Towards a photon-number-resolving detector free of systematic errors

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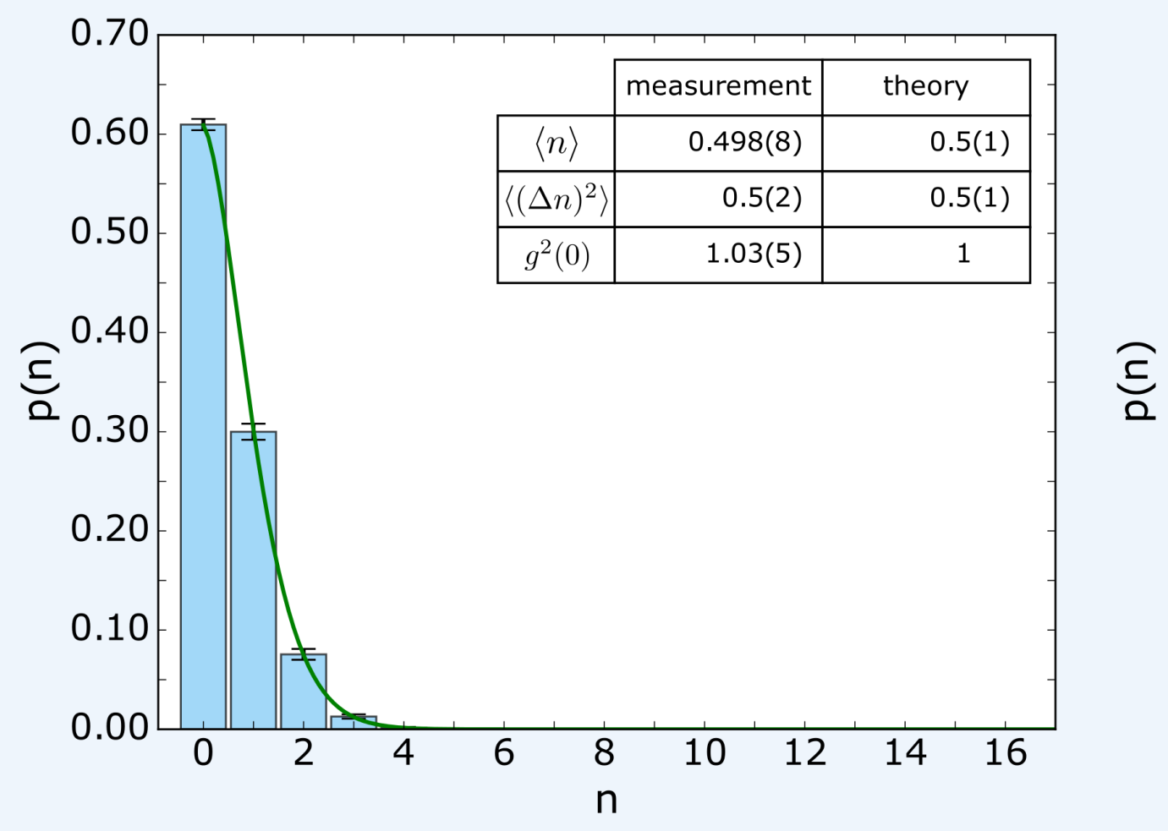
Abstract

We built a photon-number-resolving detector (PNRD) consisting of a tunable free-space optical multiport network and a sufficient number of single-photon avalanche diodes. The detector features precise balancing with no crosstalk between the individual detection ports and other systematic errors. Subsequent data processing is based on a real-time measurement of all the possible coincidence events between the ports. High-fidelity photostatistics reconstruction is verified for various sources of light including laser, single- and few-mode thermal sources, photon-subtracted thermal light, and a set of several single-photon emitters.

Coherent states

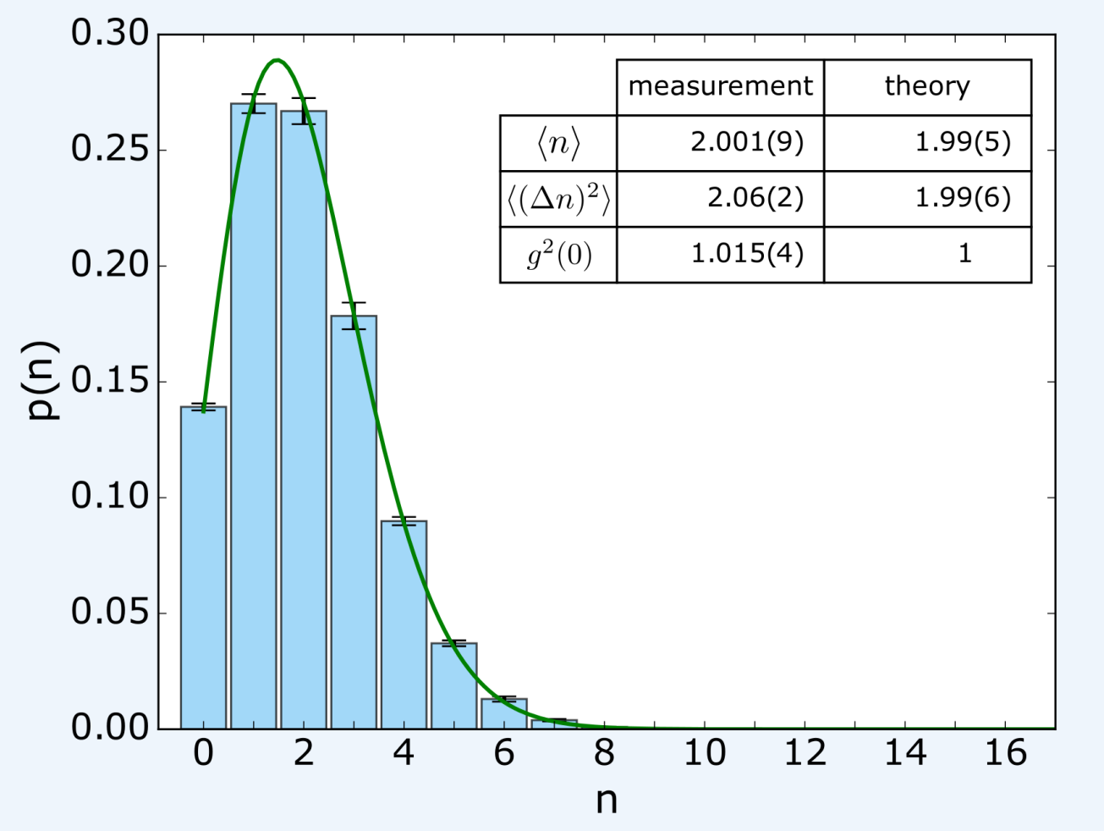
We employ a ns-pulsed source with variable repetition rates between 0.5 MHz and 8 MHz. To produce sub-nanosecond pulses of light, a laser diode (805 nm) in gain switching regime was used.

