The recent discovery of the Scalar Boson at CERN

J.Iliopoulos

Ecole Normale Supérieure, Paris

7th Regional meeting on String Theory

Crete, June 19, 2013

WWW

WWW

- **Where**

WWW

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

WWW

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


LHCb
ATLAS
CERN
CERN
SUISSE
FRANCE
SPS 7 km
ALICE
CMS
LHC 27 km

Journée historique : 4 Juillet 201

CMS:Joe Incandela

ATLAS: Fabiola Gian

Englert,
Higgs

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- **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?**

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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**

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

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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, because of chirality
- **For the intermediaries of the interactions**
  The gauge bosons, because of gauge invariance

A problem of mass

or, why are we not pure spirits!

- **In the Standard Model masses are generated through the Englert-Brout-Higgs mechanism**

A problem of mass

or, why are we not pure spirits!

- **In the Standard Model masses are generated through the Englert-Brout-Higgs mechanism**
- I am not fat. I was just born with too many Higgs bosons!

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

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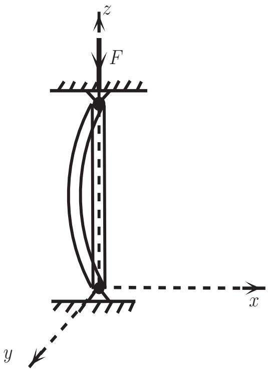
  - A critical point
  - Instability of the symmetric solution
  - The ground state is degenerate ⇒ Massless excitations

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:

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

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

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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 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.

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    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

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- Two parallel stories
- The Theory of Superconductivity
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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

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

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

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

  "Random Phase Approximation in the Theory of Superconductivity"

  In BCS ⇒ 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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  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

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

  "Gauge Invariance and Mass"

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

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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.

Correct answer to Gilbert

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?**

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

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

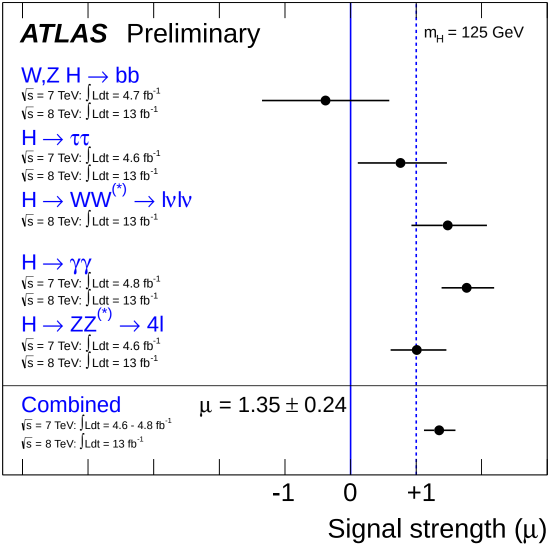
SSB: Gauge Symmetries. Later developments

