

Experimental testing of three-qubit nonlocality



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Artur Barasiński (*), Antonín Černoch, Karel Lemr, Jan Soubusta

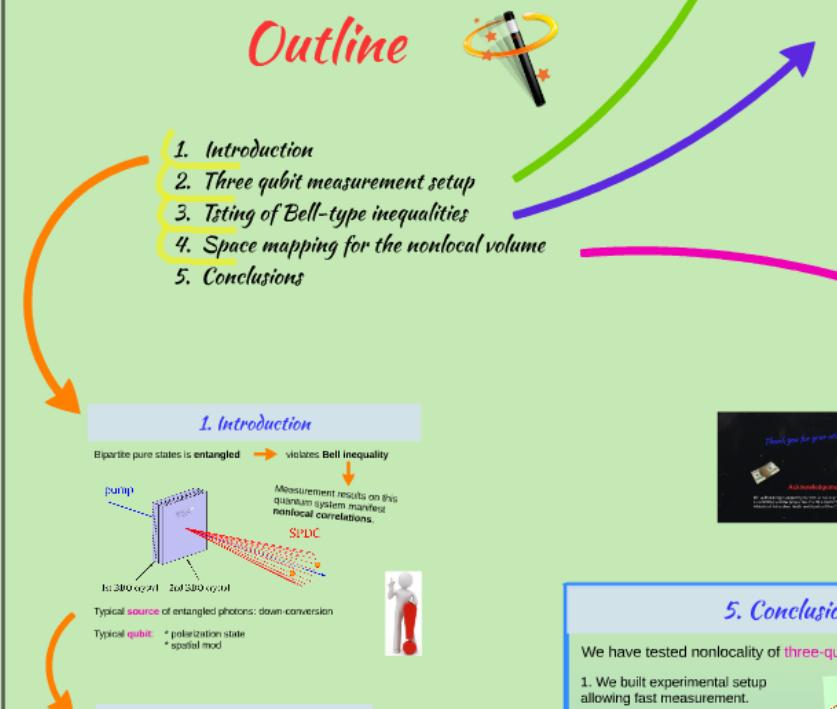
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Zielona Góra, Poland



Outline

1. Introduction
2. Three qubit measurement setup
3. Testing of Bell-type inequalities
4. Space mapping for the nonlocal volume
5. Conclusions



1. Introduction

Bipartite pure states is entangled → violates Bell inequality



Typical source of entangled photons: down-conversion
Typical qubit: * polarization state
* spatial mode

Which states we want to generate?

Three-qubit states, generalized Greenberger-Horne-Zeilinger

$|000\rangle\langle 000| + |111\rangle\langle 111| - \sqrt{2}|\psi_+\rangle\langle\psi_+|$

Nonlocal volume is monotonic with increasing angle theta.

Projection of qubit A Projection of qubit B Projection of qubit C

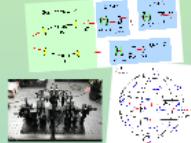


Please you for your attention!
Acknowledgments

5. Conclusions

We have tested nonlocality of three-qubit GHZ states.

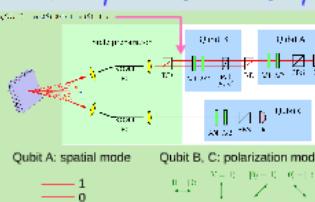
1. We built experimental setup allowing fast measurement.
2. We tested nonlocality using four Bell-type Inequalities for optimal projections.
3. We started nonlocal volume measurements.



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2. Three qubit measurement setup



Qubit A: spatial mode Qubit B, C: polarization mode

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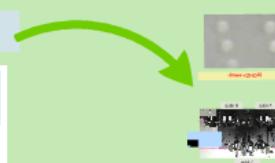
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3. Testing of Bell-type inequalities

To test three-qubit nonlocality, 285 Bell-type inequalities were formulated.

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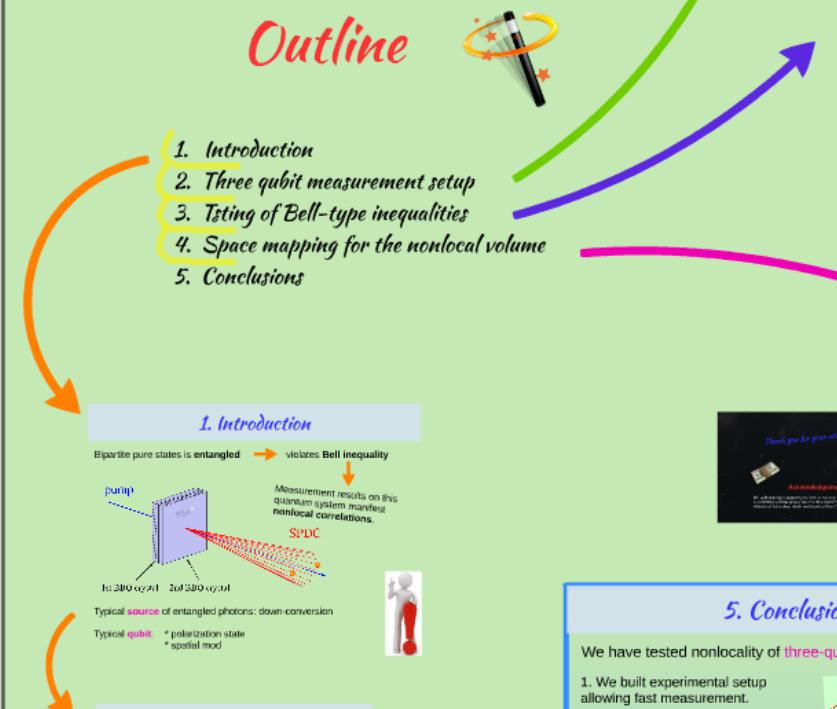
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Bipartite pure states is entangled → violates Bell inequality



Typical source of entangled photons: down-conversion
Typical qubit: * polarization state
* spatial mode

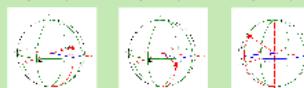
Which states we want to generate?

