Experimental testing of three-qubit nonlocality

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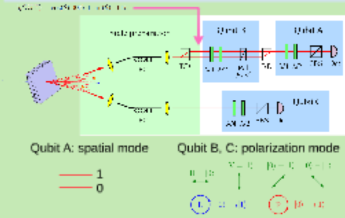
Artur Barasiński (*), Antonín Černoch, Karel Lemr, Jan Soubusta

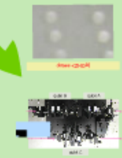
Joint Laboratory of Optics of Palacky University and Institute of Physics CAS, Faculty of Science, PU, 17. listopadu 12, 771 46 Olomouc;

(*) Institute of Physics, University of Zielona Góra, Z. Szafrana 4a, 65-516, Zielona Góra, Poland

Outline

2. Three qubit measurement setup





3. Testing of Bell-type inequalities

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

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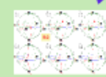
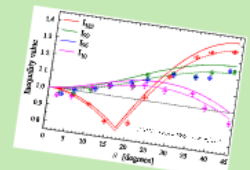
We normalized all inequalities.

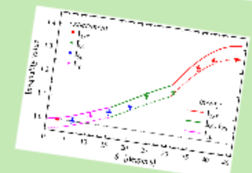
$I_{ineq} \in \langle -1, 1 \rangle$ means no correlations

$I_{ineq} > 1$ nonlocal correlations

Maximal violation for optimal 3-qubit projections.
Optimal projections resulted from numerical simulation.

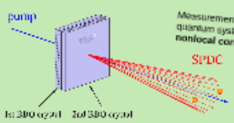






1. Introduction

Bipartite pure states is **entangled** → violates **Bell inequality**
↓
Measurement results on this quantum system manifest **nonlocal correlations**.



Typical source of entangled photons: down-conversion

Typical qubit: * polarization state
* spatial mod

Which states we want to generate ?

Three-qubit states, generalized Greenberger–Horne–Zeilinger

$$|GHZ\rangle = \cos\theta|000\rangle + \sin\theta|111\rangle \qquad \theta \in \langle 0, \pi/4 \rangle$$

Nonlocal volume is monotonic with increasing angle theta.

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

[2] D. M. Greenberger, *et al.*, American Journal of Physics **58**, 1131 (1990).

4. Space mapping for the nonlocal volume

We project three qubits ABC according to equally spaced map.

- one qubit: 20 projections
- three qubits: 20*20*20
  = 8 000 measurements
  1s+2.5s → 8 hours
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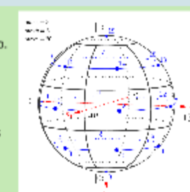
$$\{A_0, A_1, B_0, B_1, C_0, C_1\}$$

$20^6 = 64\,000\,000$ combinations



Whole mapping OR random walk?

[5] I. Arkhipov, *et al.*, Scientific Reports **8**, 16955 (2018).
[6] A. Barasiński, Scientific Reports **8**, 12306 (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.

References:

[1] V. Lipinska, F. J. Curchod, A. Máttar, and A. Acín, New Journal of Physics 20, [illegible] (2018).
[2] D. M. Greenberger, M. A. Horne, A. Shimony, and A. Zeilinger, American Journal of Physics 58, 1131 (1990).
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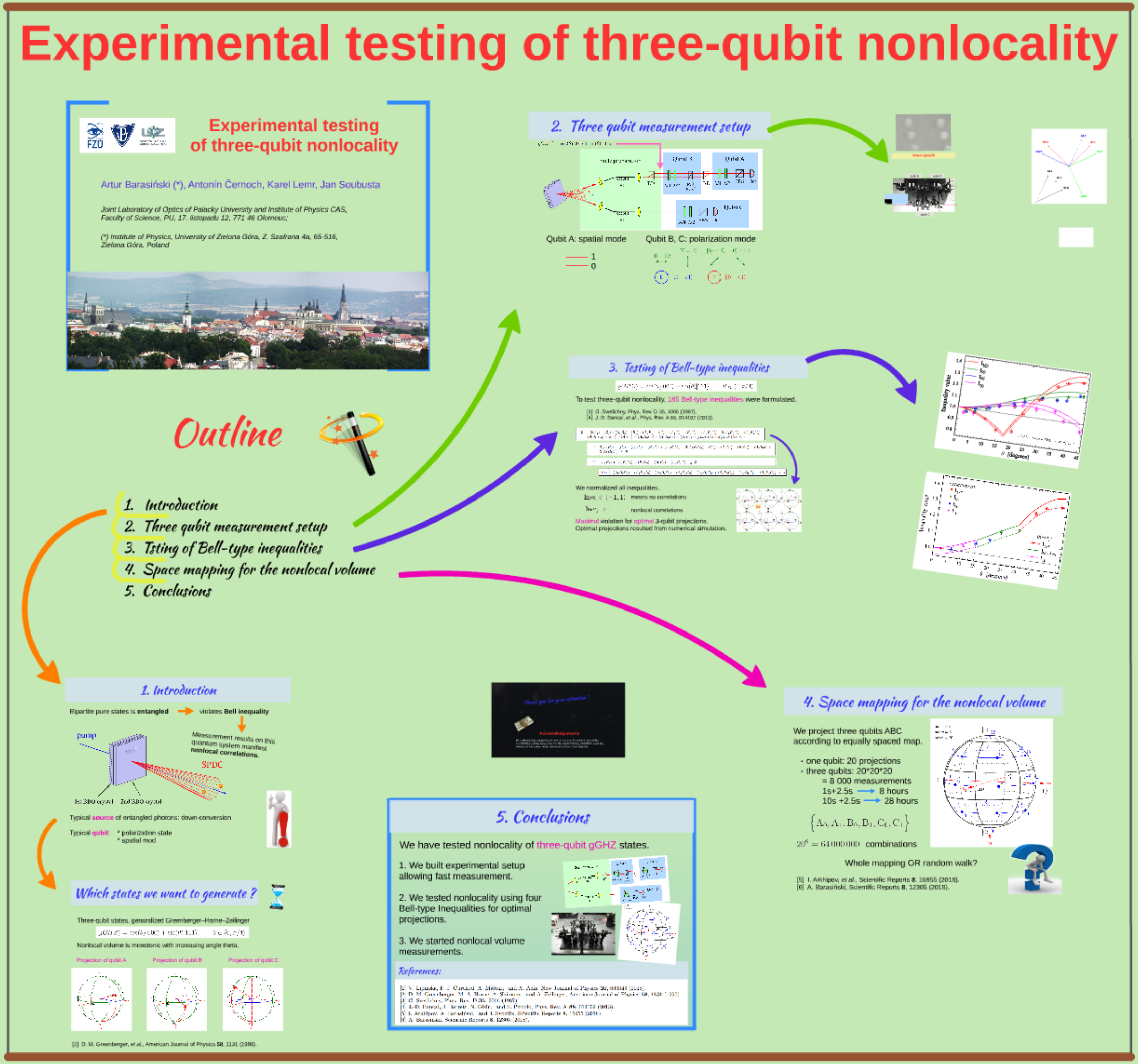
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Outline
1. Introduction
2. Three qubit measurement setup
3. Tsting of Bell-type inequalities
4. Space mapping for the nonlocal volume
5. Conclusions
2. Three qubit measurement setup
Qubit A: spatial mode
Qubit B, C: polarization mode
3. Testing of Bell-type inequalities
To test three-qubit nonlocality, 185 Bell-type inequalities were formulated.
We normalized all inequalities.
Maximal violation for optimal 3-qubit projections.
Optimal projections resulted from numerical simulation.
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Bipartite pure states is entangled violates Bell inequality
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pump
SPDC
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Projection of qubit B
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We have tested nonlocality of three-qubit gGHZ states.
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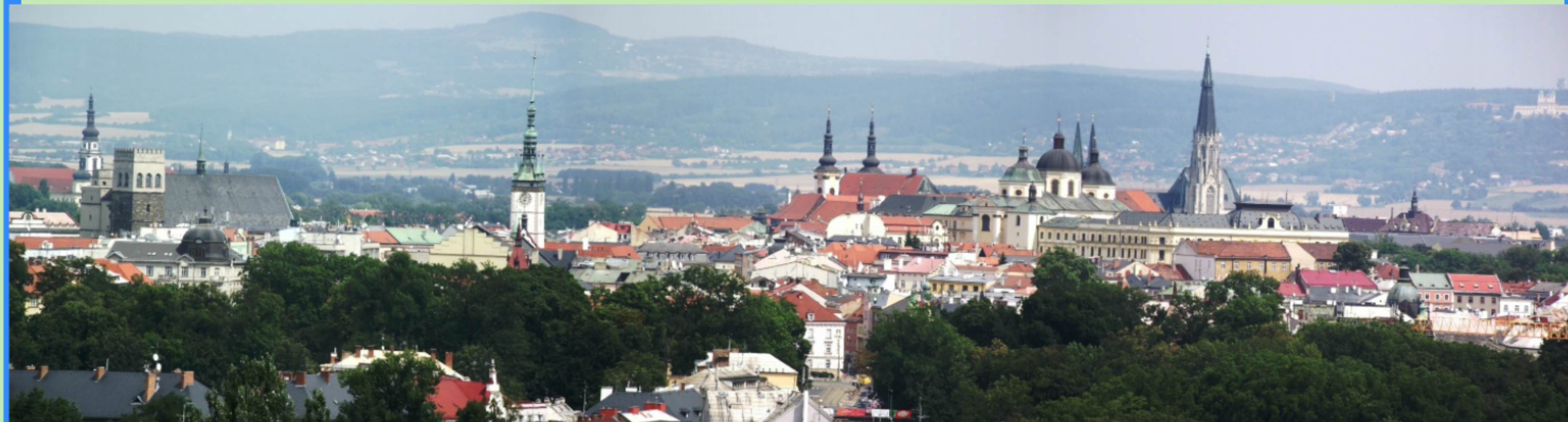

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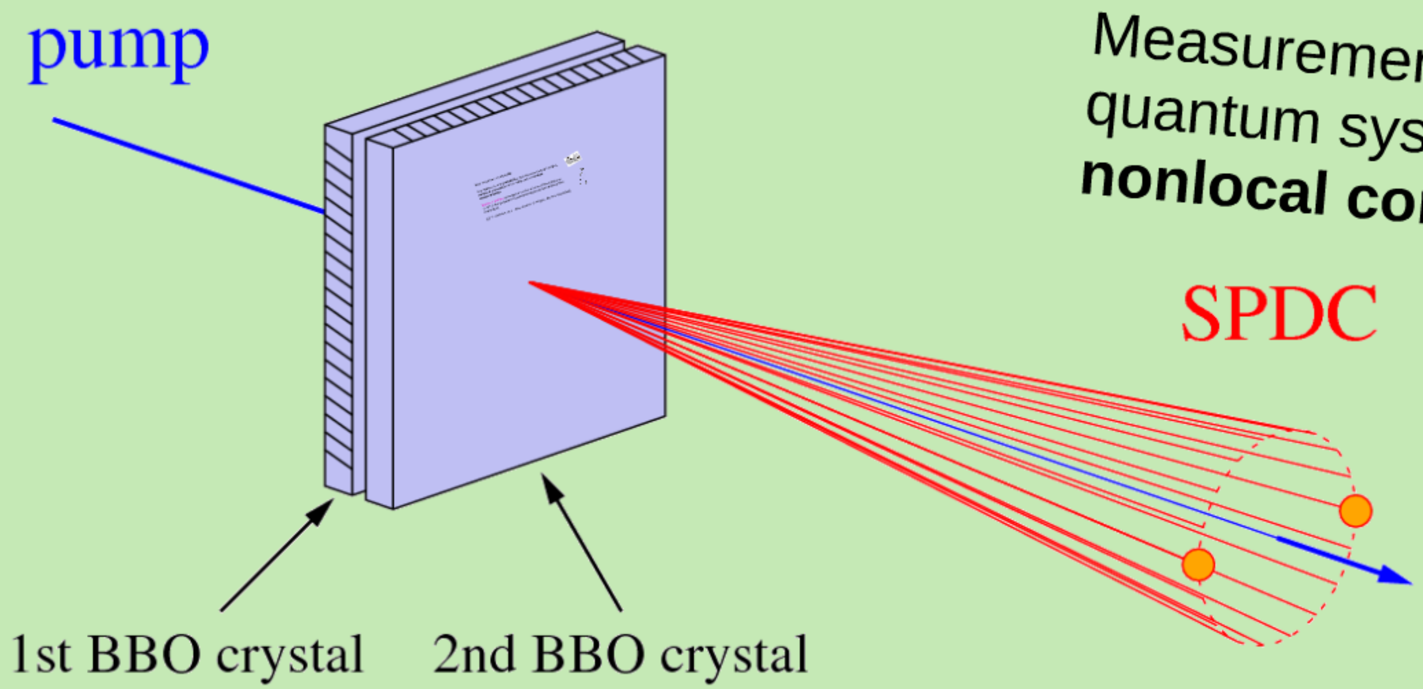

