How masses have been generated in the early Universe

J.Iliopoulos

Ecole Normale Supérieure, Paris

Warsaw, June 3 2013

WWW

WWW

- **Where**

WWW

- **Where**
- **What**

WWW

- **Where**
- **What**
- **Why**


LHCb
ATLAS
CERN
CERN
SUISSE
FRANCE
CMS
ALICE
LHC 27 km

Journée historique : 4 Juillet 201

CMS:Joe Incandela

ATLAS: Fabiola Gian

Englert,
Higgs

- **The recent discovery of a new particle at CERN made headlines in world media**

- **The recent discovery of a new particle at CERN made headlines in world media**

- **The discovery itself was a triumph of technology and ingeniouity**

- **The recent discovery of a new particle at CERN made headlines in world media**

- **The discovery itself was a triumph of technology and ingeniouity**

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

Contents

- A problem of mass
- Brief Historical Remarks
- The next Steps
- Do we understand the Physics?

A problem of mass

or, why are we not pure spirits!

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

A problem of mass

or, why are we not pure spirits!

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

- **The most natural solution would be to have $m = 0$ for all elementary particles**

A problem of mass

or, why are we not pure spirits!

- **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

A problem of mass
or, why are we not pure spirits!

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

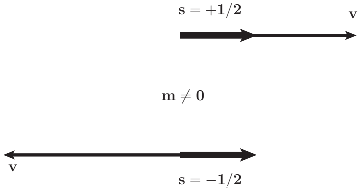
- **The most natural solution would be to have $m = 0$ for all elementary particles**

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

- **For the intermediaries of the interactions**
  The gauge bosons

A problem of mass
or, why are we not pure spirits!

For the fermions because of chirality
We need both chiralities in order to build a massive fermion
But weak interactions use only one



A problem of mass

or, why are we not pure spirits!

- **For the gauge bosons $m = 0$ is a geometrical property**

A problem of mass

or, why are we not pure spirits!

- **For the gauge bosons** $m = 0$ **is a geometrical property**
- Imagine a field theory formulated on a space-time lattice.

$$\Psi(x) \quad \Rightarrow \Psi_i \quad ; \quad \partial\Psi(x) \quad \Rightarrow (\Psi_i - \Psi_{i+1})$$

$$\Psi(x) \to e^{i\theta}\Psi(x) \quad \Rightarrow \Psi_i \to e^{i\theta}\Psi_i$$

A problem of mass
or, why are we not pure spirits!

- **For the gauge bosons $m = 0$ is a geometrical property**
- Imagine a field theory formulated on a space-time lattice.

  $\Psi(x) \quad \Rightarrow \Psi_i \quad ; \quad \partial\Psi(x) \quad \Rightarrow (\Psi_i - \Psi_{i+1})$

  $\Psi(x) \to e^{i\theta}\Psi(x) \quad \Rightarrow \Psi_i \to e^{i\theta}\Psi_i$
- Under global transformatios, *i.e.* θ constant:

  Both $\bar{\Psi}_i\Psi_i$ and $\bar{\Psi}_i\Psi_{i+1}$ remain invariant

A problem of mass
or, why are we not pure spirits!

- **For the gauge bosons $m = 0$ is a geometrical property**
- Imagine a field theory formulated on a space-time lattice.

  $\Psi(x) \quad \Rightarrow \Psi_i \quad ; \quad \partial\Psi(x) \quad \Rightarrow (\Psi_i - \Psi_{i+1})$

  $\Psi(x) \rightarrow e^{i\theta}\Psi(x) \quad \Rightarrow \Psi_i \rightarrow e^{i\theta}\Psi_i$
- Under global transformatios, *i.e.* θ constant:

  Both $\bar{\Psi}_i\Psi_i$ and $\bar{\Psi}_i\Psi_{i+1}$ remain invariant
- 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

or, why are we not pure spirits!

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

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

  The term $\bar{\Psi}_i U_{i,i+1} \Psi_{i+1}$ is now invariant. In the continuum limit the field U becomes the gauge potential A

A problem of mass

or, why are we not pure spirits!

