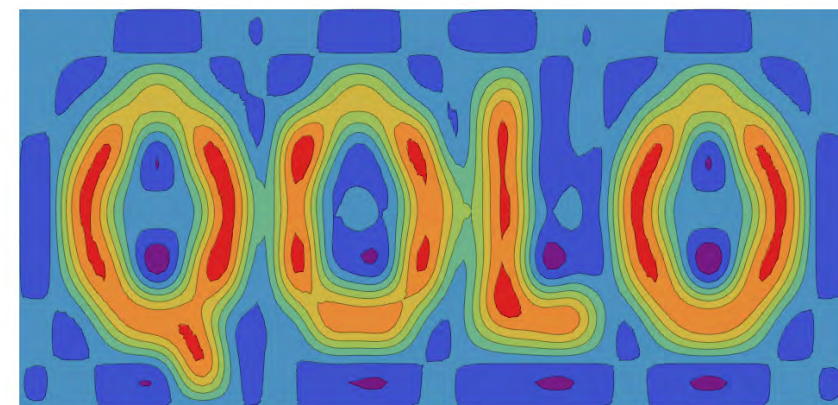# Quantum controlled-Z gate for weakly interacting qubits

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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 oscilators coupled to light.

## Linear optical quantum CZ gate with weak interferometric coupling
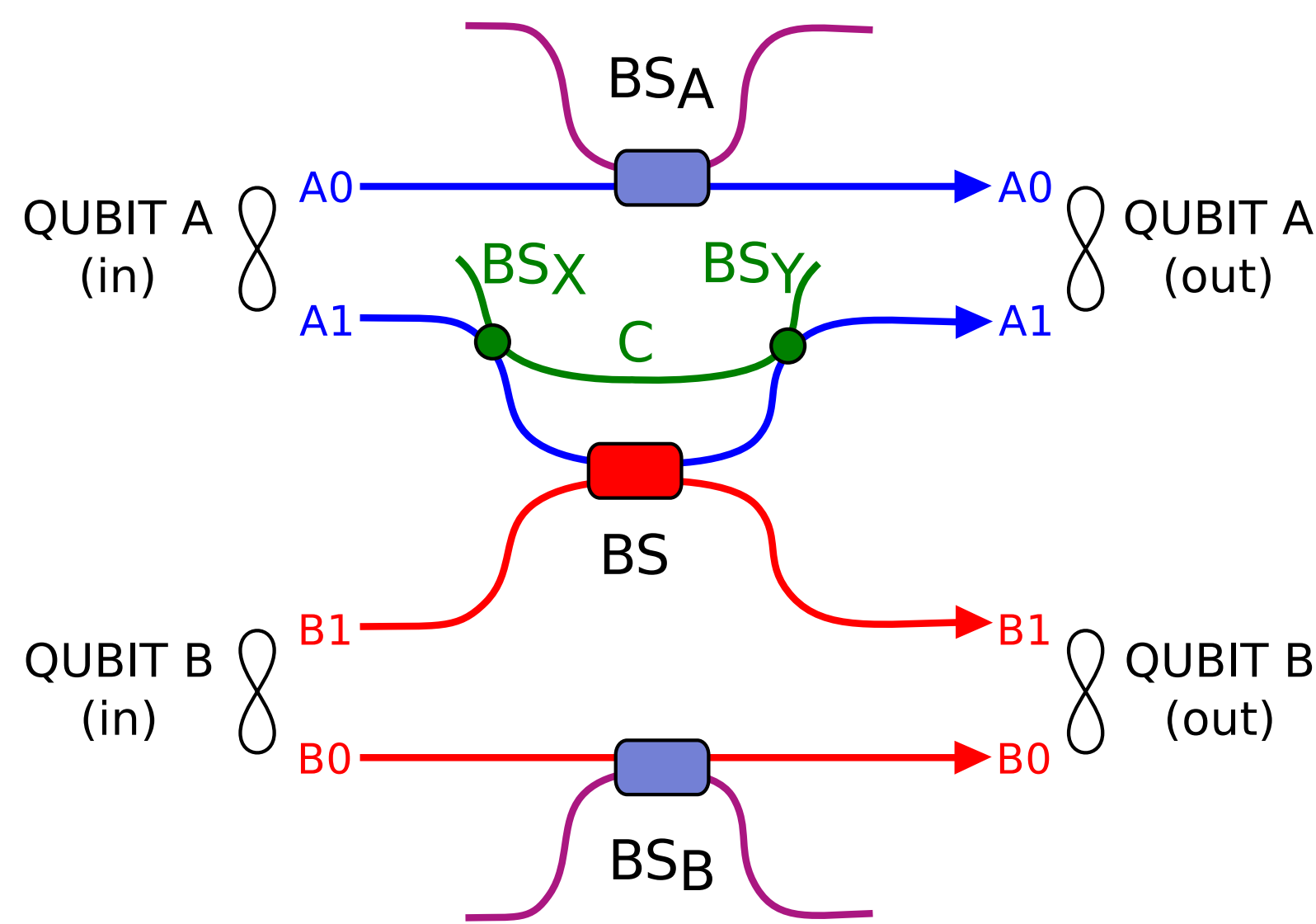
Qubits are encoded into paths of single photons and gate operates in coincidence basis. For a weak regime, the BS transmittance is $R < 1/2$. To recover CZ operation we introduce auxiliary mode C