

# **REALISM VERSUS QUANTUM MECHANICS:**

## **IMPLICATIONS OF SOME RECENT EXPERIMENTS**

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1. What do we mean by “realism” in physics?
2. Local realism: The EPR-Bell setup
3. Three recent EPR-Bell experiments\*
4. Macrorealism: The temporal Bell inequalities (TBI)
5. Two recent TBI experiments†

\* B. Hensen et al., Nature 526, 682 (2015) (“Delft”)  
 L. K. Shalm et al. Phys. Rev. Letters 115, 250402 (2015) (“NIST”)  
 M. Giustina et al, Phys. Rev. Letters 115, 250401 (2015) (IQOQI”)

† J.A. Formaggio et al., PRL 117, 05042 (2016)  
 (raw data: MINOS collaboration, AIP Conf. Proc. 1666, (“MINOS”)  
 110004 (2015))  
 G. C. Knee et al., arXiv: 1601.03728 (2016) Nature (“NTT”)  
 Communications, in press)



# What do we/can we mean by “realism”?

## Philosophers discuss “reality” of (e.g.)

the human mind  
the number 5  
moral facts

atoms (electrons, photons...)

.....



but, difficult to  
think of input  
from physics

So: in what sense can physics as such say something about “realism”?

(My) proposed definition:

At any given time, the world has a definite value of any property which may be measured on it (irrespective of whether that property actually is measured)

To make this proposition (possibly) experimentally testable, need to extend it to finite “parts” of the world.

Irrespective of the universal validity (or not) of QM, what can we infer about this proposition

directly from experiment?

quantum mechanics



# Non-realism: Deep Thought or a Soft Option?

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**Abstract** The claim that the observation of a violation of a Bell inequality leads to an alleged alternative between nonlocality and non-realism is annoying because of the vagueness of the second term.

**Keywords** Nonlocality · Bell inequality · Realism · Measurement problem

## 1 Introduction

In recent years the violation of Bell's inequality has often been interpreted as either a failure of locality or of realism (or of both). The problem with such a claim is that it is not clear what realism in this context should mean. In this note my goal is to look for a definition of realism compatible with the claim that it has been falsified.<sup>1</sup> Sometimes realism is defined as the hypothesis that every physical quantity always has a value.<sup>2</sup> But then, either this value is inaccessible, hence unphysical, or this value can be revealed by appropriate measurements (to arbitrary good approximation, at least in principle). Hence, these measurements have predetermined outcomes and realism is nothing but a fancy word for determinism. If so, first, why should one use the word local realism instead of local determinism? And second, Bell's inequality

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<sup>1</sup>My personal definition of realism—that clearly has not been falsified—is another issue. For me realism means [2], very briefly, that physical systems possess properties preexisting and independent of whether we measure the system or not; however these preexisting properties do not determine measurement outcomes, but only their propensities. Accordingly, there are realistic random events that reflect preexisting properties, as required by realism, simply the reflection is not deterministic.

<sup>2</sup>For example, in [1] A. Zeilinger et al. define realism as “the assumption that measurement outcomes are well defined prior to and independent of the measurements”.

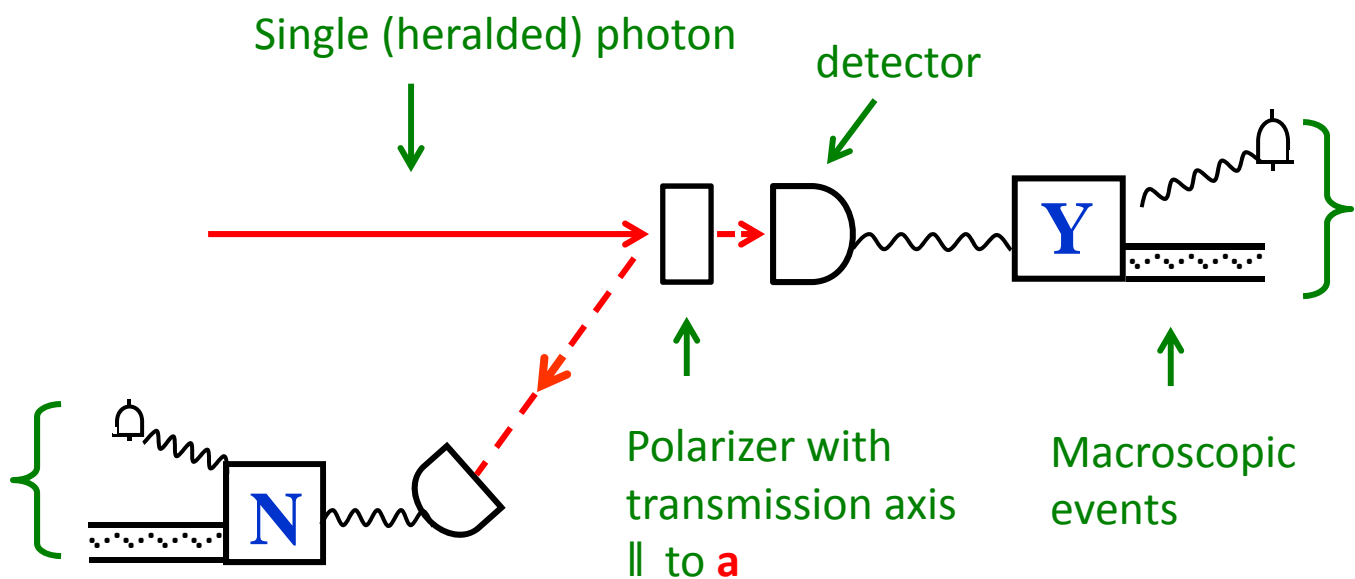
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## THE SIMPLEST CASE: A TWO STATE SYSTEM

