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The Issue of ‘Local Realism’ in the Foundations of Quantum Mechanics

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- Quantum mechanics (QM) is not only an incredibly successful physical theory

- It is also a scientific theory with deep implications on the way we interpret the natural world and our relationship with it

- For this reason, QM appears to require an *interpretation* to a greater extent than other theories, an interpretation through which we should be able to connect the formal structure with the empirical world – a connection that still turns out to be controversial as far as QM is concerned

But what does «*interpretation of QM*» exactly mean?

A plausible answer might sound as follows :

“A satisfactory interpretation of quantum mechanics would involve several things. It would provide a way of understanding the central notions of the theory which permits a clear and exact statement of its key principles. It would include a demonstration that, with this understanding, quantum mechanics is a consistent, empirically adequate and explanatorily powerful theory. And it would give a convincing and natural resolution of the “paradoxes”.

I should like to add a further constraint: *that a satisfactory interpretation of quantum mechanics should make it clear what the world would be like if quantum mechanics is true*.”

R. Healey, *The Philosophy of Quantum Mechanics. An Interactive Interpretation*, Cambridge University Press 1989, p. 6

- One of the most challenging questions that arise from the attempt to understand “what the world would be like if quantum mechanics is true” is the question of **Local Realism**, depicted as follows in a recent note in *Nature* by Howard Wiseman:

> “The world is made up of real stuff, existing in space and changing only through local interactions – this local-realism hypothesis is about the most intuitive scientific postulate imaginable. But QM implies that it is false”
>
> H. Wiseman, “Death by experiment for local realism”, *Nature* 2015

- But is really **this** local-realism hypothesis that QM shows to be untenable?

- The issue is controversial, since it is connected to the Bell non-locality theorem: it is according to this theorem that **local realism** would be false

- As we will see, there is a long story concerning what is the fate of a ‘realistic’ attitude toward QM and whether the Bell theorem has really anything to do with ‘realism’

- Historically, the issue goes back to the Einstein critical stance toward QM, a stance that has been often presented in simplistic terms and that, on the contrary, raises interesting questions

- When we try to consider as a whole the philosophical significance of the Einstein critical stance, the relationship between Einstein’s and Bell’s work turns out to be fundamental

- The relation Einstein-Bell can provide an interesting, unifying thread across some of the main issues in the field of the philosophy and foundations of quantum mechanics

- Moreover, the investigation on that relation can work effectively in both directions: as a matter of fact, Einstein and Bell epistemologies and foundational views of physical reality – far from being simply one the negation of the other – turn out on the contrary to enlighten each other, although in complex ways

Why can the investigation on the Einstein-Bell relation work effectively in both directions?

For at least two, essential motivations:

❑ On the one hand, the Bell results are among the post-Einsteinian scientific achievements that most call into question some crucial features of the Einstein own image of the physical world

❑ On the other hand, the field of the interpretation of the Bell results turned out to be a sort of lens from which to look at some of the original Einstein’s foundational views, a lens that more often than not produced serious distortions (not by chance, these distortions are often also distortions of the significance of the Bell results themselves!)

In addition to this sort of controversy, there are more substantial issues concerning the Einstein-Bell relation and its implications for the foundations of QM

On the one hand, it is beyond doubt that there are specific aspects of the Bell achievements (in addition to certain features of QM), from which a view of physical reality emerges that is hard to reconcile with an Einsteinian viewpoint.

Two claims, in particular: the **PRE-EXISTENCE** claim and the **LOCALITY** claim

- The **PRE-EXISTENCE** claim:

  A standard physical system has at all times a whole bunch of pre-existing properties – encoded in its state – no matter whether there is a measurement interaction or not

In «Quantum Mechanics and Reality», a short paper published in 1948 on the philosophical journal *Dialectica* that Einstein reproduces in a letter to Born (see *The Born-Einstein Letters 1916-1955*, new ed. Macmillan 2005, pp. 167-8), we can read:

«If one asks what, irrespective of QM, is characteristic of the world of ideas of physics, one is first of all struck by the following: **the concepts of physics relate to a real outside world, that is, ideas are established relating to things such as bodies, fields, etc., which claim a 'real existence' that is independent of the perceiving subject** – ideas which, on the other hand have been brought into a secure a relationship as possible with the sense-data. It is further characteristic of of these physical objects that they are thought of as arranged in a space-time continuum.»

