Does God play dice?

How to test if quantum theory is correct?

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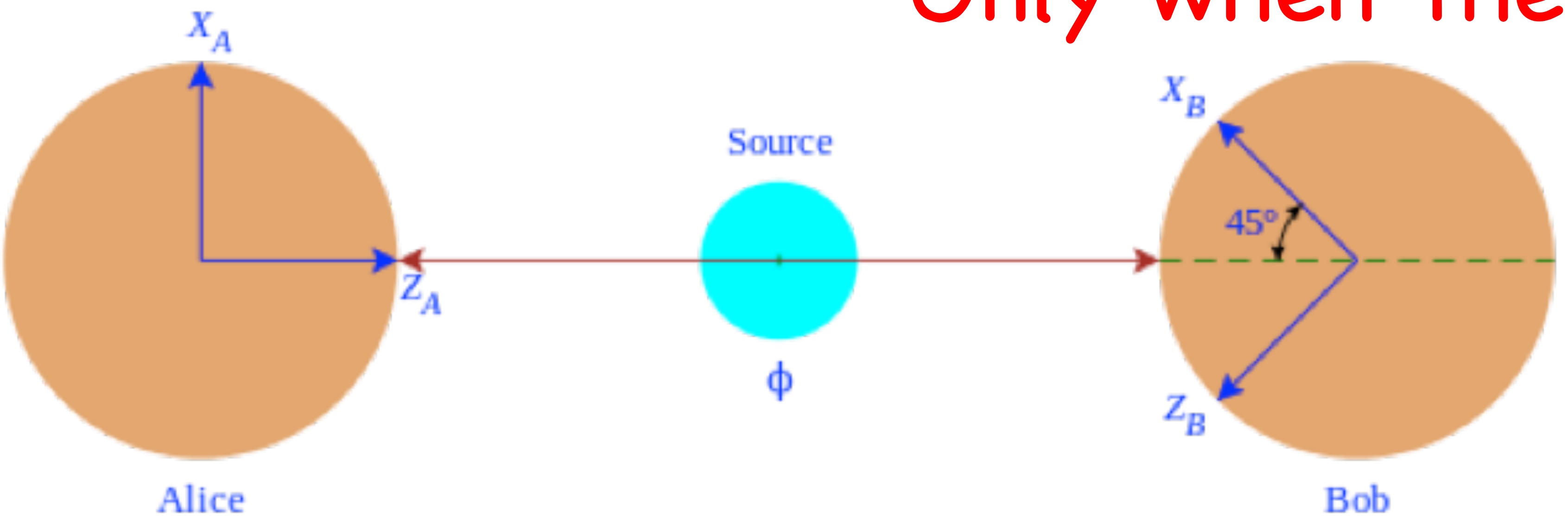
Einstein—Podolsky—Rosen Paradox

- Two anti-correlated electrons
  - Measure both spins along the same axis: yields opposite results (↑↓or ↓↑)
  - Measure only one spin: the other spin becomes known (immediately)

