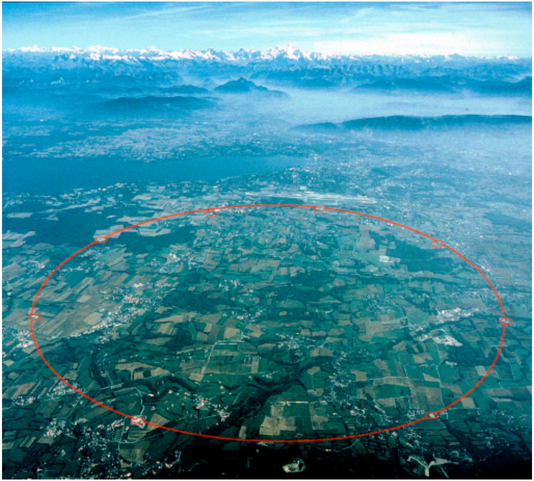
A Theorist's Take on Higgs Physics

Tilman Plehn

Universität Heidelberg

Innsbruck, 5/2013

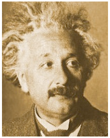
The LHC



The LHC


Neasden
Dollis Hill
Willesden Green
Kilburn
Golders Green
Hampstead
Hampstead Heath
Gospel Oak
Tufnell Park
Upper Holloway
Finsbury Park
Arsenal
Holloway Road
Finchley Road & Frognal
Belsize Park
Kentish Town West
Kentish Town
Chalk Farm
Caledonian Road
Camden Road
Highbury & Islington
Canonbury
Brondesbury Park
West Hampstead
Brondesbury
Finchley Road
Swiss Cottage
St. John's Wood
Camden Town
Mornington Crescent
Caledonian Road & Barnsbury
Kilburn High Road
South Hampstead
King's Cross St. Pancras
Paddington
Edgware Road
Baker Street
Great Portland Street
Euston
Angel
Old Street
Warren Street
Euston Square
Regent's Park
Farringdon
Liverpool Street
Marylebone
Russell Square
Barbican
Shoreditch
Bayswater
Goodge Street
Chancery Lane
Moorgate
Holland Park
Notting Hill Gate
Lancaster Gate
Bond Street
Oxford Circus
Holborn
Tottenham Court Road
St. Paul's
Bank
Aldgate East
Queensway
Marble Arch
Covent Garden
Aldgate
High Street Kensington
Hyde Park Corner
Green Park
Cannon Street
Leicester Square
Mansion House
Piccadilly Circus
Knightsbridge
Monument
Tower Hill
Tower Gateway
Charing Cross
Gloucester Road
Sloane Square
St. James's Park
Blackfriars
Temple
River Thames
Rotherhithe
Earl's Court
South Kensington
Victoria
Westminster
Embankment
London Bridge
Bermondsey
Canada Water
Fulham Broadway
Waterloo
Surrey Quays
Southwark
Borough
Pimlico
Lambeth North
East London line is closed for major line extension work to become part of the London Overground network.

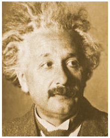
The LHC



Einstein: beam energy to particle mass $E = mc^2$

- smash 4 TeV protons onto 4 TeV protons [energy unit GeV: proton mass]
  produce anything that interacts with quarks and gluons
  search for it in decay products
  repeat every 25-50 ns
- huge detectors, actual data, commuting to CERN $\longrightarrow$ experiment
  field theory, strong opinions, working in villas $\longrightarrow$ theory

The LHC



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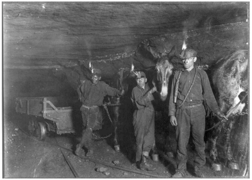
life as an experimentalist



life as a theorist

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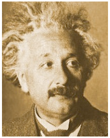

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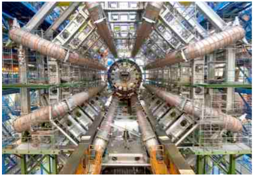
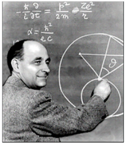


life as a theorist

Weak interaction



Massive interaction particles: bosons

– Fermi 1934: weak interactions $[n \to p e^- \bar{\nu}_e]$
  point-like $(2 \to 2)$ amplitude $\mathcal{A} \propto G_F E^2$
  probability/ unitarity violation $[E < 600\ \text{GeV}]$
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– Yukawa 1935: massive particles
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  unitary fermion amplitude $\mathcal{A} \propto g^2 E^2/(E^2 - M^2)$
  unitarity violation in $WW \to WW$ $[E < 1.2 \text{ TeV}]$
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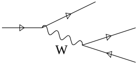

