Approaching maximal precision of Hong-Ou-Mandel interferometry with non-perfect visibility

Othmane Meskine[1], *Eloi* Descamps[1], *Arne* Keller[1,2], *Aristide* Lemaître[3], *Florent* Baboux[1], *Sara* Ducci[1,*] and *Pérola* Milman[1]

[1]Université Paris Cité, CNRS, Laboratoire Matériaux et Phénomènes Quantiques, 75013 Paris, France
[2]Département de Physique, Université Paris-Saclay, 91405 Orsay, France
[3]Université Paris-Saclay, CNRS, Centre de Nanosciences et de Nanotechnologies, 91120, Palaiseau, France

Abstract. This work explores precision limits in two-photon Hong-Ou-Mandel interferometry under non-perfect visibility. A theoretical model is developed and experimentally validated using different quantum states. A remarkable ratio of 0.97 between the experimental precision and the quantum limit is observed, establishing a new benchmark in the field.

1 Introduction

In quantum mechanics, the precision achieved in parameter estimation using a quantum state as a probe is determined by the measurement strategy employed. The quantum precision limit, a fundamental boundary, is defined by the intrinsic characteristics of the state and its dynamics. Theoretical results have revealed that in interference measurements with two possible outcomes, like the Hong-Ou-Mandel interference, this limit can be reached under ideal conditions of perfect visibility and zero losses [1]. However, in practice, this cannot be achieved, so precision never reaches the quantum limit. But how do experimental setups approach precision limits under realistic circumstances? In this work, we provide a general model for precision limits in two-photon Hong-Ou-Mandel interferometry for non-perfect visibility and validate it experimentally using different quantum states. We reveal the existence of an optimal scenario, where we observe a remarkable ratio of 0.97 between the experimental precision and the quantum limit, establishing a new benchmark in the field [2].

2 Main Text

2.1 Theoretical model

In a typical metrological protocol, a probe evolves dynamically depending on a parameter θ to be estimated, and its measurement outcome is used to estimate θ. Precision is bounded by the Cramer-Rao bound $\delta\theta \geq 1/\sqrt{NF(\theta)}$, where $F(\theta)$ is the Fisher information (FI) and N is the number of measurements. When using quantum resources, like individual photons in a Hong-Ou-Mandel (HOM) experiment, one can define the quantum Fisher information (QFI). In this case, precision is limited by the quantum Cramer Rao (QCR) $\delta\theta \geq 1/\sqrt{V\mathcal{F}}$, where $\mathcal{F}$ is the QFI. The QCR bound represents the quantum precision limit. Finding an experimental measurement strategy where $F(\theta) = \mathcal{F}$ is not straightforward.

In the HOM experiment, the QCR bound can be reached under perfect visibility. Attempts to reach this bound have led to remarkable precision in time delay τ estimations [3, 4]. The probe used is a biphoton state $|\psi\rangle = \iint d\omega_1 d\omega_2 f(\omega_1,\omega_2) a_1^\dagger(\omega_1) a_2^\dagger(\omega_2) |0\rangle$ where $f(\omega_1,\omega_2)$ is the joint spectral amplitude. We model the dependency of the coincidence probability $P_c(\tau)$ with the HOM visibility as:

$$P_c(\tau) = \frac{1}{2} - \frac{V}{2} W(0,\tau) \tag{1}$$

where $W(0,\tau)$ is the Wigner function associated with the function $f_-(\omega_-)$, defined by : $f(\omega_1,\omega_2) = f_-(\omega_-) f_+(\omega_+)$, with $\omega_\pm = \omega_1 \pm \omega_2$. The FI is then given by:

$$F(V,\tau) = V^2 \frac{(W'(0,\tau))^2}{1 - V^2 W^2(0,\tau)} \tag{2}$$

In this work, we are interested in understanding how $\tilde{F}_V = \max_\tau F(V,\tau)$ approaches $\mathcal{F}$ as a function of the visibility V for different quantum states. Eq.2 allows us to identify a relation with the effective phase space occupation of the state's Wigner function: indeed, the scaling of $\tilde{F}_V$ with V is connected to how far the quantum state is from saturating the time-frequency Heisenberg uncertainty principle. For this reason, while Gaussian states minimize the FI's scaling with visibility, states with large effective areas in time frequency phase space, like Schrödinger cat (SC)-like states, maximize it, making them remarkably robust in HOM-based quantum metrology.

