The Pragmatic QFT Measurement Problem: A Tale of Two Detector Models

Daniel Grimmer - PoP Grunch

Reuben College, University of Oxford

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C3. The textbook models concerning measurement of QFT are handwavy and deeply unphysical. Fixing this requires QFT-compatible models of our detector systems.

C4. There are two state-of-the-art detector models being used today: UDW and FV. Are these enough to restore evidential support and physicality to quantum theory?

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How are we to model/understand the measurement of quantum systems?

But exactly which measurement problem am I here concerned with?

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Both questions are interesting, but the first one is more important since if unanswered its consequences are more severe.

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2. Where The Spoils Were Won (QFT-land or NonRel QM-land?)
3. What Blocks Their Way Home (Textbook models don't work, why?)
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This would be a bad situation, but not a foundational crisis.

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However, today we no longer view this as an assumption. Rather it is result derived from QFT and the light-matter interaction.

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There is such thing as no non-relativistic light.

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Avalanche detection? Maybe

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Without a satisfactory understanding of how to model measurements involving QFTs, we risk losing the whole of quantum theory's evidential support (and maybe its physicality too).

Outline

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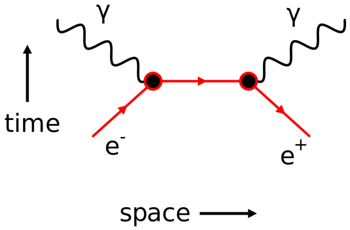
What Blocks Their Way Home

In most textbooks, measurements of quantum fields are discussed in terms of scattering problems. The outgoing particles are picked up by some (un-described) detectors.



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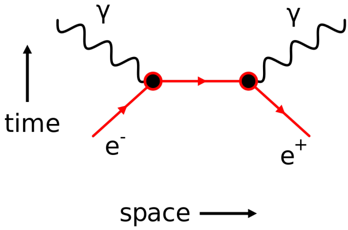

However, as a growing portion of the physics community is becoming aware[2,3,4,5], such hand-wavy models of measurement are deeply unphysical.

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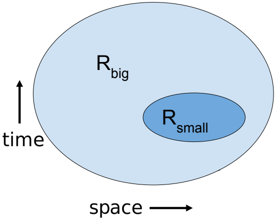

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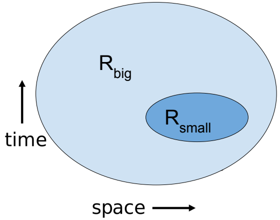
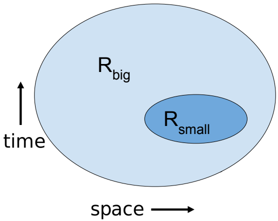


Bob understands how to do projective measurement in non-relativistic QM but doesn't know much about QFT. Luckily his friend Alice does.
(Also, Bob really doesn't want to model his detection system if possible.)

Bob's First Thought

Bob's first thought is that his lab equipment in R_{big} tells him something like: "There are exactly three particles in R_{small} at locations $x_1(t)$, $x_2(t)$, and $x_3(t)$" and that this exactly determines what is going on in R_{small}.



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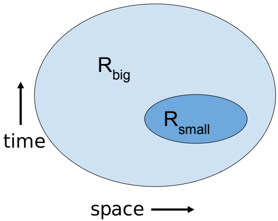

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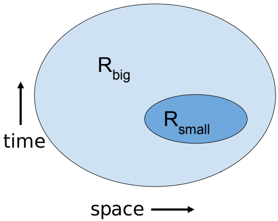

Bob asks Alice if there is any projective operator in QFT which fits this description. If so, maybe his measurement device does that?

Alice say no, for many reasons that sort of thing is not possible in QFT.

No Local Finite Rank Projectors

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Refresher) Suppose I measure the angular momentum of an atom and find $\ell = 1$. To update the state I should apply the rank-3 projector:

$$\hat{P}_{\ell=1} = |\ell = 1, m = 1\rangle\langle 1, 1| + |1, 0\rangle\langle 1, 0| + |1, -1\rangle\langle 1, -1|$$

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Contrast) Measuring whether a Q.H.O. is in an "even" or "odd" state.

