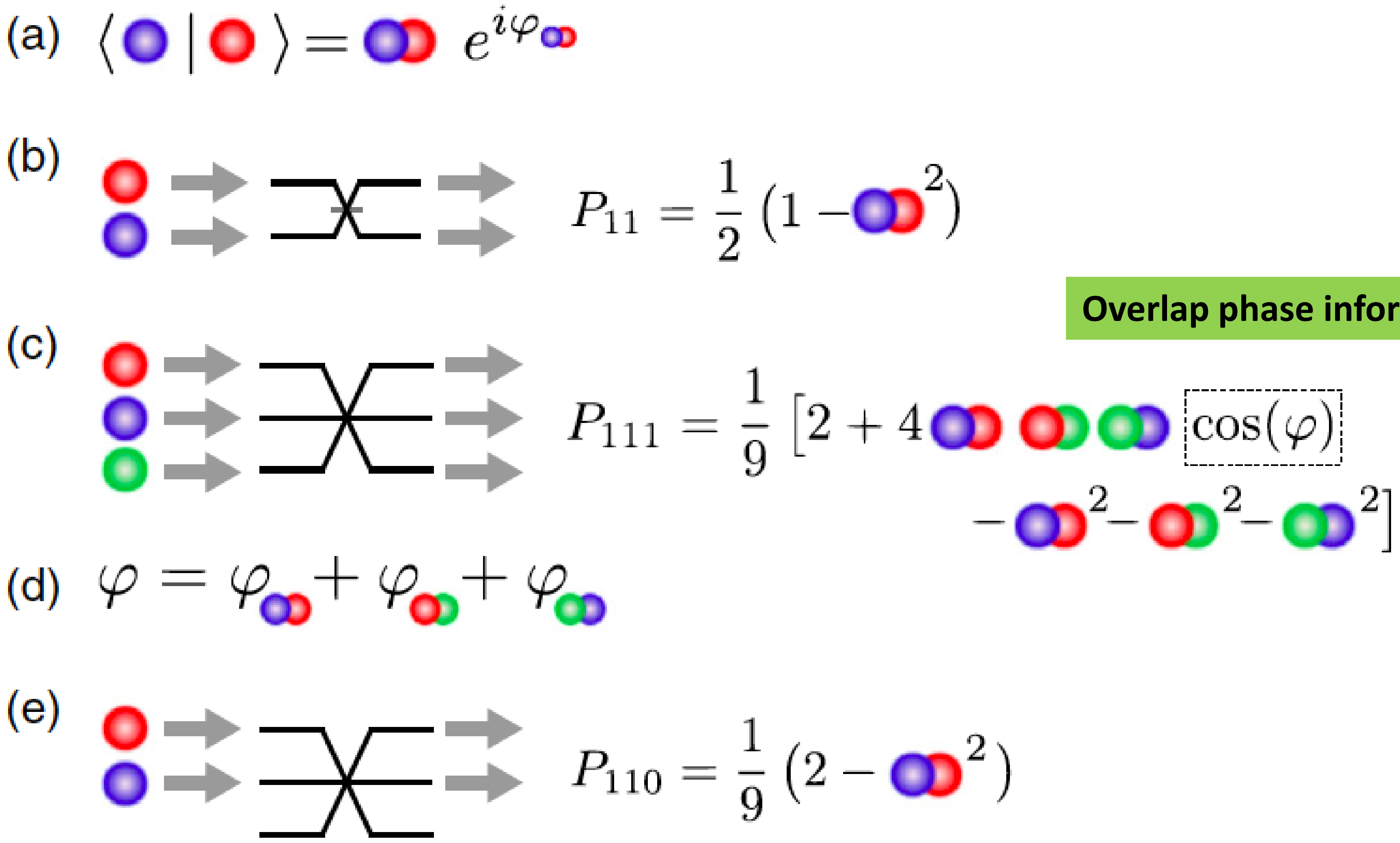
$$\frac{2\langle I_a I_b\rangle}{\langle (I_a + I_b)^2\rangle} \le \frac{1}{2}$$