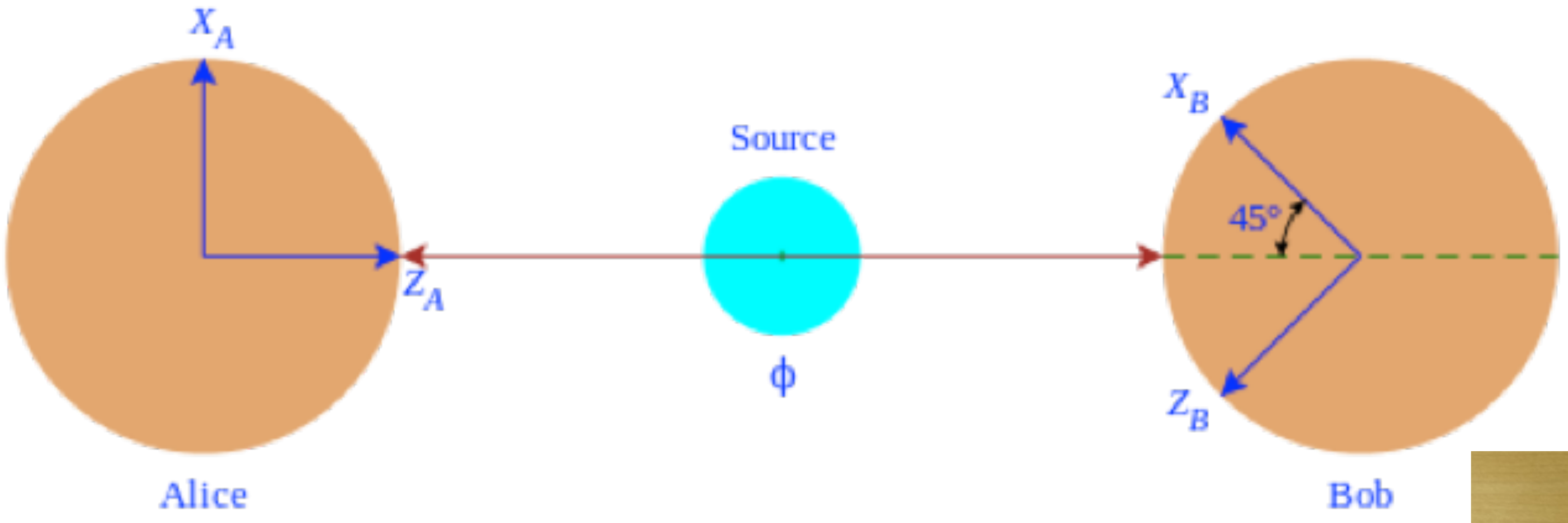
Can quantum mechanics violate the constraint of speed of light?

Only when the Bell's ring!

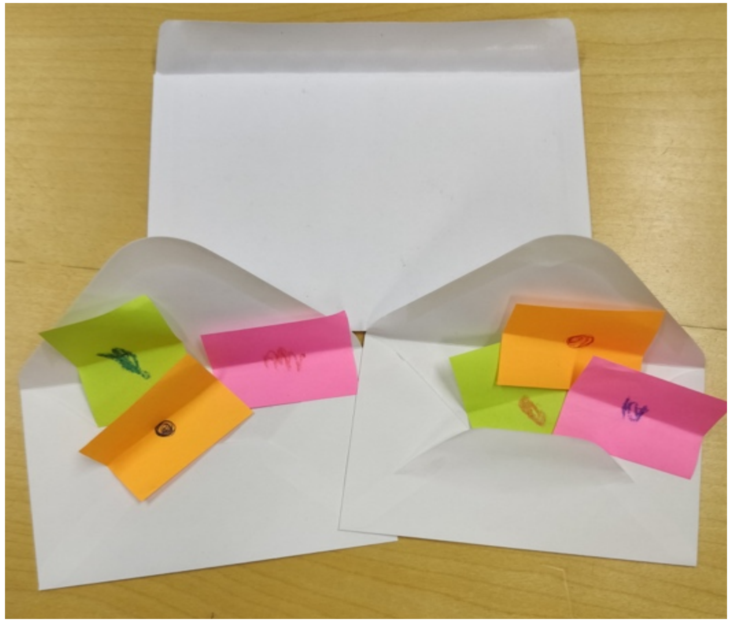


We need to rotate detectors randomly

Envelope experiment



We rotate detectors randomly



- Big envelope: two medium envelopes
- Medium envelope: three small envelopes
  - three detector angles
- Red and blue dots: electron spin (↑ or ↓)

Envelope experiment rules

Correlations

Probability that we see 1r, 2r at the table:

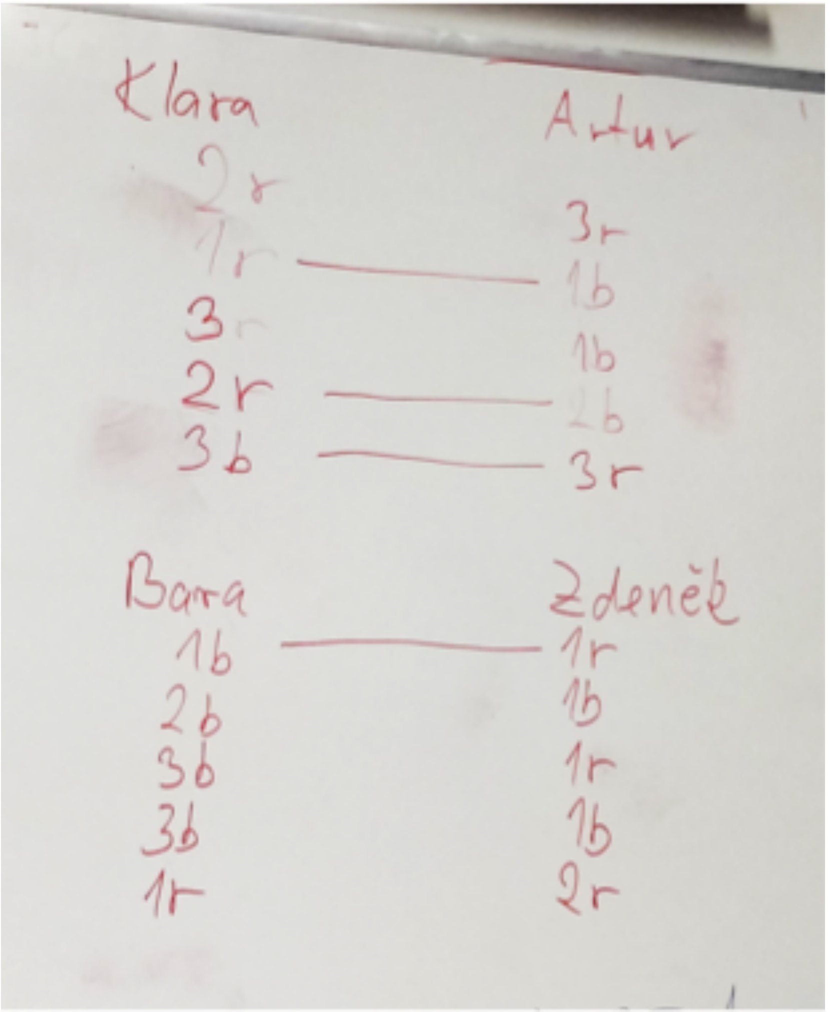
$$p(1r, 2r)$$

Correlations: $p(1r, 1r) = p(2r, 2r) = p(3r, 3r) = 0$

Bell's inequality

$$p(1r, 2r) + p(2r, 3r) - p(1r, 3r) \geq 0$$

Does quantum theory satisfy this?



