Experimental measurement of the collectibility of two-qubit states

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Quantum entanglement

- quantum entanglement is an **intriguing phenomenon**
- heavily investigated since its conception in 1935 (EPR paper)

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Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

A. EINSTEIN, B. PODOLSKY AND N. ROSEN, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 25, 1935)

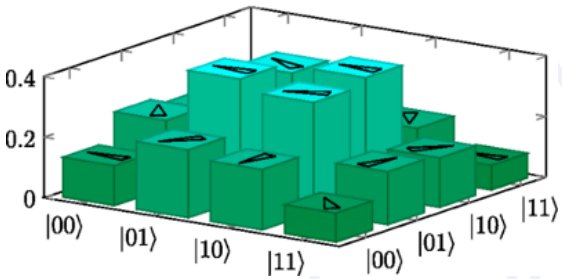
- has significant **impact on how we perceive nature**

philosophical

technological

Quantifying entanglement

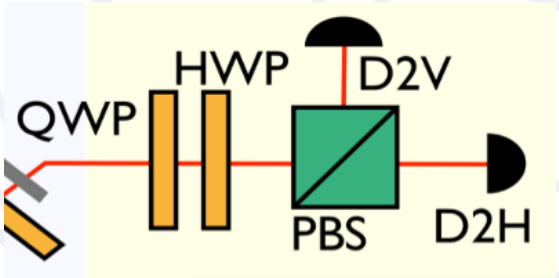
- entanglement quantification is **still an open problem**
- three conceptually distinct approaches have emerged:



state tomography

✗ requires a large number of measurements

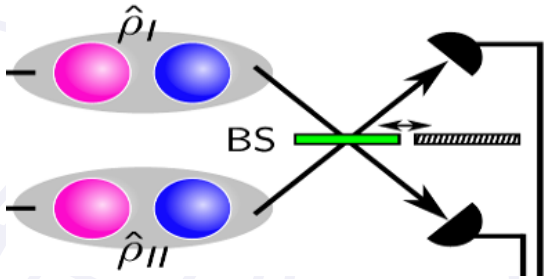
- e.g. PTP criterion



local measurements + their correlation

✗ often requires some a priory information

- e.g. CHSH ineq.



collective measurements

✗ experimentally challenging

✓ should not scare us!

- e.g. Bovino *et al.* PRL **95**, 240407 (2005)

The collectibility

- one specific method for entanglement detection (and quantification)
- uses **collective measurements**
- proposed in 2011:

PRL **107,** 150502 (2011) PHYSICAL REVIEW LETTERS week ending 7 OCTOBER 2011

Collective Uncertainty Entanglement Test

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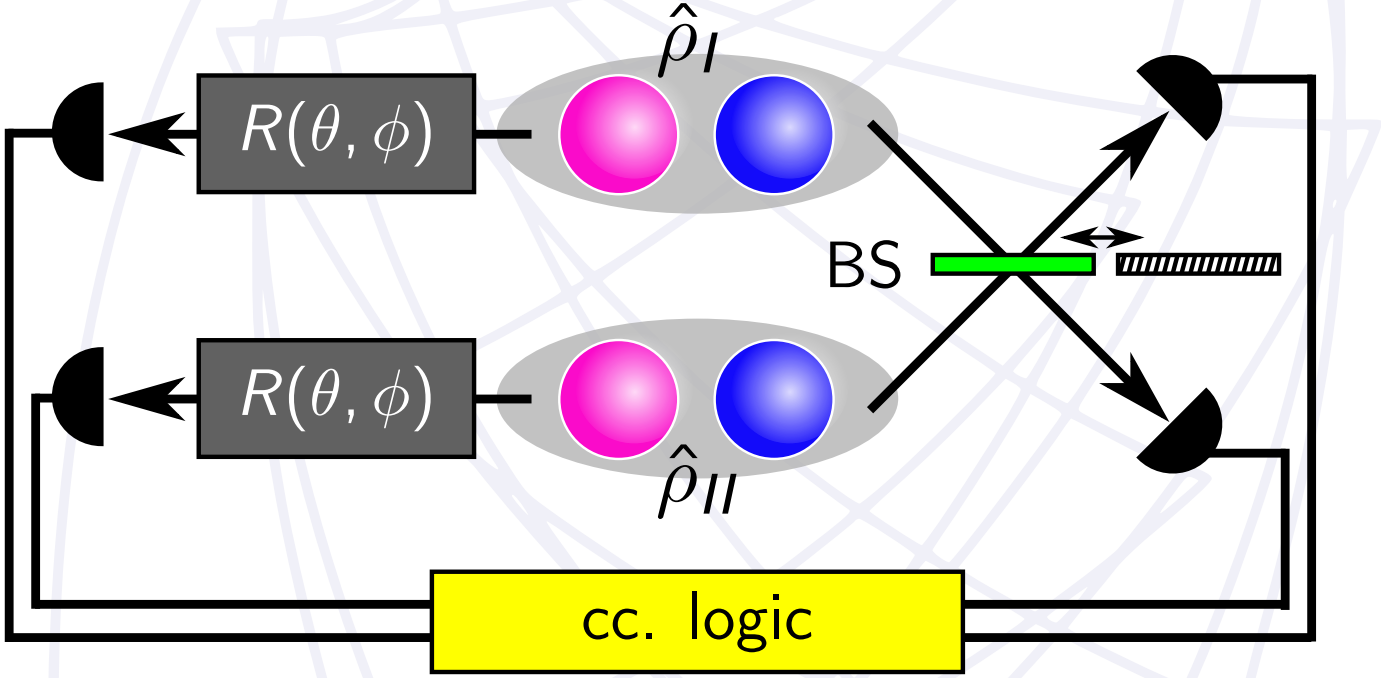
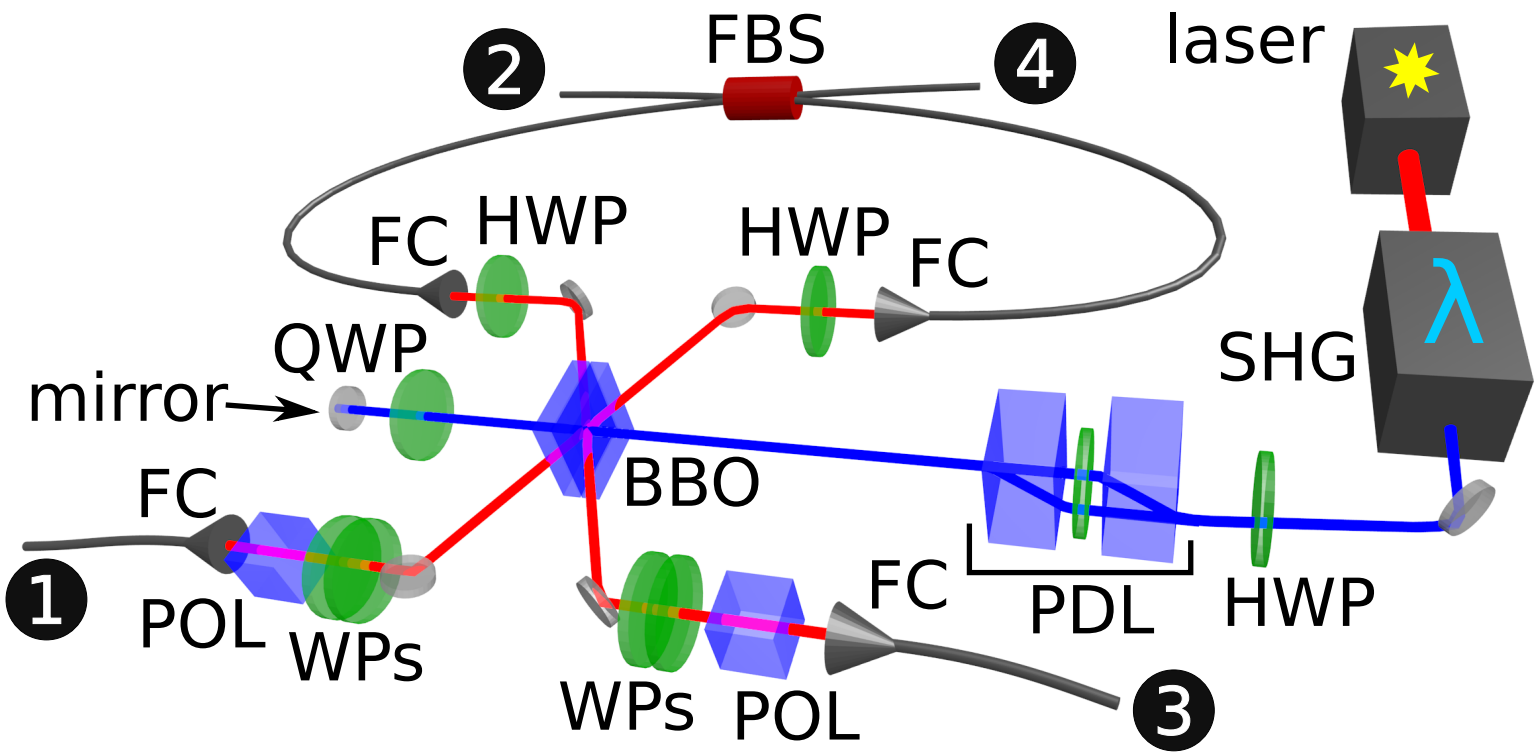
- generalized to mixed states in 2012

