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Experimental few-copy multi-particle entanglement detection

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arXiv:1809.05455 [quant-ph]

CoQuS ComplexQuantumSystems

FWF Der Wissenschaftsfonds.

VDS VIENNA - DOCTORAL - SCHOOL - PHYSICS

Outline

- **Motivation**;
- **Theoretical background**: entanglement detection as a probabilistic procedure;
  - Detecting entanglement in cluster states.
- **Experiment**: generation of a six-qubit cluster state at telecommunication wavelengths;
- **Results**: entanglement verified in the state with high confidence;
- **Conclusions**: outlooks and perspectives.

Motivation

- Reliable verification of quantum entanglement is a considerable challenge when dealing with large-scale quantum systems;

- Complete quantum state tomography:

✓ best method for inferring full information about a quantum state;

✗ unfeasible for large systems due to the exponential growth of the number of measurement settings with the size of the system.

- Witness operator: its mean value measured to be less than zero states the presence of entanglement in the system;

Experimental Detection of Multipartite Entanglement using Witness Operators

Mohamed Bourennane, Manfred Eibl, Christian Kurtsiefer, Sascha Gaertner, Harald Weinfurter, Otfried Gühne, Philipp Hyllus, Dagmar Bruß, Maciej Lewenstein, and Anna Sanpera

Phys. Rev. Lett. **92**, 087902 – Published 26 February 2004

- But still many copies of the quantum state are required.

The goal

Given a large quantum state, verify whether entanglement is present in it by minimizing time and resources.

- Our approach:

npj | Quantum Information

Article | OPEN | Published: 15 February 2018

Single-copy entanglement detection

Aleksandra Dimić & Borivoje Dakić

npj Quantum Information **4**, Article number: 11 (2018) | Download Citation

Simple example: the singlet state

$$|\psi^-\rangle = \frac{|01\rangle - |10\rangle}{\sqrt{2}}$$

- The singlet state shows perfect anti-correlation in all the Pauli bases:

$$\langle X \otimes X\rangle = \langle Y \otimes Y\rangle = \langle Z \otimes Z\rangle = -1$$

$$M_1 = \frac{\mathbb{1} - X \otimes X}{2} \rightarrow 1$$

$$M_2 = \frac{\mathbb{1} - Y \otimes Y}{2} \rightarrow 1$$

$$M_3 = \frac{\mathbb{1} - Z \otimes Z}{2} \rightarrow 1$$

- The probability of success is

$$P_{|\psi^-\rangle} = \left\langle \frac{M_1 + M_2 + M_3}{3} \right\rangle = 1 = p_e$$

- And for an arbitrary separable state ρ_{sep}?

- Not possible to obtain success from all the three measurements M_1, M_2, M_3:

$$P_{\rho_{sep}} = \left\langle \frac{M_1 + M_2 + M_3}{3} \right\rangle \leq \frac{2}{3} = p_s$$

