# Experimental measurement of nonlinear entanglement witness for hyper-entangled states

MULTIPHOTON QUANTUM LAB
@ RCPTM, PALACKÝ UNIVERSITY

multiphoton.upol.cz


Vojtěch Trávníček[1], Karol Bartkiewicz[1,3], Antonín Černoch[1,2] and Karel Lemr[1]

[1] Joint Laboratory of Optics, Palacký University in Olomouc, Czech Republic

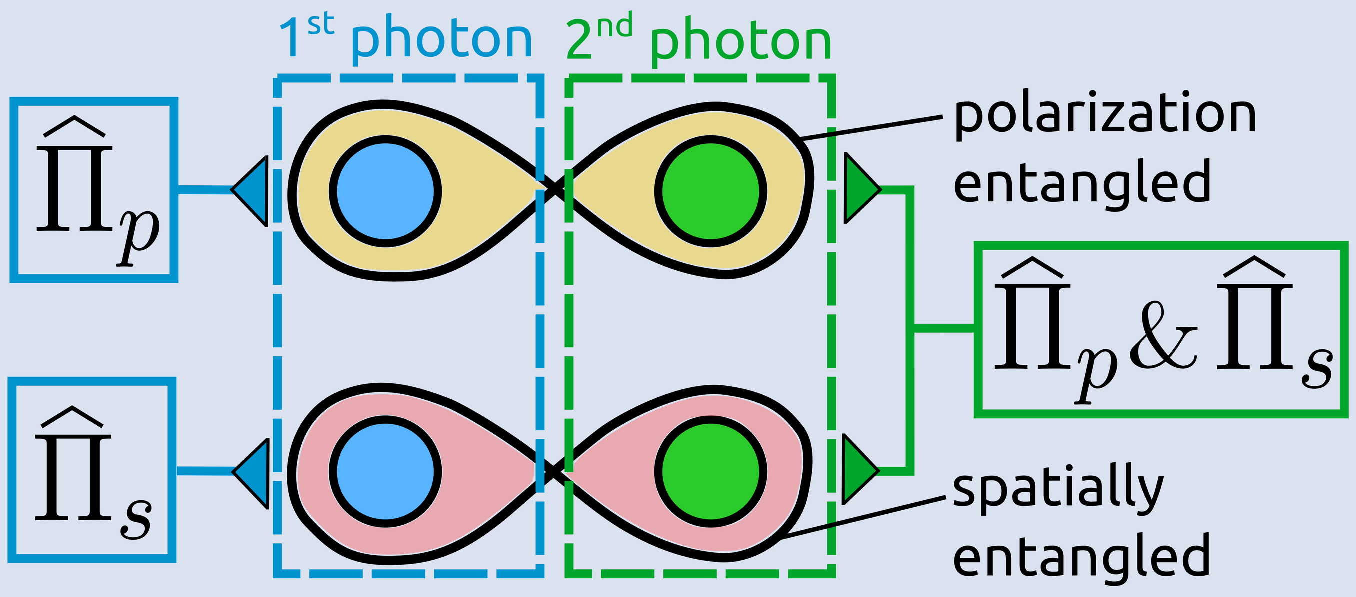
[2] Institute of Physics of Czech Academy of Sciences, Joint Laboratory of Optics of PU and IP AS CR, Olomouc, Czech Republic

[3] Faculty of Physics, Adam Mickiewicz University, Poznań, Poland


REGIONAL CENTRE OF ADVANCED TECHNOLOGIES AND MATERIALS

## Nonlinear entanglement witness for hyper-entangled states

Several non-linear witnesses have been proposed to detect entanglement in one degree of freedom e.g. [1-4]. Our reaserch adopts this concept to test hyper-entangled states. Instead of multiple copies of investigated state, we use only one copy of the hyper-entangled state, but adress all degrees of freedom simultaneously.




The initial state $\hat{\rho}_p = \hat{\rho}_s$ is encoded into polarization and spacial modes of the photon pair. The first photon is then subjected to projections $\hat{\Pi}_p, \hat{\Pi}_s$ which are independent in polarization and spacial mode. The second photon is projected onto a singlet state $|\psi^-\rangle = \frac{1}{\sqrt{2}}(|0_p 1_s\rangle - |1_p 0_s\rangle)$, where the two degrees of freedom are adressed at the same time.