Collectibility – principle of operation for two-qubit states



- **ingredients:** 2 copies of a two-qubit state
- one particle from each copy subjected to local projection measurements
- the other two particles overlap on a balanced beam splitter

Collectibility – experimental setup



- BBO crystal cascade pumped by fs laser pulse on its way there and back
- two polarization encoded photon pairs generated (tunable state)
- local polarization projections + HOM interference

Collectibility – measurement procedure

- **polarization projections** on photons 1 and 3:

  all combinations of **horizontal** ($|H\rangle$), **vertical** ($|V\rangle$) and **diagonal** ($|D\rangle = \frac{1}{\sqrt{2}}(|H\rangle + |V\rangle)$) projections

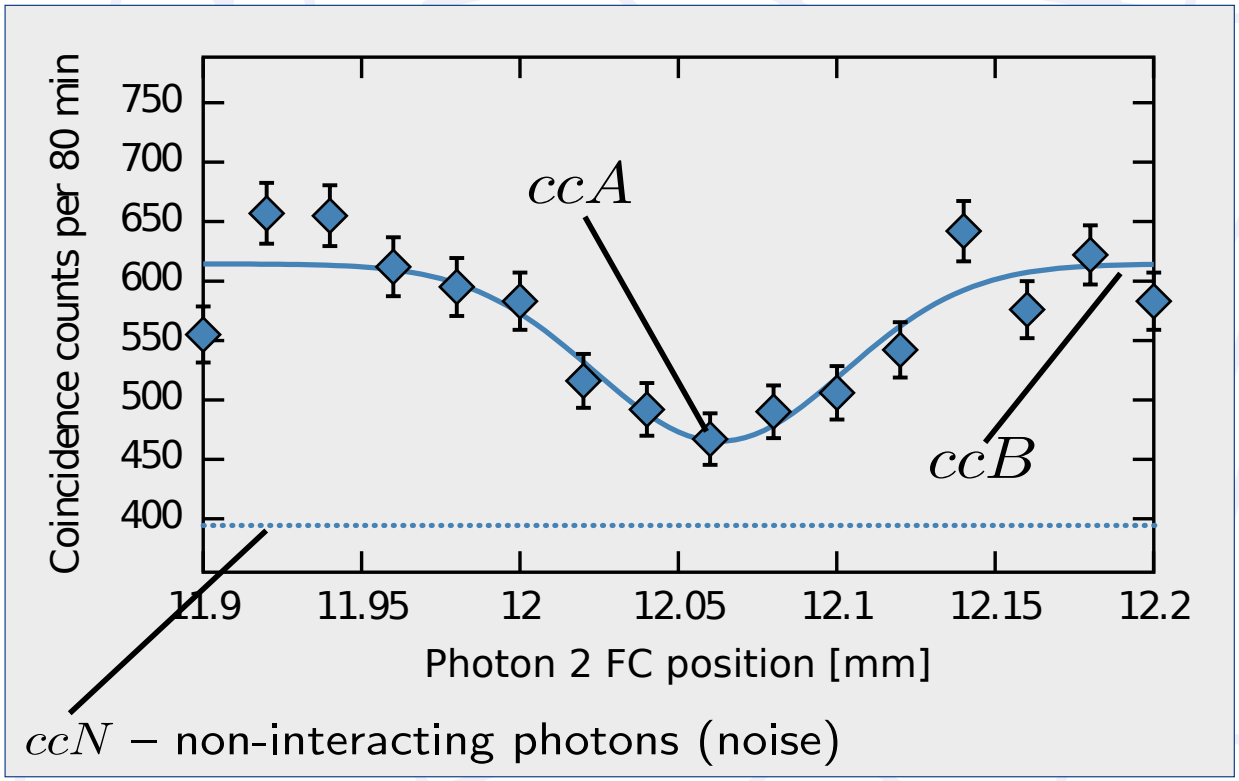
- simultaneously letting photons 2 and 4 **impinge on a beam splitter**

  measuring with wave-packets **overlapping in time** (HOM interference) and **not overlapping** (used for intensity normalization)

- recording rates of **4-fold coincident detections**

Collectibility – data processing

- we observe a **HOM dip** as function of temporal overlap between photons 2 and 4



