How do we know it's the Higgs?

From the discovery of a new particle to the understanding of its properties

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The Higgs Boson and Beyond

KITP, UC-Santa Barbara, May, 21st 2016

Very special time for particle physics

The Large Hadron Collider (LHC) has been exploring unchartered ground and has already delivered milestone results.

- Run I ($\sqrt{s} = 7 - 8$ TeV):
  discovered a new particle (Standard-Model Higgs boson?)
- Run II ($\sqrt{s} = 13 - 14$ TeV):
  will reach new energy thresholds and deliver unprecedented statistics
  $\hookrightarrow$ precision study of the discovered *Higgs boson*
  $\hookrightarrow$ possible discovery of other new particles

The Higgs-boson discovery could validate the Standard Model while providing the first handle to explore its completions.

Standard-Model Higgs Boson (H), abridged

- Some fundamental ideas, the backbone of our discussion:
  - $\hookrightarrow$ physical systems are determined by their symmetry properties;
  - $\hookrightarrow$ elementary particles and their interactions are a realization of fundamental symmetries of nature;
  - $\hookrightarrow$ Standard Model (SM): particle masses not allowed by symmetry, but symmetry recovered if masses generated dynamically $\leftrightarrow$ symmetries of the dynamics not reflected in the energy spectrum;
  - $\hookrightarrow$ not all masses in the SM are the same: *force* vs. *matter* particles.

- The SM before the Higgs boson: everything known except M_H. Precision measurement of the SM can constrain M_H.

- The SM after the Higgs boson: knowing M_H fixes the SM Higgs-boson interactions, we can calculate all H production and decay processes.

- The LHC can measure the Higgs-boson couplings: any deviations from the SM pattern will indicate new physics, *if established with sufficient accuracy.*

Symmetries shape the physical world

Physical systems described by the Standard Model of Particle Physics span incredibly many orders of magnitude, from macroscopic scales to roughly 10^{-20} m (zeptometer):

- $\hookrightarrow$ macroscopic scales $\rightarrow$ classical systems
- $\hookrightarrow$ microscopic scales $\rightarrow$ quantum systems

and can be relativistic or non-relativistic depending on the energy regime.

Yet, for any physical system (from classical to quantum):
to a symmetry of the system is associated a conserved physical quantity.

Symmetry: "*the property of remaining invariant under certain changes (as of orientation in space, of the sign of the electric charge, of parity, or of the direction of time flow) used of physical phenomena and of equations describing them.*"

- $\hookrightarrow$ observing a physical system gives us hint of the symmetries at play
- $\hookrightarrow$ we can translate them into the mathematical description of the system: equations of motion, physical states, energy spectrum, etc.

The symmetries that make the world as we know it ...

- ▷ *translations*:
  conservation of energy and momentum $\to$ "particles", $p^2 = m^2$!
  where $p^\mu = (E, \vec{p})$ $(\mu = 0, 1, 2, 3)$, $p^2 = p^\mu p_\mu = E^2 - \vec{p}^2$ (c=1)
- ▷ *Lorentz transformations* (rotations and *boosts*):
  conservation of angular momentum (orbital and *spin*),
  - $\hookrightarrow$ s=0: scalar particles or *scalars* (*scalar bosons*)
  - $\hookrightarrow$ s=1/2: spinor particles *fermions*
  - $\hookrightarrow$ s=1: vector particles or *vector bosons* (*gauge bosons*)
- ▷ *discrete Lorentz transformations* (P,T,C,CP,...):
  conservation of corresponding "*labels*" or "*quantum numbers*";

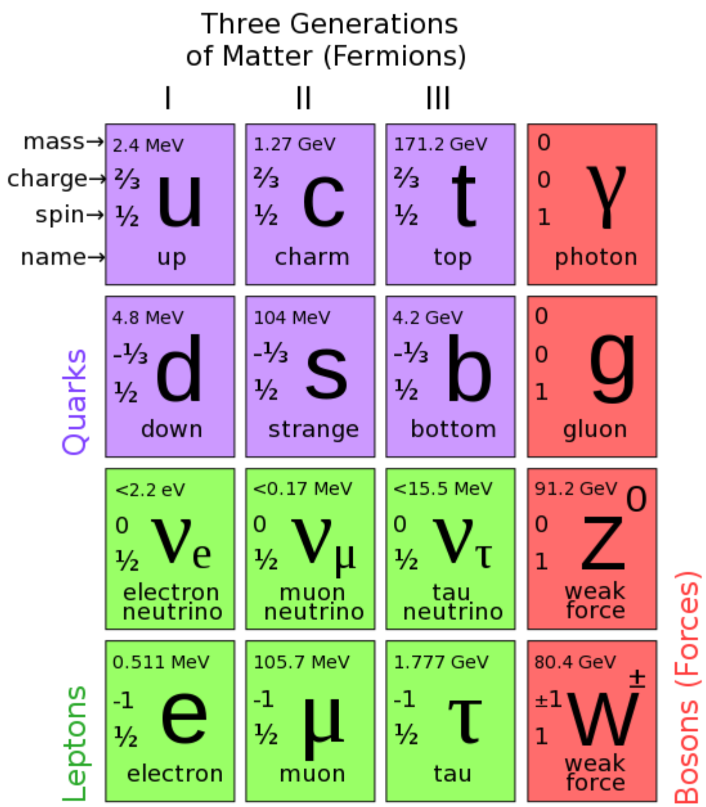
Plus

- ▷ *global transformations of internal degrees of freedom* (special "*rotations*")
  conservation of corresponding quantum numbers;
- ▷ *local transformations of internal degrees of freedom* ("rotations" with $\theta = \theta(x)$):
  define the interaction of fermion (s=1/2) and scalar (s=0) particles in terms of exchanged vector (s=1) massless particles $\longrightarrow$ "forces"

Requiring different global and local symmetries defines a theory!

The Standard Model of particle physics

"*The Standard Model of particle physics is a theory concerning the electromagnetic, weak, and strong nuclear interactions, as well as classifying all the subatomic particles known*". But how?



