

Quantum entanglement negationism

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After addressing climate change denial on the [IFT youtube channel](#)...



... and flat-earth conspiracism on [The Conversation](#)...



... time is due to get serious and address... Entanglement negationism!

Quantum entanglement

Quantum entanglement

What is quantum entanglement?

A pure state of a **quantum system** composed by two sub-systems **A** and **B** is **separable** if it can be written as

$$|\psi\rangle = |a\rangle_A \otimes |b\rangle_B$$

Otherwise, it is entangled, e.g. something like

$$|\psi\rangle = |a_1\rangle_A \otimes |b_1\rangle_B + |a_2\rangle_A \otimes |b_2\rangle_B$$

A typical example of entanglement is the combination of two spin-1/2 systems in the spin-0 configuration

$$|\psi\rangle = |\uparrow\rangle_A \otimes |\downarrow\rangle_B - |\downarrow\rangle_A \otimes |\uparrow\rangle_B$$

Quantum entanglement

Meaning?

For pure states of a bipartite system,

when we address **quantum entanglement**,

we are testing whether the subsystems have *individual* states,

or if otherwise, the system in that state can only be described as a whole.

Common misconception in pop media & non-experts:



When we act on one system we provoke a change in the other.

That is not entanglement. That is *steering*.

Quantum entanglement

Systems that are not in a pure state are described by a **density operator**

A density operator describing a composite system is **separable** if it can be written as

$$\rho_{\text{sep}} = \sum_n p_n \rho_n^A \otimes \rho_n^B$$

Note: in general, one has something like

$$\rho = \sum_{ijkl} \rho_{ij}^{kl} |\psi_i\rangle\langle\psi_j| \otimes |\phi_k\rangle\langle\phi_l|$$

Thus, separability means a particular form for matrix elements

$$\rho_{ij}^{kl} = \sum_s (\rho_A)^s_{ij} (\rho_B)^s_{kl}$$

null hypothesis for
entanglement test

Quantum entanglement

When discussing entanglement it is **not** a condition that the Hilbert spaces \mathcal{H}_A and \mathcal{H}_B correspond to different particles.

High-energy physics examples:

▶ $t \rightarrow bW$: entanglement between spins of b , W and o.a.m.

JAAS 2402.14725

▶ $H \rightarrow ZZ / WW$: entanglement between spins of Z / W and o.a.m.

JAAS 2403.13942

▶ $H \rightarrow ZZ / WW$: entanglement between spin and momentum of a single Z / W boson

JAAS 2512.02104

Quantum entanglement

Recap

When we consider **quantum entanglement**, we are testing whether a **quantum system** with two or more parts is in a *factorisable* state or not.

Might be, might be not.

For mixed states, this includes also probabilities.

When not, it means that the system in that state can only be described as a whole.

Entanglement is NOT discussed, or even conceived, for classical systems

Bell nonlocality

Bell nonlocality

For pure entangled states, a measurement on one party *steers* the state of the other one.

$$|\psi\rangle = |\uparrow\rangle_A \otimes |\downarrow\rangle_B - |\downarrow\rangle_A \otimes |\uparrow\rangle_B$$

measure A → $|\downarrow\rangle_A \otimes |\uparrow\rangle_B$

measure A → $|\uparrow\rangle_A \otimes |\downarrow\rangle_B$

effect on B

This was disliked by Einstein, Podolsky and Rosen.

EPR '35

spooky action at a distance!

Possible solutions:

- introduce hidden variables
- accept spooky action at a distance

however, see [JAAS 2509.04436](#) and pop science article [here](#)

Bell nonlocality

Bell showed in 1964 that local hidden variable (LHV) theories could not explain certain types of correlations that are present in QM.

Imagine we have two spin-1/2 systems measured by resp. Alice and Bob.

Each system has its own 'settings' \vec{n}_A and \vec{n}_B [direction to measure spins]

A set of hidden variables λ predetermines the results A and B (± 1) of measurements by Alice and Bob.

$A(\vec{n}_A, \lambda)$ ← Alice's results do not depend on Bob's settings
 $B(\vec{n}_B, \lambda)$ ← Bob's results do not depend on Alice's settings } locality

The average value of $A \times B$ with settings \vec{a} and \vec{b} is

$$\langle (\vec{\sigma}_A \cdot \vec{a})(\vec{\sigma}_B \cdot \vec{b}) \rangle \rightarrow E(\vec{a}, \vec{b}) = \int d\lambda p(\lambda) A(\vec{a}, \lambda) B(\vec{b}, \lambda)$$

probability distribution for λ

Bell nonlocality

Bell then showed that

$$|E(\vec{a}, \vec{b}) - E(\vec{a}, \vec{c})| \leq 1 + E(\vec{b}, \vec{c})$$

Quantum systems can violate this inequality.