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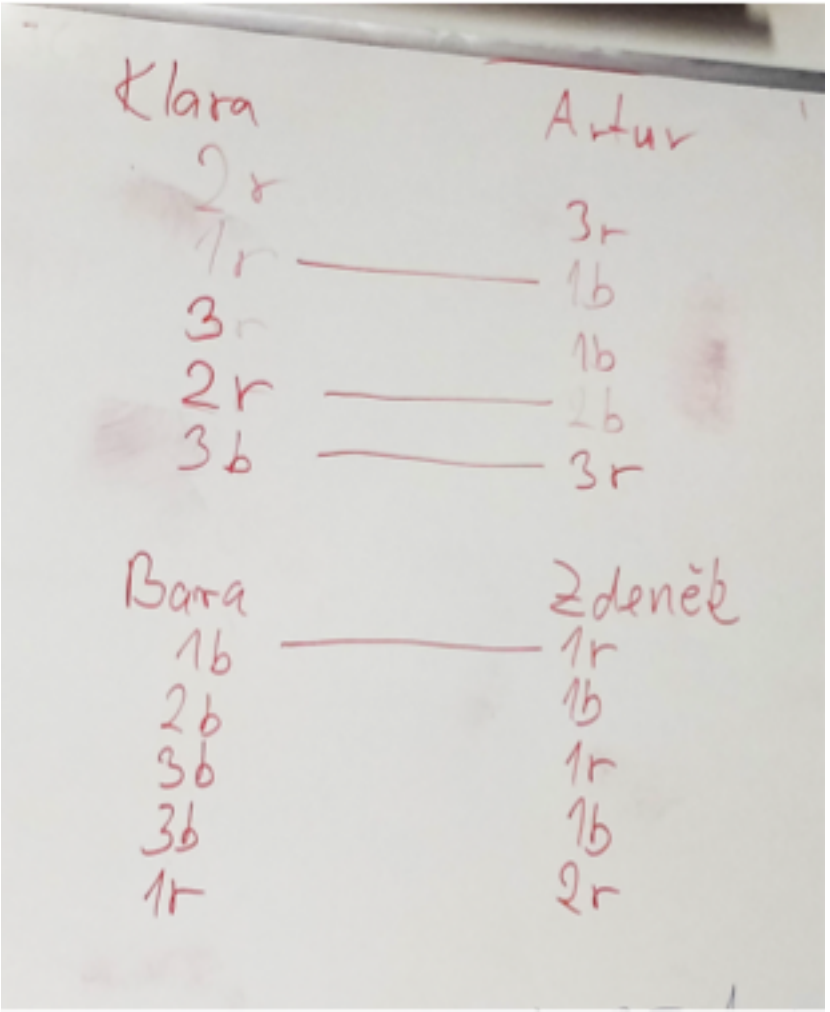
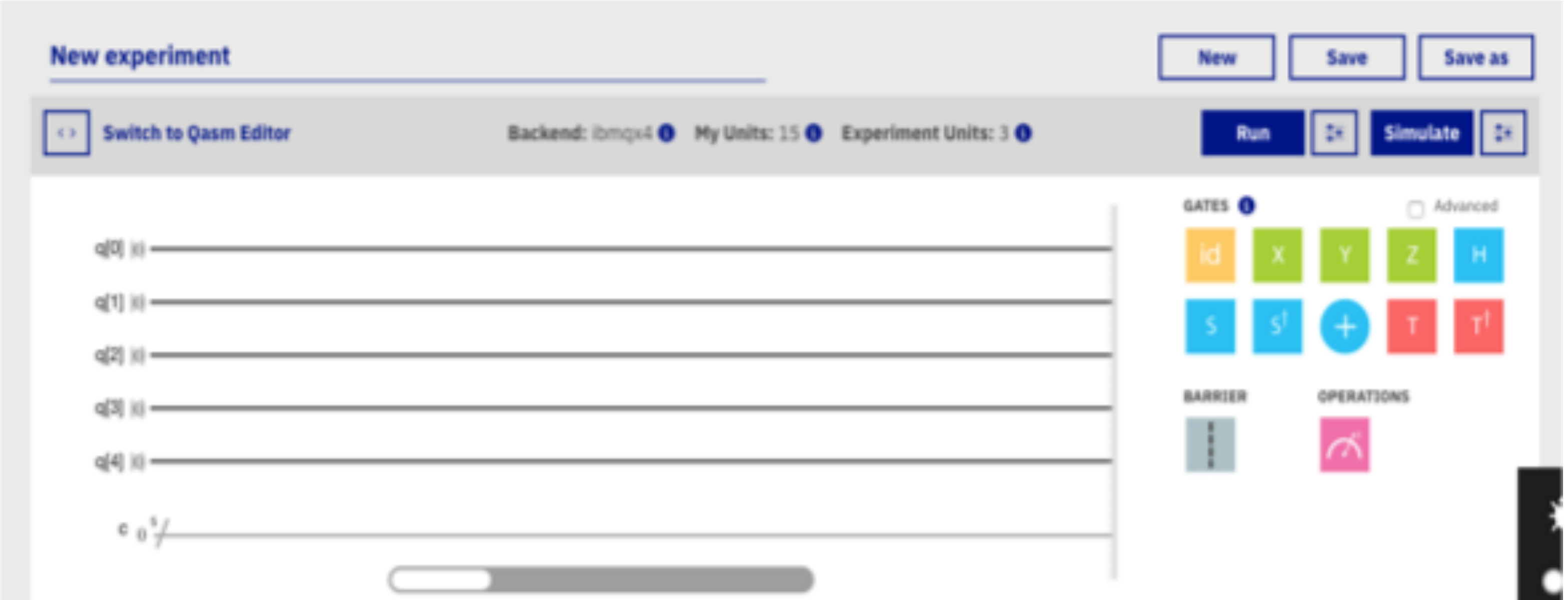
Let's do it on a quantum computer!



