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Particle Physics for specialists

The Brout-Englert-Higgs mechanism and the Higgs boson

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Recap of what we know so far

- Our understanding of fundamental physics is based on Relativistic Quantum Field Theory together with the gauge principle, which states that the theory invariant under certain gauge transformation (symmetry) determines properties of the interaction.

$$\partial_\mu\left(\frac{\partial\mathcal{L}}{\partial(\partial_\mu\phi)}\right)-\frac{\partial\mathcal{L}}{\partial\phi}=0, \qquad L=\int d^3x\mathcal{L}$$

Lagrangian density and field equations of motion e.g. QED

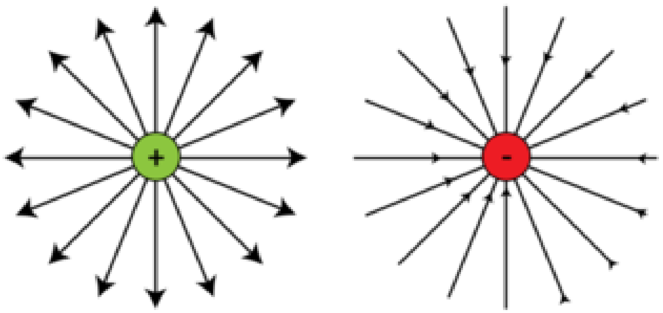
$$<\phi_F\left|e^{-iHT}\right|\phi_I>=\int\mathcal{D}\phi(t)exp\left\{i\int_0^T dtL\right\}$$

Path integrals, perturbation theory and Feynman diagrams

- Standard Model is SU(3)xSU(2)xU(1) gauge theory and breaks into $\text{SU(3)}_{\text{colour}}$ and $\text{SU(2)xU(1)}_{\text{electroweak}}$.
- Not gauge invariant theories are NOT renormalizable, hence physically meaningless!
- In the following, we will be concerned mostly with the electroweak part of the SM.

The most famous infinity in classical physics

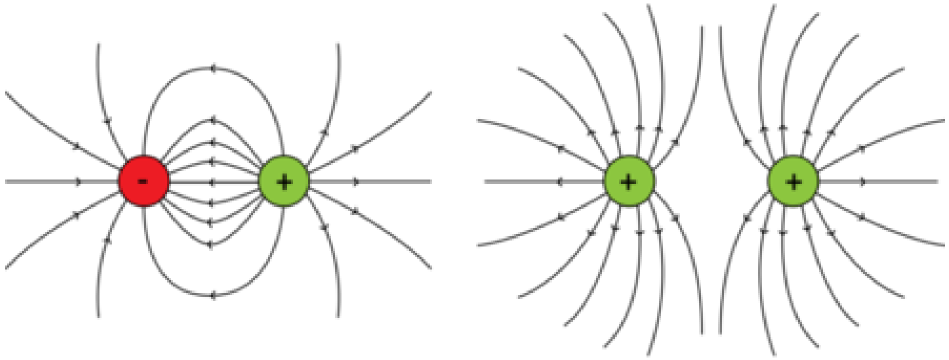
Electric Fields of Individual Charged Particles (Point Charges):



Electric field lines of a positive point charge

Electric field lines of a negative point charge

Interacting Electric Fields of Two Charged Particles:



Positively and Negatively Charged Particles

Two Positively Charged Particles

We obtain meaningful physical quantities by subtracting infinities!

$$\infty - \infty = \Delta$$

RENORMALIZATION

In a QFT in order for this “trick” to work the theory must be invariant under certain intrinsic symmetry (gauge) which generates considered interaction (U(1) in case of QED)

One cannot allow terms in the Lagrangian that violate gauge symmetry. ☹

Let us have a glance at QED, to start with…

$$\mathcal{L} = \bar{\psi}(x)(i\gamma^{\mu}\partial_{\mu} - m)\psi(x)$$

Fermionic Lagrangian $\boxed{c = \hbar = 1}$
⇒ Dirac Equation for a free fermion field

$$\psi(x) \to e^{if(x)}\,\psi(x),$$
$$\bar{\psi}(x) \to e^{-if(x)}\,\bar{\psi}(x)$$

Local U(1) gauge transformation
of fermion fields

Gauge invariance of the Lagrangian density requires introduction of a vector potential, and corresponding covariant derivative:

$$A_{\mu} \to A_{\mu} + \tfrac{1}{e}\partial_{\mu} f(x)$$

Local U(1) gauge transformation
of the vector field *A*

$$D_{\mu} \equiv \partial_{\mu} - ieA_{\mu}$$

The covariant derivative

Lorentz covariant and gauge invariant **QED** Lagrangian density:

$$\mathcal{L}_{\mathrm{QED}} = \underbrace{i\bar{\psi}(x)\gamma^{\mu}\partial_{\mu}\psi(x)}_{\text{kinetic term}} - \underbrace{m\bar{\psi}(x)\psi(x)}_{\text{mass term}} + \underbrace{e\bar{\psi}(x)\gamma^{\mu}A_{\mu}\psi(x)}_{\text{interaction term}} - \underbrace{\tfrac{1}{4}F_{\mu\nu}F^{\mu\nu}}_{\substack{\text{EM free field}\\ \frac{1}{2}(B^2 - E^2)}}$$

$$F_{\mu\nu} = \partial_{\mu}A_{\nu} - \partial_{\nu}A_{\mu}$$

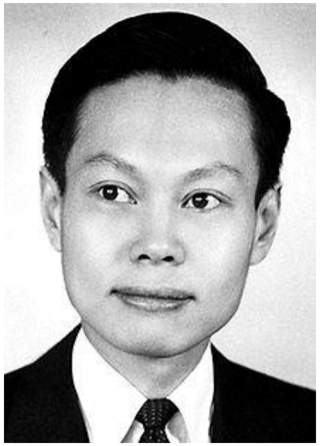
The gauge invariant EM field strength tensor

Let us have a glance at QED, to start with…

$\cancel{-\frac{1}{2}m^2 A_\mu A^\mu}$ mass term is manifestly NOT gauge invariant!

Photon is massless!

- The Yang-Mills fields (1954) resulting from gauge invariance of the Lagrangian are massless.
- The mechanism works alright for the QED! ☺
- So far so good!
- It is also adequate in description of Quantum Chromodynamics (QCD). ☺
- But weak interactions are mediated by massive gauge bosons! ☹



Yang Chen-Ning

Robert L. Mills

Same holds for SU(3) gauge invariant QCD

Lorentz covariant and SU(3) gauge invariant **QCD** Lagrangian density:

$$\mathcal{L}_{\mathrm{QCD}} = \bar{q}\left(i\gamma^{\mu}\partial_{\mu} - m\right)q + g_s(\bar{q}\gamma^{\mu}T_a q)G_{\mu}^{a} - \tfrac{1}{4}G_{\mu\nu}^{a}G_{a}^{\mu\nu}$$

$$G_{\mu}^{a} \rightarrow G_{\mu}^{a} - \frac{1}{g_s}\,\partial_{\mu}\alpha_a - f_{abc}\,\alpha_b G_{\mu}^{c}$$

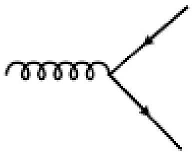
Local SU(3) gauge transformation of the colour field

$$G_{\mu\nu}^{a} = \partial_{\mu}G_{\nu}^{a} - \partial_{\nu}G_{\mu}^{a} - g_s f_{abc} G_{\mu}^{b}\, G_{\nu}^{c}$$

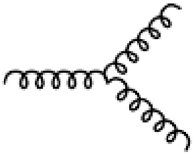
The gauge invariant colour field strength tensor

Gluons are massless!

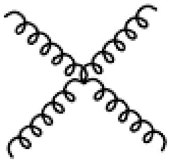
But, as opposed to photon, gluons have self-interactions. Non-abelian nature of the SU(3) gauge group generates self interactions of gauge bosons - gluons (SU(3) generators - 3x3 Gell-Mann matrices do not commute!)



Analogous to photon exchange of QED



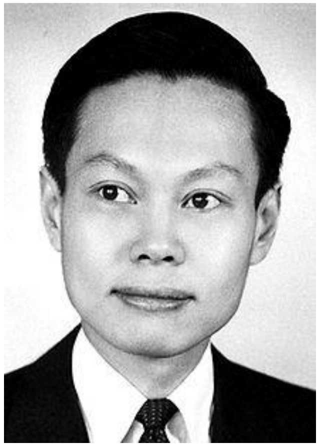
3-gluon vertex

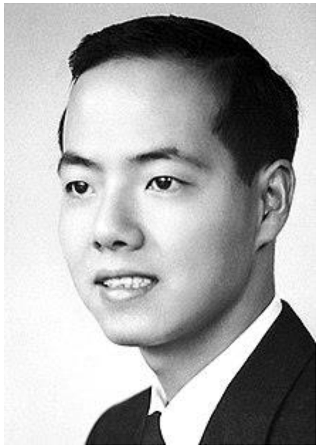


4-gluon vertex

Not the end of SM problems…

- In 1957 Yang & Lee postulated that in weak interactions parity might not be conserved.
- An experiment proposed by Lee and conducted by Ms Wu confirmed the fact.
- All known fermions undergo weak interactions.
- All fermions of the SM are massless ☹


Yang Chen-Ning


Lee Tsung-Dao

Nobel Prize in Physics 1957

$$\psi_L = \tfrac{1}{2}(1-\gamma_5)\,\psi, \qquad \bar{\psi}_L = \tfrac{1}{2}\bar{\psi}\,(1+\gamma_5) \qquad \text{left chiral}$$

$$\psi_R = \tfrac{1}{2}(1+\gamma_5)\,\psi, \qquad \bar{\psi}_R = \tfrac{1}{2}\bar{\psi}\,(1-\gamma_5) \qquad \text{right chiral}$$

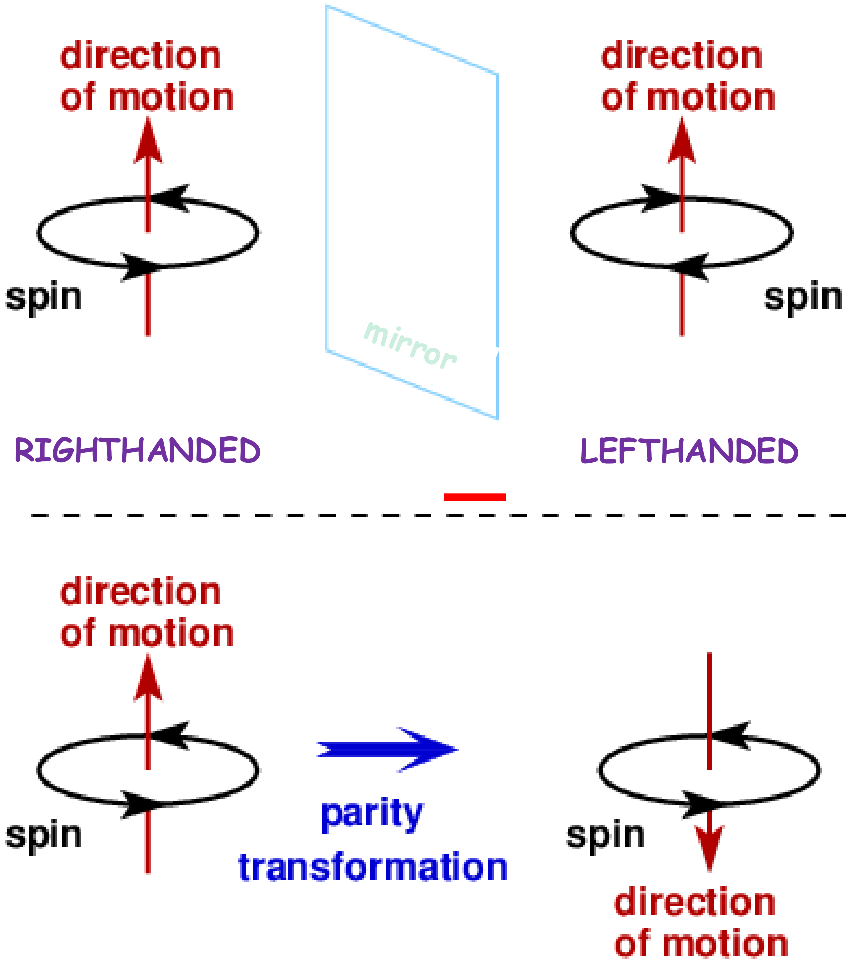
$$\cancel{m\bar{\psi}\psi} = m\bar{\psi}\left[\tfrac{1}{2}(1-\gamma_5) + \tfrac{1}{2}(1+\gamma_5)\right]\psi = m(\bar{\psi}_R\psi_L + \bar{\psi}_L\psi_R)$$

manifestly **NOT** SU(2)xU(1) gauge invariant!


Wu Chien-Shiung

Weakly interacting fermions are massless!

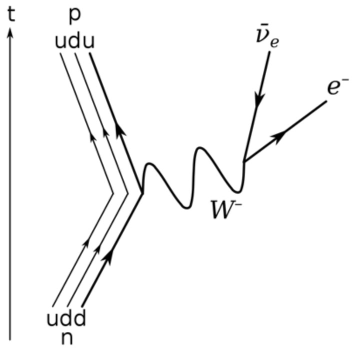
Weak interactions do not conserve parity…



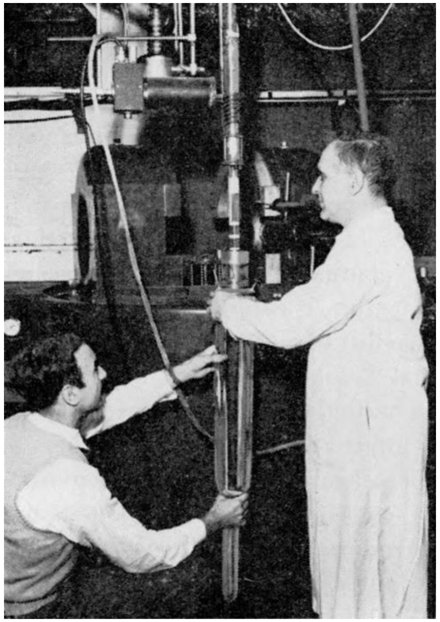
The Wu experiment

The experiment monitored the decay of cobalt-60 (^{60}Co) atoms that were aligned by a uniform magnetic field (the polarizing field) and cooled to near absolute zero so that thermal motions did not ruin the alignment

$${}^{60}_{27}\mathrm{Co} \rightarrow {}^{60}_{28}\mathrm{Ni} + e^{-} + \bar{\nu}_e + 2\gamma$$



The beta decay



Finally, let us turn towards the Electroweak unification

In analogy to QED, gauge invariance generates interaction:

$$\mathrm{U(1)_Y}: \qquad -i\frac{g'}{2}J^Y_\mu B^\mu = ig'\bar{\psi}\gamma_\mu\frac{Y}{2}\psi B^\mu$$

$$\mathrm{SU(2)_L}: \qquad -ig\mathbf{J}_\mu\cdot\mathbf{W}^\mu = -ig\bar{\chi}_L\gamma_\mu\mathbf{T}\cdot\mathbf{W}^\mu\chi_L, \qquad \chi_L = \begin{pmatrix}\psi_u\\ \psi_d\end{pmatrix}_L = \frac{1}{2}(1-\gamma_5)\begin{pmatrix}\psi_u\\ \psi_d\end{pmatrix}$$

Charged and Neutral Current interaction Lagrangian density:

$$\mathcal{L}_{\mathrm{CC}} = -i\frac{g}{2}\left(J^1_\mu W^{\mu 1} + J^2_\mu W^{\mu 2}\right) = -i\frac{g}{\sqrt{2}}\left(J^+_\mu W^{\mu +} + J^-_\mu W^{\mu -}\right)$$

$$\mathcal{L}_{\mathrm{NC}} = -gJ^3_\mu (W^3)^\mu - i\frac{g'}{2}j^Y_\mu B^\mu =$$

$$-i\left[g\sin\theta_W J^3_\mu + g'\cos\theta_W\frac{j^Y_\mu}{2}\right]A^\mu - i\left(g\cos\theta_W J^3_\mu - g'\sin\theta_W\frac{j^Y_\mu}{2}\right)Z^\mu =$$

$$-ieJ^{em}_\mu A^\mu - i\frac{g}{\cos\theta_W}J^{NC}_\mu Z^\mu = -ieJ^{em}_\mu A^\mu - i\frac{e}{\sin\theta_W\cos\theta_W}J^{NC}_\mu Z^\mu$$

Where we have identified the EM coupling constant and the corresponding charge:

$$\boxed{e = g\sin\theta_W = g'\cos\theta_W, \qquad\qquad Q = T^3 + \frac{Y}{2}}$$

Finally, let us turn towards the Electroweak unification

$$J_\mu^i = \bar{\chi}_L \gamma_\mu \tau_i \chi_L,$$

$$J_\mu^{em} = J_\mu^3 + \frac{1}{2} J_\mu^Y$$

$$J_\mu^{NC} = J_\mu^3 - \sin^2\theta_W J_\mu^{em} = \cos^2\theta_W J_\mu^3 - \sin^2\theta_W \frac{1}{2} J_\mu^Y$$

$$J_\mu^+ = \frac{1}{2}\left(J_\mu^1 + iJ_\mu^2\right) = \bar{\chi}_L \gamma_\mu \tau_+ \chi_L, \qquad J_\mu^- = \frac{1}{2}\left(J_\mu^1 - iJ_\mu^2\right) = \bar{\chi}_L \gamma_\mu \tau_- \chi_L$$

$$\tau_+ = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}, \qquad \tau_- = \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix}$$

the charge rising and lowering operators

$$\mathbf{W}_\mu \to \mathbf{W}_\mu - \frac{1}{g}\,\partial_\mu \boldsymbol{\alpha} - \boldsymbol{\alpha} \times \mathbf{W}_\mu$$

SU(2) gauge field transformation

Nonabelian nature of the gauge group generates self interactions of gauge bosons!

$$\mathbf{W}_{\mu\nu} \to \partial_\mu \mathbf{W}_\nu \partial_\nu \mathbf{W}_\mu - g\mathbf{W}_\mu \times \mathbf{W}_\nu$$

SU(2) field strength tensor

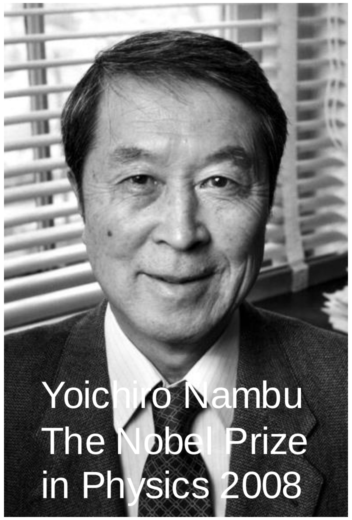
$$D_\mu \equiv \partial_\mu + ig\frac{\tau_a}{2} W_\mu^a + ig'\frac{Y}{2} B_\mu$$

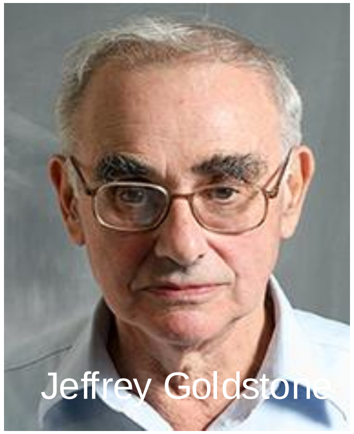
the SU(2)xU(1) covariant derivative

The problem and proposed solution

- The Lagrangian must be gauge invariant which implies massless bosons mediating the interactions.
- Weak interactions do not conserve parity which implies that all SM fermions must be massless.

