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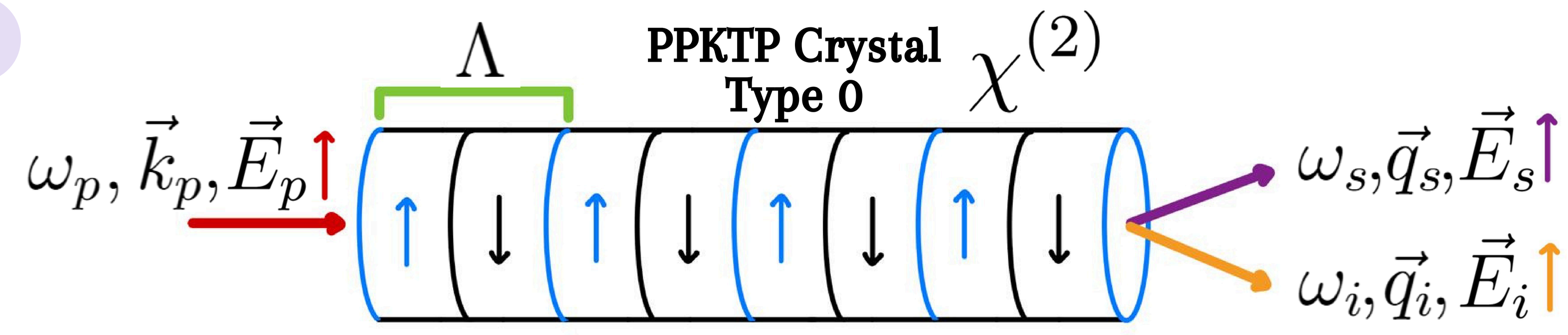
Exploring Entanglement in Photon Pairs Generated by PPKTP Nonlinear Crystals

Abstract

Spontaneous Parametric Down-Conversion (SPDC) in periodically poled Potassium Titanyl Phosphate (PPKTP) nonlinear crystals is a prominent method for generating entangled photon pairs for quantum information technologies. We quantify entanglement and optimize temperature tuning for collinear emission and degenerate spectra. We analyzed Joint Spectrum Intensity (**JSI**) at different temperatures. Successfully extracted the Schmidt number (**K**) by applying a Gaussian fit and Singular Value Decomposition (**SVD**).

Spontaneous Parametric Down-Conversion

A monochromatic *pump* photon converts into a correlated *signal-idler* pair, generating an entangled two-photon state.



Quasi-Phase-Matching (QPM) conditions are obtained.

$$\Delta k_{\text{QPM}} = k_p - k_s - k_i - \frac{2\pi}{\Lambda} \approx 0 \quad \textbf{Momentum}$$

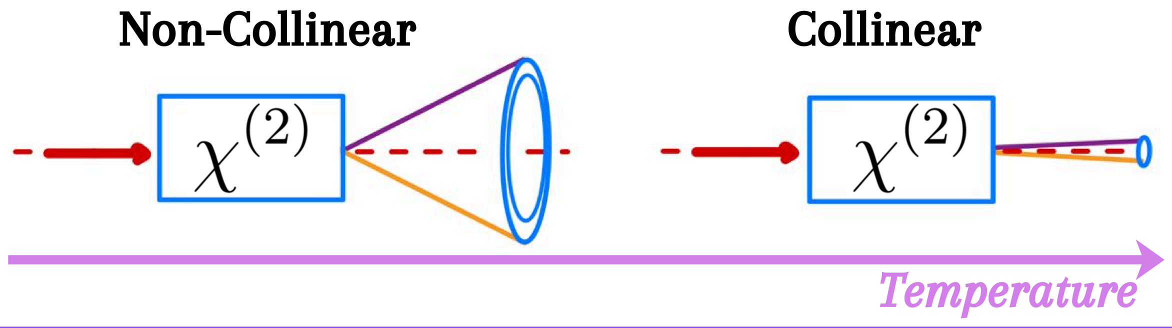
$$\omega_p = \omega_s + \omega_i \quad \textbf{Energy}$$

Biphoton state → $$|\Psi\rangle = |0\rangle + \int d^2\vec{q}_s \int d^2\vec{q}_i \int d\omega_s \int d\omega_i \Psi(\omega_s, \vec{q}_s, \omega_i, \vec{q}_i)\hat{a}_s^\dagger(\omega_s, \vec{q}_s)\hat{a}_i^\dagger(\omega_i, \vec{q}_i)|0\rangle$$

→ Correlations in *continuous variables.*

Temperature Tuning

The crystal's poling period, Λ(T), is highly dependent on temperature, leading to different emission regimes.



