Insights and puzzles in particle physics

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Abstract

- Discuss the insights gained in particle physics during the past 50 years: qualitative properties of the Standard Model.
- Draw attention to the many puzzling aspects that are beyond our present understanding of the basic laws of nature.
- Proceed more or less chronologically, start with the situation at the beginning of the 1960ies.

Situation at the beginning of the 1960ies

- Nuclear structure, nuclear reactions, processes responsible for the energy production in the sun, α-decay, . . .
  were well understood already fifty years ago.
- Many attempts at formulating a theory of the strong interaction based on elementary fields for baryons and mesons were undertaken, Yukawa interaction for the strong forces, perturbation theory with coupling constants of order 1, . . .

uncountable PhD theses 1945 -1965

I was lucky: my thesis advisor was John Klauder

- Absolutely nothing worked even halfway, beyond general principles like Lorentz invariance, causality, unitarity

$\Rightarrow$ analyticity, dispersion relations, CPT theorem, spin + statistics

Situation at the beginning of the 1960ies

- There was considerable progress in renormalization theory, but faith in quantum field theory was in decline, even concerning Quantum Electrodynamics. "Infinitites are wiped under the carpet"
- In particular, many people strongly doubted that the strong interaction can be described by a local quantum field theory.
- Replace quantum field theory by S-matrix theory ?
  Heated debates Pietschmann, Eur. Phys. J. **H36** (2011) 75

Landau's assessment of the situation

L. D. Landau, in Pauli Memorial Volume (1960) pp. 245-248

> *We are driven to the conclusion that the Hamiltonian method for strong interaction is dead and must be buried, although of course with deserved honor.*

> *By now the nullification of the theory is tacitly accepted even by theoretical physicists who profess to dispute it. This is evident from the almost complete disappearance of papers on meson theory and particularly from Dyson's assertion that the correct theory will not be found in the next hundred years.*

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The basis of Landau's pessimistic conclusion is clearly spelled out:

. . . effective interaction always diminishes with decreasing energy . . .

. . . at weak coupling, the β-function is positive . . .

Standard Model

- Fifty years ago, the quantum field theory of the strong interaction consisted of a collection of beliefs, prejudices and assumptions. Quite a few of these turned out to be wrong.

  The remaining ones are still with us . . .

- Our understanding of the laws of nature made remarkable progress in the 8 years between
  - discovery of the quark model (1964)
  - discovery of Quantum Chromodynamics (1972)

Standard Model

All of the known forces except gravity
are generated by **gauge fields**.

Quarks, Aces

- The pattern of the many strongly interacting particles observed by 1964 can qualitatively be understood if they are not elementary but contain constituents. Gell-Mann, Zweig 1964
- Zweig called the constituents ‘aces’, Gell-Mann used the name ‘quarks’, borrowed from James Joyce.

Story told by Lochlainn O’Raifeartaigh:

James Joyce once visited an agricultural exhibit in Germany. There he saw the advertisement "Drei Mark für Musterquark". Joyce was fond of playing around with words and in this way came up with the famous passage in Finnegans Wake:

> *Three quarks for Muster Mark!*
> *Sure he has not got much of a bark*
> *And sure any he has it’s all beside the mark.*

Quarks, Aces

- Three constituents of spin $\frac{1}{2}$ are needed: $\mathbf{u}, \mathbf{d}, \mathbf{s}$
- *Baryons* contain 3 quarks

  $\mathbf{p} = \mathbf{uud} \qquad \mathbf{n} = \mathbf{udd} \qquad \mathbf{\Sigma}^+ = \mathbf{uus} \qquad \mathbf{\Xi^0} = \mathbf{uss}$
- *Mesons* consist of a quark and an antiquark:

  $\pi^+ = \mathbf{u\bar{d}} \qquad \mathbf{K}^+ = \mathbf{u\bar{s}} \qquad \rho^+ = \mathbf{u\bar{d}}, \ldots$
- Earlier prediction (based on symmetry alone):

  $\mathbf{\Omega}^- = \mathbf{sss}$ Gell-Mann 1962
- Experimental discovery Brookhaven 1964

Colour

- Quarks carry an internal quantum number
- Greenberg had introduced an internal degree of freedom of this type in 1964, referring to this as "parastatistics".
- In 1965, Bogolubov, Struminsky & Tavkhelidze, Han & Nambu and Miyamoto independently pointed out that some of the problems encountered in the Quark Model disappear if the **u**, **d** and **s** quarks occur in 3 states, "three-triplet model".
- Today, the new quantum number is called **colour**. Gell-Mann

Where are the quarks ?