- A possible way out could be a **spontaneous symmetry breaking**. The ground state is asymmetric although the underlying theory remains gauge invariant.
- Such an effect was known in superconductivity.
- Yoichiro Nambu (1960) suggested a similar mechanism could give masses to elementary particles.
- Weinberg & Salam & Goldstone (1962): "*In a manifestly Lorentz-invariant quantum field theory, if there is a continuous symmetry under which the Lagrangian is invariant, then either the vacuum state is also invariant or there must exist spinless particles of zero mass*."
- These massless scalars are known as **Nambu-Goldstone bosons** - none of which had ever been seen!
- Weinberg discouraged by the futility of their conclusion: *'Nothing will come of nothing; speak again!'* (King Lear)


Yoichiro Nambu
The Nobel Prize
in Physics 2008

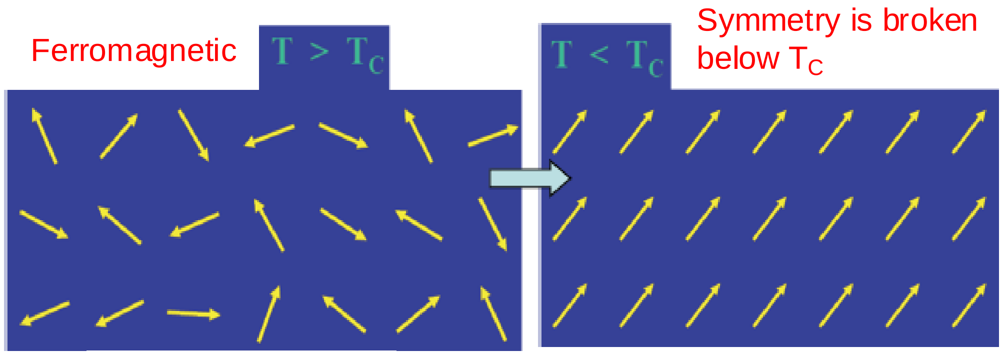

Jeffrey Goldstone

Symmetry-breaking without breaking the symmetry

- Spontaneous breaking of symmetry occurs when the ground state or vacuum state does not share the symmetry of the underlying theory

- It is ubiquitous in condensed matter physics

- Often there is a high-temperature symmetric phase, and a critical temperature below which the symmetry is spontaneously broken
  - crystallization of a liquid breaks the rotational symmetry
  - Curie-point transition in ferromagnetic

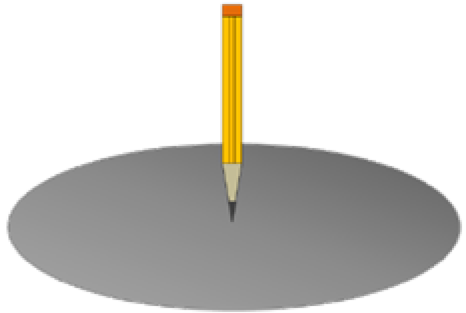


Symmetry is broken below T_C

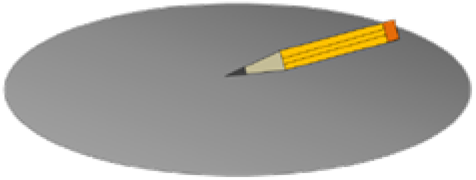
Isotropic system

Distinct orientation

- The rotational symmetry of the pencil around its axis implies that the pencil is equally likely to fall in any direction.



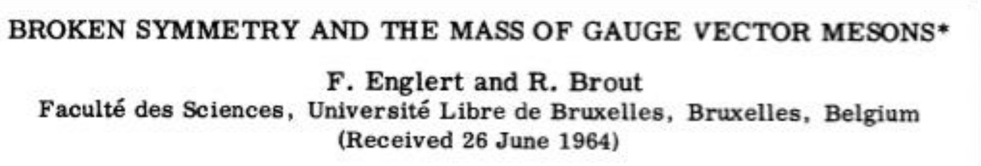
- However, perform the experiment once, and the pencil must fall in some direction.



- The resulting state of the pencil breaks the rotational symmetry, **although the rotational symmetry of the laws that govern the falling pencil remain intact**.

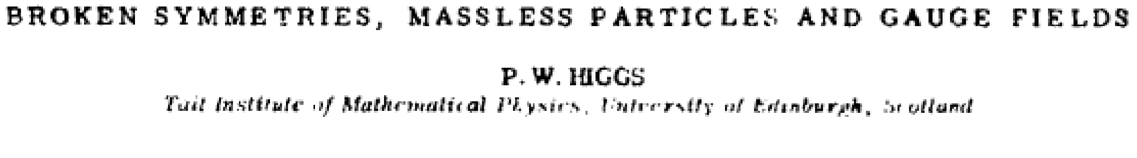
Brout-Englert-Higgs-Hagen-Guralnik-Kibble **field and… the Higgs boson (1964)**

T.Kibble G.Guralnik R.C.Hagen F.Englert R.Brout & P.Higgs



BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

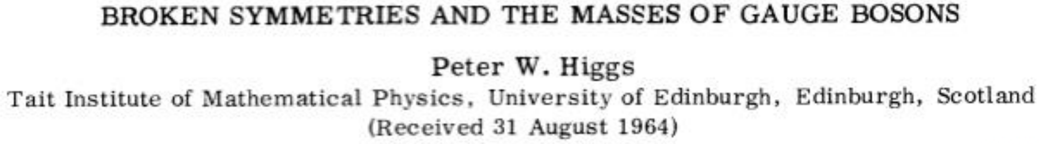
F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)



BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

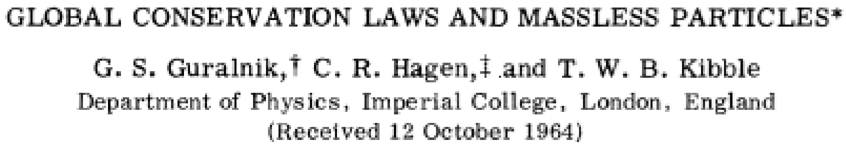
P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 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)



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)

The Brout-Englert-Higgs (BEH) mechanism in the SM

$$\phi = \sqrt{\tfrac{1}{2}}\begin{pmatrix}\phi_1 + i\phi_2\\ \phi_3 + i\phi_4\end{pmatrix}$$

4 DoF of the SU(2) doublet complex scalar field

$$\mathcal{L} = (\partial_\mu\phi)^\dagger(\partial^\mu\phi) - V(\phi), \qquad V(\phi) = \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$

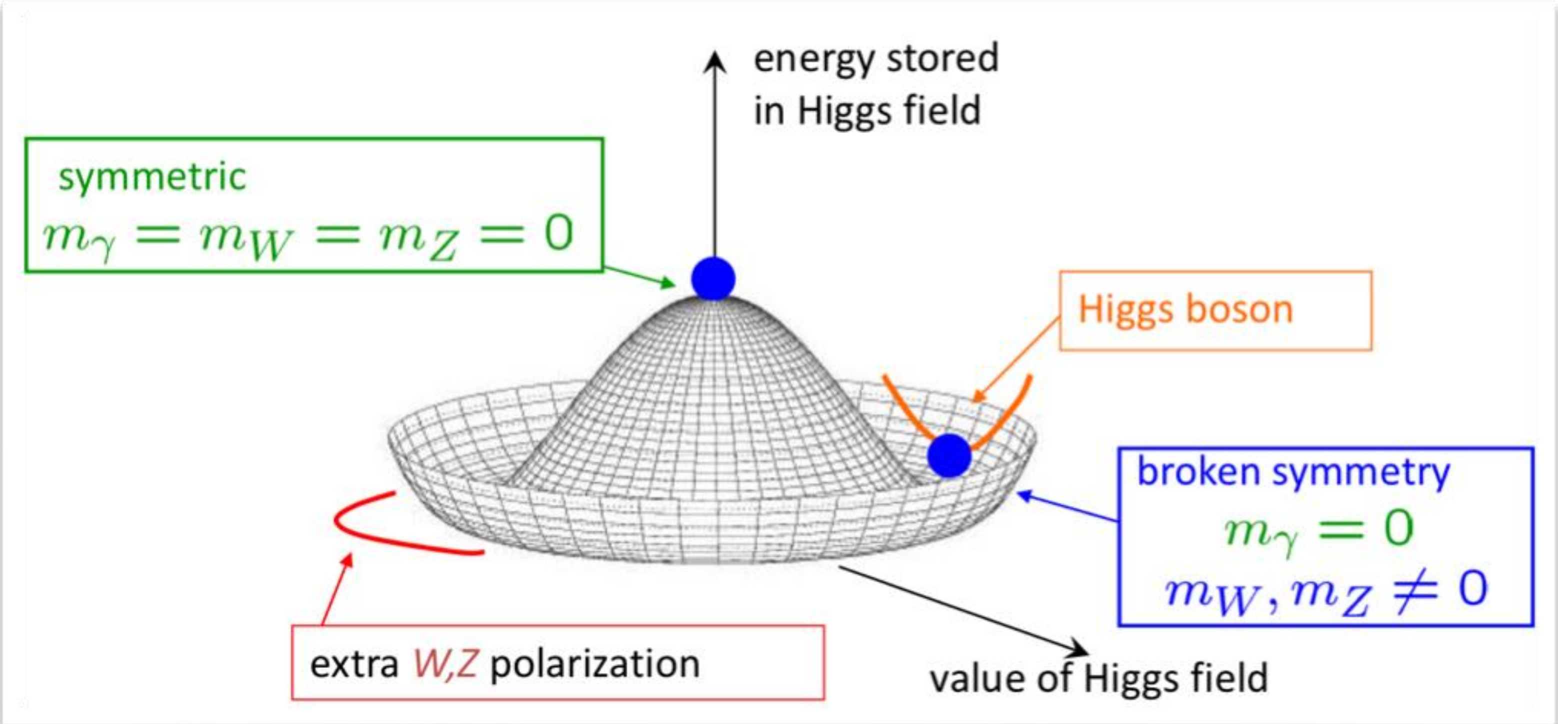
Has to be negative for BEH mechanism to occur

The usual requirement:

$$\mathcal{L} = \left|\left(\partial_\mu + ig\mathbf{T}\cdot\mathbf{W}_\mu + ig'\frac{Y}{2}B_\mu\right)\phi\right|^2 - V(\phi)$$

the SU(2)xU(1) gauge invariant

Imagine it in 4D!



The Brout-Englert-Higgs (BEH) mechanism in the SM

$$\phi_0 = \sqrt{\tfrac{1}{2}}\begin{pmatrix} 0 \\ \upsilon + h(x) \end{pmatrix}, \quad \upsilon \equiv \sqrt{-\tfrac{\mu^2}{2\lambda}}$$

(arbitrary) choice of the vacuum state, ϕ_0

The $U(1)_{em}$ remains unbroken:

$$0 = Q = T^3 + \tfrac{Y}{2}, \qquad \phi_0 \rightarrow \phi_0' = e^{i\alpha(x)Q}\phi_0 = \phi_0 \qquad T = \tfrac{1}{2},\ T^3 = -\tfrac{1}{2},\ \mathrm{Y{=}1}$$

Only a neutral scalar may acquire vacuum expectation value - vev (charge conservation!)

We now consider just the SU(2)xU(1) interaction terms of the ϕ field:

$$\left|\left(ig\frac{\tau}{2}\cdot\mathbf{W}_{\mu} + ig'\frac{Y}{2}B_{\mu}\right)\phi_0\right|^2$$

$$= \frac{1}{8}\left|\begin{pmatrix} gW_{\mu}^3 + g'B_{\mu} & g(W_{\mu}^1 - iW_{\mu}^2) \\ g(W_{\mu}^1 + iW_{\mu}^2) & -gW_{\mu}^3 + g'B_{\mu}\end{pmatrix}\begin{pmatrix}0\\ \upsilon\end{pmatrix}\right|^2$$

$$= \left(\tfrac{1}{2}\upsilon g\right)^2\frac{1}{2}\left[\left(W_{\mu}^1\right)^2 + \left(W_{\mu}^2\right)^2\right] + \frac{1}{8}\upsilon^2\left[gW_{\mu}^3 - g'B_{\mu}\right]^2 + 0\left[g'W_{\mu}^3 + gB_{\mu}\right]^2$$

$$= \left(\tfrac{1}{2}\upsilon g\right)^2 W_{\mu}^{+}W^{-\mu} + \tfrac{1}{2}\left(\tfrac{1}{2}\upsilon\sqrt{g^2 + g'^2}\right)^2\left[\frac{gW_{\mu}^3 - g'B_{\mu}}{\sqrt{g^2 + g'^2}}\right]^2 + 0\left[\frac{g'W_{\mu}^3 + gB_{\mu}}{\sqrt{g^2 + g'^2}}\right]^2$$

…plus terms for the field excitation h(x) – the Higgs boson!

The Brout-Englert-Higgs (BEH) mechanism in the SM

The Nambu-Goldstone DoF’s have been transferred to “eaten by ” the gauge bosons which acquired mass and longitudinal polarisation.

This is the **BEH mechanism**.

We are now ready to identify the eigenstates of EW bosons:

$$W_\mu^{\pm} \equiv \frac{W_\mu^1 \mp W_\mu^2}{\sqrt{2}} \qquad M_W = \frac{1}{2} \upsilon g$$

$$Z_\mu \equiv \frac{g W_\mu^3 - g' B_\mu}{\sqrt{g^2 + g'^2}} \qquad M_Z = \frac{1}{2} \upsilon \sqrt{g^2 + g'^2}$$

$$A_\mu \equiv \frac{g' W_\mu^3 + g B_\mu}{\sqrt{g^2 + g'^2}} \qquad M_A = 0$$

Coupling to higgs ~M_V
Amplitude: M ~ M_V^2
σ ~|M|^2 x phase space factor

And we recognize the θ_W as a result of the EW symmetry breaking:

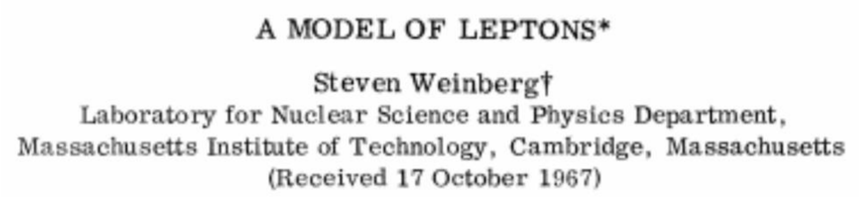
$$Z_\mu \equiv \cos\theta_W W_\mu^3 - \sin\theta_W B_\mu$$

$$A_\mu \equiv \sin\theta_W W_\mu^3 + \cos\theta_W B_\mu$$

$$\frac{M_W}{M_Z} = \cos\theta_W \qquad \cos\theta_W = \frac{g}{\sqrt{g^2 + g'^2}} \qquad \sin\theta_W = \frac{g'}{\sqrt{g^2 + g'^2}}$$

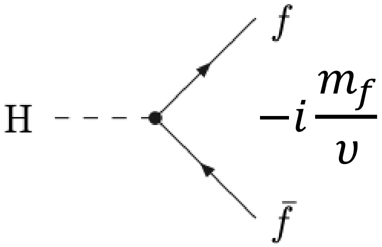
The Yukawa of the SM

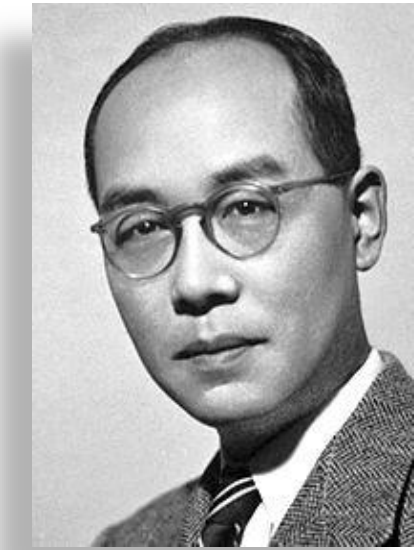
- The Yukawa interactions are not strictly needed for the Electroweak symmetry breaking via the BEH mechanism.
- However, they give us a very appealing opportunity to dynamically introduce masses of otherwise massles fermion fields (Weinberg '67)



A MODEL OF LEPTONS*

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





Hideki Yukawa
Nobel Prize 1949

for electron:

$$\mathcal{L}_Y = -G_e\left[(\bar{\nu}_e,\bar{e})_L\begin{pmatrix}\phi^+\\ \phi^0\end{pmatrix} e_R + \bar{e}_R(\bar{\phi}^+,\bar{\phi}^0)\begin{pmatrix}\nu_e\\ e\end{pmatrix}_L\right]$$

The Lagrangian is gauge invartiant!

$$\begin{pmatrix}\phi^+\\ \phi^0\end{pmatrix} \to \sqrt{\frac{1}{2}}\begin{pmatrix}0\\ v+h(x)\end{pmatrix} \quad \Rightarrow \quad \mathcal{L}_Y = -\sum_f \underbrace{m_f\bar{\psi}\psi}_{\text{mass}} - \underbrace{\frac{m_f}{v}\bar{\psi}\psi h}_{\text{interaction}}$$

Coupling to higgs ~m_f
Amplitude: M ~m_f
σ ~|M|^2 x phase space factor

for quarks:

$$\mathcal{L}_Y = -G_d^{ij}(\bar{u}_i,\bar{d}'_i)_L\begin{pmatrix}\phi^+\\ \phi^0\end{pmatrix} d_R + iG_u^{ij}(\bar{u}_i,\bar{d}'_i)_L\tau_2\begin{pmatrix}\phi^+\\ \phi^0\end{pmatrix}^* u_R + h.c.$$

Let's take a look at the Higgs potential once again...

$$\phi = \sqrt{\tfrac{1}{2}}\begin{pmatrix}\phi_1 + i\phi_2 \\ \phi_3 + i\phi_4\end{pmatrix}$$

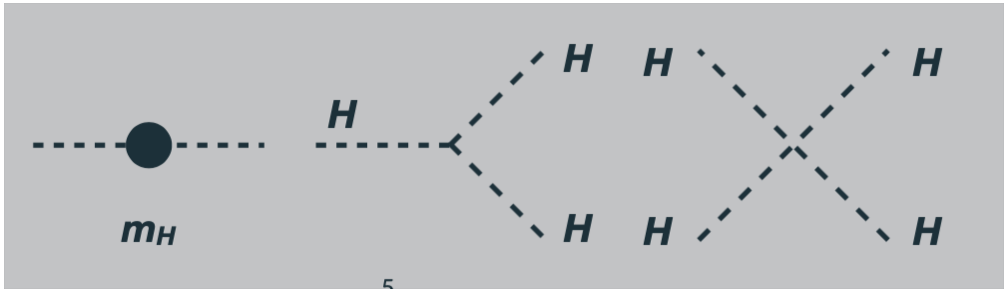
4 DoF of the SU(2) doublet complex scalar field

$$\mathcal{L} = (\partial_\mu \phi)^\dagger (\partial^\mu \phi) - V(\phi), \qquad V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$

$$\phi_0 = \sqrt{\tfrac{1}{2}}\begin{pmatrix}0 \\ v + h(x)\end{pmatrix}, \quad \upsilon \equiv \sqrt{-\tfrac{\mu^2}{2\lambda}}$$

the vacuum state and the physical higgs

$$V(\phi) \sim \;\; \lambda v^2 h(x)^2 \quad + \quad \lambda v\, h(x)^3 \quad + \quad \tfrac{1}{4}\lambda h(x)^4$$



$$m_h^2 = 2\lambda v^2 = |\mu|$$

not predicted by the theory

$$\boxed{m_h = 125\ \text{GeV}, v = 246\ \text{GeV} \rightarrow \lambda \approx 0.13}$$

Idea of the Higgs field

Empty space filled with invisible ”force” – the Higgs field

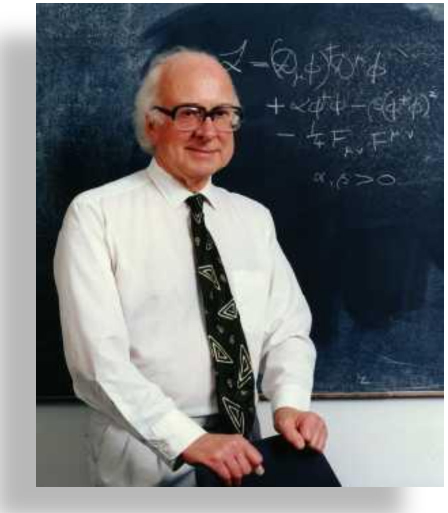
The Higgs field clusters around the particle – gives mass

And Higgs particle itself as excitation of the Higgs field

Recap of what constitutes the cornerstone of the SM

- The Higgs field fills all of space and has no external source
- The Higgs boson is an elementary excitation of the field. It must be a scalar particle.
- Some particles – including the Higgs boson itself – interact with the field; they are massive. Stronger interaction –> higher mass.
- Photons, gluons, (neutrinos) do not interact at all; they are massless.
- Masses are controlled by free parameters called Yukawa Couplings (the strength of the coupling to the Higgs field)

- The Higgs Boson has a mass, but the **mass is not predicted** by the theory - we had to find it **experimentally**!



Finding the Higgs particle was the only way to confirm the bold idea !