Not subject to Cauchy inequality

~~$\frac{2\langle I_a I_b\rangle}{\langle (I_a + I_b)^2\rangle} \le \frac{1}{2}$~~ in QM

$$\hat{\rho} = \int d^2\alpha P(\alpha)|\alpha\rangle\langle\alpha| \to \langle I^n\rangle = \langle \hat{I}^n\rangle$$

partially identical photons

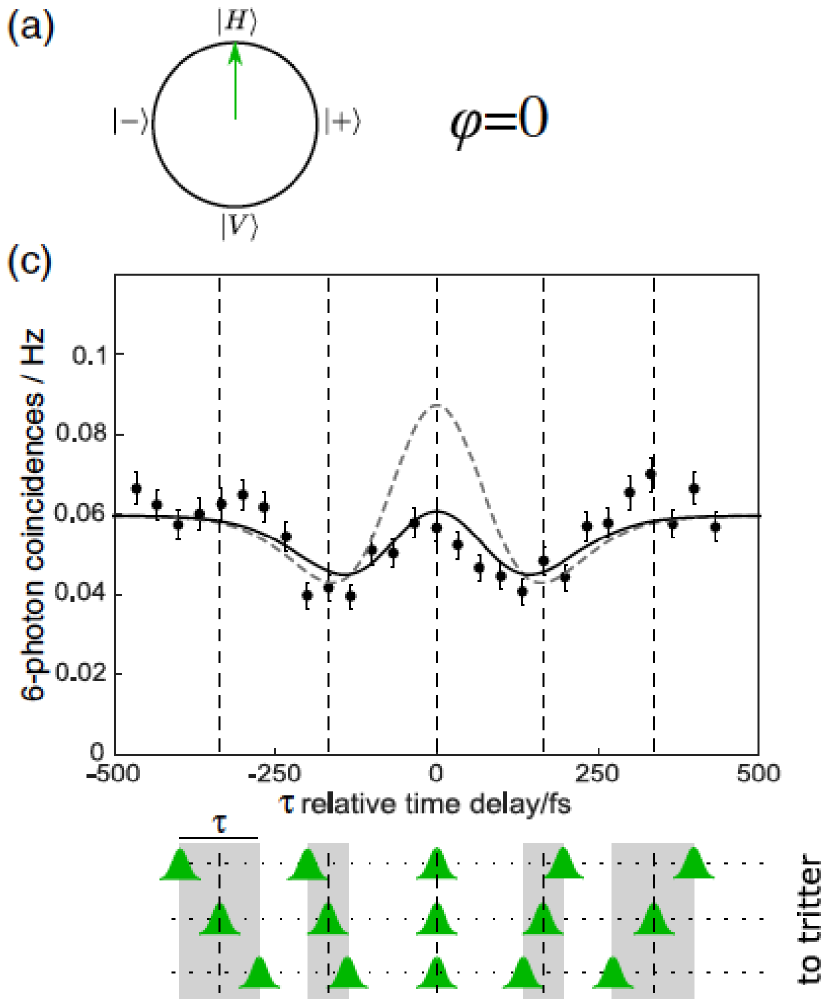


Overlap phase information becomes relevant

PRL 118, 153603 (2017)