A more useful formulation of Bell-like inequalities for two spin-1/2 systems is provided by the so-called CHSH inequalities [Clauser, Horne, Shimony, Holt, '69](#)

Alice measures two spin observables A, A' . Bob measures two spin observables B, B' . [All normalised to unity]. Then, [LHV theories](#) predict

$$|\langle AB \rangle - \langle AB' \rangle + \langle A'B \rangle + \langle A'B' \rangle| \leq 2$$



these are spin correlation observables

Bell nonlocality

One can show violation of CHSH inequalities

if one finds spin observables A, A' for Alice and B, B' for Bob

such that in some state [pure or not] the inequality is violated

However, this does not automatically rule out LHV. There can be **loopholes!**



Loophole-free measurements were made with photons

The Nobel Prize in Physics 2022

Alain Aspect

“for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science”



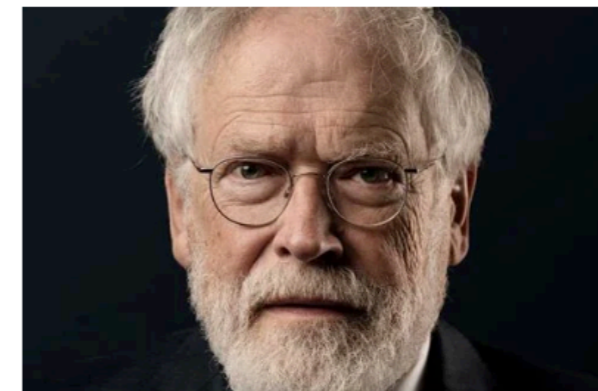
John F. Clauser

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Anton Zeilinger

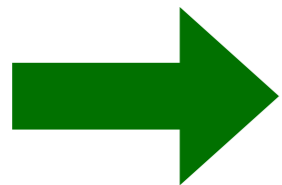
“for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science”



Bell nonlocality

At colliders, there is an obvious loophole: we are not measuring spins! For example, for top quarks

$$\frac{1}{\Gamma} \frac{d\Gamma}{d\Omega} = \frac{1}{4\pi} \{1 + \alpha[\langle S_1 \rangle \sin \theta \cos \phi + \langle S_2 \rangle \sin \theta \sin \phi + \langle S_3 \rangle \cos \theta]\}$$



Expected values of spin operators are **determined** from angular distributions **using SM** as theoretical framework.

In addition, we do not **freely chose the direction** to measure spin, as we should in order to avoid conspiracies that reproduce QM results.

Therefore, **we are not probing locality...**

In fact, LHV models can be built that accommodate angular distributions produced in decays

Abel, Dittmar, Dreiner, '92

Bell nonlocality

Moreover, non-local hidden variable theories can violate CHSH inequalities.