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

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

  The term $\bar{\Psi}_i U_{i,i+1} \Psi_{i+1}$ is now invariant. In the continuum limit the field U becomes the gauge potential A

- The matter fields live on the lattice points.

A problem of mass

or, why are we not pure spirits!

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

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

  The term $\bar{\Psi}_i U_{i,i+1} \Psi_{i+1}$ is now invariant. In the continuum limit the field U becomes the gauge potential A
- The matter fields live on the lattice points.
- The gauge potentials live on the oriented lattice links

A problem of mass

or, why are we not pure spirits!

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

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

  The term $\bar{\Psi}_i U_{i,i+1} \Psi_{i+1}$ is now invariant. In the continuum limit the field U becomes the gauge potential A
- The matter fields live on the lattice points.
- The gauge potentials live on the oriented lattice links
- On the lattice gauge invariance establishes a long range order.

A problem of mass

or, why are we not pure spirits!

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

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

  The term $\bar{\Psi}_i U_{i,i+1} \Psi_{i+1}$ is now invariant. In the continuum limit the field U becomes the gauge potential A
- The matter fields live on the lattice points.
- The gauge potentials live on the oriented lattice links
- On the lattice gauge invariance establishes a long range order.
- The gauge bosons are massless.

Brief Historical Remarks

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

Brief Historical Remarks I.

- **Spontaneous Symmetry Breaking** (Euler??)
  - A critical point

Brief Historical Remarks I.

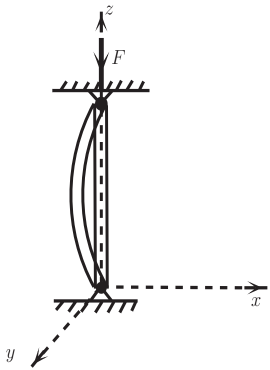
- **Spontaneous Symmetry Breaking** (Euler??)
  - A critical point
  - Instability of the symmetric solution

Brief Historical Remarks I.

- **Spontaneous Symmetry Breaking** (Euler??)
  - 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:

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

  They correspond to lower energy.

Brief Historical Remarks I.

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

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

  They correspond to lower energy.
- What happened to the original symmetry?

Brief Historical Remarks I.

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

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

  They correspond to lower energy.
- What happened to the original symmetry?
- The ground state is degenerate. $\Rightarrow$

Brief Historical Remarks I.

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

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

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

Brief Historical Remarks I.

- **An example from Quantum Mechanics**
  - A Ferromagnet: $H = -J \sum \vec{S}_i \cdot \vec{S}_{i+1}$. $J > 0$

Brief Historical Remarks I.

- **An example from Quantum Mechanics**
  - A Ferromagnet: $H = -J \sum \vec{S}_i \cdot \vec{S}_{i+1}$. $J > 0$
  - The interaction favours order; The thermal fluctuations favour disorder.

Brief Historical Remarks I.

- **An example from Quantum Mechanics**
  - A Ferromagnet: $H = -J \sum \vec{S}_i \cdot \vec{S}_{i+1}$. $J > 0$
  - The interaction favours order; The thermal fluctuations favour disorder.
  - For $T < T_c$ order wins: We have long range correlations.

Brief Historical Remarks I.

- **An example from Quantum Mechanics**
  - A Ferromagnet: $H = -J \sum \vec{S}_i \cdot \vec{S}_{i+1}$. $J > 0$
  - The interaction favours order; The thermal fluctuations favour disorder.
  - 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 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.

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.

  - Yoichiro Nambu Phys. Rev. Lett. **4** (1960) 380

    Axial vector current conservation in weak interactions

    The pion as the massless excitation of SSB.

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.
  - Yoichiro Nambu Phys. Rev. Lett. **4** (1960) 380

    Axial vector current conservation in weak interactions

    The pion as the massless excitation of SSB.
  - Y. Nambu and G. Jona-Lasinio Phys. Rev. **122** (1961) 345

    Dynamical Models of Elementary Particles based on an Analogy with Superconductivity.