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

  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. ⇒

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

The Hunting is over. Taming of the beast


ATLAS Preliminary
m_H = 125 GeV
W,Z H → bb
$\sqrt{s}$ = 7 TeV: $\int Ldt$ = 4.7 fb^{-1}
$\sqrt{s}$ = 8 TeV: $\int Ldt$ = 13 fb^{-1}
H → ττ
$\sqrt{s}$ = 7 TeV: $\int Ldt$ = 4.6 fb^{-1}
$\sqrt{s}$ = 8 TeV: $\int Ldt$ = 13 fb^{-1}
H → WW$^{(*)}$ → lνlν
$\sqrt{s}$ = 8 TeV: $\int Ldt$ = 13 fb^{-1}
H → γγ
$\sqrt{s}$ = 7 TeV: $\int Ldt$ = 4.8 fb^{-1}
$\sqrt{s}$ = 8 TeV: $\int Ldt$ = 13 fb^{-1}
H → ZZ$^{(*)}$ → 4l
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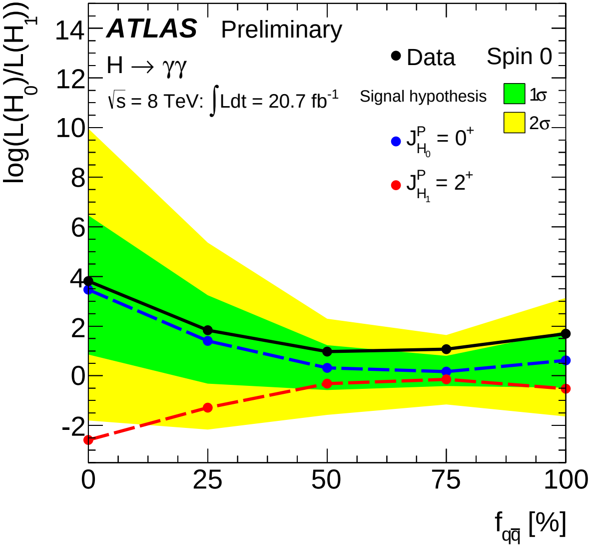
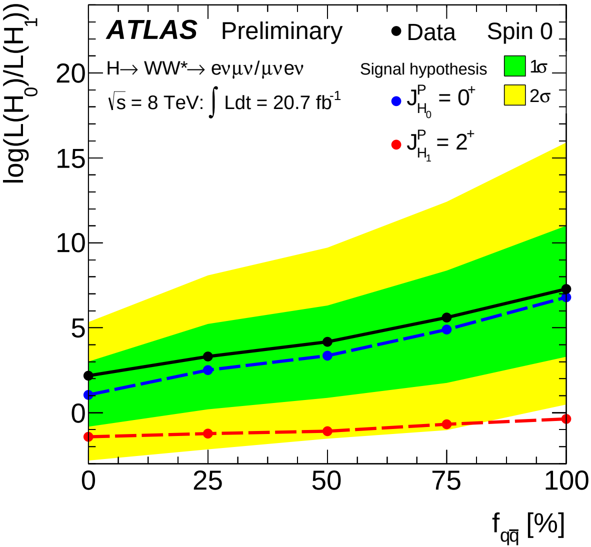
Combined
μ = 1.35 ± 0.24
$\sqrt{s}$ = 7 TeV: $\int Ldt$ = 4.6 - 4.8 fb^{-1}
$\sqrt{s}$ = 8 TeV: $\int Ldt$ = 13 fb^{-1}
-1
0
+1
Signal strength (μ)


ATLAS Preliminary
H → γγ
√s = 8 TeV: ∫Ldt = 20.7 fb^{-1}
● Data
Spin 0
Signal hypothesis
🟩 1σ
🟨 2σ
● $J^P_{H_0} = 0^+$
● $J^P_{H_1} = 2^+$
log(L(H$_0$)/L(H$_1$))
14
12
10
8
6
4
2
0
-2
0
25
50
75
100
f$_{q\bar{q}}$ [%]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Signal hypothesis
1σ
2σ
J^P_H0 = 0+
J^P_H1 = 2+
log(L(H0)/L(H1))
f_qq̄ [%]
0
5
10
15
20
0
25
50
75
100

The next steps

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

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

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- Elementary versus Composite

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

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  No new strong interactions at the 100 GeV range ⇒ 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.

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- 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 $U(1)_{\mathrm{em}}$

