Weak Measurements for Reutilizing Entanglement

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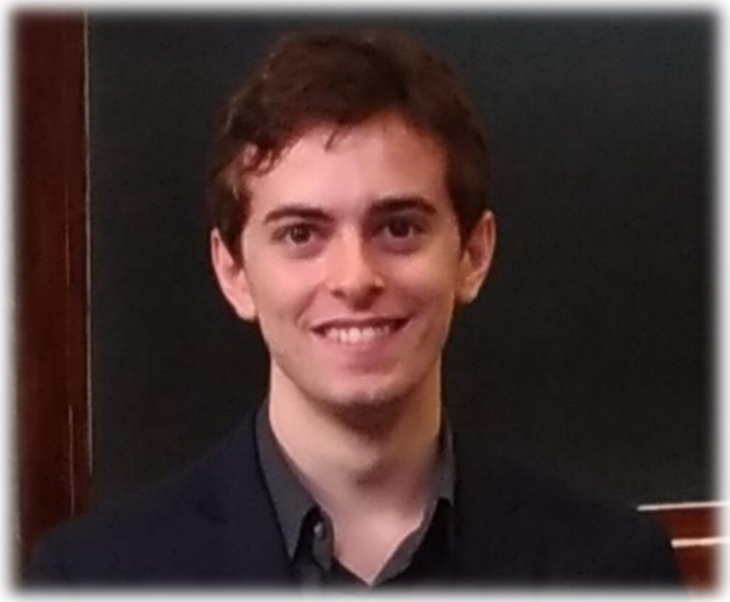
Webinar «Is Quantum Theory Exact? Exploring Quantum Boundaries»

About me

- PhD Student at QuantumFuture, led by Prof. Villoresi and Prof. Vallone
- The group focuses on experimental quantum communication and technologies



Quantum future
The shift in the communication paradigm

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UNIVERSITÀ DEGLI STUDI DI PADOVA

DIPARTIMENTO DI INGEGNERIA DELL'INFORMAZIONE

Weak values

Coupling → Evolution → Post-selection → Ancilla readout

$$|\psi\rangle \otimes |0_A\rangle$$

$$U = e^{-ig\, S \otimes P_A}$$

$$\approx \mathbb{I} - ig\, S \otimes P_A$$

$$\Pi_\phi (U|\psi\rangle \otimes |0_A\rangle)$$

$$\Pi_\phi \otimes O_A$$
$$(U|\psi\rangle \otimes |0_A\rangle)$$

$$|0_A\rangle - i\,\frac{g}{\hbar}\,\frac{\langle\phi|S|\psi\rangle}{\langle\phi|\psi\rangle}\,P_A|0_A\rangle$$

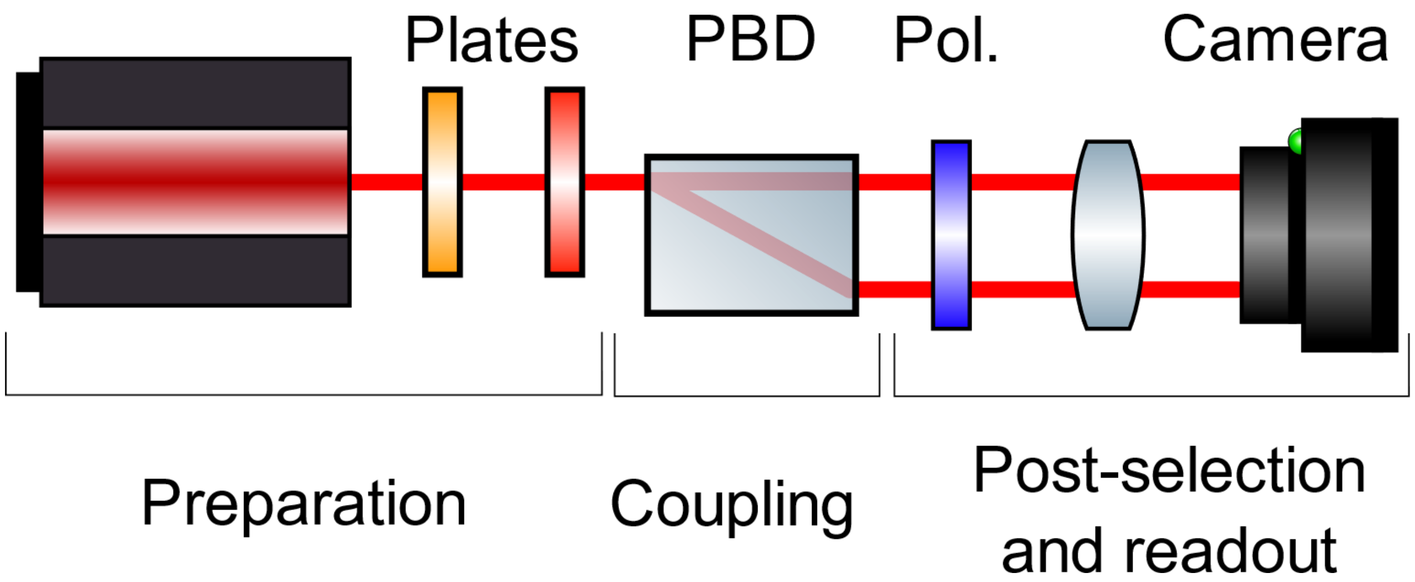
Aharonov *et al*, Phys. Rev. Lett. **60**, 1351, 1988

Weak values

$$|1_A\rangle \approx |0_A\rangle - i\frac{g}{\hbar}\langle\hat{S}^W\rangle_\psi^\phi P_A|0_A\rangle$$

$$\Re\left(\langle\hat{S}^W\rangle_\psi^\phi\right) \approx \frac{1}{g}\langle\hat{X}_A\rangle_{1_A}$$

$$\Im\left(\langle\hat{S}^W\rangle_\psi^\phi\right) \approx \frac{2\Delta_x^2}{g\hbar}\langle\hat{P}_A\rangle_{1_A}$$