In QFT all local measurements must leave an infinite number of options open. Nothing can "exactly determine what is going on in R_{small}".

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No Local Number Operator

Bob comes to Alice the next day asks her if there is any projective operator in QFT which could tell us “There are three particles in R_{small} (wherever they may be)” thinking this would leave an infinite number of options open.

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Roughly, this is because $\hat{N}(R_{\text{small}})$ would count $+1$ particles for all of the particle-antiparticle pair production events in R_{small} and would consequently diverge terribly.

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Their conversation continues on like this for a long time

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Alice is telling Bob what is and is not well-defined in QFT. The best she can do is to provide Bob with a full menu of what it is **theoretically possible** to projectively measure in QFT.

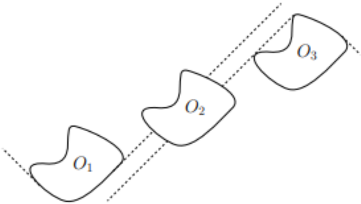

FIG. 1. Schematic spacetime diagram of the relative causal position of the regions O_1, O_2 and O_3.

Suppose this happens. Alice provides necessary and sufficient conditions[9][10] for what it is **theoretically possible** to projectively measure in QFT without breaking causality.

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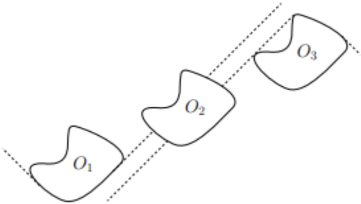

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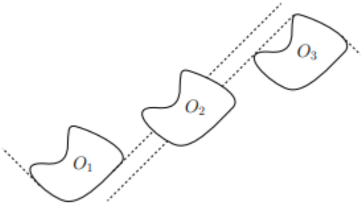

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Is Bob any closer to explaining how his lab equipment works? I think Bob needs to bite the bullet and give us a QFT-compatible model of his detection process.

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Superficially, this shows up as mathematical blunders which either

a) violate the central 'commandments' of relativity (covariance, causality and locality)
b) or disrespect the local algebraic structure of QFT (now a Type III rather Type I von Neumann algebra).

Outline

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2.✓ Where The Spoils Were Won (QFT-land or NonRel QM-land?)

3.✓ What Blocks Their Way Home (Textbook models don't work, why?)

4. A Tale of Two Detector Models (UDW versus FV)

5. Measurement Chains and Cuts

A Tale of Two Detector Models

There are two state-of-the-art approaches to modeling the measurement of quantum fields[12]:

- Fewster Verch (FV) framework: a quantum field acts as a localized probe on upon another quantum field, all formalized within the framework of Algebraic QFT.
- Unruh DeWitt (UDW) detectors: a non-relativistic atom-like probe is coupled to the quantum field.

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We can compare these on two sets of criteria:

- How well does each model preserve the central 'commandments' of relativity: covariance, causality and locality?
- How well does each model connect with experimental practice?

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$\hat{\phi}(t,x)$ - field being probed,
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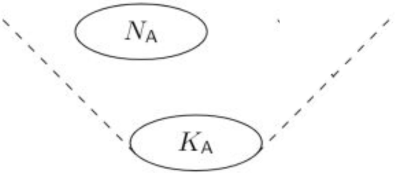

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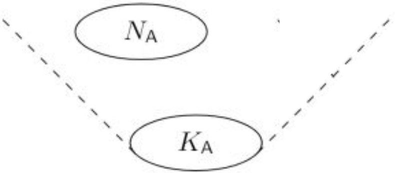

There is then a "processing region" N_A where the probe field is measured.

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Moreover, FV uses one QFT to measure the other QFT. At the end we are still left wondering how to measure a QFT.

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For a point-like detector with some trajectory, $\rho(t,x) = \chi(t)\delta(x - \gamma(t))$.

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A: Imperfectly, but with well understood and controllable issues[17][18].

