After the Higgs Discovery

A Colloquium at Ben Gurion University

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NOBEL

THE TIMES OF ISRAEL

Tel Aviv University professor shares Nobel Prize in physics

...rvivor, wins prestigious prize with Peter Higgs

BY AP AND TIMES OF ISRAEL STAFF | October 8, 2013, 2:01 pm |

Physicists François Englert of Belgium and Peter Higgs of Britain won the 2013 Nobel Prize in physics for their discovery of the Higgs particle, it was announced on Tuesday.

Englert, 80, is a Sackler Professor by Special Appointment in the School of Physics and Astronomy at Tel Aviv University, among other appointments, and is a Holocaust survivor.

The university has had “a deep connection” with Englert for many years, the TAU spokesman’s office told the Times of Israel on Tuesday.

“Professor Englert is a Belgian Jew, a professor emeritus at the University of Brussels and has had close research ties with the Tel Aviv University for the past thirty years,” the TAU said in a statement, adding that Englert is a senior professor of special status at the TAU School of Physics who regularly visits, teaches and consults on research.

During a special lecture in Tel Aviv in April, the university said, Engler delivered a lecture explaining the work for which he has just received the Nobel Prize.

In awarding the Nobel Prize, the Royal Swedish Academy of Sciences cited the two scientists for the “theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles.”

In 2004, Englert, Higgs and Robert Brout won the Wolf prize, an Israeli award handed out by the Wolf Foundation and seen as a precursor to the Nobel.

Englert’s main appointment is at the Université Libre de Bruxelles, where he has held positions


Argentina
Armenia
Australia
Austria
Azerbaijan
Belarus
Brazil
Canada
China
Czech Republic
Denmark
France
Georgia
Germany
Greece
Israel
Italy
Japan
Morocco
Netherlands
Norway
Poland
Portugal
Romania
Russia
Serbia
Slovakia
Slovenia
Spain
Sweden
Switzerland
Taiwan
Turkey
UK
USA
CERN
JINR
ATLAS
Collaboration

2012: A Watershed Year in Particle Physics

Discovery of the Higgs particle; with it completion of the *Standard Model of Elementary Particles*

Today explore the significance of this discovery, and what it says about the future direction of elementary particle physics.

The Big Questions in Physics c. 1974

What are the laws of nature which govern the four forces: strong, electromagnetic, weak and gravitational interactions. Electromagnetic interactions well understood: “gauge interaction" (electromagnetism) mediated by vector particles (photons).

By that time, inklings of a basic picture::

Strong, weak, and electromagnetic interactions: all gauge interactions, mediated by vector particles. Limited evidence for each beyond the electromagnetic.

The Gauge Principle

Familiar for electromagnetism. Scalar, vector potentials: ϕ, $\vec{A}$. $\vec{E}$ and $\vec{B}$, and more generally the laws of electromagnetism are invariant under the replacements:

$$\phi \to \phi + \frac{\partial \omega}{\partial t}; \quad \vec{A} \to \vec{A} - \vec{\nabla}\omega. \tag{1}$$

Here ω is an arbitrary *function* of space and time.

Including the electron (wave function or field), have also:

$$\psi \to e^{i\omega}\psi \tag{2}$$

This invariance under multiplication by a phase is called a "$U(1)$ symmetry".

Generalization: Yang and Mills

1954: Yang and Mills propose a generalization, to symmetries which are more intricate. Simplest would be a generalization to transformations (groups) more complicated – and interesting – than the U(1) of electromagnetism.

In general, a group has a number of generators. In the case of the group of rotations ($SU(2)$), there are three, corresponding to rotations about the x, y, and z axes, $\vec{J}$.

In the theory of Yang and Mills, there is one *massless* vector field, like the photon, for each generator. So for a version with the gauge group $SU(2)$, there area three massless gauge fields.

PHYSICAL REVIEW VOLUME 96, NUMBER 1 OCTOBER 1, 1954

Conservation of Isotopic Spin and Isotopic Gauge Invariance*

C. N. YANG † AND R. L. MILLS
Brookhaven National Laboratory, Upton, New York
(Received June 28, 1954)

It is pointed out that the usual principle of invariance under isotopic spin rotation is not consistant with the concept of localized fields. The possibility is explored of having invariance under local isotopic spin rotations. This leads to formulating a principle of isotopic gauge invariance and the existence of a **b** field which has the same relation to the isotopic spin that the electromagnetic field has to the electric charge. The **b** field satisfies nonlinear differential equations. The quanta of the **b** field are particles with spin unity, isotopic spin unity, and electric charge $\pm e$ or zero.

