The Pragmatic QFT Measurement Problem and the need for a Heisenberg-like Cut in QFT

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Despite quantum theory's remarkable success at predicting the statistical results of experiments, many philosophers worry that it nonetheless lacks some crucial connection between theory and experiment. Such worries constitute the Quantum Measurement Problems. One can broadly identify two kinds of worries: 1) pragmatic: it is unclear how to model our measurement processes in order to extract experimental predictions, and 2) realist: we lack a satisfying ontological account of measurement processes. While both issues deserve attention, the pragmatic worries have worse consequences if left unanswered: If our pragmatic theory-to-experiment linkage is unsatisfactory, then quantum theory is at risk of losing both its evidential support and its physical salience. Avoiding these risks is at the core of what I will call the *Pragmatic Measurement Problem*.

Fortunately, the pragmatic measurement problem is not too difficult to solve. For non-relativistic quantum theory, the story goes roughly as follows: One can model each of quantum theory's key experimental successes on a case-by-case basis by using a measurement chain. Somewhere along this measurement chain it is pragmatically necessary to cross the quantum-classical divide by invoking a pragmatic Heisenberg cut. Past this case-by-case measurement framework, one can then strive for a wide-scoping measurement theory capable of modeling all (or nearly all) possible measurement processes, e.g. our usual projective measurement theory. As a bonus, proceeding this way also gives us a physically meaningful characterization of the theory's observables.

But how does this story have to change when we move into the context of quantum field theory (QFT)? It is well known that in QFT almost all projective measurements violate causality, allowing for faster-than-light signaling; These are Sorkin's impossible measurements. It has been argued in the physics literature that because of this we need a new (or at least refined) measurement theory for QFT. I will argue, however, that aside from some technical complications, moving into a QFT context changes essentially nothing regarding how we can and should model quantum measurements. The story ought to proceed exactly as before: We ought to first use measurement chains to build up a case-by-case measurement framework for QFT. This will require us to cross the QFT-non-QFT divide at some point along the measurement chain. From here we can then strive for both a new wide-scoping measurement theory for QFT and a new characterization of its observables. This paper ends by briefly reviewing the state of the art in the physics literature regarding the modeling of measurement processes involving quantum fields.

Keywords: quantum measurement problem; quantum field theory; observables; observables of QFT; Heisenberg cut; measurement chain;

I. INTRODUCTION: ANOTHER QUANTUM MEASUREMENT PROBLEM

It is incontestable that quantum theory has been remarkably successful at predicting the statistical results of a wide range of experiments. However, despite its many predictive successes, many philosophers and physicists are nonetheless worried that quantum theory lacks some crucial connection between theory and experiment. Various dissatisfactions with various theory-to-experiment disconnects each deserve the title "A Quantum Measurement Problem": How should we understand/model measurement processes involving quantum systems?

Indeed, there is a wide literature aimed at identifying what the measurement problem is exactly. See, for instance Maudlin's "Three Measurement Problems" [1] among many others [2–5]. The quantum measurement problems have also been much-discussed in the context of quantum field theory (QFT) [6–14]. Adding to these discussions, this paper will introduce a new set of worries (which I will call the *pragmatic measurement problem*) regarding how measurements are to be modeled. Before discussing these issues in the context of QFT, allow me to first introduce them in a non-relativistic context.

In order to differentiate the various quantum measurement problems from each other, it is perhaps best to start from a version of quantum theory which (hopefully nearly) every physicist and philosopher is dissatisfied with. I have in mind the parts of non-relativistic quantum theory which students are urged to focus on after they are told to "Shut up, and calculate!". Let us call this *the sophomore's quantum theory*. Students are

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here taught to model quantum experiments as follows.[1] The sophomore is first told the following two tautologies: All measurements are of some observable and, moreover, all observables are measureable. The sophomore is then told that quantum theory's observables are exactly the self-adjoint operators. In order to model a measurement of a given self-adjoint operator, $\hat{Q}$, one begins by computing its eigensystem, $\hat{Q} = \sum_{\text{out}} q_{\text{out}} \left|\text{out}\right\rangle \left\langle \text{out}\right|$. The projectors, $\hat{\pi}_{\text{out}} = \left|\text{out}\right\rangle \left\langle \text{out}\right|$, appearing in this decomposition define a projection-valued measure (PVM). Next one takes the given initial conditions, $\left|\text{in}\right\rangle$, and applies the given unitary evolution, $\hat{U}$. The sophomore is told that putting these computations together unambiguously yield a statistical prediction of the experiment's outcome via the Born rule, $p(\text{out}|\,\hat{U},\text{in}) = |\left\langle \text{out}\right|\hat{U}\left|\text{in}\right\rangle|^2$.

Many physicists and philosophers are dissatisfied with the sophomore's quantum theory, claiming that it lacks the right kind of connection between theory and experiment, and rightly so. One can broadly distinguish two types of worries surrounding quantum measurement: pragmatic worries and realist worries. Pragmatic worries are methodological in nature and aim at clarifying how exactly these statistical predictions are to be pulled out of the theory. Specifically, they ask how should one *model* real-life measurement processes as a matter of experimental practice? By contrast, realist worries are aimed at establishing an ontological account of the measurement process. Realist worries ask: How should the measurement process be *understood*? See, for instance, Maudlin's "Three Measurement Problems" [1] all of which I classify as realist/ontological worries.

The sophomore's quantum theory fails on both the pragmatic and realist fronts. Its realist failures are well known, but its pragmatic failures deserve some further comment. Firstly, the sophomore has misidentified the observables of quantum theory (see Secs. II D and III A). The deeper issue, however, is that the sophomore's quantum theory does not, in fact, give us unambiguous (or even approximate) statistical predictions for real-life experiments. While it is true that statistical predictions are unambiguously associated with initial states, unitaries, and projectors, (recall, $p(\text{out}|\,\hat{U},\text{in}) = |\left\langle \text{out}\right|\hat{U}\left|\text{in}\right\rangle|^2$) these themselves have not yet been suitably connected with our real-life experimental setups. Specifically, the sophomore has no answer to the following questions:[2] Under what conditions is it appropriate to model this piece of lab equipment using a PVM? If it is appropriate, then exactly which PVMs am I allowed to use and when? How can one go about determining approximately which observable this apparatus measures? There may be ready answers to these questions pre-written on the sophomore's problem sheets, but show them a piece of real-life lab equipment and watch them falter.

Often the sophomore may intuitively guess which PVM to use and when. It is highly intuitive that in modeling a double-slit experiment the right PVM is (at least approximately) the position projectors, $\hat{\pi}_{\text{out}} = \left|x\right\rangle \left\langle x\right|$. Moreover, it is intuitive that the right time is (at least approximately) when the electron hits the detection screen. For most practical purposes this is effectively what happens. Indeed, it may often be the case that the sophomore's guesses consistently give accurate-enough predictions. But ultimately, they are nothing more than just that: guesses. It goes without saying that this method of connecting theory with experiment is deeply unsatisfying.

I should here clarify what exactly the pragmatic measurement problem is asking for. Importantly, it is not an ontological problem; I am not asking the sophomore to base their prediction on an ontological account of the measurement process. Rather, it is a methodological problem which applies equally well to anti-realist or pragmatic interpretations of quantum theory: Indeed, every scientific theory must provide us with a robust account of how predictions can and should be made from it. Namely, we need a satisfactory account of how one is allowed to *model* both the system in question and the measurement process. The above critique thus highlights a devastating methodological failure of the sophomore's quantum theory; A theory-to-experiment linkage which relies so blatantly upon intuitive guessing simply cannot do the work we require of it.

As I will now discuss, in comparison with the realist measurement problem, these pragmatic worries have far worse consequences if left unanswered. It is helpful to distinguish two senses in which our scientific theories are about reality [15]. Firstly, they may have ontological aspirations of representing and/or describing reality. This is the domain of the realist measurement problem. But why should we believe that our scientific theories have any right to be "about reality" in the first place? Ultimately, our theories earn this right by a process of complex sustained bi-directional contact with experimental practice. That is, our scientific theories get their right to be meaningful from their (often messy [15]) connection to our systems of measurement devices and approximation techniques. This is the domain of the pragmatic measurement problem. What is at risk is the linkage between theory and reality which is mediated by real-life experimental practice. Without a clear understanding of this pragmatic connection between theory and experimental practice, quantum theory is at risk of losing both its evidential support and its physical salience.

Fortunately, as well as having worse consequences, the pragmatic measurement problem is also much easier to

[1] A sophisticated sophomore may also learn about selective and non-selective measurements as well as post-measurement state updates via Lüders rule. Moreover, they may also learn about density matrices, $\hat{\rho}$, and Positive Operator-Valued Measures (POVMs), $\hat{E}_{\text{out}} \geq 0$, i.e., non-ideal measurements. In terms of POVMs, Born's rule is $p(\text{out}|\,\hat{U},\,\text{in}) = \text{Tr}(\hat{E}_{\text{out}}\hat{U}\hat{\rho}_{\text{in}}\,\hat{U}^\dagger)$. The pragmatic worries discussed below apply equally well to this sophisticated sophomore.

[2] The same complaint holds for the sophisticated sophomore discussed in footnote 1 with POVM replacing PVM.

address than the realist's worries. All one needs to do is to develop a framework for modeling the relevant measurement processes in a sufficient level of dynamical detail [15–17].[3] Past this minimal solution to the pragmatic measurement problem, one can then strive for a measurement theory which is applicable to all (or nearly all) measurement processes. (For non-relativistic quantum theory, we have our usual PVM/POVM measurement theory.) Having such a measurement theory is not only highly convenient for modeling experiments but is also theoretically fruitful: It can give us a physically meaningful characterization of the theory's observables.

Given all of this, it makes sense to address the pragmatic measurement problem before the realist one. As compelling as the realist's worries are, one might say: Let us first work on bringing home the spoils of quantum theory's experimental successes; We can then worry about the ontology of the theory later, once we have better footing.

One might here protest that the realist and pragmatic measurement problems ought to be solved together. Indeed, this is a possibility: Developing an ontological account of the measurement process (e.g., Bohmian mechanics and GRW) might show us how to model a great many different measurement processes. Importantly, however, it also might not; Having a satisfying ontological account of the measurement process does not automatically give us a tractable way of modeling quantum theory's key experimental successes. For instance, it may be the case that directly simulating the ontological development of an experiment is computationally infeasible. Alternatively, modeling these experiments may require us to go outside of the scope of whichever ontological account we have in mind (e.g., into QFT [18, 19]). In either of these cases, we would still suffer the consequences of the pragmatic measurement problem. Thus, solving the realist measurement problem does not automatically address the pragmatic measurement problem. (Nor vice-versa.)

As the above discussion has shown, the pragmatic and realist measurement problems are separate problems, with separate difficulties, consequences, and solution criteria. While one may hope to solve them simultaneously, this is far from compulsory. Indeed, given how contentious the ontology of quantum theory is, it makes sense to first address the pragmatic measurement problem in an ontology-neutral way. Even if one is committed to later give an ontology-laden solution, one can reasonably proceed this way thinking: At least in the meantime we will have a working understanding of quantum theory's measurement processes and observables.

In practice this is exactly what has happened: While the realist measurement problem continues to be fiercely debated, the pragmatic measurement problem has long since been satisfactorily addressed (at least within the purview of non-relativistic quantum theory).[4] Said differently, while the ontology of non-relativistic quantum theory is contentious, its experimental predictions are clear, as are the allowed methods for extracting these predictions from the theory. Moreover, we even have an ontology-neutral characterization of this theory's observables. As I will discuss in Sec. II, the key notions here are measurement chains and Heisenberg cuts; In these terms one can achieve an ontology-neutral solution to the pragmatic measurement problem, at least for non-relativistic quantum theory.

The Pragmatic Measurement Problem in QFT

The main subject of this paper, however, is the pragmatic measurement problem in the context of quantum field theory (QFT). Namely, I consider *The Pragmatic QFT Measurement Problem*:[5] How should one model measurement processes involving quantum fields? How must our measurement framework for QFT differ from our usual non-relativistic measurement framework? Can we model QFT-involved measurements using PVMs and POVMs in roughly the ways we are used to? How do the observables of QFT differ from the observables of non-relativistic quantum theory?

Much of the above discussion of the pragmatic vs realist measurement problems carries over unchanged into QFT. Namely, in comparison with the realist QFT measurement problem, the pragmatic QFT measurement problem has worse consequences if neglected; Quantum field theory would then be at risk of losing both its evidential support and its physical salience. Fortunately, as before, it is also much easier to address. In fact, the difficulty gap between the realist and pragmatic measurement problems arguably widens for QFT; Certain ontological issues become notably more difficult in QFT.[6] Hence, we have extra reason to seek out an ontology-neutral approach to the pragmatic QFT measurement problem. As I recommended above: Let us first work on bringing home the spoils of quantum theory's experimental successes; We can then worry about the ontology of the theory later, once we have better footing.

This spoils-before-ontology approach raises the following question: For quantum theory generally, where were these metaphorical spoils won? While establishing a detailed answer to this question is not essential for the main

[3] There is ample room for discussion regarding the exact standards to which these models ought to conform; These standards ought to be high, but contextually reasonable. See Sec. II for further discussion.

[4] The experimental purview of non-relativistic quantum theory might be notably smaller than one thinks [18, 19]. See the quote from Wallace in the next subsection.

[5] As before, these pragmatic issues ought to be distinguished from the much-discussed realist/ontological issues within QFT. [6–14]

[6] Namely, certain strategies adopted by hidden variable and collapse approaches fail in relativistic contexts [6, 7].

philosophical points made in this paper, it will help us to determine what is at stake. Namely, if quantum field theory is required in order to model some/many/most of quantum theory's key experimental successes, then failing to address the pragmatic QFT measurement problem is troublesome/severe/catastrophic.

One might feel that the stakes here are significantly lower than in the non-relativistic context: Can't one adequately model almost all of quantum theory's key experimental successes without QFT? Wallace has recently argued for the following perhaps surprising claim:

> For a quantum experiment to be modellable entirely within NRQM . . . not only the system being measured, but the apparatus doing the measurement, would have to be within the scope of NRQM. Such systems plausibly exist . . . But experiments like this comprise only quite a small fraction of the experiments performed within 'non-relativistic' quantum mechanics. [19, p. 21]

Importantly, Wallace arrives at this conclusion for fairly basic conceptual reasons, not a demand for hyper-accuracy. Ultimately, this would mean that if we cannot establish an adequate pragmatic link between QFT and experimental practice then not only quantum field theory but nearly the whole of quantum theory is at risk of losing its evidential support and physical salience.