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.
  - Yoichiro Nambu Phys. Rev. Lett. **4** (1960) 380

    Axial vector current conservation in weak interactions

    The pion as the massless excitation of SSB.
  - Y. Nambu and G. Jona-Lasinio Phys. Rev. **122** (1961) 345

    Dynamical Models of Elementary Particles based on an Analogy with Superconductivity.
  - 1962-1970: Current Algebras, Chiral Lagrangians, PCAC,....

Brief Historical Remarks III.

• Spontaneous Symmetry Breaking in the presence of Gauge Interactions

- Two parallel stories

Brief Historical Remarks III.

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

- Two parallel stories
- The Theory of Superconductivity

Brief Historical Remarks III.

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

- Two parallel stories
- The Theory of Superconductivity
- The Gauge Theories of Elementary Particles

Brief Historical Remarks III.

• 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

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

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

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

- 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.

  Reference to Anderson.

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.

  Reference to Anderson.

- 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

- The introduction of the Yang-Mills theories forced theorists to re-examine the connection between gauge invariance and mass.

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

- The introduction of the Yang-Mills theories forced theorists to re-examine the connection between gauge invariance and mass.

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

  "Gauge Invariance and Mass"

  $\Pi_{\mu\nu}(q) = \Pi(q^2)\left(g_{\mu\nu} - \frac{q_\mu q_\nu}{q^2}\right) \qquad \Pi(0) \neq 0 \Rightarrow m \neq 0$

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

- The introduction of the Yang-Mills theories forced theorists to re-examine the connection between gauge invariance and mass.

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

  "Gauge Invariance and Mass"

  $$\Pi_{\mu\nu}(q) = \Pi(q^2)\left(g_{\mu\nu} - \frac{q_\mu q_\nu}{q^2}\right) \qquad \Pi(0) \neq 0 \Rightarrow m \neq 0$$

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

  "Gauge Invariance and Mass II"

  The Schwinger Model (2-d QED)

  Note: No references to superconductivity

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

- 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."

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

- 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."

- 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?

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?

- 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

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

- 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.

References include Goldstone, Gilbert, Brout+Englert (published), Higgs (preprint)

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?**

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.

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. Measure as many branching ratios as possible.

  $$\Gamma_{b\bar{b}} \quad \Gamma_{\tau^+\tau^-}, \; ....$$

  Is $\Gamma_{\gamma\gamma}$ too big?

The next steps

The Hunting is over. Taming of the beast

- Study its properties. Measure as many branching ratios as possible.

  $$\Gamma_{b\bar{b}} \quad \Gamma_{\tau^+\tau^-}, \; ....$$

  Is $\Gamma_{\gamma\gamma}$ too big?

- How many are there?

The next steps

The Hunting is over. Taming of the beast

- Study its properties. Measure as many branching ratios as possible.

  $$\Gamma_{b\bar{b}} \quad \Gamma_{\tau^+\tau^-}, \ \ldots.$$

  Is $\Gamma_{\gamma\gamma}$ too big?

- How many are there?

- Elementary versus Composite

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

The next steps

The Hunting is over. Taming of the beast

- Study its properties. Measure as many branching ratios as possible.

  $\Gamma_{b\bar{b}} \quad \Gamma_{\tau^+\tau^-}$, ...

  Is $\Gamma_{\gamma\gamma}$ too big?

- How many are there?

- Elementary versus Composite

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

- Need for a dedicated collider??

Do we understand the Physics?

TABLE OF ELEMENTARY PARTICLES		
QUANTA OF RADIATION		
Strong Interactions		Eight gluons
Electromagnetic Interactions		Photon (γ)
Weak Interactions		Bosons W^+ , W^- , Z^0
Gravitational Interactions		Graviton (?)
MATTER PARTICLES		
	Leptons	Quarks
1st Family	ν_e , e^-	u_a , d_a , $a = 1, 2, 3$
2nd Family	ν_μ , μ^-	c_a , s_a , $a = 1, 2, 3$
3rd Family	ν_τ , τ^-	t_a , b_a , $a = 1, 2, 3$
HIGGS BOSON		

Table: This Table shows our present ideas on the structure of matter. Quarks and gluons do not exist as free particles and the graviton has not yet been observed.