Our method can be used for fast diagnostics of hyper-entangled states because it only needs four measurements to certify whether the state is hyper-entangled or not. The drawback of this method is that if one loses entanglement in either or both degrees of freedom the result in terms of entanglement witness will be the same, therefore one can not say what went wrong.

## Entanglement witness $W(\hat{\rho})$

$$W(\hat{\rho}) = \tfrac{1}{2}[\eta + P^2(1-2p_{00}) + (1-P)^2(1-2p_{11}) + 2P(1-P)(1-2p_{01}) - 1] \quad [2]$$

$$p_{++} = Prob(|\psi^-\rangle\langle\psi^-| \hat{\Pi}_{p(|0\rangle+|1\rangle)\frac{1}{\sqrt{2}}} \otimes \hat{\Pi}_{s(|0\rangle+|1\rangle)\frac{1}{\sqrt{2}}})$$

$$\eta = 16P(1-P)\sqrt{p_{00}p_{11}} + 4p_{++}$$

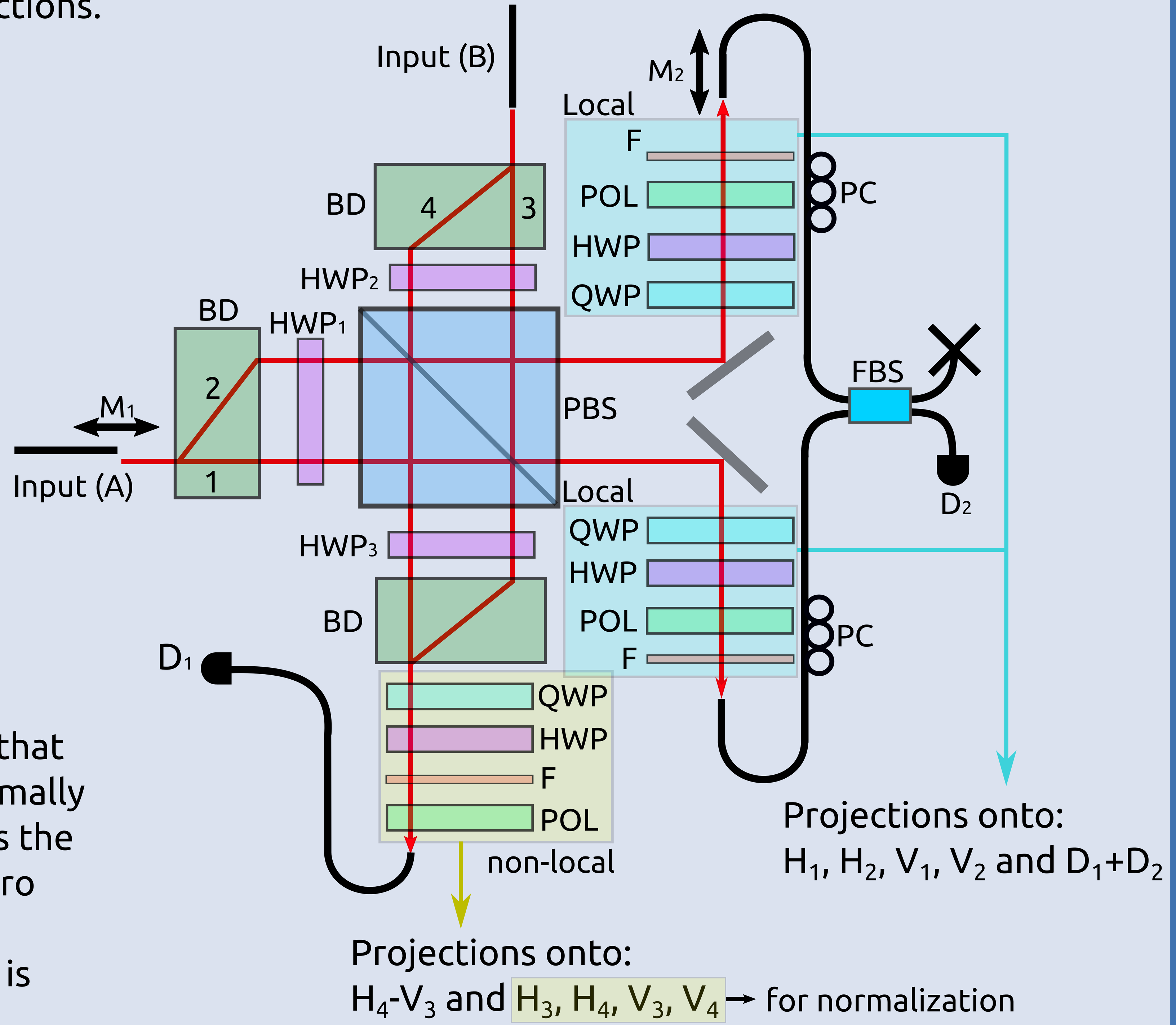
$$p_{ij} = Prob(|\psi^-\rangle\langle\psi^-| \hat{\Pi}_{pi} \otimes \hat{\Pi}_{sj})$$

