First event signalling correlations

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This work introduces the notion of First Event Signalling (FES) correlations in multipartite scenario where the first measurement on one subsystem influences the measurement outcomes of all the other local subsystems. It is shown that these correlations are related to bilocal ones but stronger than their variations proposed earlier. We propose a new Bell inequality which is satisfied by all FES models. Then we show quantum mechanical violation of this inequality, which can be regarded as an alternative definition of a stronger type of genuine multipartite nonlocality and a proof that quantum mechanics exhibits even more powerful correlations than those already known. We also introduce another Bell inequality which is satisfied by all bilocal correlations but violated by FES. The study of our new inequalities and the ones introduced previously allows us to analyze the relation between different types of tripartite nonlocality which reveals a very complex and interesting structure.

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Introduction - After the formulation of Bell’s Theorem showing the incompatibility between quantum mechanics and local realism [1] and the discovery of the famous CHSH inequality [2], the studies of nonlocality naturally evolved to more general scenarios. One direction was to devise inequalities involving more parties [3], the other to consider stronger than quantum (QM) correlations [4]. Of particular interest is the intersection of these approaches: generalized multipartite correlations. Research in this area was pioneered by Svetlichny who introduced the notion of bilocal (BL) inequalities [5–7]. They are satisfied by every theory in which the set of parties can be divided into two groups sharing only classical correlations while any type of probability distribution is allowed inside both groups. This “anything goes” behaviour in the groups clearly allows for some probability distributions impossible in quantum mechanics but the most interesting result of [5] was that there are QM correlations which violate BL inequalities. This leads to the introduction of the notions of genuine multiparty entanglement and nonlocality. The idea of BL correlations was further developed in [9] where two, weaker versions of them were introduced: no-signalling bilocal (NSBL) and time-ordered bilocal (TOBL) to understand genuine tripartite nonlocality from a better physical as well as operational point of view [8, 10]. Further study of TOBL models lead to a powerful result in the foundations of quantum theory which states that it cannot be derived with only two-partite informational principles [11, 12].

In this work we introduce another category of correlations: first event signalling (FES). We present a complete analysis of their relation to different bilocal and quantum ones. To this end we introduce two new Bell inequalities and analyze in the context of FES the ones form [5, 9]. We show that the new correlations form a strictly larger class than TOBL and NSBL. Then we move to the relation between FES, bilocal and quantum correlations. We demonstrate that for each of these sets there are probability distributions which are a member of this set but not of the other two. Moreover, we also prove that for each of them there are inequalities which are violated by the other two. This reveals the complicated structure of tripartite nonlocality. Our results also imply that the quantum theory exhibits a stronger type of multipartite correlations than previously known.

Bilocal correlations - We begin by defining BL, TOBL and NSBL correlations. Let us consider a three-partite system where the observables $X,Y,Z$ are measured by the first, second and third party yielding outcomes $a,b,c$ respectively. The BL, NSBL and TOBL correlations are defined as follows [5, 8, 9]:

\begin{align}
\text{BL:} \quad P(a, b, c|X, Y, Z) &= \\
&= \sum_{\lambda_1} q_{\lambda_1} P_{\lambda_1}(a|X)P_{\lambda_1}(b, c|Y, Z) \\
&\quad + \sum_{\lambda_2} q_{\lambda_2} P_{\lambda_2}(b|Y)P_{\lambda_2}(a, c|X, Z) \\
&\quad + \sum_{\lambda_3} q_{\lambda_3} P_{\lambda_3}(c|Z)P_{\lambda_3}(a, b|X, Y)
\end{align}

\begin{align}
\text{NSBL:} \quad P(a, b, c|X, Y, Z) &= \\
&= \sum_{\lambda_1} q_{\lambda_1} P_{\lambda_1}(a|X)P_{\lambda_1}^{NS}(b, c|Y, Z) \\
&\quad + \sum_{\lambda_2} q_{\lambda_2} P_{\lambda_2}(b|Y)P_{\lambda_2}^{NS}(a, c|X, Z) \\
&\quad + \sum_{\lambda_3} q_{\lambda_3} P_{\lambda_3}(c|Z)P_{\lambda_3}^{NS}(a, b|X, Y)
\end{align}