to partly bypass interaction on BS. Mode A1 is coupled to bypass mode C by BS_X with transmittance T_X. After 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 succes: $P_S = R^2 T_X T_Y / 4$.
The probability is maximized for: $T_X = T_Y$.

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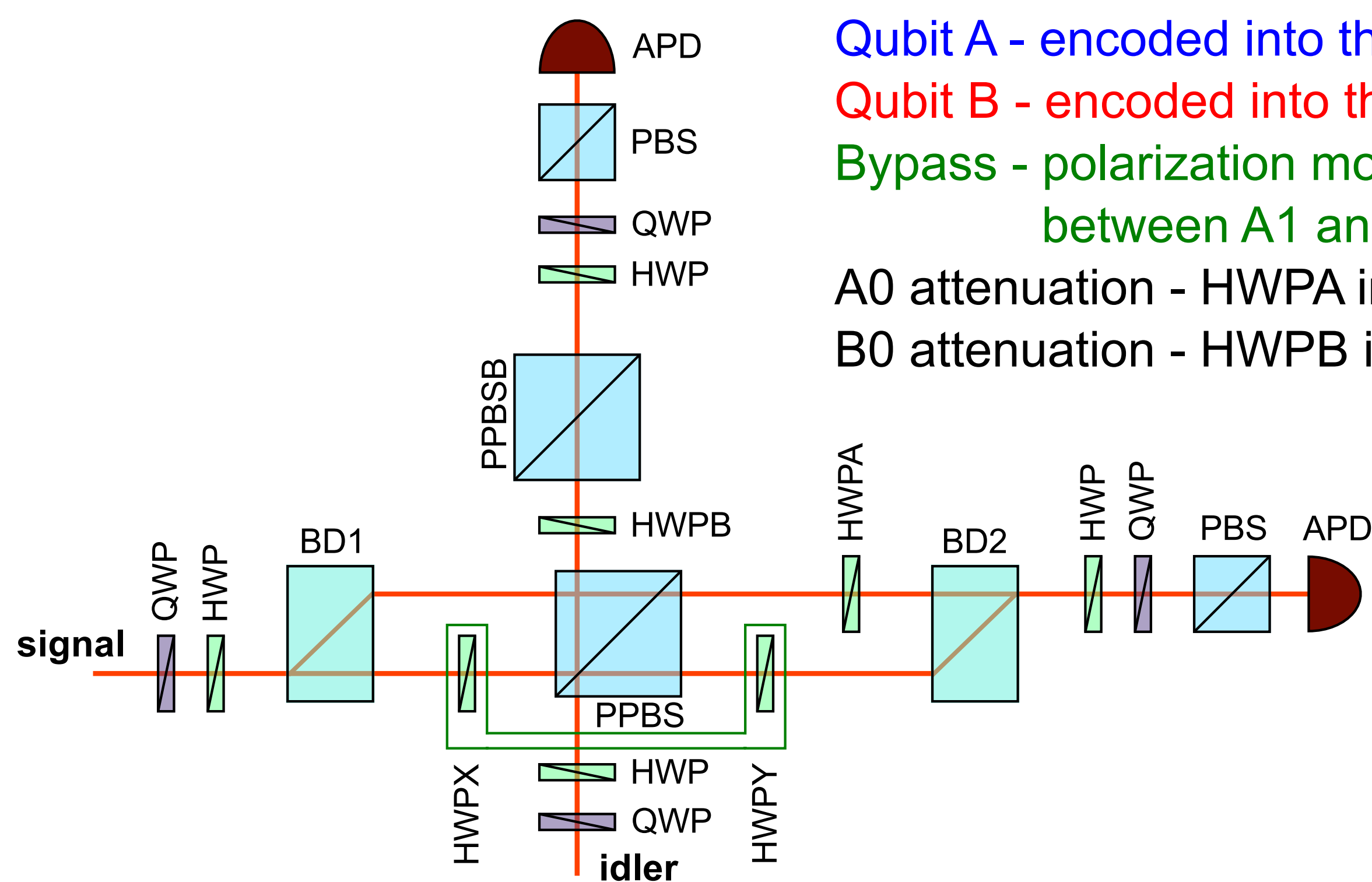
Qubit A - encoded into the path of signal photon.
Qubit B - encoded into the polarization mode of idler photon.
Bypass - polarization mode of the signal photon, coupling between A1 and C mode by HWPX and HWPY.