INTRODUCTION

THE conservation of isotopic spin is a much discussed concept in recent years. Historically an isotopic spin parameter was first introduced by Heisenberg[1] in 1932 to describe the two charge states (namely neutron and proton) of a nucleon. The idea that the neutron and proton correspond to two states of the same particle was suggested at that time by the fact that their masses are nearly equal, and that the light stable even nuclei contain equal numbers of them. Then in 1937 Breit, Condon, and Present pointed out the approximate equality of $p-p$ and $n-p$ interactions in the ^1S state.[2] It seemed natural to assume that this equality holds also in the other states available to both the $n-p$ and $p-p$ systems. Under such an assumption one arrives at the concept of a total isotopic spin[3] which is conserved in nucleon-nucleon interactions. Experi-

* Work performed under the auspices of the U. S. Atomic Energy Commission.
† On leave of absence from the Institute for Advanced Study, Princeton, New Jersey.
[1] W. Heisenberg, Z. Physik **77**, 1 (1932).
[2] Breit, Condon, and Present, Phys. Rev. **50**, 825 (1936). J. Schwinger pointed out that the small difference may be attributed to magnetic interactions [Phys. Rev. **78**, 135 (1950)].
[3] The total isotopic spin **T** was first introduced by E. Wigner, Phys. Rev. **51**, 106 (1937); B. Cassen and E. U. Condon, Phys. Rev. **50**, 846 (1936).

vanishes. Corresponding arguments in the **b** field case do not exist[13] even though the conservation of isotopic spin still holds. We have therefore not been able to conclude anything about the mass of the **b** quantum.

A conclusion about the mass of the **b** quantum is of course very important in deciding whether the proposal of the existence of the **b** field is consistent with experimental information. For example, it is inconsistent with present experiments to have their mass less than that of the pions, because among other reasons they would then be created abundantly at high energies and the charged ones should live long enough to be seen. If they have a mass greater than that of the pions, on the other hand, they would have a short lifetime (say, less than 10^{-20} sec) for decay into pions and photons and would so far have escaped detection.

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12 J. Schwinger, Phys. Rev. **76**, 790 (1949).

13 In electrodynamics one can formally prove that $G_{\mu\nu}k_\nu=0$, where $G_{\mu\nu}$ is defined by Schwinger's Eq. (A12). ($G_{\mu\nu}A_\nu$ is the current generated through virtual processes by the arbitrary external field A_ν.) No corresponding proof has been found for the present case. This is due to the fact that in electrodynamics the conservation of charge is a consequence of the equation of motion of the electron field alone, quite independently of the electromagnetic field itself. In the present case the **b** field carries an isotopic spin and destroys such general conservation laws.

Are the Yang Mills Quanta Massless?

Apart from the photon, we don't know of any other massless vector particles in nature. So while interesting, the relevance of the Yang-Mills idea to nature was not clear. Perhaps, somehow, the vector fields ("gauge bosons") could be a little bit massive.

Schwinger: argued that perhaps they might be, and gave an example in an unrealistic number of dimensions, $2 = 1 + 1$.

More compelling realization: Phil Anderson, 1962. Motivated, in part, by an idea of Sakurai's that the ρ mesons (which form a triplet of isospin) might be the gauge bosons of an underlying $SU(2)$ of isospin.

These ideas fleshed out by Higgs, Brout and Englert, Hagel Guranlnik, and Kibble.

PHYSICAL REVIEW VOLUME 130, NUMBER 1 1 APRIL 1963

Plasmons, Gauge Invariance, and Mass

P. W. Anderson
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received 8 November 1962)

Schwinger has pointed out that the Yang-Mills vector boson implied by associating a generalized gauge transformation with a conservation law (of baryonic charge, for instance) does not necessarily have zero mass, if a certain criterion on the vacuum fluctuations of the generalized current is satisfied. We show that the theory of plasma oscillations is a simple nonrelativistic example exhibiting all of the features of Schwinger's idea. It is also shown that Schwinger's criterion that the vector field $m \neq 0$ implies that the matter spectrum before including the Yang-Mills interaction contains $m=0$, but that the example of superconductivity illustrates that the physical spectrum need not. Some comments on the relationship between these ideas and the zero-mass difficulty in theories with broken symmetries are given.

RECENTLY, Schwinger[1] has given an argument strongly suggesting that associating a gauge transformation with a local conservation law does not necessarily require the existence of a zero-mass vector boson. For instance, it had previously seemed impossible to describe the conservation of baryons in such a manner because of the absence of a zero-mass boson and of the accompanying long-range forces.[2] The problem of the mass of the bosons represents the major stumbling block in Sakurai's attempt to treat the dynamics of strongly interacting particles in terms of the Yang-Mills gauge fields which seem to be required to accompany the known conserved currents of baryon number and hypercharge.[3] (We use the term "Yang-Mills" in Sakurai's sense, to denote any generalized gauge field accompanying a local conservation law.)

