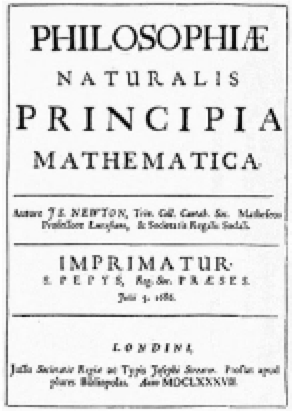
# Elementary Particle Physics: theory and experiments

**The Spontaneous Symmetry Breaking mechanism**
**The Higgs boson hunting at LEP and Tevatron**
**Discovery of the Higgs boson at LHC**
**Measurements: mass, spin, couplings**
**Latest results: Lepton-Photon (January 2022)**

**Follow lectures by M. Kado and M. Martinez at HASCO schools.**
**Slides by E. Di Marco at Lepton-Photon 2021 conference**

Prof. dr hab. Elżbieta Richter-Wąs


PHILOSOPHIÆ
NATURALIS
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# Not the origin of Mass

- Gallilean and Newtonian concept of mass :

Inertial mass (F=ma) Gravitational mass (P=mg)

Single concept: conserved intrinsic property of matter where the total mass of a system is the sum of its constituents

- Einstein : Does the mass of a system depend of its energy content?

Mass = rest energy of a system or $m_0=E/c^2$

- Atomic level : binding energy ~O(10eV) which is ~$10^{-8}$ of the mass
- Nuclear level (nucleons) : binding energy ~2% of the mass
- Nucleon level (partons) : binding energy ~98% of the mass

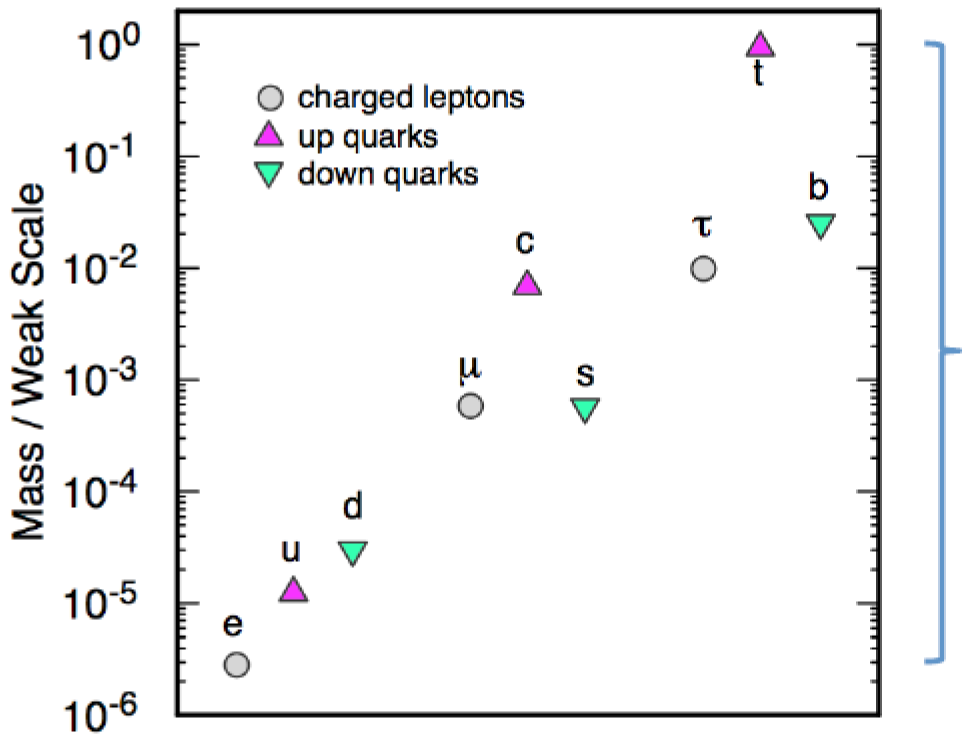
Most of the (luminous) mass in the universe comes from QCD confinement energy

**The insight(s) of the BEH mechanism :**

Making the weak force weak (short range, or W and Z bosons massive) and allowing fermion masses in the theory

