State updates in quantum field theory

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Conceptual foundations of QFT, Vienna, June 2026

Comm. Math. Phys. **378** (2020) 851 `arXiv:1810.06512` - CJF and R Verch

Measurement in quantum field theory, `arXiv:2304.13356` CJF and R Verch

Phys. Rev. D **103** (2021) 025017 `arXiv:2003.04660` - CJF + H Bostelmann and M Ruep

`arXiv:2511.11348`, CJF and CKM Klein + further work in progress

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Q1(c) Consider a quantum system with state space $\mathbb{C}^3$ and suppose observable

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is measured with outcome 3. What is the state immediately after the measurement?

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Answer By inspection, the vector $\psi = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 0 & -1 \end{pmatrix}^T$ is an eigenvector of A with eigenvalue 3. The other eigenvalues are 2 (obvious) and 1 (as $\operatorname{Tr} A = 6$), so there is no degeneracy. Hence the state after measurement is ψ. ☺

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Ideal For all projectors P compatible with A, $\mathrm{Prob}(P \mid \varphi) = 1 \implies \mathrm{Prob}(P \mid \psi) = 1$.

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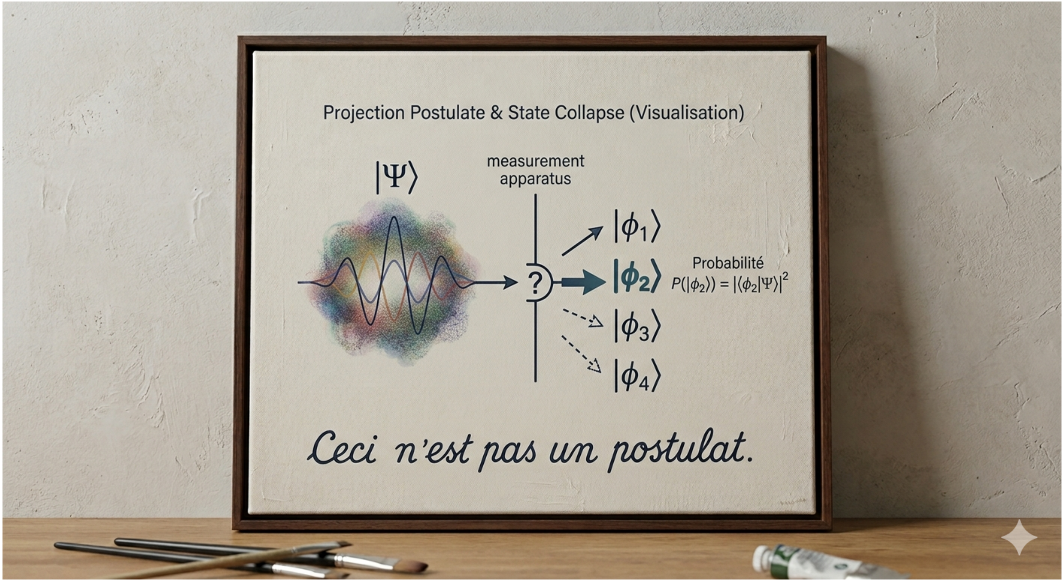
The projection postulate is not a postulate. It is a consequence of specific assumptions about the type of measurement and can only apply to certain observables.


Projection Postulate & State Collapse (Visualisation)
|Ψ⟩
measurement apparatus
?
|φ1⟩
|φ2⟩
|φ3⟩
|φ4⟩
Probabilité
P(|φ2⟩) = |⟨φ2|Ψ⟩|^2
Ceci n'est pas un postulat.

State updates in QFT — the potential problems

Adding to the woes of measurement in QM

- 'Immediately after' loses meaning due to relativity of simultaneity

State updates in QFT — the potential problems

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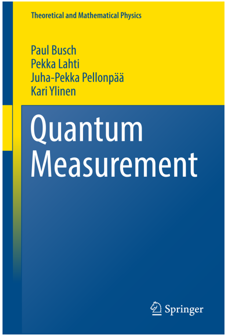
- In curved spacetimes things are worse: no preferred time coordinates or foliations
- By-hand attempts to extend QM rules to QFT encounter problems of superluminal information transfer or impossible measurements (see later) Sorkin

Modelling measurements in QFT CJF & R Verch

Idea: model the measurement process, combining modern accounts of Quantum Measurement Theory and (algebraic) QFT in curved spacetimes.



