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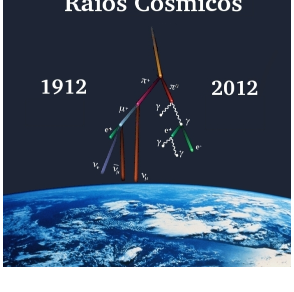

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The holistic structure of causal quantum theory, its implementation in the Einstein-Jordan conundrum and its violation in some recent particle theories

Dedicated to the memory of Jürgen Ehlers

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Abstract

Recent insights into the conceptual structure of localization in QFT ("modular localization") led to clarifications of old unsolved problems. The oldest one is the Einstein-Jordan conundrum which led Jordan in 1925 to the discovery of quantum field theory. This comparison of fluctuations in subsystems of heat bath systems (Einstein) with those resulting from the restriction of the QFT vacuum state to an open subvolume (Jordan) leads to a perfect analogy; the globally pure vacuum state becomes upon local restriction a strongly impure KMS state. This phenomenon of localization-caused thermal behavior as well as the vacuum-polarization clouds at the causal boundary of the localization region places localization in QFT into a sharp contrast with quantum mechanics and justifies the attribute "holstic". In fact it positions the E-J Gedankenexperiment into the same conceptual class as the cosmological constant problem and the Unruh Gedankenexperiment and the problem of the cosmological constant. The holistic structure of QFT resulting from "modular localization" also leads to a revision of the conceptual origin of the crucial crossing property which entered particle theory at the time of the bootstrap S-matrix approach but suffered from incorrect use in the S-matrix settings of the dual model and string theory.

The new point of view, which strengthens the autonomous aspect of QFT, also comes with new messages for gauge theory by exposing the clash between Hilbert space structure and pointlike localization for massless higher spin fields. It hopefully also will contribute to its solution.

1 Preface

The subject of this paper grew out of many discussions I had with Jürgen Ehlers after he moved to Potsdam/Golm in the 90s as the founding director of the AEI. This led to a renewal of our old contacts in the late 50s when I, before taking up particle physics, attended Jordan's relativity seminar in Hamburg in which Ehlers played the leading role. When we met again more than 4 decades later, his scientific interests as the director of the newly founded AEI had widened considerably beyond classical general relativity. He wanted to understand some points of Jordan's early work on quantum field theory (QFT) especially those around the dawn of quantum field theory in Jordan's dispute with Einstein and the reasons behind the subsequent reluctance of Jordan's coauthors Born and Heisenberg to accept his contribution to the famous "Dreimännerpapier" which nowadays is viewed as the cradle of QFT. On the other hand he felt that he should at least have some basic understanding of some of the areas pursued at the AEI outside his own research in general relativity and astrophysics. In particular he became interested in two conceptual points about which we had many discussions:

1. to understand some subtle points in Jordan's dispute with Einstein's thermal subvolume fluctuation argument, a kind of Gedankenexperiment which Einstein proposed to lend theoretical support to his notion about quanta of light. After some critical remarks in his 1924 thesis which led to an interesting published critical reply by Einstein, Jordan embraced Einstein's idea and claimed that the quantization of classical wave equation leads to an identical fluctuation behavior, although the origin of the thermal aspect in a ground state problem of quantum theory (QT) remained a mystery. The Gedankenexperiment behind this dispute was referred to as the *Einstein-Jordan conundrum* in *[1]*.

2. to obtain a better vantage point for a critical foundational encounter with string theory which was (and still is) is strongly represented at the AEI, but which Ehlers suspected to be conceptually flawed.

He asked me to look at some of Jordan's papers from a contemporary point of view [2], especially at papers which were left out by historians. These activities led to the 2003 conference in Mainz dedicated to the 100th birthday of Jordan (proceedings 2007 [3]). Ehlers presented the E-J issue in his talk and placed it into the same conceptual setting as the attempts to understand the cosmological constant in terms of fluctuation properties of quantum matter [3]. After his death in 2008, I looked more thoroughly at this Einstein-Jordan "conundrum"; I realized why it was so fascinating and at the same time so hard to understand without knowing advanced QFT. Above all, it necessitates a holistic view of QFT which I share with an increasing number of foundational minded quantum field theorist [19], and whose further clarification is the main motivation for writing this paper. Meanwhile both of the above problems have undergone a conceptual clarification [22] [4] [26] [58] [5] [28].

The E-J dispute led Jordan to propose the first quantum field theoretical model in order to study the quantum analog of Einstein's thermal fluctuations in open subvolumes. His ideas became a separate section in the famous Dreimännerarbeit [6]. This caused some ruffling of feathers with his coauthors Born and Heisenberg [1]. From a modern point of view the picture painted in some historical reviews, namely that this was a typical case of a young brainstorming innovator set against a scientific establishment (represented by Born) is not quite correct. However Born and Heisenberg had valid reasons to consider Jordan's fluctuation calculations as incomplete, to put it mildly; conceding this does however not lessen Jordan's merits as the discoverer of QFT.

One reason why this discovery of QFT was not fully embraced at the time was that, although a free field on its own (staying with its linear properties) is a quite simple object, the questions Jordan, following Einstein, asked about energy fluctuations in open subvolumes is anything but simple even from a modern point of view. It only can be satisfactory answered with the help of advanced ideas which relate the restriction of the vacuum to the observables of a spacetime subvolume with thermal properties and vacuum polarization ("split inclusions" of modular localized algebras [20]). To get a feeling for the difficulty, one only has to imagine that QFT would have started with the conceptual similar, but computational somewhat simpler presentable Unruh Gedankenexperiment [7]. Both Gedankenexperiments point towards a little known and still somewhat mysterious layer of QFT which does not make its appearance in the standard setting of Lagrangian or functional quantization. The main reason why in the present discussion the Unruh Gedankenexperiment plays a more important role as an analog to the E-J conundrum than black holes with their thermal Hawking radiation, is to alert the reader to the fact that the thermal aspect of localization is not due to the curvature of curved space time. Rather a metric-defined black hole horizon defines an *objective* (observer-independent) spacetime boundary of inside/outside localization, whereas an observer-independent localization in Minkowski space is not possible. Another reason is of course that the calculations for the Unruh Gedankenexperiment and the E-J Gedankenexperiment are simpler[1].

The thermal manifestation of pure pure states upon restricted to localized spacetime regions favors Jacobson's [8] view about a close connection of gravity with thermodynamic laws, although his arguments are predominantly classical. Using the appearance of the Bondi-Metzner-Sachs group as a subgroup of holographic projections onto nullsurfaces [26], it became recently possible [9] to significantly tighten this connection. Although it is well known, it should be mentioned here that the KMS property of wedge-localized algebras was discovered by Bisognano and Wichmann [20] and then connected with properties of Unruh horizons by Sewell; this work was significantly extended in [10]. A more mathematical presentation of modular theory with many additional references can be found in [11]. To these observations we add in this paper an *observable microscopic effect*: the high energy *crossing identity for on-shell matrixelements (formfactors, scattering amplitudes) as a consequence of the thermal KMS property of wedge localization.*

This deeper layer of QFT, compatible with (but not visible) in perturbation theory and the textbook formalism of QFT, is always present. In fact the crossing property of formfactors and scattering amplitudes and their observational consequences in high energy scattering shows that this structure has been always with us in a more real way than that of a Gedankenexperiment [5].

[1]The E-J Gedankenexperiment in Jordan's low dimensional (chiral) model is exactly soluable (section 5).

In this paper we will make a connection of these little known structural properties with "modular localization" and its consequences with respect to thermal properties and vacuum polarization. Whereas the parallelism to classical theories implied by quantization is shared between quantum mechanics (QM) and QFT, this other more foundational layer of modular localization sets them maximally apart; it shows an unaccustomed "holistic" side of QFT. Closely related is the problem of the range of the classical parallelism underlying quantization. It has been taken for granted that this formalism is universal whereas in reality it turns out to be rather restricted. Certain *classical* Lagrangians as e.g. that of a relativistic classical particle and those which have been invented in order to describe embeddings of lower dimensional theories into higher dimensional ones (the source-target embedding) do not pass upon quantization to their expected quantum counterparts[2] (section 9). On the other hand there are many more well-defined quantum field theories than there are Lagrangian interactions in connection with factorizing models (section 7). The modular localization setting of QFT is an intrinsic property of QFT and as such free of such imperfections, although its greater distance from classical and geometric intuition is a hurdle which will only be overcome in due time.

These new facts also confirm that, worse than Ehlers had expected, string theory does not only suffer from a mismatch between grand promises and meager results, but it is beset by irreparable conceptual flaws (section 9). There is of course a deep irony in the fact that both problems, the understanding of thermal aspects of localization and a critical account of string theory are conceptually connected through an incomplete/incorrect understanding of modular localization (section 4).

I deeply regret that I cannot share this knowledge with Ehlers anymore, but at least I would like to acknowledge his role in sparking my interest in something which I thought at the beginning to be only part of history. Whereas the conceptual clarifications behind the E-J dispute leads to the central properties of causal quantum theory, the outcome in the case of string theory confirms that it is the result of a subtle misunderstanding at a place where most errors in the conceptual twilight zone between QFT and QM occurred: *localization*. This explains the origin of the title and the content of the present paper.

The new concept leads also to a better comprehension of fundamental aspects of QFT which where described in recipe form without having been properly understood. An example is the "crossing property" which together with scattering theory has played a foundational role on the crossroad between particles and fields [5]. As already mentioned this property is on the same conceptual layer as the E-J as well as the Unruh Gedankenexperiment, except that it is not "Gedanken" but has measurable consequences in the real world. One is the asymptotic equality of two-particle scattering with its image resulting from interchanging an incoming with an outgoing particle under simultaneous change of particle with antiparticle (so that charge conservation is preserved) [12]. Recent research [5][36] revealed that particle crossing follows from the KMS property of wedge localization and hence is conceptually proximate to the setting of the Unruh effect and the solution of the E-J conundrum. This is a holistic aspect of QFT which leads to a foundational critique of the dual model and string theory.

[2] In the particle case this is immediatly clear since there is no frame-independet quantum mechanical position operator and the impossibility for obtaining covariant quantum strings from the quantization of a Nambu-Goto Lagrangian is explained in section .

Misunderstandings resulting from the holistic structure which distinguishes QFT from QM are not limited to string theory. Many ideas which originated in the orbit of string theory but can be separately considered are now open to criticism. An example is the idea of embedding of a source space QFT into a "target space" and its opposite, namely that of dimensional reduction. It will be shown that although both ideas comply perfectly with classical fields and QM, they run into series problems with the holistic nature of QFT. Even where one does not expect any problems, namely geometric views of QFT (as e.g. the Atiyah-Witten program of the 70-80s), the holistic nature creates serious problems and may account for the fact that the main impact of these ideas has been the amelioration of mathematical knowledge of physicists than that of particle physics. The Lagrangian reformulation of the current algebra of the multi-component massless Thirring model and its representation theory in form of the Wess-Zumino-Witten-Novikov topological model did not help physics. Whereas the perturbation theory of standard Lagrangians is at least consistent with the holistic properties of QFT, the geometrical content of a Lagrangian with a topological aspect cannot be reconciled with the presence of vacuum polarization and thermal aspects of localization[3]. It is therefore no surprise that computations on these models are done within the representation theoretical setting starting from currents.

The point here is that the mathematical notion of geometry is context-independent whereas the holistic nature of QFT forces geometric aspect to be extremely context-dependent. The geometry of internal symmetries (target space symmetries, a misnomer) which results from the foundational DHR analysis of superselection sectors [20] prevents the occurrence of anything but compact group symmetries at least for theories in $d \geq 1+3$. For chiral theories there exists no sharp division between spacetime/inner and in the vast region of non-rational theories this restriction is not valid. Nevertheless noncompact groups are generally still not implemented. The only known exception is a sigma model which carries the d=10 superstring representation of the Poincare group; but even in this case the result is a *dynamical infinite component pointlike free field* (with bad distributional behavior) and not a string-localized field. In all those illustrations there exists no such restriction on classical source-target relations, i.e. the Polyakov Lagrangian defines a perfect classical model.

