How masses have been generated in the early Universe

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- **But the excitement was mainly due to its potential theoretical significance**

Contents

A problem of mass

or, why are we not pure spirits!

- **Why most, but not all, particles are massive?**

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- **For the constituants of matter**
  Spin 1/2 fermions

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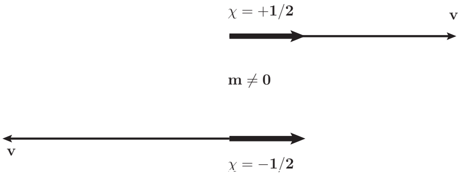
- **Why most, but not all, particles are massive?**
- **The most natural solution would be to have $m = 0$ for all elementary particles**
- **For the constituants of matter**
  Spin 1/2 fermions
- **For the intermediaries of the interactions**
  The gauge bosons

A problem of mass

For the fermions because of chirality

We need both chiralities in order to build a massive fermion

But weak interactions use only one



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- Under gauge transformations, *i.e.* $\theta(x) \Rightarrow \theta_i$, the term:

  $\bar{\Psi}_i\Psi_{i+1}$ transforms in $e^{-i\theta_i}\bar{\Psi}_i\Psi_{i+1}e^{i\theta_{i+1}}$

A problem of mass

- We need a field to *connect* the points i and $i+1$

  $U_{i,i+1}$ which transforms as $U_{i,i+1} \rightarrow e^{i\theta_i} U_{i,i+1} e^{-i\theta_{i+1}}$

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- The matter fields live on the lattice points.
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- On the lattice gauge invariance establishes a long range order.
- The gauge bosons are massless.

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- **Proposed such a mechanism almost fifty years ago. It predicted the existence of a new particle!**

Brief Historical Remarks

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- Never read old papers with to-day's knowledge
- Beware of changes in notation and terminology

Brief Historical Remarks

- **I. Spontaneous Symmetry Breaking**
- **II. Spontaneous Br. of Chiral Symmetry**
- **III. Spontaneous Br. of a gauge Symmetry**

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- **Spontaneous Symmetry Breaking** (Archimedes??)
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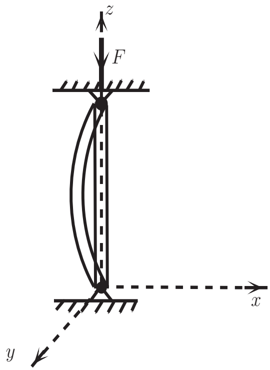
  - A critical point
  - Instability of the symmetric solution
  - The ground state is degenerate $\Rightarrow$ Massless excitations

Brief Historical Remarks I.

- **An example from Classical Mechanics**



$$IE\frac{d^4X}{dz^4} + F\frac{d^2X}{dz^2} = 0 \quad ; \quad IE\frac{d^4Y}{dz^4} + F\frac{d^2Y}{dz^2} = 0$$

$X = X'' = Y = Y'' = 0$ for $z = 0$ and $z = l$

A symmetric solution always exists: $X = Y = 0$

Brief Historical Remarks I.

- For $F \geq F_{cr} = \frac{\pi^2 EI}{l^2}$ asymmetric solutions appear:

  $X = C \sin kz \quad ; \quad kl = n\pi \quad ; \quad n = 1, \ldots \quad ; \quad k^2 = F/EI$

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- What happened to the original symmetry?
- The ground state is degenerate. $\Rightarrow$
- We cannot predict which direction the rod is going to bend

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- **An example from Quantum Mechanics**
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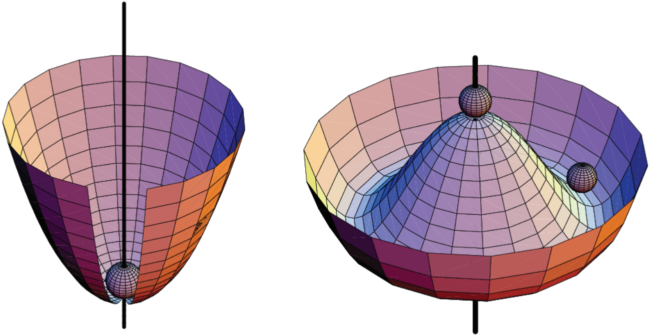
  - For $T < T_c$ order wins: We have long range correlations.
  - In quantum physics this implies zero mass particles

    The Goldstone particles

Brief Historical Remarks I.

The famous Mexican hat example

Visualisation 2D de la brisure spontanée de symétrie



Brief Historical Remarks II.

- **Spontaneous Breaking of Chiral Symmetry**
  - M. Gell-Mann and M. Lévy Nuov. Cim. **16** (1960) 605

    The axial vector current in beta decay

    The celebrated σ-model. No explicit mentioning of spontaneous symmetry breaking.

