SIXTIES
MECCANO
The hobby that grows with the boy
Years of fun in every Outfit
Space... Speed... Beauty
The HUMBER SUPER SNIPE
ROOTES MOTORS LIMITED

Weak interactions

β decay: ${}^{A}_{Z}N \rightarrow {}^{A}_{Z+1}N + e + \bar{\nu}$

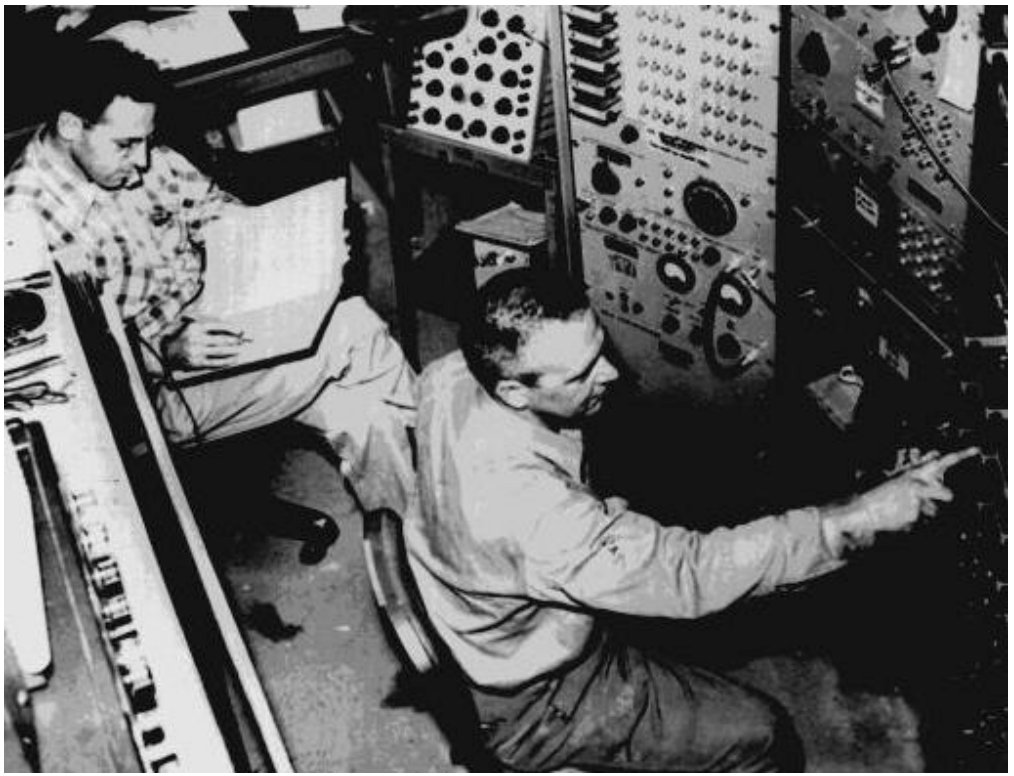
$$L = -\frac{G_F}{\sqrt{2}} \bar{\psi}_p \gamma_\mu \left(1-\gamma_5\right) \psi_n \; \bar{\psi}_e \gamma^\mu \left(1-\gamma_5\right) \psi_\nu + \text{h.c.}$$

Fermi theory (1934)

Parity violation; Wu (1957)

Discovery of the neutrino

Cowan Reines (1956)



Pauli (1930)

RADIO-SCHWEIZ AG. **RADIOGRAMM - RADIOGRAMME** RADIO-SUISSE S.A.

SBZ1311 ZHW UW1844 FM BZJ116 WH CHICAGOILL 56 14 1310

PLC 00253

Erhalten - Reçu **„VIA RADIOSUISSE"** Befördert - Transmis

von - de	Stunde - Heure	NAME - NOM	nach - à	Stunde - Heure	NAME - NOM
NEWYORK			Brieftelegramm		

No. 74 15 VI. 56 --1 10

NACHLASS
PROF. W. PAULI

LT
PROFESSOR W PAULI
ZURICH UNIVERSITY ZURICH

Per Post
(1)

NACHLASS
PROF. W. PAULI

WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

FREDERICK REINES AND CLYDE COWN
BOX 1663 LOS ALAMOS NEW MEXICO

Nr. 20 6500 × 100 3/54

Frederick REINES and Clyde COWAN
Box 1663, LOS ALAMOS, New Mexico

Thanks for message. Everything comes to him who knows how to wait.

Pauli

ed. 15.6.56 / 15.35h
also night letter

Electromagnetic interactions

QED: the triumph of QFT

Feynman Schwinger Tomonaga Dyson

Strong interactions

The failure of QFT

Yukawa (1934)

$$m_\pi \approx \frac{\hbar}{c\, r_{\text{nucleus}}} \approx 100 \text{ MeV}$$

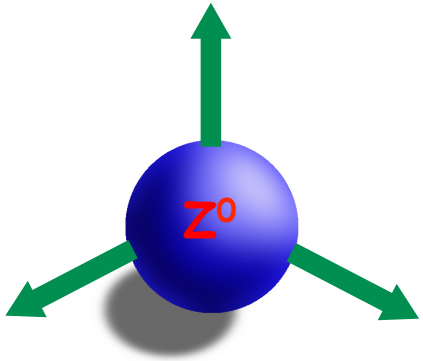
Anderson (1936): discovery of the pion (oops…)

Occhialini and Powell (1947):
discovery of the pion

The failure of QFT

Yang and Mills

$$A_\mu \rightarrow A_\mu + \partial_\mu \Lambda \qquad \text{forbids} \qquad M_A^2 \, A_\mu A^\mu$$



Two problems

- Gauge symmetry implies massless vector bosons
- SSB implies massless scalars

PHYSICAL REVIEW VOLUME 125, NUMBER 1 JANUARY 1, 1962

Gauge Invariance and Mass

JULIAN SCHWINGER
Harvard University, Cambridge, Massachusetts, and University of California, Los Angeles, California
(Received July 20, 1961)

It is argued that the gauge invariance of a vector field does not necessarily imply zero mass for an associated particle if the current vector coupling is sufficiently strong. This situation may permit a deeper understanding of nucleonic charge conservation as a manifestation of a gauge invariance, without the obvious conflict with experience that a massless particle entails.

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.

It is likely, then, considering the superconducting analog, that the way is now open for a degenerate-vacuum theory of the Nambu type[9] without any difficulties involving either zero-mass Yang-Mills gauge bosons or zero-mass Goldstone bosons. These two types of bosons seem capable of "canceling each other out" and leaving finite mass bosons only. It is not at all clear that the way for a Sakurai[3] theory is equally uncluttered. The only mechanism suggested by the present work (of course, we have not discussed non-Abelian gauge groups) for giving the gauge field mass is the degenerate vacuum type of theory, in which the original symmetry is not manifest in the observable domain. Therefore, it needs to be demonstrated that the necessary conservation laws can be maintained.

