Testing Quantum Mechanics with Weak and Protective Measurements

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MIQC2

Weak measurements

Weak measurements [Aharonov et al., PRL 60 (1988)]: little information is extracted from a single measurement, but the state does NOT collapse.

Weak value: $$\langle \widehat{A} \rangle_w = \frac{\langle \psi_f | \widehat{A} | \psi_i \rangle}{\langle \psi_f | \psi_i \rangle}$$

Pre-selected state: $|\psi_i\rangle$

Post-selected state: $|\psi_f\rangle$

Von Neumann coupling between an observable $\widehat{A}$ and a pointer observable $\widehat{P}$:

$$\widehat{U} = \exp(-ig\widehat{A} \otimes \widehat{P})$$

Projective measurement (post-selection on $|\psi_f\rangle$): $\widehat{\Pi}_f = |\psi_f\rangle\langle\psi_f|$

$$|\phi_{out}\rangle = \widehat{\Pi}_f \widehat{U} |\phi_{in}\rangle = \widehat{\Pi}_f \widehat{U} |\psi_i\rangle \otimes |f_i\rangle$$

$\widehat{X}$ and $\widehat{P}$ canonically conjugated

In the weak interaction regime approximation:

$$\langle \widehat{X} \rangle = \frac{\langle \phi_{out} | \widehat{X} | \phi_{out} \rangle}{\langle \psi_i | \widehat{\Pi}_f | \psi_i \rangle} = g \ \mathrm{Re}[\langle \widehat{A} \rangle_w]$$

Weak measurements

$$\langle \widehat{A} \rangle_w = \frac{\langle \psi_f | \widehat{A} | \psi_i \rangle}{\langle \psi_f | \psi_i \rangle}$$

$$\widehat{U} = \exp(-ig\widehat{A} \otimes \widehat{P})$$

$$\widehat{\Pi}_f = |\psi_f\rangle\langle\psi_f|$$

Some interesting properties:

- $\langle \widehat{A} \rangle_w$ is a complex number
- $\mathrm{Re}[\langle \widehat{A} \rangle_w]$ is unbounded!

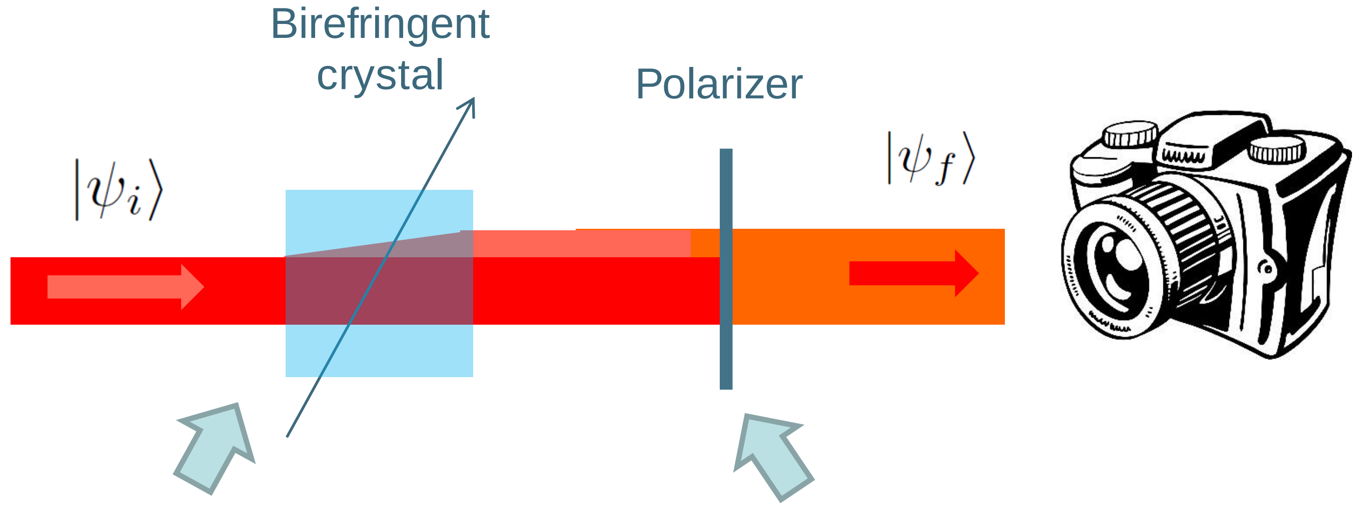
❑ **Metrology**:

- Amplification of measurement of coupling strength, without amplifying unrelated noise [Boyd et al.]:
  - Light beam displacement [Kwiat et al.]
  - Angular deflection [Dixon et al.]

❑ **Foundations of Quantum Mechanics**:

- Measurement of incompatible observables on the same particle [Mitchinson et al.]
- Tests of Quantum Contextuality [Pusey]
- Hints on Quantum Mechanics interpretations [TSVF, Aharonov et al., …]

Weak measurement implementation



$$\widehat{U} = \exp(-ig\widehat{A} \otimes \widehat{P})$$

$$\widehat{\Pi}_f = |\psi_f\rangle\langle\psi_f|$$

$$\widehat{A} \longrightarrow \widehat{\Pi}_V = |V\rangle\langle V|$$

We measure the position observable $\widehat{X}$,
canonically coniugated to the pointer observable $\widehat{P}$

$$\langle\widehat{X}\rangle = g\mathrm{Re}[\langle\widehat{\Pi}_V\rangle_w]$$

WMs and Quantum Contextuality

PRL **116,** 180401 (2016) PHYSICAL REVIEW LETTERS week ending 6 MAY 2016

Experiment Investigating the Connection between Weak Values and Contextuality

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Weak value measurements have recently given rise to a great amount of interest in both the possibility of measurement amplification and the chance for further quantum mechanics foundations investigation. In particular, a question emerged about weak values being proof of the incompatibility between quantum mechanics and noncontextual hidden variables theories (NCHVTs). A test to provide a conclusive answer to this question was given by Pusey [Phys. Rev. Lett. **113**, 200401 (2014)], where a theorem was derived showing the NCHVT incompatibility with the observation of anomalous weak values under specific conditions. In this Letter we realize this proposal, clearly pointing out the connection between weak values and the contextual nature of quantum mechanics.

DOI: 10.1103/PhysRevLett.116.180401

WMs and Quantum Contextuality

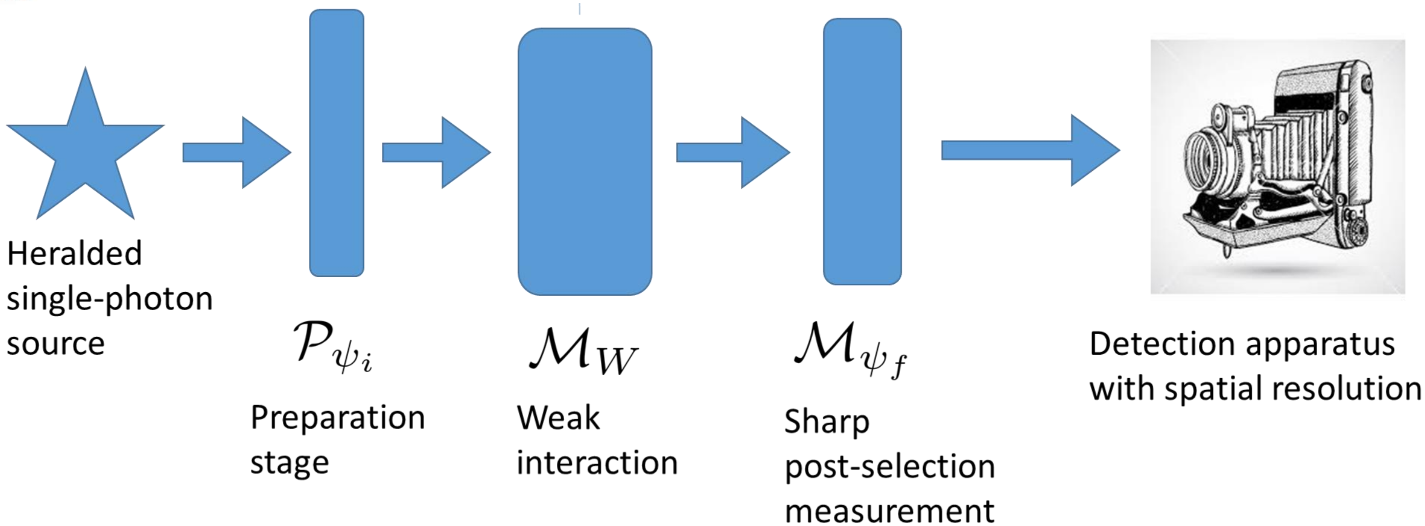
Non-Contextual Hidden Variable Theory: ontological model of an operational theory where, if two experimental procedures are operationally equivalent, then they have equivalent representations in such model [Spekkens, PRA 71 (2005)].

The measurement outcome depends only on the Hermitian operator associated with the measurement, not on the ones measured simultaneously with it: each observable has a predetermined value, independent of the context.

Question: Can Weak Values be a signature of Quantum Contextuality?

Answer: Yes! But only under specific conditions [Pusey, PRL 113 (2014)].

