<u>Project title:</u> Taking photos of quantum entanglement.

<u>Context:</u> Quantum entanglement is a central resource in quantum computing and communication. Currently, the workhorse of most implementations is entanglement between qubits i.e. two-dimensional quantum systems, such as photon polarization. However, it is known that quantum systems entangled in higher dimensions offer some advantages compared to qubits, such as a higher information capacity and increased noise resistance, which is particularly interesting for real-world applications [1].

In photonics, high-dimensional entangled states are easily created by producing pairs of photons via spontaneous parametric down conversion (SPDC). In such a process, conservation of momentum and energy imply that the two photons are generated in a coherent superposition of different momenta and energies. Considering for example the transverse spatial degree of freedom, the state $|\psi\rangle = \sum_{k=-\infty}^{\infty} \lambda_i |k, -k\rangle$ is an example of a (pure) two-photon state entangled in high dimensions, expressed in the k-basis (where k is the transverse momentum) [2]. Similar high-dimensional entangled state can also be produced harnessing the spectral degree of freedom [3].

Producing optical high-dimensional entangled states is thus a well-established process. However, several challenges remain before they can be used in applications. Among them, **the certification and quantification of entanglement in many dimensions is a crucial one**. Indeed, full-state tomography for bipartite system of local dimension d requires measurement in $(d+1)^2$ global product bases, which becomes quickly impractical in high dimensions. To mitigate this issue, many previous works used assumptions about the underlying quantum state, such as the purity of the state or perfect correlations [4]. However, this does not allow for unambiguous certification, which is crucial for real-world applications.

<u>Objective:</u> In this doctoral project, the student will investigate the problem of the certification of high-dimensional entanglement in photonics system. Specifically, they will develop experimental and theoretical approaches to certify high-dimensional spatial entanglement of unknown quantum states in an efficient (fast) and reliable (no assumptions) way. Tackling this challenge is a necessary step before any practical quantum information processing protocols based on high-dimensional entangled states can be developed.

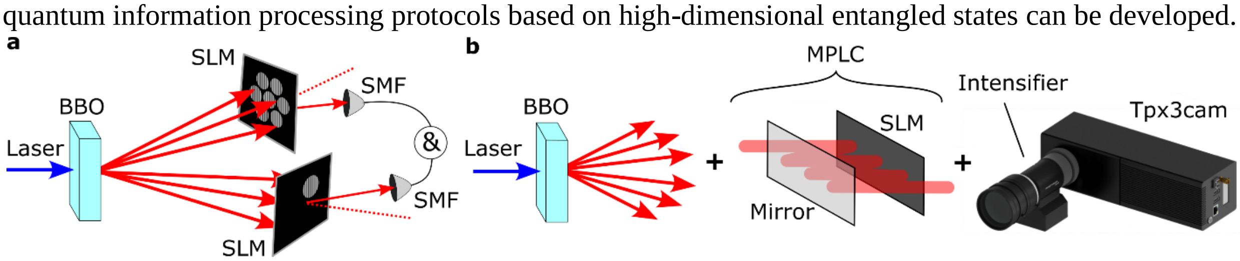

Figure 1. a. *Single-outcome measurement technique. Two spatial light modulators (SLM) inject specific spatial modes into single mode fibers (SMF) connected to single-photon detectors and a coincidence counter (&).* ***b.*** *In our project, coincidences are detected between all pixel pairs of an i-Tpx3cam camera after choosing the measurement basis with a multi-plane light converter (MPLC). High-dimensional entanglement is produced by SPDC in a Beta Barium Borate (BBO) crystal illuminated by a blue diode laser.*

<u>Scientific approach:</u> <u>Generation:</u> To generate high-dimensional spatial entanglement, the student will produce photon pairs by SPDC using a BBO crystal and a blue laser, an established expertise in our team.

<u>Detection:</u> The state-of-the-art experimental technique to measure high-dimensional spatial entanglement consists in analyzing the quantum state sequentially using so-called *single-outcome projective measurements* [5] (Fig.1.a). This method enables to detect photon coincidences in different spatial bases whose results can violate some separability criteria established in theory [6]. However, it has two major drawbacks. First, it is time-consuming. In the case of a bipartite state with local dimension d, it requires performing at least $2d^2$ consecutive measurements, making this task impractical in high dimensions. Second, it necessarily leaves the fair-sampling loophole open. Indeed, for the latter to be closed, one must ensure that all possible output states are measured simultaneously. Such a flaw would not be acceptable in an adversarial scenario, such as quantum key distribution, as it would compromise the protocol security.