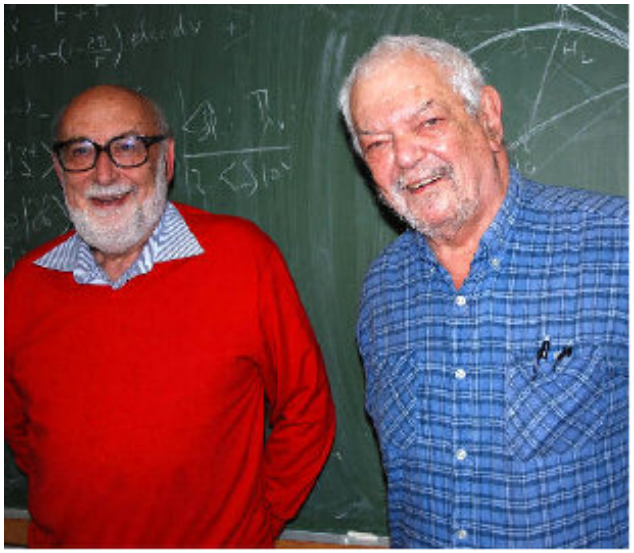
BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

It is of interest to inquire whether gauge vector mesons acquire mass through interaction[1]; by a gauge vector meson we mean a Yang-Mills field[2] associated with the extension of a Lie group from global to local symmetry. The importance of this problem resides in the possibility that strong-interaction physics originates from massive gauge fields related to a system of conserved currents.[3] In this note, we shall show that in certain cases vector mesons do indeed acquire mass when the vacuum is degenerate with respect to a compact Lie group.

those vector mesons which are coupled to currents that "rotate" the original vacuum are the ones which acquire mass [see Eq. (6)].

We shall then examine a particular model based on chirality invariance which may have a more fundamental significance. Here we begin with a chirality-invariant Lagrangian and introduce both vector and pseudovector gauge fields, thereby guaranteeing invariance under both local phase and local γ_5-phase transformations. In this model the gauge fields themselves may break the γ_5 invariance leading to a mass for the original Fermi field. We shall show in this case



BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

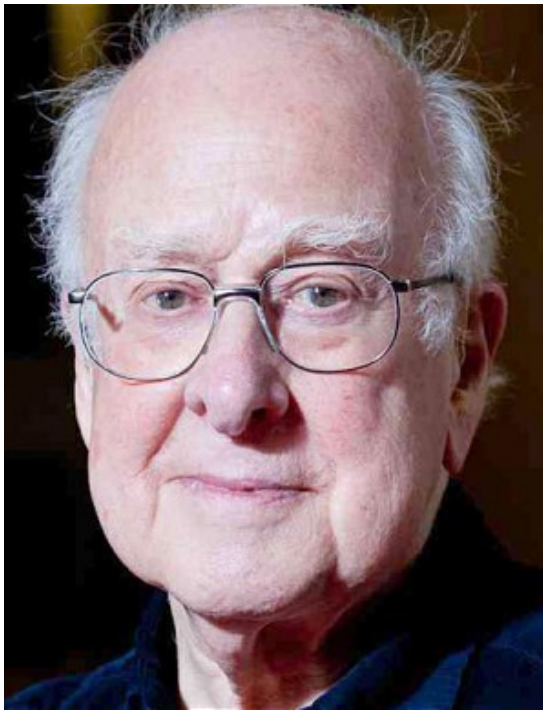
P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

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)



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]

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.

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

$$\mathfrak{L}_0'=-\tfrac{1}{4}F_{\mu\nu}F^{\mu\nu}-\tfrac{1}{2}m_1^2B_\mu B^\mu-\tfrac{1}{2}g^{\mu\nu}\partial_\mu\chi\partial_\nu\chi-\tfrac{1}{2}m_0^2\chi^2. \quad (24)$$

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

PHYSICAL REVIEW VOLUME 155, NUMBER 5 25 MARCH 1967

Symmetry Breaking in Non-Abelian Gauge Theories*

T. W. B. KIBBLE
Department of Physics, Imperial College, London, England
(Received 24 October 1966)

According to the Goldstone theorem, any manifestly covariant broken-symmetry theory must exhibit massless particles. However, it is known from previous work that such particles need not appear in a relativistic theory such as radiation-gauge electrodynamics, which lacks manifest covariance. Higgs has shown how the massless Goldstone particles may be eliminated from a theory with broken $U(1)$ symmetry by coupling in the electromagnetic field. The primary purpose of this paper is to discuss the analogous problem for the case of broken non-Abelian gauge symmetries. In particular, a model is exhibited which shows how the number of massless particles in a theory of this type is determined, and the possibility of having a broken non-Abelian gauge symmetry with no massless particles whatever is established. A secondary purpose is to investigate the relationship between the radiation-gauge and Lorentz-gauge formalisms. The Abelian-gauge case is reexamined, in order to show that, contrary to some previous assertions, the Lorentz-gauge formalism, properly handled, is perfectly consistent, and leads to physical conclusions identical with those reached using the radiation gauge.

A MODEL OF LEPTONS*

Steven Weinberg†
Laboratory for Nuclear Science and Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 17 October 1967)

$$\mathfrak{L} = -\tfrac{1}{4}(\partial_\mu \vec{A}_\nu - \partial_\nu \vec{A}_\mu + g\vec{A}_\mu \times \vec{A}_\nu)^2 - \tfrac{1}{4}(\partial_\mu B_\nu - \partial_\nu B_\mu)^2 - \bar{R}\gamma^\mu(\partial_\mu - ig'B_\mu)R - L\gamma^\mu(\partial_\mu + ig\vec{t}\cdot\vec{A}_\mu - i\tfrac{1}{2}g'B_\mu)L$$

$$-\tfrac{1}{2}|\partial_\mu\varphi - ig\vec{A}_\mu\cdot\vec{t}\varphi + i\tfrac{1}{2}g'B_\mu\varphi|^2 - G_e(\bar{L}\varphi R + \bar{R}\varphi^\dagger L) - M_1{}^2\varphi^\dagger\varphi + h(\varphi^\dagger\varphi)^2. \quad (4)$$

$$M_W = \tfrac{1}{2}\lambda g. \quad (9)$$

The neutral spin-1 fields of definite mass are

$$Z_\mu = (g^2 + g'^2)^{-1/2}(gA_\mu{}^3 + g'B_\mu), \quad (10)$$

$$A_\mu = (g^2 + g'^2)^{-1/2}(-g'A_\mu{}^3 + gB_\mu). \quad (11)$$

Their masses are

$$M_Z = \tfrac{1}{2}\lambda(g^2 + g'^2)^{1/2}, \quad (12)$$

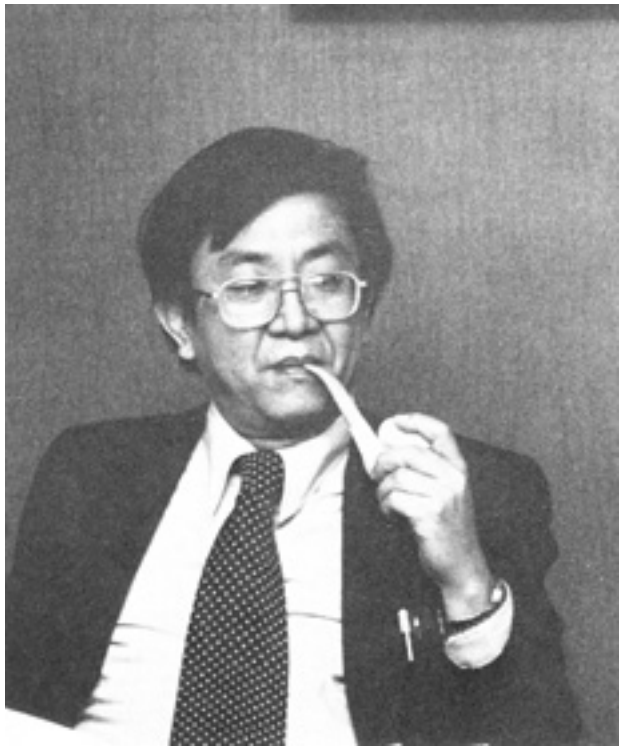
$$M_A = 0, \quad (13)$$

so A_μ is to be identified as the photon field.

