Department of Optics, Faculty of Science, Palacký University Olomouc
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Quantum optical experiments focused on quantum information processing

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Supervisor: Prof. RNDr. Miloslav Dušek Dr.
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Laboratory of quantum optics

Outline

- **Motivation + introduction + methods**
- **Individual experiments**
- **Conclusion**

Motivation + introduction

- **Experimental implementation**

⟶ linear-optical quantum protocols for quantum information processing

⟶ linear-optical quantum gates

Motivation + introduction

- **Experimental implementation**

→ linear-optical quantum protocols for quantum information processing

→ linear-optical quantum gates

- linear optics – bulk and fiber
- quantum bits (qubits) → photons → polarization
  → path/way/spatial
- manage their interaction
  → single-photon or two-photon interference
  → detection (projective measurement), post-selection

Motivation + introduction

- **fiber Mach-Zehnder interferometer**

  ⟶ active phase stabilization at single photon level

  ⟶ complex interferometric layouts - advanced stabilization metods

Motivation + introduction

- **fiber Mach-Zehnder interferometer**
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- **integrated electro-optical phase modulator**
  - ⟶ encoding of phase into qubit
  - ⟶ active phase stabilization of the interferometer
  - ⟶ part of an electro-optical feed-forward

Motivation + introduction

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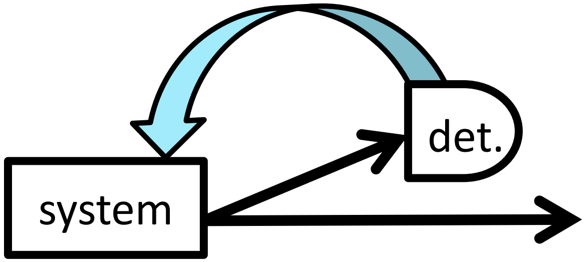
- feed-back



Motivation + introduction

- **fiber Mach-Zehnder interferometer**
  - → active phase stabilization at single photon level
  - → complex interferometric layouts - advanced stabilization metods

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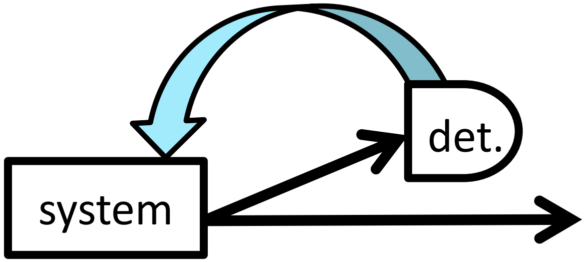
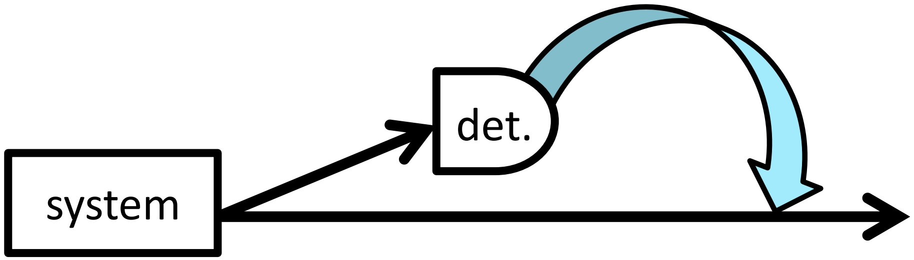


- feed-forward



Experiments

- quantum **gate** [1]
- quantum **state transfer**, its limitations given by particles properties [2] and interaction [5]
- **discrimination** of devices [3] and quantum measurements [4]

[1] **Increasing efficiency of a linear-optical quantum gate using electronic feed-forward**, M. Miková, H. Fikerová, I. Straka, M. Mičuda, J. Fiurášek, M. Ježek, and M. Dušek, Physical Review A **85**, 012305 (2012).

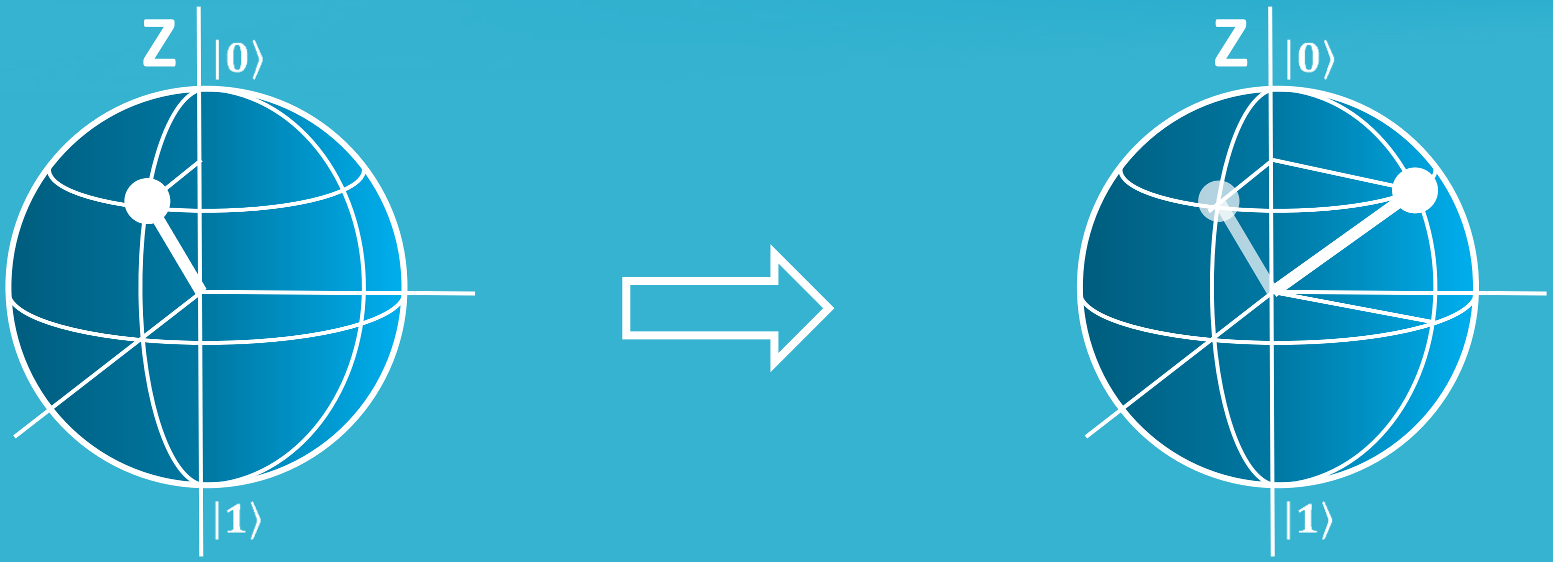
[2] **Carrying qubits with particles whose noninformational degrees of freedom are nonfactorable**, M. Miková, H. Fikerová, I. Straka, M. Mičuda, M. Ježek, M. Dušek, and R. Filip, Physical Review A **87**, 042327 (2013).

[3] **Experimental implementation of unambiguous quantum reading**, M. Dall'Arno, A. Bisio, G. M. D'Ariano, M. Miková, M. Ježek, and M. Dušek, Physical Review A **85**, 012308 (2012).

[4] **Optimal entanglement-assisted discrimination of quantum measurements**, M. Miková, M. Sedlák, I. Straka, M. Mičuda, M. Ziman, M. Ježek, M. Dušek, and J. Fiurášek, Physical Review A **90**, 022317 (2014).

[5] **Faithful conditional quantum state transfer between weakly coupled qubits**, M. Miková, I. Straka, M. Mičuda, V. Krčmarský, M. Dušek, M.Ježek, J. Fiurášek, and R. Filip, Scientic Reports **6**, 32125 (2016).

Programmable quantum phase gate



$$\alpha|0\rangle + \beta|1\rangle \qquad \alpha|0\rangle + e^{i\varphi}\beta|1\rangle$$

[i] Vidal, L. Masanes, J. I. Cirac, Phys. Rev. Lett **88**, 047905 (2002)

[ii] M. Mičuda, M. Ježek, M. Dušek, J. Fiurášek, Phys. Rev. A **78**, 062311 (2008)

[1] M. Miková, H. Fikerová, I. Straka, M. Mičuda, J. Fiurášek, M. Ježek, and M. Dušek, *Increasing efficiency of a linear-optical quantum gate using electronic feed-forward*, Physical Review A **85**, 012305 (2012).

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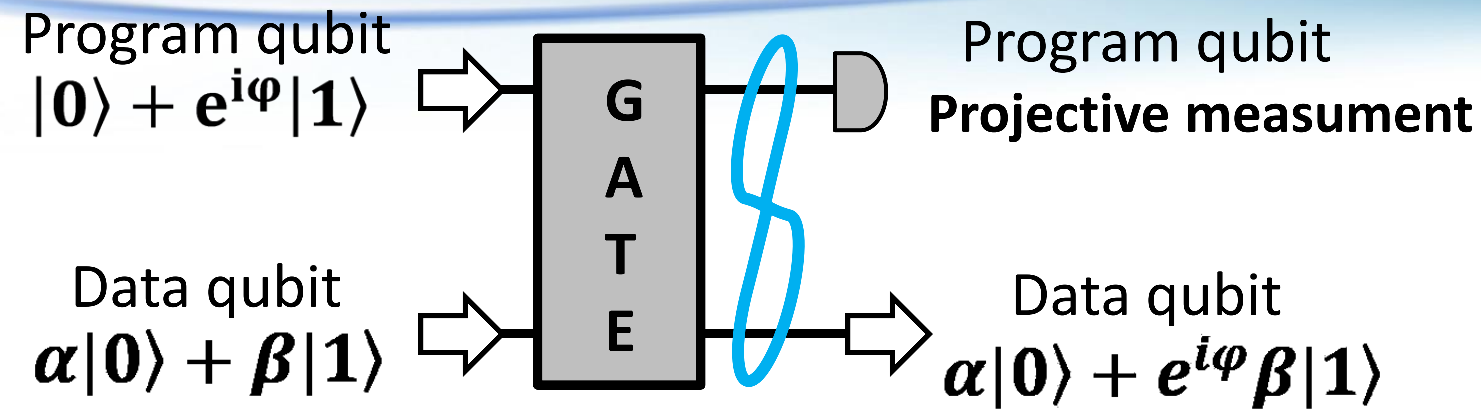


Program qubit
$|0\rangle + e^{i\varphi}|1\rangle$

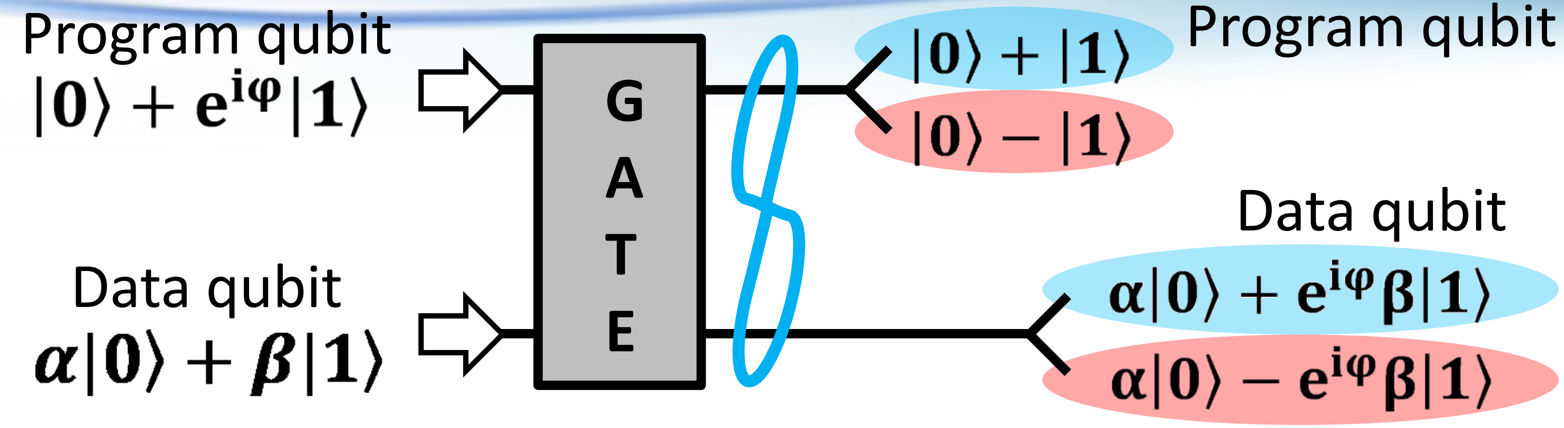
Data qubit
$\alpha|0\rangle + \beta|1\rangle$