Entanglement Cuantification

SVD is performed on the target state to obtain the **Schmidt decomposition**

$$\Psi(\omega_s, \vec{q}_s, \omega_i, \vec{q}_i) = \sum_{k=0}^{\infty} \sqrt{\lambda_k} u_k(\omega_s, \vec{q}_s) v_k(\omega_i, \vec{q}_i)$$

Post-selected state

We are focus on **time-frequency** correlations.

$\psi(\omega_s, \omega_i) \to K_\omega$ $\qquad$ $\psi(\vec{q}_s, \vec{q}_i) \to K_{\vec{q}}$

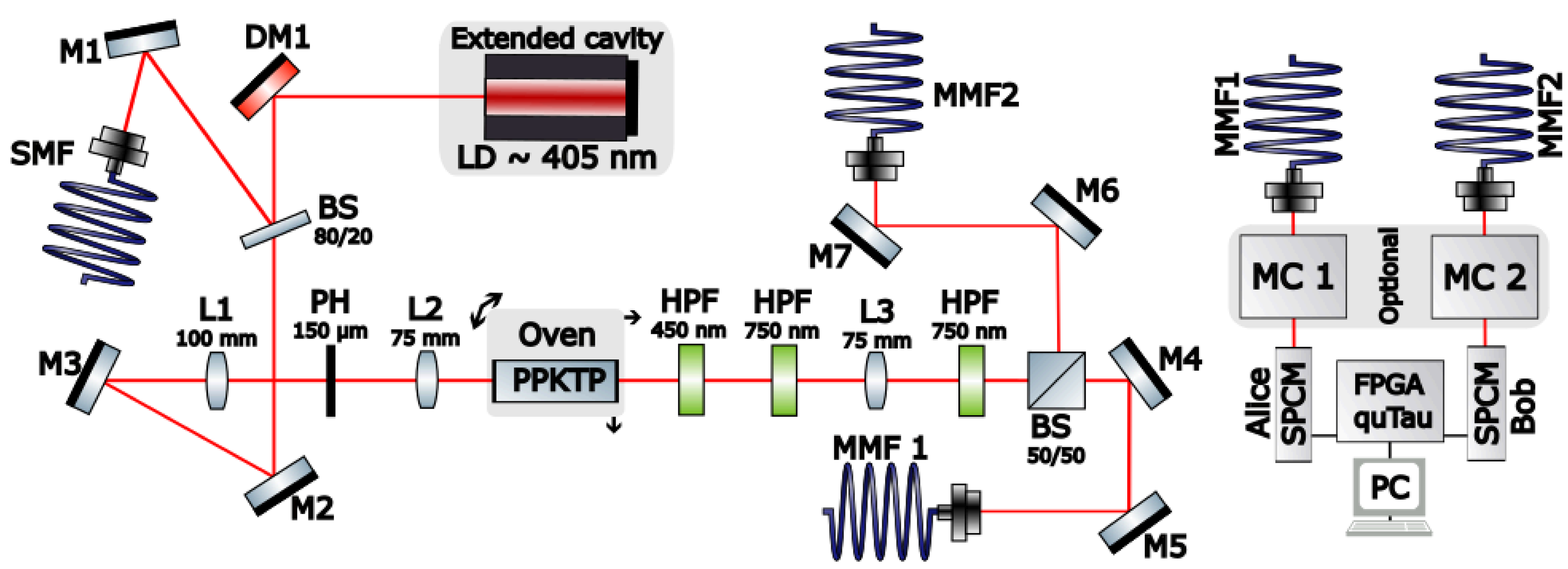
$$K_{\text{full}} \neq K_\omega \cdot K_{\vec{q}}$$

Schmidt Number quantify quantum correlations.