Three-qubit states, generalized Greenberger-Horne-Zeilinger

$$|\phi_0\rangle\langle\phi_0| = |\phi_1\rangle\langle\phi_1| + |\phi_2\rangle\langle\phi_2| + |\phi_3\rangle\langle\phi_3|$$

Nonlocal volume is monotonic with increasing angle theta.

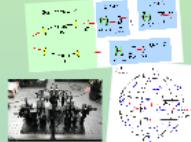
Projection of qubit A Projection of qubit B Projection of qubit C



5. Conclusions

We have tested nonlocality of three-qubit GHZ states.

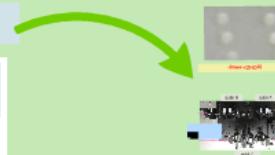
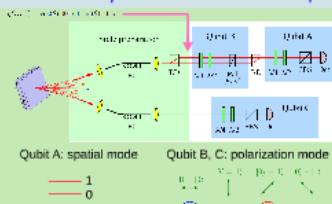
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2. Three qubit measurement setup



3. Testing of Bell-type inequalities

To test three-qubit nonlocality, 245 Bell-type inequalities were formulated.

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[113] A. Barasiński et al., *Phys. Rev. A* **202**, 012113 (2023).

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Experimental testing of three-qubit nonlocality

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Zielona Góra, Poland*



Outline



1. Introduction
2. Three qubit measurement setup
3. Testing of Bell-type inequalities
4. Space mapping for the nonlocal volume
5. Conclusions

1. Introduction

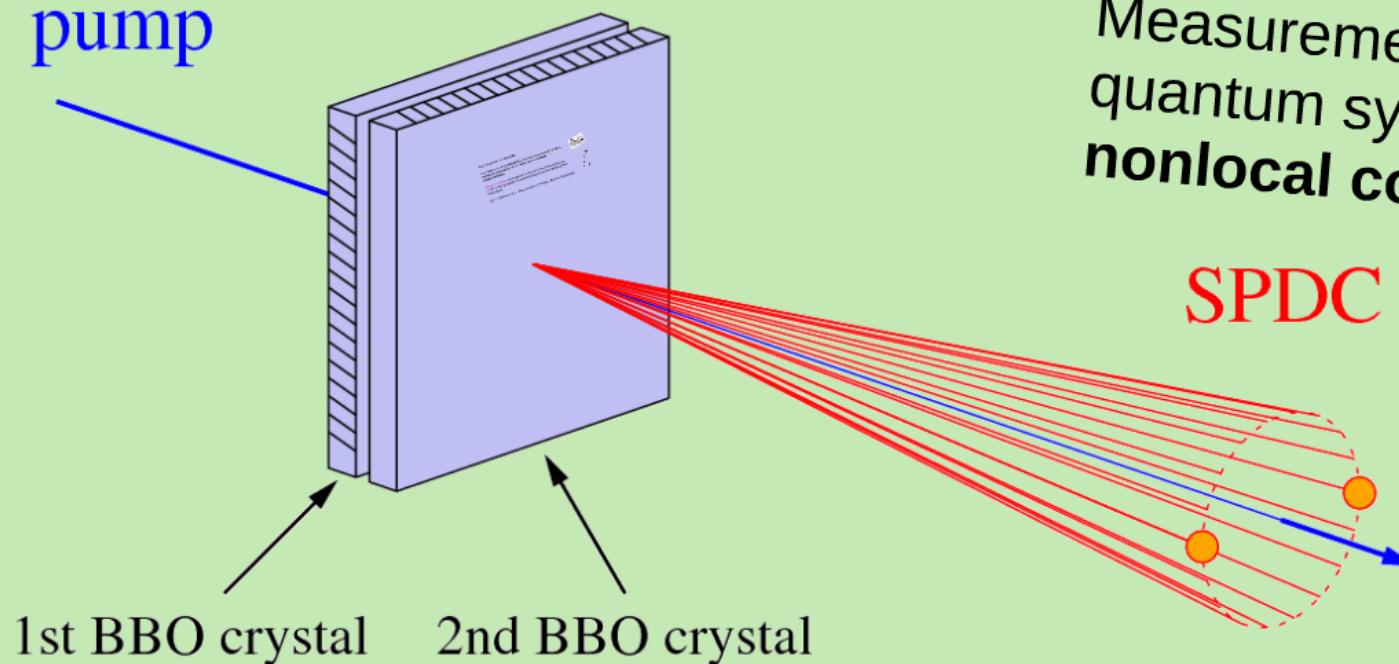
Bipartite pure states is **entangled**



violates **Bell inequality**

Measurement results on this quantum system manifest **nonlocal correlations**.

SPDC



Typical **source** of entangled photons: down-conversion

Typical **qubit**: * polarization state
* spatial mod

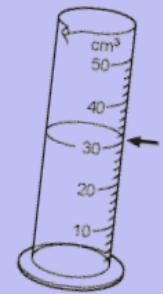


New measure of nonlocality:

It is defined as the **probability**, that the pure state will display **nonlocal correlation** when subjected to **random measurements**.

Nonlocal volume corresponds to the volume of the subspace in which the projection measurements prove nonlocality of the input state.

[1] V. Lipinska, *et al.*, New Journal of Physics **20**, 063043 (2018).



Which states we want to generate ?