(Microscopic) example: photon polarization



“Question” posed to photon:

Are you polarized along **a**?

Experimental fact:

for each photon, **either** counter Y clicks (and counter N does not) **or** N clicks (and Y does not).

natural “paraphrase”:

**when asked**, each photon answers either “yes” ( $A = +1$ ) or “no” ( $A = -1$ )

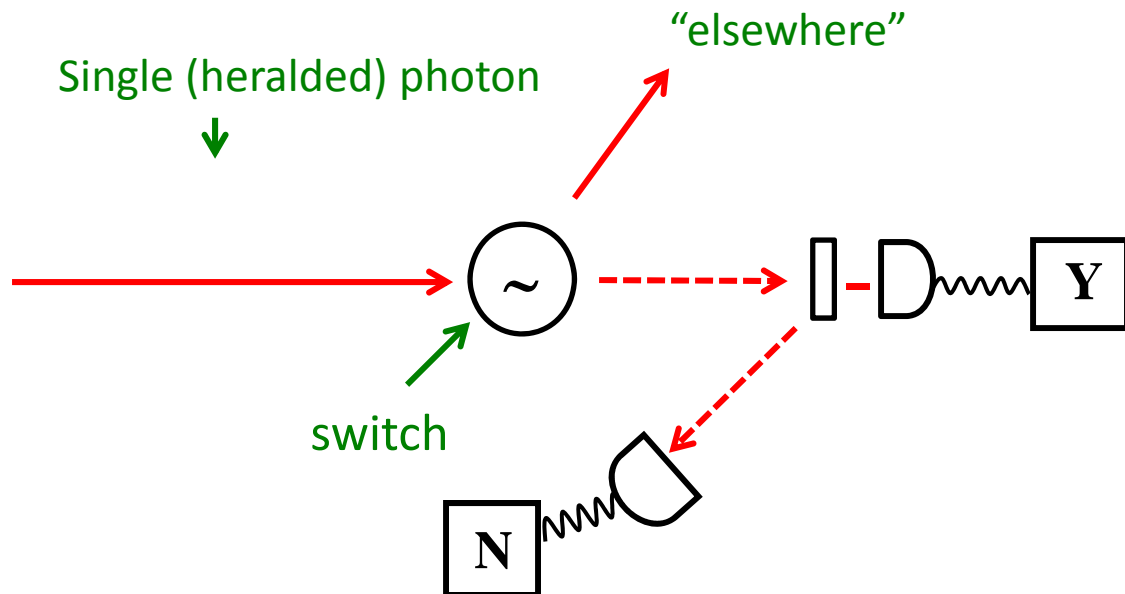
But: what if it is **not** asked?

Single (heralded) photon  $\rightarrow$  (no measuring device...)



## MACROSCOPIC COUNTERFACTUAL DEFINITENESS (MCFD)

(Stapp, Peres...)



Suppose a given photon is directed “elsewhere”.

What does it mean to ask “does it have a definite value of  $A$ ?”

A possible quasi-operational definition:

Suppose photon had been switched into measuring device:

Then:

Proposition I (truism?): It is a fact that **either** counter Y would have clicked ( $A = +1$ ) **or** counter N would have clicked ( $A = -1$ )