A0 attenuation - HWPA in conjunction with BD2.
B0 attenuation - HWPB in conjunction with PPBSB.
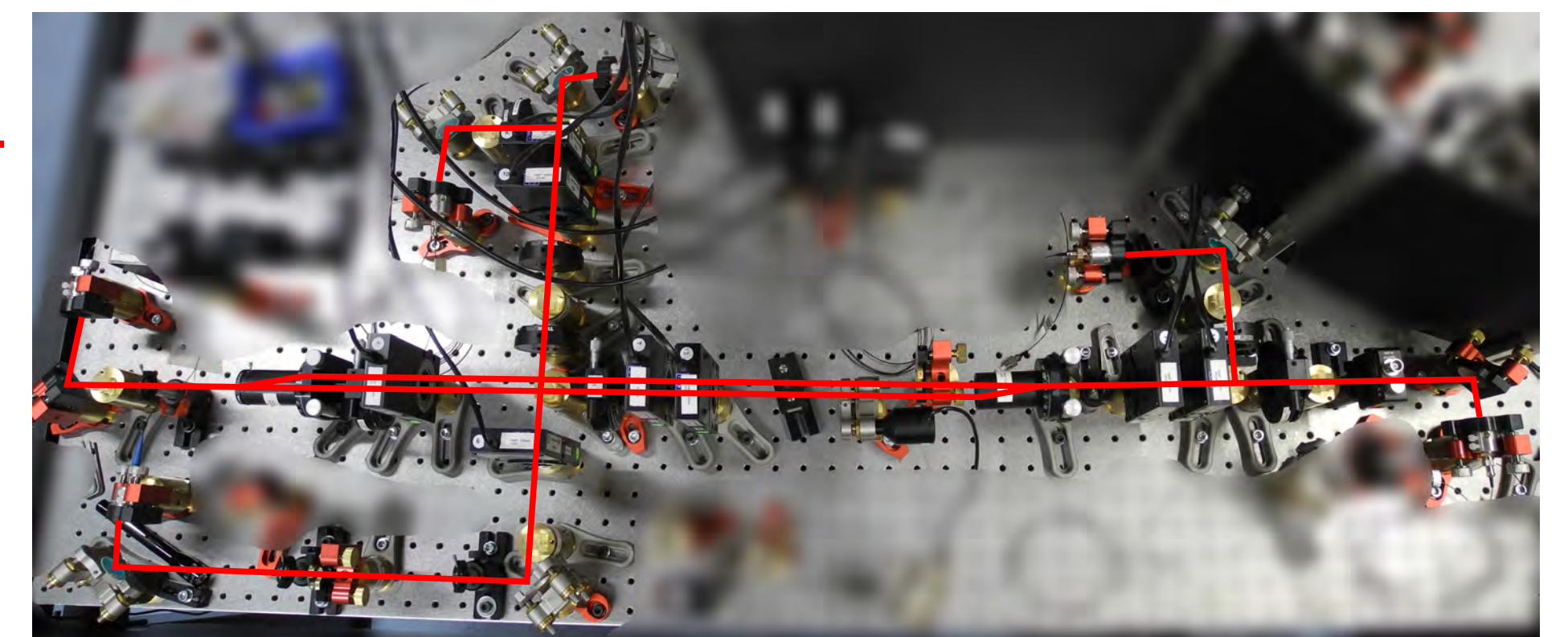
Coupling strength between modes A1 and C:

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