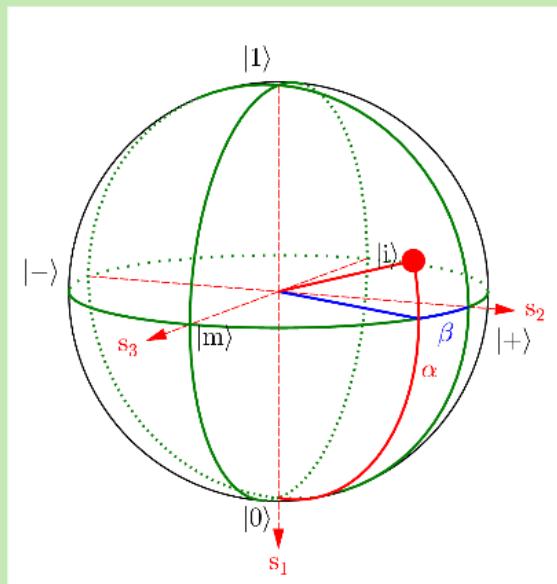


Three-qubit states, generalized Greenberger–Horne–Zeilinger

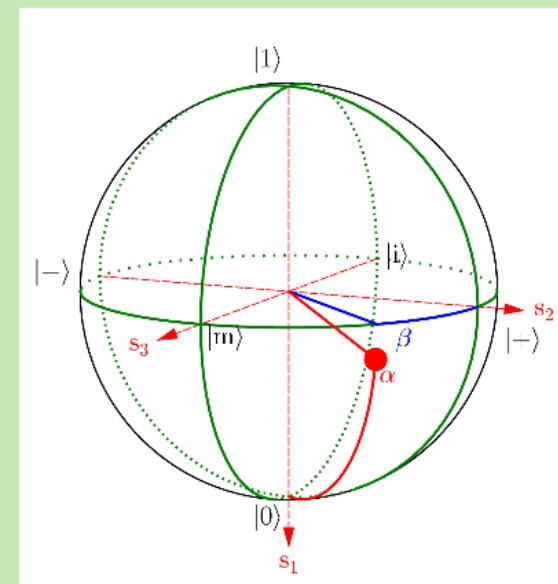
$$|gGHZ\rangle = \cos(\theta)|000\rangle + \sin(\theta)|111\rangle, \quad \theta \in \langle 0, \pi/4 \rangle.$$

Nonlocal volume is monotonic with increasing angle theta.

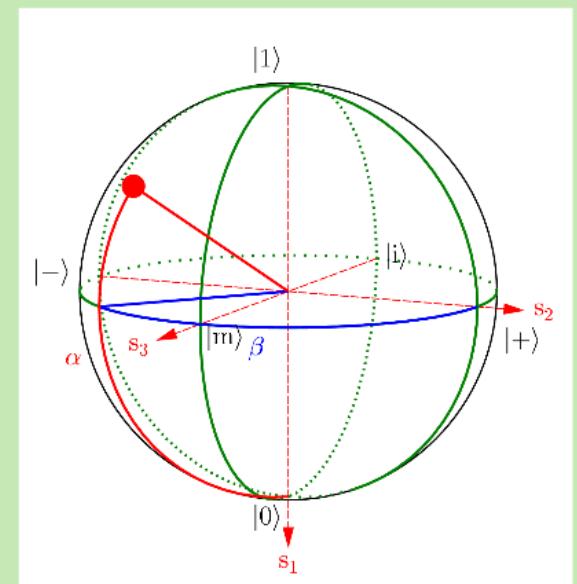
Projection of qubit A



Projection of qubit B



Projection of qubit C



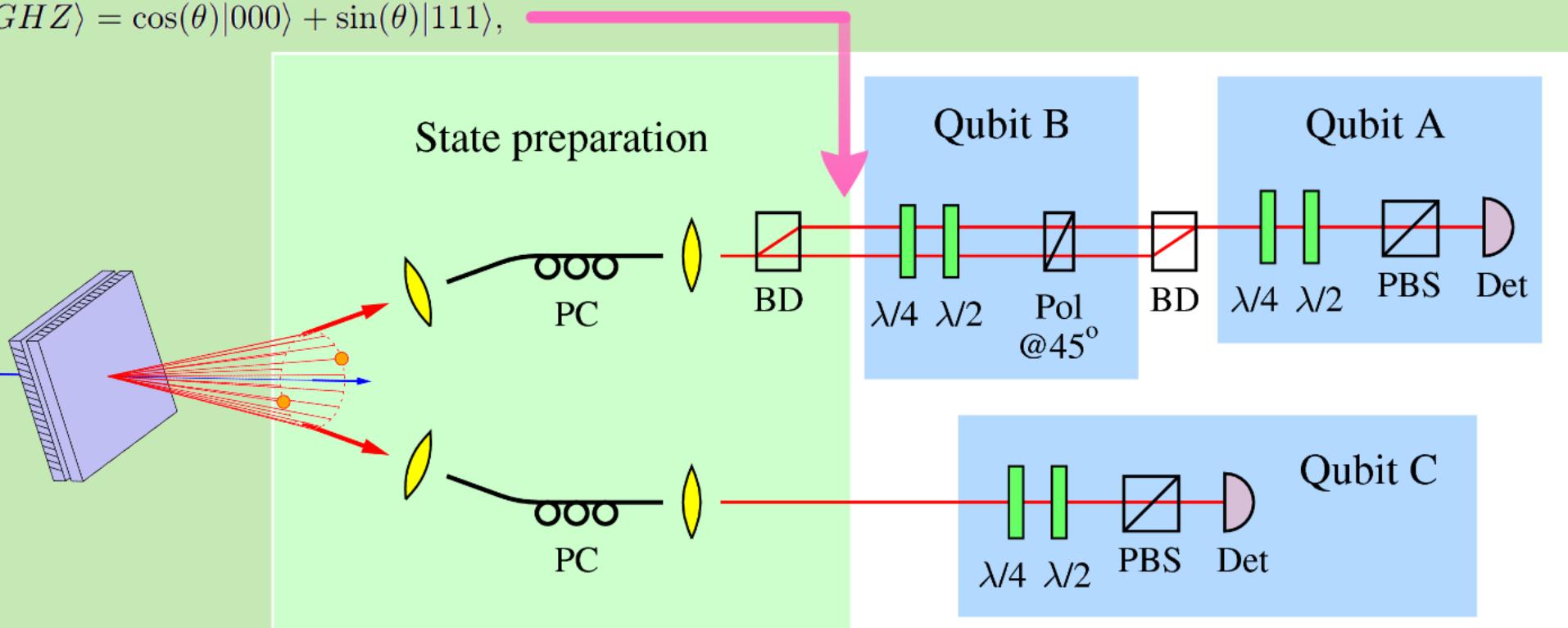
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2. Three qubit measurement setup