Program qubit
Projective measument

Data qubit
$\alpha|0\rangle + e^{i\varphi}\beta|1\rangle$

Programmable quantum phase gate

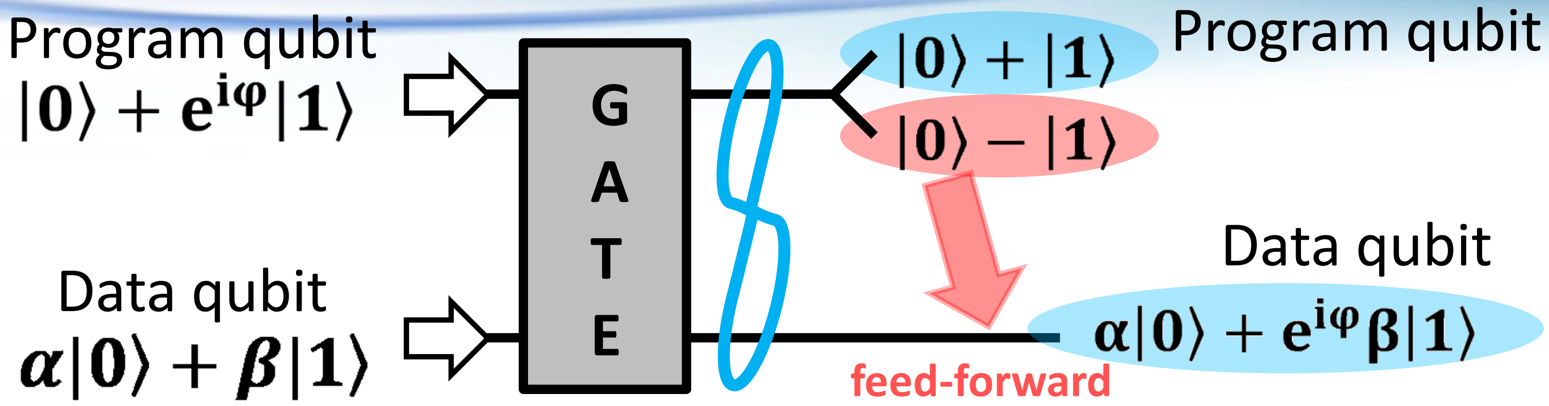
IDEA



GOAL: increase success probability of the gate from 25% to 50% (theoretical limit)

Programmable quantum phase gate

IDEA



Program qubit

$|0\rangle + e^{i\varphi}|1\rangle$

Data qubit

$\alpha|0\rangle + \beta|1\rangle$

$|0\rangle + |1\rangle$

$|0\rangle - |1\rangle$

Program qubit

Data qubit

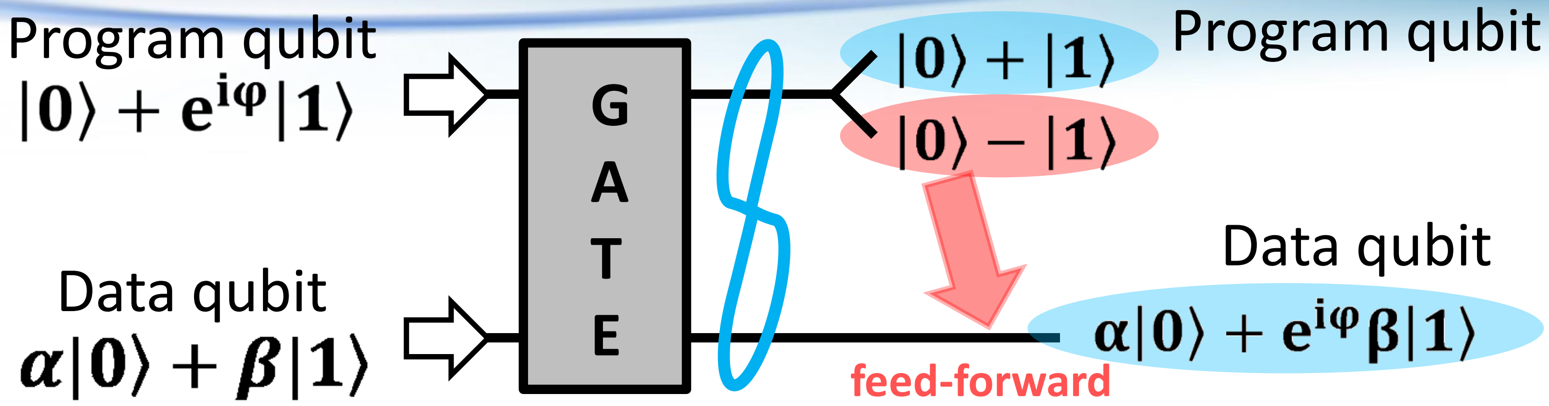
$\alpha|0\rangle + e^{i\varphi}\beta|1\rangle$

feed-forward

GOAL: increase success probability of the gate from 25% to 50% (theoretical limit)

Programmable quantum phase gate

IDEA



Program qubit

$|0\rangle + e^{i\varphi}|1\rangle$

Data qubit

$\alpha|0\rangle + \beta|1\rangle$

GATE

$|0\rangle + |1\rangle$

$|0\rangle - |1\rangle$

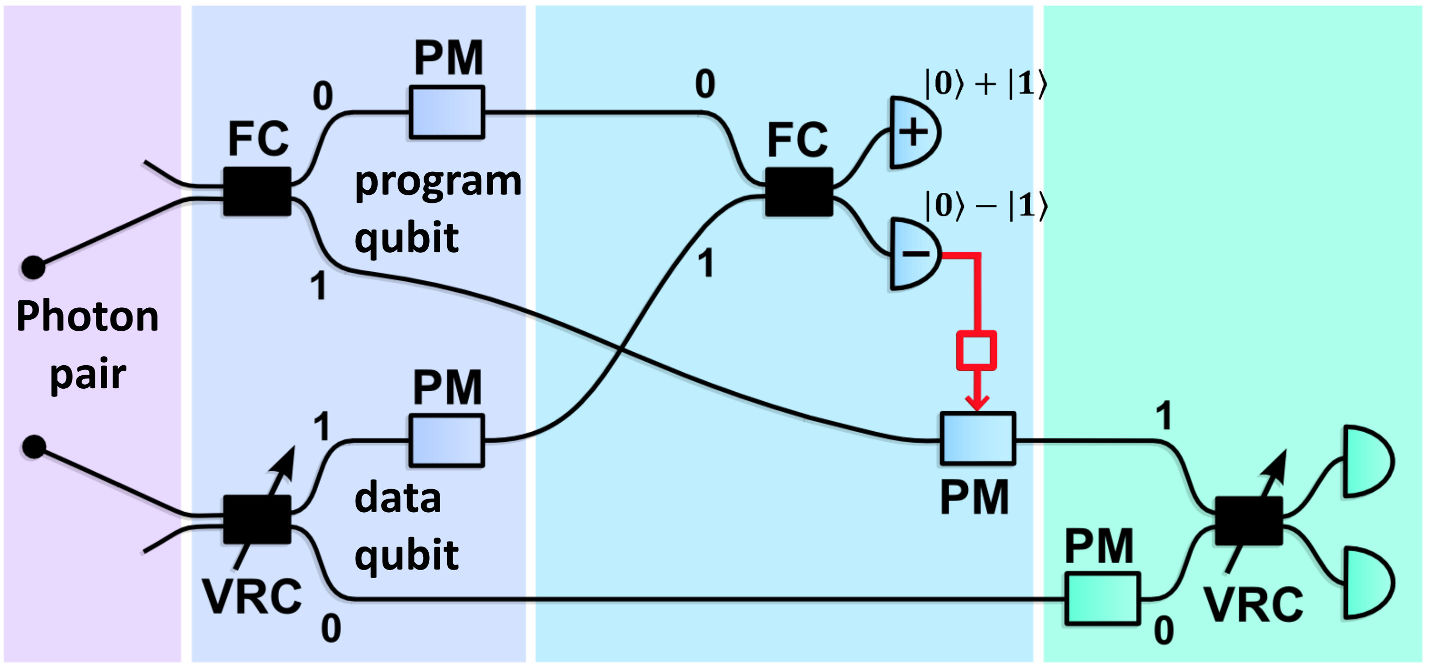
Program qubit

Data qubit

$\alpha|0\rangle + e^{i\varphi}\beta|1\rangle$

feed-forward

EXPETIMENT



Photon pair

FC

VRC

PM

program qubit

data qubit

0

1

$|0\rangle + |1\rangle$

$|0\rangle - |1\rangle$

+

−

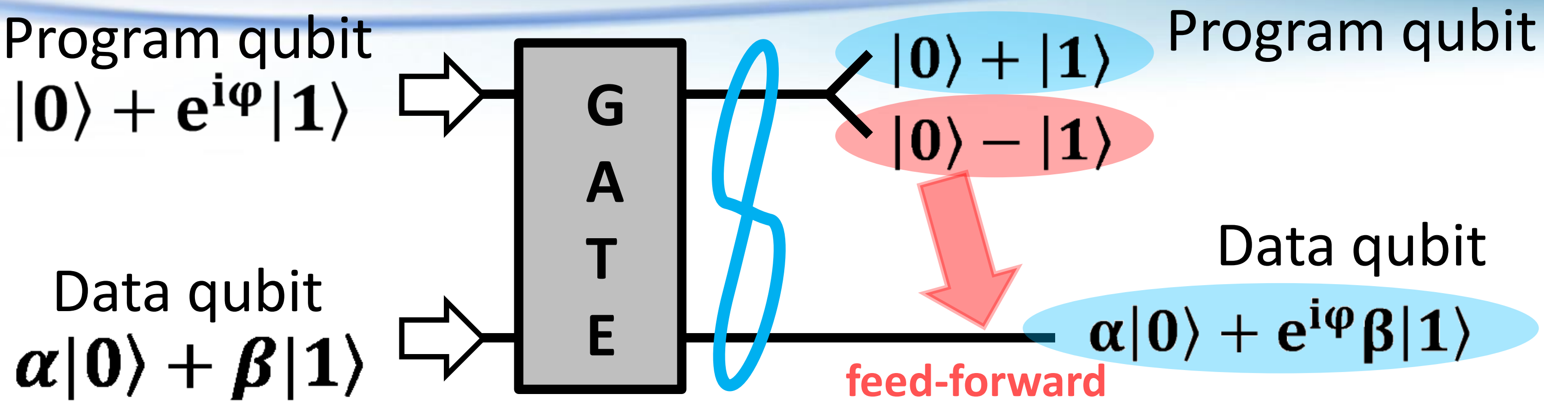
State preparation

Gate

Output state analysis

Programmable quantum phase gate

IDEA



Program qubit
$|0\rangle + e^{i\varphi}|1\rangle$

Data qubit
$\alpha|0\rangle + \beta|1\rangle$

G
A
T
E

$|0\rangle + |1\rangle$
$|0\rangle - |1\rangle$
Program qubit

Data qubit
$\alpha|0\rangle + e^{i\varphi}\beta|1\rangle$

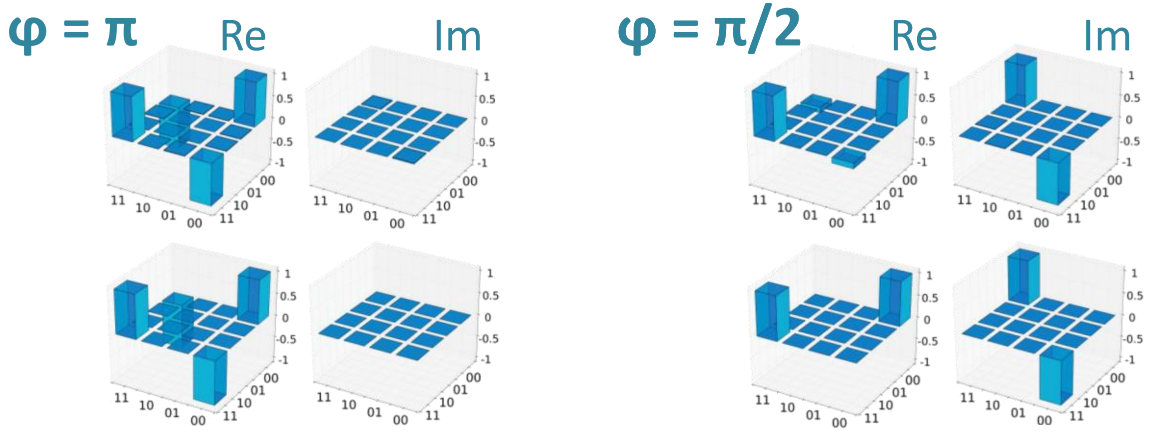
feed-forward

RESULTS

	success probability	average proc.fidelity
WITHOUT feed-forward	= 25%	= 97.9 ± 00.5 %
WITH feed-forward	= 50%	= 97.6 ± 00.3 %

Choi matrix
rekonstructed

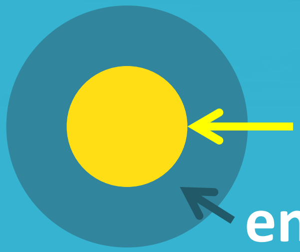
ideal



φ = π Re Im

φ = π/2 Re Im

Measure of effective indistinguishability of particles



particle – qubit carrier

qubit - internal degree of freedom used for information encoding

environment - noninformational internal degree of freedom

[2] M. Miková, H. Fikerová, I. Straka, M. Mičuda, M. Ježek, M. Dušek, and R. Filip, *Carrying qubits with particles whose noninformational degrees of freedom are nonfactorable*, Physical Review A **87**, 042327 (2013).