WMs and Quantum Contextuality



$$\text{Initial and final states are non-orthogonal}: \quad p_{\psi_f} := \mathbb{P}\left(\text{PASS}|\mathcal{P}_{\psi_i}, \mathcal{M}_{\psi_f}\right) > 0$$

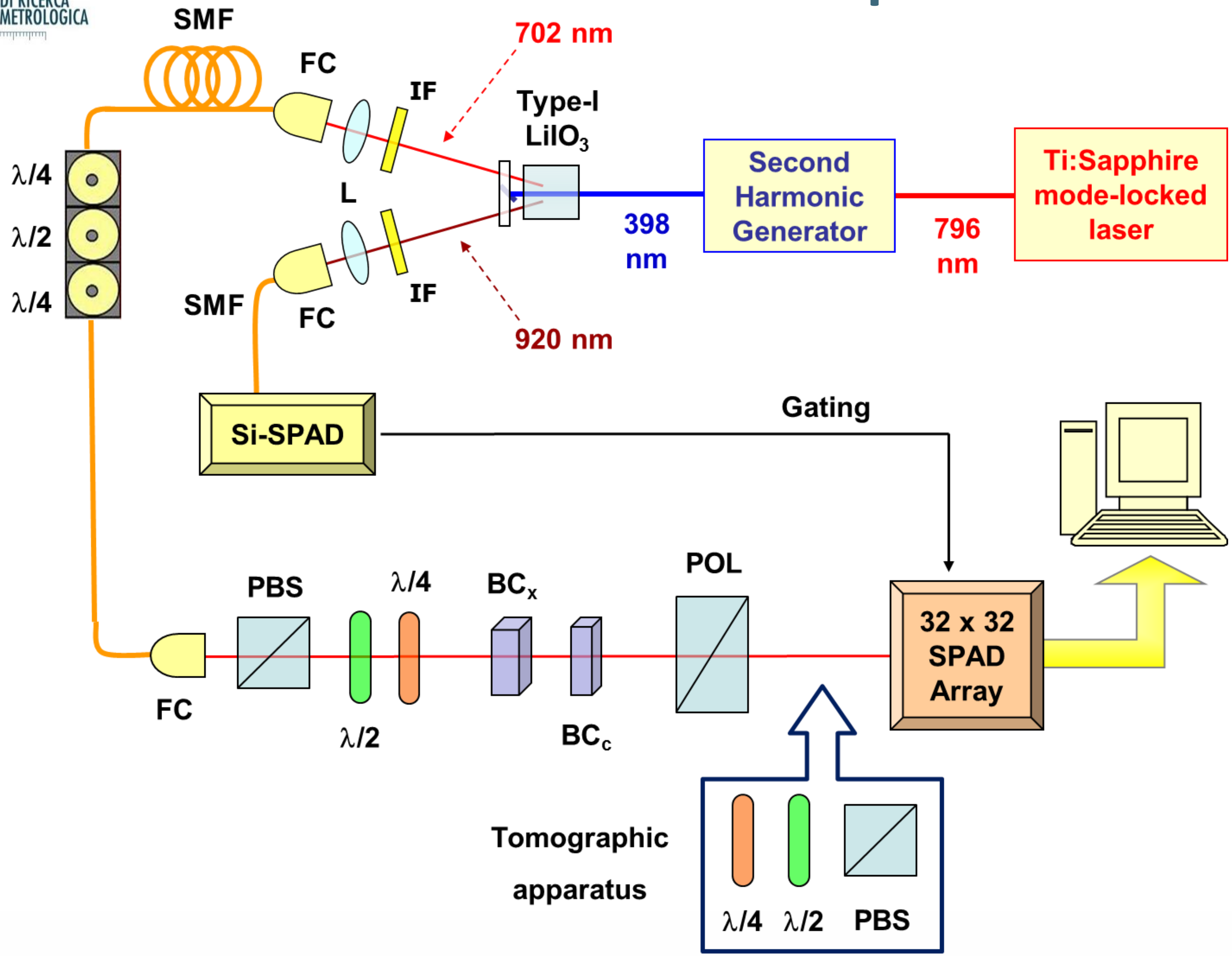
$$\text{Without post-selection: } \mathbb{P}\left(x|\mathcal{P}, \mathcal{M}_W\right) = p_n(x-g)\mathbb{P}\left(1|\mathcal{P}, \mathcal{M}_\Pi\right) + p_n(x)\mathbb{P}\left(0|\mathcal{P}, \mathcal{M}_\Pi\right) \quad \forall \mathcal{P}$$

$$\exists\, p_d : \quad \mathbb{P}\left(\text{PASS}|\mathcal{P}, \mathcal{M}_W, \mathcal{M}_{\psi_f}\right) = (1-p_d)\mathbb{P}\left(\text{PASS}|\mathcal{P}, \mathcal{M}_{\psi_f}\right) + p_d\mathbb{P}\left(\text{PASS}|\mathcal{P}, \mathcal{M}_d\right) \quad \forall \mathcal{P}$$

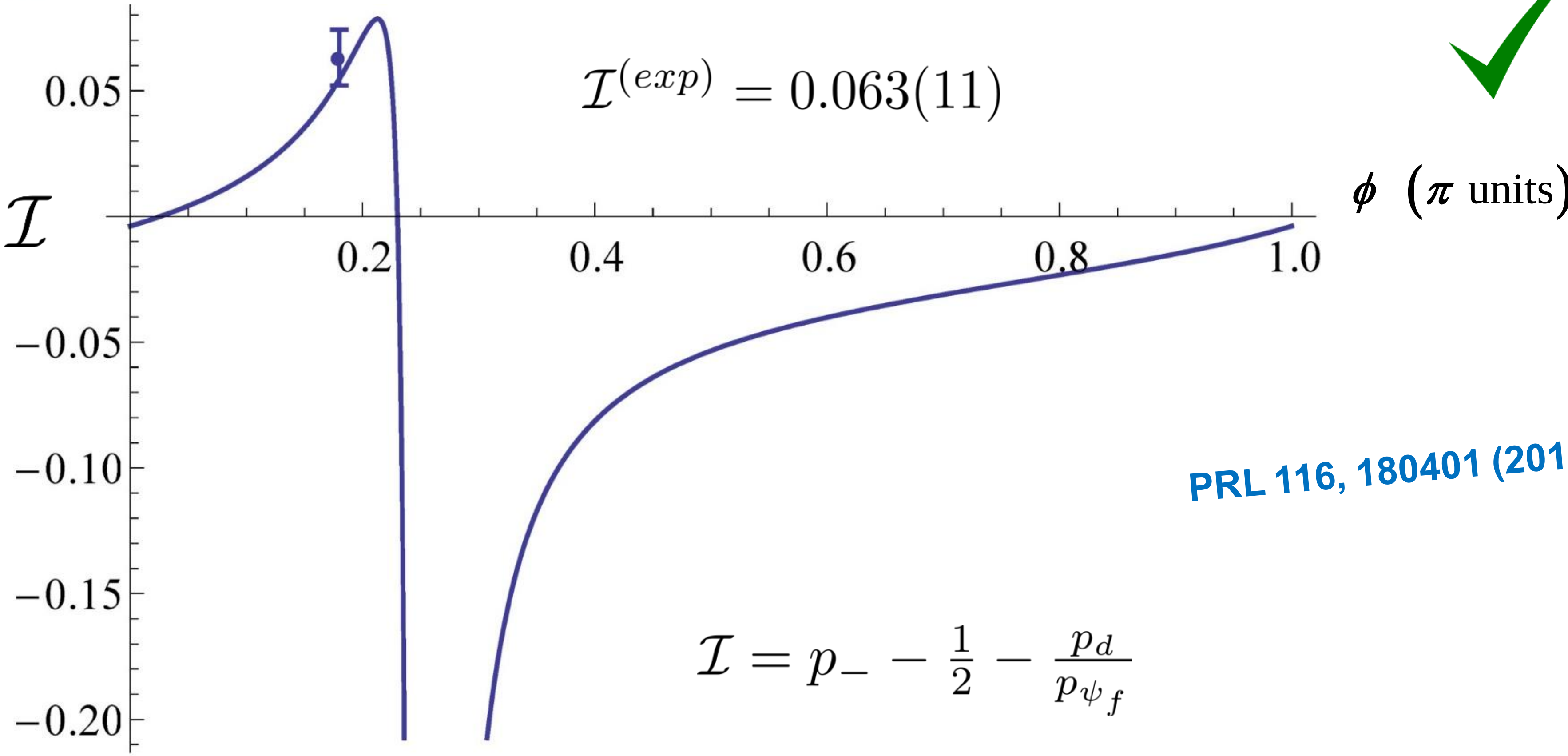
$$p_- := \left(p_{\psi_f}\right)^{-1} \int_{-\infty}^{0} \mathbb{P}\left(x, \text{PASS}|\mathcal{P}_{\psi_i}, \mathcal{M}_W, \mathcal{M}_{\psi_f}\right) \mathrm{d}x : \quad \mathcal{I} = p_- - \frac{1}{2} - \frac{p_d}{p_{\psi_f}} > 0$$

No non-contextual model satisfying outcome determinism for sharp measurements

Setup


SMF
FC
IF
702 nm
Type-I
$LiIO_3$
Second
Harmonic
Generator
Ti:Sapphire
mode-locked
laser
λ/4
λ/2
λ/4
L
398
nm
796
nm
SMF
FC
IF
920 nm
Si-SPAD
Gating
PBS
λ/4
BC_x
POL
32 x 32
SPAD
Array
FC
λ/2
BC_c
Tomographic
apparatus
λ/4
λ/2
PBS