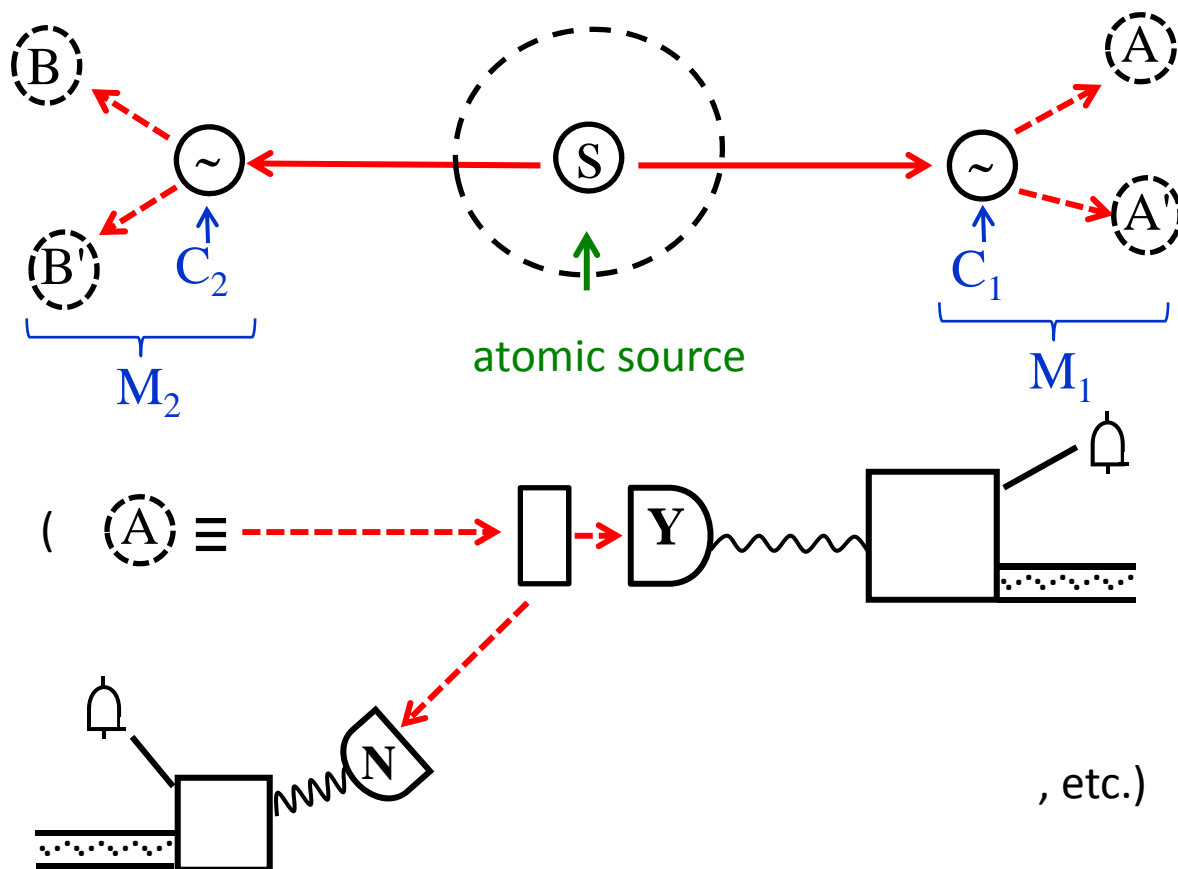


Proposition II (MCFD): **Either** it is a fact that counter Y would have clicked (i.e. it is a fact that  $A = +1$ ) **or** it is a fact that counter N would have clicked ( $A = -1$ )

**Realism  $\cong$  proposition II?**



## THE EPR-BELL EXPERIMENTS (idealized)



CHSH inequality: all objective local theories (OLT's) satisfy the constraints

$$\langle AB \rangle_{\text{exp}} + \langle A'B \rangle_{\text{exp}} + \langle AB' \rangle_{\text{exp}} - \langle A'B' \rangle_{\text{exp}} \leq 2 \quad (*)$$

(\*) is violated (by predictions of QM, and) (prima facie) by experimental data.

Note: for purposes of refuting local realism, use of "source" is inessential! (correlations can be generated any way we please).



Objective local theories (OLT's) defined by conjunction of

- (1) Realism (“objectivity”) – physical systems have definite properties whether or not these are observed.
- (2) Locality – no causal influence can propagate with velocity  $> c$  ← speed of light
- (3) Absence of retrocausality (“induction”): future cannot affect present/past

[Note: in SR (2)  $\rightarrow$ (3), but we want to consider more general scenarios]





## Proof of CHSH inequality:

1. For any given pair, quantities  $A, B, A', B'$  exist and take values  $\pm 1$ .
2. By (2) and (3), value of  $A$  independent of whether  $B$  or  $B'$  measured at distant station (and vice versa)
3. Hence for any given pair, the quantities  $AB, AB'$  etc. exist, with  $A$  taking **the same** value ( $\pm 1$ ) in  $AB$  and in  $AB'$  (etc.)
4. Then grade-school algebra  $\Rightarrow$ 

$$AB + A'B + AB' - A'B' \leq 2$$
5. Thus when measured on **same** ensemble,
 
$$\langle AB \rangle + \langle A'B \rangle + \langle AB' \rangle - \langle A'B' \rangle \leq 2$$
6. While strictly speaking we should write the experimentally measured correlation as  $\langle AB \rangle_{\text{exp}} \equiv \langle AB \rangle_{AB}$ , by (3)  $\langle AB \rangle_{AB} = \langle AB \rangle_{AB'}$ , etc.  $\equiv \langle AB \rangle$ 

