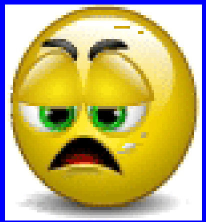
Particles of the Standard Model:

Higgs Boson

1. Why a Higgs Boson?
2. The Higgs mechanism
   - . . . again formulas . . . . . . 
3. Systematics:
   - counting the degrees of freedom
4. Experimental evidence
   - History of the discovery

Why a Higgs Boson ?

- The Standard Model is a chiral gauge field theory

→ it is described with massless fermion fields

- the gauge symmetries enforce massless vector bosons

- But we have

  ★ massive fermions: leptons and quarks

  ★ massive vector bosons: $W^{\pm}$ and Z^0

- Solution: the Higgs mechanism

The Higgs Mechanism

- **Ingredients:**
  - ⋆ scalar fields
  - ⋆ continuous local symmetries = gauge symmetries
  - ⋆ the vacuum
- **Result**
  - ⋆ gauge symmetries are spontaneously broken
  - ⋆ the scalar fields develop
    a vacuum expectation value (vev)
  - ⋆ other fields can acquire masses due to the vev

symmetry breaking

Example: chess:

- the rules of chess are in principle
  - absolutely symmetric
  - for both players
- i.e. the rules how the pieces move are the same for black and white

  but:

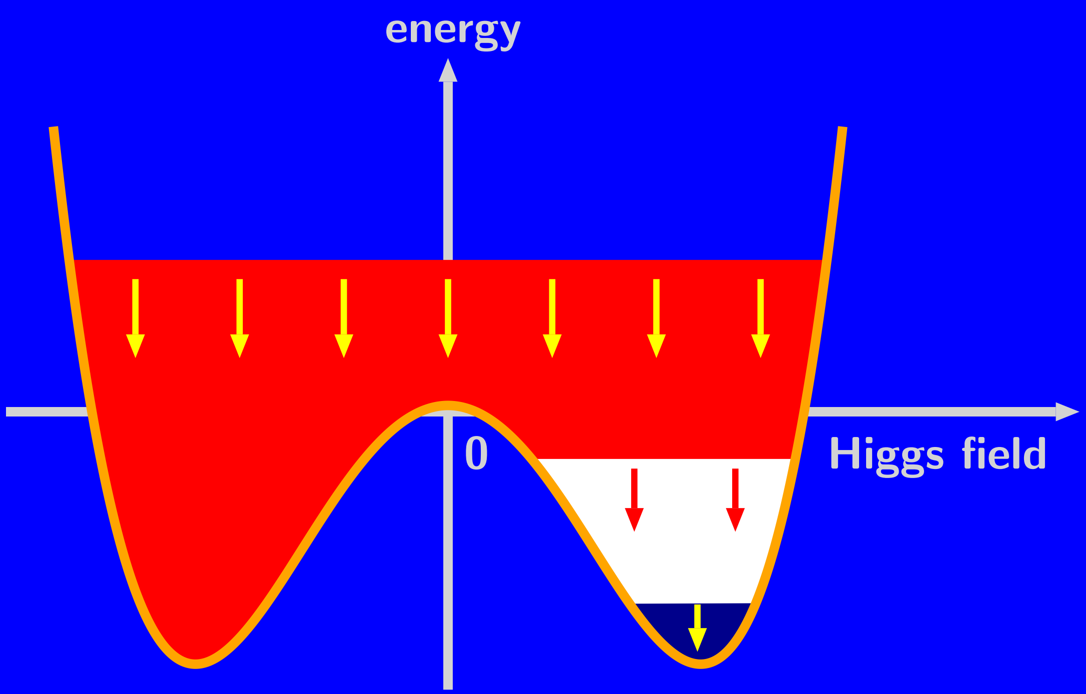
- the symmetry is broken at the beginning due to the initial setup of the pieces
- therefore
  - ➡ a bishop never can change the color of the field it is standing on

symmetry breaking

★ the origin of mass

In the SM, masses of particles are an effect of symmetry breaking:

- originally, all particles are massless, but interact with the Higgs field
- due to spontaneous symmetry breaking
  - ★ the value of the Higgs field is non-zero in the vacuum (=vev)
- the interaction with this vev produces the mass of particles



★ hot universe

- shortly after the big bang

particles are massless

★ cold universe

- condensed into an asymmetric state

particles get a mass

spontaneous symmetry breaking

Gauge groups of the Standard Model

- In the Standard Model
  - the abelian $U(1)_Y$ Hypercharge is broken
  - the $SU(2)_L$ symmetry of the left-handed fermions is broken
  - the $SU(3)_{\text{color}}$ of the strong interaction is unbroken
- the fundamental representation of $SU(2)_L$ is a complex 2-vector
- the gauge transformation of the broken symmetries are
  - for $U(1)_Y$: $\phi \to \phi' = e^{i\alpha_Y}\phi$
  - for $SU(2)_L$: $\phi \to \phi' = U\phi$ with $U = e^{i\alpha_a \frac{\sigma^a}{2}}$
- we can parametrize the Higgs field as

$$\phi = \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} = \begin{pmatrix} \chi^- \\ v + (h + i\chi_3)/\sqrt{2} \end{pmatrix} = v \begin{pmatrix} 0 \\ 1 \end{pmatrix} + \chi$$

  - this can be done by a suitable choice of α_Y and α_a

Gauge fields and covariant derivative

- the covariant derivative D_μ is given by the gauge fields
  - for $U(1)_Y$ the coupling is g' and the gauge field is B_μ
  - for $SU(2)_L$ the coupling is g and the gauge fields are

$$\widehat{W}_\mu = \sum_{a=1}^{3} W_\mu^a \frac{1}{2}\sigma^a = \frac{1}{2}\begin{pmatrix} W_\mu^3 & W_\mu^1 - iW_\mu^2 \\ W_\mu^1 + iW_\mu^2 & -W_\mu^3 \end{pmatrix} = \frac{1}{2}\begin{pmatrix} W_\mu^3 & \sqrt{2}W_\mu^+ \\ \sqrt{2}W_\mu^- & -W_\mu^3 \end{pmatrix}$$

  - the field strengths tensors are
    * $B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$

    and
    * $W_{\mu\nu}^a = \partial_\mu W_\nu^a - \partial_\nu W_\mu^a + g\epsilon^{abc} W_\mu^b W_\nu^c$

- the covariant derivative is $D_\mu = \partial_\mu - ig'B_\mu - ig\widehat{W}_\mu$
- the Lagrangian has to be invariant under $U(1)_Y$ and $SU(2)_L$:

$$\mathcal{L} = (D^\mu \phi)^\dagger (D_\mu \phi) - \tfrac{1}{2}\mu^2 \phi^\dagger \phi - \tfrac{1}{4}\lambda(\phi^\dagger\phi)^2 - \tfrac{1}{4}B_{\mu\nu}B^{\mu\nu} - \tfrac{1}{4}W_{\mu\nu}^a W^{a\,\mu\nu}$$

Spontaneous broken gauge symmetry

- The vacuum is the state of minimal energy
- without kinetic terms, it is only given by the potential

$$V(\phi) = \tfrac{1}{2}\mu^2\phi^\dagger\phi + \tfrac{1}{4}\lambda(\phi^\dagger\phi)^2$$

- for $\mu^2 < 0$, this minimum is at $|\phi| := \sqrt{|\phi_1|^2 + |\phi_2|^2} = \sqrt{\frac{-\mu^2}{\lambda}} =: v$
  - ϕ aquires a vacuum expectation value (vev)

- with our choice of ϕ we have $\phi^\dagger\phi = v^2 + \sqrt{2}vh + |\chi|^2$ and

$$\begin{aligned} V(\chi) &= \tfrac{1}{2}\mu^2(v^2 + \sqrt{2}vh + |\chi|^2) + \tfrac{1}{4}\lambda(v^2 + \sqrt{2}vh + |\chi|^2)^2 \\ &= \tfrac{1}{2}\mu^2v^2 + \tfrac{\lambda}{4}v^4 + \tfrac{1}{2}(\mu^2 + \lambda v^2)(\sqrt{2}vh + |\chi|^2) + \tfrac{1}{4}\lambda(\sqrt{2}vh + |\chi|^2)^2 \\ &= \tfrac{1}{4}\mu^2v^2 + \tfrac{1}{2}\lambda v^2h^2 + \tfrac{\sqrt{2}}{2}\lambda vh|\chi|^2 + \tfrac{\lambda}{4}|\chi|^4 \\ &= \tfrac{1}{4}\mu^2v^2 - \tfrac{1}{2}\mu^2h^2 + \tfrac{\sqrt{2}}{2}\lambda vh|\chi|^2 + \tfrac{\lambda}{4}|\chi|^4 \end{aligned}$$