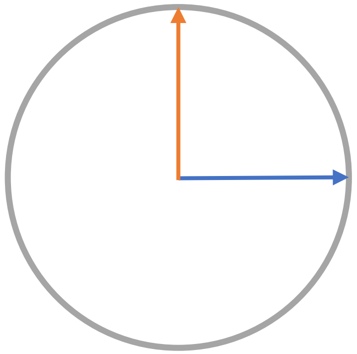
Weak Measurements

Coupling → **Evolution** → **Ancilla readout**

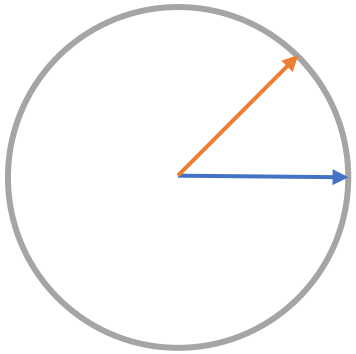
$|\psi\rangle \otimes |0_A\rangle$

$U = e^{-ig\, S \otimes P_A}$

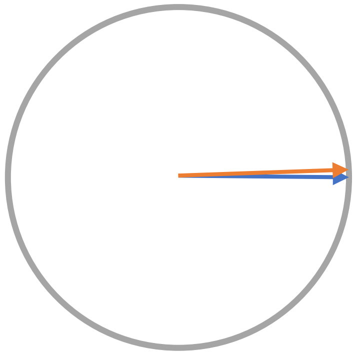
$Tr\,[O_A(U|\psi\rangle \otimes |0_A\rangle)]$



Projective



Generic weak



Weak approximation

Aharonov *et al.*, Phys. Rev. Lett. **60**, 1351, 1988

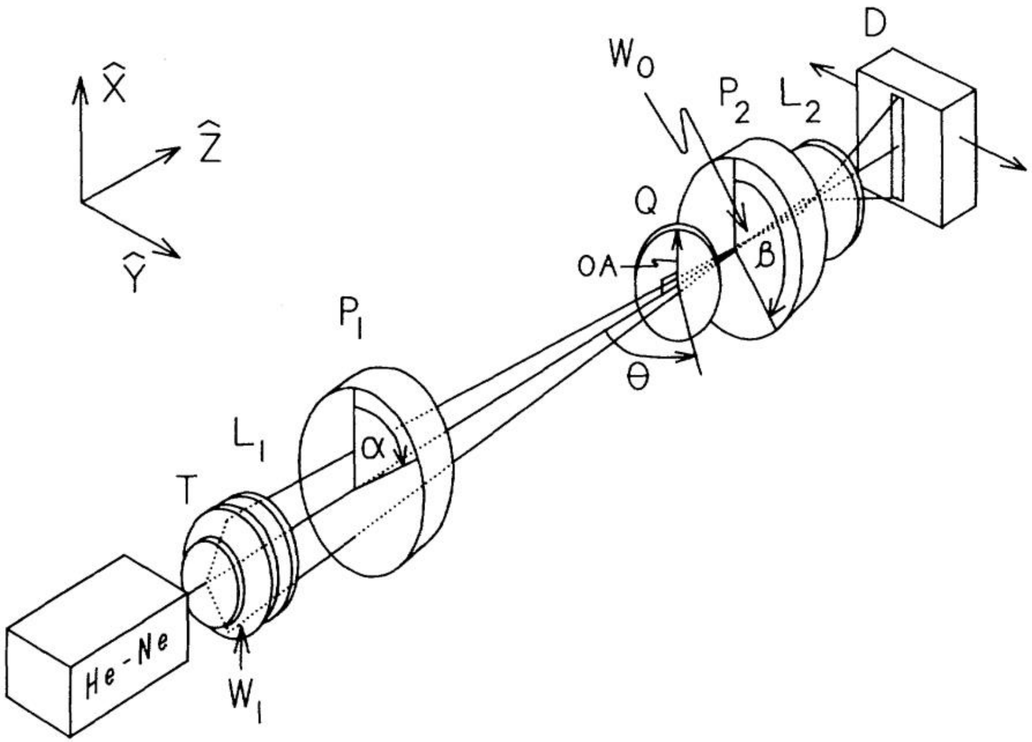
Applications of WVs and WMs

Amplification of small quantities through post selection

$$\Re\left(\langle \hat{S}^W \rangle_\psi^\phi\right) \approx \frac{1}{g} \langle \hat{X}_A \rangle_{1_A} \longrightarrow g \approx \frac{\langle \hat{X}_A \rangle_{1_A}}{\Re\left(\langle \hat{S}^W \rangle_\psi^\phi\right)}$$

Examples:

- First measurement of a weak value [Ritchie *et al*., Phys. Rev. Lett. **66**, 1107, 1991]
- Spin Hall effect of light [Hosten and Kwiat, Science **319**, 787, 2008]
- Angular deflection [Dixon *et al*. Phys. Rev. Lett. **102**, 1, 2009]
- Imbert-Fedorov effect [Jayaswal *et al*., Opt. Lett. **39**, 2266, 2014]