Given that the route home for some/many/most of quantum theory's experimental spoils runs through quantum field theory, our next question becomes: What novel issues arise when one attempts to model measurement processes involving quantum fields? My answer to this question is as follows: *Aside from some technical complications, moving into a quantum field theoretic context changes essentially nothing regarding how we can and should model quantum measurements.* As anti-climactic as this answer sounds, it stands in stark contrast to how this question is typically discussed in the physics literature (more on this momentarily).

Since I am saying that nothing much changes as we move into QFT, I must start by discussing how the pragmatic measurement problem has already been solved for non-relativistic quantum theory. Sec. II will introduce the notions of measurement chains and Heisenberg cuts. I will then show how they can be leveraged against the pragmatic measurement problem. This section will argue that it is pragmatically necessary to take a Heisenberg cut (i.e., to cross the quantum-classical divide) when modeling any real-life quantum measurement. This section will also begin to correct the sophomore's mistaken ideas about observables (n.b., "observables" $\neq$ "self-adjoint operators").

With this story established, I will then argue in Sec. III that the pragmatic QFT measurement problem ought to be approached in exactly the same way. By contrast, much of the physics literature regarding measurement in QFT tends to focus on how our understanding of measurement must change as we move into QFT. Namely, they are focused on the fact that most POVM measurements violate the central 'commandments' of relativity (covariance, causality, and locality) [13, 14, 20–35] or otherwise disrespect the QFT's local algebraic structure. See, for instance, Sorkin's impossible measurements [27] which enable faster-than-light signaling.

I will argue against what I feel is a natural reaction to the existence of such impossible measurements. One might be tempted to retreat into QFT-land and then to develop exact formal criteria to distinguish between the possible and the impossible measurements. Some feel that we need to rebuild, from within QFT, a new relativistically-safe understanding of its measurement processes and observables. As I will argue in Sec. III A, however, this formal exact isolationist approach goes too far and ultimately robs the observables of QFT of any physical salience. Instead, we ought to opt for an informal approximate understanding of QFT's observables mediated by Heisenberg-like cuts. (Just as we must take a Heisenberg cut to cross the quantum-classical divide, we must take a QFT-cut to cross the QFT-non-QFT divide). In sum, we ought to proceed just as we did for non-relativistic quantum theory.

Finally, Sec. IV will review the state of the art in the physics literature regarding the modeling of QFT-involved measurement processes. What tools do physicists currently have available to them for making QFT-cuts? The primary two tools which I will discuss are the Fewster Verch (FV) framework [23–25, 29, 36], and the Unruh-DeWitt detector model [20, 28, 35, 37–48]. A measurement theory for QFT based on Unruh-DeWitt detectors has recently been put forward [20]. As I will argue, this is (at least currently) the best approach available for achieving a wide-scoping measurement theory for QFT and for identifying its observables in a physically meaningful way.

II. MEASUREMENT CHAINS AND HEISENBERG CUTS

This section will elaborate on my above claim that for non-relativistic quantum theory the pragmatic measurement problem has been solved. Namely, I will discuss how this problem can be addressed in an ontology-neutral way in terms of measurement chains and pragmatic Heisenberg cuts. Firstly, Sec. II A will introduce the notions of measurement chains and Heisenberg cuts via some example scenarios. Next, Sec. II B will introduce a helpful taxonomy regarding the different kinds of Heisenberg cuts which are available to us. Then, Sec. II C will distinguish two versions of the pragmatic measurement problem and show how they can each be addressed using measurement chains and Heisenberg cuts. Finally, Sec. II D will make some progress towards identifying the observables of non-relativistic quantum theory (n.b., "observables" $\neq$ "self-adjoint operators").

A. Examples of Measurement Chains and Heisenberg Cuts

In practice, we often model our experiments in terms of a measurement chain. Roughly, a measurement chain models an experiment as a sequence of interactions which carries the measured information from the systems being measured to some record-keeping device. To give an abstract example: System A interacts with system B which then interacts with system C which then ... which then interacts with system R, our record-keeping device. (More will be said momentarily about the freedom one has in starting and ending measurement chains.)

For a more concrete example, we may be interested in a certain amplitude associated with an atom in a certain superposition. Our experiment may proceed as follows: An atom in a superposition emits a photon which is detected by a photomultiplier which triggers a small current which turns on a transistor which ... which displays a number on a screen which the experimenter writes in her notepad.

To be clear, throughout this paper the term "measurement chain" does not refer to the linear sequence of *physical systems/interactions* which carry the measured information, per se. Rather, here, the measurement chain is a formalization of these systems which the experimenter invents for the purposes of modeling her experiment. There may be multiple acceptable ways of parsing a given physical scenario into a formalized measurement chain.

Indeed, given an experiment, it is not always clear where we ought to place either the start or the end of the measurement chain.[7] Regarding initialization, we can always ask for the initial conditions of our initial condition. Regarding the late stages of the experiment, it is unclear where to stop: the computer screen, the experimenter, her notepad, etc. One promising way to proceed is to schematize the observer [15], thereby getting the laboratory inside the theory, so to speak. Such considerations would need to be built into whichever high but contextually reasonable standards we adopt for our models. The results of this paper do not depend sensitively on how this is done.

The above-discussed example of a measurement chain is laid out horizontally in Fig. 1. It is important to note that while in this example, moving horizontally happens to move us into larger, more complex systems with more degrees of freedom, this is accidental. Horizontal movement in this diagram indicates only that we are moving from one system to another sequentially towards the end of the experiment. One can easily imagine experiments where advancing forward in the experiment temporarily moves the measured information into a smaller system.

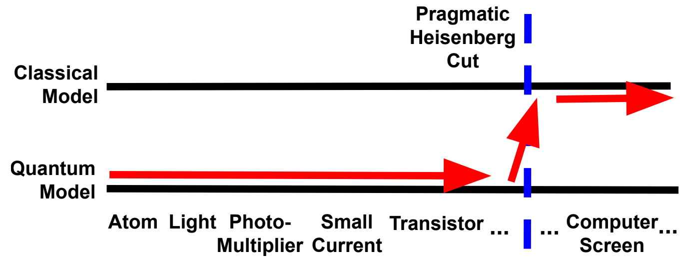

Figure 1. The measurement chain of a simple atomic experiment. The black lines show two possible types of models: quantum or classical. The red arrow shows which part of the experiment we are modeling with which theory. The dashed blue line shows where we are taking the pragmatic Heisenberg cut. That is, where we switch from modeling the experiment in a quantum way to a classical way.

(Indeed, such a scenario is displayed in Fig. 2.) The two horizontal black lines in Fig. 1 represent two types of model that we could have for each part of our experiment (here, either classical and quantum). The red arrows indicate how we are going to model each part of the experiment.

One thing which should be stressed here is that one can model one's experiment in terms of a measurement chain regardless of one's ontological preferences regarding non-relativistic quantum theory. For instance, for a Bohmian, a classical model would mean any model which does not include the wavefunction (i.e., classical physics) whereas quantum models do include the wavefunction.

It is also important to note that the path that the red arrow takes through this diagram is, in large part, a free choice of the experimenter.[8] The location of the red arrow does not mean that this or that system *is* quantum/classical. All that this indicates is that, for the purposes of modeling this experiment, this particular experimenter has chosen to model this system as such.

However, importantly, it is not the case that any part of an experiment can be successfully modeled using any theory. In practice, there are always going to be some restrictions. Sometimes for the sake of accuracy it will be necessary to model a given system in a quantum way. Sometimes for computational or technological reasons it will not be feasible to model a given system in a quantum way (forcing us to model it classically). Sometimes it will be conceptually necessary to model a given system in a quantum way. (If one accepts Bohr's doctrine of classical concepts, then it is necessary for conceptual reasons to model the end of an experiment in a classical way.) For these and other reasons, the possible routes which the red arrows may make through these diagrams are limited.

[7] There is also an interesting question regarding the middle of the measurement chain: Where along the measurement chain does the modeling-burden shift from the theorist to the experimenter? See Sec. II C for further discussion.

[8] Towards the end of this subsection, the path of this red arrow in these figures will be related to the historical notion of Heisenberg cuts and to Bohr's doctrine of classical concepts.

With these restrictions in mind, it may occur that modeling some part of our measurement chain in a quantum way is both conceptually mandatory and technically infeasible. For instance, imagine a chemical reaction between two large biomolecules for which subtle quantum effects are unavoidably relevant. In this case we simply cannot (yet) model this experiment satisfactorily. Hence, we cannot say what quantum theory predicts for this experiment, although we may have a sophomoric guess. Even if we do guess right, however, this experiment cannot in good faith be counted towards quantum theory's empirical support.

To better understand how these modeling restrictions work in practice, it is perhaps best to work through a familiar example. Consider a double-slit experiment conducted with electrons being modeled by the measurement chain shown in Fig. 2. Note that two red arrows are shown. The bottom red line opts for a quantum model whenever possible, whereas the top red line opts for a classical model wherever possible.

The experiment begins with many lab operations. As discussed above, there is some freedom in picking where exactly the measurement chain starts. However, whatever one chooses, the preliminary lab operations can be described classically. Indeed, it is infeasible to model these lab operations with quantum theory. Recall that our purpose here is to provide an actual fully-modeled account of real-life experiments in order to extract statistical predictions from them. Thus both of the red arrows in Fig. 2 *must* start on the top line.

These lab operations set up a current which travels through a filament in our cathode ray tube. This heats the filament which begins to thermally emit electrons. These electrons are then grabbed by an electric field and accelerated through a small aperture. All of these steps can be modeled classically without conceptual error or critical loss of accuracy. Hence the upper red arrow in Fig. 2 stays on the top row. All of these steps can be feasibly modeled quantumly. Hence the bottom red arrow in Fig. 2 jumps to the bottom row.

The next part of the experiment (the motion of these electrons through the double-slit apparatus) must be modeled with quantum theory. There are both conceptual issues and accuracy issues with modeling this part classically. Hence both of the red arrows *must* be on the bottom row here.[9]

When the electrons reach the final screen, they enter into a semiconductor. There they are detected by causing a cascading avalanche of electric discharge. These electrons jumping over the semiconductor's band gap requires a quantum model. Hence both red arrows *must* be on the bottom row here.

However, once enough electrons are moving, we can describe them collectively as a small (but classical) current. This current activates a transistor. Some (but not all) transistors make use of quantum effects, but let's assume this one doesn't. All of these steps can be modeled classically without conceptual error or critical loss of accuracy. Hence the upper red arrow in Fig. 2 moves to the top row. All of these steps can feasibly be modeled quantumly. Hence the bottom red arrow in Fig. 2 moves along the bottom row.

The sequence of events which follows the activation of this transistor can all be described classically. Indeed, just as at the start of the experiment, it is infeasible to model the end of this experiment quantumly. As discussed above, there is some freedom in picking where exactly the measurement chain ends. However, whatever one chooses this part of the experiment can and must be described classically. Computer screens and humans and notepads are simply too large and complicated to model in a quantum way (at least for now and likely forever).

As this example hopefully makes clear, whenever we have a measurement chain, part of which requires a quantum model, we will have to at some point after this switch from modeling the measurement chain quantumly to non-quantumly (i.e., classically). In connection with the historical term, let us call wherever we happen to make this switch a *Heisenberg cut*.[10] When the pragmatic nature of this Heisenberg cut needs to be emphasized, I will describe it as a "pragmatic Heisenberg cut".

This example should hopefully also make clear that there is nothing fundamental about the placement of the pragmatic Heisenberg cut. Indeed, one can believe the world to be quantum through-and-through and still make use of this cut for modeling purposes. Past the cut, we are no longer *modeling* the measurement apparatus using quantum theory; This is very different from the measurement apparatus no longer *being* quantum past the pragmatic Heisenberg cut.

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[9] Note that there is nothing quantum per se about electrons moving through an aperture; Whether we can ignore quantum effects present at this point in the experiment depends sensitively on what's coming later. As I will discuss in Sec. II C, this point is relevant for modeling experiments involving Wigner's friend.

[10] The view adopted here regarding Heisenberg cuts is compatible with how Heisenberg himself saw them. Before reading the following quote from Heisenberg it should be noted that for him the object–instrument divide and the quantum-classical divide coincide [49]:

> In this situation it follows automatically that, in a mathematical treatment of the process, a dividing line must be drawn between, on the one hand, the apparatus which we use as an aid in putting the question and thus, in a way, treat as part of ourselves, and on the other hand, the physical systems we wish to investigate. . . . The dividing line between the system to be observed and the measuring apparatus is immediately defined by the nature of the problem but it obviously signifies no discontinuity of the physical process. For this reason there must, within certain limits, exist complete freedom in choosing the position of the dividing line [49, p. 3].

Note that for Heisenberg the location of the cut is not a physical discontinuity but is rather a free (albeit limited) choice made in the process of modeling.

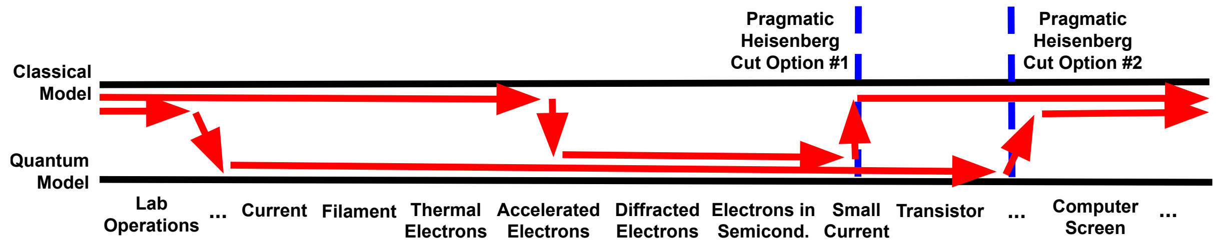

Figure 2. One possible measurement chain of a double-slit experiment is shown. The black lines show two possible types of models: quantum or classical. Each of the red arrows shows which parts of the experiment we are modeling with which theory. The bottom red line opts for a quantum model whenever possible, whereas the top red line opts for a classical model wherever possible. The dashed blue line shows where these two approaches to modeling this experiment place their respective pragmatic Heisenberg cuts.

