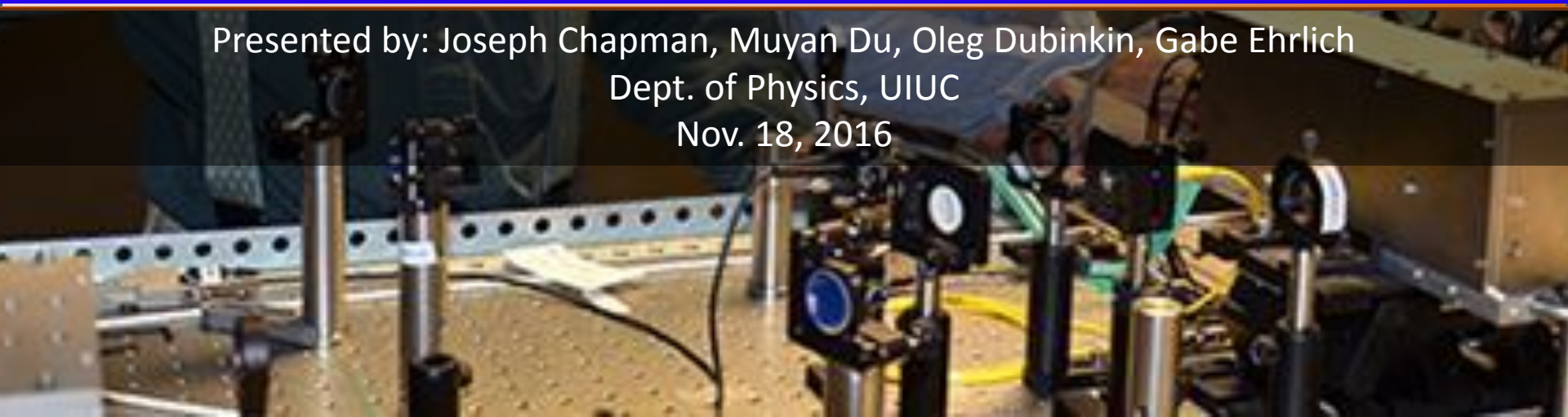




# “Exploring the Limits of Quantum Nonlocality with Entangled Photons”

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# The Paper

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## **Exploring the Limits of Quantum Nonlocality with Entangled Photons**

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# Outline

## **1 Background**

Local realism

Bell inequality

## **2 Experimental setup**

Entanglement state preparation

## **3 Analysis & Results**

CHSH inequality and Tsirelson Bound

Tilted inequality

Chained inequality

## **4 Critique & citations**

## **5 Conclusion**

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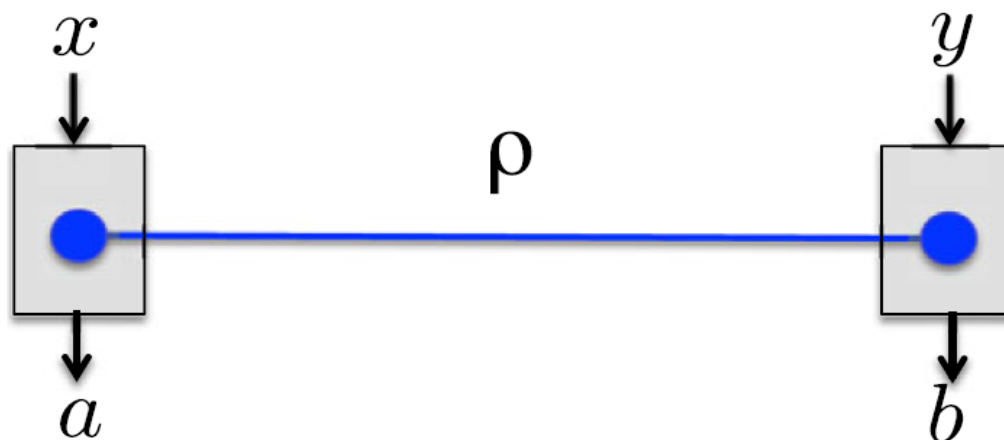
# Physical Concepts : Local Realism

- Local Realism
  - Realism:  
Measurement outcome depends deterministically on setting and hidden variables  $\lambda$ .
  - Locality:  
Outcome does not depend on the settings of the other measurement.