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    The pion as the massless excitation of SSB.

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  - 1962-1970: Current Algebras, Chiral Lagrangians, PCAC,....

Brief Historical Remarks III.

• **Spontaneous Symmetry Breaking in the presence of Gauge Interactions**

- Two parallel stories

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• **Spontaneous Symmetry Breaking in the presence of Gauge Interactions**

- Two parallel stories
- The Theory of Superconductivity
- The Gauge Theories of Elementary Particles
- They developed independently and often ignored each other

Spontaneous Symmetry breaking in the Theory of Superconductivity

- L.D. Landau and B.L. Ginzburg JETP **20** (1950) 1064

$$\Delta\vec{A} = ... + \frac{4\pi e^2}{mc^2}|\Psi|^2\vec{A} \quad \Rightarrow \quad \vec{A}(x) \sim \vec{A}(0)e^{-x/\lambda}$$

Note: no-one in the subsequent list refers to this paper

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- Bardeen, Cooper and Schrieffer (BCS) Phys. Rev. **108** (1957) 1175

- P.W. Anderson Phys. Rev. **112** (1958) 1900 ; **110** (1958) 827

  "Random Phase Approximation in the Theory of Superconductivity"

  In BCS $\Rightarrow$ Mass gap, $+$ Longitudinal waves

  From the Abstract : "The theory.... is gauge invariant *to an adequate degree throughout.*"

Spontaneous Symmetry breaking in the Theory of Superconductivity

- P.W. Anderson Phys. Rev. **130** (1963) 439

  "Plasmons, Gauge invariance and Mass"

  Shows that BCS exemplifies Schwinger's programme.

  From the Abstract : "Schwinger has pointed out that the Yang-Mills vector boson (*He only considers Abelian theories*) ......does not necessarily have zero mass.....We show that the theory of plasma oscillations is a simple non-relativistic example exhibiting all of the features of Schwinger's idea."

Spontaneous Symmetry breaking in the Theory of Superconductivity

- Yoichiro Nambu Phys. Rev. **117** (1959) 648

  "Quasi-Particles and Gauge Invariance in the Theory of Superconductivity"

  BCS theory in the Hartree-Fock approximation. Shows the existence of solutions with a mass gap. Correct discussion of the properties of gauge invariance.

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- J. Goldstone Nuov. Cim. **19** (1961) 154

  "Field Theories with "Superconductor" Solutions.

  Although the word "Superconductor" appears in the title, the paper is a field theory example of what became known as "The Goldstone Theorem".

Spontaneous Symmetry breaking in the Gauge Theories of Elementary Particles. Early attempts

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- Julian Schwinger Phys. Rev. **125** (1962) 397

  "Gauge Invariance and Mass"

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- Julian Schwinger Phys. Rev. **128** (1962) 2425

  "Gauge Invariance and Mass II"

  The Schwinger Model (2-d QED)

  Note: No references to superconductivity

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- In fact, Schwinger had understood the connection earlier.

  From Feynman's Summary Talk at the Aix-en-Provence Conference on Elementary Particles, Sept. 14-20 1961:

  "…..Since gauge invariance is usually believed to imply that the mass [of the gauge bosons] is zero, the first prediction of these theories ….. is disregarded. Schwinger pointed out to me however, that one can use gauge invariance to prove that the mass of the real photon is equal to zero, only if one assumes that in the complete dressed photon, there is a finite amplitude to find the undressed one."

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- M. Lévy Phys. Lett. **7** (1963) 36 ; Nucl. Phys. **57** (1964) 152

  Non-local, gauge invariant, QED with a massive photon

Spontaneous Symmetry breaking in the Gauge Theories of Elementary Particles. Early attempts

- On the one hand we had Goldstone Theorem : Sp. Sym. Br. $\Rightarrow$ A massless particle.

  On the other we had Anderson's non-relativistic counter example.

  Could we find relativistic analogues?

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- A. Klein and B.W. Lee Phys. Rev. Lett. **12** (1964) 266

  Does Spontaneous Breakdown of Symmetry Imply Zero-Mass Particles?

  M. Baker, K. Johnson, B.W. Lee Phys. Rev. **133 B** (1964) 209

  Broken Symmetries and Zero-Mass Bosons

Spontaneous Symmetry breaking in the Gauge Theories of Elementary Particles. Early attempts

- W. Gilbert Phys. Rev. Lett. **12** (1964) 713

  "Broken Symmetries and Massless Particles"

  A no-go Theorem !!