# Not explaining the flavor Hierarchy

Replacing mass terms by Yukawa couplings

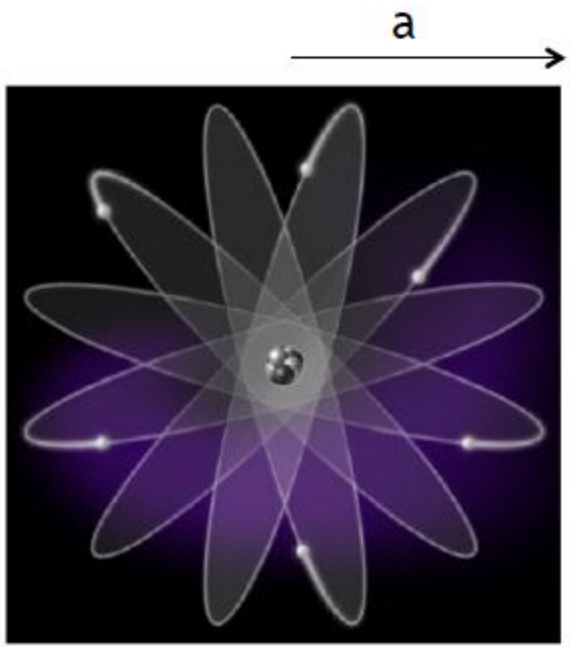



~6 orders of magnitude

Neutrinos are not even on the scale!

The BEH sector includes most of the free parameters of the Standard Model

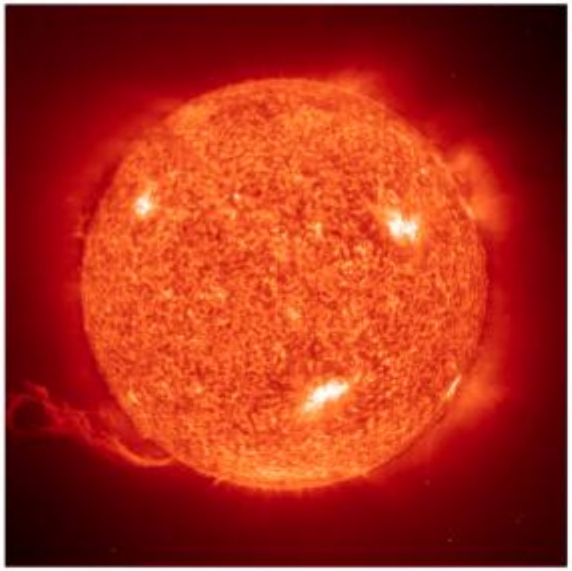
# How Would it Be Without Elementary Particle Masses?




Electron mass ($m_e$ = 511 keV)

Bohr Radius $a = 1/(a_{EM}\ m_e)$ so :

If $m_e = 0$ : Then no atomic binding



W boson mass ($m_W$ = 81 GeV)

$G_F \sim (M_W)^{-2}$

If no or lower W mass : shorter combustion time at lower temperature

Everything would be completely different!

## Historical context and roots of the Standard Model and Higgs Mechanism

1864-1958 - Abelian theory of quantum electrodynamics

1933-1960 - Fermi model of weak interactions

1954 - Yang-Mills theories for gauge interactions...

1957-59 – Schwinger, Bludman and Glashow introduce W bosons for the weak charged currents…

…birth of the idea of unified picture for the electromagnetic and weak interaction in …

$$SU(2)_L \times U(1)_Y$$

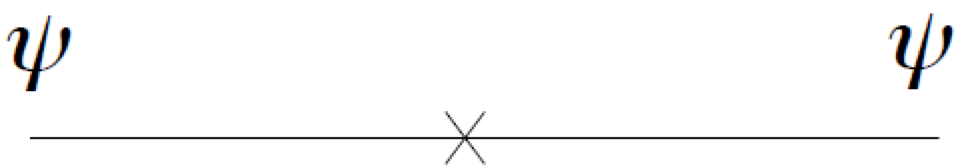
Caution, not unified in the sense of unified forces, only unique framework

… but local gauge symmetry forbids gauge bosons and fermion masses.

