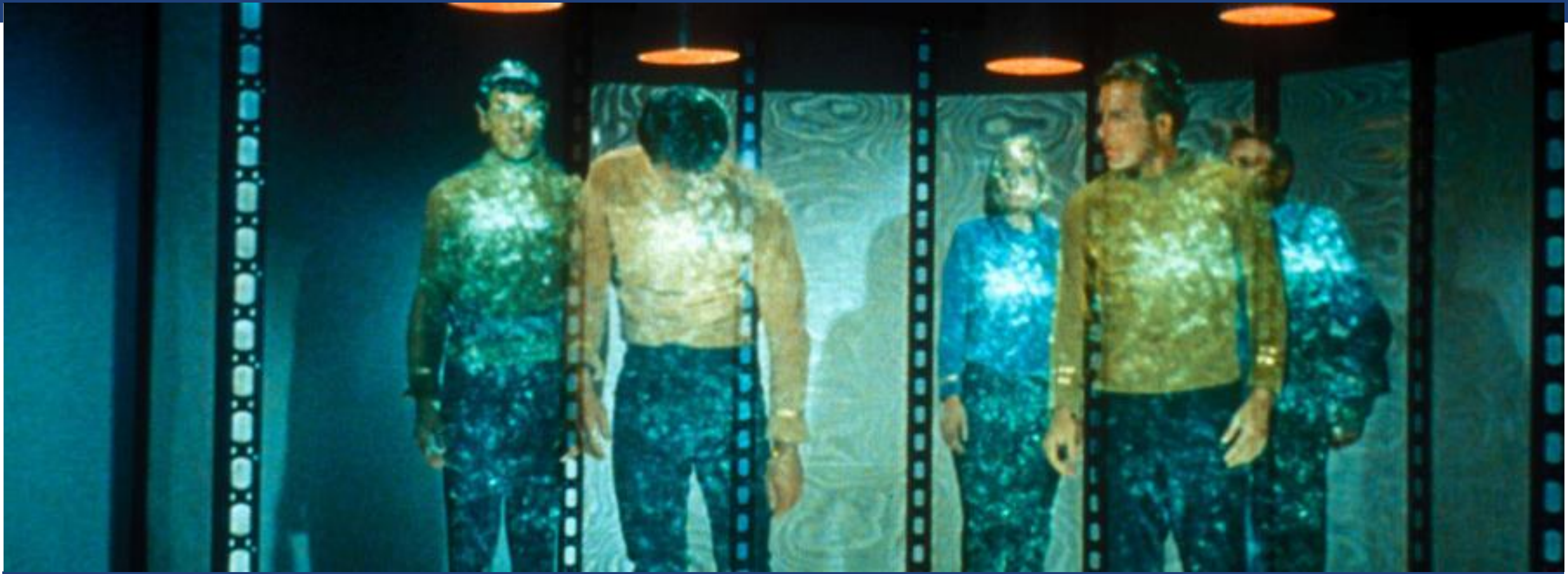
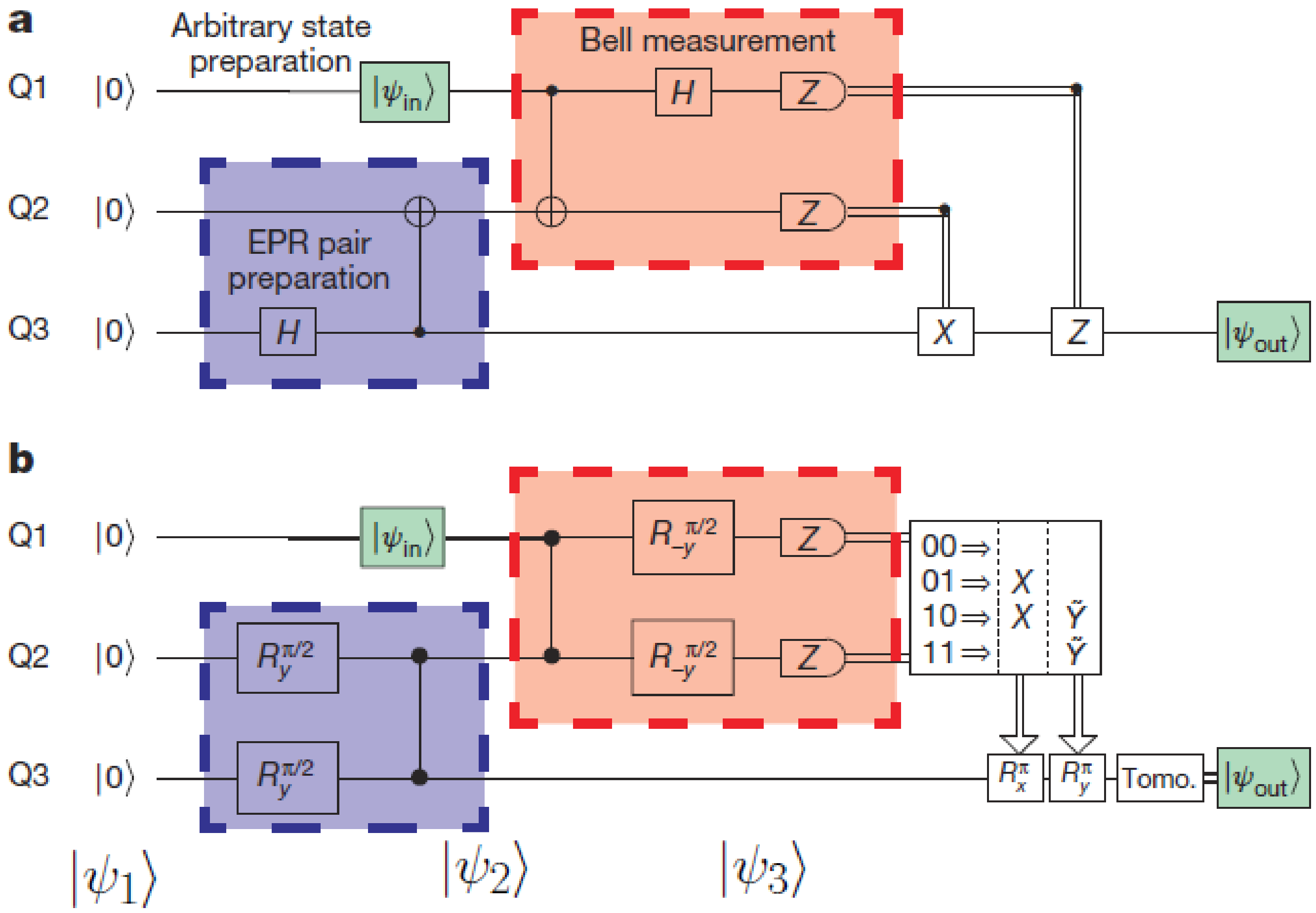
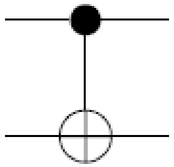