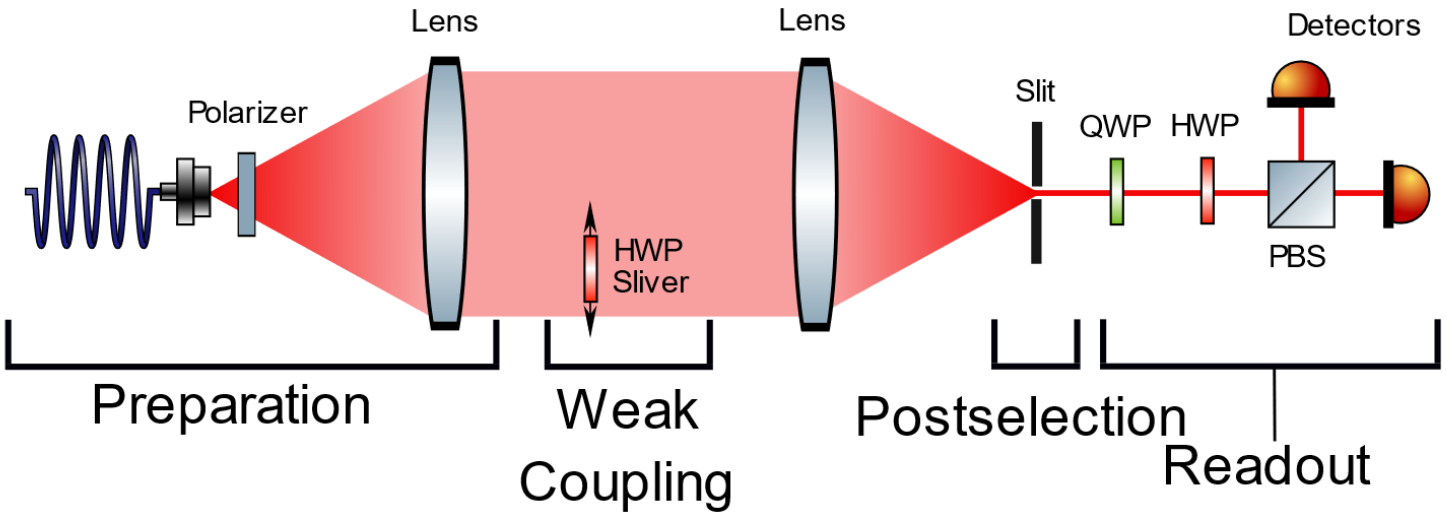


Ritchie *et al*., Phys. Rev. Lett. **66**, 1107, 1991

Applications of WVs and WMs

Quantum state reconstruction

$$\langle \Pi_x^W \rangle_\psi^{p_0} = \frac{\langle p_0 | x \rangle \langle x | \psi \rangle}{\langle p_0 | \psi \rangle} \propto \langle x | \psi \rangle$$

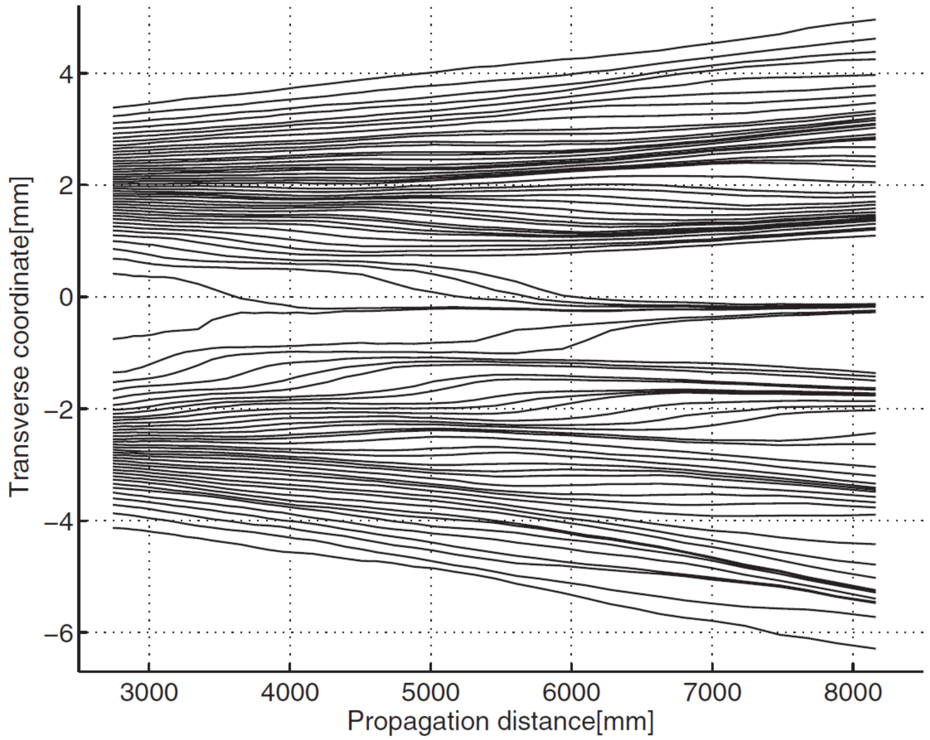


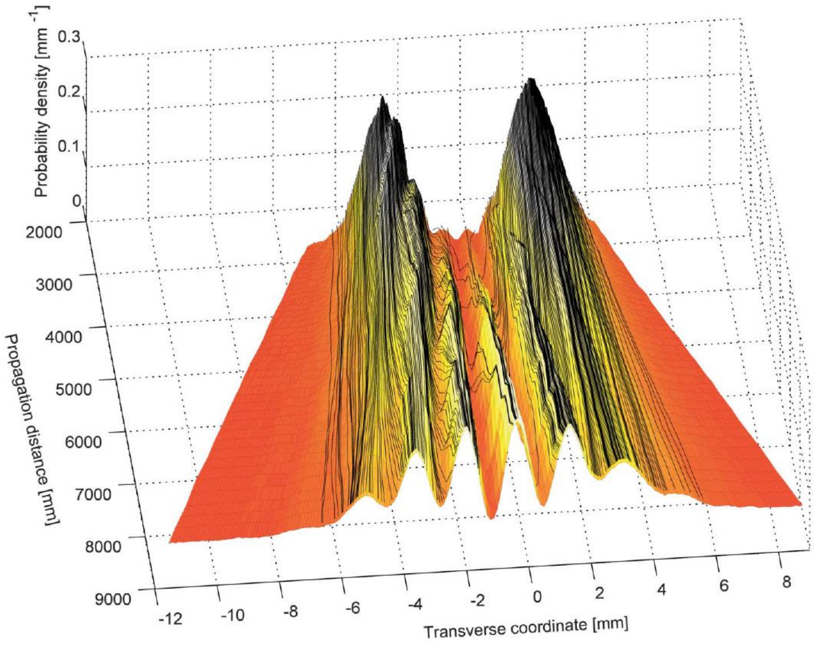
Works with:

- Pure states [Lundeen *et al.*, Nature **474**, 188, 2011]
- Mixed states [Thekkadath *et al.*, Phys. Rev. Lett. **117**, 120401, 2016]
- Strong measurements [Calderaro *et al.*, Phys. Rev. Lett. **121**, 230501, 2018]