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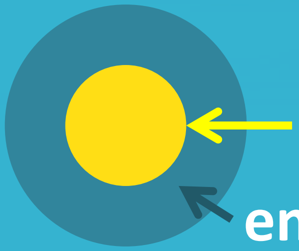

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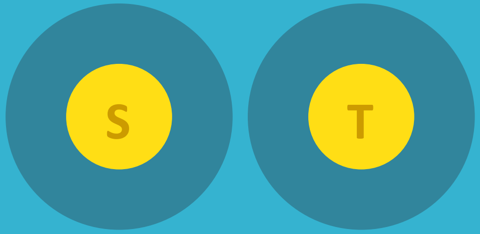
Measure of indistinguishability – **overlap** of quantum states of particles **S** and **T**



only for factorable states

[iii] M. Hendrych, M. Dušek, R. Filip, J. Fiurášek, Phys. Lett. A **310**, 95 (2003)

[2] M. Miková, H. Fikerová, I. Straka, M. Mičuda, M. Ježek, M. Dušek, and R. Filip, *Carrying qubits with particles whose noninformational degrees of freedom are nonfactorable*, Physical Review A **87**, 042327 (2013).

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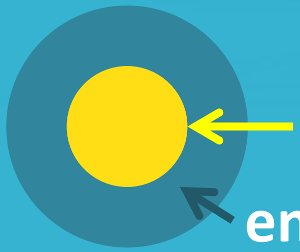

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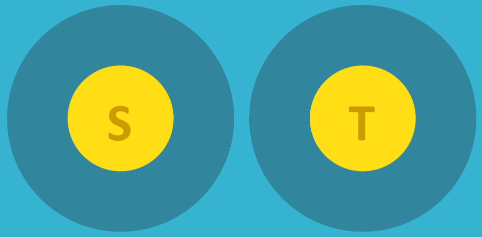
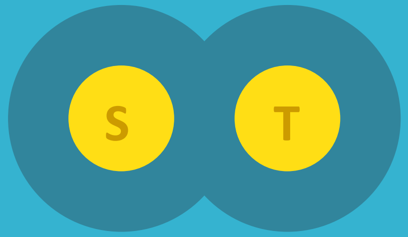


only for factorable states

X



Are the environments of particles really factorable?!

[iii] M. Hendrych, M. Dušek, R. Filip, J. Fiurášek, Phys. Lett. A **310**, 95 (2003)

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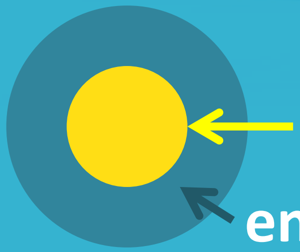

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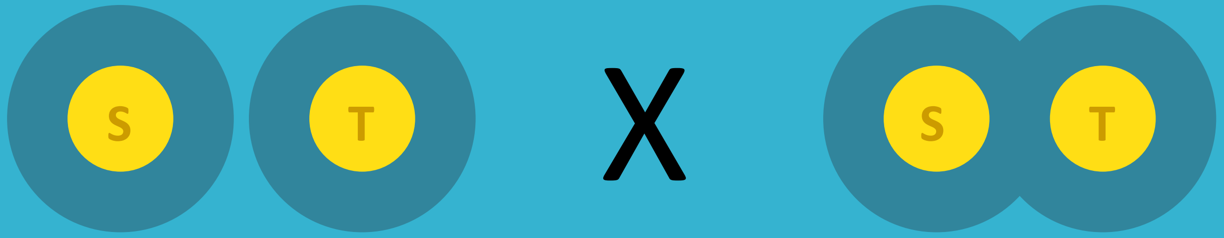


only for factorable states

Are the environments of particles really factorable?!

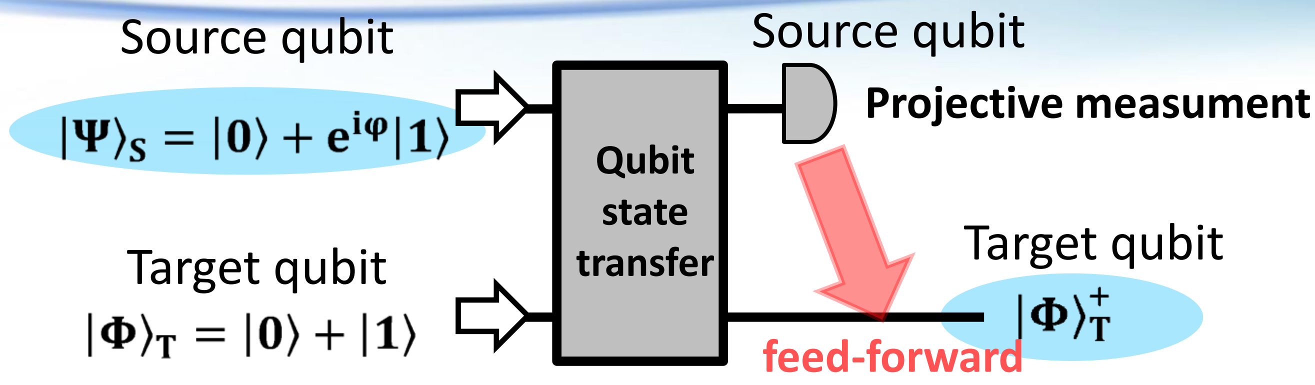
Directly measurable parameter, ***D***, ($0 \leq |D| \leq 1$).

- **quantifies the effective indistinguishability** of inaccessible degrees of freedom of particles carrying qubits (which can be even entangled with an external environment)
- **determines an upper bound of quantum state transfer quality**

[2] M. Miková, H. Fikerová, I. Straka, M. Mičuda, M. Ježek, M. Dušek, and R. Filip, *Carrying qubits with particles whose noninformational degrees of freedom are nonfactorable*, Physical Review A **87**, 042327 (2013).

Qubit-state transfer

IDEA



Source qubit

$|\Psi\rangle_S = |0\rangle + e^{i\varphi}|1\rangle$

Target qubit

$|\Phi\rangle_T = |0\rangle + |1\rangle$

Qubit state transfer

Source qubit

Projective measument

Target qubit

$|\Phi\rangle_T^+$

feed-forward

Ideal case $|D|=1$

Particles behave in the same way as if they are factorable, even if they actually do not!

Final target qubit state

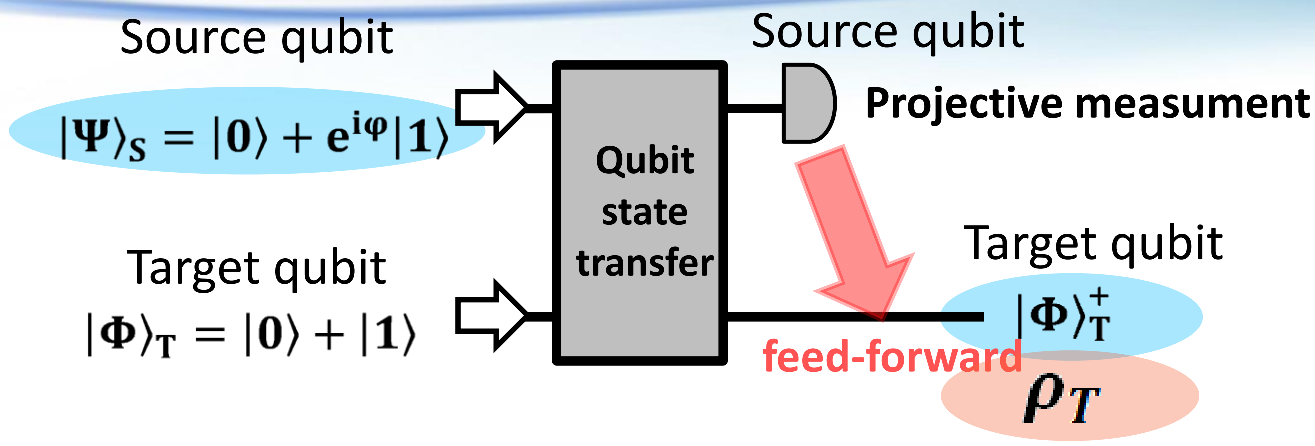
$$|\Phi\rangle_T^+ = |0\rangle + e^{i\varphi}|1\rangle$$

Overlap of output and input states

= 1

Qubit-state transfer

IDEA



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Qubit state transfer

Source qubit

Projective measument

feed-forward

Target qubit

$|\Phi\rangle_T^+$

ρ_T

Ideal case |*D*|=1

Particles behave in the same way as if they are factorable, even if they actually do not!

Final target qubit state

$$|\Phi\rangle_T^+ = |0\rangle + e^{i\varphi}|1\rangle$$

Overlap of output and input states

= 1

Real case |*D*|≠1

Final target qubit state

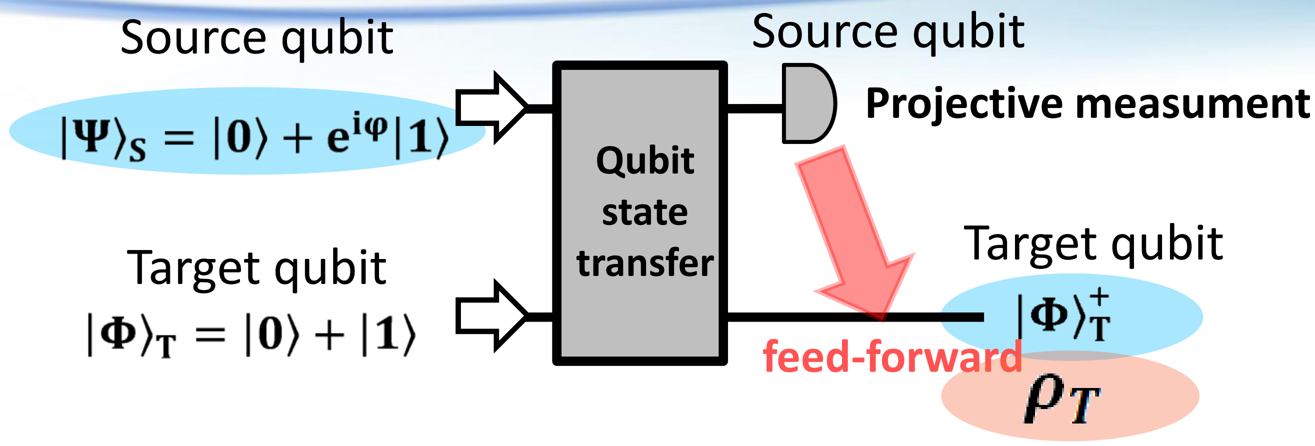
$$\rho_T = \frac{1+D}{2}|\Psi\rangle_s\langle\Psi| + \frac{1-D}{2}|\Psi^\perp\rangle_s\langle\Psi^\perp|$$

