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Wolfhart Zimmermann: Life and work

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Abstract

In this report, I briefly describe the life and work of Wolfhart Zimmermann. The highlights of his scientific achievements are sketched and some considerations are devoted to the man behind the scientist.

The report is understood as being very personal: at various instances I shall illustrate facets of work and person by anecdotes.

1. Introduction

The present report is based on a colloquium talk given at the end of a memorial symposium to honour Wolfhart Zimmermann:
Max Planck Institute for Physics, Munich (May 22–23, 2017)

I borrowed freely from the following obituaries:

Physik-Journal **15** (2016) Nr. 12 S.50	W. Hollik, E. Seiler, K. Sibold
Nucl. Phys. **B193** (2016) 877–878	W. Hollik, E. Seiler, K. Sibold
IAMP News Bulletin, Jan. 2017 p. 26–30	M. Salmhofer, E. Seiler, K. Sibold

2. The beginning

Wolfhart Zimmermann was born on February 17, 1928 in Freiburg im Breisgau (Germany) as the son of a medical doctor. He had an older sister with whom he liked to play theater and, when

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visiting Gymnasium, to talk to in "Giganisch" – a language which he invented, because he found Latin too easy.

In 1946 he entered the university in Freiburg to study mathematics and physics.

As far as lectures and seminars are concerned WZ was somewhat sceptical about their usefulness for him: "Either they were too fast or too slow for me. Either I had to think about the new content – then I was too slow. Or I understood it instantly, then I was too fast and the lecture boring."

A good measure to evaluate this statement and to put it in the right perspective is to look at the facts. Already in 1950 he finished with a doctoral degree in mathematics. His thesis was devoted to topology [1], published in [2]. He once told that he had written an earlier dissertation, but abandoned it because he found out that the main result could be proven in a much simpler way, hence considered this work as inadequate for a doctoral degree. He published a further article on topology [3]. These papers were written in style and spirit of BOURBAKI, on which he commented privately "I can read BOURBAKI like the newspaper."

3. LSZ – the first highlight

In 1952 Wolfhart Zimmermann joined the group of Werner Heisenberg at the Max-Planck-Institut für Physik in Göttingen as a Research Associate, a position which he held until 1957. Remarkably, his first physics paper [4] did not deal with quantum field theory (QFT), but with the thermodynamics of a Fermi gas in interaction. He bought his ticket to Heisenberg's group, later called "der Feldverein", with a paper on the bound state problem in field theory [5]. It was co-authored by Vladimir Glaser, a Croatian physicist, who was to accompany Wolfhart Zimmermann on his scientific way for a long time. Truly famous, however, were three papers [6–8] written together with Harry Lehmann and Kurt Symanzik. They contained what later was coined the "LSZ formalism" of quantum field theory. Based on the principles of Lorentz covariance, unitarity and causality of Green functions and the S-matrix they provided the first axiomatic formulation of quantum field theory. Lehmann, Glaser and Zimmermann [9] then, conversely, gave sufficient conditions which a set of functions has to fulfil such that these functions give rise to a field theory in the sense of LSZ.

LSZ did not refer to perturbative expansions, but nevertheless proved to be greatly successful in its perturbative realization and thus extremely powerful in practice. Until the present day it serves as the most efficient description of scattering amplitudes in particle physics.

The key idea is the following: in the remote past and future a scattering experiment (idealized) deals with *free* particles, whereas interaction takes place only in a finite region of spacetime. The respective fields are related by the *asymptotic condition*:

$$\phi(x) \underset{x^0\to\pm\infty}{\longrightarrow} \sqrt{z}\,\phi_{\substack{out\\in}}(x), \tag{1}$$

where z is a number and $\phi_{\substack{out\\in}}$ are free fields which satisfy the field equations

$$\left(\Box + m^2\right)\phi_{\substack{out\\in}}(x) = 0, \tag{2}$$

whereas $\phi(x)$ is an interacting field. The limit is understood in the weak sense, i.e. it is valid only for matrix elements. (In parentheses we note that this notion of weak convergence which is of utmost importance has presumably been introduced by LSZ for the first time in the theory of particle physics.)