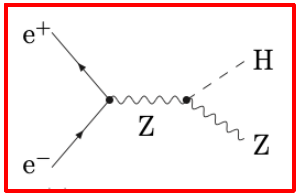
- In early 80s Higgs boson was assumed of key importance! The only missing piece of the SM jigsaw:
    - SM worked so well that the boson had to be present

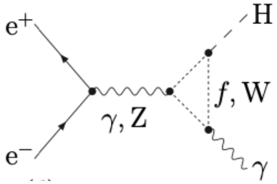
- But it required collider energetic enough to produce it.
- Finding the Higgs was one of the main objectives of the LHC

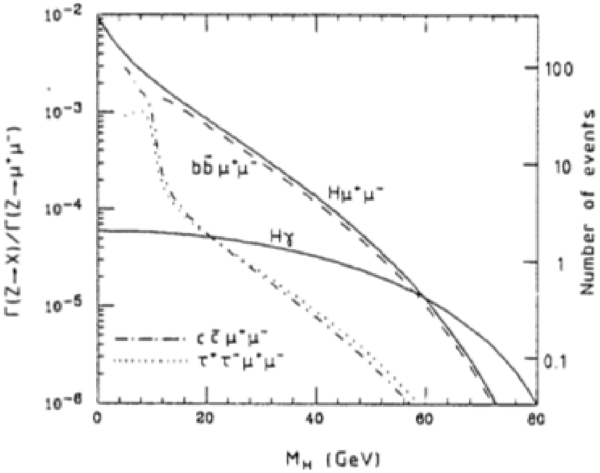
Quest for a Higgs Boson at LEP (e^+e^-)

LEP 1 $(\sqrt{s} = m_Z)$

1989-95 (~17M Z)

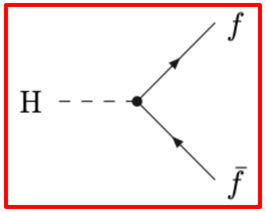






The dominant production process would be the higgs strahlung. Additionally, due to clean leptonic Z decays (e^+e^-, $\mu^+\mu^-, \nu\bar{\nu}$) this was the only channel probed.

In the relevant mass range, the dominant decay to a pair f *b* quarks ($m_H > \sim 10$ GeV), or lighter quarks and leptons for lower higgs masses.



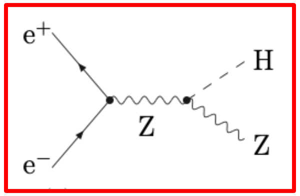
Higgs-boson mass range from 0 to approximately 65 GeV could be probed @LEP1, the four experiments (ALEPH, DELPHI, L3, OPAL) excluded higgs masses below m_H<63.9 GeV.

Due to exponentially falling x-section, increase of data statistics would not increase the reach of LEP1 significantly

Quest for a Higgs Boson at LEP (e^+e^-)

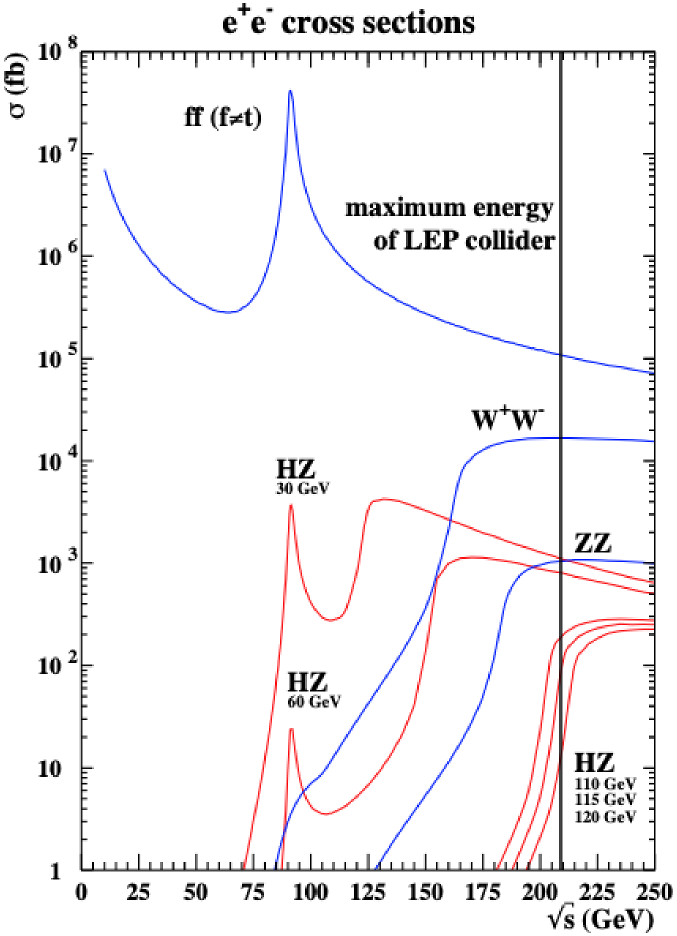
LEP 2 ($\sqrt{s} < 209\text{GeV}$)

1995-2000 (2.5 fb^{-1} @ $\sqrt{s} < 209$)



The higgs strahlung remains dominant.
Better S/B. Bkg mostly WW/ZZ.
In Z^*->ZH, Z is produced on-shell.
This allows to exploit apart from (e^+e^-, $\mu^+\mu^-$, $\nu\bar{\nu}$) also the hadronic Z decays (2 jets with invariant mass of the Z)

The dominant decay to a pair of *b* quarks (tagging of *b*-jets essential!). But H->$\tau\tau$ exploited as well.

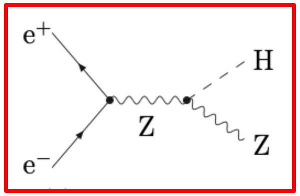


@LEP2, higgs-boson mass was probed up to approximately 120 GeV (kinematic limit)
The combined result from the four experiments (ALEPH, DELPHI, L3, OPAL) excluded higgs masses below m_H<114.4 GeV @ 95% CL.

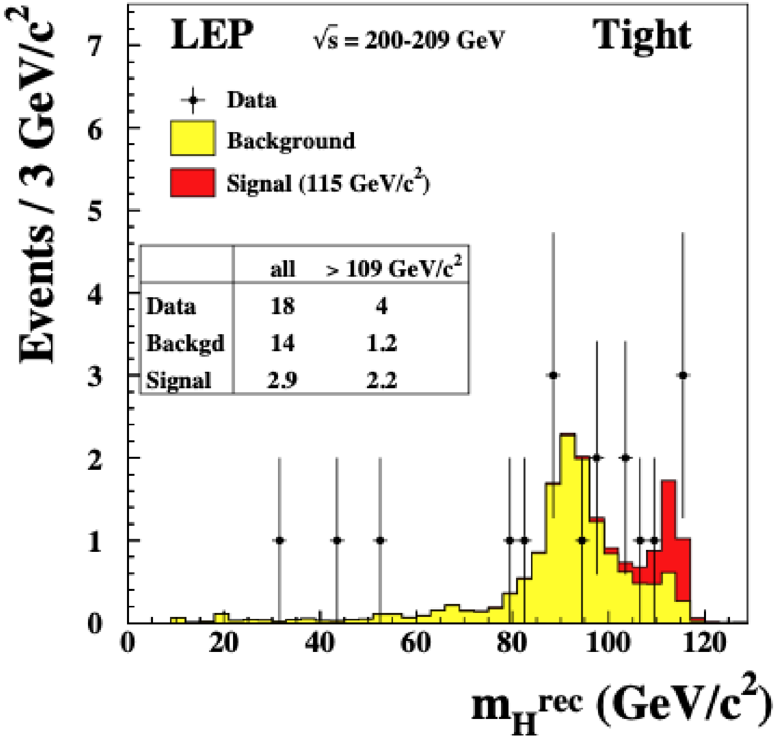
Quest for a Higgs Boson at LEP (e^+e^-)

LEP 2 ($\sqrt{s} < 209\text{GeV}$)

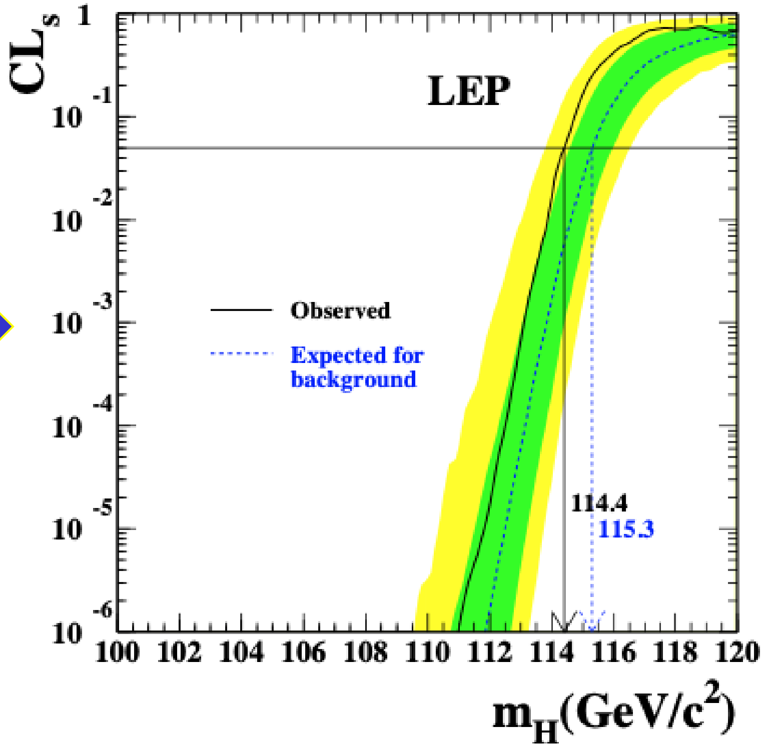
1995-2000 (2.5 fb^{-1} @ $\sqrt{s} < 209$)



($H\to bb$)($Z\to qq$), ($H\to bb$)($Z\to \nu\nu$), ($H\to bb$)($Z\to l^+l^-$), ($H\to bb$)($Z\to \tau^+\tau^-$), ($H\to \tau^+\tau^-$)($Z\to qq$)



	all	> 109 GeV/c²
Data	18	4
Backgd	14	1.2
Signal	2.9	2.2



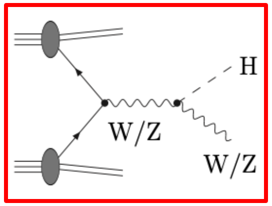
The combined result from the four experiments (ALEPH, DELPHI, L3, OPAL) excluded higgs masses below $m_H < 114.4$ GeV (exp. 115.3) @ 95% CL.

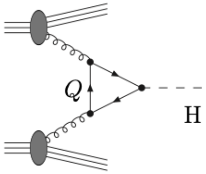
It was really close!!!

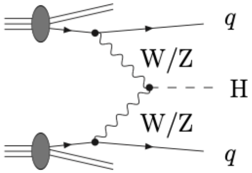
Quest for a Higgs Boson at the Tevatron ($p\bar{p}$)

Tevatron II ($\sqrt{s} = 1.96$ TeV)

2001-2011 (~10 fb^{-1})



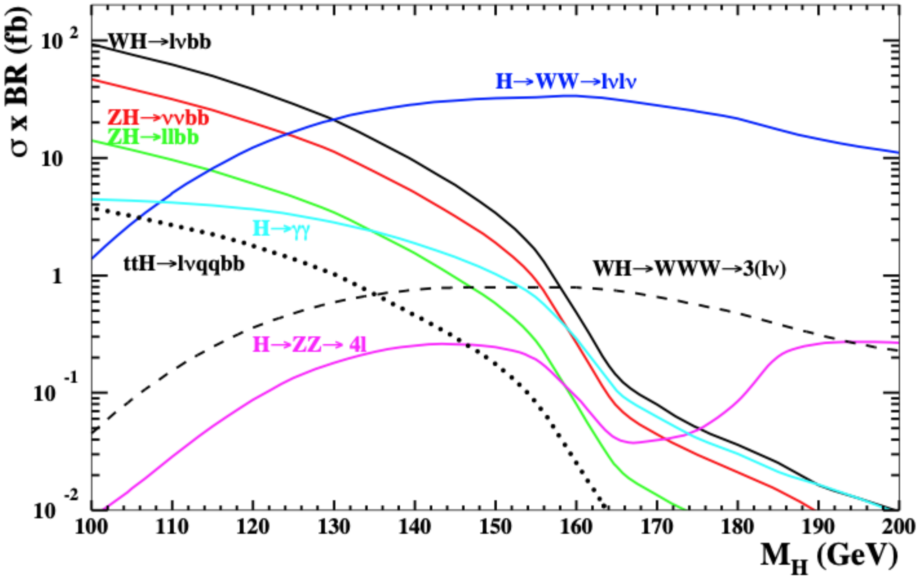




The g-g fusion has the largest x-section, but can be exploited only in leptonic higgs decays - trigger!. ($WW \rightarrow l\nu l\nu, ZZ \rightarrow 4l, ZZ \rightarrow 4\nu$)

The most significant process is the associated production (VH), with subsequent higgs decay to *b* quarks.

MVA techniques used to discriminate higgs signal against background.

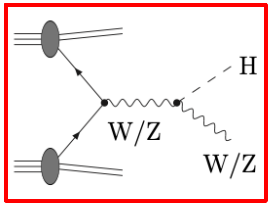


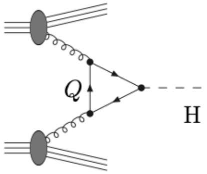
Higgs-boson was searched for in the mass range from 90 to 200 GeV.
The two experiments (CDF, D0) excluded higgs masses [90, 109] and [149, 182] GeV.
An excess of 3.0σ for m_H=125 GeV was observed.

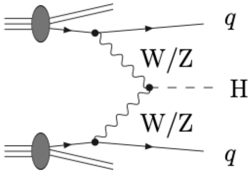
Quest for a Higgs Boson at the Tevatron ($p\bar{p}$)

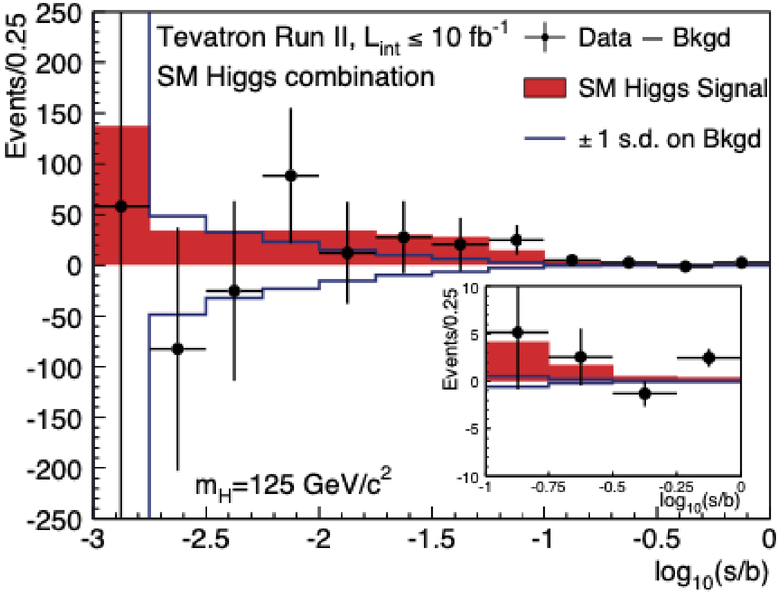
Tevatron II ($\sqrt{s} = 1.96$ TeV)

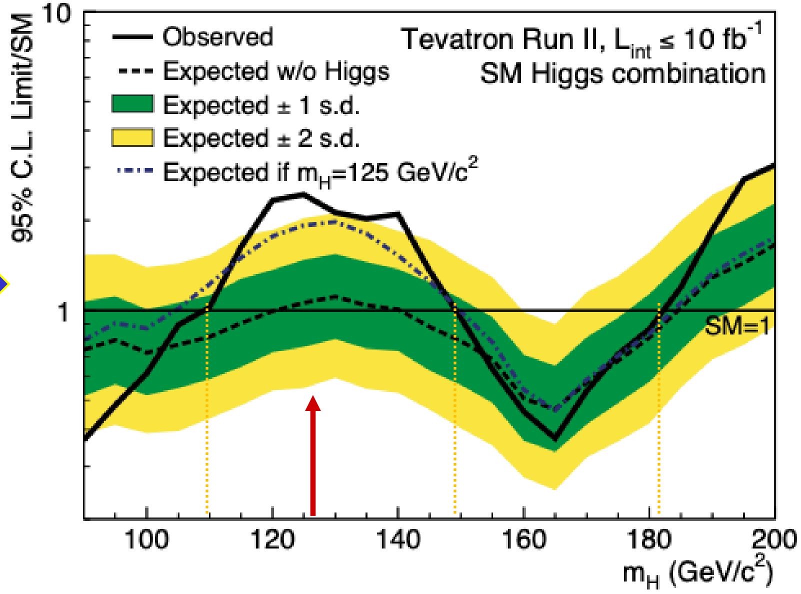
2001-2011 (~10 fb^{-1})







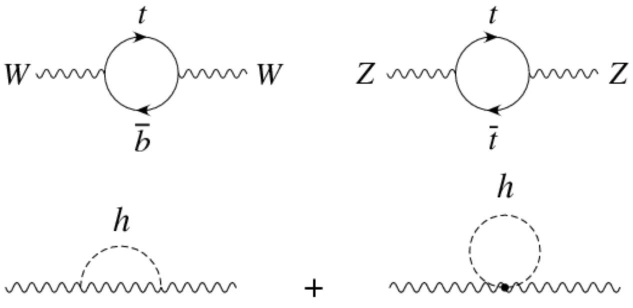




The two experiments (CDF, D0) excluded higgs masses [90, 109] and [149, 182] GeV.

At the same time, an excess of ~3.0σ for m_H=125 GeV was observed.

Before LHC turned on - EW fit of the Higgs mass



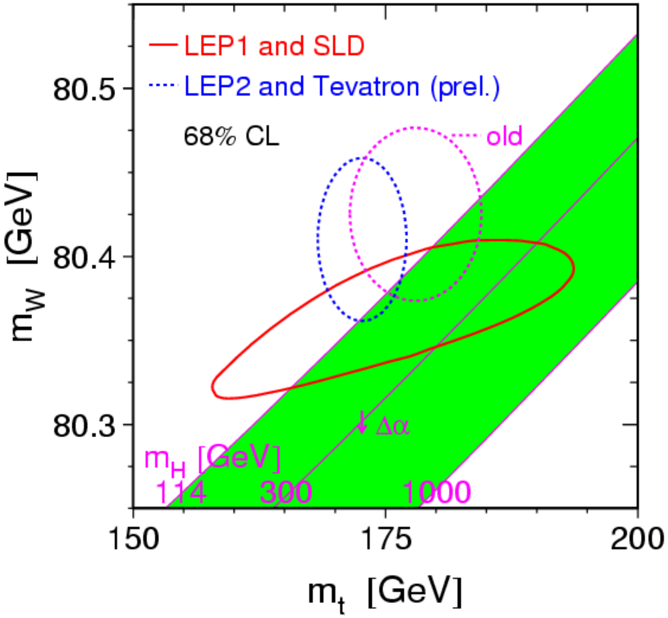
$$(\Delta r)_{\rm top} \approx -\frac{3G_F \boxed{m_t^2}}{8\sqrt{2}\pi^2}\frac{c_W^2}{s_W^2}$$

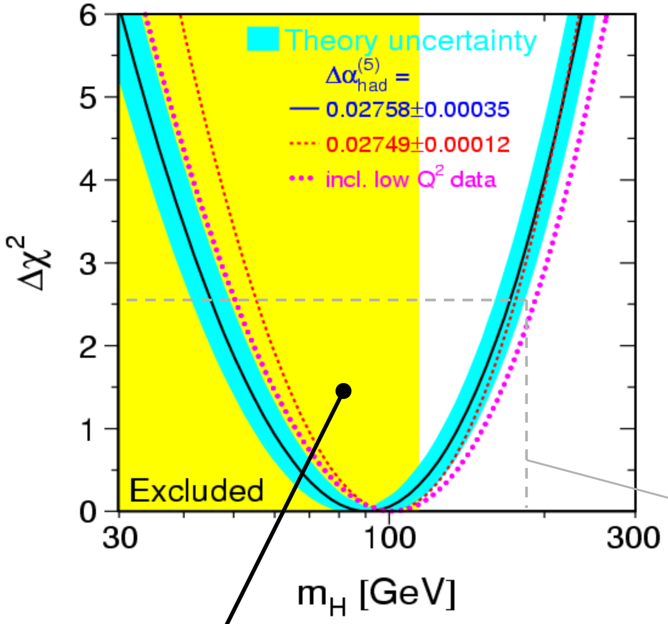
$$(\Delta r)_{\rm Higgs} \approx \frac{11 G_F M_Z^2 c_W^2}{24\sqrt{2}\pi^2}\boxed{\ln\frac{m_h^2}{m_Z^2}}$$

only logarithmic dependence

$$M_W^2 = \frac{\frac{\pi\alpha}{\sqrt{2}G_F}}{s_W^2(1-\boxed{\Delta r})}$$

$$s_W^2 \equiv 1 - \frac{M_W^2}{M_Z^2}.$$





LEP direct: m_H>114.4 @ 95% CL

Status of summer 2005 (hep-ex/0511027):

Top quark mass = 172.7 +- 2.9 GeV (Tevatron)

m_W=80.410 +-0.032 GeV (LEP)

$m_H=91_{-32}^{+45}$ GeV/c^2

m_H<186 GeV/c^2 @ 95% CL (theory incl.)