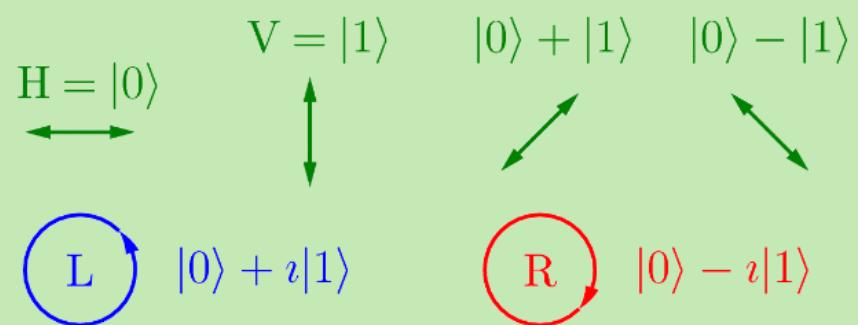
$$|gGHZ\rangle = \cos(\theta)|000\rangle + \sin(\theta)|111\rangle,$$



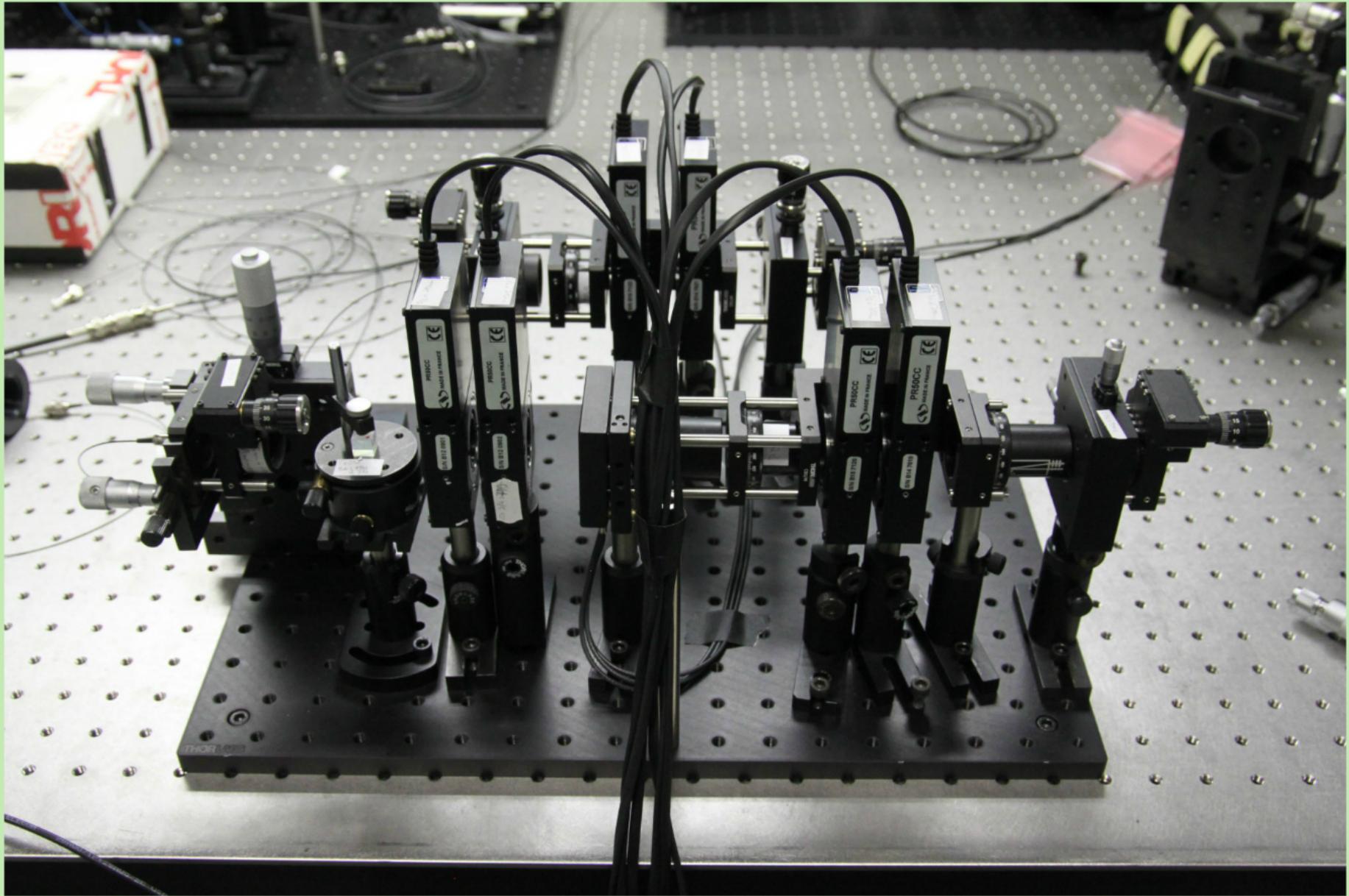
Qubit A: spatial mode

— 1
— 0

Qubit B, C: polarization mode

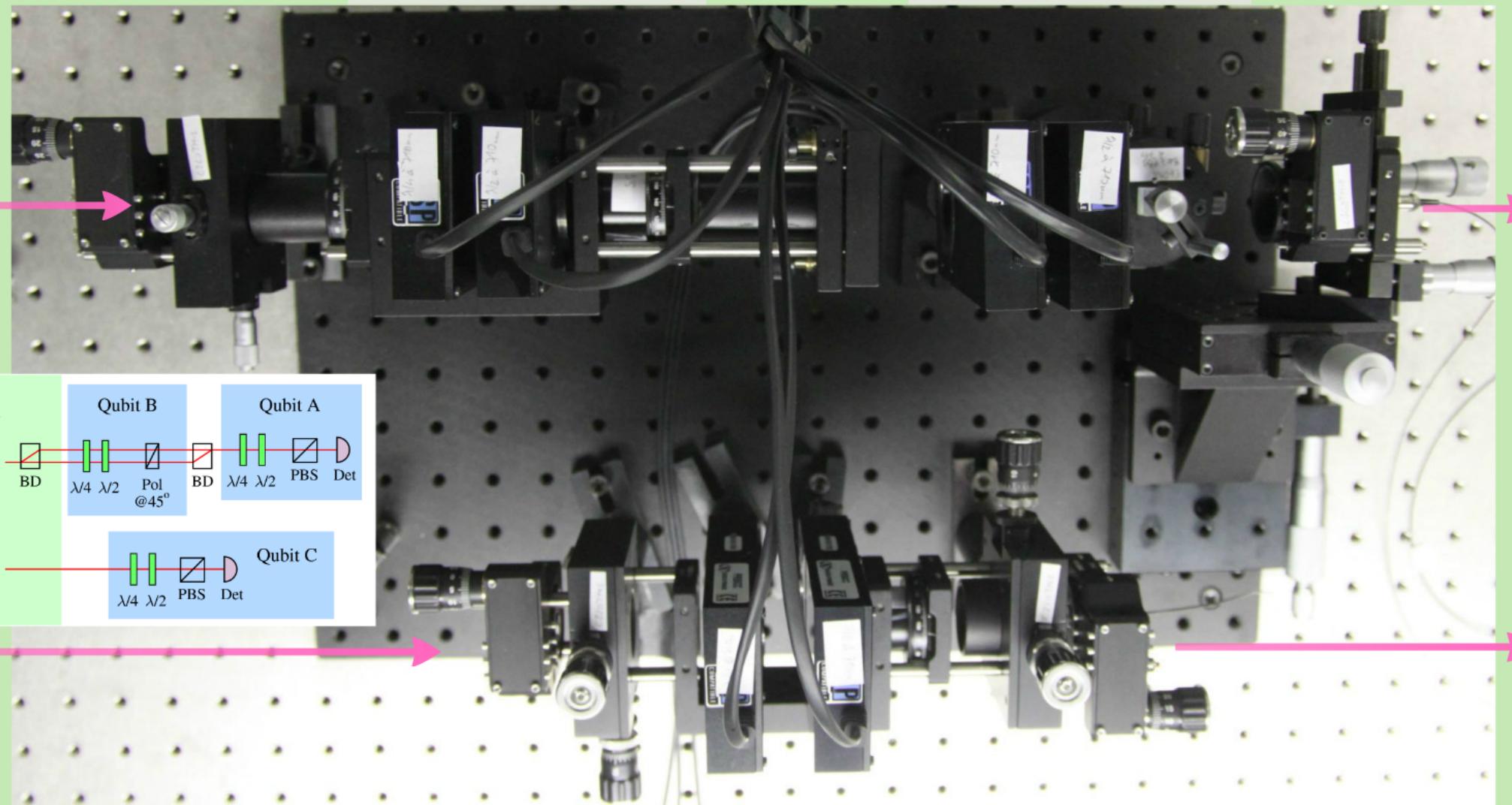


|gGHz> setup



qubit B

qubit A



qubit C

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3. Testing of Bell-type inequalities

$$|gGHZ\rangle = \cos(\theta)|000\rangle + \sin(\theta)|111\rangle, \quad \theta \in \langle 0, \pi/4 \rangle.$$

To test three-qubit nonlocality, **185 Bell-type inequalities** were formulated.

[3] G. Svetlichny, Phys. Rev. D 35, 3066 (1987).

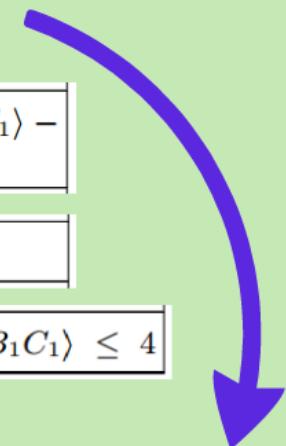
[4] J.-D. Bancal, *et al.*, Phys. Rev. A 88, 014102 (2013).

10	$-2\langle A_1 \rangle - \langle B_0 \rangle + \langle A_1 B_0 \rangle - \langle B_1 \rangle + \langle A_1 B_1 \rangle - \langle C_0 \rangle + \langle A_1 C_0 \rangle + \langle B_0 C_0 \rangle - \langle A_0 B_0 C_0 \rangle + 2\langle A_1 B_0 C_0 \rangle + \langle A_0 B_1 C_0 \rangle + \langle A_1 B_1 C_0 \rangle - \langle C_1 \rangle + \langle A_1 C_1 \rangle + \langle A_0 B_0 C_1 \rangle + \langle A_1 B_0 C_1 \rangle + \langle B_1 C_1 \rangle - \langle A_0 B_1 C_1 \rangle + 2\langle A_1 B_1 C_1 \rangle \leq 6$
----	--

96	$2\langle A_0 B_0 \rangle - \langle C_0 \rangle - \langle A_0 C_0 \rangle - \langle B_0 C_0 \rangle + \langle A_0 B_0 C_0 \rangle - 2\langle A_1 B_1 C_0 \rangle - \langle C_1 \rangle + \langle A_0 C_1 \rangle + \langle B_0 C_1 \rangle + \langle A_0 B_0 C_1 \rangle - 2\langle A_1 B_1 C_1 \rangle \leq 6$
----	---

99	$\langle A_1 B_1 \rangle + \langle A_0 B_0 C_0 \rangle + \langle B_1 C_0 \rangle + \langle A_1 C_1 \rangle - \langle A_0 B_0 C_1 \rangle \leq 3$
----	--

185	$-\langle A_0 B_0 C_0 \rangle - \langle A_1 B_0 C_0 \rangle + \langle A_0 B_1 C_0 \rangle - \langle A_1 B_1 C_0 \rangle - \langle A_0 B_0 C_1 \rangle + \langle A_1 B_0 C_1 \rangle - \langle A_0 B_1 C_1 \rangle - \langle A_1 B_1 C_1 \rangle \leq 4$
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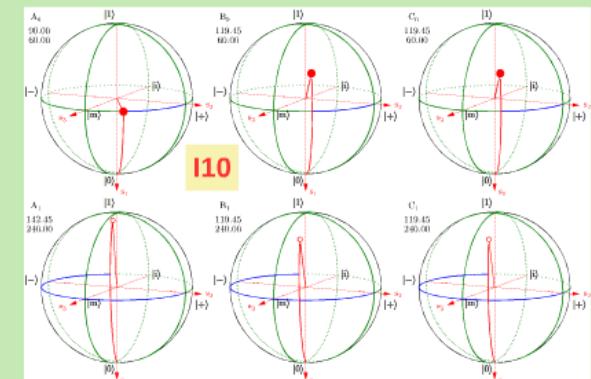
We normalized all inequalities.

