Arianna Borrelli
Wuppertal University - DFG-Project-Cluster "Epistemology of the LHC"

The recent observation at the LHC from a historical perspective:
The Story of the Higgs

Focus of *this* historical perspective: the Higgs and origin of mass

"the Higgs is the key to understand the origin of mass"

How did the (age-old) question of the origin of mass become connected to a scalar field?

many formulas and experiments back up the statement above and similar ones....

...but a connection between scalar fields, the vacuum, symmetry and mass generation was stronlgy stated in words much before today's formulas (and experiments) were there....

....I shall focus on this “story” and its role as a motor of research

Mid 1950's: QED established, but lots of new particles found!

J. Schwinger "A theory of the fundametal interactions" *AP* (1957)

"This note is an account of some developments in an effort to find a description of the present stock of elementary particles within the framework of the theory of quantized fields. [...] We shall attempt to describe the massive, strongly interacting particles by means of fields with the smallest spin appropriate to the statistics, 0 and 1/2 [evtl. 1]. We suppose that the various intrinsic degrees of freedom are dynamically exhibited by specific interactions, each with its characteristic symmetry properties, and that the final effect of interactions with successively lower symmetry is to produce a spectrum of physically distinct particles from initially degenerate states [...] dynamical origin of mass"

dynamical ~ properties of theory after/through renormalization

dynamical properties are due to an "unknown physical agency"

- but: in the paper only the Lagrangian level is discussed!

Fields: Ψ (n, p ...), $\Phi_{(1)}$ (π-mesons), $\Phi_{(0)}$ (hypoth. σ-meson)

The scalar field $\Phi_{(0)}$ (σ-meson) has a special role:

"The unique properties of the σ-field [...]: As a field which is scalar under all operations [...] $\Phi_{(0)}$ has a nonvanishing expectation value in the vacuum [and so] a suitable [fermion] mass constant might emerge"

when $\Phi_{(0)} \longrightarrow \Phi_{(0)} - \mu/g$ **then** $g\Phi\Psi\Psi \longrightarrow g\Phi\Psi\Psi - \mu\Psi\Psi$

weak interactions? triplet: photon + 2 charged vector bosons ...

"we again use the $\Phi_{(0)}$ field to remove three-dimensional internal symmetries and produce mass for charged particles"

Schwinger's idea are taken up by many authors....

1960: Gell-Mann&Levy's σ-model: Schwinger's σ-field construct is used to produce partial conservation of weak axial current:

> *"The fact that the σ coupling is responsible for the nucleon mass is a curious property of the model. Unless we can explain all masses, or at least all baryon masses, in a similar way, it is not very satisfactory"*

1959-1961: Salam&Ward build upon Schwinger's idea

- photon + 2 charged vector bosons are EW-gauge bosons
- the σ-field breaks the gauge symmetry with its VEV
- .... giving mass to the charged gauge bosons

all statements are only backed up by discussions at the level of the Lagrangian (no "dynamical" computations), but the connection to dynamical mass generation is strongly stated

In the meantime: Heisenberg & collaborators (1958ff.)

Key idea: symmetric theory of non-linear spinor interactions
---(nonperturbative effects)---> variety of particle phenomena

the "symmetry reduction" is due to a asymmetrical vacuum state - asymmetrical solution to symmetric equations:

“the asymmetrical ground level is not properly a vacuum, but rather a “world” state which constitutes the basis for the existence of elementary particles”

the vacuum acts as an "infinite reservoire" of quantum numbers

However, Heisenberg was never able to construct a phenomenologically satisfactory model, but his ideas found some support in solid-state-physics

1961 - Nambu&Jona Lasinio

Analogy: superconductivity ↔ strong interactions

Theory of superconductivity (1958-60: BCS, quasi-particles):
- based on electromagnetic interactions...
- ...but apparently no EM-gauge symmetry!

superconducting states are nonperturbative, asymmetrical solutions of the symmetric equations of electromagnetism

electrons, nuclei ↔ hypoth. massless fermions (Heisenberg!)
quasi-particles ↔ massive nucleons
collective excitations ↔ pions (bound states of nucleons)