Describes measurement chain in QM

Little attention to QFT

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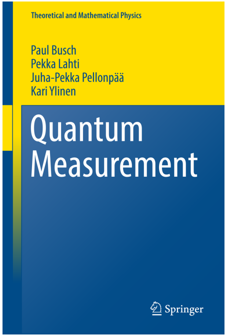

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Conceptual framework for QFT

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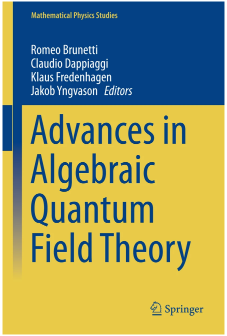

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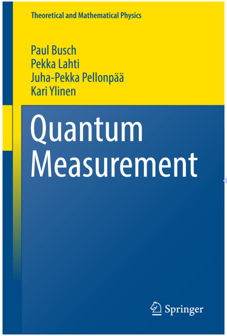

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Little attention to QFT

System, probe & coupling all described in QFT

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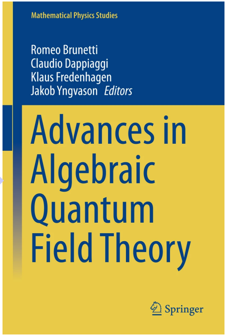

Everything you need to know about AQFT (for this talk)

AQFT describes a QFT $\mathcal{A}$ on spacetime $\boldsymbol{M}$ in terms of $*$-algebras of local observables $\mathcal{A}(\boldsymbol{M}; O)$ labelled by spacetime regions $O \subset M$.

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Main assumptions

- $O_1 \subset O_2 \implies \mathcal{A}(\boldsymbol{M}; O_1) \subset \mathcal{A}(\boldsymbol{M}; O_2)$. Isotony
  In particular $\mathcal{A}(\boldsymbol{M}; O) \subset \mathcal{A}(\boldsymbol{M}) := \mathcal{A}(\boldsymbol{M}; M)$.
- if $O_1 \subset O_2$ contains a Cauchy surface of O_2 then $\mathcal{A}(\boldsymbol{M}; O_1) = \mathcal{A}(\boldsymbol{M}; O_2)$ Timeslice
- Elements of $\mathcal{A}(\boldsymbol{M}; O)$ with $A^* = A$ are observable in O.
  Typical example – a quantum field averaged within O.

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States are linear maps $\omega : \mathcal{A}(M) \to \mathbb{C}$ so $\omega(\mathbf{1}) = 1$, $\omega(A^*A) \geqslant 0$.
$\omega(A) =$ expectation of A in state ω.

Any QFT worth the name should be representable in this way.

Measurement schemes for QFT CJF–Verch

Describe the system and probe by QFTs $\mathcal{A}$, $\mathcal{B}$ on spacetime $\boldsymbol{M}$ (globally hyperbolic).
$\mathcal{A}(\boldsymbol{M})$ = alg. of system observables on $\boldsymbol{M}$; $\mathcal{A}(\boldsymbol{M}; N)$ = subalgebra localisable in N.
Compare:

- the uncoupled combination $\mathcal{U}$ of $\mathcal{A}$ and $\mathcal{B}$

$$\mathcal{U}(\boldsymbol{M}; N) = \mathcal{A}(\boldsymbol{M}; N) \otimes \mathcal{B}(\boldsymbol{M}; N)$$

- a coupled combination $\mathcal{C}$ with bounded coupling region K in spacetime.

Only assumption: $\mathcal{C}$ and $\mathcal{U}$ coincide 'outside' K.

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Then by the isotony and timeslice assumptions, there are isomorphisms

$$\tau^{\pm} : \mathcal{U}(\boldsymbol{M}) \to \mathcal{C}(\boldsymbol{M})$$

reflecting the identifications between the two theories at early $(-)$ and late $(+)$ times.
The scattering map $\Theta = (\tau^{-})^{-1} \circ \tau^{+}$ is an automorphism of $\mathcal{U}(\boldsymbol{M})$.

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$$\varepsilon_\sigma(B) = \eta_\sigma(\Theta \mathbf{1} \otimes B), \qquad \text{where } \eta_\sigma(X \otimes Y) = \sigma(Y)X \text{ defines } \eta_\sigma : \mathcal{U}(\boldsymbol{M}) \to \mathcal{A}(\boldsymbol{M}),$$

in the sense of value reproducibility

$$\omega(\varepsilon_\sigma(B)) = \mathbb{E}(\text{experimental outcome on coupled system}).$$

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This has many good properties but we need to pass to the question of state updates.