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In a scattering experiment n_i particles are prepared in an initial state and go over into n_f particles in the final state. The transition is described by the S-operator with matrix elements S_{fi}. Those are given by the famous *LSZ-reduction* formula

$$S_{fi} = \langle f|i\rangle \equiv \langle p_1 \dots p_{n_f}|q_1 \dots q_{n_i}\rangle \tag{3}$$

$$= \left(\frac{-1}{\sqrt{z}}\right)^{n_f+n_i} \lim \prod_{k=1}^{n_f}(p_k^2 - m^2)\prod_{j=1}^{n_i}(q_j^2 - m^2)\tilde{G}(-p_1, ..., -p_{n_f}, q_1, ..., q_{n_i}) \tag{4}$$

$$= \left(\frac{i}{\sqrt{z}}\right)^{n_f+n_i} \prod_{k=1}^{n_i}\int dx_k e^{-iq_k x_k}(\Box_{x_k} + m^2)\prod_{j=1}^{n_f}\int dx_j e^{ip_j y_j}(\Box_{y_j} + m^2) \times G(y_1 \dots y_{n_f}, x_1 \dots x_{n_i})|_{\substack{q_k^0=\omega_k \\ p_j^0=\omega_j}}$$

(with lim: $p_k^2 \to m^2$, $q_j^2 \to m^2$, $p_k^0 > 0$, $q_k^0 > 0$).

Here $G(y_1, \dots, y_{n_f}, x_1, \dots, x_{n_i})$ denote the Green functions

$$G(y_1, \dots, y_{n_f}, x_1, \dots, x_{n_i}) = \langle T\varphi(y_1)...\varphi(x_{n_i})\rangle, \tag{5}$$

the vacuum expectation value of the time ordered product of field operators.

They thus permit to calculate the S-matrix and are themselves determined by equations of motion.

An important generalization of this reduction formula expresses the matrix elements of a (composite) operator $\mathcal{O}$ in terms of the Green functions with an insertion (details see below).

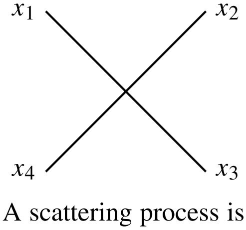
$$\langle p_1, ..., p_n|\mathcal{O}(x)|q_1, ..., q_l\rangle = \left(\frac{-1}{\sqrt{z}}\right)^{n+l} \lim \prod_{k=1}^{n}(p_k^2 - m^2)\prod_{j=1}^{l}(q_j^2 - m^2) \times \times \tilde{G}_{\mathcal{O}(x)}(-p_1, ..., -p_n, q_1, ..., q_l)$$

$$G_{\mathcal{O}(x)}(y_1, ..., y_n, x_1, ...x_l) = \langle T\mathcal{O}(x)\varphi(y_1)...\varphi(x_l)\rangle$$

$$\langle T\mathcal{O}(x)\varphi(y_1)...\varphi(x_l)\rangle = R\langle T : \mathcal{O}^{(0)}(x) : \varphi^{(0)}(y_1)...\varphi^{(0)}(x_l)e^{\frac{i}{\hbar}\int \mathcal{L}^{(0)}_{\text{int}}}\rangle$$

Historical remark: Another axiomatic formulation of QFT was initiated by Wightman (1956). The relation of the LSZ-scattering theory to those axioms and clarification of the role of fundamental fields were given by Haag (1958, 1959) and in particular by Ruelle (1962).

As mentioned above these formulae for Green functions and the S-matrix can be satisfied in a perturbative manner. In practice the most often employed technique is in terms of diagrams as introduced by Feynman. With every elementary interaction one associates a vertex (symbolizing the specific interaction) and emanating lines which stand for particles propagating in spacetime.



A scattering process is described by diagrams where these elementary vertices are linked by lines. The vertices and lines are interpreted in terms of mathematical prescriptions, the "Feynman

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rules", which eventually permit to calculate Green functions and the S-matrix. In the most naive version diagrams are ordered according to the number of vertices they are made of; this results into a power series of coupling constants: the perturbation series. Since the diagrams mimic physical processes, they are intuitively appealing and, therefore were overwhelmingly used in particle physics (and beyond: e.g. in condensed matter physics). But, of course, the mathematical expressions for Feynman rules have to be derived by a consistent algorithm. Usually it exploits the *Gell-mann-Low* formula for Green functions

$$G(x_1, ..., x_n) = \langle T(\phi(x_1)...\phi(x_n))\rangle \tag{6}$$

$$= \frac{\left\langle T\left(\phi^{(0)}(x_1)...\phi^{(0)}(x_n)e^{i\int \mathcal{L}^{(0)}_{\text{int}}}\right)\right\rangle}{\left\langle e^{i\int \mathcal{L}^{(0)}_{\text{int}}}\right\rangle} \tag{7}$$