mean photon number 0.5



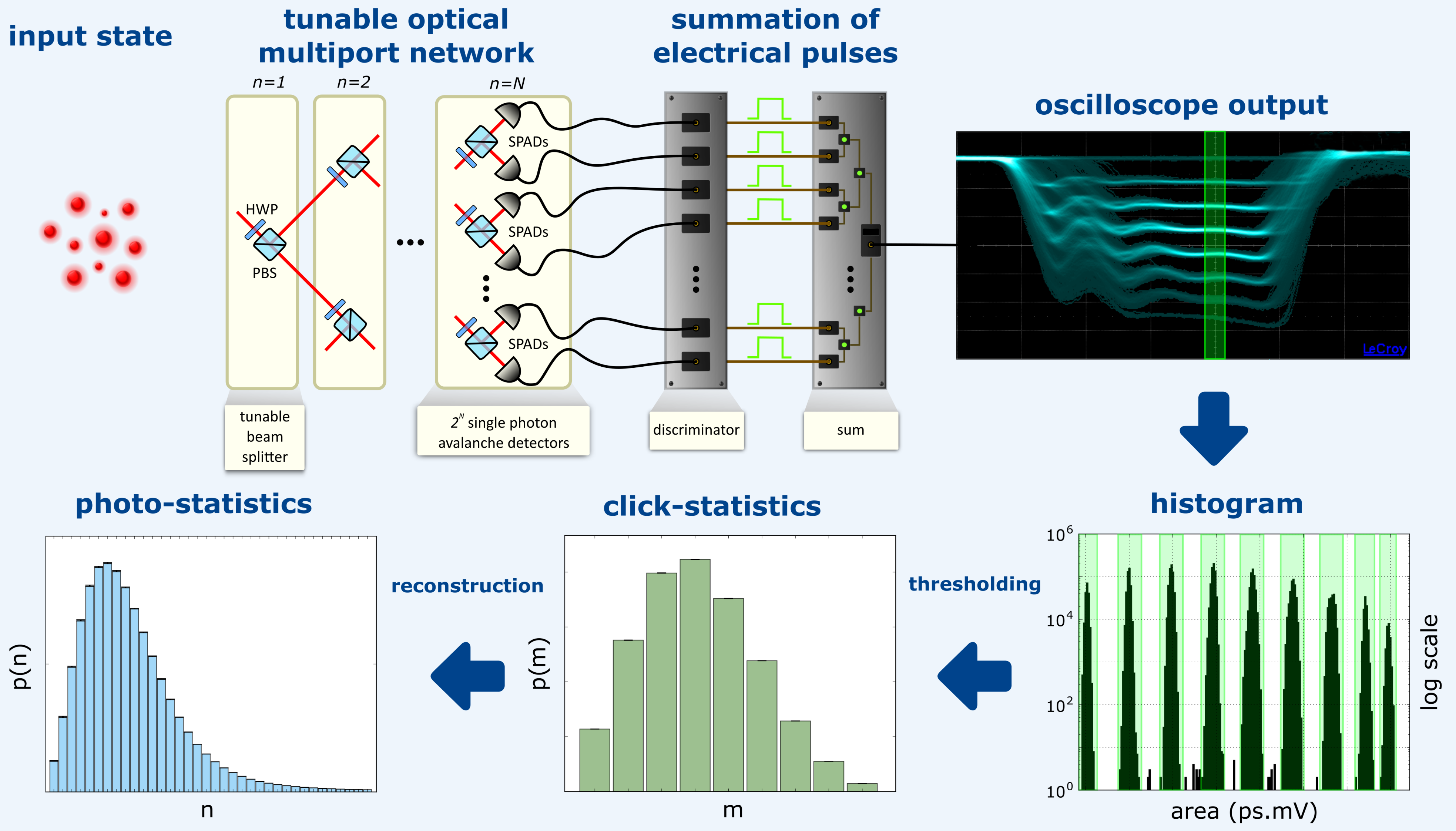
	measurement	theory
$\langle n\rangle$	0.498(8)	0.5(1)
$\langle(\Delta n)^2\rangle$	0.5(2)	0.5(1)
$g^2(0)$	1.03(5)	1

mean photon number 2.0



	measurement	theory
$\langle n\rangle$	2.001(9)	1.99(5)
$\langle(\Delta n)^2\rangle$	2.06(2)	1.99(6)
$g^2(0)$	1.015(4)	1