  Sp. Sym. Br. $\Rightarrow \ \exists\, A \quad < 0|[Q, A]|0 > \ \neq \ 0 \qquad (1)$

  $\mathcal{A}_\mu(k) = \int d^4x e^{ikx} < 0|[j_\mu(x), A(0)]|0 >= k_\mu F(k^2) \qquad (2)$

  by Lorentz invariance and $F(k^2) \neq 0$ by (1)

  But $\quad k^\mu \mathcal{A}_\mu = 0 \quad \Rightarrow \quad k^2 F(k^2) = 0 \quad F(k^2) \sim \delta(k^2) \quad \Rightarrow$

  A massless particle

  In a non-relativistic theory (2) does not hold.

  Problem: Find the error!

Spontaneous Symmetry breaking in the Gauge Theories of Elementary Particles. The solution

- F. Englert and R. Brout Phys. Rev. Lett. **13** (1964) 321

  The solution as we know it to-day, using elementary scalar fields.

  Some remarks on the possibility of dynamical symmetry breaking.

  Abelian, Non-Abelian and chiral models are considered.

  The motivation was mainly centred in strong interactions.

  References include SSB (Nambu *et al*), Schwinger and Sakurai.

Spontaneous Symmetry breaking in the Gauge Theories of Elementary Particles. The solution

- P. Higgs Phys. Lett. **12** (1964) 132

  Explicit example answering Gilbert's objection. The Abelian model in the Coulomb gauge.

  References include SSB, Klein+Lee and Gilbert

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- P. Higgs Phys. Rev. Lett. **13** (1964) 508

  Explicit example of the Abelian model. Discussion of the $SU(3)$ Sakurai model for strong interactions.

  Explicit connection between would-be Goldstone modes and longitudinal polarisations of the massive vector bosons.

  Connection with superconductivity.

  References include Goldstone, Anderson, Brout+Englert, Sakurai.

- **Spontaneous Symmetry breaking in the Gauge Theories of Elementary Particles. The solution**
  G.S. Guralnik, C.R. Hagen and T.W.B. Kibble Phys. Rev. Lett. **13** (1964) 585

  Detailed discussion of the Abelian model. Explicit counting 3=2+1.

  Vague connection to superconductivity. No references.

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- T.W.B. Kibble Phys. Rev. **155** (1967) 1554

  Extension of the discussion to the non-Abelian case

  The counting of massless particles in the case of a partial breaking

The Synthesis

S. Weinberg Phys. Rev. Lett. **19** (1967) 1264

The Englert-Brout-Higgs mechanism in the electroweak interactions. The same mechanism gives masses to the fermions.

SSB: Gauge Symmetries. Conclusions:

The Englert-Brout-Higgs Mechanism

• The vector bosons corresponding to spontaneously broken generators of a gauge group become massive.

• The corresponding Goldstone bosons decouple and disappear from the physical spectrum.

• Their degrees of freedom become the longitudinal components of the vector bosons.

• Gauge bosons corresponding to unbroken generators remain massless.

• There is always at least one physical, massive, scalar particle.

• The same mechanism gives masses to the fermions.

SSB: Gauge Symmetries. Later developments

- **What is precisely broken?**

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  The consequences of the symmetry are encoded in the invariance under BRST transformations. This invariance is not broken.

SSB: Gauge Symmetries. Later developments

- **What is precisely broken?**
- In the continuum theory gauge invariance is explicitly broken by the gauge fixing condition. $\Rightarrow$

  The consequences of the symmetry are encoded in the invariance under BRST transformations. This invariance is not broken.
- In the lattice formulation gauge symmetry is exact. $\Rightarrow$

  Elitzur's Theorem: There exists no local order parameter for a gauge symmetry in which the fields take values in a compact manifold.

The next steps

The Hunting is over. Taming of the beast. Study its properties. Is it *the* Higgs particle?

- Spin and Parity are OK

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- Elementary versus Composite

  No new strong interactions at the 100 GeV range $\Rightarrow$ Elementary??

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- Need for a dedicated collider??

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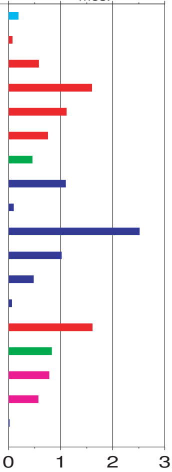
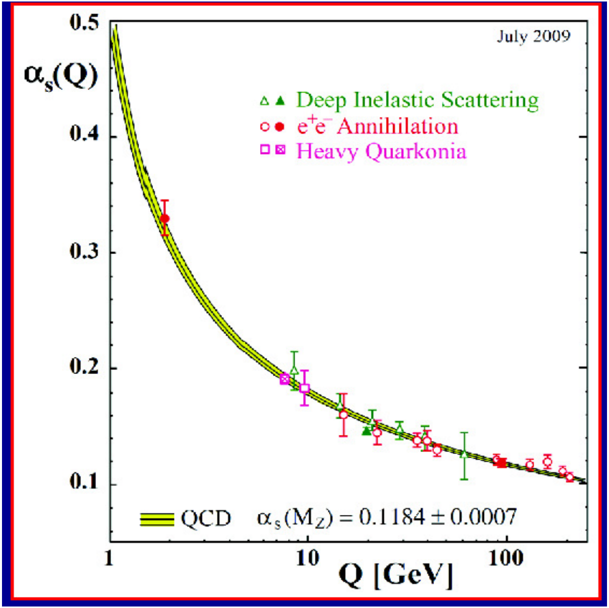
- At the non-perturbative level

