

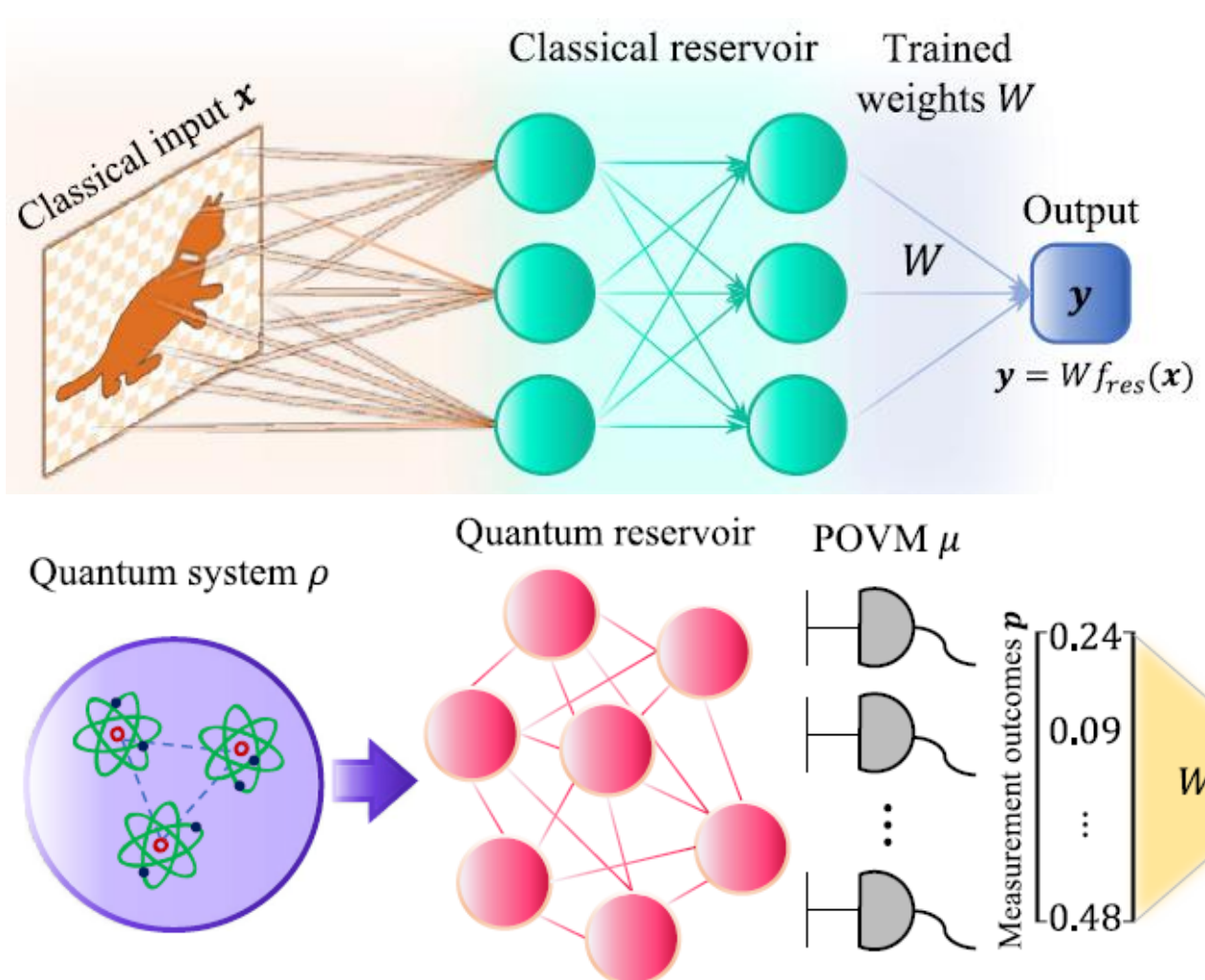
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CLASSICAL VS. QUANTUM EXTREME LEARNING MACHINES

Quantum extreme learning machines (QELMs) have recently emerged as promising tools for both classical and quantum information processing without requiring fault-tolerant hardware. Compared to classical extreme learning machines, QELMs offer enhanced expressivity and an exponential reduction in resource requirements, while retaining simple and robust training procedures.