Three photon coincidences

$|\phi_1\rangle = |t_1\rangle \otimes |H\rangle$



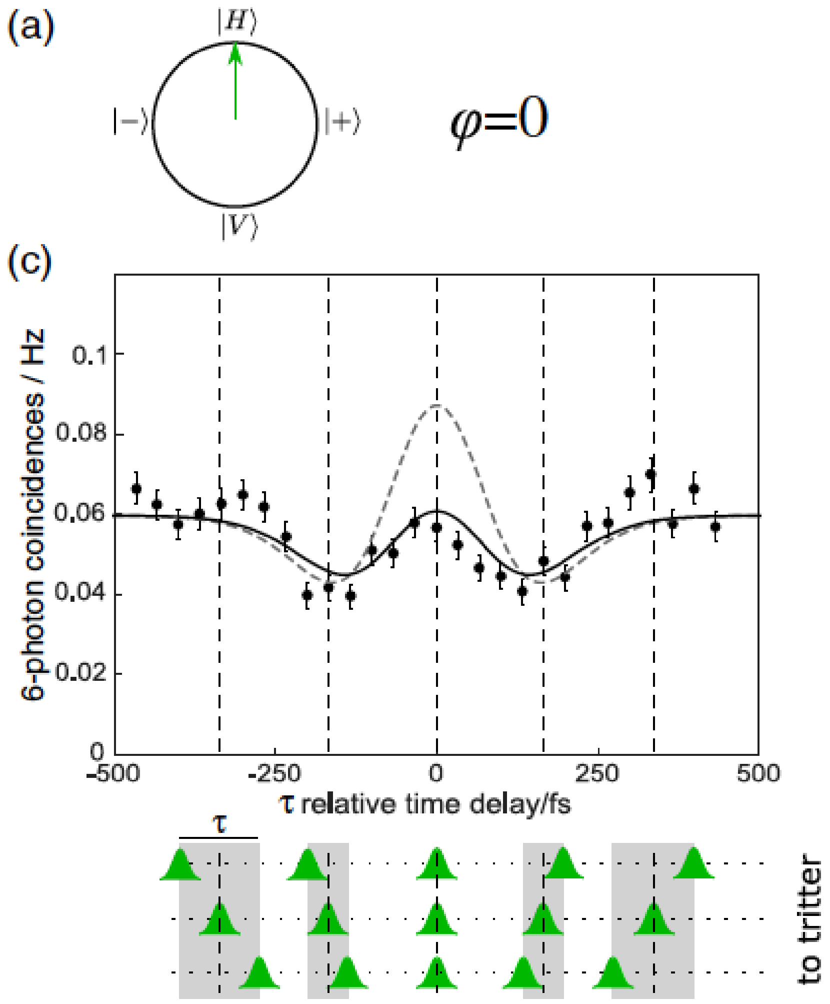
No bunching effects

Lim and Beige, New J. Phys 7, 155 (2005)

PRL 118, 153603 (2017)

$$|\phi_1\rangle = |t_1\rangle \otimes |H\rangle$$

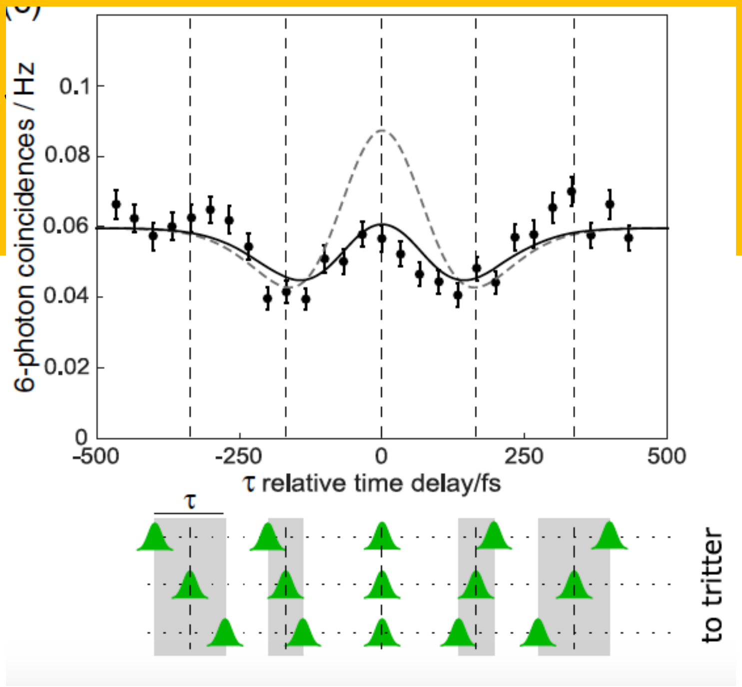
Three photon coincidences



No bunching effects

PRL 118, 153603 (2017)