χ^2 contribution: $\Delta m_W \sim 0.007 \times \Delta m_t$

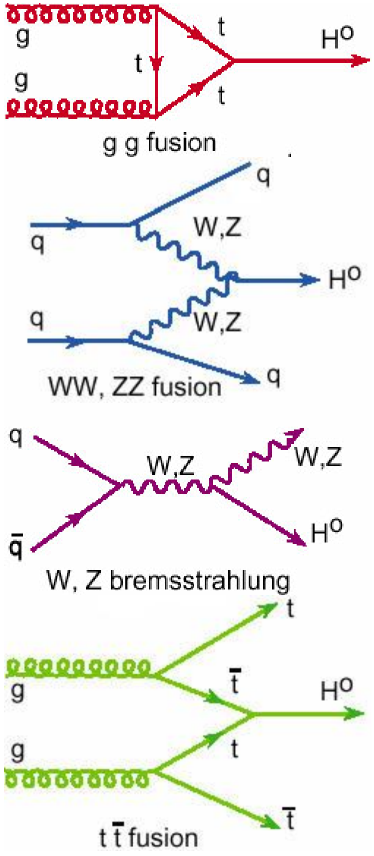
LHC goal: $\Delta m_t \sim 1$ GeV/c^2

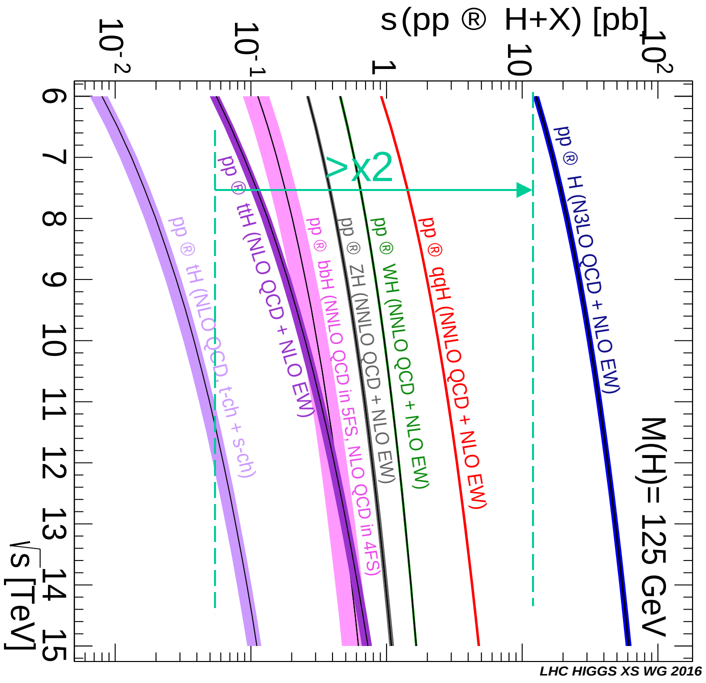
Hope to go down to $\delta m_W \approx 0.015$ GeV @LHC

Production and Decay of the SM Higgs Boson at the LHC

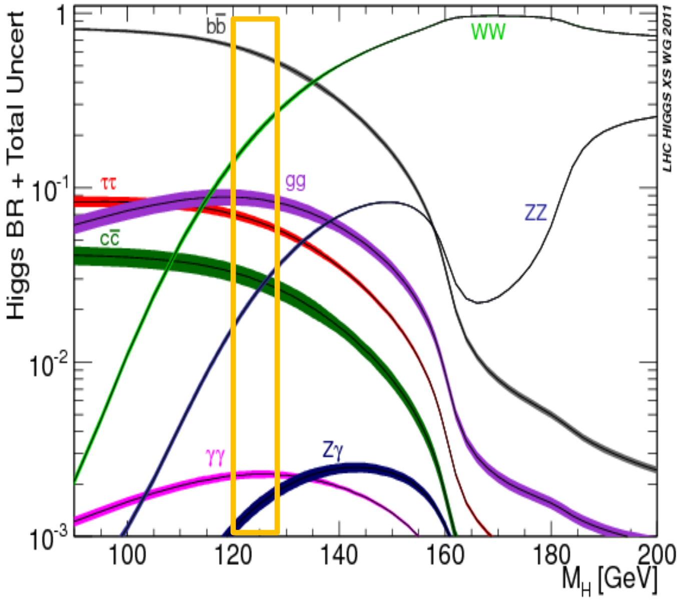
Production (gg Fusion dominant)

Higgs coupling proportional to mass ⇒ Higgs generaly decays to heaviest particles possible





← production @ LHC



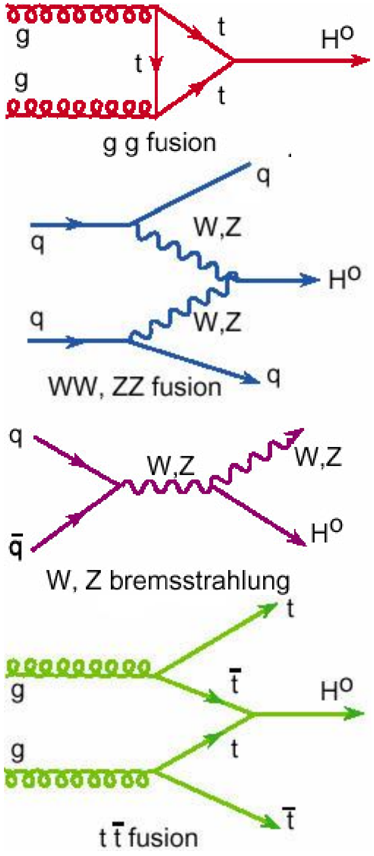
Higgs decay branching →

Production and Decay of the SM Higgs Boson at the LHC

Production (gg Fusion dominant)

Higgs coupling proportional to mass ⇒ Higgs generaly decays to heaviest particles possible

@13 TeV



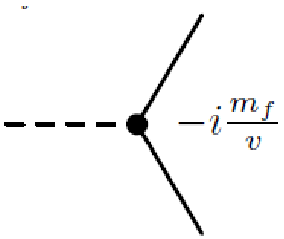
88%
(~48.6pb)

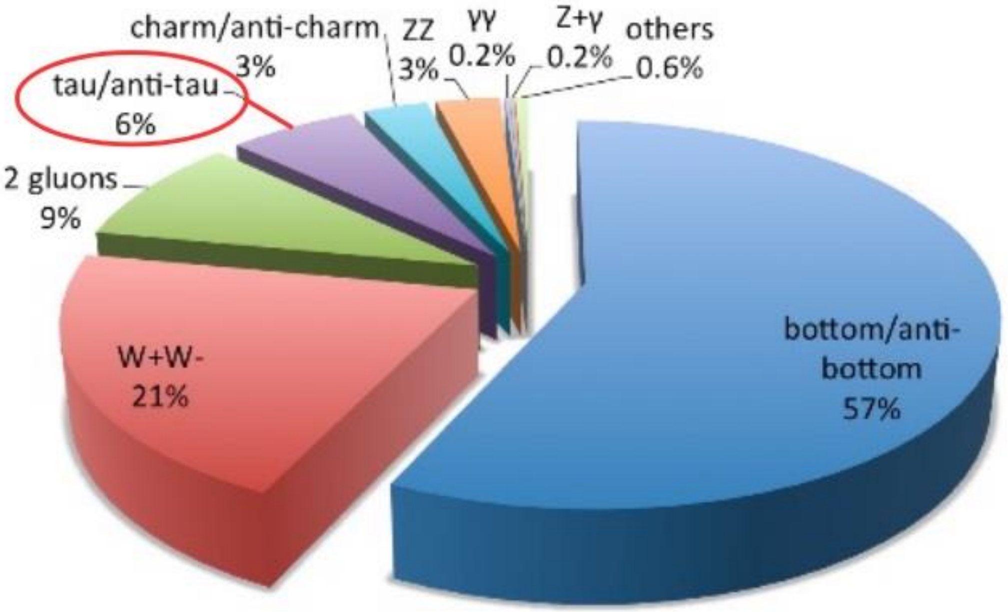
7%
(~3.8pb)

4%
(~2.2pb)

1%
(~0.5pb)

Decays of
125 GeV higgs boson





ATLAS Detector

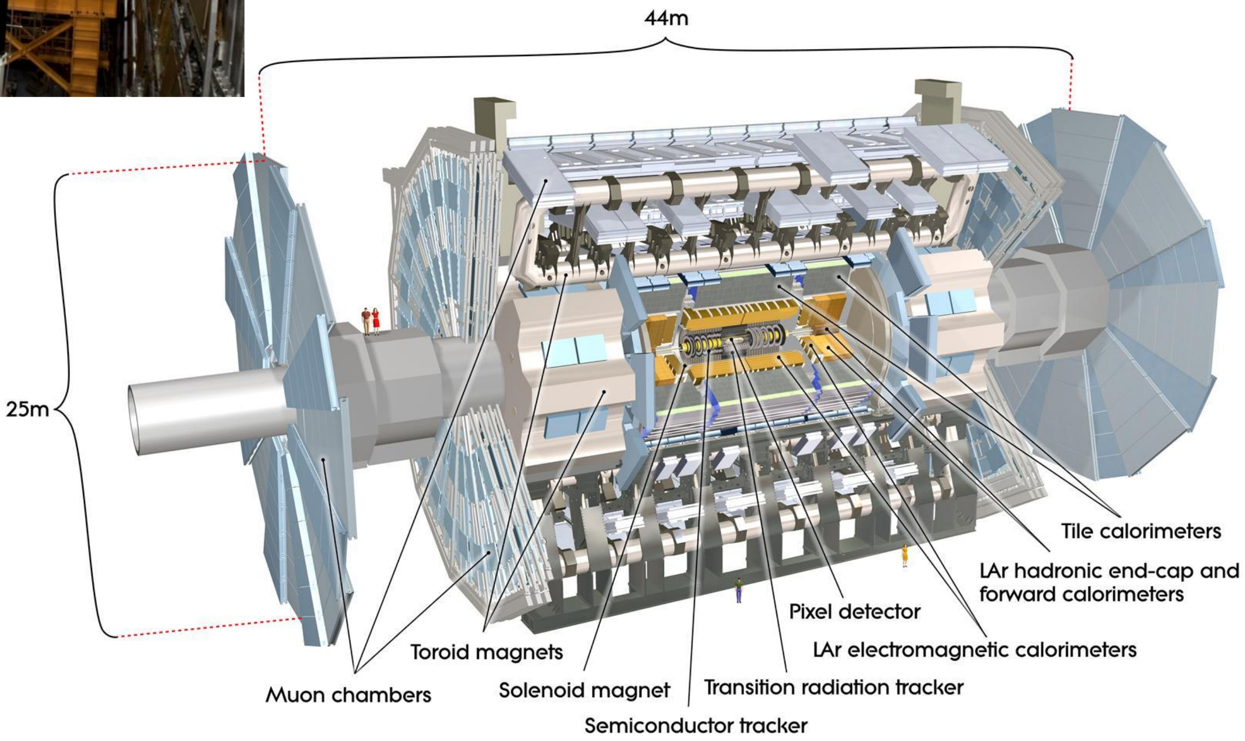
	ATLAS
Magnetic field	2 T solenoid + toroid: 0.5 T (barrel), 1 T (endcap)
Tracker	Silicon pixels and strips + transition radiation tracker $\sigma/p_T \approx 5 \cdot 10^{-4} p_T + 0.01$
EM calorimeter	Liquid argon + Pb absorbers $\sigma/E \approx 10\%/\sqrt{E} + 0.007$
Hadronic calorimeter	Fe + scintillator / Cu+LAr (10λ) $\sigma/E \approx 50\%/\sqrt{E} + 0.03$ GeV
Muon	$\sigma/p_T \approx 2\%$ @ 50GeV to 10% @ 1TeV (Inner Tracker + muon system)
Trigger	L1 + HLT (L2+EF)