$$\boxed{\delta = p_e - p_s}$$

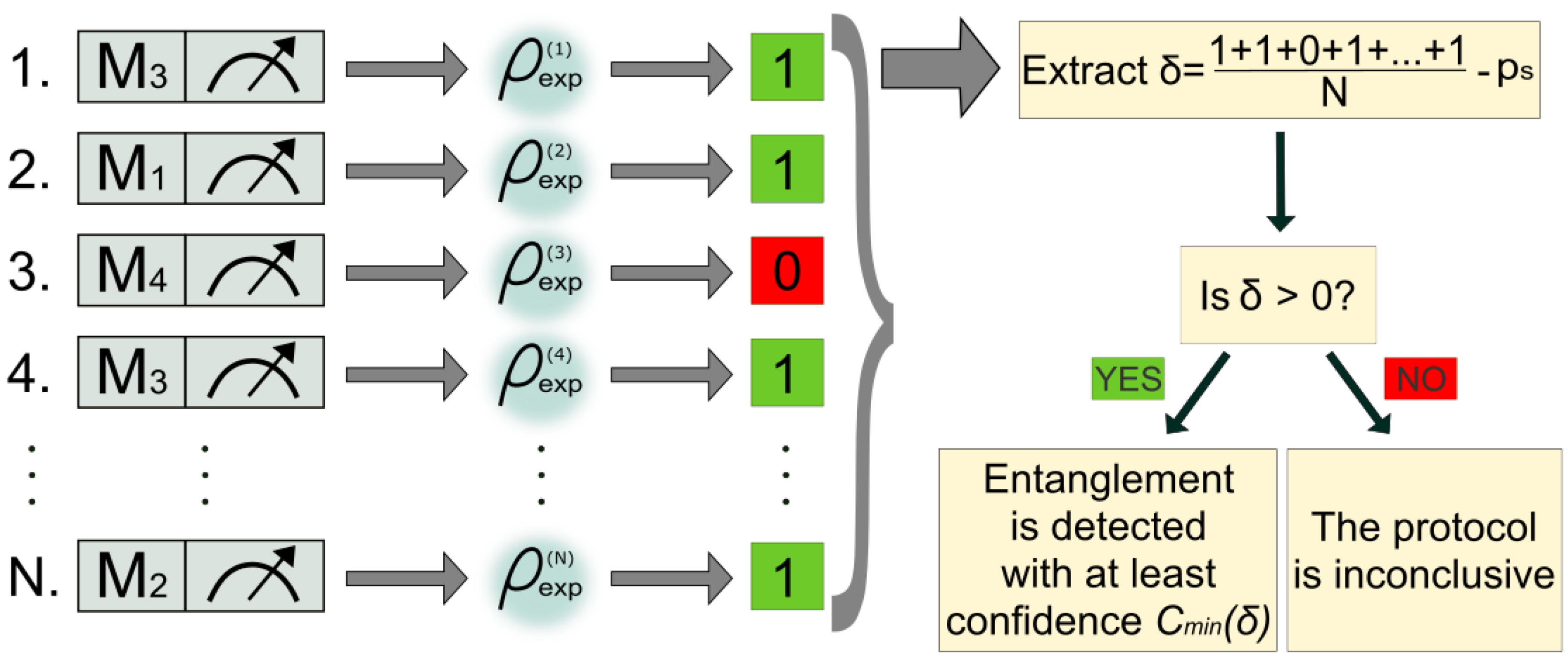
The general protocol (in experiments)

- Define binary observables M_i such that they return 1 (success) or 0 (failure);
- Pick them randomly *N* times and apply them to the state;
- It is shown[1] that the probability that $\delta > 0$ for an arbitrary separable state goes exponentially fast to zero with *N*:

$$P(\delta) \leq e^{-D(p_s+\delta||p_s)N}$$

- Therefore, the confidence for entanglement detection grows exponentially fast in *N*:

$$C(\delta) = 1 - P(\delta) \geq 1 - e^{-D(p_s+\delta||p_s)N} = C_{\min}(\delta)$$



We recall that…

$$\delta = p_e - p_s$$

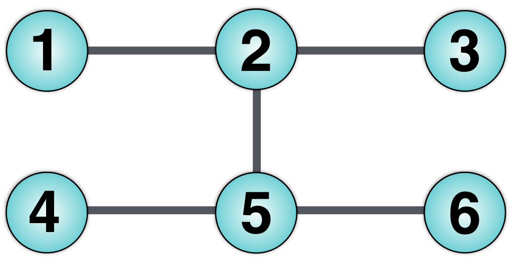
$$P_{|\psi^-\rangle} = \left\langle \frac{M_1+M_2+M_3}{3} \right\rangle = 1 = p_e$$