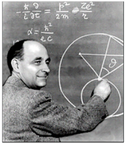

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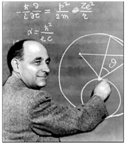

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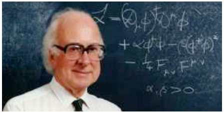

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  unitary through Higgs particle
  particle masses allowed
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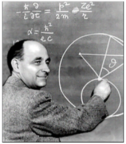

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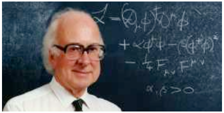

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fundamental weak-scale scalar

– 't Hooft & Veltman 1971: renormalizability
no $1/M$ couplings allowed
theory valid to high energy
Standard Model with Higgs fundamental

Higgs boson

Lagrangians with famous problems

- Lagrangian from 2nd year physics [Hamiltonian with wrong sign between potential and kinetic term]
- QED plus massive scalar field [$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$]

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2} \left(\partial_\mu \phi \right)^2 - \frac{1}{2} m_\phi^2 \phi^2$$

- symmetries of Lagrangian = symmetries of theory

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- symmetries of Lagrangian = symmetries of theory
- spontaneous symmetry breaking
  symmetric Lagrangian with non-symmetric vacuum: $\langle \phi \rangle = v = 246$ GeV
- problem 1: Goldstone's theorem
  breaking $SU(2)_L \times U(1)_Y \to U(1)_Q$ produces 3 massless scalars
- problem 2: massive gauge theories
  massless gauge bosons have 2 polarizations, massive have 3, and $3 \neq 2$

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Higgs-related papers [also Brout & Englert; Guralnik, Hagen, Kibble]

– 1964: combining two problems to one predictive solution

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

In a recent note[1] it was shown that the Goldstone theorem,[2] that Lorentz-covariant field theories in which spontaneous breakdown of symmetry under an internal Lie group occurs contain zero-mass particles, fails if and only if

about the "vacuum" solution $\varphi_1(x)=0$, $\varphi_2(x)=\varphi_0$:

$$\partial^\mu\{\partial_\mu(\Delta\varphi_1)-e\varphi_0A_\mu\}=0, \qquad (2a)$$

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A detailed discussion of these questions will be presented elsewhere.

It is worth noting that an essential feature of the type of theory which has been described in this note is the prediction of incomplete multiplets of scalar and vector bosons.[8] It is to be expected that this feature will appear also in theories in which the symmetry-breaking scalar fields are not elementary dynamic variables but bilinear combinations of Fermi fields.[9]

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[1]P. W. Higgs, to be published.
[2]J. Goldstone, Nuovo Cimento 19, 154 (1961); J. Goldstone, A. Salam, and S. Weinberg, Phys. Rev. 127, 965 (1962).

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PHYSICAL REVIEW VOLUME 145, NUMBER 4 27 MAY 1966

Spontaneous Symmetry Breakdown without Massless Bosons*

PETER W. HIGGS†
Department of Physics, University of North Carolina, Chapel Hill, North Carolina
(Received 27 December 1965)

We examine a simple relativistic theory of two scalar fields, first discussed by Goldstone, in which as a result of spontaneous breakdown of $U(1)$ symmetry one of the scalar bosons is massless, in conformity with the Goldstone theorem. When the symmetry group of the Lagrangian is extended from global to local $U(1)$ transformations by the introduction of coupling with a vector gauge field, the Goldstone boson becomes the longitudinal state of a massive vector boson whose transverse states are the quanta of the transverse gauge field. A perturbative treatment of the model is developed in which the major features of these phenomena are present in zero order. Transition amplitudes for decay and scattering processes are evaluated in lowest order, and it is shown that they may be obtained more directly from an equivalent Lagrangian in which the original symmetry is no longer manifest. When the system is coupled to other systems in a $U(1)$ invariant Lagrangian, the other systems display an induced symmetry breakdown, associated with a partially conserved current which interacts with itself via the massive vector boson.