$\uparrow$   
 ensemble on which  $A$  and  $B$  measured
7. Hence
 
$$\langle AB \rangle_{\text{exp}} + \langle A'B \rangle_{\text{exp}} + \langle AB' \rangle_{\text{exp}} - \langle A'B' \rangle_{\text{exp}} \leq 2, \quad \text{QED.}$$



## The most obvious “loopholes” in EPR-Bell experiments (pre- 11/15)

- (1) “locality”: event of (e.g.) switching at  $C_1$  not spacelike separated from detection in  $M_2$
- (2) “freedom of choice”: switching at  $C_{1,2}$  may not be truly “random”
- (3) “detection”: if counters not 100% efficient, detected particles may not be representative sample of whole.

Until Nov. 2015, many experiments had blocked 1 or 2 loopholes, but none had blocked all 3 simultaneously.

Why?

Blocking of (1) requires spacelike separation of switching at  $C_1$  and detection at  $M_2$  and blocking of (2) requires (inter alia) spacelike separation of switching at  $C_1$  and emission at  $S$  (or equivalent)



easy for photons,  
difficult for  
e.g. atoms

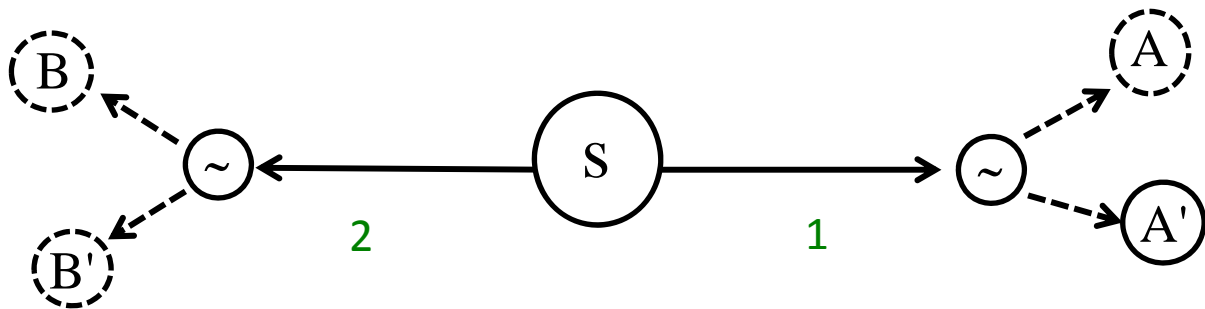
Blocking of (3) requires detector efficiency  $>82.8\%$  for CHSH (or  $67\%$  for Eberhard, see below)

easy for atoms,  
etc., difficult for  
photons

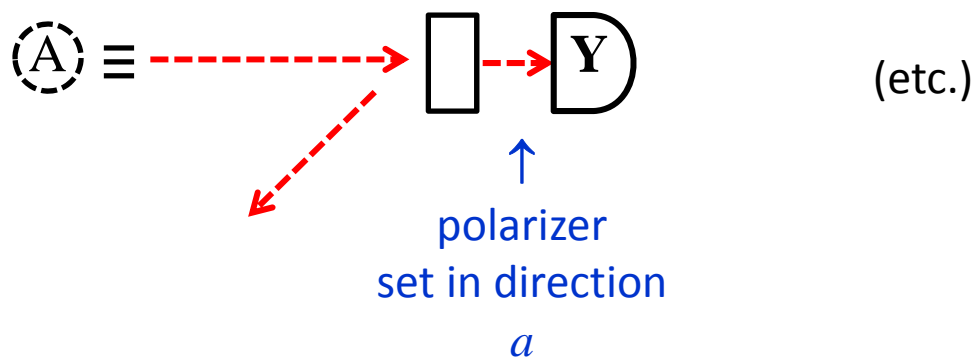
To exclude giant “conspiracy of Nature” need to block all 3 loopholes simultaneously! (“holy grail” of experimental quantum optics)



A useful extension of CHSH inequality (Eberhard):



but now:



(so don't mind whether nondetected particles had polarization  $\perp$   $\mathbf{a}$ , or were simply not detected because of inefficiency of counter).

Eberhard inequality:

$$J \equiv p(++|ab) - p(+0|ab') - p(0+|a'b) - p(++|a'b') \leq 0$$

where, e.g.,

$p(+0|ab) \equiv$  probability that with particles switched into detectors A, B, detector A fires and B does not.

Inequality is valid independently of detection efficiency  $\eta$ , but predictions of QM violate it only for  $\eta > 67\%$ .