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TOBL: \[ P(a, b, c|X, Y, Z) = \sum_{\lambda_1} q_{\lambda_1} P_{\lambda_1}(a|X)P_{\lambda_1}^{X\rightarrow Y}(b|Y, X, a)P_{\lambda_1}^{X\rightarrow Z}(c|Z, X, a) \]
\[ + \sum_{\lambda_2} q_{\lambda_2} P_{\lambda_2}(b|Y)P_{\lambda_2}^{Y\rightarrow X}(a|X, Y, b)P_{\lambda_2}^{Y\rightarrow Z}(c|Z, Y, b) \]
\[ + \sum_{\lambda_3} q_{\lambda_3} P_{\lambda_3}(c|Z)P_{\lambda_3}^{Z\rightarrow X}(a|X, Y, c)P_{\lambda_3}^{Z\rightarrow Y}(b|Y, Z, c). \]

where \( \sum_{\lambda_1} q_{\lambda_1} + \sum_{\lambda_2} q_{\lambda_2} + \sum_{\lambda_3} q_{\lambda_3} = 1 \), \( P_{\lambda_1}(b|Y, X, a) \) is any no-signaling distribution, \( P_{\lambda_2}^{Y\rightarrow X}(a|X, Y, b) \) is any one-way signaling distribution where information is send from the second party to the third. It was shown that NSBL \( \subseteq \) TOBL \( \subseteq \) BL [8, 9].

First event signalling correlations - Now we introduce a new notion of multipartite correlations. In the tripartite scenario, we assume, (i) all parties have a local hidden variable description, (ii) in each run of the experiment one particle can signal information to all the others. As a consequence of these two assumptions, a joint probability \( P(a, b, c|X, Y, Z) \) can be written as

\[ P(a, b, c|X, Y, Z) = \sum_{\lambda_1} q_{\lambda_1} P_{\lambda_1}(a|X)P_{\lambda_1}^{X\rightarrow Y}(b|Y, X, a)P_{\lambda_1}^{X\rightarrow Z}(c|Z, X, a) \]
\[ + \sum_{\lambda_2} q_{\lambda_2} P_{\lambda_2}(b|Y)P_{\lambda_2}^{Y\rightarrow X}(a|X, Y, b)P_{\lambda_2}^{Y\rightarrow Z}(c|Z, Y, b) \]
\[ + \sum_{\lambda_3} q_{\lambda_3} P_{\lambda_3}(c|Z)P_{\lambda_3}^{Z\rightarrow Y}(b|Y, Z, c)P_{\lambda_3}^{Z\rightarrow X}(a|X, Y, c). \]

Unlike in the case of the BL correlations, there exists a toy theory which yields probability distributions like (4). Consider a universe with a preferred frame of reference. It is known that in such a world possibility of superluminal signalling does not lead to paradoxes, and all events can be ordered chronologically. In this preferred reference frame measurement event can always be unambiguously identified as occurring first. We allow this particle to send the information about the choice and the outcome of the measurement to all the other parties. Hence, we call these first event signalling (FES) correlations. Note that we do not know what this preferred frame of reference is and it can change in time. Moreover the particles can have access to shared randomness so in each round the measurement on a different one can be the first. It can be emphasized that FES is defined with respect to the time ordering in a fixed reference frame avoiding the possibility of backward causality, whereas BL correlations are not well defined in this aspect as pointed out in [8, 9].

