Higgs discovery at the LHC

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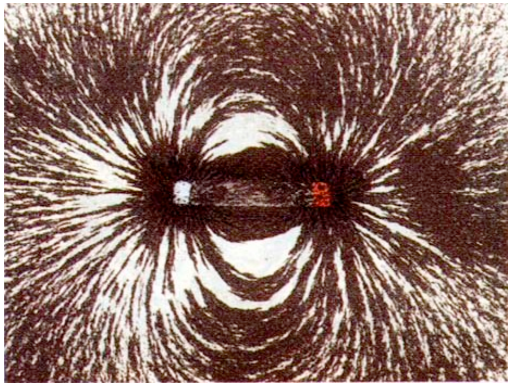
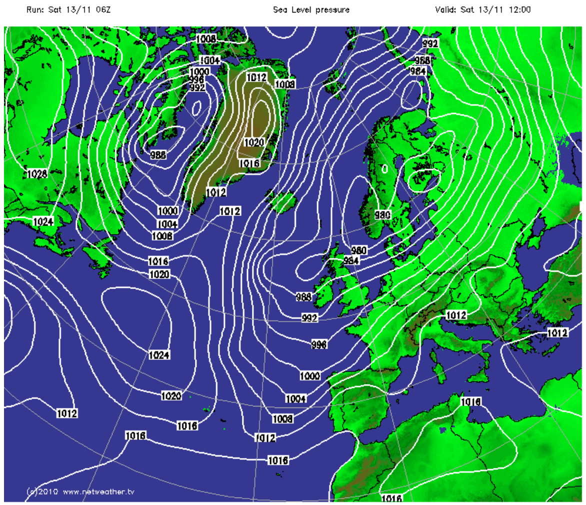
The Higgs mechanism

The Higgs field and the Higgs mechanism



Vector field :
Magnetic field, the wind velocities in the atmosphere …



Scalar field :
Atmospheric pressure

Brout-Englert-Higgs field (scalaire, complexe)

The couplings of the elementary particles with the Higgs field → mass

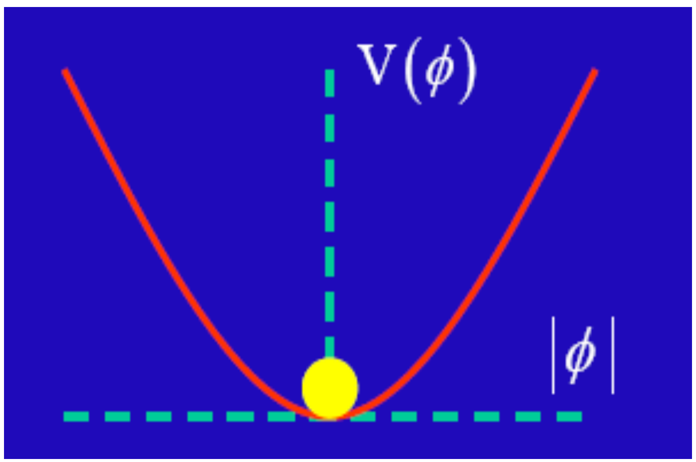
Let's take a scalar particle Φ : $L = \frac{1}{2}(\partial_\mu \phi)^2 - V(\phi)$

Scalar potential *V(Φ)* : mass term and interactions : $V(\phi) = \frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4$

Minimum : $\frac{\partial V(\phi)}{\partial \phi} = \phi\left(\mu^2 + \lambda\phi^2\right) = 0$

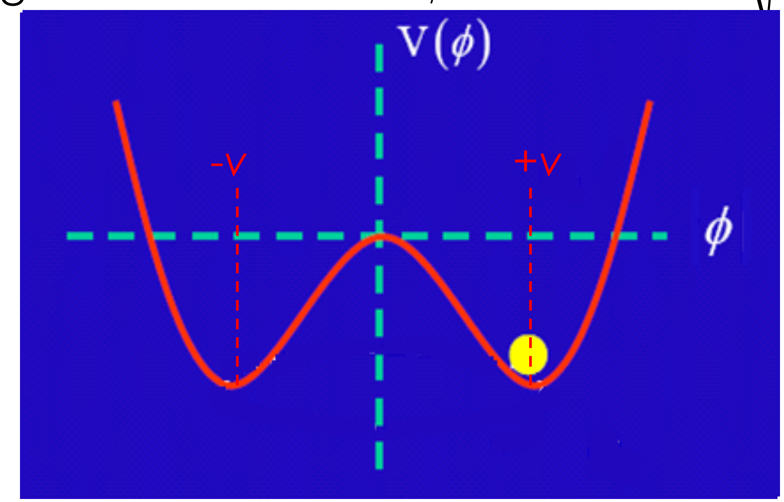
"vacuum expectation value"

If λ>0 and $\mu^2 > 0$ trivial minimum : the ground state



If λ>0 and $\mu^2 < 0$

Degenerate minima : $\phi = \pm v$ with v=$\sqrt{\frac{-\mu^2}{\lambda}}$



Φ=0 is not the minimum !

By the choice of the minimum the symmetry is broken

This is spontaneous symmetry breaking

Perturbative calculations : expand around the minimum (Φ=v or Φ=-v)

$$\phi(x) = v + \eta(x)$$

$$L = \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2}\mu^2\phi^2 - \frac{1}{4}\lambda\phi^4$$

$$L' = \frac{1}{2}(\partial_\mu \eta)^2 - \lambda v^2 \eta^2 - \lambda v \eta^3 - \frac{1}{4}\lambda\eta^4 \;\; + \text{constant terms}$$

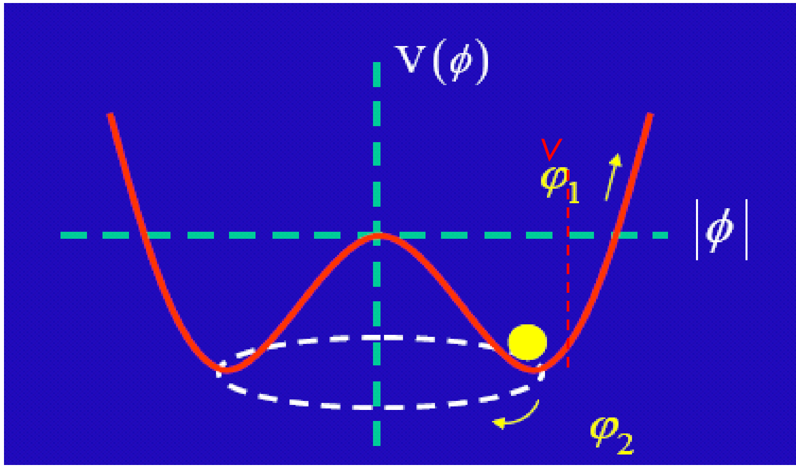
Mass term : $M = \sqrt{2\lambda v^2} = \sqrt{-2\mu^2}$

If one uses a complex scalar field $\Phi = 1/\sqrt{2}(\phi_1 + i\Phi_2)$

$$L = (\partial_\mu \phi^+)(\partial^\mu \phi) - \lambda(\phi^+\phi)^2 - \mu^2\phi^+\phi$$

If $\lambda>0$ and $\mu^2< 0$

Degenerate minima $\phi_1^2 + \phi_2^2 = v$ with $v=\sqrt{\frac{-\mu^2}{\lambda}}$



$M^2_{\phi_1} = -2\mu^2 > 0$ The Φ_1 field has a mass (just as before)

$M^2_{\phi_2} = 0$ No corresponding mass term for the Φ_2 field : the theory has a massless scalar : the Goldstone boson.

In Φ_1 and Φ_2 directions the potential behaves differently : flat in Φ_2 → massless boson

The Higgs mechanism in the Standard Model

Use a doublet of complex fields

$$\phi = \begin{pmatrix} \phi^{+} \\ \phi^{0} \end{pmatrix} = \begin{pmatrix} \frac{1}{\sqrt{2}}(\phi_1 + i\phi_2) \\ \frac{1}{\sqrt{2}}(\phi_3 + i\phi_4) \end{pmatrix}$$

electroweak unification + spontaneous symmetry breaking :

$$L = (D_\mu \phi^+)(D^\mu \phi) - \lambda(\phi^+\phi)^2 - \mu^2 \phi^+\phi$$

$$D^\mu \phi = \left[\partial^\mu + igW^\mu + ig' y_\phi B^\mu\right]\phi$$

$$\left|\langle 0|\phi^0|0\rangle\right| = \sqrt{\frac{-\mu^2}{2\lambda}} = \frac{v}{\sqrt{2}}$$ and $$\left|\langle 0|\phi^+|0\rangle\right| = 0$$

keep U(1)$_{em}$ invariance

spontaneous symmetry breaking : $\phi(x) = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$

The coupling to the gauge boson is obtained via the covariant derivatives (long calculation) :

$$L = (D_\mu \phi^+)(D^\mu \phi) = \frac{1}{2}\partial_\mu H \partial^\mu H + \frac{g^2}{4}(v+H)^2\left[W_\mu^+ W^\mu + \frac{1}{\cos^2\theta_W} Z_\mu^+ Z^\mu\right]$$

No $A_\mu A^\mu$ term : $M_\gamma=0$

Massive weak gauge bosons :

$$M_W = \frac{1}{2} v g$$

$$M_Z = \frac{1}{2}\frac{vg}{\cos\theta_W}$$

This is what we wanted to obtain !

v is not known it can be computed using the muon decay rate

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2} = \frac{1}{2v^2}$$

→ v~246 GeV

The Higgs boson :

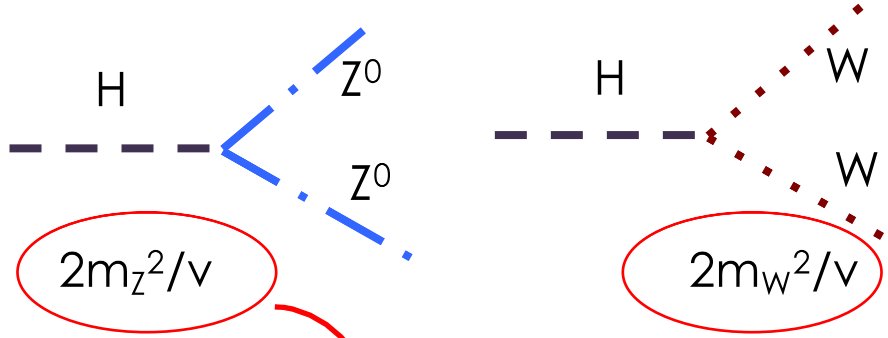
As shown before $M_H = \sqrt{-2\mu^2}$ it is a free parameter

If one writes the full lagrangian one sees Higgs self-coupling and Higgs couplings to the gauge bosons

These couplings are proportional to the masses

Higgs self coupling

Higgs coupling to the gauge bosons



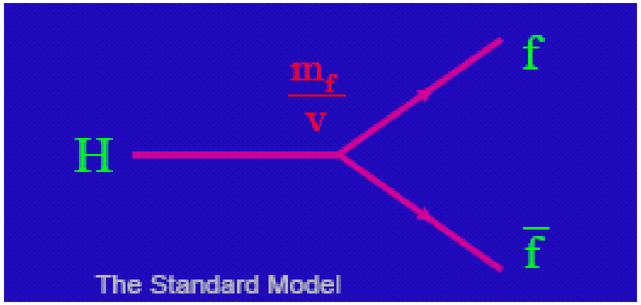
Couplings proprotionnal to the mass of the Higgs

→ Crucial test of the model

v can be computed using the muon decay rate
→ couplings fixed

The Higgs and the fermions :

The fermions masses are free parameters :



The couplings are fixed : m_f/v

Experimental consequence : the Higgs boson will decay preferentially to heavy particles