Overlap of output and input states

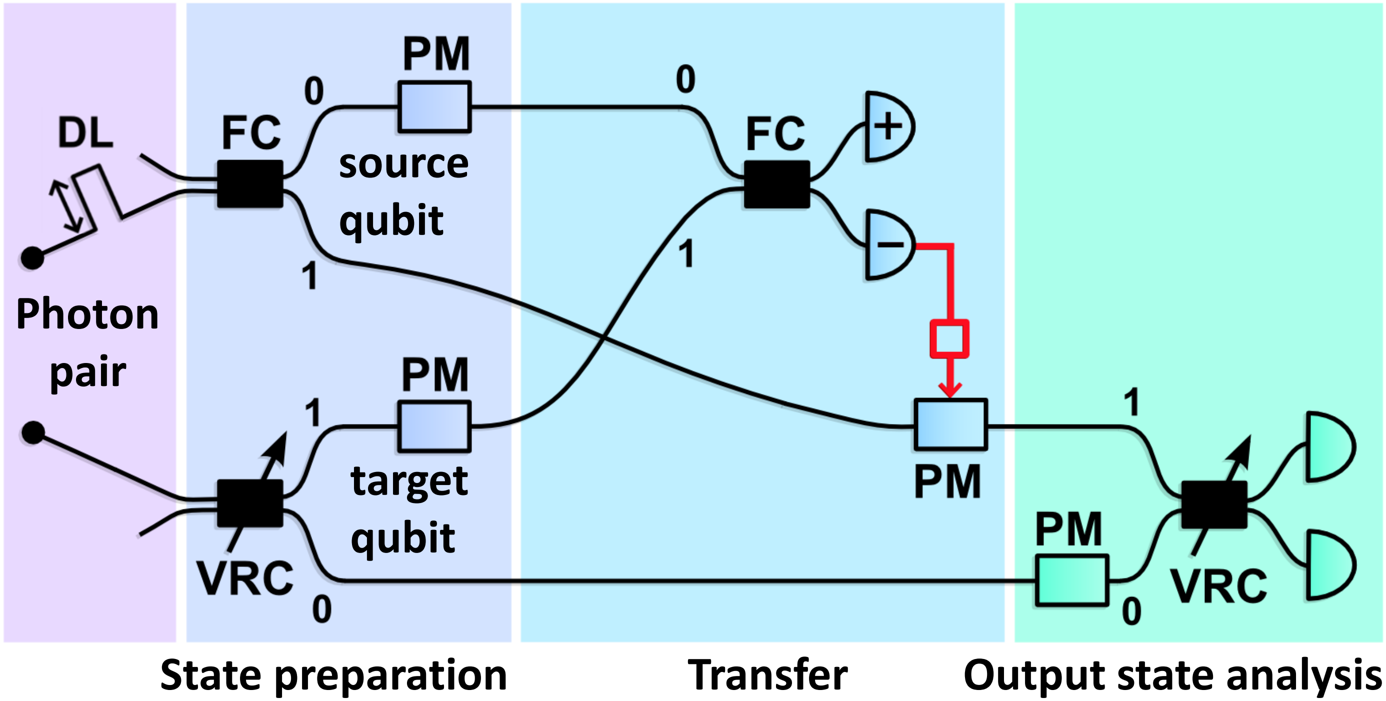
$$= \langle\Psi|_S\rho_T|\Psi\rangle_S = \frac{1+D}{2}$$

Qubit-state transfer

IDEA

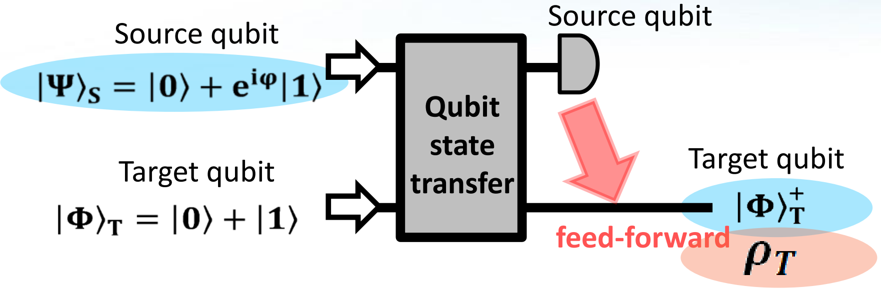


EXPETIMENT



Qubit-state transfer

IDEA



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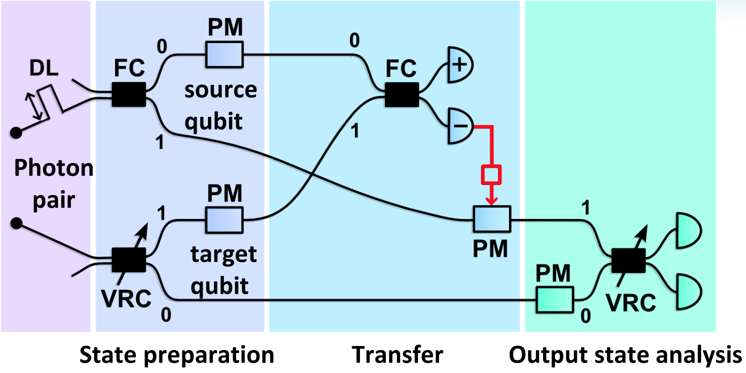
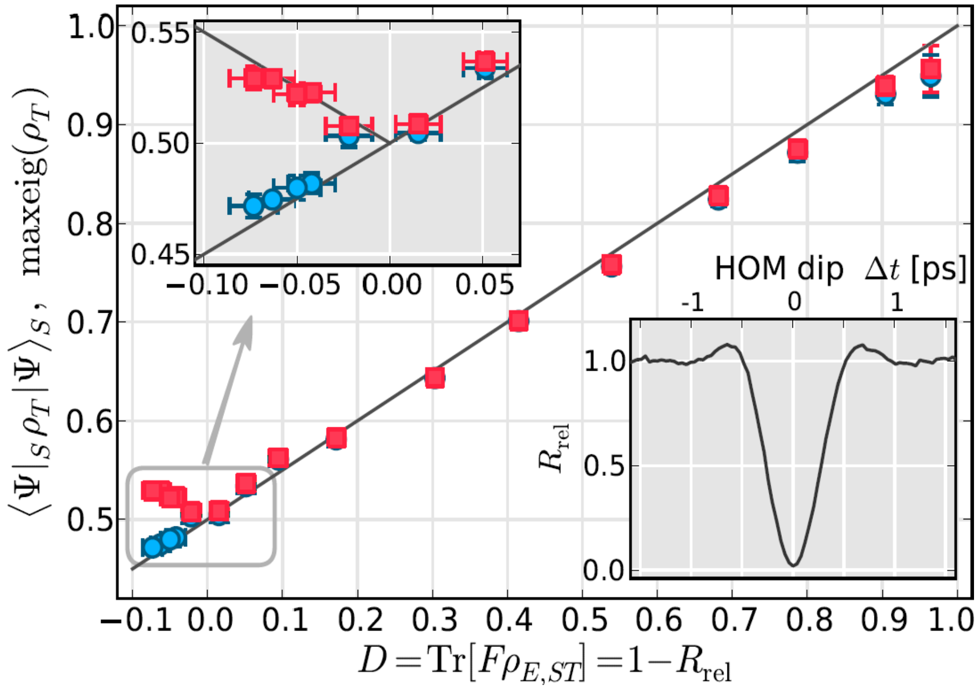
ρ_T



RESULTS



● overlap of output and input states $\langle\Psi|_S\rho_T|\Psi\rangle_S$

🟥 maximal eigenvalues of output states ρ_T

— theoretical predictions

Perfect quantum reading

Discrimination between two general unitary operations U_1 and U_2

[3] M. Dall'Arno, A. Bisio, G. M. D'Ariano, M. Miková, M. Ježek, and M. Dušek,
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Physical Review A **87**, 012308 (2012).

Perfect quantum reading

Discrimination between two general unitary operations U_1 and U_2

$$U_1 = W^{\dagger} U W, \quad U_2 = W^{\dagger} I W,$$ W - unitary matrix , I - identity operation

It is unitary-equivalent to discrimination between U and I

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Special case of U → action of a BS → R_V of BS → optical memory record

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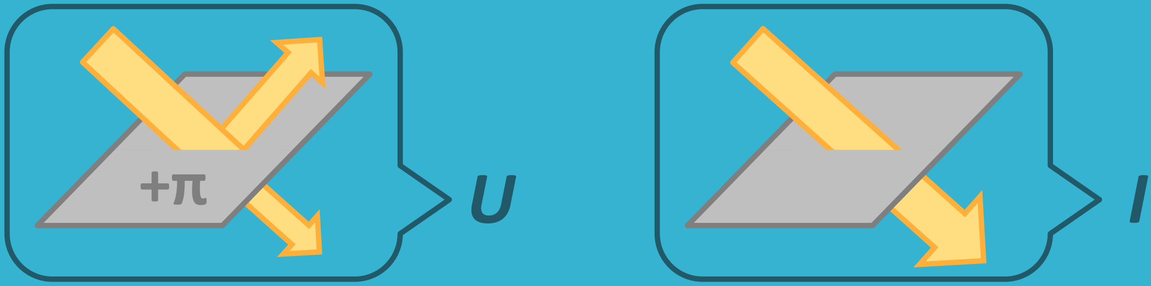

Devices are called according to the performed operations.

[3] M. Dall'Arno, A. Bisio, G. M. D'Ariano, M. Miková, M. Ježek, and M. Dušek, *Experimental implementation of unambiguous quantum reading*, Physical Review A **87**, 012308 (2012).

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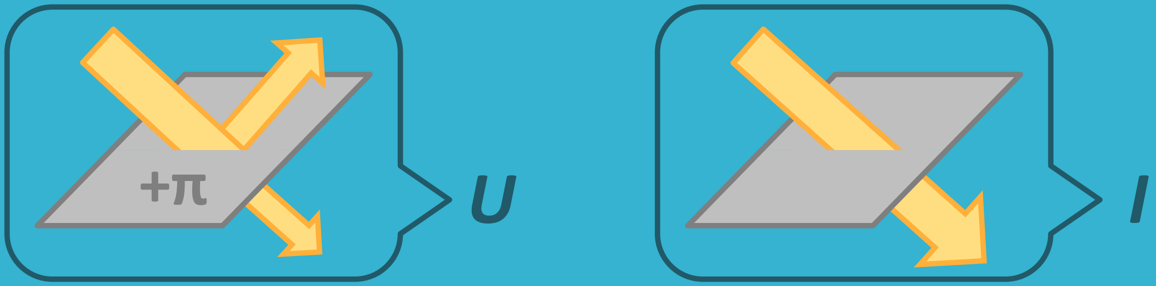


Devices are called according to the performed operations.

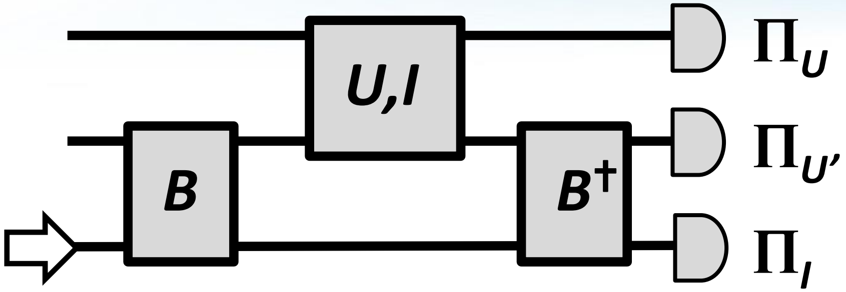
Discrimination between devices U and I corresponds to reading of the memory record.

What is the lowest energy necessary for the reading?

[3] M. Dall'Arno, A. Bisio, G. M. D'Ariano, M. Miková, M. Ježek, and M. Dušek, *Experimental implementation of unambiguous quantum reading*, Physical Review A **87**, 012308 (2012).