In 1964, John Bell made the EPR paradox testable

- Bell inequalities express bounds on the statistics of space-like separated measurements in local hidden variable (LHV) theories.
- Quantum mechanics will violate Bell inequality

# The CHSH Bell inequality



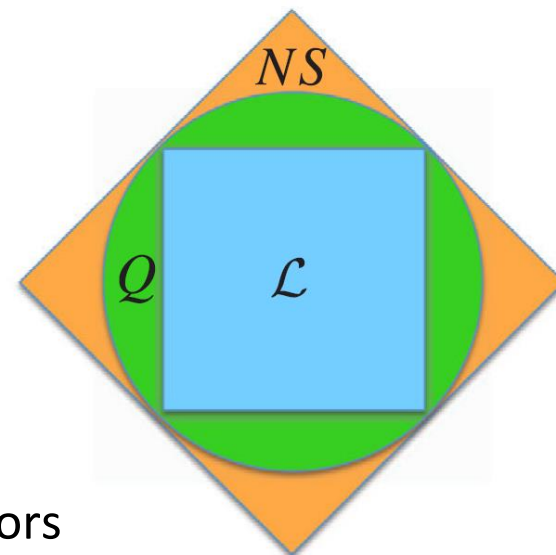
$$\mathcal{S}_{\text{CHSH}} = E_{11} + E_{12} + E_{21} - E_{22} \stackrel{\mathcal{L}}{\leq} 2$$

$E_{xy} \equiv p(a = b|x, y) - p(a \neq b|x, y)$  = measurement correlation function

$\mathcal{S}_{\text{CHSH}} = 2$  Bound of correlations in local hidden-variable theory ( $\mathcal{L}$ )

$\mathcal{S}_{\text{CHSH}} = 2\sqrt{2}$  Bound of quantum theory, Tsirelson's Bound ( $\mathcal{Q}$ )

$\mathcal{S}_{\text{CHSH}} = 4$  Bound of relativistically causal theory, non-signaling ( $\mathcal{NS}$ )



CHSH: Clauser-Horne-Shimony-Holt; named after creators

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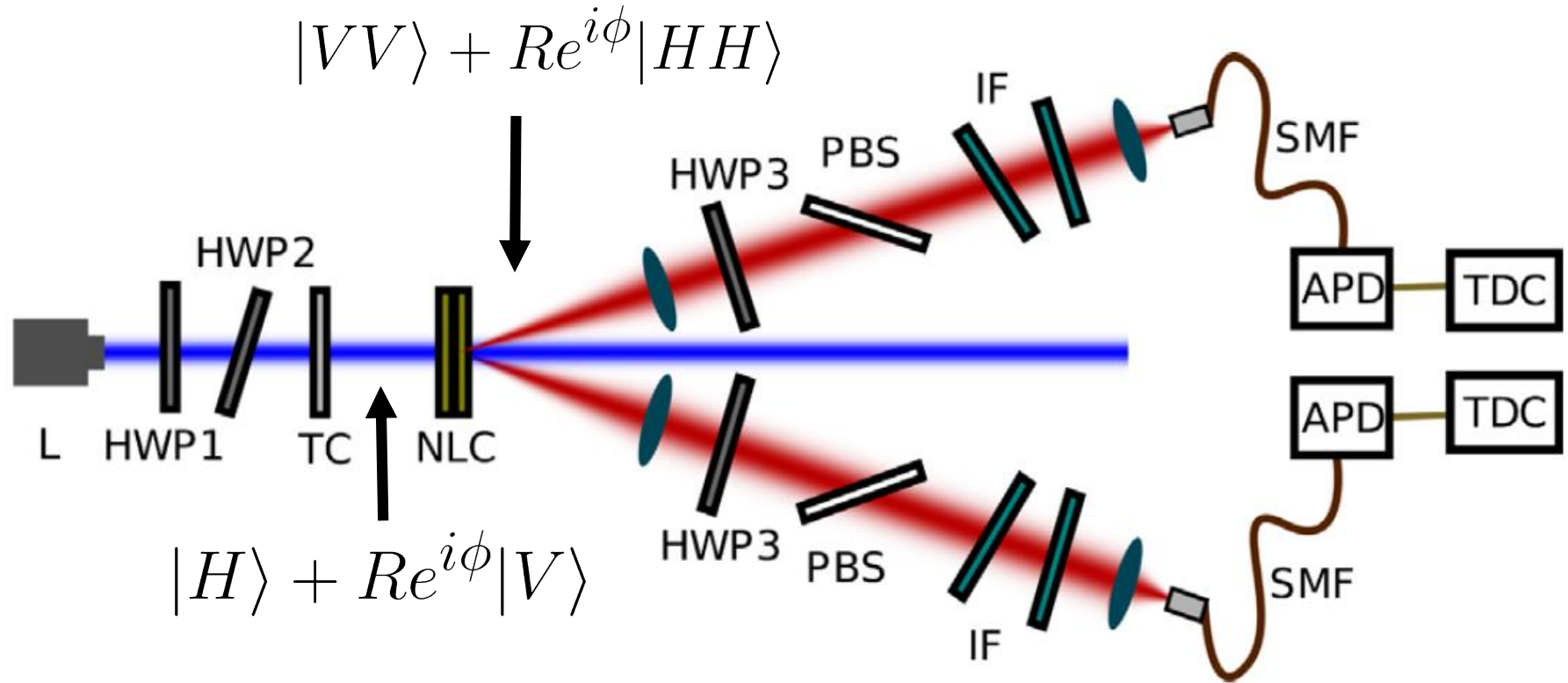
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# Experimental Setup for Creating Entangled Photons