At this point one may wonder: if the application of a pragmatic Heisenberg cut is a matter of non-fundamental pragmatic concern only, then do we really need it to make sense of the quantum measurement problem? One may ask: If we believe that the world is quantum through-and-through, then why would it be necessary to connect our quantum model of reality with a (known-to-be-incorrect) classical model of reality in order to model measurements within it? Can't we have a quantum-native understanding of quantum measurements?

This line of questioning conflates the realist and pragmatic worries about quantum measurements which I have taken care to distinguish in Sec. I: i.e., modeling versus understanding. If anyone wants to make such all-quantum-all-the-time demands on the realist side of the debate, they are more than welcome to. That is, one's ontological account of the measurement process might happen entirely within quantum theory. However, as the above discussion has hopefully shown, this attitude is not tenable on the pragmatic side.

It is no more problematic for quantum theory to depend on classical theory for its empirical support (and physical salience) than it is for general relativity to depend upon quantum theory (e.g., to model atomic clocks). Indeed, it is commonplace for scientific theories to depend on one another for metrological support; The biologist may rightfully outsource their metrological duties to an organic chemist when they are asked too many detailed questions about their measurement processes. What is important is that the scientific community collectively can give good models of its measurement processes.

The situation here is much like proof in mathematics, we do not require mathematicians to individually give all of the details of their proofs in terms of elementary logical operations. We do, however, demand that if we were to press the issue then they would collectively be able to give us such a long, detailed proof. Analogously, what we aspire to here is a computationally tractable connect-the-dots model-to-model account of real-life quantum experiments. This being possible is necessary in order to claim them as evidential support for quantum theory. My claim is that (at least currently and likely forever) a pragmatic Heisenberg cut is necessary for this.

It is perhaps possible (although I strongly doubt it) that we will one day be able to model the late parts of our experiments (including the experimenter) as quantum systems. However, even this possibility would not necessarily avoid the need for a Heisenberg cut. Suppose that one can somehow model an experiment up to and including the experimenter in a quantum way. It could still be the case that one can only parse the result of that experiment by means of taking some sort of classical approximation (i.e., taking a Heisenberg cut) on the experimenter right at the end [50].[11] We cannot have a quantum-native understanding of measurement without a quantum-native understanding of the observer. Thus, in the absence of both tremendous computing capabilities and a quantum-native understanding of observers, taking a pragmatic Heisenberg cut is necessary for any satisfactory model of any quantum experiment.

In fact, not only is it pragmatically necessary to take a Heisenberg cut at some point, we ought to do so explicit and intentional way. Indeed, a mishandling of the pragmatic Heisenberg cut is one of the main dangers in trying to give a satisfactory model of quantum experiments. It is at the interface between our quantum and classical models that we need the most care both mathematically and conceptually. Handling this cut somewhere explicitly in the terms of either the dynamics or kinematics of our models is far superior to the sophomore's strategy of intuitively guessing. Indeed, as I will discuss in Sec. II C, the success of the sophomore's hand-waving about PVMs/POVMs measurements is largely underwritten in terms of measurement chains and Heisenberg cuts. Before discussing this, however, it is worthwhile

[11] For a historical view of this kind, see Bohr's doctrine of classical concepts [51]. It also should be noted that Bohmians may be able to avoid this last point: No last-minute classical approximation is needed on their theory since the classical result of the experiment (i.e., particle positions) is manifestly there in their description of the experiment's final state.

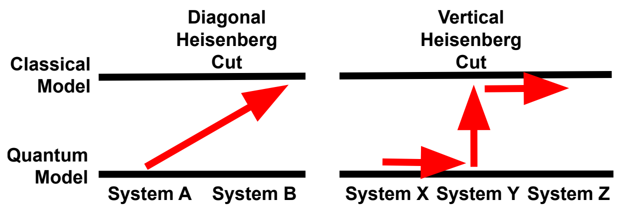

Figure 3. The two possible ways of taking a pragmatic Heisenberg cut: diagonally (during an interaction) and vertically (in between interactions). On the left we have an example of a diagonal Heisenberg cut: system A is modeled quantumly and system B classically. Their interaction couples two systems modeled in different theories. On the right, we have an example of a vertical Heisenberg cut: The interaction between system X and Y is modeled within quantum theory, whereas the interaction between Y and Z is modeled classically. In between these interactions we apply some classical approximation scheme to Y while it is approximately isolated.

to provide a taxonomy of all the ways one might take a Heisenberg cut.

B. A Taxonomy of Heisenberg Cuts: Vertical and Diagonal

As defined above, a pragmatic Heisenberg cut occurs wherever along the measurement chain we switch from modeling our experiment quantumly to classically. But how might we model our way across the quantum-classical divide? This subsection will introduce a useful taxonomy for classifying Heisenberg cuts. Given that a measurement chain is ultimately just a collection of interactions which are ordered in some way, there are only two ways to cross the divide: In between interactions, or during an interaction. Let us call these vertical and diagonal Heisenberg cuts respectively (for reasons which will become clear soon, see Fig. 3).

Vertical Heisenberg Cuts

Regarding vertical Heisenberg cuts: Consider a pair of interactions between three systems: system X (which we model quantumly) and system Y (which we can model either quantumly or classically) and system Z (which we model classically). We model the interaction between X and Y quantumly and the interaction between Y and Z classically. In between these two interactions (after X and before Z) we apply some classical approximation scheme to system Y in isolation. See the right side of Fig. 3 and notice that the red arrow moves vertically at system Y, hence the name "vertical cut".

Some examples of vertical Heisenberg cuts of varying quality are:[12]

1) taking some sufficiently decohered quantum state, and using the Born rule to map it onto a probability distribution,

2) taking a quantum state whose Wigner function [52] (i.e., the state's quasi-probability distribution in phase space) happens to be positive and reinterpreting it as a genuine probability distribution,

3) taking a minimum uncertainty quantum state and mapping it onto the definite classical state with matching expectation values.

4) taking a Bohmian state (i.e., a wavefunction plus particle positions) and discarding the wavefunction for future calculations.

among many other possibilities [53].

In general, making such vertical cuts will be justified to differing degrees in different contexts. In order to address the pragmatic measurement problem, it is crucial that we understand when such classical approximations are and are not pragmatically justified. It is by-and-large experimental practice which grounds our knowledge of the regimes of applicability of such approximations [15].

Vertical cuts push the quantum-to-classical transition onto the kinematics (as opposed to the dynamics). To see this, note that if one's measurement chain contains only vertical cuts then every system-to-system interaction is modeled as either classical-to-classical or quantum-to-quantum. Somewhere along the measurement chain, the state of some system must be able to be accurately (and feasibly) modeled in both ways.

Diagonal Heisenberg Cuts

Regarding diagonal Heisenberg cuts: Consider an interaction between system A (which we model quantumly) and system B (which we model classically). See the left side of Fig. 3 and notice that the red arrow moves diagonally between systems A and B, hence the name "diagonal cut".

Unlike with the vertical cuts discussed above, diagonal cuts push the quantum-to-classical transition onto the dynamics (as opposed to the kinematics). To see this, note that if one's measurement chain contains only diagonal cuts then every system is modeled as classical or as quantum. Diagonal Heisenberg cuts occur wherever there is a dynamical quantum-to-classical interface.

[12] We might also have vertical Heisenberg cuts which proceed in the reverse direction. That is, we may also have principled ways of mapping classical states onto quantum states. For example, the reverse of each of the above discussed examples are sometimes justified.

As a simple (admittedly artificial) example consider the following pair of coupled differential equations:

$$\partial_t \,|\psi_\mathrm{A}(t)\rangle = \left(\frac{\hat{p}_\mathrm{A}^2}{2\,m_\mathrm{A}} + U_\mathrm{A}(\hat{x}_\mathrm{A}) + V(\hat{x}_\mathrm{A} - y_\mathrm{B}(t))\right)|\psi_\mathrm{A}(t)\rangle$$
$$m_\mathrm{B}\,\partial_t^2 y_\mathrm{B} = -\partial_{y_\mathrm{B}} U_\mathrm{B}(y_\mathrm{B}) - \partial_{y_\mathrm{B}} V(y_\mathrm{B} - \langle\hat{x}_\mathrm{A}(t)\rangle) \qquad (1)$$

for some potential functions U_A, U_B and V. Here we have a wavefunction, $|\psi_\mathrm{A}(t)\rangle$, and a classical position, $y_\mathrm{B}(t)$, each evolving under their free dynamics, U_A and U_B, plus an interaction term, V.

Note that the dynamics of $|\psi_\mathrm{A}(t)\rangle$ depends on $y_\mathrm{B}(t)$. Note also that the dynamics of $y_\mathrm{B}(t)$ depends on $|\psi_\mathrm{A}(t)\rangle$ through its expectation value, $\langle\hat{x}_\mathrm{A}(t)\rangle = \langle\psi_A(t)|\,\hat{x}_\mathrm{A}\,|\psi_\mathrm{A}(t)\rangle$. These equations describe a two-way dynamical interface here between a quantum and a classical system (n.b., this model includes back-reactions). Such a quantum–to-classical coupling is typically called semi-classical.

Beyond such semi-classical treatments, however, there has been a significant amount of research into hybrid theories which mix quantum and classical systems in more substantial ways. For an overview, see [54] and references therein. To summarizing their findings:

> Whereas it is certainly possible to construct hybrid systems, these constructions typically ask for the introduction of hybrid concepts absent in a straight classical-quantum product. These hybrid theories are not derivable from a straightforward purely quantum theory: They incorporate new physics. This explicitly warns us about the toy-model nature and heuristic character of the different frameworks analyzed above. [54, p. 3]

Fortunately, however, for the purposes of modeling experiments heuristic toy-models which introduce new physics are allowed. Namely, they are allowed so long as the errors introduced by this "new physics" are small-enough, well-understood, and well-controlled. Roughly, we can use such toy models so long as the model-induced errors bars in the theoretical prediction are smaller than the experimental error bars.

C. Addressing the Core and Extended Pragmatic Measurement Problems Non-relativistically

Having introduced measurement chains and a taxonomy of Heisenberg cuts, we are now in a position to see how they can help us address the pragmatic measurement problem for non-relativistic quantum theory. Before this, however, allow me to distinguish between an easier and a harder version of this problem. I will call these the core and extended pragmatic measurement problems respectively.

Introducing and Solving the Core Problem

What the pragmatic measurement problem threatens is our theory's evidential support and physical salience. That is, it puts at risk our theory's empirically supported connection with reality. As such any minimal solution to these worries must give a *measurement framework*: a satisfactory account of how to model the measurement processes of at least the theory's key experimental successes, potentially on a case-by-case basis. The task of developing such a measurement framework is the *core pragmatic measurement problem.* Solving the core problem would restore empirical support to our theory's key experiments.

It is easy to see how measurement chains and Heisenberg cuts can be used to solve the core pragmatic measurement problem: Analyzing any given quantum experiment in these terms gives us a road map to guide us in modeling its specific measurement processes. In particular, these road maps have the dangerous areas ahead clearly marked out (i.e., the quantum-classical divide). Fortunately, these maps also provide us with multiple possible routes for navigating around these dangers (i.e., we have a taxonomy of Heisenberg cuts).

Using these road maps, we can go about giving satisfactory predictions for quantum experiments and gaining evidential support from them, at least on a case-by-case basis. This already gives us a working measurement framework for non-relativistic quantum theory. We are already in a much better position than relying on the sophomore's strategy of: 1) hoping that the measurement process in question can be modeled with a PVM, and 2) hoping that they have guessed the right PVM and applied it at the right time.

Introducing the Extended Problem

It should be noted, however, that solving the core problem does not allow us to say anything about measurement processes in general. For this, one would need a *measurement theory*: a principled account regarding how to model all (or nearly all) of the theory's measurement processes in a holistic and wide-scoping way. The task of developing such a measurement theory is the *extended pragmatic measurement problem.*

As I will now discuss, solving the extended pragmatic measurement problem allows for the typical division of labor between theorists and experimenters. To see this first recall from above that in order to secure empirical support from an experiment it is necessary to model every part of the measurement chain in at least some dynamical detail. Let us briefly consider three cases of how this modeling burden might be split between the theorists and the experimenters.

In the first case, the modeling burden falls entirely on the theorist. They would then need to make full predictions of experimental outcomes: e.g., "After one hour (as counted by this specific kind of clock) the gas will have this pressure (as measured by this specific kind of pressure gauge)". This does not sound like the sort of thing theorists typically do. Typically, they share the modeling burden with the experimenter.

In the second case, the modeling burden is split between the theorist and the experimenter. In this case the theorist can talk directly in terms of observables making half-way predictions: e.g., "After one hour, the gas will have this pressure. (*Implicitly:* I trust that you, the experimenter, know what I mean and have robust techniques for measuring what I am calling 'durations' and 'pressures'.)." Of course, while the theorist is here omitting many metrological details, they don't disappear; Instead, they must be accounted for by the experimenter. Namely, it then falls upon the experimenter to set up an appropriate (and sufficiently well-modeled) measurement apparatus.[13] Ultimately, the theorist's ability to talk so casually in terms of observables rests upon an (often under-discussed) mountain of experimental practice.

A third possibility (and in my view the most realistic one) is that the experimenter takes on the full burden themselves, addressing the whole of their experiment from its initialization to its final outcome. In this scenario the theorists only play a background role working on the theories which the experimenter invokes in generating their models and making their predictions. Otherwise, the theorist is free to theorize. As in the previous case, the theorist here can adopt a habit of speaking casually in terms of observable, secure in the knowledge that "someone, somewhere, knows how to measure something".[14]

As these three scenarios demonstrate, the theorist's habit of casually talking in terms of observables depends upon us having a wide-scoping measurement theory for the theory in question. The remainder of this section will be spent developing a measurement theory for non-relativistic quantum theory. Following this, in Sec. II D I will then use this measurement theory to help us identify the observables of non-relativistic quantum theory (n.b., "observables" $\neq$ "self-adjoint operators").

Before addressing the extended pragmatic measurement problem, however, it is worth briefly reflecting on the following two questions: Should we expect that our scientific theories generically have a unified wide-scoping account of their measurement processes (e.g., our PVM/POVM measurement theory)? And should we expect this measurement theory to give rise to a nice and tidy characterization of its observables (e.g., that they are subset of the POVMs)? Personally, I see no reason why we should expect either of these in general, (e.g., for QFT, or for quantum gravity); The fact that non-relativistic quantum theory has both of these is remarkable to me.