"*The Standard Model is a quantum field theory based on the local symmetry group* $SU(3)_c \times SU(2)_L \times U(1)_Y$*.*"

$SU(3)_c \to$ strong force (g)

$SU(2)_L \times U(1)_Y \to$ electroweak force (W, Z, γ)

particle multiplets:

$$\left.\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L , \begin{pmatrix} u \\ d \end{pmatrix}_L \leftrightarrow \underbrace{\begin{pmatrix} u & u & u \\ d & d & d \end{pmatrix}_L}_{SU(3)} \right\} SU(2)$$

$$e_R \ , \ u_R = (u\ u\ u)_R \ , \ d_R = (d\ d\ d)_R$$

The symmetry of the Standard Model asks for all particles to be massless.

A theorist view of the SM monster formula . . .!

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$
$$+ i \bar{\psi} \not{D} \psi + h.c.$$
$$+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$
$$+ |D_\mu \phi|^2 - V(\phi)$$

Particles as manifestations of particular physical systems: *quantum fields*

Ex. *classical field*: electromagnetic field $\xrightarrow{QED}$ photon!

$\psi_i \rightarrow$ fermions (quarks and leptons)
$F^{\mu\nu}$, $D_\mu \rightarrow$ vector bosons (g,γ,Z,$W^\pm$)
$\phi \rightarrow$ scalar (Higgs boson!)

Think of $\mathcal{L}$, the *Lagrangian*, as a function of the energy of the system that completely describes its dynamics.

$\hookrightarrow$ equations of motion

All particles ($\leftrightarrow$fields) seem to play a very similar role!

- Why: $m_\gamma, m_g = 0 \longrightarrow$ long-range forces
  while $M_W, M_Z \simeq 80 - 90$ GeV $\longrightarrow$ short-range forces?
- Why such a huge hierarchy in fermion masses when all fermions should be massless?

The idea of mass through symmetry breaking . . .

by Englert and Brout; Higgs; Guralnik, Hagen, and Kibble

VOLUME 13, NUMBER 9 PHYSICAL REVIEW LETTERS 31 AUGUST 1964

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)

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

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

VOLUME 13, NUMBER 20 PHYSICAL REVIEW LETTERS 16 NOVEMBER 1964

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

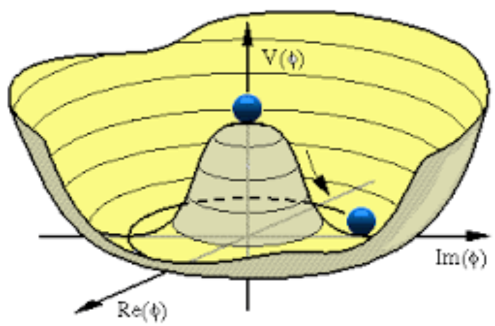
G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

Main idea: the original symmetry (of $\mathcal{L}$) is broken by the choice of the lower energy state (*ground* or *vacuum* state)

$\hookrightarrow$ several examples in magnetic systems

$$\mathcal{L}_\phi = |D_\mu \phi|^2 - V(\phi) \text{ with } V(\phi) = \mu^2 |\phi|^2 + \frac{\lambda}{4} |\phi|^4$$

The scalar potential $V(\phi)$ can have one or (infinite) many equivalent minima ($\rightarrow$ground states) depending on the sign of μ^2



Electroweak *phase transition*:

$\langle|\phi|\rangle = 0 \rightarrow \langle|\phi|\rangle = v \neq 0$

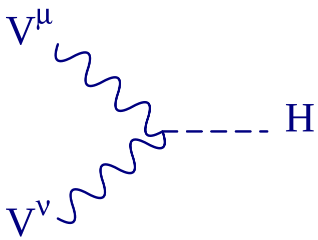
$\hookrightarrow$ Choosing one particular minimum breaks the original symmetry

$\hookrightarrow$ All particles interacting with ϕ (i.e. with the $\leftrightarrow$ Higgs boson) acquire a mass, in particular $W^\pm$ and Z

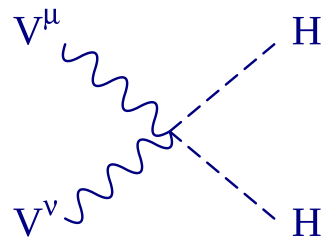
$\rightarrow$ short-distance force obtained through the interaction with the scalar field, of which the Higgs boson is the particle manifestation.

As a consequence:

- Z and $W^{\pm}$ acquire mass: $\boxed{M_W = g\frac{v}{2}}$ and $\boxed{M_Z = \sqrt{g^2 + g'^2}\frac{v}{2}}$
  and have the interactions with the Higgs-boson of the form ($V = W, Z$):

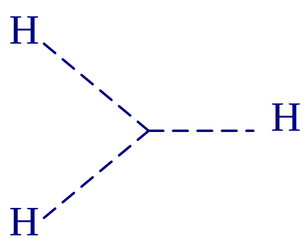


$$= 2i\frac{M_V^2}{v}g^{\mu\nu}$$

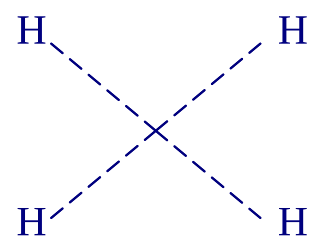


$$= 2i\frac{M_V^2}{v^2}g^{\mu\nu}$$

- the Higgs boson itself acquires mass $\boxed{M_H = -2\mu^2 = 2\lambda v^2}$
  and have self-interactions:



$$= -3i\frac{M_H^2}{v}$$



$$= -3i\frac{M_H^2}{v^2}$$

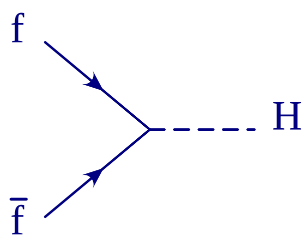
Fully determined by two parameters, e.g M_H and v $\rightarrow$ very constrained

- g, g' $\leftrightarrow$ g, e weak/electromagnetic couplings, not arbitrary
- v measured in μ-decay: $v = (\sqrt{2}G_F)^{-1/2} = 246$ GeV
- M_H now measured at the LHC, $M_H \simeq 125$ GeV

$\longrightarrow$ Very predictive!