I. INTRODUCTION

THE idea that the apparently approximate nature of the internal symmetries of elementary-particle physics is the result of asymmetries in the stable solutions of exactly symmetric dynamical equations, rather than an indication of asymmetry in the dynamical

appear have been used by Coleman and Glashow[3] to account for the observed pattern of deviations from $SU(3)$ symmetry.

The study of field theoretical models which display spontaneous breakdown of symmetry under an internal Lie group was initiated by Nambu,[4] who had noticed[5]

Higgs boson

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II. THE MODEL

The Lagrangian density from which we shall work is given by[29]

$$\mathcal{L} = -\tfrac{1}{4} g^{\kappa\mu} g^{\lambda\nu} F_{\kappa\lambda} F_{\mu\nu} - \tfrac{1}{2} g^{\mu\nu} \nabla_\mu \Phi_a \nabla_\nu \Phi_a + \tfrac{1}{4} m_0^2 \Phi_a \Phi_a - \tfrac{1}{8} f^2 (\Phi_a \Phi_a)^2. \quad (1)$$

In Eq. (1) the metric tensor $g^{\mu\nu} = -1$ $(\mu = \nu = 0)$, $+1$ $(\mu = \nu \neq 0)$ or 0 $(\mu \neq \nu)$, Greek indices run from 0 to 3 and Latin indices from 1 to 2. The $U(1)$-covariant derivatives $F_{\mu\nu}$ and $\nabla_\mu \Phi_a$ are given by

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i. Decay of a Scalar Boson into Two Vector Bosons

The process occurs in first order (four of the five cubic vertices contribute), provided that $m_0 > 2m_1$. Let p be the incoming and k_1, k_2 the outgoing momenta. Then

$$M = i\{ e[a^{*\mu}(k_1)(-ik_{2\mu})\phi^*(k_2) + a^{*\mu}(k_2)(-ik_{1\mu})\phi^*(k_1)] - e(ip_\mu)[a^{*\mu}(k_1)\phi^*(k_2) + a^{*\mu}(k_2)\phi^*(k_1)] - 2em_1 a_\mu^*(k_1) a^{*\mu}(k_2) - f m_0 \phi^*(k_1)\phi^*(k_2) \} .$$

By using Eq. (15), conservation of momentum, and the transversality ($k_\mu b^\mu(k) = 0$) of the vector wave functions we reduce this to the form

Higgs boson

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– 1966: original Higgs phenomenology

– 1976 etc: collider phenomenology

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

A discussion is given of the production, decay and observability of the scalar Higgs boson H expected in gauge theories of the weak and electromagnetic interactions such as the Weinberg-Salam model. After reviewing previous experimental limits on the mass of the Higgs boson, we give a speculative cosmological argument for a small mass. If its mass is similar to that of the pion, the Higgs boson may be visible in the reactions $\pi^- p \to Hn$ or $\gamma p \to Hp$ near threshold. If its mass is $\lesssim$300 MeV, the Higgs boson may be present in the decays of kaons with a branching ratio $O(10^{-7})$, or in the decays of one of the new particles: $3.7 \to 3.1 + H$ with a branching ratio $O(10^{-4})$. If its mass is $\lesssim$4 GeV, the Higgs

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We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

Higgs
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$\Rightarrow$ Higgs boson predicted from mathematical field theory

Higgs boson

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Higgs field vs Higgs particle

– fundamental SM gauge symmetry $SU(2)_L \times U(1)_Y$
observed unbroken: electromagnetism $U(1)_Q$

– forbidden by $SU(2)_L$ but allowed by $U(1)_Q$:
weak gauge boson masses $m_{W,Z}$
fermion masses of kind $m_f \bar{\psi}_L \psi_R$

$\Rightarrow$ masses proportional to expectation value of Higgs field $\langle \phi \rangle = v = 246$ GeV

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– complex $SU(2)$ doublet ϕ:
3 Goldstone modes eaten as longitudinal W and Z
4th physical mode $\langle \phi \rangle = \langle v + H \rangle = v$