ATLAS Collaboration

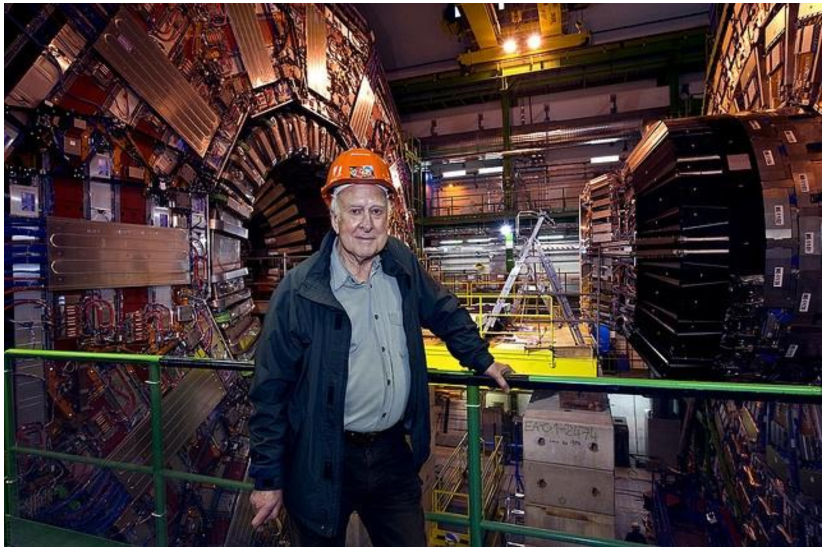
38 Countries

175 Institutions

3000 Scientific Authors total



CMS Detector

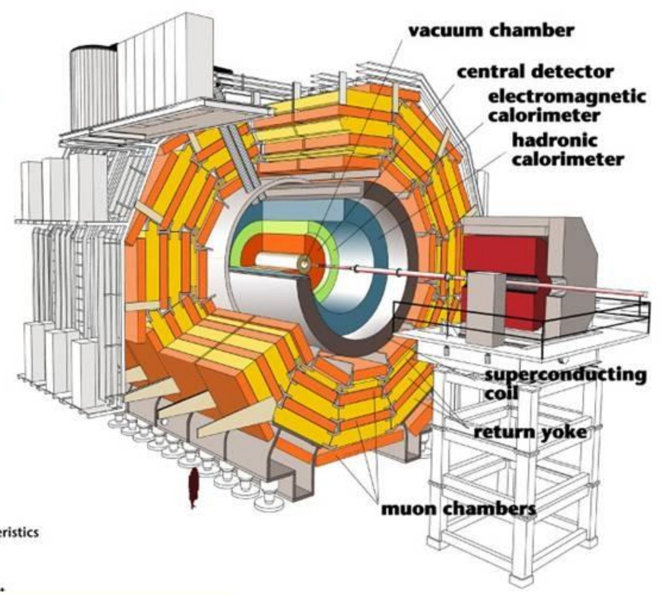


CMS Collaboration

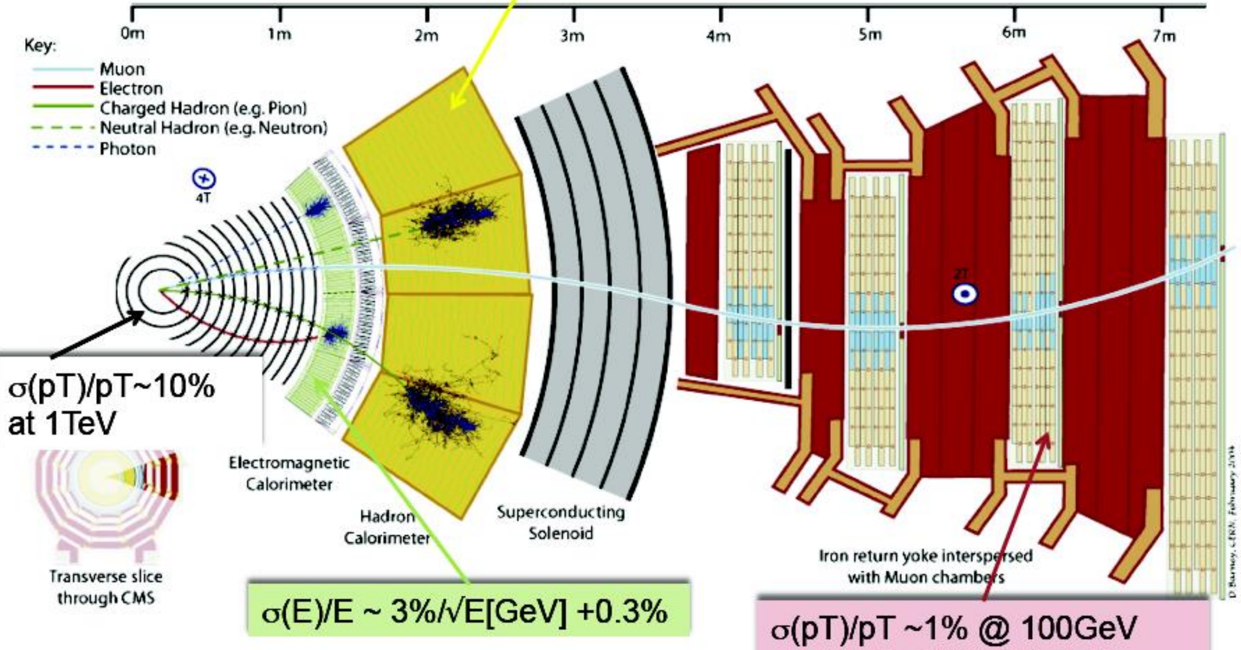
42 Countries

182 Institutions

3300 Scientific Authors total



σ(E_T)/E_T ~ 100%/√E_T[GeV] +5%

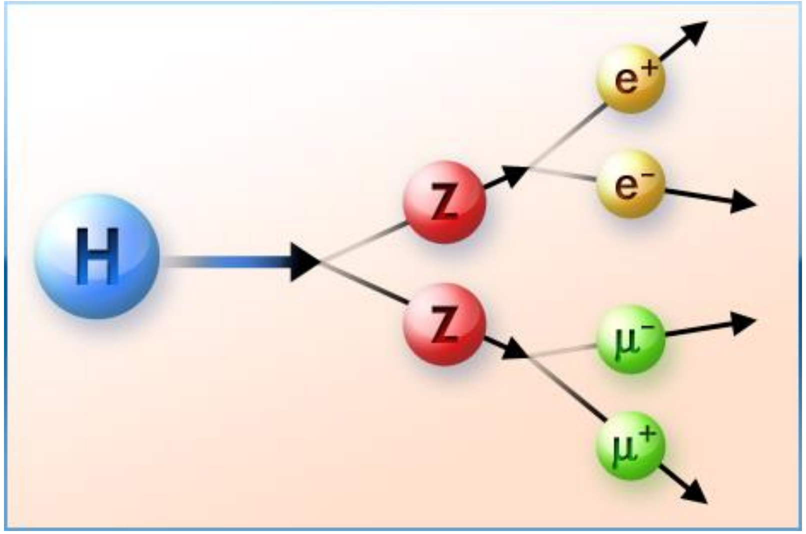


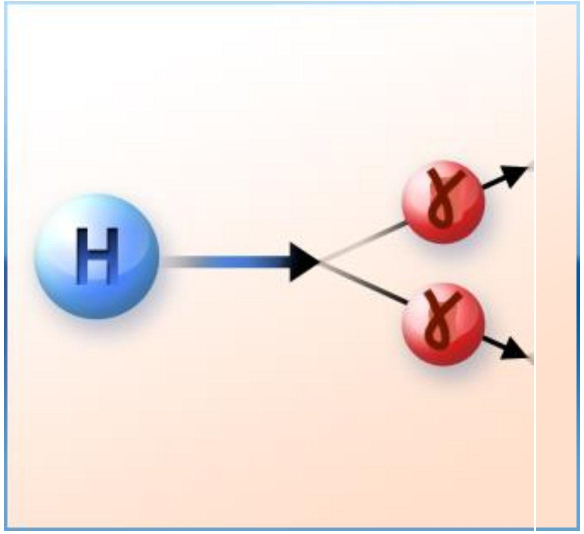
σ(pT)/pT~10% at 1TeV

σ(E)/E ~ 3%/√E[GeV] +0.3%

σ(pT)/pT ~1% @ 100GeV
σ(pT)/pT ~10% @1 TeV

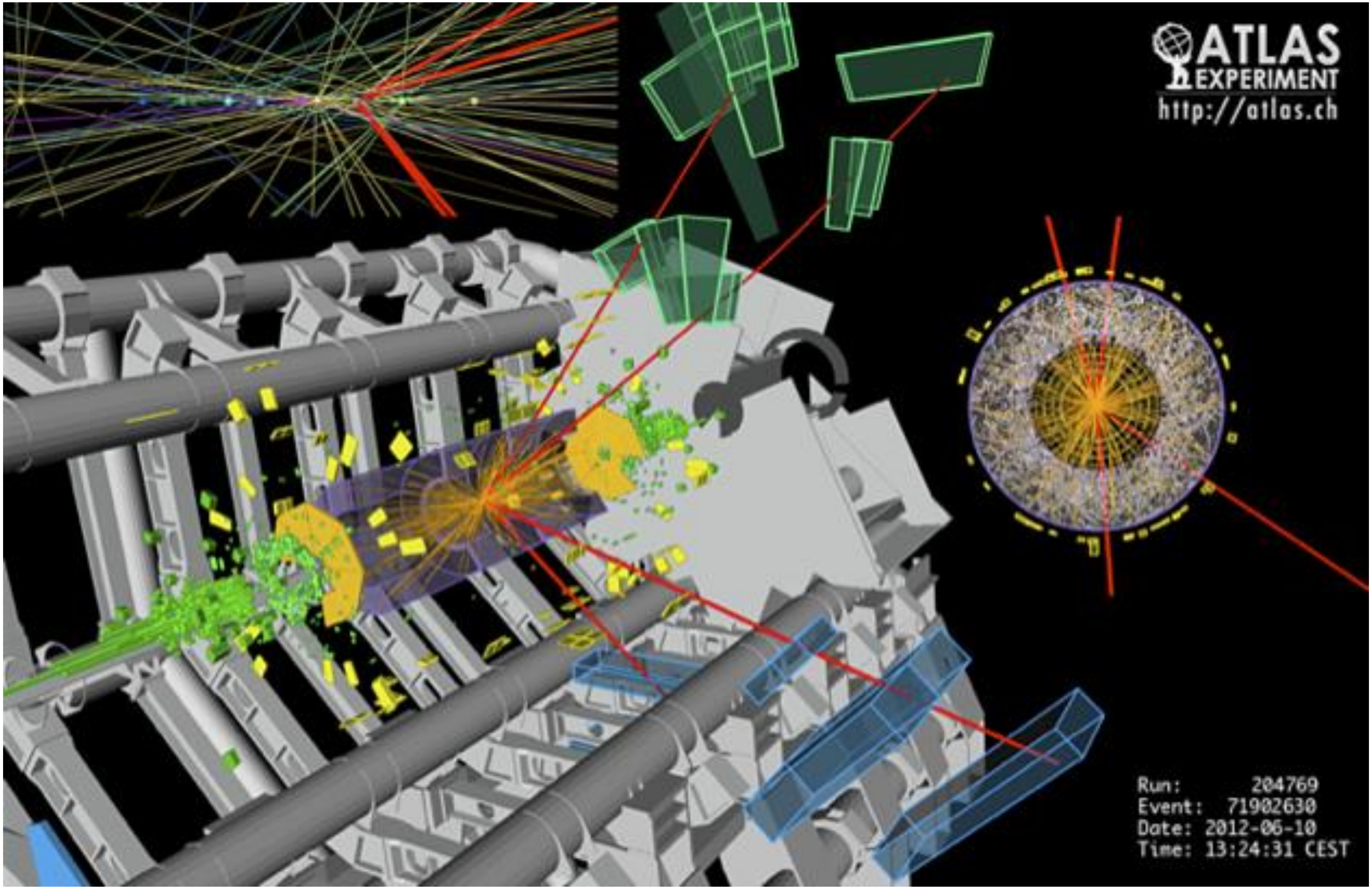
How was the Higgs Boson finally observed?



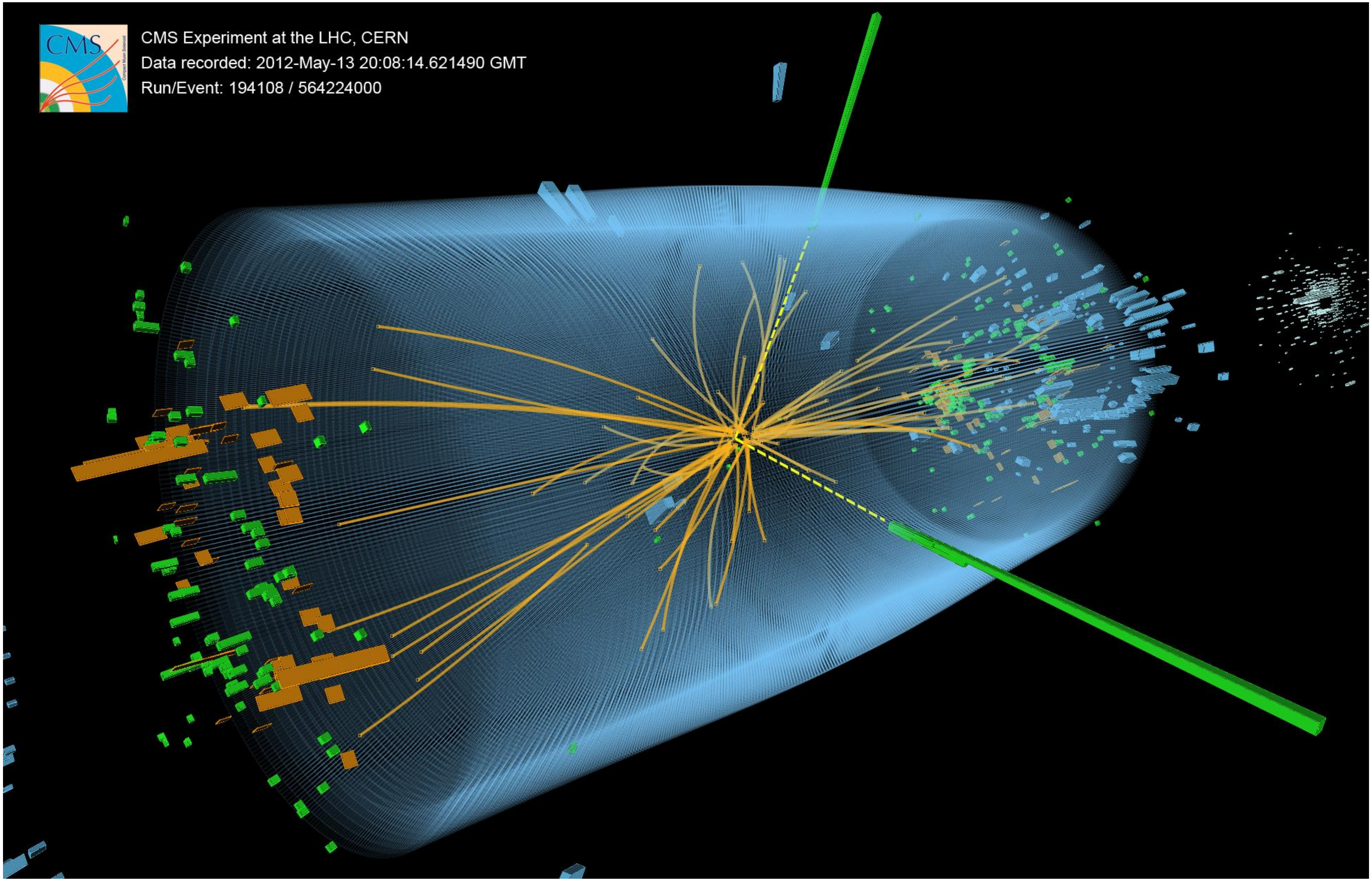


"Golden" decay chanels. Give the largest chance of detection!
(compromise between the rate and amount of background)

$H \rightarrow ZZ^{*} \rightarrow 4l$ candidate



$H \rightarrow \gamma\gamma$ candidate



2012

CERN, 4 July 2012

Discovery of a Higgs-like particle decaying to gauge bosons

2012

CERN, 4 July 2012

2013 NOBEL PRIZE IN PHYSICS

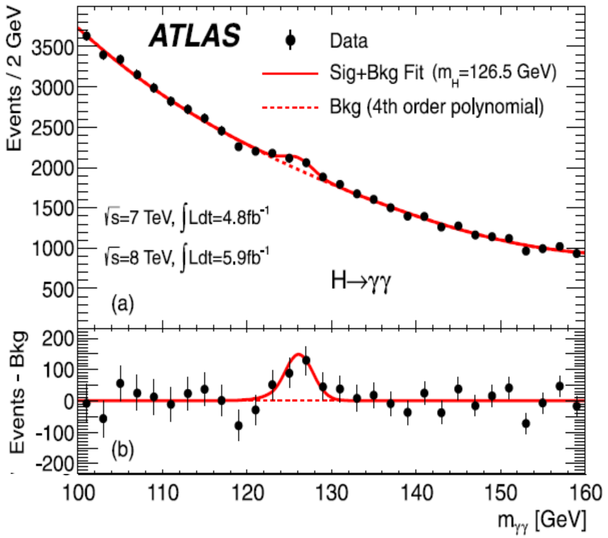
François Englert
Peter W. Higgs

© The Nobel Foundation. Photo: Lovisa Engblom.

… what was observed

$H \rightarrow \gamma\gamma$

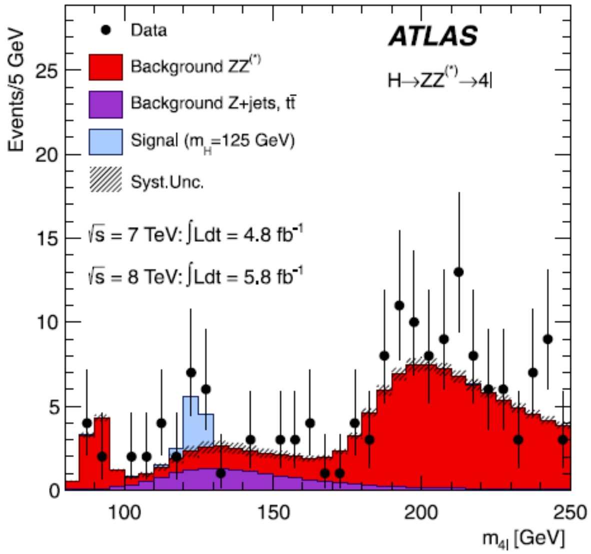
$H \rightarrow ZZ^{*} \rightarrow 4l$

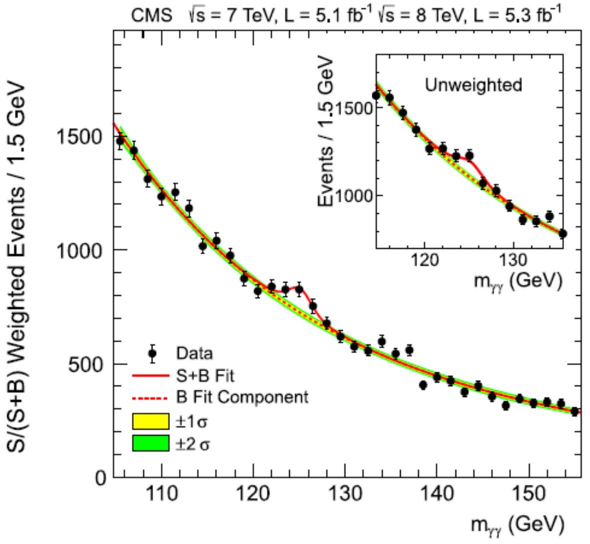


ATLAS

126.0±0.4 (stat)±0.4 (sys) GeV

GS = 5.1σ

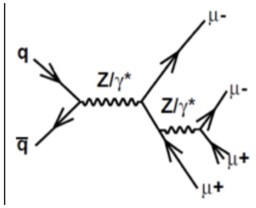


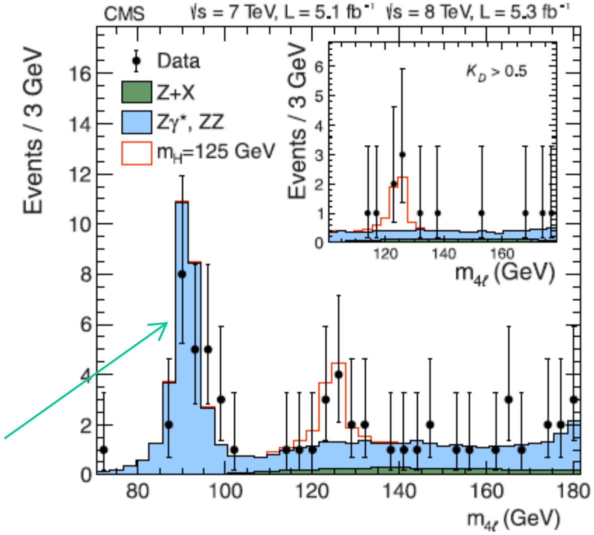


CMS

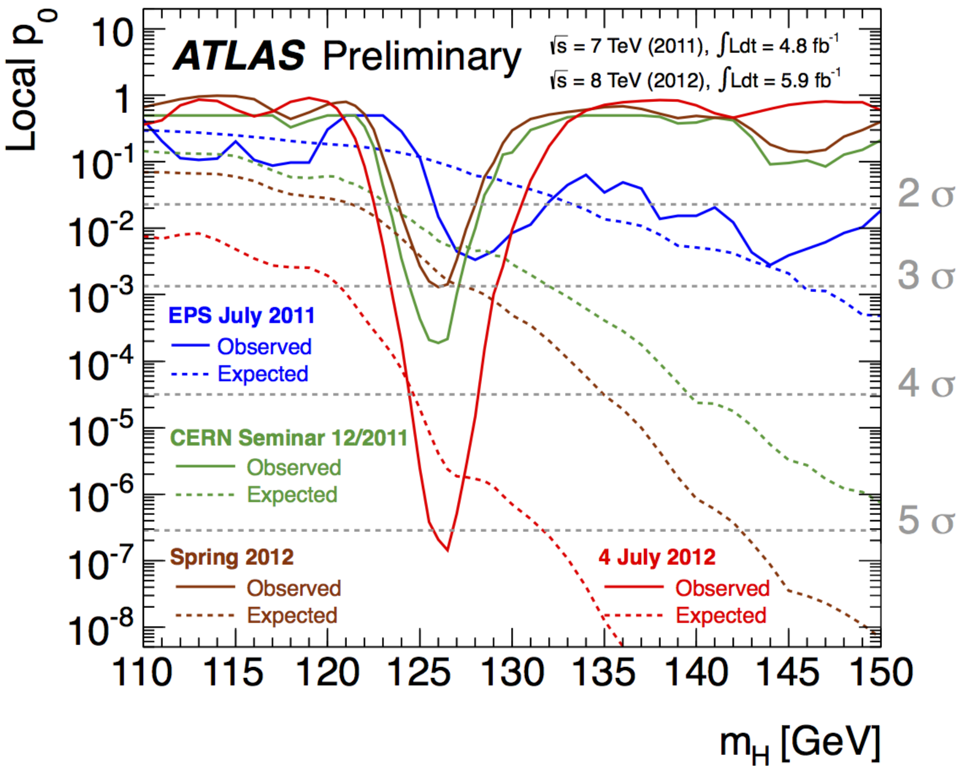
125.3±0.4 (stat)±0.5 (sys) GeV

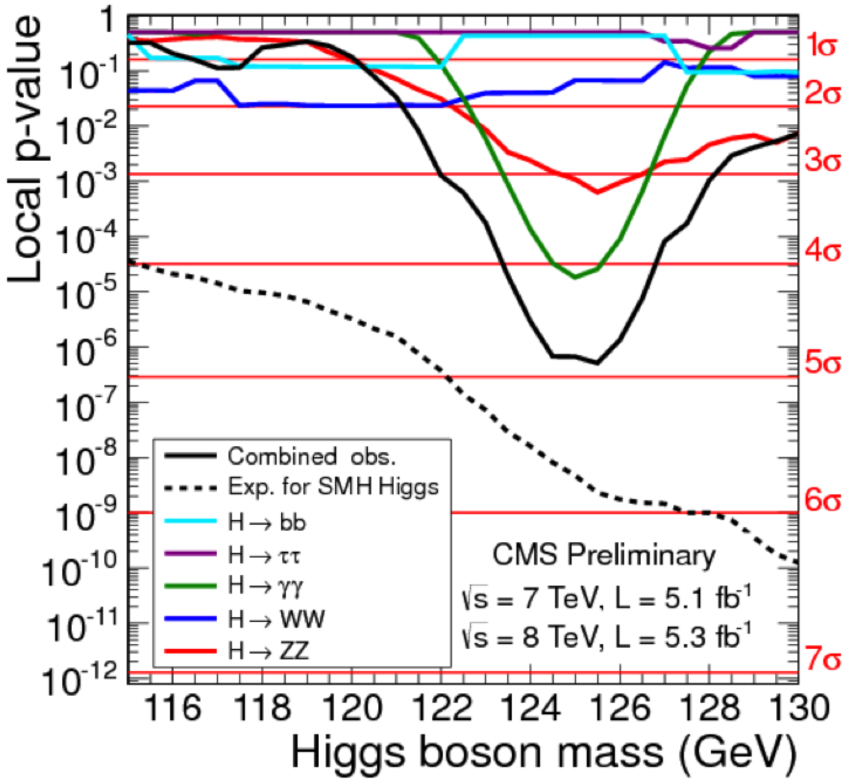
GS = 4.6σ





… and the conclusion!



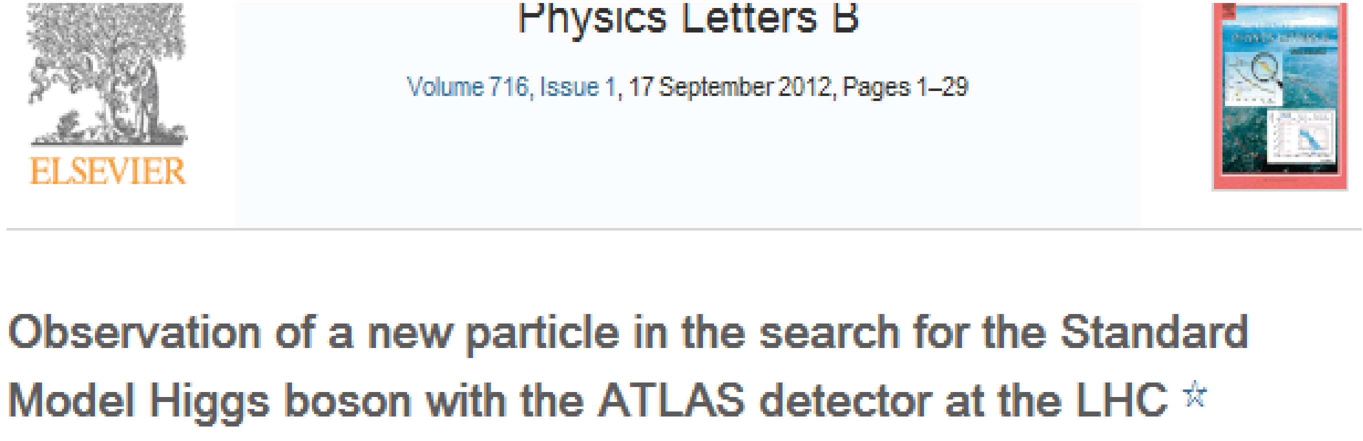


We observe an excess of events at m_H 126.5 GeV with local significance 5.0 σ
The excess is driven by the two high mass resolution channels:
$H \rightarrow \gamma\gamma$ (4.5 σ) and $H \rightarrow ZZ^* \rightarrow 4l$ (3.4 σ)

We have observed a new boson with a mass of 125.3 ± 0.6 GeV at
4.9 σ significance !

Owing to Landau-Yang theorem, decaying to a *γγ* pair, it cannot be a vector boson. It has to be either a scalar or a tensor (spin=2). The latter option, was quickly experimentally excluded.