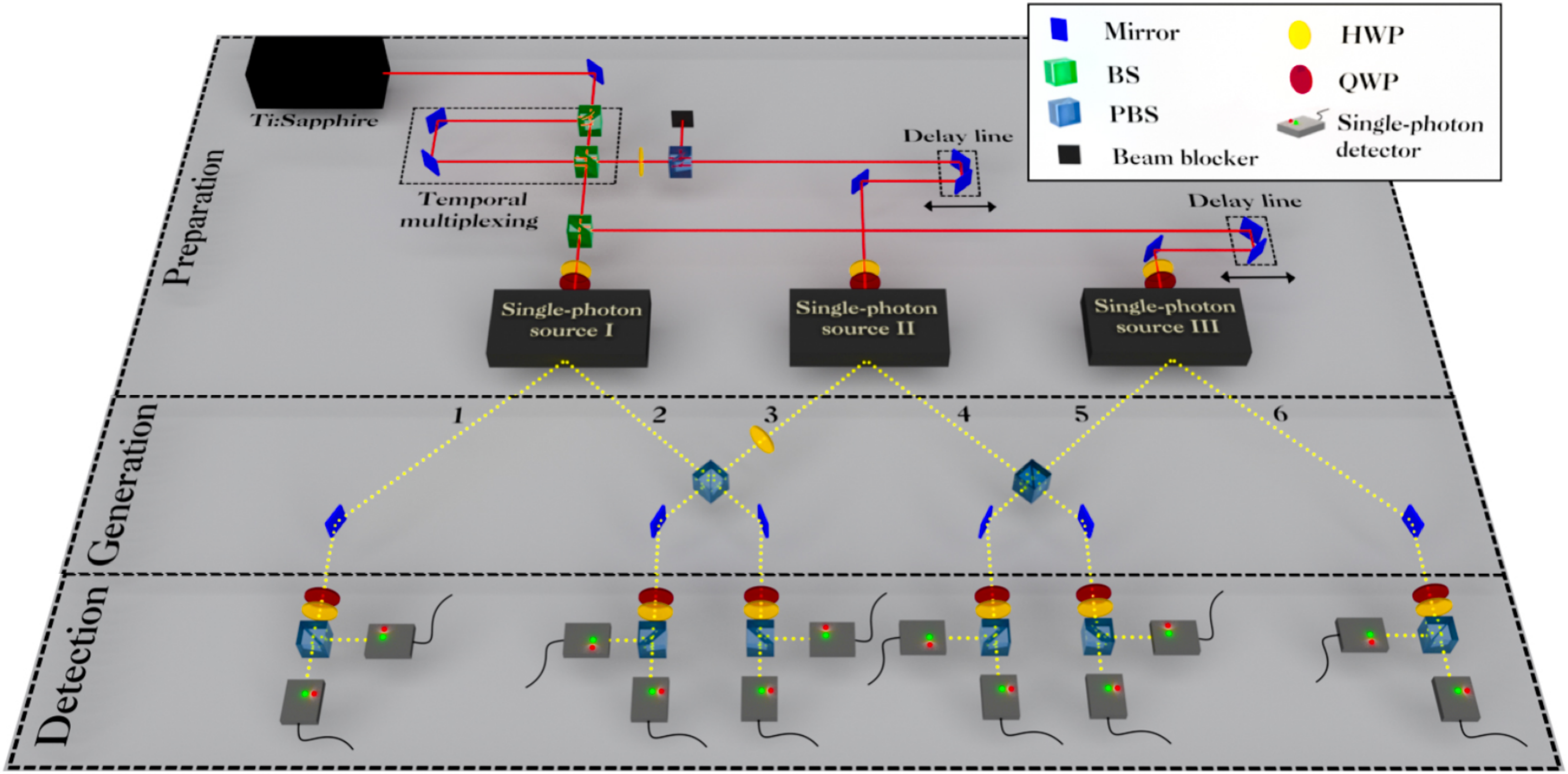
$$P_{\rho_{sep}} = \left\langle \frac{M_1+M_2+M_3}{3} \right\rangle \leq \frac{2}{3} = p_s$$

[1] Dimić, A. & Dakić, B. Single-copy entanglement detection. *npj Quantum Information* **4(1)**, 11 (2018).