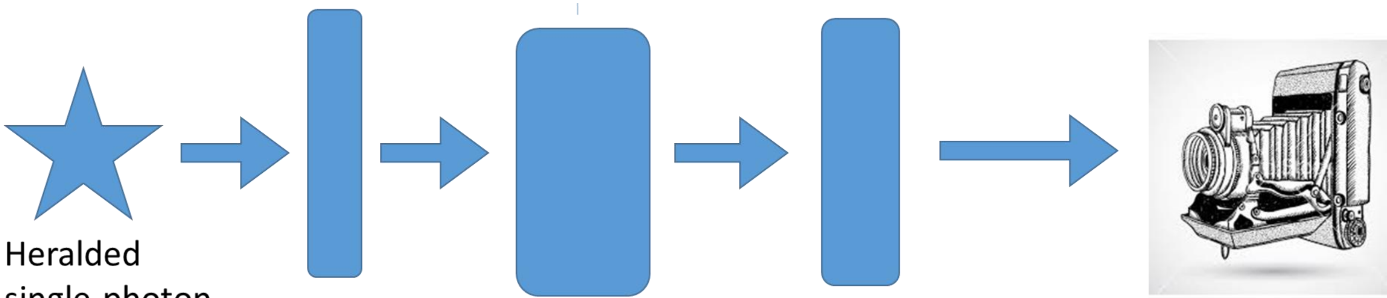
Condition 4: non-contextual bound violation



PRL 116, 180401 (2016)

- input state: $|-\rangle = \frac{1}{\sqrt{2}}(|H\rangle - |V\rangle)$
- post-selection state: $|\psi_f\rangle = \cos\phi|H\rangle + \sin\phi|V\rangle$ $\quad (\mathcal{I}^{(exp)} : \ \phi = 0.18\pi)$
- From experimental parameters: $p_d = 0.0019(2)$

WM and Contextuality: final check



Heralded single-photon source

$\mathcal{P}_{\psi_i}$ Preparation stage

$\mathcal{M}_W$ Weak interaction

$\mathcal{M}_{\psi_f}$ Sharp post-selection measurement

Detection apparatus with spatial resolution

PRL 116, 180401 (2016)

Initial and final states are non-orthogonal : $p_{\psi_f} := \mathbb{P}\left(\text{PASS}|\mathcal{P}_{\psi_i}, \mathcal{M}_{\psi_f}\right) > 0$

Without post-selection: $\mathbb{P}\left(x|\mathcal{P}, \mathcal{M}_W\right) = p_n(x-g)\mathbb{P}\left(1|\mathcal{P}, \mathcal{M}_\Pi\right) + p_n(x)\mathbb{P}\left(0|\mathcal{P}, \mathcal{M}_\Pi\right) \; \forall \mathcal{P}$

$\exists \, p_d : \quad \mathbb{P}\left(\text{PASS}|\mathcal{P}, \mathcal{M}_W, \mathcal{M}_{\psi_f}\right) = (1-p_d)\mathbb{P}\left(\text{PASS}|\mathcal{P}, \mathcal{M}_{\psi_f}\right) + p_d \mathbb{P}\left(\text{PASS}|\mathcal{P}, \mathcal{M}_d\right) \; \forall \mathcal{P}$

$p_- := \left(p_{\psi_f}\right)^{-1} \int_{-\infty}^{0} \mathbb{P}\left(x, \text{PASS}|\mathcal{P}_{\psi_i}, \mathcal{M}_W, \mathcal{M}_{\psi_f}\right) \mathrm{d}x : \quad \mathcal{I} = p_- - \frac{1}{2} - \frac{p_d}{p_{\psi_f}} > 0$

No non-contextual model allowed: weak measurements proved Quantum Contextuality

Sequential Weak Measurements

PRL 117, 170402 (2016) PHYSICAL REVIEW LETTERS week ending 21 OCTOBER 2016

Measuring Incompatible Observables by Exploiting Sequential Weak Values

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One of the most intriguing aspects of quantum mechanics is the impossibility of measuring at the same time observables corresponding to noncommuting operators, because of quantum uncertainty. This impossibility can be partially relaxed when considering joint or sequential weak value evaluation. Indeed, weak value measurements have been a real breakthrough in the quantum measurement framework that is of the utmost interest from both a fundamental and an applicative point of view. In this Letter, we show how we realized for the first time a sequential weak value evaluation of two incompatible observables using a genuine single-photon experiment. These (sometimes anomalous) sequential weak values revealed the single-operator weak values, as well as the local correlation between them.

DOI: 10.1103/PhysRevLett.117.170402

Joint and sequential weak measurements

Weak values *«challenge one of the canonical dicta of QM: that non commuting observables cannot be simultaneously measured»*

«the fact that one hardly disturbs the systems in making WM means that one can in principle measure different variables in succession» [Mitchison, Jozsa and Popescu, PRA 76 (2007)]

Joint weak measurement

Resch et al., PRL 92, 130402 (2004)

$$\widehat{U} = \exp[-i(g_x \widehat{A} \otimes \widehat{P}_x + g_y \widehat{B} \otimes \widehat{P}_y)]$$

$$\langle \widehat{X}\widehat{Y} \rangle = \frac{1}{4} g_x g_y \mathrm{Re} \left[\langle \widehat{A}\widehat{B} + \widehat{B}\widehat{A} \rangle_w + \right.$$
$$\left. + 2 \langle \widehat{A} \rangle_w^* \langle \widehat{B} \rangle_w \right]$$

Sequential weak measurement

Mitchinson et al., PRA 76, 062105 (2007)

$$\widehat{U}_y = \exp(-i g_y \widehat{B} \otimes \widehat{P}_y)$$

$$\widehat{U}_x = \exp(-i g_x \widehat{A} \otimes \widehat{P}_x)$$

$$\langle \widehat{X}\widehat{Y} \rangle = \tfrac{1}{2} g_x g_y \mathrm{Re} \left[\langle \widehat{A}\widehat{B} \rangle_w + \langle \widehat{A} \rangle_w^* \langle \widehat{B} \rangle_w \right]$$