## Experimental setup and measurement

Two polarization-entangled photons are generated in a BBO crystal cascade and each brought to one input port. The beam dividers then transform polarization entanglement into spatial entanglement and the two photons interact on a polarizing beam splitter where they get entangled in polarization again.

The hyper-entangled state is consequently subjected to local and non-local polarization projective measurements in mode A and B respectively. Local or non-local in our concept stands for measurements implemented separately respectively jointly on the two degrees of freedom.

The amount of entanglement, in terms of entanglement witness, is then derived from correlations between coincidence rates of individual projections.

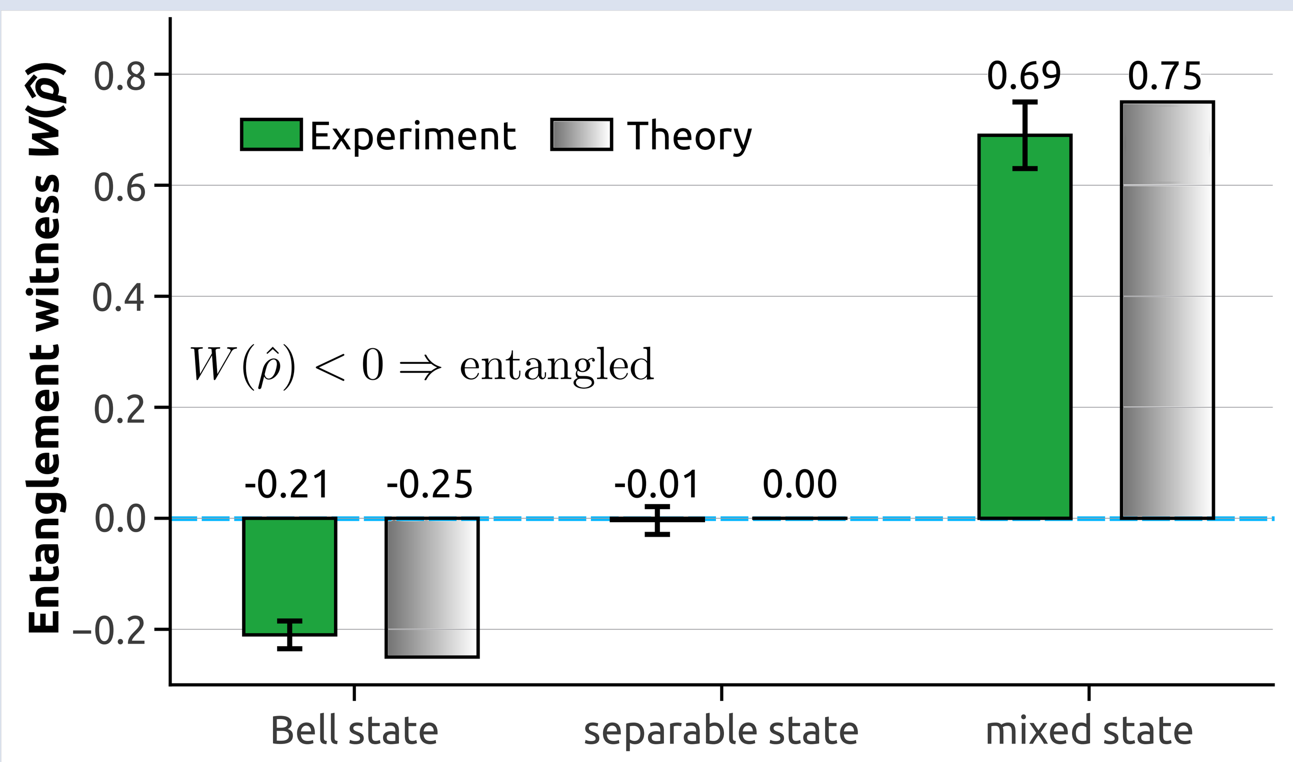



Polarization encoding: $H \sim 0\,; V \sim 1$

Spatial encoding: $\#1\ \&\ \#3 \sim 0$

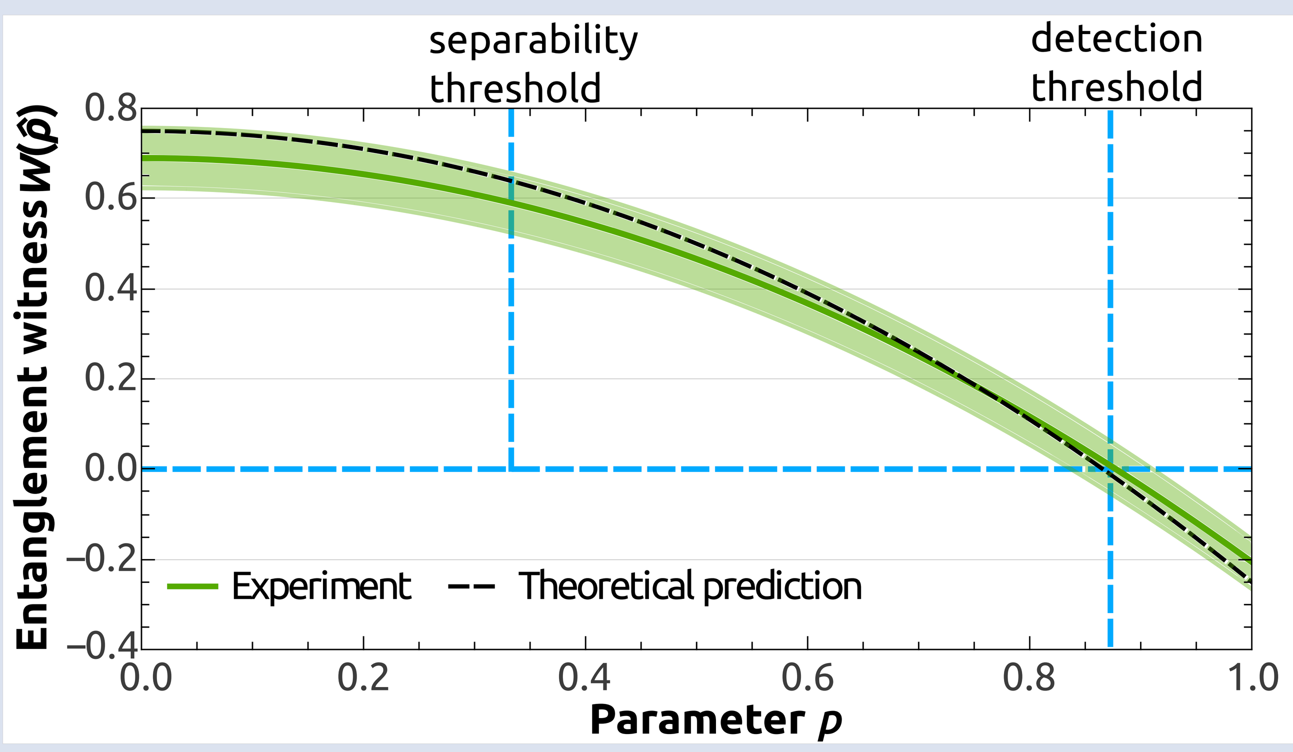
$\#2\ \&\ \#4 \sim 1$

## Results




$\frac{1}{\sqrt{2}}(|HH\rangle + |VV\rangle)$ $\quad |HV\rangle \quad \frac{1}{4}\hat{\mathbb{1}}$