Quantum teleportation with SC qubits

Concept:Quantum Circuit



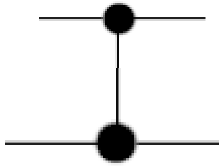


$$= \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

$$X = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

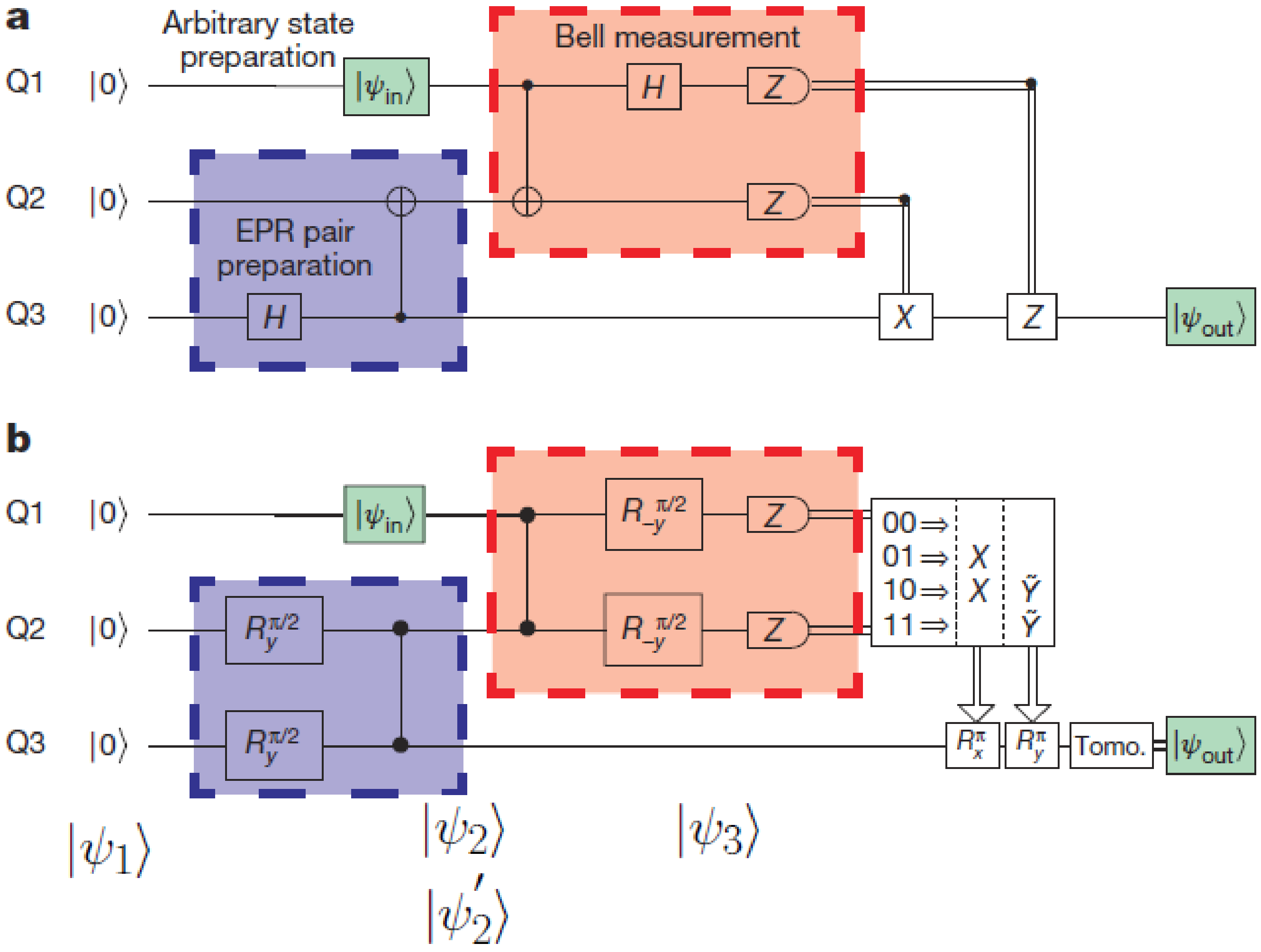
$$R_Y(\pi/2) = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ -1 & 1 \end{pmatrix} \qquad Z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$R\_Y(\pi/2) = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & -1 \\ 1 & 1 \end{pmatrix} \qquad Y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$$