At the same time, but independently

- masses are given to elementary fermions via Yukawa interactions $(\bar{\psi}_i y_{ij} \psi_j \phi \to y_f \bar{f} f H)$ s.t. upon EWSB $\boxed{m_f = y_f v}$
  and the Higgs boson interacts with fermions according to



$$= -i\frac{m_f}{v} = -iy_f$$

Less robust: dependence on several arbitrary parameters (y_f)

↪ it describes the hierarchy of fermion masses, but does not explain it

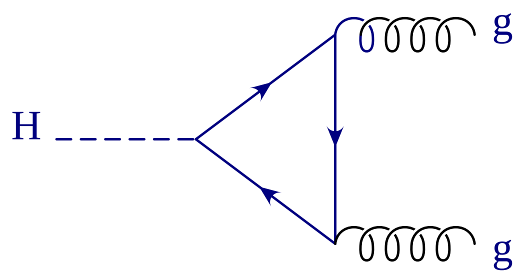
↪ clearly a preferred link to physics beyond the SM

↪ testing the SM pattern of $f\bar{f}H$ couplings will be a crucial step.

With these building blocks one can derive all Higgs-boson production and decay processes, and calculate their rates.

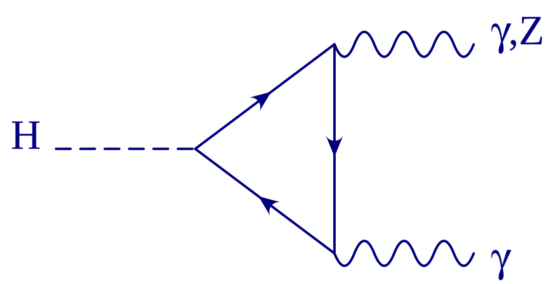
Some important *loop-induced couplings*

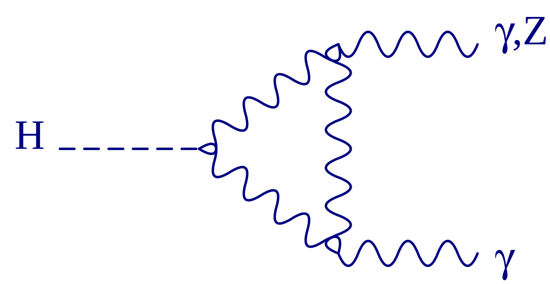
▷ Hgg coupling, main SM Higgs-boson production at the LHC:



dominated by top-quark loop

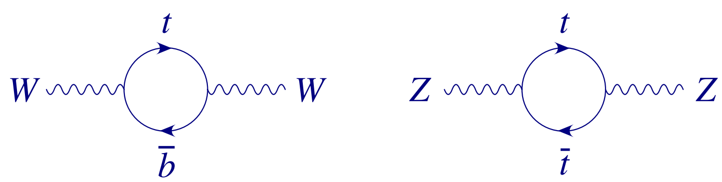
▷ $H\gamma\gamma$ and $H\gamma Z$ couplings, give rare but clean decay modes:



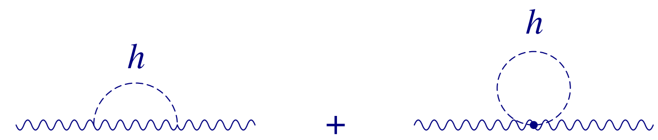


They are most likely to receive sizable contributions from unknown particles running in the loop (no corresponding elementary coupling in the SM).

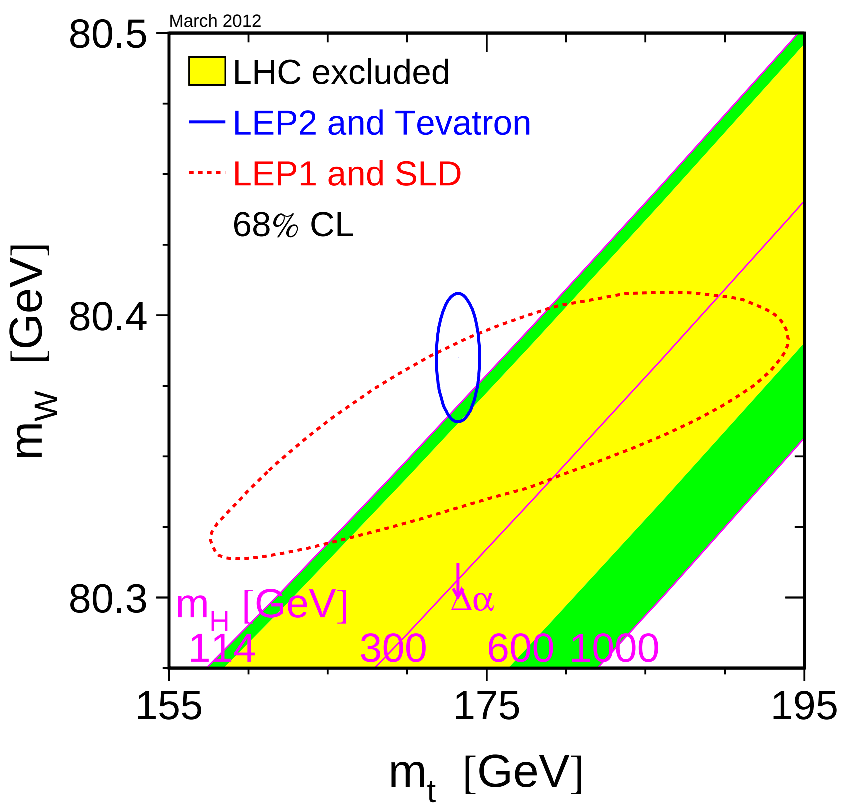
SM Higgs-boson mass range: constrained by EW precision fits



and



Testing the consistency of the SM at the quantum level!