Spontaneous broken gauge symmetry

- the potential is no longer zero, when there is no field!
- the real part h got a mass term with a mass $m_h^2 = -\mu^2 > 0$
- the imaginary χ_3 and charged parts χ^- have no mass: $m_\chi^2 = 0$
  - they became Goldstone Bosons !
- The covariant derivative of ϕ is

$$
\begin{aligned}
D_\mu \phi &= \left[\partial_\mu - i g' B_\mu \begin{pmatrix} \frac{1}{2} & 0 \\ 0 & \frac{1}{2} \end{pmatrix} - i g \frac{1}{2} \begin{pmatrix} W_\mu^3 & W_\mu^1 - i W_\mu^2 \\ W_\mu^1 + i W_\mu^2 & -W_\mu^3 \end{pmatrix} \right] \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} \\
&= \begin{pmatrix} \partial_\mu - \frac{i}{2} g' B_\mu - \frac{i}{2} g W_\mu^3 & -\frac{i}{\sqrt{2}} g W_\mu^+ \\ -\frac{i}{\sqrt{2}} g W_\mu^- & \partial_\mu - \frac{i}{2} g' B_\mu + \frac{i}{2} g W_\mu^3 \end{pmatrix} \begin{pmatrix} \chi^- \\ v + (h + i\chi_3)/\sqrt{2} \end{pmatrix} \\
&= -\frac{i}{2} v \begin{pmatrix} \sqrt{2} g W_\mu^+ \\ g' B_\mu - g W_\mu^3 \end{pmatrix} + D_\mu \chi
\end{aligned}
$$

Spontaneous broken gauge symmetry

defining the fields

- $W_\mu^\pm := \frac{1}{\sqrt{2}}(W_\mu^1 \mp iW_\mu^2)$, $Z_\mu := \frac{g}{g_z}W_\mu^3 - \frac{g'}{g_z}B_\mu$, and $A_\mu := \frac{g'}{g_z}W_\mu^3 + \frac{g}{g_z}B_\mu$
- the coupling constants
  - $g_z^2 = g^2 + g'^2$, and $g_e = \frac{g'g}{g_z}$ (electric coupling constant),
  - $\sin\theta_w = \frac{g'}{g_z} =: s_w$ . . . weak mixing angle or Weinberg angle
- we get $D_\mu\phi = \begin{pmatrix} \partial_\mu\chi^+ - \frac{i}{\sqrt{2}}vgW_\mu^+ \\ \frac{1}{\sqrt{2}}\partial_\mu(h + i\chi^0) + \frac{i}{2}vg_zZ_\mu \end{pmatrix} - igV\chi$
- and $(D^\mu\phi)^\dagger(D_\mu\phi)$

$$= |\partial_\mu\chi^+ - i\frac{gv}{\sqrt{2}}W_\mu^+|^2 + \frac{i}{2}|\partial_\mu h + i\partial_\mu\chi^0 + i\frac{g_zv}{\sqrt{2}}Z_\mu|^2 + ig(V,\chi)^3 + g^2V^2\chi^2$$

  - where the last two terms indicate three or more fields the bilinear terms give

- kinetic terms for the scalar fields

$$\frac{1}{2}(\partial^\mu h)(\partial_\mu h) + (\partial^\mu \chi^-)(\partial_\mu \chi^+) + \frac{1}{2}(\partial^\mu \chi^0)(\partial_\mu \chi^0)$$

- mixing terms between the Goldston bosons and the longitudinal modes of the vector bosons:

$$\frac{igv}{\sqrt{2}} W_\mu^- \partial^\mu \chi^+ - \frac{igv}{\sqrt{2}} W_\mu^+ \partial^\mu \chi^- + \frac{g_z v}{\sqrt{2}} Z_\mu \partial^\mu \chi^0$$

- mass terms for the gauge bosons:

$$\frac{g^2 v^2}{2} W_\mu^+ W^{-\mu} + \frac{g_z^2 v^2}{4} Z_\mu Z^\mu = m_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2} m_Z^2 Z_\mu Z^\mu$$

- W- and Z-bosons have different masses: $m_W^2 = \frac{g^2 v^2}{2}$ and $m_Z^2 = \frac{g_z^2 v^2}{2}$
- their ratio is (on tree level) $\cos\theta_w = \frac{m_W}{m_Z}$ is the Weinberg angle

this is the Higgs effect !

masses for the fermions

- coupling the mass less fermions to the Higgs doublet
  - the terms have to be invariant under $U(1)_Y$ and $SU(2)_L$!
  - left-handed doublets together with Higgs doublet under $SU(2)_L$:

$$(\bar{\nu}_\ell, \bar{\ell}_L) \cdot \phi = \bar{\nu}_\ell \phi_1 + \bar{\ell}_L \phi_2 \qquad (\bar{u}_L, \bar{d}_L) \cdot \phi = \bar{u}_L \phi_1 + \bar{d}_L \phi_2$$

and

$$\det \left[(\bar{u}_L, \bar{d}_L)^\top, \phi^* \right| = \det \begin{vmatrix} \bar{u}_L & \phi_1^* \\ \bar{d}_L & \phi_2^* \end{vmatrix} = \bar{u}_L \phi_2^* - \bar{d}_L \phi_1^*$$

  - the right-handed singlets have to guarantee $U(1)_Y$ conservation:

$$(\bar{\nu}_\ell \phi_1 + \bar{\ell}_L \phi_2) \ell_R \qquad (\bar{u}_L \phi_1 + \bar{d}_L \phi_2) d_R \qquad (\bar{u}_L \phi_2^* - \bar{d}_L \phi_1^*) u_R$$

- introducing vevs and Yukawa matrices $Y_\ell = \frac{m_\ell}{v}$, $Y_d = \frac{m_d}{v}$, $Y_u = \frac{m_u}{v}$
  - that can mix generations and allow for CP-violation
- we get the fermion mass terms

$$\mathcal{L} = m_\ell \bar{\ell}_L \ell_R + m_d \bar{d}_L d_R + m_u \bar{u}_L u_R$$

degrees of freedom

only $SU(2) \times U(1)$ bosons

massless theory

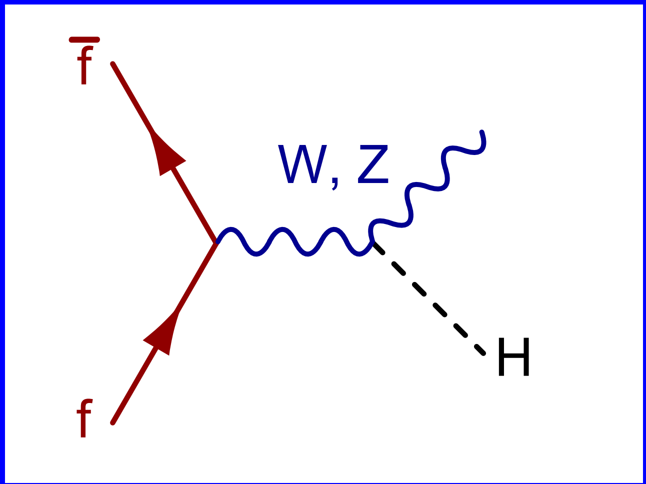
#	particles	dof
1	complex scalar doublet	4
4	massless gauge bosons (B, W^i)	8
0	massive gauge bosons	0
		12

massive theory

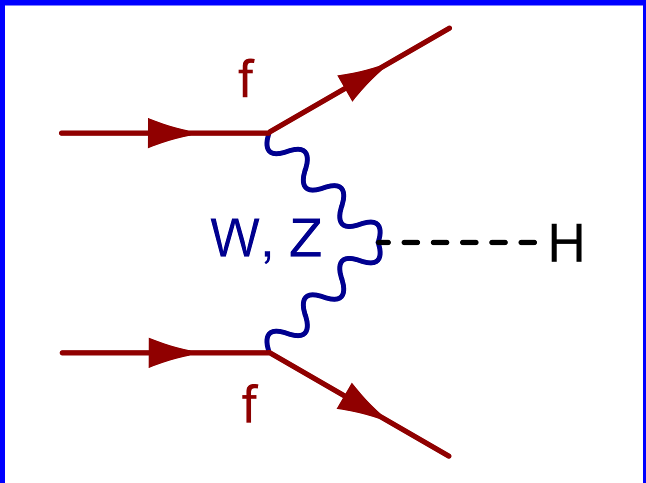
#	particles	dof
1	real scalar field (Higgs)	1
1	massless gauge boson (photon)	2
3	massive gauge bosons ($W^\pm$, Z^0)	9
		12

