Supplementary Note 1 for Ultra-efficient generation of time-energy entangled photon pairs in a InGaP Photonic Crystal Cavity

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I. TIME-ENERGY ENTANGLEMENT WITH THE BICHROMATIC & NANOBEAM CAVITIES

All the measurements presented in the main text have been performed on the bichromatic InGaP cavity. An additional measurement of the time-energy entanglement made with a InGaP nanobeam is also given in this work. Here we quickly present this nanobeam cavity, that is detailed in [1].

The nanobeam cavity is a one dimensional line of holes, whose period is tapered to establish a parabolic potential for the optical field, as for the bichromatic cavity. It is evanescently coupled to an underlying silicon waveguide. An SEM image of the cavity is given in fig.1. Details on the design, the characterisation of the internal generation rate and its dependence to the tuning mechanism have been extensively described in [1]. The experimental setup to perform the time-energy entanglement measurement is also given in fig.1. It is very similar to the setup described in the "Methods" for the bichromatic cavity. The main difference lies in the use of Bragg filters as notch filters to suppress the remaining pump photons while the signal and idler photons are still transmitted. These filters have very low insertion loss (1 dB). They can be used in this case because the tuning method is based on a sweep of the sample temperature as explained in ref [1], leaving the pump laser wavelength unchanged. The triplet of resonances have an average Q-factor of 4×10^4. The pump power used is 250 μW, which is much larger compared to the bichromatic cavity due to an higher initial mismatch (- 13.4 GHz) and lower Q-factors. The maximum coincidence rate of $\approx$ 17.5 Hz is measured. Histograms are acquired as described for the bichromatic cavity, but in this case, after 30 seconds of integration due to the smaller coincidence rate. The measured raw visibility is 93.1 $\pm$ 3.4 %. It is shown in fig.2, that gives the complete set of time-energy entanglement measurements performed in this work : (a - c) are the three Bell curves for the bichromatic cavity and (d) the measurement with the nanobeam cavity. The comparison between the results obtained with the

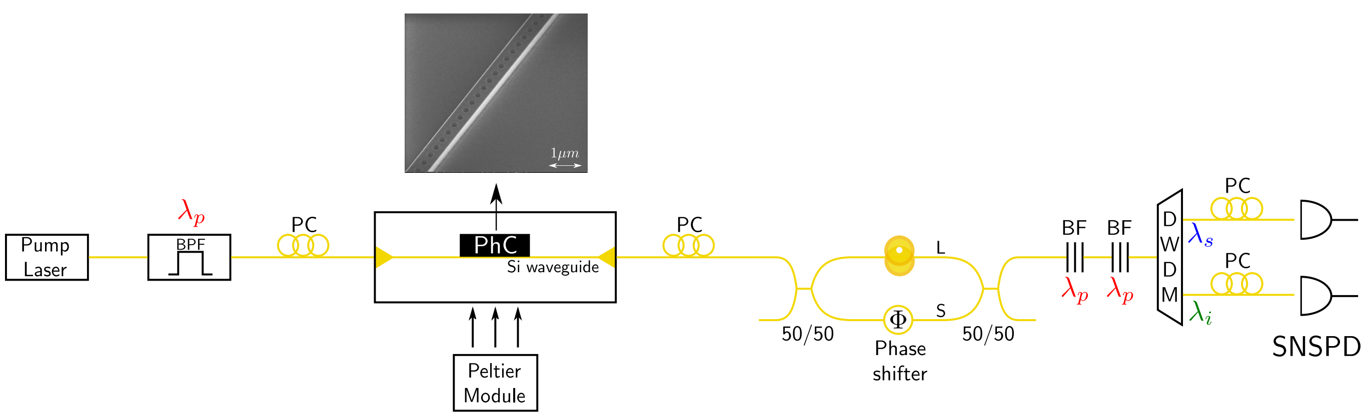

FIG. 1: Experimental setup for the measurement of time-energy entangled photon pairs with a nanobeam cavity. $\lambda_{p,s,i}$ is the wavelength of the pump, signal and idler photons respectively. BPF stands for bandpass filter, PC for polarization controller, BF for Bragg filter, DWDM for dense wavelength division multiplexing and SNSPD for Superconducting nanowire single-photon detectors. An SEM picture of the nanobeam cavity is also given.