$M_{\rm H}$ only free parameter of the SM:

$$\Downarrow$$

$$m_W = 80.385 \pm 0.015 \text{ GeV}$$

$$m_t = 173.2 \pm 0.90 \text{ GeV}$$

$$\Downarrow$$

$$M_H = 94^{+29}_{-24} \text{ GeV}$$

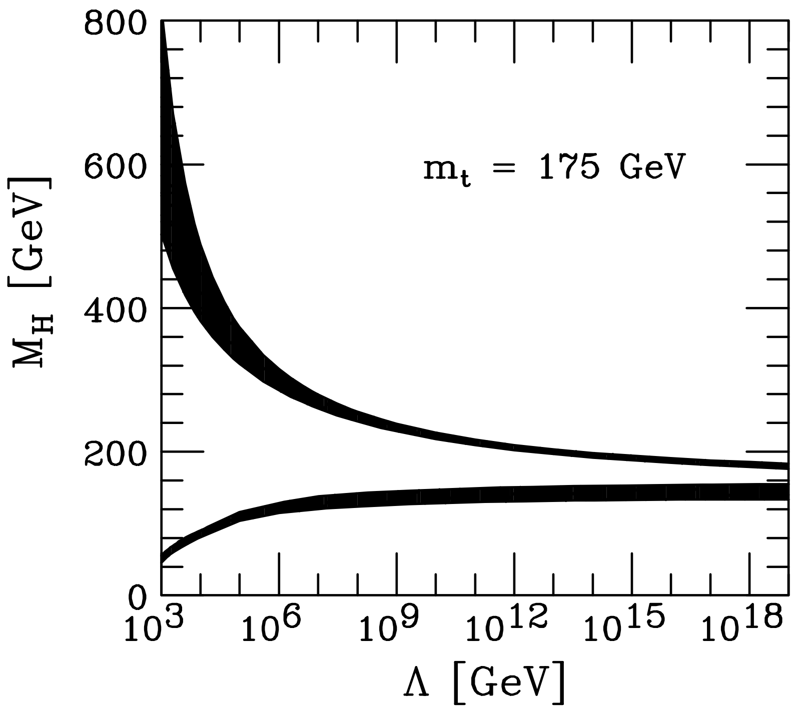
$$M_H < 152\,(171) \text{ GeV}$$

LHC→ $\boxed{M_{\rm H} = 125.09 \pm 0.24 \;\; \text{GeV}}$

Increasing precision will continue to provide an invaluable tool to test the consistency of the SM and its extensions: indirect constraints.

Other theoretical constraints on M_H in the Standard Model

SM as an effective theory valid up to a scale Λ. The Higgs sector of the SM actually contains two unknowns: $\boxed{M_H \text{ and } \Lambda}$.



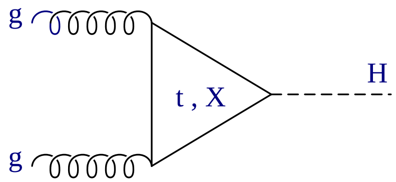
Bounds given by:

- $\longrightarrow$ unitarity
- $\longrightarrow$ triviality
- $\longrightarrow$ vacuum stability
- $\longrightarrow$ fine tuning

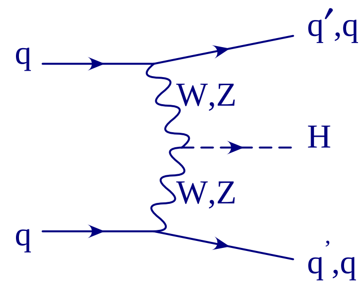
M_H determines the range of validity of the SM theory.

SM Higgs-boson production modes at the LHC (pp)