$$= \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

Concept:Quantum Circuit



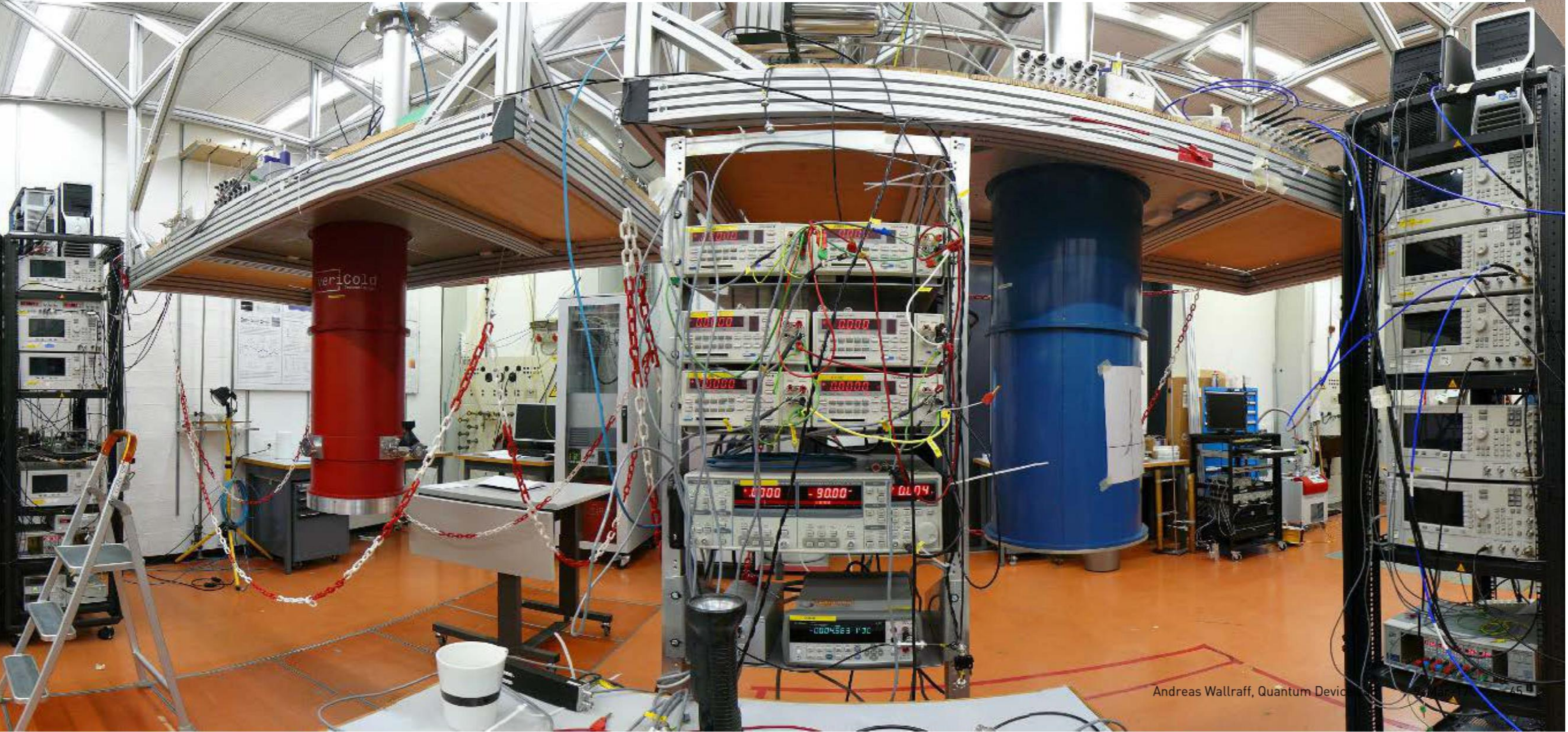
$$|\psi_1\rangle = |0\rangle \otimes |0\rangle \otimes |0\rangle$$