Remarks

- All interactions are produced by the exchange of virtual quanta. For the strong, e.m. and weak interactions they are vector (spin-one) fields, while the graviton is assumed to be a tensor, spin-two field.

Remarks

- All interactions are produced by the exchange of virtual quanta. For the strong, e.m. and weak interactions they are vector (spin-one) fields, while the graviton is assumed to be a tensor, spin-two field.
- The constituents of matter appear to be all spin one-half particles. They are divided into quarks, which are hadrons, and "leptons" which have no strong interactions.

Remarks

- All interactions are produced by the exchange of virtual quanta. For the strong, e.m. and weak interactions they are vector (spin-one) fields, while the graviton is assumed to be a tensor, spin-two field.
- The constituents of matter appear to be all spin one-half particles. They are divided into quarks, which are hadrons, and “leptons” which have no strong interactions.
- Each quark species appears under three forms, often called “colours” (no relation with the ordinary sense of the word).

Remarks

- All interactions are produced by the exchange of virtual quanta. For the strong, e.m. and weak interactions they are vector (spin-one) fields, while the graviton is assumed to be a tensor, spin-two field.
- The constituents of matter appear to be all spin one-half particles. They are divided into quarks, which are hadrons, and “leptons” which have no strong interactions.
- Each quark species appears under three forms, often called “colours” (no relation with the ordinary sense of the word).
- Quarks and gluons do not appear as free particles. They form a large number of bound states, the hadrons.

Remarks

- All interactions are produced by the exchange of virtual quanta. For the strong, e.m. and weak interactions they are vector (spin-one) fields, while the graviton is assumed to be a tensor, spin-two field.
- The constituents of matter appear to be all spin one-half particles. They are divided into quarks, which are hadrons, and "leptons" which have no strong interactions.
- Each quark species appears under three forms, often called "colours" (no relation with the ordinary sense of the word).
- Quarks and gluons do not appear as free particles. They form a large number of bound states, the hadrons.
- Quarks and leptons seem to fall into three distinct groups, or "families". Why?

Remarks

- All interactions are produced by the exchange of virtual quanta. For the strong, e.m. and weak interactions they are vector (spin-one) fields, while the graviton is assumed to be a tensor, spin-two field.
- The constituents of matter appear to be all spin one-half particles. They are divided into quarks, which are hadrons, and "leptons" which have no strong interactions.
- Each quark species appears under three forms, often called "colours" (no relation with the ordinary sense of the word).
- Quarks and gluons do not appear as free particles. They form a large number of bound states, the hadrons.
- Quarks and leptons seem to fall into three distinct groups, or "families". Why?
- The sum of all electric charges inside any family is equal to zero.

The Interactions

- **The Gauge Theory of** $U(1) \times SU(2) \times SU(3)$

The Interactions

- **The Gauge Theory of** $U(1) \times SU(2) \times SU(3)$
- $U(1) \times SU(2)$ is spontaneously broken to $U(1)_{\rm em}$

  It describes the electromagnetic and the weak interactions

  $W^{\pm}$ and Z^0 become massive; The photon is massless

The Interactions

- **The Gauge Theory of** $U(1) \times SU(2) \times SU(3)$
- $U(1) \times SU(2)$ is spontaneously broken to $U(1)_{\mathrm{em}}$

  It describes the electromagnetic and the weak interactions

  $W^{\pm}$ and Z^0 become massive; The photon is massless
- $SU(3)$ remains unbroken

  It describes the strong interactions

  The eight gluons are massless

The Interactions

- **The Gauge Theory of** $U(1) \times SU(2) \times SU(3)$
- $U(1) \times SU(2)$ is spontaneously broken to $U(1)_{\rm em}$