production at LEP

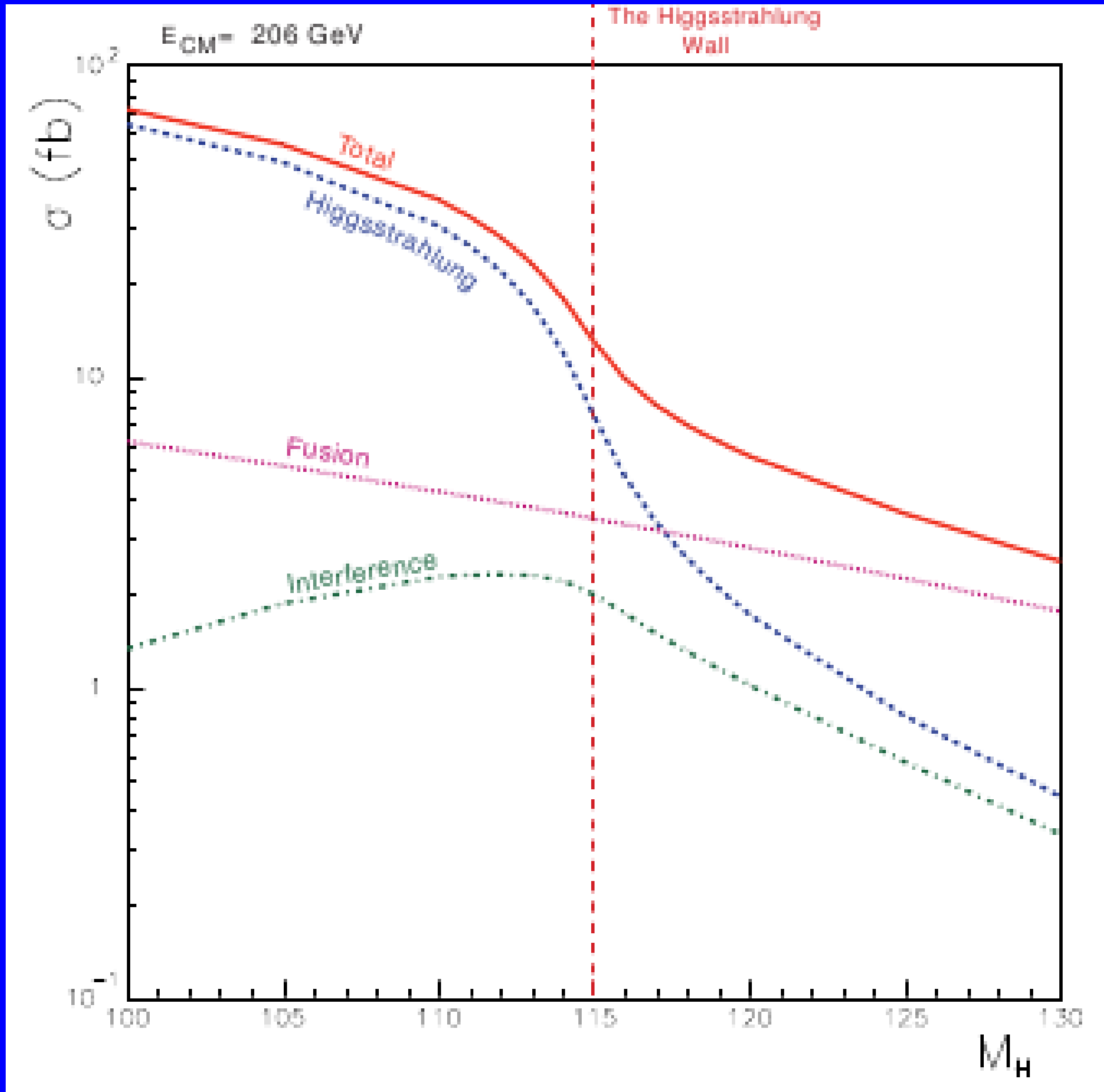
Higgs-strahlung



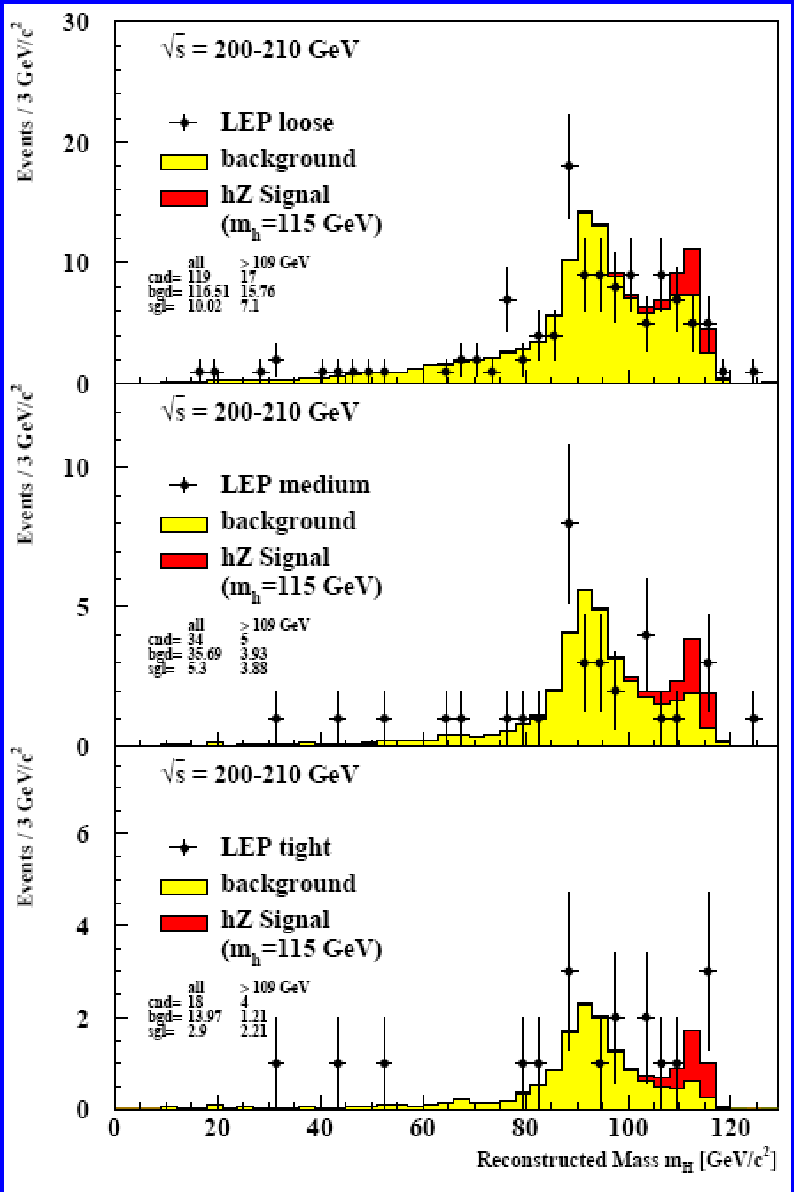
Higgs-fusion



Higgs production cross section



exclusion by LEP I & II



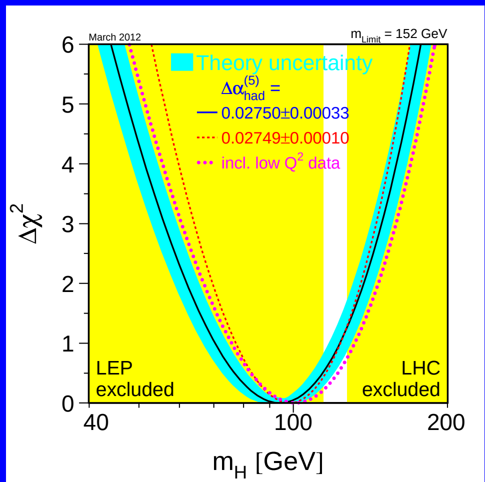
→ comparison between an expected (calculated) distribution and the measured distribution of events

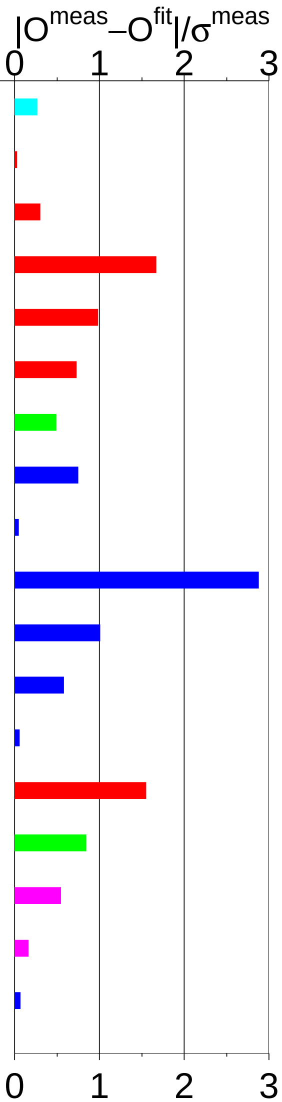
← measured mass distribution

hints: electroweak precision measurements

- very precise measurements allow the comparison with precise calculations
- all loop calculations depend on the masses of all the particles in the loop!