  It describes the electromagnetic and the weak interactions

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

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

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The Interactions

- **The Gauge Theory of** $U(1) \times SU(2) \times SU(3)$
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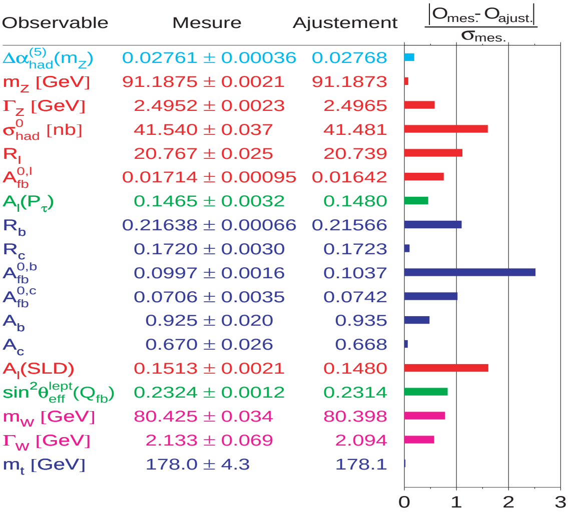
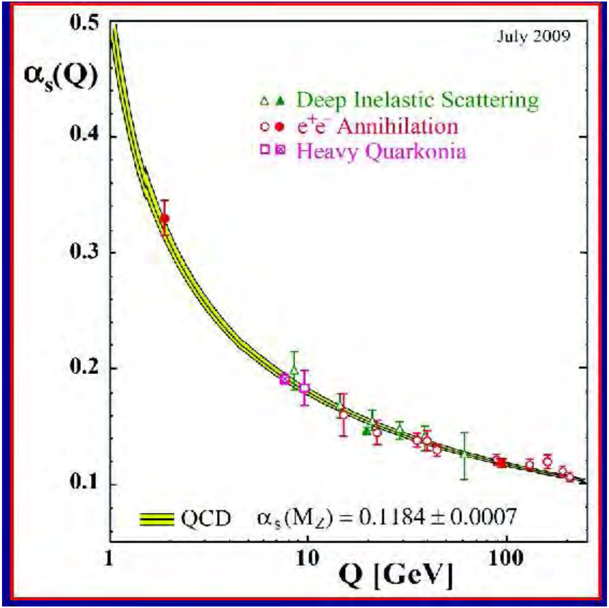
  The eight gluons are massless
- **The Standard Model has been enormously successful**



Observable	Mesure	Ajustement
$\Delta\alpha^{(5)}_{had}(m_Z)$	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^0_{had} [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A^{0,l}_{fb}$	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
$A^{0,b}_{fb}$	0.0997 ± 0.0016	0.1037
$A^{0,c}_{fb}$	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
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	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
$\alpha_s(Q)$
0.4
0.3
0.2
0.1
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]

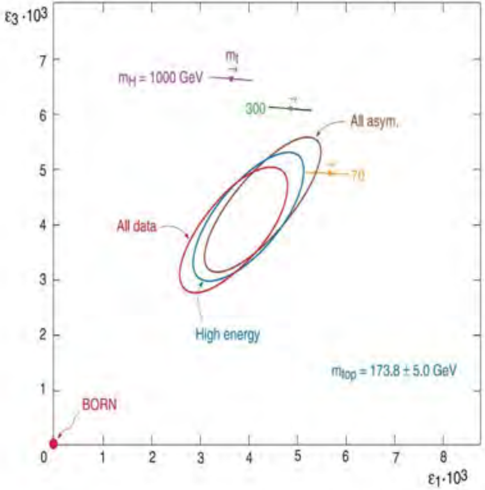


Figure 6: Data vs theory in the ϵ_3-ϵ_1 plane (notations as in fig.5)

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

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

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- 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.

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  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).

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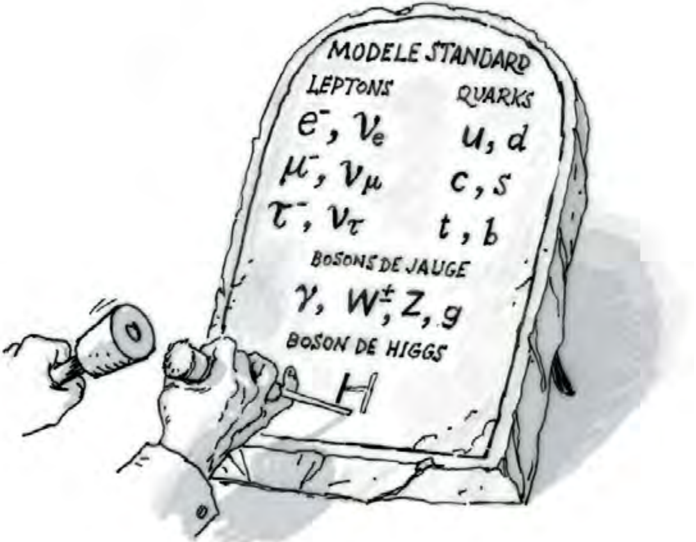
- The final touch: The recent discovery of the Brout-Englert-Higgs scalar


MODELE STANDARD
LEPTONS
QUARKS
e^-, ν_e
u, d
μ^-, ν_μ
c, s
τ^-, ν_τ
t, b
BOSONS DE JAUGE
$\gamma, W^\pm, Z, g$
BOSON DE HIGGS
H

Do we understand the Physics

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- But here we see the particle!

