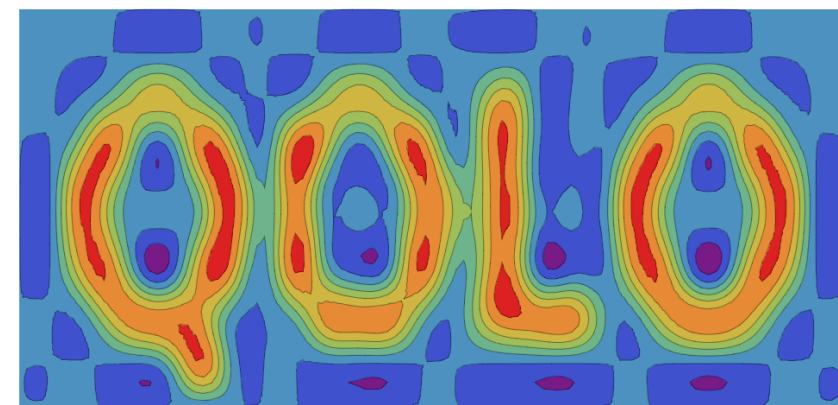




# Quantum controlled-Z gate for weakly interacting qubits



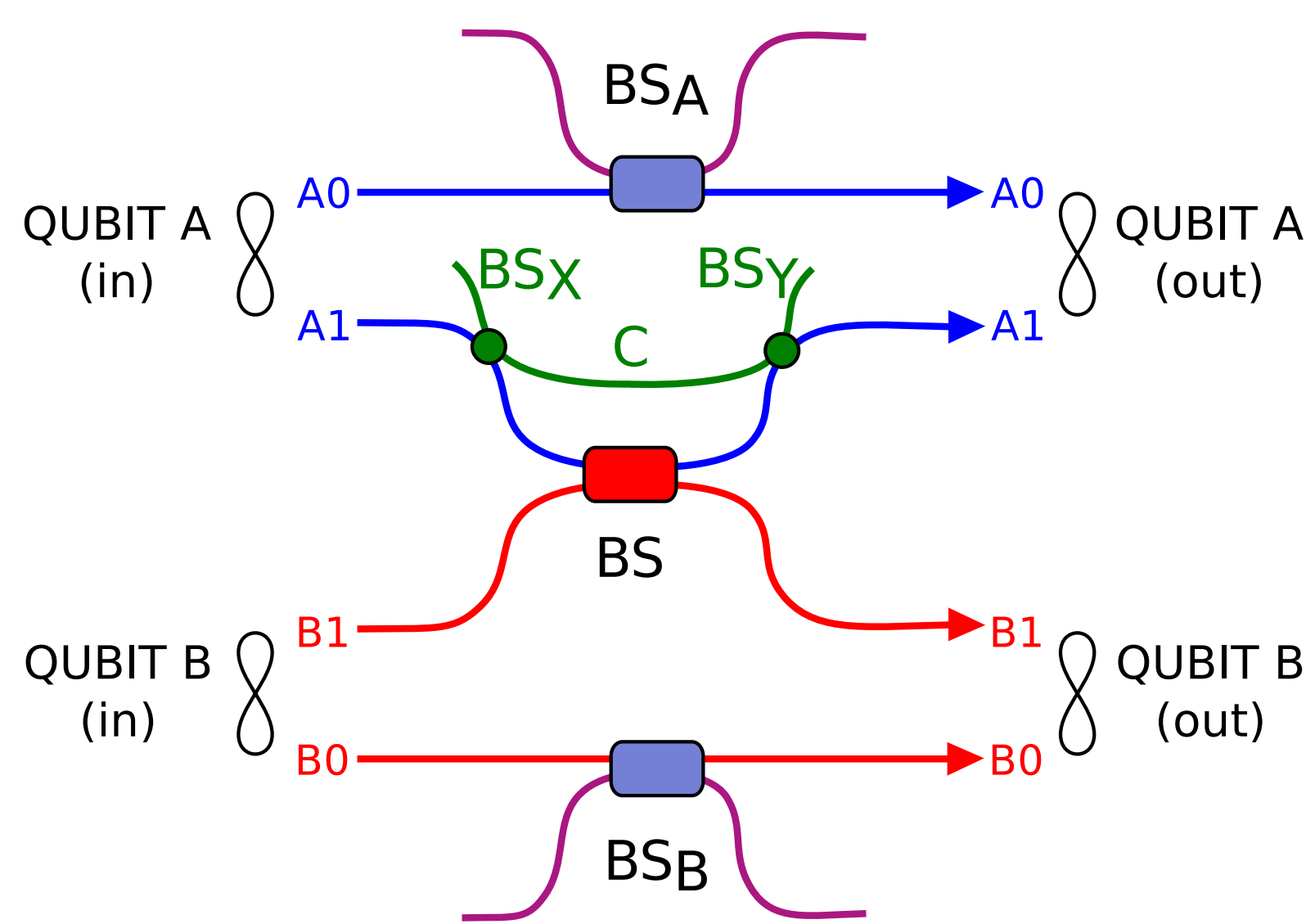
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## Abstract

