Control of spatial correlations: Experimental implementation and its role on open quantum system dynamics and two-photon imaging

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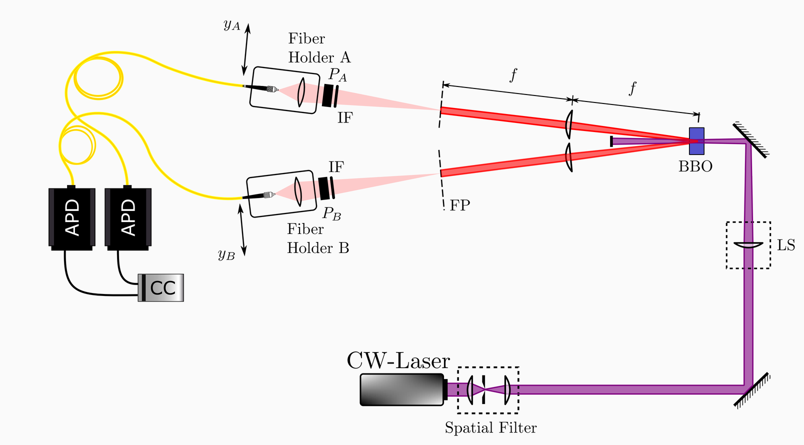
Introduction

The control of correlations of paired photons in different degrees of freedom has been of interest for its role in practical applications. In this work, we report the experimental control of the spatial correlations of paired photons and exploit this capability to study the effects of having different spatial correlations on open quantum systems and imaging procedures:

- **Experimentally**, we control the spatial correlations of paired photons produced by spontaneous parametric down conversion (SPDC) by using the waist of the pump beam as the tuning parameter.
- **Two-photon imaging:** we take advantage of the experimental capability of controlling the spatial correlations in a unique setup and observe the effects of different types of spatial correlations on ghost images.
- **Open quantum system dynamics:** we propose an all-optical setup in which a pair of entangled polarization photons is coupled with their transverse momentum degree of freedom, that plays the role of a bosonic environment, to simulate an open quantum system dynamic. We have found that controlling the initial transverse correlations, the evolution of the central system can exhibit a Markovian or non-Markovian behaviour.

The Source: Type II Non-colinear SPDC



- **The state at the output face of the crystal**

$$|\psi\rangle \propto \sum_{\sigma\neq\sigma'}\int d\mathbf{q}_s d\mathbf{q}_i \int d\Omega_s d\Omega_i \times \Phi_{\sigma\sigma'}(\mathbf{q}_s,\Omega_s,\mathbf{q}_i,\Omega_i)\,|\mathbf{q}_s,\Omega_s;\sigma'\rangle\,|\mathbf{q}_i,\Omega_i;\sigma'\rangle$$

with polarizations $\sigma,\sigma'=\{H,V\}$.

- **Mode function**

$$\Phi_{\sigma\sigma'}(\mathbf{q}_s,\Omega_s,\mathbf{q}_i,\Omega_i)=\mathcal{N}\beta(\Omega_s,\Omega_i)\times \exp\left[-\frac{\mathrm{w}_p^2(\Delta_0^2+\Delta_1^2)}{4}-\gamma\left(\frac{\Delta_k L}{2}\right)^2+i\frac{\Delta_k L}{2}\right]$$