Applications of WVs and WMs

Path and interference in two-slit interferometer

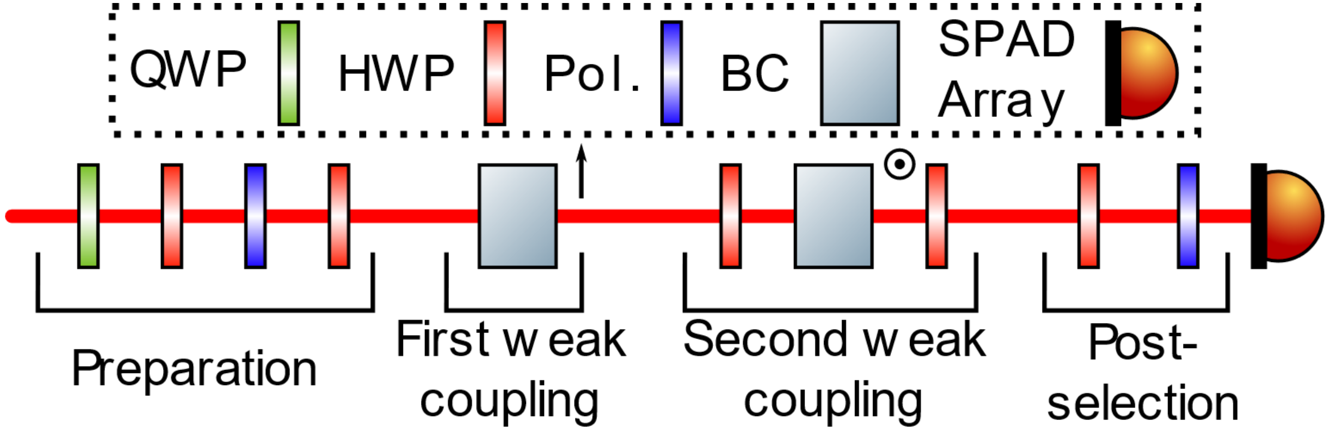




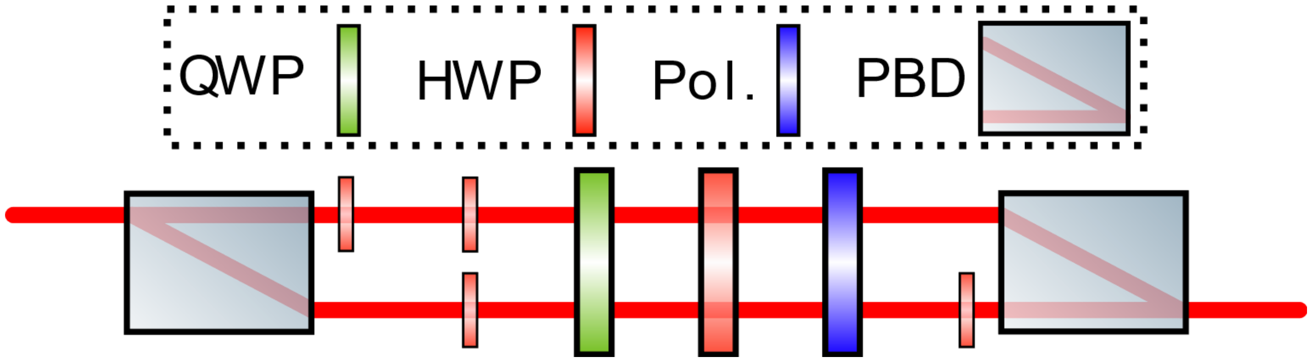
Kocsis *et al.*, Science **332**, 1170, 2011

Applications of WVs and WMs

Measurement of products of incompatible observables



Piacentini *et al.*, Phys. Rev. Lett. **117**, 170402, 2016

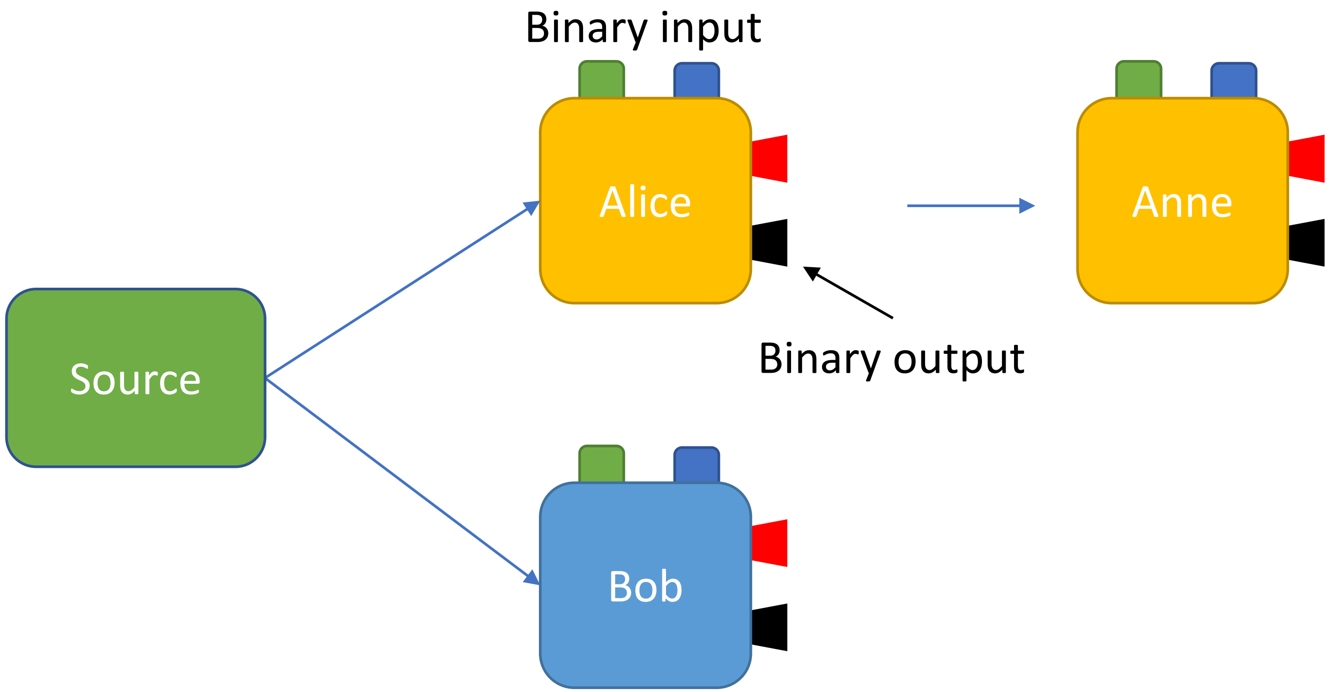


Chen *et al.*, Opt. Expr. Lett. **27**, 6089, 2019

Entanglement

- The characteristic trait of quantum mechanics [Schrödinger, Math. Proc. Cambridge. Ph. Soc. **31**, 555, 1935]
- A resource:
  - Cryptography [Ekert, Phys. Rev. Lett. **67**, 661, 1991]
  - Teleportation [Bennett *et al*., Phys. Rev. Lett. **70**, 1895, 1993]
  - Metrology [Giovannetti *et al*., Science **306**, 1330, 2004]
  - Device-independent protocols [Pironio *et al*., New J. Phys. **18**, 100202, 2016]
- Certification of entanglement does not require assumptions
- Entanglement is fragile