The purpose of this article is to point out that the familiar plasmon theory of the free-electron gas exemplifies Schwinger's theory in a very straightforward manner. In the plasma, transverse electromagnetic waves do not propagate below the "plasma frequency," which is usually thought of as the frequency of long-wavelength longitudinal oscillation of the electron gas. At and above this frequency, three modes exist, in close analogy (except for problems of Galilean invariance implied by the inequivalent dispersion of longitudinal and transverse modes) with the massive vector boson mentioned by Schwinger. The plasma frequency is equivalent to the mass, while the finite density of electrons leading to divergent "vacuum" current fluctuations resembles the strong renormalized coupling of Schwinger's theory. In spite of the absence of low-frequency photons, gauge invariance and particle conservation are clearly satisfied in the plasma.

In fact, one can draw a direct parallel between the dielectric constant treatment of plasmon theory[4] and Schwinger's argument. Schwinger comments that the commutation relations for the gauge field A give us one sum rule for the vacuum fluctuations of A, while those for the matter field give a completely independent value for the fluctuations of matter current j. Since j is the source for A and the two are connected by field equations, the two sum rules are normally incompatible unless there is a contribution to the A rule from a free, homogeneous, weakly interacting, massless solution of the field equations. If, however, the source term is large enough, there can be no such contribution and the massless solutions cannot exist.

The usual theory of the plasmon does not treat the electromagnetic field quantum-mechanically or discuss vacuum fluctuations; yet there is a close relationship between the two arguments, and we, therefore, show that the quantum nature of the gauge field is irrelevant. Our argument is as follows:

The equation for the electromagnetic field is

$$p^2 A_\mu = (k^2 - \omega^2) A_\mu(\mathbf{k},\omega) = 4\pi j_\mu(\mathbf{k},\omega).$$

[1] J. Schwinger, Phys. Rev. **125**, 397 (1962).
[2] T. D. Lee and C. N. Yang, Phys. Rev. **98**, 1501 (1955).
[3] J. J. Sakurai, Ann. Phys. (N. Y.) **11**, 1 (1961).
[4] P. Nozières and D. Pines, Phys. Rev. **109**, 741 (1958).

Understanding the Higgs mechanism

(Name is probably a historical accident due to Weinberg.)

Came from consideration of a related phenomenon: spontaneous symmetry breaking.

Common in condensed matter systems. E.g. laws of nature are invariant under rotations, but physical systems (and the world immediately around us) are not. The alignment of the spins in a magnet, for example, breaks the symmetry. Can occur because energy of the system is lowered if the spins are aligned in *some* direction.

Physical consequence: low energy excitations (it doesn't take much energy to point all of the spins in some other direction.

In a relativistic system: a massless particle.

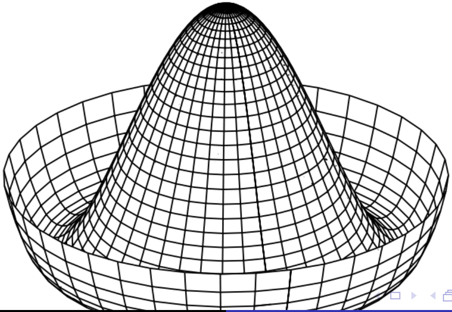
The Goldstone Phenomenon

In a relativistic system, one can imagine a scalar field, which transform under a symmetry. This might be rotation by a phase,

$$\phi \to e^{i\alpha}\phi \tag{3}$$

or more intricate; $\vec{\phi}$ might be a vector under an isospin-like symmetry.

The question is the potential energy for ϕ. Symmetry breaking occurs if it looks like:



The massless particle (Goldstone boson) is the excitation corresponding to motion around the bottom of the well.

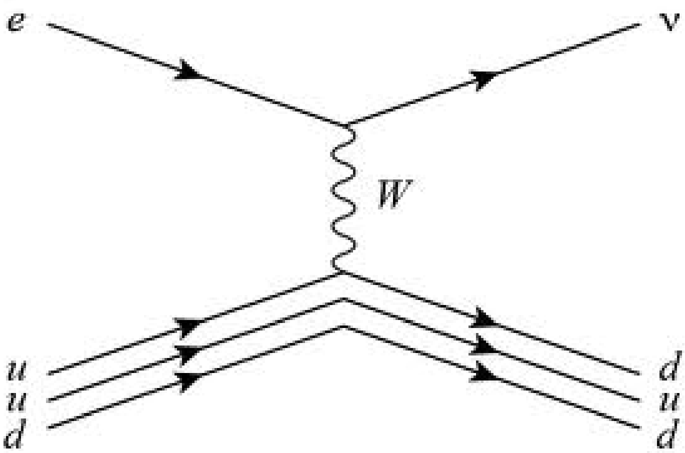
The Higgs phenomenon occurs if the symmetry (motion around the bottom of the potential well) is a gauge symmetry; each point along the bottom is equivalent to every other point. *There is no massless Goldstone boson.*

When this happens, the gauge bosons, as first noted by Anderson, are massive.