Local hidden variables

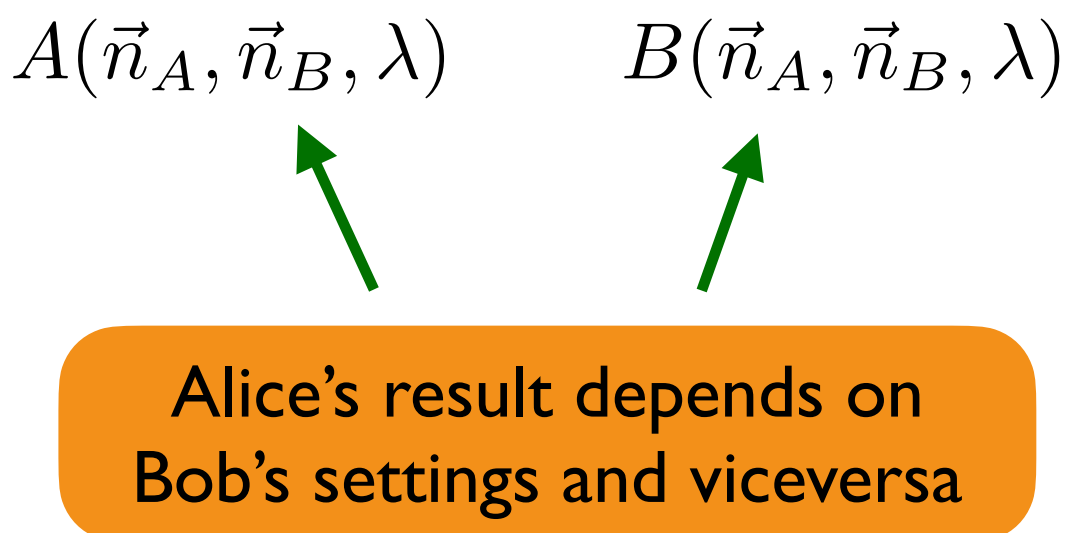
$$A(\vec{n}_A, \lambda)$$

$$B(\vec{n}_B, \lambda)$$

Nonlocal hidden variables

$$A(\vec{n}_A, \vec{n}_B, \lambda)$$

$$B(\vec{n}_A, \vec{n}_B, \lambda)$$



Alice's result depends on
Bob's settings and viceversa

de Broglie-Bohm theories, a.k.a. Bohmian mechanics, are explicitly nonlocal.

However, there is not a *Bohmian Field Theory* that incorporates particle production, etc. even if this theory was formulated in the 50s.

Quantum
entanglement
negationism

Quantum entanglement negationism

Last summer two negationist papers appeared, stirring confusion

A critical appraisal of tests of locality and of entanglement versus non-entanglement at colliders

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Abstract

It has been argued more than 30 years ago that it is not possible to test locality at colliders, due to the inability to directly measure non-commuting observables such as spin components in current collider experiments. Recently, there has been a lot of phenomenological and experimental activity around testing locality via Bell-type experiments or entanglement versus non-entanglement in a collider environment. These results seem to evade the earlier no-go theorem by indirectly measuring spin correlations via their relation to angular correlations between momenta. We perform a careful study of the feasibility of such an approach. We scrutinize the relationship between spin and angular correlations in both quantum mechanics and local hidden variable theories. Our conclusion is that it is currently **not possible to perform a logically coherent set of experimental measurements at colliders that would allow one to test locality or entanglement versus non-entanglement**. This reaffirms the earlier no-go theorem. We stress that the no-go theorem does not apply to measurements of observables inspired from entanglement and Quantum Information Theory to test the Standard Model of particle physics.

Colliders are Testing neither Locality via Bell's Inequality nor Entanglement versus Non-Entanglement

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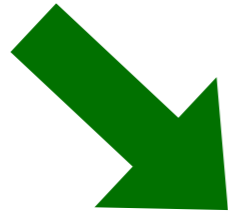
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ABSTRACT: Recently there has been an increased interest in possible tests of locality via Bell's inequality or tests of entanglement at colliders, in particular at the LHC. These have involved various physical processes, such as $t\bar{t}$, or $\tau^+\tau^-$ production, or the decay of a Higgs boson to 2 vector bosons $H \rightarrow VV^*$. We argue that *none* of these proposals constitute a test of locality via Bell's inequality or a test of quantum entanglement versus non-entanglement. In all cases what is measured are the momenta of the final state particles. Using the construction proposed by Kasday (1971) in a different context, and adapted to collider scenarios by Abel, Dittmar, and Dreiner (1992), it is straightforward to construct a local hidden variable theory (LHVT) which exactly reproduces the data. This construction is only possible as the final state momenta all commute. This LHVT satisfies Bell's inequality and is by construction *not* entangled. Thus a test of locality via Bell's inequality or **a test of entanglement versus non-entanglement is inherently *not* possible**.

Quantum entanglement negationism

Their argument

collider data can be explained by a theory of local hidden variables



at colliders we have no proof that processes are described by quantum mechanics



we cannot claim to measure entanglement

Quantum entanglement negationism

#1: It has been shown that for a bipartite quantum system

Bell non-locality \subset entanglement

Werner, '89

meaning that you have

entangled states

for which the result of all projective measurements can be described by a

local hidden-variable model

so indeed, entanglement and Bell non-locality are distinct notions.

Tests of entanglement cannot, and never
could, probe nonlocality

Quantum entanglement negationism

#2: When addressing entanglement of a quantum state one is

assuming the system is described by quantum mechanics

and testing a specific quantum property of the state.

Denying the possibility of testing entanglement at colliders is as absurd as

claiming that one is unable to measure Newton's constant G

because in the measurement we are assuming Newton's law.

It is **not a circular argument** to assume a model and measure one parameter or test a property

Quantum entanglement negationism

#3: Strictly speaking, we do NOT have proof that QM is correct, even in the experiments with photons.



Non-local hidden variable theories evade Bell inequalities

Should we strip these people from their prize then?

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I don't think so. We can NEVER be fully sure ANY theory is correct in physics

Quantum entanglement negationism

#4: is it reasonable to **assume QM** in the measurement of, say, $t t$ -bar entanglement?