The Higgs scalar meson plays a role in making a spontaneously broken gauge theory finite. An example is given in Primack's discussion in which he shows that the Higgs scalar contribution is necessary to remove logarithmic divergences from one loop diagrams of fermion-fermion scattering. H. Quinn[103] has given a very interesting discussion as to the role of the Higgs meson in making two-loop contributions to fermion-antifermion scattering finite. The following is a brief summary of her result.

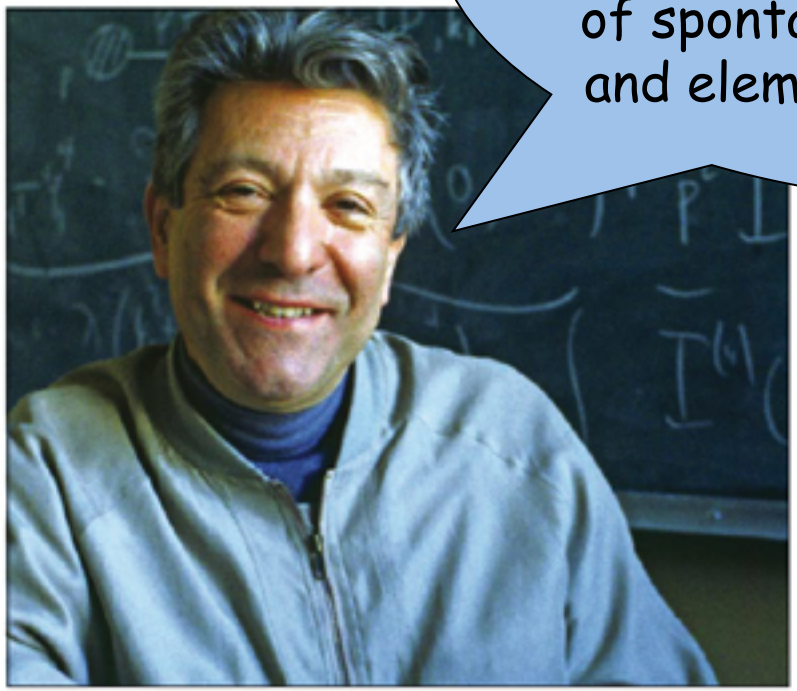
In order for the amplitude for $\nu\bar{e} \to \nu\bar{e}$ to be finite, the amplitude for $\nu\bar{e} \to W^+W^-W^+$ must grow at most like s^{-1} as $s \to \infty$. In a massive Yang-Mills theory, Vainshtein and Khriplovich[104] have shown that this condition is not met for the production of three longitudinally polarized vector bosons. When the extra term arising from the Higgs meson exchange (see Figure 5) is added to the above it cancels the leading term that grows like const $s^{-\frac{1}{2}}$ as $s \to \infty$, leaving an amplitude of order m_W/s, which is sufficiently convergent.

This is an explicit demonstration of the role of the Higgsian scalar in making the S-matrix finite from the viewpoint of the S-matrix theory, and repudiates the view that the Higgsian scalar is an artifact peculiar to operator field theory.



We do not wish 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.

Ellis Gaillard Nanopoulos (1976)



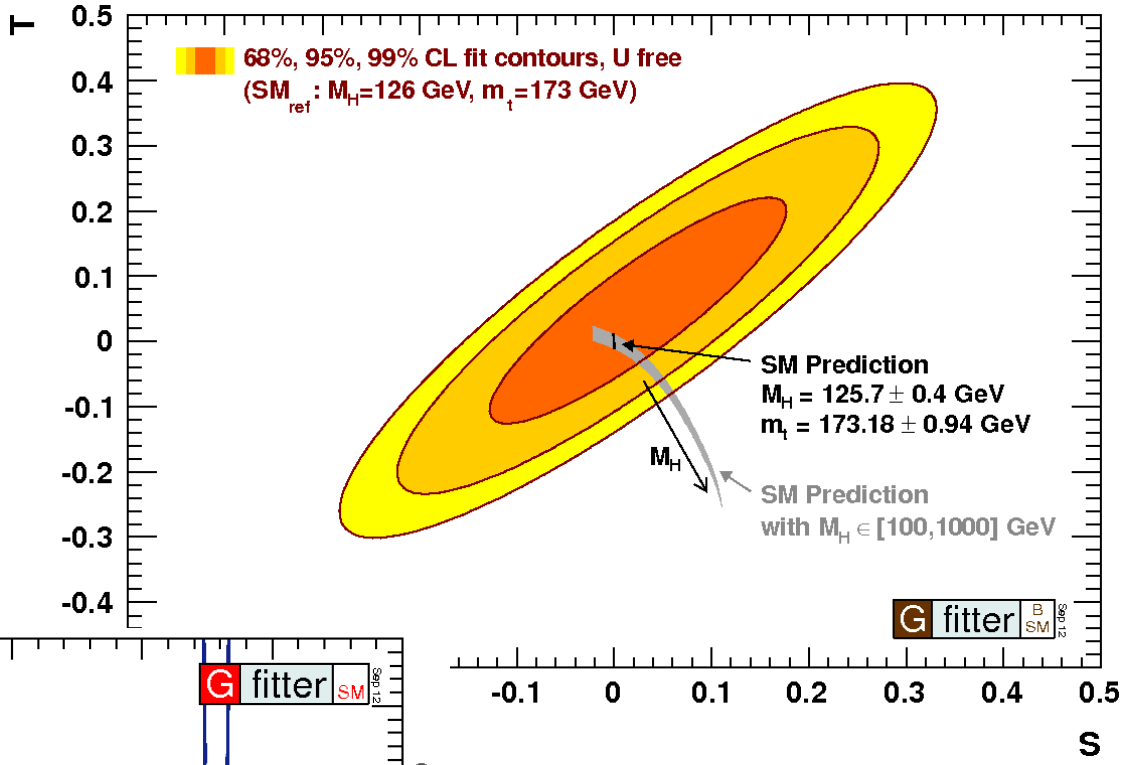
Several people believe, and I share this view, that the Higgs scheme is a convenient parametrization of our ignorance concerning the dynamics of spontaneous symmetry breaking and elementary scalar particles do not exist