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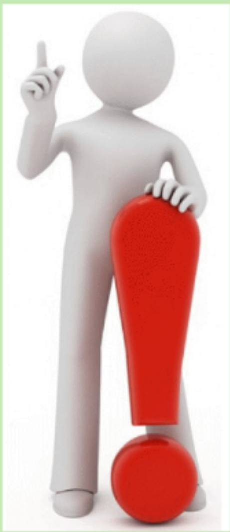
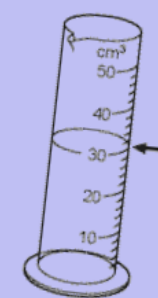


New measure of nonlocality:

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 imput state.



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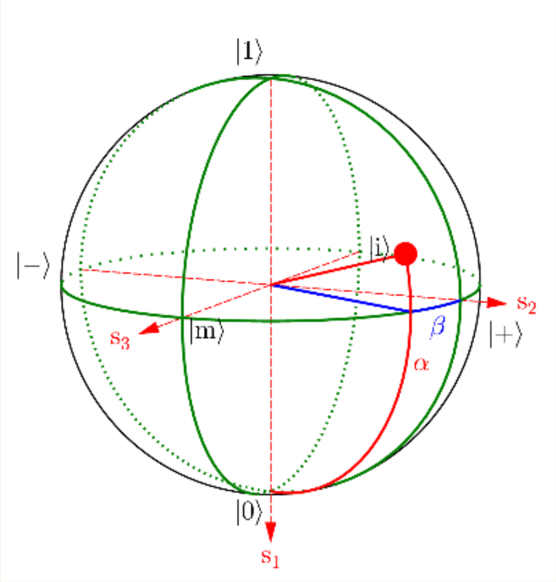
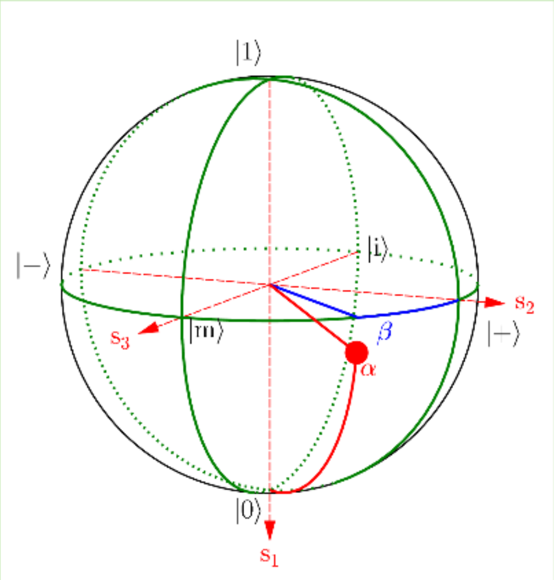
$$|gGHZ\rangle = \cos(\theta)|000\rangle + \sin(\theta)|111\rangle, \qquad \theta \in \langle 0, \pi/4\rangle.$$

Nonlocal volume is monotonic with increasing angle theta.