The nonobservance of the holistic aspects of QFT may also explain why the Lagrangian quantization approach led to an almost 40 year stagnation in gauge theory, where it did not really address the deep clash between localization and Hilbert space structure which occurs in all $(m = 0, s \geq 1)$ Wigner representations (section 8). In this case the holistic aspect does not invalidate the old observations, it only adds new ones which incorporated also operators which cannot be point-like generated.

The next section starts the presentation of the archetype of the holistic structure of QFT: Jordan's fluctuation problem as the QFT counterpart of Einstein's thermal fluctuations in a subvolume of blackbody radiation. It also generates some sympathetic understanding for Born's and Heisenberg's critical distance to Jordan's project, which finally led up to Heisenberg's discovery of vacuum polarization (sections 3). The latter is the direct consequence of the modular localization concept (section 4) whose formulation

[3]Whereas papers on a pure mathematical subjects as the Langlands program pass the moderation of hep-th, the present paper would not. The reason for choosing math-ph is that the moderator is not an ideologue. and has a better understanding of physics..

in Jordan's model leads to the resolution of the E-J conundrum (section5). The range of application of modular localization is widened in sections 6, and 7, and in section 8 it is shown that these new ideas may even bring new impulses to the hugely unfinished business of gauge theory.

My posthumous thanks go to Jürgen Ehlers who introduced me to a fascinating topic from the genesis of QFT which still exerts its conceptual spell over actual particle theory.

2 A brief sketch of the history of the E-J Gedanken-experiment

- Einstein (1909, more details 1917 in [13]): calculation of mean square fluctuations in an open subvolume in statistical mechanics of black body radiation shows two components: wave- and particle-like ("Nadelstrahlung").as intrinsic theoretical support for photons in addition to the observational support coming from the photoelectric effect.

- Jordan in his thesis (1924, [14]) argued that the particle-like component $\sim \bar{E}_\nu h\nu$ is not needed for equilibrium.

- Einstein's reaction (ZfPh 1924 [15]) consisted in the statement that Jordan's argument is mathematically correct but physically flawed (the absorption is incorrectly described), but he praised Jordan's statistical innovation ("Stosszahlansatz").

- 1925 appearance of the first model of QFT in Jordan's section of the Dreimännerarbeit [6] as an QFT analog of Einstein's thermal fluctuation discussion. Jordan used a chiral current model which he thought of as a 2-dim. photon. He found the same two contributions in the quantum fluctuations.

It is well known that Einstein preferred the old (Bohr-Sommerfeld) QT to the new Goettingen QT, especially after Born's introduction of probabilities, a concept which he rejected on philosophical grounds. What must have been unexpected for Jordan however is that his coauthors Born and Heisenberg for completely different reasons also maintained a critical distance.

For Jordan this critical encounter with Einstein's idea of coexistence of individual wave/particle components in thermal fluctuations, but now adapted to QT at T=0, was his "Damascus epiphany" from where, by combining the idea of corpuscular quantum matter with de Broglie's matter waves, he developed the idea of a matter and wave unity in QFT leaving the point of view in his thesis which Einstein criticized far behind. Despite the correspondence of his quantum fluctuations with Einstein's thermal fluctuation, there remained a difference in interpretation; Einstein rejected Jordan's interpretation of viewing the wave and the particle component as two manifestation of only one quantum object.

A presentation of the beginnings of particle theory would be incomplete without mentioning Dirac's important role. Although Jordan's view that everything (waves or particles) which (mathematically) *can be* quantized according to the unifying rules of QFT *must be* quantized according to the same rules prevailed as the central structure of the new theory, there is no doubt that Dirac's more conservative approach to use QFT for light and (relativistic) QM for matter was extremely successful and led to discoveries (as hole theory) which, even when it became clear that they failed on higher order perturbation theory as a consequence of the vacuum polarization structure, left a permanent mark in the existence of antiparticles. His ability to extract important prevailing concepts out of non-prevailing theories is unmatched in particle physics. Finally, at the beginning of the 50s, Dirac made his peace with QFT.

Concerning Jordan's contribution to the Dreimännerarbeit, it is easy to agree with Schweber [17], Darrigol [16], Duncan and Jannsen [1] that the paper contains the first QFT. But the somewhat reserved attitude of his coauthors is also understandable from a modern viewpoint, even though they were not able to articulate their reservations at that time. From a modern point of view one could argue that the uneasiness with Jordan's calculation was an early manifestation of the *holistic nature of QFT* as compared with QM; to apply calculation methods taken from QM generally leads to violations of this holistic nature. One may decompose a relativistic local free quantum field into quantum mechanical oscillators, but this may create more harm than good if one asks questions in which specially nonlinear functions of a linear free field play a role. the problem starts when one considers composites of a free field; using the global oscillators in local vacuum fluctuation calculation runs the risk of incorrect approximations (next section). The collection of global oscillators has no simple connection with the restriction of the covariant ground state to the region of spacetime localization. This restriction to local observables imparts the properties of a thermal KMS state; in other words the particular observable becomes part of a entirety (Gesamtheit) of observables which share the same localization region (section 4).

This is precisely the viewpoint of QFT which Haag introduced in 1957 [18] and later called it "local quantum physics [20]. His idea of interpreting the spatial extend of a measuring device and the duration of its activation as an observable localized in the corresponding spacetime region fulfilling Einstein causality and an appropriately formulated causal propagation was (and still is) metaphoric if not to say naive, a fact which is easily seen by Unruh's description of a wedge-localized observer. But it turned out to be the key to the foundational properties of QFT.

The often heard statement that free fields are "nothing more than a collection of infinitely many harmonic oscillators" is of no help to a student of QM who understands oscillators but did not yet come across free fields. The rest of this article will be dedicated to convince the reader that the notion of "holistic" which is mostly used in the animate world to express that life cannot be understood in terms of the chemical composition of the living body is also useful in QFT if one substitutes "life" by the principle of "modular localization".

This holistic aspect is a subtle issue which only recently attracted special interests, notably in a paper by Hollands and Wald [19] in connection with conceptual questions about the "cosmological constant problem". These authors got annoyed by a widespread misunderstandings about QFT in calculations in which problems of the cosmological constant were treated in the spirit of a quantum mechanical problem of occupation of (global) energy levels. The calculation with a cutoff at the Planck mass leads to a gigantic result.

The cosmological constant from the holistic QFT treatment on the other hand is typically of the order of the inverse of the radius of the universe, which is the more credible calculation, but unfortunately it gives a much too small value. The authors favor the holistic approach because it is not only preferred from a theoretical viewpoint, but it is also more flexible for changes in the physical assumption. The title of their paper already reveals its main result: "Quantum Field Theory Is Not Merely Quantum Mechanics Applied to Low Energy Effective Degrees of Freedom"[4]. They give various other simple Illustrations of the holistic aspect which separates QFT from (second quantized) QM. Returning to the E-J fluctuation problem it is interesting to note that Ehlers in his Mainz symposium contribution [3] makes a connection of unknown aspects of the E-J fluctuation problem with that of the cosmological constant.

As mentioned before, one of the most common conceptual confusions is caused by the naive identification of free fields with a collection of oscillators. This is particular dangerous in computations of fluctuations in open subsystems as for the E-J conundrum. In a recent historical review of Jordan's discovery of QFT [1], the thermal aspect has been added by hand by coupling the alleged quantum mechanical system to an external heat bath in the belief that in QT the pure global vacuum state cannot pass to a impure KMS state. This is correct in QM but incorrect in QFT. Jordan himself does not mention the thermal issue, so we do not know whether he had an intuitive understanding about a problem whose resolution was far above the conceptual possibilities of those times.

Heisenberg (˜1929) challenged Jordan in correspondences about the presence of a $ln\varepsilon^{-1}$ contribution from *vacuum polarization* at the two endpoints [1] where $\varepsilon =$ *attenuation length* conceded to vacuum polarization (v. p.) or measure of "fuzzyness" of boundary[5]; this was missing in Jordan's calculations. It is consistent with the historical records to believe that the imperfections in Jordan's work on QFT were the motor behind Heisenberg's 1934 publication about vacuum fluctuations (which is one of the sharpest indicators of the holistic aspects of QFT against QM).

3 Vacuum polarization, holistic properties

In 1934 Heisenberg [21] finally published his findings about v. p. in the context of conserved currents. Whereas conserved currents In QM lead to well-defined partial charges associated with a volume V

$$\partial^\mu j_\mu = 0,\ Q_V^{clas}(t) = \int d^3x j_0^{clas}(t,\mathbf{x}) \tag{1}$$

$$Q_V^{QM}(t) = \int d^3x j_0^{QM}(t,\mathbf{x}),\ Q_V^{QM}(t)\Omega^{QM} = 0$$

[4]The conceptual content of this paper permits to add: QFT is also not geometry with QM and/or statitical mechanics added.

[5]Heisenberg's view in terms of a fuzzy boundary is closer to the LQP formulation of QFT than the indroduction of momentum space cutoffs. Whereas in the latter case one does not know what one is doing to the Hilbert space and the observables, the former procedure as implemented by the "split construction" [20] is a construction within a given theory.

there are no sharp defined "partial charge" Q_V in QFT

$$Q(f_{R,\Delta R},g_T)=\int j_0(\mathbf{x},t)f_{R,\Delta R}(\mathbf{x})g_T(t)d\mathbf{x}dt,\ f_{R,\Delta R}=\begin{pmatrix} 1, & \|x\|\leq R \\ 0, & \|x\|\geq R+\Delta R \end{pmatrix},\ g_T\rightarrow\delta \tag{2}$$

$$lim_{R\rightarrow\infty}Q(f_{R,\Delta R},g_T)=Q,\ \ \|Q(f_{R,\Delta R},g_T)\Omega\|\equiv F(R,\Delta R)\overset{\Delta R\rightarrow 0}{\sim}C_n(\frac{R}{\Delta R})^{n-2}ln(\frac{R}{\Delta R})$$

The *dimensionless* partial charge $Q(f_{R,\Delta R},g_T)$ depends on "thickness" (fuzziness) $\Delta R=\varepsilon$ of boundary and becomes the f and g independent (and hence t-independent i.e. conserved) global charge operator in the large volume limit. The deviation from the case of QM are caused by v. p.. Whereas the latter fade out in the $R\rightarrow\infty$ limit, they grow to a logarithmically modified power behavior for $\Delta R\rightarrow 0$.

Connected the Heisenberg v. p. is the more singular property of causally localized quantum fields as operator-valued distributions (only 2 decades after Heisenberg's v.p.). But the most profound physical understanding (which reveals thermal aspects together with v. p.) comes from considering $\mathcal{O}$ localized operators as members of a local operator algebra $\mathcal{A}(\mathcal{O})$ (next section)

Here are some more comments on the misleading statement "free quantum fields are nothing more than a collection of oscillators" which often students of QFT are exposed to. The free Schrödinger field and that of QFT are

$$a_{QM}(\mathbf{x},t)=\frac{1}{(2\pi)^{\frac{3}{2}}}\int e^{i\mathbf{px}-\frac{\mathbf{p}^2}{2m}}a(\mathbf{p})d^3p,\ \ [a(\mathbf{p}),a^*(\mathbf{p}')]=\delta^3(\mathbf{p}-\mathbf{p}') \tag{3}$$

$$A_{QFT}(x)=\frac{1}{(2\pi)^{\frac{3}{2}}}\int\left(e^{-ipx}a(\mathbf{p})+e^{ipx}a^*(\mathbf{p})\right)\frac{d^3p}{2\sqrt{\mathbf{p}^2+m^2}}$$

In both cases the global algebra is the irreducible algebra of all operators $B(H)$, but the local algebras are very different. Whereas in the case of QM the generated operator algebra remains of the same type $B(H_V)$ (called type I_∞), the *local algebras of QFT* $\mathcal{A}(\mathcal{O}_V)$ ($\mathcal{O}_V$ causal completion of V) are factor algebras of hyperfinite type III_1 called the *monad* (every concrete monad is isomorphic to the abstract one), the physics counterpart of the monads in Leibnitz's philosophical view of reality. (the only place where a monad appears in QM is in the thermodynamic limit of thermal Gibbs systems).