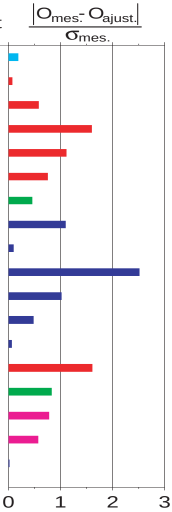
  It describes the electromagnetic and the weak interactions

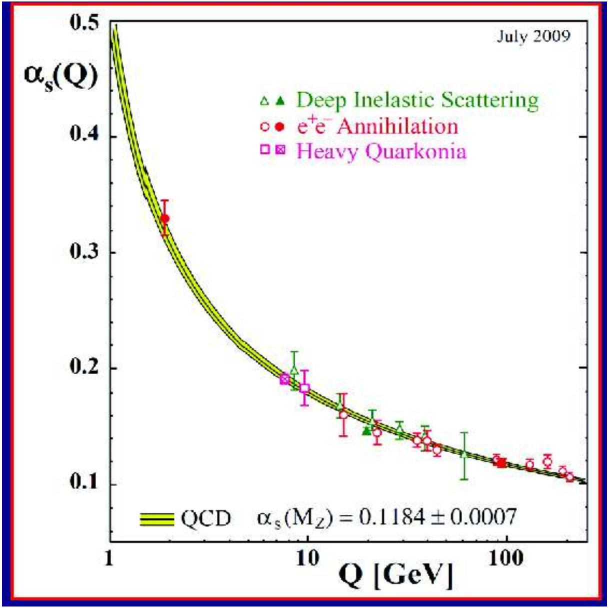
  $W^{\pm}$ and Z^0 become massive; The photon is massless
- $SU(3)$ remains unbroken

  It describes the strong interactions

  The eight gluons are massless
- **The Standard Model has been enormously successful**

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





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

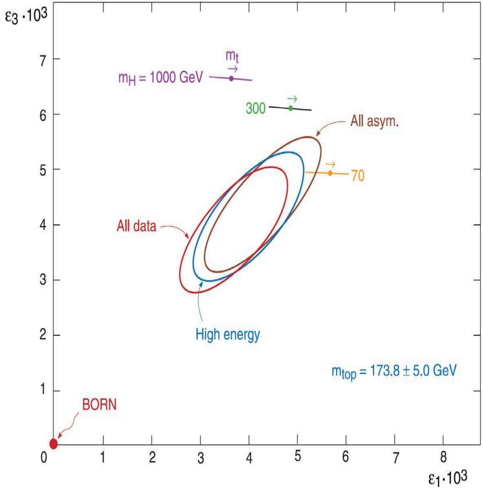


Figure 6: Data vs theory in the ϵ_3-ϵ_1 plane (notations as in fig.5)

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

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

The Standard Model and experiment

The precision of the measurements often led to successful predictions of new Physics.

The Standard Model and experiment

The precision of the measurements often led to successful predictions of new Physics.

- The discovery of weak neutral currents by Gargamelle in 1972

  $$\nu_\mu + e^- \rightarrow \nu_\mu + e^- \quad ; \quad \nu_\mu + N \rightarrow \nu_\mu + X$$

  Both, their strength and their properties were predicted by the Model.

The Standard Model and experiment

The precision of the measurements often led to successful predictions of new Physics.

- The discovery of weak neutral currents by Gargamelle in 1972

  $\nu_\mu + e^- \to \nu_\mu + e^- \quad ; \quad \nu_\mu + N \to \nu_\mu + X$

  Both, their strength and their properties were predicted by the Model.

- The discovery of charmed particles at SLAC in 1974

  Their presence was essential to ensure the absence of strangeness changing neutral currents, ex. $K^0 \to \mu^+ + \mu^-$

  Their characteristic property is to decay predominantly in strange particles.

The Standard Model and experiment

The precision of the measurements often led to successful predictions of new Physics.

- The discovery of weak neutral currents by Gargamelle in 1972

  $\nu_\mu + e^- \to \nu_\mu + e^- \quad ; \quad \nu_\mu + N \to \nu_\mu + X$

  Both, their strength and their properties were predicted by the Model.

