Quantum Non-Gaussian Depth of Single-Photon States

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Abstract

We introduce and experimentally explore the concept of the quantum non-Gaussian depth of single-photon states with a positive Wigner function. The depth measures the robustness of a single-photon state against optical losses. The directly witnessed quantum non-Gaussianity withstands significant attenuation, exhibiting a depth of 18 dB, while the nonclassicality remains unchanged. Quantum non-Gaussian depth is an experimentally approachable quantity that is much more robust than the negativity of the Wigner function. Most importantly, we use it to reveal significant differences between otherwise strongly nonclassical single-photon sources.

Single-photon states

We consider three kinds of single-photon states:

- ideal single-photon state

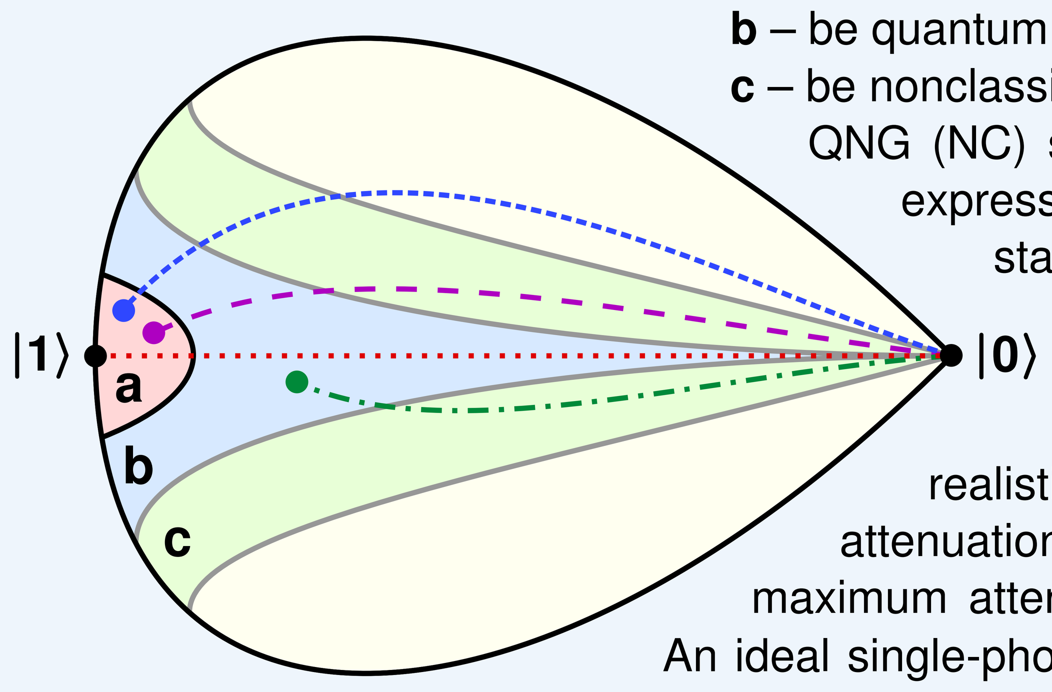
  $P_0|0\rangle\langle 0| + P_1|1\rangle\langle 1|$
- high-quality single-photon state

  $(1 - P_1 - P_{2+})|0\rangle\langle 0| + P_1|1\rangle\langle 1| + P_{2+}|2\rangle\langle 2|,\quad P_{2+} \ll P_1$
- realistic single-photon state

  (any experimentally generated state)

In our protocol-independent approach, we want to test how well a realistic state retains the features of the ideal state (Wigner function negativity, NC, QNG). Considering that any optical application inevitably includes losses, the endurance of quantum features with respect to losses—depth—becomes imperative.

Quantum state sets



A single-photon state can:
a – have negative Wigner function
b – be quantum non-Gaussian (QNG)
c – be nonclassical (NC)

Sufficient conditions:

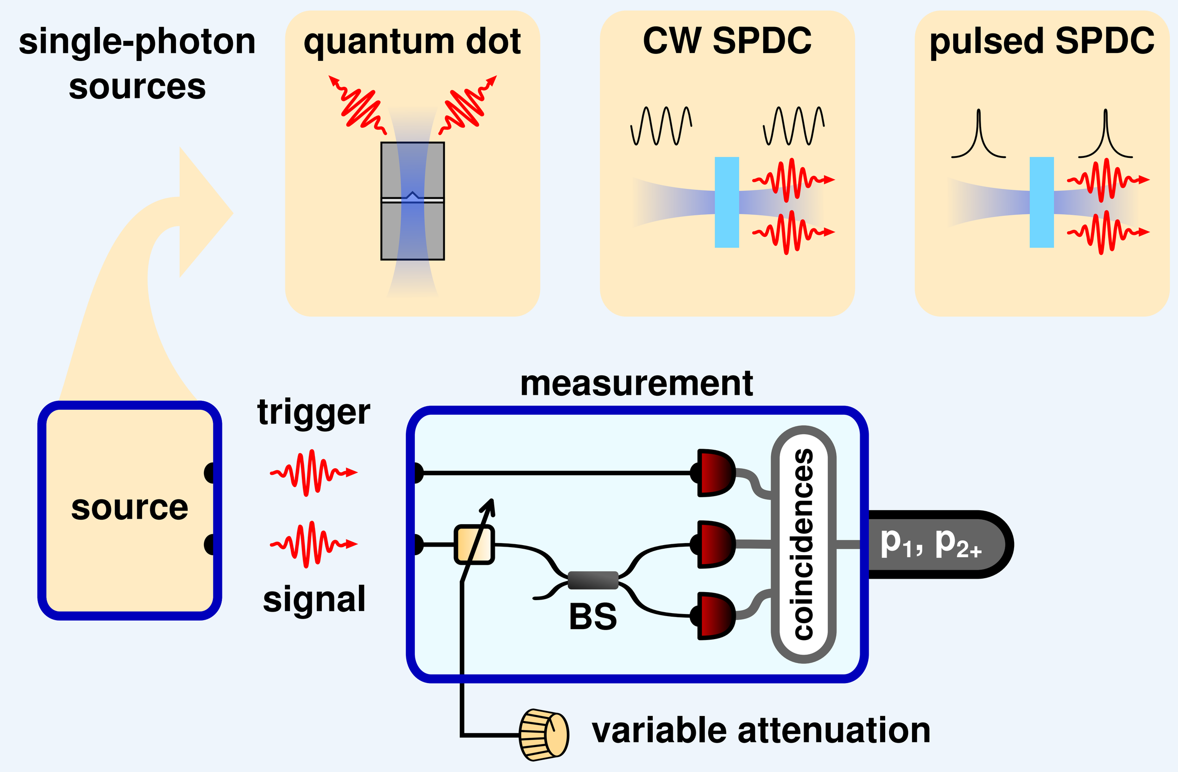
NC: $P_{2+} < \frac{1}{2}P_1^2$

QNG: $P_{2+} < \frac{2}{3}P_1^3$

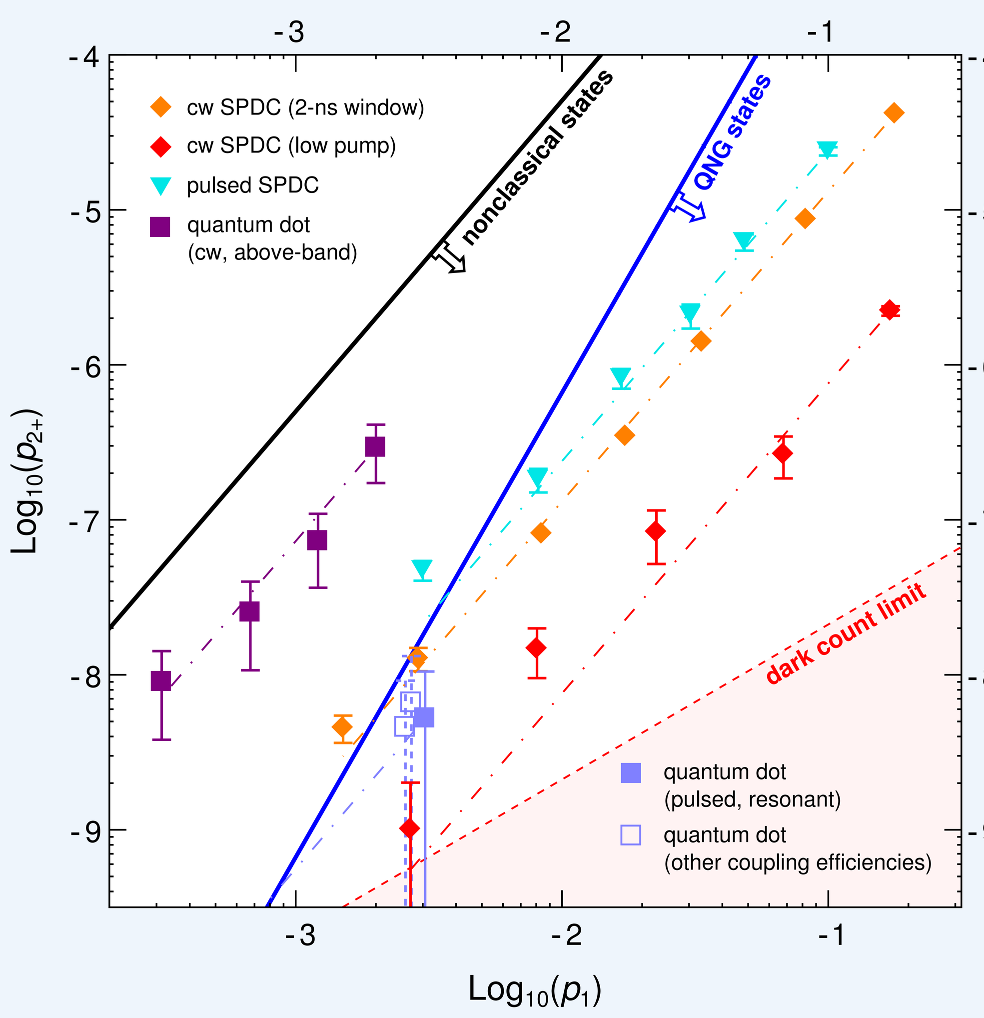
QNG (NC) states are defined as quantum states that are inexpressible as statistical mixtures of Gaussian (coherent) states [1]. These sets have a hierarchy illustrated on the figure. The grey borders represent NC and QNG witnesses (see inequalities above). The points and non-solid lines represent various realistic quantum states and their respective paths under attenuation. The depth of a quantum feature is defined as the maximum attenuation, at which this feature is still recognizable. An ideal single-photon state $P_0|0\rangle\langle 0| + P_1|1\rangle\langle 1|$ (red dotted line) is an extremal case of an infinite QNG depth. The green dot-dashed line represents realistic single-photon states with positive Wigner function, as generated by common sources (see definitions on the left). The negativity of the Wigner function requires $P_1 > 0.5$ and is very challenging to fulfil. Assuming a high-quality single-photon state, the NC depth is infinite. Finally, QNG depth proves to be a measurable and robust quantity. In this work, we confirmed these properties and proved that our realistic single photons can be considered high-quality [2].

Measuring the QNG depth

NC and QNG witnesses can be conveniently estimated using a simple autocorrelation scheme [3]. The depth is then verified using a variable attenuator.
In our work we used three different systems to generate heralded single-photon states. Of these, two were based on spontaneous parametric down-conversion (SPDC) in a nonlinear crystal. One was type-II collinear with continuous-wave (cw) pumping [3], the other employed a pulsed pumping in a Sagnac configuration [4]. The third system was an InAs/GaAs single quantum dot [5, 6].