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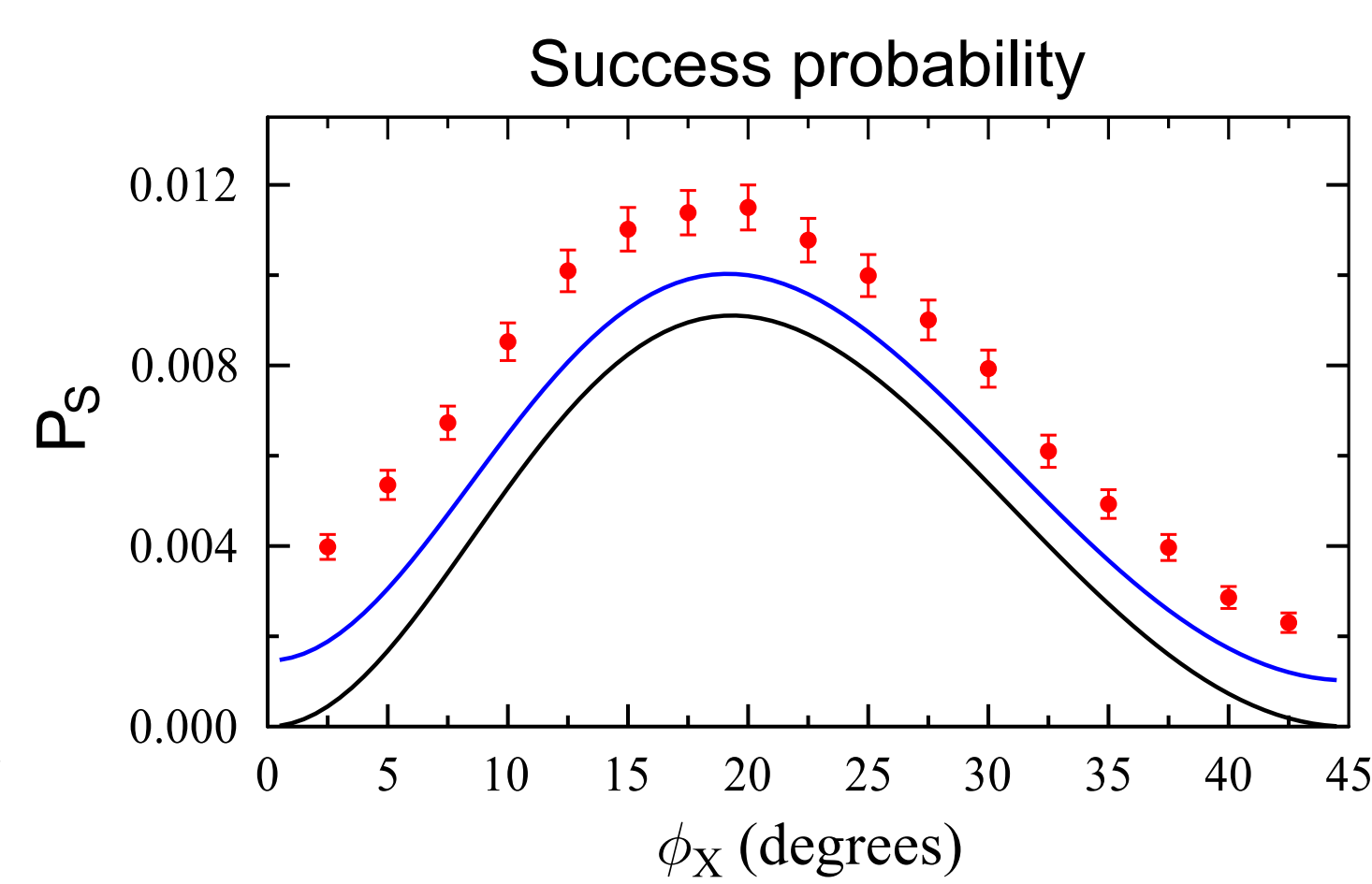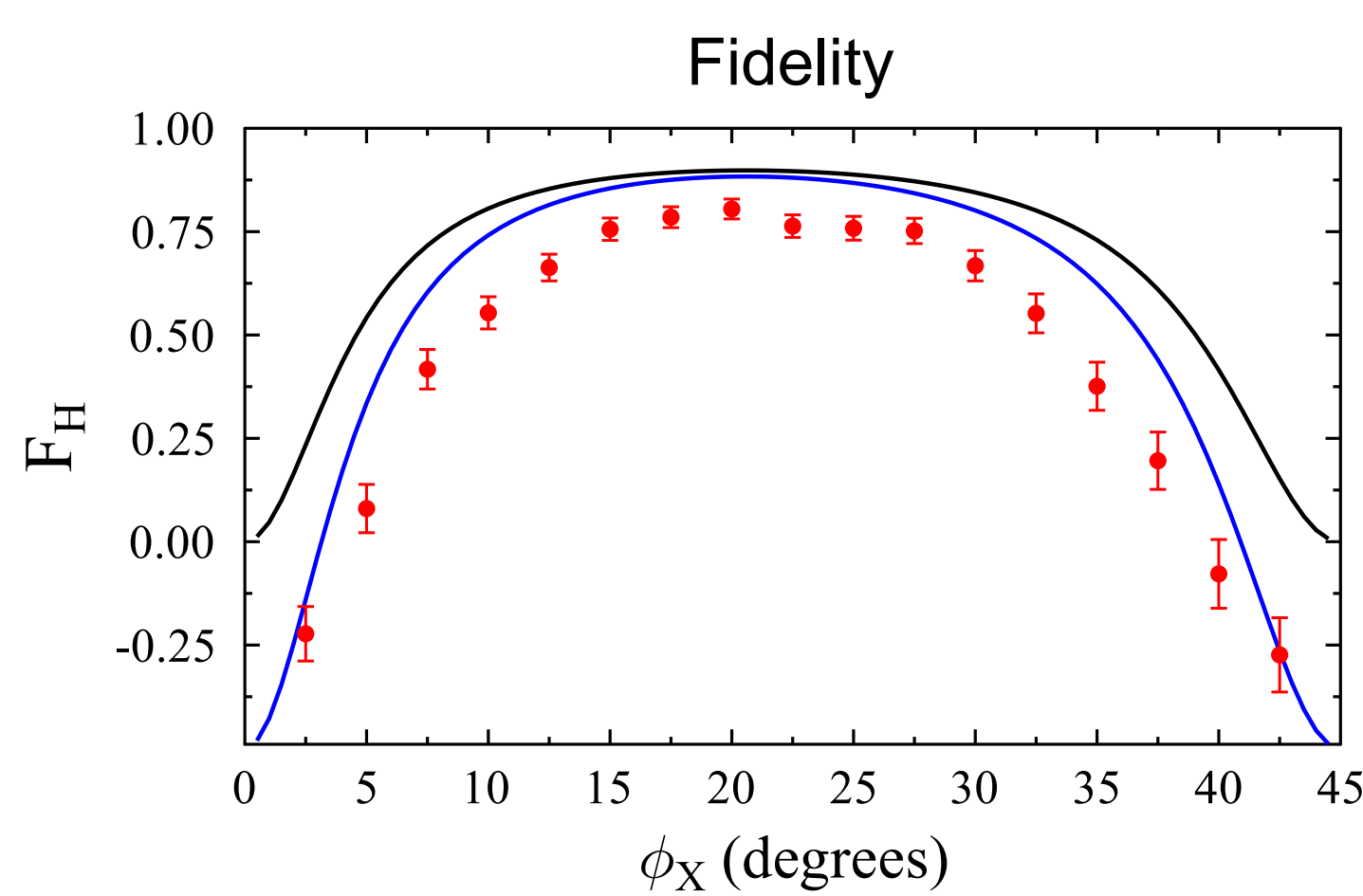
Gate fidelity: $F_\chi = Tr[\chi \chi_{CZ}]/(Tr[\chi]Tr[\chi_{CZ}])$
Hoffmann bound on quantum process fidelity: $F_H = F_1 + F_2 - 1 \leq F_\chi$