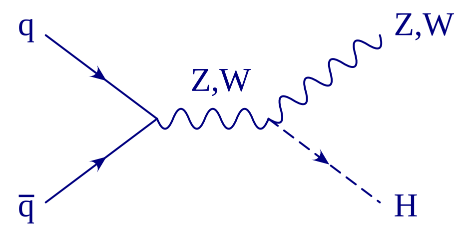
$gg \to H$



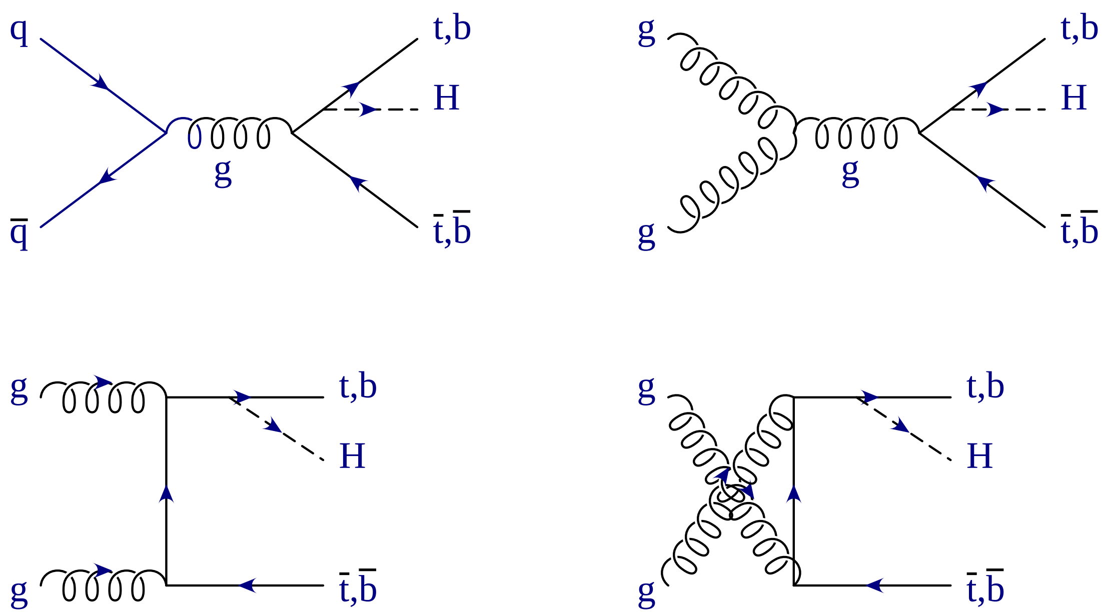
$qq \to qqH$



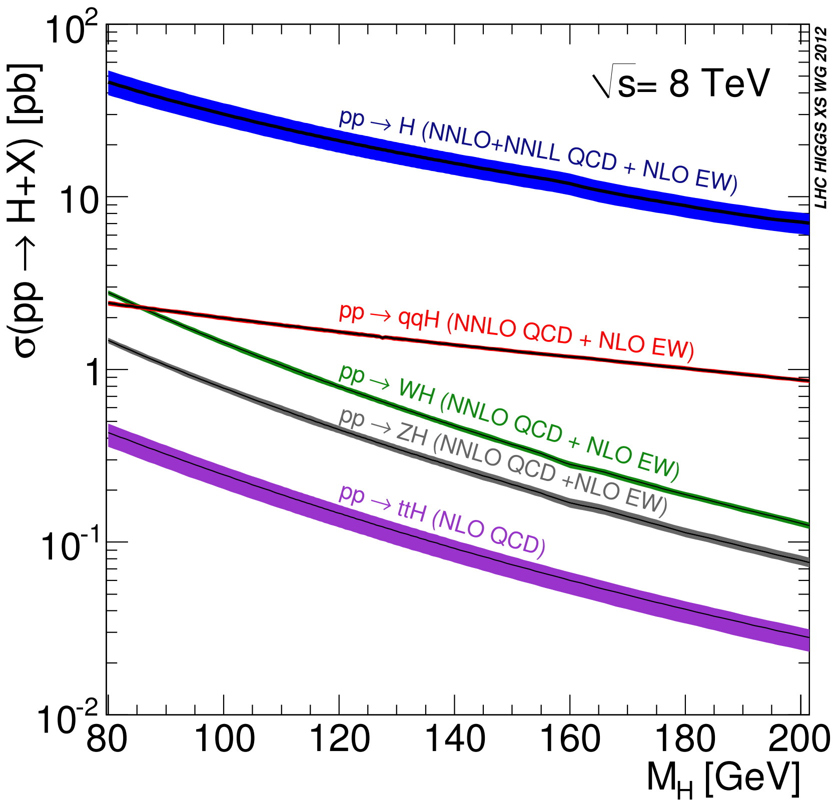
$qq \to WH, ZH$

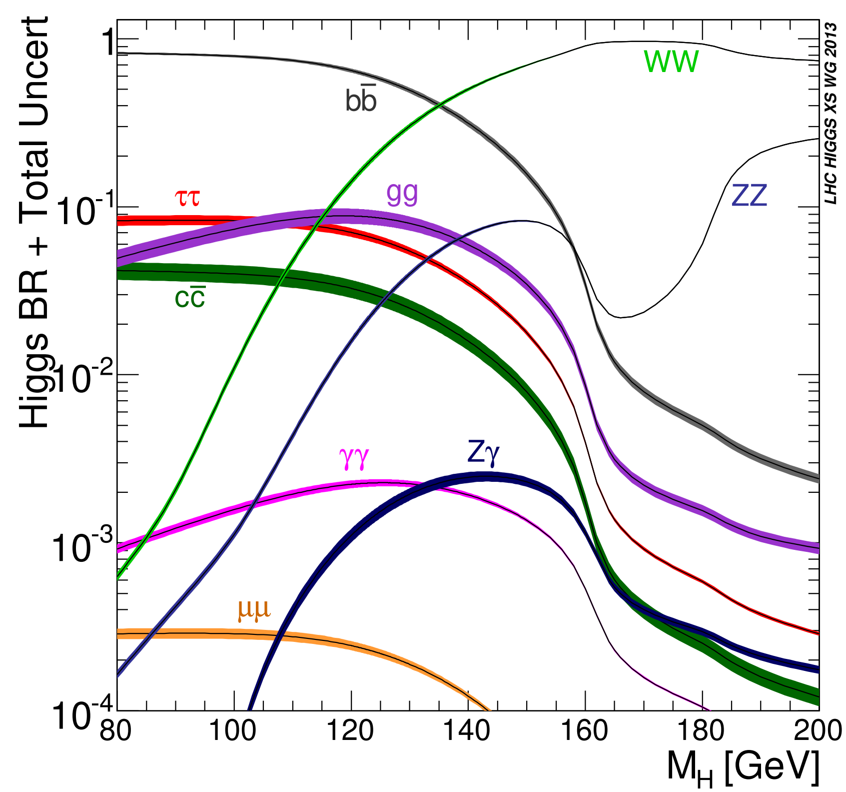


$q\bar{q}, gg \to t\bar{t}H, b\bar{b}H$



Theoretical predictions for H production and decay rates





→ Observables are a combination of production and decay channels
Ex: discovery came mainly through:

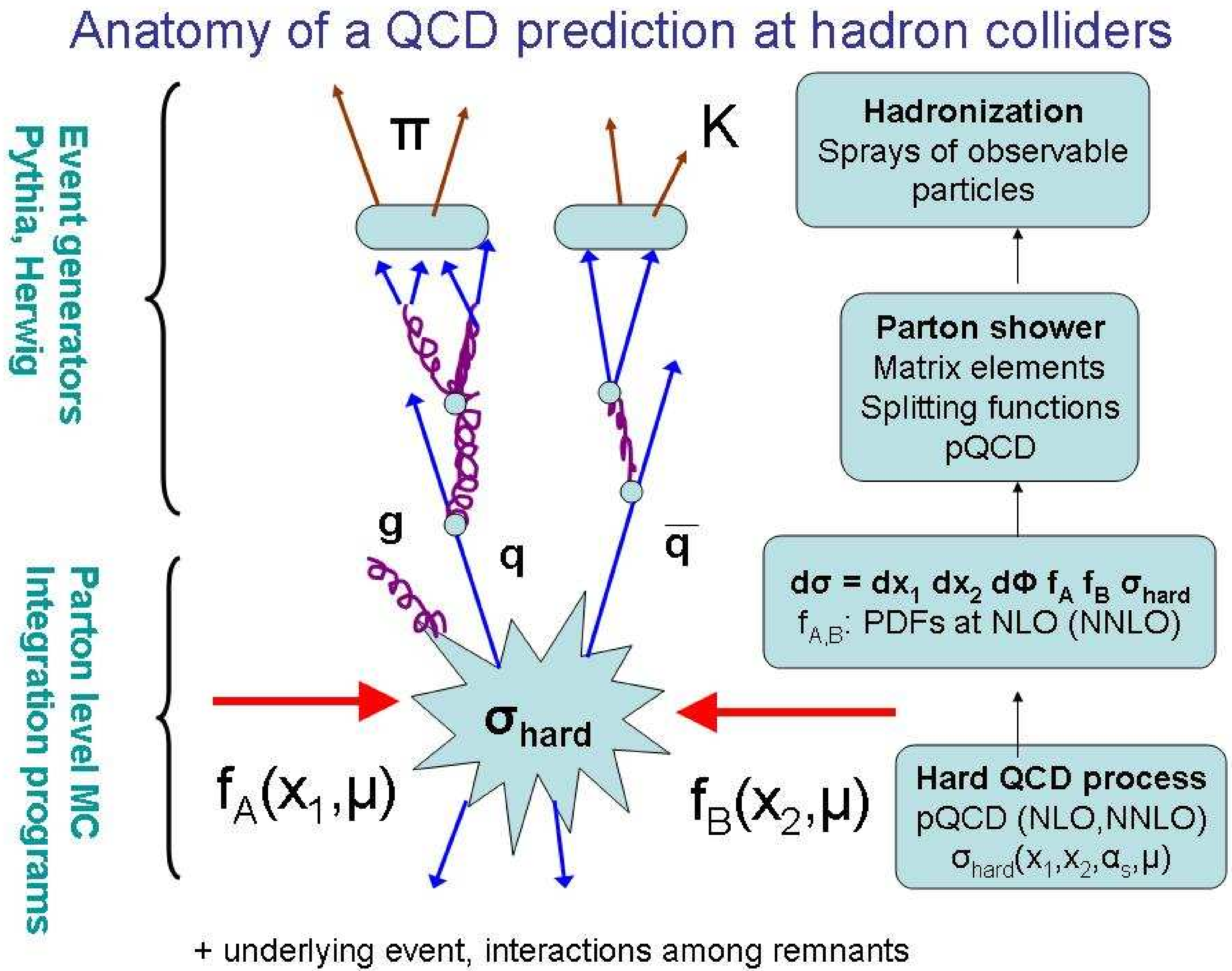
$H \to \gamma\gamma$ (untagged,VBF)