2.2 Experimental demonstration

We validate our model by implementing a HOM interferometer using two-photon states described by various

---

[*] e-mail: sara.ducci@u-paris.fr

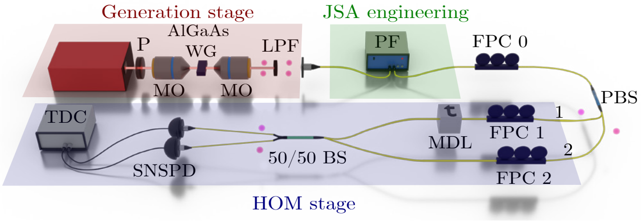

Figure 1. Experimental setup for investigating the metrological performance of the Hong-Ou-Mandel (HOM) experiment.

functions $f_{-}(\omega_{-})$, demonstrating different scaling behaviors with visibility V (Fig. 1). An AlGaAs Bragg reflection waveguide [5] is used to generate polarization-entangled photon pairs via type II Spontaneous Parametric Down-Conversion (SPDC) at telecom wavelengths. The joint spectral amplitude (JSA) is engineered by postmanipulation through a programmable filter. Our study includes three different filter shapes: a rectangular filter, a Gaussian filter, and a combination of two rectangular filters corresponding to energy-matched channels, allowing the engineering of a Schrodinger Cat (SC)-like state. Photon pairs, leaving the filter, are separated by a polarizing beam splitter (PBS) and enter the HOM interferometer. Control over polarization distinguishability and temporal delay is done with fibered polarization controllers (FPS) and a motorized optical delay line (MDL), respectively. Photons are recombined at a 50/50 beam splitter (BS) and detected by superconducting nanowires single photon detectors (SNSPD), with temporal correlations analyzed by a time-to-digital converter (TDC).

The experimental results (points) are reported in (Fig2), together with the theoretical prediction (lines). Remarkably high visibilities exceeding 99% are achieved with all the engineered states. The SC-like state exhibits the most favorable scaling behavior, while the Gaussian state displays a less optimal one. For a visibility value of about 99.4%, the ratio drops from 0.97 for the SC-like state to 0.85 for the Gaussian state, demonstrating the effectiveness of our model across different state configurations.

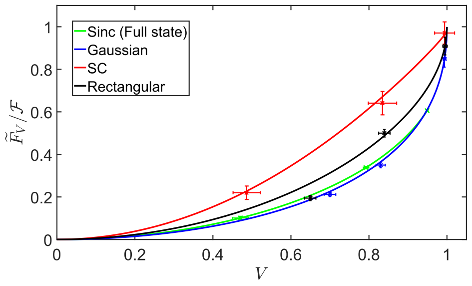

Figure 2. Scaling of the ratio $\tilde{F}_V/\mathcal{F}$ for different biphoton states with respect to the HOM interferogram visibility V.

References

[1] E. Descamps et al., "Time-frequency metrology with two single-photon states: Phase-space picture and the Hong-Ou-Mandel interferometer", *Phys. Rev. A 108, 013707* (2023)

[2] O. Meskine, E. Descamps et al. "Fundamental limitations of time measurement precision in Hong-Ou-Mandel interferometry", arxiv:2309.10633 (2023),

[3] A. Lyons et al. , "Attosecond-resolution Hong-Ou-Mandel interferometry" *Science Advances* 4, aap9416(2018)

[4] Y. Chen et al., "Hong-Ou-Mandel interferometry on a biphoton beat note", *npj Quant Inf* 5, 43 (2019).

[5] F. Appas et al., "Nonlinear Quantum Photonics With AlGaAs Bragg-Reflection Waveguides," *J. Lightwave Technol.* 40, 7658-7667 (2022),