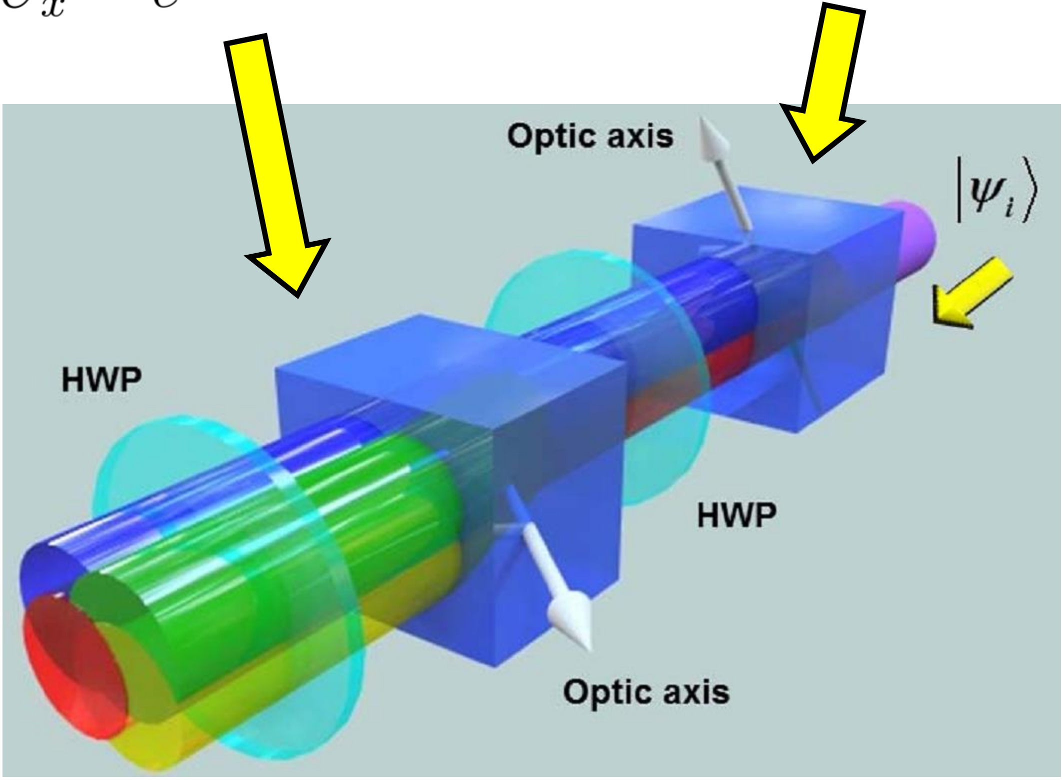
Sequential weak measurement

$$\hat{A} \longrightarrow \hat{\Pi}_V = |V\rangle\langle V|$$

$$\hat{B} \longrightarrow \hat{\Pi}_\psi = |\psi\rangle\langle \psi|$$

$$|\psi\rangle = \cos\theta|H\rangle + \sin\theta|V\rangle$$

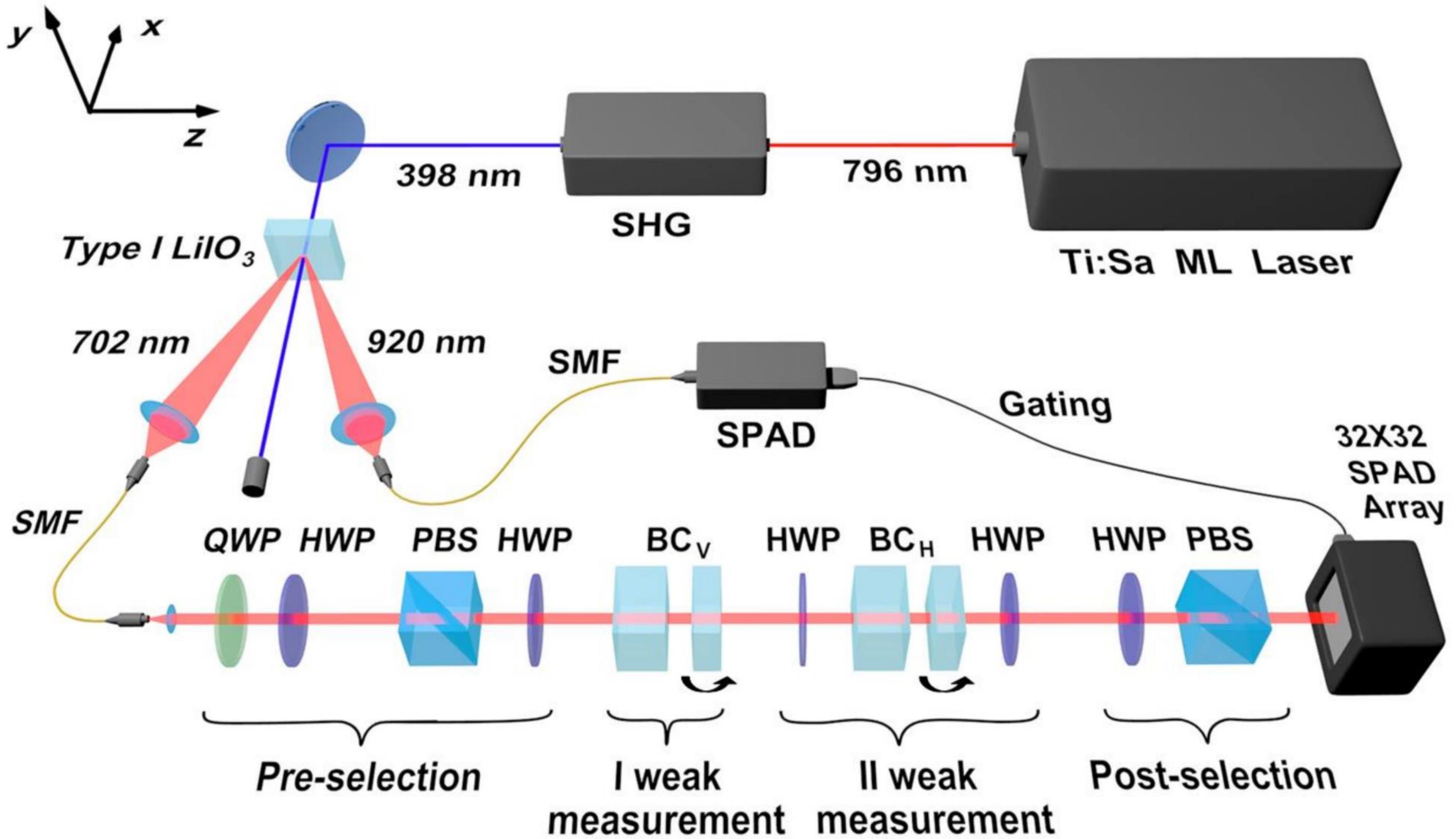
$$\hat{U}_x = e^{-ig_x \hat{\Pi}_\psi \otimes \hat{P}_x} \qquad \hat{U}_y = e^{-ig_y \hat{\Pi}_V \otimes \hat{P}_y}$$



Linearly polarized pre- and post-selection states $|\psi_i\rangle$, $|\psi_f\rangle$

$$\begin{cases} \langle \hat{X} \rangle = g_x \langle \hat{\Pi}_\psi \rangle_w \\ \langle \hat{Y} \rangle = g_y \langle \hat{\Pi}_V \rangle_w \\ \langle \hat{X}\hat{Y} \rangle = \frac{1}{2} g_x g_y \left(\langle \hat{\Pi}_\psi \hat{\Pi}_V \rangle_w + \langle \hat{\Pi}_\psi \rangle_w \langle \hat{\Pi}_V \rangle_w \right) \end{cases}$$

SETUP



y
x
z
398 nm
SHG
796 nm
Ti:Sa ML Laser
Type I LiIO3
702 nm
920 nm
SMF
SPAD
Gating
32X32
SPAD
Array
SMF
QWP
HWP
PBS
HWP
BCV
HWP
BCH
HWP
HWP
PBS
Pre-selection
I weak
measurement
II weak
measurement
Post-selection

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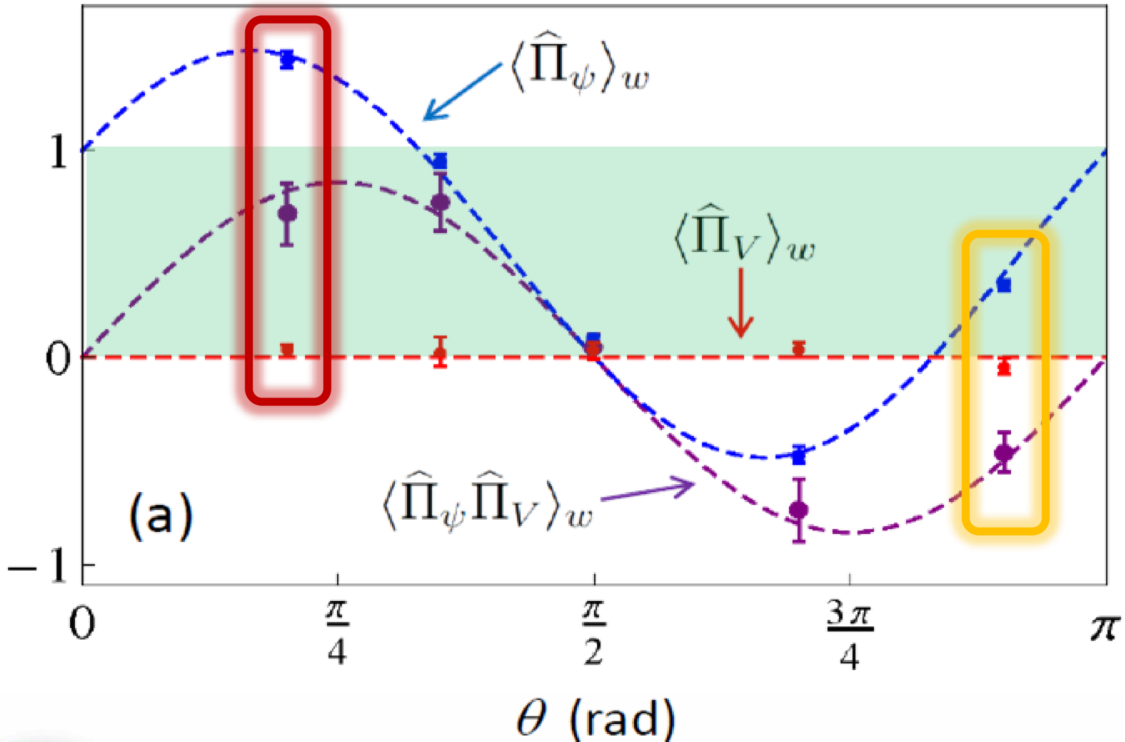
Results

Measured weak values (data points) compared with the theoretical predictions

$$\widehat{\Pi}_V = |V\rangle\langle V| \qquad \widehat{\Pi}_\psi = |\psi\rangle\langle\psi| \qquad (|\psi\rangle = \cos\theta|H\rangle + \sin\theta|V\rangle)$$

$$|\psi_i\rangle = 0.588|H\rangle + 0.809|V\rangle \qquad |\psi_f\rangle = |H\rangle$$



$$\langle\widehat{\Pi}_V\rangle_w = 0.03(3)$$
$$\langle\widehat{\Pi}_\psi\rangle_w = 1.44(4)$$
$$\langle\widehat{\Pi}_\psi\widehat{\Pi}_V\rangle_w = 0.69(15)$$

$$\langle\widehat{\Pi}_V\rangle_w = 0.04(3)$$
$$\langle\widehat{\Pi}_\psi\rangle_w = 0.35(4)$$
$$\langle\widehat{\Pi}_\psi\widehat{\Pi}_V\rangle_w = -0.46(10)$$

PRL 117, 170402 (2016)

Results

Measured weak values (data points) compared with the theoretical predictions

$$\widehat{\Pi}_V = |V\rangle\langle V| \qquad \widehat{\Pi}_\psi = |\psi\rangle\langle\psi| \qquad (|\psi\rangle = \cos\theta|H\rangle + \sin\theta|V\rangle)$$