Although at first sight the difference in (3) appears to be small (a different Fourier transform of the $a(\mathbf{p})^\#$ with a different energy dependence and the appearance of both frequencies in QFT) the structural differences in the two QTs which these two fields generate are enormous[6]. The relative commutator has an effective size of the order of the Compton wave length and as such does not reveal the enormity of structural difference. The restriction of the vacuum to localized operator algebras of QFT yields an impure KMS state, just like the thermodynamic limit state in Einstein's statistical fluctuation argument, so there is no reason to introduce an external coupling to a heat bath in order to force the correspondence to Einstein's calculation. This property will be presented in more details in the next section.

[6]They become more pronounced in the flucuation properties of composites (e.g. the energy-momentum tensor) which enter the E-J conundrum.

Whether the non-observance of the holistic aspect leads to big errors or not depends on the kind of question one is interested in. Looking just at an effective measure for the difference of the causal localization of QFT and the Born-Newton-Wigner localization of wave functions (related to the quantum mechanical position operator, which brings the probability concept into QT), one may think that the relative difference in terms of the effective measure of a Compton wave length leads to small corrections. But there is no uniform estimate of vacuum polarizations and the message coming from other manifestations of vacuum polarization properties is quite different. However one can show that the discrepancy between causal- and position operator- based localization disappears in the large time asymptotic limit[7], which is crucial for obtaining covariant scattering probabilities (cross sections). In QFT both localizations are important, modular localization (see next section) for causal (i.e. subluminal) propagation and the non-covariant effective particle localization only to be used in asymptotic timelike relations (where they stay effectively subluminal). QM on the other hand only realizes the latter; the acoustic velocity is an effective velocity in this sense.

The difference between the causal localization and that related to a position operator acting on wave functions comes out most strongly in the possibility to characterize QFT in terms of nets of operator algebras $\mathcal{A} = \{\mathcal{A}(\mathcal{O})\}_{\mathcal{O}\subset M}$ (algebraic quantum field theory (AQFT), local quantum physics (LQP)). LQP was very successful in showing that all physical concepts and questions which appeared in the standard setting of QFT have a counterpart in LQP. This means that all problems of particle physics find their explanation in spacetime localization properties. Taking a historical view of this fact one may say that the dream which began in classical physics with Faraday and Maxwell found its continuation in LQP.

A particular radical illustration of this point is the reconstruction of a net of operator algebras from the relative modular position of a finite number of copies of the monad [22]. For chiral theories on the lighray one needs two monads realized in a shared Hilbert space in the position of a modular inclusion, for d=1+2 this "modular GPS" construction needs three. In d=1+3 six positioned monads [23] to create the full reality of a quantum matter world including its Poincaré symmetry (and hence Minkowski spacetime) from abstract modular groups as well as inner symmetries via the DHR superselection theory which determines the kind of quantum matter. This possibility of obtaining concrete models by modular positioning of a finite number of copies of an abstract monad is the "strongest holistic outing of QFT". Apart from d=1+1 factorizing (integrable) models where it was used for the existence proof, QFT has not yet reached the stage where such holistic properties can be applied to controlled approximations. An extension to curved spacetime would be very interesting; th simplest question in this direction is the modular construction of the local diffeomorphism group on the circle in the setting of chiral theories.

These structural insights are presently far removed from the constructive level of realistic QFTs. But this may not remain so; in certain 2-dimensional families of models (sections 5,6) these ideas played already a crucial role in showing their mathematical

[7]This is similar to the formation of the speed of sound in QM as an asymptotically defined effective velocity. The appearance of components beyond the speed of sound before the asymptotic limit is irrelevant

existence as well as for the explicit construction of particle matrixelements of localized operators (formfactors). This also includes the existence proof of chiral models [24] and factorizing models [25] by operator algebraic methods. These construction methods may seem exotic to someone who has learned QFT by the classical parallelism of Lagrangian- or functional- quantization, but the latter, despite their intuitive appeal, only lead to divergent perturbative series whereas the former allow a nonperturbative mathematical control. In QM one has powerful spectral methods which lead to mathematical controlled approximation methods of individual operators, even if the model is not integrable. The counterpart of this in the context of QFT would be a proof of nontriviality of compactly localized intersections of nontrivial wedge-localized algebras which are the basic building blocks of LQP. The E-J conundrum shows that even in interaction-free QFT there are questions concerning fluctuation in open subsystems which cannot be answered in terms of textbook physics dealing with individual operators.

4 Modular localization and its thermal manifestation

In the following we collect some properties which form the nucleus of LQP and which give a direct understanding of the properties mentioned in the preface. Since localized subalgebras in QFT $\mathcal{A}(\mathcal{O})$ are known to act cyclic and separating on the vacuum (the Reeh-Schlieder property [20]), the conditions for the validity of the Tomita-Takesaki modular theory are fulfilled. The theory secures the existence of the Tomita operator $S_{\mathcal{O}}$ whose polar decomposition

It has been known for a long time that the algebraic strucure underlying free fields allows a functorial interpretation in which operator subalgebras of the global algebra $B(H)$ are the functorial images of subspaces of the Wigner wave function spaces ("second quantization"[8]), in particular the spacetime localized algebras are the images of localized subspaces.

LQP generalizes QFT in the sense that it does not narrow it down to perturbation theory and to any Lagrangian quantization or any other quantization parallelism; as the more fundamental theory QFT has the right not to be told by less fundamental theories how it should arrange its outing. It also deemphasises individual operators in QFT in favour of entireties ("Gesamtheiten") of operators. This intends to model the situation in the laboratory where the experimentalist measures spacetime coincidences between spacetime events; all the rich particle data including the nature of spin and internal quantum numbers are obtained by repetitions and refinements of such observations based on counters which which fill a compact spatial region and remain switched on only for a limited time. This metaphoric idea was used as the start of a very successful theory (see the next sections) where the entirety of operators sharing the same localization region $\mathcal{O}$ are idealized as an operator algebra $\mathcal{A}(\mathcal{O})$. These observable operator algebras commute for spacelike separation of the region and as a result of the causal nature of localization one, can without loss of generality, assume that $\mathcal{O} = \mathcal{O}''$ i.e. the region is causally closed. As almost all successful idealizations, also this one is based on a metaphor. What is

[8]Not to be confused with quantization; to quote a famous saying by Ed Nelson: "quantization is an art, but second quantization is a functor".

really behind this metaphor can be studied in the Unruh Gedankenexperiment where it is shown that to localize counter hardware in a noncompact wedge region one has to uniformly accelerate the counters in a specific way [7]. For compact localization . as in the Einstein-Jordan conundrum the main interest is however not to think about its realization in terms of hardware, but rather to understand why the restriction of the the vacuum to such a localization region leads to a singular impure state which is always thermal (KMS with respect to some unknown but existing modular Hamiltonean). LQP places these properties into the center and considers Lagrangian quantization as a legitimate but very limited way; in particular because all the renormalized perturbative series diverge and give no information about the conceptual status of a theory.

The mathematical description of causal localization of operator algebras is based on a important property which physicists developed in the first half of the 60s in connection with statistical mechanics of open systems [30] and mathematicians in connection with the study and later the classification of von Neumann operator algebras [31]; the relation with causal localization came only later [32]. As mentioned before, the prerequisite for the application of the Tomita-Takesaki modular theory to problems of localized algebras is the cyclic and separating action[9] of $\mathcal{A}(\mathcal{O})$ on the vacuum, is always fulfilled. The T-T theory the existence of an unbounded antilinear involution $S_{\mathcal{O}}$with a dense domain $domS_{\mathcal{O}}$ which contains all "algebra- or field- states" of the form $A\Omega$ which can be associated with the $\mathcal{O}$-localized algebra $\mathcal{A}(\mathcal{O})$ and obeys the relation

$$S_{\mathcal{O}}A\Omega = A^*\Omega,\ A \in \mathcal{A}(\mathcal{O}),\ S_{\mathcal{O}} = J\Delta^{\frac{1}{2}},\ J\ antiunitary,\ \Delta^{it}\ modular\ unitary \tag{4}$$

$$\mathcal{O} = W\ \curvearrowright\ S_W = J\Delta^{\frac{1}{2}}, \Delta^{it} = U(\Lambda_W(-2\pi t)),\ J_W = S_{scat}J_0,\ \Lambda_W\ is\ W\ preserving\ boost$$

The modular unitary gives rise to a modular automorphism of the localized algebra $\mathcal{A}(\mathcal{O})$ which in the case of the wedge can be shown to be the boost automorphism. Modular theory attributes the role of a *relative modular invariant to the S-matrix in addition to its role in scattering theory.* J and J_0 are (up to a π rotation which preserves the edge of the wedge) the TCP transformation of the interacting and the associated (by scattering theory) free theory. For the mathematical proof of this geometric aspect within the Wightman setting of QFT see [32] and for one which uses the formulation of scattering theory within the algebraic setting [33].

Since it is not possible to present a selfconsistent account of the mathematical aspects of this theory in a setting as the present one, the aim in the rest of this section will be to raise awareness about its physical content. It has been known for a long time that the algebraic strucure associated to free fields allows a functorial interpretation in which operator subalgebras of the global algebra $B(H)$ are the functorial images of certain real subspaces of the Wigner wave functions (the famous so-called "second quantization"[10]), in particular the spacetime localized algebras are the images of localized real subspaces. This means that the issue of localization to some extend can be studied in the simpler form of

[9]Cyclic means that $\mathcal{A}(\mathcal{O})\Omega$ is dense in H and separating means that $\mathcal{A}(\mathcal{O})$ does not contain operators which annihilate the vacuum.

[10]Not to be confused with quantization; to quote a famous saying by Ed Nelson: "quantization is an art, but second quantization is a functor".

localized subspaces of the Wigner particle representation space (unitary positive energy representations of the $\mathcal{P}$-group). These localized subspaces can be defined in a completely intrinsic way i.e. only using operators from the positive energy representation of P; one takes the one particle action u of the w-preserving Lorentz group and the reflection j along the edge of the wedge and forms the unbounded one-particle operator

$$\begin{aligned} &\mathfrak{s}_W = \mathfrak{u}(\mathfrak{f}_W(-i\pi))j_W,\ \mathfrak{s}_W^2 \subset 1 \\ &\mathfrak{s}_W\psi = \bar{\psi},\ K_W = \{\varphi \in dom\mathfrak{s}_W; \mathfrak{s}_W\varphi = +\varphi\},\ \mathfrak{s}_W i\varphi = -i\varphi \\ &K_W \text{ "}is\ standard\text{"} : K_W \cap iK_W = 0,\ K_W + iK_W\ dense\ in\ H_1 \end{aligned} \tag{5}$$

where $\bar{\psi}$ describes a particle with the conjugate charge. Of course the global Hilbert space of one-particle wave functions H_1 contains the conjugate wave function, but the crux of the s-action is that if one restricts H_1 to the dense subspace of W-localized wave functions defined in terms the operator $\mathfrak{s}_W$ which in turn is intrinsically defined in terms of the unitary representation of the Poincaré group, the theory contains an operator which implements the star operation on a localized dense subspace which is in turn determined by this property. The properties in (5) result simply from the commutativity of $\Lambda_W(\chi)$ with the reflection j on the edge of the wedge; since j is anti-unitary commutes with the unitary boost, there will be a change of sign in its action on the analytic continuation of u, i.e. it has all the properties of a modular Tomita operator and it is easy to check that it acts on wedge-localized wave function by complex conjugation where in the presence of charge quantum numbers the particle wave function is mapped into its antiparticle. The K-spaces $K(\mathcal{O})$ for causally closed sub-wedge regions $\mathcal{O}$ can be obtained by intersections; it may however turn out the the latter are trivial i.e. $\cap_{W\supset\mathcal{O}}K(W)$ (see below).

