Quantum Causality: from superpositions of clocks to quantum correlations with no causal order

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Quantum physics differs from classical physics in that no definite values can be attributed to observables independently of the measurement context. However, the notion of time and of causal order preserves such an objective status in the theory: all events are assumed to be ordered according to "time flow" such that every event is either in the future, in the past or space-like separated from any other event. The possible interplay between quantum mechanics and general relativity may, however, require superseding such a paradigm. I will approach this problem in two steps. Firstly, I will consider spatial interference of a "clock" – a time-evolving (internal) degree of freedom of a particle – that ticks at different rates in different regions of background space–time. While the "time as shown by the clock" is not a common parameter for different amplitudes in the superposition, there is still the notion of global time. Secondly, I will introduce a quantum framework where no reference is made to any global time or causal order, and show that the framework allows for quantum correlations for which one cannot say that one event is before or after the other.