CLASSICAL ELM	QUANTUM ELM
Classical bit string at the input that feeds a feed-forward neural network (the reservoir). The input information is sequentially processed through multiple and untrained hidden layers.	A quantum system at the input interacts with an auxiliary quantum system (the reservoir). The input information is transferred from the input quantum state to the reservoir. The interconnections between the reservoir nodes are not optimized during training.
The state of the output neurons is measured. The outcome is deterministic.	The state of the reservoir nodes is measured. The outcome is probabilistic.
Only the weights of the output layer are trained through supervised learning and linear regression.	

L. Innocenti et al., Commun. Phys. 6.1 (2023): 118.

BRIDGING THE TWO WORLDS TOGETHER

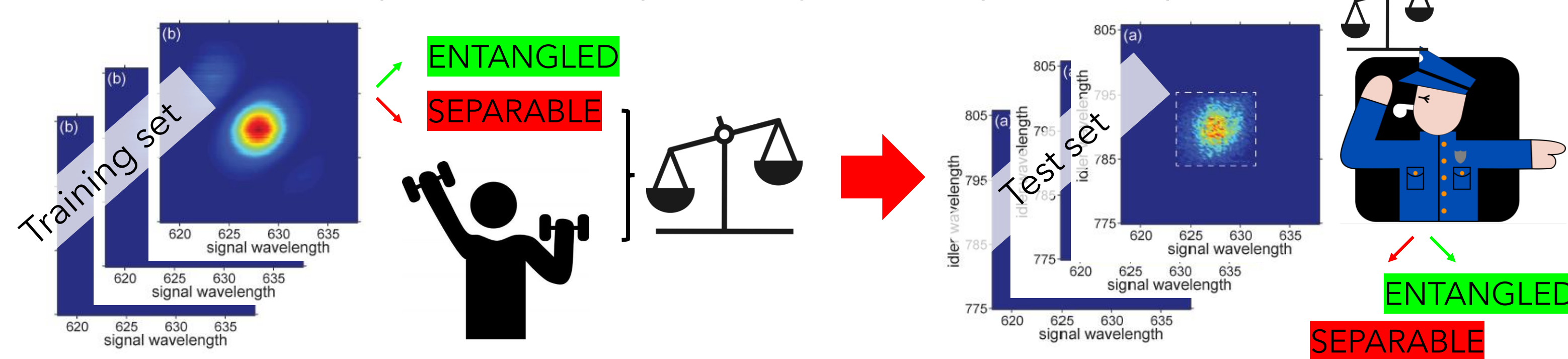
The scalability of QELMs is fundamentally limited by the need to estimate expectation values of output observables through repeated measurements, a consequence of the probabilistic nature of quantum mechanics. This requirement results in long acquisition times and increased sensitivity to experimental drifts, which become more severe as the system size and training dataset grow.

Can we tackle this issue by mapping the intensity of a strong macroscopic signal onto the expectation value of an observable at the output of the QELM? Under some conditions, yes!

In quantum optics, a procedure has been developed to map the correlations of photon-pairs emitted by weak spontaneous parametric processes into the stronger intensity of stimulated emission coherent beams - **Stimulated Emission Tomography (SET)**