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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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- No elementary scalars.

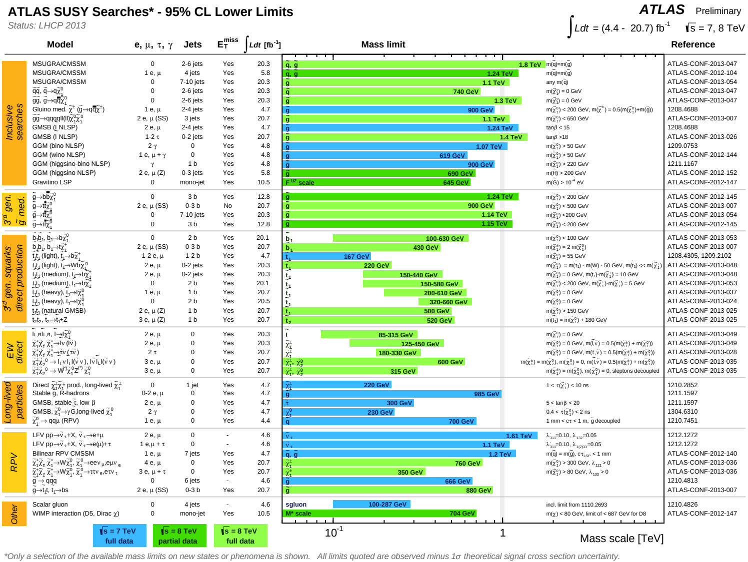
  Does not seem to work

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.