### EPR-Bell Experiments of Nov – Dec. 2015

<u>First author affiliation</u>	<u>System</u>	<u><math>C_1 - M_2</math> distance</u>	<u>Inequality tested</u>	<u>Value of (<math>K - 2</math>) or J</u>	<u>Quoted significance</u>
Delft	electron spins	1.3 km	CHSH	0.42	0.019/0.039
NIST	photon polarization	185m	Eberhard	$2 \times 10^{-7}$	$< 2.3 \times 10^{-3}$
IQOQI	photon polarization	58m	Eberhard	$7 \times 10^{-7}$	$< 10^{-30}$ [sic!]

⇒ local realism is dead?

What are the outstanding loopholes?

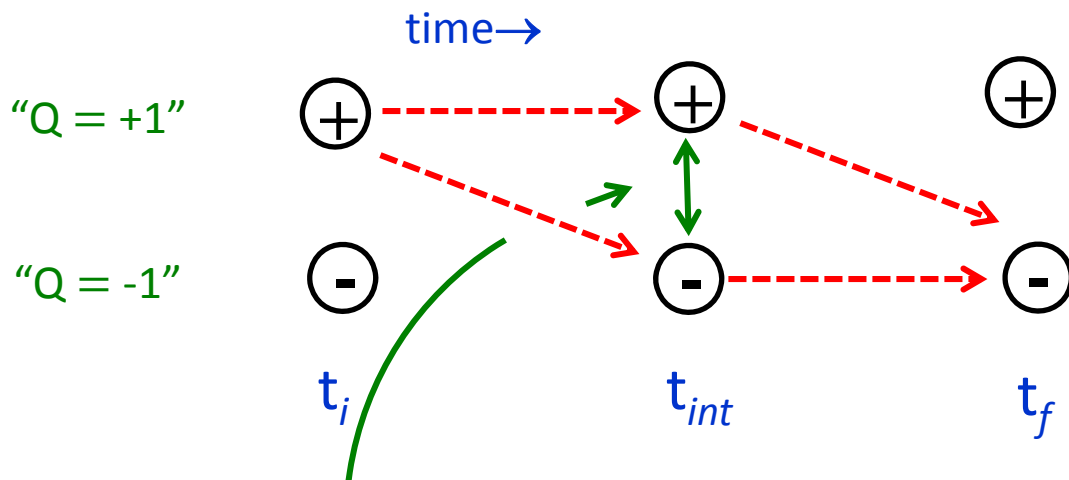
- (1) Superdeterminism probably untestable
- (2) retrocausality probably untestable
- (3) collapse locality ?

at what point in the “measurement” process was a definite outcome realized?



Can experiment (of a different kind) say anything about this?

## MACROSCOPIC QUANTUM COHERENCE (MQC)



macroscopically  
distinct states

Example: “flux qubit”:



Existing experiments: if raw data interpreted in QM terms, state at  $t_{int}$  is **quantum superposition** (not mixture!) of states  $\oplus$  and  $\ominus$ .

↑: how “macroscopically” distinct?  
(cf: arXiv: 1603.03992)



## Analog of CHSH theorem for MQC (“temporal Bell inequality”)\*

Any **macrorealistic** theory satisfies constraint

$$-2 \leq \langle Q(t_1)Q(t_2) \rangle_{\text{exp}} + \langle Q(t_2)Q(t_3) \rangle_{\text{exp}} + \langle Q(t_3)Q(t_4) \rangle_{\text{exp}} - \langle Q(t_1)Q(t_4) \rangle_{\text{exp}} \leq 2$$

or setting (e.g.)  $t_4 = t_1$ ,

$$\langle Q(t_1)Q(t_2) \rangle_{\text{exp}} + \langle Q(t_2)Q(t_3) \rangle_{\text{exp}} + \langle Q(t_3)Q(t_1) \rangle_{\text{exp}} \geq -1$$

(and similar) (Note: correlations  $\langle Q(t_i)Q(t_j) \rangle$  for different  $i$  and/or  $j$  must be measured on **different runs**.)

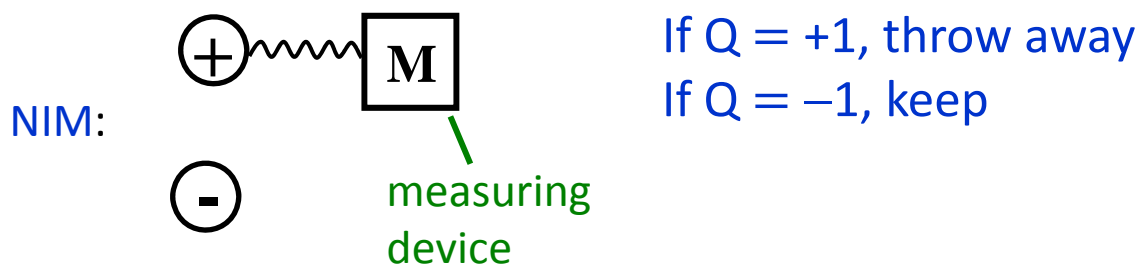
which is violated (for appropriate choices of the  $t_j$ ) by the QM predictions for an “ideal” 2-state system (e.g.  $t_1 = 0, t_2 = 2\pi/3, t_3 = 4\pi/3$ )