In the simple model proposed by Higgs, can think of the universe as pervaded by the scalar field. It is constant most everywhere. The lowest excitations, ripples in this Higgs field, are massive particles (corresponding to climbing out of the well); it is these excitations which are called the “Higgs particle". The mass of the Higgs particle is independent of the mass of the gauge boson; it is another parameter in the theory.

Setting for the Higgs Particle

Returning to the big questions in particle physics, by the 1960's, the weak interactions were well understood. Fermi had long ago proposed that they arose from the exchange of a massive particle, and it appeared that they were best accounted for by the exchange of a vector particle; actually two charged vector particles, $W^{\pm}$. It was natural to speculate that these particles were the vector mesons of the Yang-Mills theory, but until the work of Higgs et al, it was not understood how this might be. In 1967, Weinberg and Salam, independently, proposed that the weak interactions are described by a Yang-Mills theory, with gauge group $SU(2)$.



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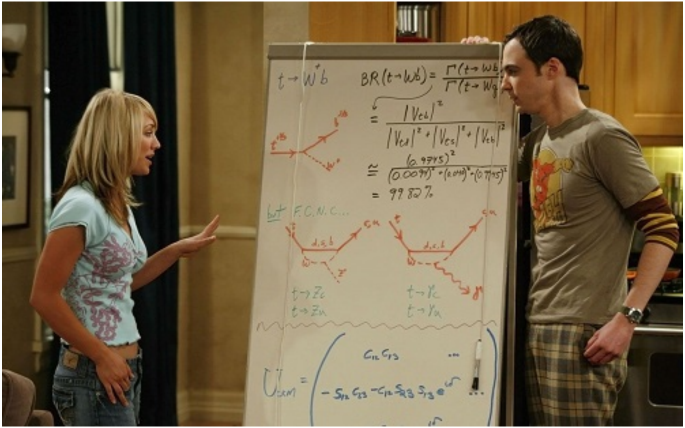
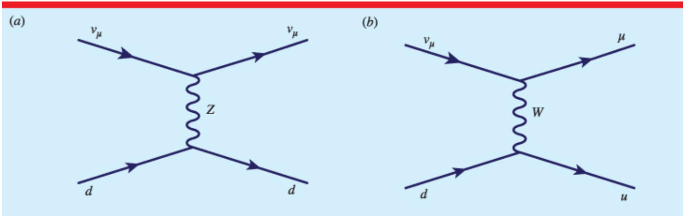

t → W+ b
BR(t→Wb) =
but F.C.N.C...

The Weinberg-Salam theory predicted the existence of a third massive gauge boson, which was electrically neutral. Corresponding processes ("weak neutral currents") were soon discovered). In subsequent years, the detailed predictions were verified. Accelerators with sufficient energy to produce the W and Z particles were built, and the predictions of the theory for these particles and there couplings were verified.


(a)
ν_μ
ν_μ
Z
d
d
(b)
ν_μ
μ
W
d
u

The Strong Interactions

Within a few years, a theory of strong interactions, also based on Yang-Mills theory, was proposed. This theory does not have massless spin one vector bosons, nor does it have a Higgs effect. It exhibits, instead, what is called confinement. Firmly establishing this theory took some time, but it is now rigorously tested. So by the late 1990's, we could claim to understand completely the questions which we listed earlier, with the Higgs boson being the one missing piece.

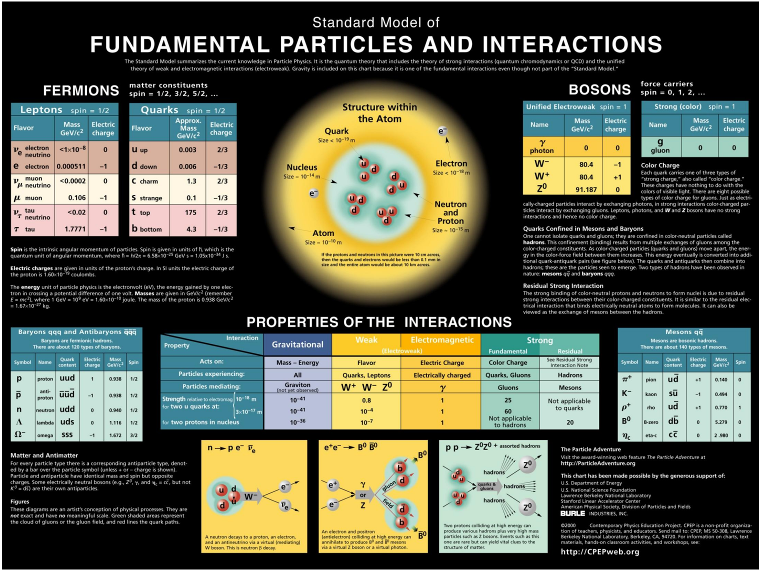
QCD (the theory of the strong interactions) has been tested to a high degree of accuracy as well, both at very high energies and at low energies (using the method of lattice gauge theories.