Solving the Extended Problem

What would it take to solve the extended pragmatic measurement problem for non-relativistic quantum theory? As I discussed in Sec. II A, when modeling experiments involving quantum systems one must in practice make a Heisenberg cut somewhere along the measurement chain. Continuing the road map metaphor introduced above, it is as if there is a long river (the quantum-classical divide) which we are required to cross somewhere. The above-discussed measurement framework gives us, for each experiment, various routes and crossing methods: We might ford the river here or we might swim across there. In order to upgrade this measurement framework into a measurement theory, we need to identify some way of crossing this river which is near-universally applicable: e.g., one can always take the ferry.

In order to find a measurement theory for non-relativistic quantum theory, we need to find some standardized way of making Heisenberg cuts with near-universal applicability. We are tremendously lucky that such a thing is, in fact, possible for non-relativistic quantum theory. Indeed, in terms of wide applicability, one way of crossing the quantum-classical divide stands out from the rest:[15] namely, by using decoherence theory and then the Born rule. As I will now discuss, by making such Heisenberg cuts one can justify (at least pragmatically) the sophomore's use of our usual PVM/POVM measurement theory.[16]

Let us now restrict our attention to vertical Heisenberg cuts which are facilitated by decoherence theory and the

[13] One might want to include among the observables quantities which are only hypothetically observable. For instance, gravitational waves were hypothetically observable long before they were actually observed. Talk of hypothetical observables is physically meaningful insofar as we can reasonably expect that experimenters could, in principle, measure it.

[14] This phrase is taken from a talk [55] given by Chris Fewster. His work on the pragmatic QFT measurement problem will be discussed further in Sec. IV.

[15] As I mentioned in Sec. II B, there are many other ways of making pragmatic Heisenberg cuts. For instance, given a Bohmian state one might be justified in simply discarding the wavefunction from future calculations, keeping only the particle positions. Such a Bohmian Heisenberg cut might be justified under a wide range of conditions within non-relativistic quantum theory. However, its regime of applicability is limited to non-relativistic scenarios which do not cover a large portion of quantum theories empirical success [18, 19]. Hence, Bohmian Heisenberg cuts are insufficient for my goals of recovering quantum theory's empirical support and of learning lessons for quantum field theory.

[16] It should be stressed that within my analysis the only thing special about crossing the quantum-classical divide in this decoherence way is its general applicability. If one could find another equally general way of crossing the quantum-classical divide, one can equally well use that to underwrite a different complementary measurement theory. This is an interesting possibility which may shed new light on justifications for the Born rule. Unfortunately, however, this falls outside of the scope of this paper.

Born rule. Where along the measurement chain are we justified in taking this specific kind of pragmatic Heisenberg cut? Luckily, to this we have a general answer: one can take such a pragmatic Heisenberg cut once enough decoherence has occurred that the possibility of spontaneous wide-scale recoherence (although not mathematically impossible) is practically inconceivable. That is, for modeling purposes, it does not matter where we put such a pragmatic Heisenberg cut so long as it is at a scale where quantum effects are (and will forever remain) irrelevant in practice.

The above "and will forever remain" caveat is a critically important one. Indeed, the validity of such a Heisenberg cut will always depend on the context surrounding the measurement procedure under consideration. In particular, one cannot simply decide in the middle of modeling a quantum measurement to take such a Heisenberg cut without knowing beforehand what the rest of the measurement procedure will be like.

No matter how small quantum coherence effects appear to be in the middle of an experiment, there is always a possibility that the coherence effects are brought back to their full force. (Such a carefully orchestrated large-scale recoherence is, in fact, exactly what quantum computers are designed to do.) Moreover, even if within one experiment the quantum coherence effects never again become relevant, they may once again become relevant in other future measurements involving correlated systems. The consideration of measurements made by observers who themselves live inside of a giant quantum computer capable of wide-scale (observers included) recoherence, leads to interesting Wigner's friend-like puzzles.

As this caveat shows, the strategy of applying decoherence theory and then the Born rule is not applicable in all conceivable measurement scenarios. With these caveats noted, however, once enough decoherence has occurred one can take such a vertical Heisenberg cut by applying the Born rule. This method of analyzing measurement processes is near-universal in scope and so hence gives us, as desired, a measurement theory for non-relativistic quantum theory.

Let us next work out what measurement theory this is specifically. One can imagine modeling a generic measurement process along the following lines: The first steps of the measurement process transfer quantum information about the to-be-measured system into the measurement apparatus. This part of the measurement process can be modeled unitarily. Then decoherence happens, diagonalizing the state of the apparatus in whatever basis is dynamically picked out by the decoherence process (See Sec. 1 of [56]). This part of the measurement process can be modeled as projective. One then takes a vertical Heisenberg cut by applying the Born rule and models the rest of the experiment classically.

Combining all of these steps together (using Naimark's dilation theorem) one finds that the total effect can be modeled as a Positive Operator-Valued Measure (POVM). For notational simplicity, let us assume that there are only a finite possible number of outcomes (indexed by α in some alphabet, $\alpha \in A$). A POVM is then a collection of operators, $\{\hat{E}_\alpha\}$, with $0 \leq \hat{E}_\alpha \leq \hat{\mathbb{1}}$ and $\sum_{\alpha\in A} \hat{E}_\alpha = \hat{\mathbb{1}}$. When such a measurement is applied to a given quantum state, $\hat{\rho}$, Born's rule says that the outcome labeled α occurs with probability $p_\alpha = \text{Tr}(\hat{E}_\alpha \hat{\rho})$.

One notable fact about POVMs is that they are nonideal in the following sense: Repeating the same POVM measurement twice back-to-back might yield different results each time. There is, however, a special subset of the POVMs (namely, the Projection-Valued Measures or PVMs) for which repeated measurement yields a fixed result. Such ideal measurements occur when the POVM operators, $\{\hat{E}_\alpha\}$, are a collection of orthogonal projectors, $\{\hat{\pi}_\alpha\}$. While such a PVM treatment of measurement is theoretically convenient, it ought to be thought of as an idealization, which is strictly speaking impossible. Indeed, ideal projective measurements have infinite resource costs and violate the third law of thermodynamics [57].

We thus have some rough answers to the sophomore's questions: One is justified in modeling a quantum measurement as a POVM when a sufficient amount of decoherence has occurred (and Wigner's friend isn't around). One is moreover justified in using a PVM when one's measurement apparatus is sufficiently ideal (even if this is, strictly speaking, impossible). Let us call these the POVM and PVM criteria respectively. The sophomore is next asked: Supposing these criteria are satisfied, which PVM/POVM is one allowed to use, and how do we know this? Unsurprisingly, the answers to these questions follow from investigating the dynamical details of the particular measurement apparatus in question.

Three surprising (to me) aspects of the above story ought to be stressed. Firstly, it is surprising that such a uniform treatment of measurement processes arises from the mathematics of quantum theory (after assuming that the PVM/POVM criteria are satisfied); Secondly, it is surprising that there exist such criteria which allow for such a broad and uniform analysis of measurement processes. Thirdly, it is a surprising contingent fact about the world that these criteria are so very often satisfied in real-life experimental scenarios. It is these remarkable facts which underwrites (at least pragmatically) the sophomore's casual use of our usual PVM/POVM measurement theory.

Our present results can be summarized as follows: Under minor assumptions, one is justified in modeling nearly any quantum measurement process as a POVM (with the specific POVM being determined by detailed dynamical considerations). Indeed, it is the design of the measurement apparatus and the nature of its interaction with the to-be-measured system and its environment which determines what is being measured.

If the sophomore takes this lesson to heart, then all of their modeling issues are solved. Recall from Sec. I that the primary issue with the sophomore's approach is that they are guessing: Their choice of PVM/POVM had no grounding in experimental practice. If, however, the sophomore were to follow along with the above story, then they might justify both the form of their guess (a PVM/POVM) and the specific PVM/POVM which they have guess; This would makes them guesses no more.

D. Observables in Non-Relativistic Quantum Theory

Before applying these lessons in a QFT context, let us first (partially) revise the sophomore's understanding of the term "observables". (A full revision must wait until Sec. III A.) Recall from Sec. I that the sophomore has been taught the following tautologies: All measurements are of some observable and all observables are measureable. Further, the sophomore has been taught (incorrectly) to equate the term "observables" with the term "self-adjoint operators". Hence, the sophomore currently thinks of measurements primarily in terms of self-adjoint operators.

After a bit of reflection, however, the sophomore can be convinced that it is better to instead think of measurements directly in terms of PVMs. As I discussed in Sec. II C, the set of projectors, $\{\hat{\pi}_\alpha\}$, which an (idealized) measurement device implements is fixed by the dynamical details of the measurement process itself. The same is not true for any real values, q_α, which may be associated with the measurement outcomes, $\alpha \in A$. To see this, imagine a measurement of some angle which is ultimately displayed by the position of an indicator needle against some marked scale. This scale is marked in three ways: in both radians and degrees as well as with a uniform marking of $\sin(\theta) \in [0, 1]$. For this measurement, it is ambiguous what the values, q_α, should be in this case, but it remains clear what the projectors, $\hat{\pi}_\alpha$, are.

Indeed, it is not hard to think of measurements whose outcomes, $\alpha \in A$, cannot be reasonably associated with any real values, $q_\alpha \in \mathbb{R}$. For instance, a measurement outcome might be indicated by some flashing lights which are labeled with letters not numbers. Alternatively, the flashing lights could be labeled by complex numbers. In general, these labels $\alpha \in A$ could be structured (or unstructured) in absolutely any way one wishes. Namely, these labels may or may not facilitate the computation of meaningful expectation values.

This is an important lesson as some physicists mistakenly think of observables as maps from quantum states into real numbers. Namely, $\hat{Q} : \rho \mapsto \langle \hat{Q} \rangle \coloneqq \mathrm{Tr}(\hat{Q}\,\hat{\rho})$ with $\langle \hat{Q} \rangle \in \mathbb{R}$ being the expectation value of the measurement of $\hat{Q}$.[17] This understanding of measurement is incorrect for two reasons. Firstly, it is far too narrow; Not all measurements admit expectation value. Secondly, while one can in general extract a unique PVM from a self-adjoint operator $\hat{Q}$, one cannot do so in general for POVMs; multiple distinct sets of POVMs, $\{\hat{E}_\alpha\}$, might sum to the same $\hat{Q} = \sum_\alpha q_\alpha \hat{E}_\alpha$ and hence yield exactly the same expectation values.

Taking the above lessons into account, the sophomore might now revise their view to equate the term "observables" with POVMs instead of self-adjoint operators. This is a step in the right direction, but as I will discuss in Sec. III A, this is still not quite right: Not all POVMs are measureable, some are dynamically forbidden on grounds of symmetry, thermodynamics, and/or relativity.[18] Further discussion of these impossible measurements and how we ought to respond to them, however, is best delayed until after we moved into a QFT context.

III. APPROACHING THE PRAGMATIC QFT MEASUREMENT PROBLEM

The previous section has reviewed how measurement chains and Heisenberg cuts can be leveraged in order to solve the pragmatic measurement problems (both core and extended) for non-relativistic quantum theory. The rest of this paper will be spent applying the lessons we have learned so far to the *The Pragmatic QFT Measurement Problem*: How should one model measurement processes involving quantum fields? How must our measurement framework for QFT differ from our usual non-relativistic measurement framework? Can we model QFT-involved measurements using PVMs and POVMs in roughly the ways we are used to? How do the observables of QFT differ from the observables of non-relativistic quantum theory?

As I discussed in Sec. I, I believe that the pragmatic QFT measurement problem ought to be addressed in largely the same way as it was in the non-relativistic context. I claim that: *Aside from some technical complications, moving into a quantum field theoretic context changes essentially nothing regarding how we can and should model quantum measurements.* Namely, we ought to begin by using measurement chains and cuts to establish a case-by-case measurement framework for QFT. From here, we can then strive for a wide-scoping measurement theory (analogous to our PVM/POVM measurement theory). This will allow us to achieve a physically meaningful characterization of the observables of QFT.

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[17] It should be noted that a set of POVMs $\{\hat{E}_\alpha\}$ can be thought of as a set of maps from quantum states into real numbers. Namely, $\hat{E}_\alpha : \rho \mapsto p_\alpha \coloneqq \mathrm{Tr}(\hat{E}_\alpha\,\hat{\rho})$ with $p_\alpha \in \mathbb{R}$ being the probability of outcome α. Thus, there is a sense in which real numbers have a special place in measurements. This is not because measurement outcomes, q_α, must be real but rather because measurement probabilities, p_α, must be real.

[18] Moreover, even if a given POVM is dynamically allowed, it does not give us the full story. If one cares about post-measurement state update then one must additionally specify operators, $\{\hat{M}_\alpha\}$, with $\hat{E}_\alpha = \hat{M}_\alpha^\dagger \hat{M}_\alpha$.

My approach ought to be contrasted with how much of the current physics literature approaches these issues. This literature is by-and-large focused on the technical differences between QFT and non-relativistic quantum theory. In strong contrast with my view articulated above, they tend to stress that our understanding of observables and measurement processes must change significantly when we move into a quantum field theoretic context. Namely, it has been much-discussed [13, 14, 20–35] in recent years that one cannot naively transplant our usual PVM/POVM measurement theory from non-relativistic quantum theory into QFT.

The novel issues which arise around measurement in QFT can be traced to certain non-trivial mathematical differences between QFT and non-relativistic quantum theory (e.g., new causal and algebraic structures at play). Proceeding naively, one is led to make mathematical blunders which either violate the central 'commandments' of relativity (covariance, causality, and locality) [13, 14, 27, 31–35] or otherwise disrespect the QFT's local algebraic structure. For these reasons, it has been argued we need a new (or at least refined) measurement theory for quantum field theory, see for instance [20, 21, 24].

What I find dissatisfying about this way of approaching the pragmatic QFT measurement problem is that it seeks too directly a fully-formed measurement theory for QFT analogous to our usual measurement theory for non-relativistic quantum theory. Relatedly, it seeks too directly a characterization of the "observables" of QFT. Ultimately, my issue with such approaches is that they are attempting to proceed directly to the end of the story rather than starting at the beginning. As I discussed in Sec. II, our ability to casually invoke observables and PVMs/POVMs in non-relativistic contexts is the end of a long story which begins with a discussion of measurement chains and Heisenberg cuts. The main message of this paper is that in order to properly address the pragmatic QFT measurement problem one ought to start from the beginning of this story, not the end. Namely, one ought to start by investigating measurement chains and cuts in a QFT context.