(Here I skip over the different formulations of conditions such as ‘Einstein-locality’, ‘Bell-locality’ and the like)

The **LOCALITY** claim:
No objective property of a physical system *S* can be affected by operations performed on physical systems isolated from *S*

where, consistently with the ‘spirit’ of the **PRE-EXISTENCE** claim, an ‘objective’ property is a property that satisfies the (slightly reformulated) EPR criterion :

If, without disturbing a physical system *S*, we can predict with certainty — or with probability 1 — the value **q** of a physical quantity **Q** pertaining to *S*, then **q** represents an objective property of *S.*

The **PRE-EXISTENCE** claim and the **LOCALITY** claim interact in an interesting way: see for instance the argument in Einstein's *Autobiographical Notes*

"There is to be a system which at the time *t* of our observation consists of two partial systems S_1, and S_2, which at this time are spatially separated [....] The total system is to be completely described through a known ψ-function ψ_{12} in the sense of quantum mechanics. All quantum theoreticians now agree upon the following: If I make a complete measurement of S_1, I get from the results of the measurements and from ψ_{12} an entirely definite y-function ψ_2 of the system S_2. The character of ψ_2 then depends upon what kind of measurement I undertake on S_1."

“Now it appears to me that one may speak of the real factual situation of the partial system S_2. Of this real factual situation, we know to begin with, before the measurement of S_1, even less than we know of a system described by the ψ-function. But on one supposition we should, in my opinion, absolutely hold fast: **the real, factual situation of the system S_2 is independent of what is done with the system S_1 which is spatially separated from the former.**”

According to the type of measurement which I make of S_1, I get, however, a very different ψ_2 for the second partial system…Now, however, the real situation of S_2 must be independent of what happens to S_1. For the same real situation of S_2 it is possible therefore to find, according to one’s choice, different types of ψ-function. (One can escape from this conclusion only by either assuming that the measurement of S_1 (telepathically) changes the real situation of S_2 or by denying independent real situations as such to things which are spatially separated from eath other. Both alternatives appear to me entirely unacceptable.)”

Albert Einstein: Philosopher-Scientist, a cura di P.A. Schilpp,
“Library of Living Philosophers”, Tudor, Evanston,1949, p. 85

It is quite clear, then, that here Einstein takes for granted both

- that there is something out there that is ‘the real factual situation’ of a quantum system (Pre-Existence)

and

- that such situation cannot be affected by operations conducted on far-away quantum systems: the Locality assumption plays exactly the role of preventing the *already existing real factual situation* from being affected by operations performed on distant systems

- In this framework, Pre-Existence works as a pre-conditions for the conceivability of Locality

- That, in certain circumstances, QM is unable to account for this kind of ‘real situations/states’ of the physical systems under scrutiny was for Einstein *exactly* the main source of dissatisfaction toward QM

- The aim of the EPR argument is in principle exactly that of emphasizing this fact as clearly as possible

- It can be safely said that Einstein would have longed for a theory able to overcome this defect *in general* and *at the outset*, namely a formulation of QM able *in principle* to contemplate ‘real states’ as encoding sets of pre-existing properties

- Bell was very clear, however, that the pre-existence claim *cannot* hold in this form in any formulation of QM, completed or not

- Even in the formulation which in other respects is the most ‘realistic’ among the existing versions of QM – i.e. Bohmian mechanics – there are strictly speaking no pre-existing properties of the quantum systems except position (all other properties make sense only in experimental settings)

- It is ironic to note, however, that many misunderstandings of the Bell work derive *exactly* from attributing to Bell himself the endorsement of some sort of the **PRE-EXISTENCE** claim (the starting point is the ‘realism’ assumption in the EPR argument: cp. the later discussion on ‘local realism’)

It was already in his paper «On the problem of hidden variables in QM» (published in 1966 but written in 1963, *before* the paper that contains the first formulation of the Bell inequality) that Bell remarked how unreasonable it was to require pre-existence.

With reference to the ‘no-hidden-variable’ proofs provided in the preceding years by von Neumann, Gleason and Jauch-Piron, Bell wrote:

«[...] these demonstrations require from the hypothetical dispersion free states not only that appropriate ensembles thereof should have all measurable properties of quantum mechanical states, but certain other properties as well. These additional demands appear reasonable when results of measurements are loosely identified with properties of isolated systems.