We propose and experimentally demonstrate a scheme for conditional implementation of a maximally entangling quantum controlled-Z gate between two qubits whose coupling can be arbitrarily weak. We show that the weak inter-qubit coupling can be enhanced by quantum interference. Both before and after the interqubit interaction, one of the qubits is coherently coupled to an auxiliary quantum level, and finally it is projected back onto the qubit subspace. This procedure enhances the inter-qubit interaction strength although the coupling to auxiliary quantum level can be considered as a local bypass that allows the qubit to partly avoid the interaction with the other qubit. Since this bypass is introduced only to one of the qubits, the scheme is suitable for hybrid architectures such as atomic clouds or optomechanical oscillators coupled to light.

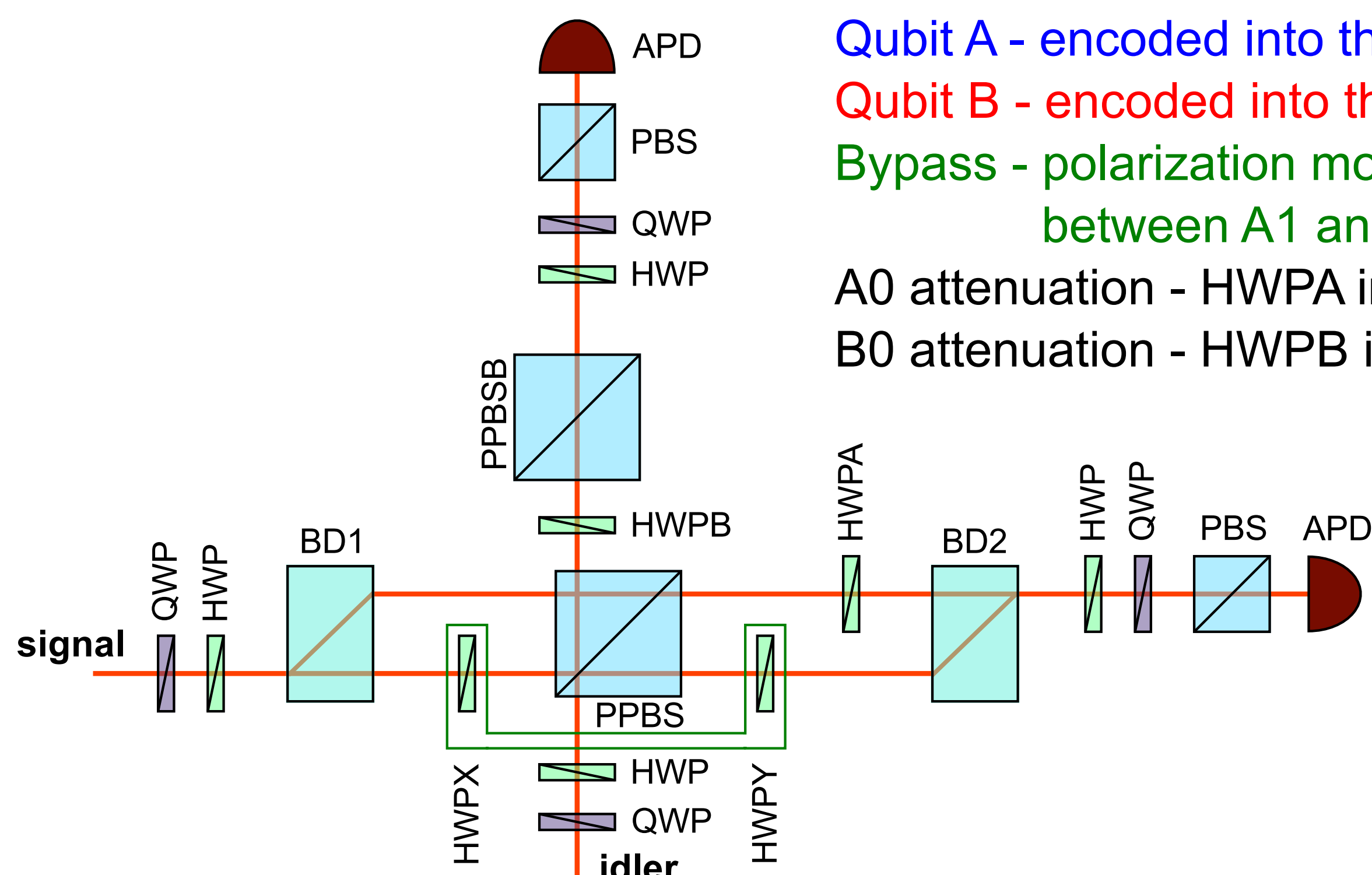
## Linear optical quantum CZ gate with weak interferometric coupling