- The Quark Model offers a remarkably simple and successful picture, explains the observed pattern of energy levels – but $\boxed{\text{why do the quarks not show up in experiment ?}}$

⇒ The existence of quarks was considered doubtful.
"Such particles [quarks] presumably are not real but we may use them in our field theory anyway . . ."

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⇒ Conceptual basis of such a cuisine ?

Gauge fields

- Prototype: electromagnetic field. Maxwell 1865

  Survived relativity and quantum theory, unharmed.

⇒ Quantum Electrodynamics, QED

- field picture: $\vec{\mathbf{E}}, \vec{\mathbf{B}}$ particle picture: γ photon
  Source of the field: electric charge.
- Key property: QED has a local symmetry, gauge invariance.
  Symmetry group: U(1)
  QED is the gauge field theory of U(1)

⇒ The symmetry completely fixes the e.m. interaction in terms of

$$\frac{\mathbf{e^2}}{\mathbf{4\pi}} = \frac{1}{137.035\,999\,074\,(44)}$$

Sommerfeld 1916

⇒ The e.m. interaction is understood, except for this mysterious number, which has resisted explanation for almost a century.

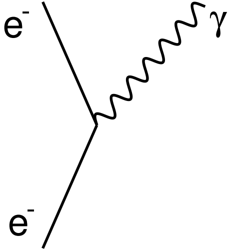
Generalization

- The symmetry group U(1) can be replaced by a larger group, for instance SU(2) or SU(3). Yang & Mills 1954
- Gauge invariance then requires the occurrence of more than one gauge field: 3 in the case of SU(2), 8 for SU(3).
- Standard Model: the interactions among the constituents of matter are generated by three distinct gauge fields.

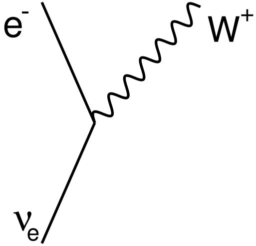
interaction	group	dim.	particles	source	coupling
electromagnetic	U(1)	1	γ	charge	$\mathbf{e}$
weak	SU(2)	3	$W^+ W^- Z$	flavour	$\mathbf{g}_\mathrm{w}$
strong	SU(3)	8	gluons	colour	$\mathbf{g}_\mathrm{s}$

- Alchemist sign for Standard Model: SU(3)×SU(2)×U(1)

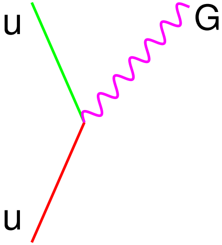
Gauge field interactions



electromagnetic
QED
charge
γ
e



weak
QFD
flavour
$W^\pm$,Z
$\mathbf{g}_w$



strong
QCD
colour
gluons
$\mathbf{g}_s$

The Standard Model is a miracle

- Since a long time, it is known that the microscopic world is governed by three types of interaction:

  electromagnetic, weak, strong

- These have qualitatively very different properties.
  - strong $\simeq$ weak ??
  - $\frac{1}{r}$ – potential describes an interaction of long range

    strong and weak interactions are of short range !
  - Photons can be seen by eye, gluons not,

    etc. etc. etc.

All of the known forces except gravity generated by the same kind of fields, gauge fields ?

Why are the three interactions so different ?

The behaviour of the interactions at long distance differs

1. Photons do not have charge, but gluons do have colour.

⇒
- Force between two electrons falls off with the distance.
- Force between two quarks does not fall off.

2. In addition to the gauge fields, there are **Higgs fields**.

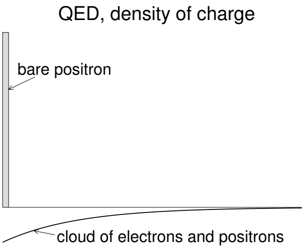
⇒ Suppress the weak interaction at long distance.

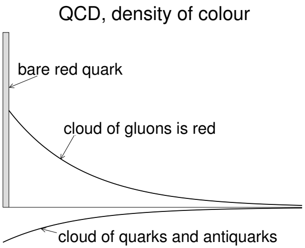
1. Why is QED different from QCD ?

- Mathematical origin of the difference between QED and QCD:
  - The gauge group of Quantum Electrodynamics is U(1).
    U(1) is abelian: $\mathbf{x_1} \cdot \mathbf{x_2} = \mathbf{x_2} \cdot \mathbf{x_1}$
  - The gauge group of Quantum Chromodynamcs is SU(3).
    SU(3) is not abelian: $\mathbf{x_1} \cdot \mathbf{x_2} \neq \mathbf{x_2} \cdot \mathbf{x_1}$

⇒ The e.m. and strong interactions
behave differently at long distance.