- we define ratios $r_{IJ} = \frac{ccA_{IJ} - ccN}{ccB_{IJ} - ccN}$, for $I, J = \{|H\rangle, |V\rangle, |D\rangle\}$

Collectibility – calculations

- we use the obtained ratios r_{IJ} to calculate the **collectibility witness**

$$\begin{aligned} W(\hat{\rho}) \quad = \quad & \frac{1}{2}\Big[\eta + \xi^2\,(1 - r_{HH}) \\ & + (1-\xi)^2\,(1 - r_{VV}) \\ & + 2\xi\,(1-\xi)\,(1 - r_{HV}) - 1\Big], \end{aligned}$$

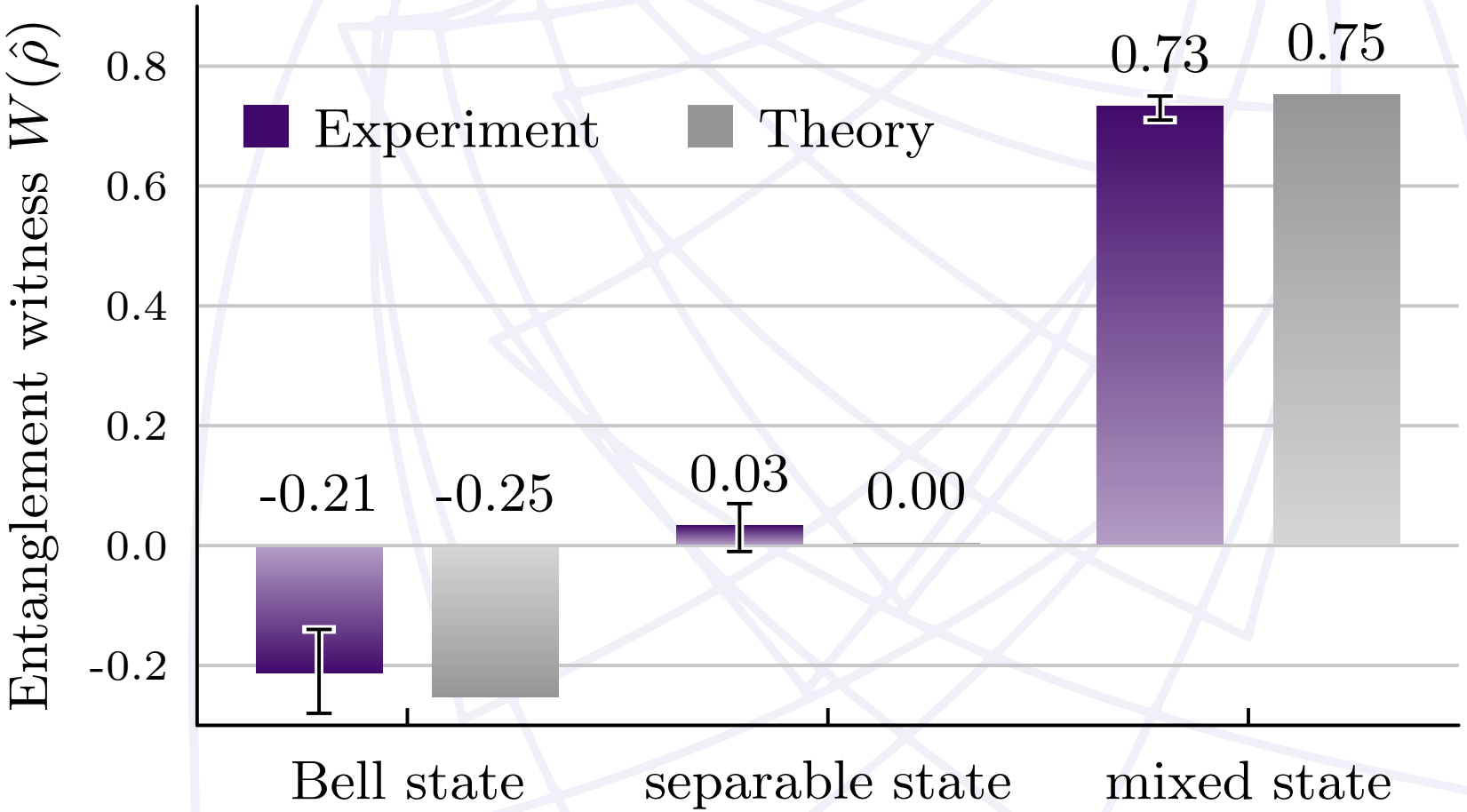
where

$$\eta = 8\xi\,(1-\xi)\,\sqrt{r_{HH} r_{VV}} + 2 r_{DD},$$