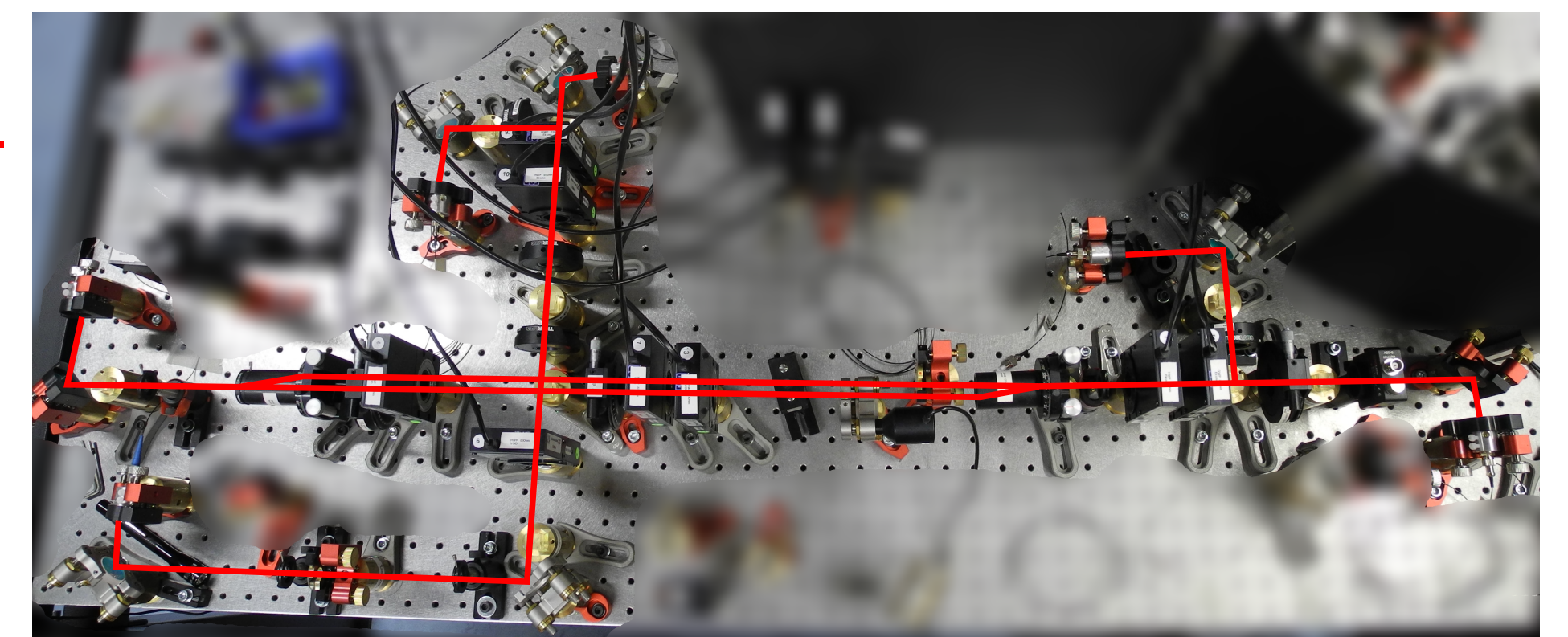
Qubits are encoded into paths of single photons and gate operates in coincidence basis. For a weak regime, the BS transmittance is  $R < 1/2$ . To recover CZ operation we introduce auxiliary mode C to partly bypass interaction on BS. Mode A1 is coupled to bypass mode C by  $BS_X$  with transmittance  $T_X$ . After mode A1 and B1 interact on BS, modes A1 and C are recombined by  $BS_Y$  with transmittance  $T_Y$ . Modes A0 and B0 are suitably attenuated by coupling them to auxiliary vacuum modes via  $BS_A$  and  $BS_B$ .