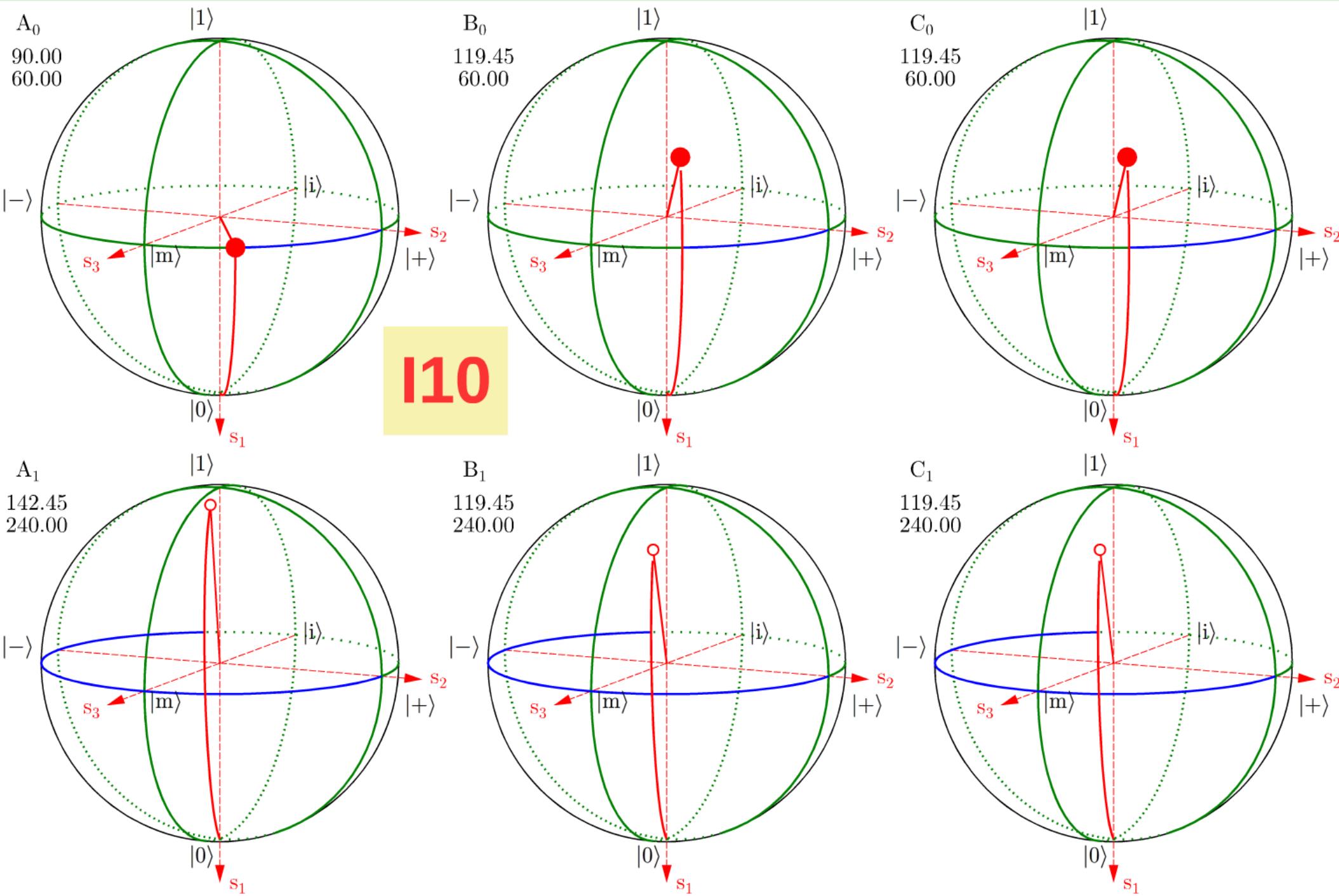
Ineq $\in \langle -1, 1 \rangle$ means no correlations