Perfect quantum reading

IDEA



Π – photo-counter

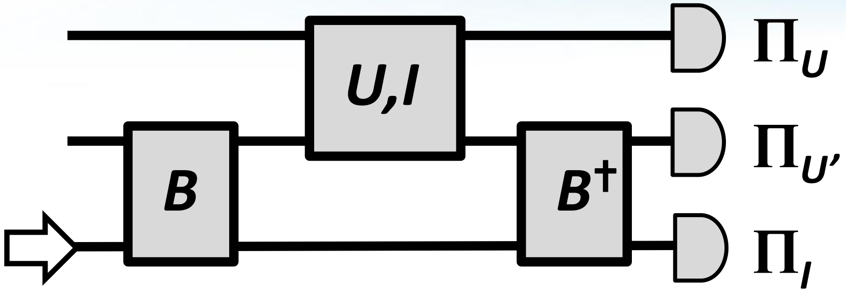
U,I – discriminated device

B – beam splitter

$T_B=1/(1+\sqrt{R_V})$, $T_B+R_B=1$

Perfect quantum reading

IDEA



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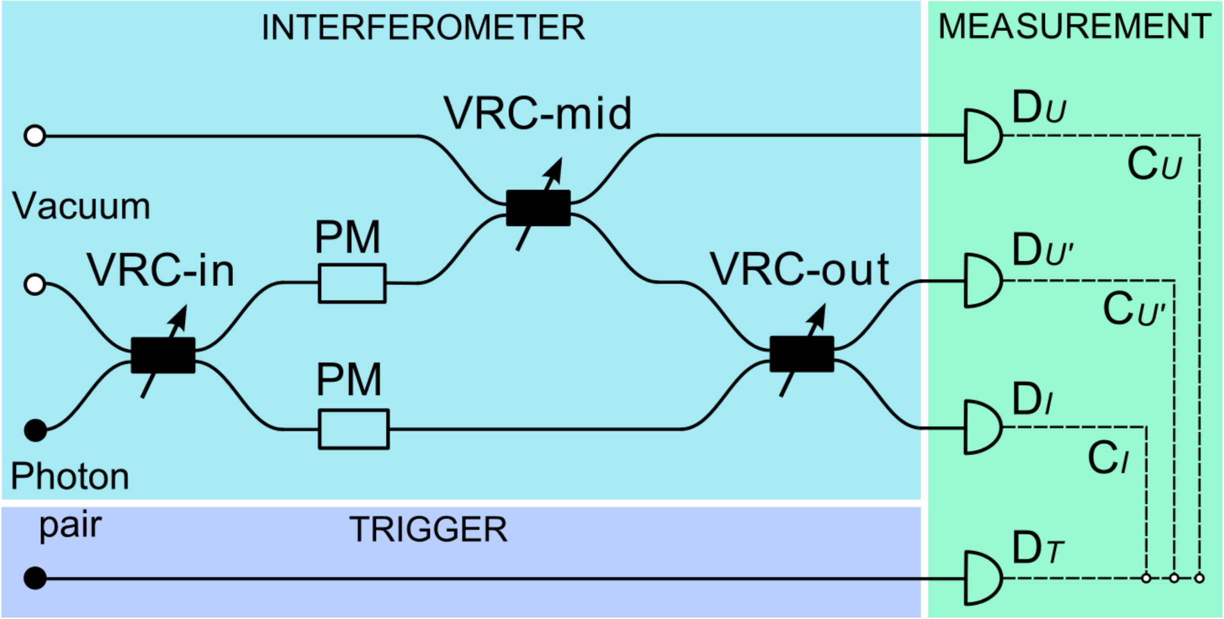
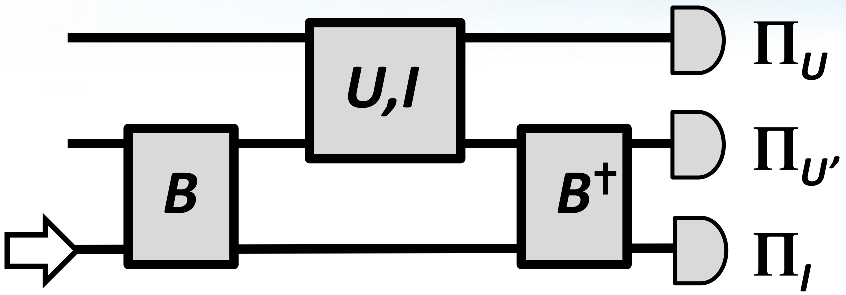
EXPETIMENT



Perfect quantum reading

IDEA



Π – photo-counter

U,I – discriminated device

B – beam splitter

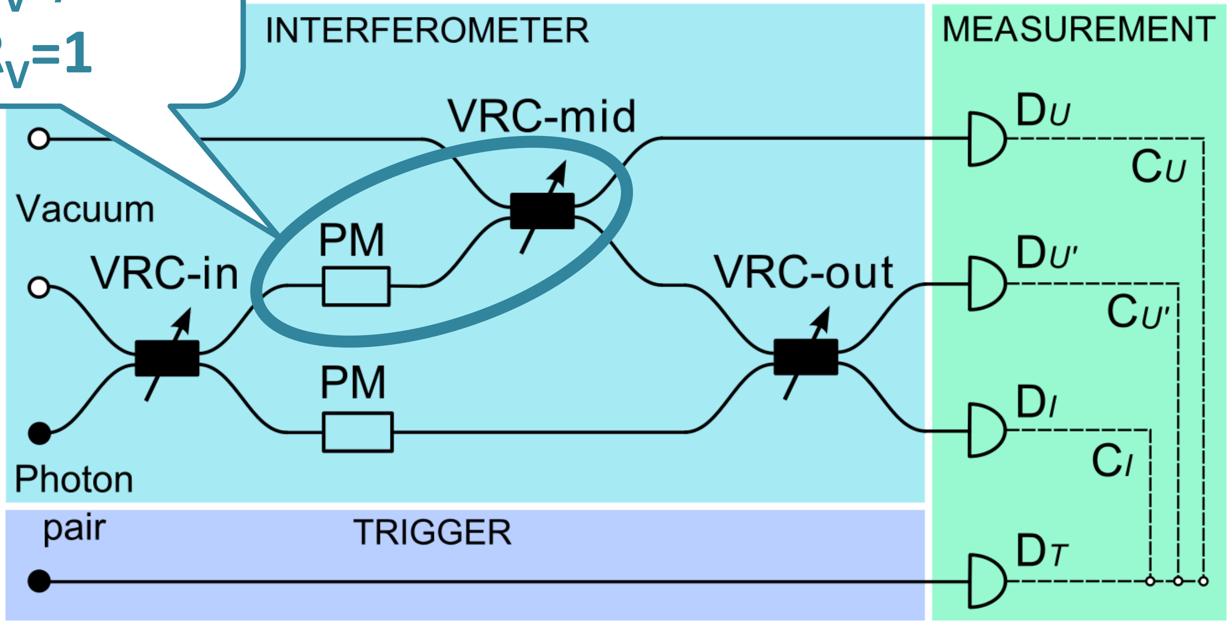
$T_B=1/(1+\sqrt{R_V})$, $T_B+R_B=1$

EXPETIMENT

device

U → $R_V \neq 1 + \pi$

I → $R_V=1$



Perfect quantum reading

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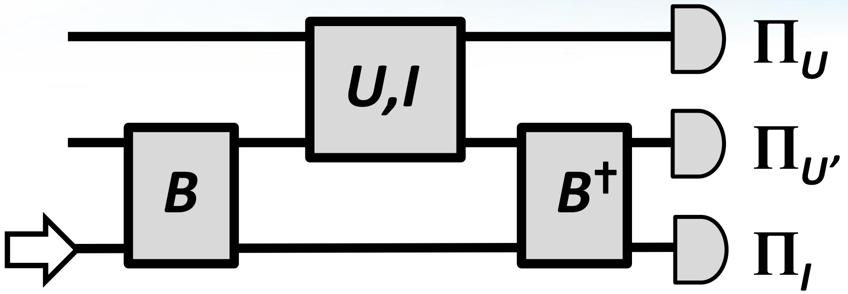


Π – photo-counter

U,I – discriminated device

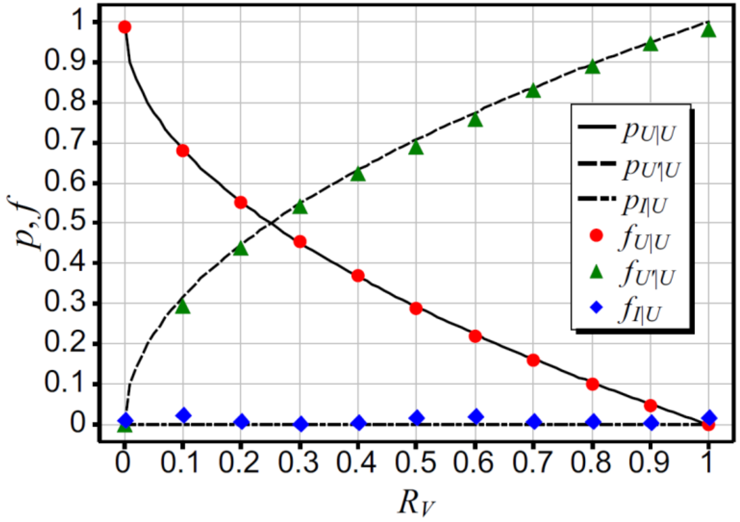
B – beam splitter

$T_B=1/(1+\sqrt{R_V})$, $T_B+R_B=1$

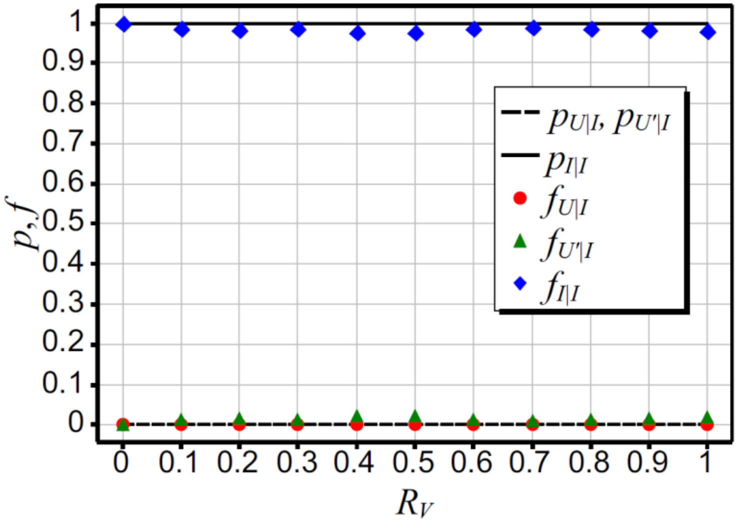
For the reading - used just a fraction of photon energy

RESULTS

device *U*



device *I*

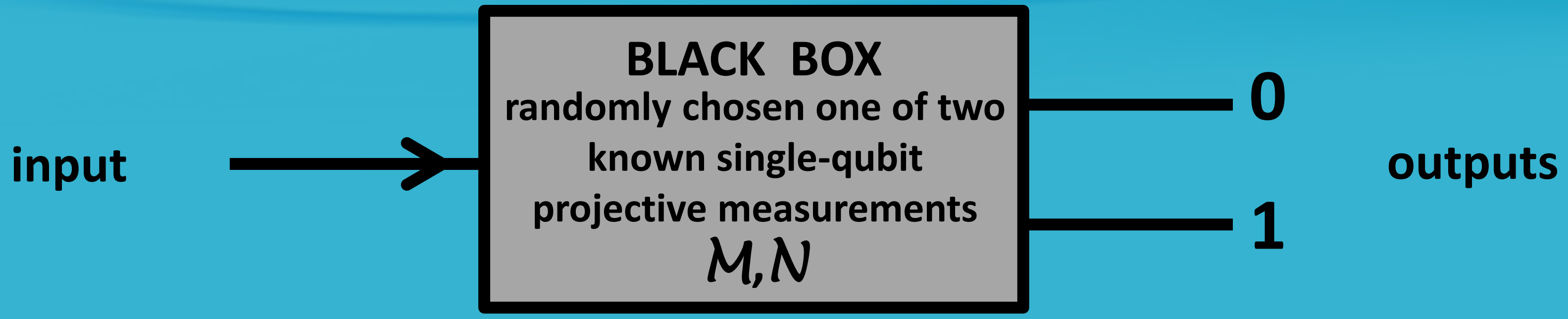


$p_{X|Y}$ – theoretical conditional probability of photon detection (by the detector *X* given that the unknown device is *Y*)

$f_{X|Y}$ – relative frequency measured

where X = U,U', I and Y = U, I.

