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

Omar Calderón-Losada, Paul Diaz, Juan A. Urrea, Daniel F. Urrego and Alejandra Valencia

Laboratorio de óptica cuántica, Universidad de los Andes, Bogotá, Colombia

Universidad de los Andes Colombia

Quantum Optics IX

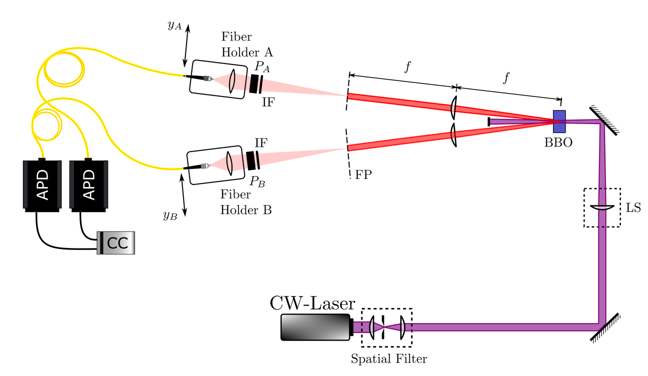
Email: o.calderon31@uniandes.edu.co
Webpage: http://opticacuantica.uniandes.edu.co

Introduction

The control of correlations of paired photons in different degrees of freedom has been of interest for practical applications. In this work, we report the experimental control of the spatial correlations of paired photons and discuss how to 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 to 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, which plays the role of a bosonic environment, to simulate an open quantum system dynamic.

The Source: Type II Non-colinear SPDC



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

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

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

- **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**

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

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

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

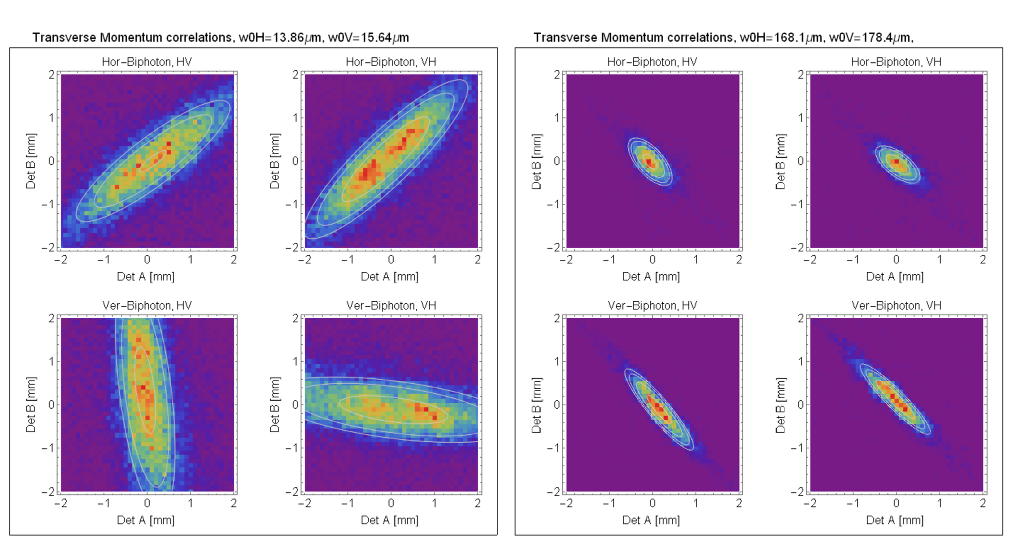
$$\tilde{\Phi}_{\sigma\sigma'}(\mathbf{q}_s,\mathbf{q}_i) = \int d\Omega_s d\Omega_i f_s(\Omega_s) f_i(\Omega_i)\Phi_{\sigma\sigma'}(\mathbf{q}_s,\Omega_s,\mathbf{q}_i,\Omega_i) = \mathcal{N}\exp\left[-\frac{1}{4}\mathbf{q}^\intercal\mathcal{A}\mathbf{q} + i\mathbf{b}^\intercal\cdot\mathbf{q}\right]$$

with $\mathbf{q} = (q_s^x, q_s^y, q_i^x, q_i^y)$, $\mathcal{A}$ is a 4×4 real-valued, symmetric matrix and $\mathbf{b}$ a 4-dimensional vector. Besides, $\tilde{\Phi}_{VH}(\mathbf{q}_s,\mathbf{q}_i) = \tilde{\Phi}_{HV}(\mathbf{q}_i,\mathbf{q}_s)$.