The conncetion with causal localization is of course a property which come from the physical context. The general setting of modular real subspaces is a Hilbert space which contains a real subspace $K \subset H$ which is standard in the above sense. The S-operator is then defined in terms of K and iK.

The above application to the Wigner representation theory of positive energy representations[11] also includes the infinite spin representations which lead to semiinfinite string-localized wave functions i.e. there are no pointlike covariant wave function-valued distributions which generate these representation; they are genuinely string-licalized in contrast to their better known superstring counterparts which only share the name. The application of the above mentioned second quantized functor converts the modular localized subspaces into a net of $\mathcal{O}$-indexed interaction-free subalgebras $\mathcal{A}(\mathcal{O})$. Interacting field theories can of course not be obtained in this way; as mentioned before in this case one can start with the Wightman setting or the LQP algebraic formulation with the additional assumption that the theory has a complete scattering interpretation (its Hilbert space is a Wigner-Fock space).

But as it happens often in physics, if one arrives at a foundational property which has been derived from lesser fundamental setting one changes the setting in such a way the the less fundamental properties are derived as consequences of the foundational principle. This means in particular that renormalized perturbation and all the other within the

[11]The positive energy condition is absolutely crucial for obtaining the prerequisites (5) of modular localization.

setting of formal power series expansions rigorous statement must also be reproducable in the new setting; this has been verified to a large extend.

The algebraic setting interms of modular localization also gives rise to a physically extremely informative type of of inclusion of two algebras which share the vacuum state, the so-called *modular inclusions* $\mathcal{A} \subset \mathcal{B}$ where modular means that the modular group of the bigger $\Delta_{\mathcal{B}}^{it}$ compresses (or extends) the smaller algebra. A modular inclusion forces the two algebras automatically to be of the monad type. The above mentioned "GPS construction of a QFT" from a finite number of monads positioned in a common Hilbert space uses this concept in an essential way. It is perhaps the most forceful illustration of the holistic nature of QFT.

There are two physical properties which always accompany modular localization and which are interesting in their own right

- *KMS property* from restriction of global vacuum to $\mathcal{A}(\mathcal{O})$. By ignoring the world outside $\mathcal{O}$ one gains infinitely many KMS modified commutation properties with modular Hamiltonians $\hat{K}$ associated to the $\widehat{\mathcal{O}}$ restricted vacuum.

$$\begin{aligned} &\langle AB\rangle = \left\langle Be^{-K}A\right\rangle, \quad \Delta = e^{-K},\ A,B \in \mathcal{A}(\mathcal{O}),\ infinitly\ many\ \widehat{K}\quad for\ \widehat{\mathcal{O}} \supset \mathcal{O} \qquad (6)\\ &\langle AB\rangle \neq \langle A\rangle \langle B\rangle \quad if\ \ [A,B]=0\ in\ contrast\ to\ QM \end{aligned}$$

For chiral theories on the lightray there is a rigorous derivation of the localization entropy for an interval with vacuum attenuation length ε (surface fuzziness) from the well-known linear length $L \to \infty$ behavior (the "one-dimensional volume factor" L). They are related as $ln\varepsilon^{-1} \sim L \times kT$. This *inverse Unruh effect* plays an important role in the full understanding of the E-J conundrum presented in the next section.

- Higher dimensional localization entropy. In this case there are rather convincing arguments that the limiting behavior for $\varepsilon \to 0$ for the dimensionless entropy is the same as in the increase of the dimensionless partial charge (2). This suggests[12] that the heat bath entropy and the localization entropy are related in n-dimensional spacetime by [26] (the *weak form of the inverse Unruh effect* [27])

$$V_{n-1}\left(kT\right)^{n-1}|_{T=T_{\rm mod}} \simeq \left(\frac{R}{\Delta R}\right)^{n-2} ln\left(\varepsilon^{-1}\right) \qquad (7)$$

The logarithmic factor corresponds to the light-like direction on the lightfront and the n-2 power represent the n-2 transverse directions. V_{n-1} is the well known thermodynamic volume factor (made dimensionless by the kT powers) and the ΔR represents the thickness of a light sheet of a sphere of radius R and corresponds to the attenuation distance for the vacuum polarization. The logarithmic ε-factor corresponds to the mentioned lightlike length and its fuzzy boundary $ln\varepsilon^{-1}\tilde{}L \cdot kT$ so that $V^{n-2} \times L\ \tilde{}\ V^{n-1}$

[12]Both the large distance thermodynamic divergence and the short distance "split" divergence of localized algebras involve approximations of monads by type I_∞ factors and it is suggestive to look for a connection. For n=2 there is a rigorous derivation (see last section).

i.e. transverse volume×lightlike L written in a dimensionless way since entropy is dimensionless. A dimensionless matter-dependent factor (which is expected to be identical on both sides) has been omitted. The vacuum polarization of individual operators obeys the same formula, but for the thermal property of localization it must be viewed as part of an "entirety" (Gesamtheit) $\mathcal{A}(\mathcal{O})$. The relation (7) points at a more foundational conjecture: a heat bath KMS thermodynamic limit state which defines a global monad and a KMS state resulting from restriction of a pure state onto a local monad differ in their physical parametrization (the *weak inverse Unruh effect*[13]). Note that increase of entropy with the tightening of localization as expressed by the right-hand side of (7) may be viewed as a substitute for Heisenberg's uncertainty relations which together with the frame-dependent position operator has no conceptual place in QFT.

The holographic projection onto a nullsurface reduces the original symmetry but at the same time leads to a tremendous symmetry enlargement [26] containing the infinite Bondi-Metzner-Sachs symmetry which in turn contains a copy of the Poincaré group.

5 The E-J conundrum, Jordan's model

Jordan took as his photon field in the quantum field theoretic side of the E-J conundrum the massless chiral current associated to a chiral free field[14]

$$\begin{aligned} &\partial_\mu \partial^\mu \Phi(t,x) = 0,\ \Phi(t,x) = V(u) + V(v),\ u = t + x,\ v = t - x \\ &j(u) = \partial_u V(u),\ j(v) = \partial_v V(v),\ \ \langle j(u), j(u')\rangle \sim \frac{1}{(u - u' + i\varepsilon)^2} \\ &T(u) =: j^2(u) :,\ T(v) =: j^2(v) :,\ \ [j(u), j(v)] = 0 \end{aligned} \tag{8}$$

Theorem 1 *([27][29]) A global chiral operator algebra $\mathcal{A}(\mathbb{R})$ associated with the heat bath representation at temperature $\beta = 2\pi$ is isomorphic to the vacuum representation restricted to the half-line chiral algebra such that*

$$\begin{aligned} (\mathcal{A}(\mathbb{R}), \Omega_{2\pi}) &\cong (\mathcal{A}(\mathbb{R}_+), \Omega_{vac}) \\ (\mathcal{A}(\mathbb{R})', \Omega_{2\pi}) &\cong (\mathcal{A}(\mathbb{R}_-), \Omega_{vac}) \end{aligned} \tag{9}$$

The isomorphism intertwines the translations of $\mathbb{R}$ with the dilations of $\mathbb{R}_+$ and extends to the local (interval) algebras as:

$$(\mathcal{A}((a,b)), \Omega_{2\pi}) \cong (\mathcal{A}((e^a, e^b)), \Omega_{vac}) \tag{10}$$

The isomorphism holds for all chiral models.

[13] The "inverse" refers to the fact that the non-geometric commutant "region" of a heat-bath situation is incorporated into the "living space" of a local net of algebras in a global pure state. "Weak" means that only the entropy relation of such a picture can be established.

[14] Before Wigner's representation theoretical classification of particles physicists believed that as in QM, the spacetime dimension did not play an important role in presenting matters of principles [2].

The proof starts from a thermal KMS state for the translational Hamiltonian on a lightlike line .The closure of the full algebra $\mathcal{A}(-\infty, +\infty)$ in the KMS representation defines (via the GNS representation) an operator algebra $\mathcal{M}$ which, as all thermal representations of global algebras of open systems is a monad i.e. of the same type as the local algebras in QFT. Let $\mathcal{N} \subset \mathcal{M}$ be its half-space algebra in therm. representation. It is easy to check that this defines a modular inclusion of two monads. But such an inclusion defines a full chiral net of interval-indexed operator algebras, which is the algebraic characterization of a chiral theory [27]. This is a special case of the aforementioned algebraic characterization of QFT in terms of a modular positioning of a finite number of monads

The mean square energy fluctuation in a subinterval requires to compute the fluctuations of integrals over the energy density $T(u)$ and compare them to the calculation in a thermal heat bath calculation (the Einstein side). But the present consideration shows that both are structurally (independently of the chiral model) identical, so this is in particular true in case of Jordan's quantum fluctuation model.

Properties of states depend on the algebra: a monad does not have pure states nor density matrices but only admits rather singular impure states as singular (non Gibbs) KMS states.

6 New insights into QFT from modular setting

An important new insight into "particles & fields" comes from a new conceptual view of the *crossing property* of formfactors, every formfactor is analytically connected with the vacuum polarization formfactor

$$\begin{aligned} &\langle 0 \left| B \right| p_1, ..p_n \rangle^{in} = \ {}^{out}\langle -\bar{p}_{k+1}.., -\bar{p}_n \left| B \right| p_1, ..p_k \rangle^{in}_{con} \\ &B \in \mathcal{B}(\mathcal{O}),\ \mathcal{O} = W,\ \bar{p} = antiparticle\ of\ p \end{aligned} \tag{11}$$

The S-matrix crossing follows via LSZ scattering formalism from formfactor crossing. Formally (without the analyticity) crossing is supported by the LSZ formalism, but without analytic continuation the crossing identity is a tautology. The physical content of (11) consists in the statement that the right hand sight is not only an object which can be expressed in terms of a time-ordered correlation function within the same model, but is even the analytic continuation of another on-shell quantity: the crossed formfactor.

As will be seen, the process of crossing some incoming momenta into their outgoing (backward mass-shell antiparticle) counterpart is nothing else than the cyclic KMS commutation relation[15] with a wedge affiliated Lorentz boost generator as the KMS Hamiltonian. This changes the conceptual setting of crossing from what it was thought to be at the time of the bootstrap- and the dual model- project. Who among the dual model followers has thought at the time that the foundational crossing property, without which the dual model and ST would never have been constructed, is in the same conceptual boot as the Unruh [7] effect? Whereas the latter will probably forever (together with the Einstein-Jordan subvolume fluctuation idea) remain a Gedankenexperiment (albeit one

[15]The replacement of the thermal Gibbs representation, which for open systems (in the thermodynamic limit) ceases to make mathematical sense [30], by the Kubo-Martin-Schwinger analytic boundary formulation.

which characterizes foundational properties of a successful theory) the consequences of crossing are obswevationally accessible e.g. in the comparison of the high energy limit of a process with its crossed counterpart [12].

For a special case (elastic scattering) Bros, Epstein and Glaser [35] derived crossing from properties of Wightman functions within the rather involved setting of functions of several analytic variables. These methods are similar to those which Källén and Wightman used in their (later abandoned) project of finding the analyticity domain of the 3-point function. Presumably the reason why these methods were given up at the beginning of the 70s was that the relation between mathematical expenditure and physical gain was too unfavorable.