They are seen to be quite unreasonable when one remembers with Bohr ‘the impossibility of any sharp distinction between the behaviour of atomic objects and the interaction with measuring instruments which serve to define the conditions under which the phenomena appear’».

J.S. Bell, «On the problem of hidden variables in QM», in *Speakable and Unspeakable*, CUP 2004, p. 2

It is (the first instance of) what Abner Shimony* called a «judo-like manoeuvre»: to use the Bohr *dictum* itself in order to show how implausible the early no-hidden-variable proofs turned out to be, *exactly because they* ***did*** *assume something like the pre-existence claim*.

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* «Contextual hidden variable theories and Bell’s inequalities», *British Journal for the Philosophy of Science* **35**, 1984, pp. 25-45

As to Locality, the content of the Bell theorem is essentially that this claim either cannot hold in any (single-world?) formulation of QM : the theorem justifies then a tension between QM and a local view of physical reality – although the exact nature and implications of this tension is still highly controversial.

This is Einstein:

«An essential aspect of this arrangement of things in physics is that they lay claim, at a certain time, to an existence independent of one another, provided these objects ‘are situated in different parts of space’. Unless one makes this kind of assumption about the independence of the existence (the ‘being-thus’) of objects which are far apart from one another in space, which stems in the first place from everyday thinking – physical thinking in the familiar sense would not possible. It is also hard to see any way of formulating and testing the laws of physics unless one makes a clear distinction of this kind.»

(taken again from the Einstein paper «QM and reality)

...and these are some references of Bell himself to the implication of his own non-locality theorem:

«For me then this is the real problem with quantum theory: the apparently essential conflict between any sharp formulation and fundamental relativity. That is to say, we have an apparent incompatibility, at the deepest level, between the two fundamental pillars of contemporary theory»

Bell, «Speakable and Unspeakable in QM», in *Speakable and Unspeakable*, p. 172

«The obvious definition of 'local causality' does not work in QM, and this cannot be attributed to the 'incompleteness' of that theory»

Bell, «La nouvelle cuisine», in *Speakable and Unspeakable*, p. 245

All this notwithstanding, it must be stated as clearly as possible that

In the EPR argument the Pre-Existence claim is not an independent presupposition, since the EPR criterion is not equivalent to the Pre-Existence claim

Namely, although Einstein himself assumed intuitively both Pre-Existence and Locality, in the EPR argument the latter is sufficient to **derive** the former

After all, the EPR criterion is a very weak assumption, that in itself says absolutely nothing on whether the system under scrutiny *actually possesses definite properties independently from any interaction*: let us see then the EPR argument more in detail

In the Bohm reformulation of the EPR argument, we have a composite quantum system S_1+S_2 of a pair of spin-1/2 particles S_1 and S_2

The composite system is prepared at a time t_0 in the singlet state Ψ

$$\Psi = 1/\sqrt{2}\,(|1,+>_{\mathbf{n}}\,|2,->_{\mathbf{n}} - |1,->_{\mathbf{n}}\,|2,+>_{\mathbf{n}}),$$

where **n** denotes a generic spatial direction.

We take into account the measurements concerning the spin components along given directions, whose possible outcomes are only two (conventionally denoted by ‘+1’ and ‘-1’).

We assume also that the spin measurements on S_1 and S_2 are performed when S_1 and S_2 occupy two mutually isolated spacetime regions R_1 and R_2 .

According to QM, we know that

if the state of S_1+S_2 at time t_0 is Ψ, then the (reduced) states of the subsystems S_1 and S_2 at time t_0 are respectively

$$\rho(1,\Psi)=1/2(\mathbf{P}_{|1,+>\,\mathbf{n}} + \mathbf{P}_{|1,->\,\mathbf{n}}),$$

$$\rho(2,\Psi)=1/2(\mathbf{P}_{|2,+>\,\mathbf{n}} + \mathbf{P}_{|2,->\,\mathbf{n}}),$$

(**EPR-1**)

so that, for any **n,**

$$\mathrm{Prob}_{\rho(1,\Psi)}\,(\mathrm{spin}_{\,\mathbf{n}}\text{ of }S_1 = +1) = \mathrm{Prob}_{\rho(1,\Psi)}\,(\mathrm{spin}_{\,\mathbf{n}}\text{ di }S_1 = -1) = 1/2$$

$$\mathrm{Prob}_{\rho(2,\Psi)}\,(\mathrm{spin}_{\,\mathbf{n}}\text{ di }S_2 = +1) = \mathrm{Prob}_{\rho(2,\Psi)}\,(\mathrm{spin}_{\,\mathbf{n}}\text{ di }S_2 = -1) = 1/2$$