Double violation of the CHSH inequality

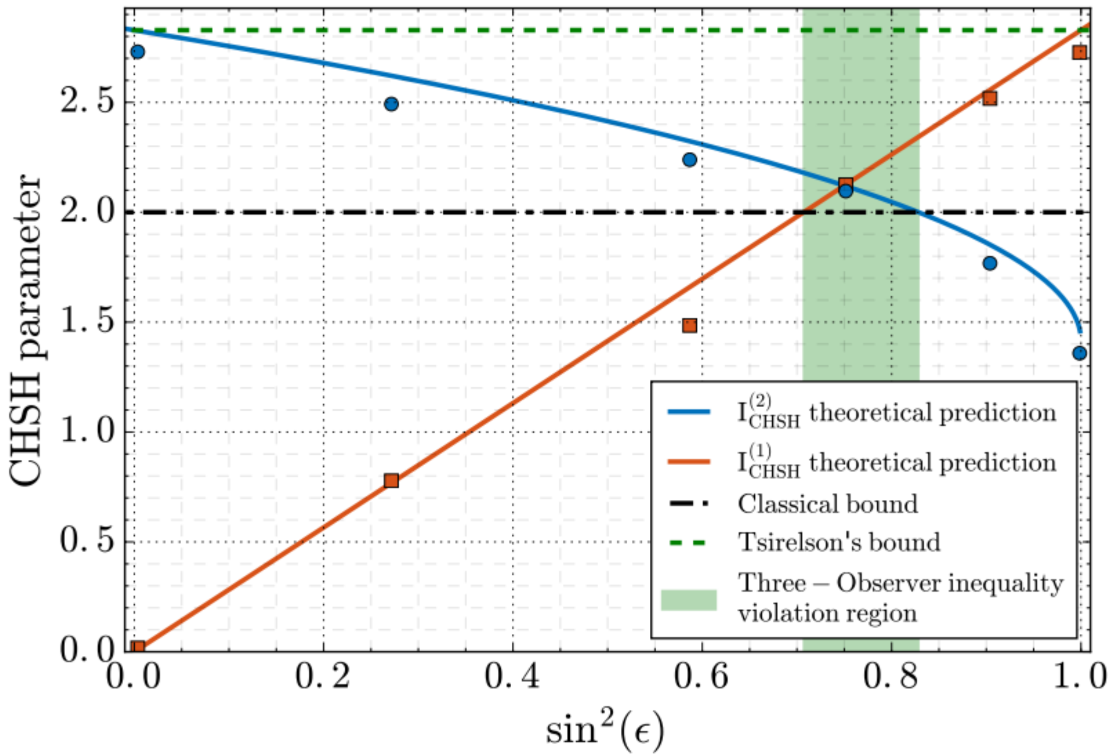


$$S_{CHSH} = \langle A_0 B_0 \rangle + \langle A_0 B_1 \rangle + \langle A_1 B_0 \rangle - \langle A_1 B_1 \rangle > 2$$

Weak measurements do not destroy entanglement, and at the same time can certify its presence

Silva *et al.*, Phys. Rev. Lett. **114**, 250401, 2015

Double violation of the CHSH inequality



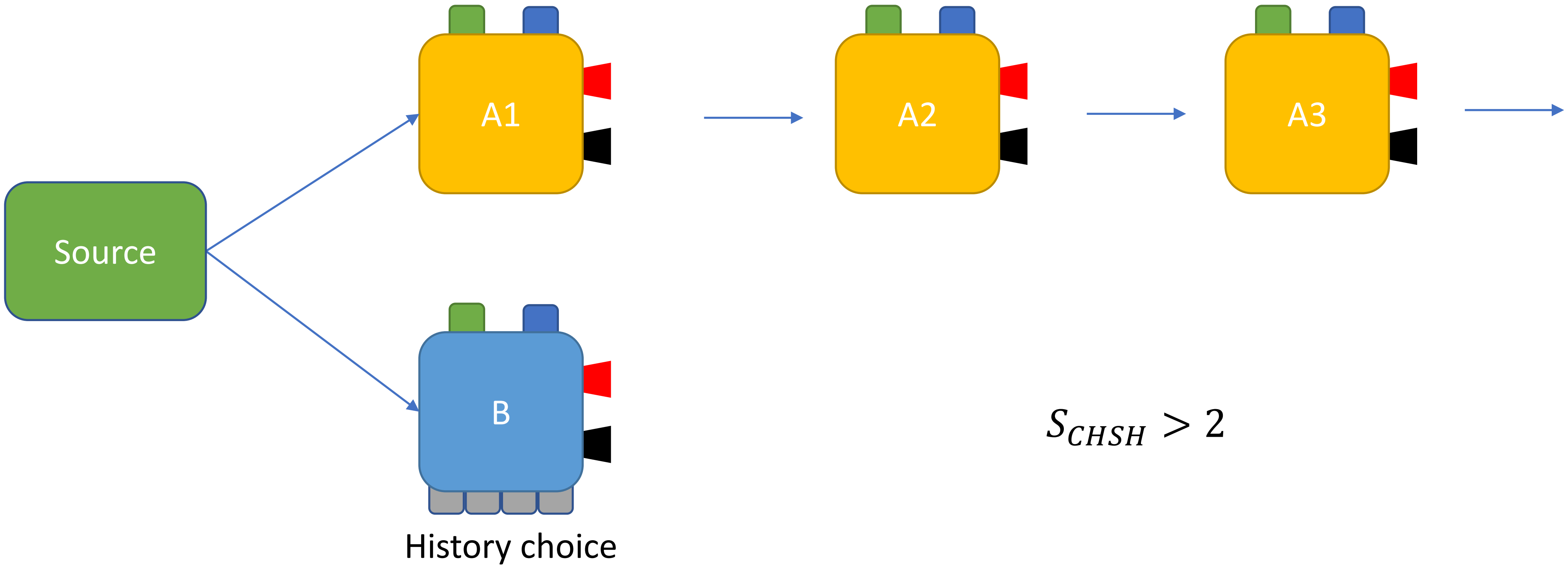
Schiavon *et al.*, Quantum Sci. And Tech. **2**, 015010, 2017