Still, much is not understood. Providing a rigorous mathematical proof of confinement (as opposed to numerical evidence) is one of the Clay prizes; solve it and you win 1 M$.

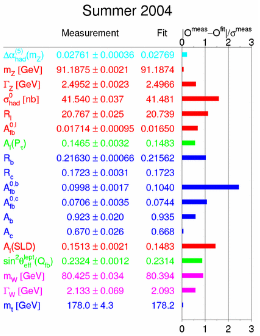
Clay Prize Problem: Yang-Mills and Mass Gap

The laws of quantum physics stand to the world of elementary particles in the way that Newton's laws of classical mechanics stand to the macroscopic world. Almost half a century ago, Yang and Mills introduced a remarkable new framework to describe elementary particles using structures that also occur in geometry. Quantum Yang-Mills theory is now the foundation of most of elementary particle theory, and its predictions have been tested at many experimental laboratories, but its mathematical foundation is still unclear. The successful use of Yang-Mills theory to describe the strong interactions of elementary particles depends on a subtle quantum mechanical property called the "mass gap:" the quantum particles have positive masses, even though the classical waves travel at the speed of light. This property has been discovered by physicists from experiment and confirmed by computer simulations, but it still has not been understood from a theoretical point of view. Progress in establishing the existence of the Yang-Mills theory and a mass gap and will require the introduction of fundamental new ideas both in physics and in mathematics.

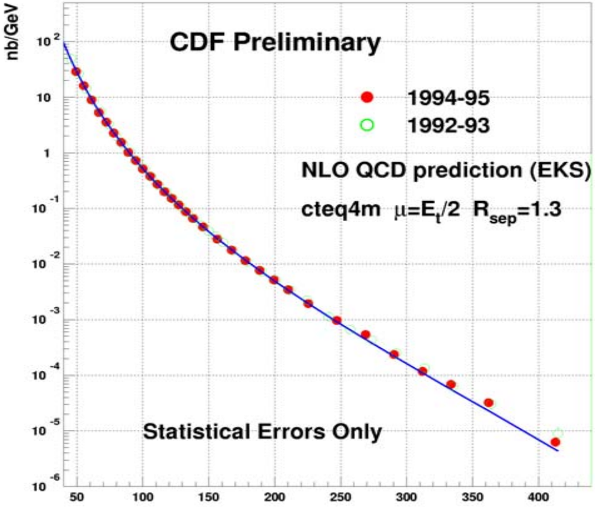
The Standard Model is Well Established



Precision Tests of the Electroweak Theory



QCD Tests



nb/GeV
CDF Preliminary
1994-95
1992-93
NLO QCD prediction (EKS)
cteq4m μ=E_t/2 R_sep=1.3
Statistical Errors Only
10^2
10
1
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
50
100
150
200
250
300
350
400

Discovery of the Higgs: July 4, 2012

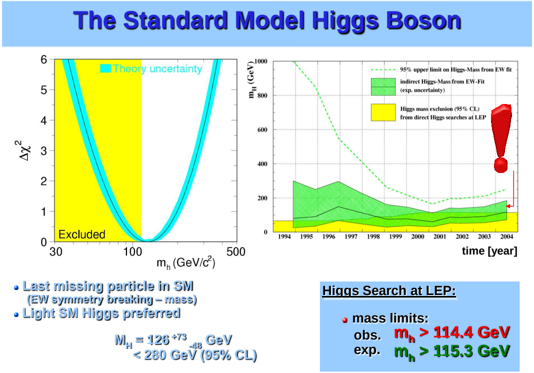
The challenge: Higgs couplings to a particle are proportional to its mass. So coupling to electron is of order 10^{-5}, to muon 10^{-3}, etc. Rates go as square.

Worse, most processes involving Higgs resemble other processes in the Standard Model, so Huge Backgrounds!

E.g. Higgs decays mainly to b quarks since heaviest. But lots of processes in QCD produce B quarks. Extremely hard to find the Higgs signal.