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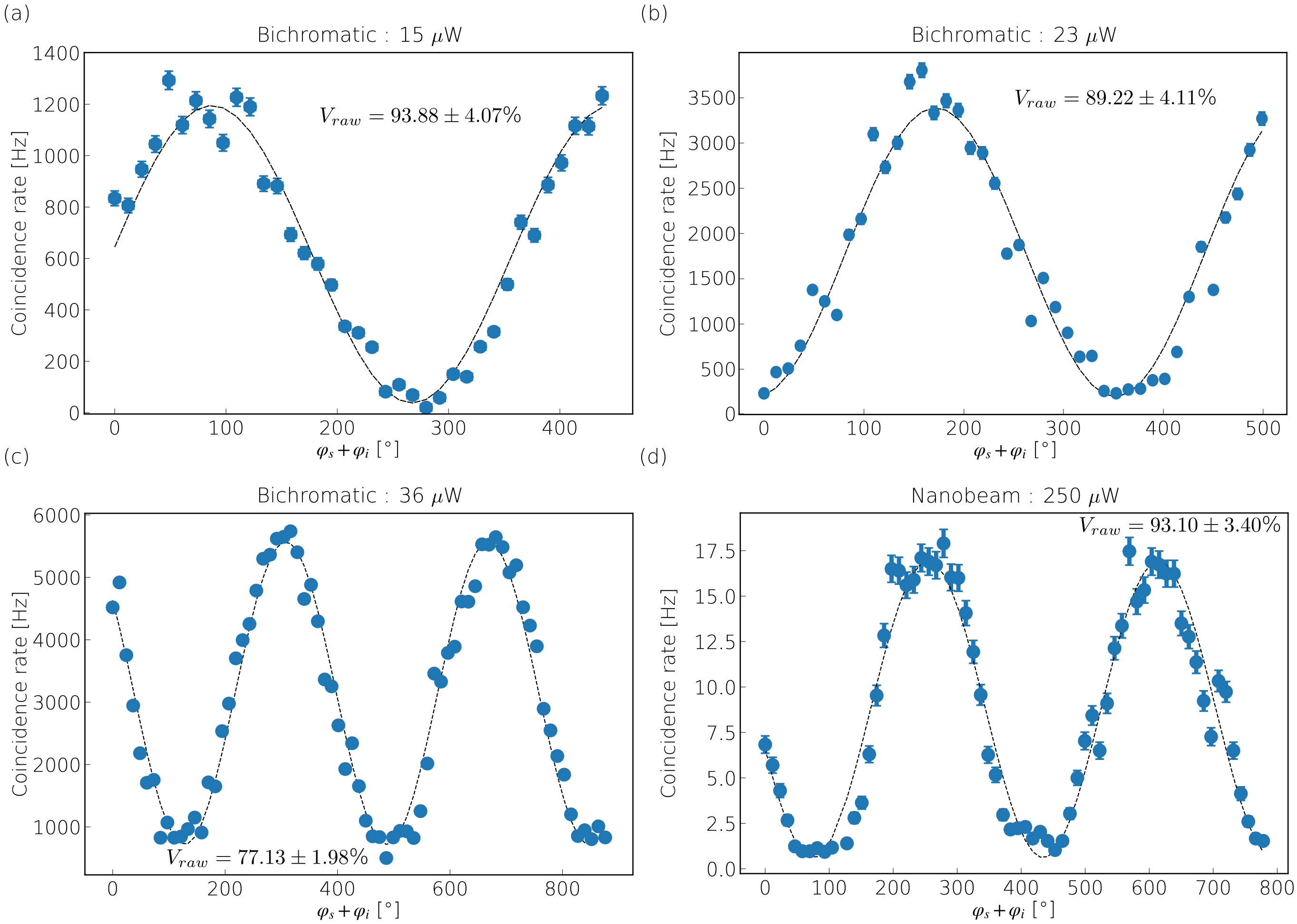

FIG. 2: Bell curves of time-energy entanglement : all results. (a - c) : bichromatic cavity for different pump powers. (d) : nanobeam cavity.

bichromatic and nanobeam cavities are difficult to compare as the experimental setups and the properties of the cavity are very different.