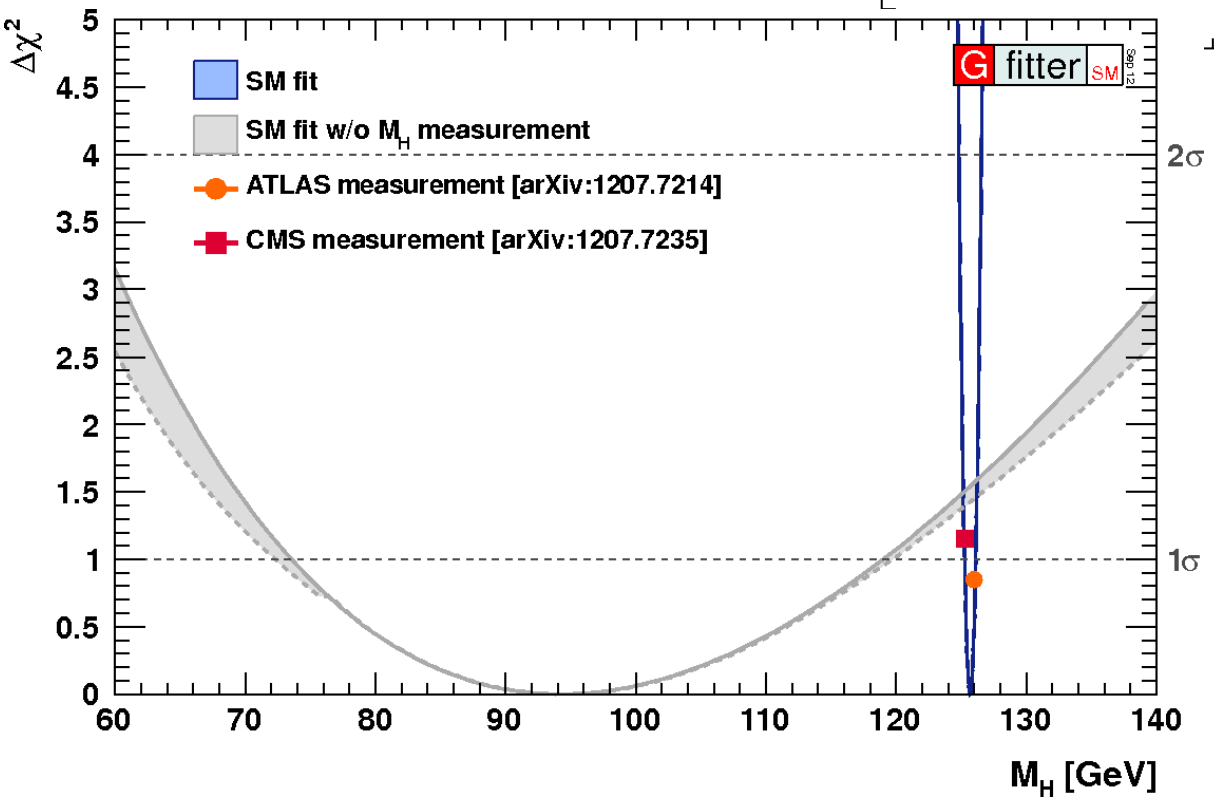
Iliopoulos, Einstein Symposium (1979)

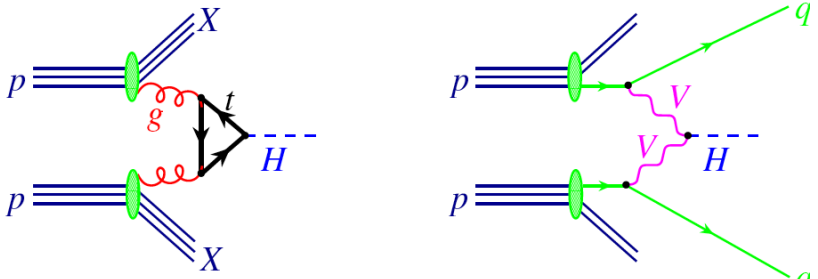
It seems to me that the problem No.1 of high energy physics are scalar particles. The search for these particles is extremely important mainly because of their vital role in symmetry breaking.

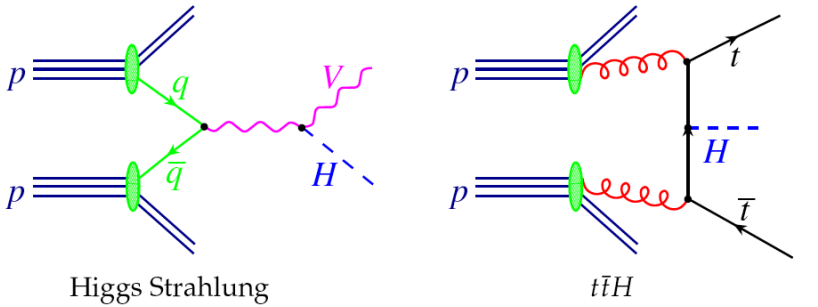
Okun, Lepton-Photon (1981)

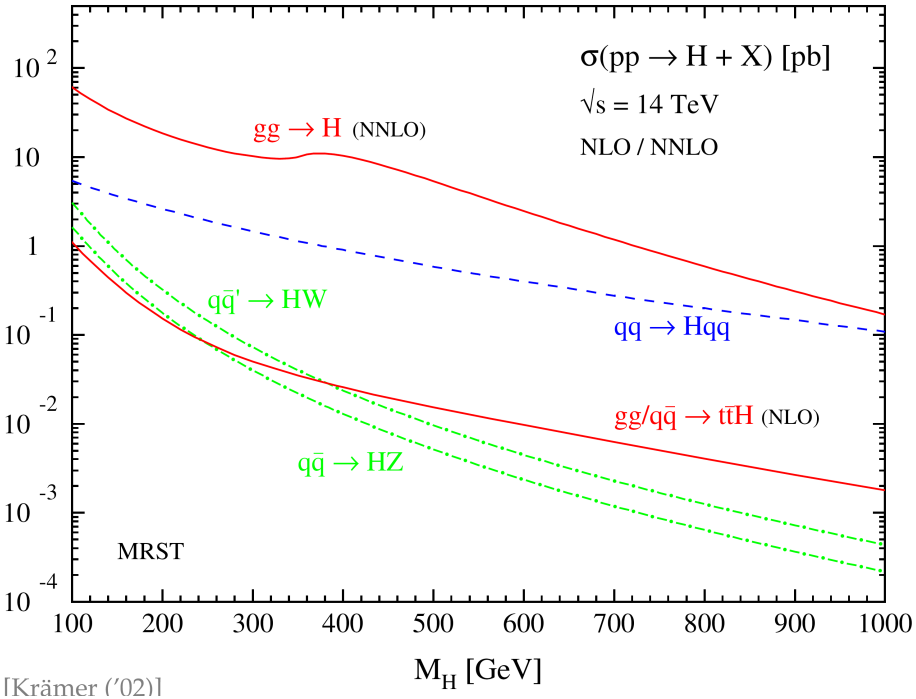
LEP: $m_H > 114$ GeV



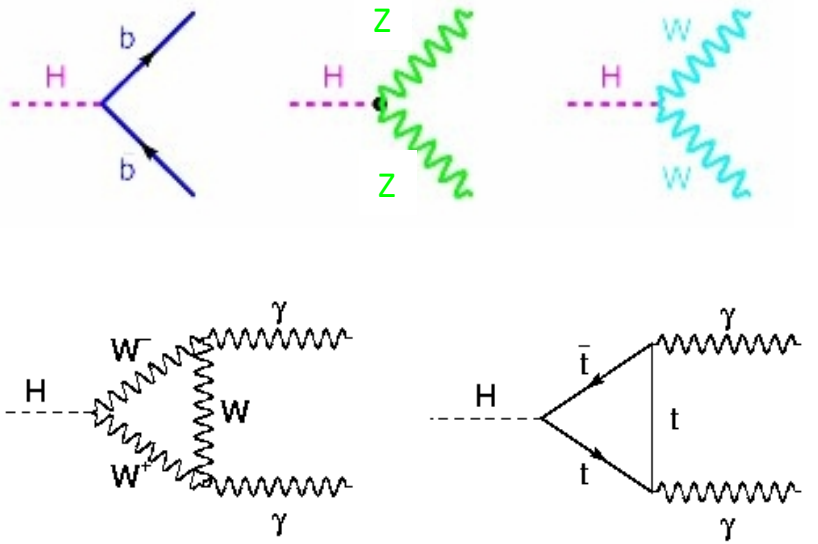



p
p
X
X
g
t
H
Gluon fusion
p
p
q
q
V
V
H
Weak-Boson Fusion


p
p
q
q̄
V
H
Higgs Strahlung
p
p
t
H
t̄
ttH


σ(pp → H + X) [pb]
√s = 14 TeV
NLO / NNLO
gg → H (NNLO)
qq̄' → HW
qq → Hqq
gg/qq̄ → ttH (NLO)
qq̄ → HZ
MRST
M_H [GeV]