$H \to ZZ$ (untagged)

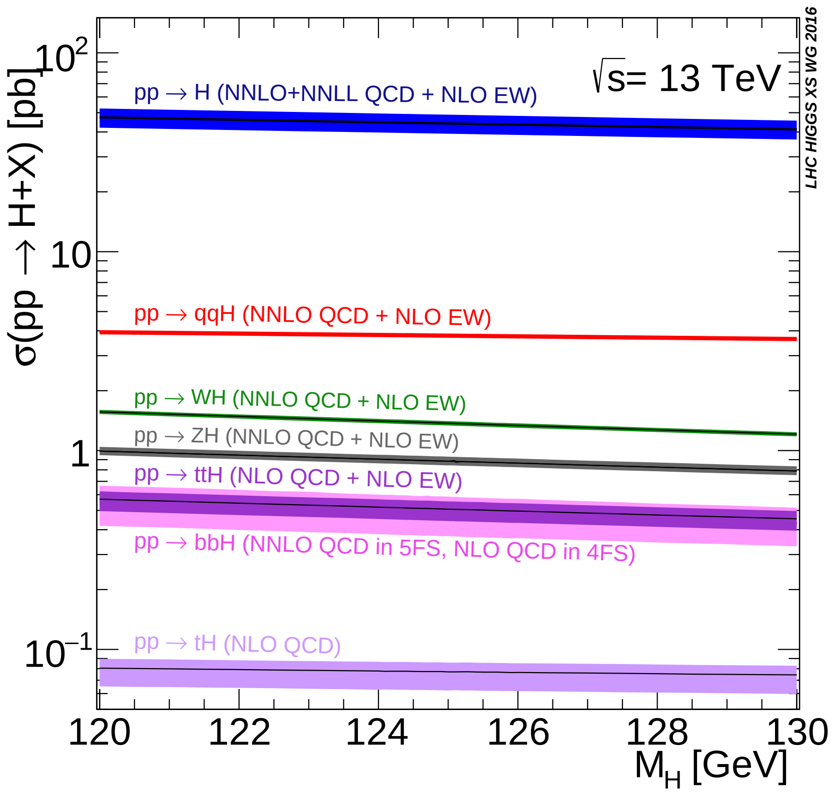
$H \to WW$ (untagged, VBF)

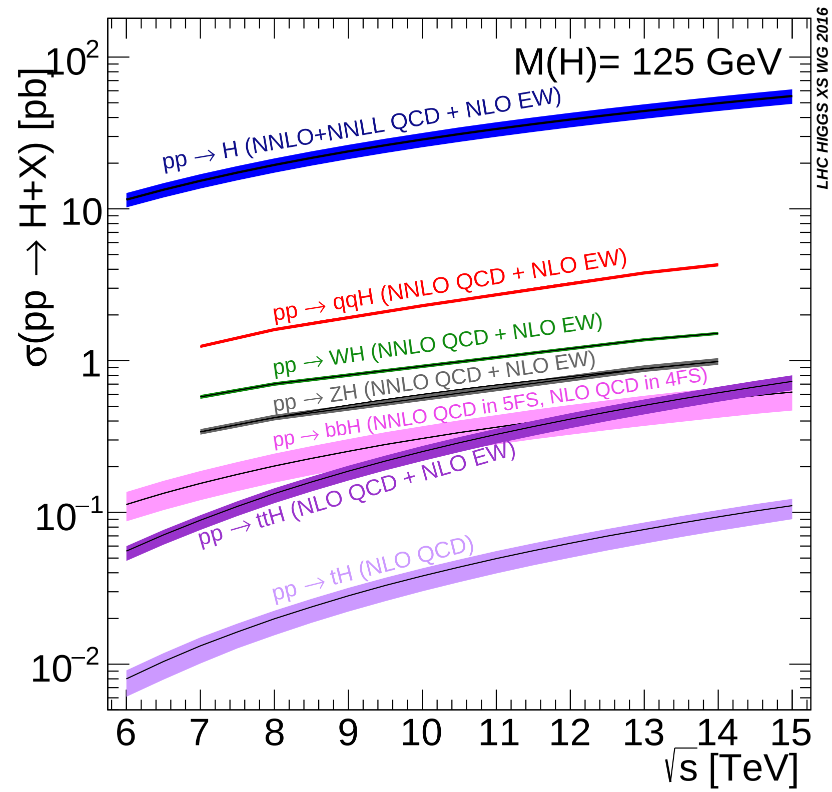
→ Bands represent theoretical uncertainty. What goes into it? How do we control it systematically?