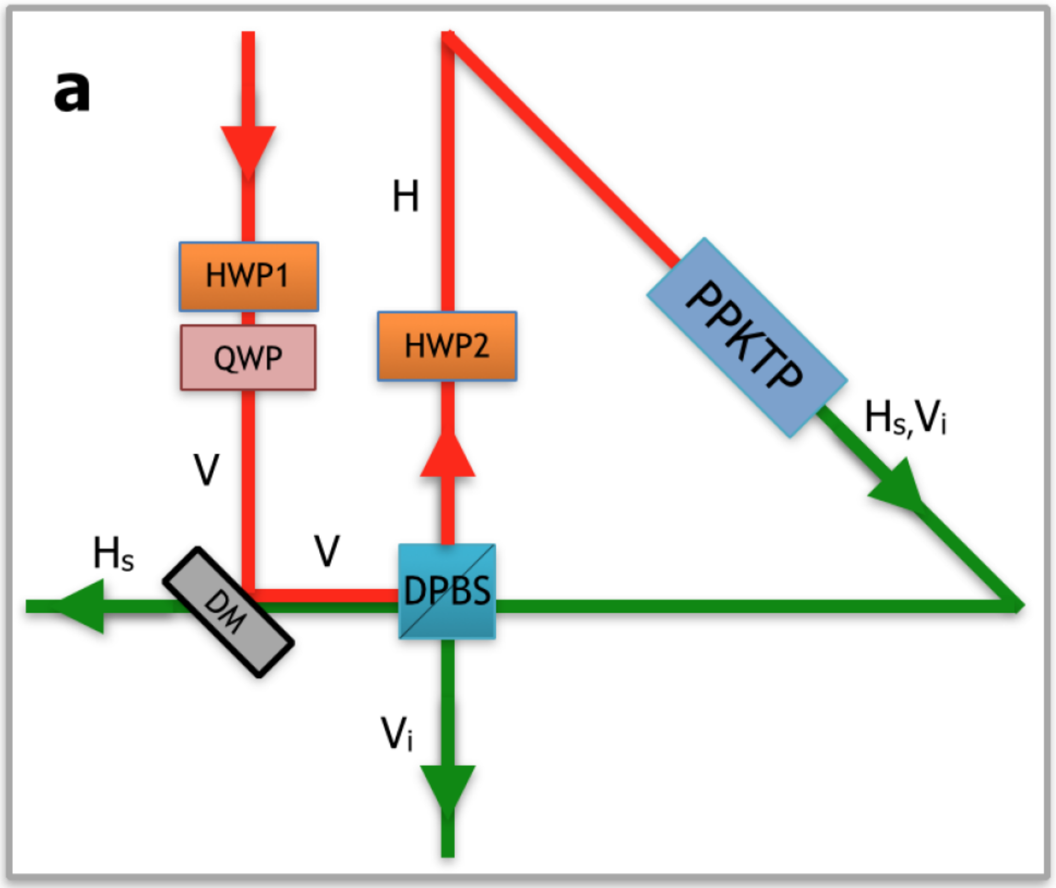
Six-qubit cluster state generation

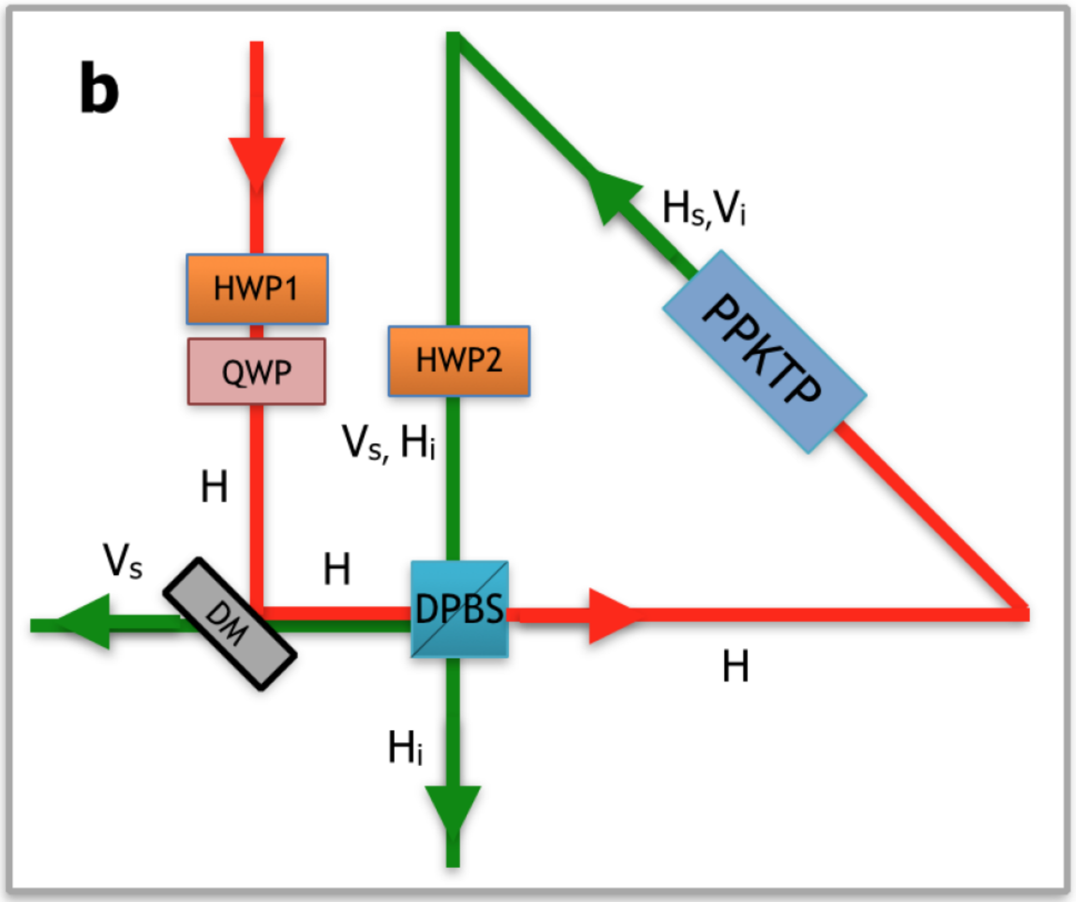
$$|Cl_6\rangle = \frac{1}{2}(|H_1H_2H_3H_4H_5H_6\rangle + |H_1H_2H_3V_4V_5V_6\rangle + |V_1V_2V_3H_4H_5H_6\rangle - |V_1V_2V_3V_4V_5V_6\rangle)$$