[Krämer ('02)]


H
b
b
H
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Z
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W
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W
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t̄
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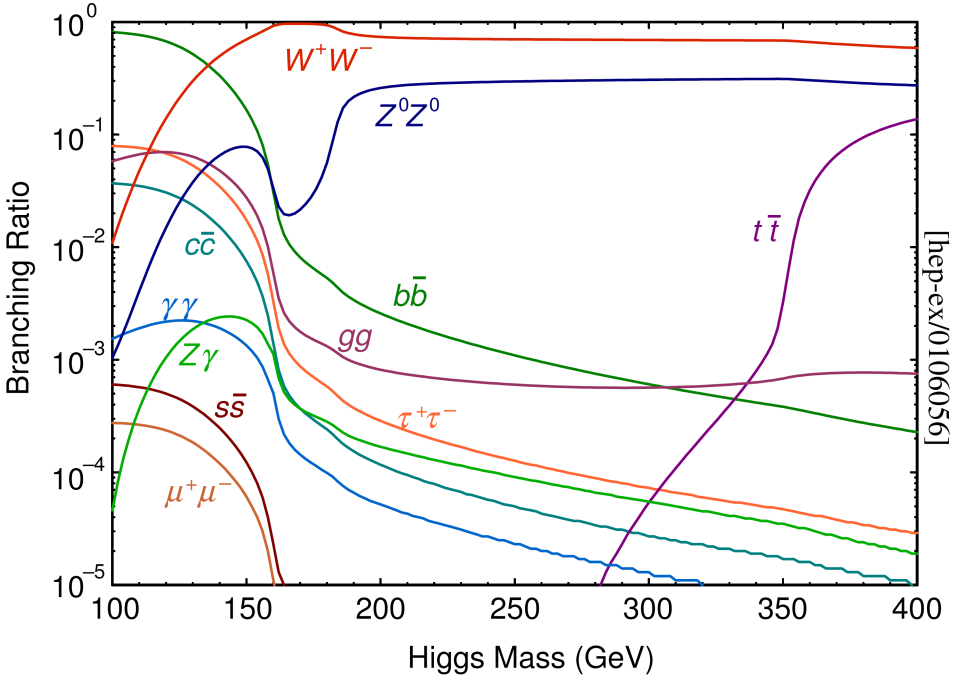
γ
γ


Branching Ratio
Higgs Mass (GeV)
W⁺W⁻
Z⁰Z⁰
cc̄
γγ
Zγ
ss̄
μ⁺μ⁻
bb̄
gg
τ⁺τ⁻
t t̄
[hep-ex/0106056]

√s	gg	VBF	WH	ZH	ttH
7 TeV	15 pb	1.2 pb	0.6 pb	0.3 pb	0.08 pb
8 TeV	19 pb	1.6 pb	0.7 pb	0.4 pb	0.1 pb
14 TeV	50 pb	4.2 pb	1.5 pb	0.9 pb	0.6 pb

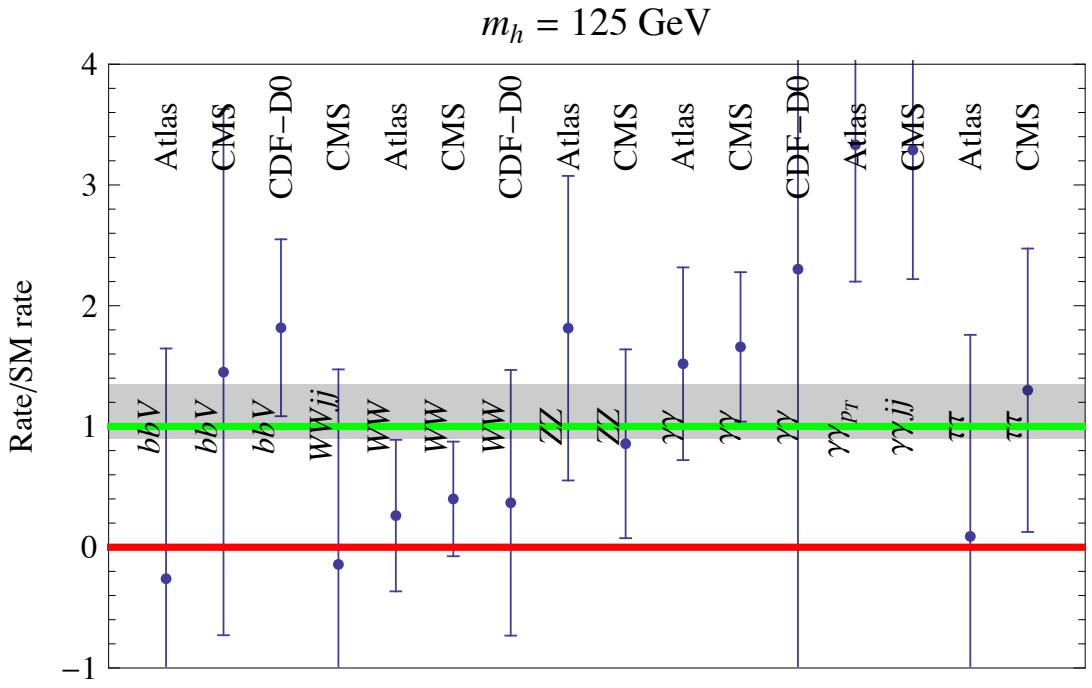
m_H [GeV]	bb %	WW %	gg %	ττ %	ZZ %	cc %	γγ %	Zγ %	μμ %	Γ [MeV]
125	58	21	8.6	6.3	2.6	2.9	0.23	0.15	0.02	4.1
126	56	23	8.5	6.1	2.9	2.8	0.23	0.16	0.02	4.1

- All decay modes can be measured except *cc*
- Test of *H* couplings: b, W, Z, g, γ, t, τ, μ, γZ, invisible

$$BR(H \to f) = \frac{\Gamma(H \to f)}{\Gamma_{SM} + \Gamma_{inv}} = (1 - BR_{inv})\, BR_{SM}(H \to f)$$