I will begin to address the pragmatic QFT measurement problem in terms of measurement chains and cuts in Sec. III B. Before this, however, allow me to briefly discuss some of the technical differences which arise when one attempts to model QFT-involved measurements. Namely, Sec. III A will briefly introduce some of these causality-violating measurements, namely Sorkin's impossible measurements.

One common reaction to Sorkin's impossible measurements is that one ought to retreat back into QFT-land and then develop exact formal criteria to distinguish between the possible and the impossible measurements. Some feel that we need to rebuild, from within QFT, a new relativistically-safe understanding of its measurement processes and observables. As I will argue in Sec. III A, however, this formal exact isolationist ap-

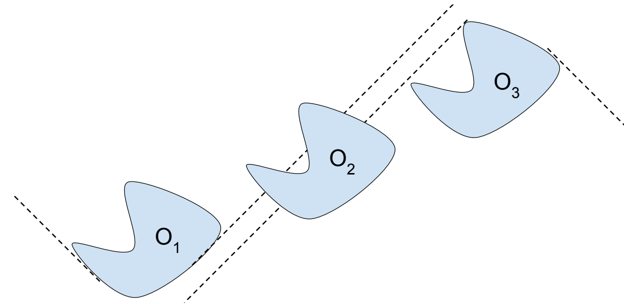

Figure 4. The impossible measurement scenario considered in Sorkin's [27]. Notice that regions O_1 and O_3 are space-like separated from one another. There is a mathematically well-defined local POVMs in the algebra associated with O_2 which enables faster-than-light signaling from O_1 to O_3. Thus not all mathematically well-defined local operations are dynamically allowed.

proach goes too far and ultimately robs the observables of QFT of any physical salience. Specifically, I will argue that the existence of impossible measurements in QFT is nothing new: non-relativistic quantum theory already has its own impossible measurements. I claim that these impossible measurements ought to be understood and managed identically in either case.

A. More Sophomoric Issues: Impossible Measurements and Observables

Let us return to where we left our sophomore in Sec. II D. The sophomore knows the following tautologies: All measurements are of some observable and all observables are measureable. Further, the sophomore currently equates the term "observables" with the term "POVMs". Given this, the sophomore would be shocked to learn that some measurements are impossible (or, equivalently, that some observables are unobservable). A much-discussed example of impossible measurements in the context of QFT are Sorkin's impossible measurements. Sorkin [27] was the first to notice that naively implementing PVM/POVM measurements in QFT results in faster-than-light signaling. See Fig. 4. Roughly, there are some mathematically well-defined local PVMs/POVMs in region O_2 which will allow for signaling from region O_1 to region O_3. Importantly, however, not all measurement operations yield faster-than-light signaling.

An intuitive way to respond to such impossible measurements is to first formally categorize them, and then remove them from our official list of observables. Note that these impossible POVM measurements are well-defined in QFT and, moreover, the relativistic principles which they violate can also be formulated within QFT. Hence, the task of identifying exactly which POVMs are relativistically safe can be conducted entirely within the formalism of QFT. Indeed, working entirely within QFT one can strive for an exact formal criterion which distinguishes the relativistically safe POVMs from the unsafe ones. We do, in fact, have such criteria (at least for real scalar QFT in a globally hyperbolic spacetime [21, 22].) Let us call this the formal exact isolationist approach to identifying QFT's observables.

One may be tempted to call these relativistically-safe POVMs the "observables of QFT". This would be wrong, however, for several reasons which I will now discuss in turn. Firstly, knowing that such measurements do not allow for faster-than-light signaling, does not guarantee that they are dynamically possible; They might violate other laws of physics (e.g, conservation laws, thermodynamics, etc.). Indeed, the fact that some POVMs are dynamically impossible can already be seen in non-relativistic quantum theory. As I mentioned in Sec. II D, some POVMs (namely, the PVMs) are impossible on thermodynamic grounds. They have infinite resource costs and violate the third law of thermodynamics [57].

Another way in which some POVMs might be dynamically impossible is if they violate our conservation laws and/or super-selection rules. Under certain dynamics it may be impossible for states with different charges (e.g., $|q\rangle$ and $|q'\rangle$) to be put into superposition. Consider the self-adjoint operator $\hat{Q} = |q\rangle\langle q'| + |q'\rangle\langle q|$. The eigenstates of $\hat{Q}$ are disallowed by such a super-selection rule for charge. Hence, state update under the corresponding PVM is dynamically impossible.

Let us suppose that we have identified every possible way in which POVMs might be dynamically impossible. Removing these from our consideration one would be left with only the dynamically-safe POVMs. Presumably, one could derive some formal criteria which exactly identify these dynamically-safe POVMs. Conceivably, these formal criteria could be found through an isolated investigation of QFT (without connecting it to non-relativistic quantum theory or to classical theory). Thus, the formal exact isolationist approach seems to be alive and well (so far). Might the set of dynamically-safe POVMs arrived at in this way then be called the "observables of QFT"?

First let me say that such exact formal criteria are definitely worth having in our tool belt. However, as tempting as it is to call these POVMs "the observables of QFT", I think that formal exact isolationist approach is fundamentally wrong-headed. One hint that something has gone wrong here is that, on this approach, all of our usual PVMs will be deemed unobservable on thermodynamic grounds. A deeper issue is that no purely formal characterization of a theory's observables can be physically salient.

As I have discussed in Sec. II A, our theories get both their empirical support and their physical salience through (unavoidably messy) contact with experimental practice. Any physically meaningful notion of observables must come into a similarly messy contact with experimental practice. Indeed, as I discussed in Sec. II C, casual talk of observables gets its right to be physically meaningful through its connections with experimental practice. Hence, a completely formal characterization of a theory's observables cannot be physically salient. Given such a formal characterization, we would then be (just like the sophomore) left to guess which observable our lab equipment measures. Chasing a theory's observables in this way is like a dog chasing a car, we would have no idea what to do with it once we caught it.[19]

Applying this conclusion to quantum theory (including QFT) reveals two other issues with the formal exact isolationist approach. As I have discussed in Sec. II A, quantum theory (and hence QFT) depend upon classical theory for both their empirical support and physical salience. Hence, no isolationist approach to identifying observables is tractable. Moreover, crossing the quantum-classical divide is unavoidably an approximate business. Therefore, we must (and, hence, are allowed to) pick out the observables of QFT in an inexact approximate way. This is what makes it okay for PVMs to sometimes be counted among our observables even though they are thermodynamically impossible. As I will discuss in Sec. IV, this is what makes it okay to sometimes model experiments using POVMs which allow for faster-than-light signaling (so long as these modeling errors are well-understood and well-controlled).

In sum, as laudable as the formal exact isolationist approach is, its three attributes each come into conflict with a demand that our notion of "observables" is grounded in experimental practice. Instead, a physically meaningful notion of observables must be informal, approximate, and arrived at through careful consideration of Heisenberg-like cuts. While the above discussion has been targeted at identifying the observables of QFT, the same conclusions also hold for identifying the observables of non-relativistic quantum theory. Thus, moving into a QFT context does not introduce any discontinuity in our how ought to approach observables and measurement processes.

B. Returning to the Pragmatic QFT Measurement Problems

We are now in a position to address the pragmatic measurement problem in QFT along the same lines as we did in the non-relativistic context. Let us begin, as before, with a sophomoric approach which (hopefully nearly) everyone finds dissatisfying. How are sophomores taught to model measurements involving quantum fields, for instance, in high-energy particle physics experiments? A sophomore might be taught to model such experiments as follows: One is first given some input states (e.g., spin-states, kinetic energies, relative phases) of some inbound

[19] Indeed, the authors of [21] recognize that "it would be useful to construct an explicit dictionary between update maps and specific probe models". A further connection would then need to be made between these probe models and real-life experimental practice.

particles. From here, one can use the given dynamics to compute the scattering amplitudes which emerge from their collision. Specifically, one computes the amplitude which is outbound within some solid angle (namely, in the direction of the experiment's particle detector). Finally, one applies the given PVM/POVM measurement (of particle number, or phase, or quadrature, etc.) to determine the detector's response rate.

Hopefully, this approach to modeling measurements is just as unsatisfying as it was in the non-relativistic case. Indeed, it fails for exactly the same reasons that the sophomore's quantum theory does (see Sec. I). While the relevant mathematical objects may be given to the sophomore on their problem sheets, they will have no good answer to the following questions: Under what conditions is it appropriate to model this particle detector as implementing a POVM on the field? If it is appropriate, then exactly which POVMs am I allowed to use and when? How can one go about determining approximately which observable this apparatus measures? As before, if the sophomore is to do better than guessing, they will need to model in some detail the relevant measurement process. But how exactly should one go about modeling measurements involving quantum fields? This is the Pragmatic QFT Measurement Problem.

To make things concrete, let us suppose the sophomore is confronted with an experiment in which β-radiation is picked up by a Geiger counter. The sophomore might intuitively guess that the Geiger counter is doing something like a local particle number measurement. Indeed, for most practical purposes, this is effectively what happens; This, despite the fact that there are no well-defined local number operators in QFT [13]. Recall from the discussion in Sec. III A that just because a POVM is, strictly speaking, impossible doesn't mean that we can't use it to model an experiment. Indeed, we might reasonably invoke "local particle density" as an observable. The issue then is as follows: If we are going to invoke a measurement which we know is strictly speaking impossible, then we need some careful justification and re-assurances. In a non-relativistic context, we would need to justify the use of a thermodynamically impossible PVM. In just the same way, the sophomore owes us a justification for their choice (i.e., their guess) of relativistically impossible POVM. How might the sophomore justify their guess?

If pressed on this question the sophomore might give the following answer: "You are asking the wrong person. The details regarding which quantum measurement the particle detector implements (including its fidelity and error rates) can be found written on the box in which it was delivered. Moreover, this tomographic information itself was painstakingly gathered by the manufacturer as a part of their quality control measures." As I discussed in Sec. II A, such an outsourcing answer is allowed. We must then follow up with the manufacturer. At some point, however, somebody is going to have to give us a satisfactory model of this Geiger counter as it sits in some measurement chain.

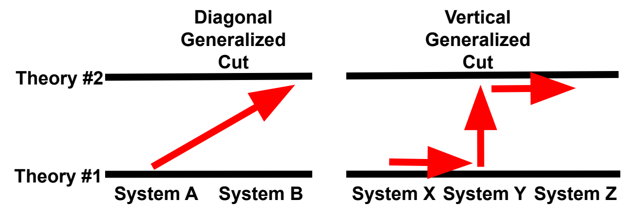

Figure 5. The two possible ways of taking a generalized cut: diagonally (during an interaction) and vertically (in between interactions). On the left we have an example of a diagonal cut: system A is modeled in Theory 1 and system B in Theory 2. Their interaction couples two systems modeled in different theories. On the right, we have an example of a vertical cut: The interaction between system X and Y is modeled within Theory 1, whereas the interaction between Y and Z is modeled within Theory 2. In between these interactions we apply some approximation scheme to Y while it is isolated.

Thus, we are led as before to address the pragmatic measurement problem in terms of measurement chains. In Sec. II A I argued that in modeling quantum experiments it is pragmatically necessary to make a Heisenberg cut (i.e., to cross the quantum-classical divide) at some point along the measurement chain. By the exact same reasoning, it is necessary to make a QFT-cut (i.e., to cross the QFT-non-QFT divide) whenever part of the measurement chain must be modeled using QFT.

The notion of a QFT-cut has already been introduced in [28] although it was there called a *relativistic cut*. However, this name is apt to cause confusion because it is not *relativity* per se which we must cut away from. To clarify this terminology, a QFT-cut occurs anywhere along the measurement chain where we switch from a QFT model to a non-QFT model. As I will discuss further in Sec. IV, there are a variety of ways in which one might go about making a QFT-cut. In addition to the vertical vs diagonal distinction introduced in Sec. II B, one can jump from QFT into a wide variety of different theories. See Fig 5.

A few other related cuts deserve mentioning and naming at this point. If one feels that the particularly troublesome part of QFT measurements is the fact that it describes things as a field, one might be interested in a field-cut. This is where we switch from modeling our measurement chain as a field (e.g., a relativistic quantum field, a non-relativistic quantum field, or a classical field) to not as a field (e.g., a qubit, a collection or classical point particles, or a nuclear spin degree of freedom).

Alternatively, one might feel that the troublesome part of QFT measurements is the fact that things are relativistic, i.e., that our models are set in a locally Lorentzian spacetime. In this case one might be interested in a relativistic cut. If that name is already taken, we might instead call this a Lorentz-cut where we switch from modeling our measurement chain in a locally Lorentzian spacetime to something else, e.g., a locally Galilean spacetime. For instance, we might move from relativistic QFT to non-relativistic QFT.

Finally, one might feel that the troublesome part of QFT measurements is the fact that its algebraic structure is that of a Type III rather than a Type I von Neumann algebra [58, 59]. In this case one might be interested in a Type III algebra-cut where we switch from modeling our measurement chain with a Type III algebraic structure to anything else, e.g. a Type I algebraic structure. For instance, we might move from relativistic QFT to non-relativistic quantum theory.

One might be interested in all of the above, or many other subtle variations thereof. However, if we are beginning from a QFT then all of the above are examples of a QFT-cut (or in the terminology of [28], a relativistic cut). As such, for the rest of this paper I will focus on QFT-cuts generally, where we switch from using a QFT model to using anything else. Of particular interest, however, are cases in which we switch from QFT to anything we know better how to model measurements of (e.g.: classical physics, special relativity, general relativity, or even non-relativistic quantum theory).

However exactly it is to be implemented, it is pragmatically necessary to make a QFT-cut somewhere along the measurement chain for any QFT-involved experiment. Indeed, just as in the non-relativistic context, one ought to do so explicitly and intentionally. It is at the interface of our QFT and non-QFT models that we need the most care both mathematically and conceptually. Handling one's QFT-cut intentionally and explicitly is much better than the sophomoric strategy of guessing which measurement is being implemented.

As in the non-relativistic case, one can use these notions of chains and cuts to solve the core pragmatic QFT measurement problem. Recall that the core problem demands that we produce a measurement framework for QFT which is capable of modeling its key experimental successes on a case-by-case basis. Continuing the road map metaphor introduced in Sec. II C, a good understanding of measurement chains and QFT-cuts would give us a road map for modeling any given QFT-involved experiment. Namely, these road maps would have the dangerous areas ahead clearly marked out (i.e., the QFT-non-QFT divide) as well as multiple routes around them (i.e., various possible QFT-cuts).