⇒ Higgs particle H coupling proportional to masses

Higgs boson

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In terms of Higgs potential

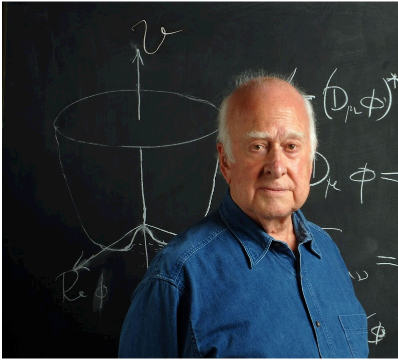
$$V = \mu^2 |\phi|^2 + \lambda |\phi|^4$$

minimum at $\phi = \frac{v}{\sqrt{2}}$

$$\frac{\partial V}{\partial |\phi|^2} = \mu^2 + 2\lambda |\phi|^2 \quad \Rightarrow \quad \frac{v^2}{2} = -\frac{\mu^2}{2\lambda}$$

excitation $\phi = \frac{v + H}{\sqrt{2}}$

$$m_H^2 = \frac{\partial^2 V}{\partial H^2}\bigg|_{\text{minimum}} = 2\lambda v^2$$



LHC

Things you never dared to ask...

- $N_{\text{events}} = \sigma \cdot \mathcal{L}$ ['cross section [fb] times luminosity [1/fb]']
- signal: everything new, exciting and rare
  background: yesterday's signal
- Standard Model w/o Higgs: background theory
  QCD: evil background theory
- jet: everything except for leptons/photons
  crucial: what makes a jet [q, g, b, τ, W, H, t]
- always statistics: $\sigma_{b\bar{b}} \sim 10^7 \sigma_H$

$\Rightarrow$ discovery $\#\sigma \sim N_S/\sqrt{N_B} > 5$ [background fake probability $p_0 < 5.8 \times 10^{-7}$]

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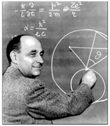
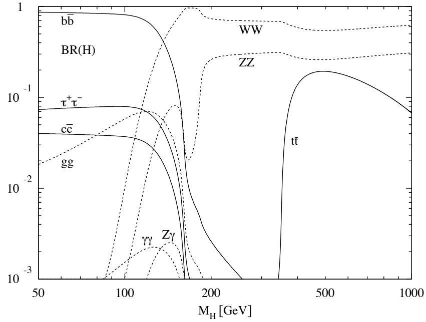
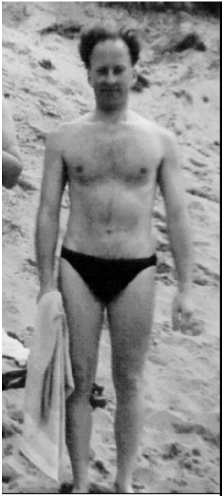


Higgs searches

Higgs decays easy

– weak-scale scalar coupling proportional to mass
– off-shell decays below threshold
– decay to $\gamma\gamma$ via W and top loop





A sure sighting of a higgs... Peter Higgs on the shores of the Firth of Fourth by Prof J D Jackson, July 1960

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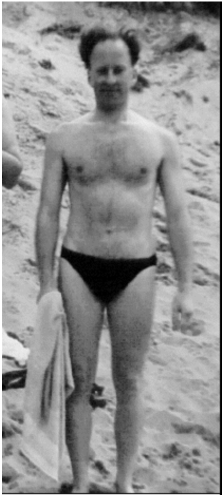

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Who built this gluon–gluon collider with experiments excellent at photon reconstruction to find a particle which couples to mass???

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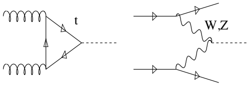
gluon fusion production loop induced [$\sigma \sim$ 15000 fb]
weak boson fusion production with jets [$\sigma \sim$ 1200 fb]



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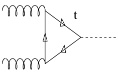

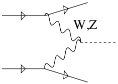

– easy channels for 2011-2012
  $pp \to H \to ZZ \to 4\ell$ fully reconstructed
  $pp \to H \to \gamma\gamma$ fully reconstructed
  $pp \to H \to WW \to (\ell^- \bar{\nu})(\ell^+ \nu)$ large BR

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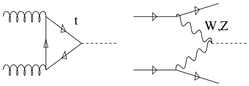

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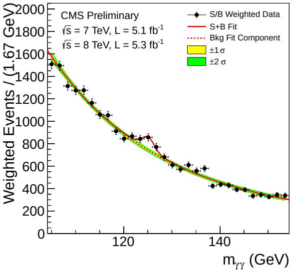
- harder channels from 2012

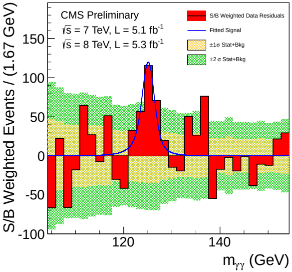
  $pp \to H \to \tau\tau$ plus jets
  $pp \to ZH \to (\ell^+\ell^-)(b\bar{b})$ boosted
  etc...