$$K = \frac{1}{\sum_k \lambda_k^2}$$

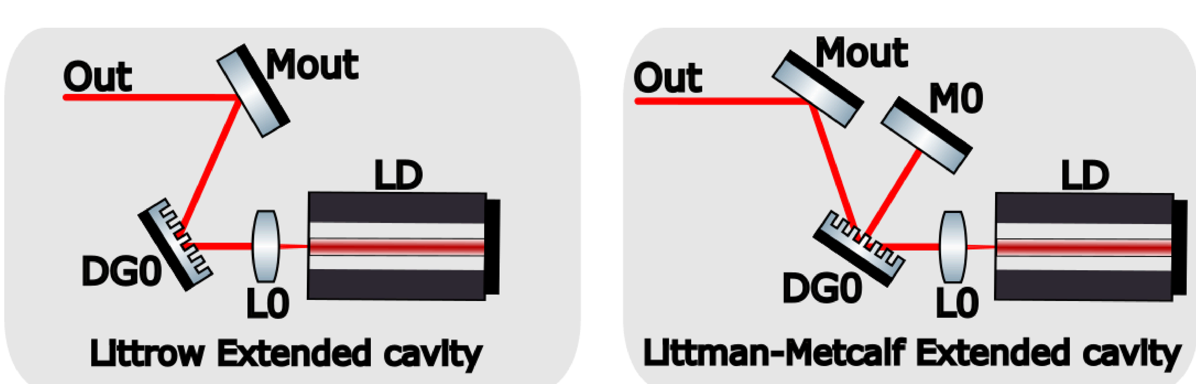
$K = 1$ → Product State
$K > 1$ → Entangled State

Experimental Setup



Our PPKTP Crystal is extremely sensible to wavelenght variations.

We build an extended cavity that allows a single-mode behavior on our pump source.



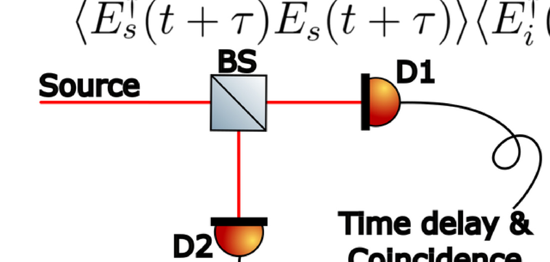
Detection

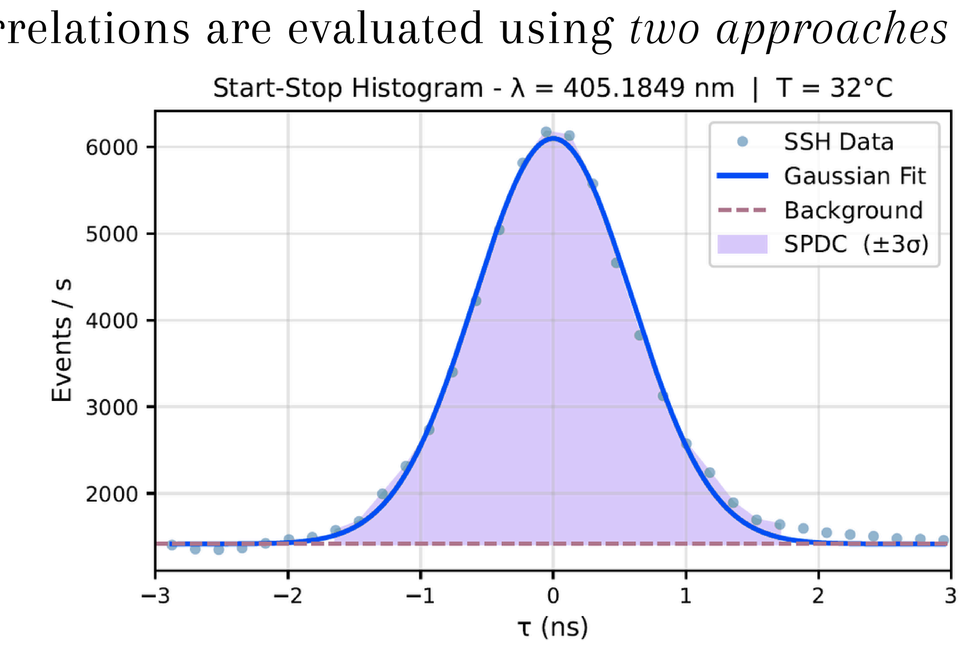
Signal-idler photon correlations are evaluated using *two approaches*

Temporal

A HBT interferometer measures the second order correlation function.