$$|\psi_2\rangle = |\psi_{in}\rangle \otimes \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$

$$|\psi_2'\rangle = \frac{1}{2}|\psi_{in}\rangle \otimes (|00\rangle - |01\rangle - |10\rangle - |11\rangle)$$

$$\begin{aligned}|\psi_3\rangle = &\frac{1}{2}[|00\rangle(\alpha|0\rangle + \beta|1\rangle) \rightarrow I \\ &+ |10\rangle(\alpha|0\rangle - \beta|1\rangle) \rightarrow Z \\ &+ |01\rangle(\alpha|1\rangle + \beta|0\rangle) \rightarrow X \\ &+ |11\rangle(\alpha|1\rangle - \beta|0\rangle)] \rightarrow Y\end{aligned}$$

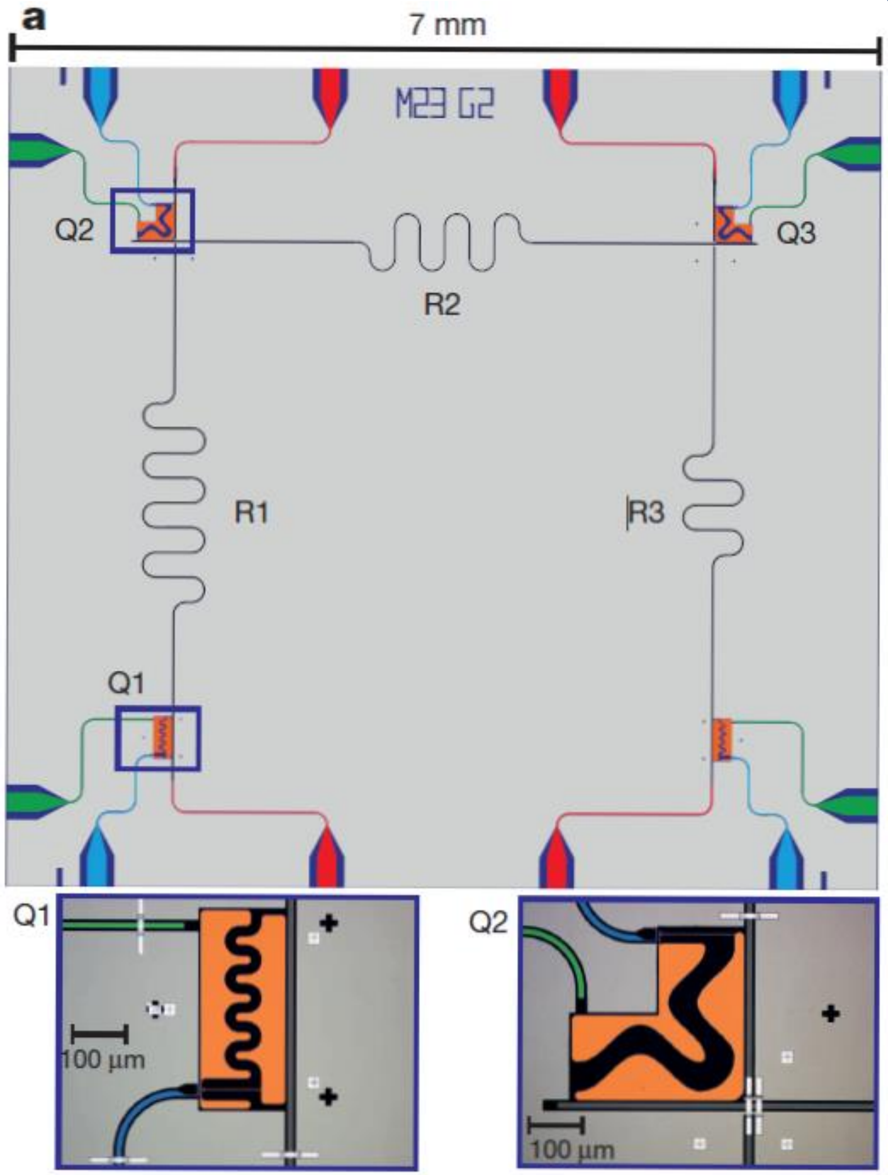
Experimental Setup



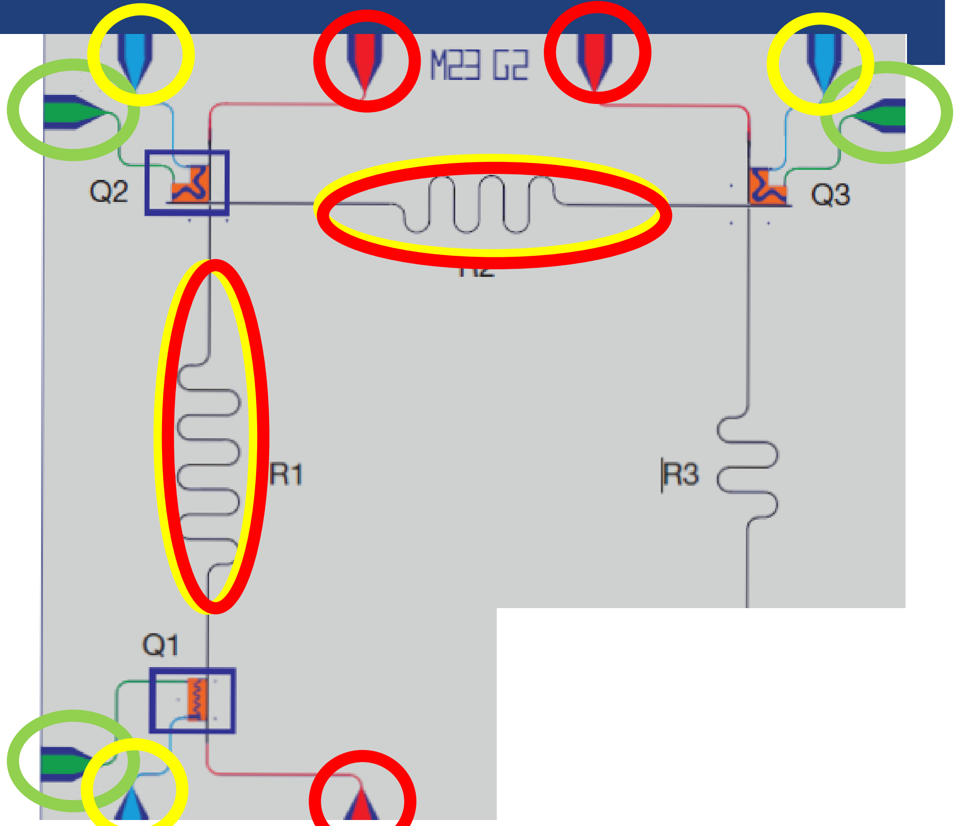
Experimental Setup
➡ Requirements

- Creation of Entangled Qubit-Pair ✓
- Two-Qubit Bell measurement ✓
- Classical Feed-Foreward ✓
- Run Protocoll at high Rate ✓