# How Does Mass Appear in a Lagrangian

$$m\bar{\psi}\psi$$

In Terms of Feynman Diagram



# 1960

## Spontaneous Symmetry Breaking (SSB) - Global Symmetry

The Goldstone theorem is where it all began…

Massless scalars occur in a theory with SSB (or more accurately where the continuous symmetry is not apparent in the ground state).

Originates from the work of Landau (1937)

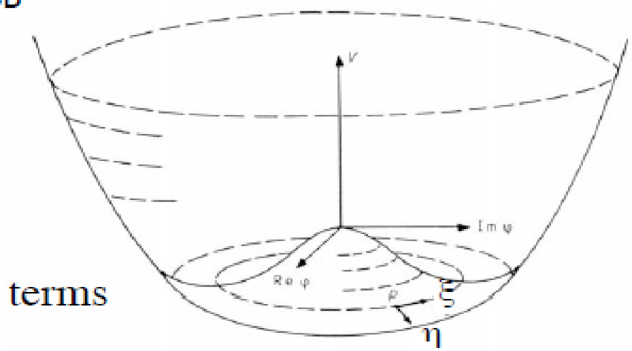
From a simple (complex) scalar theory with a U(1) symmetry

$$\varphi = \frac{\phi_1 + i\phi_2}{\sqrt{2}} \qquad L = \partial_\nu \varphi^* \partial^\nu \varphi - V(\varphi) \qquad V(\varphi) = \mu^2 \varphi^* \varphi + \lambda(\varphi^* \varphi)^2$$

The Lagrangian is invariant under : $\varphi \rightarrow e^{i\alpha}\varphi$

$$v = -\frac{\mu^2}{\lambda}$$

Shape of the potential if $\mu^2<0$ and $\lambda>0$ necessary for SSB and be bounded from below.




Change frame to local minimum frame :

$$\varphi = \frac{v + \eta + i\xi}{\sqrt{2}}$$

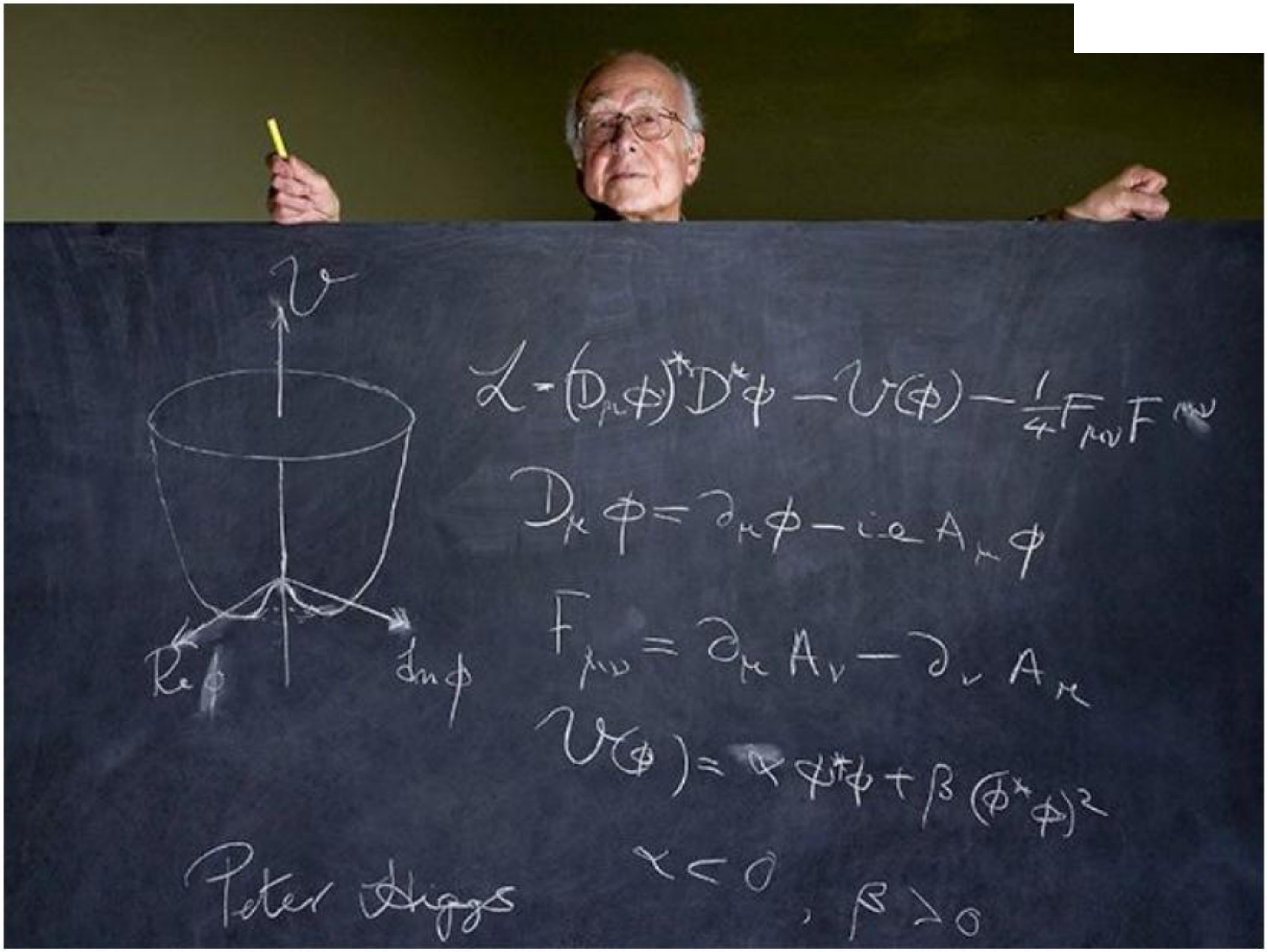
No loss in generality.