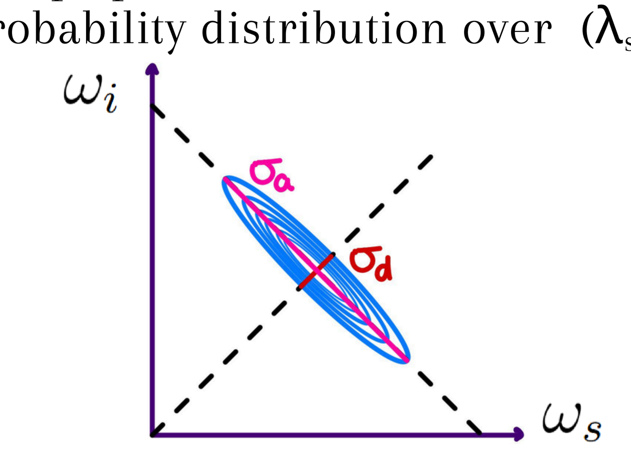
$$g^{(2)}(\tau) = \frac{\langle \hat{E}_s^\dagger(t+\tau)\hat{E}_i^\dagger(t)\hat{E}_i(t)\hat{E}_s(t+\tau)\rangle}{\langle \hat{E}_s^\dagger(t+\tau)\hat{E}_s(t+\tau)\rangle\langle \hat{E}_i^\dagger(t)\hat{E}_i(t)\rangle}$$





Spectral

Two monochromators measure the JSI. Maps photon coincidences as a 2D probability distribution over (λs, λi).