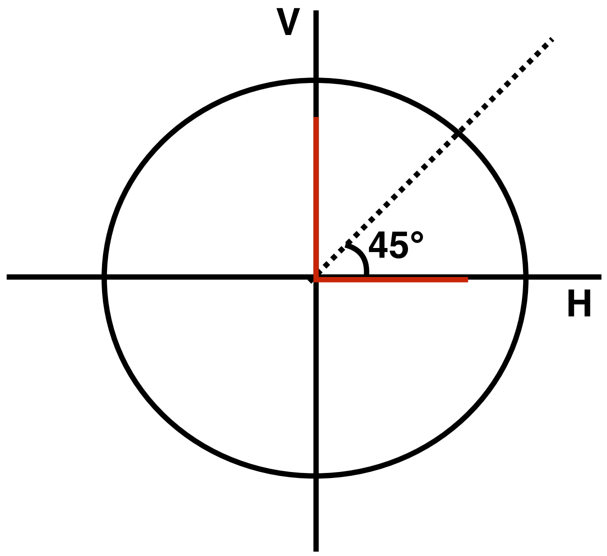


The single-photon source



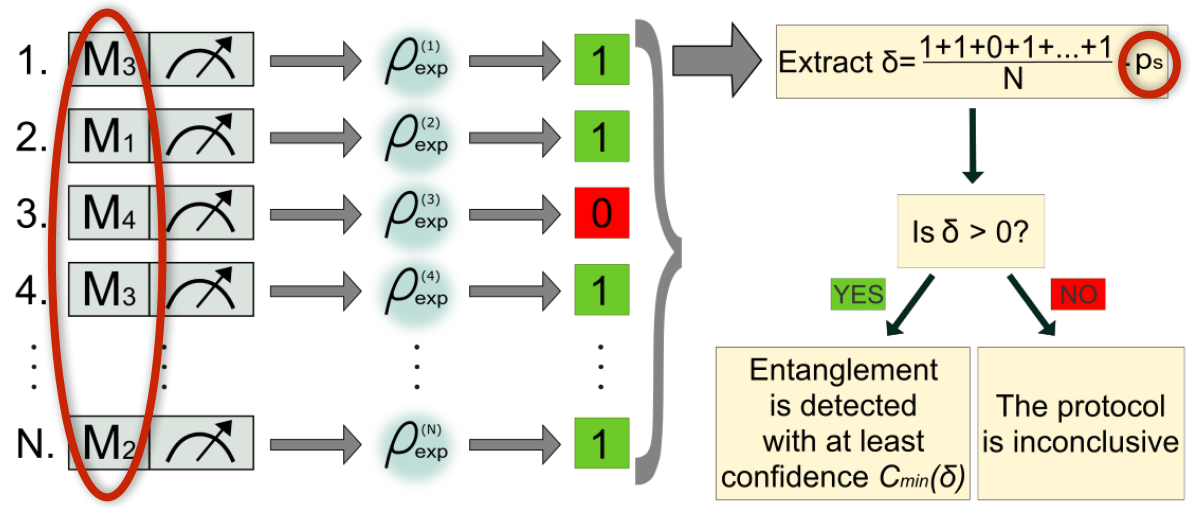


- If the pump is 45 degree polarized, both signal and idler take the same output;
- $|\psi^-_{1,2}\rangle = \dfrac{|H_1\rangle|V_2\rangle - |V_1\rangle|H_2\rangle}{\sqrt{2}}$



Adaption of the protocol to our state

- It means finding the M_i operators and the separable bound p_s for our state;



- We start from two witness operators and translate them into our probabilistic protocol[2]:

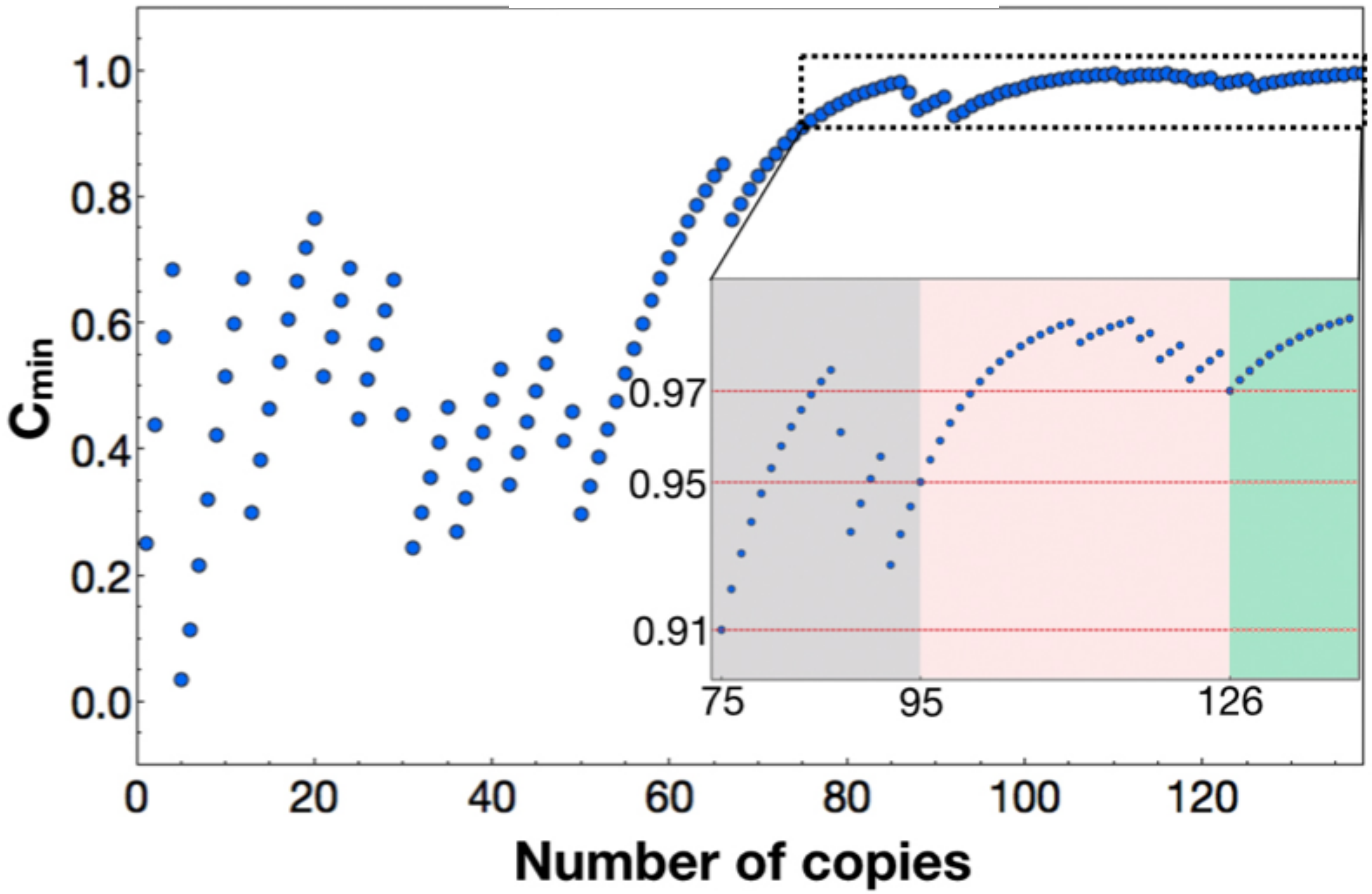
$W_1 = 3\mathbb{1} - 2\left(\prod_{k=1,3,5} \frac{\mathbb{1}+G_k}{2} + \prod_{k=2,4,6} \frac{\mathbb{1}+G_k}{2}\right)$	$W_2 = \frac{1}{2}\mathbb{1} - \vert Cl_6\rangle\langle Cl_6\vert$
$\{M_1 = \prod_{k=1,3,5} \frac{\mathbb{1}+G_k}{2},$ $M_2 = \prod_{k=2,4,6} \frac{\mathbb{1}+G_k}{2}\}$	$M_k = \frac{\mathbb{1}+S_k}{2}$ where $k = 1, ..., 2^6$
$p_{s1} = \frac{3}{4}$	$p_{s2} = \frac{3}{4}$

[2] Tóth, G. & Gühne, O. Detecting genuine multipartite entanglement with two local measurements. *Phys. Rev. Lett.* **94(6),** 060501 (2005).

Experimental results

$$W_1 = 3\mathbb{1} - 2\left(\prod_{k=1,3,5}\frac{\mathbb{1}+G_k}{2} + \prod_{k=2,4,6}\frac{\mathbb{1}+G_k}{2}\right)$$

2 measurements sampled N=150 times.