Relation between different sets of correlations - Let us consider FES correlations, in which one of the two observables \( X, Y, Z \in \{0, 1\} \) producing binary outcome \( a, b, c \in \{+, -\} \) is measured on the particle 1, 2, 3 respectively. Given the fact that observable \( X \) is measured first on particle 1 and the outcome is \( a \), from the definition of FES (4) one can infer the existence of a joint probability distribution of the measurement outcomes on the other two particles in the form \( P_{\lambda_1}(b^0, b^1, c^0, c^1|X, a) \) related to a particular hidden state \( \lambda_1 \). The index of lambda being 1 denotes that the first measurement is performed on particle 1; \( b^0(1), c^0(1) \) denotes the outcomes when \( Y = 0(1), Z = 0(1) \) are measured on particles 2 and 3 respectively. Clearly, the probability of obtaining the outcomes \( b, c \) depends on the measurement setting \( X \) and the outcome \( a \) of the first particle. Similarly, we can define \( P_{\lambda_2}(a^0, a^1, b^0, b^1, c^0, c^1|Y, b) \) and \( P_{\lambda_3}(a^0, a^1, b^0, b^1, c^0, c^1|Z, c) \) when particle 2 or 3 is measured first. The observed joint probability for finding, say \( a^0 = +, b^0 = +, c^0 = + \) denoted as \( P(a^0+, b^0+, c^0+) \) is given by the following expression

\[ P(a^0+, b^0+, c^0+) = \sum_{\lambda_1} q_{\lambda_1} P_{\lambda_1}(a^0+, b^0+, c^0+) \]
\[ + \sum_{\lambda_2} q_{\lambda_2} P_{\lambda_2}(a^0+, b^0+, c^0+) + \sum_{\lambda_3} q_{\lambda_3} P_{\lambda_3}(a^0+, b^0+, c^0+) \]

for \( \sum_{\lambda_1} q_{\lambda_1} + \sum_{\lambda_2} q_{\lambda_2} + \sum_{\lambda_3} q_{\lambda_3} = 1 \), where the joint probabilities \( P_{\lambda_1}(a^0+, b^0+, c^0+) \), \( P_{\lambda_2}(a^0+, b^0+, c^0+) \), \( P_{\lambda_3}(a^0+, b^0+, c^0+) \) are marginals of the overall joint probability,

\[ P_{\lambda_1}(a^0+, b^0+, c^0+) = \sum_{b^1, c^1 = \pm} P_{\lambda_1}(a^1+, b^1+, c^1|0, +) \]
\[ P_{\lambda_2}(a^0+, b^0+, c^0+) = \sum_{a^1, c^1 = \pm} P_{\lambda_2}(a^1+, a^1+, c^1|0, +) \]
\[ P_{\lambda_3}(a^0+, b^0+, c^0+) = \sum_{a^1, b^1 = \pm} P_{\lambda_3}(a^1+, a^1+, b^1|0, +). \]

Here, we use the shorthand notation, in which the joint probability distributions indexed by \( \lambda_1, \lambda_2, \lambda_3 \) are conditioned on \( (X, a), (Y, b), (Z, c) \) respectively. For the demonstration of fundamental features of FES and its relation to quantum mechanical (QM) correlations in the subsequent part, we will use the description of FES given by (5)-(6).

We start by showing that TOBL (and hence NSBL) is a proper subset of FES. To see this consider a tripartite inequality satisfied by TOBL correlations given in [9],

\[ T = 2P(a^1+, b^1+, c^1+) - 2P(a^1+, b^1+, c^0-) - 2P(a^1+, b^0-, c^1+) - 2P(a^0-, b^1+, c^1+) - P(a^0+, b^0+, c^1+) - P(a^0+, b^1+, c^0+) - P(a^1+, b^0+, c^0+) \leq 0. \]

Lets concentrate on FES correlations where particle 1 is always measured first i.e. for all \( \lambda_2 \) and \( \lambda_3 \) \( q_{\lambda_2} = q_{\lambda_3} = 0 \). Such particular scenario will be considered several times in this work, so we denote it by FES-1 = \( \sum_{\lambda_1} q_{\lambda_1} P_{\lambda_1}(a|X)P_{\lambda_1}^{X\rightarrow Y}(b|Y, X, a)P_{\lambda_1}^{X\rightarrow Z}(c|Z, X, a) \).
If the overall FES-1 joint probability is such that, for all $\lambda_1$,

$$P_{\lambda_1}(a^0-, b^0+, c^0+) = 1,$$

$$P_{\lambda_1}(+, +, +, -|0, -) = P_{\lambda_1}(+, +, +, +|1, +) = 1$$

then,

$$P(a^1+, b^1+, c^1+) = P(a^1+, b^0+, c^0+) = 1$$

and all other probabilities appearing in (7) vanish. This gives $T = 1$ and violates the inequality (7). In [9] it was shown that QM correlations can be used to obtain $T$ as high as 0.1408.