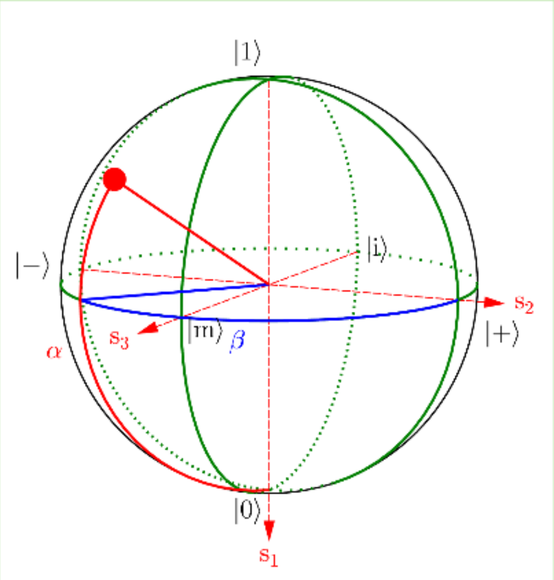
Projection of qubit A



Projection of qubit B



Projection of qubit C



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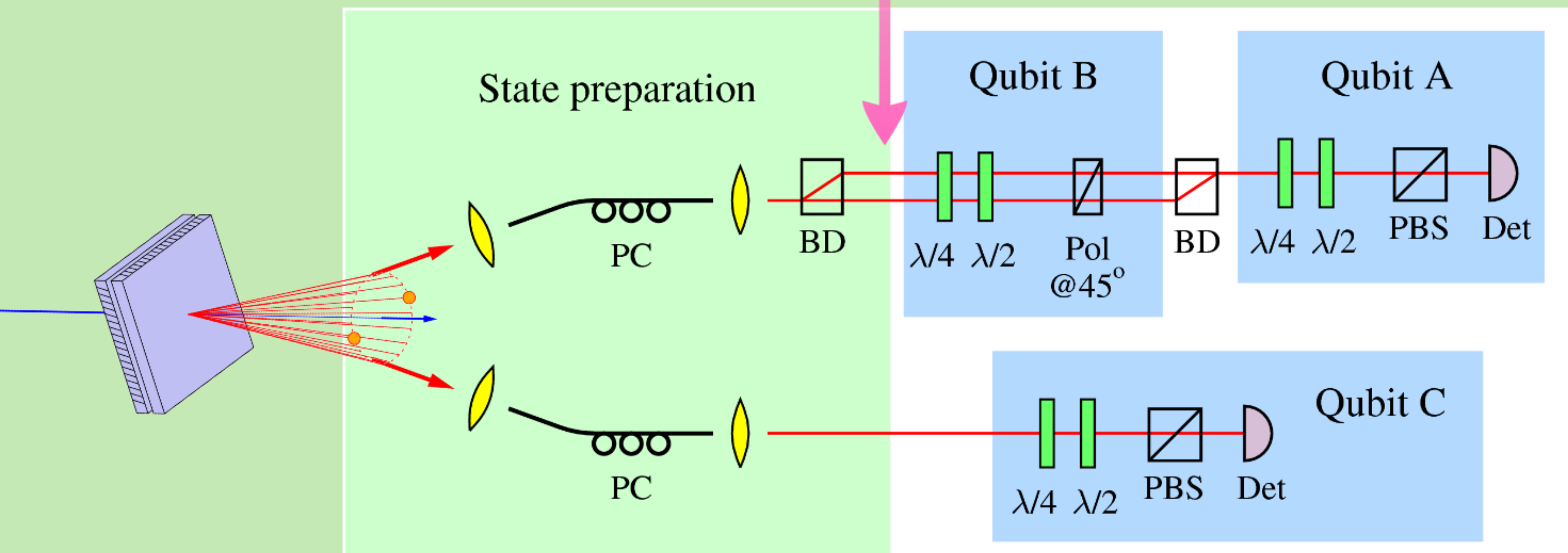

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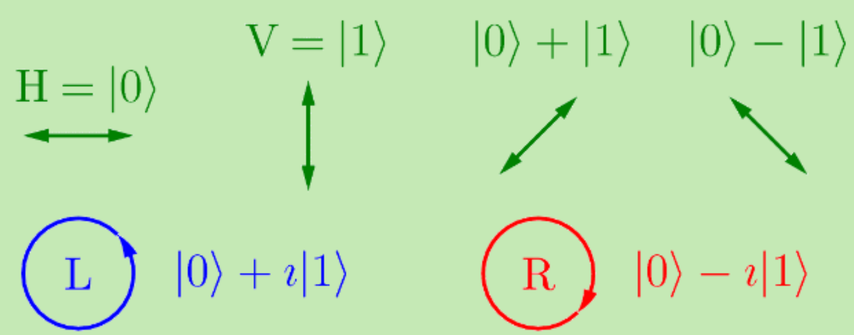
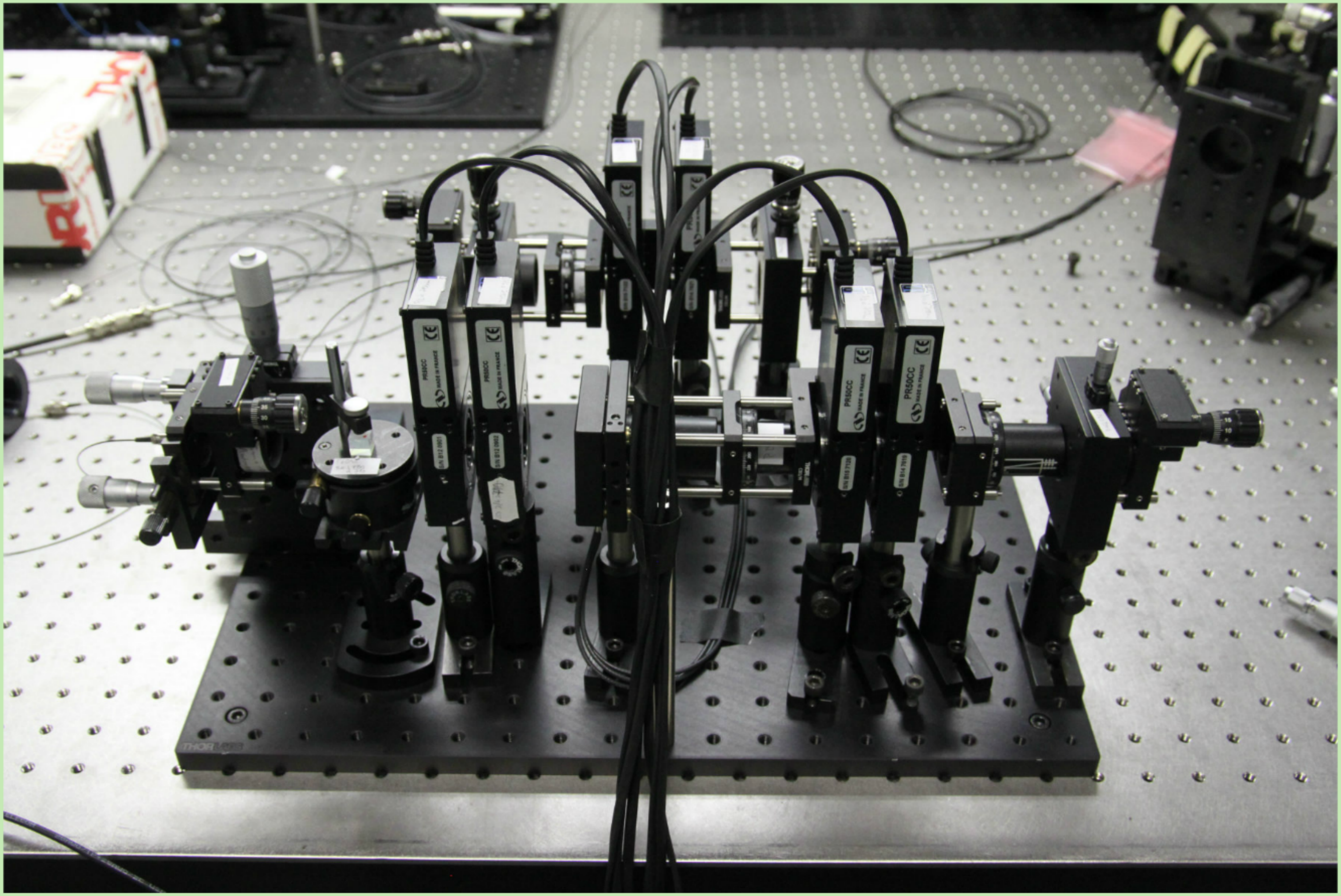
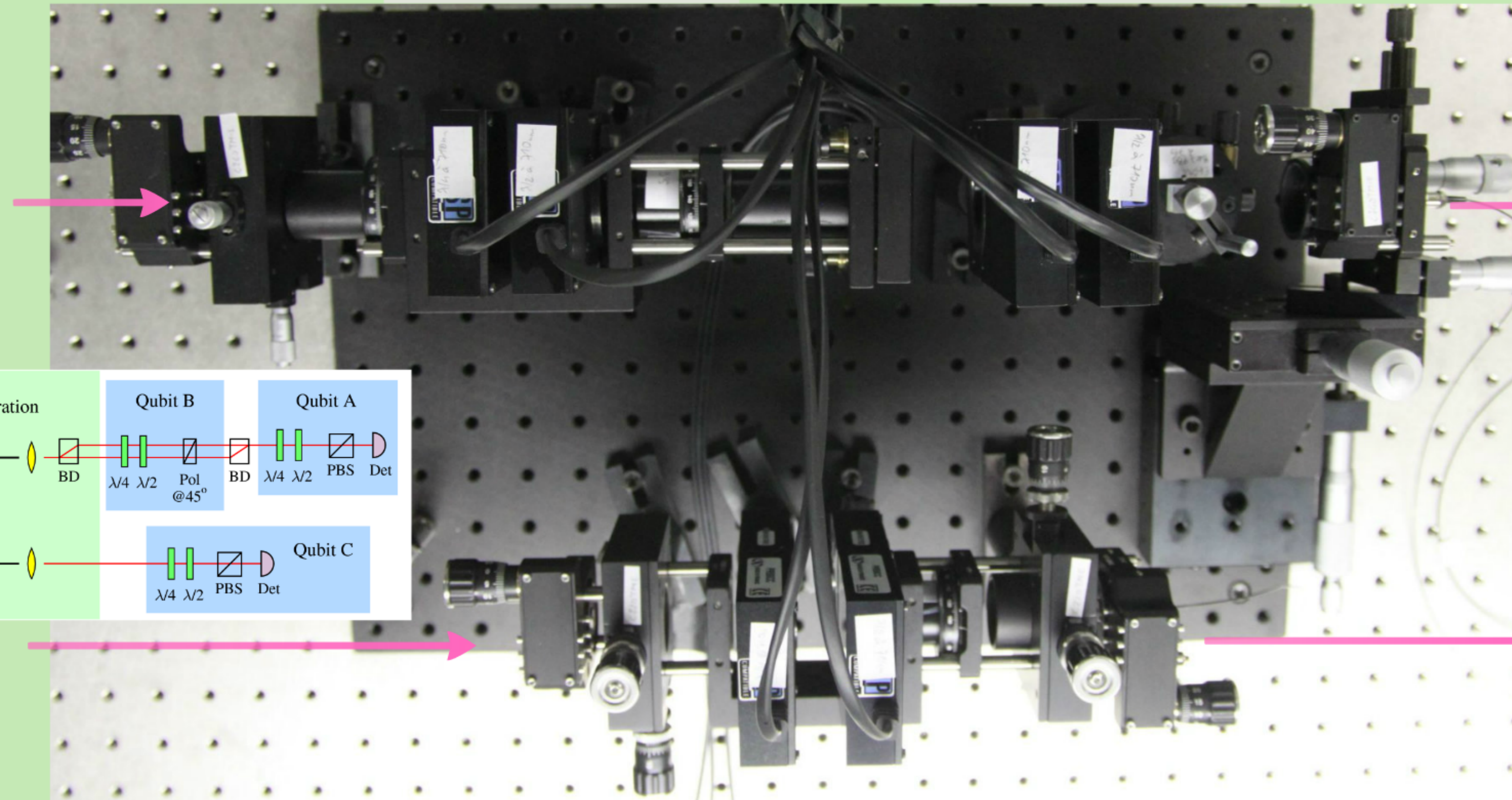