For the S-operator this is tantamount to the *Dyson* formula

$$S = Te^{i\int \mathcal{L}_{\text{int}}} \tag{8}$$

On this level it is (almost) evident that the fundamental axioms – Lorentz covariance, unitarity and causality – are satisfied. For the subsequent discussion it is crucial to observe that the propagator for a (real, spinless) field

$$\tilde{\Delta}_c(p) = \frac{i}{p^2 - m^2 + i\varepsilon} \tag{9}$$

is, mathematically speaking, not a function, but rather a distribution. This can be seen by calculating the product at the same point $\Delta_c(x-y)\Delta_c(x-y)$. The result is infinite, hence apriori meaningless. It implies that many of the Feynman diagrams containing closed loops are meaningless. Therefore one faces the problem to give mathematical meaning to such expressions and at the same time not to violate the fundamental axioms in doing so. Of course, theoreticians (notably Schwinger and Dyson) found ways to go around this difficulty, but it required much further work, in particular by Bogoliubov and Parasiuk and Hepp to provide satisfactory solutions. A particularly appealing and useful one was given by Wolfhart Zimmermann (see below).

4. Intermediate years

In 1957 Wolfhart Zimmermann left Göttingen and held positions at the Institute for Advanced Study in Princeton and the University of Hamburg. From there he was visiting the Physics Department of UCB (Berkeley), CERN, and the University of Vienna. Into this period fall studies of the bound state problem, of one-particle singularities of Green's functions and, more generally, of the analyticity structure of scattering amplitudes. In 1962 he was appointed professor of physics at New York University. Visits led him to The Enrico Fermi Institute (Chicago) and IHES (Institut des Hautes Études Scientifiques, Bures-sur-Yvette, France). At this time it is noteworthy that he contributed to the so-called relativistic $SU(6)$-symmetry, which in hindsight turned out to prepare the way to supersymmetry, because anticommutators entered the scene to form Jordan algebras, as pointed out by Hironari Miyazawa. This structure was later understood to define a super-algebra, i.e. graded algebra.

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5. Renormalization theory – the second highlight

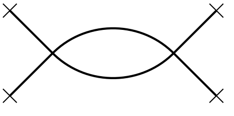
5.1. Finite diagrams, equations of motion, symmetries

The absolute landmark work of the next period is dedicated to renormalization theory. Bogoliubov, Parasiuk, Hepp (BPH) had worked out a recursive prescription of rendering Feynman diagrams finite. In a first step Wolfhart Zimmermann solved this recursion explicitly with the help of his "forest formula" which located potentially divergent "renormalization parts" such that they do not "overlap", i.e. influence each other uncontrollably. In a second step he introduced subtractions in momentum space for every Feynman diagram such that the resulting integrals become *absolutely* convergent (as compared to *conditional* convergence in BPH) [10,11]. Within this BPHZ renormalization scheme, as it is now called, one is not only able do derive S-matrix elements, but also the Green functions involving arbitrary composite operators. Thus, this method made it possible to study rigorously e.g. equations of motions, currents and symmetries in Quantum Field Theory. In particular it was now possible to define precisely the notion of anomalies, providing a fruitful link to mathematics, and also, from the point of view of physics, exhibiting truly quantum mechanical effects, not present on the classical level. Pivotal is a set of identities between different normal products introduced by and named after Zimmermann. These identities have meaning even beyond perturbation theory.

Let us now go in more detail.