Observable	Mesure	Ajustement
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02761 ± 0.00036	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1873
Γ_Z [GeV]	2.4952 ± 0.0023	2.4965
σ_{had}^{0} [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01642
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21638 ± 0.00066	0.21566
R_c	0.1720 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0997 ± 0.0016	0.1037
$A_{fb}^{0,c}$	0.0706 ± 0.0035	0.0742
A_b	0.925 ± 0.020	0.935
A_c	0.670 ± 0.026	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.425 ± 0.034	80.398
Γ_W [GeV]	2.133 ± 0.069	2.094
m_t [GeV]	178.0 ± 4.3	178.1

$\frac{|O_{mes.} - O_{ajust.}|}{\sigma_{mes.}}$





July 2009
$\alpha_s(Q)$
Deep Inelastic Scattering
e^+e^- Annihilation
Heavy Quarkonia
0.5
0.4
0.3
0.2
0.1
QCD $\alpha_s(M_Z) = 0.1184 \pm 0.0007$
1
10
100
Q [GeV]

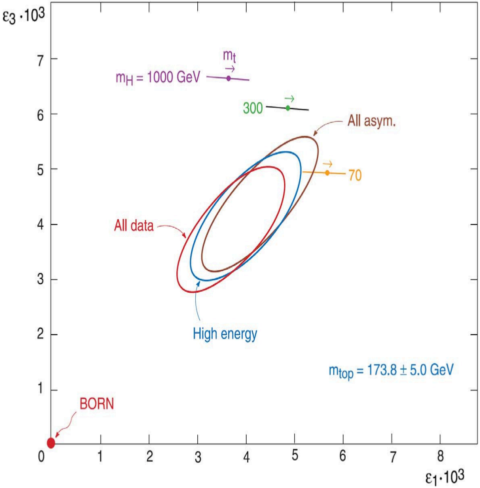
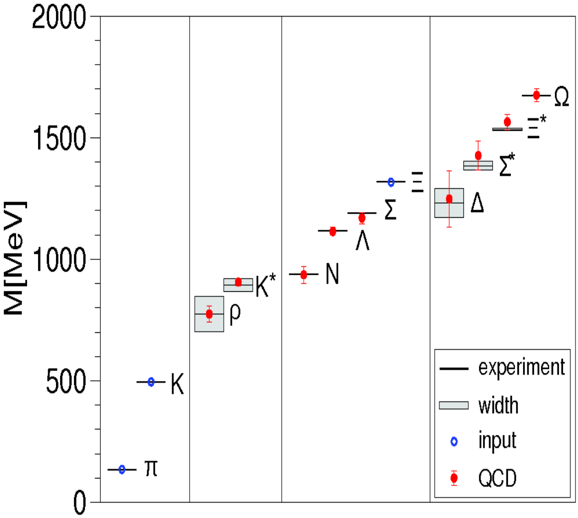


Figure 6: Data vs theory in the ϵ_3-ϵ_1 plane (notations as in fig.5)

$$\epsilon_1 = \frac{3 G_F m_t^2}{8\sqrt{2}\pi^2} - \frac{3 G_F m_W^2}{4\sqrt{2}\pi^2} \tan^2\theta_W \ln\frac{m_H}{m_Z} + \ldots \qquad (1)$$

$$\epsilon_3 = \frac{G_F m_W^2}{12\sqrt{2}\pi^2} \ln\frac{m_H}{m_Z} - \frac{G_F m_W^2}{6\sqrt{2}\pi^2} \ln\frac{m_t}{m_Z} + \ldots \qquad (2)$$

QCD spectrum: BMW collaboration, Science 322, 1224 (2008)



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- Do we need a third world, The world of scalars?

  Many arbitrary parameters. Their masses are unstable Why??

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- The unit operator $\sim \Lambda^4 \mathbf{1}$???

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- Could the scalars become also geometrical?

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- Question: Is there a space on which Internal symmetry transformations act as Diffeomorphisms?

- Answer: Yes, but it is a space with non-commutative geometry.

  A space defined by an algebra of matrix-valued functions

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- **Great discoveries do not mark an end but a beginning**