The modern conceptual understanding came from the recognition that crossing is a consequence of modular KMS for wedge localization[16]. It involves different algebras acting in the same Hilbert space and sharing the same $\mathcal{P}$-representation. To get some technicalities out of the way, let us first formulate the KMS relation for the case without interactions. Let $B(A)$ be a composite of a free field $A(x)$ i.e. either a point-like Wick-ordered polynomial or a Wick-ordered polynomial in a smeared free fields $A(f_i)$ with $suppf \subset \mathcal{O}$ such that that

$$\langle B : A(g_1)..A(g_k) :: A(h_1)..A(h_l) :\rangle \neq 0, \quad B,\ A \ \prec \mathcal{A}(W) \tag{12}$$

$$\overset{KMS}{=} \langle : A(h_1)..A(h_l) : \Delta\ B : A(g_1)..A(g_k) :\rangle\,, \ \Delta^{it} = U(L(-2\pi t))$$

$$\langle 0\,|B|\,p_1, .p_k, q_{k+1}.., q_{k+l}\rangle = \langle -\bar{q}_1, .., -\bar{q}_l\,|B|\,p_1, ..., p_k\rangle_{con} \tag{13}$$

i.e. the fields affiliated with the interaction-free operator algebra localized on the wedge obey the thermal KMS relation[17] (second line), with the modular Hamiltonian being the generator of the wedge-preserving boost operation. By carrying out the Wick contraction and converting the free fields acting on the vacuum into particle states, one obtains the free particle form of the crossing relation in the last line. In shuffling the $A(h)$ fields and the modular Δ operator to the bra-vacuum one must pay attention to the modular relation $\Delta J_0 \Delta^{\frac{1}{2}} = \Delta^{\frac{1}{2}} J_0$ which is important for $p \rightarrow -\bar{p}$. For $0 < Imt < \pi$ the expectation values are analytic functions, but on the distribution-valued boundaries one finds delta function contributions on both sides which come from poles; the above prescription correspond precisely the omission of such terms (indicated by the subscript *con*) which in terms of fields are nothing but terms from Wick contractions.

Now we come to the much more subtle case with interactions; we use the notation: $\mathcal{B}(W) =$ interacting algebra, $\mathcal{A}_{in}(W) =$ free algebra; now the letter B stands for an operator affiliated with the interacting algebra. Any W-localized field affiliated to the $\mathcal{B}$-algebra $B \prec \mathcal{B}(W)$ which creates a state in $domS_{\mathcal{B}(W)} = domS_{\mathcal{A}_{in}(W)}$ has a bijectively related image in $\mathcal{A}(W)$ ("emulation" of free field structure in $\mathcal{B}(W)$ [5][28])

$$: A_{in}(f_1)...A_{in}(f_n) : \longrightarrow (: A_{in}(f_1)...A_{in}(f_n) :)_{\mathcal{B}(W)},\ suppf \subset W \tag{14}$$

$$: A_{in}(f_1)..A_{in}(f_n) : |0\rangle = (: A_{in}(f_1)..A_{in}(f_n) :)_{\mathcal{B}(W)}\,|0\rangle\,,\ f \rightarrow \ \check{f}$$

[16]It shares the connection between locality and analyticity with the old derivation, but instead of going back to the Wightman functions, the analyticity is channeled through the more foundational properties of modular localization.

[17]The vacuum restricted to $\mathcal{A}(\mathcal{O})$ looses its global groundstate property and becomes a thermal state.

where $\check{f}$ is the wavefunction associated the testfunction f. Its existence is secured by modular theory applied to the wedge region. The KMS relation from which the particle crossing is to be derived reads [29]

$$\left\langle B(A_{in}^{(1)})_{\mathcal{B}(W)}(A_{in}^{(2)})_{\mathcal{B}(W)}\right\rangle = \left\langle (A_{in}^{2})_{\mathcal{B}(W)}\Delta B(A_{in}^{1})_{\mathcal{B}(W)}\right\rangle \tag{15}$$

$$\Delta(A_{in}^{(2)})_{\mathcal{B}(W)}^{*}\left|0\right\rangle = \Delta^{\frac{1}{2}}J_0 A_{out}^{(2)}\left|0\right\rangle \tag{16}$$

All free operators have been "emulated" within the interacting algebra and the problem in extracting a crossing relation consists in a reconversion back into in/out particles on both sides of the KMS relation. Whenever an emulated k-fold Wickproduct acts on the vacuum it can be reconverted into a particle state; the nontrivial problem is to convert the emulated Wick-product in the middle

$$\left\langle 0\left|B(A_{in}^{(1)})_{\mathcal{B}(W)}\right|p_1,..p_k\right\rangle$$

into a particle states. Imagining a decomposition of the unknown emulated operator $(A_{in}^{(1)})_{\mathcal{B}(W)}$ into a series of Wick-ordered operators and Wick-ordering the action of this operator on the k-particle state one obtains one overall Wick-ordered operator which is reasonable for the n-particle state on the left hand side of (11) and contributions from contractions with the k-particle states which have been left out. These contraction terms actually have a very rich structure and are nontrivial even in the case of factorizing theories [34]. in particle states. Within the overall Wick ordering the emulated operator commutes with the particle creation operators and hence meets the vacuum whereupon the emulation can be undone and the result van be written as a n=k+l particle state. Omitting the contraction term one arrives at (11). For more details we refer to [36].

7 Model construction of "integrable" QFT

The word integrable appears here in quotation marks because the standard definition in classical and quantum mechanics in terms of sufficient many conservation laws is less appropriate in QFT where a fundamental definition should avoid the quantization parallelism and refer directly to the foundational modular localization and its two physical companions, the vacuum polarization and the thermal manifestation. A useful definition which accomplishes this is in terms of the above emulations for operators in $\mathcal{A}_{in}(W)$ in terms of operators in $\mathcal{B}(W)$. In general we only know that the emulated operator fulfills $(A_{in}(f))_{\mathcal{B}(W)}\left|0\right\rangle = A_{in}(\check{f})\left|0\right\rangle$ where $\check{f}$ is the mass-shell projected wave function associated with the W-supported test function. The conversion into free field or particle actions or particle states is only possible for the action on the vacuum. For the action on other states the emulated operators reveal that they are part of an interacting theory and lead to rather complicated expressions. Their free field action on the vacuum led to the terminology vacuum-polarization-free-genertors (PFG)

In [37] it was shown that there exists a sharp division between two types of theories in terms of the domain properties of their emulated PFGs, namely "temperate" PFGs in which the domain of the unbounded emulated operators is translation invariant (similar to domains of Wightman fields) and theories with non-temperate domains. Since the emulation refers to a wedge-localized algebra, the normal case is that the domain is only invariant under those Poincaré transformations which leave the wedge invariant. The temperateness condition leads to a trivial S-matrix for $d \geq 1+2$ but allows precisely those models in d=1+1 with a nontrivial purely elastic S-matrix which are known under the name of factorizing models and are known to be integrable in the above sense and in the sense that one can explicitly compute their formfactors. Their emulated one-particle operators Theories with tempered PFGs admit nontrivial S-matrices only in d=1+1 and even there the S_{scat} operator is purely elastic which is the characteristic feature of factorizing (integrable) models. In this case the emulated one-particle operators are closely related to the Zamolodchikov-Faddeev operators [38] consisting of a creation and annihilation part

$$(A_{in}(f))_{\mathcal{B}(W)} = \int_{H_\pm} Z(p)\check{f}(p)\frac{d^3p}{2p_0} \tag{17}$$

which fulfill the Zamolodchikov-Faddeev commutation relations. Non-temperate theories lead to emulation with a significantly more complicated algebraic structure.

These d=1+1 interacting models are the first models in the history of QFT with nontrivial (noncanonical) short distance behavior for which it was possible to establish their mathematical existence. The idea was to show that the double-cone algebra, which can be represented as the intersection of two PFG-generated wedge algebras, is a nontrivial monad which acts on the vacuum in a cyclic and separating matter and by covariance gives rise to a net of algebras whose S-matrix is identical to the structure function in the Zamolodchikov algebra. Point-like fields are just generators (operator-valued distributions) of these algebras [25]. In addition to the abstract nontrivial existence proof of a factorizing model. one also wants to compute explicitly some objects in such a model; this has been achieved for the formfactors of factorizing models. This algebraic construction of factorizing models also reveals that the collection of viable QFTs (insofar viable can be used in d=1+1) is much larger than those which can be associated with a Lagrangian; this corresponds to the fact that there are by far more crossing analytic, Poincaré invariant and unitary elastic S-matrices than local Lagrangian interactions. For each such S-matrix one can construct the formfactors of a local QFT [34].

Non of the physically important d=1+3 can be constructed in this way since integrability in QFT is limited to d=1+1, however, as mentioned before, there is a good chance for establishing at least their existence. The situation in QFT cannot be better than in QM, where solutions in closed form are limited to integrable models. But there methods of functional analysis (spectral theory of selfadjoint operators) at least permit to establish the mathematical well-definedness of models as well as the elaboration of mathematically controlled approximations. There is justified hope that the above emulation idea in operator algebras, which is intimately related with the properly understood crossing, may be able to achieve the same in QFT: an existence proof as well as a controlled approximations.

The role of the S-matrix in the modular localization setting has no relation to what is called the Stueckelberg-Bogoliubov-Shirkov S(g) which is really a generating operator functional for time ordered correlations. In this connection it is interesting to note that Stueckelberg was a severe critic of Heisenberg's idea of a pure S-matrix approach by bringing in the large timelike aspect of microcausality in addition to its spacelike cluster factorization which Heisenberg already accounted for. In playing around by demanding the validity of the large time structure for *all* distances and restricting in a completely ad hoc way the interaction to a point, he found the Feynman rules of QFT but left the pure S-matrix setting. It is somewhat unfortunate that his perturbatively determined operator functional $S(g)$ (generating time-ordered functions) is often referred to as an S-matrix. The true S-matrix of e.g. integrable models is well known but $S(g)$ is presumably an object which is mathematically meaningful only in perturbation theory[18].

The problem of an understanding of a more detailed structure of the contact terms in the general crossing relation is crucial for a new approximation scheme based on the above ideas. In the factorizing case the complete answer is known.

8 Impact of modular localization on gauge theories

Modular localization has no impact on renormalized perturbation theory. This is not surprising since in those formulations which are ultraviolet-finite (as the Epstein-Glaser method) causal locality is implemented order by order as a pointlike property and the knowledge about the class of pointlike composites (the Borchers class) is sufficient. In fact perturbation theory is nothing else than the implementation of the locality principle for a given free field content combined with the requirement that the maximal scaling degree for coalescing points in the time-ordered functions remains bounded by 4 (in d=1+3). If this can be achieved one arrives at a theory with a finite number of parameters with a renormalization group transforms within this parameter space, in short a renormalizable theory. Within the use of pointlike fields, the number of renormalizable couplings is finite and it ends at spin s=1 for which the evocation of the gauge formalism permits at least to calculate that part of the theory which is generated by charge neutral pointlike observables. Using string-like localized fields with the short distance dimension d=1 (which exist for any spin) renormalizable theories in the sense of power counting exist for all s; but this may be pyrrhic victory unless the interaction leads to a pointlike generated subalgebra, as in case of s=1 (more below). In any case the perturbative classification of interactions is tantamount to the classification of realizations of the causal locality principle and only to a minor degree to the construction of concrete operators (as in QM). The perturbative formalism is a self-runner in the sense that even if one uses methods which contradict the holistic spirit of QFT as cutoffs or regularizations in intermediate steps, one will inevitably arrive at the same result.

For zero mass higher spin, starting from s=1, there is a fundamental clash between Hilbert space structure on the one hand and pointlike locality (more generally: localization in compact spacetime regions), a clash which has no counterpart in classical theory [39], where, at least formally, vectorpotentials are pointlike fields with constraints which can be dealt with using the classical field formalism of Batalin-Vilkovisky and Becchi-Rouet-Stora-Tuytin[19]. The quantization approach based on this formalism inevitably resolves the mentioned clash in terms of a "ghost-formalism" in which the pointlike generators of

[18]For superrenormalizable polynomial scalar couplings in d=1+1 for which everything works in agreement with the dreamworld of Lagrangians and functional integrals one also expects the nonperturbative existence of $S(g)$.