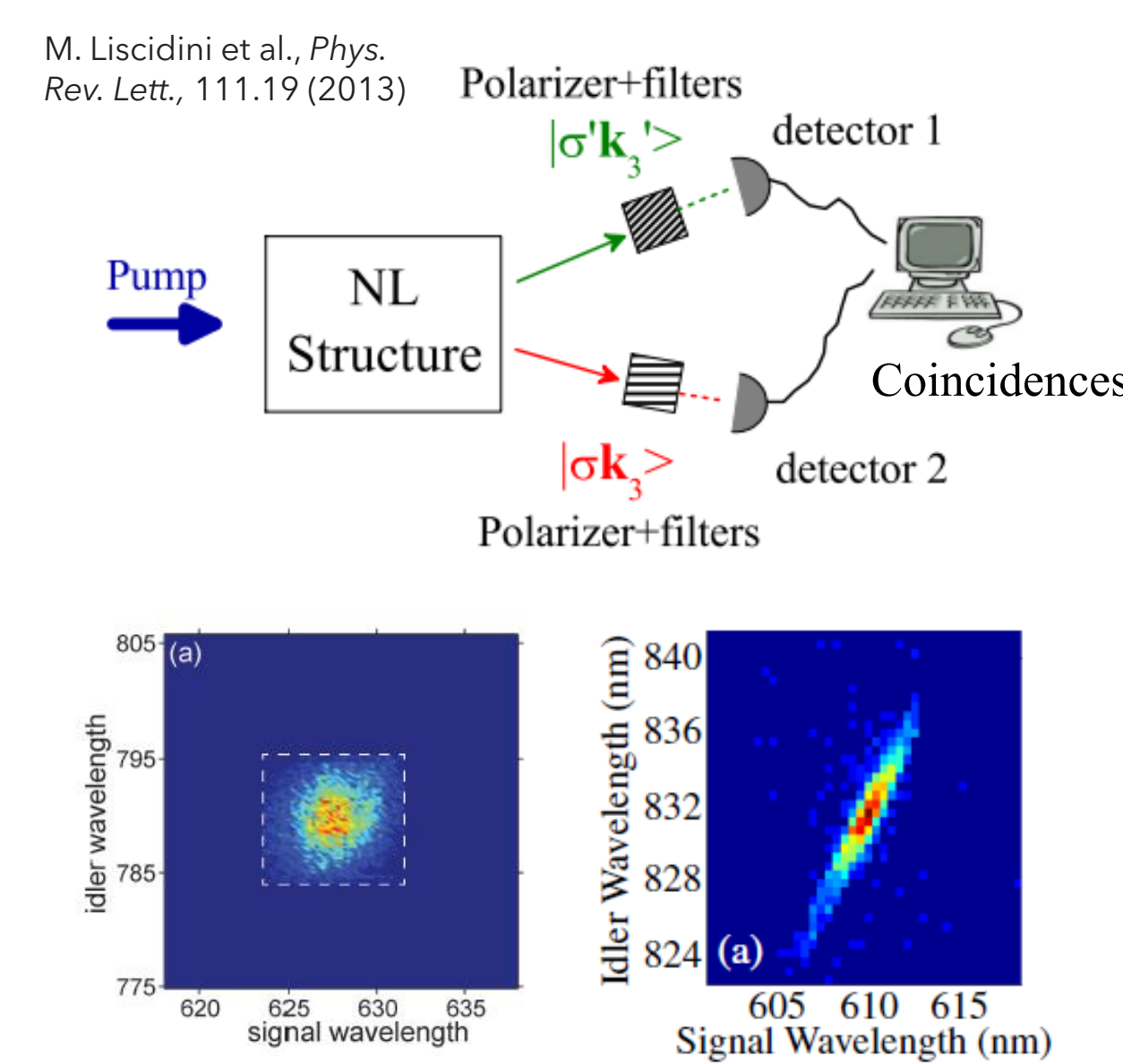
THE IDEA

Perform fast and precise classical training of the QELM with SET
Test predictions on previously unseen quantum input states