- For point-like detectors there are essentially no problems.
- For smeared detectors, there are Sorkin-like signalling issues and some issues with time-orderings. But in regimes where its reasonable to talk about first-quantized atoms, these issues are managable.

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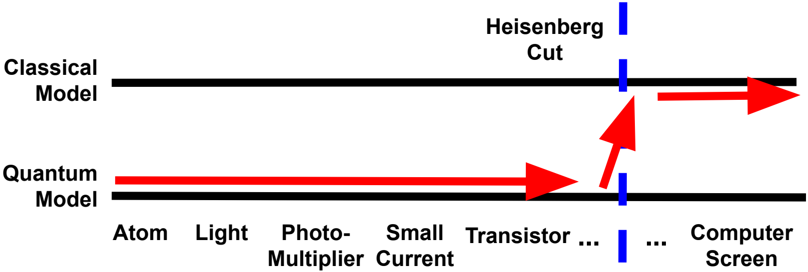
A measurement chain is the sequence of steps in our experiment which carry the measured information from one regime to another.

Ex) An atom in a superposition emits a photon which is detected by a photo-multiplier which triggers a small current which turns on a transistor which... which displays a number on a screen.

Heisenberg Cuts

At some point along the chain we take a *Heisenberg cut* and switch from modeling things quantum-ly to classically.



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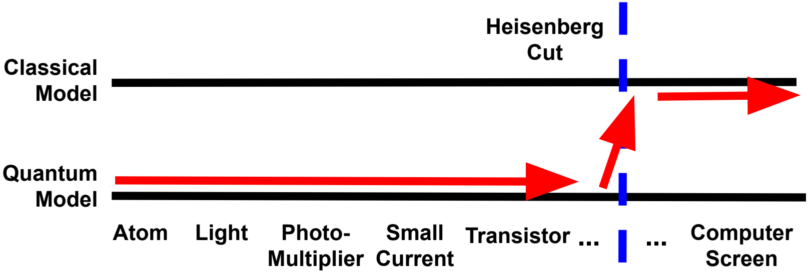
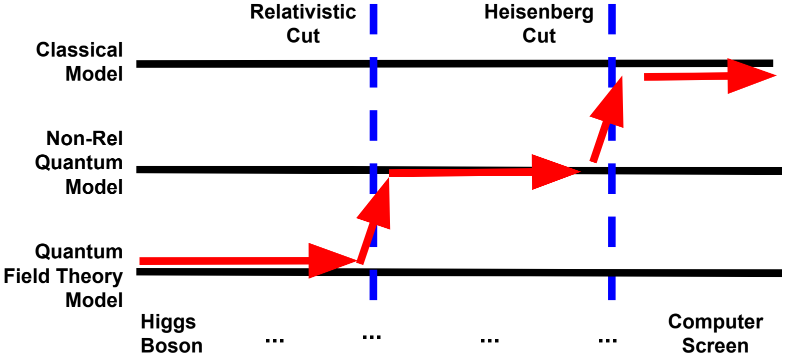


There is nothing fundamental about the placement of the Heisenberg cut. As long as we place it late enough (after the last quantum phenomena) we will get good predictions.

Do we need a relativistic cut?

I suggest that in modeling the QFT/non-relativistic QM divide that at some point we need to make a *relativistic cut*.



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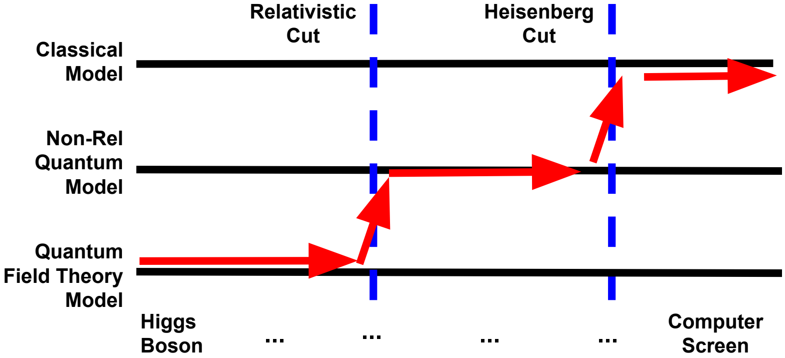
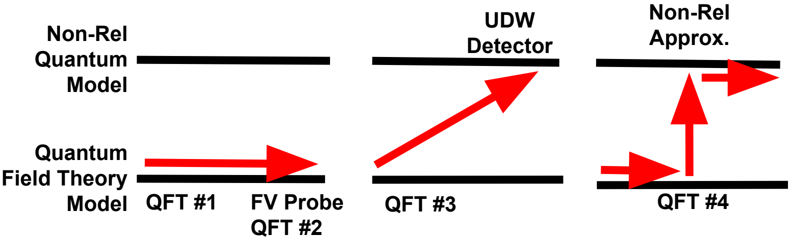