In this project, the student will use a radically different technique for measuring high-dimensional entanglement, based on a recently developed camera technology: an intensified(i)-Tpx3cam camera [7] (Fig.1.b). In theory, using a camera for such a task has the advantage of collecting all the output spatial modes and the potential to operate much faster than single-outcome measurement since all modes are detected in parallel. In practice, however, certification of high-dimensional entanglement has never been achieved using a camera without making strong assumptions about the detected quantum state. Camera technologies used for these attempts included EMCCD, SPAD array and i-CMOS [8]. The two reasons for this failure are (i) the poor quality of photon coincidence detection performed by these camera technologies (noise, artifacts, …), and (ii) the absence of accurate entanglement certification protocols adapted to camera detection. These problems will be solved gradually during the thesis, with three intermediate objectives:

<u>Goal 1 (0-1st year): Improving coincidence measurement with an i-Tpx3cam camera.</u> To improve the quality of photon coincidence detection, the student will use this new camera (Fig.1.b) and rely on the expertise of our team in this field. The Tpx3Cam is an event-driven camera with 256×256 pixels, which time-stamps the single photons continuously with a time resolution of 2ns [7]. We tested this camera in our lab last summer and it showed promising performances [9]. The first goal will be to build a photon-pair coincidence measurement experiment using this camera, optimize it and compare its performances to other technologies. We will be helped by our collaborator Prof.A.Nomerotski (USA), who is an expert of this camera.

<u>Goal 2 (1st-2nd year): Developing experimental protocols to certify entanglement.</u> Almost all high-dimensional entanglement certification protocols have been developed to be implementable with single-outcome measurement technique. In particular, a central point is to have an experimental access to several measurement bases, such as MUBs [6], which is very difficult when using a camera and conventional optics (lenses, mirrors). The second goal will be to develop an experimental method to perform such a change of spatial basis. Based on the team expertise in wavefront shaping, we plan to achieve that by developing a multi-plane-light-converter with a spatial light modulator. Then, the certification protocols will be adapted to this new architecture, in collaboration with theorists from the group of Markus Hubert in Vienna.

<u>Goal 3 (2st-3nd year): Robustness to noise.</u> Once the system will be operational, it will be interesting to carefully assess its performance in term of noise resistance. For this, it will probably be necessary to develop theoretical and experimental models to simulate the noise. For example, one can imagine the noise source to be some ambient light falling on the camera, and then determine the level of 'noise' to which the entanglement can still be certified. This last goal will be more exploratory.

<u>Potential impact:</u> Having a fast and reliable approach to certify high-dimensional entanglement can be a game changer for the emerging field of high-dimensional quantum information processing. Based on preliminary results [9], we believe we can certify more than 500 dimensions of entanglement in just a few minutes without assumptions, while the fastest single-outcome measurement technique so far requires about 3 hours of acquisition for 55 certified dimensions [10]. We would then make an important step towards the practical deployment of applications based on high-dimensional entanglement. In the longer term, we could consider developing a high-dimensional quantum key distribution system using this detection technology.

<u>Suitability to the initiative and institute:</u> The project fits perfectly into the Doctoral Program Initiative in quantum information launched by the Sorbonne Quantum Information Center. Indeed, it has potential for impact in the broad field of quantum information processing, especially for quantum cryptography. It involves developments related to the physics of high-dimensional entangled states (theoretical and experimental) but has also an important computational dimension since advanced data processing algorithms will have to be developed for detecting coincidences and measuring entanglement with the camera. In addition, this project will enrich the scope of research of the institute, since the study of high-dimensional entangled states in the discrete variable regime is not explored there (to my knowledge). In return, it will also strongly benefit from the expertise of other researchers, especially from those exploring multimode quantum optics in the continuous variable regime (e.g. N.Treps and E.Diamanti groups).

<u>Research environment:</u> The student will join a dynamic research team led by H. Defienne in the Paris Institute of Nanoscience (INSP). It is currently composed of 2 PhD students. Lab and office space will be provided to the student upon arrival. Note that, even if H. Defienne has recently received an ERC starting grant on quantum imaging, the proposed project is out of its scope and cannot be funded on it.

<u>References:</u> [1] *Nat.Rev.Phys., 2*(7), 365-381. (2020) [2] *Physics Reports* **495**, 87–139 (2010) [3] *Physical review letters, 120*(5), 053601 (2018) [4] *Nature* 546(7660), 622–626 (2017) [5] *Nature* 412(6844), 313–316 (2001) [6] *Nat.Phys.14*(10), 1032-1037 (2018) [7] *Nuclear Instruments and Methods in Physics Research Section A. 937*, 26-30 (2019) *[8]* Nat.Com. 3(1), 984 (2012), *npj Quant. Info., 6*(1), 94 (2020), Optica 4, 272-275 (2017). [9] *arXiv:2302.03756* (2023) [10] *Quantum, 4*, 376 (2020)