$$L = \frac{1}{2}\underbrace{\partial_\nu \xi \partial^\nu \xi}_{\text{Massless scalar}} + \frac{1}{2}\partial_\nu \eta \partial^\nu \eta + \underbrace{\mu^2 \eta^2}_{\text{Massive scalar}} + \text{interaction terms}$$

Massless scalar — Massive scalar

Nice but what should we do with these massless salars?

# 1964


$V$
Re $\phi$
Im $\phi$
$\mathcal{L} = (D_\mu \phi)^* D^\mu \phi - V(\phi) - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$D_\mu \phi = \partial_\mu \phi - ie A_\mu \phi$
$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$
$V(\phi) = \alpha \phi^* \phi + \beta (\phi^* \phi)^2$
$\alpha < 0 , \beta > 0$
Peter Higgs

# Spontaneous Symmetry Breaking (SSB) - Local Symmetry

All the players… in the same PRL issue

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)

2 pages

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)

1 page

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)

2 pages

1964 -The Higgs mechanism : How gauge bosons can acquire a mass.

## Spontaneous Symmetry Breaking (SSB) Extended to Local Symmetry

Let the aforementioned continuous symmetry U(1) be local :

$$\varphi \rightarrow e^{i\alpha(x)}\varphi$$

$\alpha(x)$ now depends on the space-time x.

The Lagrangian can now be written : $L = (D_\nu\varphi)^* D^\nu\varphi - V(\varphi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$

In terms of the covariant derivative : $D_\nu = \partial_\nu - ieA_\nu$

The gauge invariant field strength tensor : $F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$

And the Higgs potential : $V(\varphi) = \mu^2\varphi^*\varphi + \lambda(\varphi^*\varphi)^2$

Here the gauge field transforms as : $A_\mu \rightarrow A_\mu + \frac{1}{e}\partial_\mu\alpha$

Again translate to local minimum frame : $\varphi = \dfrac{v + \eta + i\xi}{\sqrt{2}}$

$$L = \frac{1}{2}\partial_\nu\xi\partial^\nu\xi + \frac{1}{2}\partial_\nu\eta\partial^\nu\eta + \mu^2\eta^2 - v^2\lambda\eta^2 + \frac{1}{2}\underbrace{e^2v^2A_\mu A^\mu} - evA_\mu\partial^\mu\xi - F^{\mu\nu}F_{\mu\nu} + \mathrm{ITs}$$

Mass term for the gauge field! But…

What about the field content?