Again, there is nothing fundamental about the placement of this cut. As long as we place it late enough (after the last QFT phenomena) we will get good predictions.

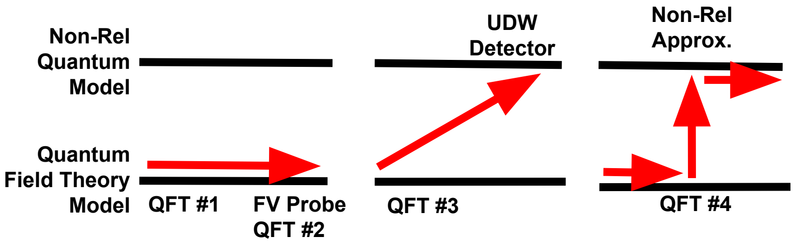
Where do the FV and UDW fit?



FV models the interaction between two QFTs and so moves us along the bottom rung.

UDW models a non-relativistic probe coupled to a QFT and so it makes a diagonal jump.

What's Missing?



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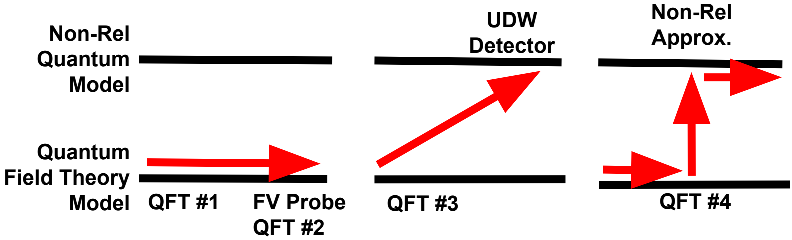
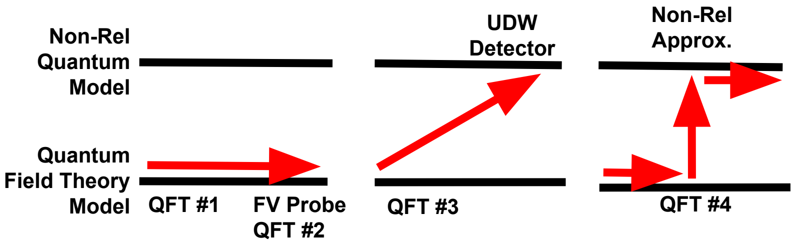


What is missing from this picture is a way to cross the divide vertically. That is, to take an isolated quantum field theory system and use some approximation scheme to map it onto a non-relativistic state.

While this is possible for some low-energy free massive QFTs, we cannot yet do the same for interacting bound states (e.g., the hydrogen atom).

Can we do enough with these tool?



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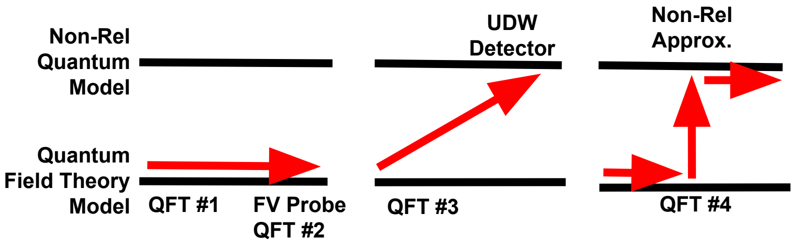

As I see it, these are the only three tools we have available currently. Each have their limitations.