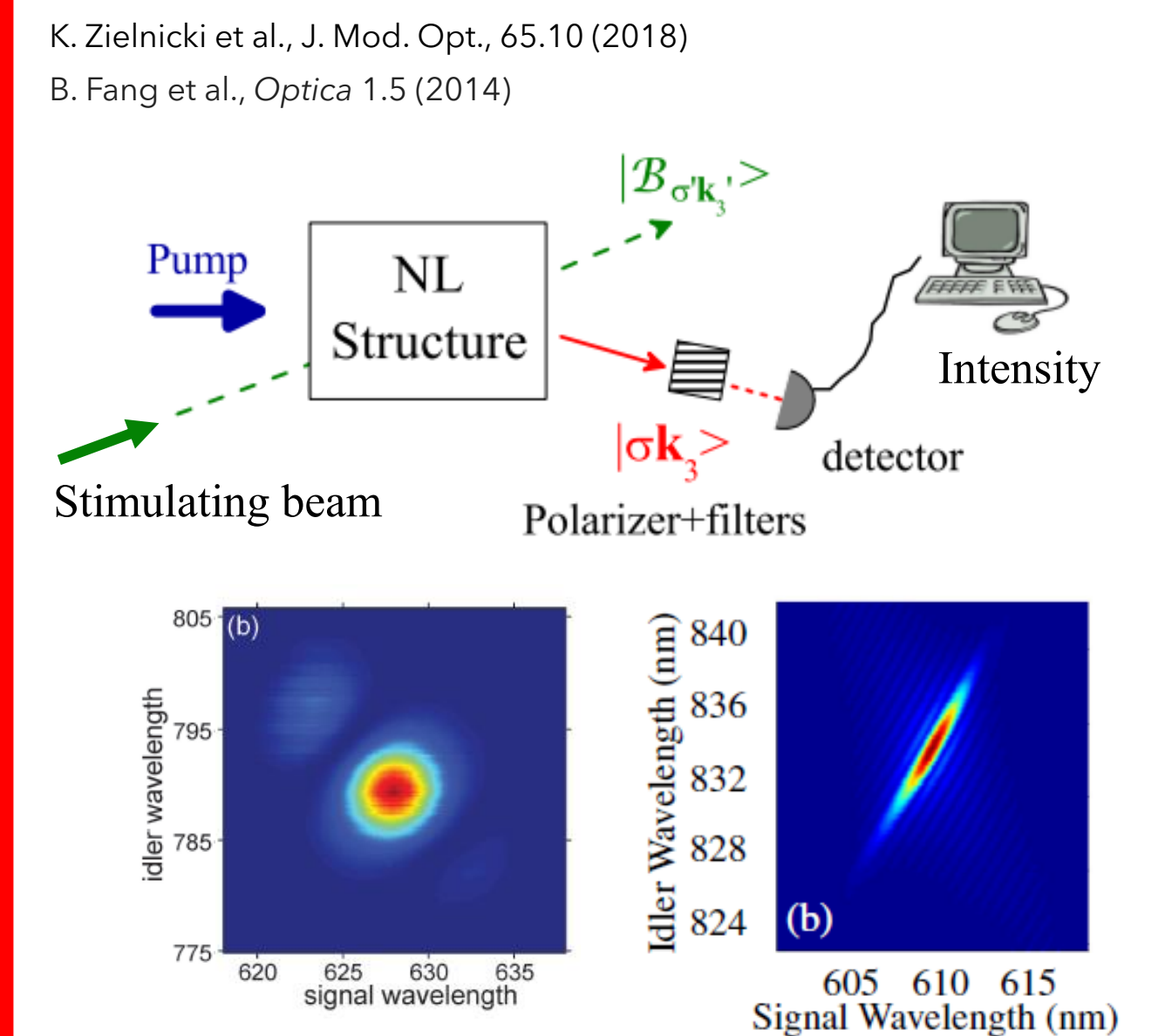
Classical training \rightarrow Determination of the weights Quantum input on trained QELM

COINCIDENCE MEASUREMENT



- Works in the two-photon regime
- Requires single photon detectors and coincidence measurements
- Hours of acquisition time for good SNR