Sec. IV will discuss some of the tools which physicists have available for making QFT-cuts. As I will discuss, the tools which we currently have available are collectively of wide enough scope to give us a measurement framework for QFT. This addresses the core pragmatic measurement problem. I see nothing which would prevent the engineer at the LHC or experimenters working in quantum optics from giving satisfactory models of their QFT-involved measurement apparatuses on a case-by-case basis. (This is not to say that I am validating current experimental practice; Past highlighting the need for QFT-cuts, I am not qualified to evaluate their methodologies).

As in the non-relativistic case, however, we may want to go beyond solving just the core pragmatic measurement problem. A case-by-case measurement framework does not allow us to talk about QFT's measurement processes generally nor does it allow us to characterize QFT's observables. To do either of these we would need to construct a wide-scoping measurement theory for QFT. Namely, the extended problem asks us to find a near universally applicable way of crossing the QFT-non-QFT divide. This raises the following question: Do we have such a wide-scoping tool for making QFT-cuts?

This concludes the philosophical portion of this paper. The next section will next review the state of the art in the physics literature as it applies to QFT-cuts. Those uninterested in these technical details can skip ahead to the conclusion. The purpose of this review it to give us a better handle on what types of QFT-cuts are available to us, and what their scopes are, both collectively and individually. As I will discuss, the current front-runner for getting us a wide-scoping measurement theory [20] for QFT is the Unruh-DeWitt detector model [28, 35, 37–48].

IV. THE STATE OF THE ART

Hopefully the above discussion raises a great many question for you: Do physicists have good tools for making QFT-cuts? What are the current possibilities and limitations for various kinds of QFT-cuts? Diagonal or vertical cuts? Crossing over into non-relativistic quantum theory or into classical physics? Are these tools collectively good enough to broadly cover all of quantum theory's QFT-involved experimental successes? Moreover, is any one of these tools of sufficient generality to allow us to induce a wide-scoping measurement theory for QFT from it? In order to answer these questions, I will need to review the current state of the art in the physics literature.

Supposing that a theoretical or experimental physicist was interested in using an explicitly formalized QFT-cut in their modeling, what tools are currently available to them? What follows is an (incomplete) catalog of the various well-developed ways of approaching and crossing a QFT-cut in the physics literature. This catalog will be organized into three sections: horizontal moves, diagonal QFT-cuts, and vertical QFT-cuts. See Fig. 6. Following this I will briefly discuss the scope of experiments that these tools cover collectively. Additionally, I will briefly discuss whether any individual tool has the wide-scoping applicability needed to induce a measurement theory for QFT.

A. Horizontal Moves

Before discussing how one might make a QFT-cut, allow me to first talk about how to approach one horizontally. The general shape of a horizontal move is shown on the left side of Fig. 6. Essentially, one QFT (QFT#1)

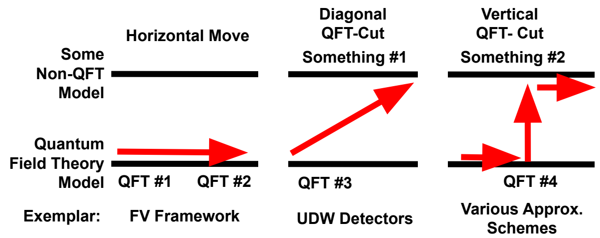

Figure 6. This figure shows the three ways that one can approach and cross a QFT-cut: horizontal moves, diagonal cuts and vertical cuts. Exemplars of these three types of moves are the Fewster Verch (FV) framework [23–25], the Unruh-DeWitt (UDW) detector model [20, 28, 35, 37–48], and various approximation schemes [53, 60] respectively.

couples to another QFT (QFT#2). Clearly, this is not a QFT-cut and so no collection of moves of this kind is the whole story.

However, of course, such moves may still be helpful in advancing us along the measurement chain until we are in a better position to make a QFT-cut. There is no issue with using a horizontal move as *part of* our measurement chain. The issue comes when one models an experiment involving QFT using only moves of this kind while neglecting to mention where exactly they take a QFT-cut. Or worse such an account might implicitly dismiss the need for a pragmatic QFT-cut altogether.

Before discussing what possibilities there are for describing interactions between QFTs, let's first talk about what sorts of isolated systems we know how to describe well with QFT. Neglecting momentarily their interaction, what types of systems QFT#1 and QFT#2 might go into the open slots in Fig. 6? (Or QFT#3 and QFT#4 for that matter?) Firstly, it should be said that we know well how to describe a wide variety of free systems using Lagrangian QFT: free scalar fields with or without mass, free electrons, free neutrinos, free photons, free Higgs particles, free gravitons (in the linearized gravity regime), etc. We can even model systems like a free proton or neutron as a free massive spinor field (assuming, of course, we ignore their quarky internal structure). Bose-Einstein condensates and some other condensed matter systems can also be treated within QFT. We can also include any small perturbative interaction term between any of these and calculate their joint evolution within perturbation theory.

What is much more difficult to do within QFT is to describe strongly interacting systems, including bound states such as atoms, or bound quark systems, or atomic nuclei. In principle, one ought to be able to consider the electromagnetic field interacting with the electron field and the proton field (pretend such a thing exists). We then ought to be able to find bound state solutions to this strongly interacting QFT which correspond to the various energy states of a first-quantized Hydrogen atom. However, these bound states of QED are remarkably difficult to treat analytically. This is difficult for such systems in isolation, let alone interacting with an external field.

One appealing option is to simulate such strongly coupled QFTs via a lattice approximation (or, equivalently, via a hard UV cutoff). One can, for instance, model some QFT scenarios accurately as a lattice of coupled harmonic oscillators. Removing the UV degrees of freedom from our QFT in this way can make them tractable to simulate [61]. Careful work however is needed in relating the observables of the continuum QFT with the observables of the lattice QFT.

To summarize: even when we are just moving along the bottom line of Fig. 6 we have a rather limited mobility here currently. We have feasibility restrictions in terms of both what systems we can consider (i.e., QFT#1 and QFT#2) as well as how they might interact with each other.

Suppose that within computational feasibility, we have two QFTs in mind and an interaction between them. What mathematical formalisms do we have for modeling this interaction? As is typical in physics, one can begin from either a Lagrangian or from a Hamiltonian formulation. However, in the case of QFT some opt to put the theory on even more secure mathematical footing by formulating it in algebraic terms, namely in Algebraic QFT [59]. For a recent philosophical debate about the differences in these approaches see [62–65]. A significant trade-off between these approaches are their differences in mathematical rigor and in practical utility.

As discussed in Sec.III, there are many technical issues which arise when one tries to apply our projective measurement theory to QFT, see Fig. 4. As fraught as this area is with mathematical stumbling blocks, some have looked to Algebraic QFT in hopes of a more secure way to approach modeling (at least parts of) measurement processes of quantum fields. In particular, the Fewster Verch (FV) framework [23–25] does this. Allow me to provide a brief overview.

Fewster Verch framework

Suppose that we can break at least a part of the measurement process down into a series of local interactions between QFTs. In particular, suppose that each of these interactions is localized in space and time, i.e. with one QFT acting as a local probe on another. The Fewster Verch (FV) framework [23–25, 29, 36] provides a model for such interactions within the mathematical rigor of Algebraic QFT. By doing so, one can be assured to be completely respectful of the central 'commandments' of relativity for at least part of the measurement chain. In particular, by describing this part of the measurement process entirely within Algebraic QFT, no causality violations of the kind shown in Fig. 4 are possible; Algebraic QFT has the fundamental principles of relativity built right into it.

To have something concrete in mind, let us consider a simple example (taken from [23, 29]) which just so happens to have an equivalent representation in Lagrangian QFT. Consider a scenario where one massive Klein Gordon field ("the probe field"), $\hat{\psi}(t,x)$, acts as a local probe another ("the system field"), $\hat{\phi}(t,x)$. The joint Lagrangian for our simple example is,

$$\begin{aligned}\mathcal{L} = &\underbrace{\frac{1}{2}(\nabla_\mu\hat{\phi}(t,x))(\nabla^\mu\hat{\phi}(t,x)) - \frac{m_1^2}{2}\hat{\phi}^2(t,x)}_{\mathcal{L}_\phi} \\ &+ \underbrace{\frac{1}{2}(\nabla_\mu\hat{\psi}(t,x))(\nabla^\mu\hat{\psi}(t,x)) - \frac{m_2^2}{2}\hat{\psi}^2(t,x)}_{\mathcal{L}_\psi} \\ &- \underbrace{\lambda\,\rho(t,x)\,\hat{\psi}(t,x)\,\hat{\phi}(t,x)}_{\mathcal{L}_I}.\end{aligned} \tag{2}$$

The first and second terms are the free Lagrangians of the system field, $\hat{\phi}(t,x)$, and the probe field, $\hat{\psi}(t,x)$, respectively. The third term couples these two fields together. In the third term, λ determines the strength of the interaction and $\rho(t,x)$ is a spacetime function which determines the interaction profile. That is, $\rho(t,x)$ determines where in space and time the two fields interact. For the purposes of modeling localized interactions, we can take $\rho(t,x)$ to be compactly supported in some spacetime region K, (i.e., $\rho(t,x)=0$ outside of K). See Fig. 7. Here N is some "processing region" in the future of K where the probe field undergoes further measurement processes.

It is important to note that the scope of interactions considered by the FV framework is much more general than this simple example. I have only specified the above interaction Lagrangian to have something concrete in mind for later comparison. In general, in the FV framework, one quantum field acts as a local probe upon another quantum field. The nature of these two fields is left completely open so long as they can both be formulated within Algebraic QFT. The nature of their interaction is left open, except that it all happens within a bounded spacetime region, K, see Fig. 7. The spacetime background for such an interaction is even left open, i.e., it could be curved.

By using these sorts of local QFT-to-QFT interactions, one might be able to describe a part of a QFT-involved measurement chain. Of course, as discussed above, we cannot hope to provide a complete modeling of any real-life measurement process exclusively in terms of QFT-to-QFT interactions. This is for two reasons. Firstly, as discussed above, we currently have a rather limited technological and computational capacity for describing interacting bound states within Lagrangian QFT (let alone Algebraic QFT). Thus, the FV framework suffers here on grounds of computational feasibility, at least currently.

Secondly, once one QFT acts as a probe on another, we are still left with the problem of how to model the measurement of the second QFT. Indeed, the FV framework does not claim to solve the quantum measurement problem (pragmatic or realist) but rather their interest is "describing a link in the measurement chain, in a covariant spacetime context" [23]. In particular, they "take it for granted that the experimenter has some means of preparing, controlling and measuring the probe and sufficiently separating it from the QFT of interest" [23] or put more simply that "someone, somewhere, knows how to measure something" [55].

In total therefore the FV framework is potentially useful (within its presently limited computational feasibility) for modeling parts of the QFT-involved measurement chains for real-life experiments. In combination with the yet-to-be-discussed diagonal and vertical cuts, it may be helpful in solving the core pragmatic measurement problem for QFT.

But what about the extended pragmatic measurement problem? Our goal there is to give a unified wide-scoping account of measurements in QFT, i.e., to identify its observables. In this extended problem we care less about computational feasibility. One might therefore expect the FV framework (and horizontal moves generally) to be more useful in the extended problem.

For instance, recent work claims to have used the FV framework to provide an "Asymptotic measurement schemes for every observable of a quantum field theory" [36] in order to "determine the set of system observables that can be measured by FV measurement schemes". Concretely, their objective is "to analyze how information about one physical structure (system) is transferred to another physical structure (probe) that is controlled by an external experimenter" [66]. In particular their interest is in the case where both the system and field are QFTs and the information is transferred via a local interaction. This is exactly the sort of thing that the FV framework is good at: working out how information moves between quantum fields which interact with each other in localized regions.

The principal limitation in [36] however is that (as is always the case with the FV framework) it explicitly assumes that the experimenter has full control over the probe field. In particular, it is assumed that they know how to extract classical information from the probe, i.e. "someone, somewhere, knows how to measure something" [55]. While this is potentially a step in the right direction, these results ultimately end up assuming that we know what the observables in the probe field are. Contrary to this methodology, I argue that the only physically meaningful way to identify the observables within QFT is to connect them with observables outside of QFT by some measurement chain which includes a QFT-cut.

Allow me to briefly give the technical details of [36] by first introducing some terminology. Within Algebraic QFT, each bounded region of spacetime R is associated with an algebra, commonly called the "algebra of observables". However, this remains to be justified as what is an observable is exactly what is at question here. This algebra includes the field operator $\hat{\phi}(t,x)$ integrated against all smooth functions compactly supported over R. Additionally, the algebra includes products and sums of these

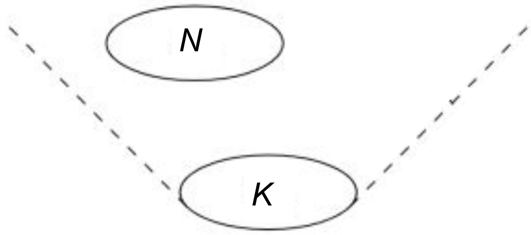

Figure 7. The bounded spacetime regions considered in [29]. The two quantum fields interact only within the coupling region K. In the future of this interaction is the "processing region" N where the probe field undergoes further measurement processes.

smeared field operators. An FV measurement scheme for a field $\hat{\phi}(t,x)$ ("the system field") specifies four things: a probe field $\hat{\psi}(t,x)$ labeled $\mathcal{P}$, an initial state for the probe field, $\rho_{\mathcal{P}}$, a unitary interaction, S, between $\hat{\phi}(t,x)$ and $\hat{\psi}(t,x)$ localized in some region K, (e.g., Eq. (2)) and finally an element of the probe algebra, B, associated with a processing region N in the future of K, see Fig. 7.

While the results of [36] are proven in terms of Algebraic QFT, it here suffices to give their translation into the usual language of Hilbert spaces. A FV measurement scheme gives a way of indirectly addressing elements of the system algebra associated with the region K. Namely for every FV measurement scheme we have

$$\mathrm{Tr}_{\mathcal{SP}}(\rho_{\mathcal{S}}\otimes\rho_{\mathcal{P}}\,S^\dagger\mathbb{1}\otimes B\,S)=\mathrm{Tr}_{\mathcal{S}}(\rho_{\mathcal{S}}\,B_{\mathrm{ind}}) \tag{3}$$

for some induced B_{ind} in the system algebra associated with K.