A massless Goldstone boson $\xi$, a massive scalar $\eta$ and a $\underbrace{\text{massive gauge boson!}}$

Number of d.o.f. : 1 1 1

Number of initial d.o.f. : 2 Oooops… Problem!

But wait! Halzen & Martin p. 326 The term $evA_\mu \partial^\mu \xi$ is unphysical

The Lagrangian should be re-written using a more appropriate expression of the translated scalar field choosing a particular gauge where h(x) is real :

$$\varphi = (v + h(x))e^{i\frac{\theta(x)}{v}}$$

Gauge fixed to absorb $\theta$

Then the gauge transformations are : $\varphi \rightarrow e^{-i\frac{\theta(x)}{v}} \varphi \qquad A_\mu \rightarrow A_\mu + \frac{1}{ev}\partial_\mu \theta$

$$L = \frac{1}{2}\partial_\nu h \partial^\nu h - \lambda v^2 h^2 - \lambda v h^3 - \frac{1}{4}\lambda h^4$$ Massive scalar : The Higgs boson

$$+(1/2)e^2 v^2 A_\mu A^\mu - F^{\mu\nu}F_{\mu\nu}$$ Massive gauge boson

$$+(1/2)e^2 A_\mu A^\mu h^2 + ve^2 A_\mu A^\mu h$$ Gauge-Higgs interaction

The Goldstone boson does not appear anymore in the Lagrangian

# 1968

2 pages

A MODEL OF LEPTONS*

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

Leptons interact only with photons, and with the intermediate bosons that presumably mediate weak interactions. What could be more natural than to unite[1] these spin-one bosons into a multiplet of gauge fields? Standing in the way of this synthesis are the obvious differences in the masses of the photon and intermediate meson, and in their couplings. We might hope to understand these differences by imagining that the symmetries relating the weak and electromagnetic interactions are exact symmetries of the Lagrangian but are broken by the vacuum. However, this raises the specter of unwanted massless Goldstone bosons.[2] This note will describe a model in which the symmetry between the electromagnetic and weak interactions is spontaneously broken, but in which the Goldstone bosons are avoided by introducing the photon and the intermediate-boson fields as gauge fields.[3] The model may be renormalizable.

We will restrict our attention to symmetry groups that connect the observed electron-type leptons only with each other, i.e., not with muon-type leptons or other unobserved leptons or hadrons. The symmetries then act on a left-handed doublet

$$L=[\tfrac{1}{2}(1+\gamma_5)]\binom{\nu_e}{e} \qquad (1)$$

and on a right-handed singlet

$$R=[\tfrac{1}{2}(1-\gamma_5)]e. \qquad (2)$$

Is this model renormalizable? We usually do not expect non-Abelian gauge theories to be renormalizable if the vector-meson mass is not zero, but our $Z_\mu$ and $W_\mu$ mesons get their mass from the spontaneous breaking of the symmetry, not from a mass term put in at the beginning. Indeed, the model Lagrangian we start from is probably renormalizable

Therefore, we shall construct our Lagrangian out of $L$ and $R$, plus gauge fields $\vec{A}_\mu$ and $B_\mu$ ...

Of course our model has too many arbitrary features for these predictions to be taken very seriously

... and $Y$ and give the electron its mass. The only renormalizable Lagrangian which is invariant under $\vec{T}$ and $Y$ gauge transformations is

Milestone PRL 1967

Assuming a third weak gauge boson the initial number of gauge boson d.o.f. is 8, to give mass to three gauge bosons at least one doublet of scalar fields is necessary (4 d.o.f.) :

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi^+ \\ \phi^o \end{pmatrix}$$

Setting aside the gauge kinematic terms the Lagrangian can be written :

$$\mathcal{L} = (D_\mu \phi)^\dagger (D^\mu \phi) - V(\phi) \qquad \begin{cases} D_\mu = \partial_\mu - ig\vec{W}_\mu.\vec{\sigma} - ig'\frac{Y}{2}B_\mu \\ V(\phi) = \mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2 \end{cases}$$

The next step is to develop the Lagrangian near : $$< \phi >= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

Choosing the specific real direction of charge 0 of the doublet is not fortuitous :

$$\phi = e^{-i\vec{\sigma}.\vec{\xi}} \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ H + v \end{pmatrix}$$

In particular for a non charged vacuum

Again choosing the gauge that will absorb the Goldstone bosons ξ...