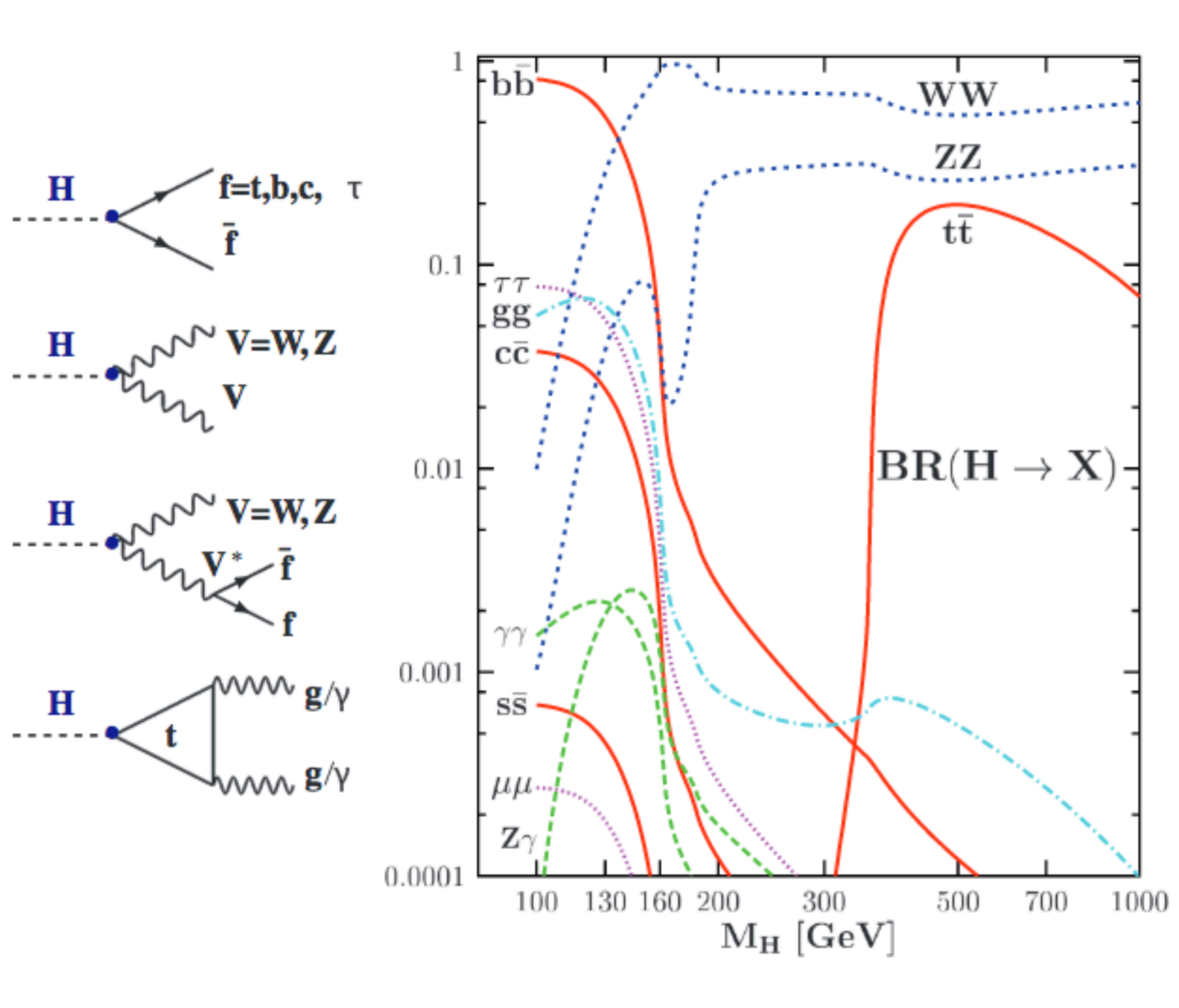
RECAP

- Complex doublet scalar field : the Higgs field : 3 components absorbed : masses to the W and Z.

- One remaining component : the Higgs boson

- Higgs field : it is the interaction of the elementary particles with the Higgs field which gives them masses

Main Higgs possible decays depend on the Higgs mass



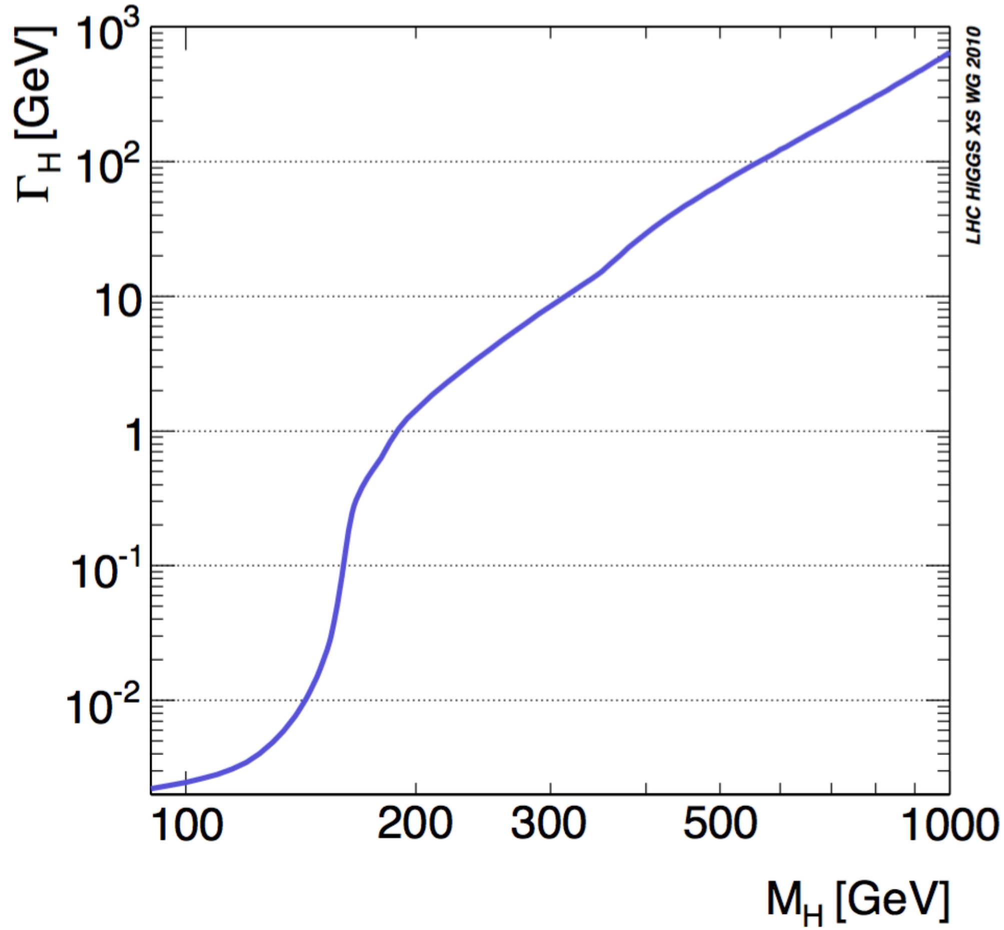
One has

$$\Gamma^h_{f\bar{f}} \approx \frac{|\boldsymbol{p}_f|}{m_h^2} \frac{\int d\Omega}{32\pi^2} \overline{|\mathcal{M}|^2} = \alpha_2 \frac{c_f}{8} \frac{m_f^2}{m_W^2} m_h.$$

c_f=3 for quarks
c_f=1 for leptons
$\alpha_2 = \alpha_{QED}/\sin^2\theta_W$

$$\Gamma^h_{WW} \approx \frac{\alpha_2 m_h^3}{16 m_W^2}.$$

$$\Gamma^h_{ZZ} \approx \frac{\alpha_2 m_h^3}{32 m_W^2}.$$



The larger the mass, the larger the width !

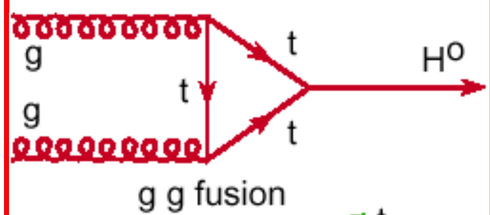
M ~ 125 GeV ⇒ Γ ~ 4 MeV


CERN/LHCC 92-3
1 October 1992
LABORATOIRE EUROPÉEN POUR LA PHYSIQUE DES PARTICULES
CERN
EUROPEAN LABORATORY FOR PARTICLE PHYSICS
CMS
The Compact Muon Solenoid
CMS
16
ating
stals
tilator/brass
leaved
Solenoid
IRON YOKE
Muon
End-Caps
Cathode Strip Ch. (CSC)
Resistive Plate Ch. (RPC)
CERN/LHCC/92-4
1 October 1992
1992
ATLAS
Letter of Intent
for a
General-Purpose pp Experiment
at the
Large Hadron Collider at CERN
Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil
Pixels & Tracker
• Pixels (100x150 μm²)
~ 1 m² 66M channels
• Silicon Microstrips
~ 210 m² 9.6M channels
Drift Tubes (DT) and
Resistive Plate Chambers (RPC)

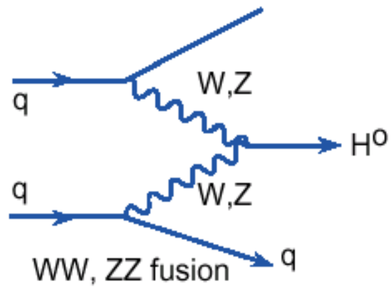
Production (at the LHC)

In the proton : light quarks and gluons → small/no direct coupling to H
→ First produce heavy particles !

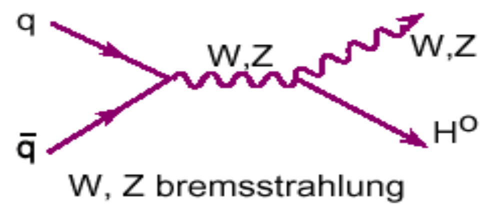
Gluon fusion

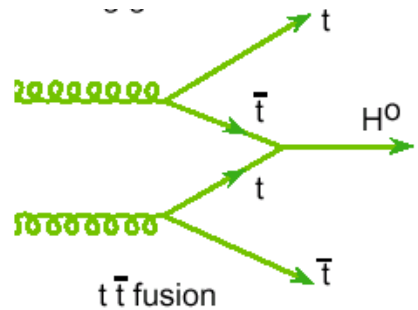


Vector boson fusion



Associated production (W/Z, tt)

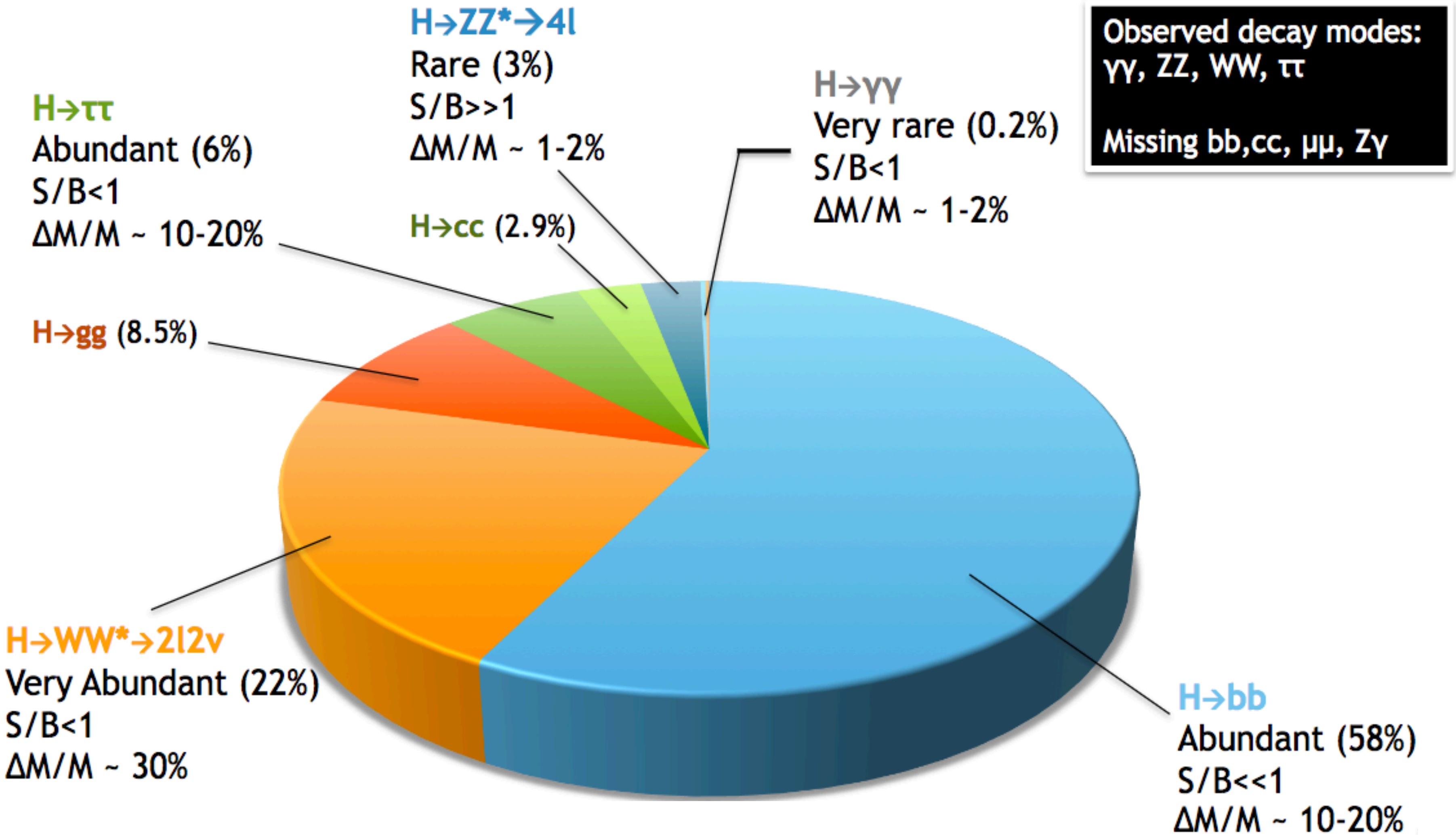




86 %   7 %   5 %   0.6 %

For a 125 GeV H boson

Decay (~~at the LHC~~)