Results



$$T_{\min} = \frac{3P_{2+}}{2P_1^3}$$

QNG depth: min. transmittance for high-quality single photons

This figure shows the measured results in terms of the estimated single-photon and multi-photon probabilities p_1, p_{2+}. The solid black and blue lines show NC and QNG witnesses, respectively. Each dataset represents a single-photon state under various attenuations. The dash-dotted lines show a theoretical prediction.
Note that all lines are parallel to the NC witness, which confirms that nonclassicality survives any attenuation. We were able to confirm a certain minimum QNG depth, represented by data points still below the solid blue line. The depth is given in dB of attenuation ($-10\,\mathrm{Log}_{10}T_{\min}$).
For cw SPDC, the experimentally confirmed depth was 17.9 dB (theoretical depth 19.6 dB); when the pump power was turned down, we were able to confirm 18 dB (31.8 dB). The pulsed SPDC gave 10.8 dB (14.5 dB). The state generated by a quantum dot excited cw above-band shows only nonclassicality and cannot be well compared to SPDC states. With resonant pulsed excitation, the quantum dot state exhibits QNG character and the theoretical depth is 5.6 dB.
It can be seen that SPDC produces single-photon states with extremely robust QNG depth. However, it has a systematically generated multi-photon component. This component is negligible for the quantum dot, but some background noise is still present. We therefore estimate that the QNG depth of the quantum dot can be improved by increasing the coupling efficiency, potentially even surpassing SPDC.

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