Then developing the covariant derivative for the Higgs field :

Just replacing the Pauli matrices :

$$D_\mu \varphi = \partial_\mu \varphi - \frac{i}{2}\begin{pmatrix} gW_\mu^3 + g' B_\mu & g(W_\mu^1 - iW_\mu^2) \\ g(W_\mu^1 + iW_\mu^2) & -gW_\mu^3 + g' B_\mu \end{pmatrix}\varphi$$

Then using : $W_\mu^\pm = \frac{W_\mu^1 \mp iW_\mu^2}{\sqrt{2}}$

$$D_\mu \varphi = \partial_\mu \varphi - \frac{i}{2}\begin{pmatrix} gW_\mu^3 + g' B_\mu & \sqrt{2} g W_\mu^+ \\ \sqrt{2} g W_\mu^- & -gW_\mu^3 + g' B_\mu \end{pmatrix}\varphi = \begin{pmatrix} 0 \\ \partial_\mu h \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \sqrt{2} g v W_\mu^+ + \sqrt{2} g h W_\mu^+ \\ -g v W_\mu^3 + g' v B_\mu - g h W_\mu^3 + g' h B_\mu \end{pmatrix}$$

For the mass terms only :

$$(D_\mu \varphi)^+ D^\mu \varphi = \partial_\mu h \partial^\mu h + \frac{1}{4} g^2 v^2 W_\mu^+ W^{-\mu} + \frac{1}{8}(W_\mu^3 \quad B_\mu)\begin{pmatrix} g^2 v^2 & -g g' v^2 \\ -g g' v^2 & g'^2 v^2 \end{pmatrix}\begin{pmatrix} W^{3\mu} \\ B^\mu \end{pmatrix}$$

Explicit mixing of $W^3$ and B.

Finaly the full Lagrangian will then be written :

$$\begin{aligned}\mathcal{L} \;=\; & \frac{1}{2}\partial_\mu H \partial^\mu H - \frac{1}{2}\lambda v^2 H^2 - \lambda v H^3 - \frac{\lambda}{4}H^4 \\ + \; & \frac{1}{2}\left[\frac{g'^2 v^2}{4}B_\mu B^\mu - \frac{g g' v^2}{2}W^3_\mu B^\mu + \frac{g^2 v^2}{4}\vec{W}_\mu.\vec{W}^\mu\right] \\ + \; & \frac{1}{v}\left[\frac{g'^2 v^2}{4}B_\mu B^\mu H - \frac{g g' v^2}{2}W^3_\mu B^\mu H + \frac{g^2 v^2}{4}\vec{W}_\mu.\vec{W}^\mu H\right] \\ + \; & \frac{1}{2v^2}\left[\frac{g'^2 v^2}{4}B_\mu B^\mu H^2 - \frac{g g' v^2}{2}W^3_\mu B^\mu H^2 + \frac{g^2 v^2}{4}\vec{W}_\mu.\vec{W}^\mu H^2\right]\end{aligned}$$

Massive scalar : The Higgs boson

Massive gauge bosons

Gauge-Higgs interaction

In order to derive the mass eigenstates :

Diagonalize the mass matrix $\frac{1}{4}\begin{pmatrix} g^2 v^2 & -g g' v^2 \\ -g g' v^2 & g'^2 v^2 \end{pmatrix} = \mathcal{M}^{-1}\begin{pmatrix} m_Z^2 & 0 \\ 0 & 0 \end{pmatrix}\mathcal{M}$

Where

$$\mathcal{M} = \begin{pmatrix} \cos\theta_W & -\sin\theta_W \\ \sin\theta_W & \cos\theta_W \end{pmatrix} \qquad \sin\theta_W = \frac{g'}{\sqrt{g^2 + g'^2}} \qquad \cos\theta_W = \frac{g}{\sqrt{g^2 + g'^2}}$$