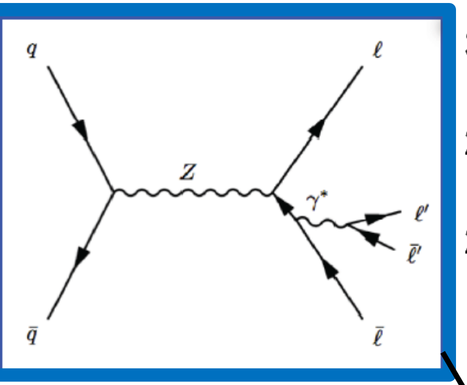
W,Z : high p_T leptons

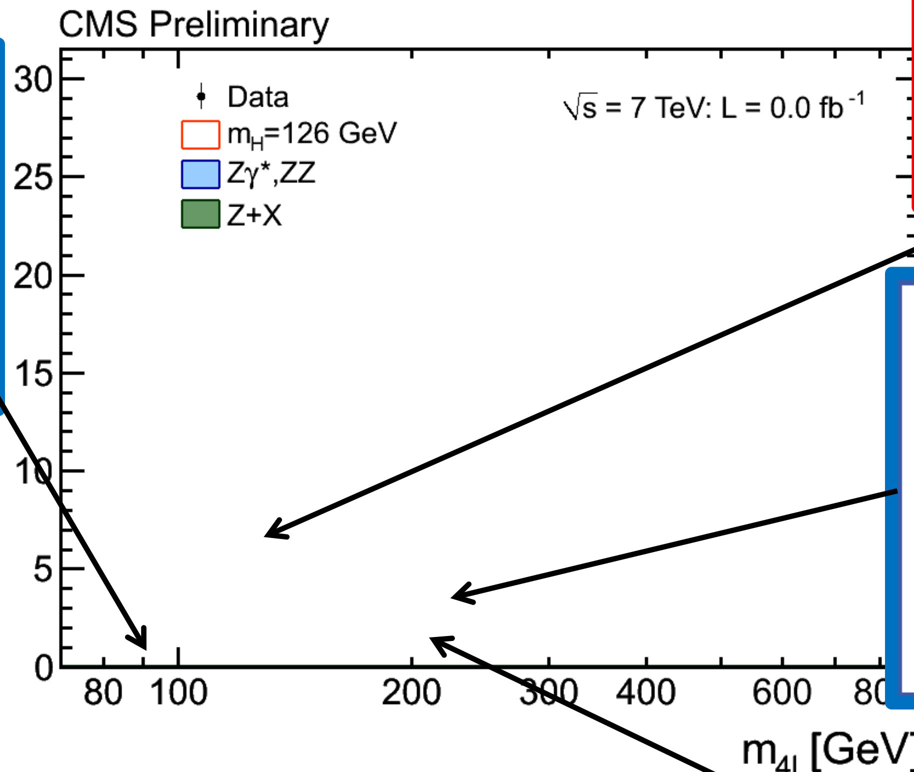
τ : low p_T leptons

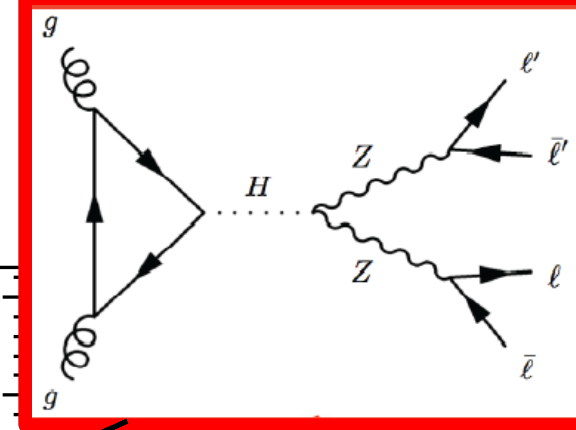
bb & ττ : importance of vertex detectors

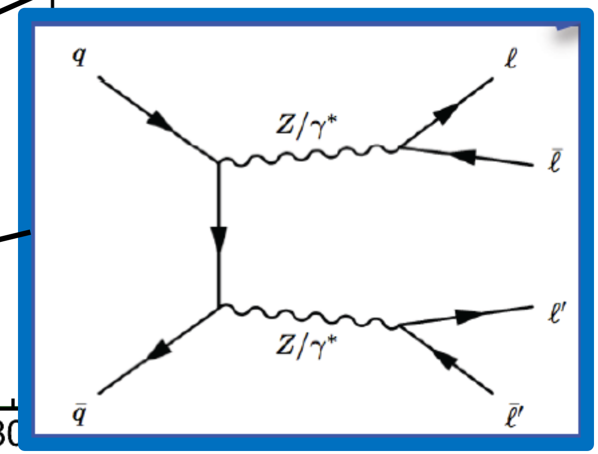
$H \to ZZ^{(*)} \to \ell\ell\ell\ell$

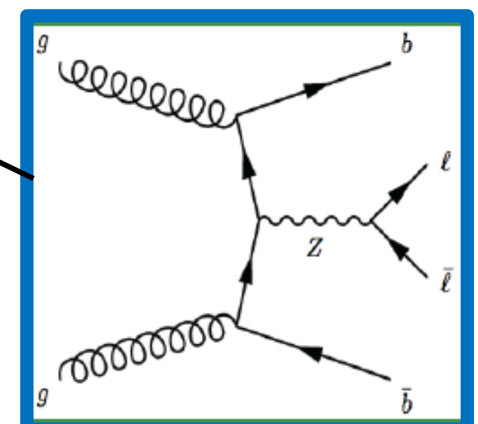
σ×B×L = 72 events







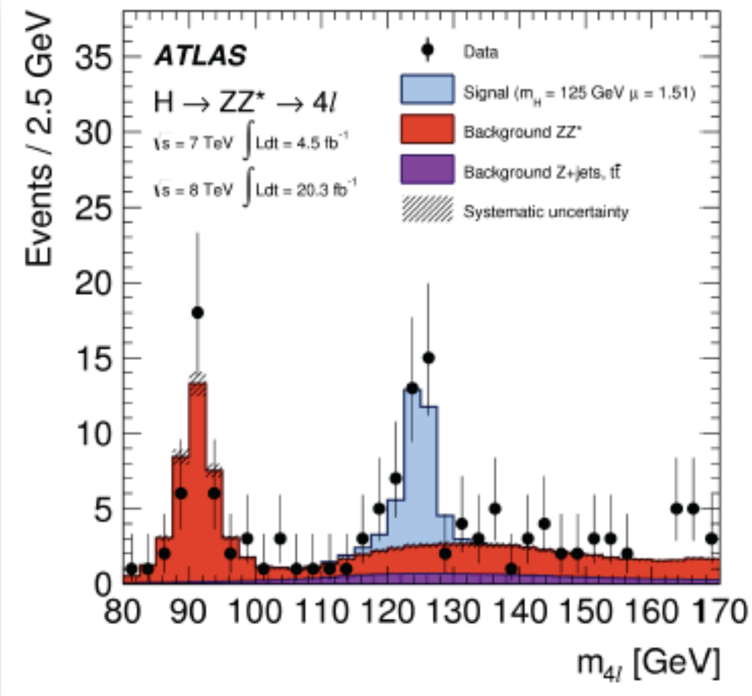




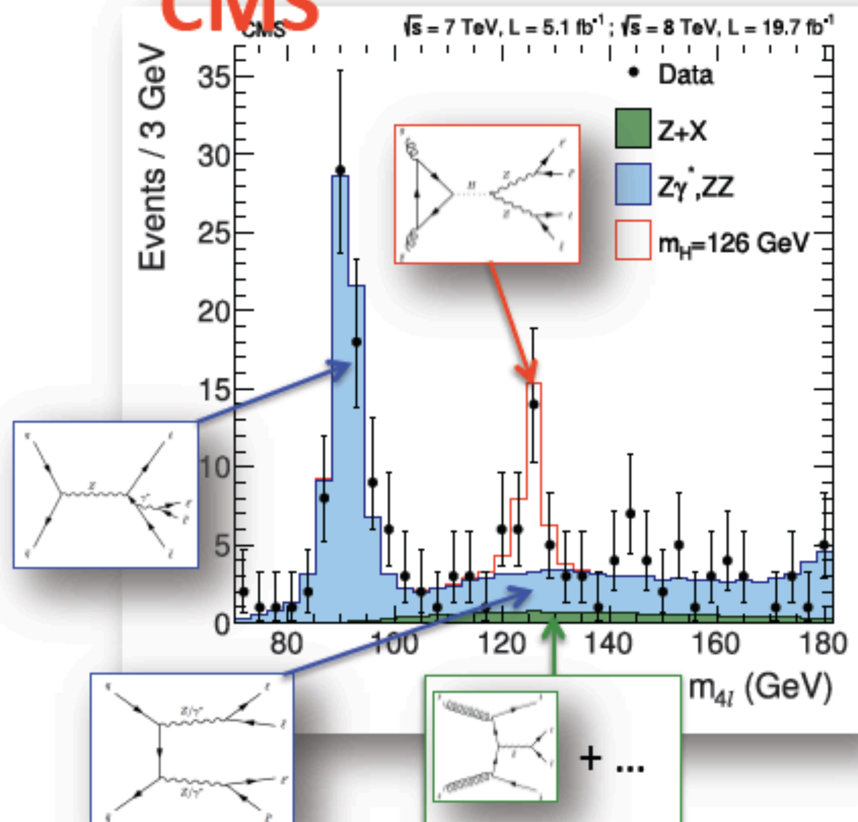
4e,4μ,2e2μ

Small event yield : 20 events
High S/B : better than 2:1
Good mass resolution (4 leptons) : 1 to 2 %
Four body decay : access to spin parity studies through the decay angles

ATLAS



CMS



significance = 8.2 (expected 5.8)
signal strength μ = 1.7 ± 0.4
m_H = 124.5 ± 0.5 GeV
Γ_H < 2.6 GeV at 95% CL

μ = 1.4 ± 0.4
@ m_H=125.4

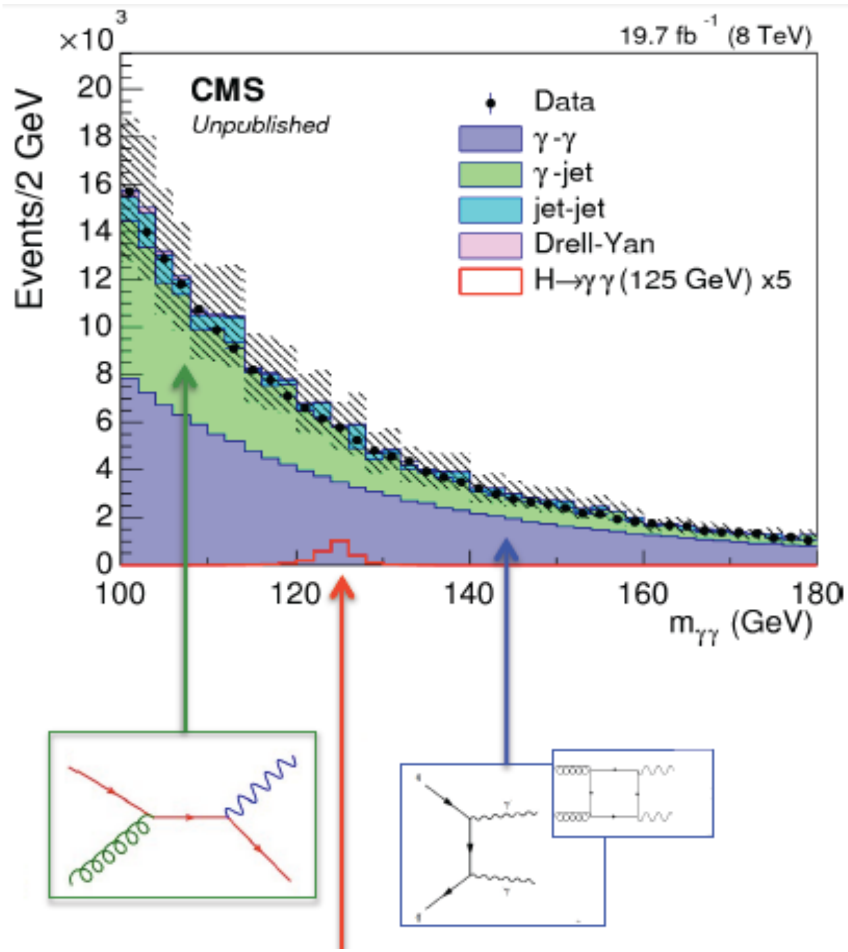
significance = 6.7 (expected 7.2)
signal strength μ = 0.9 ± 0.3
m_H = 125.6 ± 0.4 GeV
Γ_H < 3.4 GeV at 95% CL