ATLAS SUSY Searches* - 95% CL Lower Limits

Status: LHCP 2013

ATLAS Preliminary

$\int L dt = (4.4 - 20.7)\ \mathrm{fb}^{-1}$ $\sqrt{s}$ = 7, 8 TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int L dt$ [fb^{-1}]	Mass limit		Reference
Inclusive searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.8 TeV	$m(\tilde{q})=m(\tilde{g})$	ATLAS-CONF-2013-047
	MSUGRA/CMSSM	1 e, μ	4 jets	Yes	5.8	$\tilde{q}, \tilde{g}$ 1.24 TeV	$m(\tilde{q})=m(\tilde{g})$	ATLAS-CONF-2012-104
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	any $m(\tilde{q})$	ATLAS-CONF-2013-054
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 740 GeV	$m(\tilde{\chi}_1^0)$ = 0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0)$ = 0 GeV	ATLAS-CONF-2013-047
	Gluino med. $\tilde{\chi}^\pm$ ($\tilde{g}\to q\bar{q}\tilde{\chi}^\pm$)	1 e, μ	2-4 jets	Yes	4.7	$\tilde{g}$ 900 GeV	$m(\tilde{\chi}_1^0) < 200$ GeV, $m(\tilde{\chi}^\pm) = 0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	1208.4688
	$\tilde{g}\tilde{g}\to qqqqll(ll)\tilde{\chi}_1^0\tilde{\chi}_1^0$	2 e, μ (SS)	3 jets	Yes	20.7	$\tilde{g}$ 1.1 TeV	$m(\tilde{\chi}_1^0) < 650$ GeV	ATLAS-CONF-2013-007
	GMSB ($\tilde{l}$ NLSP)	2 e, μ	2-4 jets	Yes	4.7	$\tilde{g}$ 1.24 TeV	tan$\beta < 15$	1208.4688
	GMSB (l NLSP)	1-2 τ	0-2 jets	Yes	20.7	$\tilde{g}$ 1.4 TeV	tan$\beta > 18$	ATLAS-CONF-2013-026
	GGM (bino NLSP)	2 γ	0	Yes	4.8	$\tilde{g}$ 1.07 TeV	$m(\tilde{\chi}_1^0) > 50$ GeV	1209.0753
	GGM (wino NLSP)	1 e, μ + γ	0	Yes	4.8	$\tilde{g}$ 619 GeV	$m(\tilde{\chi}_1^0) > 50$ GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$ 900 GeV	$m(\tilde{\chi}_1^0) > 220$ GeV	1211.1167
	GGM (higgsino NLSP)	2 e, μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$ 690 GeV	$m(\tilde{H}) > 200$ GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale 645 GeV	$m(\tilde{G}) > 10^{-4}$ eV	ATLAS-CONF-2012-147
3rd gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	12.8	$\tilde{g}$ 1.24 TeV	$m(\tilde{\chi}_1^0) < 200$ GeV	ATLAS-CONF-2012-145
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	2 e, μ (SS)	0-3 b	No	20.7	$\tilde{g}$ 900 GeV	$m(\tilde{\chi}_1^0) < 500$ GeV	ATLAS-CONF-2013-007
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.14 TeV	$m(\tilde{\chi}_1^0) <200$ GeV	ATLAS-CONF-2013-054
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	3 b	Yes	12.8	$\tilde{g}$ 1.15 TeV	$m(\tilde{\chi}_1^0) < 200$ GeV	ATLAS-CONF-2012-145
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$ 100-630 GeV	$m(\tilde{\chi}_1^0) < 100$ GeV	ATLAS-CONF-2013-053
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}_1^\pm$	2 e, μ (SS)	0-3 b	Yes	20.7	$\tilde{b}_1$ 430 GeV	$m(\tilde{\chi}_1^\pm) = 2\, m(\tilde{\chi}_1^0)$	ATLAS-CONF-2013-007
	$\tilde{t}_1\tilde{t}_1$ (light), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	1-2 e, μ	1-2 b	Yes	4.7	$\tilde{t}_1$ 167 GeV	$m(\tilde{\chi}_1^0) = 55$ GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$ (light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	2 e, μ	0-2 jets	Yes	20.3	$\tilde{t}_1$ 220 GeV	$m(\tilde{\chi}_1^0) = m(\tilde{t}_1) - m(W) - 50$ GeV, $m(\tilde{t}_1) << m(\tilde{\chi}_1^\pm)$	ATLAS-CONF-2013-048
	$\tilde{t}_1\tilde{t}_1$ (medium), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	2 e, μ	0-2 jets	Yes	20.3	$\tilde{t}_1$ 150-440 GeV	$m(\tilde{\chi}_1^0) = 0$ GeV, $m(\tilde{t}_1)-m(\tilde{\chi}_1^\pm) = 10$ GeV	ATLAS-CONF-2013-048
	$\tilde{t}_1\tilde{t}_1$ (medium), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	0	2 b	Yes	20.1	$\tilde{t}_1$ 150-580 GeV	$m(\tilde{\chi}_1^0) < 200$ GeV, $m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^\pm) = 5$ GeV	ATLAS-CONF-2013-053
	$\tilde{t}_1\tilde{t}_1$ (heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	1 e, μ	1 b	Yes	20.7	$\tilde{t}_1$ 200-610 GeV	$m(\tilde{\chi}_1^0) = 0$ GeV	ATLAS-CONF-2013-037
	$\tilde{t}_1\tilde{t}_1$ (heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	0	2 b	Yes	20.5	$\tilde{t}_1$ 320-660 GeV	$m(\tilde{\chi}_1^0) = 0$ GeV	ATLAS-CONF-2013-024