II. STATISTIC OF THE HERALDED STATE

The second order self correlation function of the channel that is used as herald shows the characteristics of the thermal statistic as shown in fig.3, which is consistent with spontaneous emission from vacuum thermal fluctuations [2]. Due to the emission of multiple pairs, the bunching peak at zero delay is depressed compared to the single pairs emission regime ($g^2(0) = 2$), hence the purity of the state is $P = g^{(0)} - 1 < 1$.

III. RESULTS ON THE SYMMETRIC PEAK FITTING

Here are presented the results of the heuristic model discussed in the "Methods" section to fit asymmetric lineshape of the coincidence peak between signal and idler arrival times. The model has for fitting parameters these average arrival times for the start and stop channels. If a typical measured main peak in the histogram is fitted, the obtained arrival times are $\tau_1 = 32$ ps and $\tau_2 = 189$ ps, that as dwelling times of the photon in the cavity gives $Q_1 \simeq 4 \times 10^4$ and $Q_2 \simeq 2.4 \times 10^5$ for the loaded $Q-$factors. As shown in fig.4, these result are in agreement with the quality factors measured from the resonances linewidths retrieved via spectroscopic techniques (see Fig.1(d)).

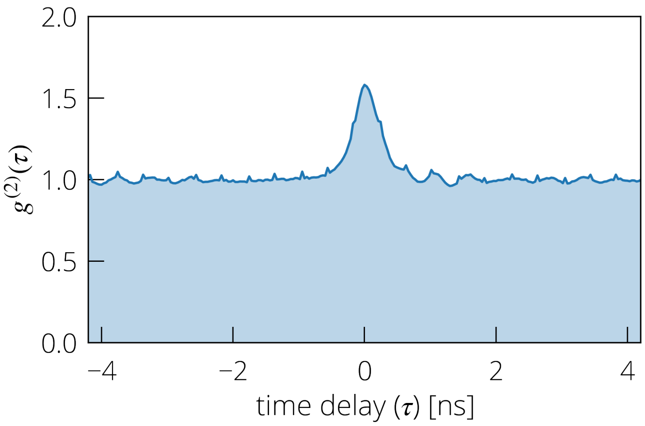

FIG. 3: Second order correlation function for the heralded channel

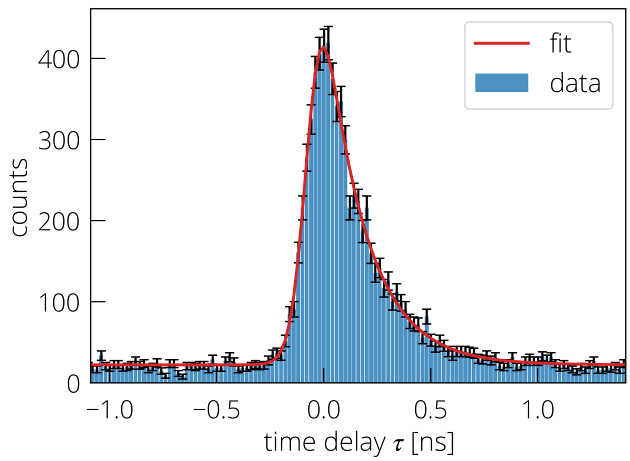

FIG. 4: Fit of the coincidence histogram using the peak function discussed in the "Methods" section. 1 second integration

[1] A. Chopin, I. Ghorbel, S. Combrié, G. Marty, F. Raineri, and A. De Rossi, Physical Review Research (2022).
[2] F. Paleari, A. Andreoni, G. Zambra, and M. Bondani, Optics Express **12**, 2816 (2004).