- **Phase matching conditions**

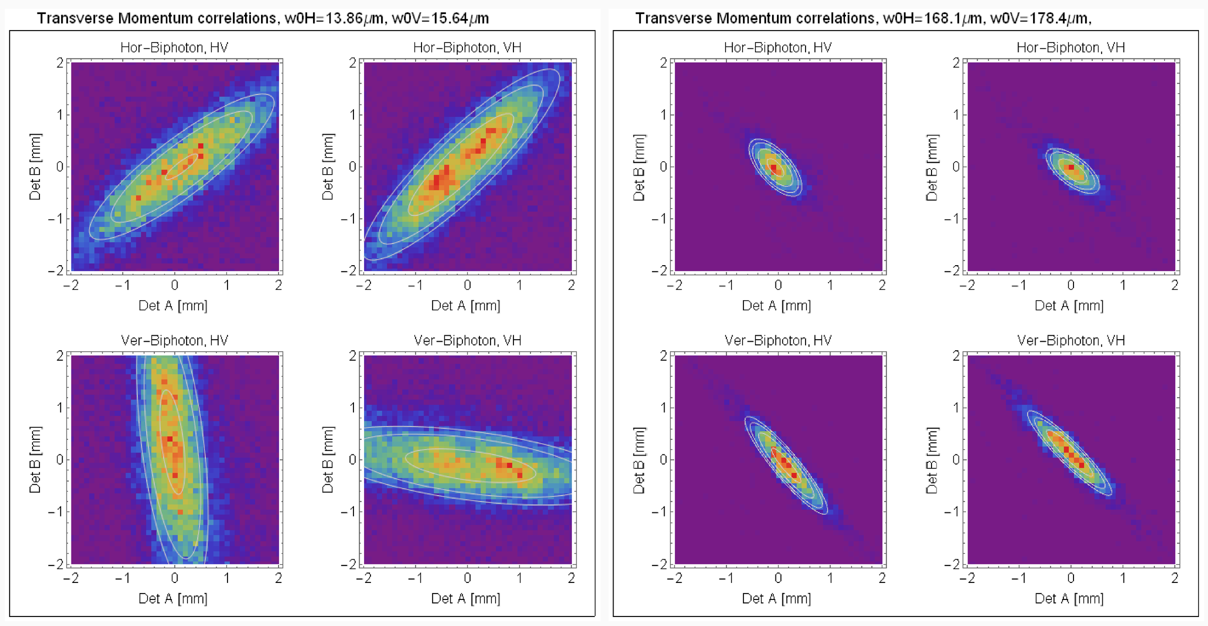
$$\begin{aligned}\Delta_0 &= q_s^x+q_i^x,\\ \Delta_1 &= q_s^y\cos\phi_s+q_i^y\cos\phi_i\\ &\quad -N_s\Omega_s\sin\phi_s+N_i\Omega_i\sin\phi_i-\rho_s q_s^x\sin\phi_s,\\ \Delta_k &= N_p(\Omega_s+\Omega_s)-N_s\Omega_s\cos\phi_s-N_i\Omega_i\cos\phi_i\\ &\quad -q_s^y\sin\phi_s+q_i^y\sin\phi_i+\rho_p\Delta_0-\rho_s q_s^x\cos\phi_e.\end{aligned}$$

- **Spatial-Type-II-SPDC quantum state**

$$|\Psi\rangle \propto \sum_{\sigma\neq\sigma'}\int d\mathbf{q}_s\int d\mathbf{q}_i\;\tilde{\Phi}_{\sigma\sigma'}(\mathbf{q}_s,\mathbf{q}_i)\,|\mathbf{q}_s;\sigma\rangle\,|\mathbf{q}_i;\sigma'\rangle\,,$$