Higgs discovery

4th of July fireworks [together over 100 subchannels]

– 'silver channel' $H \to \gamma\gamma$
  local significance 4.5σ (ATLAS), 4.1σ (CMS)





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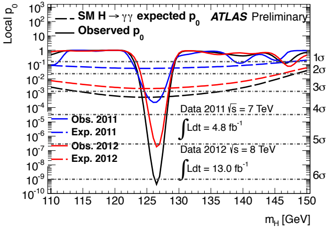

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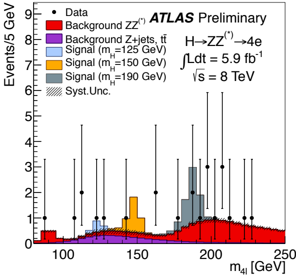
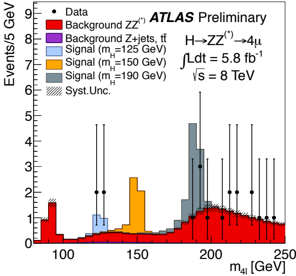
local significance 3.4σ (ATLAS), 3.2σ (CMS)





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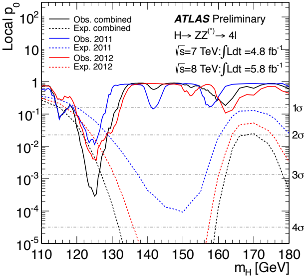

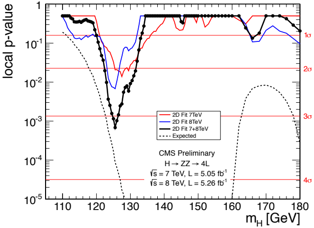

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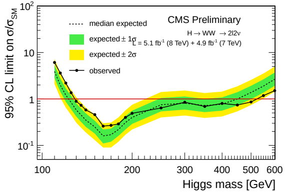

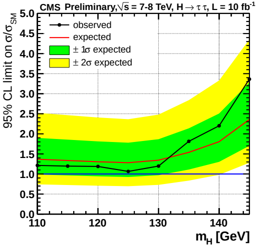

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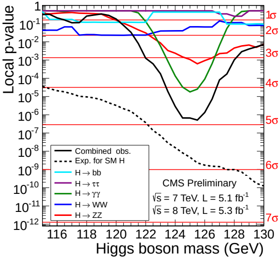
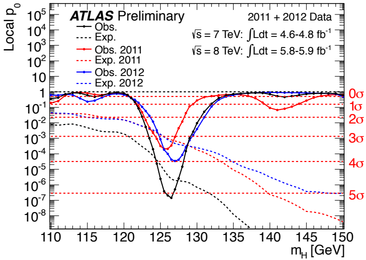
- combined 5.0σ (ATLAS), 4.9σ (CMS) [LEE 4.3σ]

$\Rightarrow$ Rolf Heuer: ‘We have it’





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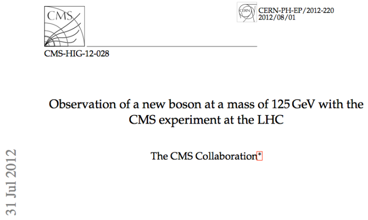


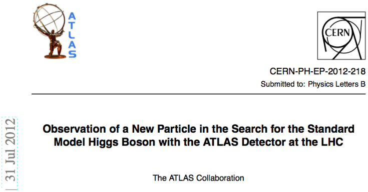
CERN-PH-EP/2012-220
2012/08/01

CMS-HIG-12-028

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC

The CMS Collaboration*

31 Jul 2012



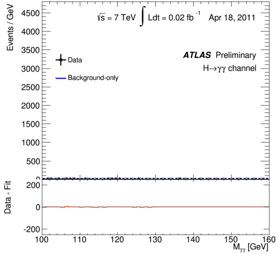
CERN-PH-EP-2012-218
Submitted to: Physics Letters B