- Run Protocoll over large distance ✗

- Superconducting Transmon Qubits Q1, Q2, Q3
- Superconducting Coplanar Waveguide Resonators R1, R2, R3
- Input and Output lines (red)
- Local flux-bias lines (blue)
- Local Microwave charge gate lines (green)
- Real-time Feed-Forward via classical Electronics

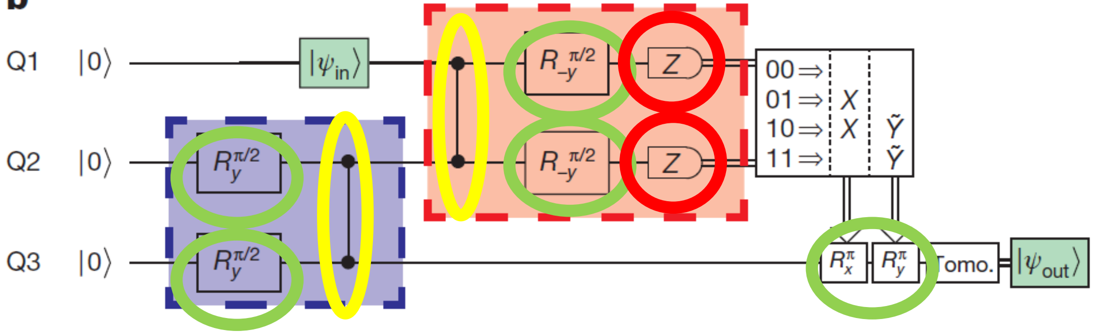


Experimental Setup
➡ Implementation



- Superconducting Transmon Qubits Q1, Q2, Q3
- Superconducting Coplanar Waveguide Resonators R1, R2, R3
  - R1: coupled to Q1, Q2, second CPHASE-gate (Bell-measurement)
  - R2: coupled to Q2, Q3, first CPHASE-gate (Entanglement)
  - R3: coupled to Q3 (Readout)
- Local Microwave charge gate lines (green)
  - Realization of single-qubit operations via π/2-Pulses
- Readout via Resonators
- Real-time Feed-Forward via classical Electronics