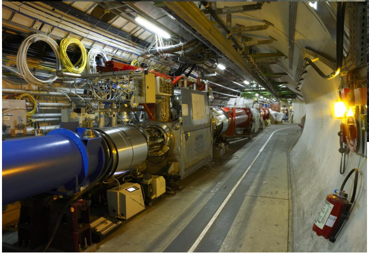
Also, many alternatives to Weinberg and Salam's proposal. Their's, in a precise sense, the simplest, but many physicists believed too simple (more later).

Prior to 2012, if simplest Higgs, much known about it.

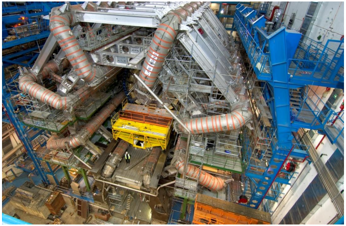


How to Look: Big accelerator, big detectors – The LHC at CERN

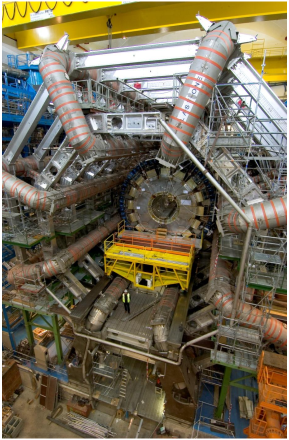
2 in 1 superconducting dipole magnet being installed in the CERN tunnel

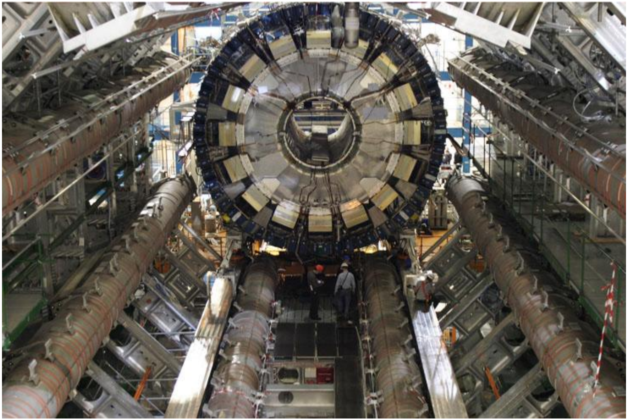


ATLAS, one of the two large detectors at the LHC (Other: CMS; ALICE will study heavy ion collisions)

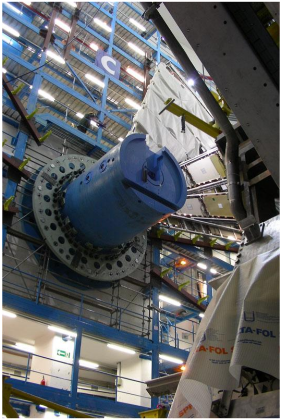


Muon superconducting Toroids in the ATLAS Detector at the LHC





Endcap Muon Sectors



SCALE OF THE PROJECT

- The stored energy in the beams is equivalent roughly to the kinetic energy of an aircraft carrier at 10 knots (stored in magnets about 16 times larger)
- There will be about a billion collisions per second in each detector.
- The detectors will record and stores “only” around 100 collisions per second.
- The total amount of data to be stored will be 15 petabytes (15 million gigabytes) a year.

  It would take a stack of CDs 20Km tall per year to store this much data.

Collide two protons each with energy 7TeV.

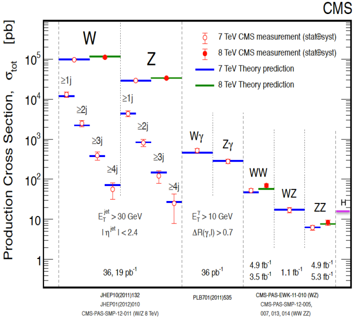
(1TeV is roughly the kinetic energy of a flying mosquito. This energy is squeezed into a region 10^{-12} of a mosquito.)

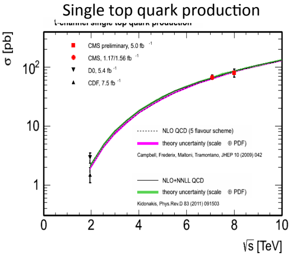
The total energy in the beam is comparable to an aircraft carrier moving at about 10 knots.