It has been observed experimentally [Schiavon *et al.*, Quantum Sci. And Tech. **2**, 015010, 2017]

Two violations is a hard limit [Mal *et al.*, Mathematics **4**, 48, 2016], unless

- Measurements have different strengths [Brown and Colbeck, Phys. Rev. Lett. **125**, 090401, 2020]
- Measurements are adapted to previous outcomes [Tavakoli and Cabello, Phys. Rev. A **97**, 032131, 2018]

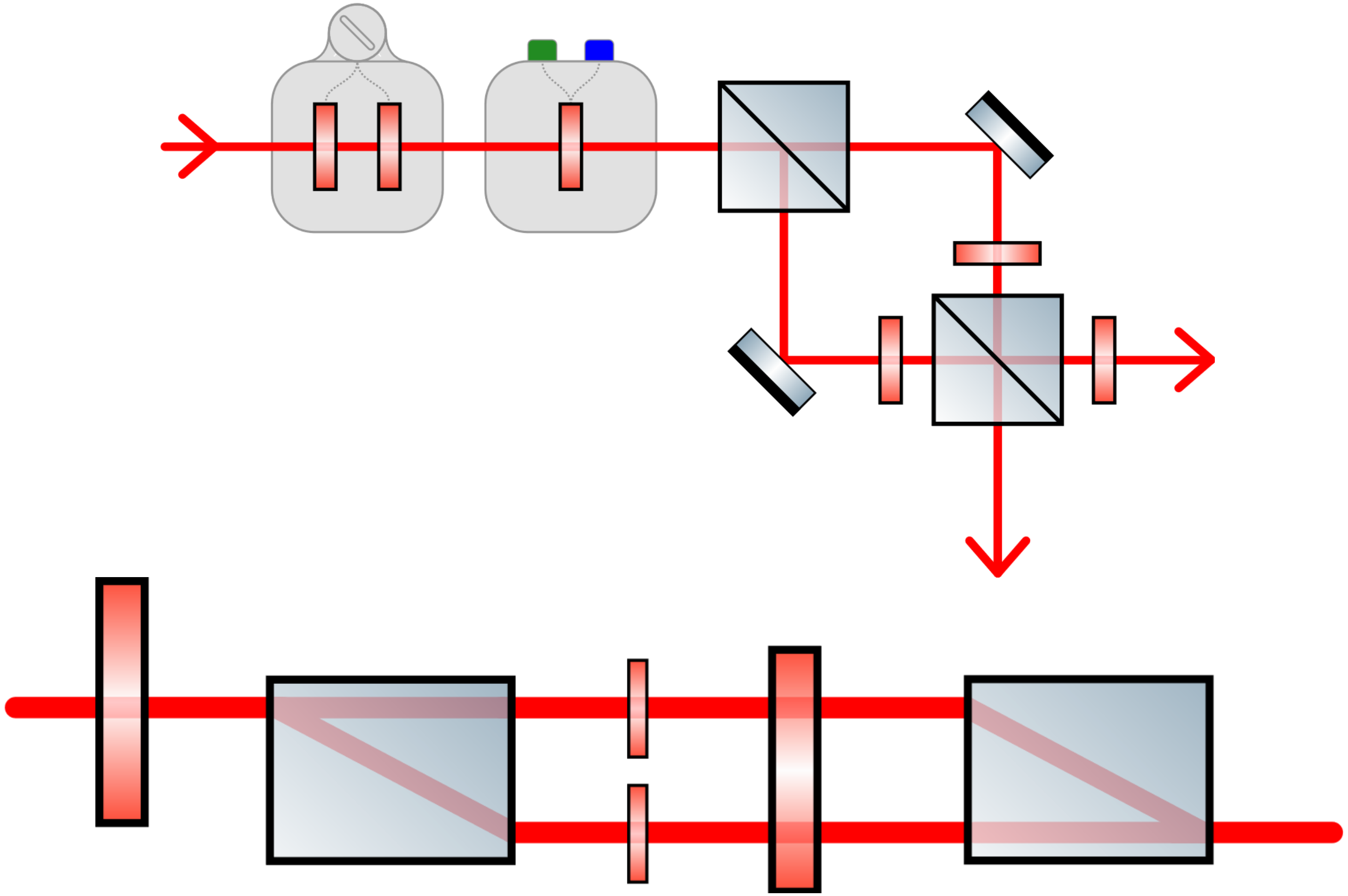
Multiple violations of the CHSH inequality



$$S_{CHSH} > 2$$

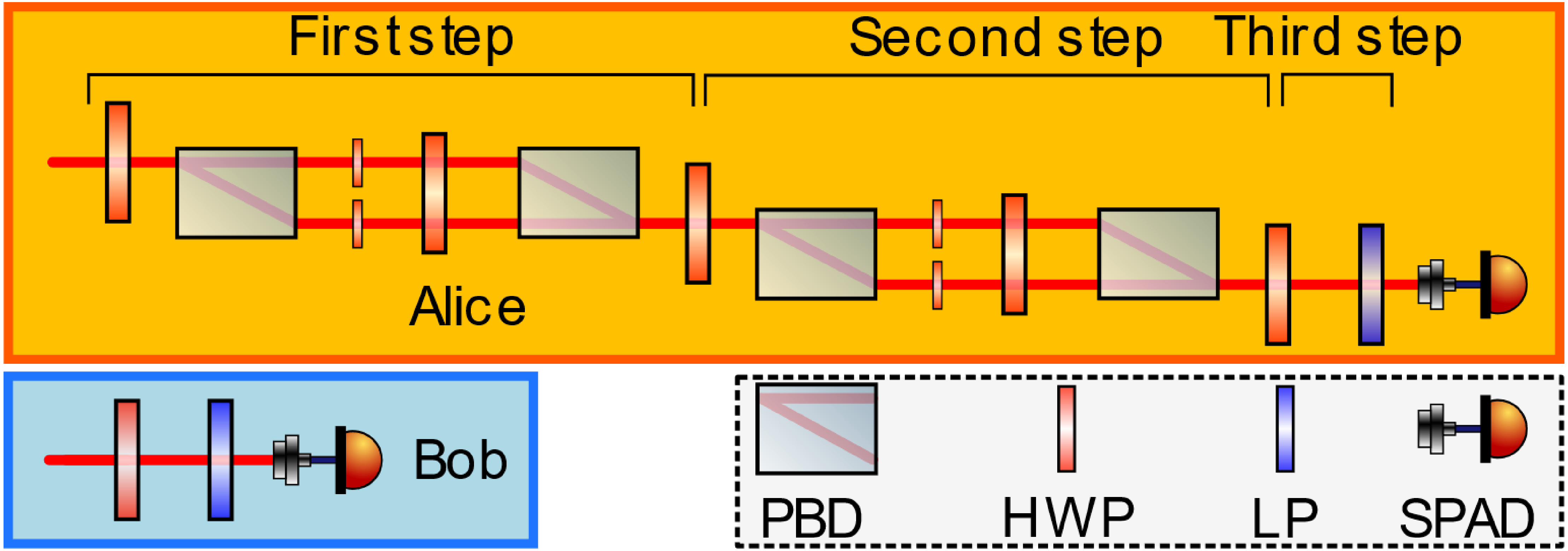
Tavakoli and Cabello, Phys. Rev. A **97**, 032131, 2018