Discrimination of quantum measurements



input

BLACK BOX

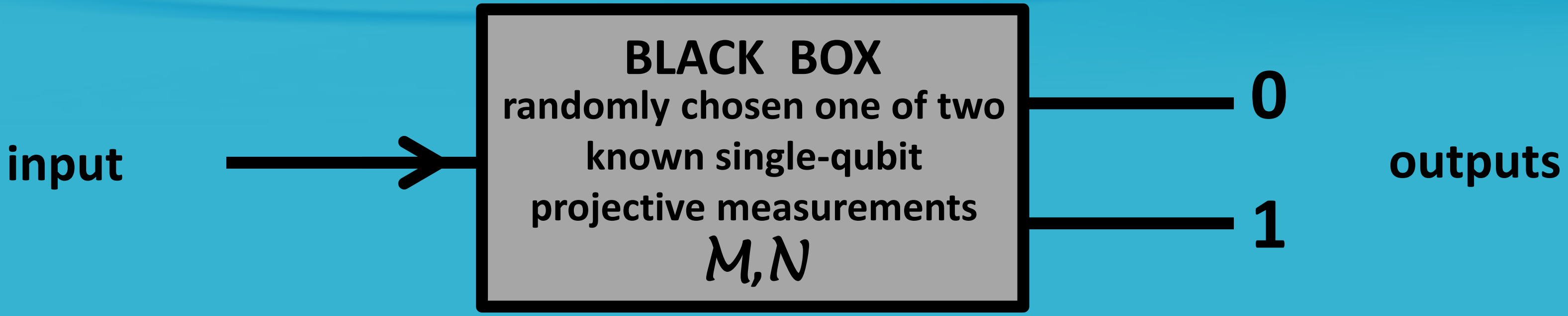
randomly chosen one of two known single-qubit projective measurements

$\mathcal{M},\mathcal{N}$

outputs

[4] M. Miková, M. Sedlák, I. Straka, M. Mičuda, M. Ziman, M. Ježek, M. Dušek, and J. Fiurášek, *Optimal entanglement-assisted discrimination of quantum measurements*, Physical Review A **90**, 022317 (2014).

Discrimination of quantum measurements



input

BLACK BOX

randomly chosen one of two known single-qubit projective measurements

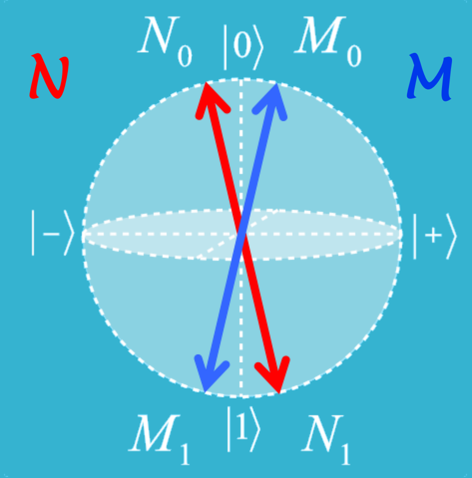
$\mathcal{M},\mathcal{N}$

0

1

outputs

Optimal discrimination of two known single-qubit quantum measurements $\mathcal{M},\mathcal{N}$ in scenario where the measurement can be performed only once



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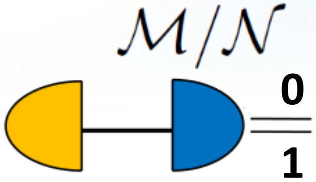
Discrimination of quantum measurements

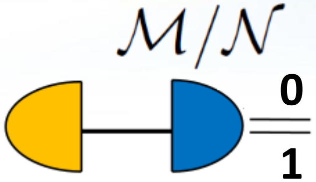
IDEA



single-qubit strategy

Discrimination of quantum measurements

IDEA



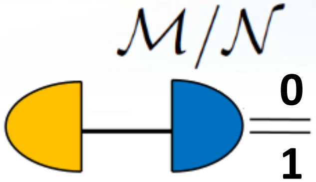
single-qubit strategy

- We can **guess**

- We can say I do not know
  = involve **inconclusive results**

Discrimination of quantum measurements

IDEA



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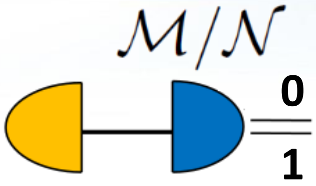
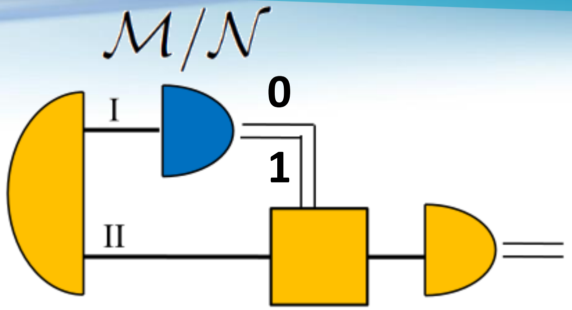
optimal single-qubit strategy

Discrimination of quantum measurements

IDEA



single-qubit strategy



optimal entanglement-assisted strategy

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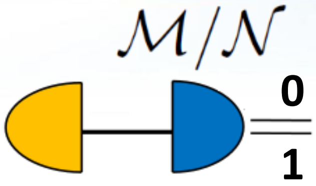
optimal single-qubit strategy

Discrimination of quantum measurements

IDEA



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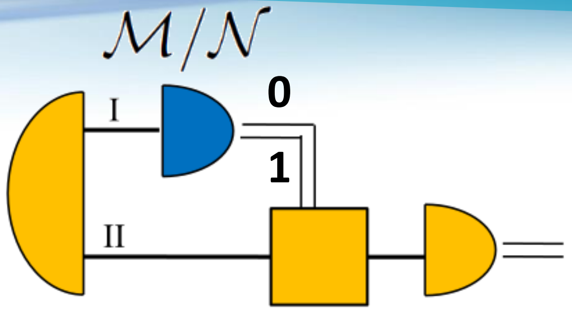
optimal single-qubit strategy

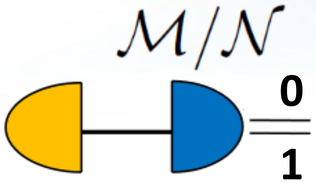


optimal entanglement-assisted strategy

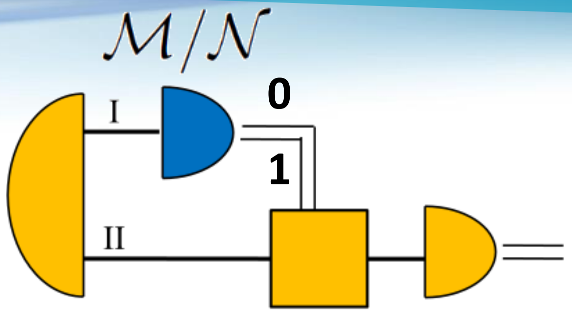
- It is optimal to employ maximally entangled singlet Bell state $|\Psi^-\rangle = (|01\rangle - |10\rangle)/\sqrt{2}$.

Discrimination of quantum measurements

IDEA



single-qubit strategy



optimal entanglement-assisted strategy

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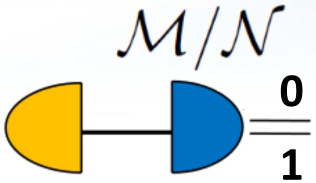
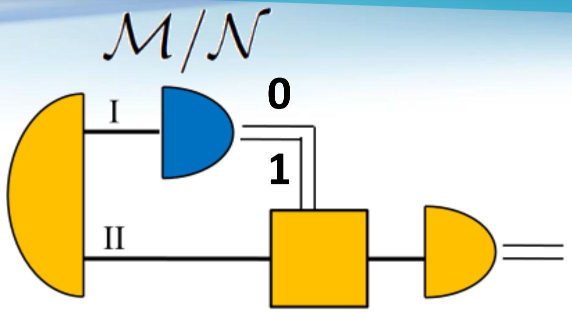
- It is optimal to employ maximally entangled singlet Bell state $|\Psi^-\rangle = (|01\rangle - |10\rangle)/\sqrt{2}$.
- Outcome **0** at q.I heralds q.II in state $|\psi^\perp\rangle$ or $|\phi^\perp\rangle$
- Outcome **1** at q.I heralds q.II in state $|\psi\rangle$ or $|\phi\rangle$

Discrimination of quantum measurements

IDEA



single-qubit strategy



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- Outcome **0** at q.I heralds q.II in state $|\psi^\perp\rangle$ or $|\phi^\perp\rangle$
- Outcome **1** at q.I heralds q.II in state $|\psi\rangle$ or $|\phi\rangle$

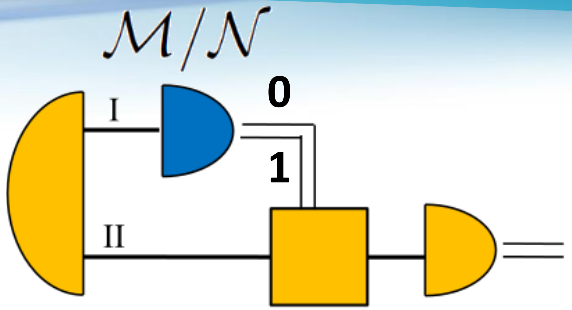
Outcome **0** at q.I → unitary operation on q.II

It suitably rotates states $|\psi^\perp\rangle$ $|\phi^\perp\rangle$.

We end up with the task to discriminate between two fixed non-orthogonal states $|\psi\rangle$ and $|\phi\rangle$.

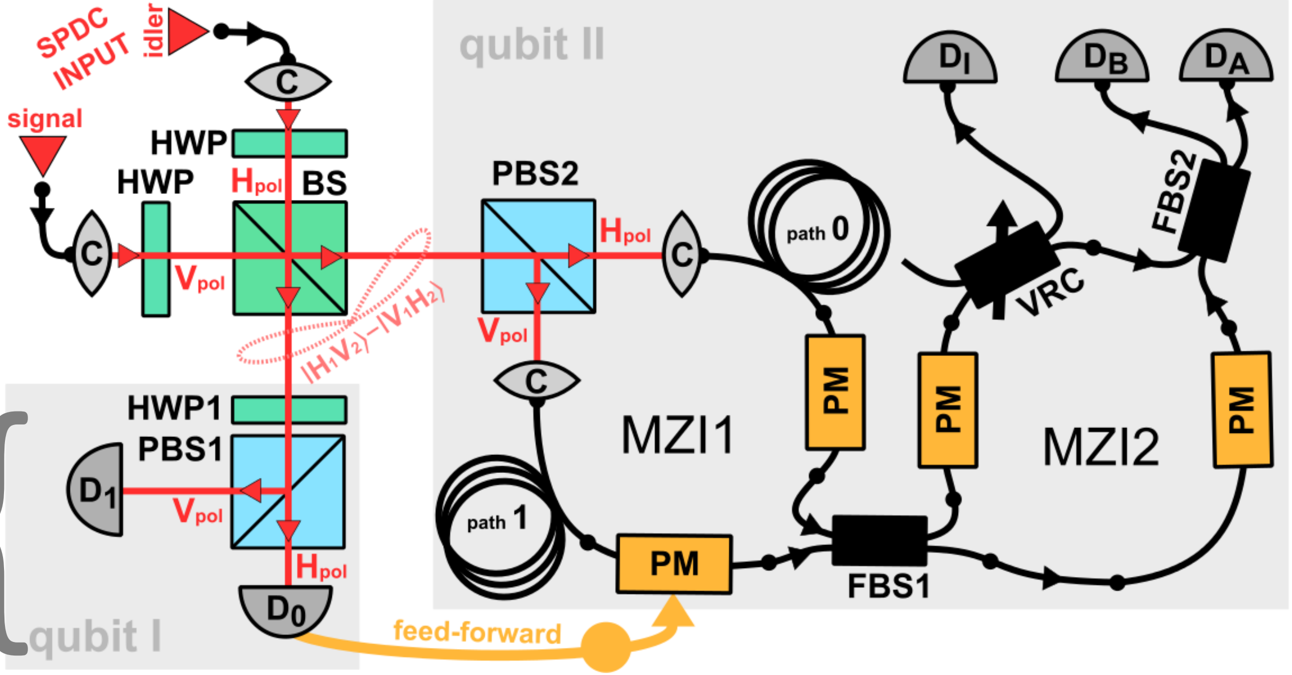
Discrimination of quantum measurements

IDEA



optimal entanglement-assisted strategy

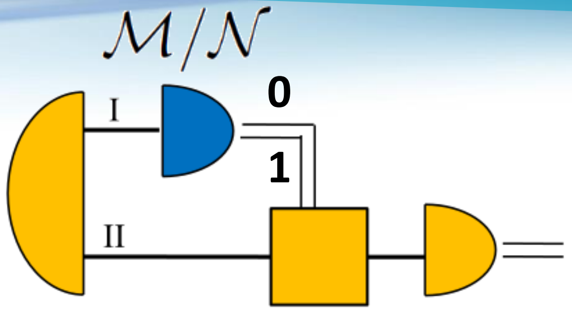
EXPETIMENT



$\mathcal{M}$ or $\mathcal{N}$

Discrimination of quantum measurements

IDEA



optimal entanglement-assisted strategy

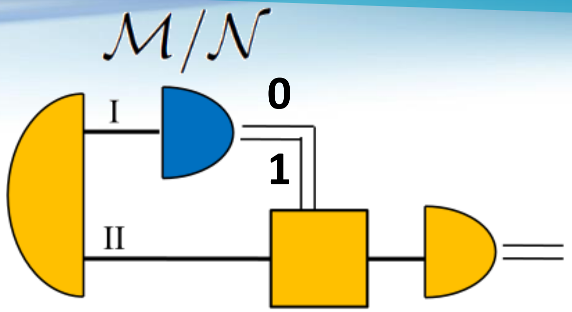
$$P_S + P_I = 1$$

P_S - prob. of **successful conclusive** results

P_I - prob. of **inconclusive** results

Discrimination of quantum measurements

IDEA



optimal entanglement-assisted strategy

$$P_S + P_I = 1$$

$$\Downarrow$$

$$P_S + P_I + P_E = 1$$

P_S - prob. of **successful conclusive** results

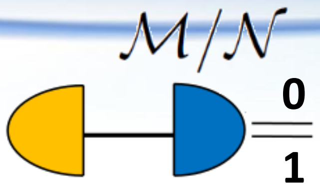
P_I - prob. of **inconclusive** results

P_E - prob. of **errorneous conclusive** results

$\tilde{P}_S = \dfrac{P_S}{1 - P_I}$ - relative prob. of **successful discrimination**