b



Experimental Setup
➡ Implementation

- Superconducting Transmon Qubits Q1, Q2, Q3
- Superconducting Coplanar Waveguide Resonators R1, R2, R3
  - R1: coupled to Q1, Q2, second CPHASE-gate (Bell-measurement)
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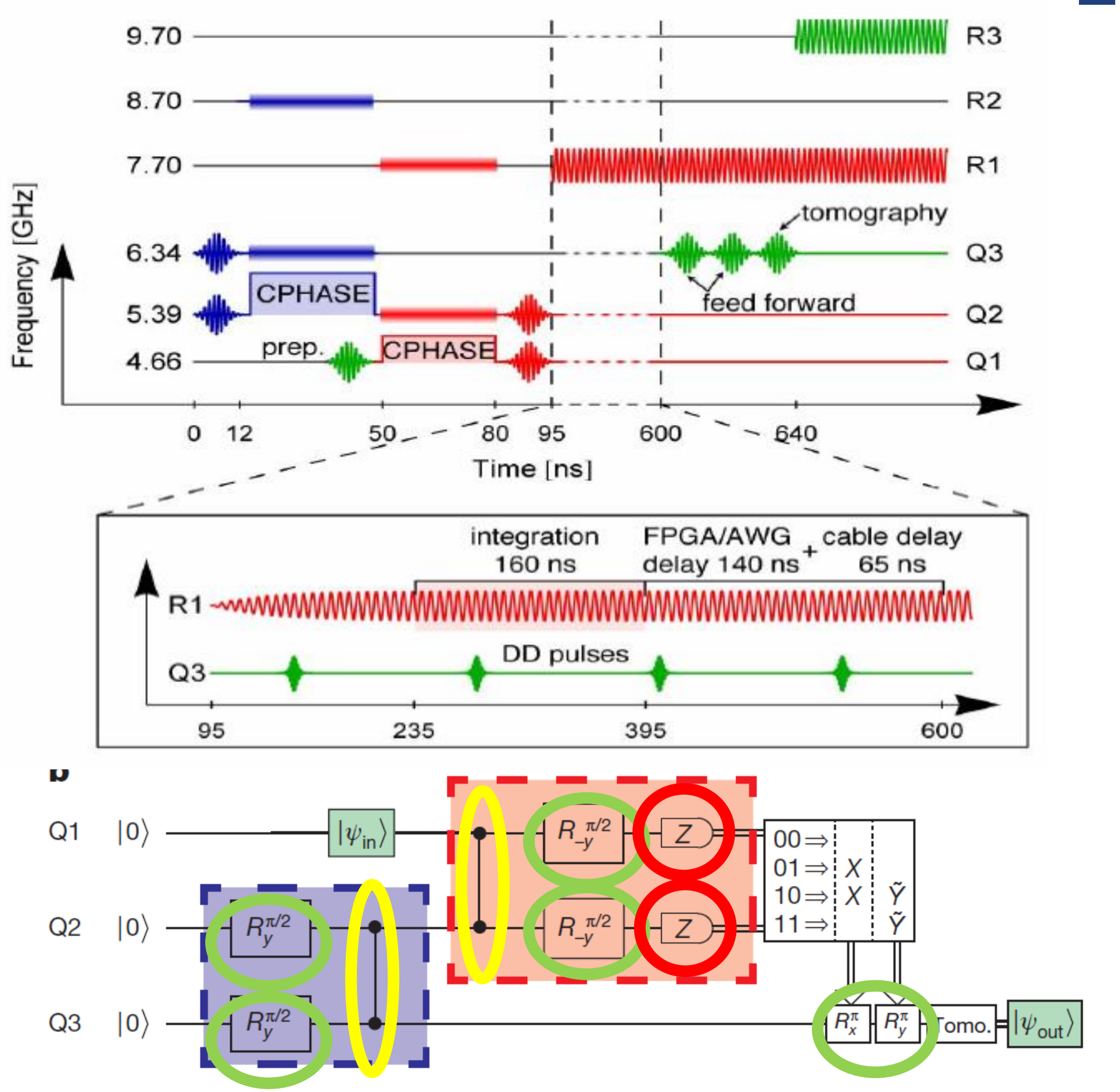
  - R3: coupled to Q3 (Readout)
- Local Microwave charge gate lines (green)
  - Realization of single-qubit operations via π/2-Pulses
- Readout via Resonators
- Real-time Feed-Forward via classical Electronics