$$\xi = \text{Prob(photon 1 in state } |H\rangle)$$

verdict: $W(\hat{\rho}) < 0 \Rightarrow$ entangled

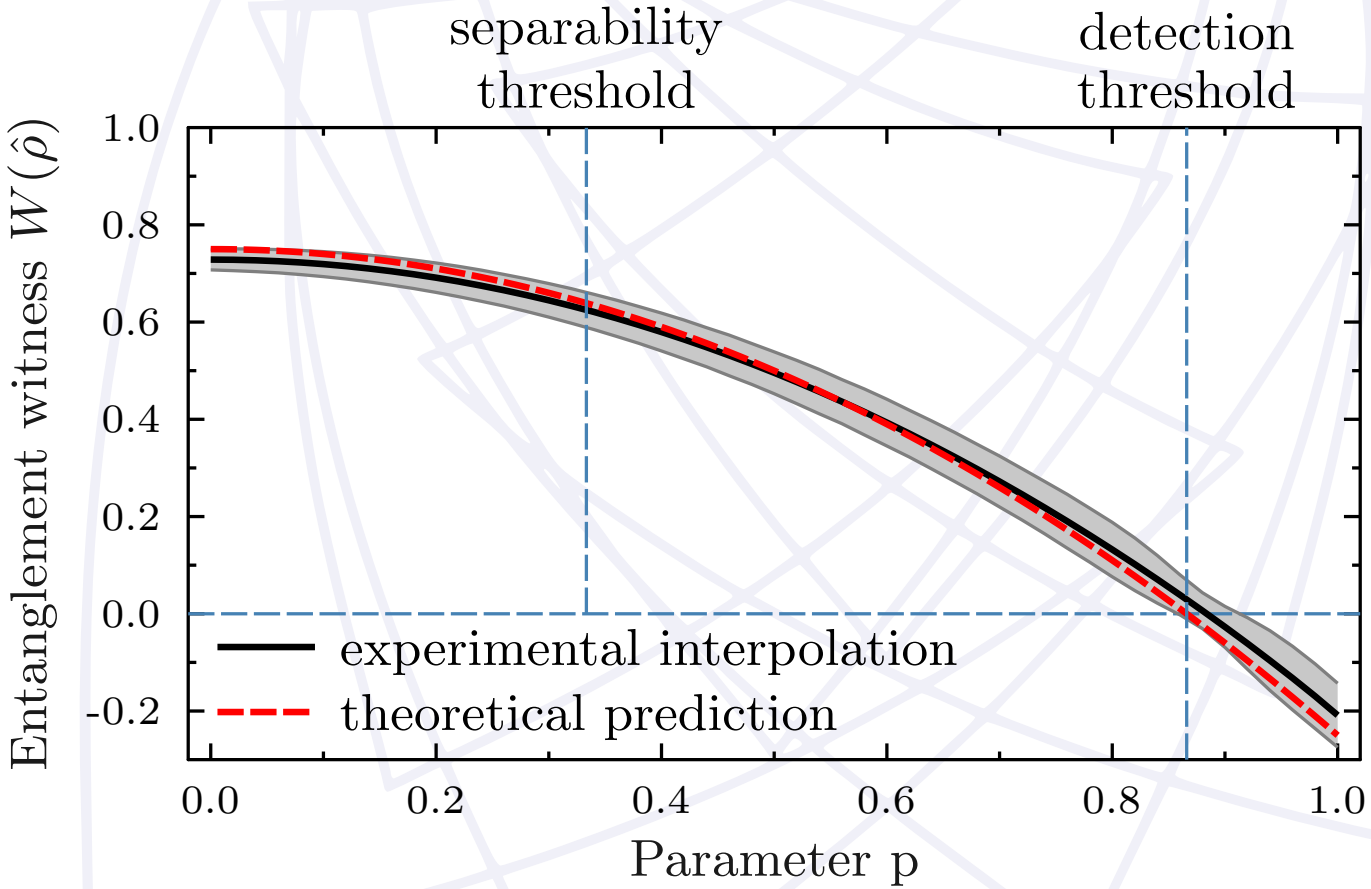
Collectibility – results



$|\Psi^-\rangle = \frac{1}{\sqrt{2}}(|HV\rangle - |VH\rangle)$ $|\psi\rangle = |HH\rangle$ $\hat{\rho} = \mathbb{I}/4$

Collectibility – results

- Werner states: $\hat{\rho}_W = p|\Psi^-\rangle\langle\Psi^-| + (1-p)\mathbb{I}/4$



- collectibility has better detection threshold than previously proposed collective measurement-based techniques

Thank you for your attention.