The Weinberg angle was actually first introduced by Glashow (1960)

## The sector of Fermions (kinematic)

Another important consequence of the Weinberg Salam Model…

A specific $SU(2)_L x U(1)_Y$ problem : $m\overline{\psi}\psi$ manifestly not gauge invariant

$$m\overline{\psi}\psi = m\overline{\psi}(\frac{1}{2}(1-\gamma^5)+\frac{1}{2}(1+\gamma^5))\psi = m(\overline{\psi}_L\psi_R+\overline{\psi}_R\psi_L)$$

- neither under $SU(2)_L$ doublet and singlet terms together
- nor under $U(1)_Y$ do not have the same hypercharge

Fermion mass terms are forbidden

Not the case for Yukawa couplings to the Higgs doublet

Then after SSB one recovers :

$$\frac{\lambda_\psi v}{\sqrt{2}}\overline{\psi}\psi + \frac{\lambda_\psi}{\sqrt{2}}H\overline{\psi}\psi$$

Which is invariant under $U(1)_{EM}$

Very important : The Higgs mechanism DOES NOT predict fermion masses

…Yet the coupling of the Higgs to fermions is proportional to their masses

## But wait…

The coupling to the Higgs fields is the following :

$$\lambda_d(\bar{u}_L, \bar{d}_L)\begin{pmatrix} 0 \\ v+h \end{pmatrix} d_R + H.C. = \lambda_d \bar{Q}_L \; \phi \; d_R$$

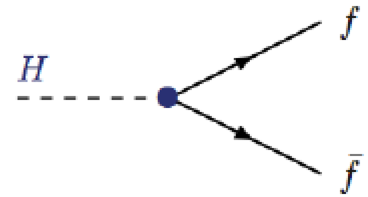
Can be seen as giving mass to down type fermions…

To give mass to up type fermions, need to use a slightly different coupling :

$$\phi^C = i\sigma_2\phi^* \qquad \lambda_u \bar{Q}_L \; \phi^C \; \bar{u}_R = \lambda_u(\bar{u}_L, \bar{d}_L)\begin{pmatrix} v+h \\ 0 \end{pmatrix} d_R + H.C.$$

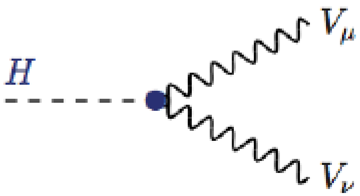
One doublet of complex scalar fields is sufficient to accommodate mass terms for gauge bosons and fermions !

... But not necessarily only one!

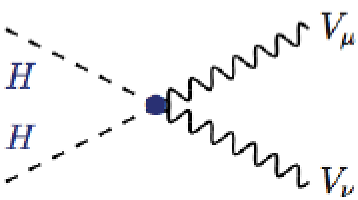



$$g_{Hff} = m_f/v$$

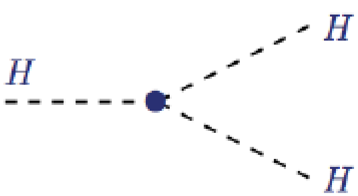
Gauge-Higgs and interactions




$$g_{HVV} = 2M_V^2/v$$

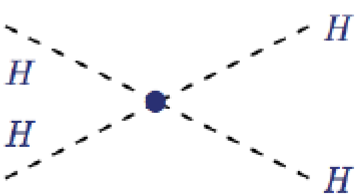



$$g_{HHVV} = 2M_V^2/v^2$$




$$g_{HHH} = 3M_H^2/v$$

More directly testable relations!




$$g_{HHHH} = 3M_H^2/v^2$$

# Prediction of the Model

Beside the existence of the Z massive neutral gauge boson…

The existence of a massive scalar :

## The Higgs Particle

Whose mass (as $\lambda$) **was** an unknown parameter of the theory

$$v = -\frac{\mu^2}{\lambda}$$

The first very important consequences of this mechanism :

1.- Two massive charged vector bosons :

$$m_W^2 = \frac{g^2 v^2}{4}$$

Corresponding to the observed charged currents

Thus v = 246 GeV

Given the known W mass and g coupling

2.- One massless vector boson : $m_\gamma = 0$

The photon correponding to the unbroken $U(1)_{EM}$

3.- One massive neutral vector boson Z :

$$m_Z^2 = (g^2 + g'^2)v^2/4$$

4.- One massive scalar particle : The Higgs boson

Whose mass is an unknown parameter of the theory as the quartic coupling λ

$$m_H^2 = \frac{4\lambda(v) m_W^2}{g^2}$$

Which of these consequences are actually predictions ?