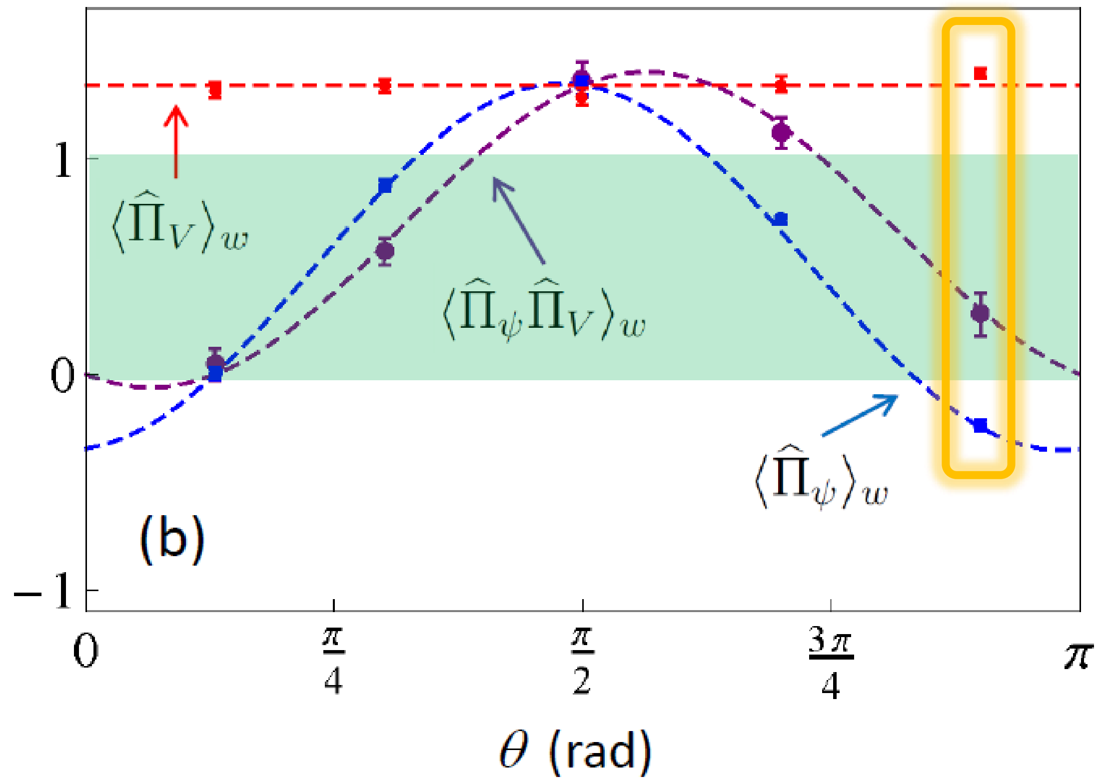
$$|\psi_i\rangle = 0.509|H\rangle + 0.861|V\rangle$$

$$|\psi_f\rangle = -0.397|H\rangle + 0.918|V\rangle$$

$$\langle\widehat{\Pi}_V\rangle_w = 1.40(4)$$

$$\langle\widehat{\Pi}_\psi\rangle_w = -0.24(3)$$

$$\langle\widehat{\Pi}_\psi\widehat{\Pi}_V\rangle_w = 0.28(10)$$



PRL 117, 170402 (2016)

Application: violation of a multiple-measurement Leggett-Garg inequality

Originally proposed to investigate macroscopic realism, Leggett-Garg inequalities can also be regarded as a tool for quantumness tests.

Sequential weak measurements allow extending the usual 3-measurement framework to a multiple-measurement one, e.g. violating the inequality:

$$|\mathcal{B}_4| = |\langle I_A I_B \rangle + \langle I_B I_C \rangle + \langle I_C I_D \rangle - \langle I_A I_D \rangle| \leq 2$$

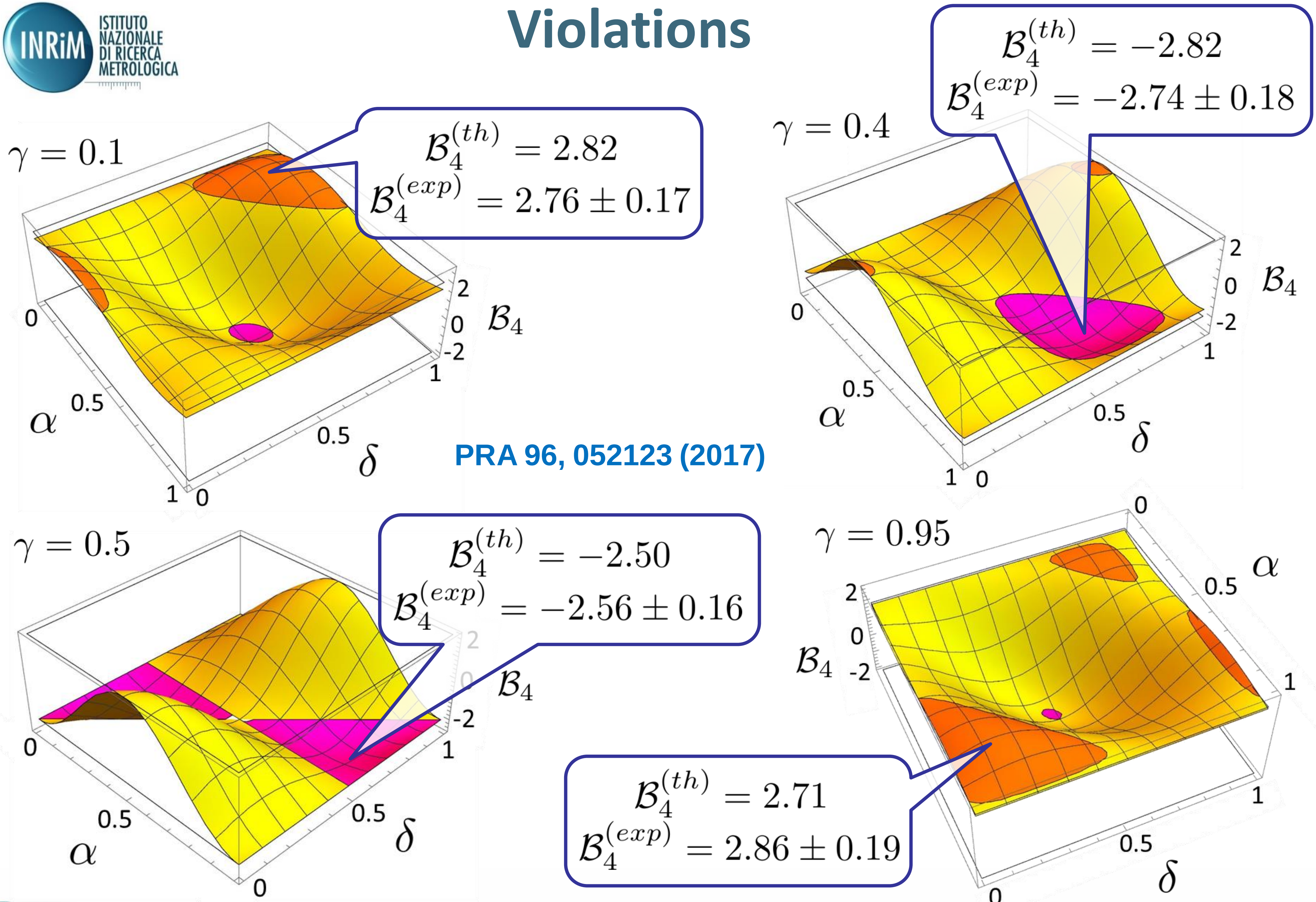
$I_A = |\psi_A\rangle\langle\psi_A| - |\psi_A^{\perp}\rangle\langle\psi_A^{\perp}|$ $\quad$ $|\psi_A\rangle = \cos\alpha|H\rangle + \sin\alpha|V\rangle$ $\quad$ (preparation)

$I_B = |\psi_\gamma\rangle\langle\psi_\gamma| - |\psi_\gamma^{\perp}\rangle\langle\psi_\gamma^{\perp}|$ $\quad$ $|\psi_\gamma\rangle = \cos\gamma|H\rangle + \sin\gamma|V\rangle$

$I_C = |H\rangle\langle H| - |V\rangle\langle V|$

$I_D = |\psi_D\rangle\langle\psi_D| - |\psi_D^{\perp}\rangle\langle\psi_D^{\perp}|$ $\quad$ $|\psi_D\rangle = \cos\delta|H\rangle + \sin\delta|V\rangle$

Violations



PRA 96, 052123 (2017)

Protective Measurements

nature physics

ARTICLES

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Determining the quantum expectation value by measuring a single photon