\*AJL and Anupam Garg, PRL **54**, 857, (1985)



Definition of “macrorealistic” theory: conjunction of

- 1) macrorealism “per se” ( $Q(t) = +1$  or  $-1$  for all  $t$ )
- 2) absence of retrocausality
- 3) noninvasive measurability (NIM) [substitutes for locality in CHSH]



In this case, unnatural to assert 1) while denying 3). NIM cannot be explicitly tested, but can make “plausible” by ancillary experiment to test whether, when  $Q(t)$  is **known** to be (e.g.)  $+1$ , a putatively noninvasive measurement does or does not affect subsequent statistics. But measurements **must be projective** (“von Neumann”).

Existing experiments use “weak-measurement” techniques (and states are not macroscopically distinct)



## Proof of TBI

1. By (1), any given member of (time) ensemble has a definite value of each of the  $Q(t_i)$ ,  $i = 1, 2, 3$ :  $Q(t_i) = \pm 1$ .
2. By (2), the value of  $Q(t_3)$  is unaffected by a noninvasive (negative-result) measurement of  $Q(t_2)$  (or  $Q(t_1)$ )
3. By (3), the value of  $Q(t_2)$  is unaffected by a measurement (whether or not noninvasive) of  $Q(t_3)$ , or by its outcome.
4. Hence for any given member of the ensemble, the quantities  $Q(t_i) Q(t_j)$  exist, with  $Q(t_i)$  taking a definite value  $\pm 1$ .
5. Grade-school algebra  $\Rightarrow$  for any given member of ensemble  $Q(t_1) Q(t_2) + Q(t_2) Q(t_3) + Q(t_3) Q(t_1) \geq -1$ .

(Boole, c. 1857)

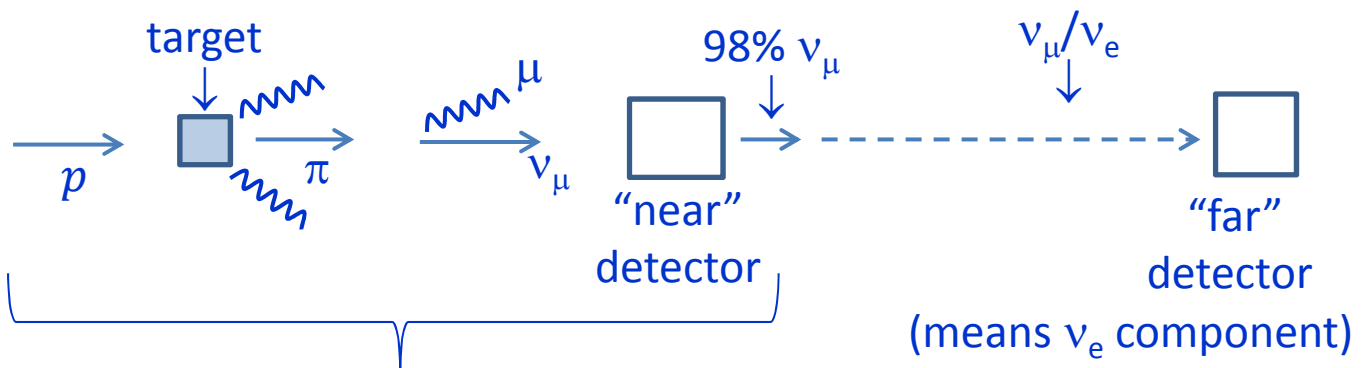
6. Thus when measured on **same** ensemble,  $\langle Q(t_1) Q(t_2) \rangle_{\text{ens}} + \langle Q(t_2) Q(t_3) \rangle_{\text{ens}} + \langle Q(t_3) Q(t_1) \rangle_{\text{ens}} \geq -1$
7. By (2) and (3), properties of ensemble depend **only on preparation** (in particular, whether or not measurement is conducted at  $t_2$  is irrelevant): hence identify  $\langle Q(t_i) Q(t_j) \rangle_{\text{exp}}$  with  $\langle Q(t_i) Q(t_j) \rangle_{\text{ens}}$
8. Hence  $\langle Q(t_1) Q(t_2) \rangle_{\text{exp}} + \langle Q(t_2) Q(t_3) \rangle_{\text{exp}} + \langle Q(t_3) Q(t_1) \rangle_{\text{exp}} \geq -1$ ,

QED





## MINOS neutrino experiment\*



FNAL, Batavia, IL  $\longleftarrow$   $\sim 750$  km  $\longrightarrow$  Soudan, MN