Classical theor



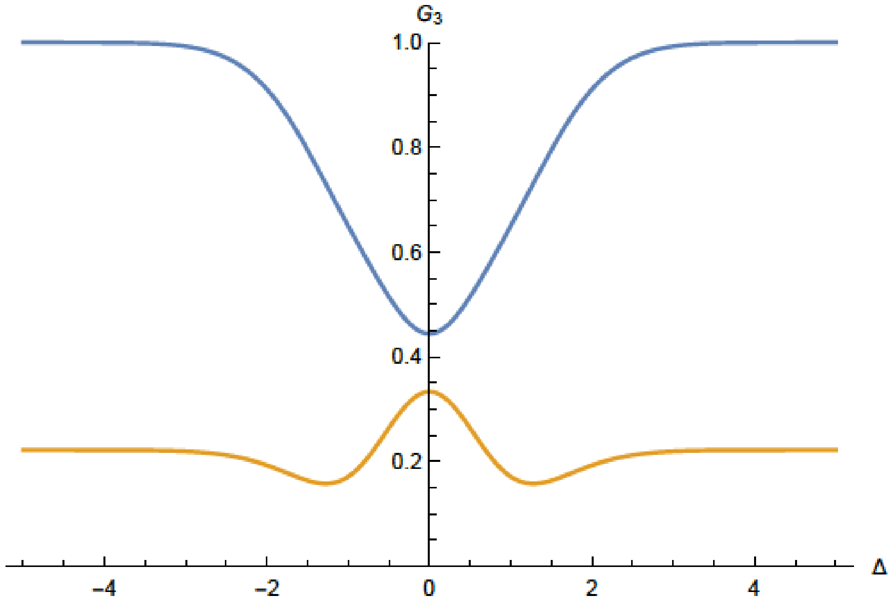
$$g_C^{(3)} = \frac{\langle I_1 I_2 I_3 \rangle}{\langle I_1 \rangle \langle I_2 \rangle \langle I_3 \rangle}$$

- Third-order correlation function

$$g_C^{(3)} = 1 + \tfrac{4}{9} r_{12} r_{23} r_{31} \cos\varphi - \tfrac{3}{9}\left(r_{12}^2 + r_{23}^2 + r_{31}^2\right)$$

$$g_Q^{(3)} = \tfrac{2}{9} + \tfrac{4}{9} r_{12} r_{23} r_{31} \cos\varphi - \tfrac{1}{9}\left(r_{12}^2 + r_{23}^2 + r_{31}^2\right)$$