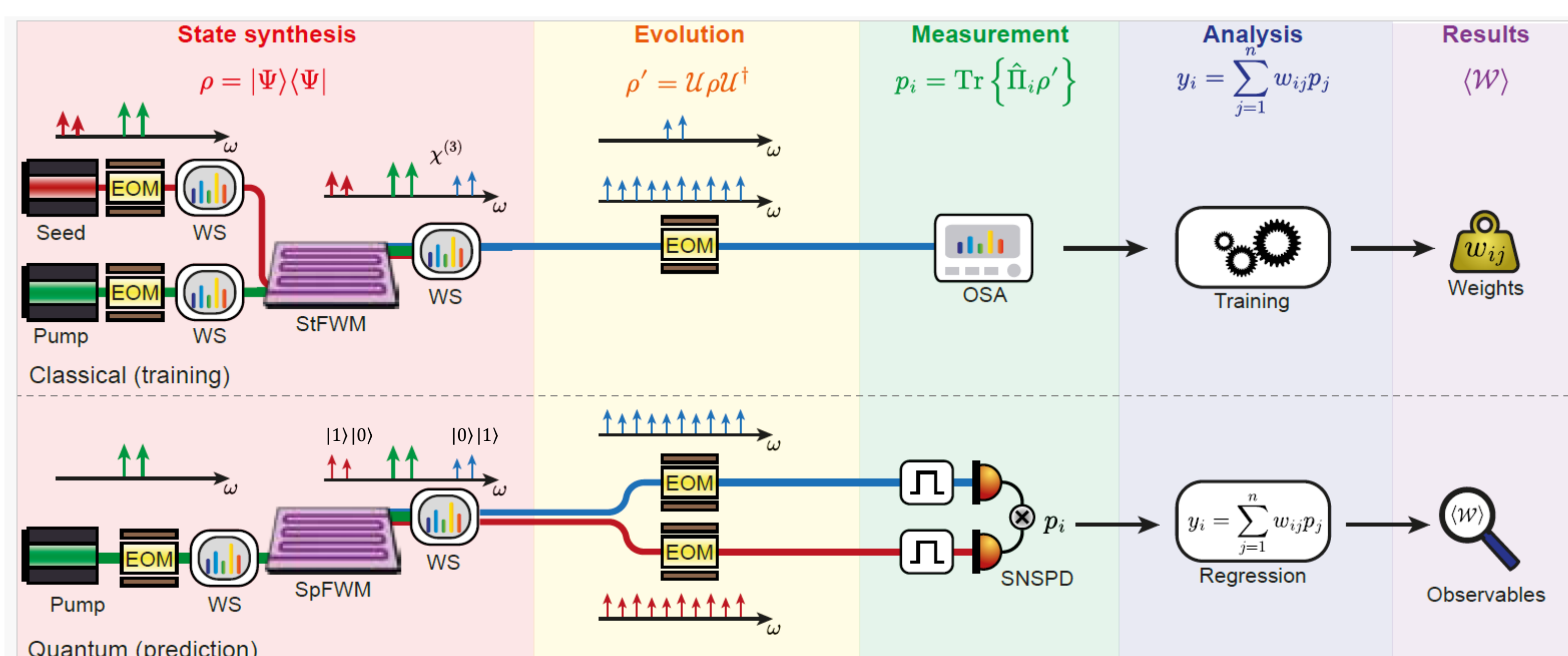
STIMULATED EMISSION TOMOGRAPHY



- Typical output powers of micro-milliwatts
- Uses photodetectors/spectrum analyzers and records the intensity
- Few seconds/minutes of acquisition time

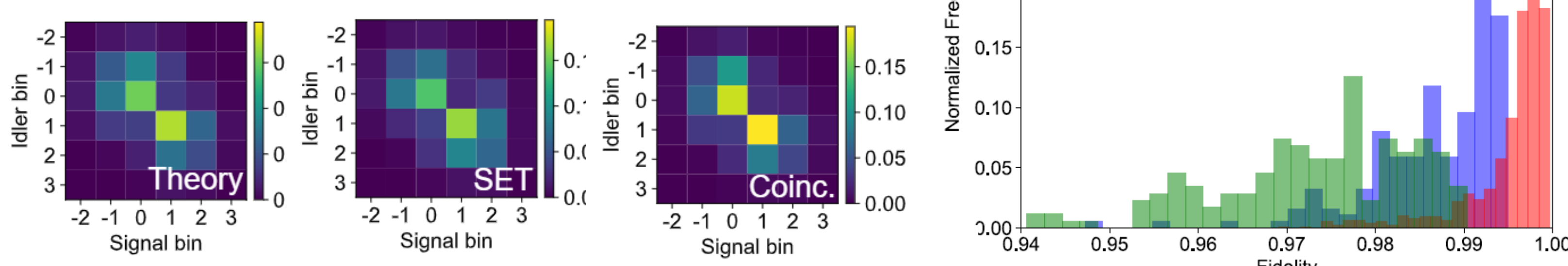
EXPERIMENTAL IMPLEMENTATION

- The QELM is implemented on a photonic platform. Two photons, generated by spontaneous four-wave mixing in a silicon waveguide, form the input qubits.
- Logical states are encoded in the photon frequency (frequency-bin encoding). A wide variety of separable and entangled states can be generated for training and test through pump engineering and a spectral pulse shaper.
- The reservoir is an electro-optic phase modulator. It implements a tight-binding Hamiltonian among frequency modes, and is also used for dimensionality expansion.
- Training is performed with stimulated emission, test is conducted by frequency resolved coincidence measurements.
- **Classical training based on stimulated emission allowed us to reduce the training time from 24 hours to 75 minutes, and to improve the SNR by two orders of magnitude compared to frequency resolved coincidence measurements.**