Experimental scheme

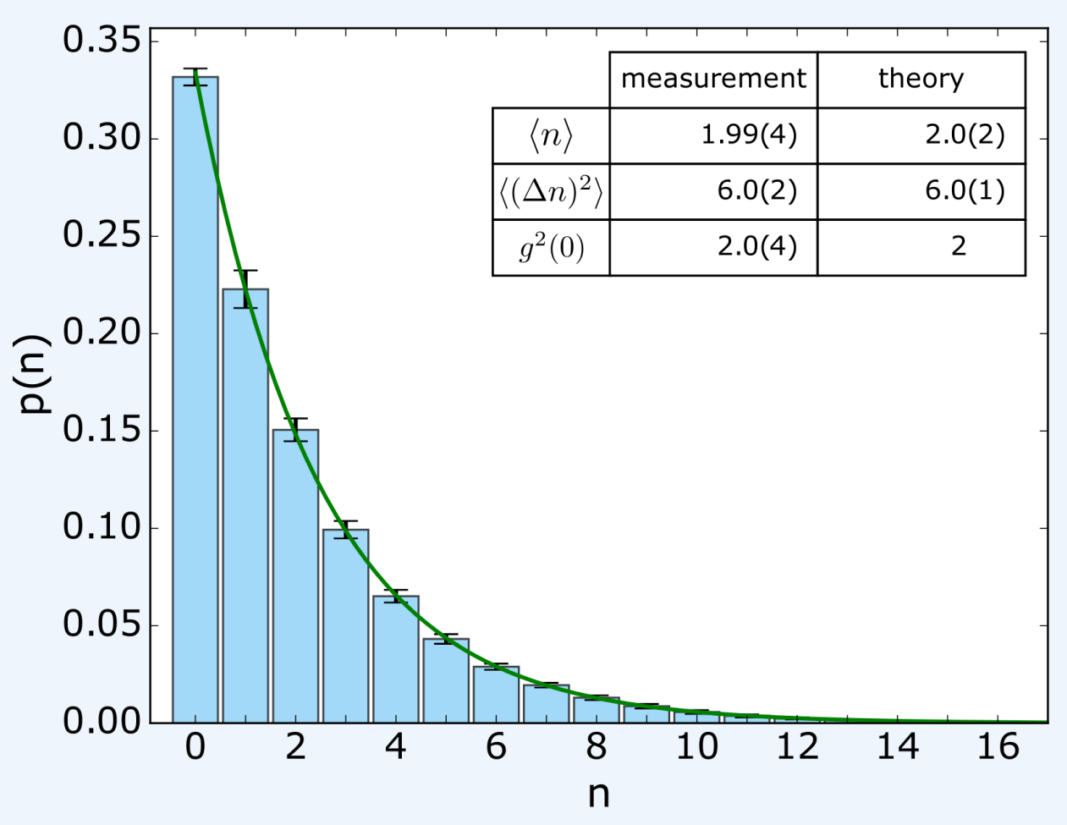


We apply statistical methodology of the maximum-likelihood estimation [1] to reconstruct photo-statistics from the multiple coincidences measured at the outputs of a passive multiport.

Thermal states

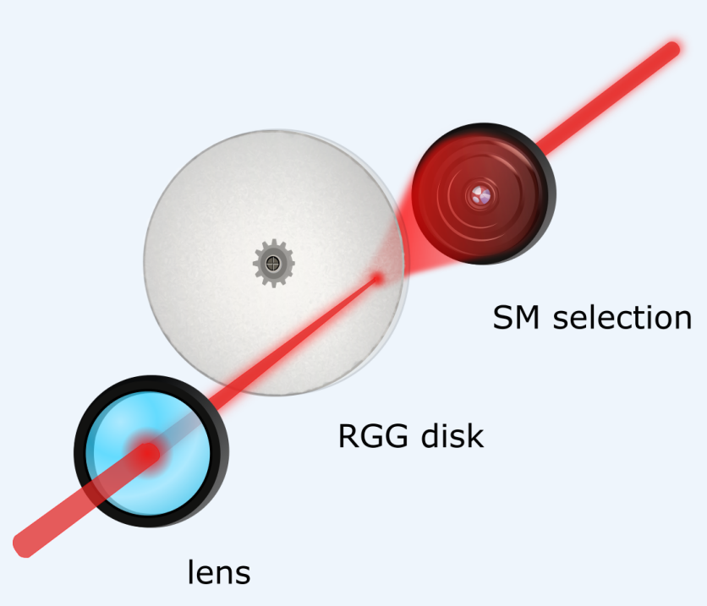
The initial thermal state is generated by temporal intensity modulation of a pulsed laser diode by a rotating ground glass (RGG) disk with a random spatial distribution of speckles. A single-mode optical fiber is placed in front of the RGG disk to collect the scattered light and select a clean single-spatial mode.

mean photon number 0.5



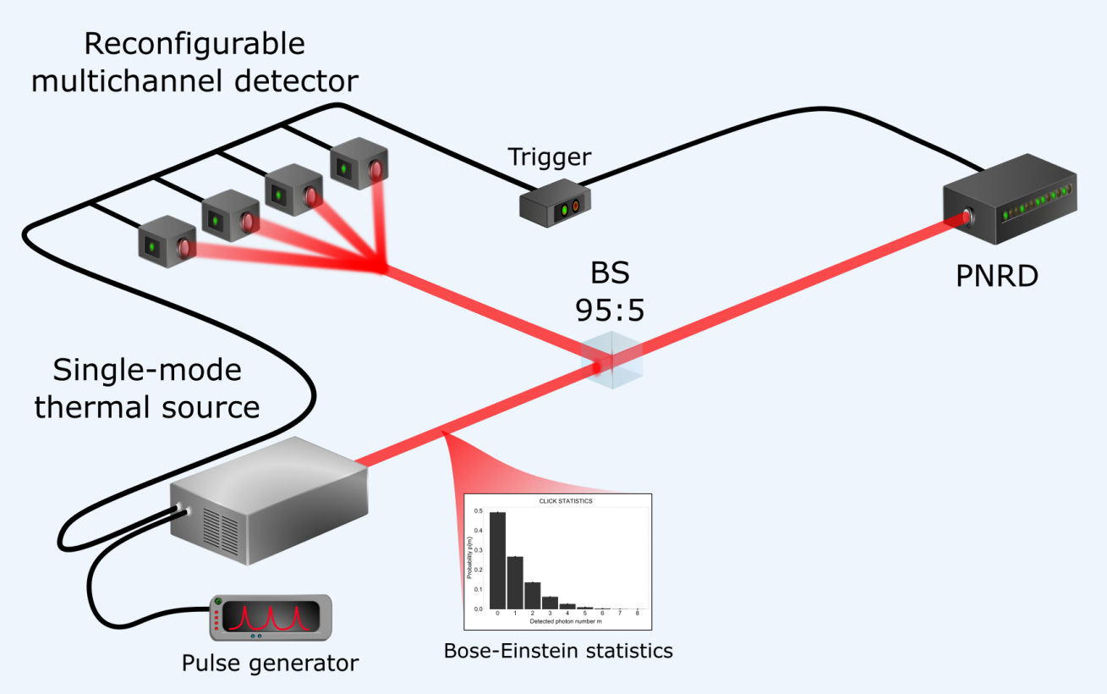
	measurement	theory
$\langle n\rangle$	1.99(4)	2.0(2)
$\langle(\Delta n)^2\rangle$	6.0(2)	6.0(1)
$g^2(0)$	2.0(4)	2