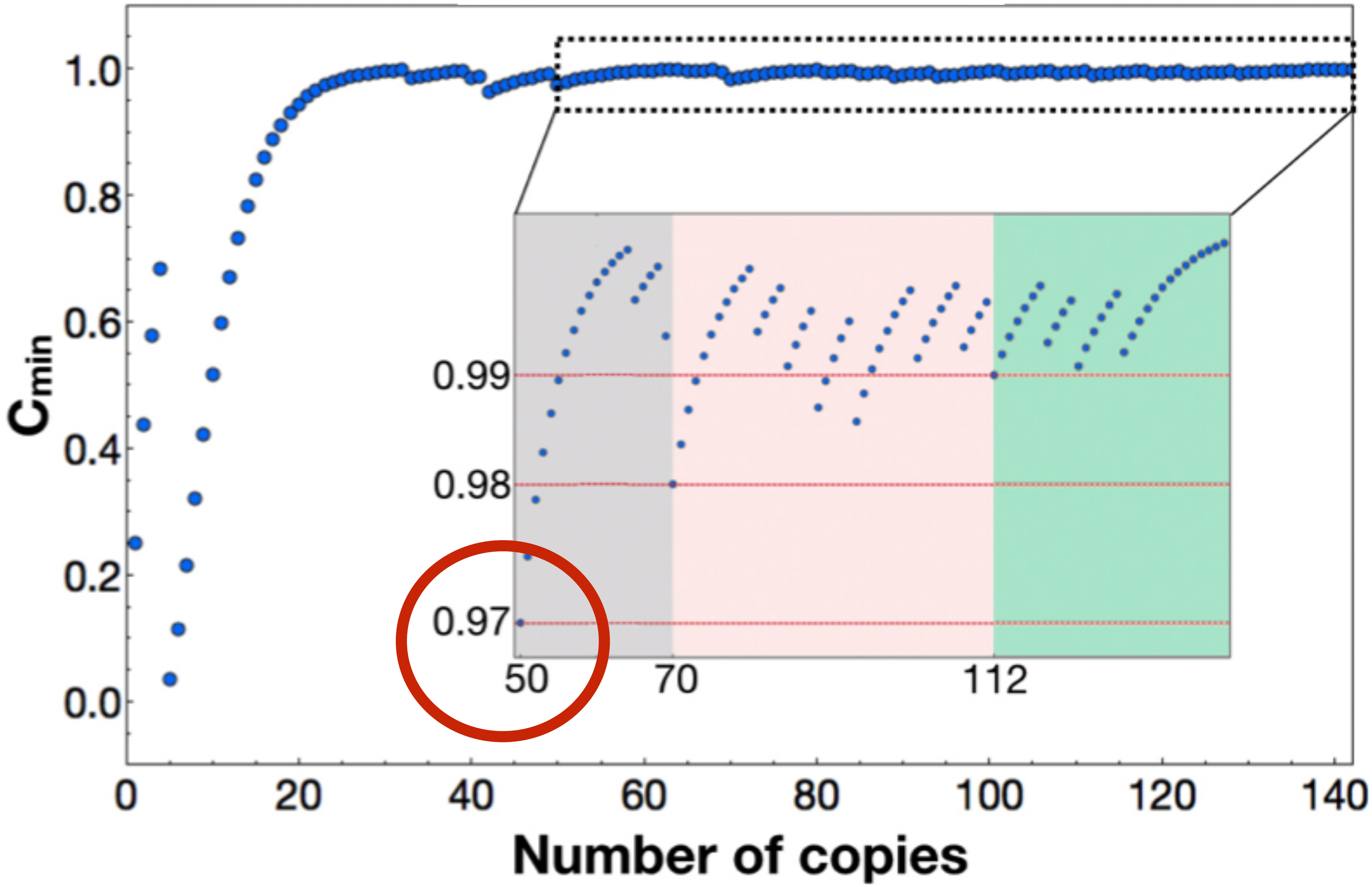
p_{s1}

$$C_{\min} = 1 - e^{-D(p_s+\delta||p_s)N}$$

Experimental results

$$W_2 = \frac{1}{2}\mathbb{1} - |Cl_6\rangle\langle Cl_6|$$

64 measurements sampled N=160 times.



Conclusions

- We provide a method to detect entanglement with high confidence with a reduced number of copies;

- The protocol is based on a probabilistic procedure and a translation of witness operators into it;

- Rather than measuring mean values of witness operators, we focus on single-copy measurements only.

The team

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