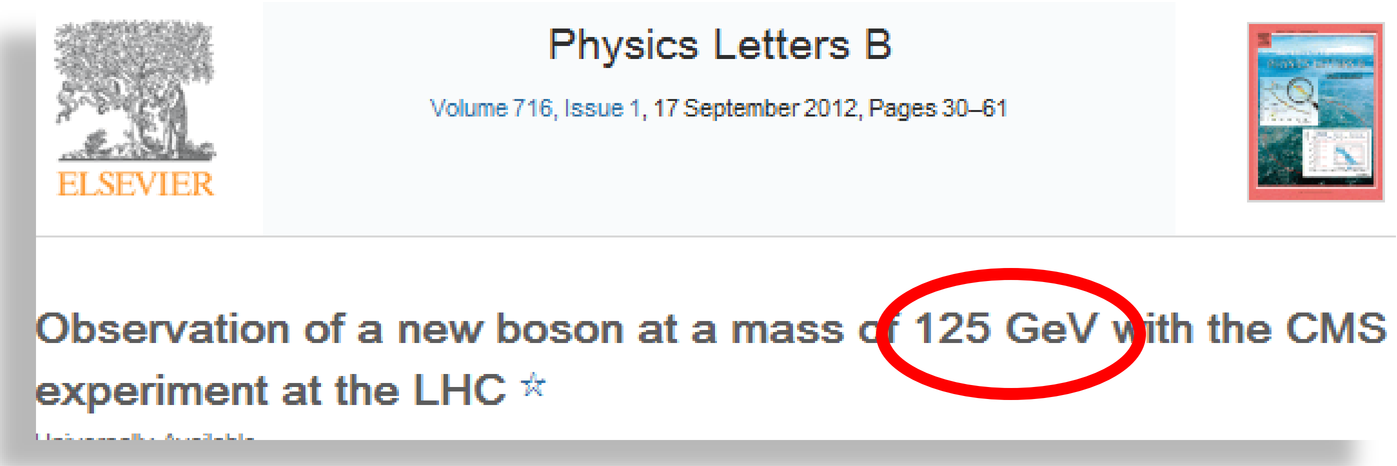
The big triumph!



Physics Letters B

Volume 716, Issue 1, 17 September 2012, Pages 1–29

Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ☆

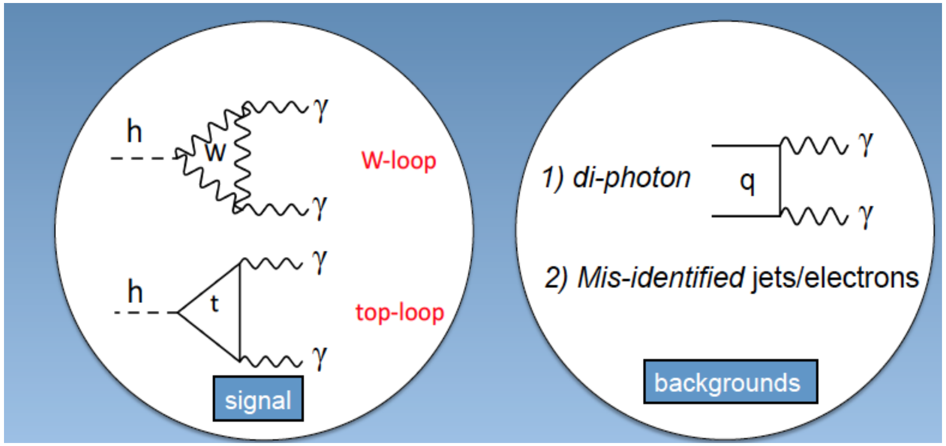


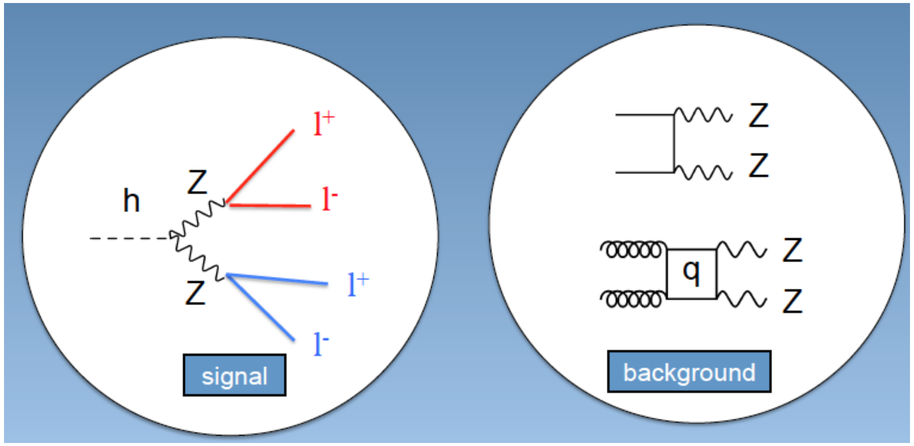
Physics Letters B

Volume 716, Issue 1, 17 September 2012, Pages 30–61

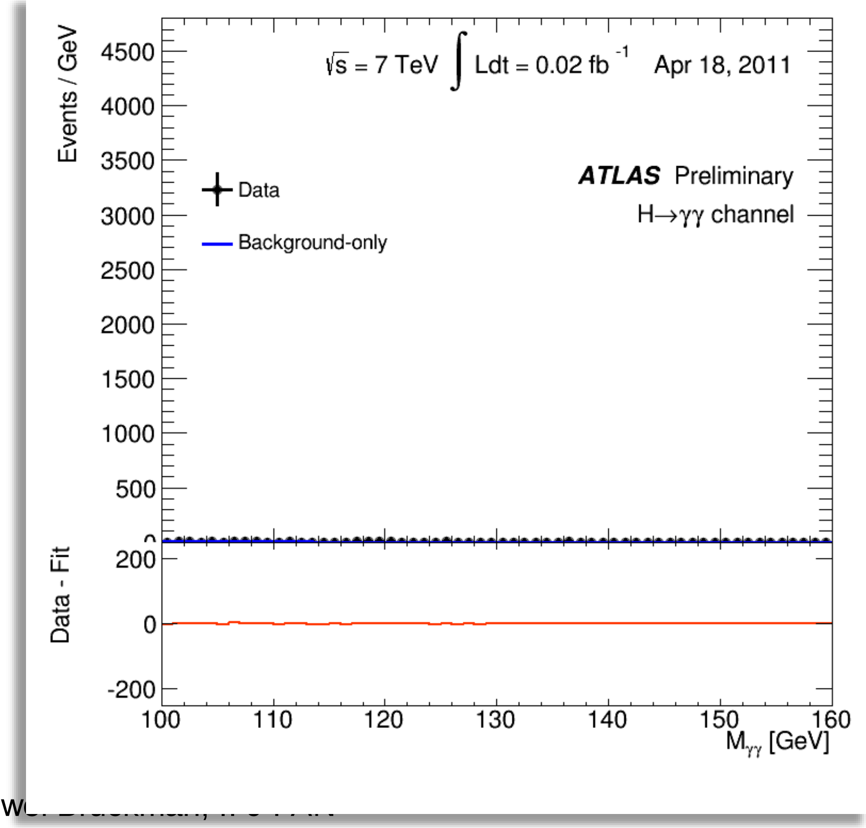
Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC ☆

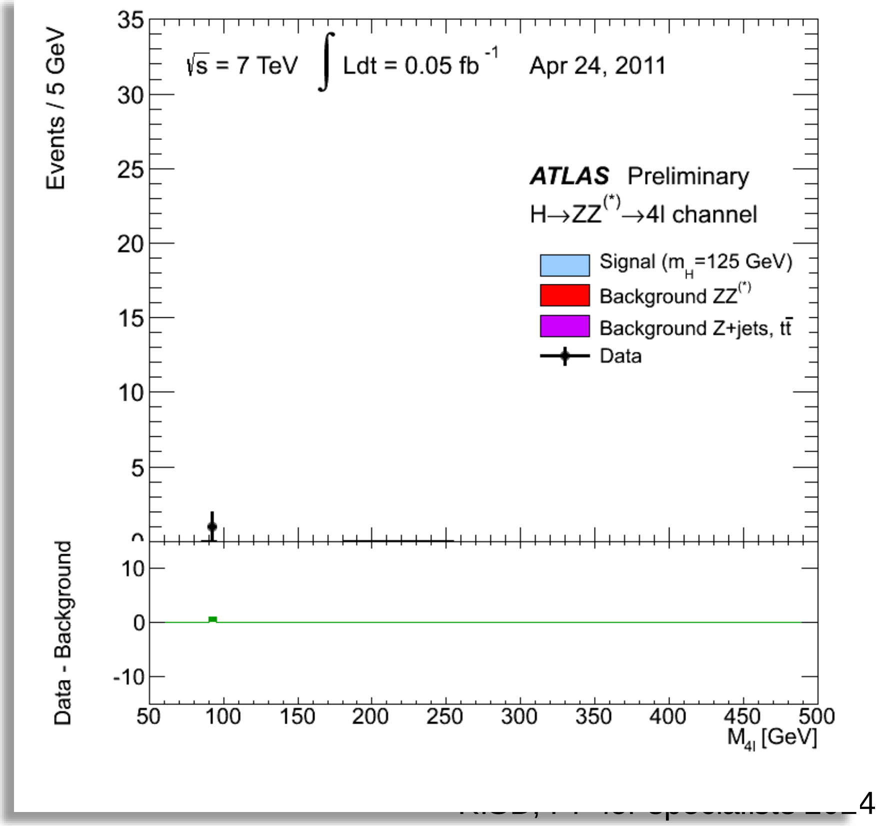
The two "cleanest" (discovery) channels - ATLAS, end 2012





RETROSPECTIVE

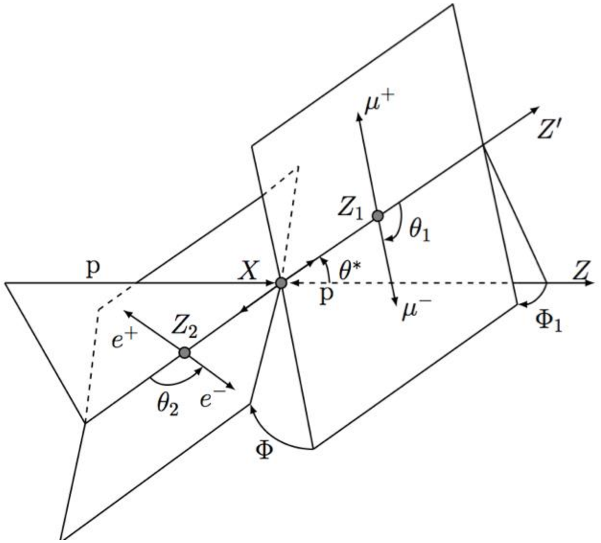


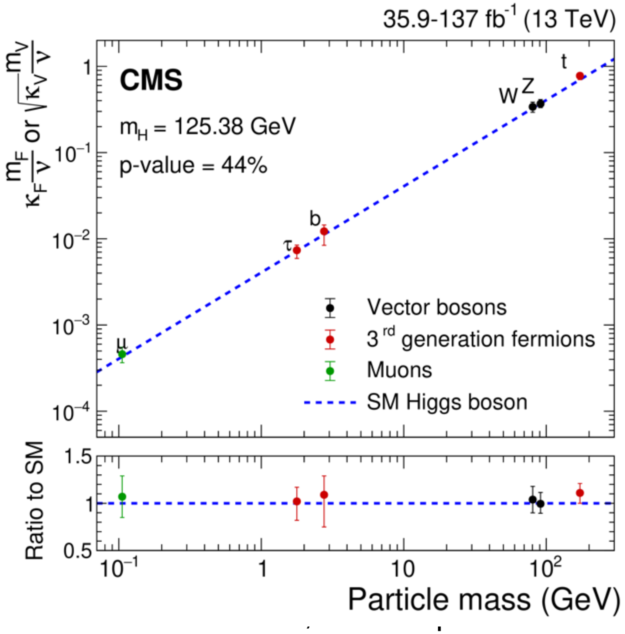


How did we know what was actually observed?

QM assures us that:

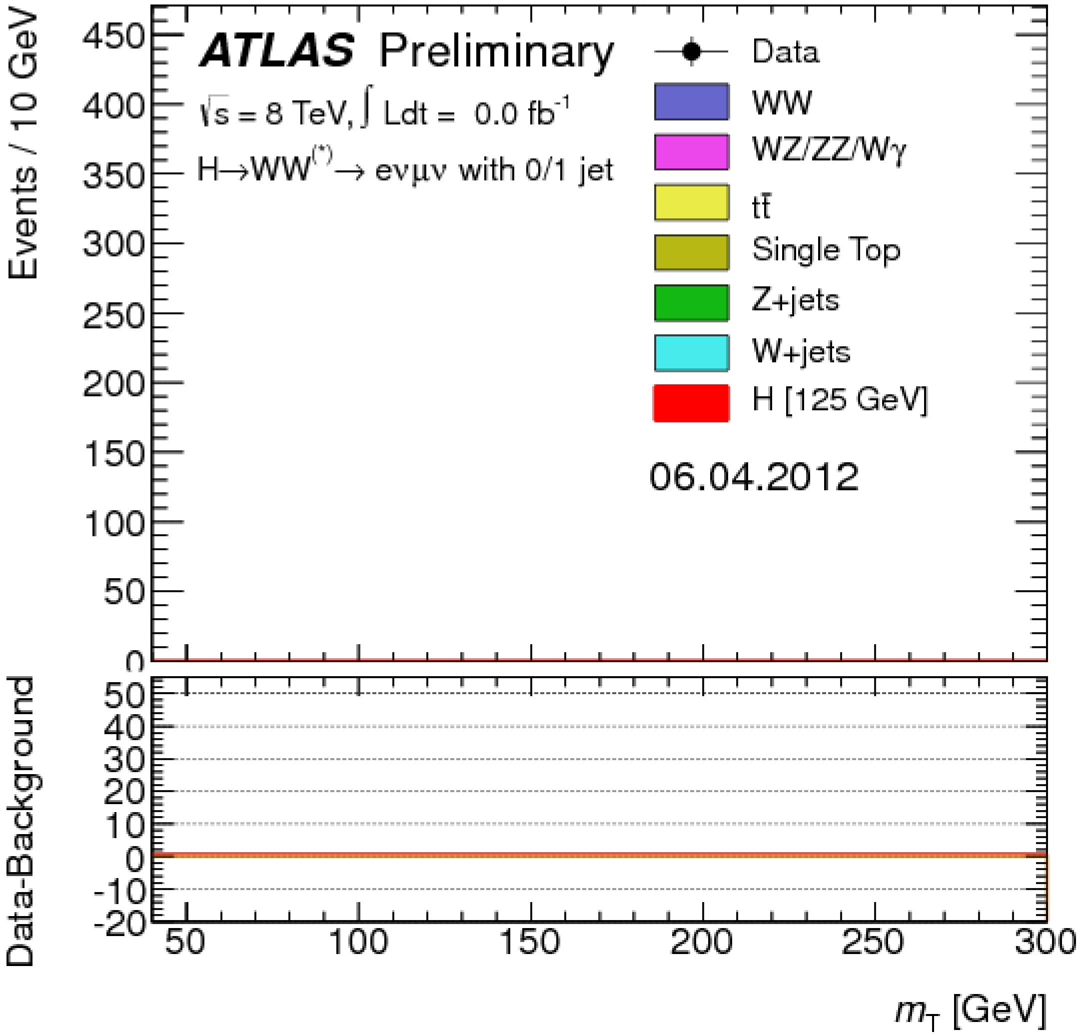
1. H->2 bosons (γγ) -> must be a boson
2. H->2 photons -> cannot be a vector boson (S=1). Options left: 0, 2.
3. Analysis of angular distributions in H->4l excluded S=2 @99% CL, fully confirming the S=0 hypothesis (scalar!)
4. Couplings to SM particles are key features of the Higgs boson – they depend on the particle mass!





$H \to WW^* \to e\nu\mu\nu$ - ATLAS, end 2012

RETROSPECTIVE

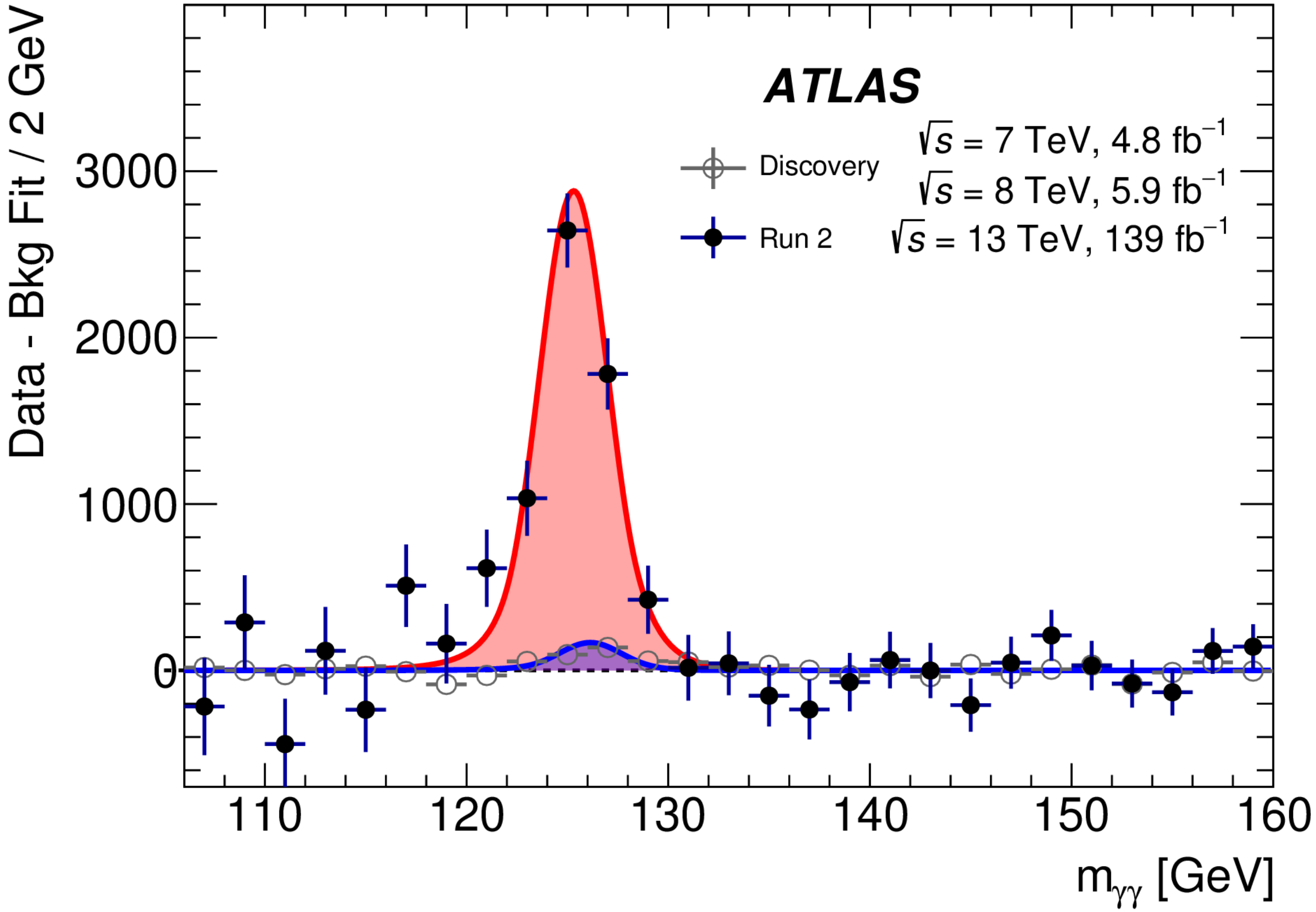


06.04.2012

$$m_{\mathrm{T}} = ((E_{\mathrm{T}}^{\ell\ell} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - |\,\mathbf{p}_{\mathrm{T}}^{\ell\ell} + \mathbf{E}_{\mathrm{T}}^{\mathrm{miss}}\,|^2)^{1/2}$$