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 e, μ (Z)	1 b	Yes	20.7	$\tilde{t}_1$ 500 GeV	$m(\tilde{\chi}_1^0) > 150$ GeV	ATLAS-CONF-2013-025
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e, μ (Z)	1 b	Yes	20.7	$\tilde{t}_2$ 520 GeV	$m(\tilde{t}_1) = m(\tilde{\chi}_1^0) + 180$ GeV	ATLAS-CONF-2013-025
EW direct	$\tilde{l}_{L,R}\tilde{l}_{L,R}$, $\tilde{l}\to l\tilde{\chi}_1^0$	2 e, μ	0	Yes	20.3	$\tilde{l}$ 85-315 GeV	$m(\tilde{\chi}_1^0) = 0$ GeV	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{l}\nu(l\tilde{\nu})$	2 e, μ	0	Yes	20.3	$\tilde{\chi}_1^\pm$ 125-450 GeV	$m(\tilde{\chi}_1^0) = 0$ GeV, $m(\tilde{l},\tilde{\nu}) = 0.5(m(\tilde{\chi}_1^\pm) + m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	0	Yes	20.7	$\tilde{\chi}_1^\pm$ 180-330 GeV	$m(\tilde{\chi}_1^0) = 0$ GeV, $m(\tilde{\tau},\tilde{\nu}) = 0.5(m(\tilde{\chi}_1^\pm) + m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-028
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \to \tilde{l}_L\nu\tilde{l}_L l(\tilde{\nu}\nu), l\tilde{\nu}\tilde{l}_L l(\tilde{\nu}\nu)$	3 e, μ	0	Yes	20.7	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 600 GeV	$m(\tilde{\chi}_1^\pm) = m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0) = 0$, $m(\tilde{l},\tilde{\nu}) = 0.5(m(\tilde{\chi}_1^\pm) + m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-035
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \to W^{(*)}\tilde{\chi}_1^0 Z^{(*)}\tilde{\chi}_1^0$	3 e, μ	0	Yes	20.7	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 315 GeV	$m(\tilde{\chi}_1^\pm) = m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0) = 0$, sleptons decoupled	ATLAS-CONF-2013-035
Long-lived particles	Direct $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ prod., long-lived $\tilde{\chi}_1^\pm$	0	1 jet	Yes	4.7	$\tilde{\chi}_1^\pm$ 220 GeV	$1 < \tau(\tilde{\chi}_1^\pm) < 10$ ns	1210.2852
	Stable $\tilde{g}$, R-hadrons	0-2 e, μ	0	Yes	4.7	$\tilde{g}$ 985 GeV		1211.1597
	GMSB, stable $\tilde{\tau}$, low β	2 e, μ	0	Yes	4.7	$\tilde{\tau}$ 300 GeV	$5 < \tan\beta < 20$	1211.1597
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	0	Yes	4.7	$\tilde{\chi}_1^0$ 230 GeV	$0.4 < \tau(\tilde{\chi}_1^0) < 2$ ns	1304.6310
	$\tilde{\chi}_1^0 \to qq\mu$ (RPV)	1 e, μ	0	Yes	4.4	$\tilde{q}$ 700 GeV	1 mm < $c\tau$ < 1 m, $\tilde{g}$ decoupled	1210.7451
RPV	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e+\mu$	2 e, μ	0	-	4.6	$\tilde{\nu}_\tau$ 1.61 TeV	$\lambda'_{311}=0.10$, $\lambda_{132}=0.05$	1212.1272
	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e(\mu)+\tau$	1 e,μ + τ	0	-	4.6	$\tilde{\nu}_\tau$ 1.1 TeV	$\lambda'_{311}=0.10$, $\lambda_{1(2)33}=0.05$	1212.1272
	Bilinear RPV CMSSM	1 e, μ	7 jets	Yes	4.7	$\tilde{q}, \tilde{g}$ 1.2 TeV	$m(\tilde{q}) = m(\tilde{g})$, $c\tau_{LSP} < 1$ mm	ATLAS-CONF-2012-140
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to ee\nu_\mu, e\mu\nu_e$	4 e, μ	0	Yes	20.7	$\tilde{\chi}_1^\pm$ 760 GeV	$m(\tilde{\chi}_1^0) > 300$ GeV, $\lambda_{121} > 0$	ATLAS-CONF-2013-036
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to\tau\tau\nu_e, e\tau\nu_\tau$	3 e, μ + τ	0	Yes	20.7	$\tilde{\chi}_1^\pm$ 350 GeV	$m(\tilde{\chi}_1^0) > 80$ GeV, $\lambda_{133} > 0$	ATLAS-CONF-2013-036
	$\tilde{g} \to qqq$	0	6 jets	-	4.6	$\tilde{g}$ 666 GeV		1210.4813
	$\tilde{g}\to\tilde{t}_1 t$, $\tilde{t}_1\to bs$	2 e, μ (SS)	0-3 b	Yes	20.7	$\tilde{g}$ 880 GeV		ATLAS-CONF-2013-007
Other	Scalar gluon	0	4 jets	-	4.6	sgluon 100-287 GeV	incl. limit from 1110.2693	1210.4826
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale 704 GeV	$m(\chi) < 80$ GeV, limit of < 687 GeV for D8	ATLAS-CONF-2012-147

$\sqrt{s}$ = 7 TeV full data

$\sqrt{s}$ = 8 TeV partial data

$\sqrt{s}$ = 8 TeV full data

**Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.*

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

  Is Kaluza-Klein the answer?

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

  A space defined by an algebra of matrix-valued functions

Conclusions

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