Conditional Entanglement Recovery by Thermal Environment Probing

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Abstract

We propose and experimentally verify a conditional cooling limit for a quantum channel going through an incoherent environment. The environment consists of a large number of independent non-interacting and non-interfering qubits. The qubits travelling through the channel can be randomly replaced by environmental qubits. We propose an extension using an auxiliary probing channel. The limit specifies when the single-qubit channel is quantum, i.e. it preserves entanglement. It is a fundamental condition for entanglement-based quantum technology.

Cooling limits

- unconditional limit

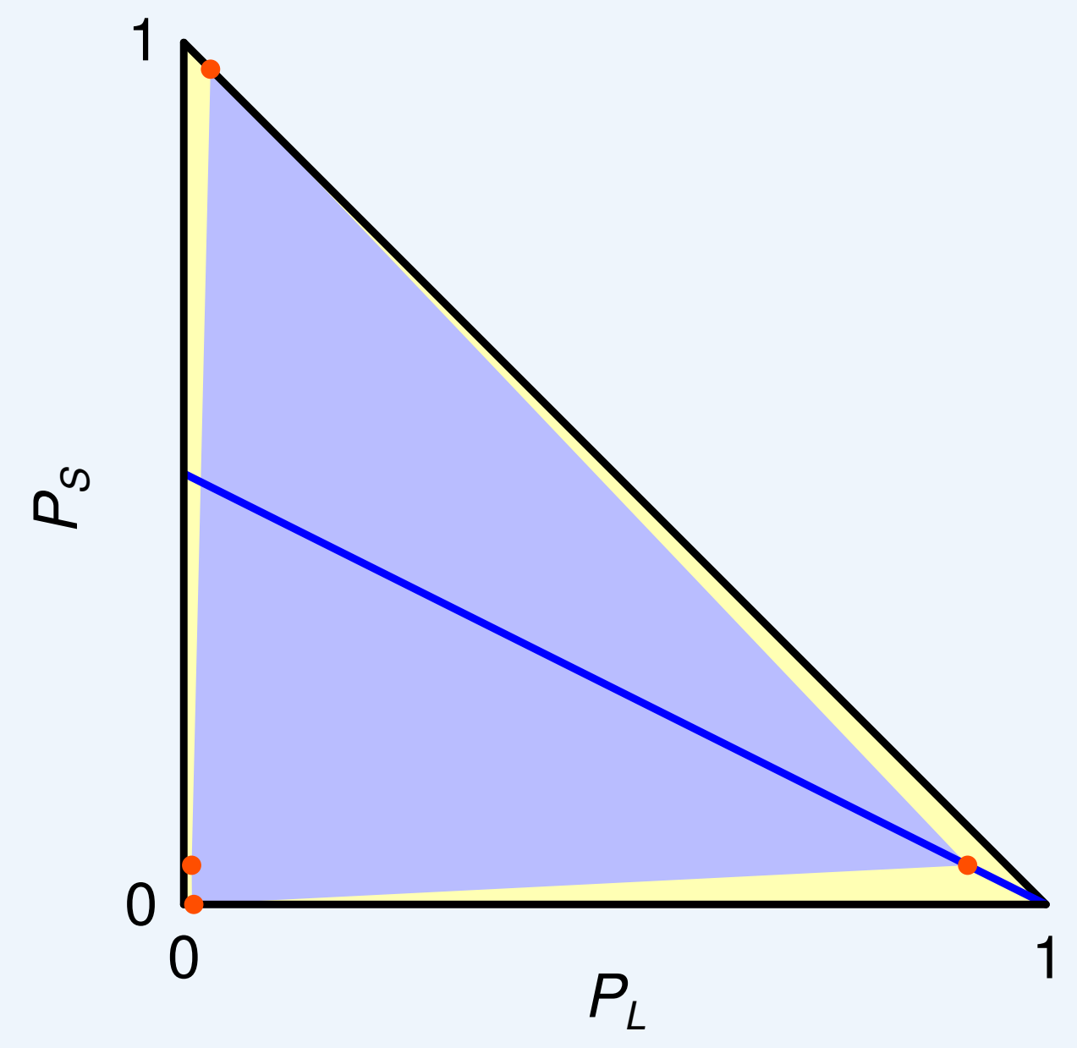
$$P_S > \frac{\sqrt{p_T(1-p_T)}}{1+\sqrt{p_T(1-p_T)}} \qquad (1)$$