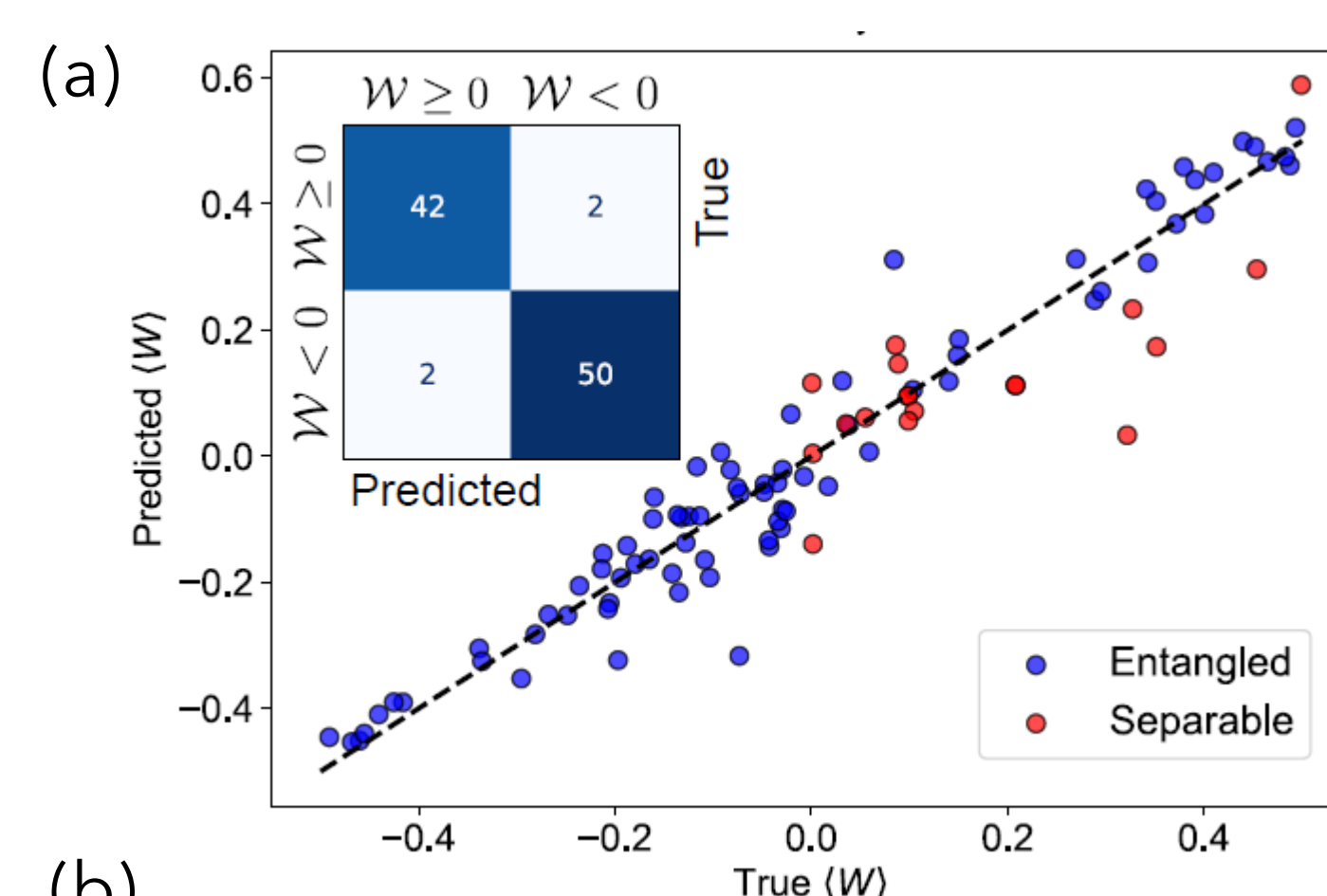


CLASSICAL TO QUANTUM CORRESPONDENCE

Quantum correlations (coincidences) among frequency bins must be mapped to classical intensity measurements (SET). This is verified with an average fidelity $> 97(4)\%$ between the two distributions (CC-SET)