QM not only predicts violations of CHSH inequalities with photons.

It also predicts $g - 2$ of the electron **to 1 part in 10^{10}** ... just to say

And for $t t$ -bar production, it predicts the existence of **quantum loop contributions**, without which the theoretical predictions would not match data at all.

We have **no experimental indication whatsoever** that QM might be wrong

Quantum entanglement negationism

#5: is it reasonable to **assume the SM** in the measurement of, say, t t -bar entanglement?

It is the **standard assumption** in most measurements and searches.

The SM has been tested in hundreds of measurements at all energies.

If one ever finds a significant disagreement with the SM prediction

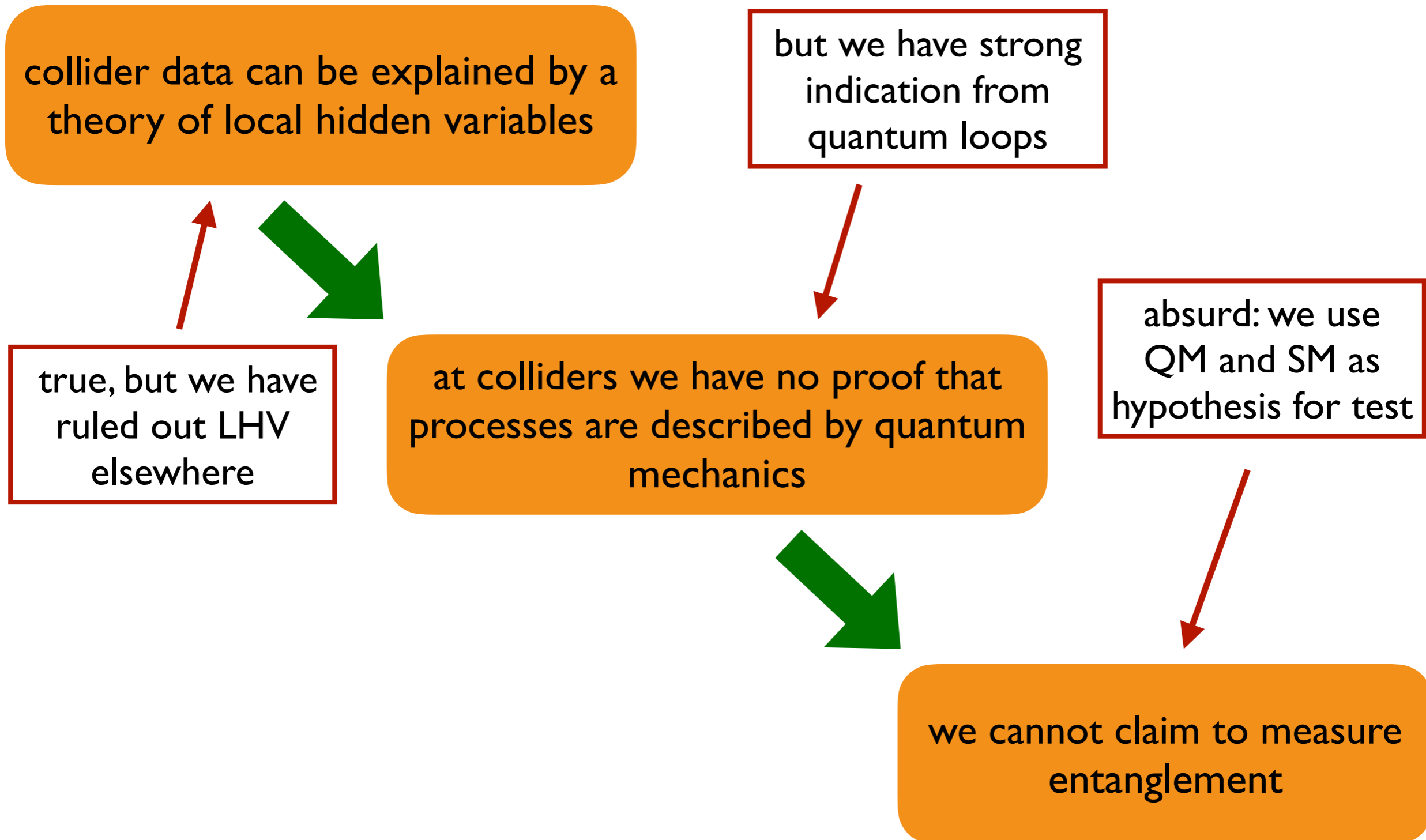
as it has already happened a number of times

one should revisit the prediction, the experimental procedure, take more data, and see if the discrepancy persists.