Fidelity

- Measure of distinguishability of two qubit states
  - ρ and σ are density matrices of states
  - $F(\rho,\rho) = 1$ and $0 \leq F \leq 1$

$$F(\rho,\sigma) = \sqrt{tr(\rho\sigma) + 2\sqrt{\det(\rho)\det(\sigma)}}$$

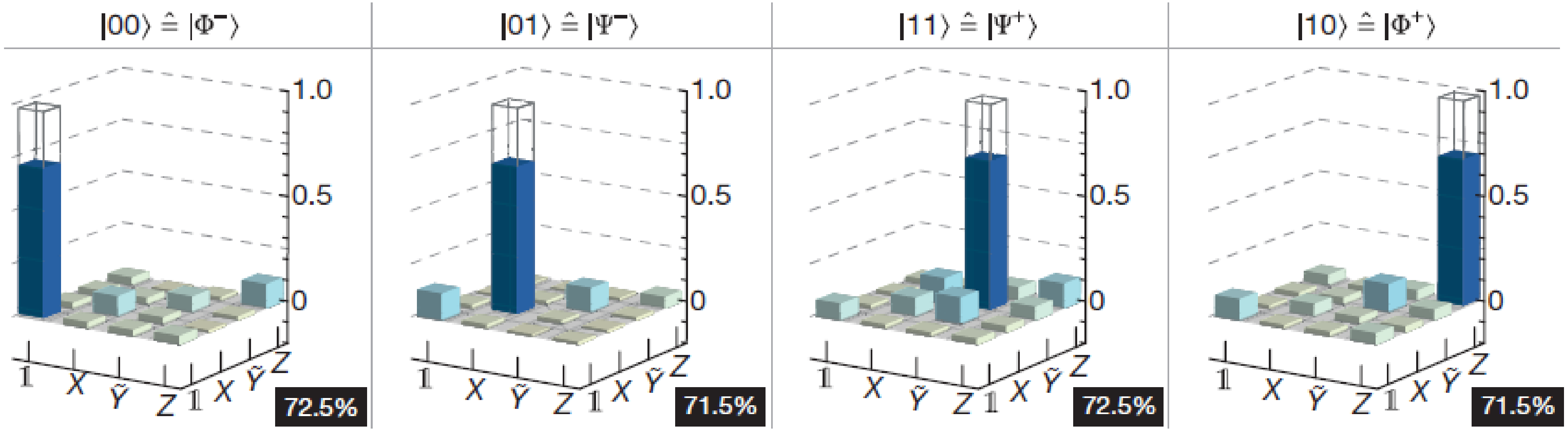
- Example: $\rho = |\Psi\rangle\langle\Psi|$ is pure

$$\rightarrow F(\rho,\sigma) = Tr\left[\sqrt{|\Psi\rangle\langle\Psi|\sigma|\Psi\rangle\langle\Psi|}\right] = \sqrt{\langle\Psi|\sigma|\Psi\rangle}\, Tr[|\Psi\rangle\langle\Psi|] = \sqrt{\langle\Psi|\sigma|\Psi\rangle}$$

If $\sigma = |\Phi\rangle\langle\Phi|$ is pure, $F(\rho,\sigma) = \sqrt{\langle\Psi|\Phi\rangle\langle\Phi|\Psi\rangle} = |\langle\Phi|\Psi\rangle|$