Ultimately, the question addressed by [36] is: Which elements of the system field's algebra at K can be indirectly measured via an FV measurement scheme (assuming we can measure any element of the probe algebra at N)? Their answer is roughly that for every element A of the system algebra at K there exists a sequence of FV measurement schemes which indirectly measure it arbitrarily well in the limit. Namely, for every A in the system algebra associated with K, we have [66]

$$\mathrm{Tr}_{\mathcal{SP}_\alpha}(\rho_{\mathcal{S}}\otimes\rho_{\mathcal{P}_\alpha}\,S_\alpha^\dagger\mathbb{1}\otimes B_\alpha\,S_\alpha)\to\mathrm{Tr}_{\mathcal{S}}(\rho_{\mathcal{S}}\,A) \tag{4}$$

for some sequence of FV measurement schemes indexed by an integer $\alpha\in\mathbb{Z}$. Thus, given full control over the probe system in the region N there is some sequence of probes, probe states and local interactions such that we can address any A in the system's algebra arbitrarily well.

In summary, the FV framework is a great tool for working out how information moves between quantum fields which interact with each other in localized regions. However, to solve either the core or extended pragmatic measurement problems for QFT it alone is not enough. We need to at some point take a step outside of QFT via a QFT-cut.

B. Vertical QFT-cuts

Let's next consider what vertical QFT-cuts are available to us currently. The general shape of a vertical QFT-cut is shown on the right side of Fig. 6. Essentially, we begin with something being modeled as a QFT (QFT#4) and then take some sort of approximation on this to arrive the very same thing now modeled as something other than a QFT (Something#2). Our freedoms in designing a vertical QFT-cut are: which theory we approximate into, what kind of QFT we begin from and relatedly what kind of non-QFT system we land on, as well as the details of our approximation scheme.

We have discussed already in the previous subsection the sorts of systems which we have a grip on how to model in QFT: free systems plus perturbative interactions and some condensed matter systems but not strongly interacting systems or bound states. Our options for QFT#4 are fixed to be among these. As for which theory to cross into, the "nearest" theory to QFT would likely be non-relativistic QFT (i.e., QFT with $c\to\infty$, or rather QFT in a Galilean spacetime). For such an approximation to work our initial QFT#4 must be massive, i.e., not light nor gravity. Massive fields may limit onto particles in a non-relativistic limit, but massless ones will not [53, 67]. For massive free states, taking such a limit gives us non-relativistic quantum particles. This alone is not enough unless we understand well how to model the measurement of non-relativistic QFTs. I am not aware of any research in this direction, but it could be a fruitful way forward.

The next nearest theory we could cut into is non-relativistic quantum theory. The question then is what we should take as Something#2? An obvious experimentally relevant system would be a first-quantized Hydrogen atom. However, this would mean that QFT#4 needs to be some second quantized description of the Hydrogen atom. As I have already discussed, describing such bound states in QFT is difficult. More research in this direction is warranted.

Another intriguing option for what non-relativistic quantum system to put for Something#2 is an Unruh-DeWitt (UDW) detector [20, 28, 35, 37–48]. These will be described in more detail in the next subsection, but roughly they are atom-like non-relativistic quantum systems which can be coupled to a quantum field in a way motivated by the light-matter interaction. In fact, recent work [60] has developed a "second quantized UDW detector", i.e., a QFT which reduces to a UDW detector in the non-relativistic limit. This an interesting avenue for future research, worthy of further development.

Finally, we can consider the possibility of approximating a QFT as a classical state of some sort. For instance, one might have a state of light described as a QFT and then switch to describing this as a classical electromagnetic field in Minkowski space. Vertical cuts of this kind seem to be experimentally relevant and deserve to be developed further.

In summary, vertical QFT-cuts are a promising possibility deserving of further research. If technical limitations surrounding second quantized atoms can be overcome, then these could have a substantial scope including many experimentally relevant systems.

C. Diagonal QFT-cuts

Finally, let's next consider what diagonal QFT-cuts are available to us currently. The general shape of a diagonal QFT-cut is shown in the center of Fig. 6. Essentially one QFT (QFT#3) couples directly to something which is not being modeled as a QFT (Something#1). As is the case for any diagonal cut, the direct coupling between system's described in fundamentally different theories poses conceptual challenges. Here, there is an inherent risk that coupling to a non-QFT system will end up breaking one of the central 'commandments' of relativity.

However, on the bright side, since quantum field theory itself provides us with no prescription for how such systems ought to interact, we have a great deal of freedom in how one might model such an interaction. In particular, our freedoms in designing a diagonal QFT-cut are: what kind of QFT we begin from, which theory we cut into, what kind of non-QFT system we cut into, and the nature of the interaction between the systems.

We have discussed in the previous subsections the sorts of systems which we have a grip on how to model in QFT: free systems plus perturbative interactions and some condensed matter systems but not strongly interacting systems or bound states. Our options for QFT#3 are fixed to be among these. As for which theory take a QFT-cut into, the "nearest" theory to QFT would likely be non-relativistic QFT (i.e., QFT with $c\to\infty$, or rather QFT in a Galilean spacetime). As far as I am aware, not much work has been put into the study of sensible dynamical couplings between QFT and non-relativistic QFT. One immediate concern is the possibility of uncontrolled faster-than-light signaling. We might have a relativistic field $\hat{\phi}_{\text{Rel}}(x)$ couples to $\hat{\phi}_{\text{Non-Rel}}(x)$ which can then send an instantaneous signal to $\hat{\phi}_{\text{Non-Rel}}(x{+}a)$ which is coupled to $\hat{\phi}_{\text{Rel}}(x+a)$. This seems problematic. More work may be needed in this direction.

The next "nearest" theory we could try to take a QFT-cut into is non-relativistic quantum theory. Significant work has been done in this direction, which will be discussed momentarily.

The last option which comes to mind is to couple our QFT to a classical system (e.g., something modeled in special relativity or general relativity). This doesn't seem terribly problematic, we could for instance have a classical Klein Gordon field interacting with the expectation value of a quantum Klein Gordon field, perhaps without back reaction. More work would need to be done motivating why such an interaction is an accurate reflection of some part of a real-life experiment, but there don't seem to be insurmountable technical difficulties here.

Unruh-DeWitt Detector Models

Let's return to the possibility of diagonal cuts into non-relativistic quantum theory. We have a lot of freedom here in designing this interaction. Of course, there are also certain things we want from this diagonal theory-to-theory coupling if it is going to be a productive part of an experimental prediction. So what ought to guide us in designing this interaction? As a first guide, we may rely on a desire to preserve the central 'commandments' relativity (covariance, causality, and locality) as much as possible. Moreover, as a second guide we may rely on a desire to accurately model parts of real-life experiments.

For instance, we might take the Something#1 system in Fig. 6 to be something atom-like and we might take QFT#3 to be the electromagnetic field (or some scalar analog thereof). In this case, under such guidance, one is quickly led [68–70] to something very much like the Unruh-DeWitt (UDW) detector model first introduced in [37].

Alternatively, we might take QFT#3 to be a graviton field (in the linear gravity regime). In this case, one is quickly led to a certain variant of the Unruh-DeWitt detector model [71–73].

One can also take Something#1 to be a fermionic quantum system which interacts with QFT#3 being a neutrino field. In this case one is led to another variant of the Unruh-DeWitt detector model [74, 75].

The possibilities for which real-life interaction we might attempt to mimic here are very general. In each case, the resulting interaction model is within the family of Unruh-DeWitt-like models. Moreover, much of the above can be done in arbitrarily curved spacetime backgrounds as well [71].

Enough discussion of abstract possibilities, concretely what do these models look like? To have something concrete in mind, let us consider a simple example (taken from [28]). Consider a simple example in which a UDW detector $\hat{\mu}$ coupled to a massive Klein Gordon fields $\hat{\phi}(t,x)$ with joint Lagrangian,

$$\begin{aligned}\mathcal{L}=&\underbrace{\frac{1}{2}(\nabla_\mu\hat{\phi}(t,x))(\nabla^\mu\hat{\phi}(t,x))-\frac{m_1^2}{2}\hat{\phi}^2(t,x)}_{\mathcal{L}_\phi}\\&+\mathcal{L}_{\text{UDW}}-\underbrace{\lambda\,\rho(t,x)\,\hat{\mu}(\tau)\,\hat{\phi}(t,x)}_{\mathcal{L}_I}.\end{aligned}\tag{5}$$

The first term is the free Lagrangian of the field. The second term $\mathcal{L}_{\text{UDW}}$ is the free Lagrangian of the non-relativistic probe system, the UDW detector. We have total freedom to pick the internal dynamics of the non-relativistic probe system. For instance, it could be a qubit, or a quantum harmonic oscillator, or a first quantized Hydrogen atom.

In the third term, λ determines the strength with which the non-relativistic probe and field couple to each other. In the third term, $\rho(t,x)$ is a spacetime function determining the interaction profile. In this context, $\rho(t,x)$ is often called the probe's smearing function, and is taken to describe the size and shape of the probe through time (more will be said about this later). Just as in the FV framework, for the purposes of modeling local measurements, we can take $\rho(t,x)$ to be compactly supported in some spacetime region, K, (i.e., $\rho(t,x)=0$ outside of K). In the third term, $\hat{\mu}$ is the degree of freedom of the non-relativistic probe which couples to the quantum field. For instance, if the probe is a harmonic oscillator, $\hat{\mu}(\tau)$ might be its number operator $\hat{n}$ or one of its quadrature operators $\hat{q}$ or $\hat{p}$.

The major difference between the FV and UDW approaches (Eq. (2) and Eq. (5)) is just that in the first case the probe system is a quantum field, $\hat{\psi}(t,x)$, and in the second case it is a non-relativistic quantum system, $\hat{\mu}$. For a more in depth comparison of the UDW detector model and the FV framework, see [28].

It's important to note that the UDW detector is not designed as a Von Neumann "pointer" measurement device, i.e., one which translates a "needle" proportional to some targeted operator in the probed field. Rather, the UDW detector is designed to be atom-like. If one measures the UDW detector after its interaction with the field, one ought to interpret this roughly as one would if an atom had coupled to the field. For instance, if the UDW probe is initially in its ground state and then is later measured to be in an excited state, one might infer that it absorbed a photon from the quantum field.

More complexly, one can use UDW detectors to model an entanglement harvesting experiment [29, 42–48]. Roughly, in such an experiment two initially uncorrelated probe systems interact locally with a quantum field in such a way that they do not have time to signal to each other. Despite this, these two probes become entangled because there was already entanglement present between the two space-like separated regions they interacted with. The benefit of such an experiment is that the entanglement in the field has been transferred into more accessible systems, both physically and mathematically. We cannot associate a Hilbert space to bounded regions in QFT and as such cannot straightforwardly compute the entanglement between these regions. The final entanglement of these probes is a witness to the initial entanglement in the field.

A great many theoretical investigations of this sort have been carried out using UDW detectors [42–48]. Such studies can even be done in curved spacetimes: one can study the entanglement structure around a black hole near the event horizon for instance.

Thus, in addition to providing a good model for many experimentally relevant systems, the UDW detector model covers a wide range of interesting hypothetical experiments, all while remaining computationally feasible.

How well do UDW-like detectors preserve the central 'commandments' of relativity: covariance, causality, and locality? Do they for instance lead to uncontrolled faster-than-light signaling in the QFT? Before answering these questions, a distinction needs to be made between two modes of applications of the UDW model. It was mentioned above that we will often wish to localize the probe's smearing function $\rho(t,x)$ within some bounded spacetime region. For instance, when the UDW detector model is derived from the light matter interaction [68–70], the smearing function $\rho(t,x)$ turns out to be determined by the overlaps of certain atomic orbitals. That is, $\rho(t,x)$ is a near-literal description of the shape of the atom in space and time.

When the size of the UDW is much smaller than all other relevant scales and the detailed shape of the detector doesn't matter much, we can also approximate the detector as being point-like. Consider a point-like detector traveling through spacetime on some time-like trajectory, $z(t)$. We can localize the interaction to this trajectory by taking $\rho(t,x)=\chi(t)\delta(x-z(t))$. Here $\chi(t)$ controls where along the trajectory the probe couples to the field (it may turn on and off) and the δ function localizes the interaction to the detector trajectory, $z(t)$. Let us call these the point-like detectors.

With this established, let us return to the question of how well do UDW-like detectors preserve the central 'commandments' of relativity. In brief, they do so imperfectly, but with well understood and controllable issues [30, 76]. For smeared detectors (i.e., non-point-like detectors) there are some slight faster-than-light signaling issues. Essentially, the issue is that if some information is taken up by the left half of the detector it can "immediately" jump to the right half of the detector and then back into the field. Basically, signals can jump across the detector instantly. This breaks no-signaling and causes some issues with the relativity of simultaneity (this coupling does not treat all relativistically compatible time-orderings equally).

However, these issues are ultimately minor [30, 76]. The time ordering issues do not appear at the lowest orders of perturbation theory. If the light-matter interaction is weak enough, then the time-ordering issues are strongly suppressed. Moreover, the size of the no-signaling violations is set by the size of our detector. Recall $\rho(t,x)$ might have compact support. If the UDW detector has a width of 3 nm then signals can only arrive at most 10 atto-seconds early. Ultimately if we care about such time-scales (of the order of the light crossing time for the atom) then we shouldn't even be allowed to talk about first-quantized atoms in the first place. Indeed, all of these commandment-breaking issues go away when we use point-like detectors.

D. The Scope of these Tools

Having reviewed the state of the physics literature, for feasible ways of crossing the QFT-cut, what ultimately are the scope of these tools? In my assessment while each tool has its limitations and more development of each of them is needed, collectively these tools have a substantial scope. Thus, I believe that collectively these tools give us a good handle on a case-by-case measurement framework for QFT. That is, collectively they can give us a solution to the core pragmatic measurement problem for QFT.

But what about the extended pragmatic measurement problem for QFT? Can these tools help us identify the observables of QFT? As discussed in Sec. III, in order to get a wide-scoping unified measurement theory for QFT we would need some near-universally available way of making QFT-cuts. In particular, we would need for at least one of these tools to have a sufficiently wide range of applicability such that nearly all QFT-involving experiments can be modeled using it. Which of the above discussed tools has the widest scope?

As I have discussed above, at least currently the UDW detector model by far has the widest scope of applicability of any of the tools currently available. Thus, if one wants to develop a wide-scoping measurement theory for QFT and to identify its observables, this is currently the most promising way forward. Indeed, a recent paper claims to have used the UDW detector model to establish a detector-based measurement theory for quantum field theory [20].