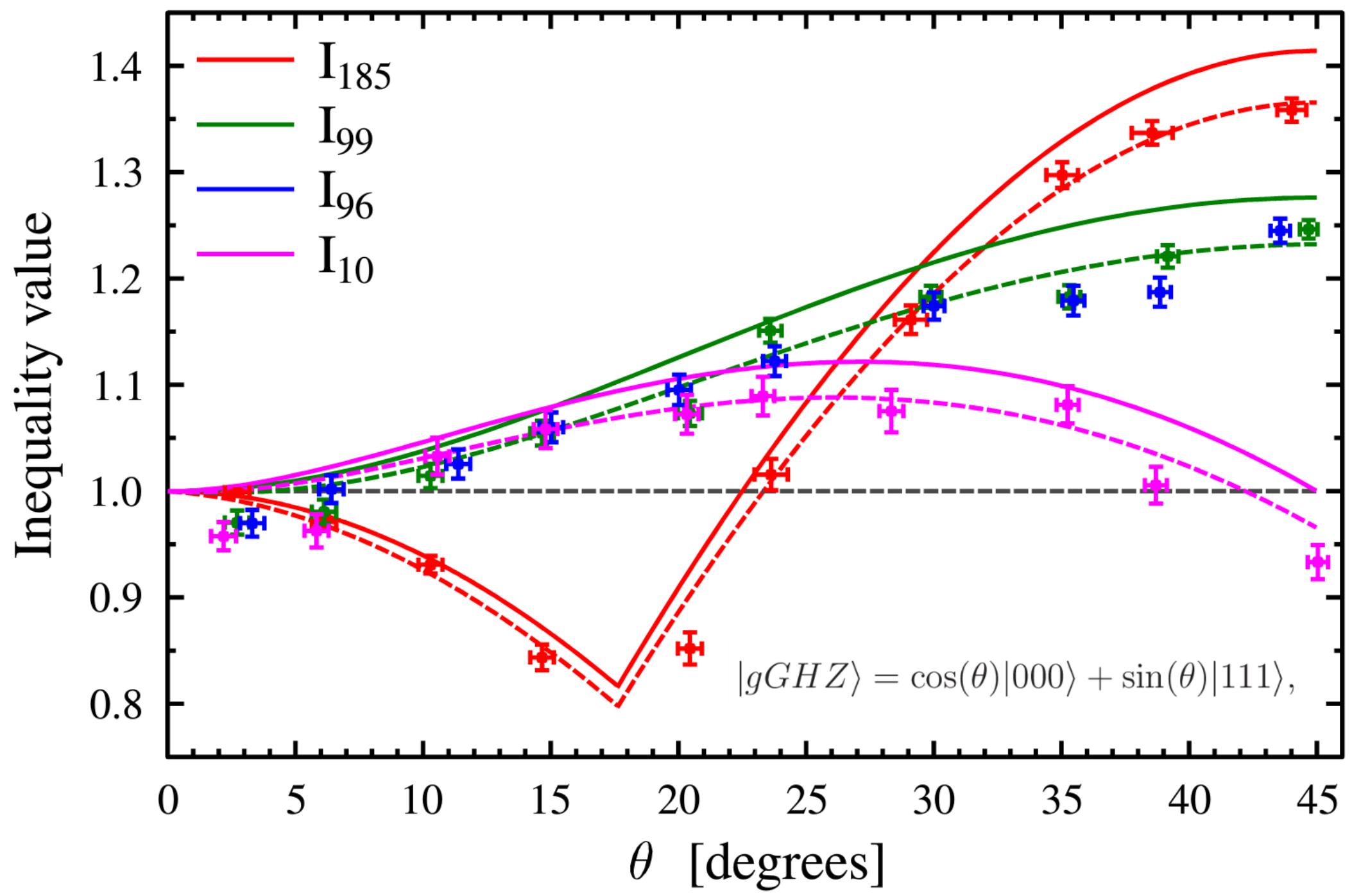
$|Ineq| > 1$ nonlocal correlations

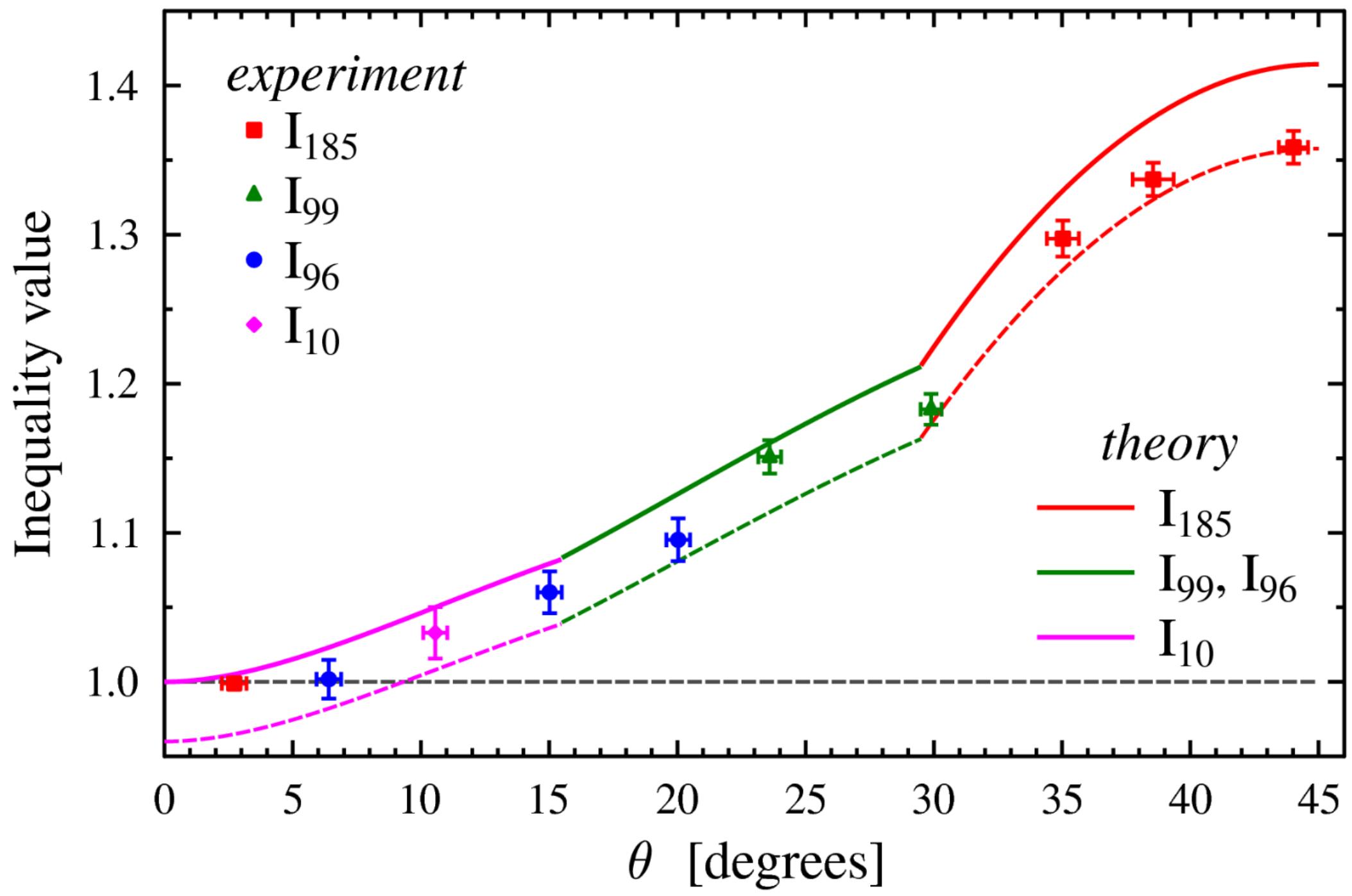
Maximal violation for optimal 3-qubit projections.

Optimal projections resulted from numerical simulation.