Compare structure of leptons and quarks





$$\boxed{\mathbf{e} < \mathbf{e}|_{\text{bare}}}$$

vacuum shields charge

$$\boxed{\mathbf{g}_s > \mathbf{g}_s|_{\text{bare}}}$$

vacuum amplifies colour

⇒ The electromagnetic and strong interactions polarize the vacuum differently.

Asymptotic freedom

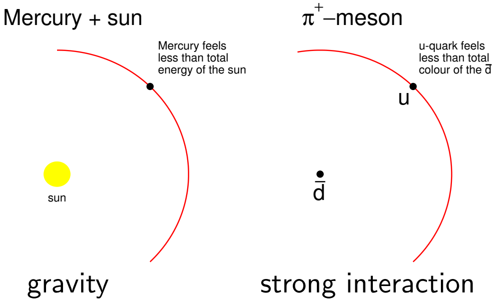
. . . effective interaction always diminishes with decreasing energy . . .

Landau 1960

- Non-abelian gauge theories are a counter-example: show the opposite behaviour.
- At weak coupling, the vacuum amplifies the interaction, the β-function is negative, "asymptotically free".

Comparison with gravity

- Source of gravitational field: energy
  Gravitational field <u>does</u> carry energy
- Source of gluon field: colour
  Gluon field <u>does</u> carry colour



- Perihelion shift of Mercury: $43'' = 50'' - \underset{\Uparrow}{7''}$ per century

Physics of vacuum polarization

- Vacuum reduces electric field of a charged source.
  Vacuum amplifies gluonic field of a coloured source.
- The difference has dramatic consequences:
  although the Lagrangians of QED and QCD
  are very similar, the properties of the electromagnetic
  and strong interactions are totally different.
- Field energy surrounding a charged particle is finite.

$\Rightarrow$ Charged particles can live alone.

- Field energy surrounding an isolated quark is not finite.
  Only colourless states have finite energy.

$\Rightarrow$ Colour is confined.

- $\nexists$ analytic proof that QCD does confine colour.
  Very good evidence from numerical simulations on a lattice.

Force between colourless objects is of short range

- Nuclear forces = van der Waals forces of QCD.
- At long distance and disregarding the e.m. interaction, the force between two nucleons is dominated by the exchange of the lightest strongly interacting particle: the π-meson.

⇒ Yukawa formula valid at long distance.

⇒ Nuclear forces are of short range: $\mathbf{r_0 = \frac{\hbar}{M_\pi c}}$ √

2. Why is QFD different from QCD ?

- The weak and strong interactions are both mediated by a non-abelian gauge field ⇒ are asymptotically free.
- Why is colour confined, flavour not ?

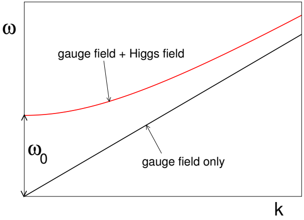
In addition to the constituents and the gauge fields, the Standard Model contains scalar fields.

- Scalar fields can modify the properties of a quantum field theory. In particular, they can give mass to a gauge field.

Englert& Brout 1964, Higgs 1964, Hagen, Guralnik & Kibble 1964

Higgs mechanism

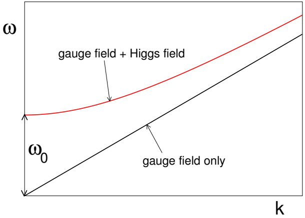
- scalar field ↔ particle without spin
  Higgs field ↔ Higgs particle
- Scalar fields may pick up a vacuum expectation value.
  Particle picture: $\boxed{\text{vacuum} = \text{condensate of Higgs particles.}}$
- Particles that interact with the Higgs particles (in particular also gauge particles) feel the presence of this medium.



$$\hbar\omega_0 = Mc^2$$

⇒ gauge particle picks up mass

Penetration depth, range of interaction



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- ∃ critical frequency ω_0
- Waves with $\omega < \omega_0$ cannot propagate.
- Penetration depth for low frequencies: $r_0 = \frac{c}{\omega_0} = \frac{\hbar}{Mc}$
    - Exchange of massless particles: $V \propto \frac{1}{r}$
    - Exchange of massive particles: $V \propto \frac{e^{-\frac{r}{r_0}}}{r}$

Quantum Flavourdynamics

- The properties of the weak interaction can be understood if
  (1) there is an SU(2) gauge field;
  (2) there is an SU(2) doublet of Higgs fields (4 real fields).