5.1.1. Finite diagrams

From its explicit expression in p-space it is clear that the propagator decreases for large p like $1/p^2$, hence (as an example) the "vertex correction"

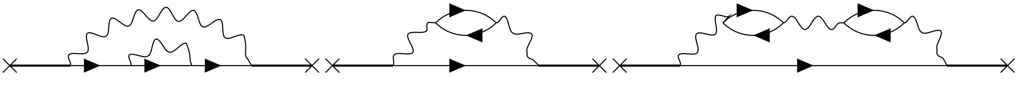


$$\sim \lambda^2 \int d^4k \frac{1}{(p-k)^2 - m^2 + i\varepsilon} \frac{1}{k^2 - m^2 + i\varepsilon}$$

$$\text{integrand} \sim (k)^0 \text{ integral} \simeq \left(\ln(\frac{\Lambda}{m}) \right)$$

leads to a logarithmically divergent integral. (Λ denotes a cut-off for the integration.) This integral becomes absolutely convergent if we subtract from the integrand the first Taylor term at $p = 0$ and introduce Zimmermann's ε's prescription ($\varepsilon_Z = \varepsilon(m^2 + \mathbf{p}^2)$). In the limit of vanishing ε the integral results into a Lorentz covariant *function*.

When checking diagrams containing more than one closed loop one faces no serious problem for *non-overlapping* diagrams like



Here one can remove the divergences by subsequently removing in an analogous way first those of the subdiagrams and thereafter that of the entire diagram. The result does in particular not depend upon in which order the subdiagrams have been subtracted.

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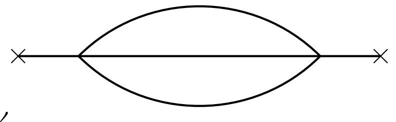
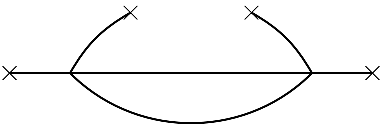
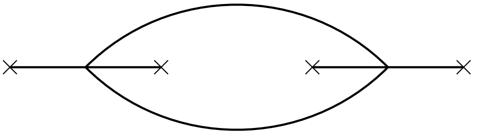
However, in diagrams like



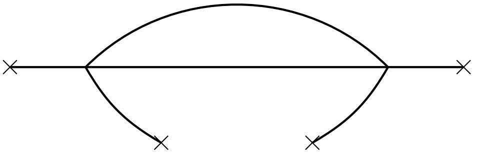
γ



λ_1



λ_2



λ_3

the removal of divergences in one of the subdiagrams λ interferes with those of the others and the removal of the overall divergence (i.e. of γ): the diagram γ contains "overlapping divergences". Here WZ invented a prescription which first of all corresponded to an explicit solution of the recursion problem involved and second dealt properly with the overlaps. This is encoded in his famous "forest formula"

$$R_\Gamma(p,k) = \sum_{U \in \mathcal{F}_\Gamma} S_\Gamma \prod_{\gamma \in U} (-t_{p^\gamma}^{d(\gamma)} S_\gamma) I_\Gamma(U) \tag{10}$$

Here the sum runs over all families of non-overlapping diagrams contained in Γ, t denotes Taylor subtractions at $p = 0$ and S relabels the momentum variables appropriately.

Instead of discussing this formula in detail I refer to a remark by Wolfhart Zimmermann: "When I had found the forest formula I tried to explain it. But somehow audiences were reluctant to follow my explanation. Very soon I abbreviated the forest formula by writing instead: $I_\Gamma - \cdots$ (subtractions).

Everybody understood then the forest formula and was happy with it."

The result is the theorem that the integral over the internal momenta of the closed loops is absolutely convergent and yields in the limit $\varepsilon_Z \to 0$ a Lorentz covariant vertex function or (for general Green functions) a Lorentz covariant distribution.

5.1.2. *Normal products, Zimmermann identity*

Once this existence result has been proved for the standard vertices of a model it is clear that one can construct composite operators via Green functions with the composite operator as a special vertex appearing in every diagram and using thereafter the respective reduction formula. In technical terms

$$\langle T\,(Q(x)\varphi(y_1)...\varphi(y_k))\rangle = \left\langle T\left(N_d[Q(x)]\varphi^{(0)}(y_1)...\varphi(y_k)^{(0)} e^{i\int \mathcal{L}_{\mathrm{int}}^{(0)}}\right)\right\rangle_{(0)}$$

Here d denotes the naive dimension of Q.