Moreover, if we perform at a time t a spin measurument on S_1 along **n** with outcome +1 (–1), a spin measurement on S_2 along **n** at a time $t' > t$ will give with certainty the outcome – 1 (+1), namely for any **n**

$$\mathrm{Prob}_{\Psi}\,[(\mathrm{spin}_{\mathbf{n}}\ \mathrm{di}\ S_1 = +1)\ \&\ (\mathrm{spin}_{\mathbf{n}}\ \mathrm{di}\ S_2 = -1)] =$$

$$\mathrm{Prob}_{\Psi}\,[(\mathrm{spin}_{\mathbf{n}}\ \mathrm{di}\ S_1 = -1)\ \&\ (\mathrm{spin}_{\mathbf{n}}\ \mathrm{di}\ S_2 = +1)] = 1. \qquad (\textbf{EPR-2})$$

Let us suppose now to perform at time $t_1 > t_0$ a spin measurement on S_1 with outcome +1. Therefore, according to (**EPR-2**), a spin measurement on S_2 along **n** at a time $t_2 > t_1$ will give with certainty the outcome $-$ 1.

Let us suppose now to assume the following condition:

REALITY – If, without interacting with a physical system *S*, we can predict with certainty - or with probability 1 - the value **q** of a quantity **Q** pertaining to *S*, then **q** represents an objective property of *S* (denoted by [**q**]).

Therefore, for $t_2 > t_1$ [$\mathbf{spin}_{\mathbf{n}} = -1$] represents an objective property of S_2. But might the objective property [$\mathbf{spin}_{\mathbf{n}} = -1$] of S_2 have been somehow "created" by the spin measurement on the distant system S_1?

The answer is NO if we assume the following condition:

LOCALITY – No objective property of a physical system *S* can be influenced by operations performed on physical systems that are isolated from *S*.

At this point, **LOCALITY** allows us to state the existence of the objective property [**spin** $_{\mathbf{n}}$ = -1] for the system S_2 also at a time t' such that

$$t_0 > t' > t_1$$

Namely, if we assume that the measurement could not influence the validity of that property at that time, it follows that the property *was holding already at time t′*, a time that *precedes* the measurement performed on the other subsystem.

But at time t' the state of S_1+S_2 is the singlet state Ψ, therefore according to (**EPR-1**) the state of S_2 is the reduced state

$$\rho(2,\Psi)=1/2(\mathbf{P}_{|2,+>\,\mathbf{n}} + \mathbf{P}_{|2,->\,\mathbf{n}}),$$

that prescribes for the property [**spin** $_{\mathbf{n}}$ = -1] of S_2 only a probability 1/2.

Let us consider finally the following condition:

COMPLETENESS – Any objective property of a physical system *S* must be represented within the physical theory that is supposed to describe *S*.

It follows that there exist properties of physical systems that, according to the REALITY condition are objective, like [$\mathbf{spin}_{\mathbf{n}} = -1$] for S_2 , but that QM does not represent as such: therefore QM is not complete. $\therefore$

Points often raised about the EPR argument

(i) **Problems with the time ordering of spin measurement events**:

since the spin measurements take place in space-like separated regions, the time ordering relation linking the two regions is not invariant, and this may affect the argument

(ii) **Unwarranted counterfactual assumption**:

in the argument we say that, even if we measured the spin component along a given direction **n**, we *might have measured* it along a different direction **n′**: in doing this, we assume that the outcome of the measurement is definite even if we did not *actually* measure it and this counterfactual reasoning is equivalent to assume that «unperformed masurements have nevertheless a result», an assumption that is unwarranted in QM

Time ordering in the EPR argument

Reply:

it can be shown the non-invariant time ordering does not affect the core of the argument, since it is possible to formulate a criterion according to which a spin property can be said to be definite or indefinite in an invariant way (G.C. Ghirardi, «Properties and events in a relativistic context: revisiting the dynamical reduction program», *Foundations of Physics Letters* 9, 1996, pp. 313-355)

Unwarranted counterfactual assumption

Reply:

The objection is ungrounded for two reasons.