## Legend:

HWP: Half-wave plate

TC: Temporal compensation

NLC: Non-linear crystal

PBS: Polarizing beamsplitter

IF: Interference filter

SMF: Single-mode fiber

APD: Avalanche photodiode

TDC: Time-to-digital converter



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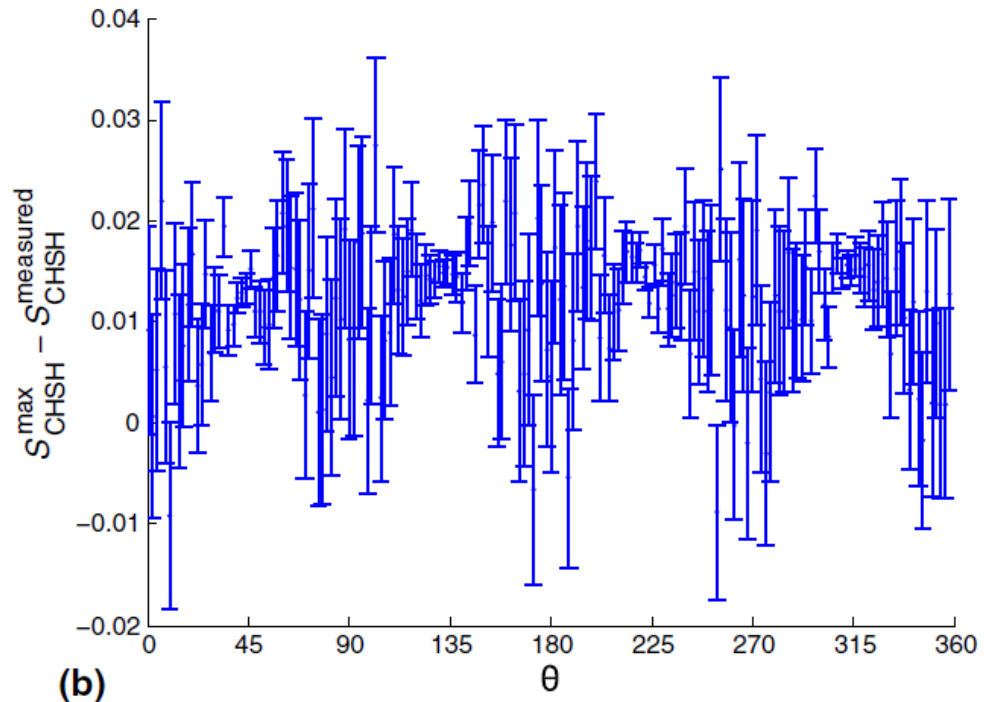
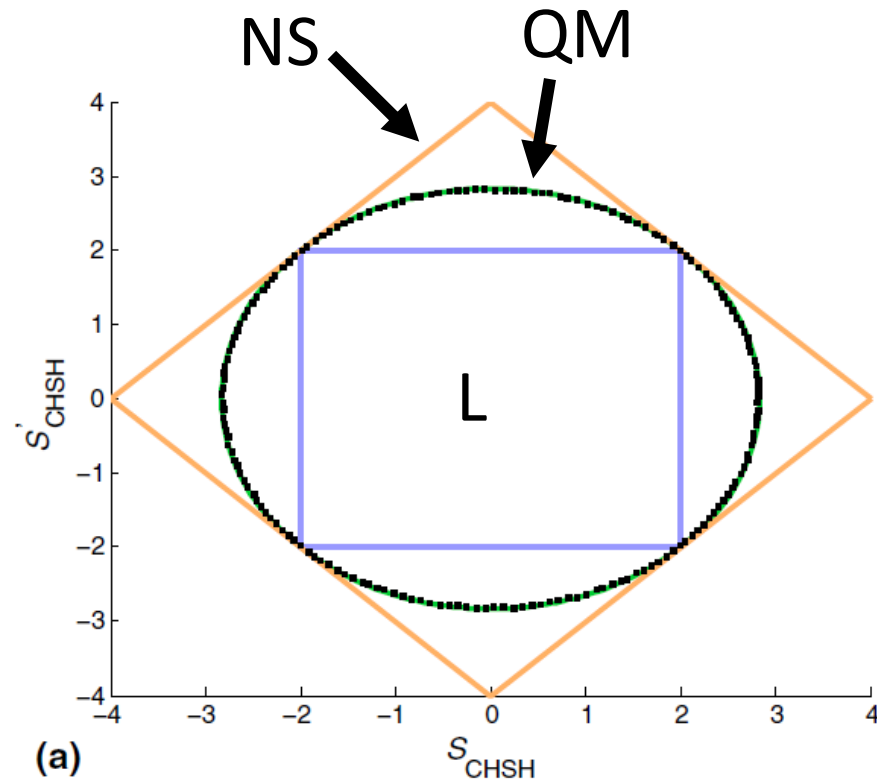
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# Experiment Respects Quantum Correlation Bounds