Single mode thermal source

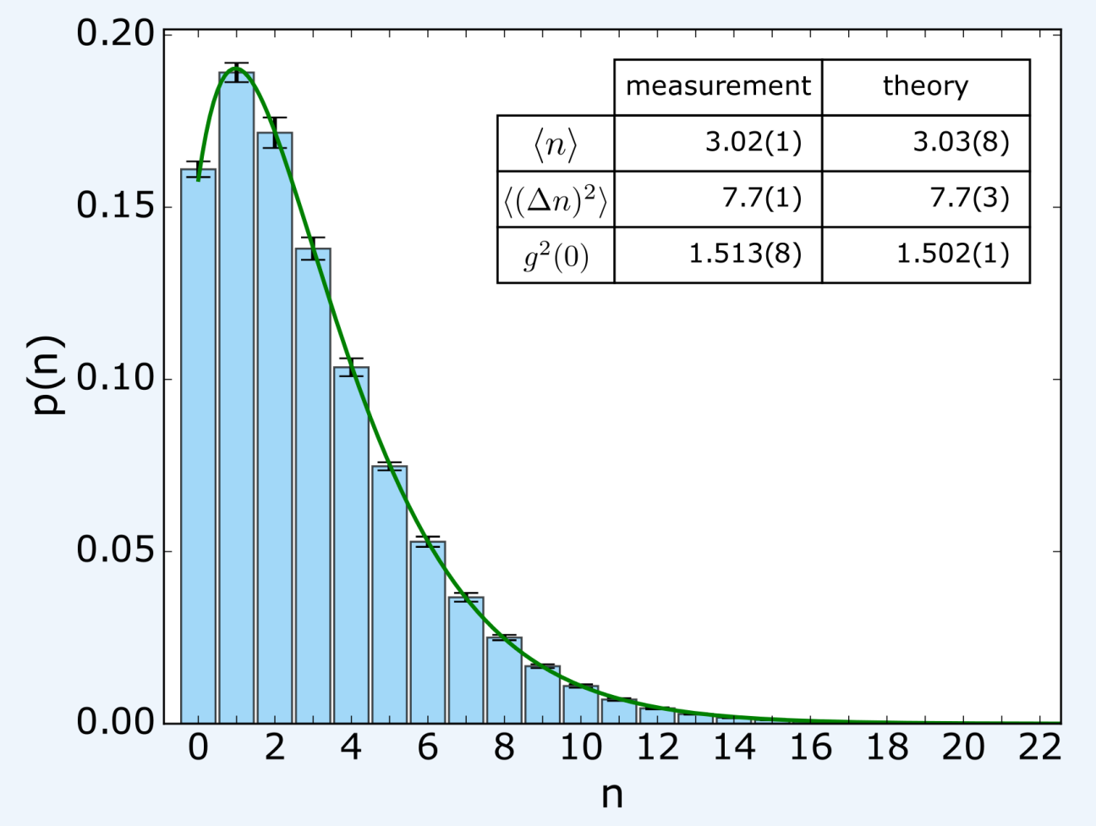


Multiple-photon substracted thermal states

Experimental optical implementation of multiple-photon subtraction

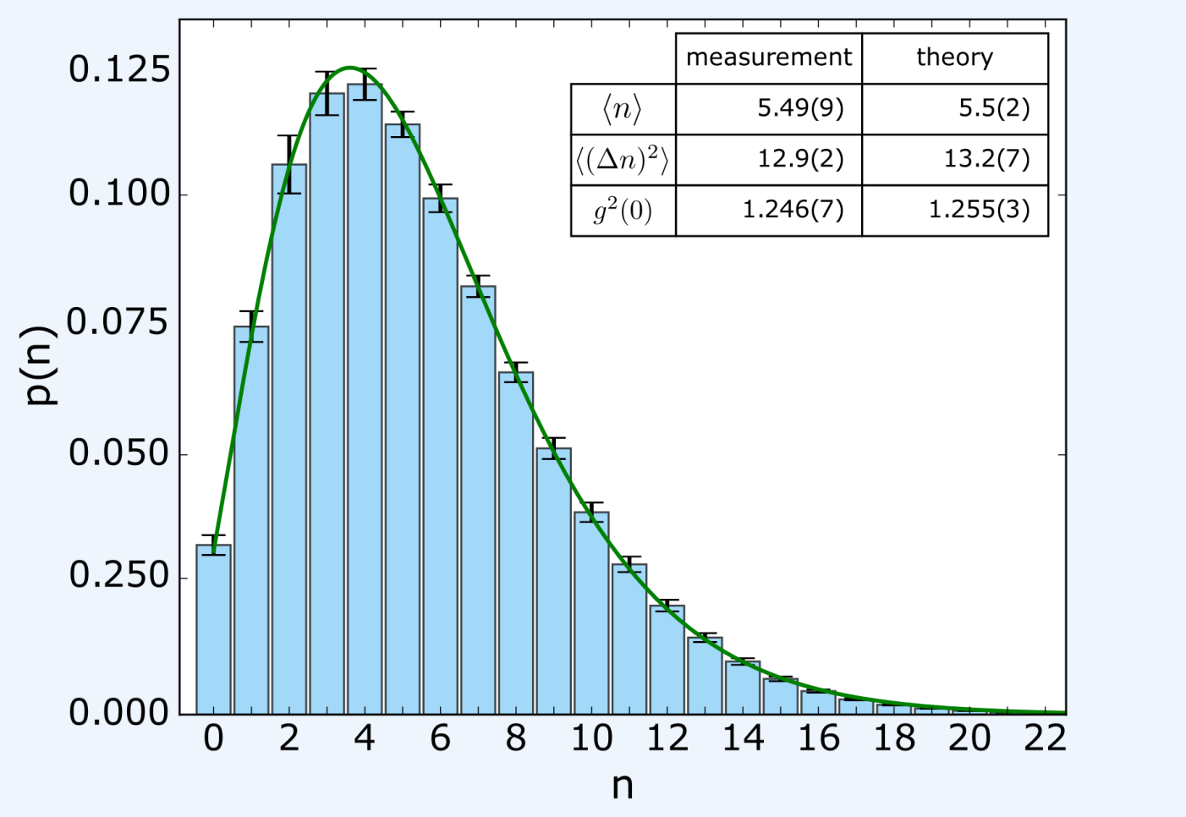


one-photon subtracted thermal state



	measurement	theory
$\langle n\rangle$	3.02(1)	3.03(8)
$\langle(\Delta n)^2\rangle$	7.7(1)	7.7(3)
$g^2(0)$	1.513(8)	1.502(1)