Extremely clear observation of the Higgs boson
Compatible with expectations (signal strength) from the SM

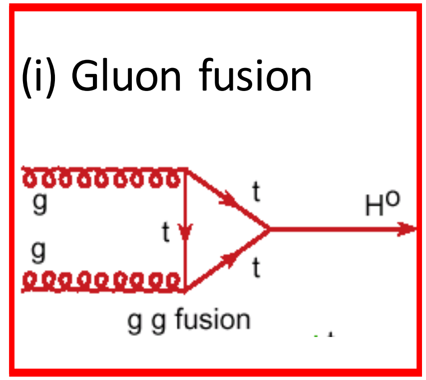
H→γγ

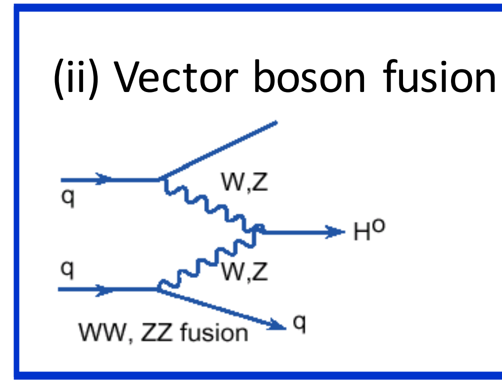
σ×B×L = 1.3K events

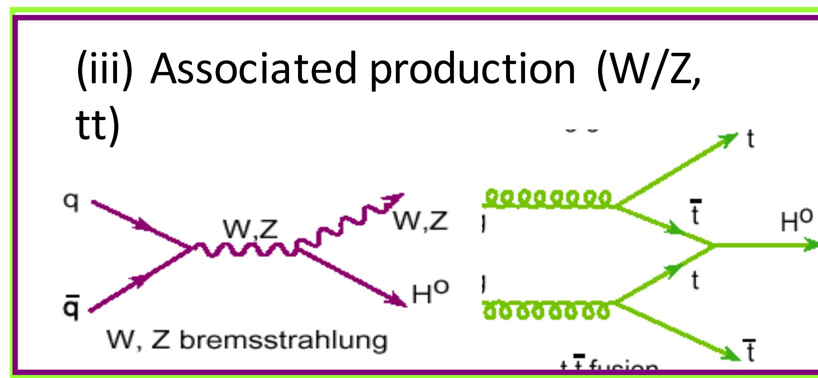
Only two high p_T photons ....
Analysis performed according to the Higgs production mode (and thus the rest of the event



Signal (x5)

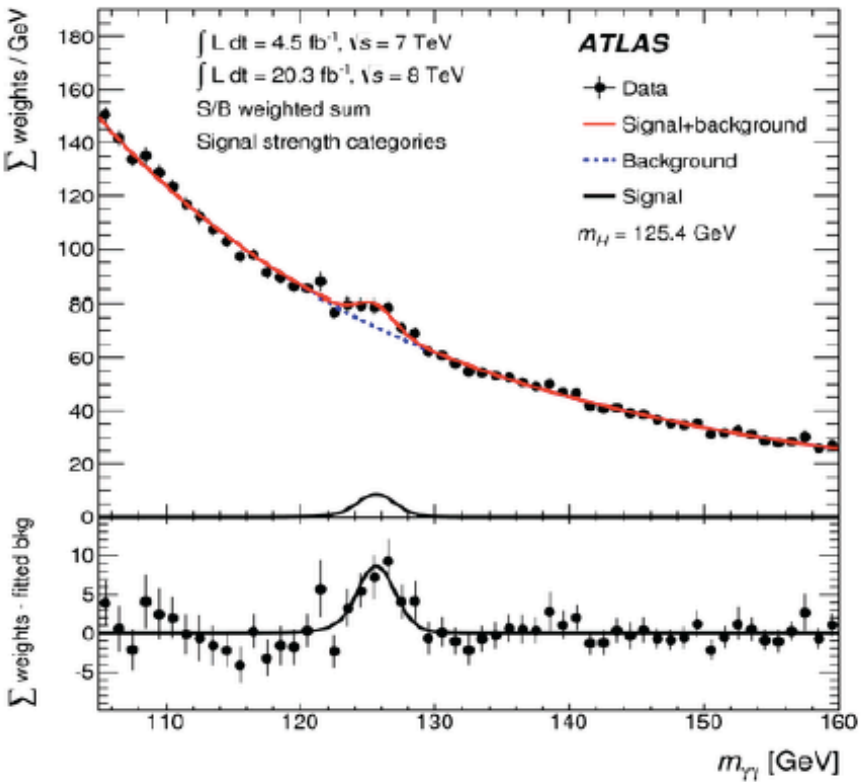






Large event yield : 470 events
Low S/B : 1:20
Good mass resolution : 1 to 2 %

ATLAS

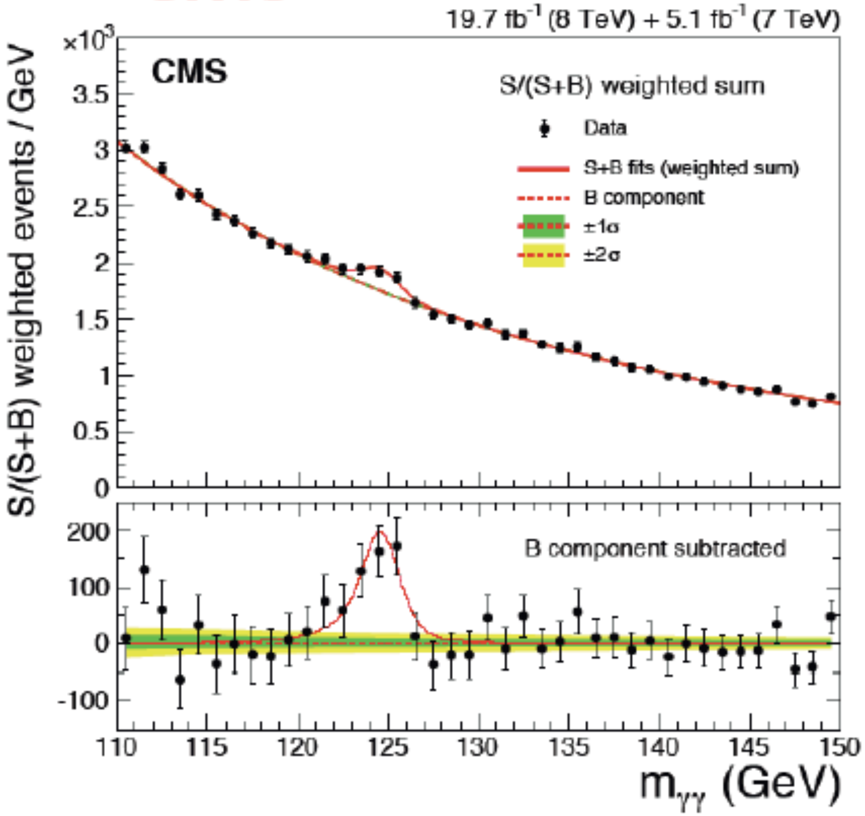


significance = 5.2 (expected 4.6)
signal strength μ = 1.2 ± 0.3

@ m_H=125.4

m_H = 126.0 ± 0.5 GeV
Γ_H < 5.0 GeV at 95% CL

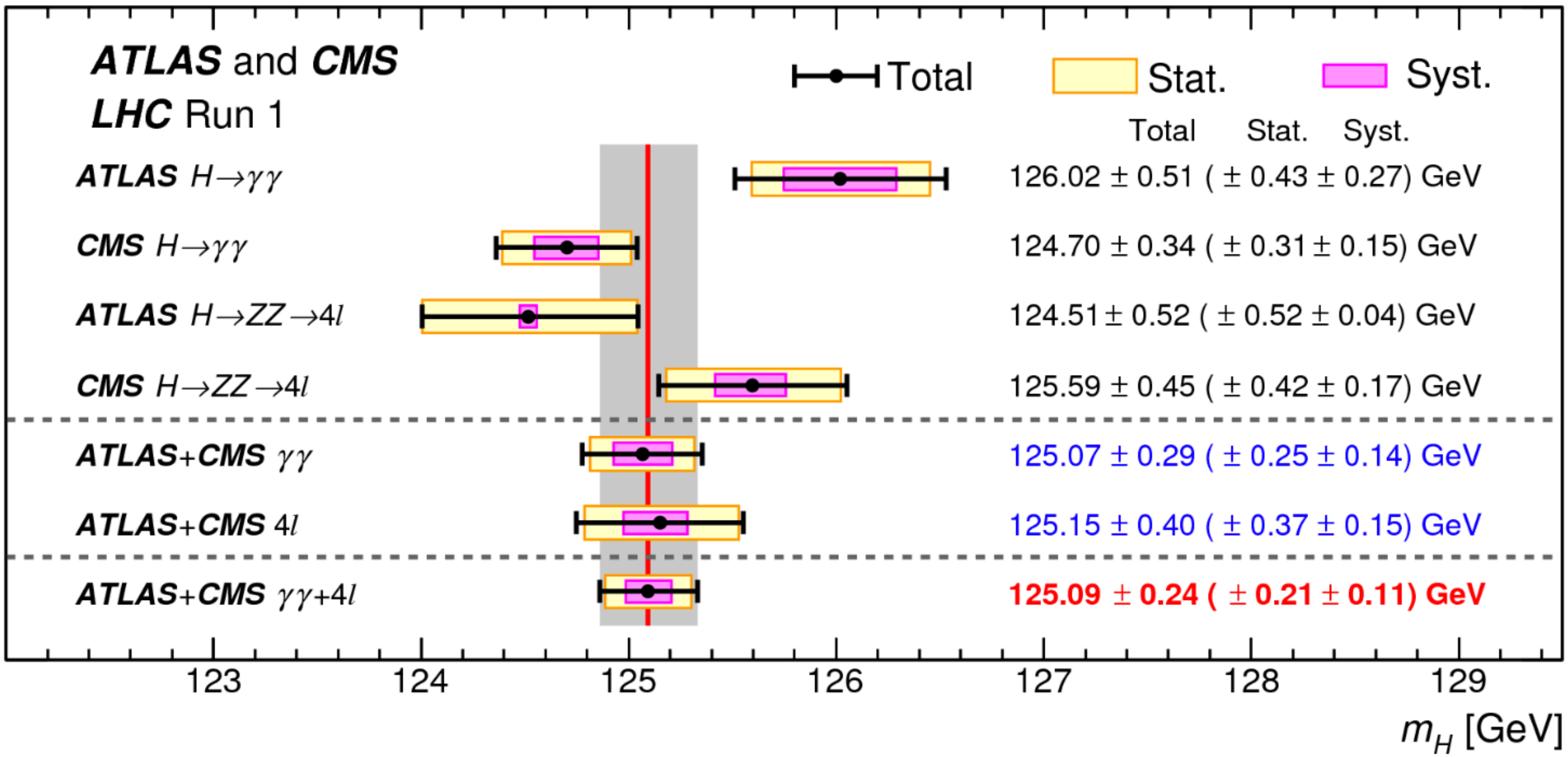
CMS



significance = 5.7 (expected 5.2)
signal strength μ = 1.1 ± 0.3
m_H = 124.7 ± 0.4 GeV
Γ_H < 3.4 GeV at 95% CL