Q vs C

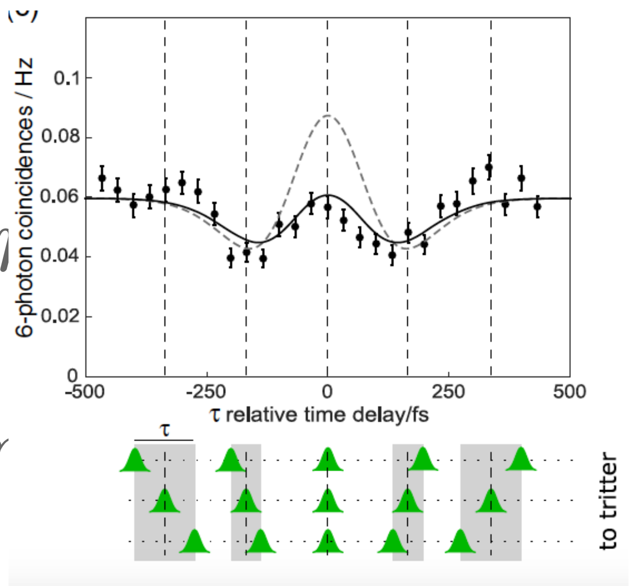


Revival of high coincidence counting is a quantum signature

Valid for input fields having identical intensities

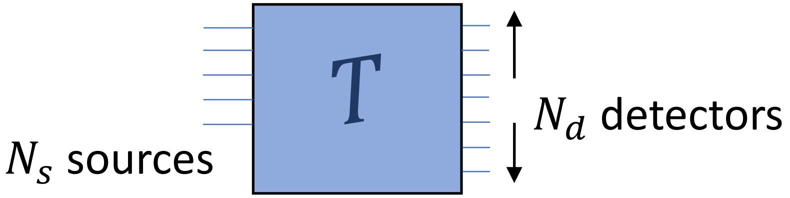
$$g_Q^{(3)} = \frac{2}{9} + \frac{4}{9} r_{12} r_{23} r_{31} \cos\varphi - \frac{1}{9}(r$$

$$g_C^{(3)} = 1 + \frac{4}{9} r_{12} r_{23} r_{31} \cos\varphi - \frac{3}{9}(r$$



Multimode Extension

Hypotheses: Independent sources emit light pulses with random phases



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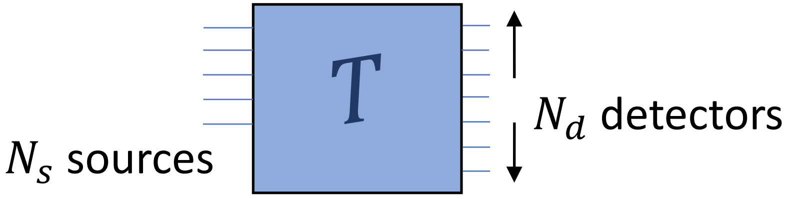


$$\bar{G}^{(cl)} = \frac{1}{\binom{M}{2}} \sum_{i<j}^{M} \frac{\langle I_i I_j \rangle}{\langle I_i \rangle \langle I_j \rangle}$$

Average correlations among all output pairs

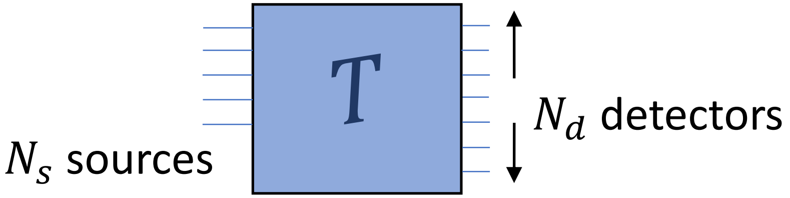
$$\mathbf{E}_\alpha(t) = \sum_\lambda \int d\omega \mathbf{g}_{\omega,\lambda} \mathrm{e}^{-i\omega t} \epsilon_{\omega,\lambda}$$

$$\mathbf{O}_i(t) = \sum_{\alpha=1}^{N} T_{i\alpha} \mathbf{E}_\alpha(t - \tau_{i\alpha})$$

Rigovacca *et al.*, PRL, **117**, 213602 (2016)

Multimode Extension

Hypotheses: Independent sources emit light pulses with random phases



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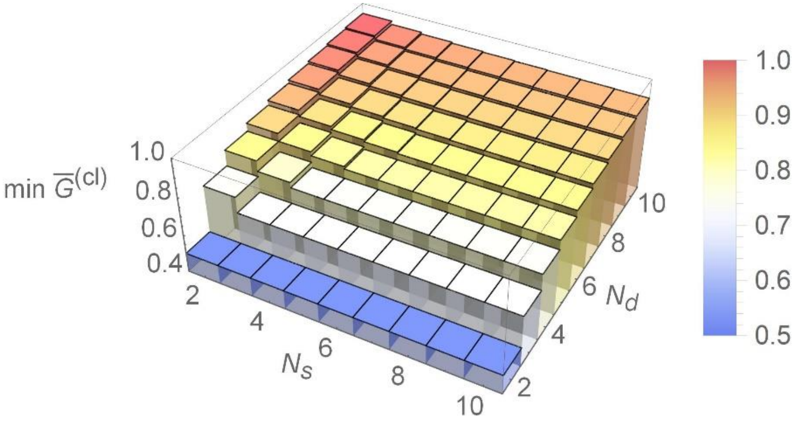
Average correlations among all output pairs

$\bar{G}^{(cl)}$ has a minimum for every N_d, N_s!