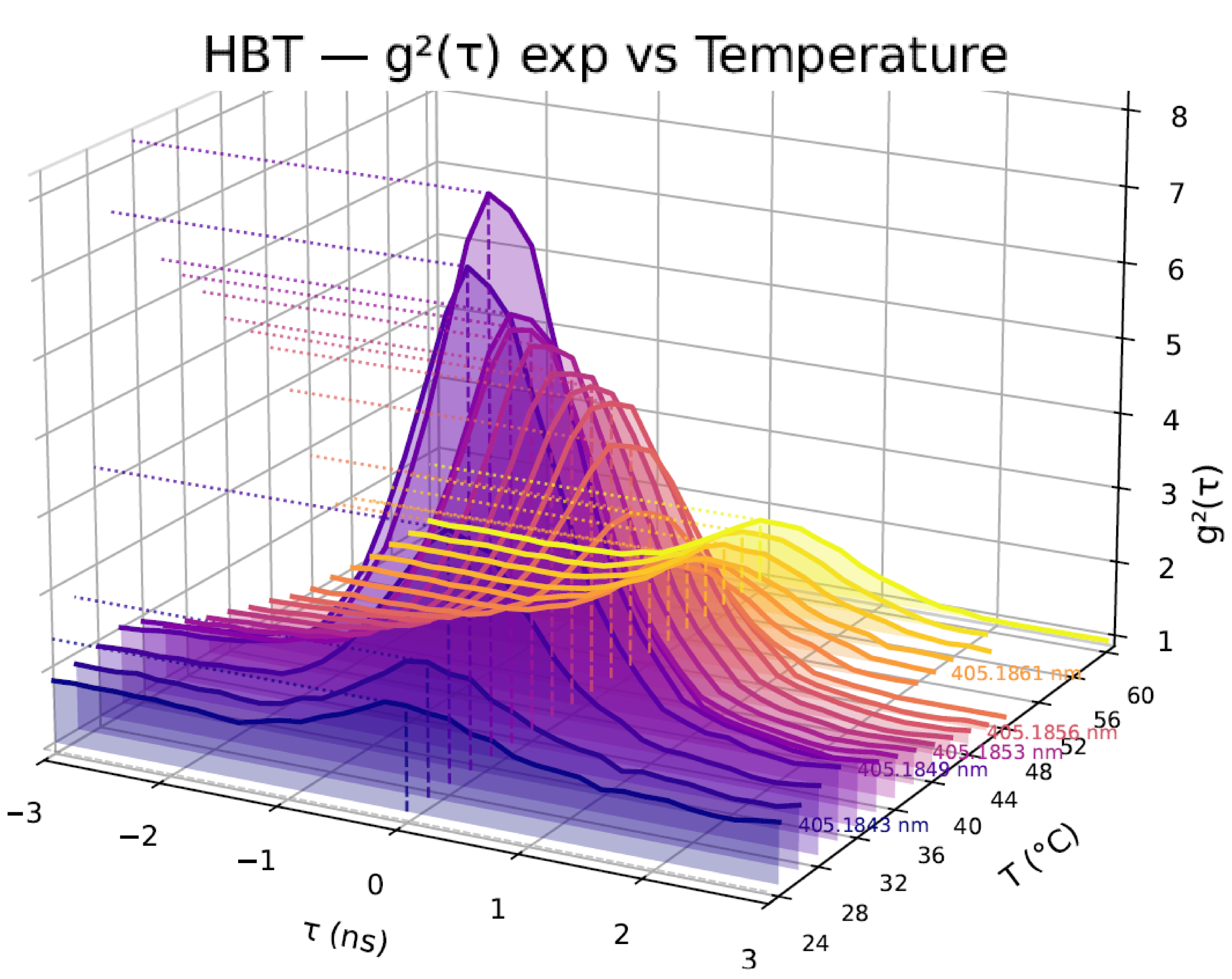


For a non-collinear emission, and suposing a *gaussian spectral amplitude* in the pump:

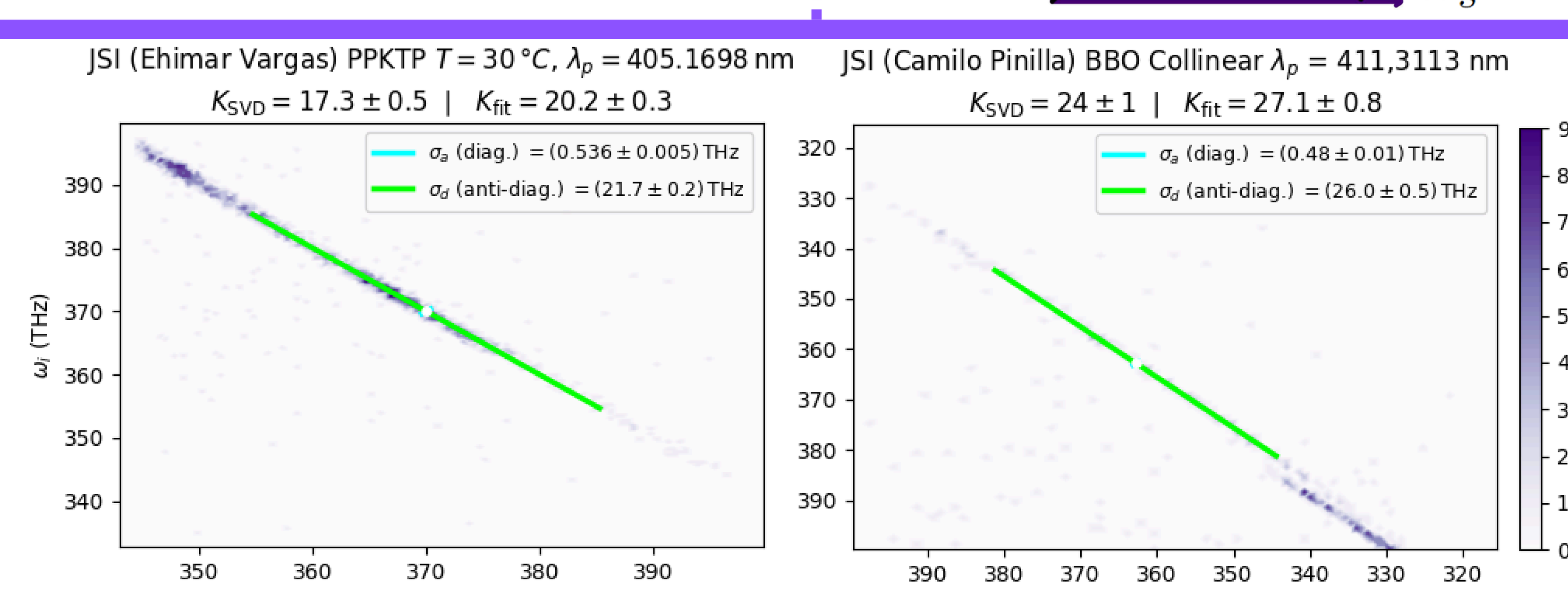
$$f(\nu_s, \nu_i) = A \exp\left\{-(\nu_s^2 + \nu_i^2)\left(\frac{1}{4\sigma_d^2} + \frac{1}{4\sigma_a^2}\right) - 2\nu_s\nu_i\left(\frac{1}{4\sigma_d^2} - \frac{1}{4\sigma_a^2}\right)\right\}$$