Hadronic (pp) processes at a glance



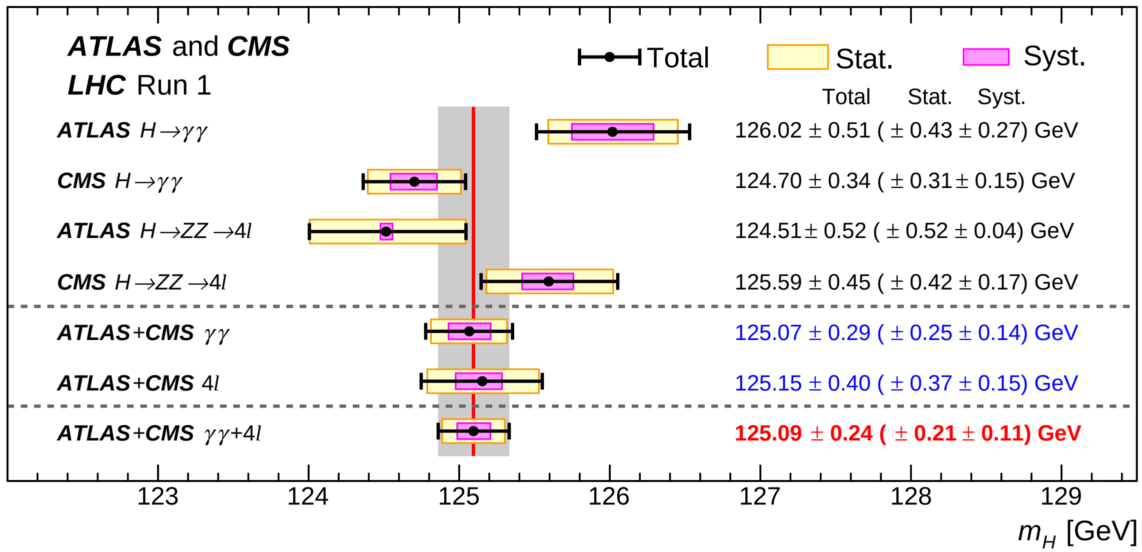
Updated for Run II





Run II opens new scenarios and requires a different level of accuracy

LHC Run I has discovered the Higgs, measured its mass and spin . . .



ATLAS+CMS, Phys. Rev. Lett. 114, 191803

M_H is now among the EW precision observables!

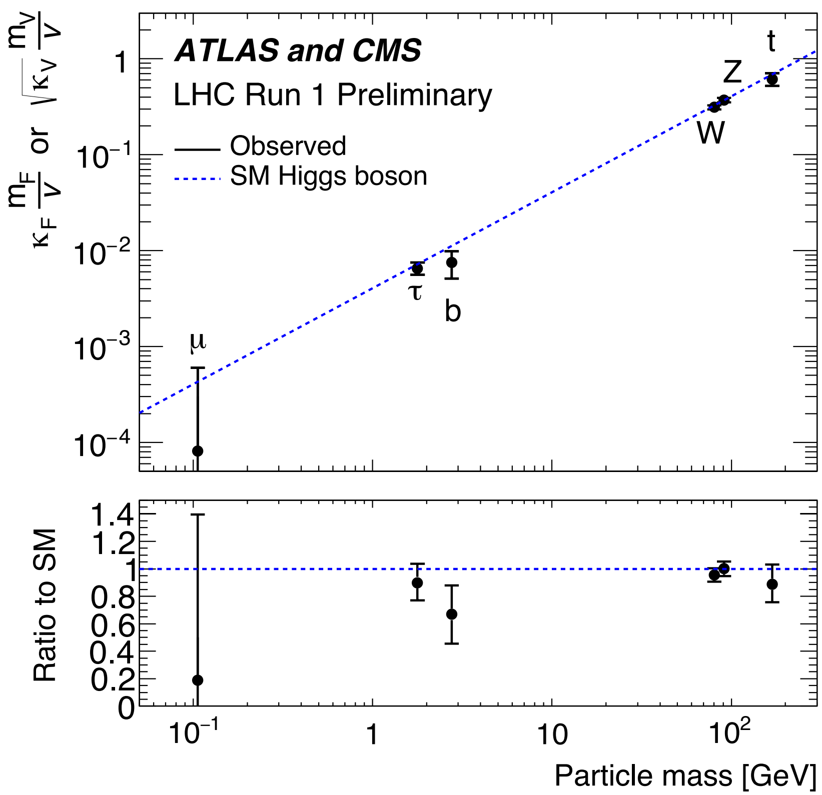
Effects of New Physics can now be more clearly disentangled in both EW observables and Higgs-boson couplings

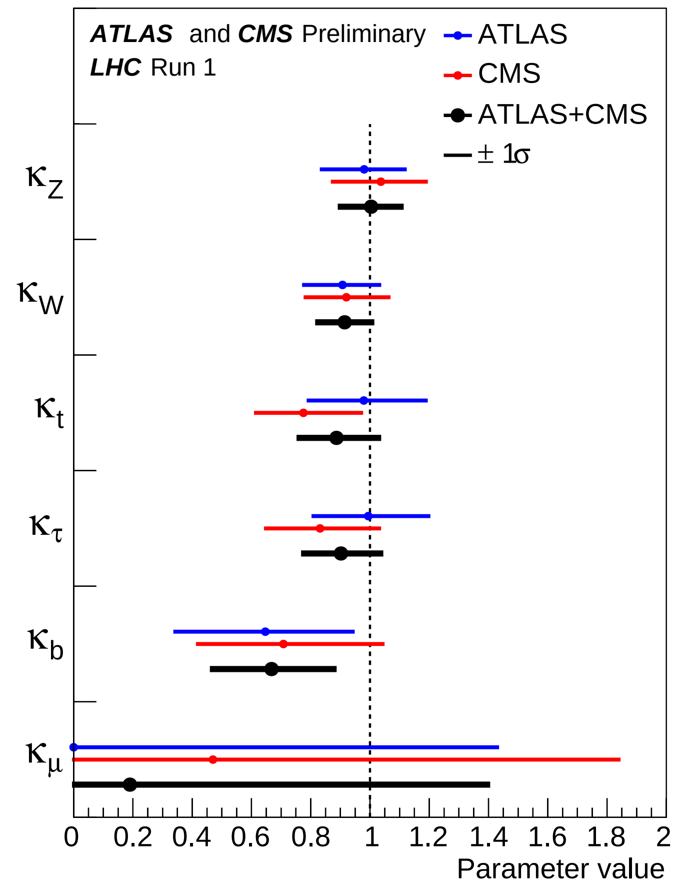
Moreover, from decays ($H \to VV$ and $H \to f\bar{f}$)