Some (sketchy) nonperturbative computations are given:
"perturbative vacuum" vs. "nonperturbative vacuum"

"The two worlds are physically distinct and outside of each other. Nevertheless, even in a particular world we can find manifestations of the invariance [e.g. neutron masses]"

1961 Salam: Nambu's model as a possibility to implement the symmetry breaking between electromagnetic and weak interactions in the Salam/Ward proposal

1961 Goldstone: non-perturbative effects are black-boxed in a (Goldstone) boson to study their consequences:

"The models [...] all have a boson field in them from the beginning. It would be more desirable to construct bosons out of fermions"

Goldstone's scalar field has a "double-well" potential and its VEV gives rise to different asymmetrical minima/vacua, but:

"A method for losing symmetry is of course highly desirable in elementary particle theory but these theories will not do this without introducing non-existent massless bosons"

1962: Goldstone, Salam & Weinberg: Further arguments in favours of the "Goldstone theorem": ***the σ-field is no good for producing mass "dynamically", but nonperturbative effects may still be a path....***

1962 Baker&Glashow "Spontaneous breakdown of elementary particle symmetries“ through nonperturbative effects

“Should not the complexities of the phenomena of elementary particle physics arise from a “simple” fundamental theory? Such a possibility was discussed by Heisenberg and co-workers [...] It is conceivable that the field equations may be highly symmetric expressions, while their solutions may reflect the asymmetries of nature. This is the philosophy we adopt in this paper [...] We propose that a nonperturbative behaviour characterizes all the interactions to which elementary particles are subject. Mass is completely dynamical; mass splittings and 'approximate symmetries' result from nonsymmetric solutions to a fully symmetric Lagrangian theory [Conclusion:] we have shown the possibility that the fundamental interactions can generate themselves from a 'bootstrap mechanism' in a theory where the bare coupling constants vanish"

1962 Schwinger "Gauge invariance and mass"

“[T]he essential point [of the computation] is embodied in the view that the observed physical world is the outcome of the dynamical play among underlying primary fields, and the relationship between these fundamental fields and the phenomenological particles can be comparatively remote, in contrast to the immediate correlation that is commonly assumed”

1964-66: Brout, Englert, Guralnik, Hagen, Higgs, Kibble black-box nonperturbative effects in Goldstone's scalar field, but as a manifestation of deeper, unexplored structure of nature, e.g.:

"The idea that the apparently approximate nature of the internal symmetries of elementary particle physics is the result of asymmetries in the stable solutions of exactly symmetric dynamical equations, rather than an indication of asymmetry in the dynamical equations themselves, is an attractive one. Within the framework of quantum field theory such as a "spontaneous" breakdown of symmetry occurs if a Lagrangian, fully invariant under the internal symmetry group, has such a structure that the physical vacuum is a member of a set of (physically equivalent) states which transform according to a nontrivial representation of the group. [...] That vacuum expectation values of scalar fields, or "vacuons," might play such a role in the breaking of symmetries was first noted by Schwinger and by Salam and Ward" (Higgs 1966)

...their results support the idea that the scalar field is "special"...

...and this idea was motivation for the (indipendent) proposals of Weinberg and Salam (1967-68) that the scalar field might gurarantee renormalizability to their unified electroweak theory:

Salam (1968): "*[masses are introduced] more gently than a brutal addition and subtraction of mass terms [...] letting the vector mesons interact with a set of scalar particles and let them acquire physical masses by assuming self-consistently that these scalar particles possess nonzero vacuum expectation values*"

Weinberg (1967) *"Is this model renormalizable? We usually do not expect so, but [our vector bosons] get their mass from the spontaneous breaking of the symmetry, not from a mass term put in at the beginning*"

No mathematical argument for renormalizability, but belief that the scalar represents a "gentle", "spontaneous" way to give mass

The proof will be delivered in 1971 by Gerhard 't Hooft using techniques developed by Benjamin Lee and others to renormalise the σ-model....

...but that is another story!

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