"Flavor" eigenstates ( $\nu_\mu, \nu_e$ ) of  $\nu$ 's different from "mass" eigenstates ( $\nu_1, \nu_2$ ) by rotation  $\theta$  ("mixing angle") in 2D Hilbert space. Hence effective Hamiltonian in **rest** frame of  $\nu$  would be

$$\hat{H}_{\text{rest}} = \frac{1}{2} \begin{pmatrix} \Delta m \cos \theta & \Delta m \sin \theta \\ \Delta m \sin \theta & -\Delta m \cos \theta \end{pmatrix}$$

and  $\nu \rightleftharpoons e$  oscillations would occur with freq.  $\Delta m$ . However, in **lab** frame, because of time dilation, we have

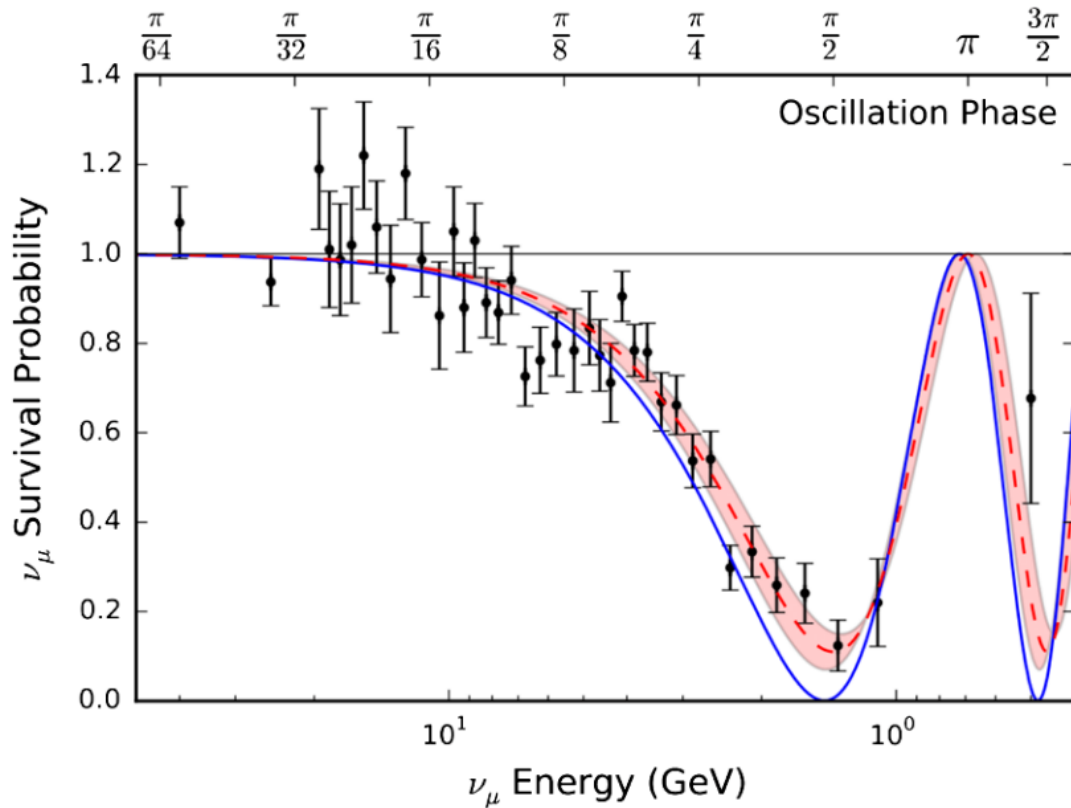
$$\hat{H}_{\text{lab}} = \frac{1}{2} \begin{pmatrix} \omega \cos 2\theta & \omega \sin 2\theta \\ \omega \sin 2\theta & -\omega \cos 2\theta \end{pmatrix} \quad \omega \cong \Delta m^2 / 2E$$

$$\begin{matrix} \uparrow \\ \cong 0.85 \end{matrix} \quad \begin{matrix} \Delta m^2 \equiv m_2^2 - m_1^2 \\ \cong 7.5 \times 10^{-5} eV^2 \end{matrix}$$

so **oscillation rate** =  $f(E)$ . Thus Formaggio et al. claim that study of  $E$ -dependence (i.e. survival rate of  $\nu_\mu$ ) is equivalent to study of time-dependence of  $\nu_e - \nu_\mu$  ratio.



\*Adamson et al., PRL 112, 191801 (2014)



Formaggio et al's conclusion: TBI violated by  $> 6\sigma$ .

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The \$64 K question: Do neutrinos with different energies belong to **the same ensemble?**

Even if true within QM (i.e.  $\nu_\mu$  state is coherent superposition of energy eigenstates), need not be true in macrorealistic theory!