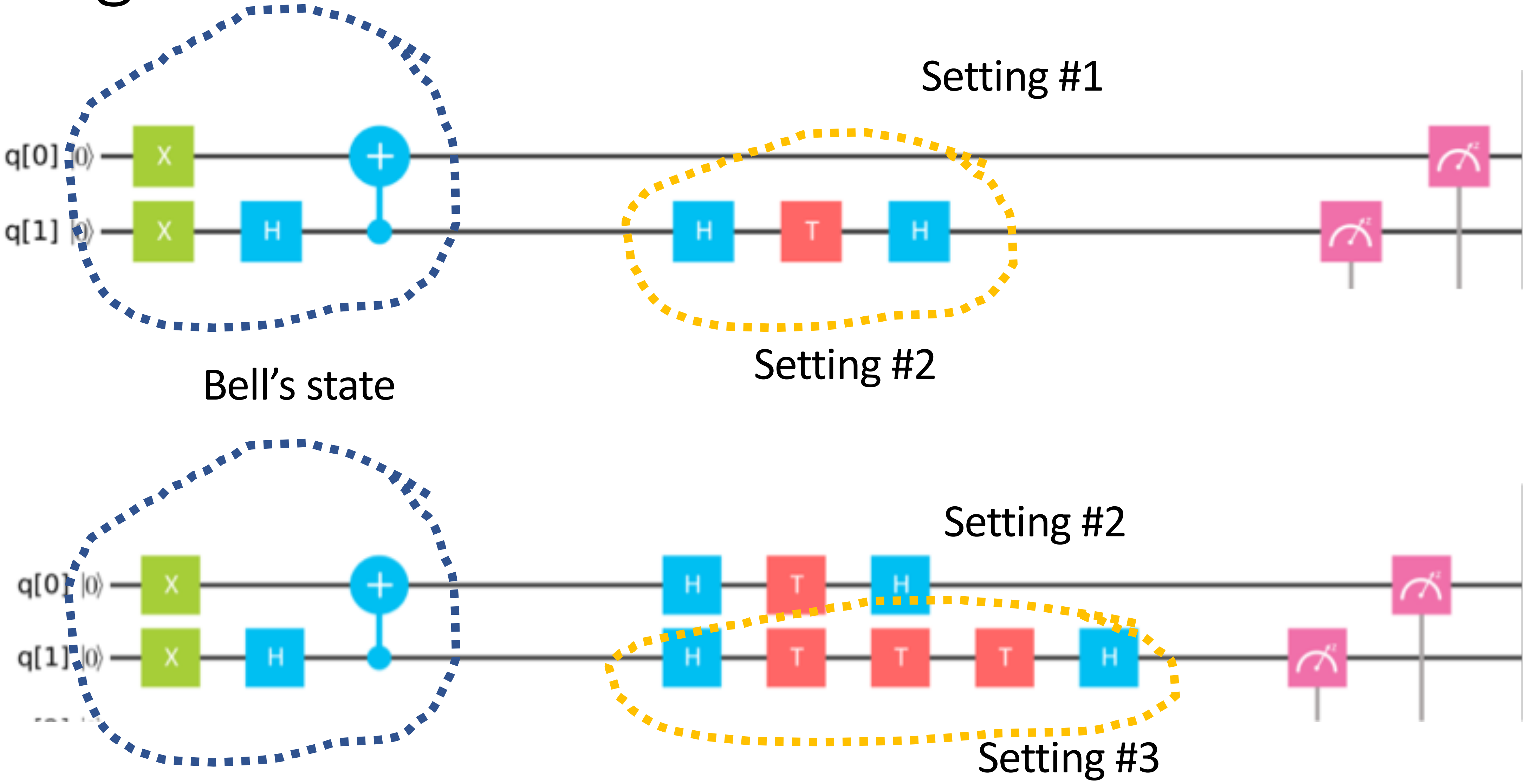
Quantum computer

Simulate electron spin by qubits

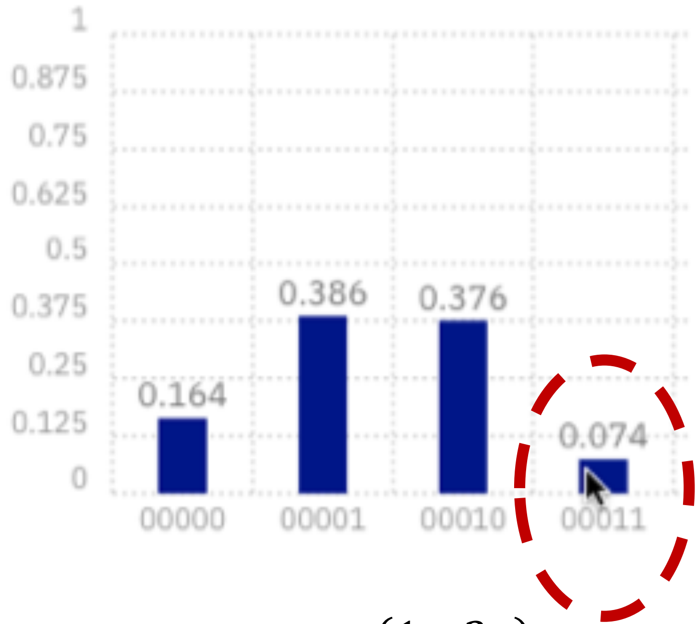
- Web interface to the IBM Q
  - Line=qubit
  - Time runs from left to right
  - Gates are placed on lines
- Experiment