three-photon subtracted thermal state

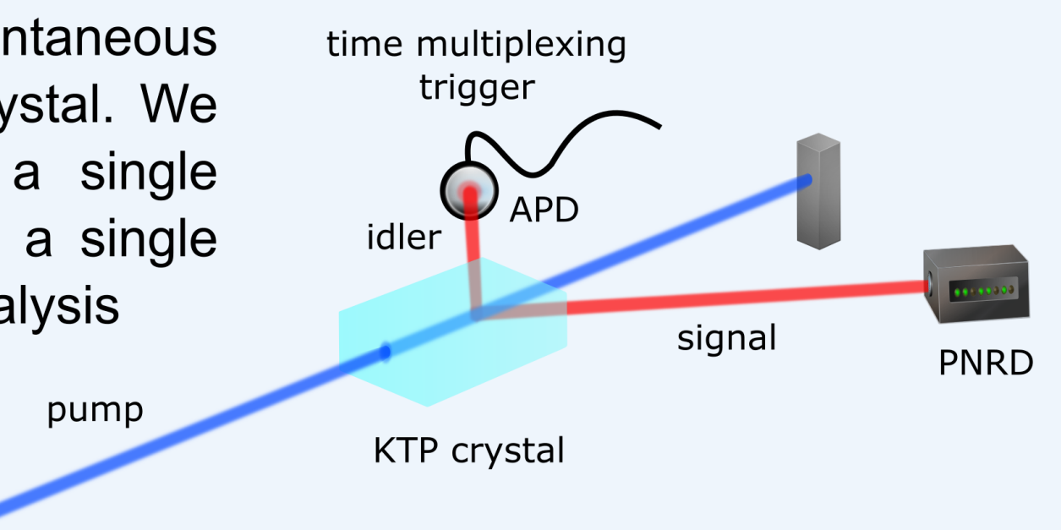


	measurement	theory
$\langle n\rangle$	5.49(9)	5.5(2)
$\langle(\Delta n)^2\rangle$	12.9(2)	13.2(7)
$g^2(0)$	1.246(7)	1.255(3)

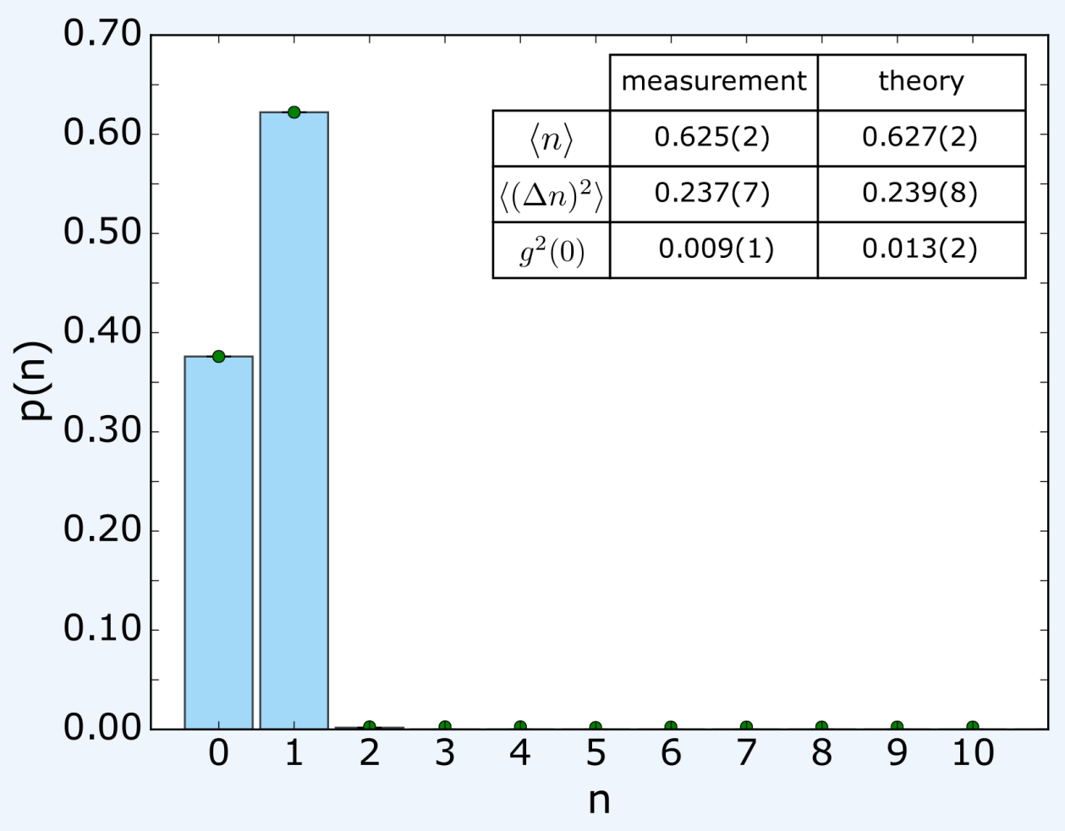
Multiple-photon subtraction from thermal state was implemented by using a low-reflectivity beam splitter (R = 5%, half-wave plate + polarizing beam splitter). Reflected photons are detected via a reconfigurable multichannel detector (multiple commercial on-off detectors). When many-fold coincidence is detected by the multichannel detector in the reflected port, the heralded optical signal in the transmitted port is analyzed by PNRD [2].