Experimental Scheme



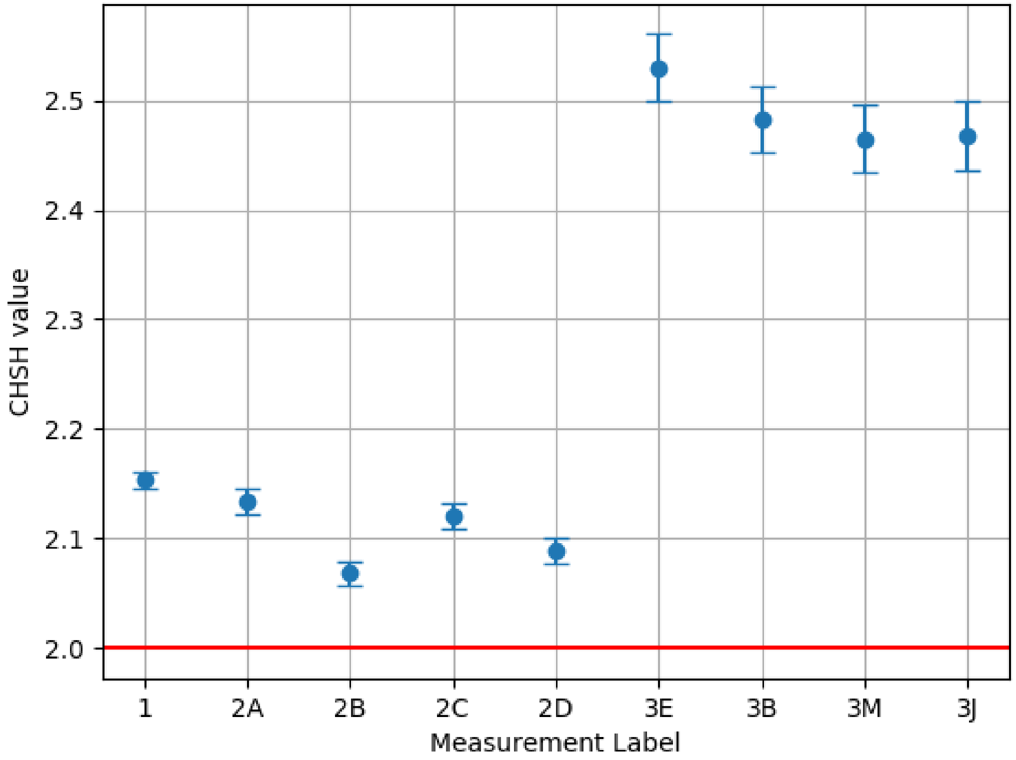
Foletto *et al.*, Phys. Rev. Appl. **13**, 044008, 2020