➜ sensitivity to particles, that can not yet be produced!



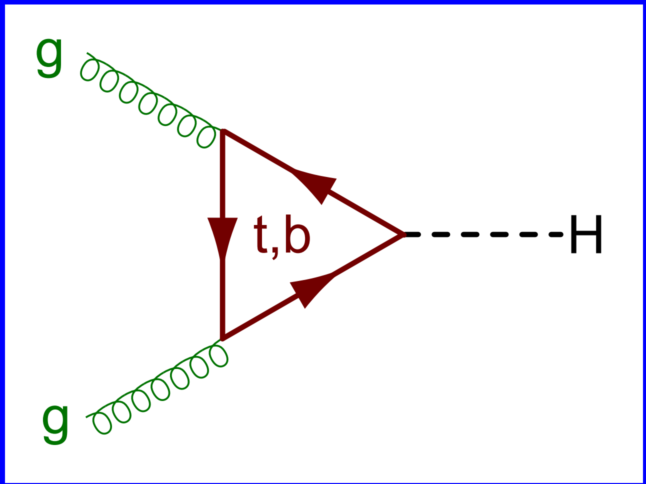


	Measurement	Fit	$\lvert O^{meas}-O^{fit}\rvert/\sigma^{meas}$
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02750 ± 0.00033	0.02759	
m_Z [GeV]	91.1875 ± 0.0021	91.1874	
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959	
σ^0_{had} [nb]	41.540 ± 0.037	41.478	
R_l	20.767 ± 0.025	20.742	
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01645	
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481	
R_b	0.21629 ± 0.00066	0.21579	
R_c	0.1721 ± 0.0030	0.1723	
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038	
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742	
A_b	0.923 ± 0.020	0.935	
A_c	0.670 ± 0.027	0.668	
A_l(SLD)	0.1513 ± 0.0021	0.1481	
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314	
m_W [GeV]	80.385 ± 0.015	80.377	
Γ_W [GeV]	2.085 ± 0.042	2.092	
m_t [GeV]	173.20 ± 0.90	173.26	