- $\to$ Spin: highly constrained to be $s = 0$
- $\to$ Parity: scalar vs pseudoscalar, exploring the structure of decay amplitudes

... and also provided measurements of its couplings

$$5\ \mathrm{fb}^{-1}@\sqrt{s} = 7\ \mathrm{TeV} + 20\ \mathrm{fb}^{-1}@\sqrt{s} = 8\ \mathrm{TeV}$$

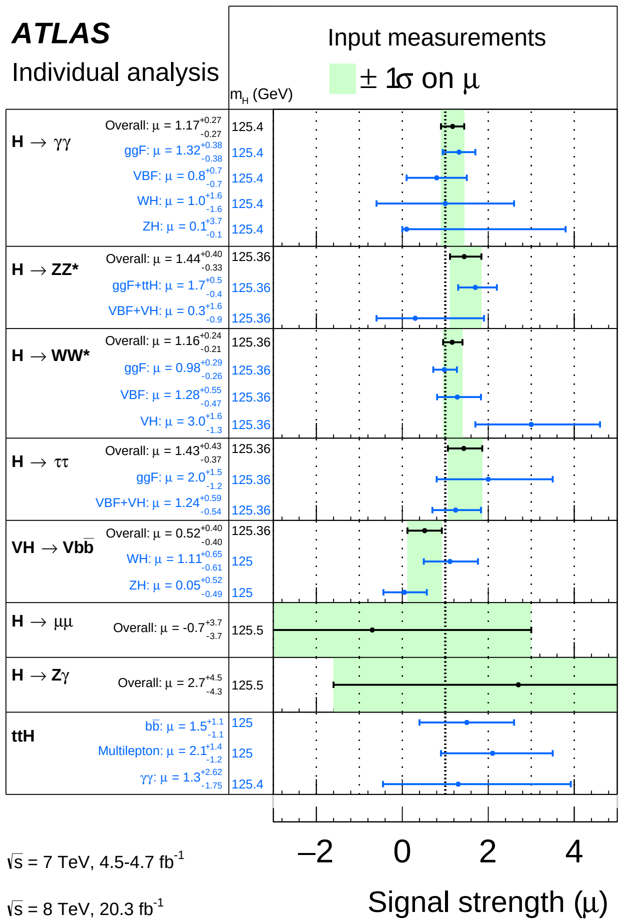


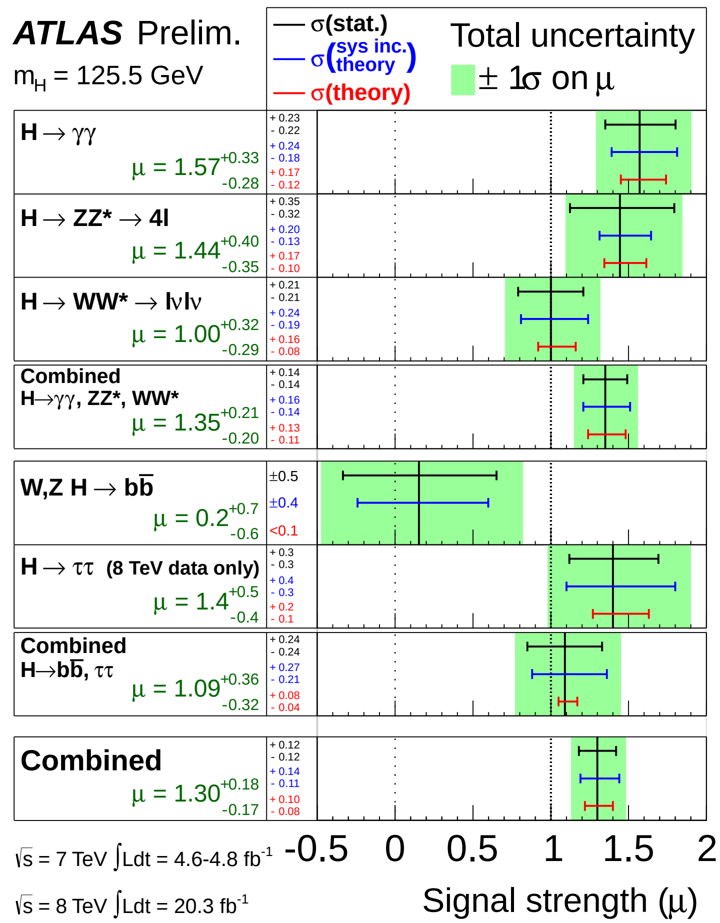


Assuming no new physics in loops, $\mathrm{BR_{BSM}} = 0$, and $\kappa_j \geq 0$, $\kappa_i = y_i^H / y_i^{H_{SM}}$

$$(\sigma \cdot BR)(ii \to H \to ff) = \sigma_{ii} \frac{\Gamma_{ff}}{\Gamma_H} = \sigma_{SM}(ii \to H) \cdot BR_{SM}(H \to ff) \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_H^2}$$

Couplings to gauge boson and top measured to 20-30%, couplings to fermions still preliminary.





ATLAS: arXiv:1507.04548

ATLAS-CONF-2014-009

Theory could become the limiting factor and this is why we are running a KITP program on

"LHC RUN 2 and the precision frontier"

Outlook

Do we really need particle masses? Yes, we probably do!
Imagine a "world without a Higgs" ...

But the Higgs-boson could be *almost* SM but not quite (composite? multi-Higgs?)

The LHC Higgs-physics program will determine the SM nature of the discovered Higgs boson, except probably for the exact structure of the potential (hard to measure the H^3 and H^4 self-couplings)

Importance of precision, both experimental and theoretical, in order to enhance the reach of the LHC.

Finding new physics will have to be reconciled with this kind of Higgs-boson.

Stay tuned!