- conditional limit

$$P_S > \frac{1}{2}\left(\sqrt{P_{TL}(4-3P_{TL})} - P_{TL}\right) \qquad (2)$$

The joint error probability $P_{TL} = p_T P_L$.
Unless $P_S + P_L \equiv 1$, the conditional limit is always less strict, allowing us to transfer entanglement for a broader range of parameters (see Results).

Parametric reach



Our proof-of-principle measurement (a) covers a one-dimensional subspace denoted by the solid blue line. In principle, the simulator can cover the whole space (yellow) using a more general coupling (b). However, a realistic entanglement source that also produces single photons limits the reachable parameters. For a case of a bright source with 20% efficiency, the reachable subspace is represented by the blue quadrilateral spanned by the red points. This area can be asymptotically stretched. On the right side, an additional attenuation right before the environment would be needed. On the side of $P_L \to 0$, we would need to either increase the efficiency of the source, or use a sub-Poissonian single-photon noise instead of a laser diode.

Acknowledgements

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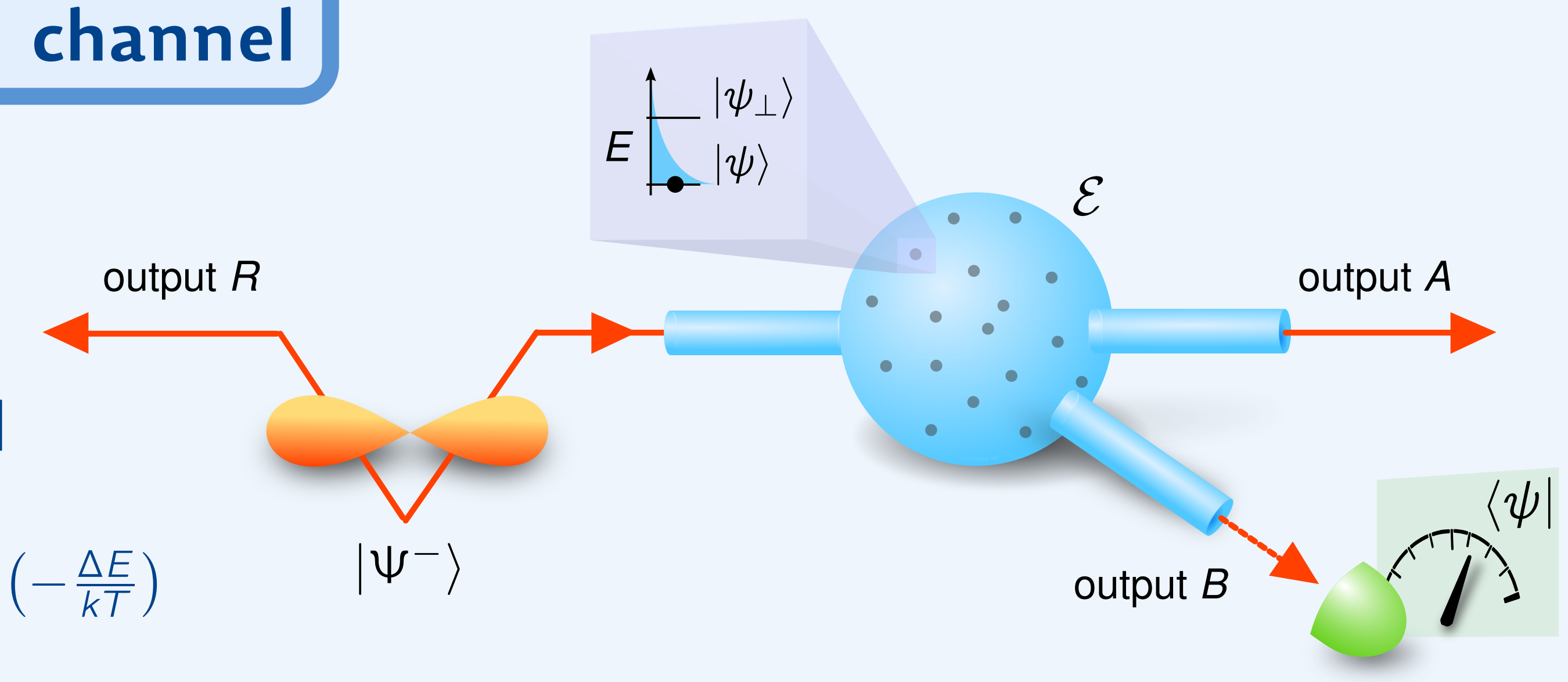
Schematic of the noisy channel