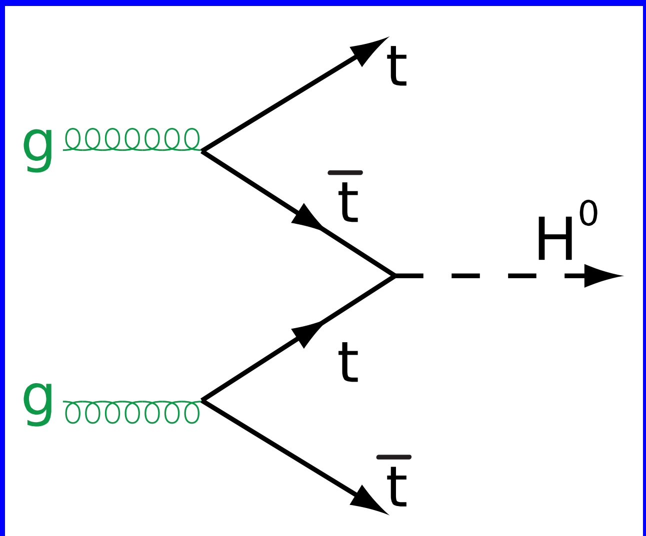
March 2012

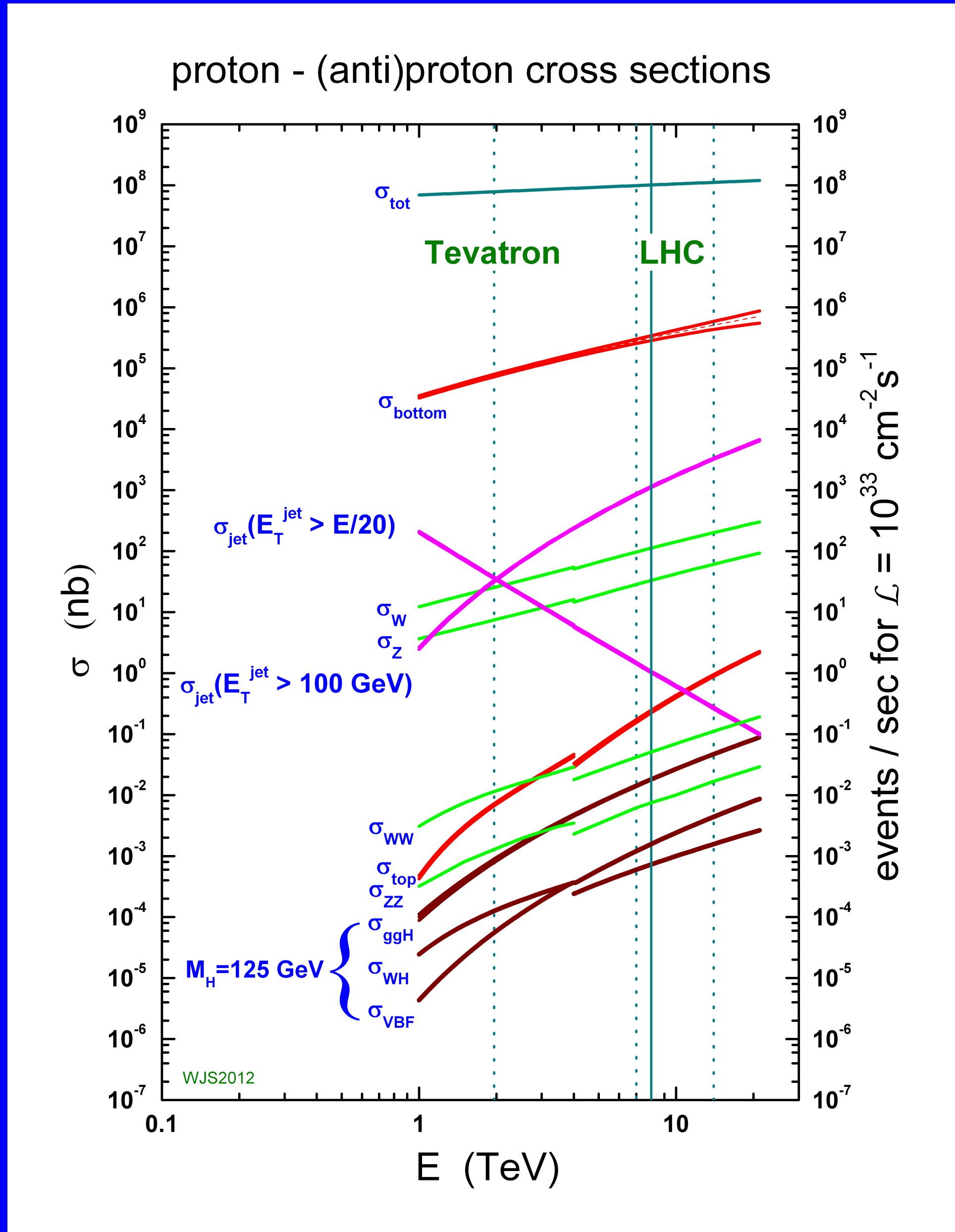
production at LHC

Higgs-gluon-fusion



top-associated-production





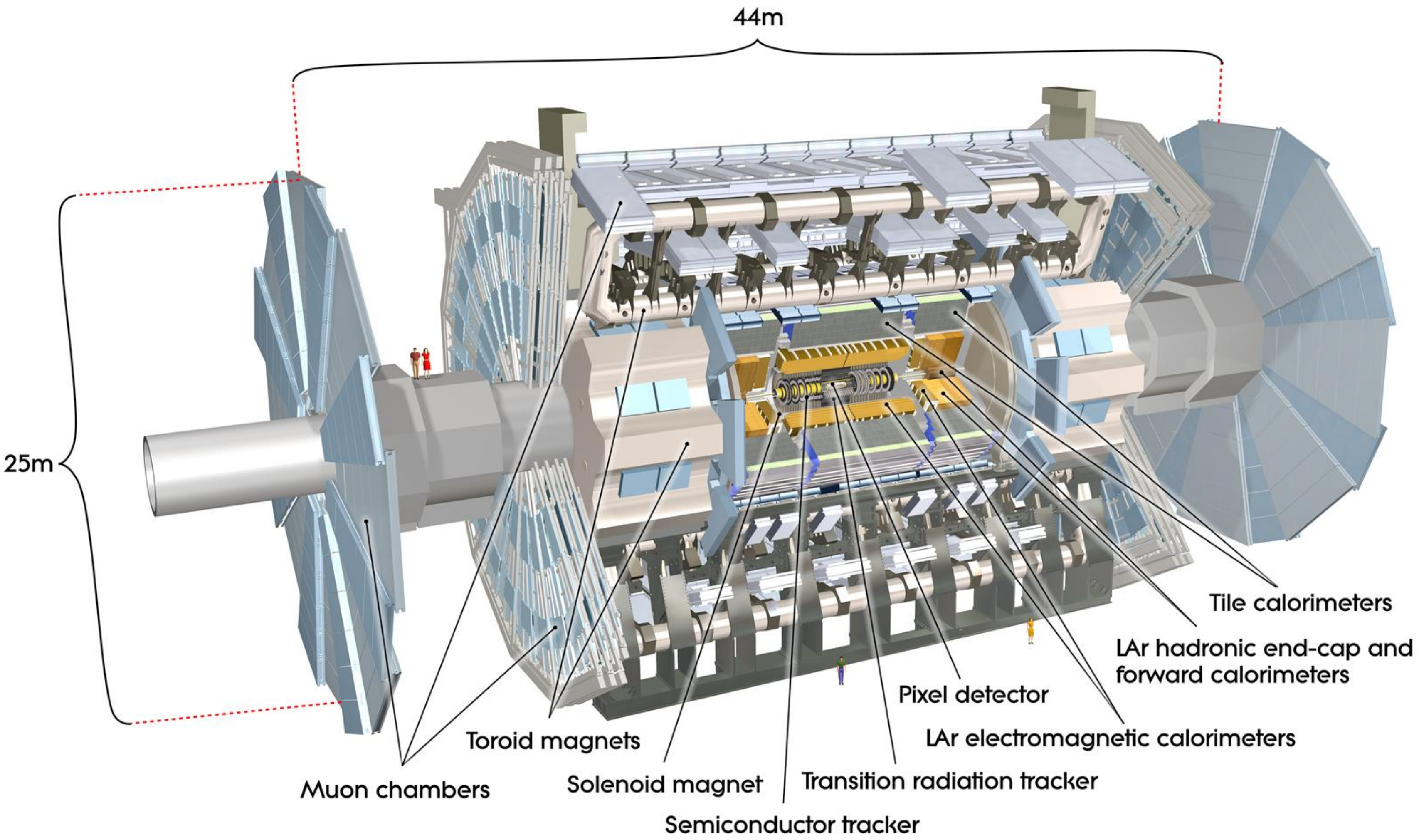
The Higgs particle — history of the experimental search

reduction of the allowed mass range

- 2004 LEP limit: $m_H > 114.4\,\text{GeV}$
  - uses data, collected from the LEP experiments until 2000
- 2010 Tevatron exclusion: $158 < m_H/\text{GeV} < 175$ is excluded
  - data from the Fermilab experiments CDF and D$\emptyset$
- July 2011 LHC exclusion: $145 < m_H/\text{GeV} < 466$ is excluded
  - data from the ATLAS and CMS from 2010 and 2011
- December 2011 LHC limits the allowed mass range
  - ATLAS: $116 < m_H/\text{GeV} < 130$
  - CMS: $115 < m_H/\text{GeV} < 127$
- July 4$^{\text{th}}$ 2012 CERN announces the detection of a boson compatible with the SM Higgs boson
  - ATLAS: $m_H \sim 126.5\,\text{GeV}$ @ 5 σ significance
  - CMS: $m_H = 125.3 \pm 0.6\,\text{GeV}$ @ 4.9 σ significance

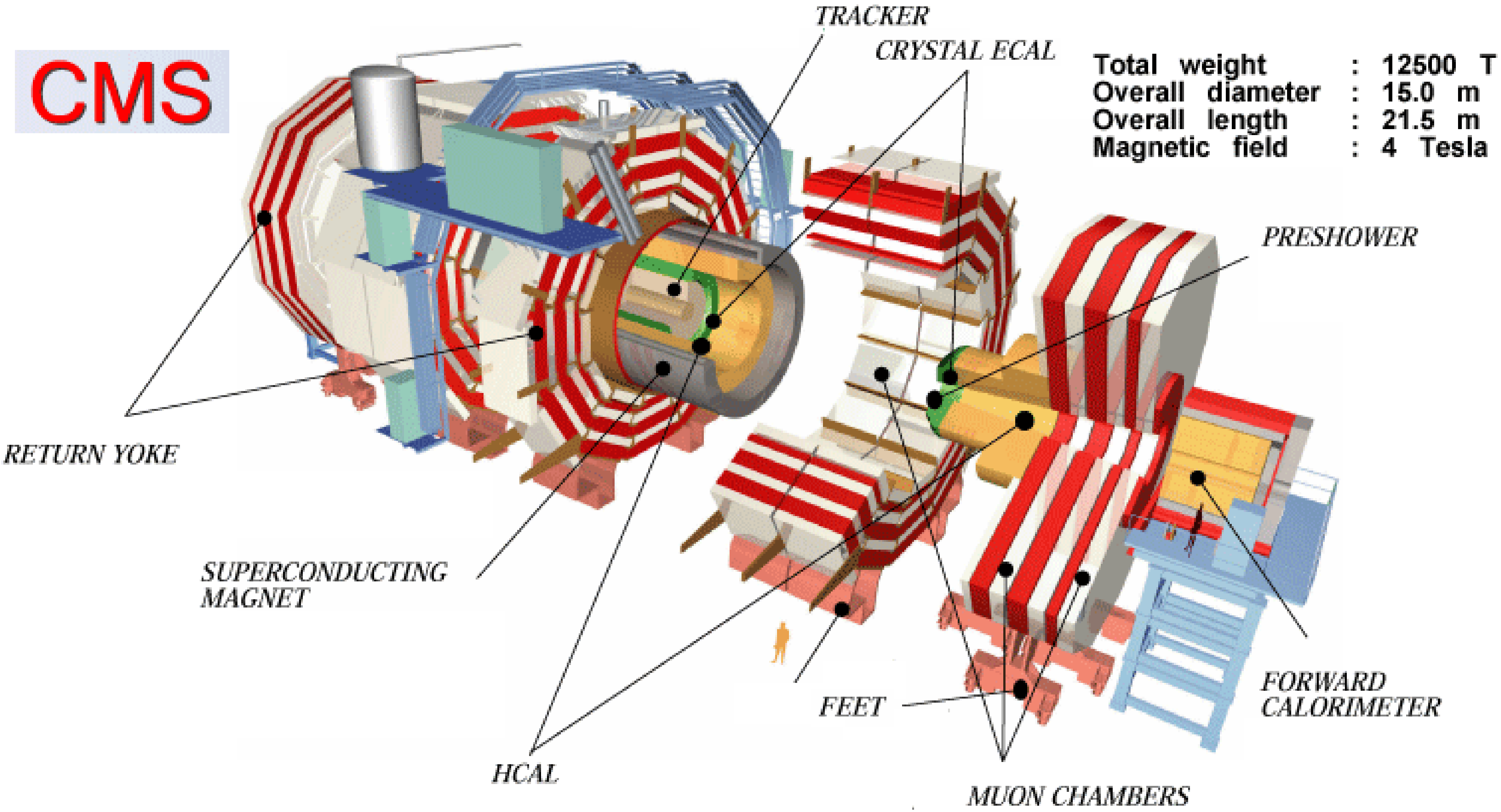
The Higgs particle — experimental search