1

LHC Now running very well: precise measurements of Standard Model processes

Precise SM measurements





Good understanding of the detector + accurate theory predictions

→ Precise measurements of the SM processes over many orders of magnitude

→ Good knowledge of the background to Higgs analyses

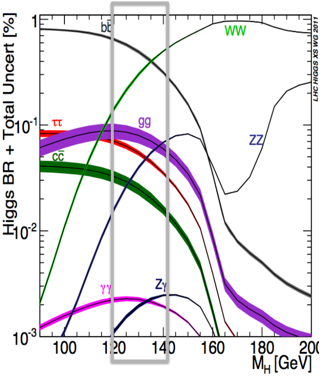
LHC: expectations for Higgs production × branching ratio for different channels:

The channels at LHC

5 decay modes exploited

	Exp Sig @125.7	σ_M/M
• bb	2.2σ	10%
• ττ	2.7σ	10%
• WW	5.1σ	20%
• ZZ	7.1σ	1-2%
• γγ	4.2σ	1-2%

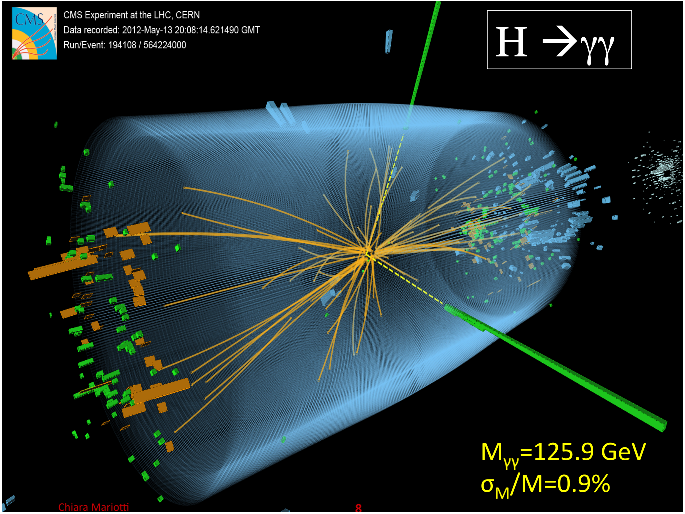
- and searches in Zγ, μμ



Chiara Mariotti 7

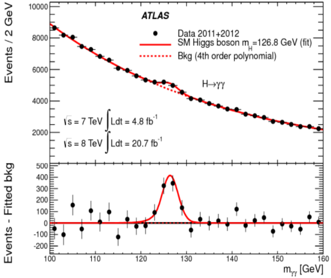
Discovery channel: $p + p \to H + X; \quad H \to \gamma\gamma$

Relatively clean, channel: $H \to \gamma\gamma$. Rare, but backgrounds lowest.

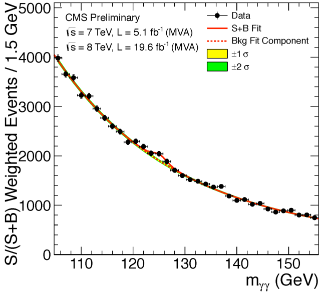

CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000
H → γγ
M_γγ=125.9 GeV
σ_M/M=0.9%
Chiara Mariotti
8

The mass distribution

ATLAS



CMS

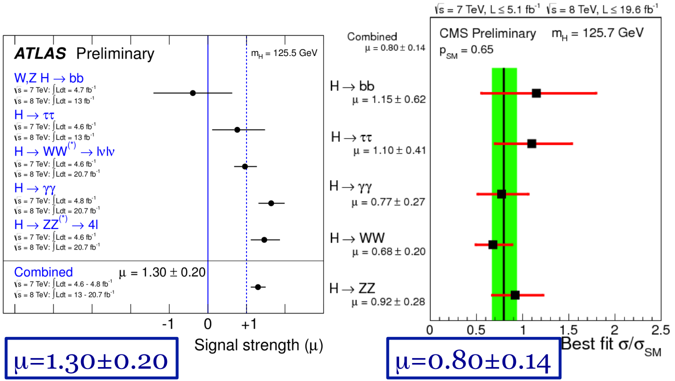


High level analysis very, very similar between Atlas and CMS:
– Categorization by S/B, resolution and p_T (ATLAS using cuts, CMS using a BDT)
– Similar di-jet categories with O(70%) purity
– Mass fit with polynomial background chosen to minimize the bias on the signal

Measurements now in several channels; good agreement with simplest Standard Model with fair statistics:

Consistency with SM hypothesis

$$\mu = \frac{\sigma \cdot \mathrm{BR}}{(\sigma \cdot \mathrm{BR})_{\mathrm{SM}}}$$



A Watershed Moment: The Standard Model Appears Complete

What comes next? Question vigorously considered worldwide. By no means are all of our questions answered.

Europe: European Strategy for Particle Physics

U.S.: Snowmass Process followed by “P5": setting priorities for the field for the next decade and more.

Japan: considering hosting the ILC, a large electron-positron collider.