Multiphoton light

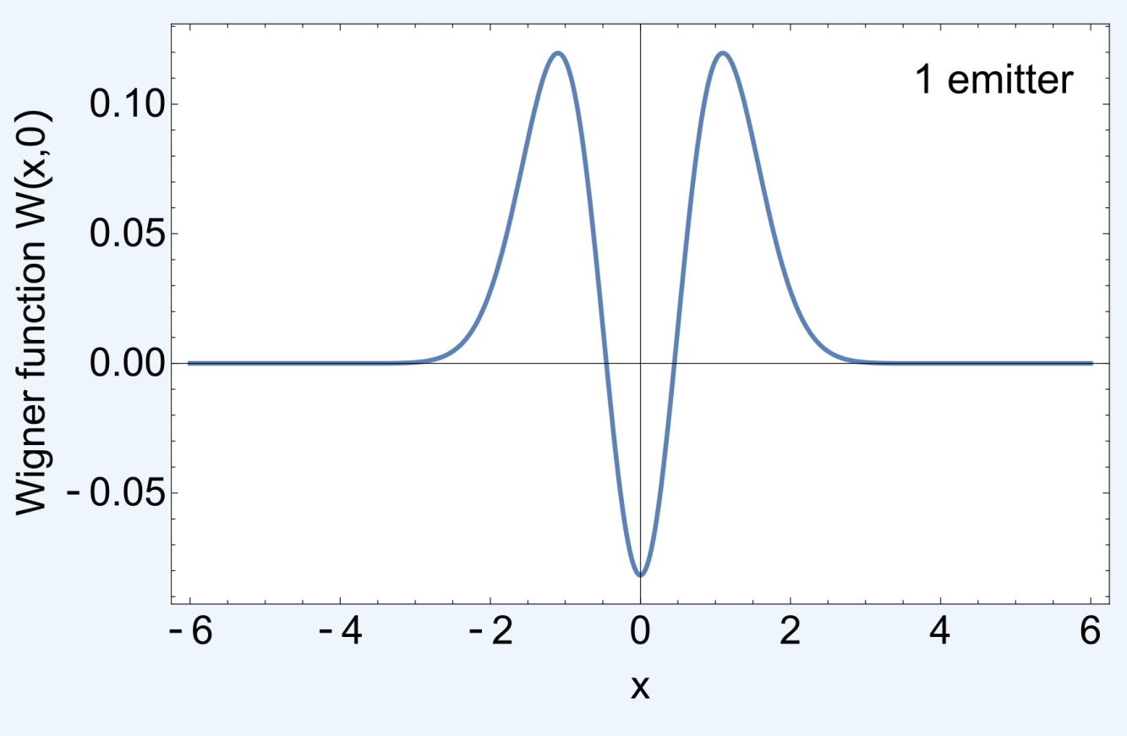
We generated multi-photon states by mixing n single-photon states together incoherently using time multiplexing. To produce an incoherent mixture of n single-photon states, we used a heralded state generated by spontaneous parametric down-conversion in a PPKTP crystal. We took n successive time windows, where a single photon was heralded, and joined them into a single temporal detection unit. The subsequent analysis is capable of recognizing multi-photon states produced by single atoms, trapped ions or solid-state emitters [3].



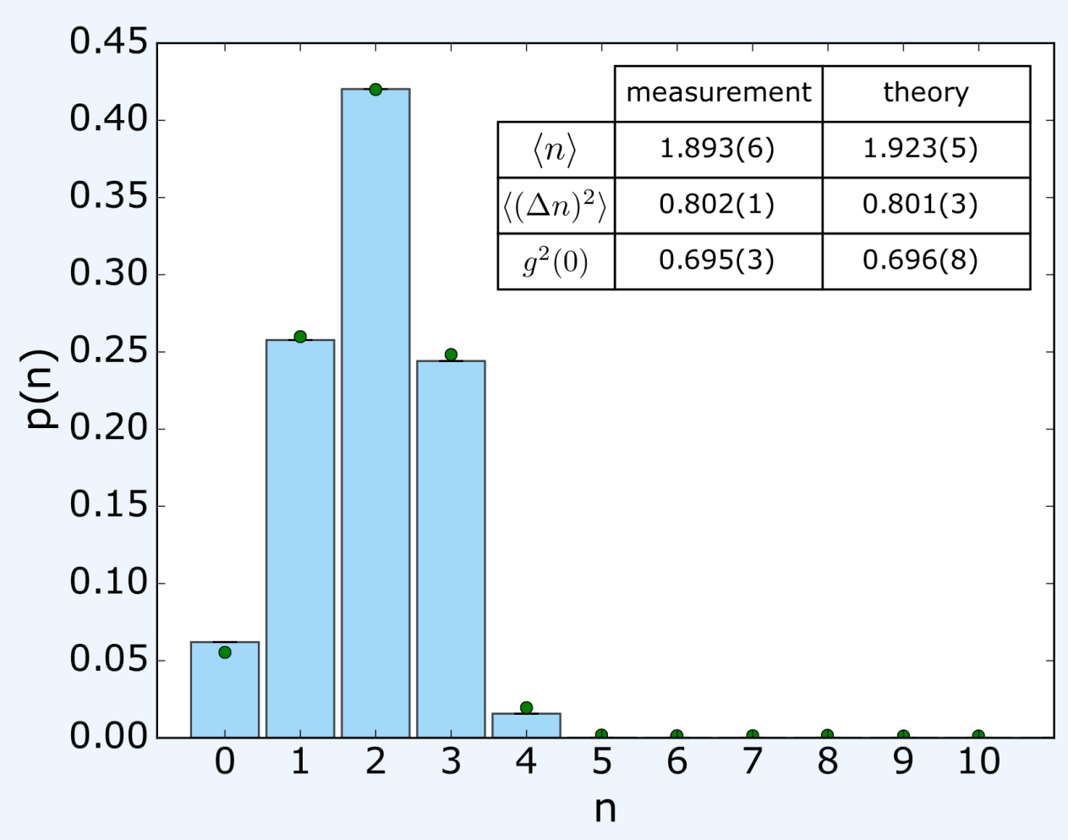
mixing of one single photon state



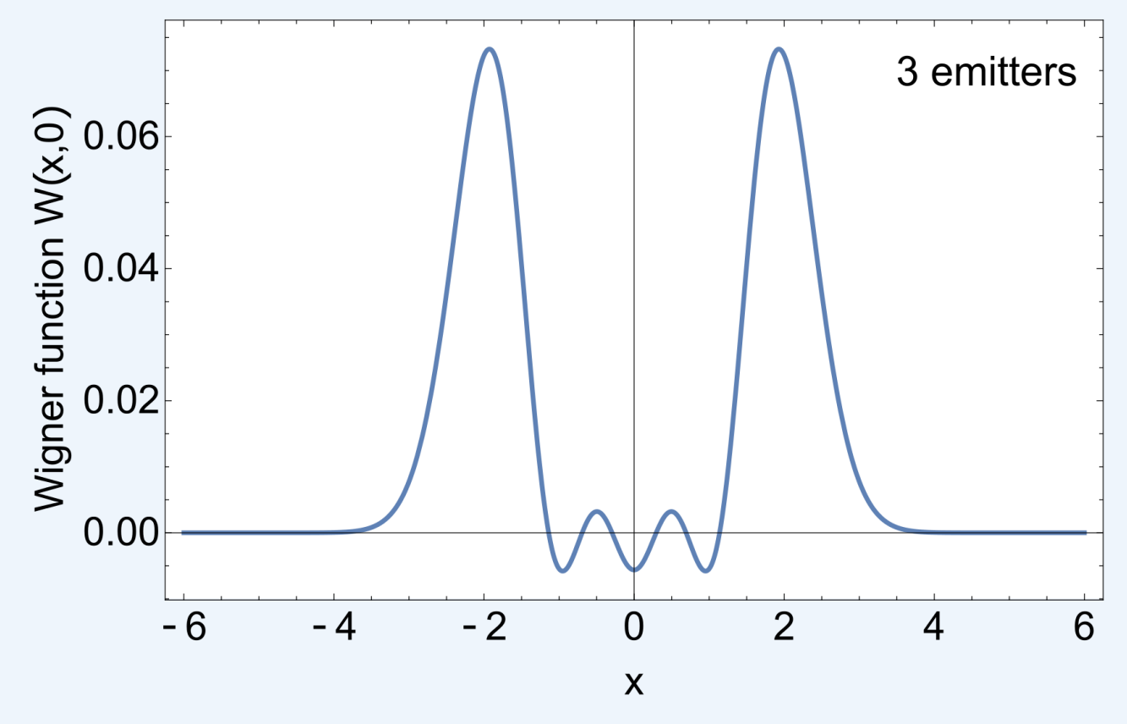
	measurement	theory
$\langle n\rangle$	0.625(2)	0.627(2)
$\langle(\Delta n)^2\rangle$	0.237(7)	0.239(8)
$g^2(0)$	0.009(1)	0.013(2)