by the Atlas detector



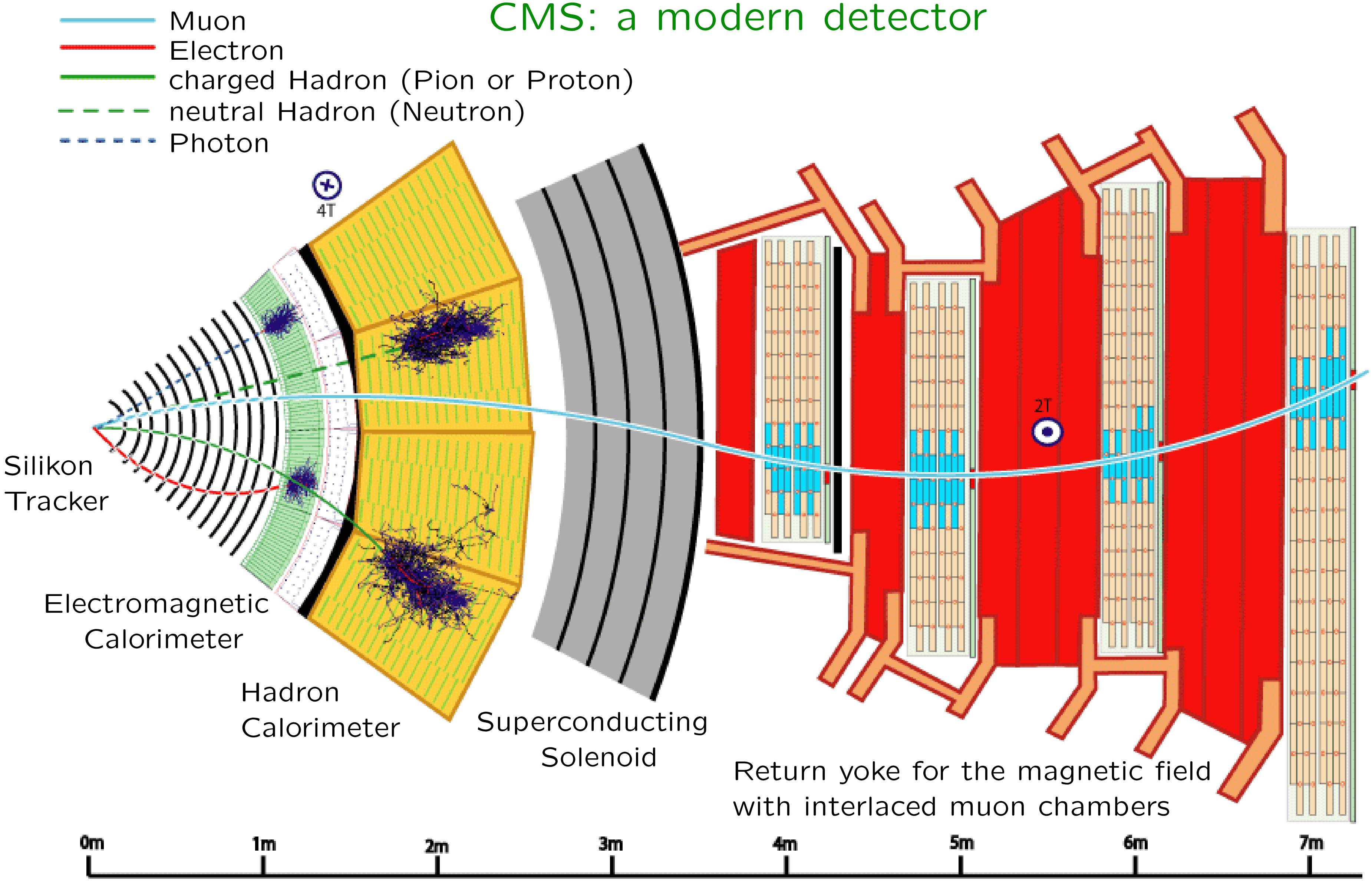
The Higgs particle — experimental search

by the CMS detector



The Higgs particle — experimental search

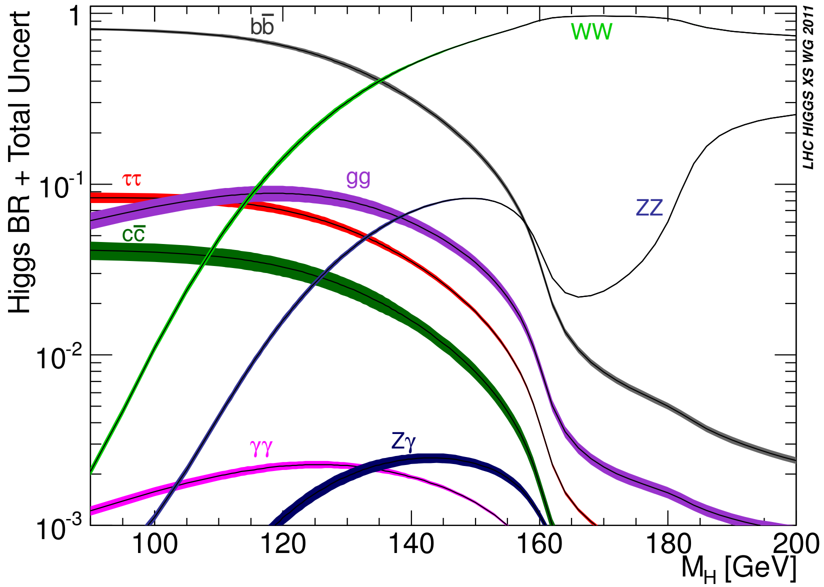
CMS: a modern detector



The Higgs particle — experimental search

How was that measurement achieved?

combining production- with decay-channels of the Higgs boson



largest branching ratios

- $b\bar{b}$, $\tau^-\tau^+$, $c\bar{c}$, and gg
  - hard to distiguish from background
- $WW \to 4q$
  - similar: also hard to distiguish from background
- $WW \to 2\ell 2\nu$
  - neutrinos are not measured ⇒ bad reconstruction

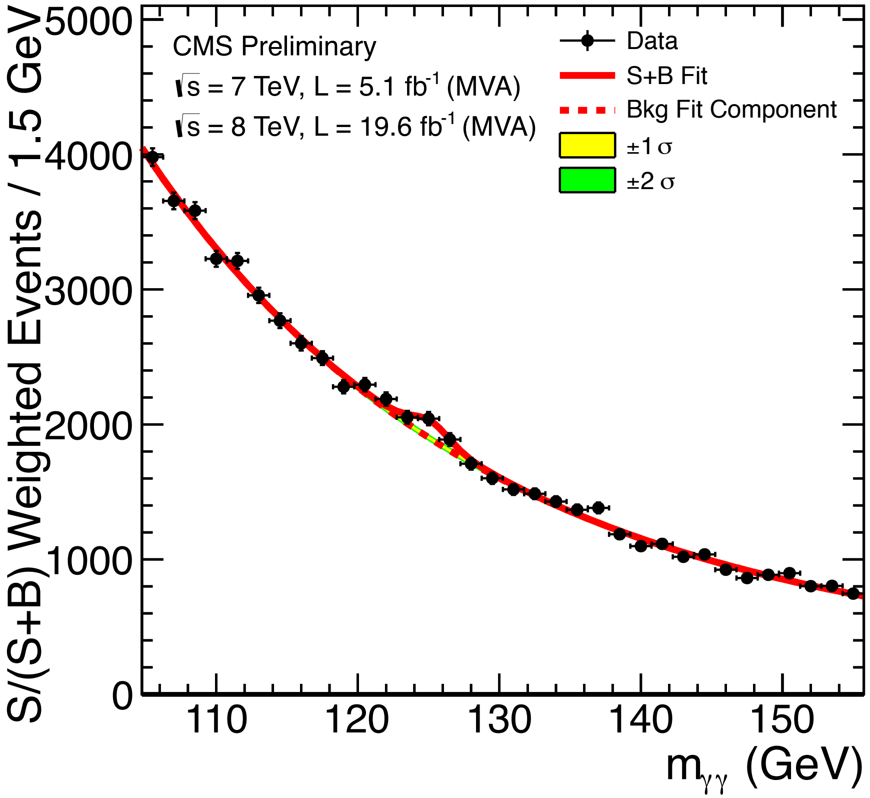
⇒ looking for $\gamma\gamma$ and $ZZ \to 4\ell$
  - has also very good mass resolution