- **Rate of Coincidences:**

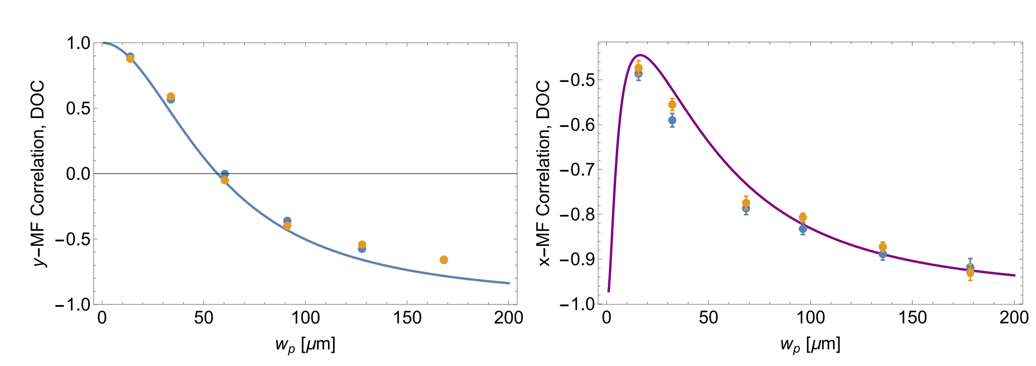
$$S_{\sigma\sigma'}(\mathbf{q}_s,\mathbf{q}_i) = |\tilde{\Phi}_{\sigma\sigma'}(\mathbf{q}_s,\mathbf{q}_i)|^2$$

Mode Function and Correlation control

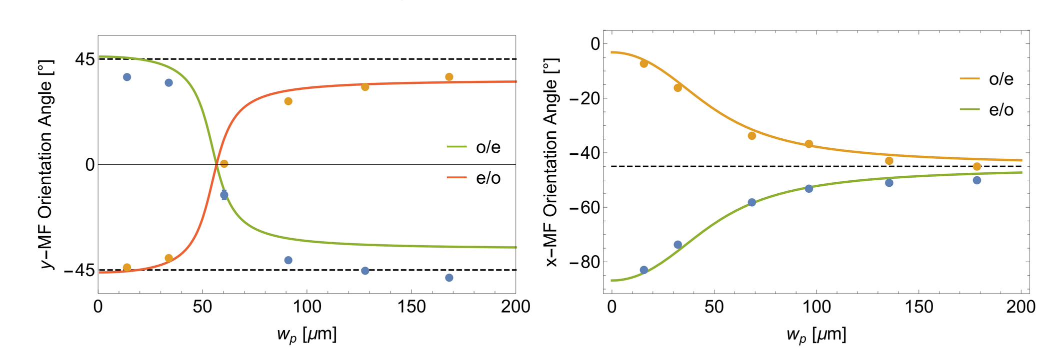


- **Degree of correlation:**

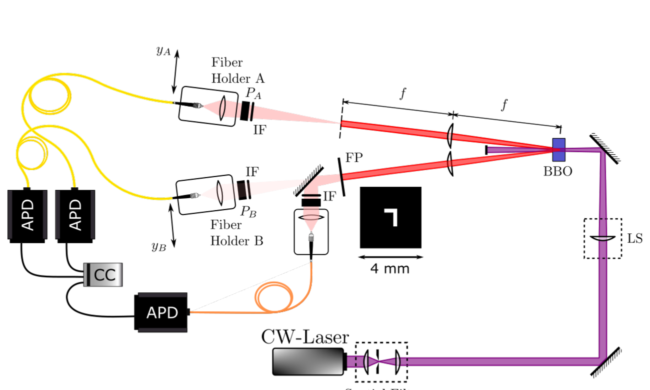
$$\kappa^\varrho = \frac{C_{si}^\varrho}{\sqrt{C_{ss}^\varrho C_{ii}^\varrho}},\qquad C_{uv}^\varrho = \langle q_u^\varrho q_v^\varrho\rangle - \langle q_u^\varrho\rangle\langle q_v^\varrho\rangle\,,\qquad (\varrho = x,y)$$



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



Ghost Imaging with tunable momentum correlation



- **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

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

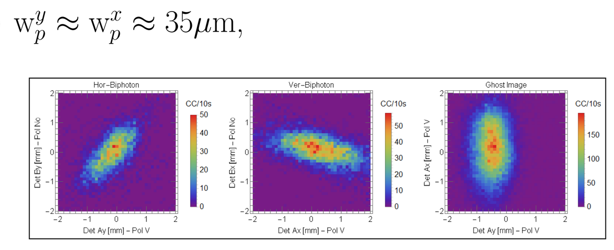
that propagates the SPDC photons with a transverse momentum $\mathbf{q}_\mu$ from the source to a plane located at a distance $2f$.