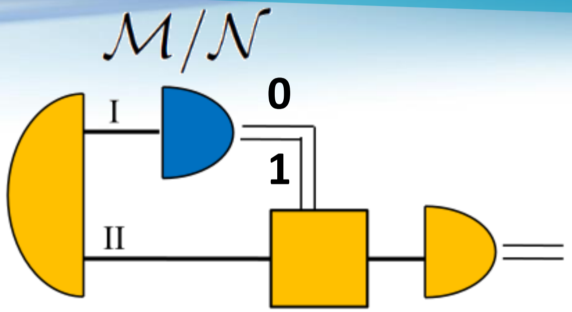
Discrimination of quantum measurements

IDEA



------ **optimal single-qubit strategy**

benchmark for our experiment

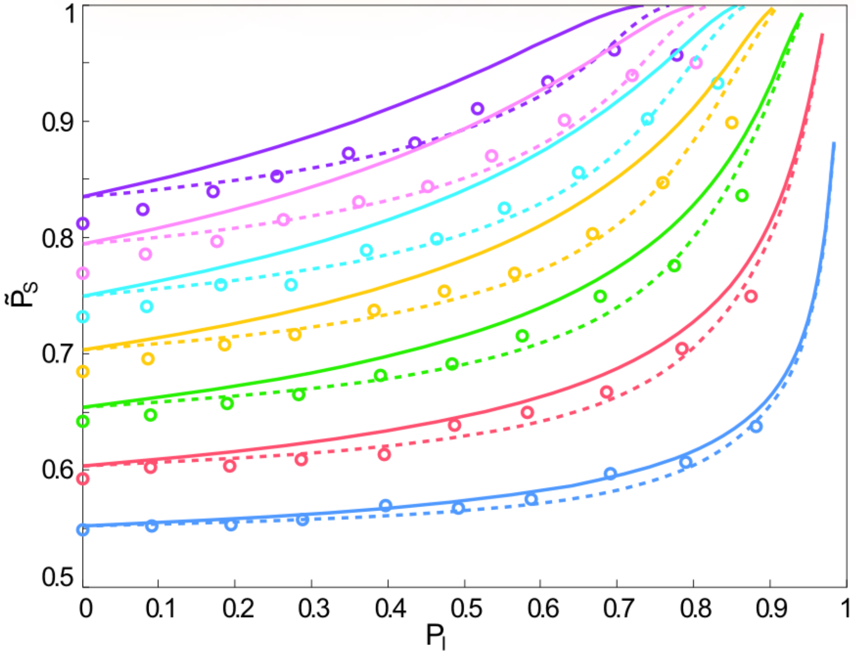


——— **optimal entanglement-assisted strategy**

RESULTS

Intermediate strategy

maximize $P_{S,}$ minimize $P_{E,}$ for a fixed fraction of P_I.



$$P_S + P_I = 1$$

$$\Downarrow$$

$$P_S + P_I + P_E = 1$$

P_S - prob. of **successful conclusive** results

P_I - prob. of **inconclusive** results

P_E - prob. of **errorneous conclusive** results

$\tilde{P}_S = \dfrac{P_S}{1 - P_I}$ - relative prob. of **successful discrimination**

Quantum state transfer protocol

→ Weak interaction → **high fidelity quantum state transfer ?**

[5] M. Miková, I. Straka, M. Mičuda, V. Krčmarský, M. Dušek, M.Ježek, J. Fiurášek, and R. Filip,
Faithful conditional quantum state transfer between weakly coupled qubits,
Scientic Reports **6**, 32125 (2016).

Quantum state transfer protocol

→ Weak interaction → high fidelity quantum state transfer ?

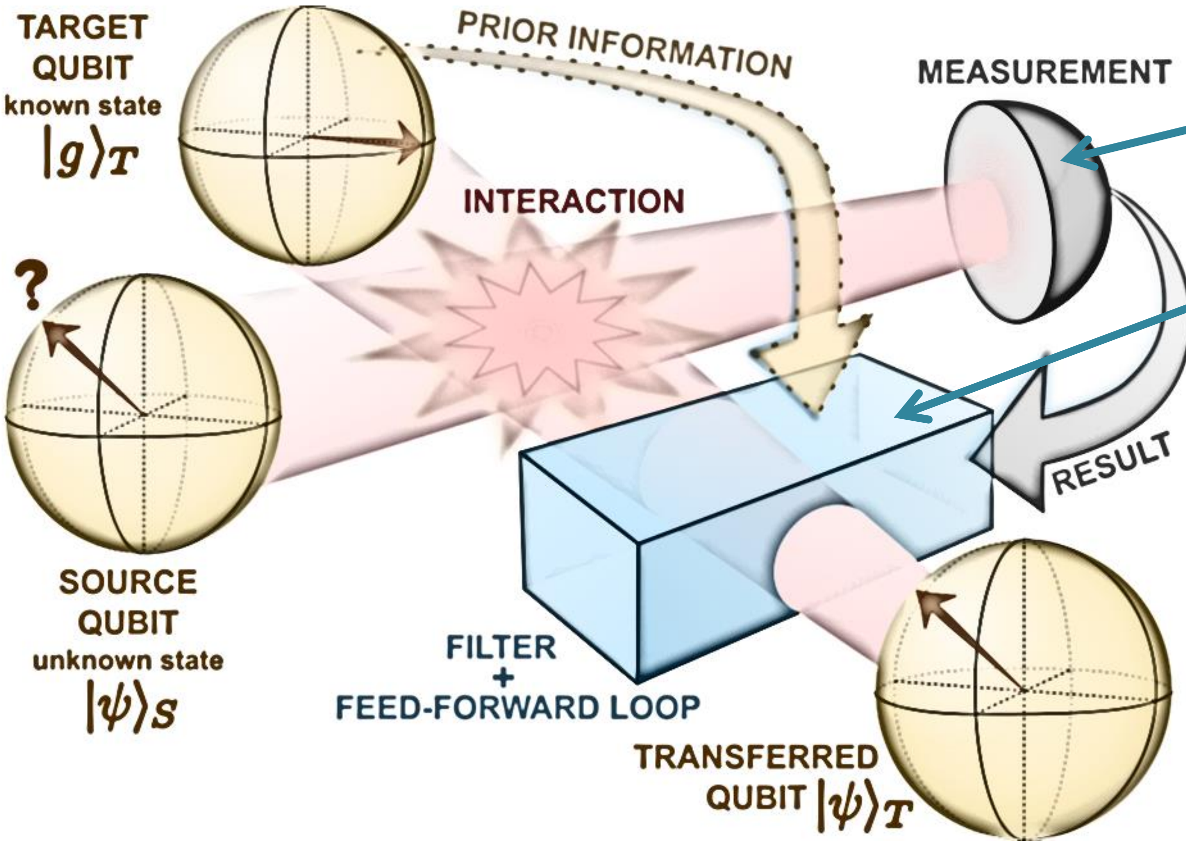
→ Quantum filtration

Experimental imperfections

[5] M. Miková, I. Straka, M. Mičuda, V. Krčmarský, M. Dušek, M.Ježek, J. Fiurášek, and R. Filip, *Faithful conditional quantum state transfer between weakly coupled qubits,* Scientic Reports **6**, 32125 (2016).

Quantum state transfer between weakly coupled qubits

IDEA

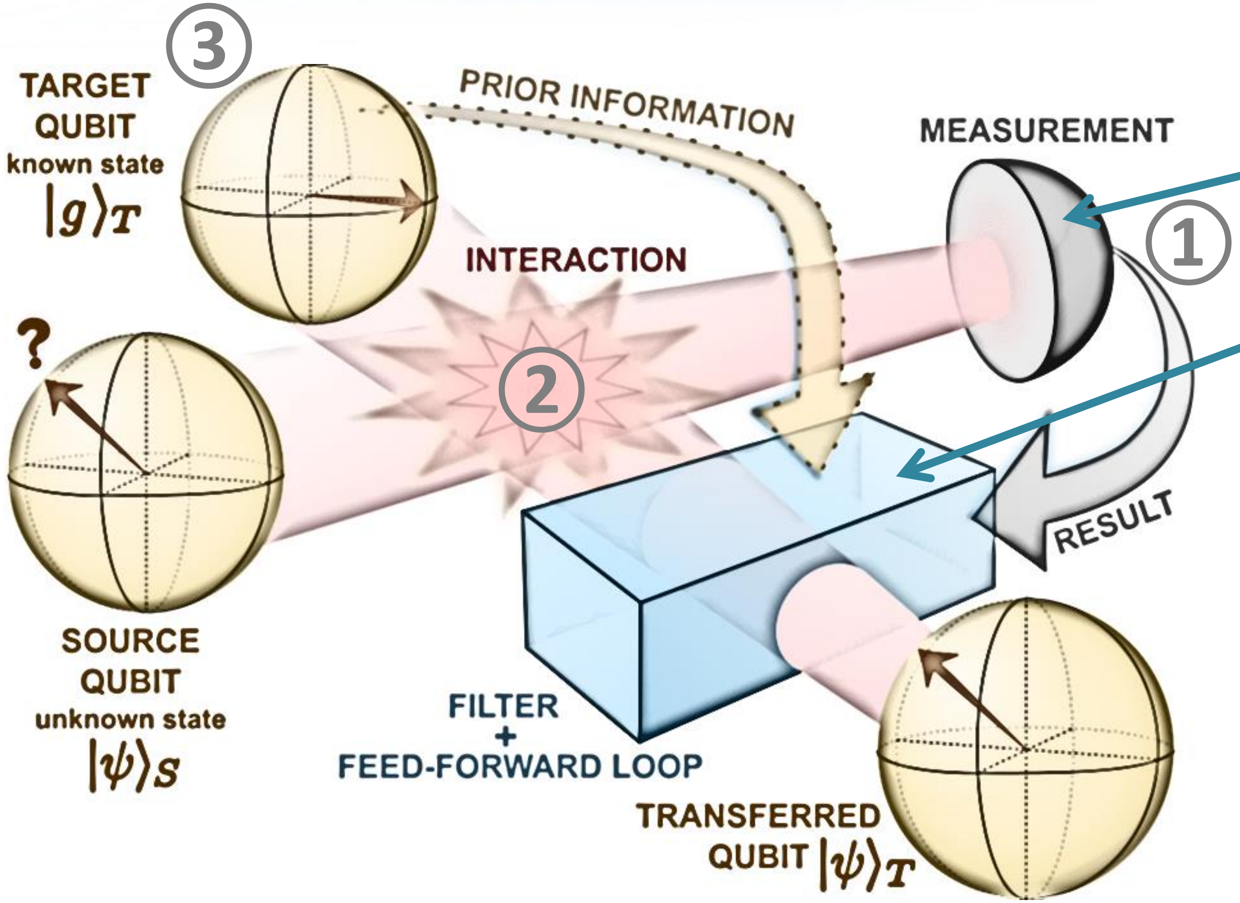


suitable measurement
on the source qubit

quantum filtering
on the target qubit

Quantum state transfer between weakly coupled qubits

IDEA



suitable measurement on the source qubit

quantum filtering on the target qubit

quantum filtering

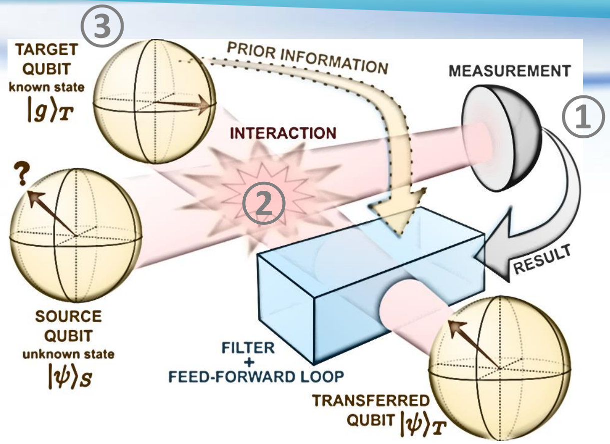
① measurement outcome

② interaction of qubis

③ initial target qubit state, parametrized by angle ω
$|g\rangle_T = \cos(\omega)\,|H\rangle + \sin(\omega)|V\rangle$