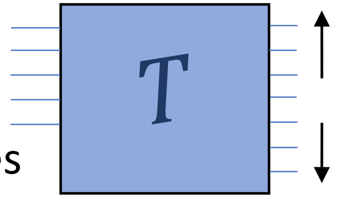
$$\min \bar{G}^{(cl)}_{N,M} = 1 - \frac{N-1}{N(M-1)} \text{ if } N \leq M$$

$$= 1 - \frac{1}{M} \text{ if } N \geq M$$

Rigovacca *et al.*, PRL, **117**, 213602 (2016)

Multimode Extension

Hypotheses: Independent sources emit light pulses with random phases



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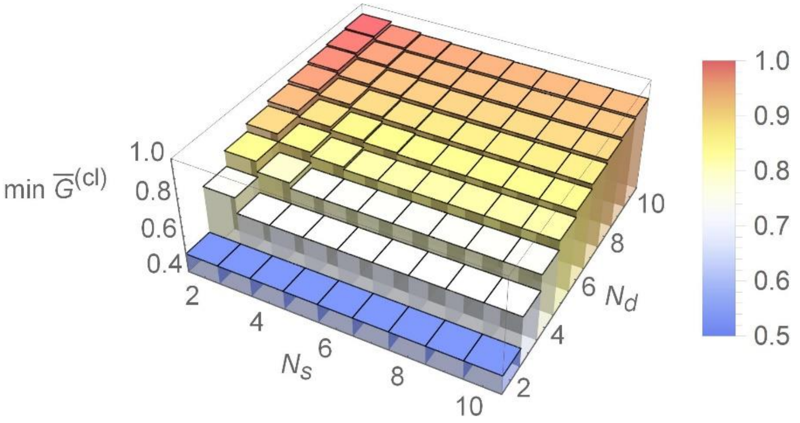


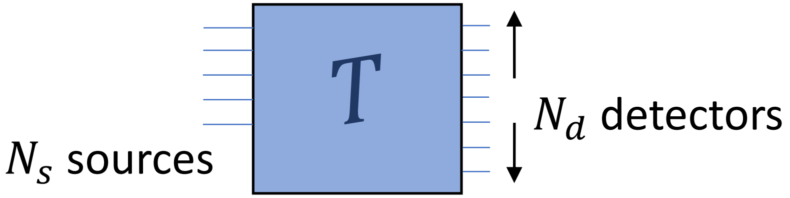
$$\min \bar{G}^{(Q)} = 1 - \frac{1+\eta}{M} \leq \min \bar{G}^{(cl)}$$

$$0 \leq \eta = -\frac{(\Delta n)^2 - \langle \hat{n} \rangle}{\langle \hat{n} \rangle^2} \leq 1$$

Rigovacca *et al.*, PRL, **117**, 213602 (2016)

Multimode Extension

<u>Hypotheses</u>: Independent sources emit light pulses with random phases



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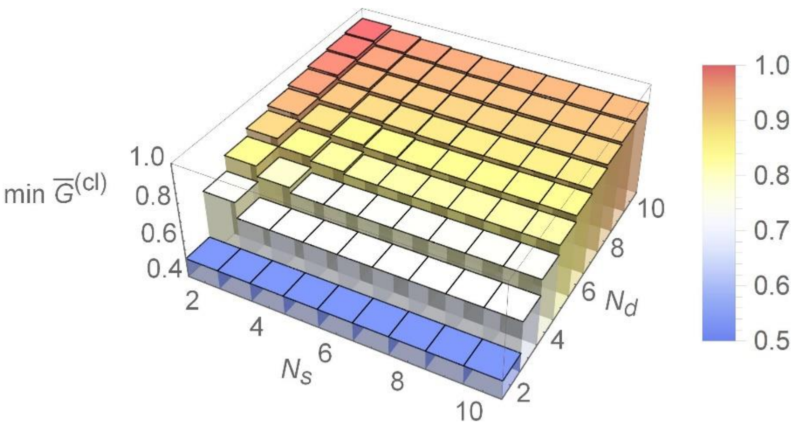