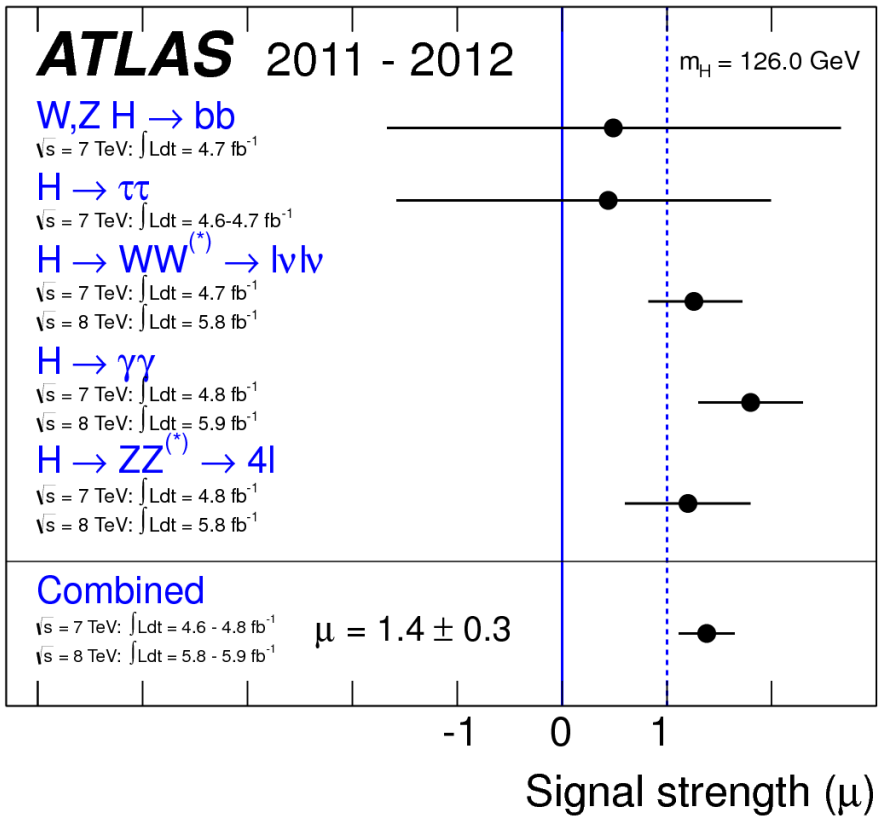
- Rich program in *H* studies can nail *H* properties

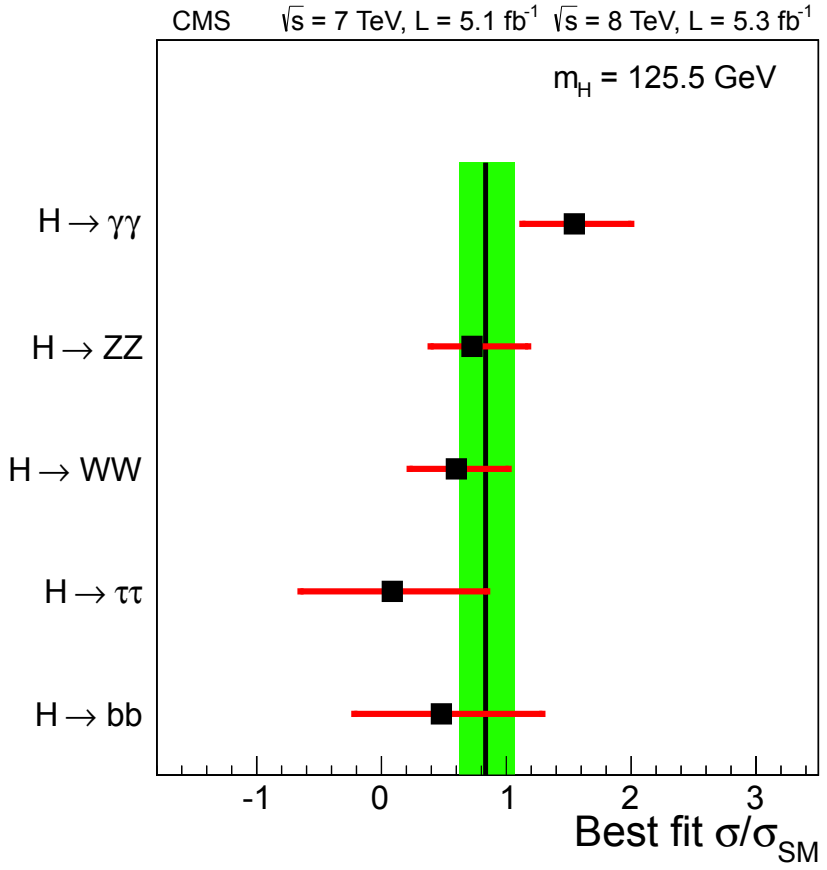
Winter 2011: first indications



- High $\Gamma(H \to \gamma\gamma)$??
- Low $\Gamma(H \to WW)/\Gamma(H \to ZZ)$?
- Low $\Gamma(H \to \tau\tau)$?