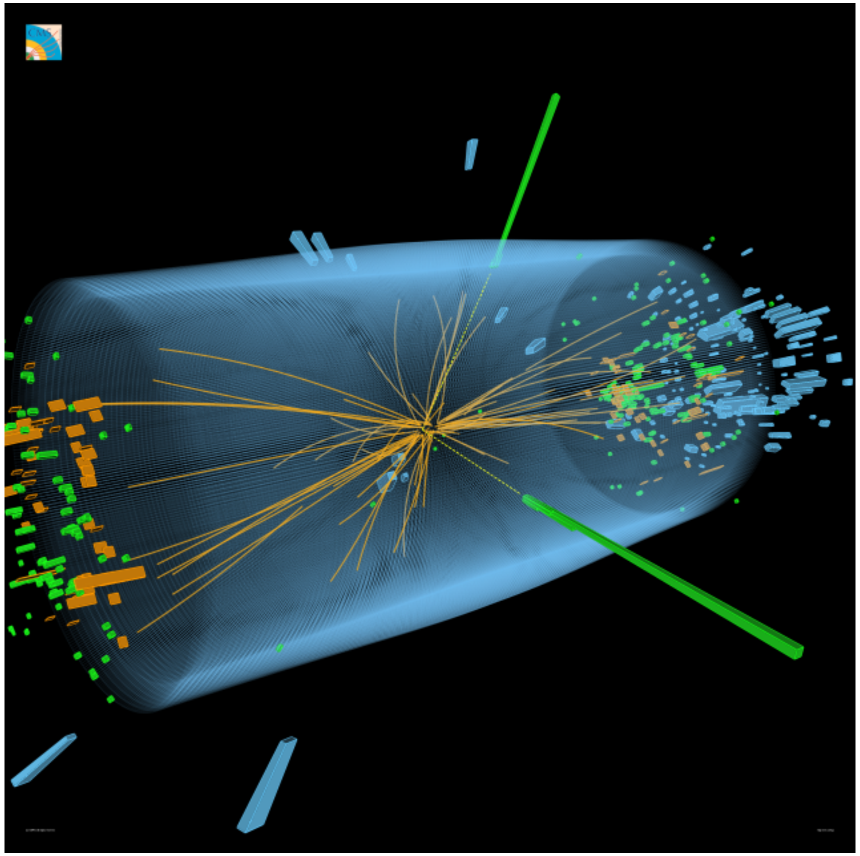
    ⇒ "golden channel"

The Higgs particle — experimental search

$H \to \gamma\gamma$

- Monte Carlo and data:
  - gives a signal on a background



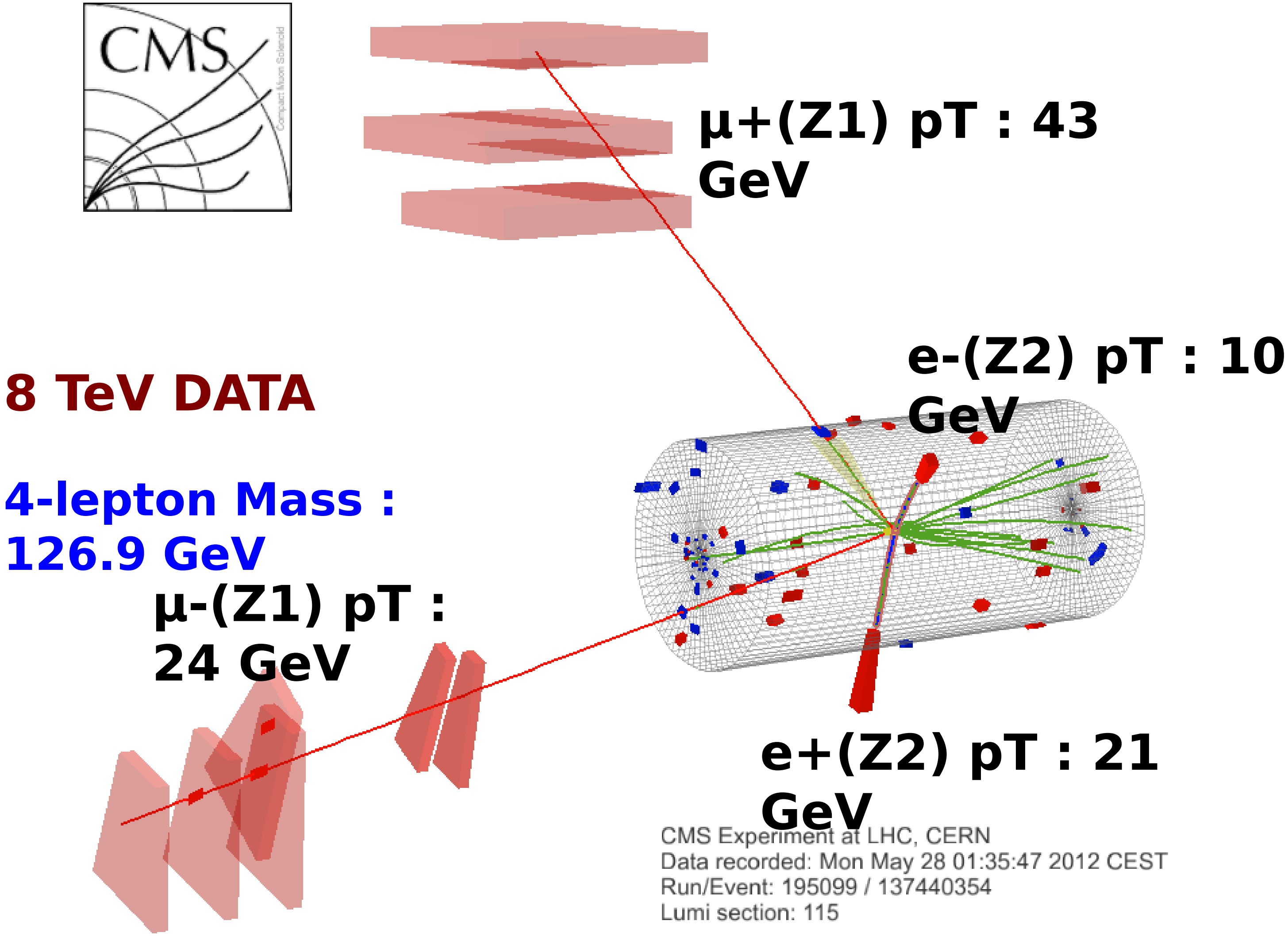


a possible $H \to \gamma\gamma$ event

with local p-value at 125 GeV with a local significance of 4.1 σ

The Higgs particle — experimental search

$H \to ZZ^* \to \mu^-\mu^+ + e^-e^+$

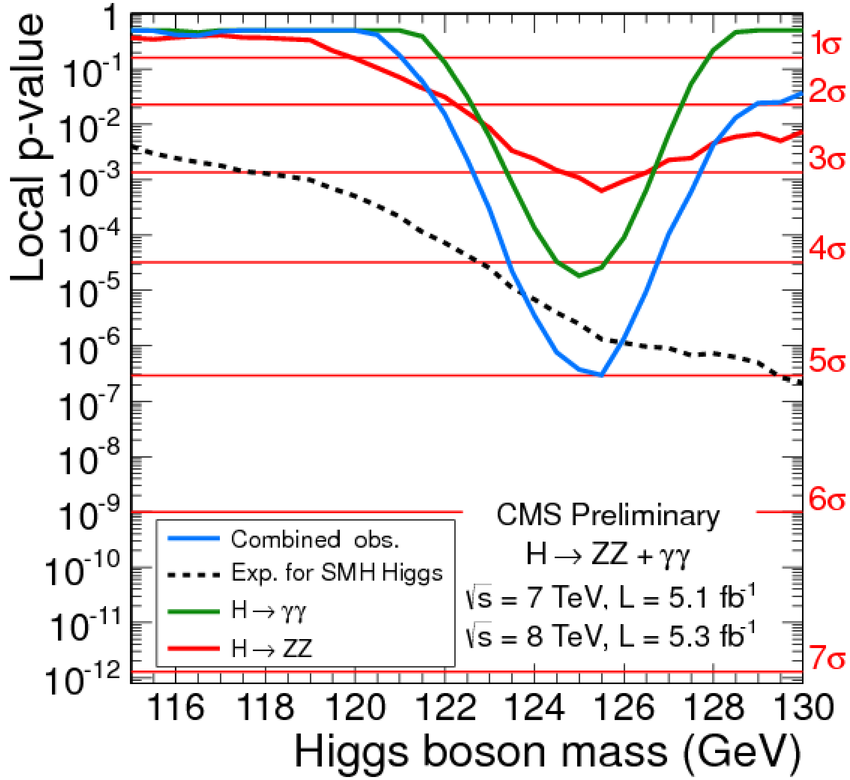


Combining $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$

- combining the high sensitivity, high mass resolution channels: $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$
  - $\gamma\gamma$ has 4.1 σ excess
  - 4ℓ has 3.2 σ excess
- near the same mass of 125 GeV

$\Rightarrow$ combined significance of 5 σ

(as of 2012 . . . now it is more)