- Many polarization measurements were taken with different settings
  - “Nonlocality”  $S_{\text{CHSH}}$  was calculated for each quadruplet of measurement settings ( $\theta$  compares settings  $x, y$  to settings  $x', y'$ )
  - An orthogonal nonlocality  $S'_{\text{CHSH}}$  was also calculated
  - Measurements lie cleanly on Tsirelson bound
- Results are consistent with no violation of quantum mechanical correlations



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# Exploring More Exotic Bell-like Inequalities

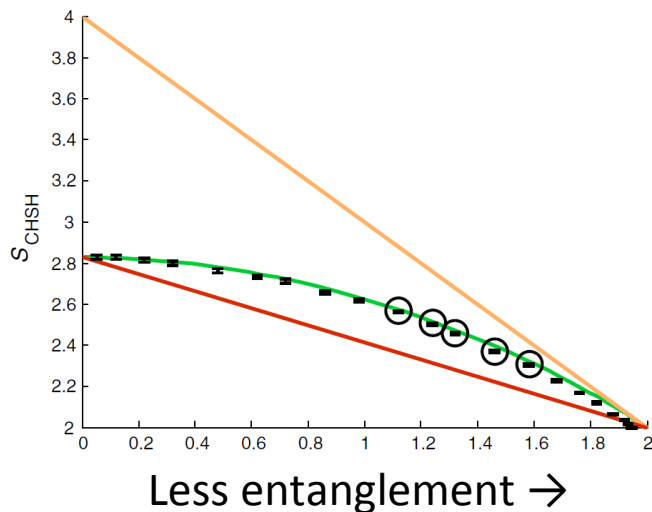
## What about nonmaximally entangled states?