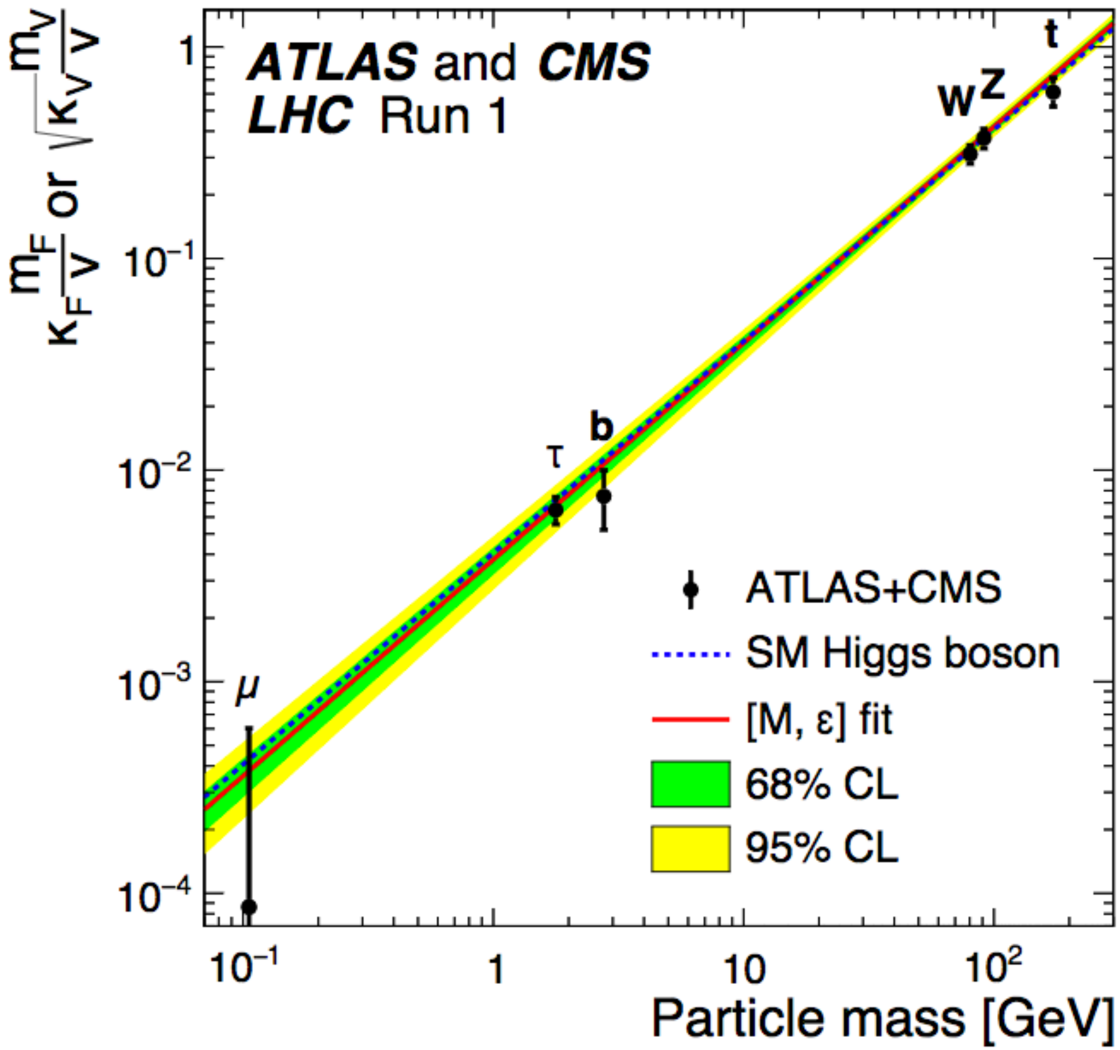
Clear observation of the Higgs boson despite the larger background level
Compatible with expectations (signal strength) from the SM

The H→ZZ→4l and the H→γγ channels allow to measure the boson mass



Precision of the order of 0.2 %

SM : couplings proportionnal to the masses of the particles

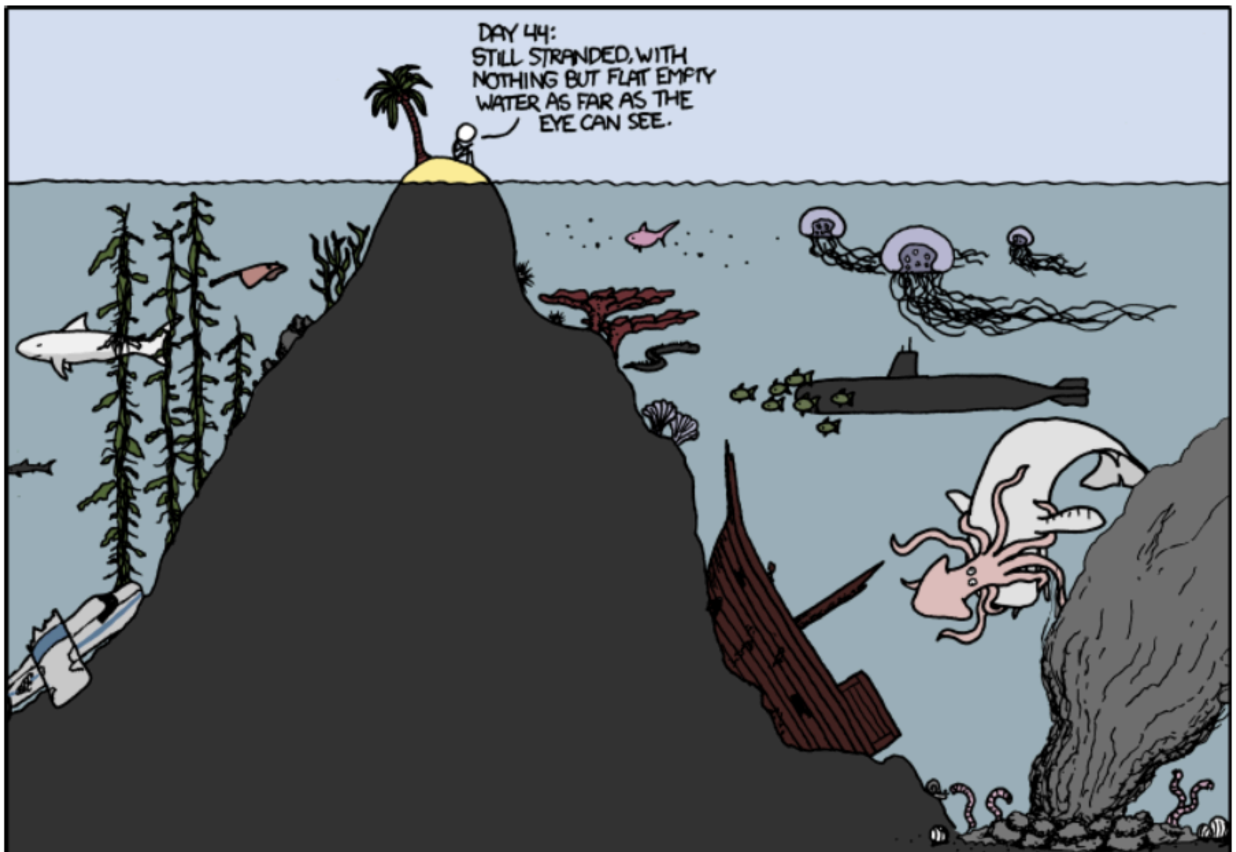


No big surprise

Run2 : in 2015 LHC restarted with a centre of mass energy of 13 TeV

But also much larger integrated luminosities
→ a lot of Higgs events
→ new decay modes
→ studies of its properties.

Up to now it looks like a Standard Model Higgs

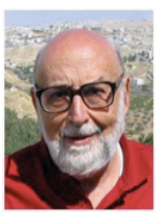


Summary

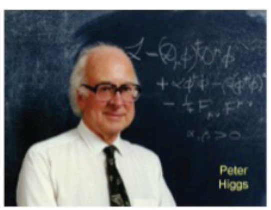
- What has been discovered at the LHC is the Higgs boson (a particle) which is the experimental proof of the existence of the Higgs field

- All Higgs boson measured properties are consistent with the SM expectations :
  - spin and parity (0^+)
  - the mass, NOT predicted by the SM is measured with a precision of 0.2 %
  - the couplings agree with those expected for a SM Higgs boson

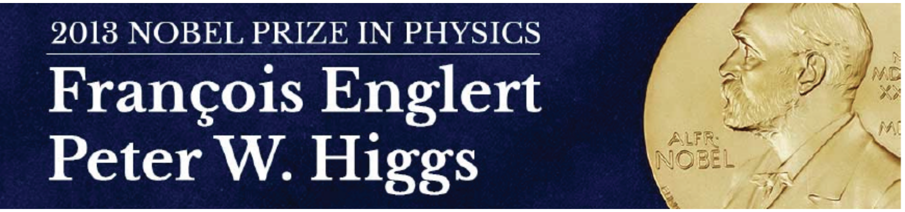
Robert Brout 1928-2011



François Englert 1932-



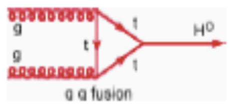
Peter Higgs 1929-

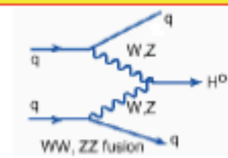


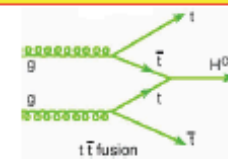
Back up slides

Number of SM Higgs bosons produced in Run 1 per experiment :

Total number of inelastic pp-collisions produced in Run I:	**1.5×10^{15}**
Total produced Higgs bosons (m_H=125 GeV):	**560,000**







m_H=125 GeV (l=e/μ)		ggF (86%)	VBF (7%)	VH (5%)	bbH (0.9%)	ttH (0.6%)
H → ZZ → 4l	0.013%	72				
H → γγ	0.23%	1,300				
H → WW → lνlν	1.1%	6,100				
H → ττ	6.3%	35,000				
H → bb	58%	✗ 270,000	42,000			
H → μμ	0.022%	120				
H → Zγ → 2l γ	0.010%	56				
H → J/ψγ → μμ γ	1.7×10^{-7}	0.1				
invisible	0.11%	✗ 590 (too small S/B at LHC, unless there is BSM H→inv)				
all others	37%	✗ 200,000 (deemed not feasible at LHC)				

all event counts are before:

- detector acceptance
- reconstruction efficiency
- event selection efficiency

Remember the number of Higgs bosons produced for Run 1 ?