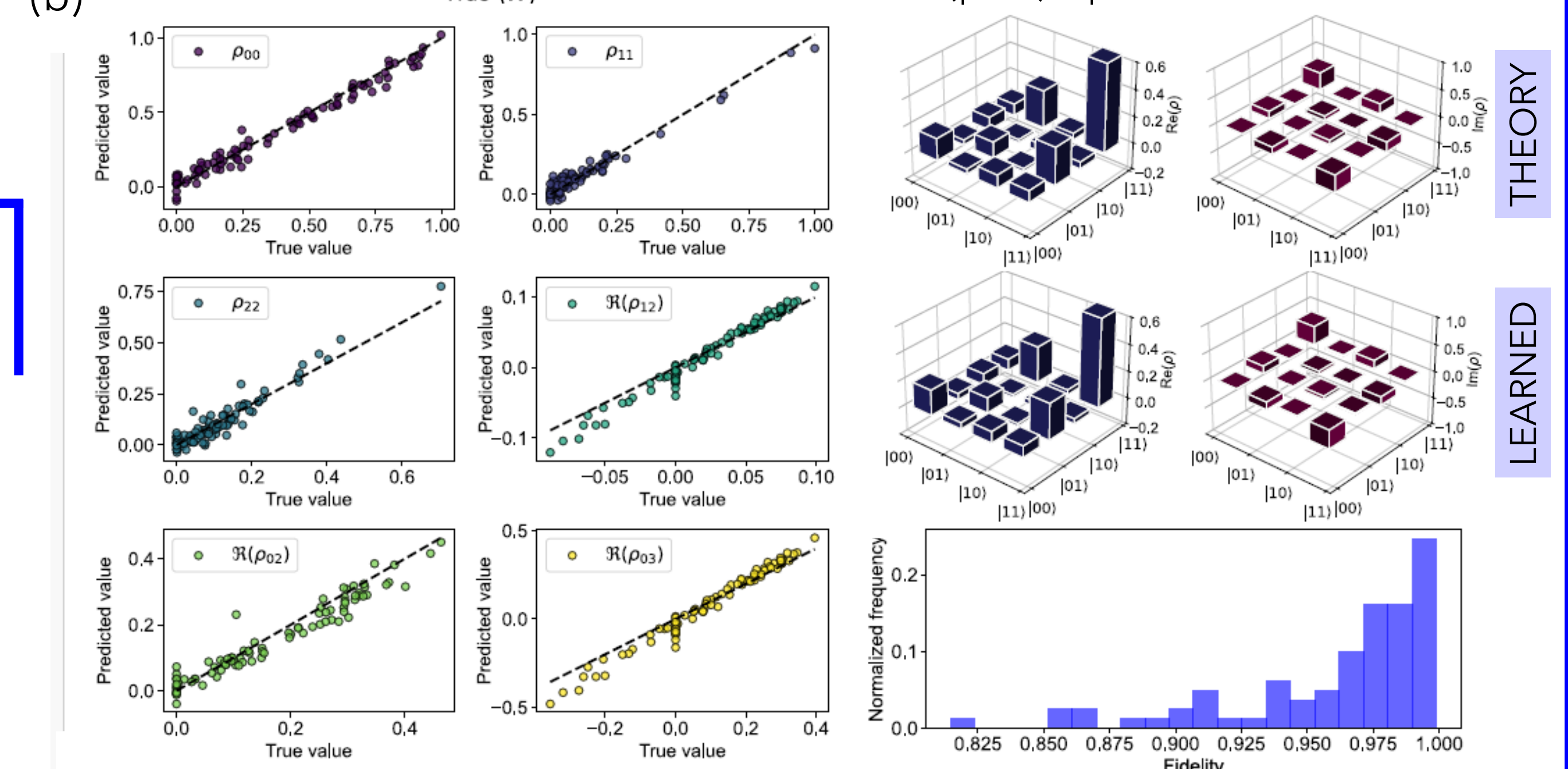
APPLICATION EXAMPLES



The QELM is trained by stimulated emission to perform different tasks, and later is tested on previously unseen quantum input states.

(a) Prediction of the entanglement witness $\langle W \rangle = \frac{1}{2} - |\Phi^+\rangle\langle\Phi^+|$, where $|\Phi^+\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$

(b) Learning of the density matrix of (pure) input states



THEORY

LEARNED