Getting to know the 125 GeV scalar

years
HIGGS boson
discovery



Run 2

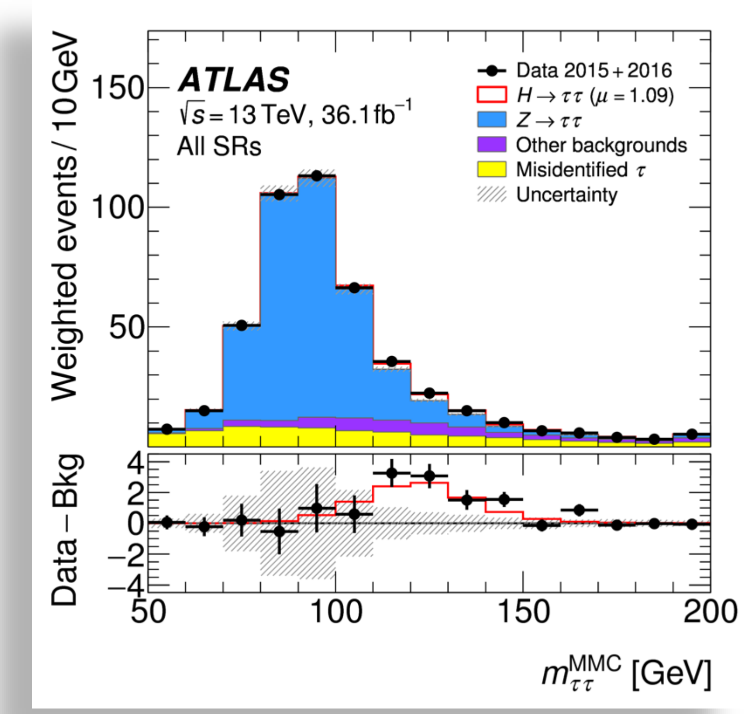
x30

Discovery

2018

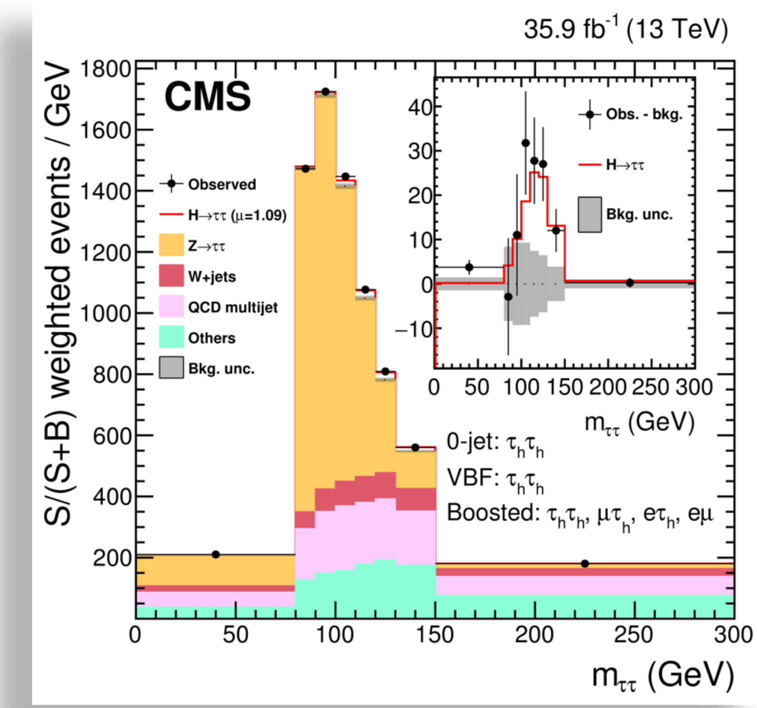
Run 2 (36 fb^{-1}) H->ττ

ATLAS



MMC: Nucl. Instrum. Meth. A 654 (2011) 481

CMS



SVFIT: J. Phys.: Conf. Ser. 513 022035

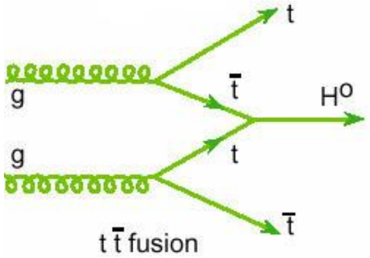
Signal strength: **μ**=1.09 +0.35-0.30
Significance: S=4.4(4.1 exp.)σ
⊕ Run 1:
Significance: S=6.4(5.4 exp.)σ

Signal strength: **μ**=1.09 +0.27-0.26
Significance: S=4.9(4.7 exp.)σ
⊕ Run 1:
Significance: S=5.9(5.9 exp.)σ

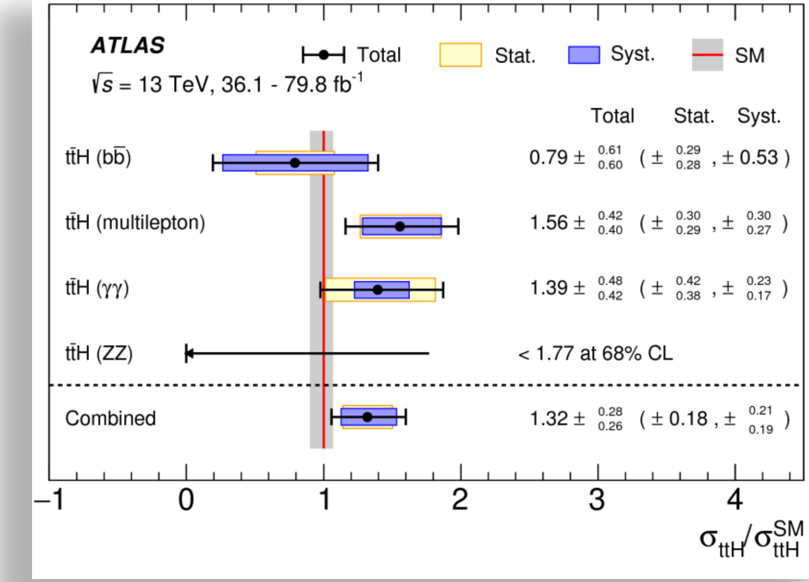
Clear observation!

2018

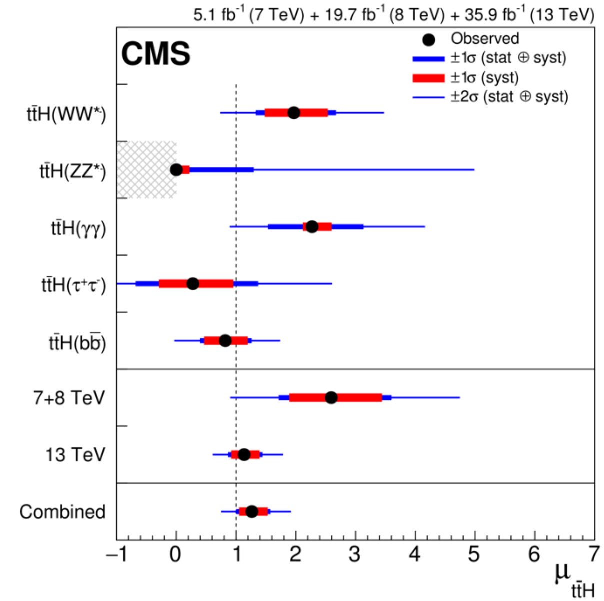
Run 2 ttH



ATLAS



CMS



Higgs decays to WW*, ZZ*, $\gamma\gamma$, $\tau\tau$, *bb* considered

Multiple categories. Final ML fit to bins in $\log_{10}$(S/B)

Signal strength: **μ**=1.32 +0.28-0.26
Significance: S=5.8(4.9 exp.)σ
⊕ Run 1:
Significance: S=6.3(5.1 exp.)σ

Signal strength: **μ**=1.23 +0.45-0.43
Significance: S=3.2(2.8 exp.)σ
⊕ Run 1:
Significance: S=5.2(4.2 exp.)σ

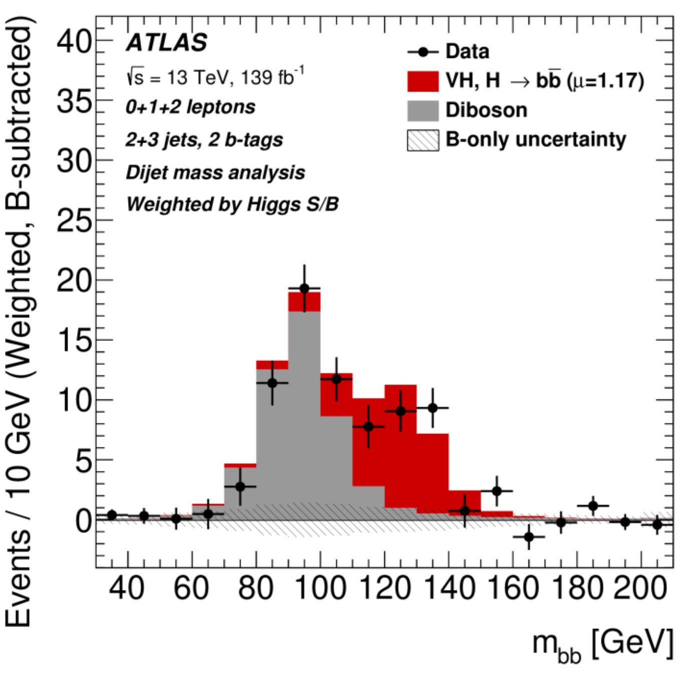
Observation! At last ☺

2020

Run 2 $(139\ \mathrm{fb}^{-1})$ VH, H->bb

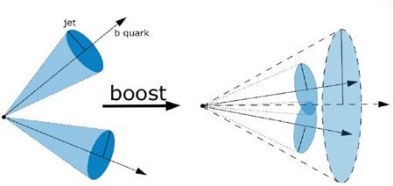
ATLAS

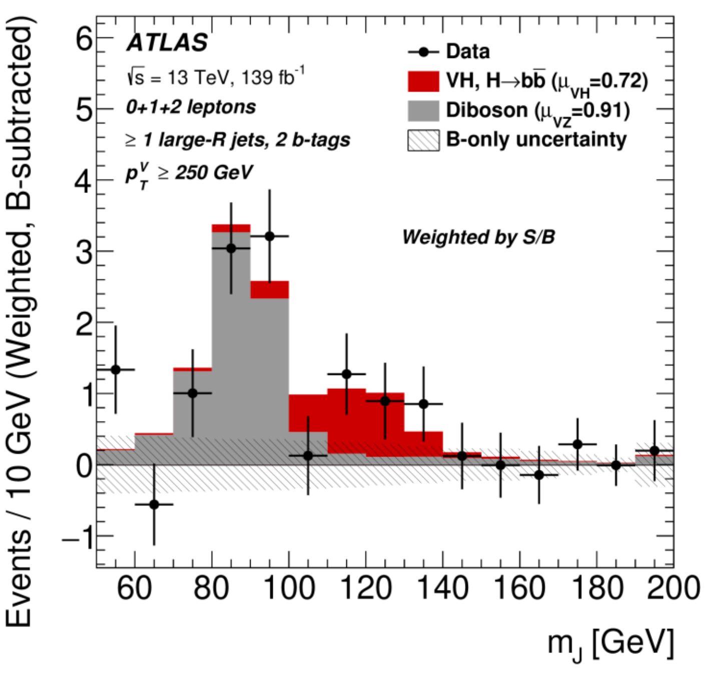
All backgrounds except VZ subtracted



Signal strength: **μ**=1.02 ±0.12 ±0.14
Significance: S=6.7(6.7 exp.)σ
Significance (ZH): S=5.3(5.1 exp.)σ

Boosted analysis: measurement at high p_T - increased sensitivity to BSM physics

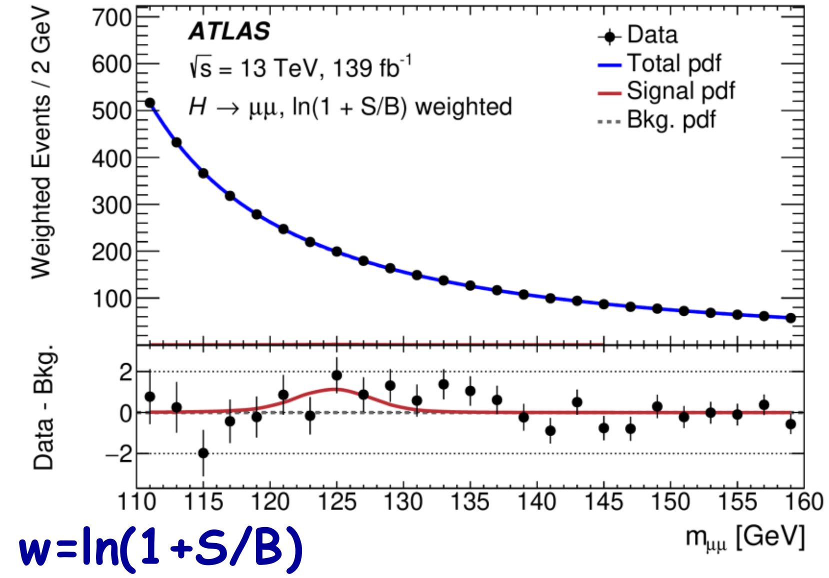




2020

H->μμ

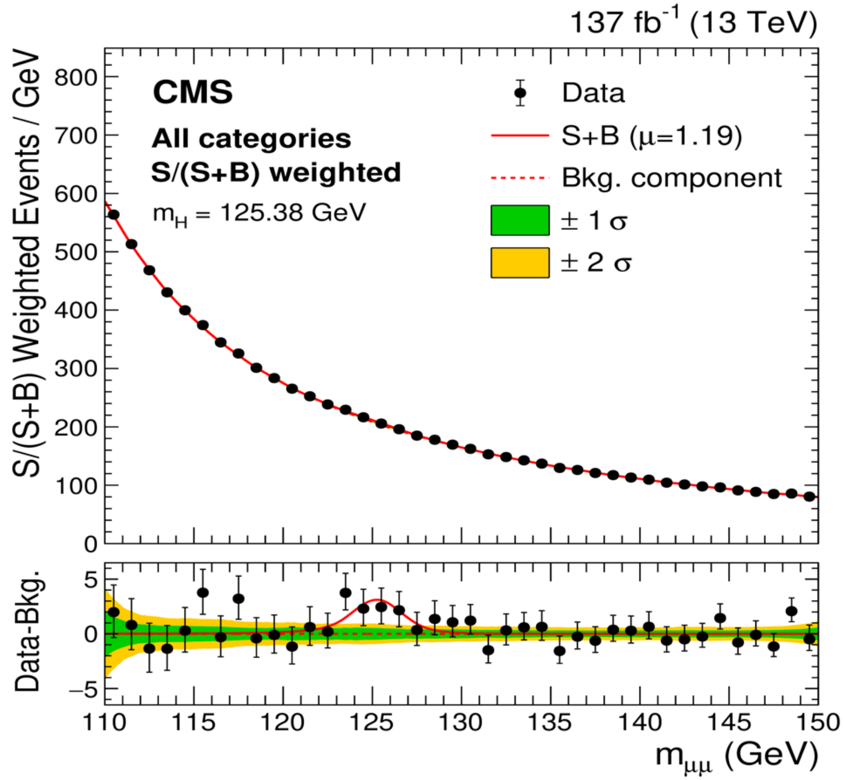
ATLAS



w=ln(1+S/B)

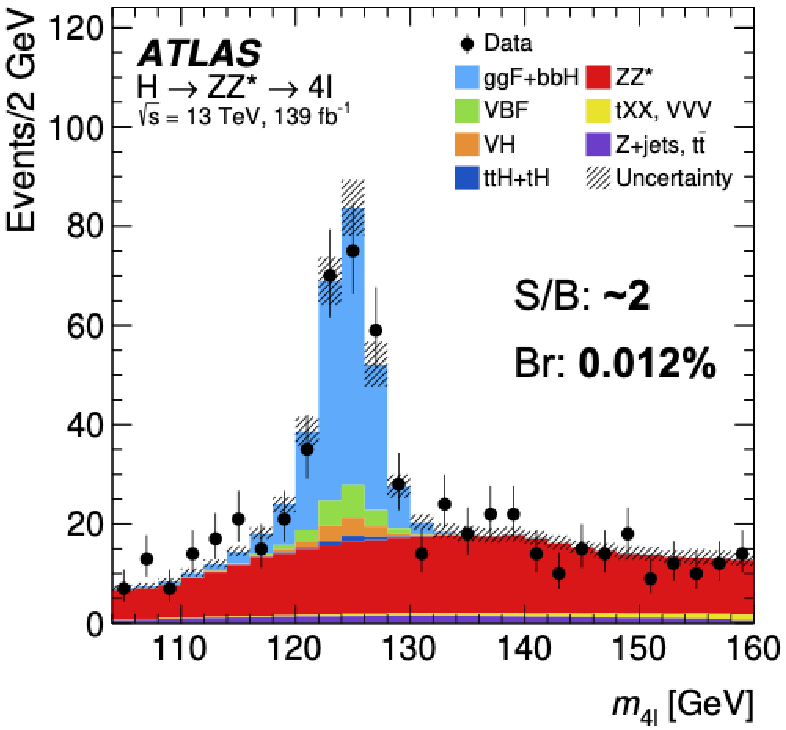
Best fit signal strength: **μ**=1.2 ± 0.6
Obs. (exp.) significance: S=2.0σ (1.7σ)

CMS



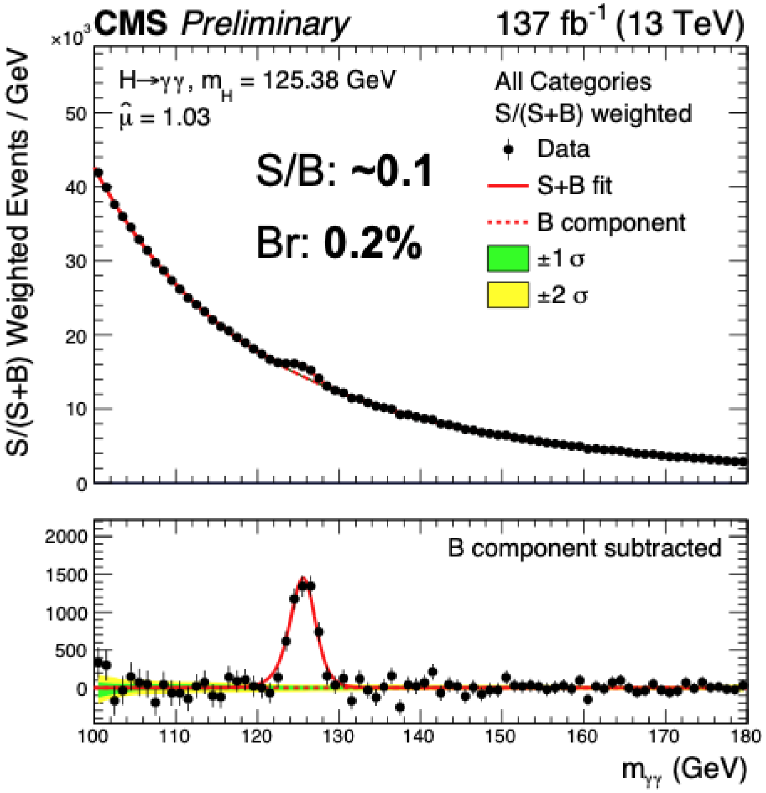
Best fit signal strength: **μ**=1.19 ± 0.41 ± 0.16
Obs. (exp.) significance: S=2.95σ (2.46σ)
⊕ Run 1 (*Phys. Lett. B* 744 (2015) 184)
Best fit signal strength: **μ**=1.19 ± 0.40 ± 0.15
Obs. (exp.) significance: S=2.98σ (2.48σ)

Where are we now?