$$K_\omega \approx \frac{\sigma_d^2 + \sigma_a^2}{2\sigma_d\sigma_a}$$ **Spectral Schmidt Number**

Results and Analysis

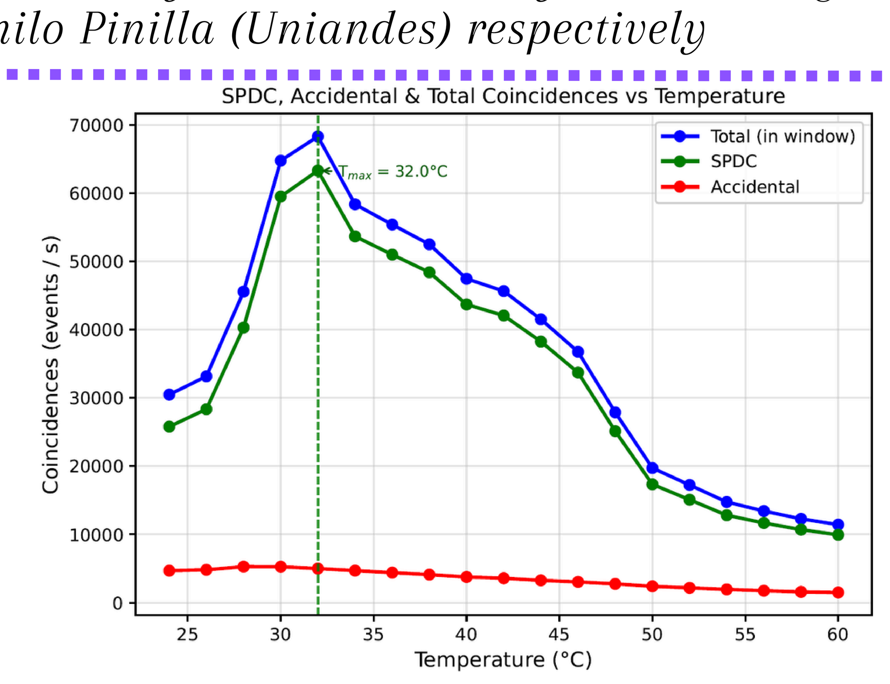


Experimental $g^{(2)}(\tau)$ for different temperatures. λ changes due to laser inestability.



JSI for PPKTP and BBO non-linear crystals measured by Ehimar Vargas (Uniandes) and Camilo Pinilla (Uniandes) respectively

Coincidences for different temperatures. Maximum SPDC events/s at T_c. Data recollecte from HBT Start-Stop Histogram



Conclusions

- Experimentally *validated* signal-idler *temporal correlations* through $g^{(2)}(\tau)$ measurements.
- *Characterized* the dependence of *coincidences* on crystal temperature.
- Successfully *extracted the Schmidt number* to quantify *frequency correlations* from SVD and fit aproximation.
- **Future Work:** Investigate entanglement in additional degrees of freedom and explore temperature sweep ranges to further map the emission regimes.

References

[1] Kevin Zielnicki et al. «*Joint spectral characterization of photon-pair sources*». Journal of Modern Optics 65.10 (2018), págs. 1141-1160. https://doi.org/10.1080/09500340.2018.1437228.
[2] H. Di Lorenzo Pires, C. H. Monken y M. P. van Exter. «*Direct measurement of transverse-mode entanglement in two-photon states*». Physical Review A 80 (2009), 022307.
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[4] J. F. Suárez Pérez, *Control experimental de las correlaciones en frecuencia de pares de fotones para una fuente de fotones individuales anunciados*, Master's thesis, Universidad de los Andes, 2018, https://hdl.handle.net/1992/34528.