$$|\Psi^-\rangle = \tfrac{1}{\sqrt{2}}\left(|\psi\rangle|\psi_\perp\rangle - |\psi_\perp\rangle|\psi\rangle\right)$$

$$\mathcal{E} = (1-p_T)|\psi\rangle\langle\psi| + p_T|\psi_\perp\rangle\langle\psi_\perp|$$

for thermal equilibrium: $p_T \propto \exp\left(-\frac{\Delta E}{kT}\right)$



An entangled state is propagated through an environment containing a large amount of incoherent particles in a noise state $\mathcal{E}$. Entanglement is evaluated between outputs R and A. With a probability $1-P_S$, the singlet is replaced by an incoherent qubit $\mathcal{E}$ from the environment. In order for the channel to be entanglement-preserving, an unconditional limit (1) must be fulfilled. In this work, we extend this limit by exploiting an auxiliary output B. The channel is then a mixture of three processes with the probabilities:

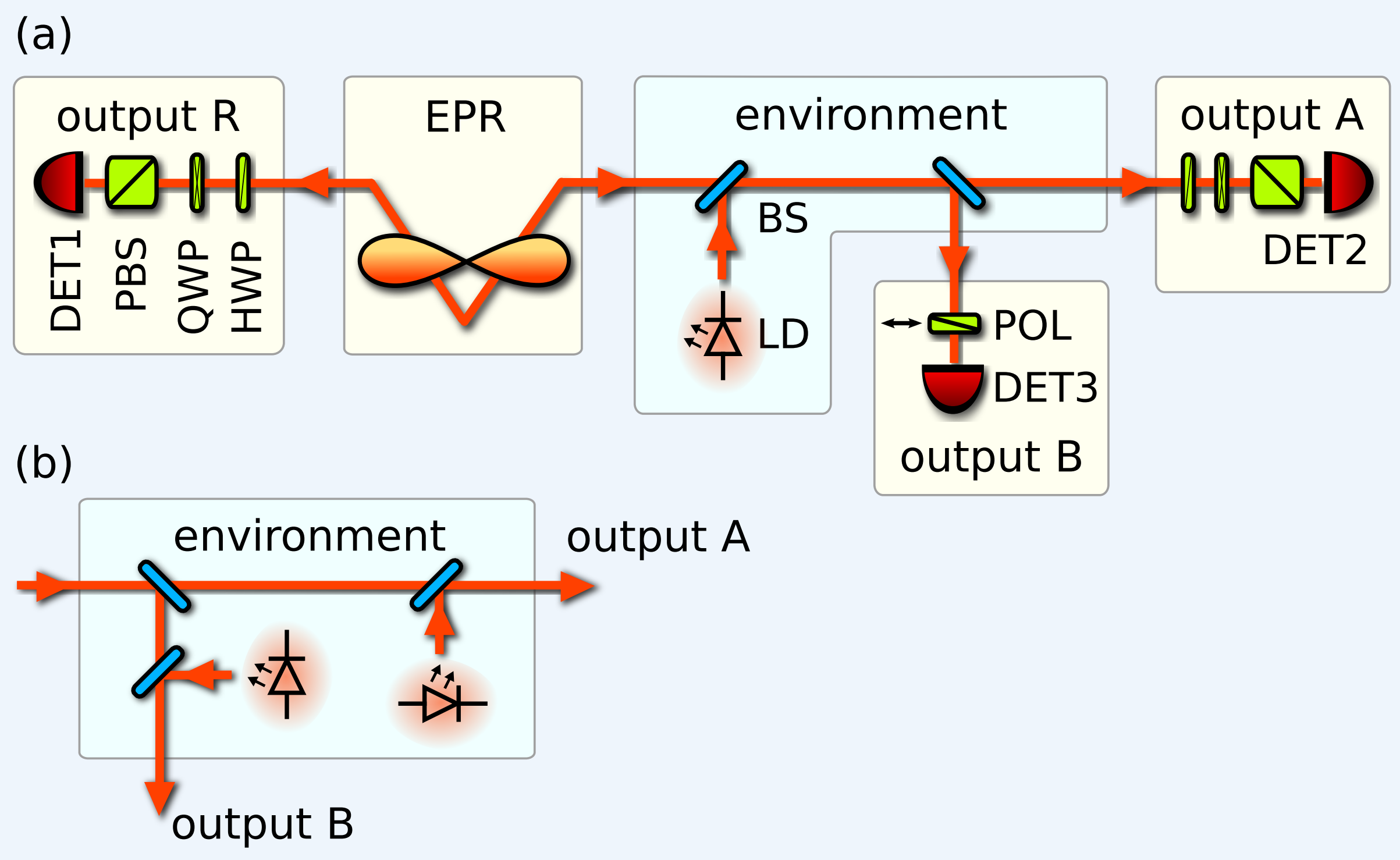
- P_S (Success) – the singlet is transmitted to A, while B couples noise
- P_F (Flip) – the singlet is redirected to B, on A we find noise
- P_L (Loss) – the singlet is lost and both A, B yield noise

We use the optimal projection of the qubit B onto the base state $|\psi\rangle$ to herald the measurement. As a result, we are able to conditionally preserve entanglement between R, A, yielding a conditional limit (2). The limits can be tested by propagating a maximally entangled singlet state $|\Psi^-\rangle$.

$$\begin{aligned}&P_S|\Psi^-\rangle\langle\Psi^-|_{\mathrm{R,A}} \otimes \mathcal{E}_{\mathrm{B}} +\\ &P_F|\Psi^-\rangle\langle\Psi^-|_{\mathrm{R,B}} \otimes \mathcal{E}_{\mathrm{A}} +\\ &P_L\frac{1}{2}\mathbb{1}_{\mathrm{R}} \otimes \mathcal{E}_{\mathrm{A}} \otimes \mathcal{E}_{\mathrm{B}}\end{aligned}$$