The probability of the gate success:  $P_S = R^2 T_X T_Y / 4$ .  
The probability is maximized for:  $T_X = T_Y$ .

## Experimental implementation



Qubit A - encoded into the path of signal photon.  
Qubit B - encoded into the polarization mode of idler photon.  
Bypass - polarization mode of the signal photon, coupling between A1 and C mode by HWPX and HWPY.  
A0 attenuation - HWPB in conjunction with BD2.  
B0 attenuation - HWPB in conjunction with PPBSB.

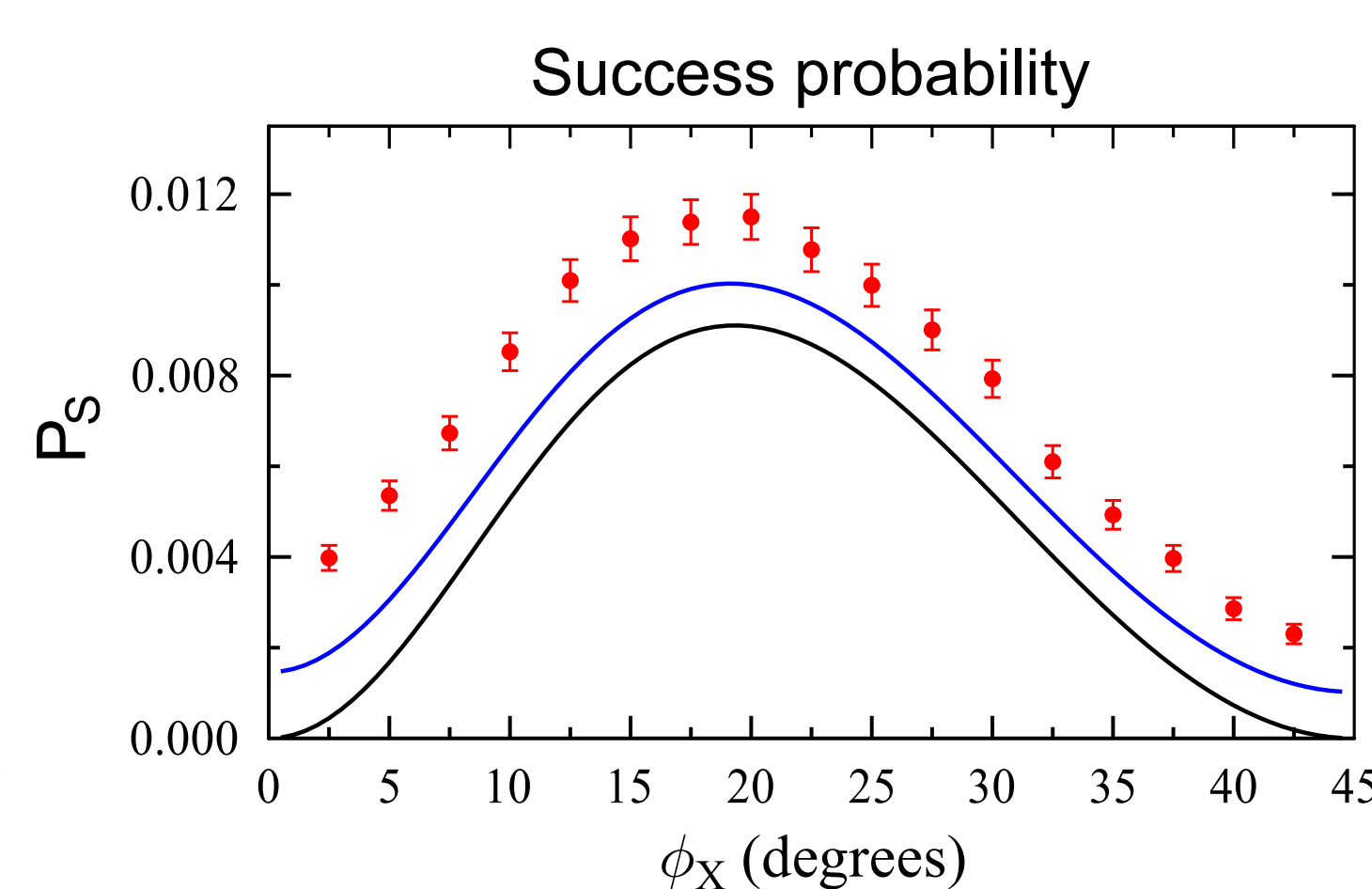
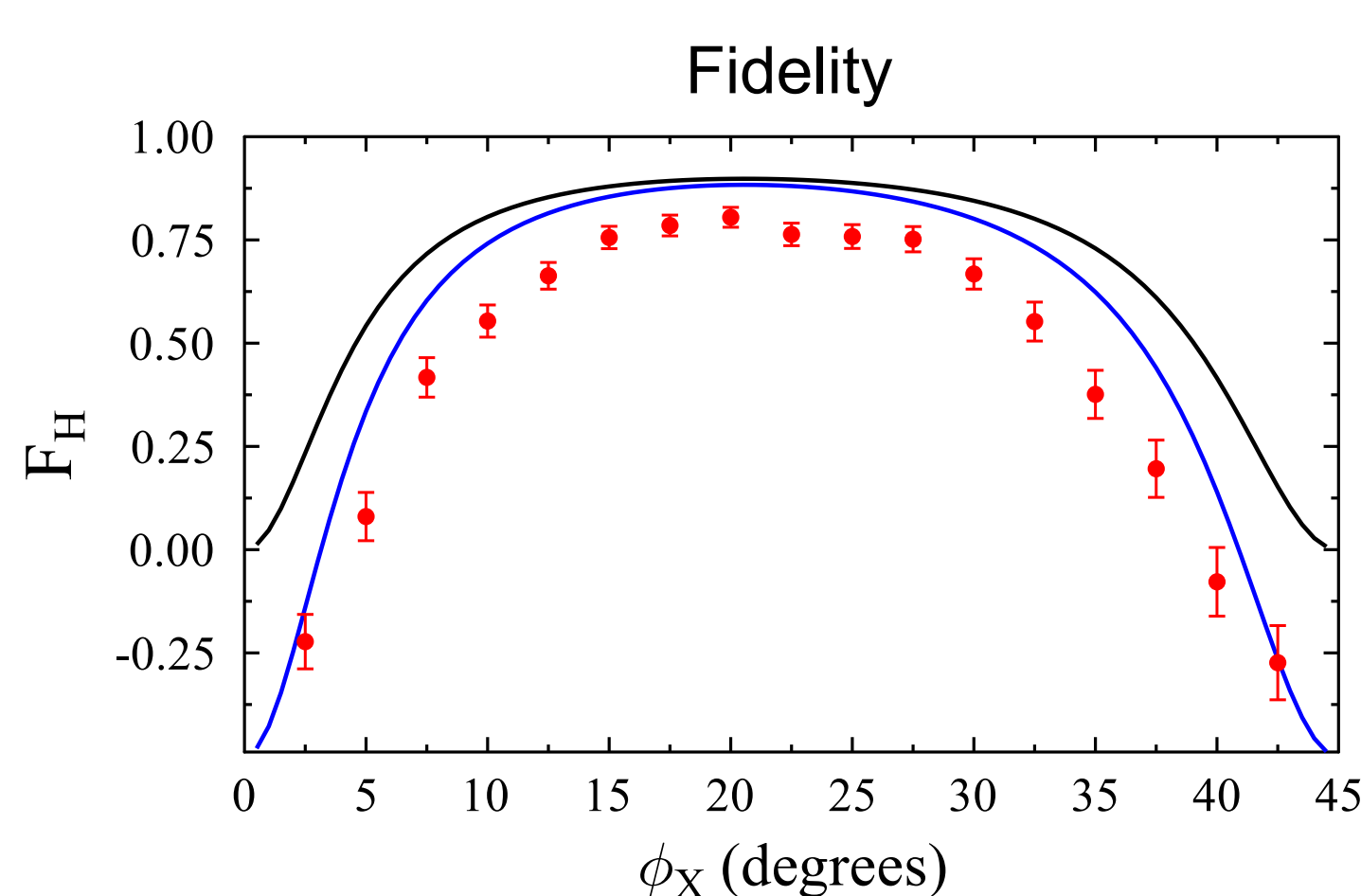