- **The Ghost Image**

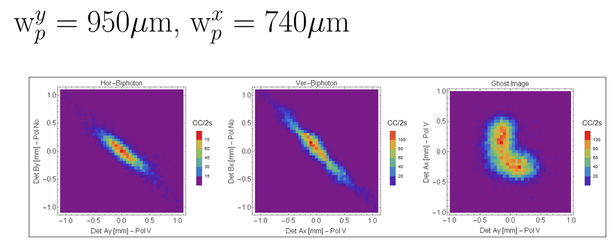
$$\mathcal{GI}_{\sigma\sigma'}(\boldsymbol{\rho}_A) \propto \int d^2\boldsymbol{\rho}_B\left|T(\boldsymbol{\rho}_B)\tilde{\Phi}_{\sigma\sigma'}\left(\frac{2\pi}{\lambda f}\boldsymbol{\rho}_A,\frac{2\pi}{\lambda f}\boldsymbol{\rho}_B\right)\right|^2.$$

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

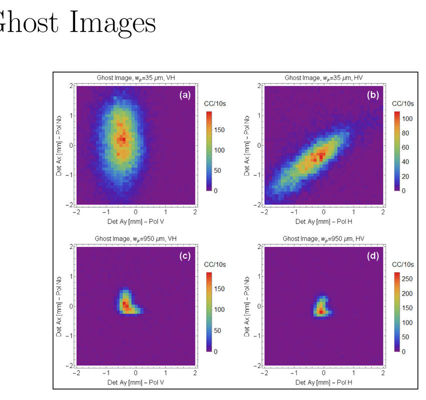
- $\mathrm{w}_p^y \approx \mathrm{w}_p^x \approx 35\mu$m,



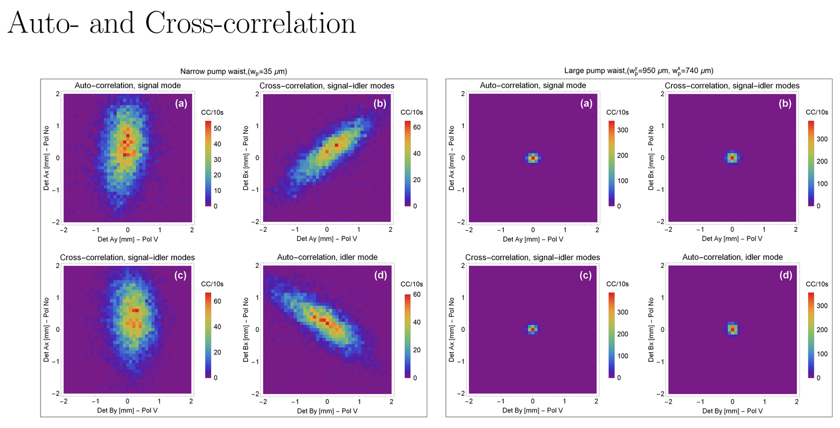
- $\mathrm{w}_p^y = 950\mu$m, $\mathrm{w}_p^x = 740\mu$m



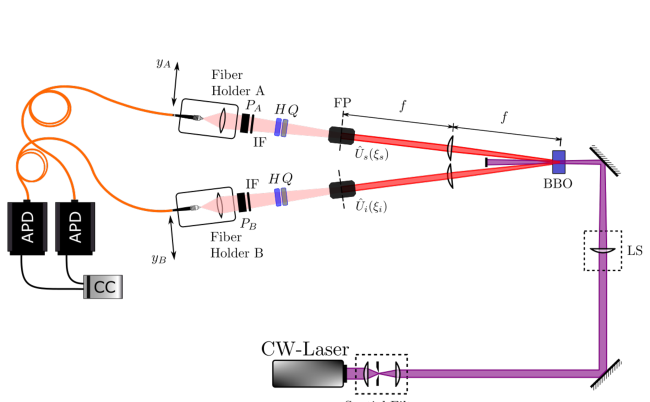
- Experimental Ghost Images



- Auto- and Cross-correlation



Quantum Dynamic - Markovian vs non-Markovian



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

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

where

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

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

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

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:**

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

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.

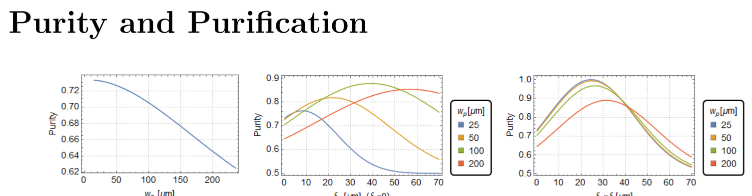
- **Purity evolution:**

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

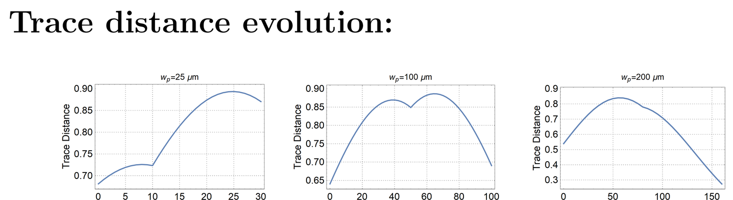
- **Trace distance:** For two initial states $\hat{\rho}_{S\pm}$ the trace distance evolves as

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

- **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.
- Our experiment allows to learn about the role of the spatial correlations of photon pairs on the resolution of ghost images.
- By controlling the initial correlation, 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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