If one inspects the convergence proof for normal products closely enough one finds that (with some restrictions) one may associate with an insertion Q a subtraction degree δ

$$\delta = d + c \qquad c \in \mathbb{N}$$

This results into the *Zimmermann* identity

$$N_\delta[Q]\cdot\Gamma = N_\varphi[Q]\cdot\Gamma + \sum_i u_i^{(Q)} N_\varphi[Q_i]\cdot\Gamma$$

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This innocently looking identity harbours all fundamental deviations of *quantum* field theory from *classical* field theory and indeed requires correspondingly deep insight into the structure of normal products.

5.1.3. Action principle, symmetries, anomalies

We introduce functional differential operators which represent field transformations. For a transformation δ^X expressed on the generating functional for vertex functions Γ they read

$$W^X \Gamma \equiv i \int d^4x\, \delta^X \varphi(x) \frac{\delta}{\delta\varphi(x)} \Gamma. \tag{11}$$

In the context of a self-interacting, massive scalar field with

$$\Gamma_{eff} = \int d^4x\, (\frac{1}{2}(\partial\varphi\partial\varphi - m^2\varphi^2) - \frac{\lambda}{4!}\varphi^4) + \Gamma_{counter} \tag{12}$$

the action principle reads

$$\delta^X \varphi(x) \frac{\delta}{\delta\varphi(x)} \Gamma = \left[\delta^X \varphi(x) \frac{\delta}{\delta\varphi(x)} \Gamma_{eff}\right] \cdot \Gamma \equiv \left[Q^X(x)\right] \cdot \Gamma \tag{13}$$

for the non-integrated transformation.

Replacing $\delta^X\varphi$ by 1 gives via *LSZ*-reduction rise to the operator field equation which has now a mathematically well-defined meaning.

Suppose that the variations δ^X satisfy an algebra, then

$$\left[W^X, W^Y\right] = i W^Z, \tag{14}$$

which implies algebraic restrictions on the insertions Q^X. Exploiting the restrictions perturbatively one can with calculations performed on the *classical* level decide whether the resulting $Q^X(x)$ can be interpreted as a variation. If this is the case one can modify suitably Γ_{eff} and arrange a symmetry. If not, one has an anomaly, the symmetry cannot be implemented on the quantum level. (After a respective observation by Wess and Zumino (1971) in an effective theory this has been enlarged to a powerful technique by Becchi, Rouet and Stora (1975).)

It is to be noted that the method is *constructive*: the insertion $Q^X(x)$ in (13) is determined uniquely and can be characterized by covariance and power counting. This is a very helpful tool in practice.

5.2. Operator product expansion

He found another, constructive way of arriving at these normal products by looking at the singularities of Green functions, expressed as sums over Feynman diagrams, when the endpoints of external lines merge to form a vertex which corresponds to a composite operator. Isolating the singularities and capturing them as coefficients of operators he arrived at the operator product expansion [12] which had been introduced by Kenneth Wilson [13]. This provided an existence proof for the operator product expansion in perturbation theory.

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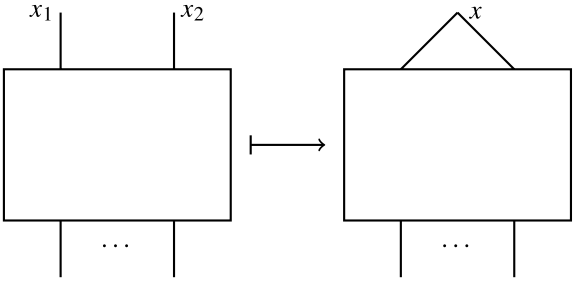
Here a diagram describing the situation for a bilinear composite operator



One studies the limit of ξ going to zero for $x = (x_1 + x_2)/2$ and $\xi = (x_1 - x_2)/2$.

In the context of the standard model of particle physics, in particular in Quantum Chromodynamics (QCD) the operator product expansion has been widely used to derive measurable quantities governing e.g. in deep inelastic scattering of electrons and neutrinos from hadrons. They confirmed their composite structure. After derivation of the directional dependence of composite operators [14] lightlike and spacelike operator product expansions were found to carry important general information on the physical processes involved. Eventually the sector of strong interactions of the standard model of particle physics was confirmed in this way.

6. Reduction of couplings – the third highlight

In 1974 Wolfhart Zimmermann became scientific member of the Max Planck Society and director at the Max Planck Institute for Physics, Munich, Germany. In 1977 he was also appointed honorary professor at the Technical University of Munich. His visits led him to Centre de Investigación y de Estudios Avanzados del IPN, Mexico City, Mexico and Purdue University West Lafayette, IN, USA.