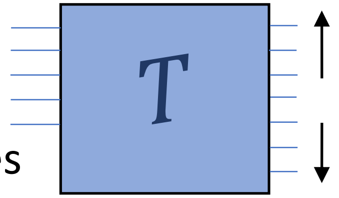
What happens with quantum input states?

- ✓ Classical threshold can be violated
- ✓ Necessity of sub-Poissonian light
- ✓ Optimality of single photons

Rigovacca *et al.*, PRL, **117**, 213602 (2016)

Multimode Extension

Hypotheses: Independent sources emit light pulses with random phases



$$\bar{G}^{(cl)} = \frac{1}{\binom{M}{2}} \sum_{i<j}^{M} \frac{\langle I_i I_j \rangle}{\langle I_i \rangle \langle I_j \rangle}$$

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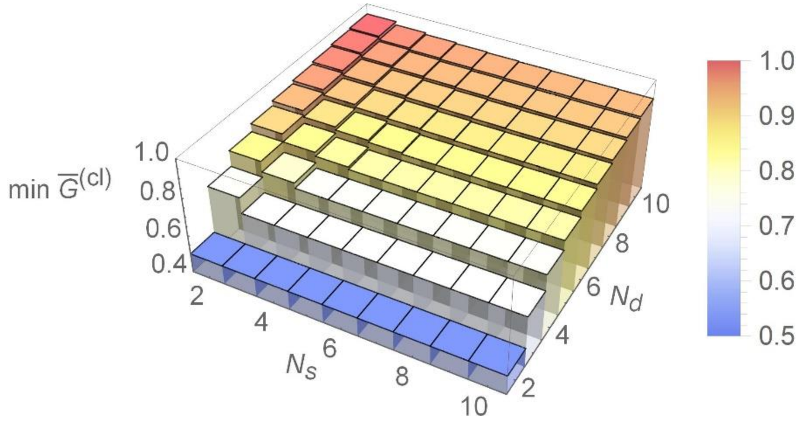

What happens with quantum input states?

- ✓ Classical threshold can be violated
- ✓ Necessity of sub-Poissonian light
- ✓ Optimality of single photons
- For identical input states, the gap shrinks with system dimensionality

Rigovacca *et al.*, PRL, **117**, 213602 (2016)

Remarks

Problem: detecting signatures of nonclassicality in a multiport linear optical interferometer

- Generalization of Hong-Ou-Mandel result
- Usefulness of low-order correlation functions
- Lower bound for classical intensity correlations
- Threshold violated with quantum states of light

Moreover:

Possibility of deducing information on sources/interferometer by the third-order correlation function

Thank you!

Rigovacca *et al.*, arXiv 1712.07259 (2017)

Rigovacca *et al.*, PRL, **117**, 213602 (2016)

Third-order correlation function

$$g_Q^{(3)} = \frac{\langle \hat{I}_1 \hat{I}_2 \hat{I}_3 \rangle}{\langle \hat{I}_1 \rangle \langle \hat{I}_2 \rangle \langle \hat{I}_3 \rangle}$$

$$g_Q^{(3)} = \frac{2}{9} + \frac{4}{9} r_{12} r_{23} r_{31} \cos\varphi - \frac{1}{9}(r_{12}^2 + r_{23}^2 + r_{31}^2)$$

$$\langle \phi_\alpha | \phi_\beta \rangle = r_{\alpha\beta} \mathrm{e}^{i\varphi_{\alpha\beta}}$$