|gGHZ> setup



qubit B qubit A



qubit C

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10	$-2\langle A_1\rangle - \langle B_0\rangle + \langle A_1B_0\rangle - \langle B_1\rangle + \langle A_1B_1\rangle - \langle C_0\rangle + \langle A_1C_0\rangle + \langle B_0C_0\rangle - \langle A_0B_0C_0\rangle + 2\langle A_1B_0C_0\rangle + \langle A_0B_1C_0\rangle + \langle A_1B_1C_0\rangle - \langle C_1\rangle + \langle A_1C_1\rangle + \langle A_0B_0C_1\rangle + \langle A_1B_0C_1\rangle + \langle B_1C_1\rangle - \langle A_0B_1C_1\rangle + 2\langle A_1B_1C_1\rangle \leq 6$
96	$2\langle A_0B_0\rangle - \langle C_0\rangle - \langle A_0C_0\rangle - \langle B_0C_0\rangle + \langle A_0B_0C_0\rangle - 2\langle A_1B_1C_0\rangle - \langle C_1\rangle + \langle A_0C_1\rangle + \langle B_0C_1\rangle + \langle A_0B_0C_1\rangle - 2\langle A_1B_1C_1\rangle \leq 6$
99	$\langle A_1B_1\rangle + \langle A_0B_0C_0\rangle + \langle B_1C_0\rangle + \langle A_1C_1\rangle - \langle A_0B_0C_1\rangle \leq 3$
185	$-\langle A_0B_0C_0\rangle - \langle A_1B_0C_0\rangle + \langle A_0B_1C_0\rangle - \langle A_1B_1C_0\rangle - \langle A_0B_0C_1\rangle + \langle A_1B_0C_1\rangle - \langle A_0B_1C_1\rangle - \langle A_1B_1C_1\rangle \leq 4$