The prime subject of his group was the formulation of gauge and supersymmetric models to all orders of perturbation theory. Only with his renormalization technique was it possible to construct such theories unambiguously.

In the course of studying asymptotically free theories like QCD, he and Reinhard Oehme were naturally led to analyze the Renormalization Group in models with several effective couplings. By eliminating the running parameter Wolfhart Zimmermann found a set of ordinary differential equations whose solutions guarantee that several "secondary" coupling constants, chosen to be functions of a "primary" one, maintain this relation in the course of renormalization. For power series solutions one is still in the realm of ordinary perturbation theory; the functional relations between the different couplings compatible with renormalization provide a generalization of the concept of symmetry [15,16]. Zimmermann called this the "principle of reduction of couplings" and applied it to various theories.

Let us be specific. Suppose a perturbatively renormalizable model has a *primary* coupling g and n *secondary* couplings λ_i, $i = 1, ..., n$. Then the effective couplings satisfy the renormalization group equations

$$\frac{d}{dt}\bar{g}(t) = \beta_g(\bar{g}, \bar{\lambda}_i) \qquad \frac{d}{dt}\bar{\lambda}_i(t) = \beta_{\lambda_i}(\bar{g}, \bar{\lambda}_i) \tag{15}$$

Eliminating the scale parameter t one arrives at

$$\beta_g(\bar{g}, \bar{\lambda}(\bar{g}))\frac{d}{d\bar{g}}\bar{\lambda}_i(\bar{g}) = \beta_{\bar{\lambda}_i}(\bar{g}, \bar{\lambda}(\bar{g})). \tag{16}$$

These are the ordinary differential equations to be solved. Since the β-functions are supposed to vanish at vanishing couplings, the differential equations are singular and require a case by case study, accompanied by stability considerations. Asking for power series solutions implies initial value conditions with no free parameter. The general solution contains as a rule n free parameters which are appropriate for this set of differential equations. They replace the couplings λ_i appearing in the original non-reduced model.

If the reduced model admits a symmetry then that will appear amongst the solutions.

Simple examples [15]:

(1) In a massless theory of one self-interacting pseudo-scalar field B and a single spinor field ψ with interactions terms

$$ig\bar{\psi}\gamma_5 B\psi - \frac{\lambda}{4!}B^4$$

there is for positive λ and sufficiently small g one uniquely determined power series solution starting with $\lambda = \frac{1}{3}(1+\sqrt{145})g^2$ embedded into a general solution with a contribution $d_{11}g^{\frac{2}{5}\sqrt{145+2}}$ + higher orders, and d_{11} arbitrary.

(2) In the massless Wess–Zumino model with the couplings g and λ of the interaction terms

$$g\bar{\psi}(A + i\gamma_5 B)\psi - \frac{\lambda}{2}(A^2 + B^2)^2$$

one finds the supersymmetric solution $\lambda = g^2$ embedded into a non-supersymmetric general solution with $\lambda = g^2 + \rho_3 g^8 + \sum \rho_j g^{2j+2}$, ρ_3 arbitrary. A third solution with $\lambda = -\frac{4}{5}g^2 + \sum \rho_j g^{2j+2}$ is not related to supersymmetry.

Notable further examples are the non-supersymmetric embeddings of models which can have $N = 2, 4$ supersymmetry.

It is an interesting result that non-abelian gauge symmetry can be found as the unique solution once one postulates rigid invariance for the embedding theory (Kraus, 1990). Further, one was able to show that many "finite" models exist, finite meaning that their β-functions vanish to all orders, hence realizing superconformal symmetry in a straightforward way as in the classical theory. In particular they scale "naively", i.e. without anomalous dimensions and also provide naive conformal behaviour.

Whereas such models are mainly of theoretical interest, it is clear that the reduction principle also has enormous phenomenological implications. Within the standard model of strong and electroweak interactions bounds on Higgs and top mass were derived.