Although FES is stronger than quantum correlations in this specific case, but this is not true in general. Before we explicate the overall relation of QM correlations with FES and BL correlations, lets define the correlation function,

$$\langle abc \rangle = P(a+, b+, c+) - P(a-, b+, c+) - P(a+, b-, c+) - P(a-, b-, c+),$$

$$+ P(a+, b-, c-) + P(a-, b-, c+) + P(a-, b+, c-) + P(a-, b-, c-).$$

It can be shown that, the following inequality introduced by Svetlichny [5] as a BL inequality, is also satisfied by FES,

$$S_3 = \langle a^0 b^0 c^0 \rangle + \langle a^0 b^1 c^0 \rangle + \langle a^1 b^0 c^0 \rangle - \langle a^0 b^1 c^1 \rangle$$

$$+ \langle a^1 b^0 c^1 \rangle - \langle a^1 b^1 c^0 \rangle - \langle a^1 b^1 c^1 \rangle \leq 4.$$ (11)

Since the left hand side of (11) is symmetric under the permutation of parties, it is sufficient to show that (11) is satisfied in the context where particle '1' is measured before others, i.e. FES-1. For a given $\lambda_1$, the quantity can be expressed as,

$$S_3 = a^0(b^0 c^0 + b^0 c^1 + b^1 c^0 - b^1 c^1) - a^1(-b^0 c^0 + b^0 c^1 + b^0 c^1 + b^0 c^0 + b^0 c^0)$$

This decomposition can be interpreted as a linear combination of two CHSH term [2] involving particle '2' and '3'. However, by definition FES-1 is local between these two particles, more precisely the hidden variable model for particle '2' and '3' might be a function of $(X, a)$ but they are local. Thus, the upper bound of (11) is 4 for any FES correlations. The maximum QM violation of (11) is known to be $4\sqrt{2} [5, 6].$

**FES inequalities** - In order to advance our analysis we now introduce three new inequalities which help us to learn more about the structure of tripartite correlations.

**Theorem 1:** In the tripartite scenario described above, the following inequality holds,

$$I = S_3 + S' \leq 5 \leq 6$$

where $S' = P(a^0+, b^0+, c^0+), P(a^0-, b^0+, c^0+) + P(a^1+, b^0+, c^0-), P(a^0+, b^0-), c^0-).$ Moreover QM allows for the values of $I$ higher than 6.

**Proof:** From Eq.(11) and the fact that algebraic maximum value of $S'$ is 2, one concludes the upper bound of (12) for BL and FES can’t be greater than 6. We notice that, the FES-1 correlation, $\forall \lambda_1$

$$P_{\lambda_1}(a^0+) = P_{\lambda_1}(a^1-1 = 1,$$

$$P_{\lambda_1}(+, +, +|0, +) = P_{\lambda_1}(+, +, +|1, +) = 1,$$

reproduces the upper bound 6.

For BL correlations we already know from [5] that $S_3 \leq 4$. We checked that $S' \leq 1$ by considering every possible deterministic BL strategy. The general ones are just linear combinations of these.

A simple calculation for the state and measurements for which the maximum violation of (11), is obtained, yields $I_{QM} = 4\sqrt{2} + 0.5 \approx 6.157.$ QED.

It is also trivial to check that $S' \leq 1$ in any no-signalling theory and hence in QM. Therefore we obtain

$$S'_{BL/QM} \leq 1 \leq S_3 \leq 2.$$ (14)

This shows that there are FES correlations which are neither in BL nor in QM.