- Bell inequality is maximally violated by maximally entangled state

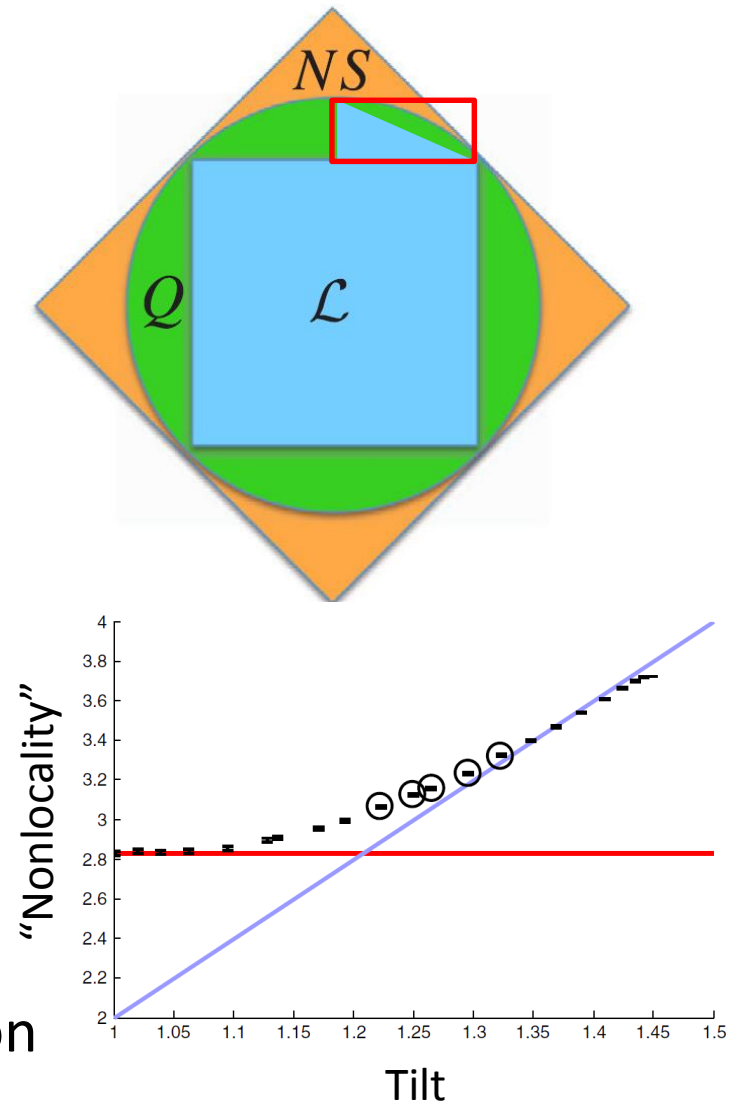
# Sometimes Less Entanglement Gives More Nonlocality

## Are maximally entangled states the weirdest?

- CHSH inequality is maximally violated by maximally entangled states
- What about a “tilted” Bell inequality?
- They found that partially entangled states exhibited the largest violations



- When tilted enough, maximally entangled states exhibited no violation



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# Chained Bell Inequality

## Basic idea



- CHSH inequality: let  $C(x,y) = p(a=b | x,y)$   
$$-2 \leq C(x,y) + C(x,y') + C(x',y) - C(x',y') \leq 2$$

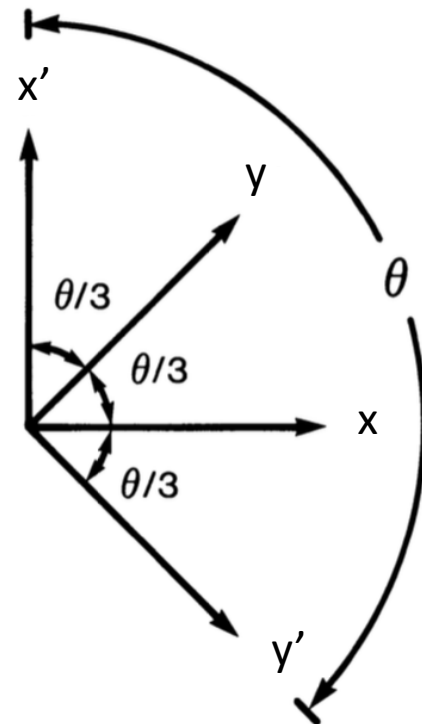
- Maximal violation for polarization analyzers:

$$C(x,y) = C(\theta_{xy}) = \cos(2\theta_{xy})$$

$$\theta_{xy} = \theta_{xy'} = \theta_{x'y} = \theta/3$$

- Resulting inequality:  $-2 \leq 3\cos(2\theta/3) - \cos(2\theta) \leq 2$

$$3[1 - \cos(2\theta/3)] \geq 1 - \cos(2\theta)$$

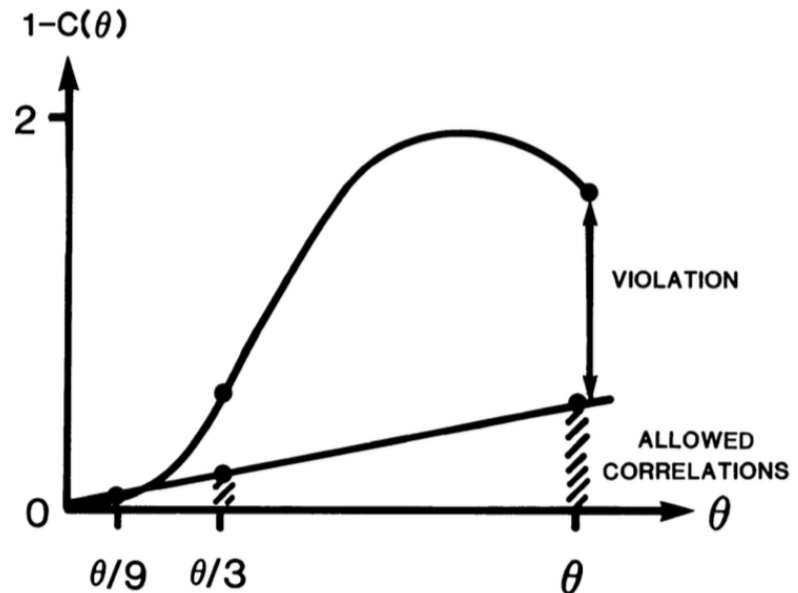
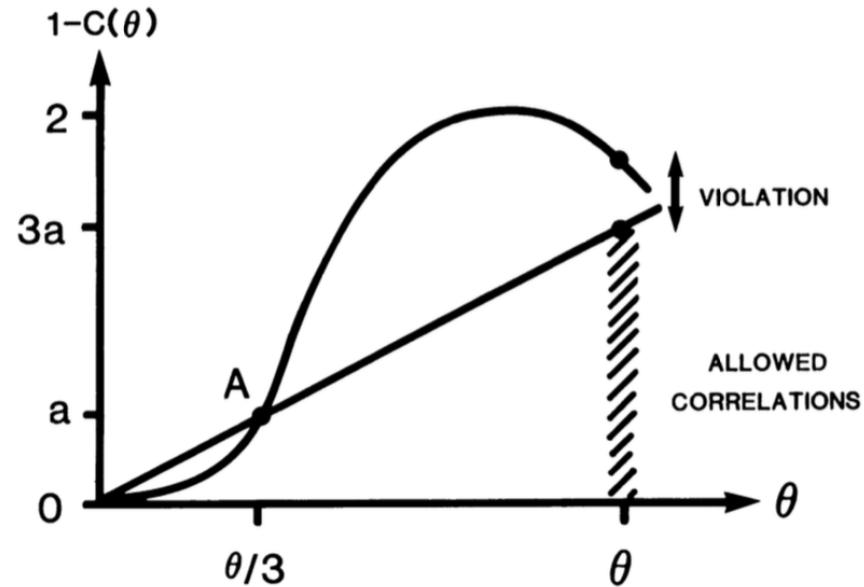


# Chained Bell Inequality

$$3[1-C(\theta/3)] \geq 1-C(\theta)$$

- Curved line follows the Quantum Mechanics predictions, while the straight line represents the Local Realistic picture
- Iterate to get the new inequality:  