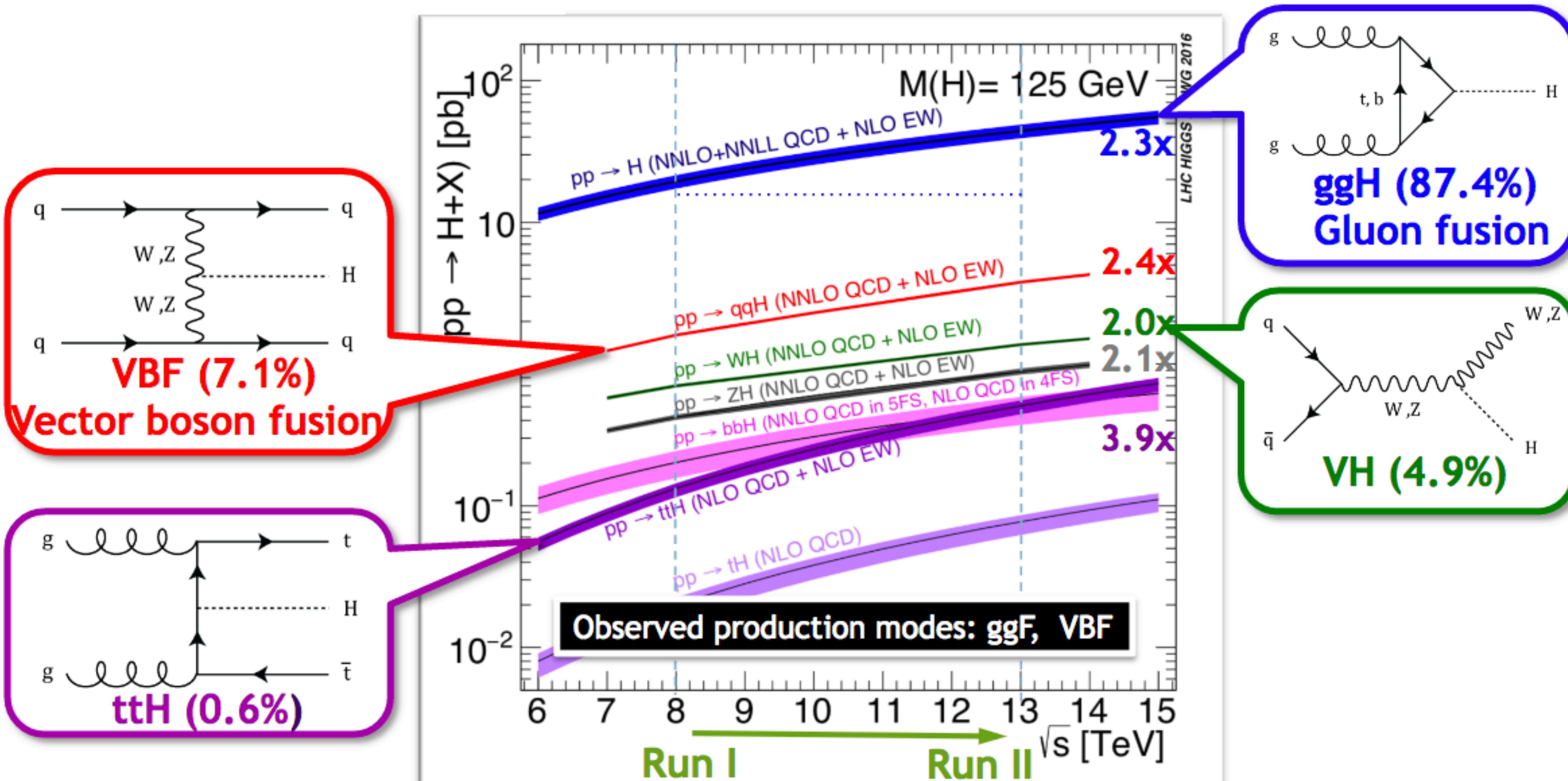
	m_H=125 GeV (l=e/μ)		ggF (86%)	VBF (7%)	VH (5%)	bbH (0.9%)	ttH (0.6%)
✓	$H \to ZZ \to 4l$	0.013%	72				
✓	$H \to \gamma\gamma$	0.23%	1,300				
✓	$H \to WW \to l\nu l\nu$	1.1%	6,100				
✓	$H \to \tau\tau$	6.3%	35,000				
?	$H \to bb$	58%	✗ 270,000	42,000			
–	$H \to \mu\mu$	0.022%	120				
–	$H \to Z\gamma \to 2l\,\gamma$	0.010%	56				
–	$H \to J/\psi\gamma \to \mu\mu\,\gamma$	1.7×10^{-7}	0.1				

all event counts are <u>before</u>:
- detector acceptance
- reconstruction efficiency
- event selection efficiency

Production (at the LHC)

In the proton : light quarks and gluons → small/no direct coupling to H
→ First produce heavy particles !

For a 125 GeV H boson :



7/8 TeV (2011/2012) **13 TeV (>2015)**

The Lagrangians *L* and *L'* are completely equivalent

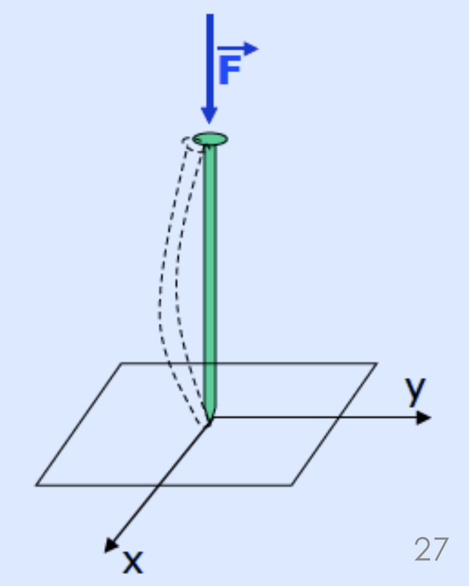
The transformation $\phi(x) = v + \eta(x)$ does not change the physics

If we were able to solve exactly *L* and *L'* we would get the same results… but we cannot, so we use perturbations theory and calculate the fluctuations around the minimum energy

If we use *L* in perturbations theory the series don't converge (Φ=0 is unstable)

The correct way is to use *L'* to expand in η around the stable minimum Φ=v.

The scalar particle described by *L'* has a mass.



We call this way the mass is generated (in fact *revealed*)

"spontaneous symmetry breaking"

The Higgs mechanism in the Standard Model

We have seen that the spontaneous symmetry breaking (performed adding a well chosen scalar field) can « modify » the mass content of the Lagrangian

Which scalar field to add in the framework of the electroweak symmetry ?

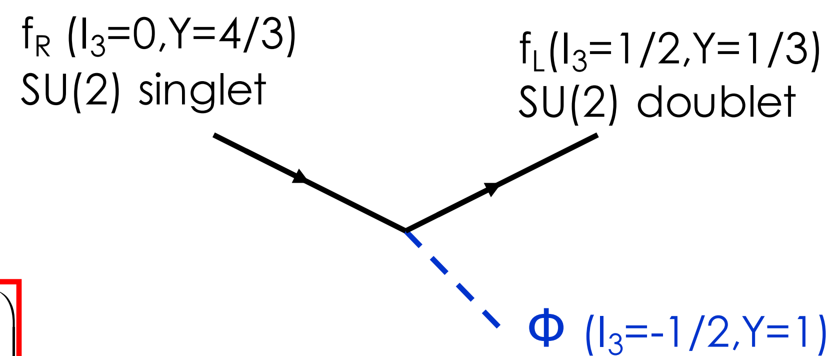
$Q = I_3 + Y/2$

Mass term for fermions:

$$-m_f \bar{f} f = -m\left(\overline{f_L} f_R + \overline{f_R} f_L\right)$$

Does not conserve I_3 nor Y (not gauge invariant)

Let's take the up case : $Q_f = 2/3$



A $f_R f_L \Phi$ coupling is gauge invariant if $I(\Phi)=1/2$

→ needs a SU(2) doublet : $\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \begin{pmatrix} \frac{1}{\sqrt{2}}(\phi_1 + i\phi_2) \\ \frac{1}{\sqrt{2}}(\phi_3 + i\phi_4) \end{pmatrix}$

$Q=I_3+Y/2$ so the charge are +1 and 0 in the doublet

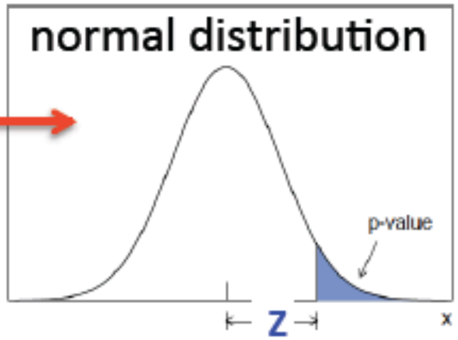
Any choice which breaks a symmetry will generate mass for the associated boson.

We want the photon to remain massless : elm should be conserved

How to quantify the presence (or the absence) of a signal ?

p-value and significance (Z)

$$p\text{-value} = P(\, n \geq n_{obs} \mid b \,)$$



p-value	Z
2.3×10^{-2}	2
1.4×10^{-3}	3
3.2×10^{-5}	4
2.9×10^{-7}	5
1.0×10^{-9}	6
1.3×10^{-12}	7

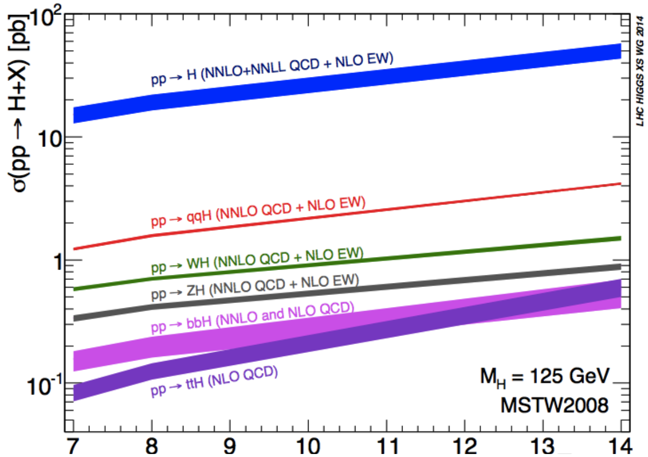
signal strength (μ) – common scale factor for signal event yields

$$n_{\text{expected}} = \mu \cdot [\, \sigma_{\text{SM H}} \cdot B(\text{H}_{\text{SM}} \rightarrow xx) \cdot L \cdot \varepsilon \,] + n_{\text{background}}$$

95% CL limits on signal strength (in absence of a significant excess):

$$\mu \text{ is excluded at 95\% CL, if :} \quad \frac{P(\, n \leq n_{obs} \mid b + \mu \cdot s \,)}{P(\, n \leq n_{obs} \mid b \,)} < 0.05$$

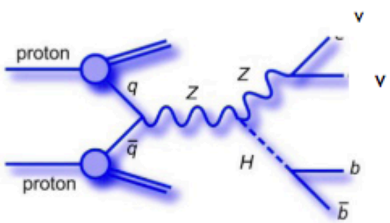
Enough events to start to search for other modes : H→ bb

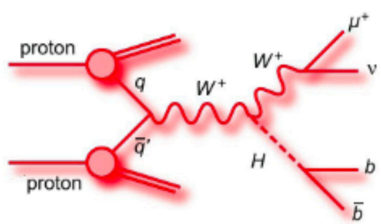


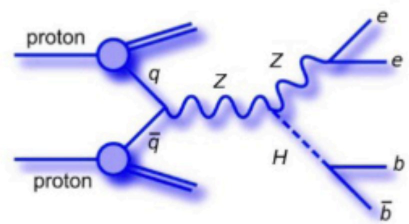
too much background

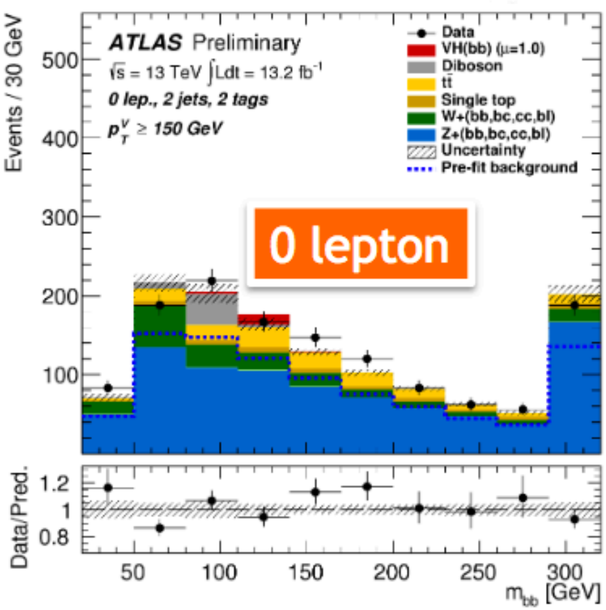
Use the extra information from associated production modes

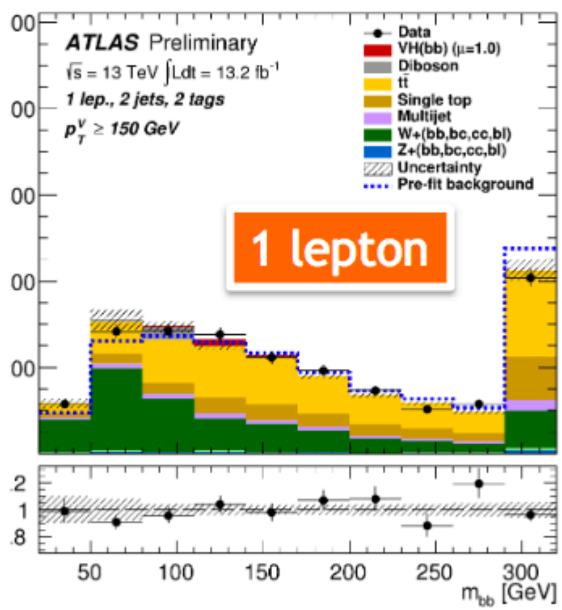
Challenging analyses !