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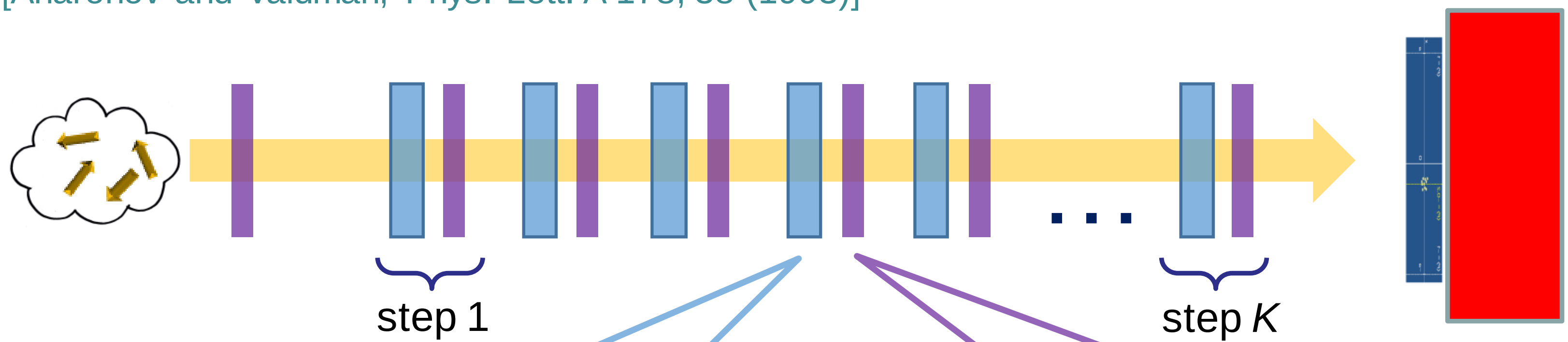
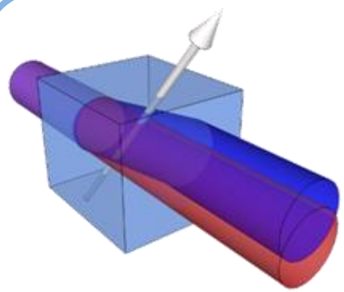
One of the most intriguing features of quantum mechanics is that variables might not have definite values. A complete quantum description provides only probabilities for obtaining various eigenvalues of a quantum variable. The eigenvalues and the corresponding probabilities specify the expectation value of a physical observable, which is known to be a statistical property of an ensemble of quantum systems. In contrast to this paradigm, here we demonstrate a method for measuring the expectation value of a physical variable on a single particle, namely, the polarization of a single protected photon. This realization of quantum protective measurements could find applications in the foundations of quantum mechanics and quantum-enhanced measurements.

Can one extract the quantum expectation value by measuring a single particle?

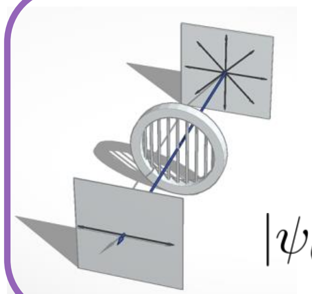
Protective Measurement (PM): the interaction is smooth enough to leave the state unchanged. The pointer shift is proportional to the average value of the observable
[Aharonov and Vaidman, Phys. Lett. A 178, 38 (1993)]





$$\widehat{U} = e^{-ig\widehat{\Pi}_H \otimes \mathbf{P}}$$

$$\widehat{\Pi}_H = |H\rangle\langle H|$$



$$\widehat{\Pi}_\theta = |\psi_\theta\rangle\langle\psi_\theta|$$

$$|\psi_\theta\rangle = \cos\theta|H\rangle + \sin\theta|V\rangle$$

Ideal case: $K \to \infty, \quad g \to 0$

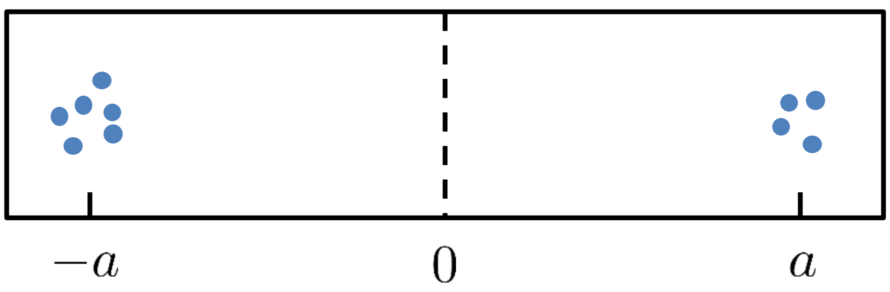
No losses, photon survival probability $p_{sur}(K) = 1$

Can one extract the quantum expectation value by measuring a single particle?

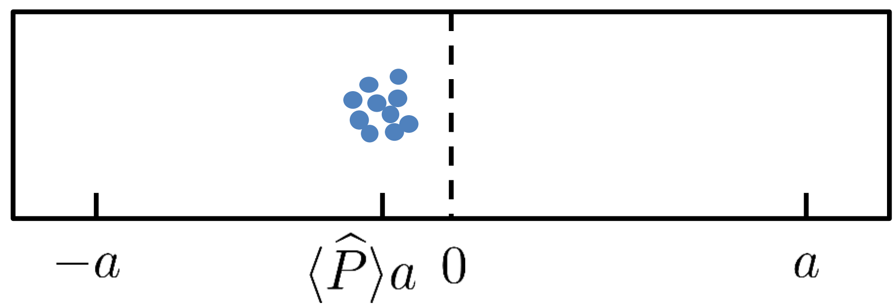
Protective Measurement (PM): the interaction is smooth enough to leave the state unchanged. The pointer shift is proportional to the average value of the observable [Aharonov and Vaidman, Phys. Lett. A 178, 38 (1993)]

Measured observable: $\widehat{P} = |H\rangle\langle H| - |V\rangle\langle V|$

Projective measurement



Protective measurement



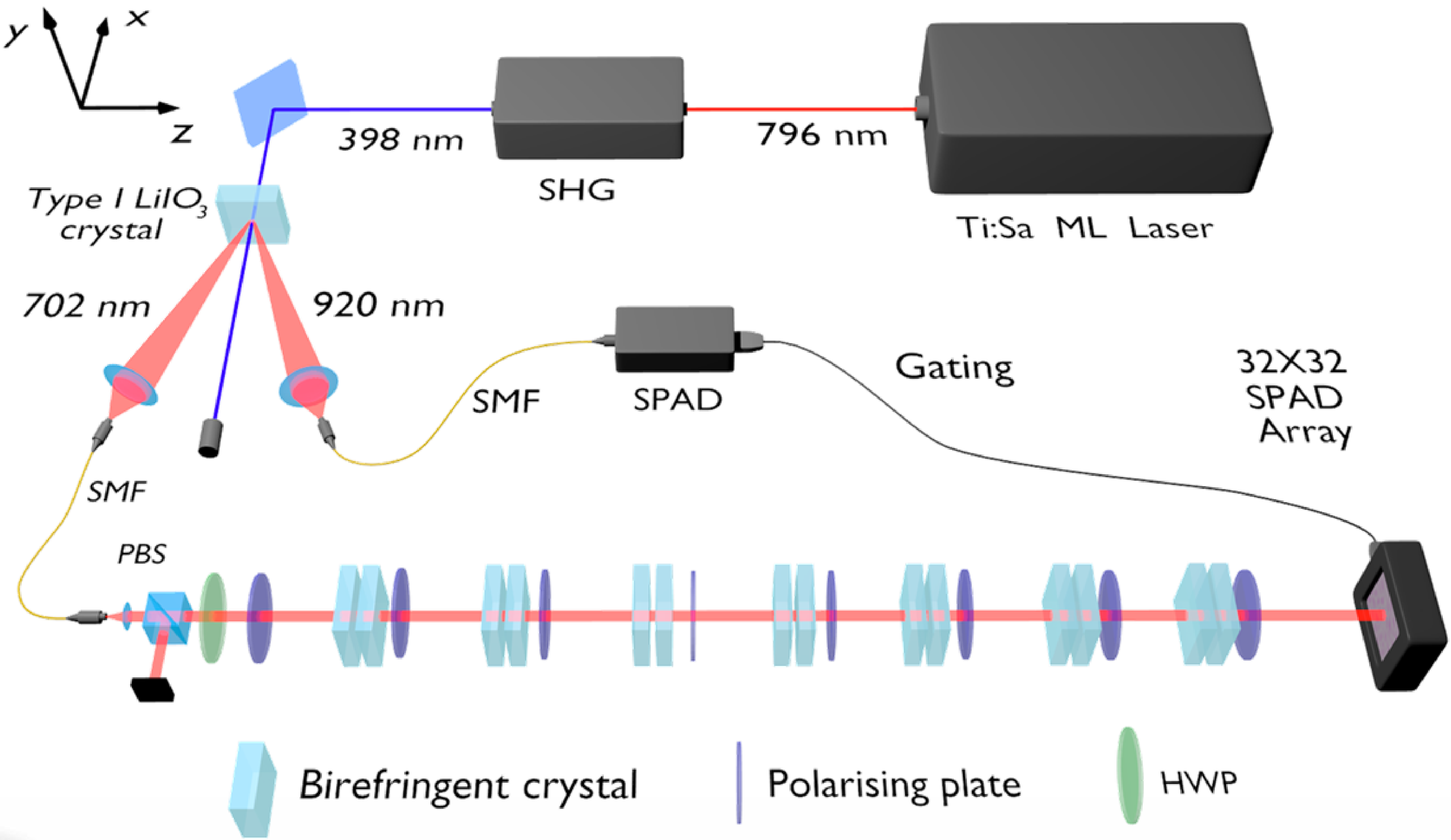
$$\langle\widehat{P}\rangle = \frac{N_a - N_{-a}}{N_a + N_{-a}}$$