Glashow, Salam, Weinberg 1967

⇒ The SU(2) gauge particles $\{W^+, W^-, Z\}$ pick up mass.

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  $\{W^+, W^-, Z\}$ have three, particles of spin 1.
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Consequence for strength of weak interaction

- Strength of the interaction is reduced:

$$\frac{g_W^2}{4\pi r} \Rightarrow \frac{g_W^2}{4\pi r} \cdot e^{-\frac{r}{r_0}} \qquad r_0 = \frac{\hbar}{M_W c}$$

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⇒ Penetration depth of the weak interaction is small:

$$r_0 = \frac{\hbar}{M_W c} \simeq 2.5 \cdot 10^{-18} \text{ m}$$

⇒ Weak interaction is of very short range.

- Effective strength at low energies:

$$\int d^3r \, \frac{g_W^2}{4\pi r} \cdot e^{-\frac{r}{r_0}} = g_W^2 r_0^2$$

⇒ At low energies, the weak interaction is weak.

Transparency of the vacuum

The vacuum contains a condensate of Higgs fields.

- The condensed particles do not carry charge.
  Photons do not notice these.

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- The condensed particles do carry flavour.
  W,Z-waves feel the presence of the condensate.
  W,Z-particles move at $v < c$, pick up mass.
  $V \propto \frac{1}{r} \Rightarrow V \propto \frac{1}{r}\, e^{-M_W r}$ weak interaction is of short range.

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The vacuum amplifies flavour as well as colour.
The Higgs condensate shields flavour, does not shield colour.

Masses of the quarks and leptons

- Fermions also interact with the Higgs condensate

$\Rightarrow$ pick up mass.

- Unfortunately, the symmetries of the Standard Model do not fix the strength of their interaction with the Higgs fields.
- Pattern of lepton and quark masses is bizarre, indeed: masses range from $10^{-2}\mathrm{eV}/\mathrm{c}^2$ to $10^{+11}\mathrm{eV}/\mathrm{c}^2$.
- Can be accommodated, but need to tune O(20) free parameters to make the SM agree with observation . . .

Beyond the Standard Model

The Standard Model leaves many questions unanswered:

- Gravity $\cap$ Quantum theory $= \emptyset$

$\Rightarrow$ Standard Model is only an effective theory for 'low' energies.

- Need to either find a renormalizable theory of gravity or find out how to implement nonrenormalizable theories. Klauder's talk
- Bound on the range of validity of the Standard Model:
  at distances of the order of the Planck length, $1.6 \cdot 10^{-35}$ m,
  quantum fluctuations of gravitational field cannot be ignored.

Beyond the Standard Model

- Neither the e.m. interaction nor the interaction among the Higgs fields are asymptotically free.

⇒ Short distances are not controlled by perturbation theory.

- Grand unification would domesticate the e.m. interaction at short distance, but the standard way of implementing this is to add further Higgs fields …
- Are there ways to implement theories that are not asymptotically free ? "Use non-perturbative methods", but how ?

Beyond the Standard Model

- Gauge fields are renormalizable in d = 4, but there is no reason for an effective theory to be renormalizable.

⇒ Why is the Standard Model renormalizable ?

- Quite a few levels of structure are seen at the present resolution. Nothing more all the way to the Planck length ?
- Astronomical observations show that there is Dark Matter. The Standard Model does not have room for that. Supersymmetric extensions do contain candidates for Dark Matter, but where are the many super-partners ?

Beyond the Standard Model

- Astronomy also shows that there is Dark Energy. May be accounted for with a cosmological constant, but why is this constant so incredibly small ?
- Why does gravity not take notice of the Higgs condensate ? Anything that carries energy ought to generate gravity.
- Why do the baryons dominate the visible matter in our vicinity ? Difficult to understand if the proton does not decay, but does it ?
- CP violation is necessary for baryogenesis, too.
  Is observed and accounted for in SM, but not understood.
- Why are there so many lepton and quark flavours ?
- Origin of the bizarre mass pattern of the leptons and quarks ?

Summary

IG Physik, Gesellschaft mit besonderer Haftung

Im Falle eines Falles
klebt ein EICHFELD
wirklich alles !

Bezugsquellennachweis

J. C. Maxwell, Royal Society Transactions 155 (1865) 459

H. Weyl, Z. Phys. 56 (1929) 330

C. N .Yang and R. Mills, Phys. Rev. 96 (1954) 191

Advertisement ca. 1973

Short distance

- At **short distance** (10^{-19} m ⟷ 2 TeV) all of the forces obey the inverse square law.

  $$\mathbf{V} = \text{constant} \times \frac{\hbar c}{\mathbf{r}} \qquad \text{interaction energy}$$

- The constant is a pure number.