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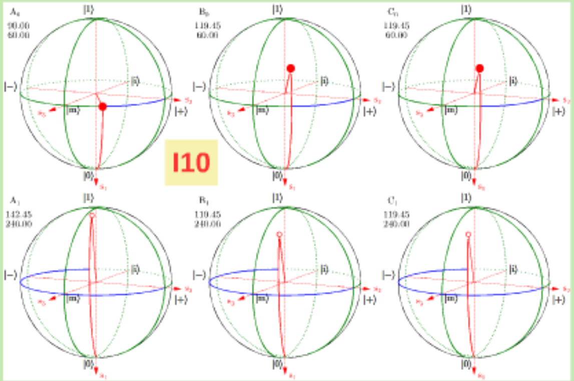
$\mathrm{Ineq} \in \langle -1, 1\rangle$ means no correlations

$|\mathrm{Ineq}| > 1$ nonlocal correlations



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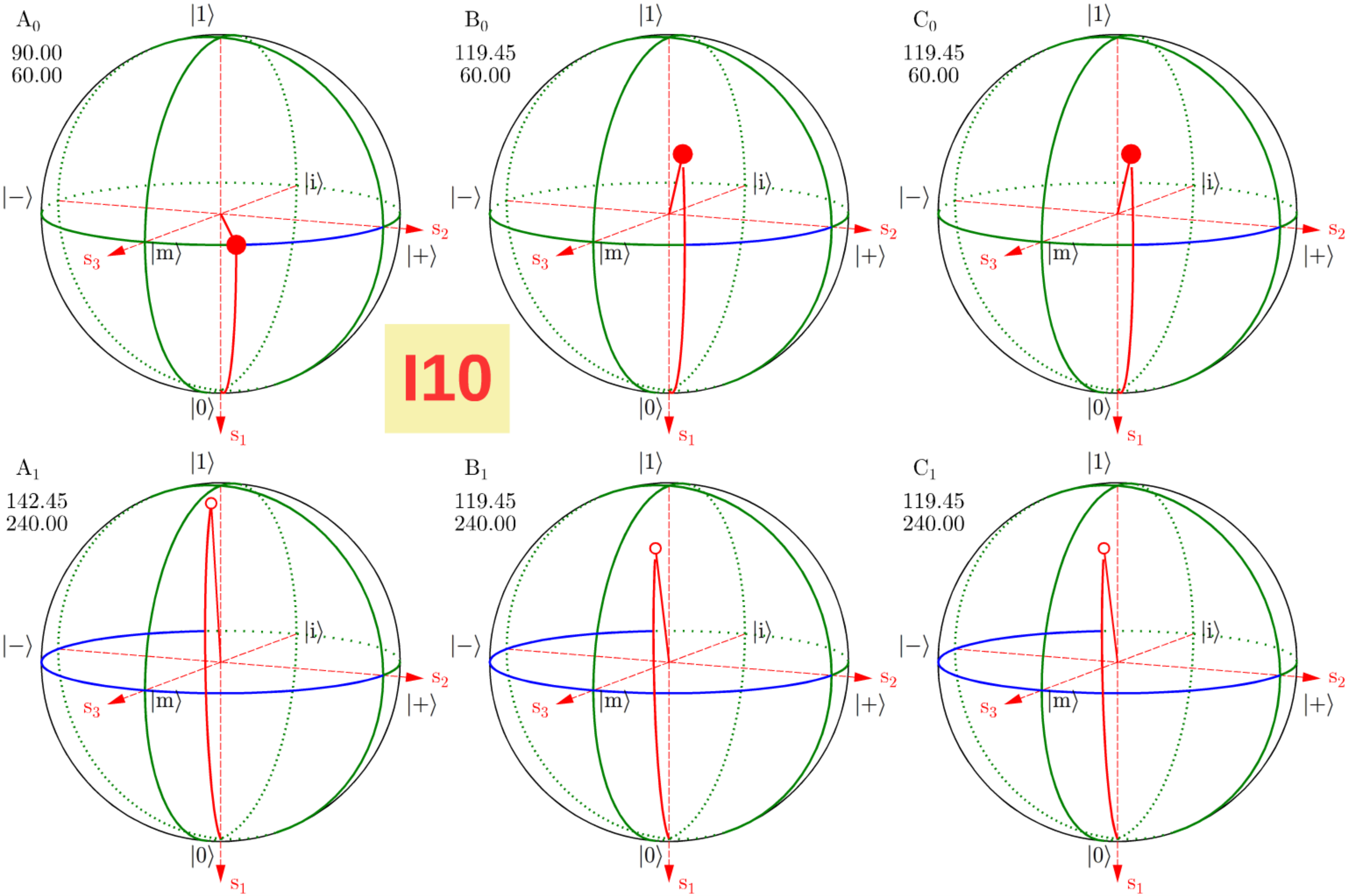
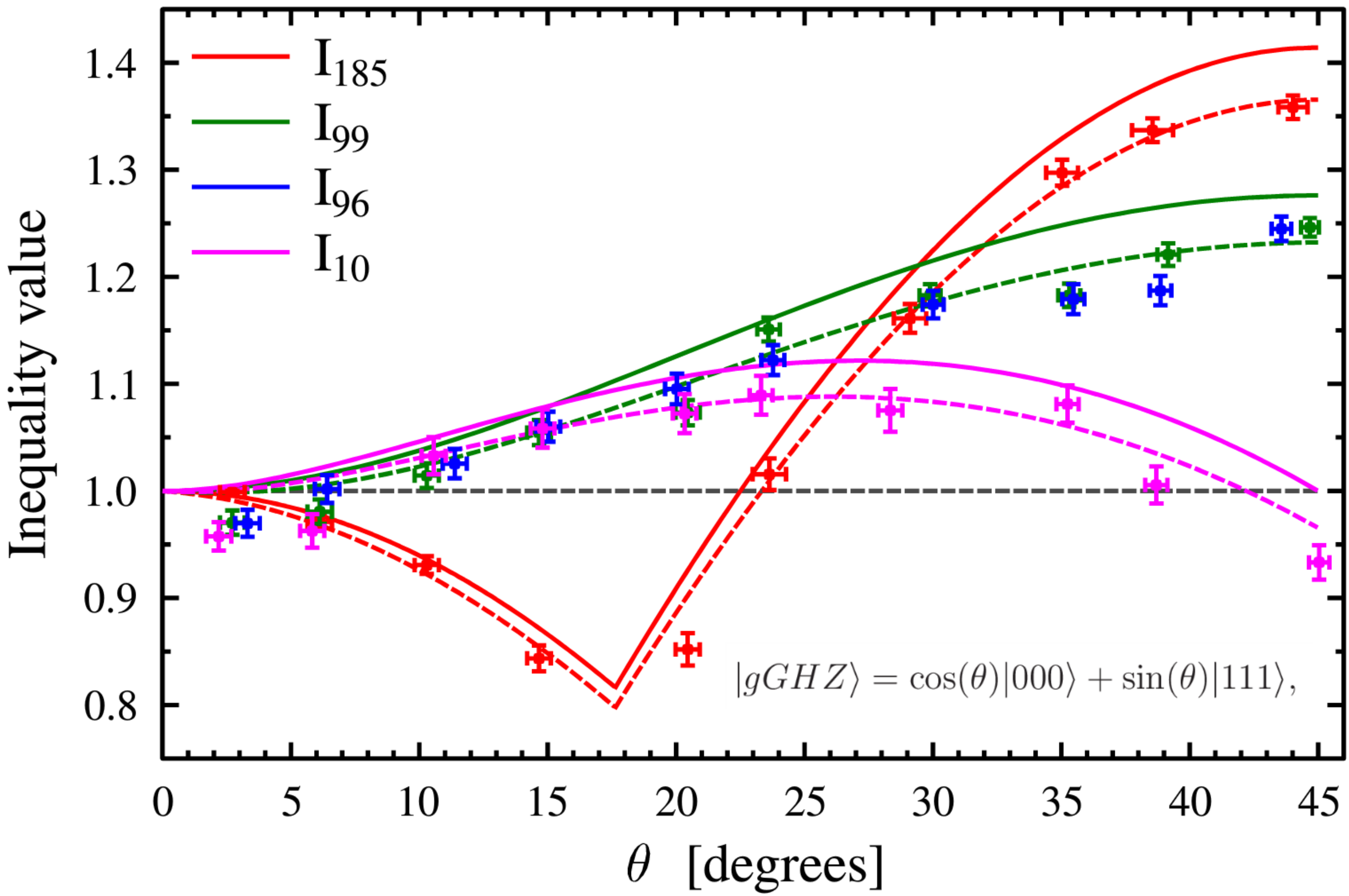
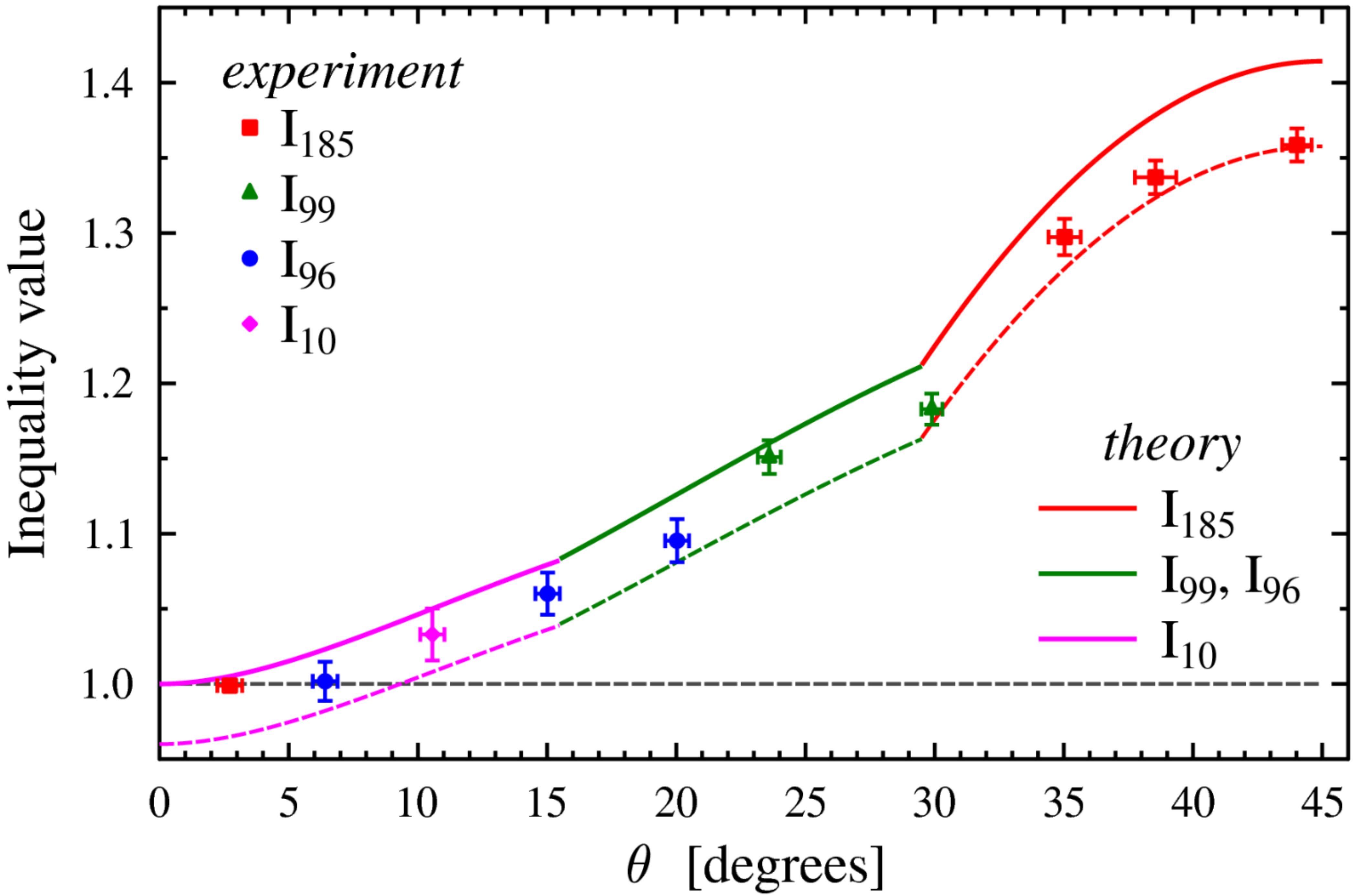