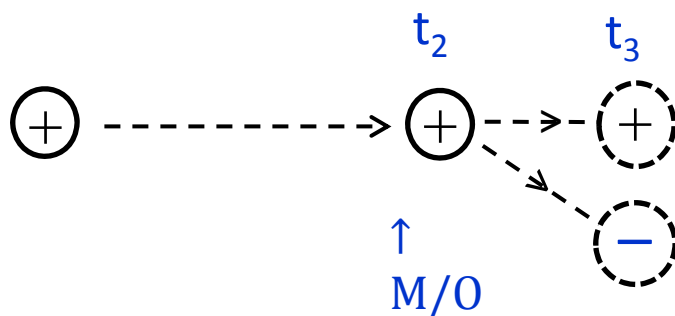
## NTT experiment

Rather than measuring 2-time correlations, check directly how far measurement (not necessarily noninvasive) at  $t_2$  affects  $\langle Q(t_3) \rangle \equiv \langle Q_3 \rangle$  for the different macroscopically distinct states and for their (putative) quantum superposition.

Define for any state  $\sigma$  at  $t=t_2^-$ ,

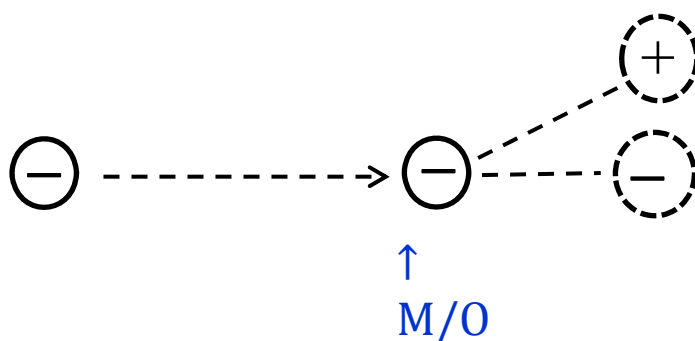
$$d_\sigma \equiv \langle Q_3 \rangle_M - \langle Q_3 \rangle_O \quad \left\{ \begin{array}{l} M \equiv \text{measurement with} \\ \text{uninspected outcome made at } t_2 \\ O \equiv \text{measurement not made at } t_2 \end{array} \right.$$

Ancillary test:  $\sigma = \oplus$



$$d_+ \equiv \langle Q_3 \rangle_M - \langle Q_3 \rangle_O$$

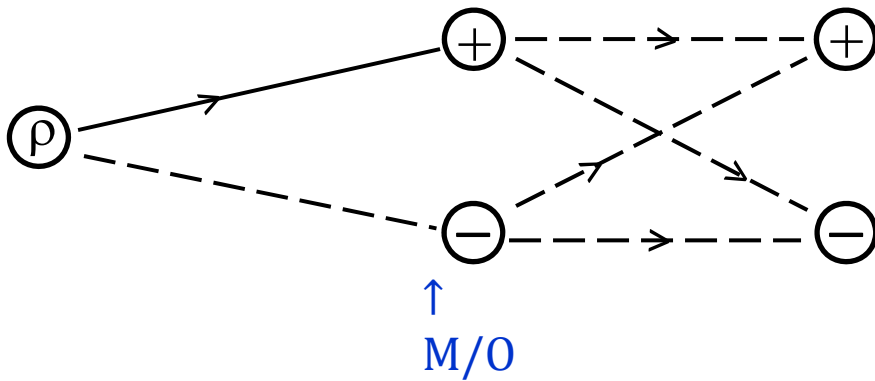
$\sigma = \ominus$



$$d_- \equiv \langle Q_3 \rangle_M - \langle Q_3 \rangle_O$$



Main experiment:



$$d_\rho \equiv \langle Q_3 \rangle_M - \langle Q_3 \rangle_0$$

$$\text{Df: } \delta \equiv d_\rho - \min(d_+, d_-)$$

$$\text{MR: } \delta > 0$$

$$\text{Expt: } \delta = -0.063$$

violates MR prediction by  $> 84$  standard deviations!



## CONCLUSION

Recap: our tentative definition of “realism” was by proposition II.

**Either** it is a fact that counter Y would have clicked, **or** it is a fact that counter N would have clicked.

This is the statement of macroscopic counterfactual definitions. So:

**Do counterfactual statements have truth-values?**  
(common sense, legal system... assume so!)

A possible view on the meaning of counterfactuals\*

“If kangaroos had no tails, they would topple over” seems to me to mean something like this: in any possible state of affairs in which kangaroos have no tails, and which resembles our actual state of affairs as much as kangaroos having no tails permits it to, the kangaroos topple over.



\*David K. Lewis, Counterfactuals, Harvard U.P. 1975

So... is it the case that in any experiment in which “everything else is the same” but we measure  $A$  instead of  $A'$ , we always get (say) +1?

Alas, no! (and NTT experiment shows this is not simply “amplification” of a microscopic indeterminacy, it is true even at a (semi-) **macroscopic** level).

So we may eventually have to conclude...



EVEN AT THE EVERYDAY LEVEL,

THERE IS NO SUCH THING AS

“WOULD HAVE”!