Coupling strength between modes A1 and C:

$$T_X = \cos^2(2\phi_X).$$

Correlated photon pairs generated by SPDC are employed. BD - calcite beam displacer that spatially separates horizontal and vertical polarization, PPBS - partially polarizing beam splitter with transmittances  $R_V = 0.313$  and  $R_H = 0.019$ , PBS - polarizing beam splitter, HWP - half-wave plate, QWP - quarter-wave plate, APD - single-photon detector.

## Results

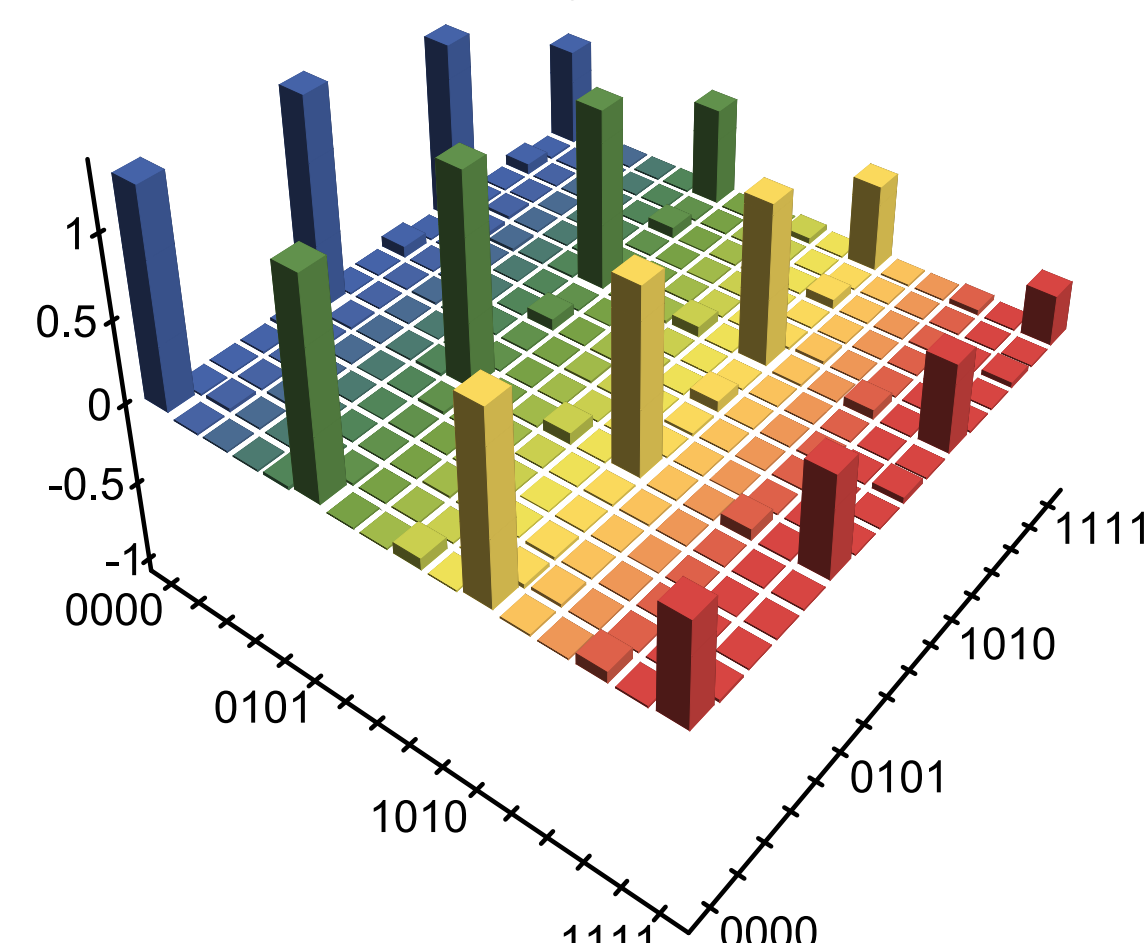