  - Bell state: **perfectly** anti-correlated
  - Rotate **qubit** instead of detector



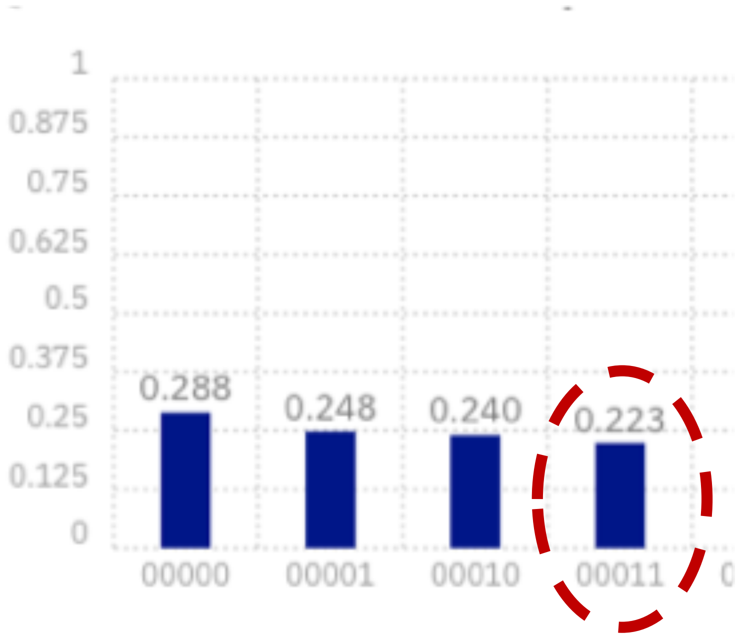
Programs


Setting #1
q[0] |0⟩
q[1] |0⟩
X
X
H
H
T
H
Setting #2
Bell's state
Setting #2
q[0] |0⟩
q[1] |0⟩
X
X
H
H
T
H
H
T
T
T
H
Setting #3