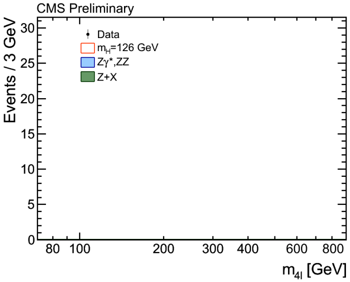
Observation of a New Particle in the Search for the Standard Model Higgs Boson with the ATLAS Detector at the LHC

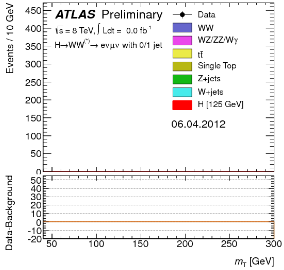
The ATLAS Collaboration

31 Jul 2012

Update







Higgs-like boson turned into

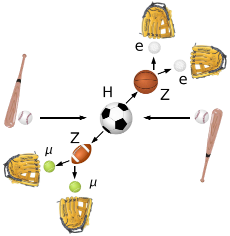
Standard-Model-like Higgs into a Higgs boson

Open questions

1. What is the 'Higgs' Lagrangian?

   – psychologically: looked for Higgs, so found a Higgs

   – CP-even spin-0 scalar expected
   spin-1 vector unlikely
   spin-2 graviton unexpected



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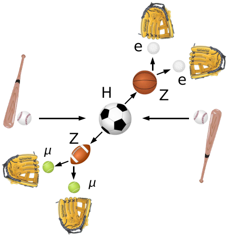

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   – ‘coupling’ after fixing operator basis

   – Standard Model Higgs or else?

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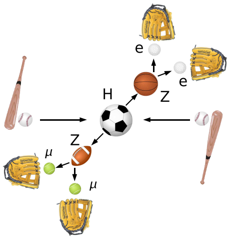

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– weak boson fusion analyses still weak

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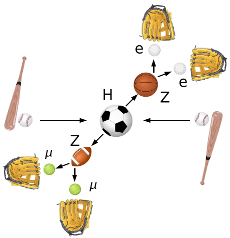

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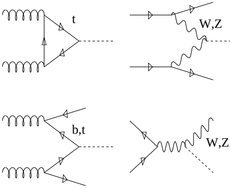
4. What does all this tell us?
   - models predicting weak-scale new physics?
   - renormalization group based Hail-Mary passes?

Couplings



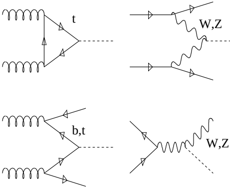
Standard-Model-inspired model

– assume: narrow CP-even scalar
Standard Model operators
couplings proportional to masses?

– couplings from production & decay combinations

$$\begin{array}{l} gg \to H \\ qq \to qqH \\ gg \to t\bar{t}H \\ qq' \to VH \end{array} \quad \longleftrightarrow \quad g_{HXX} = g_{HXX}^{\text{SM}} \; (1 + \Delta_X) \quad \longleftrightarrow \quad \begin{array}{l} H \to ZZ \\ H \to WW \\ H \to b\bar{b} \\ H \to \tau^+\tau^- \\ H \to \gamma\gamma \end{array}$$

Couplings



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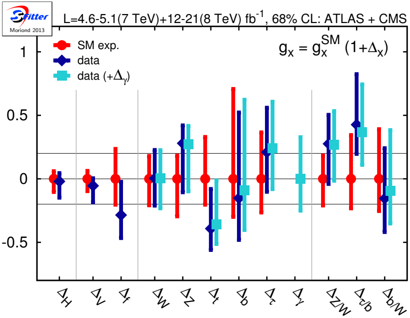
$H \to ZZ$
$H \to WW$
$H \to b\bar{b}$
$H \to \tau^+\tau^-$
$H \to \gamma\gamma$

$\Rightarrow$ almost too exactly the prediction of 1964



Problem with scalars

Theory perspective

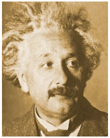
– massless $SU(3)$ and $U(1)$ gauge bosons
  massive W, Z bosons