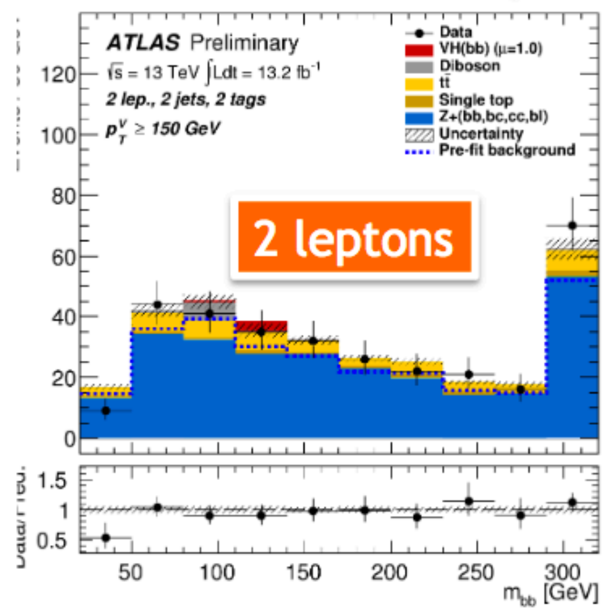


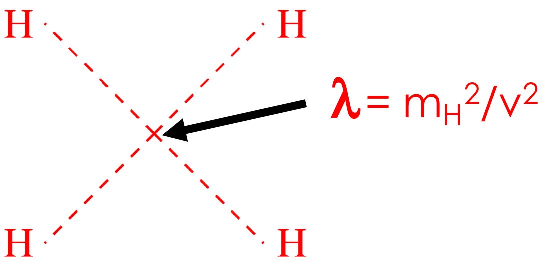


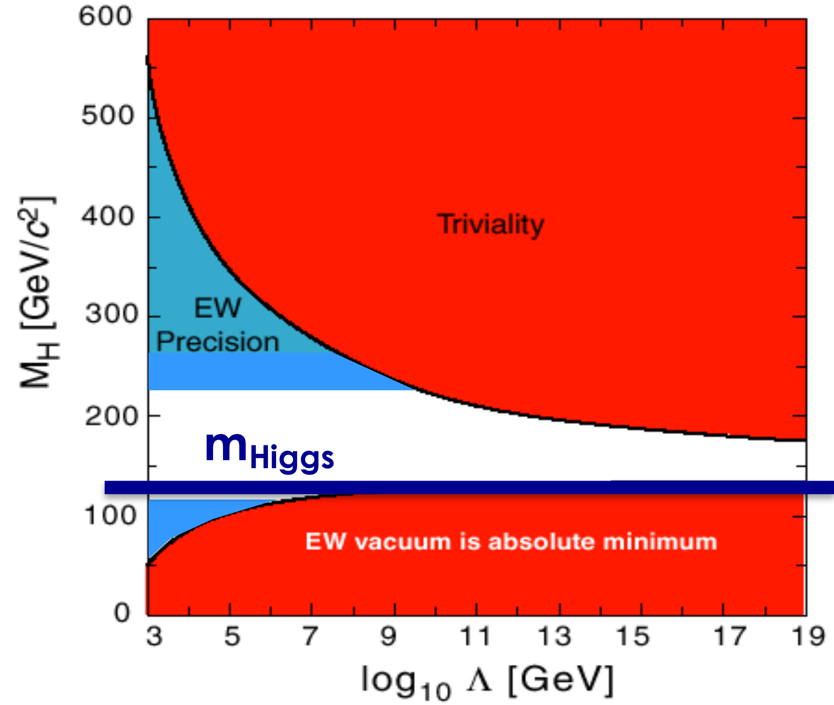












As for any other coupling constant, the particle content of the Standard Model determines the running of λ up to a scale Λ, at which the model is no longer valid.

$$0 \leq \lambda(\Lambda) \leq \infty$$

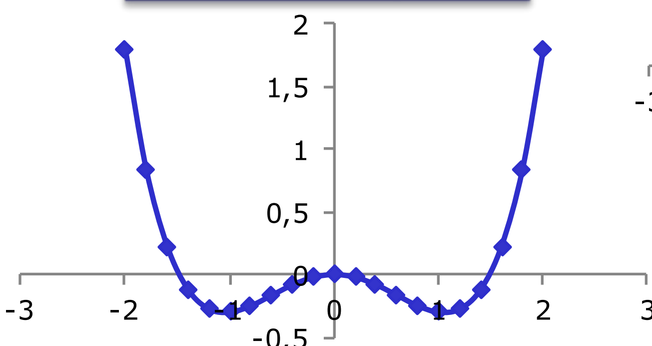
λ >0 : V(Φ) with a minimum up to the scale Λ

Vacuum stability

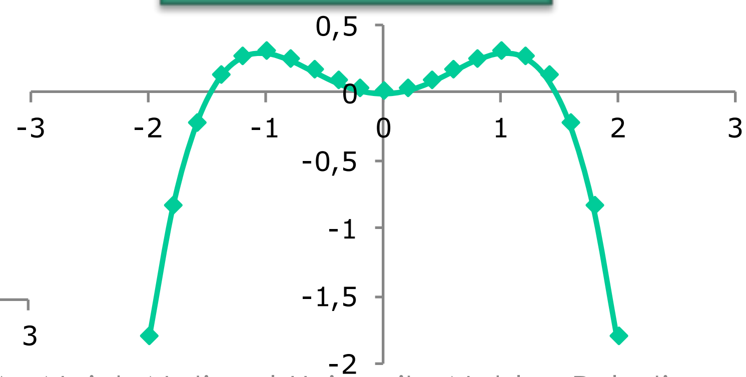
λ small : SM perturbative up to Λ Triviality bound

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

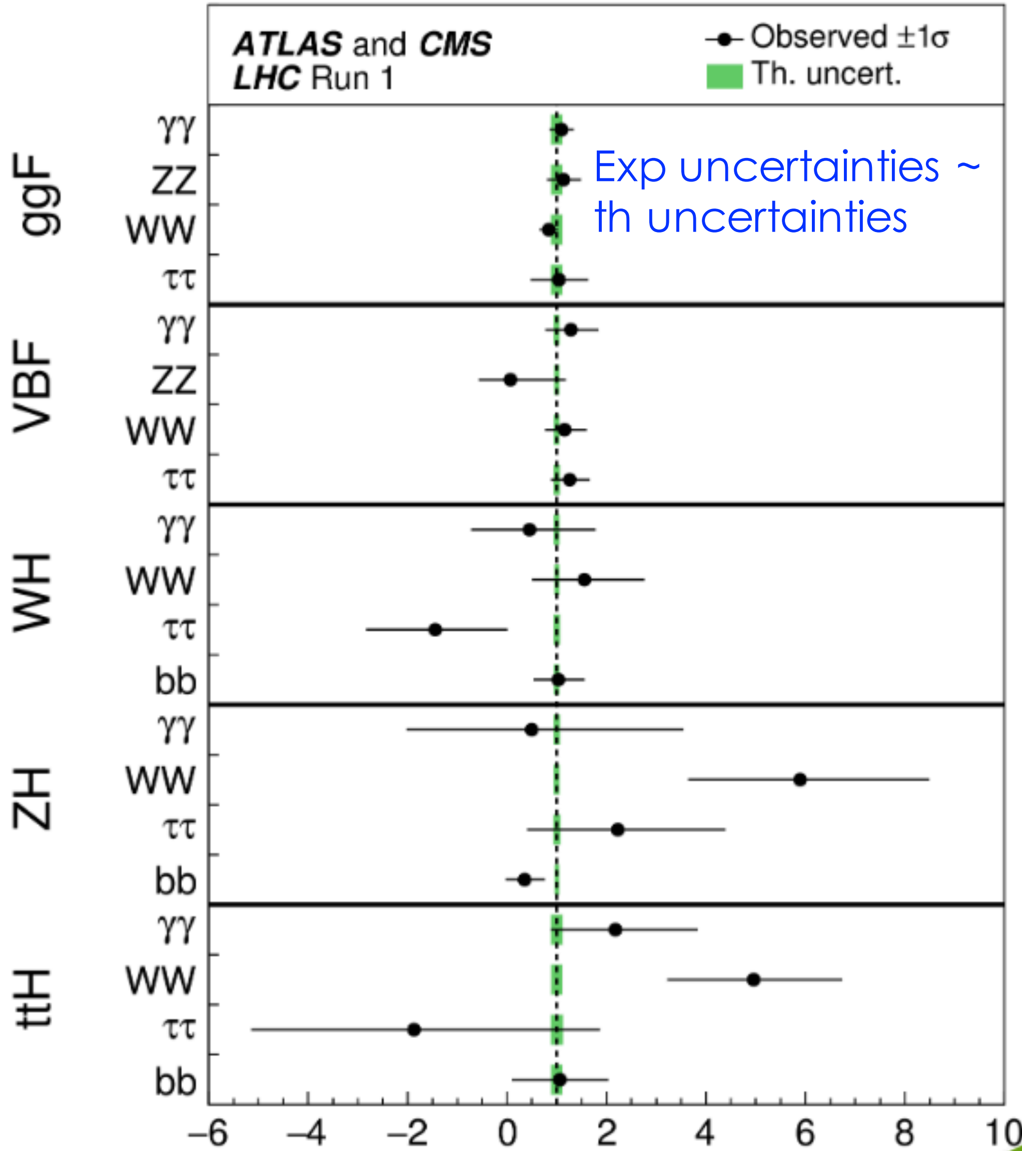
If λ>0 and $\mu^2 < 0$



If λ<0 and $\mu^2 > 0$



$$-\mu^2/\lambda > 0$$



Precision test of Higgs boson coupling strengths

CMS and ATLAS combined 7 and 8 TeV results Run 1 legacy papers:

Mass: Phys. Rev. Lett. 114, 191803
Rates and couplings: arXiv:1606.02266

Mass has been measured to 0.2% precision
m_H=125.09±0.24 GeV

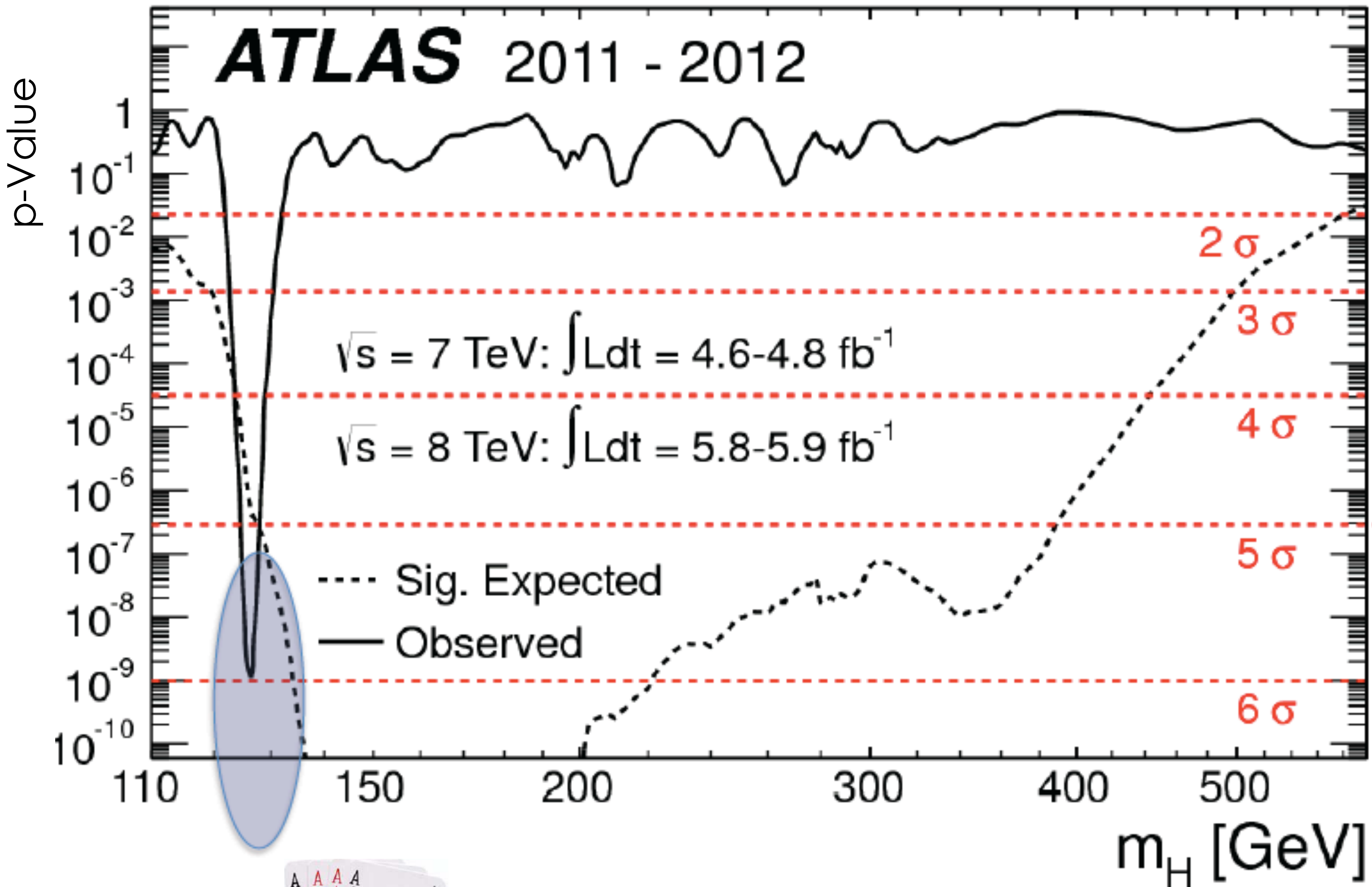
Angular distributions consistent with spin 0 and even parity