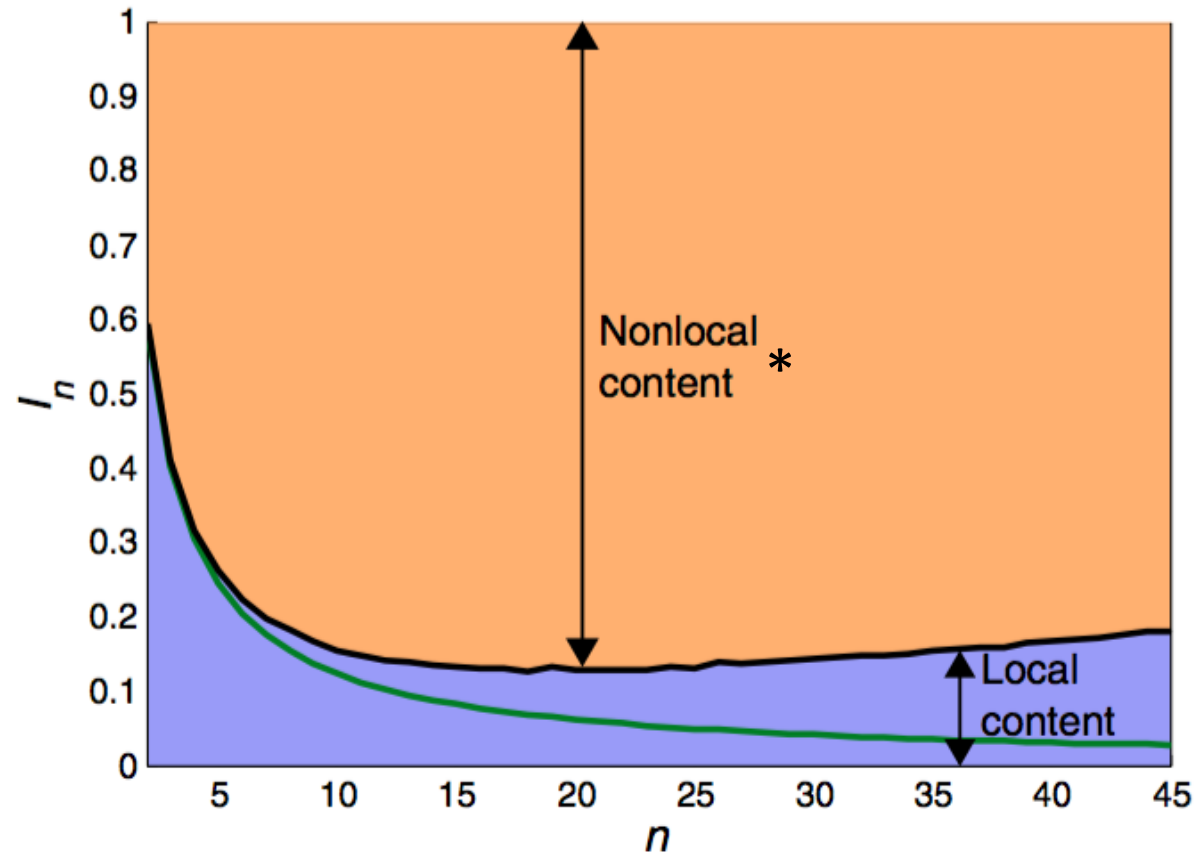
$$9[1-C(\theta/9)] \geq 3[1-C(\theta/3)] \geq 1-C(\theta)$$
- This chain of inequalities can be continued further





# Chained Bell Inequality

- Inequalities are chained up to 45
- Strongest violation at  $n=18$ ,  $I_{18}=0.126$
- As  $n$  is increased, more measurements is required and noise from imperfect state preparation becomes more noticeable



- $I_{45}$  requires 360 specific measurements along the Bloch sphere

\*Nonlocal content: percent of measurements needed to be performed with non-local resource (one that reaches NS bound in CHSH inequality) in order to reproduce results.

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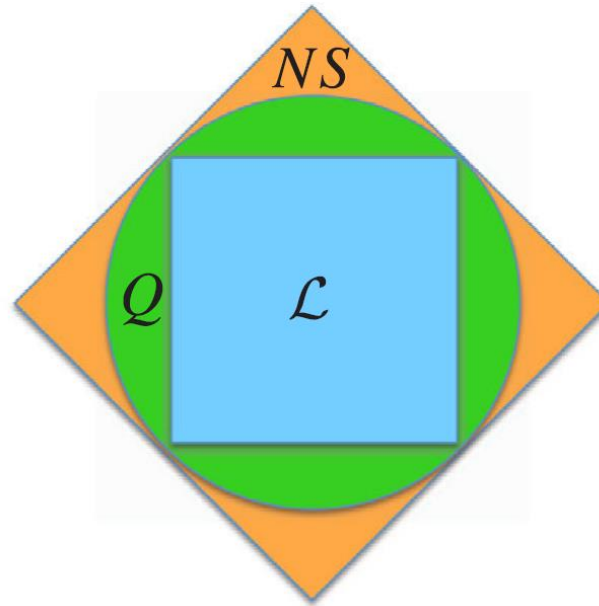
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# Critiques

- Been cited 3 times in peer reviewed publication
- Each time authors used as reference of “Look, it’s been verified experimentally”
- Some results of paper were expected (e.g., the Tsirelson Bound) making it hard to get published
- Novel and unexpected: less entanglement exhibits more non-locality
- The experiment and analysis were robustly designed to allow for accurate tests of theory

# Summary



- Experiments did not exceed Tsirelson Bound in statistically significant way
- Tilted inequality  $\rightarrow$  less entanglement, more non-locality
- Chained inequality  $\rightarrow$  max of 87% non-local content