Quantum state transfer between weakly coupled qubits

IDEA



quantum filtering:

① outcome of the **suitable measurement** on the source qubit

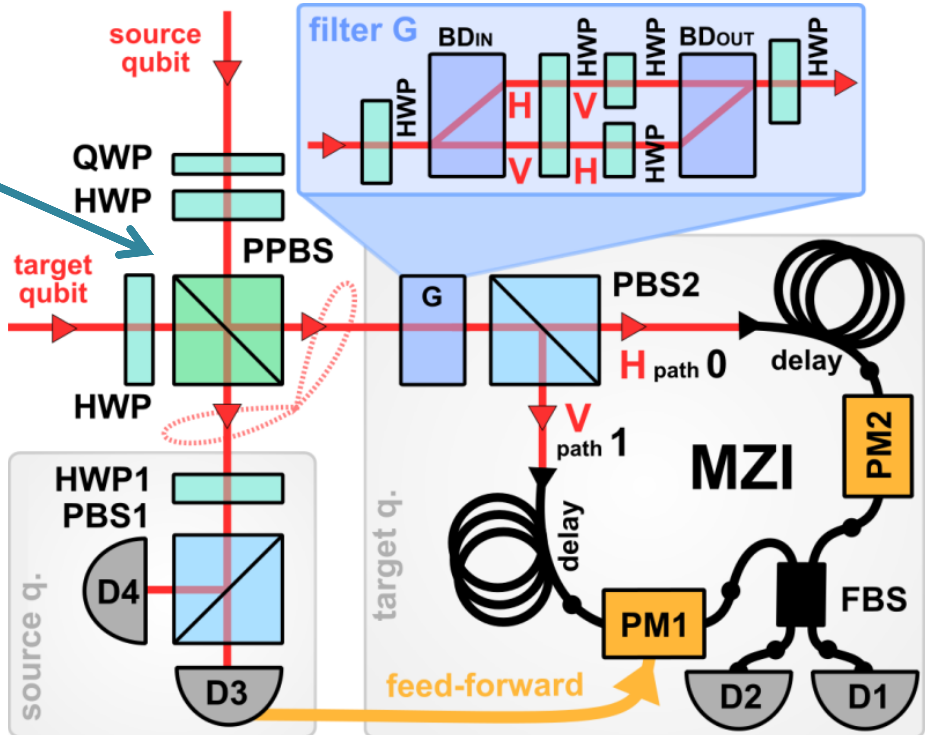
② **interaction** of qubis

③ **initial target qubit state**, parametrized by angle ω

$|g\rangle_T = \cos(\omega)\,|H\rangle + \sin(\omega)|V\rangle$

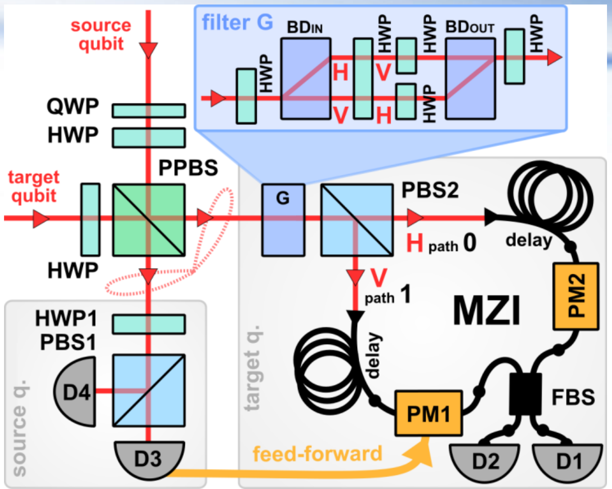
EXPETIMENT

emulation of weak interaction



Quantum state transfer between weakly coupled qubits

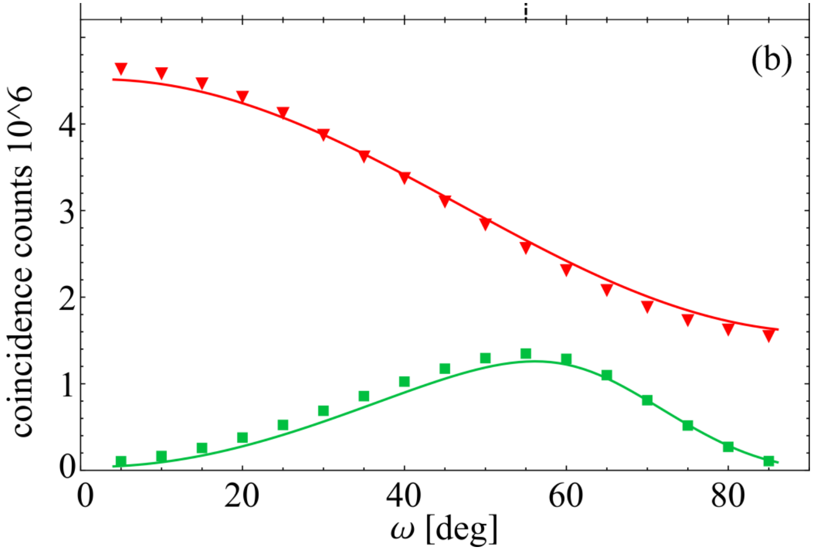
EXPETIMENT



RESULTS

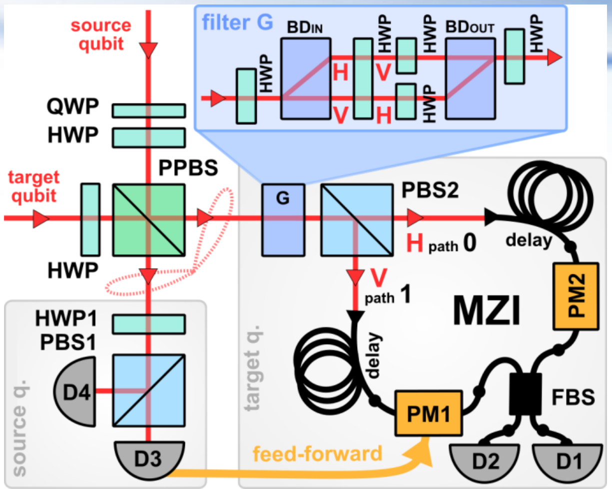
▼ G off

■ G on



Quantum state transfer between weakly coupled qubits

EXPETIMENT

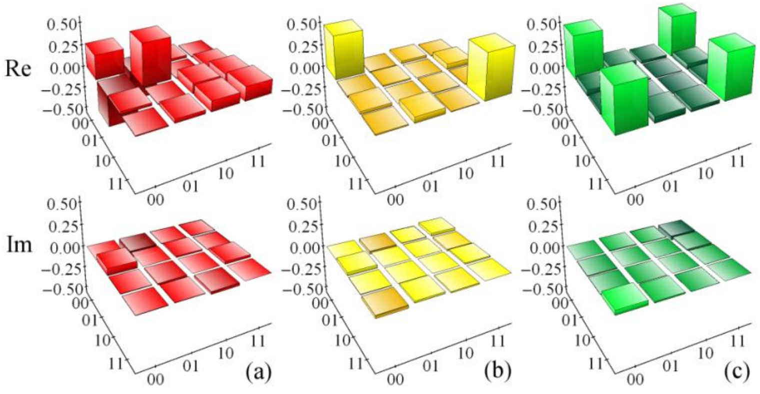


RESULTS

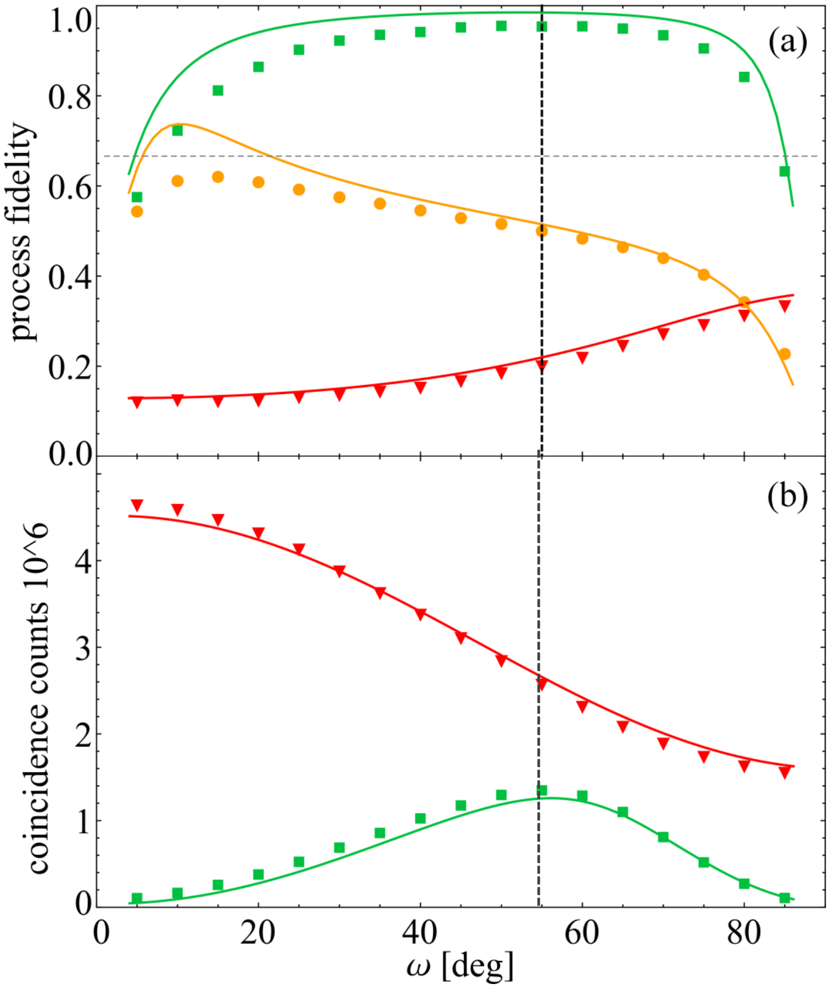
▼ **G off**
FF off

● **G on**
FF off

■ **G on**
FF on



ω=55°



Conclusion

- We **double the success probability** of the programmable linear-optical quantum phase gate via feed-forward.
- We experimentally verify usefulness of directly **measurable parameter |*D*|** which quantifies how the quantum information processing is influenced by particles in non-facrorizable state.
- We experimentally implement perfect **quantum reading** and prove its feasibility.
- We experimentally realize the optimal strategies for discrimination between two projective single-qubit quantum measurements on polarization states of single photons and demonstrate the advantage of **entanglement-based discrimination strategy** (compared to unentangled single-qubit probes).
- We experimentally verified feasibility and robustness of quantum state transfer protocol between **weakly coupled qubits** in the experiment using two photonics qubits.

Acknowledgement

- **To ALL my colleagues and co-authors**
- **This work was supported by**
  - Czech Grant Agency: 202/09/0747, GA13-20319S, 17-26143S
  - Czech Ministry of Education, Youth and Sports: LC06007, MSM6198959213
  - European Social Fund: CZ.1.07/2.3.00/20.0060
  - Palacký University: PrF-2011-015, PrF-2012-019, PrF-2013-008, IGA PrF 2014008, IGA-PrF-2015-005, IGA-PrF-2016-009, and IGA-PrF-2017-008

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Thank you for your attention