A_0
90.00
60.00
B_0
119.45
60.00
C_0
119.45
60.00
I10
A_1
142.45
240.00
B_1
119.45
240.00
C_1
119.45
240.00
$|1\rangle$
$|0\rangle$
$|-\rangle$
$|+\rangle$
$|i\rangle$
$|m\rangle$
s_1
s_2
s_3



I185
I99
I96
I10
Inequality value
θ [degrees]
|gGHZ⟩ = cos(θ)|000⟩ + sin(θ)|111⟩,
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0
5
10
15
20
25
30
35
40
45



experiment
I185
I99
I96
I10
theory
I185
I99, I96
I10
1.4
1.3
1.2
1.1
1.0
Inequality value
0
5
10
15
20
25
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35
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θ [degrees]

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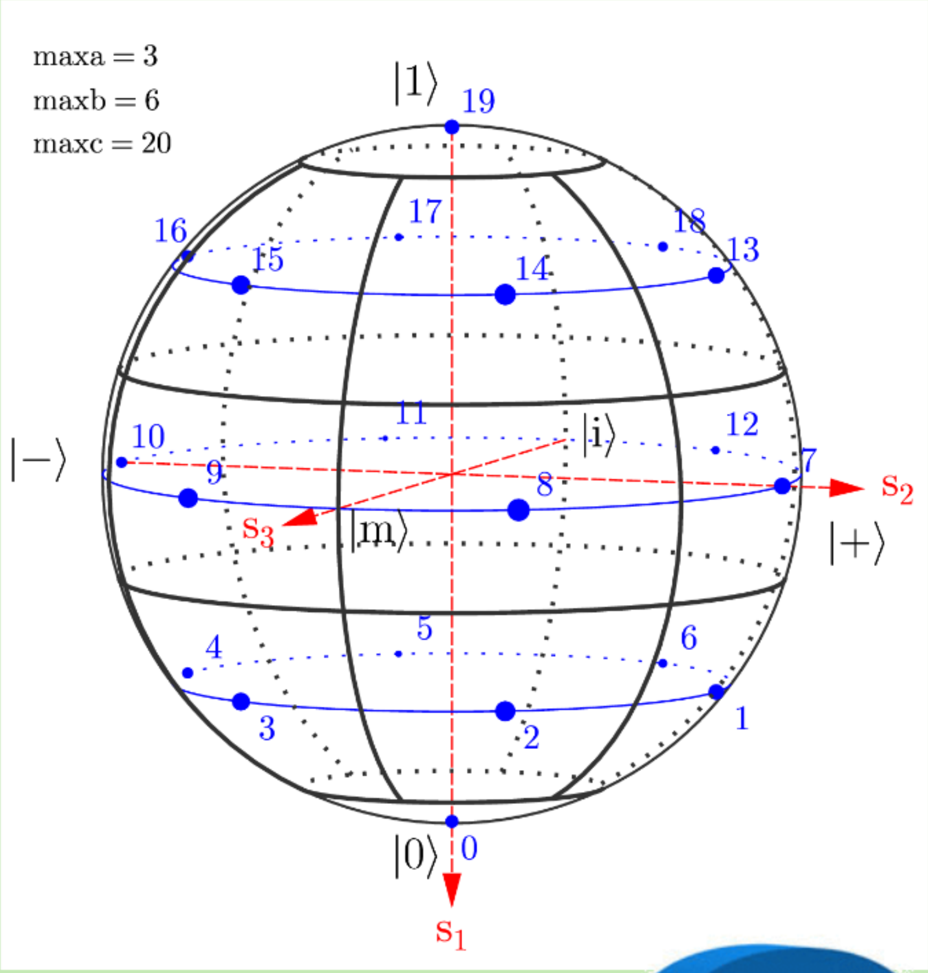

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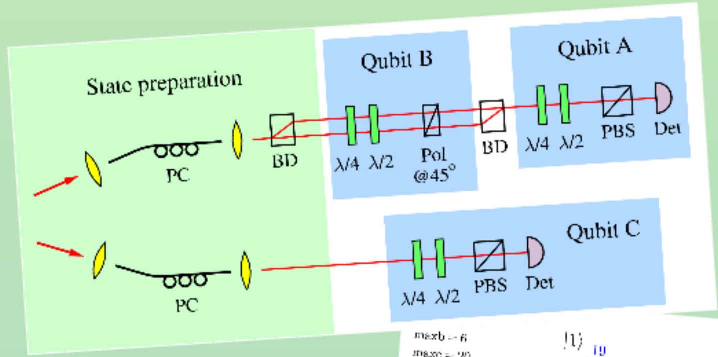

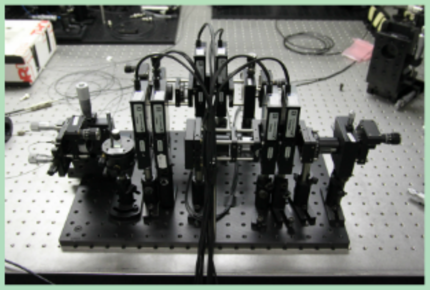

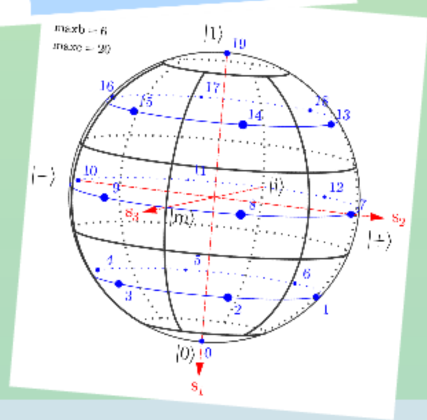

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Thank you for your attention !

Acknowledgements

We acknowledge support by the Czech Science Foundation (Grant No. 17-10003S) and the project No. CZ.02.1.01/0.0/0.0/16_019/0000754 of the Ministry of Education, Youth and Sports of the Czech Republic