All couplings are consistent with SM within 2.5σ

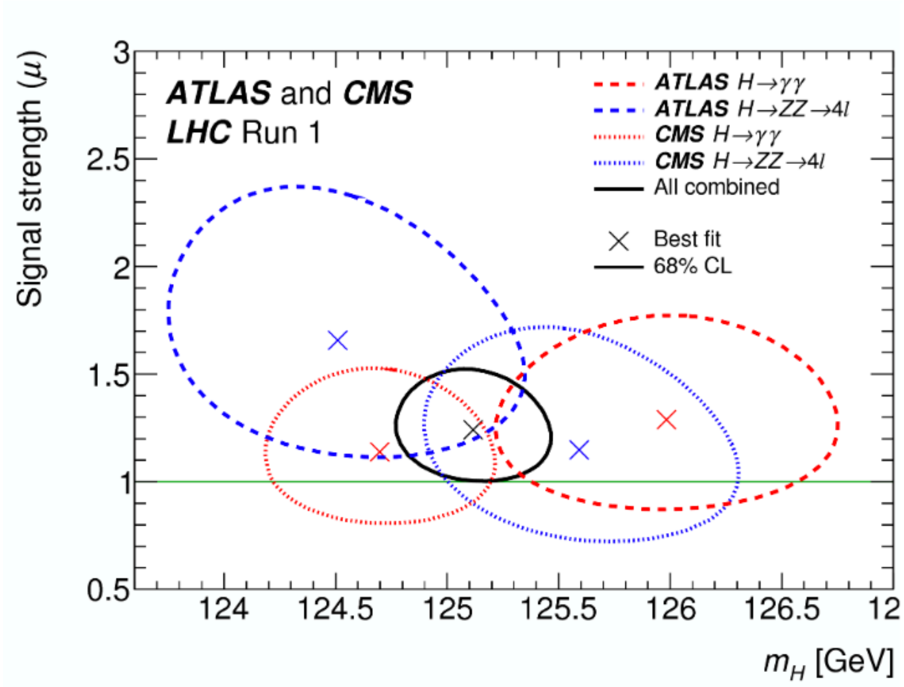
Coupling strengths

$$\mu = \frac{\sigma}{\sigma_{SM}}$$

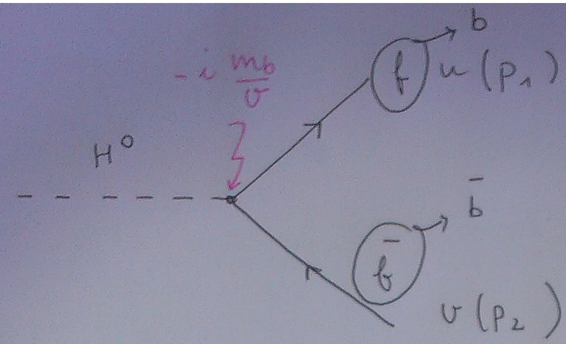
p-Value … already some time ago !



~ same probability to obtain the 4 aces in a 52 cards game in this order !


ATLAS and CMS
LHC Run 1
ATLAS H→γγ
ATLAS H→ZZ→4l
CMS H→γγ
CMS H→ZZ→4l
All combined
Best fit
68% CL
Signal strength (μ)
m_H [GeV]
3
2.5
2
1.5
1
0.5
124
124.5
125
125.5
126
126.5
12

Computation of $\Gamma(H \to bb)$



$H^0 \to f\bar{f}$

$-i\frac{m_b}{v} = \frac{-i m_b}{2M_W} g_W$

$(M_W = \frac{1}{2} g_W v)$

$$d\Gamma = \frac{p^*}{32\pi^2 M_H^2} |\bar{\mathcal{M}}|^2 \, d\Omega$$

2-body decay : $p^* = \frac{1}{2}\sqrt{M_H^2 - 4m_b^2}$

H is a spin 0 $\Rightarrow$ $d\Omega = 4\pi$

$$\Gamma = \frac{1}{8\pi} \times \frac{1}{2}\left(M_H^2 - 4m_b^2\right)^{1/2} \times \frac{1}{M_H^2} \times |\bar{\mathcal{M}}|^2$$

$$\boxed{\Gamma = \frac{1}{16\pi M_H^2}\left(M_H^2 - 4m_b^2\right)^{1/2} \times |\bar{\mathcal{M}}|^2}$$

②

$$|\bar{\mathcal{M}}|^2 = \sum_{s_1, s_2} |\mathcal{M}\mathcal{M}^*|$$

$$-i\mathcal{M} = \bar{u}(p_1) \frac{m_b}{2M_W} g_W v(p_2)$$

$$|\mathcal{M}\mathcal{M}^*| = \frac{m_b^2 g_W^2}{4M_W^2} \bar{u}(p_1) v(p_2) \bar{v}(p_2) u(p_1)$$

(1,4) (4,1) (1,4) (4,1)

⇒ number!

$$\mathrm{Tr}(\bar{u}(p_1) v(p_2) \bar{v}(p_2) u(p_1)) = \bar{u}(p_1) v(p_2) \bar{v}(p_2) u(p_1)$$

// Property of Trace under cyclic rotation

$$\mathrm{Tr}(u(p_1)\bar{u}(p_1) v(p_2) \bar{v}(p_2))$$

$$|\bar{\mathcal{M}}|^2 = \sum_{s_1 s_2} \mathrm{Tr}(\;) \times \frac{m_b^2 g_W^2}{4M_W^2}$$

$$= \frac{m_b^2 g_W^2}{4M_W^2} \mathrm{Tr}\left[\sum_{s_1} (u(p_1)\bar{u}(p_1) \sum_{s_2} v(p_2)\bar{v}(p_2))\right]$$

$$= \frac{m_b^2 g_W^2}{4M_W^2} \mathrm{Tr}\left[(\not{p}_1 + m_b \mathbb{1})(\not{p}_2 - m_b \mathbb{1})\right]$$

3

$$|\mathcal{M}|^2 = \frac{m_b^2 g_w^2}{4 M_W^2} \mathrm{Tr}\left[\not{p}_1 \not{p}_2 - m_b^2 \mathbb{1} + m_b (\not{p}_1 - \not{p}_2) \right]$$

Tr(odd number of γ matrices) = 0

$$|\mathcal{M}|^2 = \frac{m_b^2 g_w^2}{4 M_W^2} \left[4\, p_1 \cdot p_2 - 4 m_b^2 \right]$$

$$p_1 \cdot p_2 = \begin{pmatrix} m_H/2 \\ p_x \\ p_y \\ p_z \end{pmatrix} \cdot \begin{pmatrix} m_H/2 \\ -p_x \\ -p_y \\ -p_z \end{pmatrix}$$

$$= \frac{m_H^2}{4} + p^{*2} = \frac{M_H^2}{4} + \frac{M_H^2}{4} - m_b^2$$

$$p_1 \cdot p_2 = \frac{M_H^2}{2} - m_b^2$$

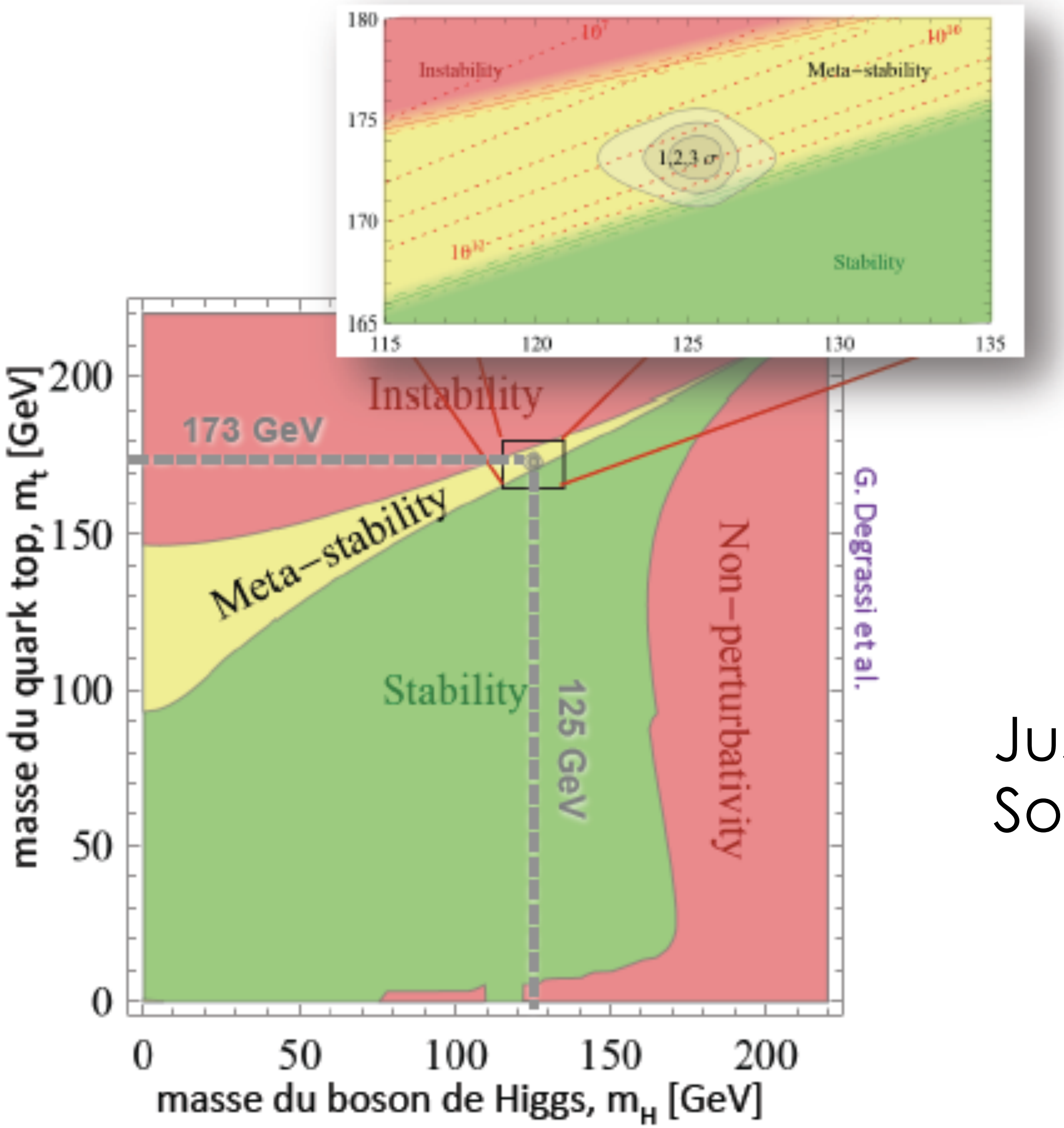
$$|\mathcal{M}|^2 = \frac{m_b^2 g_w^2}{4 M_W^2} \left[2 M_H^2 - 8 m_b^2 \right]$$

$$\boxed{|\mathcal{M}|^2 = \frac{m_b^2 g_w^2}{2 M_W^2} \left[M_H^2 - 4 m_b^2 \right]}$$

$$\Gamma = \frac{1}{16\pi M_H^2} \left(M_H^2 - 4 m_b^2\right)^{1/2} \times \frac{m_b^2 g_W^2}{2 M_W^2} \left[M_H^2 - 4 m_b^2\right]$$

$$= \frac{1}{32\pi M_W^2} \times m_b^2 g_W^2 \times \frac{1}{M_H^2} \times \left(M_H^2 - 4 m_b^2\right)^{3/2}$$

$$\boxed{= \frac{1}{32\pi M_W^2} \times m_b^2 g_W^2 \times M_H \times \left(1 - \frac{4 m_b^2}{M_H^2}\right)^{3/2}}$$



Just like that ?
Something deeper ?