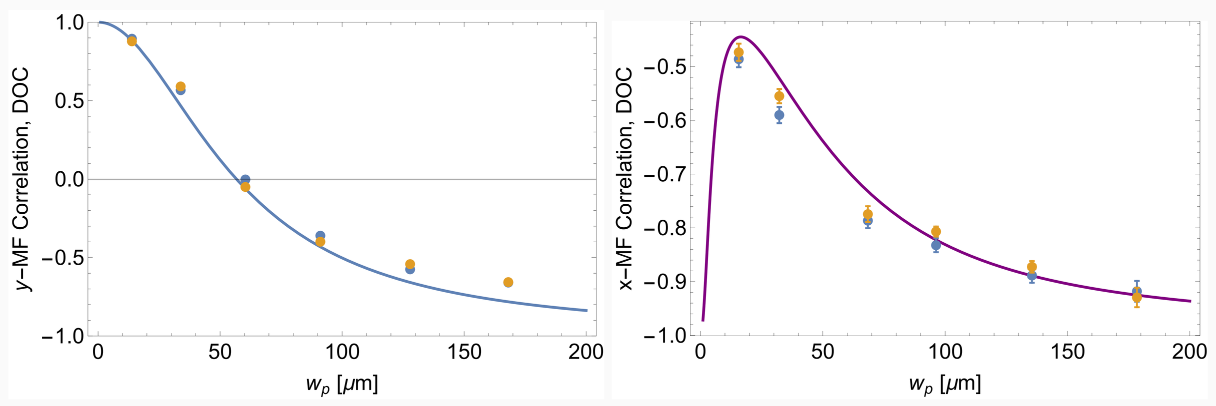
$$\begin{aligned}\tilde{\Phi}_{\sigma\sigma'}(\mathbf{q}_s,\mathbf{q}_i) &= \int d\Omega_s d\Omega_i f_s(\Omega_s)f_i(\Omega_i)\Phi_{\sigma\sigma'}(\mathbf{q}_s,\Omega_s,\mathbf{q}_i,\Omega_i)\\ &= \mathcal{N}\exp\left[-\frac{1}{4}\mathbf{q}^\intercal\mathcal{A}\mathbf{q}+i\mathbf{b}^\intercal\cdot\mathbf{q}\right]\end{aligned}$$