- The discovery of charmed particles at SLAC in 1974

  Their presence was essential to ensure the absence of strangeness changing neutral currents, ex. $K^0 \to \mu^+ + \mu^-$

  Their characteristic property is to decay predominantly in strange particles.

- A necessary condition for the consistency of the Model is that $\sum_i Q_i = 0$ inside each family.

  When the τ lepton was discovered the b and t quarks were predicted with the right electric charges.

The Standard Model and experiment

- The discovery of the W and Z bosons at CERN in 1983

  The characteristic relation of the Standard Model with an isodoublet Higgs mechanism $m_Z = m_W/cos\theta_W$ is checked with very high accuracy (including radiative corrections).

The Standard Model and experiment

- The discovery of the W and Z bosons at CERN in 1983

  The characteristic relation of the Standard Model with an isodoublet Higgs mechanism $m_Z = m_W/cos\theta_W$ is checked with very high accuracy (including radiative corrections).

- The t-quark was *seen* at LEP through its effects in radiative corrections before its actual discovery at Fermilab.

The Standard Model and experiment

- The discovery of the W and Z bosons at CERN in 1983

  The characteristic relation of the Standard Model with an isodoublet Higgs mechanism $m_Z = m_W / cos\theta_W$ is checked with very high accuracy (including radiative corrections).
- The t-quark was *seen* at LEP through its effects in radiative corrections before its actual discovery at Fermilab.
- The final touch: The recent discovery of the Brout-Englert-Higgs scalar

Do we understand the Physics

- Landau-Ginsburg vs BCS

Do we understand the Physics

- Landau-Ginsburg vs BCS
- But here we see the particle!

Do we understand the Physics

- Landau-Ginsburg vs BCS
- But here we see the particle!
- Gauge Theories contain two independent worlds:

Do we understand the Physics

- Landau-Ginsburg vs BCS
- But here we see the particle!
- Gauge Theories contain two independent worlds:
- The gauge bosons: Their number and their dynamics are determined by Geometry

Do we understand the Physics

- Landau-Ginsburg vs BCS
- But here we see the particle!
- Gauge Theories contain two independent worlds:
- The gauge bosons: Their number and their dynamics are determined by Geometry
- The fermions are arbitrary, but their dynamics is not.

Do we understand the Physics

- Landau-Ginsburg vs BCS
- But here we see the particle!
- Gauge Theories contain two independent worlds:
- The gauge bosons: Their number and their dynamics are determined by Geometry
- The fermions are arbitrary, but their dynamics is not.
- Do we need a third world, The world of scalars?

  Many arbitrary parameters. Their masses are unstable Why??

Do we understand the Physics

- Possible theoretical answers:

Do we understand the Physics

- Possible theoretical answers:
- No elementary scalars.

  Does not seem to work

Do we understand the Physics

- Possible theoretical answers:
- No elementary scalars.

  Does not seem to work
- Supersymmetry. The scalars complete the massive vector supermultiplet.

  We do not know where and how it is broken.

Do we understand the Physics

- Possible theoretical answers:

- No elementary scalars.

  Does not seem to work

- Supersymmetry. The scalars complete the massive vector supermultiplet.

  We do not know where and how it is broken.

- Could the scalars become also geometrical?

Do we understand the Physics

- Gauge transformations are:

  Diffeomorphisms *space-time*

  Internal symmetries

Do we understand the Physics

- Gauge transformations are:

  Diffeomorphisms *space-time*

  Internal symmetries

- But the internal symmetry transformations are only local in space-time.

  Is Kaluza-Klein the answer?

Do we understand the Physics

- Gauge transformations are:

  Diffeomorphisms *space-time*

  Internal symmetries

- But the internal symmetry transformations are only local in space-time.

  Is Kaluza-Klein the answer?

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

Do we understand the Physics

- Gauge transformations are:

  Diffeomorphisms *space-time*

  Internal symmetries

- But the internal symmetry transformations are only local in space-time.

  Is Kaluza-Klein the answer?

- 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

Conclusions

- **Too Early!**

Conclusions

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