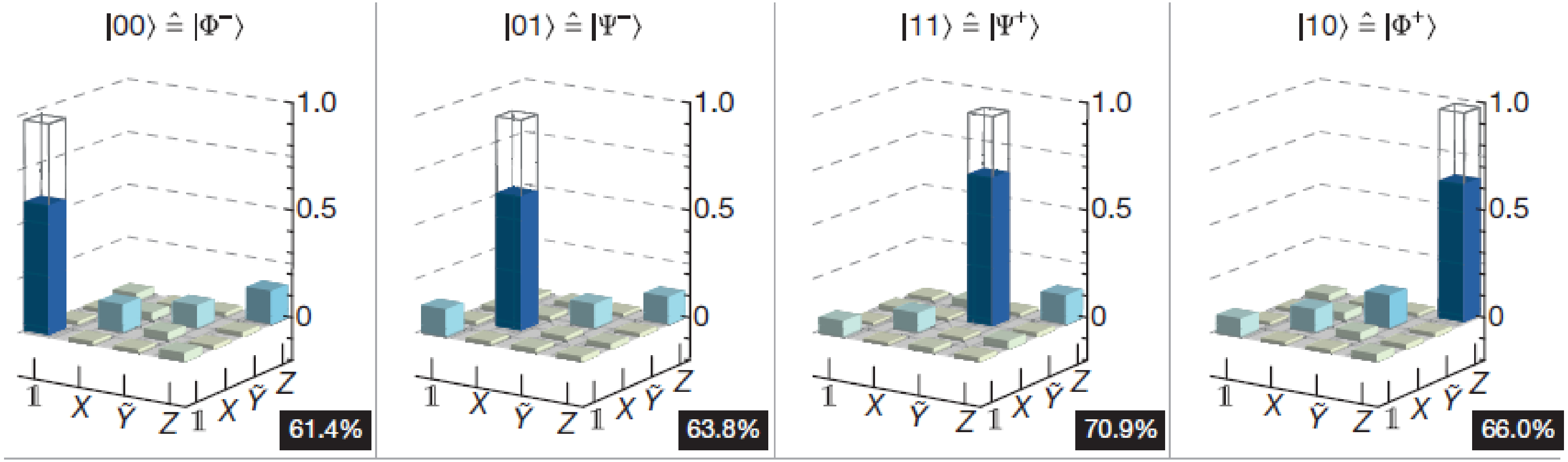
Post-Selection measurement

- Post-Selected Teleportation
  - Distinguish one of the four possible Bell-states in Q1, Q2, Discard other outcomes (e.g. $|00\rangle$)
  - Perform average process tomography conditioned on selected Bell-state (here: |00)
- Average process fidelity F=(72.0$\pm$1.4%) > 1/2
- Manly limited by relaxation and dephasing of qubits



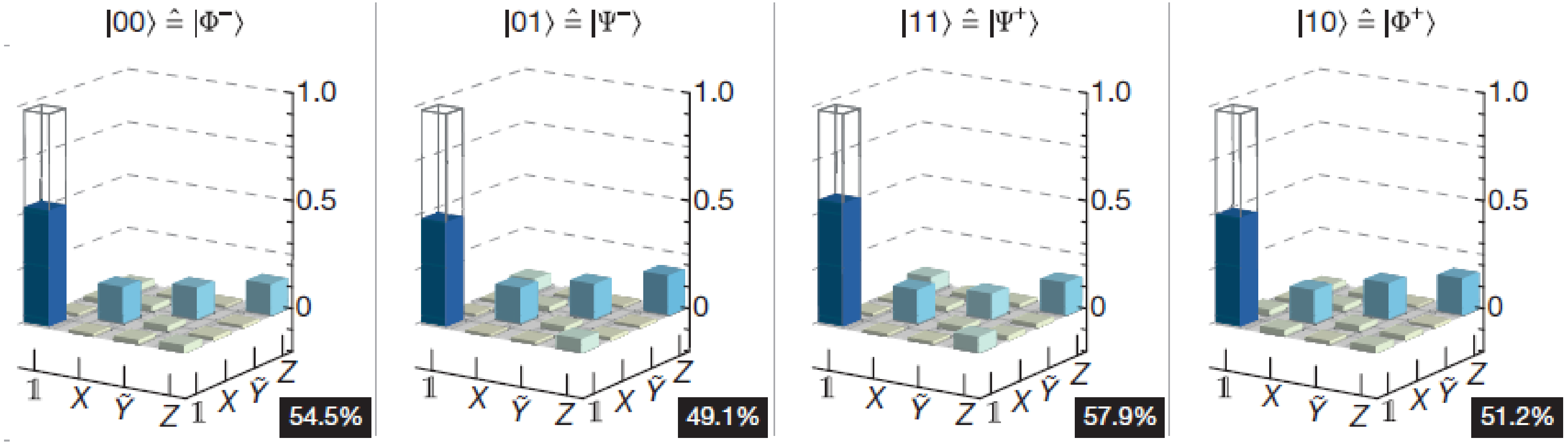
Simultaneous deterministic measurement

- Deterministic Teleportation
  - Full Determination of Q1, Q2 Bell-state, leaving out Feed-Forward / Q3-Rotation
  - Perform average process tomography of single-shot readouts
- Average process fidelity of F=(65.5±1.4%) > 1/2
- Lower fidelity due to lower fidelity of deterministic readout.



Feed-forward

- Deterministic Teleportation with Feed-Forward
  - Full Deterministic quantum Teleportation Protocoll with classical Feed-Forward
- Average process fidelity of F=(53.2±0.5%) > 1/2
- Low fidelity due to time required for feed forward in relation to coherence times of qubits



Conclusion

- Feed-Forward is necessary for quantum computing (repeaters)
- It is hard to implement due to short coherence times of qubits