Mode Function and Correlation control

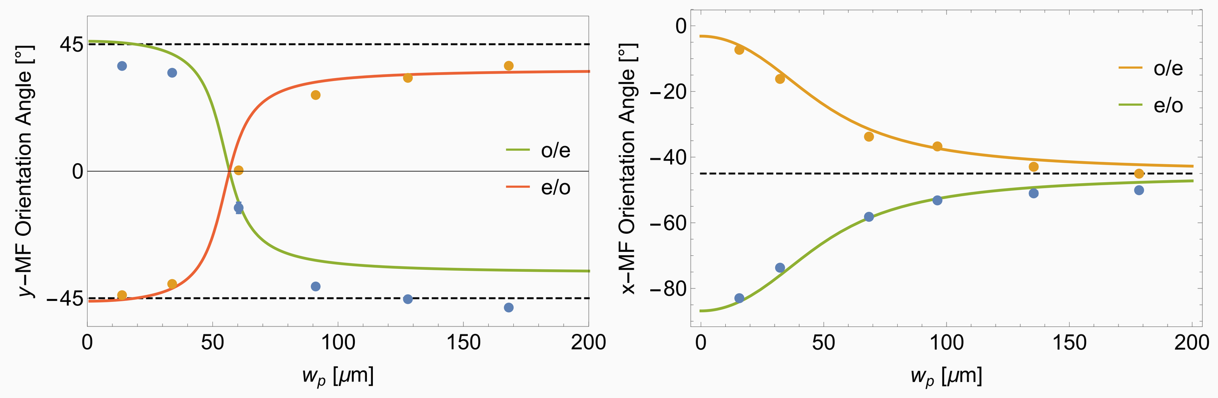


- **Degree of correlation:**

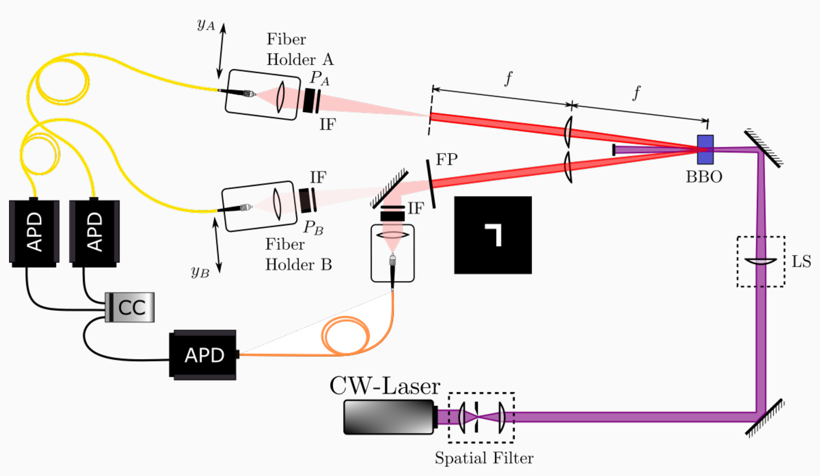
$$\kappa^\varrho=\frac{C_{si}^\varrho}{\sqrt{C_{ss}^\varrho C_{ii}^\varrho}},\qquad C_{uv}^\varrho=\langle q_u^\varrho q_v^\varrho\rangle-\langle q_u^\varrho\rangle\langle q_v^\varrho\rangle\,,\qquad(\varrho=x,y)$$



- **Mode function orientation:** The angle between the major axis of the biphoton ellipse and the corresponding horizontal axis.



Lens-less Ghost Imaging



- **Propagated MF**

$$\tilde{\Phi}_{\sigma\sigma'}(\boldsymbol{\rho}_A,\boldsymbol{\rho}_B)=\int d^2\mathbf{q}_s\int d^2\mathbf{q}_i\;\; g_s(\mathbf{q}_s,\boldsymbol{\rho}_A,z_A)g_i(\mathbf{q}_i,\boldsymbol{\rho}_B,z_B)\tilde{\Phi}_{\sigma\sigma'}(\mathbf{q}_s,\mathbf{q}_i),$$

with the Green function for a $2f$-system

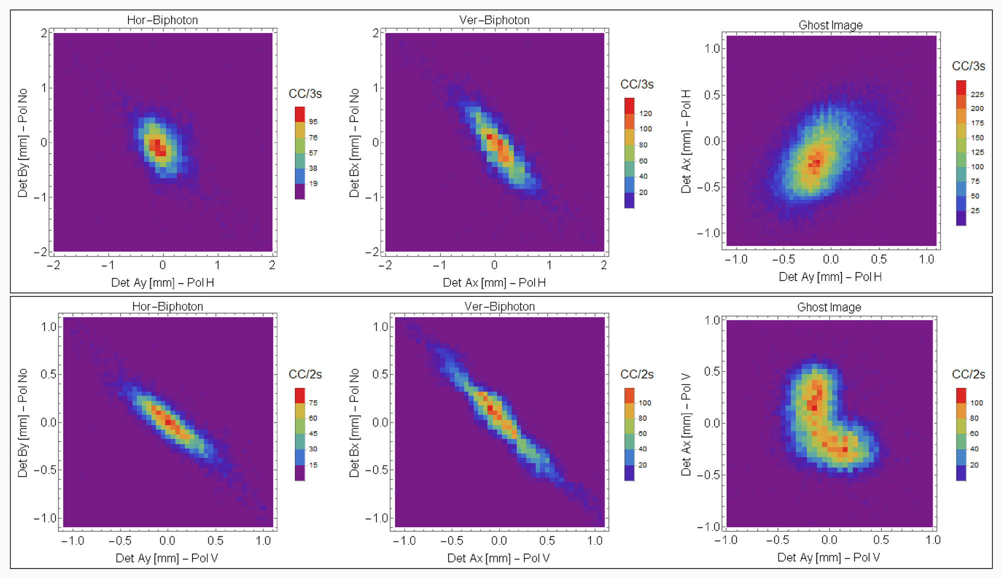
$$\begin{aligned}g_\nu(\mathbf{q}_\mu,\boldsymbol{\rho}_j,2f) &= \int d^2\boldsymbol{\rho}_\ell\int d^2\boldsymbol{\rho}_c h_\omega(\boldsymbol{\rho}_j-\boldsymbol{\rho}_\ell,f)L_f(\boldsymbol{\rho}_\ell)h_\omega(\boldsymbol{\rho}_\ell-\boldsymbol{\rho}_c,f)e^{i\mathbf{q}_\mu\cdot\boldsymbol{\rho}_c}\\ &= \mathcal{C}e^{\frac{i\pi}{\lambda f}\rho_j^2}e^{-\frac{i\lambda f}{4\pi}q_\mu^2}\delta\left(\mathbf{q}_\mu-\frac{2\pi}{\lambda f}\boldsymbol{\rho}_j\right),\end{aligned}$$