Planning the Future of U.S. Particle Physics

Report of the 2013 Community Summer Study

Conveners: M. Bardeen, W. Barletta, L. Bauerdick, R. Brock, D. Cronin-Hennessy, M. Demarteau, M. Dine, J. L. Feng, M. Gilchriese, S. Gottlieb, J. L. Hewett, R. Lipton, H. Nicholson, M. E. Peskin, S. Ritz, H. Weerts

Division of Particles and Fields Officers in 2013: J. L. Rosner (chair and corresponding author), I. Shipsey (chair-elect), N. Hadley (vice-chair), P. Ramond (past chair)

Editorial Committee: R. H. Bernstein, N. Graf, P. McBride, M. E. Peskin, J. L. Rosner, N. Varelas, K. Yurkewicz

Big questions (Snowmass theory study)

- What is the origin of the great disparity in the energy scales associated with the weak and gravitational forces? This is the hierarchy problem. It has two pieces: 1) why is there such a large disparity 2) the problem of fine tuning: any new energy threshold much above the masses of the W and Z bosons, such as the Planck scale or unification scale, tends to destabilize the Higgs boson mass through quantum corrections.
- Where do the parameters of the SM originate?
- Do the strong and electroweak forces unify at some energy scale?
- Why is the strong interaction CP conserving? Is this accounted for by an axion field, and does this axion constitute some or all of the dark matter?
- The quarks and leptons present many mysteries. Why are there repetitive generations? What accounts for the hierarchical structure of the masses and mixings of the quarks and charged leptons?

- The discovery of neutrino mass has raised new questions. What is the energy scale associated with the generation of neutrino mass? Are neutrinos their own anti-particles?
- The observed CP violation in the SM is insufficient to account for the baryon asymmetry of the Universe. What phenomena might account for this? Might they be accessible to experiments at the Energy or Intensity Frontiers?
- What is the identity of the dark matter which makes up 25% of the energy density of the Universe?
- What is the origin of the dark energy which makes up 70% of the energy density? Why is it just becoming important at the present epoch of the Universe?
- What caused the inflationary epoch, and how did the Universe end up in its current state?
- What is the nature of the quantum theory of gravitation?
- From what set of principles or structures do the laws of nature originate?

Speculations as to Answers

- Supersymmetry, a possible new symmetry of nature relating fermions and bosons, to understand the hierarchy between the Planck scale and the weak scale. In many realizations that theorists have considered, one might have expected its discovery in the first run at the LHC. Still, it remains one of the more plausible explanations, and is the subject of continued experimental and theoretical study.
- Composite Higgs models, technicolor, and Randall-Sundrum models. These provide alternative possible explanations of the hierarchy problem, and are the subject of ongoing experimental searches.
- Dark matter candidates. Weakly interacting massive particles (WIMPs) are natural in supersymmetry and several other theoretical structures; axions were invented to understand the strong CP problem. These are both topics of ongoing theoretical work and extensive experimental searches.

- String theory and other ideas for a quantum theory of gravity. String theory in particular provides a promising model for the unification of gravity and the other forces in a consistent quantum mechanical framework. It has also provided new tools for addressing problems in quantum field theory and in disparate areas of physics including heavy ion physics and condensed matter physics. It has suggested new principles (holography) and inspired ideas for particle phenomenology and physics beyond the SM. It has also inspired the invention of powerful techniques for computing scattering amplitudes.
- Leptogenesis: This is an attractive paradigm for explaining the baryon asymmetry of the Universe, which has an intimate connection with the origin of neutrino masses. Plausible indirect evidence for this mechanism would be the discovery of CP violation in the neutrino sector, the subject of tests in forthcoming long-baseline experiments. Other ideas for baryogenesis have different potential consequences.

Possible Facilities to Address Some of These Questions

- Large Hadron Collider will resume operations (approx 2015) with higher energy, luminosity. Will permit more precise measurements of Higgs properties, further exclusion (or discovery) of ideas like supersymmetry, large extra dimensions...
- Large Hadron Collider will be further upgraded for much higher luminosity. (Decisions in U.S. about level of participation).
- U.S. Improved measurement of muon $g - 2$. Will address a possible discrepancy which might point to new physics (Fermilab)
- U.S. Long Baseline Neutrino Experiment (neutrinos from Fermilab to underground detector in North Dakota): further measurements of neutrino masses and properties.

- Japan: Considering an e^+e^- linear collider. Would require U.S., European participation. Much planning already. Possible site selected. But commitment to funding is probably several years away (a major financial commitment; many competing demands on those resources).
- U.S., Japan, Europe: dark matter searches (direct, indirect)
- U.S., Japan, Europe: studies of dark energy (ground based, possibly space based).

An exciting and Remarkable Present

1. Exquisite understanding of the laws of nature. Higgs discovery and measurement of its production and decay the culmination of five decades of study of the Standard Model. Triumph for the *principle of simplicity*.
2. ILC: perhaps the tool to clinch (or not!) this story. Precision studies of the Higgs.

With our present understanding of the laws of nature, we have sharply formulated questions, and plans and facilities with which to address them.