[19]For a recent application to perturbative quantum gravity and the hope to find a frame-independent perturbative formulation see [40]..

observables are recovered in terms of gauge invariance (which in this formalism amounts to a cohomological property often presented as "BRST invariance"). A pragmatist may be satisfied with this formalism, after all there is no law against accomodating such aliens to QT as ghosts temporarily (in intermediate steps), as long as at the end of the day one becomes clean in the sense of QT and its Hilbert space structure.

There is however a strong reason which should even convince the staunchest pragmatist to think otherwise. The best conceptual motivation for stepping outside the ghost formalism comes from Wigner's representation theory. The message is that it is perfectly possible to describe a covariant vectorpotential in the Wigner space if one gives up its pointlike generation and permits semiinfinite string-like localization[20]. Of course there is nothing in the noninteracting theory which necessitates the introduction of these string-like vectorpotentials $A_\mu(x,e)$ since the Wigner representation is already generated already by the pointlike field strengths $F_{\mu\nu}(x)$. However the string-localized vectorpotentials are already helpful in the free theory in e.g. simplifying the derivation of the quantum field theoretic analog of the Aharonov-Bohm effect. Whereas the derivation in the setting of field strength is a bit involved and reveals that the line integral in Stokes theorem cannot be written in terms of a pointlike vectorpotential, the use of string-like localized vectorpotentials is straightforward and protects one from the wrong conclusion of a zero A-B effect which the unphysical pointlike potential obtained by quantization would lead to [41][39]. The A-B effect is a special case of the breakdown of Haag duality in multiple connected spacetime regions. We [43] constructed these string-like localized potentials being guided by modular localization[21], they are also accessible by more pedestrian methods.

What should really convince a pragmatist is the fact that there is an important entity which is missing in the quantization approach namely the electrically charged fields; their construction is not part of the gauge theoretic formalism. Even though the perturbative gauge formalism does not provide the physical charge carriers there are structural theorems [20] outside of gauge theory which show that their best possible localization is semiinfinite string-like which represents the *sharpest noncompact localization* (in a picture in which the point-like localization is the sharpest compact localization)[22]. The theorem on spacelike cone localizability of charged matter is based on a QFT adaptation of the Gauss law. The same kind of argument also reveals that the Lorentz symmetry is spontaneously broken in electrically charged sectors and that instead of electrically charged one-particle states one has *infraparticles* which are always surrounded by an infinite cloud of real soft photons. There are convincing arguments that the spacelike cone localization goes together with a continuos superselection rule labeled by the direction of the stringlike core of the cone. But how can one see these properties in perturbation theory? The answer is that they remain hidden. Though one may think of the Dirac-Jordan-Mandelstam

[20] In the logic of modular licalization there is no qualitative difference between compact simply connected localized (in spacetime) objects of different size since they are all generated by poitlike generators. One has to pass to noncompact localized operators and algebras in order to become aware of semiinfinite string-like generators whose presence cannot be seen in compact localized algebras [41].

[21] For the third Wigner class (the infinite spin representation) it would be very hard to find the covariant string-localized formalism without the help of modular localization.

[22] In both cases the sharp localized generators are operator-valued distributions.

formula [2]

$$\psi_{phys}(x) = \psi_{quantized}(x) e^{ie\int_x^\infty A_\mu(x')dx'^\mu} \tag{18}$$

but on the one hand it is very difficult to compute with this formula[23], and on the other hand it delegates problems of localization to the validity of an assumed "quantum gauge principle". In reality the basic causal locality principle leads next to point-like generated compactly localized chargeless variables also to noncompact string-like generated charged. For a recent reformulation of this idea within string-localized potentials and its relation to "infraparticles" see [41]

The quantum gauge principle is a clever trick which allows to understand the compactly localized neutral quantum matter without being forced to solve the more difficult problem of the semiinfinite string-localized charged matter. In fact this problem can be solved within the usual setting of perturbation theory, the main role of the gauge principle is to eliminate objects which are not part of the point-like generated observables which can be accommodated within a Hilbert space. The necessity to admit such a strong nonlocal behavior is a problem of QED which has no counterpart in the classical Faraday-Maxwell world. But is does not invalidate the classical Nahewirkungsgesetz which in the quantum context becomes generalized to causal locality and survives noncompact string-localization.

If causal localization is really the basic principle of QFT one should be able to point at a *property of the interaction* which is responsible for the noncompact localization. With the vectorpotentials being gauge-dependent point-like fields there would be no chance to understand the noncompact localization of charges since pointlike fields interacting in a pointlike manner can only produce interacting pointlike fields. To place this question into a more concrete context: what is so special about the QED interaction when other point-like interactions involving zero mass bosons as the scalar or pseudoscalar $\pi - N$ coupling with zero mass π conform with the pointlike setting?

The answer is that the string-like nature of charged fields and their associated infraparticles result from the interaction of a string-localized potentials with (formally) point-like matter fields [41]. Whereas, metaphorically speaking, the quantum matter becomes de-localized in an irreversible way, the string-like vectorpotentials, which were the culprits, shrink away by returning to the pointlike field strengths and leave the electrically charged fields behind which cannot be forced to behave in a compact localized way by any linear operation acting on them. After the generating operators of the theory have been constructed, the full content of QED can be described in terms of a point-like localized $F_{\mu\nu}(x)$ and a noncompact string-like $\psi_{ph}(x,e)$. In the nonabelian case almost nothing is known about the connection between the stringlike nature of quark and gluon fields and their invisibility on the mass shell apart from the fact that it must come from a very severe form of string localization which already affects gluons; QFT cannot produce invisibility from confinement to compact spacetime regions (for more comments see [41]).

The advantage of the use of string-localized potentials is especially evident in the case of the SchwingerHiggs mechanism. The name Schwinger is of particular importance here

[23]Its perturbative evaluation is not part of standard renormalization theory but has to be delt with by an additional perturbative formalism [2].

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because it permits recourse to a more physical explanation of interacting massive vectormesons in terms of "*electric charge screening*". Contrary to what Schwinger believed, this idea does not work with charged spinor matter, at least within the setting of perturbation theory. It does however work perfectly in QED with scalar matter: the massless string-localized matter passes to a massive string-localized potential and the final content of the theory can be generated in terms of only pointlike fields. Above all, the nonsensical wording "spontaneous symmetry breaking" which allures to Goldstone's mechanism is disposed of [42]; of course screening means that the electric charge selection rule looses its power in scattering processes. Admittedly, charge screening is somewhat more drastic than the quantum mechanical Debeye screening which only changes the range of interactions but does not affect the particles and their second quantized fields. Such a picture has the additional advantage that it does not lead to terminologies as "God's particle which gives the masses to the hadrons"; a screened particle participates in the renormalization processes the same way as any other particle.

The conditions for the success an approach based on string-localized potentials are favorable, the Epstein-Glaser approach to renormalized perturbation theory requires no Lagrangian (but only an interaction polynomial) and its reliance on causal locality nourishes the hope that an adaptation to string-localized vectorpotentials may be possible. It turns out that for any (m=0,$s \geq 1$) Wigner particle representation one can, in addition to "field strengths" (for d=2, an object $R_{\mu\nu\kappa\lambda}$ with the properties of the linearized Riemann tensor) there always exist string-localized potentials in the physical Wigner space ($g_{\mu\nu}(x,e)$ in case of s=2) with the lowest possible scale dimension $d_{sc} = 1$. On the other hand for m>0 all covariant representations are realized by pointlike fields, however their short distance dimension is always >1. Although there is no representation theoretic reason for going beyond pointlike representation, this delocalization by allowing string-localization lowers the short distance dimension and the value $d_{sd} = 1$ can still be attained for all representations. In that case. So for s=1 one has two vector fields, one point-like $A_\mu(x)$ with $d_{sd} = 2$ and a string-like $A_\mu(x,e)$ with $d_{sd} = 1$. Naturally it is the stringlike field which permits a m=0 limes to the massless vectorpotential $A_\mu(x,e)$.

It is interesting that this description does not only replace gauge transformations with a concrete operator expression for Φ from the change of string localization[24]

$$\begin{aligned} A_\mu(x,e') &= A_\mu(x,e) + \partial_\mu \Phi(x,e,e') \\ &= U(x,\Lambda(e,e'))A_\mu(x,e)U(x,\Lambda(e,e'))^* \\ U(x,\Lambda(e,e')) &= U(x)U(\Lambda(e,e'))U(x)^* \end{aligned} \tag{19}$$

but also permits to express this change as the result of a generalized e-changing Lorentz transformation (second and third line) where "generalized" means that the unitary Poincaré transformation participates in the testfunction smearing. This leads to division of operators into 3 classes: e-independent pointlike generated $(F_{\mu\nu}, j_\mu)$, mildly e-dependent (A_μ as above, $\bar{\psi}\partial_\mu\psi$) and strongly e-dependent charge-carrying operators (ψ) which spontaneaously break the Lorentz symmetry. This form of change of string direction can only

[24]In older presentations of gauge theory the relation between gauge and Lorentz-transformations was more appreciated than in modern BRST presentations.

be expected in models without A_μ selfinteractions whereas in Yang-Mills theories one expects an interaction dependent formulas describing these changes.

Even with the perturbative use of string-like interactions the structural understanding of charged matter is still not settled. The DHR theory [20] and its ensuing theory of inner symmetries [55] which constructs the physically relevant superselection sectors and the associated compact internal symmetry groups from the pointlike generated chargeless observables is not applicable in its standard form to massless theories s=1 with a Gauss law, which are known to have a much richer superselection structure. There is realistic hope that the DHR superselection analysis allows an extension to QED (see forthcoming work by Buchholz, Doplicher and Roberts). This would not solve the problem of perturbation theory of fields ψ in the before mentioned third class, but it would at least lead to a conceptual intrinsic closure without tinkering with ad hoc gauge bridges and open the way for the understanding of the origin of the on-shell invisibility of Lagrangian degrees of freedom as gluons and quarks.

It is quite interesting that the use of string-localized covariant potentials allow to write down renormalizable fourth degree polynomials which are renormalizable in the sense of power-counting for arbitrary high spins. But to book this as a victory would be premature since the problem of perturbative construction of physical higher spin models has been shifted from short distance behavior to finding point-like generated subalgebras (pointlike composites) in a theory which is generated by noncompact string-like localized fields. To phrase it differently: what is the use of a $g_{\mu\nu}(x,e)$ selfinteraction if the model has no point-local composite field strength as $R_{\mu\nu\kappa\lambda}$ and if those interactions which do (the Einstein-Hilbert interaction) continue to violate the power-counting criterion? The modular localization is the link between the content of this section with the main theme of this paper.

9 The dual model & string theory from misunderstandings about crossing and quantum localization

The incomplete understandings of the E-J conundrum had hardly any consequences for the development of QFT since it was just a Gedankenexperiment (similar to the Unruh Gedankenexperiment) without direct observational consequences. In fact, the imperfections in the Jordan fluctuation presentation may even have helped Heisenberg to think about vacuum polarizations. Nowadays we know that It belongs together with the Unruh effect [7] and the *crossing identity* to the *thermal manifestations of causal localization.*

The *bootstrap S-matrix approach* was based in the crossing property but did not contribute to its to a conceptual understanding of the origin of crossing. But since it never led to conceptional controlled concrete model calculations, this lack had no harmful consequences. Outright misunderstanding of crossing started with Veneziano's implementation of Mandelstam's S-matrix program which led to the dual model. In a tour de force, based on an artful use of Gamma and Beta functions and identities between them, Veneziano [44] produced the first version of the *dual model* in which a carefully placed infinite family of mutually dependent first order poles in the Mandelstam s and t channels in such a way that these channels were formally related by crossing. But this kind of crossing has nothing to with the crossing of particle physics which is an intrinsic property of on-shell quantities as formfactors and S-matrices.