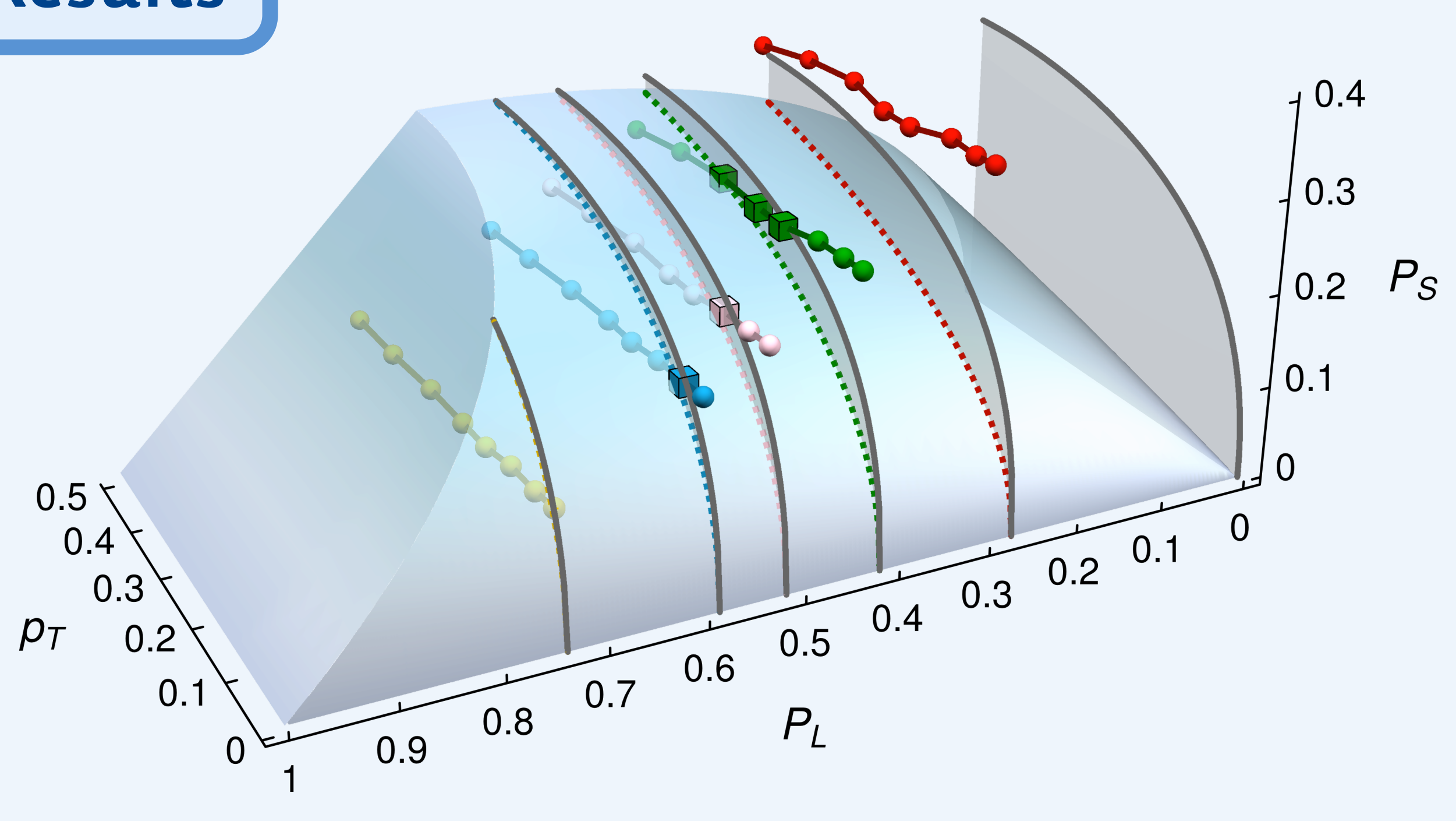
output state before any projection

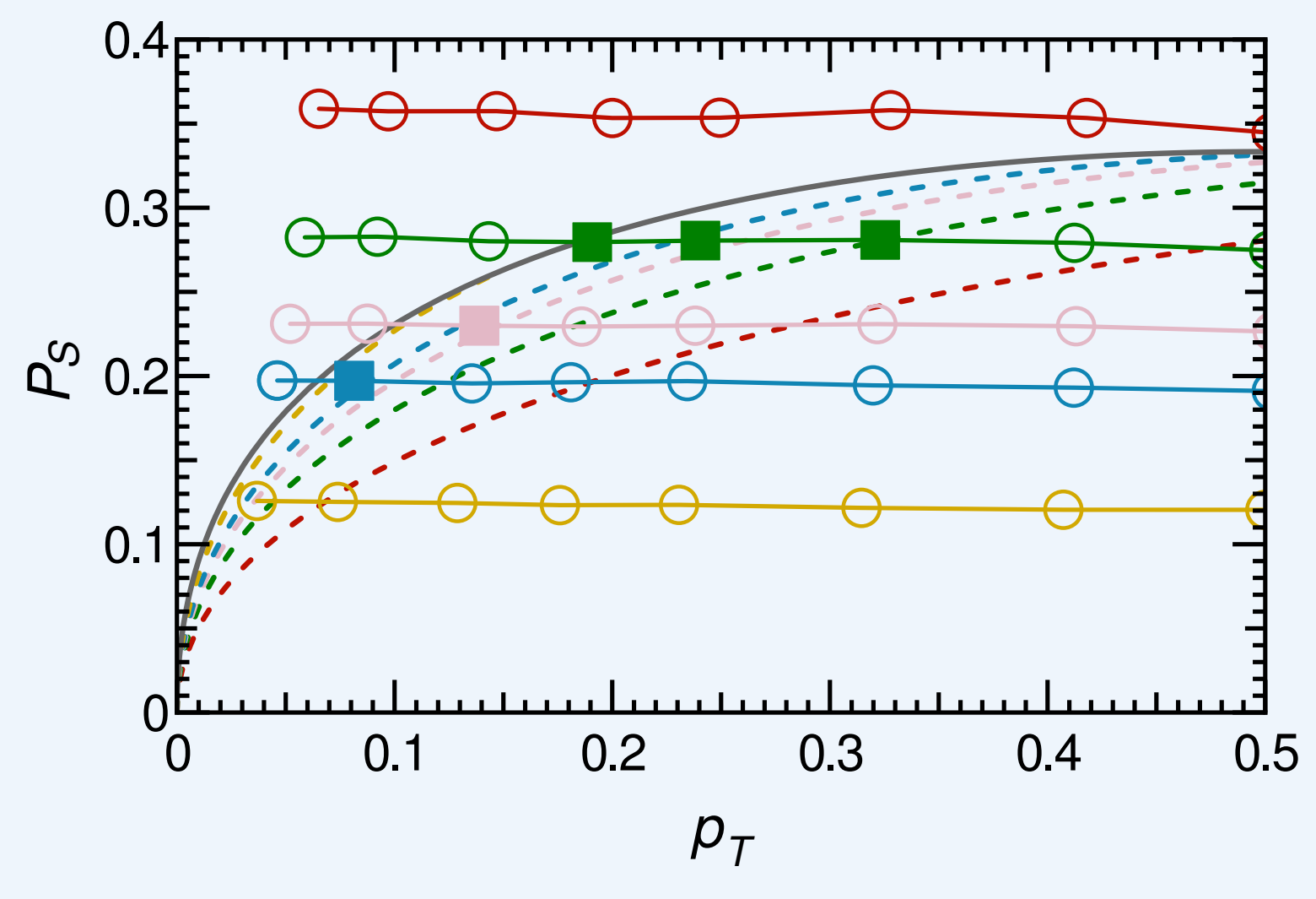
Photonic simulator



For our proof-of-principle simulation (a), we employed qubits encoded into polarization of single photons. A singlet state was conditionally generated by parametric down-conversion and incoherently mixed with a polarization noise generated by a laser diode. Both noise mixing and auxiliary probing in the environment were done using 50:50 beam splitters. A full state tomography on outputs R, A was conditioned by the projection on output B. The environment (b), where the noise is coupled to both outputs independently, represents an extension to cover a wider range of environmental parameters.

Results





The figure on the left shows the parameters p_T, P_S, P_L fitted from the measured states. Each dataset represents various polarizations of the noise for a certain noise intensity, which determines P_S, P_L. Solid grey lines represent the unconditional limit (1) and the blue surface represents the conditional limit (2). The coloured dashed lines depict (2) for individual P_L values. Cube/square points represent the states that would be separable without environment probing, but where the probing helped recover the entanglement. The space is limited by the condition $P_L + P_S \leq 1$, which visibly cuts both separability limits for higher P_L. For a clear visualisation of numerical values, see the figure on the right.

References

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