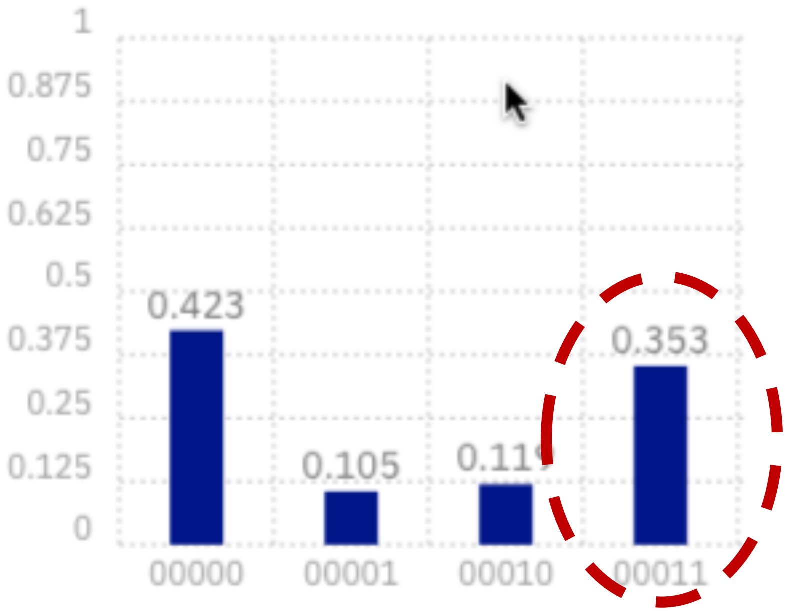
Results



$p(1r, 2r)$



$p(2r, 3r)$

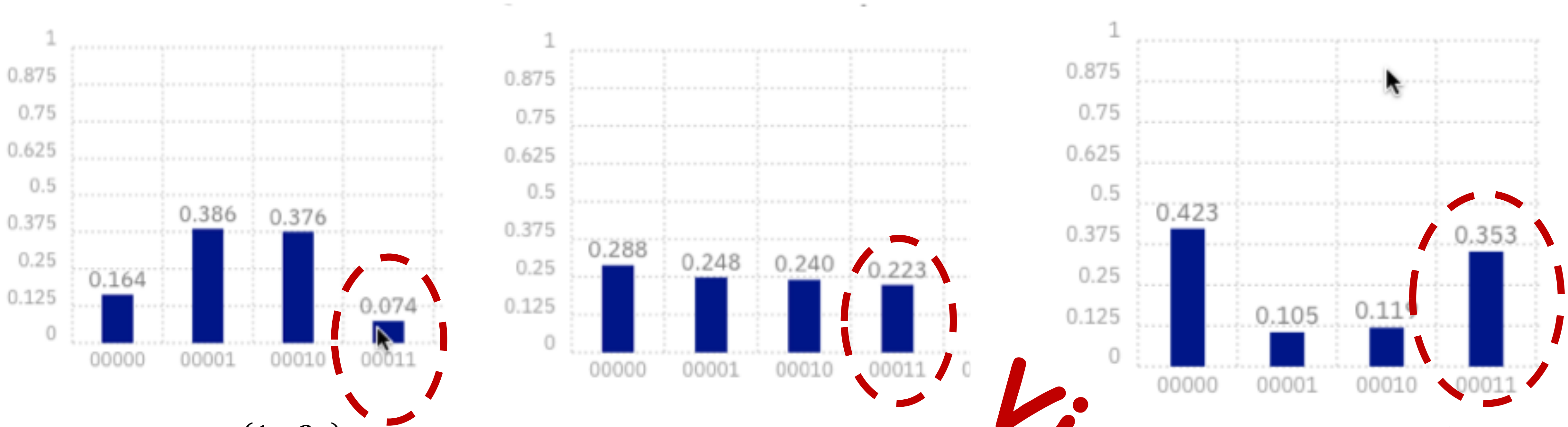


$p(1r, 3r)$

Bell's inequality: $p(1r, 2r) + p(2r, 3r) - p(1r, 3r) \geq 0$

$$0.74 + 0.223 - 0.353 = -0.056 \geq 0$$

Results



$p(1r,2r)$ $p(2r,3r)$ $p(1r,3r)$

Violated!!!

Bell's inequality: $p(1r,2r) + p(2r,3r) - p(1r,3r) \geq 0$

$$0.74 + 0.223 - 0.353 = -0.056 \geq 0$$

Conclusions

- Bell's assumptions
  1. Result is predetermined (we only choose the "small envelopes")
  2. Measurements do not influence each other
- Quantum mechanics violate Bell's inequalities

  $\rightarrow$ Either 1. or 2. is wrong
- In the quantum computer:
  - Assumption 2. is not guaranteed: due to proximity of the qubits