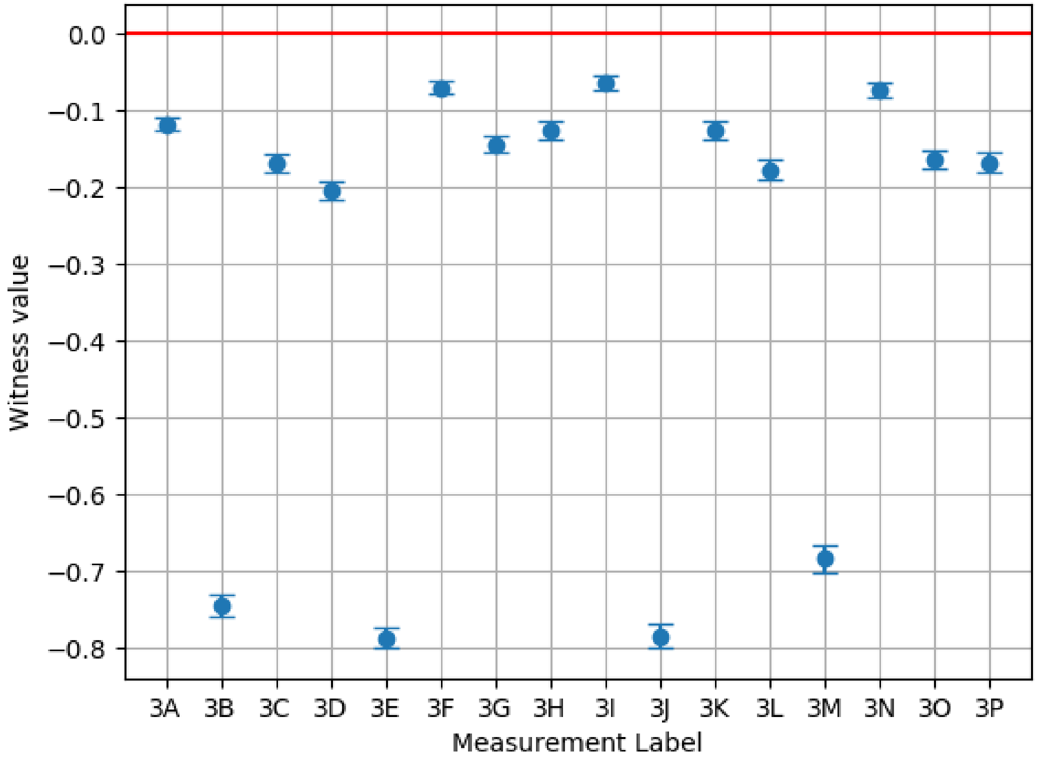
Experimental Scheme



Foletto *et al.*, Phys. Rev. Appl. **13**, 044008, 2020

Results



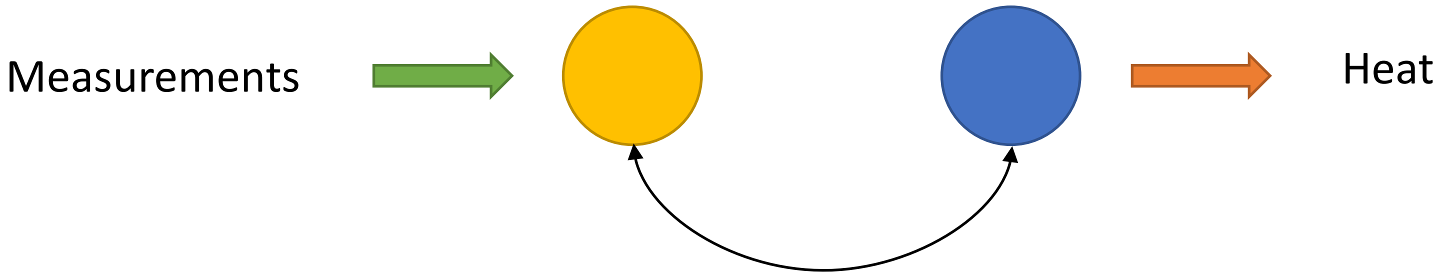


Foletto *et al.*, Phys. Rev. Appl. **13**, 044008, 2020

Applications: Fundamental tests

1. System – centric interpretation
2. Measurement choice is independent of the system
3. Limited memory
4. Landauer's principle

→ Emission of heat



Cabello *et al.*, Phys. Rev. A **94**, 052127, 2016

Applications: Fundamental tests

$\neg 2$ → No free will

$\neg 3$ → Finite systems can store infinite information

$\neg 4$ → Contradiction with experimental evidence

0 Temperature → Contradiction with the 3° law of thermodinamics

$\neg 1$ → Quantum probabilities depend on the observer

Cabello *et al.*, Phys. Rev. A **94**, 052127, 2016

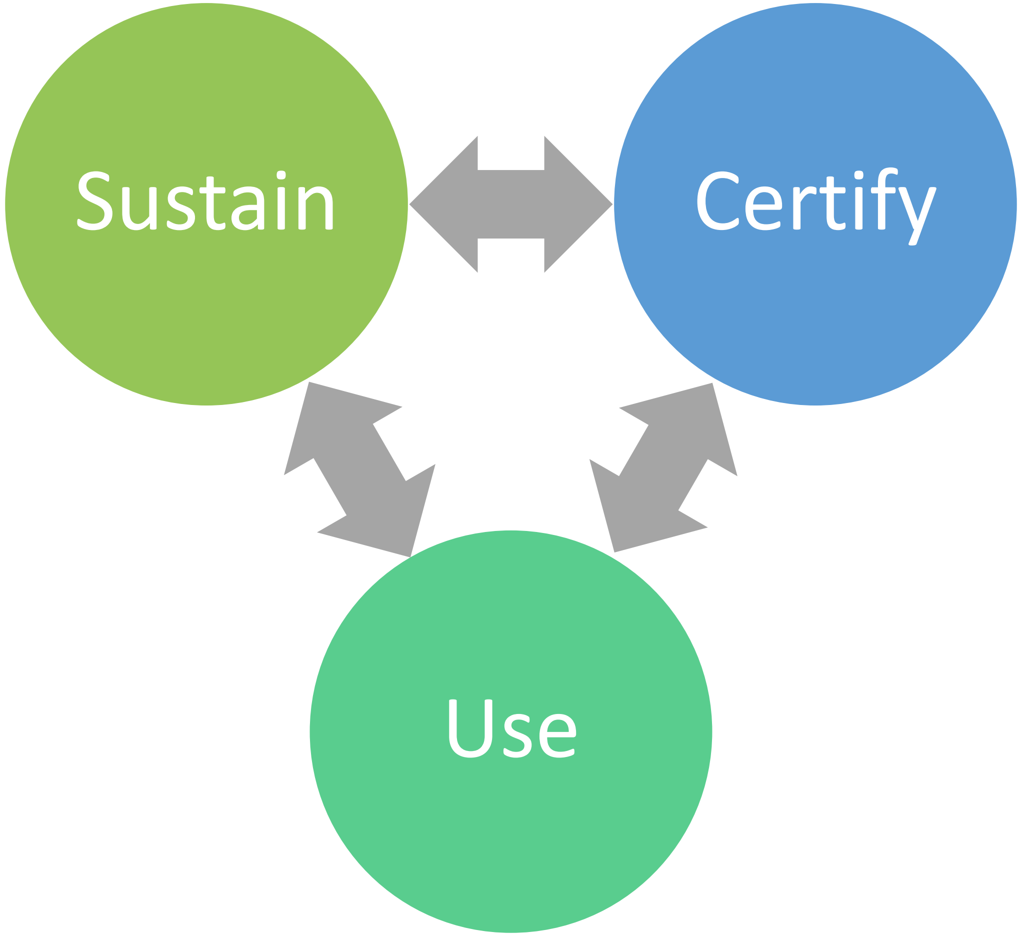
Applications: Randomness extraction

- Device-independent quantum randomness requires entanglement
- Entanglement can be certified with the violation of a Bell inequality
- Measurement outcomes can be used to generate random bits
- This can be done sequentially: many bits per entangled pair

Pironio *et al.*, Nature **464**, 1021, 2010

Curchod *et al.*, Phys. Rev. A **95**, 020102(R), 2017

Applications



Conclusions

- Weak measurements have been relevant in experiments of foundational and applied physics
- They can be used to repeatedly certify entanglement
- We have tested this experimentally with an optical setup
- Repeated use of entanglement can improve device independent protocols or distinguish interpretations of quantum theory

Bibliography

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