First, the EPR argument does not need two possible directions **n** and **n′** and goes through also with a *single* direction.

Second, even if we take the EPR counterfactual reasoning into account, we are allowed to conclude that either of S_1 or S_2 have definite spin properties:

it this were not the case, it would mean that their definiteness depends either on distant measurements (in which case *Locality* would be violated) or on the choice of the direction along which the spin measurements will be performed at a later time (in which case *No-Conspiracy* would be violated, a common and reasonable assumption of the EPR argument according to which the particle pair at the source does not know in advance what will be the direction along which spin measurements will be performed)

- So, in particular, the relation between ‘Realism’ and the EPR condition of reality needs to be carefully qualified

- Let us see then how Bell himself makes clear that, already in the very original EPR argument, it is only ‘**LOCALITY**’ that is at stake (and **not** ‘**LOCAL REALISM**’)

This is how Bell opens his celebrated 1964 paper ("On the Einstein-Podolski-Rosen Paradox", *Physics* **1** pp. 195-200, repr. in *Speakable and Unspeakable*, pp. 14-21):

"The paradox of Einstein, Podolsky and Rosen was advanced as an argument that quantum mechanics could not be a complete theory but should be supplemented by additional variables. These additional variables were to restore causality and locality. In this note that idea will be formulated mathematically and shown to be incompatible with the statistical predictions of quantum mechanics. *It is the requirement of locality, or more precisely that the result of a measurement on one system be unaffected by operations on a distant system with which it has interacted in the past, that creates the essential difficulty*." (italics added)

“Consider a pair of spin one-half particles created somehow in the singlet spin state and moving freely in opposite directions. Measurements can be made, say by Stern-Gerlach magnets, on selected components of the spins $\boldsymbol{\sigma}1$ and $\boldsymbol{\sigma}2$. If measurement of the component $\boldsymbol{\sigma}1 \cdot \mathbf{a}$, where $\mathbf{a}$ is some unit vector, yields the value +1 then, according to quantum mechanics, measurement of $\boldsymbol{\sigma}2 \cdot \mathbf{a}$ must yield the value −1 and vice versa.

Now we make the hypothesis, and it seems one at least worth considering, that if the two measurements are made at places remote from one another the orientation of one magnet does not influence the result obtained with the other.

Since we can predict in advance the result of measuring any chosen component of **σ**2, by previously measuring the same component of **σ**1, ***it follows*** that the result of any such measurement must actually be predetermined. Since the initial quantum mechanical wave function does not determine the result of an individual measurement, this predetermination implies the possibility of a more complete specification of the state.” (in Bell, *Speakable*, pp. 14–15)

It is very clear, then, that

Locality ***implies*** the pre-existence of spin properties:

this latter condition ***is not assumed*** at the outset

G.C. Ghirardi, R. Grassi, “Outcome predictions and property attribution: the EPR argument reconsidered”, *Studies in History and Philosophy of Science Part A* **25**, 1994, pp. 397-423

T. Norsen, «Against ‘realism’», *Foundations of Physics* **37**, 2007, pp. 311-340

F. Laudisa, “Non-Local Realistic Theories and the Scope of the Bell Theorem”, *Foundations of Physics* **38**, 2008, pp. 1110-1132

T. Maudlin, “What Bell Did”, *Journal of Physics A* **47**, 2014, 424010

"It is important to note that to the limited degree to which *determinism* plays a role in the EPR argument, it is *not assumed* but *inferred*. What is held sacred is the principle of 'local causality'—or 'no action at a distance'. [. . .] It is remarkably difficult to get this point across, that determinism is not a *presupposition* of the analysis."

("Bertlmann's socks and the nature of reality", 1982, in Bell, *Speakable*, p. 143, italics in the original)

"My own first paper on this subject [Bell refers here to his 1964 paper] starts with a summary of the EPR paper *from locality to deterministic hidden variables*. But the commentators have almost universally reported that it begins with deterministic hidden variables." (→ *that is, with what we called Pre-Existence*)

(a footnote (!) to "Bertlmann's socks and the nature of reality" in Bell, *Speakable*, p. 157, italics in the original)

MANY MISUNDERSTANDINGS AROUND

"In the original 1935 article, the EPR argument was conceived as an attack against the description of measurements in Copenhagen quantum theory and a criticism of the idea that Copenhagen quantum mechanics could be a *complete* description of reality.