Nowadays we know that the Mellin transforms of conformal correlations (in any spacetime dimension) produce in a natural way the generalized setting for Veneziano's ad hoc construction [45]; the pole terms arise from the properly normalized Mellin transforms of converging global operator expansions inside conformal correlations[25] and the s-t-u channels correspond to the three possibilities of applying global expansions. The dimensional spectrum of the composites in the expansion determine the location of the infinitely many poles which define the crossing symmetric meromorphic dual model function. Leaving the hypothetical question of whether one would have proposed this result as the first order S-matrix of a new pure S-matrix theory in the full knowledge of its completely different origin aside, certainly in the full sight about the true nature of the crossing in particle theory as explained before it is impossible to maintain such a viewpoint. The confusion of the field duality in conformal QFT with the crossing of particle physics is a serious conceptual error which has derailed particle theory for more than 4 decades.

String theory inherited this "original sin" of misinterpretation from the dual model. It grew out of having a more conventional description in terms of Lagrangian quantization which led to the Nambu-Goto Lagrangian. Its canonical quantization leads to an infinite component QFT which, although lacking a genuine interaction, contains operators which communicate between the levels of the infinite mass/spin tower and in this way set the spectrum of the tower. Such *dynamical infinite component fields* were looked for in vain before; the idea of embedding the Lorentz group into a more general noncompact group did not work [50]. At this point ideology began to dominate over conceptual insight. Some (at that time) young physicists [47][48] from the string community calculated the (graded) *pointlike* commutator of these fields, but they desperately avoided the p-word, calling it a string from which only one point is visible, or using similar linguistic tricks which kept them in harmony with their community.

The same outcome arises in the dual model setting which claims that the two dimensional massless sigma model of an n-component chiral current $j_i(x)$

$$\begin{aligned} g(x,Q) &= e^{i\sum Q_i\Phi_i(x)},\ \Phi_i(x) = \int_x^\infty j_i(x')dx' \\ e^{iQ\cdot\Phi(x)} &\to V(\tau,p) = e^{iP\cdot X(\tau)} \end{aligned} \tag{20}$$

which describes a chiral field carrying the multicomponent charge Q_i in a theory which has a continuous charge spectrum. The dual model use is indicated in the second line: the sigma model field is interpreted as an embedding of a one dimensional chiral source theory into a n-dimensional "target" theory with P_i being a particle momentum and $X_i(\tau)$ tracing out a position in target space[26] i.e. a "string" whose picture in the graphical world of Feynman should be a worldsheet. There simply exists no causal localizable quantum theory in which covariant operators which describe spacetime positions exist. This is also

[25] Note that the Mellin transformation, different from the Fourier transformation has no operator formulation i.e. the relation to the Hilbert space formulation is only well-defined on the conformal side.

[26] To strengthen their viewpoint, string theorist write down an action of a relativistic particle as a lower dimensional analog of string theory thus forgetting that there is no frame-independent position operator. The correct description of particle spaces is Wigner's representation theoretical approach.

the reason why the X_μ in the Polaykov action is not a spacetime variable and hence the arguments linking this action to gravity are conceptually flawed [49].

In view of the holistic aspect of causal quantum theory this reading is nonsensical; what really happens in terms of localization is that, what is called mistakenly "embedding" in ST, is correctly described by stating that all the oscillator degrees of freedom in $\Phi_i(x)$ (conveniently described in the compact circular presentation of chiral theory) *go into the internal degrees of freedom* over a localization point which corresponds to the zero mode in the Fourier decomposition. There is absolutely nothing which is string-localized in spacetime. One can of course call the collection of oscillators in the inner Hilbert space a "string" but to do this in a theory as QFT which is able to produce real spacetime strings would be careless. It is simply not possible to embed a lower dimensional QFT into a higher one, the holistic nature of QFT vetoes most ideas of a purely geometric origin. In the example at hand the the non zero chiral modes build up the mass/spin tower of a dynamical pointlike field, the chiral model looses its field theoretic localization character and the non null modes simply accommodate themselves as quantum mechanical inner degrees of freedom over one point. Another way of saying the same thing is that the τ in the sigma-model field V (20) cannot be a worldline parameter in a target space but rather characterizes changes in the composition of inner degrees of freedom (the composition within the infinite mass/spin tower). The use of this sigma model for the "dual model approximation of an S-matrix" is even more bizarre. These two interpretation are very different from the intrinsical normal use of the current algebra as the observable algebra in a representation theoretical construction of its superselection sectors and the affiliated sigma model field [51].

This is not the yet the end of the construction of "strings"; since inner symmetries in QFT are usually implemented by compact groups, there is a problem to obtain a global momentum operator P which transform according to a unitary representation of the Poincaré group. Chiral models allow noncompact inner symmetries (nonrational theories), but even there one finds that is not possible for most n; in fact only for n=10 there exists a unitary positive energy representation, the supersymmetric string representation, also referred to as the *superstring* which belongs to a sigma with a supersymmetric target space. In fact there are finitely many possibilities to realize the superstring, which string theorists claim represent an "M-theoretic" relations between fundamental spacetime models. Of course every field theorist would try explain this as a peculiarity of noncompact inner symmetries of a chiral sigma model, but string theorist are hung up on the metaphor that one is confronting a deep property of quantum spacetime.

Whereas in the E-J conundrum the holistic aspect leads to its resolution, in string theory it destroys the idea of a localized embedding and forces the would be string degrees of freedom as stated above to be internal quantum mechanical degrees of freedom stacked as an infinite mass/spin tower over one point of a pointlike relativistic field. This is possible because QM does not have an intrinsic spacetime localization in an algebraic sense[27].

[27]The probabilty interpretation was added to the operational structure of QM by Born and its non-intrinsicness still permits animated discussions between different schools about the measurement process. The main purpose of quantum mechanical localization is to obtain an effective velocity of propagation as the sound velocity or in relativistic QM an effective velocity bounded by c.

Some string theorists, upon some prodding, concede that "string" is a misleading terminology, what they are really after is a pure S-matrix for which such a terminology which refers to localization has no physical meaning. So the string terminology is only metaphoric garnish for activating the intuition for the the construction of an S-matrix with an infinite mass/spin tower. The wordsheet recipes and their analogy to Feynman diagrams serve as a kind of metaphoric lubricant. Fact is that despite great efforts involving some of the best people in this area during almost 5 decades, it was not possible to find a quantum operational presentation (in terms of operators/states) of any of these recipes.

Nowadays, with a more than 40 year distance, one can pinpoint precisely the conceptual error which led to the dual model and string theory. It is the incorrect understanding of the nature of on-shell crossing. The crossing with which Veneziano implemented his dual model was the crossing which one encounters in conformal 4-point functions. Using locality of the fields one can apply the global operator expansion in 3 different (crossed) ways. This leads to 3 in general different expansions for the same object. Dual models result from this by using the above analogy of P with multicomponent charges and of masses with anomalous dimensions. *But the particle crossing has nothing to do with this conformal formalism. It results from the holistic thermal KMS property of the wedge-localized interacting algebra and its free particle counterpart* as explained in a previous section.

The lack of an operational interpretation of Mellin transforms of conformal correlations (the mathematical name for the dual model) discourages any such attempt right from the beginning; Mellin transformed correlation function, unlike Fourier transforms, have neither a relation to Poincaré symmetries nor a simple connection with the Hilbert space structure; the positivity (unitarity) requirements on dual model (Mellin) functions are totally different than those on scattering amplitudes and formfactors in particle theory.

But the blame for moving away from the center of quantum field theory (which is marked as the connection of localization with vacuum polarization and thermal properties) cannot be placed solely on uncritical attitudes of string theory. The ill-conceived association between geometry and QFT, which ignores the holistic aspects of the latter, started in the middle of the 70s and also contributed to this development. Whereas most areas of mathematics do not care about the context in which mathematical structures appear (e.g. whether Riemann surfaces appear as concrete surfaces in three dimensions, an connections with Fuchsian groups or in any other conceivable way), the spacetime geometry in the context of modular localization in QFT is much more contextual and burdened with the holistic aspects of QFT. The before-mentioned creation of a full local net of operator algebras (including the appearance of the Poincaré group and the spacetime on which it acts) from the abstract modular positioning of a finite number of monads shows this contextual aspect in a very drastic way. As mentioned before, embeddings which are natural in geometry generally fail because the holistic quantum matter refuses to play the geometric game. Generally it is not possible to embed a lower dimensional QFT into a higher dimensional one. But the embedding of causally complete QFT with the same dimension is possible and plays an important role in the categorical setting of the principle of local covariance of QFT in curved spacetime [52].

Most of the geometric implementations of extra dimensions and their reduction by "curling up dimensions" are limited to the setting of classical field theories (Kaluza-Klein) and violate the holistic aspect of QFT. If the starting QFT permits a Euclidean version one could implement a compactification in terms of a thermalization of one direction and a conversion into a real time coordinate of another one. In some sense this may be interpreted as doing something operational on the original theory. But a quantum theory which covers all the manipulations being published under the name of "extra dimensions" and their reduction does not exist.

In the best situation the addition of a sophisticated geometry and topology to an existing models does not do any harm but it also does not enrich the quantum field theoretic side[28]; all the calculations are still done in the old-fashioned way of representation theory of currents and construction of their associated sigma model fields as they were done before the new terminology. In other cases geometric interpretations lead to results which clash with the holistic nature.

As a consequence certain things which are perfectly possible in pure geometry (either in its differential or its algebraic form) and in QM, cannot be realized in QFT.

Among the concepts which are seriously affected by the holistic nature is the concept of branes. As will be explained in more details in the next section it is the phase space degree of freedom issue which causes serious problems for the idea of branes [45] as well as the similar case of the AdS-CFT correspondence [54]. (next section). Branes are primarily quasiclassical objects and as such not fundamental; the problem starts if one tries to incorporate them into a causal QT.

Finally let us look at the problem of target spactime theories from a completely different viewpoint, one which is in certain aspects more down to earth but in another sense highly conceptual. Instead of quantizing classical structures let look for holistic aspects of QFT which cannot be understood within a quantization ideology. One of the deepest theorems is that it is impossible to obtain noncompact inner symmetries, only compact groups can feature as inner symmetries of a theory. This is the content of the DHR superselection theory [20] and the DR classification of inner symmetries [55]. Classically one can equip any field with an index which carries a finite dimensional representation of any symmetry group, compact or not. The standard form of the DHR theory is however not directly applicable to 2-dim. models since it is well known that there is no sharp separation between spacetime and inner symmetries when the statistics changes to plektonic (braid group) statistics. In addition there are two type of chiral theories, rational one which in some sense are analogs of the compact inner symmetries and the large class of purely explored nonrational models. Hence it is not excluded that the target space (the classical name which string theorist use for the inner symmetry space) carries a noncompact group as a positive energy representation of the Poincaré group. However this is very rare and only possible in d=9+1: the already mentioned famous superstring representation and its finite number of M-theoretic modifications. It is not string-localized but rather an infinite component field and the Lorentz group act on its mass/spin tower as it acts on any infinite

[28] An example is the recasting of a sigma field to a multicomponent massless Thirring model into the Lagrangian setting of a Wess-Zumino-Witten-Novikov model. The topological structure which requires to introduce a third dimension prevent the application of ordinary perturbation theory which could have been the only advantage of replacing the representation theoretical setting of a sigma model by Lagrangian quantization.

component field. If one wants to see by hook or by crook a string in this problem then it should be looked for in the inner structure above one point; what was expected to be a causal spacetime string became a "stringy" (infinite oscillators) QM i.e. in a different conceptional frame in which "localization" has no intrinsic meaning. As a result of the field theoretic form of its action (a two-dimensional sigma model field with Lorentz target indices), the Polyakov form of string theory fits most easily into this description of an infinite component field theory; with the infinite components resulting from the somewhat unusual requirement to represent a noncompact inner symmetry group, which in the QFT setting is excluded by modular localization[29].