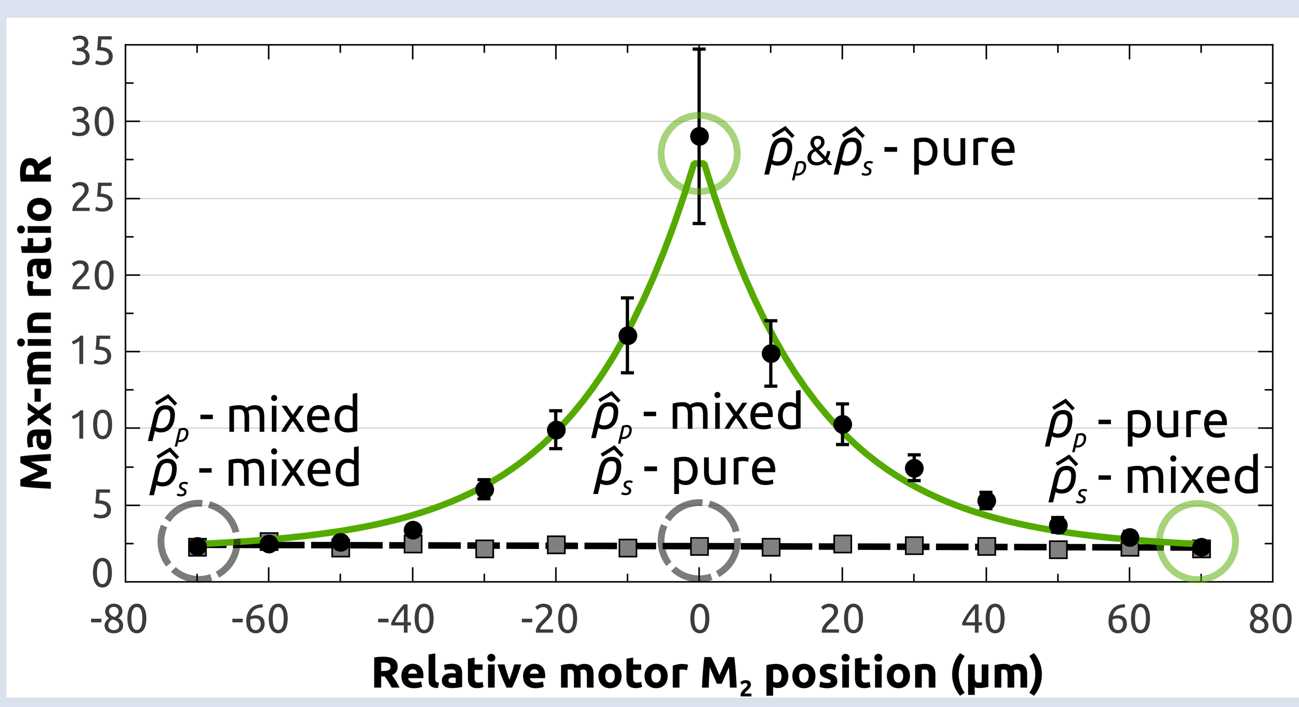
Expremental results and theoretical values of entanglement witness for three fundamental quantum states. Note that measurement of maximally entangled states yields the value of $p_{++}$ close to zero therefore negative entanglement witness is obsereved.




$$\hat{\rho}(p) = p|\Psi^-\rangle\langle\Psi^-| + (1-p)\tfrac{1}{4}\hat{\mathbb{1}}$$

Experimental measurement of entanglement witness for Werner states as a function of its parameter ***p***. Note that entanglement witness is able to detect entanglement only for ***p*** > $\sqrt{3}/2$ although Werner states are already entangled for any ***p*** > 1/3. [4]

## Generalization $\hat{\rho}_p \neq \hat{\rho}_s$




Demonstration of impact of states purities on ratio R in $p_{++}$ configuration. The scanning of interference fringe on FBS was implemented through phase shift between spatial modes 1 and 2. If one of the states becomes disentangled the ratio R goes to 1, the $p_{++}$ is then 1/4 and $W(\hat{\rho})$ is positive.

$$R = \frac{cc_{max}}{cc_{min}}$$

## References


[1] F. A. Bovino, G. Castagnoli, A. Ekert, P. Horodecki, C.M. Alves, and A. V. Sergienko, Phys. Rev. Lett. 95, 240407 (2005).

[2] Ł. Rudnicki, P. Horodecki, and K. Życzkowski, Phys. Rev. Lett. 107, 150502 (2011).

[3] Ł. Rudnicki, Z. Puchala, P. Horodecki, and K. Życzkowski, Phys. Rev. A 86, 062329 (2012).

[4] K. Lemr, K. Bartkiewicz, A. Černoch, Phys. Rev. A 94, 052334 (2016).



This research is supported by the Czech Science Foundation under the project No. 17-10003S.