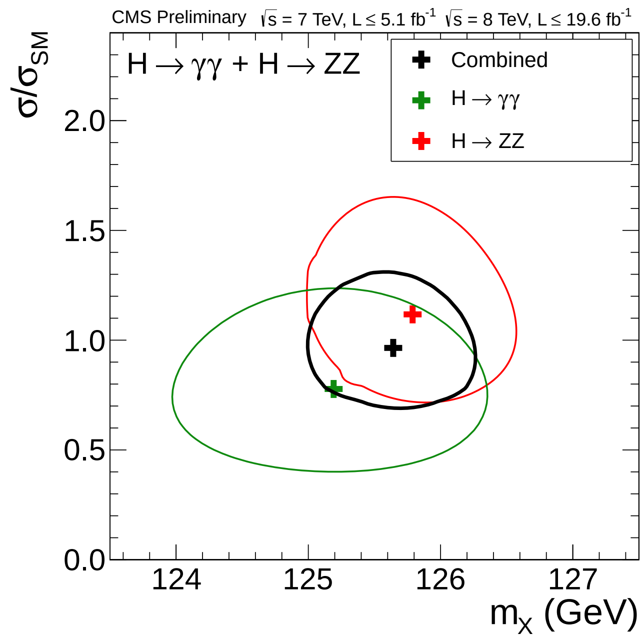


The Higgs particle — experimental search

Characterising the excess in all channels

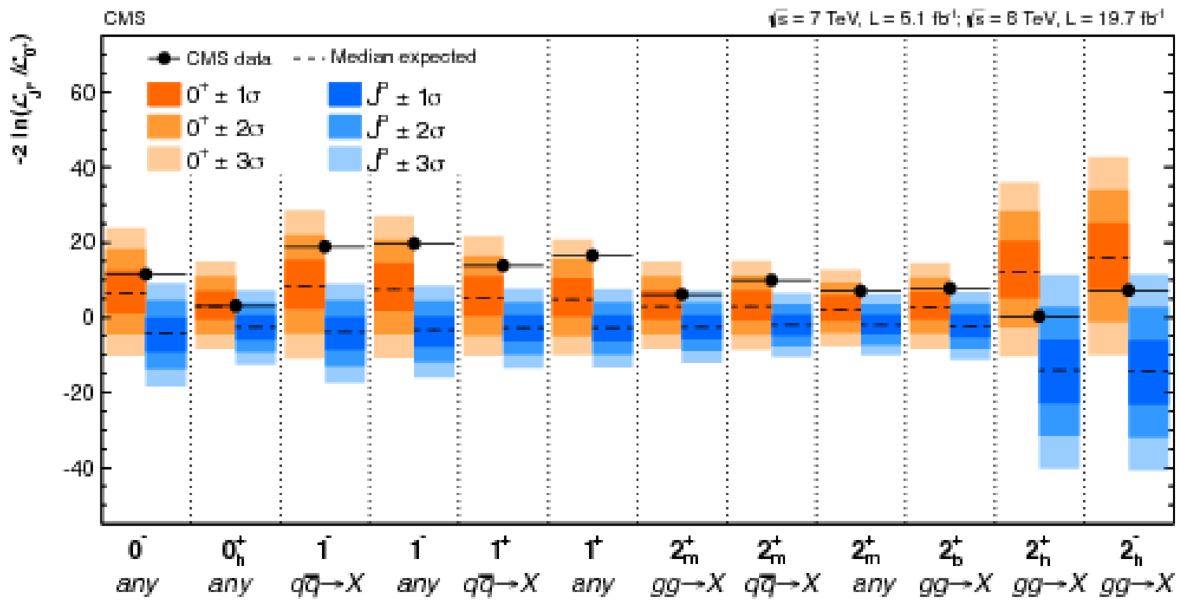
- results for the mass are self consistent
- and can be combined

  $\Rightarrow\ m_X = 125.9 \pm 0.4\ \text{GeV}$



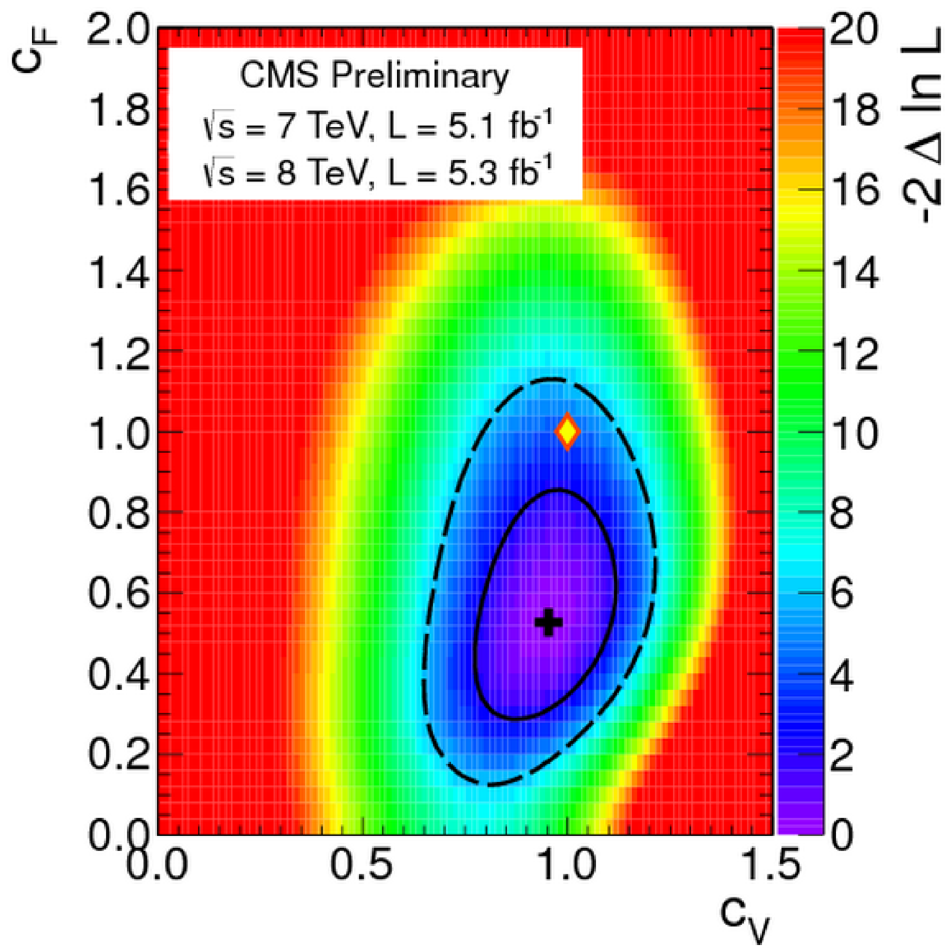
- But is it the SM Higgs boson?

  $\Rightarrow$ comparing to other hypotheses:



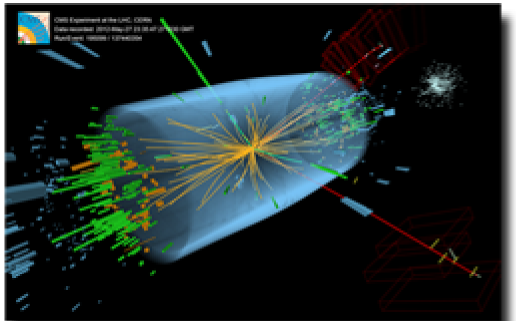
Comparing couplings to fermions and to vector bosons

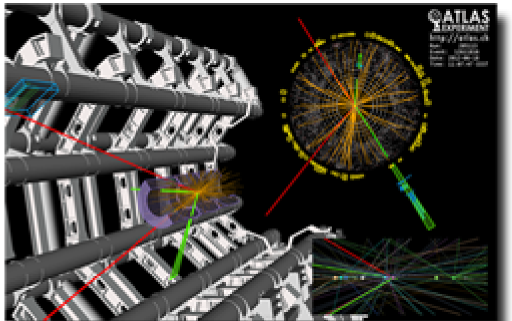
- Group the Higgs couplings into "Vectorial" and "Fermionic" sets.
- with coupling strength relative to the SM value
  - c_V for vectors
  - c_F for fermions
- use theoretical LO prediction for the loop-induced $H \to \gamma\gamma$ and $H \to gg$ vertices
- agreement with SM in 95% range
  - fermio-phobic Higgs ? . . . statistics



$\Rightarrow$ We need more data! . . . and they will come

Nobelprize in Physics 2013





Francois Englert and Peter W. Higgs