mixing of three single photon states



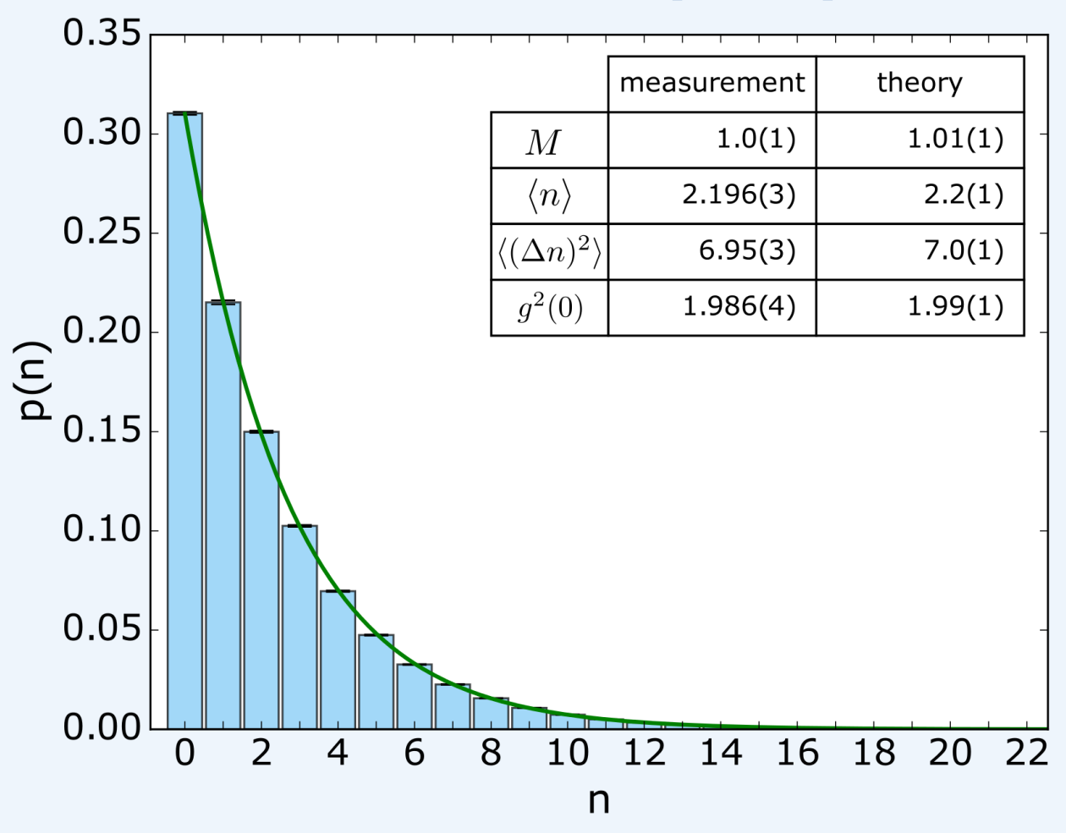
	measurement	theory
$\langle n\rangle$	1.893(6)	1.923(5)
$\langle(\Delta n)^2\rangle$	0.802(1)	0.801(3)
$g^2(0)$	0.695(3)	0.696(8)



Multimode thermal states

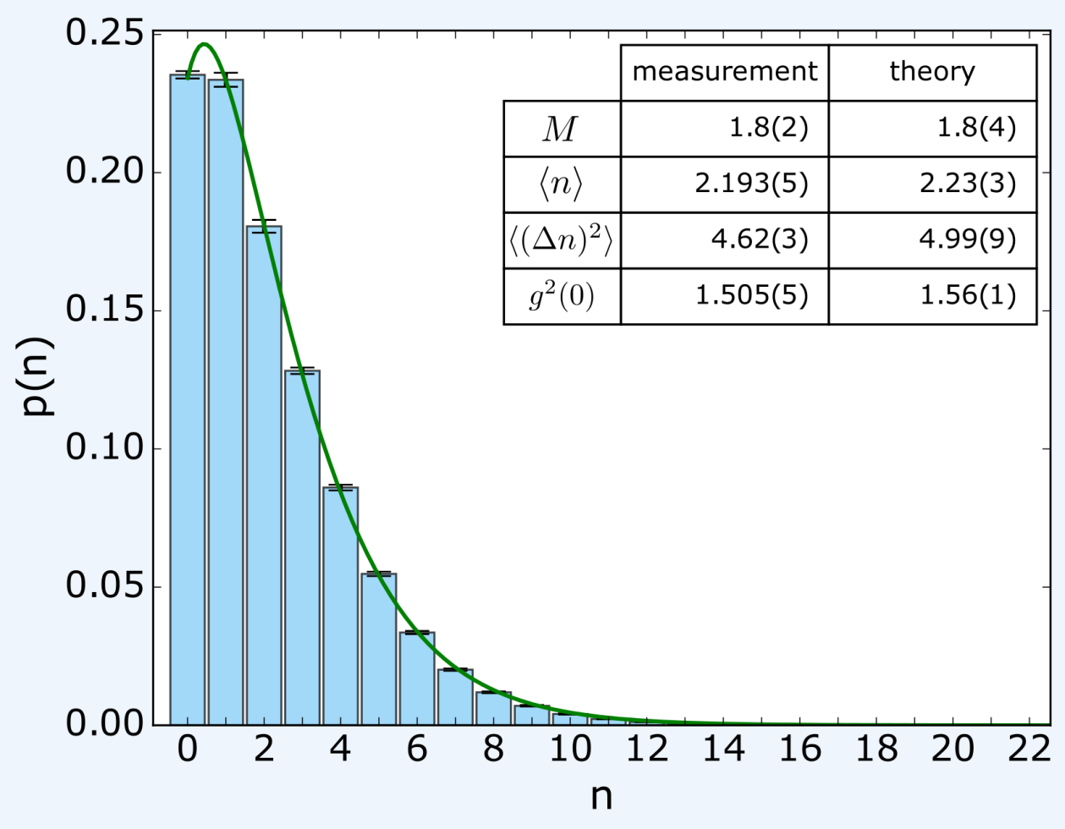
The effective number of modes M was modified by changing the size of the speckles collected via single mode optical fiber. This was achieved by changing the diameter of the laser spot on the RGG disk or the distance between disk and fibre tip.