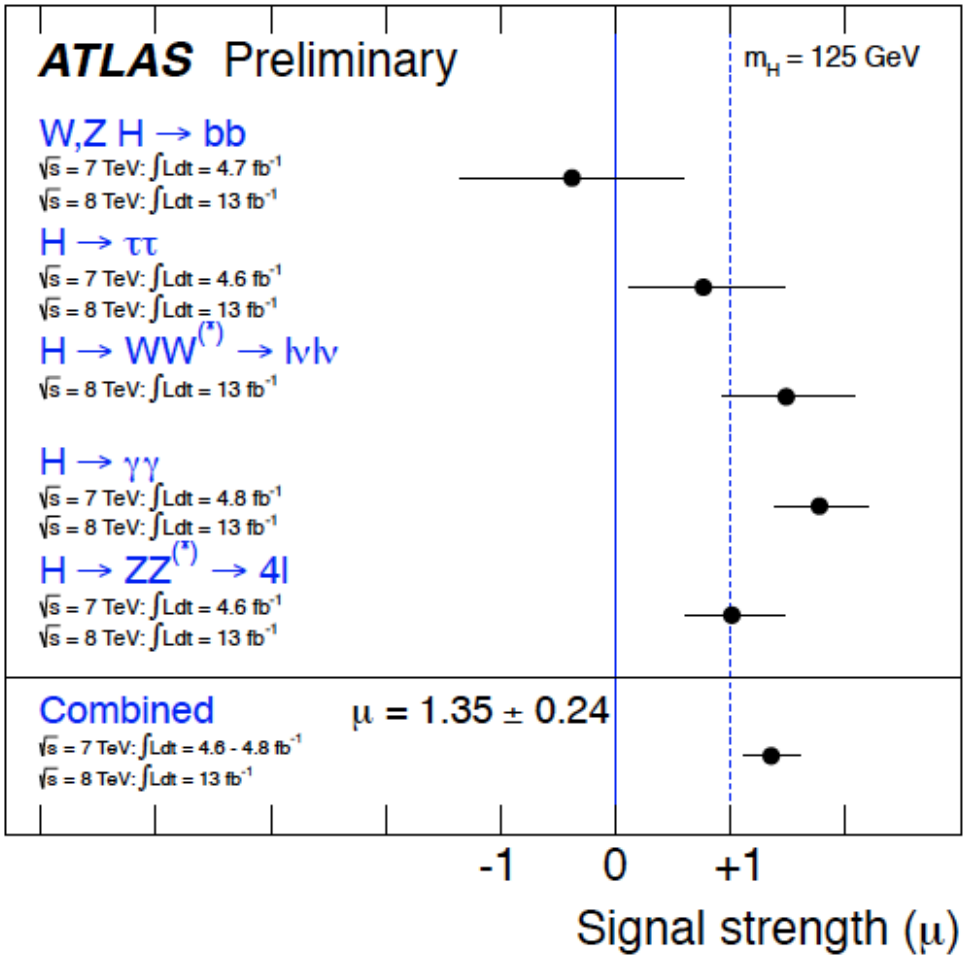
Summer 2012: Higgs discovery





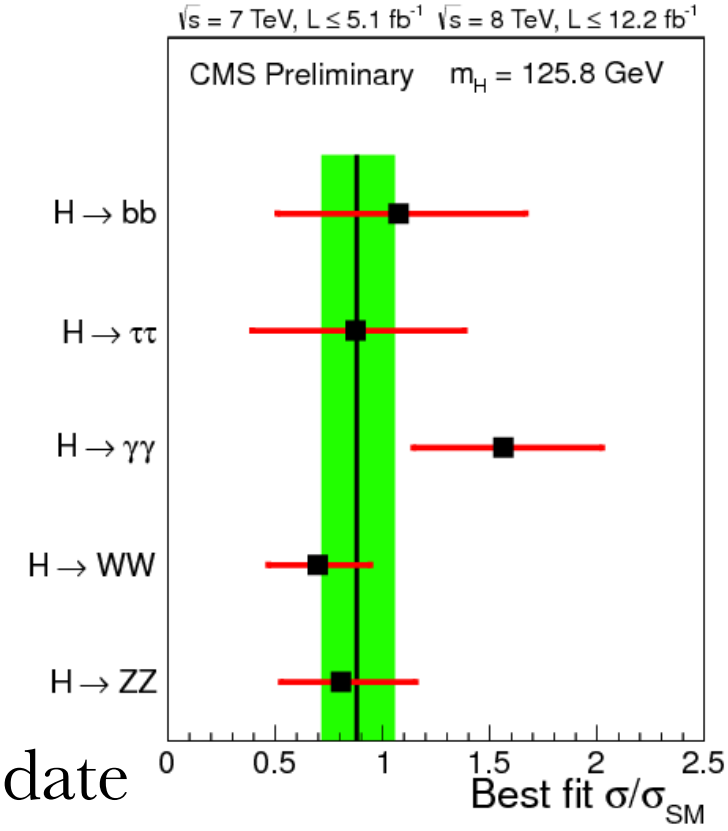
- High $\Gamma(H \to \gamma\gamma)$??
- ~~Low $\Gamma(H \to WW)/\Gamma(H \to ZZ)$?~~
- Low $\Gamma(H \to \tau\tau)$?

Winter 2012: down in precision



$$m_H = 125.2 \pm 0.3_{\text{stat}} \pm 0.6_{\text{syst}} \quad \text{(ATLAS)}$$

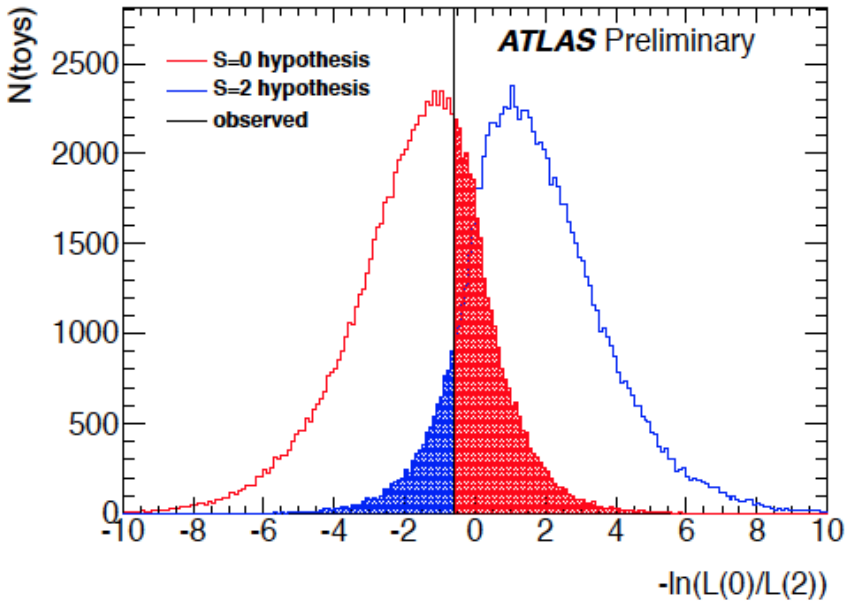
$$m_H = 125.8 \pm 0.4_{\text{stat}} \pm 0.4_{\text{syst}} \quad \text{(CMS)}$$

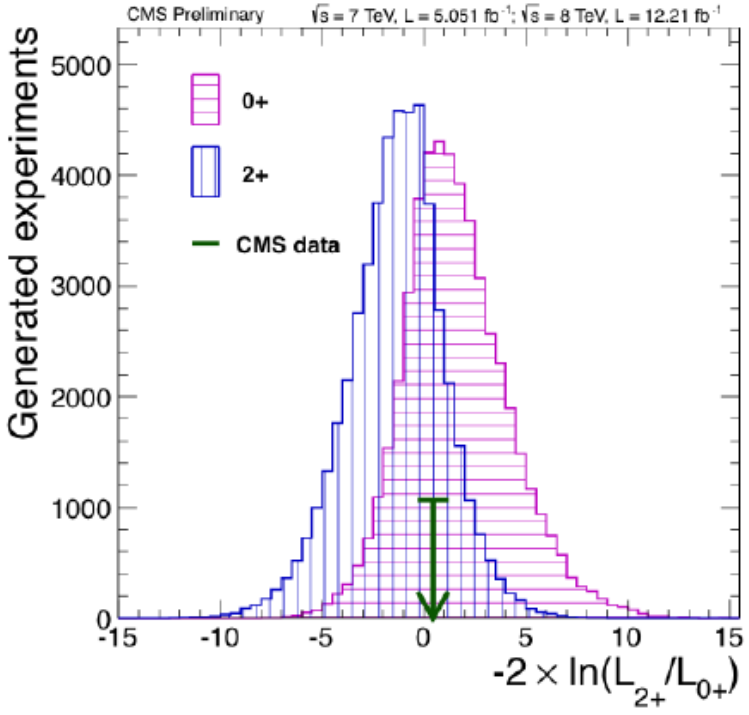


- High $\Gamma(H \to \gamma\gamma)$?? ← no update
- ~~Low $\Gamma(H \to WW)/\Gamma(H \to ZZ)$?~~
- ~~Low $\Gamma(H \to \tau\tau)$?~~