To obtain them one had to generalize the reduction principle slightly because the gauge couplings of the standard model have different asymptotic behaviour: whereas the coupling of the abelian subgroup is in the infrared asymptotically free, the couplings for the non-abelian subgroups are asymptotically free in the ultraviolet. Including two-loop corrections and using as input the values of $M_Z, \alpha_3(M_Z), sin^2\theta_W(M_Z), \alpha_{em}(M_Z)$ one found in 1991

$$m_t = 89.6 \pm 9.2 \text{ GeV}, \ m_h = 64.5 \pm 1.5 \text{ GeV}$$

At that time these values were already overruled indirectly by precision experiments – i.e. assuming the existence of Higgs and top quark, without having direct evidence for them – hence it was clear that the model had to be extended. ("clear" means the following: assuming that the coincidence of experimental values in the standard model with theoretical predictions – upon parts per million – is not a sheer accident, but rather points to the fact that naively summed up perturbation theory is much better than it has mathematically any reason to be, one concludes that a perturbation taking into account the relative magnitudes of gauge couplings is alright and thus a *partial* reduction is reasonable.) And indeed, by applying the reduction principle in this way to supersymmetric extensions of the standard model the Higgs mass was predicted two years before it was discovered [17]. Wolfhart Zimmermann was pleased by this.

7. The man behind the scientist

In 1991 he was awarded the Max-Planck-Medal, the highest prize of the German Physical Society. In 1996 he retired, but kept ties to the institute until his end.

So far we considered essentially the scientist and his work, but of course he was also a man of flesh and blood. He enjoyed eating and drinking well, showing exquisite taste also in this respect. He loved having company for dinner in his house, where his wife was a graceful and competent host. He was also well known for his generosity towards members and guests of the institute. He cared very much about his three daughters, their performance in school and later their professional and personal development. He was lover of music and theater and the flowers in his terrace garden.

Let's have a closer look at the person via anecdotes.

Why did WZ never do refereeing work for journals? His answer which comes close to how he commented lectures and seminars during his studies: "If the problem addressed in the paper is interesting I am attracted to solve it myself. If I don't find it interesting I can not press myself to read it further and just do nothing but criticising. In any case it distracts me too long from my own work."

He simply hated committee meetings, in particular those of the directorate of the institute. There was just too much of trouble and strife and bad behaviour for him. In the breaks of directorate meetings he used to come to my office to discuss physics as a kind of recreation. At some time there was a "chance" that he had to become executive director (Geschäftsführender Direktor). His comment: "Ach wissen Sie, ich habe einen Zettel in meiner Jackentasche. Darauf steht: mir kann ja nichts passieren." Indeed, nothing happened to him; a colleague of his was very eager to get this job.

In which sense if any was he the "boss" of the theory group?

Two remarks may serve as an appropriate answer. The first is when he quoted a well-known mathematician: "Mr. X at university Y said once in public: 'Ich bin ein Bonze und möchte als solcher behandelt werden.' I would never say this."

The other one is the fact that he himself filled in and kept the list of vacation days for the members of the theory group and not the administration of the institute. Clearly, he had the opinion that a scientist is most effectively controlled by his work ad not by administrative measures like presence in the institute. To the best of my knowledge there was no abuse of this freedom in the theory group, people there knew and quite well understood that their rank is being fixed by their scientific reputation.

It is obvious which sort of atmosphere is being created on such a background.

In the same spirit he supervised the guest program of the theory group. The only relevant criterion for admission was the expected scientific outcome and its quality. Mainstream arguments were not considered to be sufficient. And, of course, the program was international. No argu-

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ments like "Germany first" have ever been heard. This was seemingly trivial at that time. But it has to be made explicit today.

8. Summary

When looking at the highlights a clear pattern emerges:

- LSZ clarify basic notions in their fundamental papers. Those have been used over and over again and have become textbook knowledge.
- WZ improves the basis of renormalization theory. A wealth of papers tackles successfully the structure of models: equations of motion, symmetries, anomalies.
- WZ proves operator product expansion in Minkowski space. Measurable quantities in QCD become available; they confirm the theory.
- WZ formulates the principle of reduction of couplings. Within supersymmetric extensions of the standard model the Higgs mass can be predicted to quite some level of accuracy.

"Wenn Könige bauen, haben die Kärrner zu tun!"
(F. Schiller in den "Xenien" (1798) über Kant.)

He has ended a journey in which he not only devoted his gifts to mathematics and physics but above all of this to his family, his friends and his collaborators. We will miss him.

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