S/B: **~2**

Br: **0.012%**



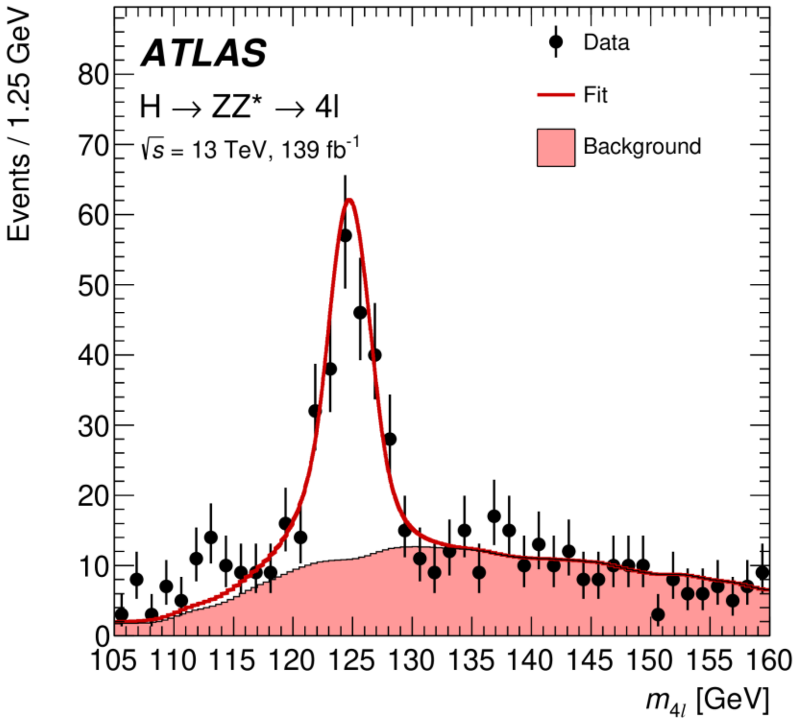
S/B: **~0.1**

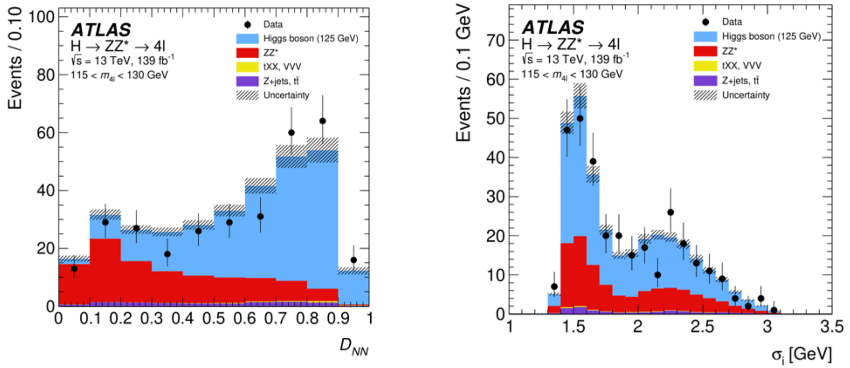
Br: **0.2%**

Precision channels (H→ZZ*→4l, H→ɣɣ) have driven the discovery and subsequent measurements in the Higgs sector.
In particular, J^{PC} has been firmly established at 0^{++} (vacuum quantum numbers)

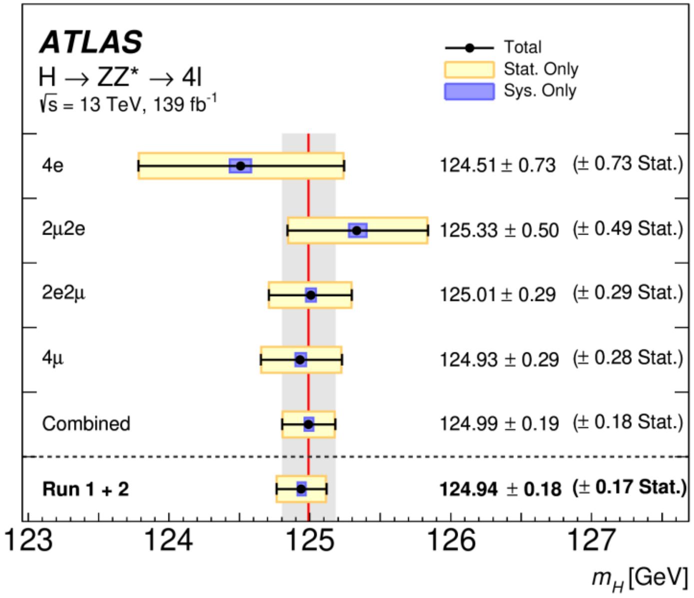
Higgs mass measurement

HIGG-2020-07





NN output to parameterise per-event resolution and composition

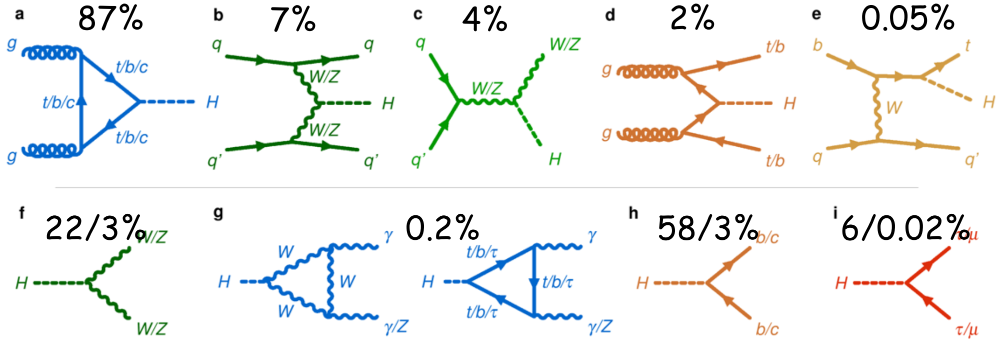


- Combined unbinned maximum-likelihood fit
- The result is statistically dominated!
- Largest systematics come from muon momentum scale and electron energy scale

Legacy Run2 Higgs mass (4l+$\gamma\gamma$ combined - both ~0.2GeV) expected @ 0.14GeV (approaching 10^{-3} precision!). We know top mass to 2x10^{-3}, W mass to 2x10^{-4}

Higgs couplings combination

10 years HIGGS boson discovery



Nature 607, pages 52-59 (2022)

$H \rightarrow ZZ^* \rightarrow l^+l^-l^+l^-$

$H \rightarrow W^\pm W^\mp \rightarrow l^\pm \nu_l l^\mp \nu_l$

$H \rightarrow \gamma\gamma$

$H \rightarrow Z\gamma$ (limit, incl.)

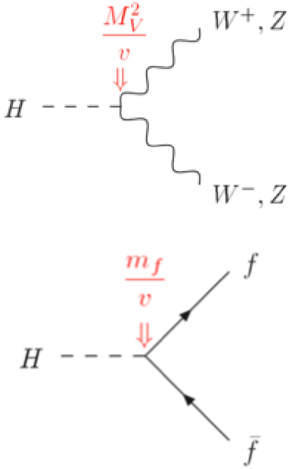
$H \rightarrow b\bar{b}$ (all but ggF)

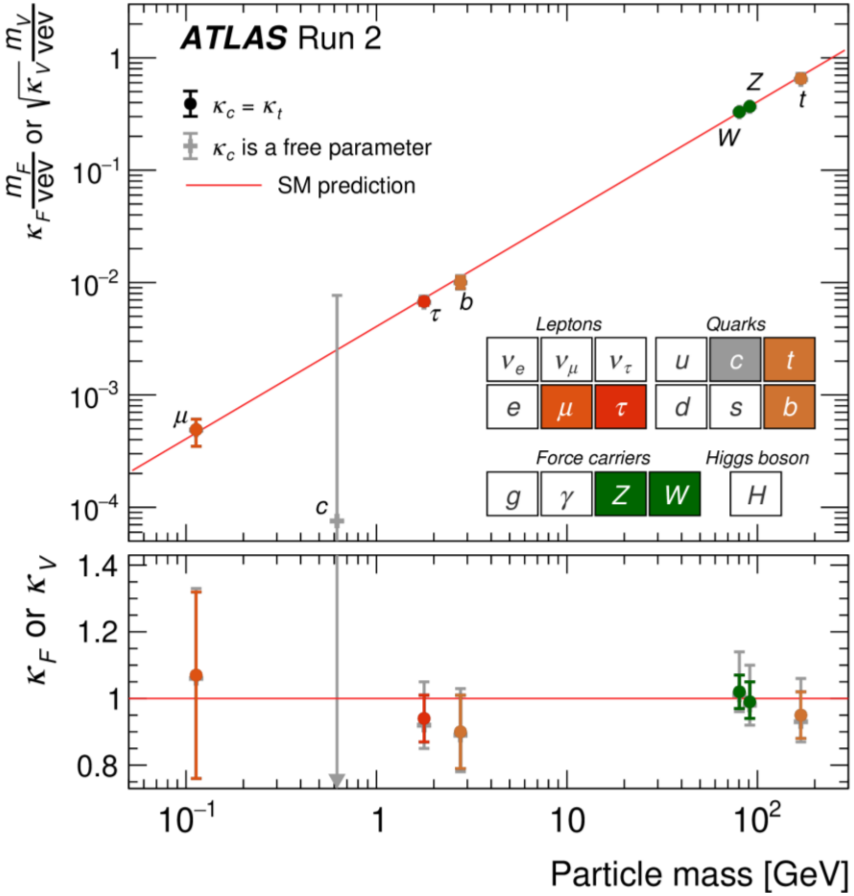
$H \rightarrow \tau^+\tau^-$

$H \rightarrow \mu^+\mu^-$

$H \rightarrow c\bar{c}$ (VBF, ZH)

$H \rightarrow$ invisible (VBF, ZH)





Excellent agreement of couplings across three orders of magnitude of particle mass!

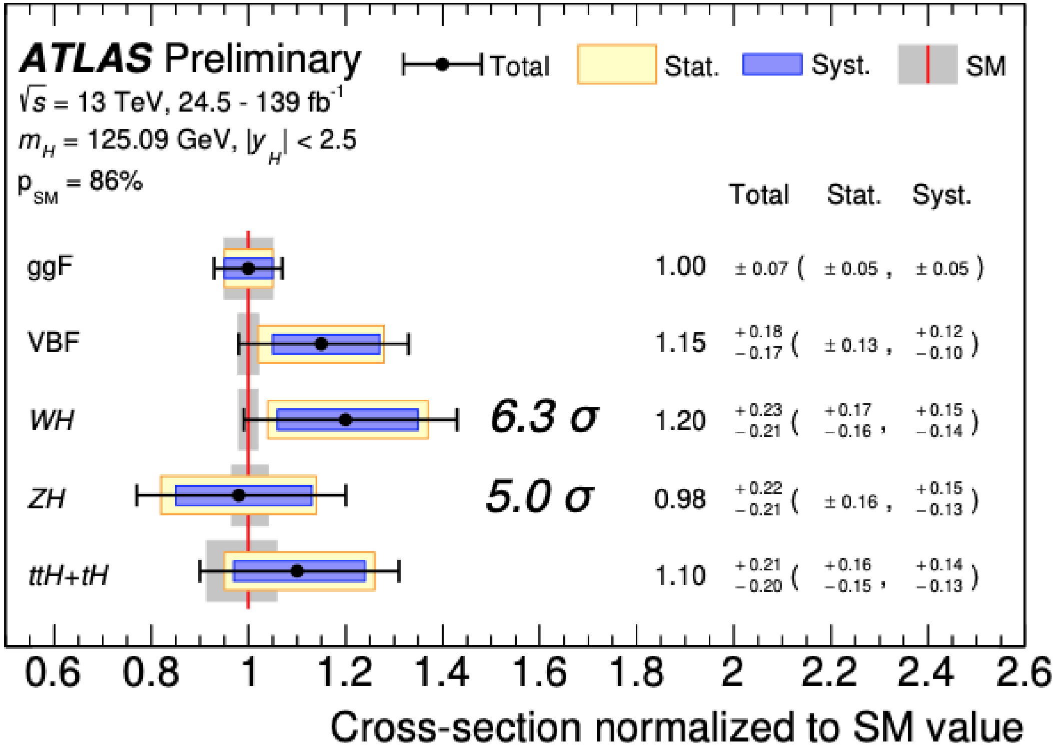
Assuming m(H) = 125.09 GeV

PRL 114 (2015) 191803

Where are we now?

6.0% $\sigma/\sigma_{SM} = 1.06 \pm 0.04\,(\text{stat.}) \pm 0.03\,(\text{exp.})\,^{+0.05}_{-0.04}\,(\text{sig. th.}) \pm 0.02\,(\text{bkg. th.})$ ATLAS-CONF-2020-027

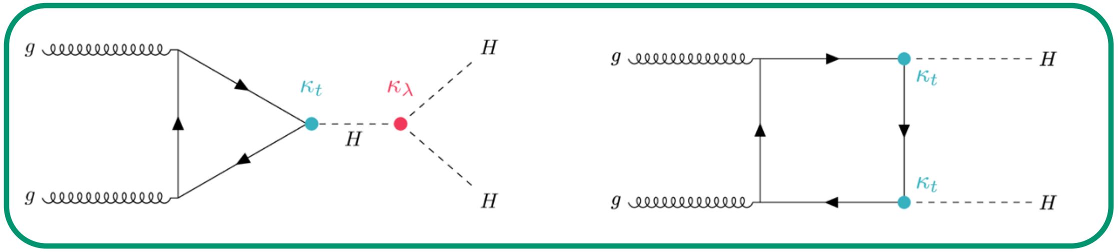
6.5% $\sigma/\sigma_{SM} = 1.02 \pm 0.04(\text{th}) \pm 0.04(\text{exp}) \pm 0.04(\text{stat}),$ CMS-HIG-19-005



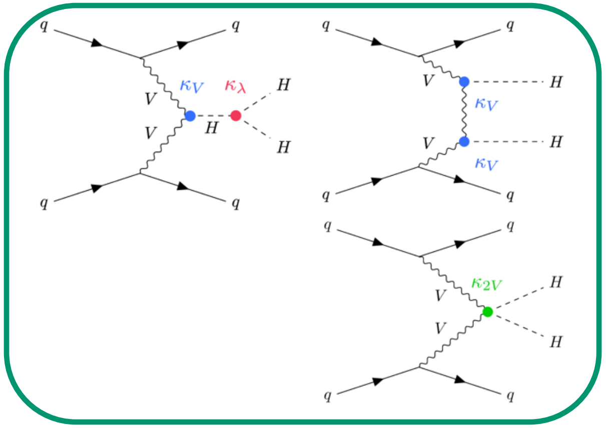
Good compatibility with the SM predictions !

Understanding the Higgs potential...

ggF: 90% of SM x-section (interfere destructively)

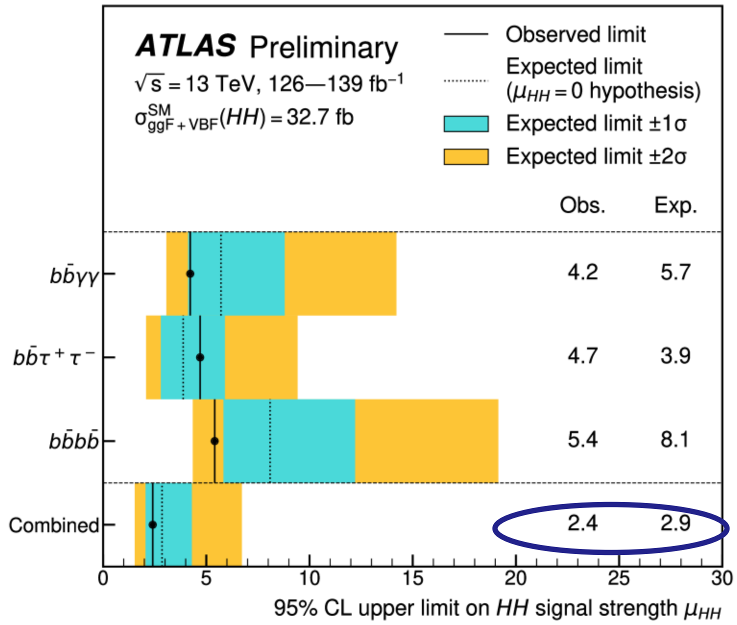


VBF: will help in the future

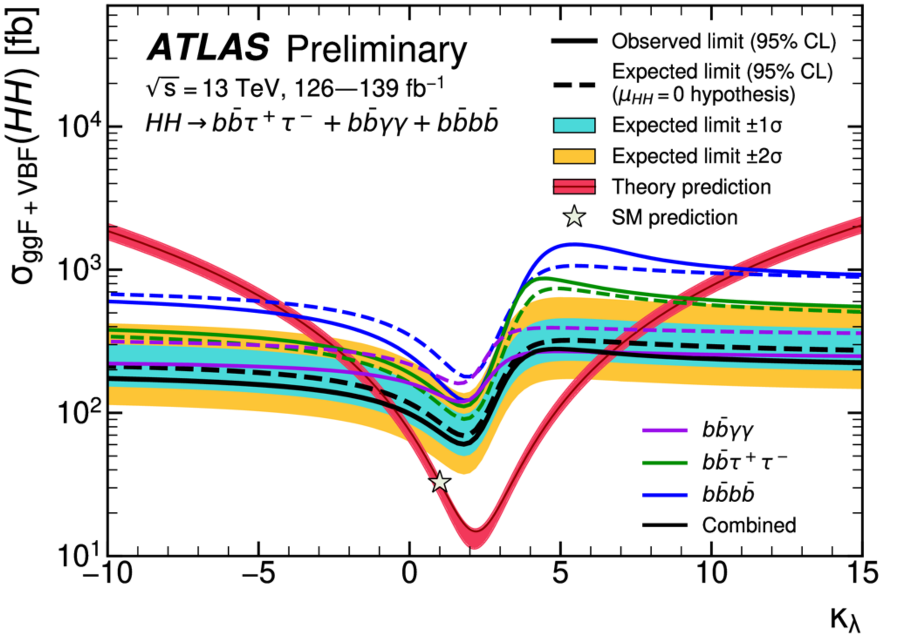


ATLAS-CONF-2022-050

$b\bar{b}\gamma\gamma$, $b\bar{b}\tau^+\tau^-$, and $b\bar{b}b\bar{b}$



Non-resonant HH search

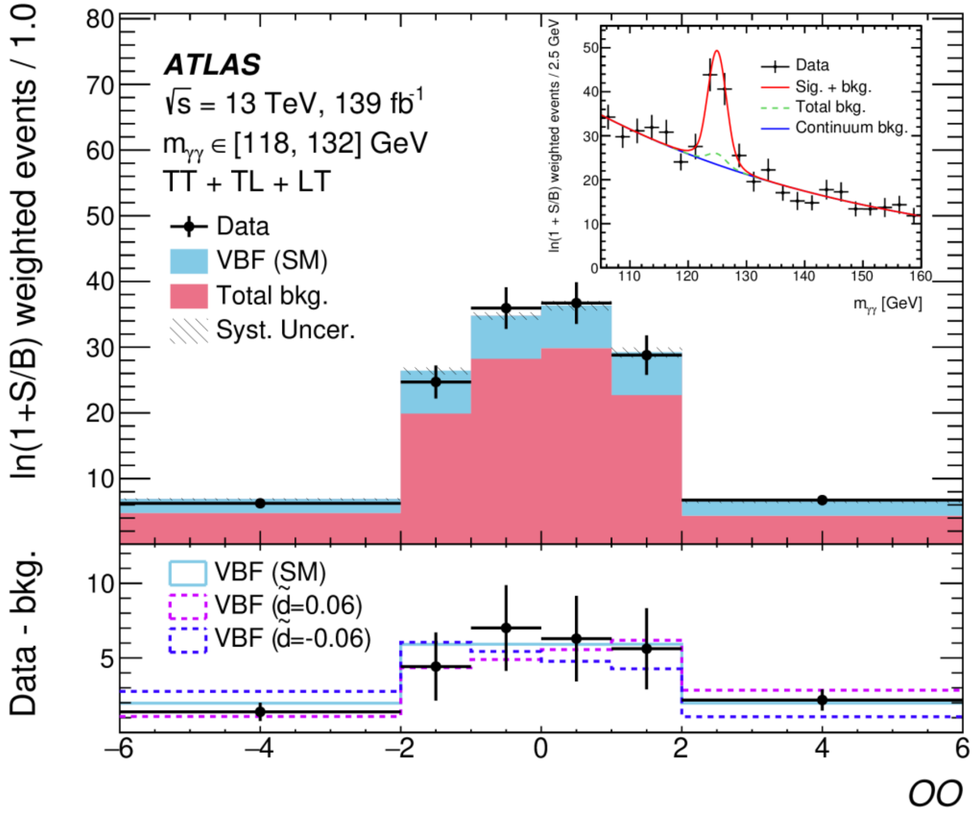


Does Higgs sector contribute to CP violation?

HIGG-2020-08

VBF $H \rightarrow \gamma\gamma$

In lack of CP-odd contribution the distribution of OO is symmetric



$$OO = 2\cdot\mathrm{Re}(\mathcal{M}^{*}_{\mathrm{SM}}\cdot\mathcal{M}_{\mathrm{CP\text{-}odd}})/|\mathcal{M}_{\mathrm{SM}}|^{2}$$

Obtained:
the most stringent constraint on the dimension-six CP-odd contribution to the H-V interaction EFT Lagrangian.

Summary

- SM desperately needed a solution to the mass problem.
- The BEH mechanism proposed back in the 60'ies was the prime candidate.
- So far, all observations are consistent with the particle observed in 2012 being the Standard Model Higgs boson.
- The particle decays into at least some of the predicted channels
- Also, production rates, BRs, spin-parity (0^+) etc. for the observed channels match the predictions by the Standard Model within the experimental uncertainties.

- The discovery of the Higgs boson finally completes the Standard Model of particle physics.

- **Is it the end of particle physics?**

Definitely NOT!
Next lecture will tell you why.

Further reading

- B.R. Martin and G. Shaw, *Particle Physics*
- A. Bettini, *Elementary Particle Physics*
- B.R. Martin, *Nuclear and Particle Physics, an Introduction*
- F. Halzen and A. Martin, *Quarks & Leptons: An Introductory Course in Modern Particle Physics*
- F. Mandl and G. Shaw, *Quantum Field Theory*