While at ST, one should not forget to comment on the analogies which string theorists use to support their claim of string localization and world surfaces. In order to prepare their unaided counterparts to be receptive to the string idea they evoke a analogy to a relativistic classical particle [56]

$$L = \sqrt{ds^2} \tag{21}$$

Whereas this Lagrangian indeed leads to a covariant (frame-independent) relativistic wordline. But this is not true in quantum theory since there is no frame-independent *quantum* description of particles, or to say it in the Wignerian way, the position operator of particle cannot be incorporated into a covariant particle representation [30]. In other words there is a space of covariant wave functions, but it cannot be attained by Lagrangian quantization. In fact Wigner was disappointed by finding the noncovariant Newton Wigner position operator inside his covariant representation (the covariant modular localization has no position operator) that he lost faith in QFT[31], even though he was one of its trailblazers. The answer one would give nowadays with the full power of modular localization at our disposal is that the modular localization of wave functions indeed preempt (via second quantization) the causal localization of observables. The failure of (21) to lead to a physical quantum theory can be overcome by field quantization. Not every Lagrangian leads via (canonical of functional) quantization to a well-defined QT and not every well-defined QFT can be connected with a Lagrangian.

There is no reason to believe that this is any better for the square root of the surface (the Nambu-Goto Lagrangian). Although a direct quantization was not possible one may use the integrability of the classical theory and try a quantization of the classical algebra of conserved charges [57]. The result has no relation to string theory and also no relation to the squared Lagrangian density which in turn is related to the Polyakov's Lagrangian. Such sigma model Lagrangians in which a low dimensional sigma model field carries noncompact inner ("target spacetime") symmetries which have nothing to do with the "source" spacetime are only classically possible, their quantum existence would contradict the holistic localization property of QFT with one exception: the 10 dimensional superstring representation. But, as mentioned before, even in this case the localization is pointlike, not string-like. Lagrangian models are never string-like and and

[29] Such an object would have too many degrees of freedom for being called "local" in the modular localization sense (and its generating field would have a short distance behavior which is not distributional).

[30] Any pure particle theory is necessarily quantum mechanical and contains no covariant objects at fine time but at best a Poincaré-invariant S-matrix fulfilling macro-causality [22]

[31] Private communication by R. Haag.

whenever string-like localized irreducible (not representable as line integrals over a point-like generator) objects appear they have no Lagrangian presentation. Particles are a delicate conceptual enteties; in the interacting case their contact with covariant fields is only through "asymptopia" where differences between the frame-dependent effective Born-Newton-Wigner localization and the field-based covariant modular localization is washed out [22][58]. The lack of a Lagrangian access to genuinely string-localized representations (as Wigner's infinite spin representation) explains why their QFT description was discovered rather late [43].

10 The holistic aspect and phase-space degrees of freedom

In a course on QM one learns that the number of "degrees of freedom" (measure for quantum states) per phase space cell is finite. Already in the beginning of the 60s it became clear that this not compatible with the causal localization in QFT which requires a compact instead of a finite set which later was sharpened to nuclearity [20], a mild form of an infinite cardinality of phase space degrees in QFT. The physical motivation was the desire to understand the connection between field localization and the presence of discrete mass states, scattering theory and asymptotic completeness, a goal which later was partially achieved. But already at that time it was clear that there exist mathematically consistent but unphysical models of QFT which lack certain properties which, at least on a formal level, Lagrangian field theories have and which can be verified in renormalized perturbation theory. It was easy to find such models among the so-called generalized free fields [46]. Whereas the "good" fields fulfill in addition to Einstein causality also a timelike causal propagation property which in the algebraic setting is often called the causal completion- or time-slice- property[32] [46],

$$\begin{aligned} &[A,B]=0,\ A\in\mathcal{A}(\mathcal{O}),\ B\in\mathcal{A}(\mathcal{O}')\subseteq\mathcal{A}(\mathcal{O})',\ \textit{Einstein causality} \\ &\mathcal{A}(\mathcal{O})=\mathcal{A}(\mathcal{O}''),\ \textit{causal completion property},\ \mathcal{O}''\ \textit{causal completion of}\ \mathcal{O} \end{aligned} \tag{22}$$

those pathological models continue to fulfill the first property but fail on the second; in fact the causal completion contains infinitely many more degrees of freedom than there were in the "initial value data" in $\mathcal{O}$. In the metaphoric spirit which presently enjoys popularity in the extra dimension and curling up of extra dimension physics this is a kind of "Poltergeist" phenomenon were, as time passes more and more degrees of freedom enter "sideways".

This is precisely what happens in the AdS_5-CFT_4 correspondence in which the degrees of freedom, which are natural in a 5-dim. QFT, are squeezed into d=1+3 CFT.

Starting with a free AdS theory one can see that the resulting conformal theory is a conformally covariant *generalized free field* which shows precisely the incriminated "causal

[32]The main motivation for the introduction of this property was precisely to exclude physical pathologies which one may meet outside the Lagrangian protection zone, assuming that Lagrangian QFT makes sense also outside of perturbation theory.

poltergeist" of sidways entering degrees of freedom which contradict the quantum analog of Cauchy propagation [54]. This is precisely what the defenders of the Maldacena conjecture [59] failed to notice[33]. It led to a tremendous number of ,publications as no particle theory subject before, a number which is only surpassed by ˜40.000 publications on supersymmetry.

For somebody who played an active role in the conceptual development of QFT it appears ironious that when the degree of freedom structure of QFT and its relation with causal localization problems was discovered it was considered as irrelevant for the progress of "real particle physics" (Lagrangian quantization). whereas now, where these concepts are really needed because holographic correspondences take place outside the Lagrangian setting, the past results are forgotten and one is met with a kind of pitiable arrogance ("the German holography") when one tries to point out the relevance of these results. mention them. If particle theory would have a built-in memory, many libraries would have large empty spaces on their shelves. At conferences even famous mathematicians as I. Singer, when talking about the successes of modern mathematics, remind the audience of the depth and importance of the Maldacena conjecture. The question whether this is a manifestation of a sociological Zeitgeist phenomenon [53] or a slip in a highly speculative science which had lost its critical breaks.

11 The sociological side

The holistic structure, which sharply separates QM from QFT, was explained in this paper in the historical context of the archetype QFT with which Pascual Jordan entered the Einstein-Jordan conundrum. But far from being just the result of an incomplete understanding at the dawn of QFT, it also marks a later more than 40 years old fault line within particle theory, which begun with the misunderstanding of the holistic localization structure of relativistic QT in the form of the dual model/string theory. More precisely it started with confusing the crossing in the Mellin transform of a conformal 4-point-function[34] coming from locality of fields, with the holistic KMS property coming from wedge localized operator algebras which turns out to lead to the analytic crossing identity.

This insight is somewhat subtle, since it is not close to the quantization portal of textbook treatment of QFT. However our critical arguments against the source-target use of sigma models are independent of such sophistication, and the question arises why this was not perceived at the time is legitimate; how could a nonexisting quantum analog of a Lagrangian description of a relativistic classical particle serve as a supporting argument for sigma model description of a relativistic quantum string? why isn't it part of general knowledge that a Lagrangian description of relativistic particles (21) does not exist[35]? And why has this closely related naive identification of the quantum sigma model with a

[33] A spacetime symmetry maintaining spatial reoganization of the degrees of freedom of abstract quantum matter does not lead to a reduction which would be necessary for causal propagation in lower dimension. Only lightfront holography changes symmetries and reduces degrees of freedom.

[34] The spacelike locality of conformal fields together with global operator expansions leads to a crossing relation in which this expansion passes to an infinite series of Mellin poles.

[35] This shortcoming of quantization was precisely the point why Wigner presented the classification of relativistic particles in a representation theoretical setting.

Lorentz group acting on "target indices" (alias the "field space" on which inner symmetries act) never been critically reviewed ?

Once a strong movement with reputable spokesmen (as the millenniums theory of everything) gets going, it polarizes the scientific community; the majority wants to participate in the great event and supplies the "pro-arguments", and a minority digs in for better times and is too timid to say that the emperor is without cloth. Here we refer again to the papers [48][47] in which a basically correct calculation of the pointlike string field commutator at the end received a "stringy" presentation.

One reason why holistic aspects entered the limelight so late, is perhaps that free field theories and perturbation theory incorporate them in a hidden way in which it is not important to understand their presence; at least if one does not ask questions about fluctuations in open subsystems, as Jordan did in response to Einstein's pro photon arguments. Since one rarely encounters such a rewarding subject with relevance for the ongoing particle theory, it was very tempting (for the present author) to look for other instances where this holistic principle was violated, in some cases even in an irreparable way.

Since present day physicists are certainly not less intelligent than they were in the good times of particle theory, an explanation cannot ignore the sociological environment. The question is: does "big science" carry the seeds of its own destruction or are these just fluctuations in fashions which come and go, and what is the time scale on which an uncorrected glitch turns into a derailment.

Conceptual flaws in a highly speculative area as particle physics in times of rapid progress were usually countered by foundational criticism and in most cases rapidly eliminated. This system of a Streitkultur has worked well into the 70s. Nowadays natural (by status) critics have increasingly become salesmen of their favorite products.

At the time of Pauli, Landau, Källén, Jost, Lehmann and others, there was a constant struggle about the best way which sometimes led to harsh personal confrontations and ruffled feathers; a flawed idea about particle theory could not have survived for long in this critical environment. Individuals may have temporarily suffered, but theories were maintained in a healthy state. Even in the US, where this kind of agressive critique is generally frowned upon, there were physicists like Oppenheimer who did not comply with the cordon of politeness. Since the 80s (the time of the second "string revolution", but perhaps already before) personal disputes about particle theory became more rare and as a consequence the foundational critical feedback slowly disappeared. The only remaining criterion for the quality of a theory was the reputation of its protagonist and the size of the community which he represents. The downside of this development was that ideas which did not have this support vanished in the mealstrom of time. One of those ideas whose presence would be useful in the present LHC era is that of the Schwinger-Higgs screening mechanism as an alternative of the meaningless but popular spontaneous symmetry breaking of gauge invariance [42]. In such a climate it is impossible for a theory which originated outside the monocultures of big communities to become known and receive a critical review.

It is hard to explain the thousands of inconclusive publications on the Maldacena conjecture and similar proposals without invoking sociology. Clearly the aim behind such mass-publications was not to clarify a scientific problem, but rather to be on the side of a career-supporting trend leading possibly (at least for some) to grants, fame and prizes. The increasing number of papers and prizes is nothing more than whistling in the dark, they hide the fact that we are living in times of stagnation. The meaning of the vernacular "many people cannot err" is meanwhile turned on its head. The observation that something similar is taken place in other branches of science [53] (i.e. that we are possibly witnessing a Zeitgeist phenomenon) is no consolation. The borderline between serious science and the entertainment industry has become fluid [60].

Some bizarre aspects of string theory and its outgrowth in form of the millennium theory of everything (the "landscape", multiverses,) have attracted the attention of philosophers and physicists as Hedrich [61], Smolin [62] and Woit [63]. This topic also entered the critical radar screen of well-educated scientifically interested laymen [64]. However critique which remains on a sociological or philosophical level without an indepth scientific backup is without effect. The value of a foundational new theory cannot be measured in terms of its distance from experiments or its relation to prevalent philosophical views; what is important is to check its internal consistency and its foundational relation to previous consistent and successful theories. In the case at hand the consistency was never questioned in the cited critical evaluations. The new results from LHC could lead to a new beginning in particle theory, if there would not be for the heavy legacy of almost 40 years of reign of a monoculture without any investment in viable alternatives.

The new direction proposed in this work requires a different conceptual setting (referred to as holistic in this paper). Although it cannot be found in standard textbooks, it is the only successful explanation of many nonperturbative observations in QFT, ranging from the "Einstein-Jordan conundrum" to the Unruh effect to the formfactor crossing.

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