one mode (M≈1)



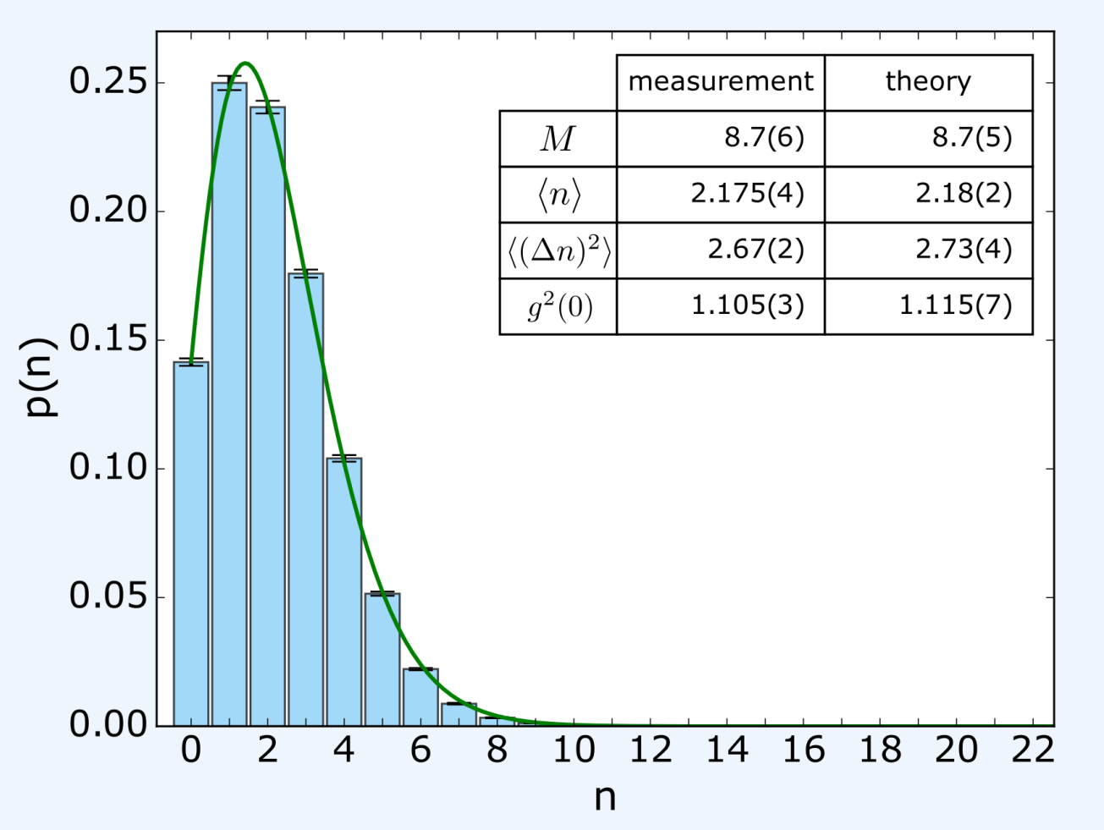
	measurement	theory
M	1.0(1)	1.01(1)
$\langle n\rangle$	2.196(3)	2.2(1)
$\langle(\Delta n)^2\rangle$	6.95(3)	7.0(1)
$g^2(0)$	1.986(4)	1.99(1)

two modes (M≈2)



	measurement	theory
M	1.8(2)	1.8(4)
$\langle n\rangle$	2.193(5)	2.23(3)
$\langle(\Delta n)^2\rangle$	4.62(3)	4.99(9)
$g^2(0)$	1.505(5)	1.56(1)

nine modes (M≈9)



	measurement	theory
M	8.7(6)	8.7(5)
$\langle n\rangle$	2.175(4)	2.18(2)
$\langle(\Delta n)^2\rangle$	2.67(2)	2.73(4)
$g^2(0)$	1.105(3)	1.115(7)

Applications

High-fidelity photon-number-resolving detectors are urgently needed for applications in quantum computing, communications and interferometry, as well as for extending the applicability of quantum detection generally (the characterization of quantum light sources...).
A photon-number-resolving detector would also be a very important tool for biological and medical imaging and low-light-level detection. Research and clinical activities deal with the analysis of fluorescent compounds for the identification and quantification of chemical reagents or for tracking or investigating biological molecules. A multiple-photon subtraction from thermal light is useful for generation and characterization of non-equilibrium states of light [2].

Conclusion

To analyze a photon distribution of an optical signal, we split the incident light into a balanced multiport terminated with single-photon avalanche photodiodes. The tunability of the spatial multiport network offers ideal balancing. Our device possesses high-fidelity photon number resolution up to 16, negligible noise, and total quantum efficiency of about 50%. Coupling between different ports (crosstalk) is impossible, as the individual ports are spatially separated into independent SPAD detectors. The dead time of the presented photon-number resolving detector is given solely by a dead time of the used SPAD. The efficiency and dead time can be further improved using superconducting nanowire single-photon detectors.

Acknowledgements

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References

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[2] J. Hloušek, et all., Work and information from thermal states after subtraction of energy quanta, in preparation (2017)
[3] I. Straka, L. Lachman, J. Hloušek, M. Miková, M. Mičuda, M. Ježek, and R. Filip, Quantum Non-Gaussian Multiphoton Light, arXiv:1611.02504 (2016)

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