![FIG. 1: Representation of the overall structure of different bilocal and FES correlations. The dashed lines represent inequalities given by (7),(11),(12),(14) and (15).](image)

**Theorem 2:** In the tripartite scenario described above, FES correlations satisfy the following inequality,

$$R_3 = P(a^0+, b^0+, c^0+) - P(a^1+, b^0+, c^0+) - P(a^0+, b^1+, c^0+) - P(a^0+, b^1-, c^1-)$$

$$- P(a^1-, b^0+, c^1-) - P(a^1-, b^1-, c^0+) \leq 0.$$ (15)

**Proof:** To show the validity of the above inequality, it is sufficient to consider only FES-1 scenario. If we expand
the joint probabilities appearing in (15) by using (6), we obtain

\[ P_{\lambda_1}(a^0_1+b^0_1+c^0_1)+P_{\lambda_1}(a^0_1+b^1_1+c^0_1) + P_{\lambda_1}(a^0_1+b^0_1+c^1_1) + P_{\lambda_1}(a^0_1-b^1_1-c^0_1) + P_{\lambda_1}(a^1_1-b^0_1+c^1_1) + P_{\lambda_1}(a^1_1-b^1_1-c^0_1) = \sum_{b^0_1,c^0_1=\pm} P_{\lambda_1}(+,b^0_1,+|1,+,+)+ \sum_{b^0_1,c^0_1=\pm} P_{\lambda_1}(b^0_1,+,+|0,+,+) + \sum_{b^0_1,c^0_1=\pm} P_{\lambda_1}(+,b^1_1,+|0,+,0) + \sum_{b^0_1,c^0_1=\pm} P_{\lambda_1}(b^0_1,-,-|0,0,0) + \sum_{b^0_1,c^0_1=\pm} P_{\lambda_1}(+,b^0_1,-|1,+,0) + \sum_{b^0_1,c^0_1=\pm} P_{\lambda_1}(b^0_1,-,+|1,+,1) = P_{\lambda_1}(a^0_1+b^0_1+c_1^0)+20 \text{ non-negative terms} \geq P_{\lambda_1}(a^0_1+b^0_1+c^0_1). \quad (16) \]

This equation is true for probabilities indexed with \( \lambda_2, \lambda_3 \) due to symmetry. This concludes the proof. QED.

By making projective measurements on the GHZ state quantum mechanics lets us violate (15) and obtain a value of 0.0364 (more on quantum violations of FES inequalities later). Note that, for the BL correlations (1) in which \( \forall \lambda_1 \),

\[ P_{\lambda_1}(a^0_1)=P_{\lambda_1}(a^1_1)=1, \quad P_{\lambda_1}(b^0_1+c^0_1)=P_{\lambda_1}(b^1_1+c^1_1)=1 \quad (17) \]

and \( q_{\lambda_2}=q_{\lambda_3}=0, \forall \lambda_2, \lambda_3 \), the LHS of (15) is 1.

Obviously, correlations which involve one-way signalling between two parties are in both FES and BL but not in QM. These results give us all the information we need to present a complete relation between FES, different bilocal and quantum correlations, which we do in Fig.1.

**Generalization to N parties** - In the N-partite system, one can consider a straightforward generalization of FES defined previously for three parties, in which the particle that is measured first simply signals to all the other \( N-1 \) particles. We now show that for correlations defined this way a generalization of (15) holds.