Locality and a strong form of realism were given for granted by EPR and completeness was argued to be incompatible with quantum-mechanical predictions.

With Bell's contribution, which showed that EPR correlations are incompatible with the existence of a hypothetical *complete local* ***realist*** theory, the argument has been mostly reinterpreted as a direct challenge to 'local realism' "

M. Smerlak, C. Rovelli, "Relational EPR",
Foundations of Physics **37** (2007), p. 427

“It is important to emphasize that the only assumptions that have gone into proving [the Bell inequality] are:

1. For each particle it is meaningful to talk about the actual values of the projection of the spin along any direction.

2. There is locality in the sense that the value of any physical quantity is not changed by altering the position of a remote piece of measuring equipment.”

C. Isham, *Lectures on Quantum Theory*, Imperial College Press, London (1995), p. 216

“What can we learn from Bell’s inequality? For physicists, the most important lesson is that their deeply held commonsense intuitions about how the world works are wrong.

The world is *not* locally realistic. Most physicists take the point of view that it is the assumption of realism which needs to be dropped from our worldview in quantum mechanics, although others have argued that the assumption of locality should be dropped instead.

Regardless, Bell’s inequality together with substantial experimental evidence now points to the conclusion that either or both of locality and realism must be dropped from our view of the world if we are to develop a good intuitive understanding of quantum mechanics. “

M.N. Nielsen and I.L. Chuang, *Quantum Computation and Information*, Cambridge University Press, Cambridge (2000) p. 117

According to the widespread ‘local-realistic’ view, the content of the Bell theorem can be summarized as

(Realism & Locality) → Bell Inequalities (B-I)

hence

Violation of the Bell Inequalities (B-I) → ¬ (Realism & Locality)

In this view, therefore, local-realistic theories would be impossible, provided QM predictions are preserved: hence

either **Realism** or **Locality** must go (or both)

This interpretation, among other things, was the main motivation for a further conjecture proposed by Leggett : what happens if we introduce non-local theories which are still realistic ?

In the Leggett framework, a new inequality is derived (Leggett inequality) and shown to be incompatible with QM, so that

VIOLATION OF THE LEGGETT INEQUALITY (L-I)

↓

¬ (**REALISM & NON-LOCALITY**)

Leggett A. “Nonlocal hidden-variable theories and quantum mechanics: an incompatibility theorem”, *Foundations of Physics* **33** (2003), pp. 1469-1493

Branciard C. *et al* “Testing quantum correlations vs. single-particle properties within Leggett’s model and beyond” *Nature Physics* vol. 4, 2008

So, if we join

VIOLATION OF THE BELL INEQUALITIES (BI) → ¬ (REALISM & LOCALITY)

and

VIOLATION OF LEGGETT INEQUALITY (L-I) → ¬ (REALISM & NON-LOCALITY)

we obtain that no realism, be it local or non-local, can survive for QM.

“We believe that the experimental exclusion of this particular class indicates that any non-local extension of local theory has to be highly counterintuitive [...] *We believe that our results lend strong support to the view that any future extension of quantum theory that is in agreement with experiments must abandon certain features of realistic descriptions*.»

Gröblacher, S et al., «An experimental test of non-local realism”,
Nature **446** (2007), pp. 871–875

The mistaken formulation of the Bell theorem in terms of 'local realism' undermines also the significance of the Leggett approach itself:

It is true that there are non-local theories that are allowed by the Bell theorem but are ruled out by the violation of the L-I (Branciard et al. 2008).

But what should be the point of proving

$$\text{QM} + \text{N-LOC } \mathbf{[+\ REALISM]} \rightarrow \text{L-I}$$

in order to deny **REALISM** (via violation of the L-I), when QM neither says nor requires anything concerning **REALISM** ?

F. Laudisa, "Non-Local Realistic Theories and the Scope of the Bell Theorem", *Foundations of Physics* **38** (2008), pp. 1110-1132

M. Egg M.,"The Foundational Significance of Leggett's Non-local Hidden-Variable Theories", *Foundations of Physics* **43** (2013), pp. 872-880

F. Laudisa, "On Leggett theories: a reply", *Foundations of Physics* 44 (2014) pp. 296-304

Thanks for your attention!