⇒ Interaction strength is fixed by 3 pure numbers.

e.m.	weak	strong
$\frac{e^2}{4\pi}$	$\frac{g_w^2}{4\pi}$	$\frac{g_s^2}{4\pi}$

Long distance

- Vacuum amplifies the interaction between quarks.

⇒ Colour is confined.

- Vacuum shields the electric charge.

⇒ Charges are free.

- Vacuum is opaque for the gauge fields of SU(2).

⇒ At low energies, the weak interaction freezes in.

- Heavy quarks and leptons decay into the light ones.
  In stable matter only e, u, d.
- At low energies, Standard Model reduces to QED + QCD:
  precision theory for the structure of matter.
  Weak interaction only generates tiny, calculable corrections.

Triumph of local quantum field theory

- The Standard Model clarified the picture enormously:

> At low energies, the properties of matter can be understood in terms of a local quantum field theory.

- Perturbation theory does lead to divergences.
- Divergences do not represent a disease, play a crucial role in our understanding of nature.
- Illustrate this with what remains of the Standard Model if all fields except the quarks and gluons are chopped off: QCD.

QCD with massless quarks

- QCD is mathematically sound, represents the first fully consistent interacting quantum field theory in 3+1 dimensions.
- In the absence of a Higgs field, the quarks are massless.
- ~~Quantum~~ Chromodynamics with massless quarks is conformally invariant: the only parameter contained in the Lagrangian, the coupling constant **g**, is dimensionless.
- For the physics of the strong interaction, it is essential that conformal symmetry does not survive quantization:
  QCD is not conformally invariant.

Why is QCD not conformally invariant ?

- Fields have infinitely many degrees of freedom. In quantum theory, need to regularize the interaction among the fields.
- Quantum field theories can be approximated by the quantum mechanics of a finite number of degrees of freedom: finite lattice spacing **a**, box of finite size.
- In order for the correlation lengths not to go astray when **a** is made smaller, the value of **g** must be changed. The strength of the interaction must be tuned: $\mathbf{g = g(a)}$.
- The dependence on **a** is determined by the β-function:

$$\mathbf{a}\frac{\mathbf{dg}}{\mathbf{da}} = -\beta(\mathbf{g})$$

Why is QCD not conformally invariant ?

- Perturbative QCD:

$$\beta(g) = -\frac{\beta_0\, g^3}{16\pi^2} + \ldots \qquad \beta_0 = 11 - \frac{2}{3}N_f$$

⇒ If g is small, $\beta(g)$ is negative

$$a\frac{dg}{da} = -\beta(g) \quad \Rightarrow \quad \frac{dg}{da} > 0$$

⇒ If a is made smaller, g must be made smaller
OK, stay in the perturbative domain if start there.

- Solution:

$$g(a) = \sqrt{\frac{8\pi^2}{\beta_0\, \ell n\left(\frac{a_{QCD}}{a}\right)}}$$

Why is QCD not conformally invariant ?

- Solution:

$$\mathbf{g(a)} = \sqrt{\frac{8\pi^2}{\beta_0\,\ell n\left(\frac{\mathbf{a}_{\mathrm{QCD}}}{\mathbf{a}}\right)}}$$

- In particular: $\mathbf{g(0) = 0}$, bare coupling constant is zero. No infinities, no carpet . . .
- $\mathbf{g}$ is dimensionless, but depends on the lattice spacing $\mathbf{a}$. $\mathbf{a}_{\mathrm{QCD}}$ is a length, fully characterizes massless QCD.

$$\Lambda_{\mathrm{QCD}} = \frac{\hbar \mathbf{c}}{\mathbf{a}_{\mathrm{QCD}}}$$

⇒ Dimensional transmutation, conformal anomaly. Intimately related to the fact that perturbation theory contains divergences: does not occur in theories with $\beta \equiv \mathbf{0}$.

QCD with massless quarks

- QCD with massless quarks has an intrinsic scale.
  Does explain the occurrence of mesons and baryons and describes their properties, albeit only approximately.
- All dimensionless physical quantities are pure numbers, determined by the theory. Cannot calculate the mass of the proton in kg units, but masses, widths, cross sections . . . can all be calculated in terms of the mass of the proton.

This is how theories should be: massless QCD does not contain a single dimensionless parameter to be adjusted to observation.

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Compared to this, the Standard Model looks rather odd ...

⇒ Much work do be done !