Suppose one of two dichotomic observables is measured on each of the spatially separated particles which are denoted by \( X_i \) and yield outcomes \( a_i \), where the index \( i \) represents the \( i^{th} \) particle. Just as in the tripartite case, we can define a joint probability distribution \( P_{\lambda_1}(a^0_1,a^0_2,...,a^0_N,\lambda_1,X_1,a_1) \) of the measurement outcomes on all the other particles, conditioned on the event that \( X_1 \) is measured first on particle '1' and the outcome \( a_1 \) is observed. Similar probability distribution can be defined for probabilities indexed by \( \lambda_2,...,\lambda_N \). We can write the marginal probability distribution \( P_{\lambda_1}(a^0_1,a^0_2,...,a^0_N) \) in the terms of the joint one

\[ P_{\lambda_1}(a^0_1+a^0_2+...+a^0_N) = \sum_{a_1^0,...,a_N^0=\pm} P_{\lambda_1}(+,a_2^1,+,a_3^1,...,+|0+,+) \quad (18) \]

and the following relation can be observed

\[ P_{\lambda_1}(a^0_1+a^0_2+...+a^0_N)+P_{\lambda_1}(a^0_1+a^1_2+,...,a^0_N)+...+P_{\lambda_1}(a^0_1,a^0_2+...+a^0_N)+P_{\lambda_1}(a^0_1+a^1_2+...+a^0_N)+...+P_{\lambda_1}(a^0_1,a^0_2+...+a^0_N)+...+P_{\lambda_1}(a^1_1,a^1_2+...+a^1_N) = P_{\lambda_1}(a^0_1+a^0_2+...+a^0_N)+V_{\lambda_1}(a^0_1,a^0_2+...+a^0_N) \quad (19) \]

Again (19) holds for any index \( \lambda_1,...,\lambda_N \) as it is symmetric under the permutation of particles. Thus we obtain the following inequality

\[ R_N = P(a^0_1+a^0_2+...+a^0_N)-P(a^0_1+a^0_2+...+a^0_N)-...-P(a^0_1+a^0_2+...+a^0_N)-P(a^1_1+a^1_2+...+a^1_N)-...-P(a^1_1+a^1_2+...+a^1_N) \leq 0 \]

or, \( R_N = P(a^0_1+a^0_2+...+a^0_N)-\sum_{j=1}^{N} P(a^0_j+a^0_1) \leq 0 \quad (20) \]

where \( a_1 \) denotes joint probability of all the particles except \( j^{th} \) particle.

**Quantum mechanical violation of FES inequalities** - To show the QM violation of the family of inequalities given by (20), we take the state

\[ |GHZ\rangle = \frac{1}{\sqrt{2}}(|000...0\rangle_N+|111...1\rangle_N) \quad (21) \]

shared by spatially separated parties [13]. We consider the measurements on each particle to be projective and lie in the same plane. Moreover the angle between the measurements corresponding to different settings of one party is the same for all parties. Therefore we can parameterize them by angles \( \phi_i \) and \( \beta \)

\[ X_i(=0) = \cos(\phi_i)\sigma_1+\sin(\phi_i)\sigma_2 \]
\[ X_i(=1) = \cos(\phi_i+\beta)\sigma_1+\sin(\phi_i+\beta)\sigma_2 \quad (22) \]

where \( \sigma_i (i \in \{1, 2, 3\}) \) are the Pauli matrices. The LHS (20) obtained with this state and measurements is

\[ R_{GHZ} = \frac{1}{2^N} \cos(\alpha) - N \cos(\alpha+\beta) \]
\[ -N \cos(\alpha+(N-1)\beta)-(2N-1), \quad (23) \]

where \( \alpha = \sum_{i=1}^{N} \phi_i \). It can be easily seen that for even \( N \) the maximum value of the quantity given by (23), is
when \((\alpha, \beta) = (0, \pi)\). For \(N = 3\) the maximum value of the above quantity is 0.0364 and it is obtained when \((\alpha, \beta) = (1.3807, 1.0472)\) in radians.

Discussion - By introducing a new set of tripartite probability distributions we were able to reveal a rich structure of correlations in this scenario. We also generalized the notion of first event signalling to any number of parties and presented a family of Bell inequalities satisfied by these correlations but violated by quantum probability distributions. This implies a new notion of genuine multipartite nonlocality and shows that quantum mechanics possesses it. Apart from further studies on this kind of correlations our work opens an intriguing area of research as it hints that in scenarios with more parties the structure of correlations may be even more interesting.

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