Deriving state updates: 1

Binary measurements correspond to effects: operators $0 \leqslant E \leqslant \mathbf{1}$ with

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- and testing the coupled system for E and F at late times,

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The probabilities for these outcomes are easily determined, e.g.,

$$\mathrm{Prob}(E\&F \mid \omega) = \underbrace{(\omega \otimes \sigma) \circ (\tau^{-})^{-1}}_{\text{early time coupled state}} \underbrace{(\tau^{+}(E \otimes F))}_{\text{late time effect}} = (\omega \otimes \sigma)(\Theta(E \otimes F)).$$

Replace E by $\mathbf{1} - E$ for $\neg E$ etc.

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Q: Is there a state ω_F so that $\mathrm{Prob}(E \mid F; \omega) = \mathrm{Prob}(E \mid \omega_F)$ for all E?
A: Yes!

$$\omega_F(E) = \frac{(\omega \otimes \sigma)(\Theta(E \otimes F))}{(\omega \otimes \sigma)(\Theta(\mathbf{1} \otimes F))} \quad \text{defines a state.}$$

ω_F is thus the correct updated state to use when conditioning on success of F.

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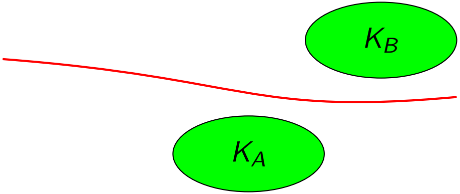
Good properties – blissful ignorance, non-spooky action at a distance – but we pass on.

Multiple causally orderable probes CJF–Verch/Bostelmann–CJF–Ruep

Probes with coupling regions $K_1, \ldots, K_N$ are causally ordered if each K_{r+1} lies outside the causal past of K_r. There may be many compatible causal orderings.



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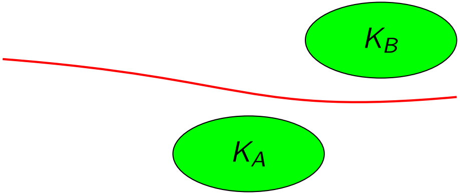

$$\Longrightarrow \quad \Theta_{AB} = \Theta_A \circ \Theta_B$$

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Theorem Assume causal factorisation between causally ordered probes. Then

- (a) testing effects A_r using the coupling corresponding to K_r

$$\mathrm{Prob}(A_{N+1}|A_1 \& A_2 \& \cdots \& A_N; \omega) = \mathrm{Prob}(A_{N+1}; ((\omega_{A_1})_{A_2})_{\ldots A_N})$$

Consequence: for spacelike separated K_r's, selective updates can be made in any order.

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- (b) if probes are coupled in causally ordered regions

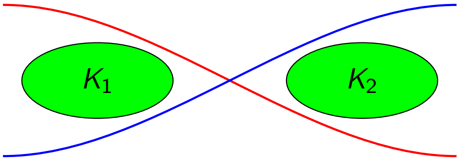
$$K_{A_1}, \ldots, K_{A_M}, K_B, K_{C_1}, \ldots, K_{C_N}$$

and effects $A_1, \ldots, A_M$, $C_1, \ldots, C_N$ are measured without selection, then

$$\mathrm{Prob}(B; \omega) = ((\omega_{A_1}^{\text{n.s.}})_{A_2}^{\text{n.s.}})_{\cdots A_N}^{\cdots \text{n.s.}}(B)$$

which depends on the past measurements, but not on the future ones.

Relativity of state updates (special case of (a))



If K_1 and K_2 are causally disjoint, then they are causally orderable in either order. By previous theorem (a) one has

$$\text{Prob}(A_2|A_1;\omega) = \text{Prob}(A_2;\omega_{A_1}), \qquad \text{Prob}(A_1|A_2;\omega) = \text{Prob}(A_1;\omega_{A_2})$$

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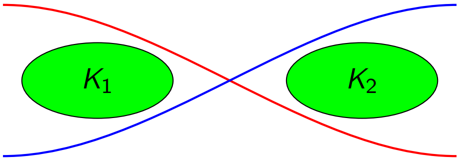

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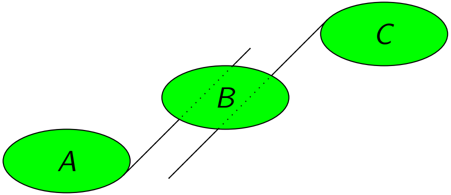
An experimenter in possession of result A_1 can update their state to predict probabilities for result A_2 and vice versa.