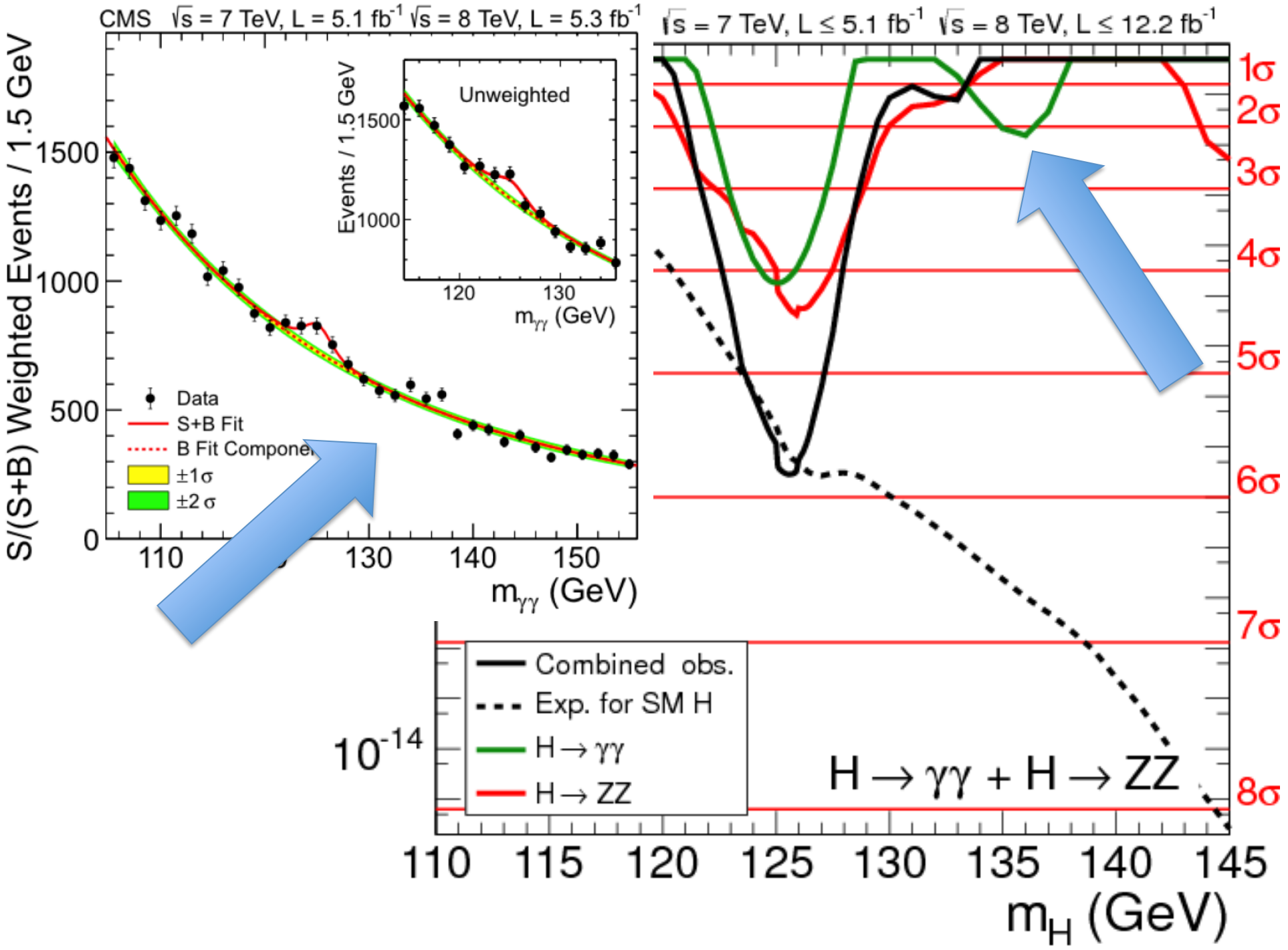
$$\text{Spin } 0 \rightarrow \gamma\gamma \quad \text{Spin } 0 \rightarrow ZZ$$

$$\text{Spin } 1 \not\rightarrow \gamma\gamma \quad \text{Spin } 1 \rightarrow ZZ$$

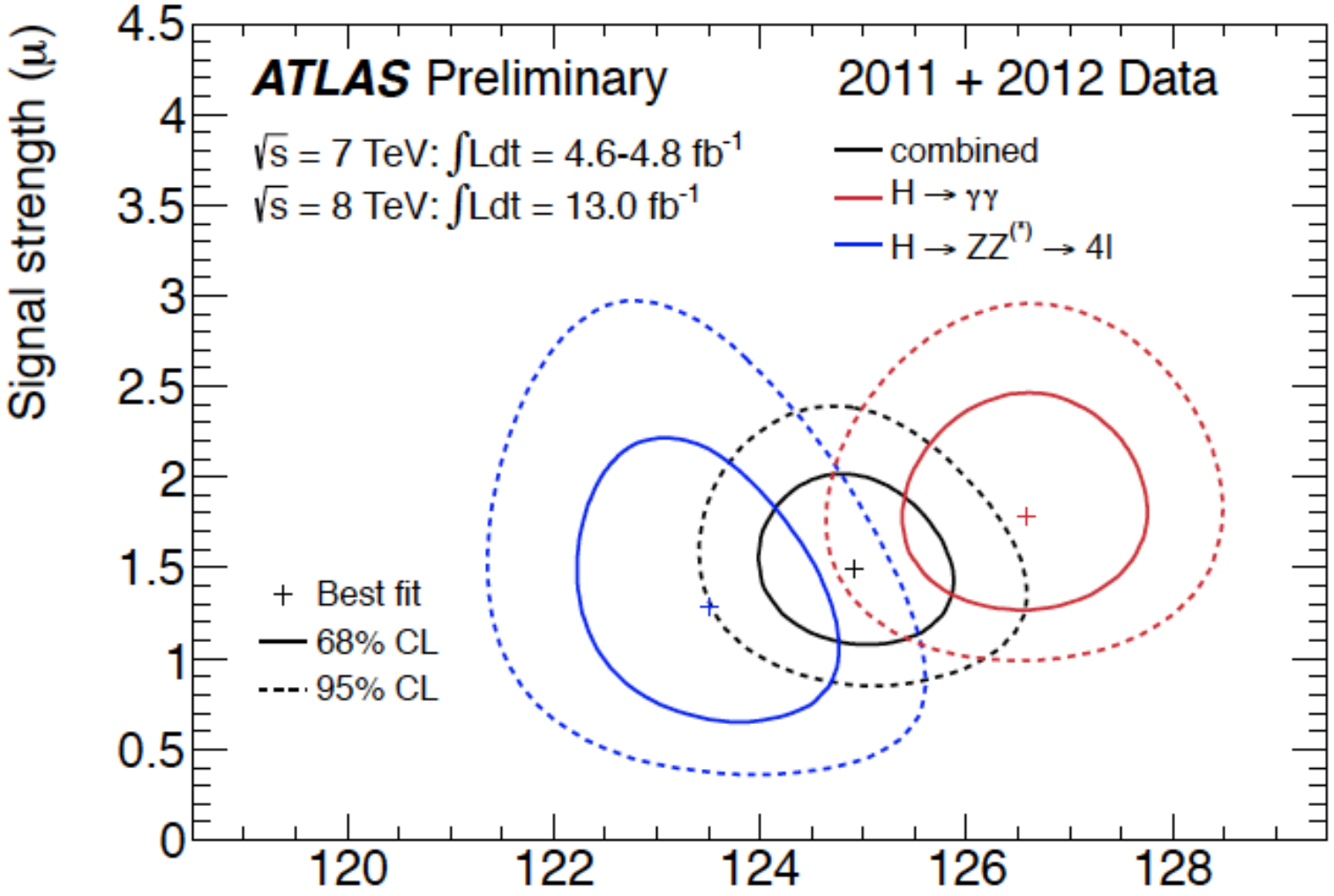




- Spin-2 hypothesis ruled out at 91% CL
- 0^- excluded at 99% CL


CMS √s = 7 TeV, L = 5.1 fb-1 √s = 8 TeV, L = 5.3 fb-1
S/(S+B) Weighted Events / 1.5 GeV
Unweighted
Events / 1.5 GeV
mγγ (GeV)
Data
S+B Fit
B Fit Componen
±1σ
±2 σ
√s = 7 TeV, L ≤ 5.1 fb-1 √s = 8 TeV, L ≤ 12.2 fb-1
1σ
2σ
3σ
4σ
5σ
6σ
7σ
8σ
Combined obs.
Exp. for SM H
H → γγ
H → ZZ
H → γγ + H → ZZ
10-14
mH (GeV)

Best fit signal strength $\hat{\mu} = 1.5^{+0.33}_{-0.29}$



$m_H = 125.2 \pm 0.3\ (stat)\ \pm\ 0.6\ (syst)$ GeV

(In-)compatible at 2.7 σ!

A fundamental discovery

- Identify the origin of a fundamental scale
- A new guise of the gauge principle
- Structure of space-time vacuum (new ether?)
- A new force of nature

… but most physicists believe that the Higgs cannot be the end of the story