that propagates the SPDC photons with a transverse momentum $\mathbf{q}_\mu$ from the source to a plane located at a distance $2f$.

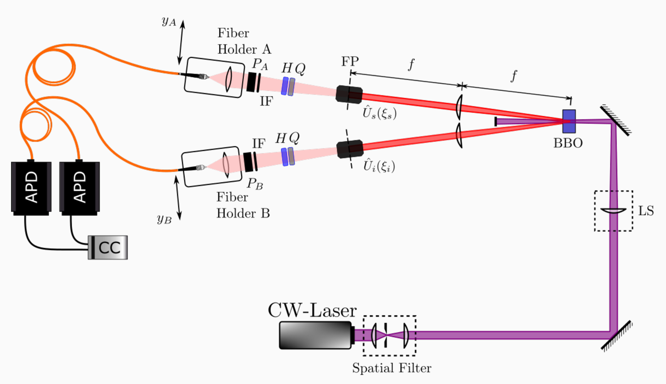
- **The Ghost Image**

$$\mathcal{GI}_{\sigma\sigma'}(\boldsymbol{\rho}_A)\propto\left|\int d^2\boldsymbol{\rho}_B T(\boldsymbol{\rho}_B)\tilde{\Phi}_{\sigma\sigma'}\left(\frac{2\pi}{\lambda f}\boldsymbol{\rho}_A,\frac{2\pi}{\lambda f}\boldsymbol{\rho}_B\right)\right|^2.$$

where $T(\boldsymbol{\rho})$ denotes the transfer function for the object to be imaged.



Quantum Dynamic - Markovian vs non-Markovian



- **Horizontal Biphoton as an initial system-environment state:** Considering $\tilde{\Phi}_{\sigma\sigma'}(q_s^y,q_i^y)=\tilde{\Phi}_{\sigma\sigma'}(q_s^x=0,q_s^y,q_i^x=0,q_i^y)$, the SPDC state reduces to

$$\begin{aligned}|\Psi\rangle &\propto \sum_{\sigma\neq\sigma'}\int dq_s^y\int dq_i^y\;\tilde{\Phi}_{\sigma\sigma'}(q_s^y,q_i^y)\,|q_s^y;\sigma\rangle\,|q_i^y;\sigma'\rangle\\ &\equiv |\Psi\rangle_{S+E}=|\Psi_{\mathrm{in}}\rangle\,,\end{aligned}$$

where

$$\tilde{\Phi}_{VH}(q_s^y,q_i^y)=\mathcal{N}\exp\left[-(\mathbf{q}^y)^\intercal\mathcal{B}\mathbf{q}^y+i\mathbf{v}^\intercal\cdot\mathbf{q}^y\right]\text{ and }\tilde{\Phi}_{HV}(q_s^y,q_i^y)=\tilde{\Phi}_{VH}(q_i^y,q_s^y).$$

- **Local Evolution operator**: $\hat{U}(\xi_s,\xi_i)=\hat{U}_s(\xi_s)\otimes\hat{U}_i(\xi_i)$, with

$$\begin{aligned}\hat{U}_\ell(\xi_\ell)\,|q_\ell^y;H\rangle &= e^{-i\xi_\ell q_\ell^y}\,|q_\ell^y;H\rangle\\ \hat{U}_\ell(\xi_\ell)\,|q_\ell^y;V\rangle &= e^{i(\xi_\ell q_\ell^y+\varphi)}\,|q_\ell^y;V\rangle\end{aligned}$$

where $\ell=\{s,i\}$, ξ_ℓ is the evolution parameter for each mode, and φ is a constant polarization-dependent phase-shift.