Assuming the **SM as starting point** is the standard practice in most experimental searches

Quantum entanglement negationism

Their argument revisited



Summary

- ▶ We see QM effects everywhere.
- ▶ QM has some open problems but there is no serious alternative theory.
- ▶ Testing entanglement presupposes the QM framework in which it is defined.
- ▶ It is legitimate to assume a theory when testing its predictions.
- ▶ Denying this principle amounts to **scientific negationism**.

Meaning & use

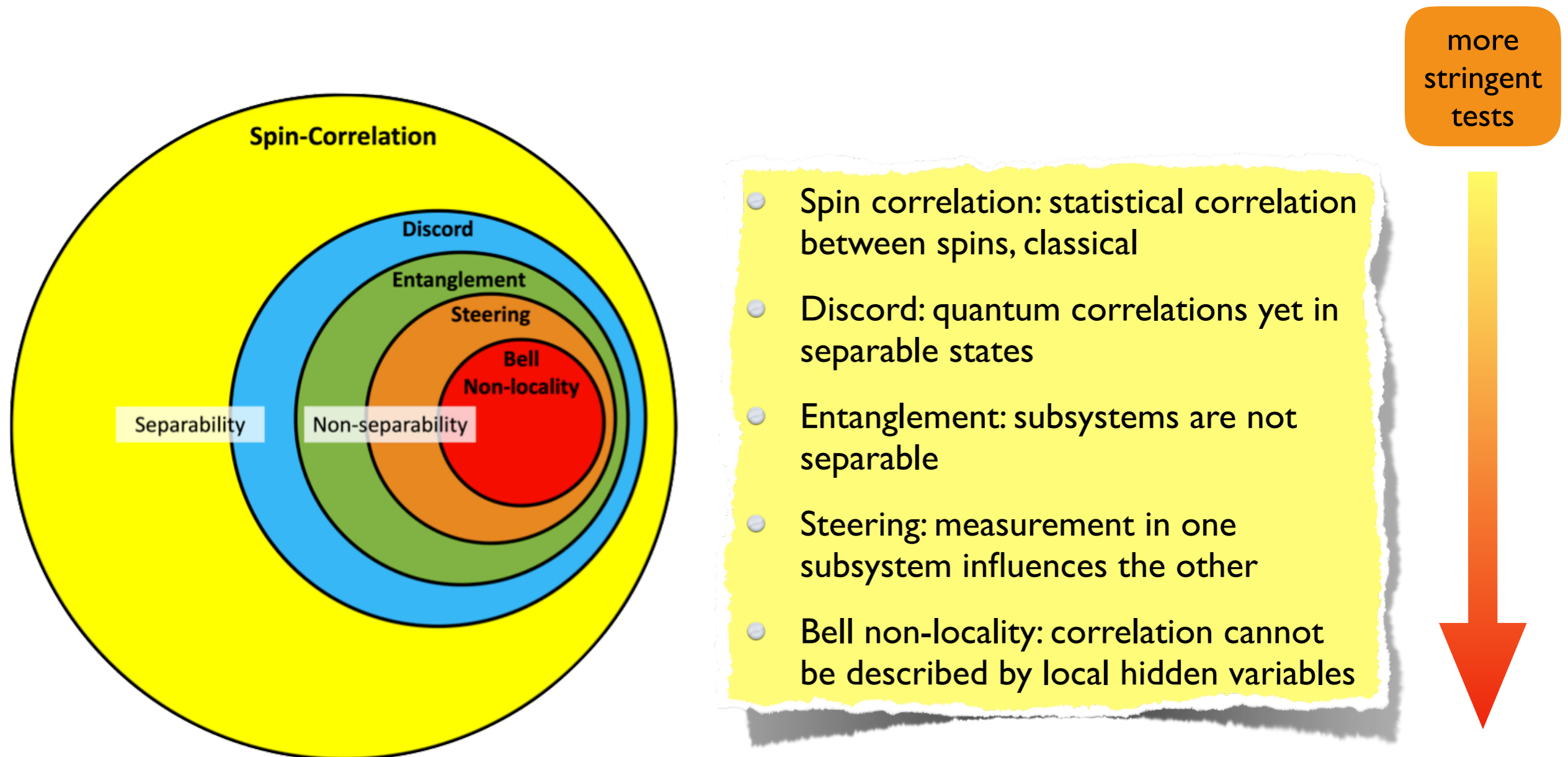
1. Negativity or hostility towards accepted beliefs, established institutions, etc.; negativism. Now *rare*.

1850-

End

Quantum correlations

There are many levels of quantum correlations! [usually considered for spins]



Captured from Yoav Afik talks