V. CONCLUSION

This paper began by distinguishing between the pragmatic and realist portions of the quantum measurement problem. Of these, I have argued that the pragmatic worries have worse consequences if left unanswered. If we lose the pragmatic connection between theory and experimental practice, the quantum theory is at risk of losing both its empirical support and its physical salience.

Fortunately, these pragmatic worries are not too hard to address. The core pragmatic measurement problem can be solved by developing a case-by-case measurement framework for modeling quantum theory's key experimental successes. Past this, one can strive for a wide-scoping measurement theory capable of modeling all (or nearly all) possible measurement processes. This would solve the extended pragmatic measurement problem and help us achieve a physically meaningful characterization of our theory's observables.

In Sec. II, I discussed how one can solve the pragmatic measurement problem in this way for non-relativistic quantum theory. Namely, thinking in terms of measurement chains gives us a road map for modeling each experiment's individual measurement processes. As I have argued, it is pragmatically necessary that we model our way across the quantum-classical divide at some point by invoking a Heisenberg cut. There are a wide variety of pragmatic Heisenberg cuts available to us. We can achieve a wide-scoping measurement theory by finding a near-universally available way of making such pragmatic Heisenberg cuts. As I have discussed, this can be achieved by appealing to decoherence theory and the Born rule. This justifies (at least pragmatically) our use of the canonical POVM measurement theory. Importantly, however, one's choice of POVM must follow from a careful dynamical investigation of the system at hand. This analysis must include a pragmatic Heisenberg cut.

In Sec. III, I have argued that we ought to approach the issue of modeling QFT-involved measurements in much the same way. Namely, we ought to first use measurement chains to build up a case-by-case measurement framework for QFT. This will require us to cross the QFT-non-QFT divide by using a pragmatic Heisenberg-like cut (what I call a QFT-cut). From here we can then strive for both a new wide-scoping measurement theory for QFT and a new characterization of its observables.

My approach stands in strong contrast to what I have called the formal exact isolationist approach to identifying QFT's observables. This approach proceeds roughly as follows. "Given that there exist impossible measurements within QFT (see Sorkin [27]), we ought identify them and get rid of them. Note that these problematic POVMs and the principles they violate can both be formalized within QFT. Hence, it should be possible to achieve an exact formal characterization of them within QFT. Removing these impossible measurements from the set of all possible POVMs ought to yield the observables of QFT." As I have argued in Sec. III A, useful as such an approach might be, it cannot deliver us a physically meaningful characterization of QFT's observables. Connecting QFT with experimental practice requires us reach outside of QFT as we cross the QFT-non-QFT divide. This requires us to make some approximation, namely a QFT-cut. The ultimate justification for the validity of such an approximation is experimental practice [15]. Hence, our understanding of QFT's observables must be informal, approximate, and arrived at through careful consideration of QFT-cuts.

In light of this conclusion, it becomes important to understand what tools physicists have for making QFT-cuts. As I have discussed in Sec. IV, physicists do have several good tools for approaching (the Fewster Verch (FV) framework [23–25, 29]) and crossing the QFT-cut (UDW detector model [28, 35, 37–48], and a handful of approximation schemes [53, 60].

But are their tools collectively good enough to secure evidential support for quantum theory? In my assessment, collectively these tools have a substantial scope. Thus, collectively these tools give us a good handle on a measurement framework for QFT solving its core pragmatic measurement problem. I see nothing which would prevent engineers and experimenters from satisfactorily modeling their QFT-involved measurement apparatus on a case-by-case basis.

But is any one of these tools on its own sufficient to give us wide-scoping unified measurement theory for QFT? As I have discussed, the UDW detector model by far has the widest scope of applicability of any of the tools currently available. Thus, if one wants to develop a wide-scoping measurement theory for QFT or to identify its observables, this appears to be the best way forward. Indeed, a recent paper claims to have used the UDW detector model to establish a detector-based measurement theory for quantum field theory [20].

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[1] T. Maudlin, Topoi **14**, 7 (1995).

[2] W. Myrvold, in *The Stanford Encyclopedia of Philosophy*, edited by E. N. Zalta (Metaphysics Research Lab, Stanford University, 2018) Fall 2018 ed.

[3] J. Bell, *Speakable and unspeakable in quantum mechanics : collected papers on quantum mechanics* (Cambridge University Press, Cambridge, 1987).

[4] D. Wallace, in *Scientific Realism and the Quantum* (Oxford University Press, 2020) https://academic.oup.com/book/0/chapter/322307015/chapter-ag-pdf/44484139/book_36983_section_322307015.ag.pdf.

[5] M. Dickson, in *Philosophy of Physics*, Handbook of the Philosophy of Science, edited by J. Butterfield and J. Earman (North-Holland, Amsterdam, 2007) pp. 275–415.

[6] J. A. Barrett, Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics **48**, 168 (2014), relativistic Causality.

[7] J. A. Barrett, Philosophy of Science **72**, 802–813 (2005).

[8] J. A. Barrett, in *Ontological Aspects Of Quantum Field Theory*, edited by M. Kuhlmann, H. Lyre, A. Wayne, and H. T. Leong (World Scientific Publishing Company, Singapore, SINGAPORE, 2002) Winter 2021 ed.

[9] M. Kuhlmann, H. Lyre, A. Wayne, and H. T. Leong, *Ontological Aspects Of Quantum Field Theory* (World Scientific Publishing Company, Singapore, SINGAPORE, 2002).

[10] H. Halvorson and M. Muger, "Algebraic quantum field theory," in *Philosophy of physics*, edited by J. Butterfield and J. Earman (North-Holland, 2007) pp. 731–864, arXiv:math-ph/0602036.

[11] H. Halvorson and R. Clifton, in *Ontological Aspects Of Quantum Field Theory*, edited by M. Kuhlmann, H. Lyre, A. Wayne, and H. T. Leong (World Scientific Publishing Company, Singapore, SINGAPORE, 2002) Winter 2021 ed.

[12] D. Dieks, in *Ontological Aspects Of Quantum Field Theory*, edited by M. Kuhlmann, H. Lyre, A. Wayne, and H. T. Leong (World Scientific Publishing Company, Singapore, SINGAPORE, 2002) Winter 2021 ed.

[13] M. Redhead, Foundations of Physics **25**, 123 (1995).

[14] D. Malament, in *Perspectives on Quantum Reality*, edited by R. Clifton (Kluwer Academic Publishers, 1996).

[15] E. Curiel, "Schematizing the observer and the epistemic content of theories," (2020), arXiv:1903.02182 [physics.hist-ph].

[16] M. Giovanelli, ""but one must not legalize the mentioned sin". phenomenological vs. dynamical treatment of rods and clocks in einstein's thought," (2014).

[17] H. R. Brown, *Physical Relativity* (Oxford University Press, Oxford, 2005).

[18] D. Wallace, "The sky is blue, and other reasons physics needs the everett interpretation," (2021), [Oxford Philosophy of Physics Seminar, Michaelmas Term 2021, 4th Nov, Timestamp 37:34].

[19] D. Wallace, "The sky is blue, and other reasons quantum mechanics is not underdetermined by evidence," (2022).

[20] J. Polo-Gómez, L. J. Garay, and E. Martín-Martínez, "A detector-based measurement theory for quantum field theory," (2021), arXiv:2108.02793 [quant-ph].

[21] I. Jubb, Phys. Rev. D **105**, 025003 (2022).

[22] L. Borsten, I. Jubb, and G. Kells, Phys. Rev. D **104**, 025012 (2021).

[23] C. J. Fewster and R. Verch, Commun. Math. Phys. **378**, 851–889 (2020).

[24] C. J. Fewster, "A generally covariant measurement scheme for quantum field theory in curved spacetimes," (2019), arXiv:1904.06944 [gr-qc].

[25] H. Bostelmann, C. J. Fewster, and M. H. Ruep, Phys. Rev. D **103**, 025017 (2021).

[26] C. Anastopoulos and N. Savvidou, Entropy **24** (2022), 10.3390/e24010004.

[27] R. D. Sorkin, "Impossible measurements on quantum fields," (1993), arXiv:gr-qc/9302018 [gr-qc].

[28] D. Grimmer, B. d. S. L. Torres, and E. Martín-Martínez, Phys. Rev. D **104**, 085014 (2021).

[29] M. H. Ruep, Classical and Quantum Gravity **38**, 195029 (2021).

[30] J. de Ramón, M. Papageorgiou, and E. Martín-Martínez, Phys. Rev. D **103**, 085002 (2021).

[31] F. Dowker, "Useless qubits in "relativistic quantum information"," (2011), arXiv:1111.2308 [quant-ph].

[32] D. M. T. Benincasa, L. Borsten, M. Buck, and F. Dowker, Class. Quantum Gravity **31**, 075007 (2014).

[33] L. Borsten, I. Jubb, and G. Kells, "Impossible measurements revisited," (2019), arXiv:1912.06141 [quant-ph].

[34] A. Ortega, E. McKay, A. M. Alhambra, and E. Martín-Martínez, Phys. Rev. Lett. **122**, 240604 (2019).

[35] A. Teixidó-Bonfill, A. Ortega, and E. Martín-Martínez, Phys. Rev. A **102**, 052219 (2020).

[36] C. J. Fewster, I. Jubb, and M. H. Ruep, "Asymptotic measurement schemes for every observable of a quantum field theory," (2022).
[37] W. G. Unruh, Phys. Rev. D **14**, 870 (1976).
[38] S.-Y. Lin and B. L. Hu, Phys. Rev. D **76**, 064008 (2007).
[39] E. G. Brown, E. Martín-Martínez, N. C. Menicucci, and R. B. Mann, Phys. Rev. D **87**, 084062 (2013).
[40] M. Hotta, A. Kempf, E. Martín-Martínez, T. Tomitsuka, and K. Yamaguchi, Phys. Rev. D **101**, 085017 (2020).
[41] E. Tjoa and E. Martín-Martínez, Phys. Rev. D **101**, 125020 (2020).
[42] A. Valentini, Phys. Lett. A **153**, 321 (1991).
[43] B. Reznik, Found. Phys. **33**, 167 (2003).
[44] A. Pozas-Kerstjens and E. Martín-Martínez, Phys. Rev. D **92**, 064042 (2015).
[45] G. V. Steeg and N. C. Menicucci, Phys. Rev. D **79**, 044027 (2009).
[46] E. Martín-Martínez, A. R. H. Smith, and D. R. Terno, Phys. Rev. D **93**, 044001 (2016).
[47] E. Martín-Martínez and N. C. Menicucci, Class. Quantum Gravity **29**, 224003 (2012).
[48] L. J. Henderson, R. A. Hennigar, R. B. Mann, A. R. H. Smith, and J. Zhang, Class. Quantum Gravity **35**, 21LT02 (2018).
[49] M. Schlosshauer and K. Camilleri (2010).
[50] D. Wallace, *The emergent multiverse [electronic resource] : quantum theory according to the Everett interpretation*, Oxford scholarship online (Oxford University Press, Oxford, 2012).
[51] M. Schlosshauer and K. Camilleri, "The quantum-to-classical transition: Bohr's doctrine of classical concepts, emergent classicality, and decoherence," (2008).
[52] C. K. Zachos, D. B. Fairlie, and T. L. Curtright, *Quantum Mechanics in Phase Space* (WORLD SCIENTIFIC, 2005) https://www.worldscientific.com/doi/pdf/10.1142/5287.
[53] J. Rosaler, *Inter-theory relations in physics: case studies from quantum mechanics and quantum field theory*, Ph.D. thesis, University of Oxford (2013).
[54] C. Barceló, R. Carballo-Rubio, L. J. Garay, and R. Gómez-Escalante, Phys. Rev. A **86**, 042120 (2012).
[55] C. J. Fewster, "Local measurement of quantum fields in curved spacetimes," (2021), [Relativistic Quantum information-Online 2020/21 - Waterloo Session 03: Wednesday February 10th, timestamp 09:45].
[56] G. Bacciagaluppi, in *The Stanford Encyclopedia of Philosophy*, edited by E. N. Zalta (Metaphysics Research Lab, Stanford University, 2020) Fall 2020 ed.
[57] Y. Guryanova, N. Friis, and M. Huber, Quantum **4**, 222 (2020).
[58] E. Witten, Rev. Mod. Phys. **90**, 045003 (2018).
[59] F. Kronz and T. Lupher, in *The Stanford Encyclopedia of Philosophy*, edited by E. N. Zalta (Metaphysics Research Lab, Stanford University, 2021) Winter 2021 ed.
[60] F. Giacomini and A. Kempf, "Second-quantized unruh-dewitt detectors and their quantum reference frame transformations," (2022), arXiv:2201.03120 [quant-ph].
[61] N. Klco and M. J. Savage, Phys. Rev. A **102**, 012619 (2020).
[62] D. Wallace, Synthese **151**, 33 (2006).
[63] D. Wallace, "Taking particle physics seriously: a critique of the algebraic approach to quantum field theory," (2011).
[64] D. Fraser, Philosophy of Science **76**, 536 (2009).
[65] D. Fraser, Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics **42**, 126 (2011), philosophy of Quantum Field Theory.
[66] M. Ruep, "Observing observables – causal measurement schemes for every observable of the linear real scalar field in curved spacetime," (2022), [Contribution to the Quantum Field Theory in Curved Spacetimes Workshop (23-27 May 2022)].
[67] W. E. Lamb, Applied Physics B **60**, 77 (1995).
[68] E. Martín-Martínez and P. Rodriguez-Lopez, Phys. Rev. D **97**, 105026 (2018).
[69] R. Lopp and E. Martín-Martínez, Phys. Rev. A **103**, 013703 (2021).
[70] R. Lopp and E. Martín-Martínez, Phys. Rev. A **103**, 013703 (2021).
[71] E. Martín-Martínez, T. R. Perche, and B. de S. L. Torres, Phys. Rev. D **101**, 045017 (2020).
[72] R. Faure, T. R. Perche, and B. d. S. L. Torres, Phys. Rev. D **101**, 125018 (2020).
[73] J. P. M. Pitelli and T. R. Perche, Phys. Rev. D **104**, 065016 (2021).
[74] B. d. S. L. Torres, T. R. Perche, A. G. S. Landulfo, and G. E. A. Matsas, Phys. Rev. D **102**, 093003 (2020).
[75] T. R. Perche and E. Martín-Martínez, Phys. Rev. D **104**, 105021 (2021).
[76] E. Martín-Martínez, T. R. Perche, and B. d. S. L. Torres, Phys. Rev. D **103**, 025007 (2021).