- **Reduced polarization density matrix:**

$$\begin{aligned}\hat{\rho}_S &= \mathrm{tr}_E\left\{\hat{U}(\xi_s,\xi_i)\,|\Psi_{\mathrm{in}}\rangle\langle\Psi_{\mathrm{in}}|\,\hat{U}^\dagger(\xi_s,\xi_i)\right\}\\ &= |\alpha|^2\,|V,H\rangle\langle V,H|+\Lambda(\xi_s,\xi_i)\,|V,H\rangle\langle H,V|\\ &\quad +\Lambda^*(\xi_s,\xi_i)\,|H,V\rangle\langle V,H|+|\beta|^2\,|H,V\rangle\langle H,V|\end{aligned}$$

with $|\alpha|^2+|\beta|^2=1$, and

$$\Lambda(\xi_s,\xi_i;\mathrm{w}_p)=\int dq_s^y dq_i^y\tilde{\Phi}_{VH}(q_s^y,q_i^y;\mathrm{w}_p)\tilde{\Phi}_{HV}^*(q_s^y,q_i^y;\mathrm{w}_p)e^{-2i\left(\xi_i q_i^y-\xi_s q_s^y\right)}$$

being the decoherence factor.

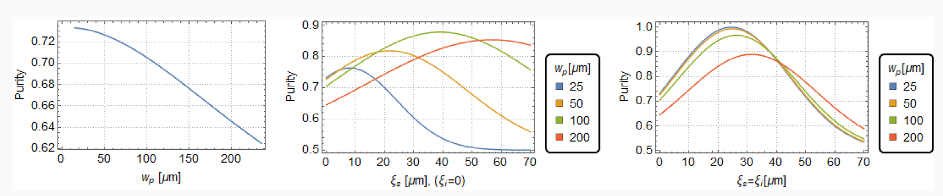
- **Purity evolution:**

$$\mathcal{P}(\xi_s,\xi_i;\mathrm{w}_p)=\frac{1}{2}+2|\Lambda(\xi_s,\xi_i;\mathrm{w}_p)|^2$$

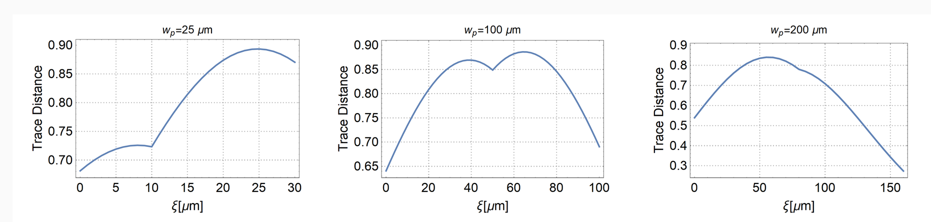
- **Trace distance:** For two initial states $\hat{\rho}_{S\pm}$ the trace distance evolves as

$$D(\xi_s,\xi_i;\mathrm{w}_p)=2|\Lambda(\xi_s,\xi_i;\mathrm{w}_p)|\cos\left(\arg\Lambda(\xi_s,\xi_i;\mathrm{w}_p)\right)$$

- **Purity and Purification**



- **Trace distance evolution:**



Final Remarks

- We have experimentally showed how DOC and orientation of MF exhibit different behaviors depending on the pump beam waist and the direction in which the correlation is been studied. The momentum distribution is also affected by the polarization post-selection.
- ALGO SOBRE GHOST
- By controlling the initial correlations, the evolution of the central system can exhibit a Markovian or non-Markovian behaviour, inducing a non-local quantum memory effect that allows to recover the purity (and entanglement) in the central system when this has been degraded by local interactions.

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