– weak-scale Higgs scalar

– generation mixing of massive quarks and leptons

– Lagrangian $\mathcal{L} \supset -m_W^2 W_\mu W^\mu - m_f \overline{\Psi}\Psi + gH\overline{\Psi}\Psi$

$\Rightarrow$ renormalizable $\Leftrightarrow$ valid to high scales $\Leftrightarrow$ fundamental



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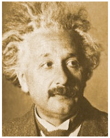
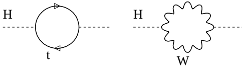


Experimental perspective

- dark matter? [solid evidence for low–scale new physics]
- quark mixing — flavor physics? [new operators above 10^4 GeV?]
- neutrino masses and mixing? [see-saw at 10^{11} GeV?]
- matter–antimatter asymmetry? [universe mostly matter?]
- gauge coupling unification? [experimental fact]
- gravity missing? [negligible at LHC]

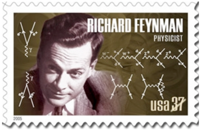
$\Rightarrow$ plenty of new physics scales

Problem with scalars



Problem with scalars

– Heisenberg: quantum corrections to Higgs mass... [$\Delta t \, \Delta E < 1$]



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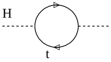
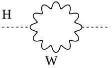




Problem with scalars

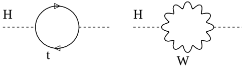
– Heisenberg: quantum corrections to Higgs mass
lead to effective theory desaster

$$m_H^2 \longrightarrow m_H^2 - \frac{g^2}{(4\pi)^2} \, \frac{3}{2} \, \frac{\Lambda^2}{m_W^2} \left[m_H^2 + 2m_W^2 + m_Z^2 - 4m_t^2 \right] + \cdots$$

– Higgs mass pulled to cut-off $\Lambda \gg 126$ GeV [where Higgs at Λ does not work]

– hierarchy problem — Higgs scalar needing stabilization?

Problem with scalars



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- Higgs mass pulled to cut-off $\Lambda \gg 126$ GeV [where Higgs at Λ does not work]
- hierarchy problem — Higgs scalar needing stabilization?

$\Rightarrow$ still no idea where the Higgs field comes from

A detailed discussion of these questions will be presented elsewhere.

It is worth noting that an essential feature of the type of theory which has been described in this note is the prediction of incomplete multiplets of scalar and vector bosons.[8] It is to be expected that this feature will appear also in theories in which the symmetry-breaking scalar fields are not elementary dynamic variables but bilinear combinations of Fermi fields.[9]

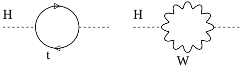
---

[1]P. W. Higgs, to be published.

[2]J. Goldstone, Nuovo Cimento 19, 154 (1961); J. Goldstone, A. Salam, and S. Weinberg, Phys. Rev. 127, 965 (1962).

[3]P. W. Anderson, Phys. Rev. 130, 439 (1963).

Problem with scalars



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⇒ still no idea where the Higgs field comes from

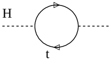
My LHC wish list

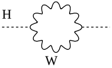
– fundamental Higgs?

– new physics stabilizing Higgs mass?

– dark matter candidate?

Problem with scalars





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lead to effective theory desaster

$$m_H^2 \longrightarrow m_H^2 - \frac{g^2}{(4\pi)^2} \, \frac{3}{2} \, \frac{\Lambda^2}{m_W^2} \left[m_H^2 + 2m_W^2 + m_Z^2 - 4m_t^2 \right] + \cdots$$

– Higgs mass pulled to cut-off $\Lambda \gg 126$ GeV [where Higgs at Λ does not work]

– hierarchy problem — Higgs scalar needing stabilization?

$\Rightarrow$ still no idea where the Higgs field comes from

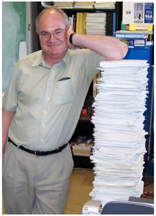
My LHC wish list

– fundamental Higgs?

– new physics stabilizing Higgs mass?

– dark matter candidate?

– or something totally different? [Uli Baur: always new physics at new scales]



Exciting times...

...for LHC physicists

– Higgs discovery after almost 50 years [waiting since Fermi]

– detailed studies just starting

– many new channels at 13 TeV

$\Rightarrow$ new ideas in high demand

Lectures on LHC Physics, arXiv:0910.4182 updated under `www.thphys.uni-heidelberg.de/~plehn/`