State update is a relative concept, depending on accessible information.

ω_{A_1} and ω_{A_2} both convey useful physical content.

Impossible measurements? Bostelmann, CJF & Ruep



- Alice chooses whether to make a nonselective measurement
- Bob certainly makes a nonselective measurement
- Sorkin 1993 Apparently typical updates by Bob allow Charlie to determine whether Alice measured, because

$$\omega_{AB}^{\text{n.s.}}(C) \neq \omega_{B}^{\text{n.s.}}(C)$$

- These must therefore be impossible measurements.

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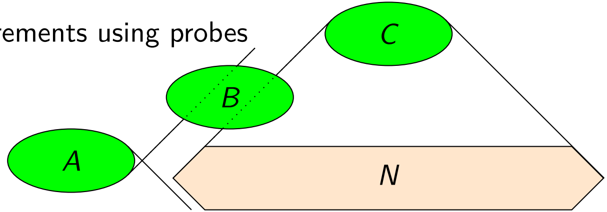
Model A and B measurements using probes



Detailed investigation of locality properties and the geometric situation gives:

$$\hat{\Theta}_B C \otimes \mathbf{1} \otimes \mathbf{1} \in \mathcal{U}(\boldsymbol{M}; N) \quad \text{for a region } N \subset K_A^{\perp} \cap M_B^{-}$$

Theorem Charlie cannot determine whether Alice has measured:

$$\omega_{AB}^{\text{n.s.}}(C) = \omega_{B}^{\text{n.s.}}(C)$$

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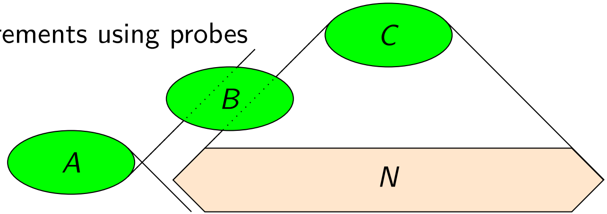

The analysis shows that the measurement scheme is free of Sorkin-type pathologies.

Key assumption – the probes and couplings are described by physics respecting locality.

Impossible measurements can only be performed using impossible apparatus.

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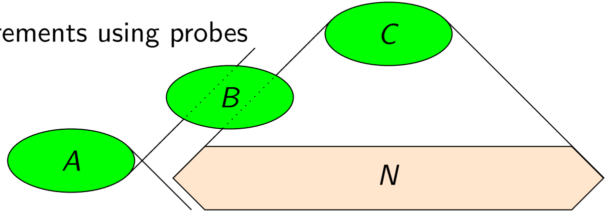

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Key assumption – the probes and couplings are described by physics respecting locality.

Impossible measurements can only be performed using impossible apparatus.

In hindsight, it turns out that the Sorkin problem concerns local implementability of operations rather then measurement as such. Even more, the same issue can be found and resolved also in classical field theories Much & Verch

What about entanglement? CJF–Klein

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  - ...spacelike separated two channel detectors
- For a 1-particle-1-antiparticle state with entangled polarisations, compute

$$\mathsf{CHSH} = 2\sqrt{2}F$$

where $0 \leqslant F \leqslant 1$ with $F \to 1$ (Tsirelson bound) in some limits and therefore $F > 1/\sqrt{2}$ (Bell bound) in a broader regime.

Some conclusions/inferences

- Modelling measurements via system–probe coupling one derives state update rules which, inter alia, resolve the Sorkin problem.
- More importantly the framework is covariant, causal, consistent and composable.
- Relativity of state update puts the notion of an absolute state into contention
- Perhaps suggests a more subjective viewpoint:
  A state is a mathematical object used to make predictions from the QFT.
  - Might reflect fact, belief, suspicion, information received...
  - Different agents may employ different states to make valid inferences.
  - Predictions may be wrong! [Eg due to erroneous beliefs or partial knowledge.]
- Everything said assumes a pragmatic viewpoint that experimental outcomes are realised and the theorist has to decide how to update the state in consequence.
  - We have not attempted to answer the question of how that happens.