Ideal scheme (black line): $R_H = 0, V_{HOM} = 1$
Theoretical model (blue line): $R_H = 0.019, V_{HOM} = 0.94$
Maximum theoretical gate fidelity at optimal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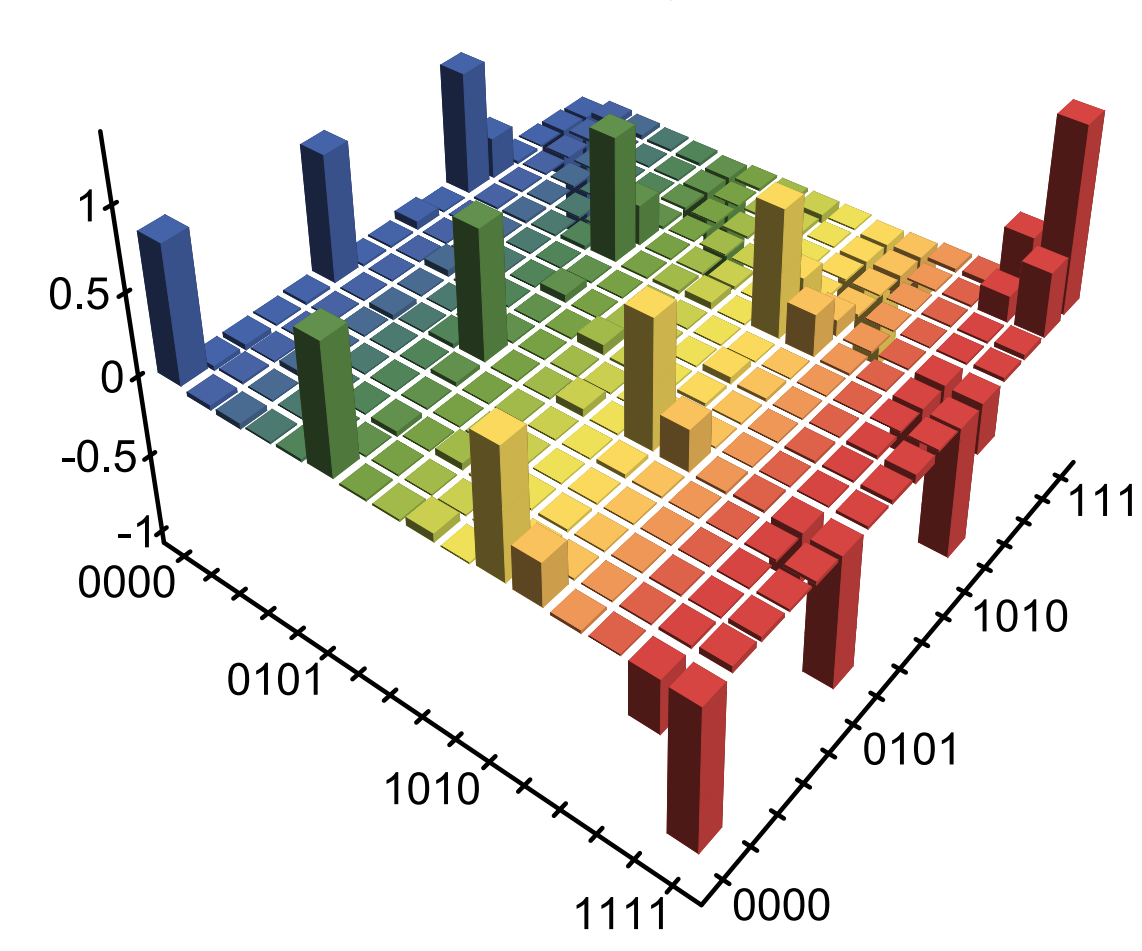$$F_\chi = 0.889$$

Quantum process tomography of CZ gate:

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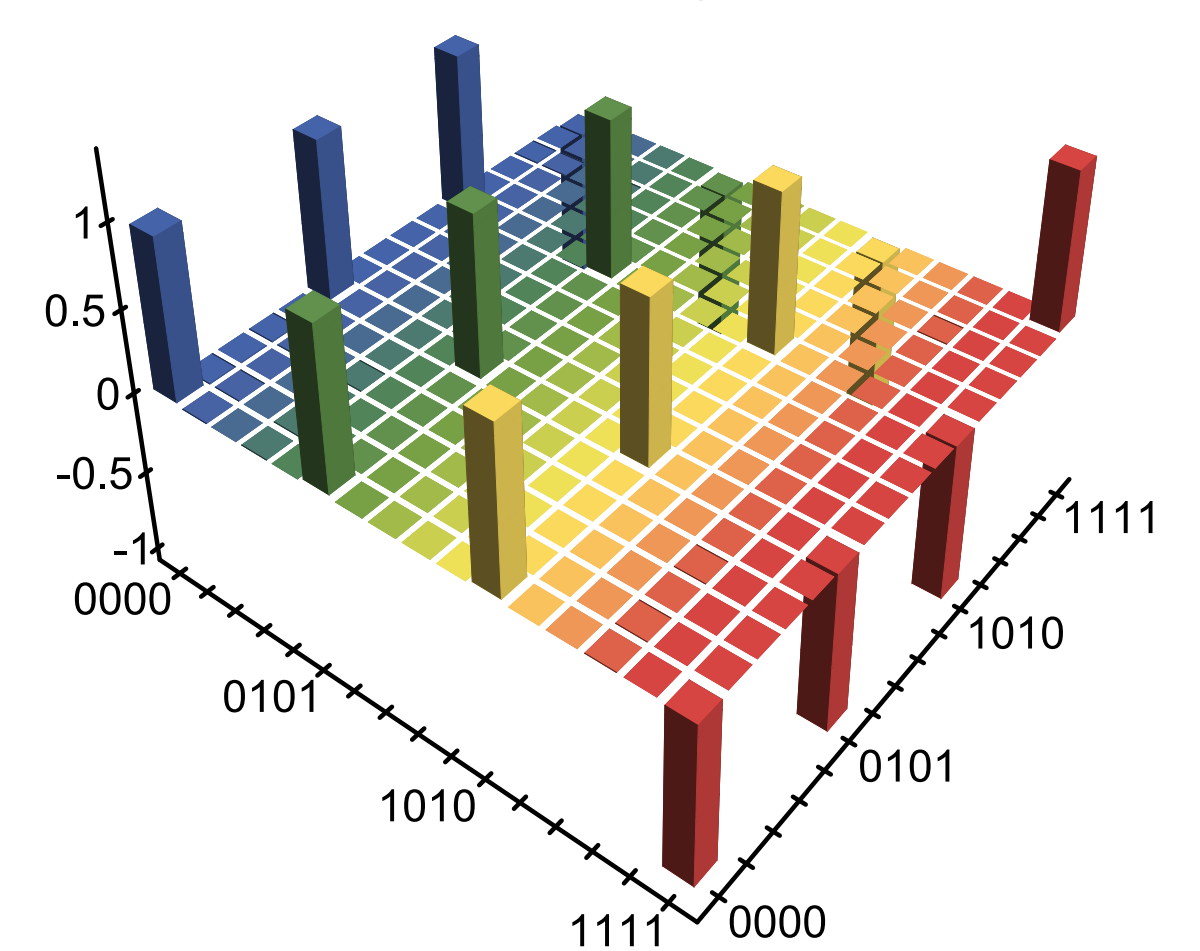- total time of 6 hours

no bypass
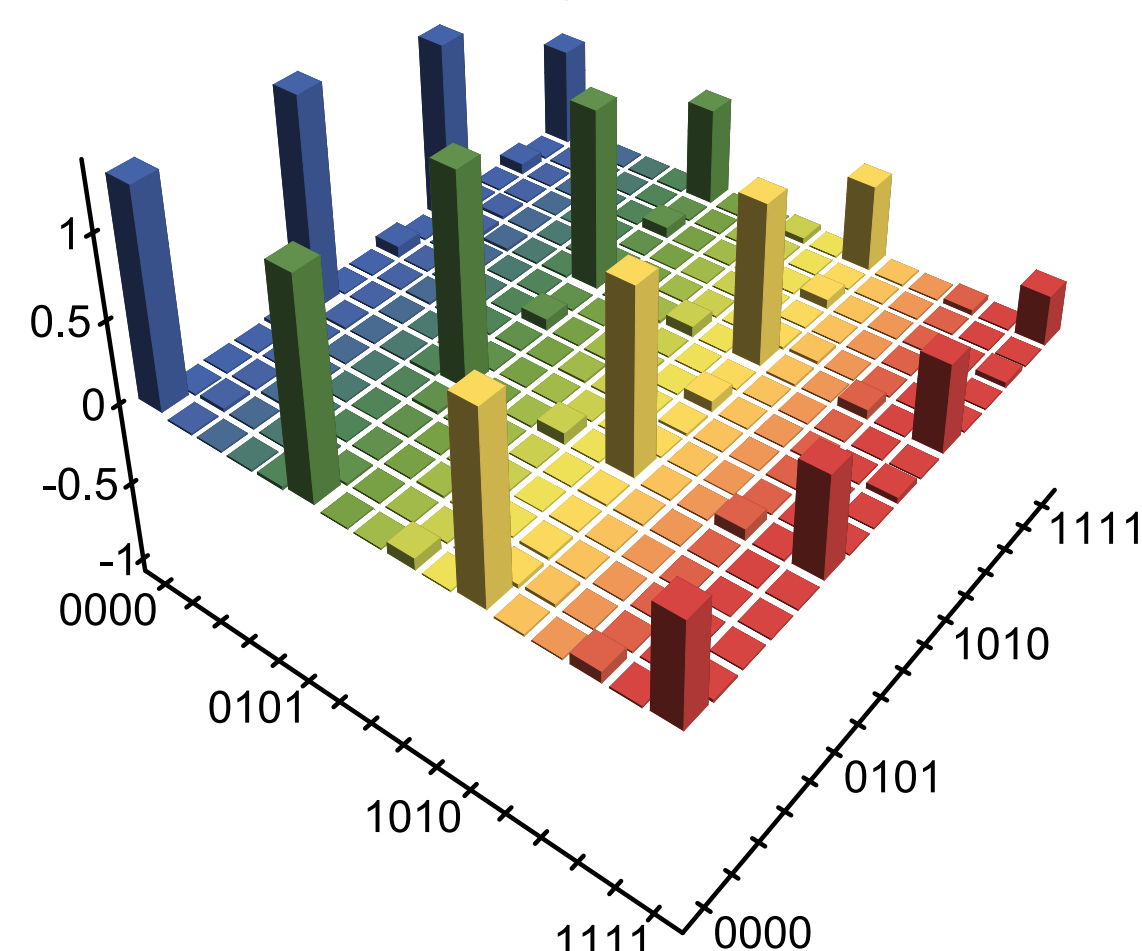
optimal bypass

$F_\chi = 0.846$

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