Gate fidelity:  $F_\chi = \text{Tr}[\chi\chi_{CZ}] / (\text{Tr}[\chi]\text{Tr}[\chi_{CZ}])$   
Hoffmann bound on quantum process fidelity:  $F_H = F_1 + F_2 - 1 \leq F_\chi$   
Ideal scheme (black line):  $R_H = 0, V_{\text{HOM}} = 1$   
Theoretical model (blue line):  $R_H = 0.019, V_{\text{HOM}} = 0.94$   
Maximum theoretical gate fidelity at optimal operating point ( $\phi_X = 20^\circ$ ):  
 $F_\chi = 0.889$

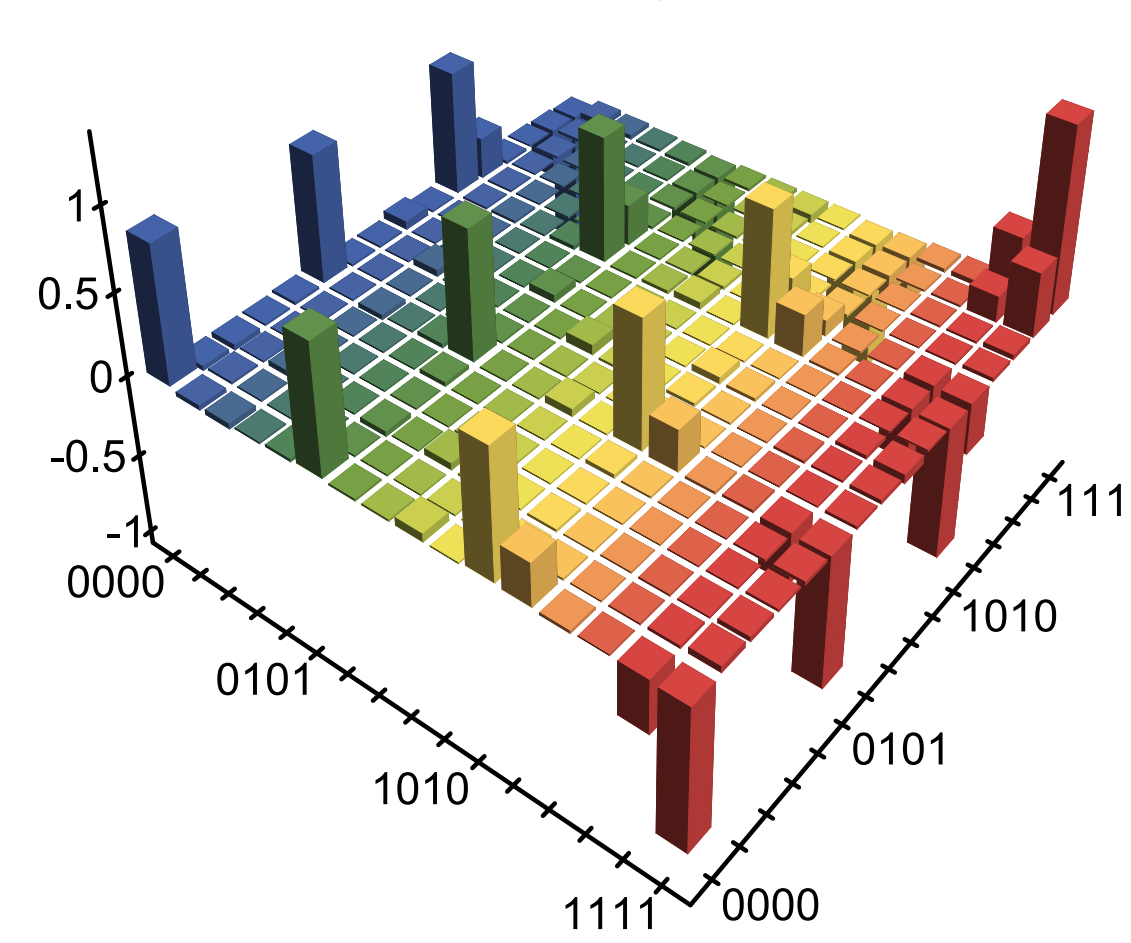
Quantum process tomography of CZ gate:

- number of preparations/measurements configuration:  $6^4 = 1296$
- 10s acquisition per configuration
- total time of 6 hours

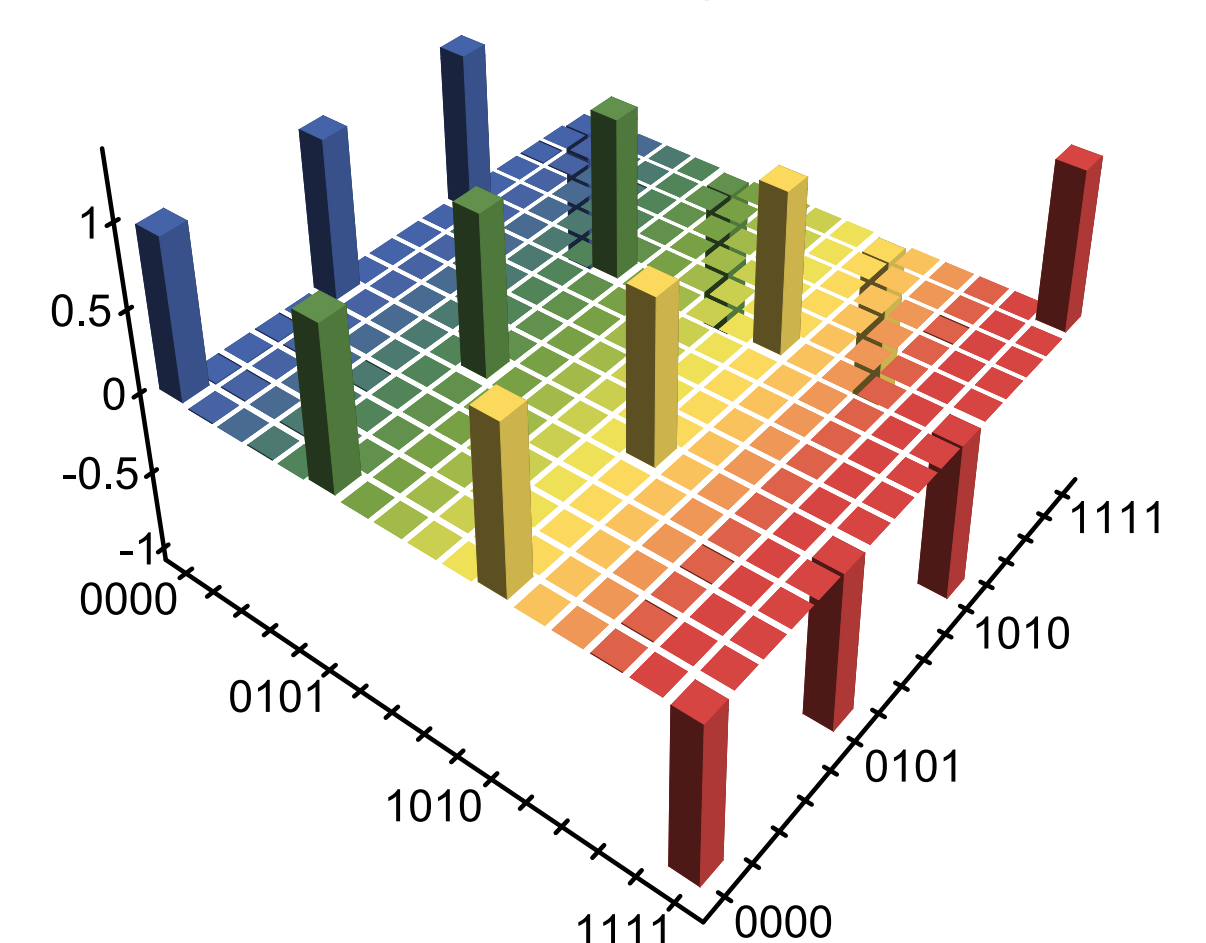
no bypass



optimal bypass



ideal CZ gate



## References

- PRL 107, 133603 (2011) PRL 94, 160504 (2005) PRA 89, 042304 (2014)  
PRA 83, 040101(R) (2011) PRA 89, 042304 (2014) PRL 111, 160407 (2013)

## Acknowledgments

This work was supported by the Czech Science Foundation (13-20319S). R.S. acknowledges support by Palacký University (IGA-PrF-2014008).