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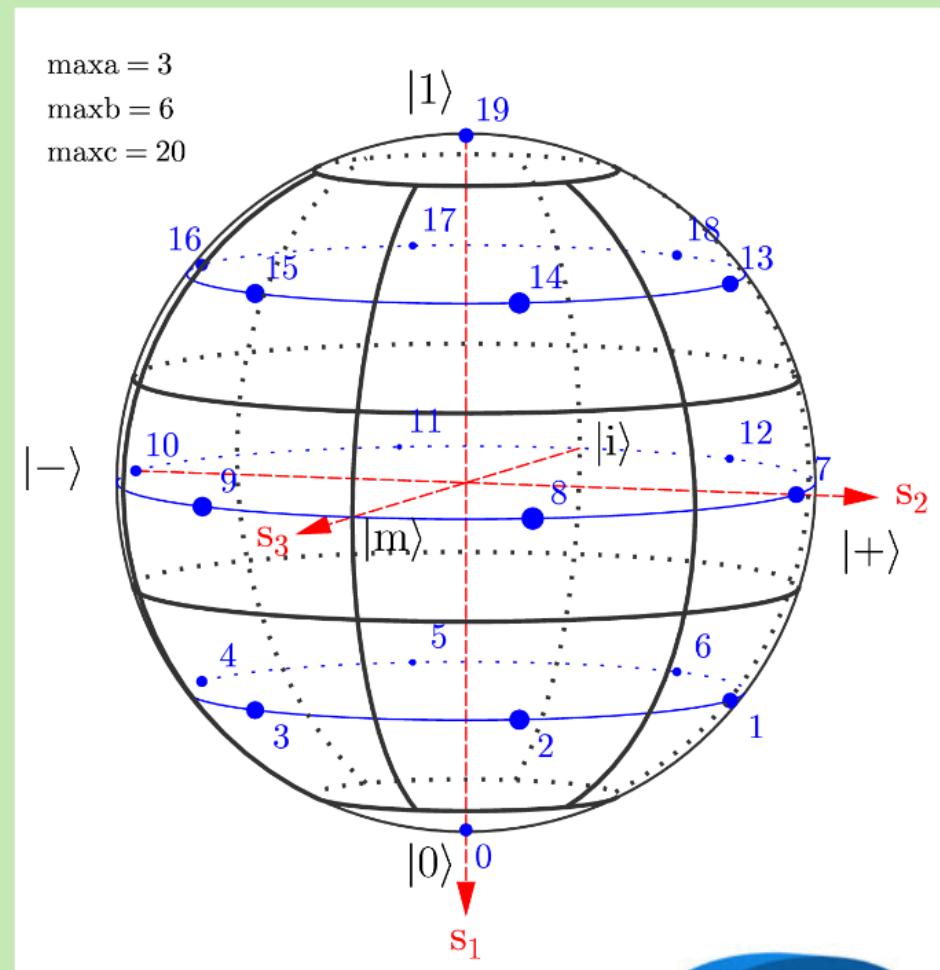
4. Space mapping for the nonlocal volume

We project three qubits ABC according to equally spaced map.

- one qubit: 20 projections
- three qubits: $20^3 = 8\ 000$ measurements
 $1\text{s} + 2.5\text{s} \rightarrow 8\ \text{hours}$
 $10\text{s} + 2.5\text{s} \rightarrow 28\ \text{hours}$

$$\left\{ A_0, A_1, B_0, B_1, C_0, C_1 \right\}$$

$$20^6 = 64\ 000\ 000 \text{ combinations}$$



Whole mapping OR random walk?

- [5] I. Arkhipov, et al., Scientific Reports **8**, 16955 (2018).
[6] A. Barasiński, Scientific Reports **8**, 12305 (2018).



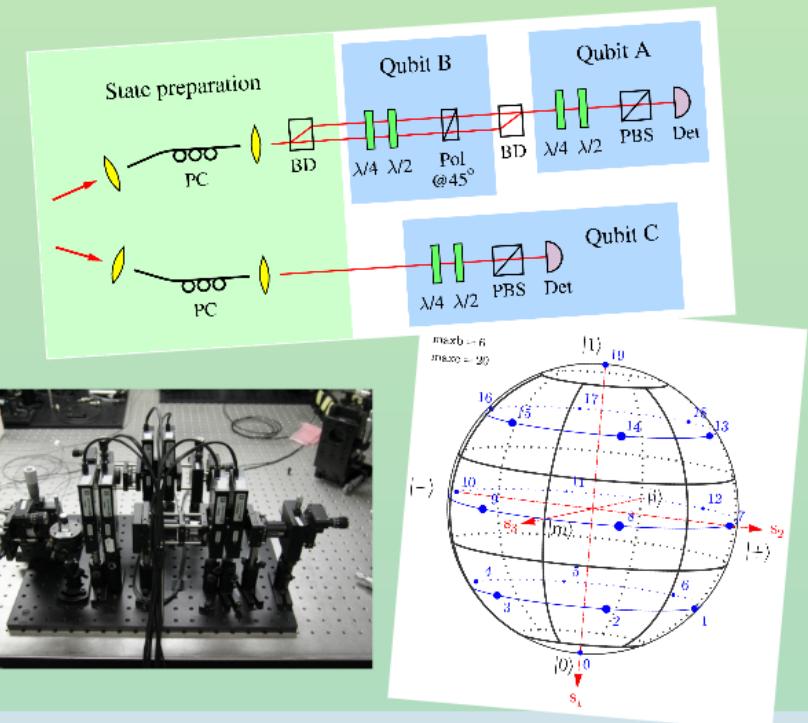
5. Conclusions

We have tested nonlocality of three-qubit gGHZ states.

1. We built experimental setup allowing fast measurement.

2. We tested nonlocality using four Bell-type Inequalities for optimal projections.

3. We started nonlocal volume measurements.



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- [4] J.-D. Bancal, J. Barrett, N. Gisin, and S. Pironio, Phys. Rev. A **88**, 014102 (2013).
- [5] I. Arkhipov, A. Barasiński, and J. Svozilík, Scientific Reports **8**, 16955 (2018).
- [6] A. Barasiński, Scientific Reports **8**, 12305 (2018).

Thank you for your attention !



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