Each photon carries the same information on $\langle\widehat{P}\rangle$

$$\langle\widehat{P}\rangle = \frac{\langle\widehat{X}\rangle}{a}$$

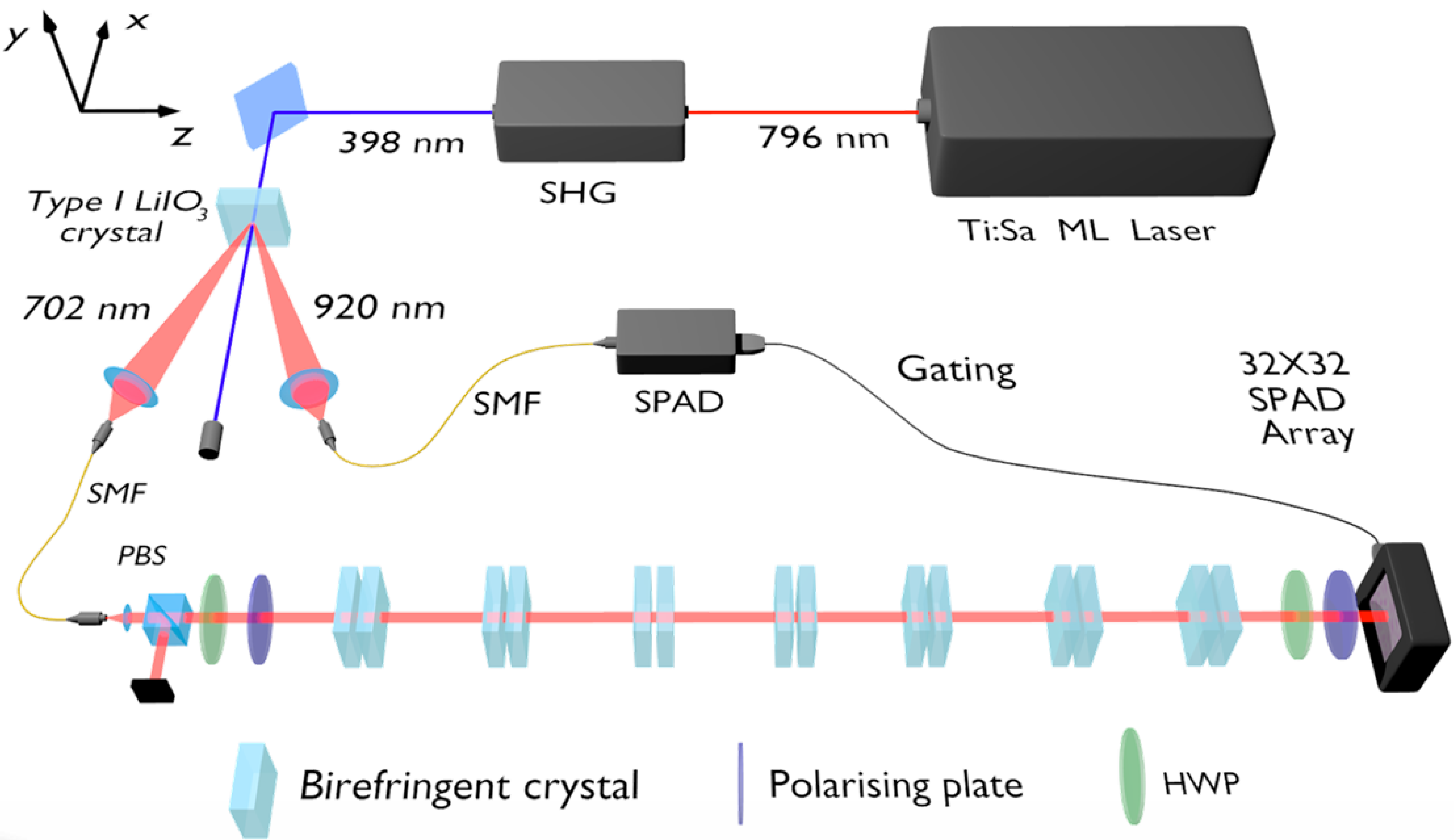
Protective measurements in the lab

$K \to \infty, \quad g \to 0, \quad p_{sur}(K) = 1$ ⇨ $K = 7, \quad g \ll 1, \quad p_{sur}(K) \lesssim 1$



Projective measurements in the lab

$K \to \infty, \;\; g \to 0, \;\; p_{sur}(K) = 1 \;\; \Rightarrow \;\; K = 7, \;\; g \ll 1, \;\; p_{sur}(K) \lesssim 1$

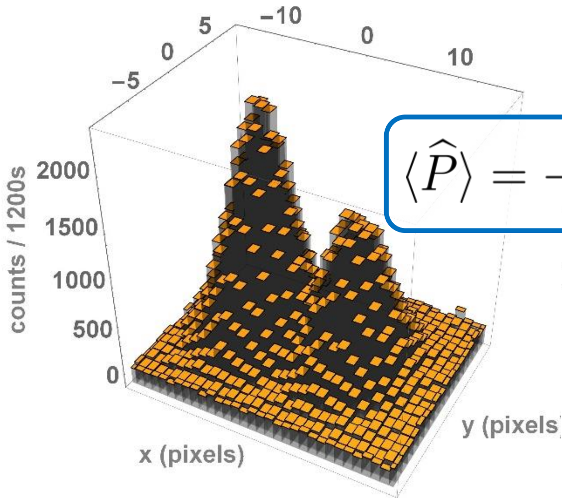


Experimental results

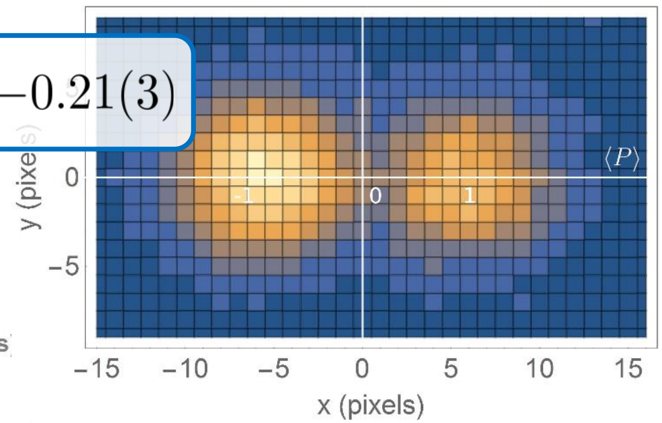
$$|\psi_{\frac{17\pi}{60}}\rangle = 0.629|H\rangle + 0.777|V\rangle \qquad \langle\widehat{P}\rangle^{th} = -0.208$$

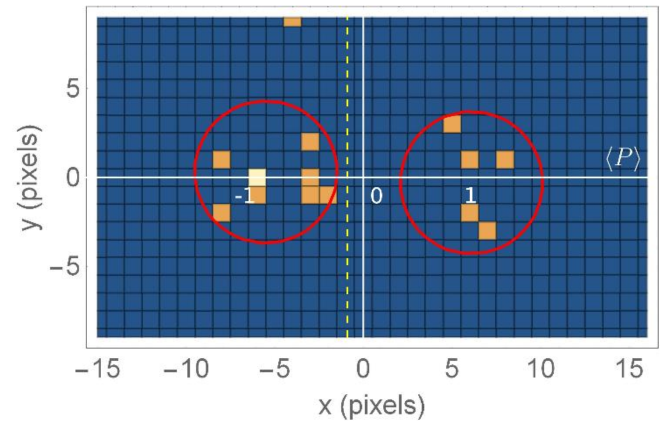
Nat. Phys. 13, 1191 (2017)