Are these three tools enough to bring home the spoils and restore evidential support and physicality to quantum theory?

Conclusion

1. I have argued that to bring home a majority of the experimental spoils of quantum theory, we need to better understand how to model measurements involving QFTs.

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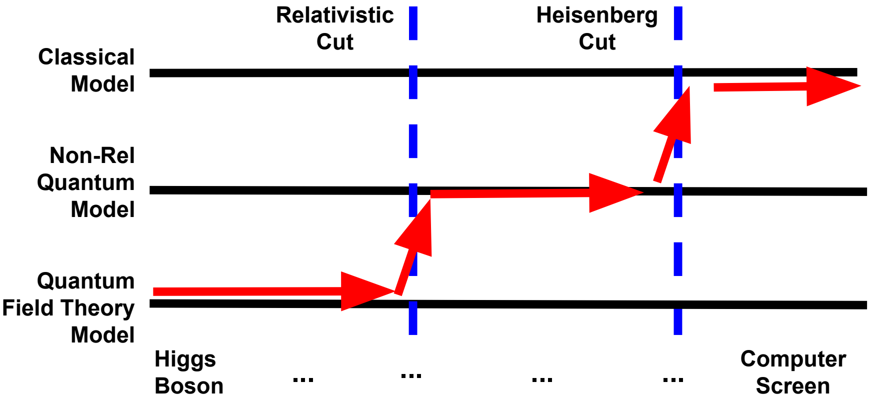
2. This unavoidably means talking about how to model detectors in QFT. Otherwise, at worst we accidentally make moves banned by QFT. At best we find a qualitative match, but don't really explain anything.
3. There are two state-of-the-art detector models being used today: UDW and FV. Together with non-relativistic approximations, these may (or may not) be enough to guide us across the *relativistic cut* which I claim is necessary.

Questions/Comments



References (1/2)

1. David Wallace: "The sky is blue, and other reasons physics needs the Everett interpretation" YouTube [37:34].
2. H. Bostelmann, C. Fewster, M. Ruep. Phys. Rev. D 103, 025017 (2021). ArXiv:2003.04660
3. C. Anastopoulos and N. Savvidou. Entropy 2022, 24(1), 4 (2021). Arxiv:2111.07983
4. J. Polo-Gómez, L. Garay, E. Martín-Martínez. Arxiv:2108.02793 (2021)
5. L. Borsten, I. Jubb, G. Kells. Phys. Rev. D 104, 025012 (2021). ArXiv:1912.06141.
6. M. Redhead. Foundations of Physics 25 (1):123-137 (1995)
7. M. Redhead. Foundations of Physics 25 (1):123-137 (1995)
8. D. Malament. Published in Perspectives on Quantum Reality (1996)
9. L. Borsten, I. Jubb, G. Kells. Phys. Rev. D 104, 025012 (2021). ArXiv:1912.06141.

References (2/2)

10. I. Jubb. Phys. Rev. D 105, 025003 (2022) ArXiv:2106.09027
11. R. Sorkin. Published in Directions in General Relativity (1993). ArXiv:gr-qc/9302018
12. D. Grimmer, B. Torres, E. Martín-Martínez. Phys. Rev. D 104, 085014 (2021). ArXiv:2108.02794
13. C. Fewster, R. Verch. Arxiv:1810.06512 (2020)
14. M. Ruep. Class. Quantum Grav. 38 195029 (2021). ArXiv:2103.13400
15. D. Grimmer, B. Torres, E. Martín-Martínez. Phys. Rev. D 104, 085014 (2021). ArXiv:2108.02794
16. R. Lopp, E. Martín-Martínez. Phys. Rev. A 103, 013703 (2021). ArXiv:2008.12785
17. J. Ramón, M. Papageorgiou, E. Martín-Martínez. Phys. Rev. D 103, 085002 (2021). ArXiv:2102.03408
18. E. Martín-Martínez, T. Perche, B.Torres. Phys. Rev. D 103, 025007 (2021). ArXiv:2006.12514