Projective measurement

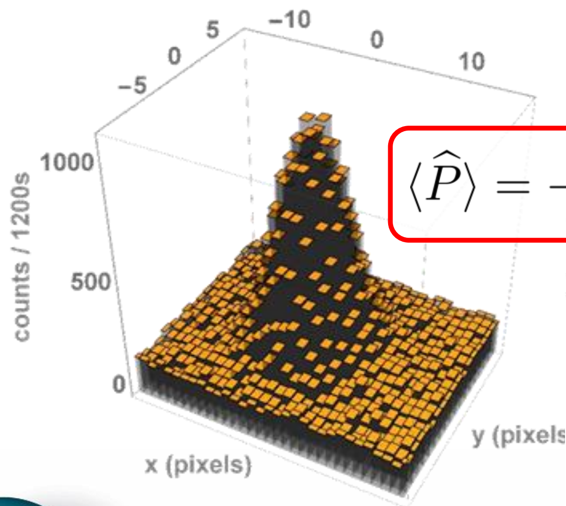


$$\langle\widehat{P}\rangle = -0.21(3)$$

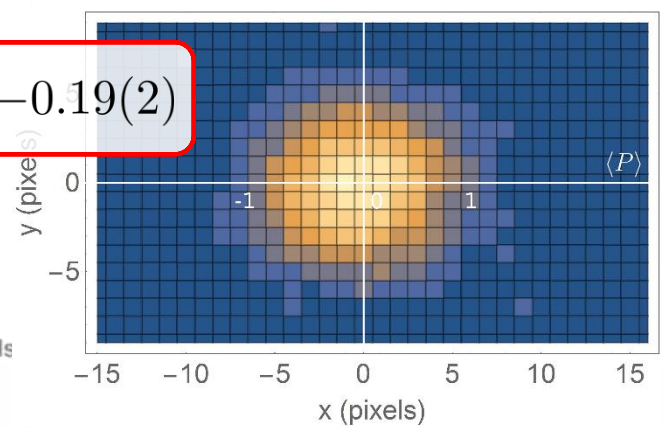


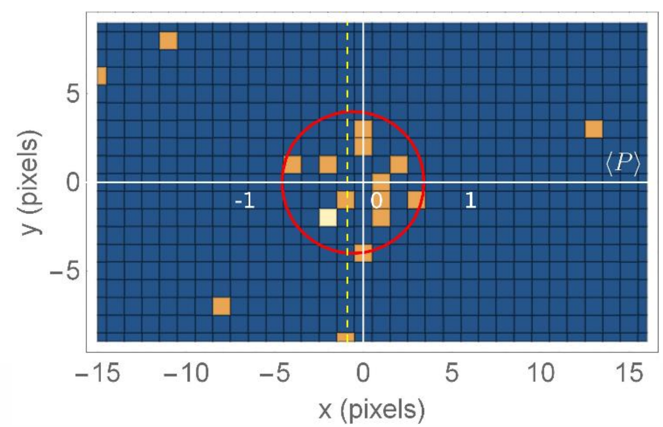


Protective measurement



$$\langle\widehat{P}\rangle = -0.19(2)$$

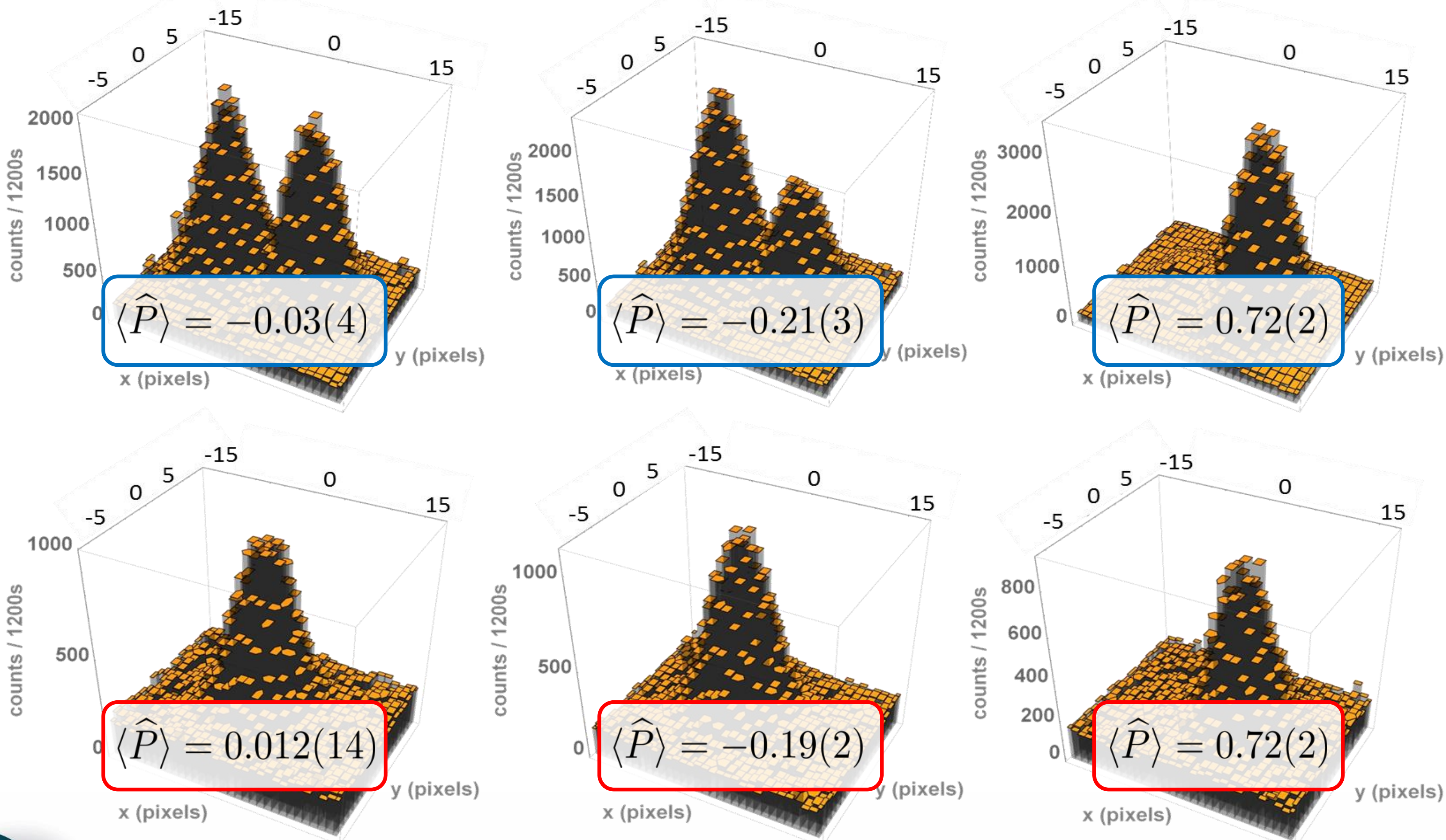




Experimental results

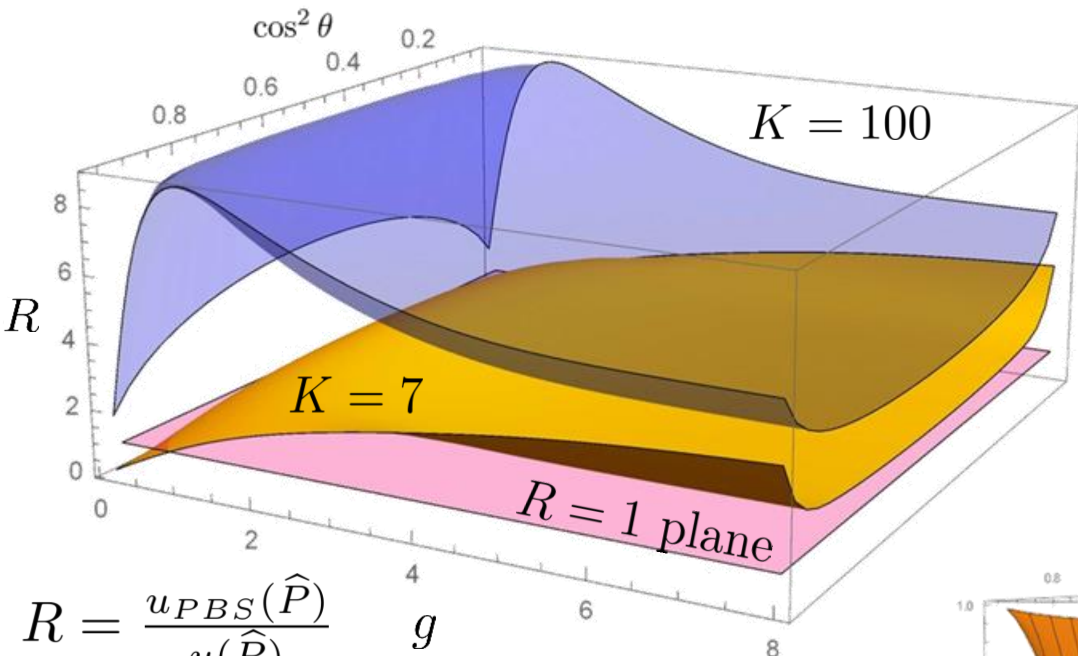
Nat. Phys. 13, 1191 (2017)

$\langle\widehat{P}\rangle^{th} = 0$ $\langle\widehat{P}\rangle^{th} = -0.208$ $\langle\widehat{P}\rangle^{th} = 0.707$



How accurate can PMs be?

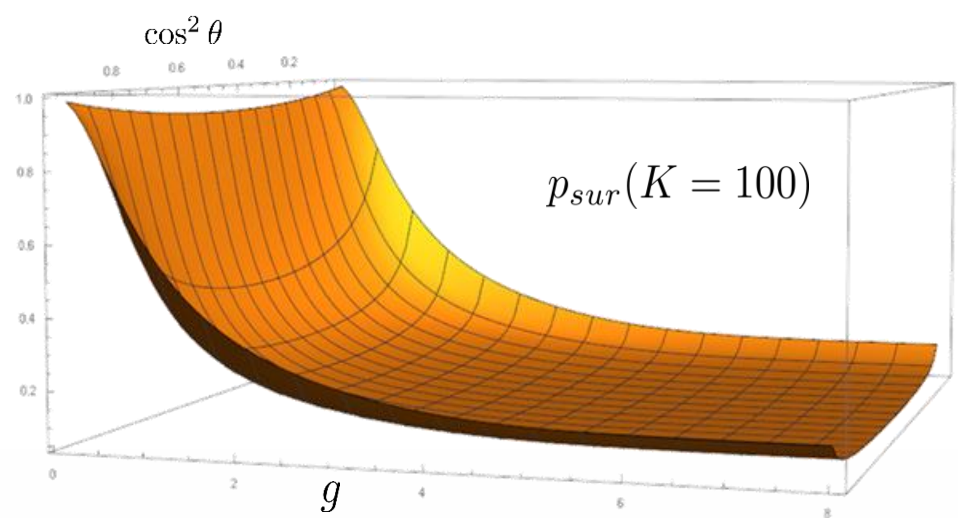
Let us compare the uncertainty on $\hat{P}$ given by a K-steps PM ($u(\hat{P})$) with the one obtained with a projective measurement ($u_{PBS}(\hat{P})$):



$$R = \frac{u_{PBS}(\hat{P})}{u(\hat{P})}$$

$u(\hat{P}) < u_{PBS}(\hat{P})$, even though in this framework projective measurements saturate the Quantum Cramér-Rao bound!

Nat. Phys. 13, 1191 (2017)



The advantage given by PMs is due to:

$$K \gg 1 \quad \rightarrow \quad p_{sur}(K) \gg (p_{sur}(1))^K$$

The weak crew

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Thanks for your attention!!