1.- The theory was chosen in order to describe the weak interactions mediated by charged currents.

2.- The masslessness of the photon is a consequence of the choice of developing the Higgs field in the neutral and real part of the doublet.

3 & 4.- The appearance of massive Z and Higgs bosons are actually predictions of the model.

One additional very important prediction which was not explicitly stated in Weinberg's fundamental paper… although it was implicitly clear :

There is a relation between the ratio of the masses and that of the couplings of gauge bosons :

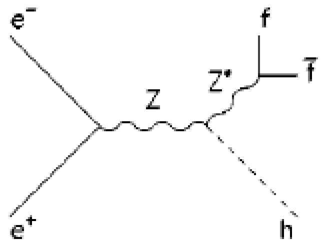
$$\frac{M_W}{M_Z} = \frac{g^2}{g^2 + g'^2} = \cos^2\theta_W \quad \text{or} \quad \boxed{\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = 1}$$

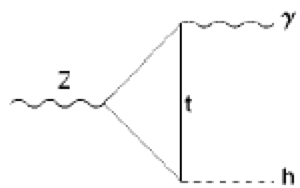
# Absolute Lower Limit on the Higgs Mass at LEP

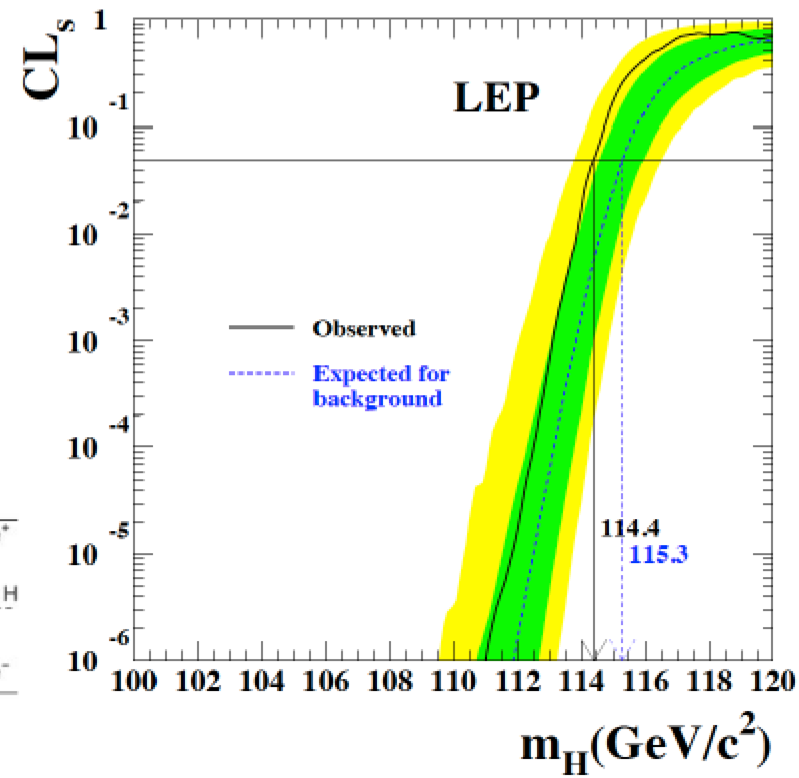
LEP1 $e^+e^-$ at COM ~$m_Z$

Various decays and topologies

Limit down to below $2m_e$ using acoplanar lepton pairs (Higgs is long lived)

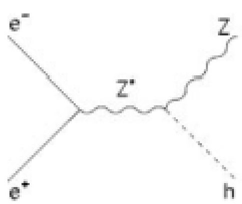


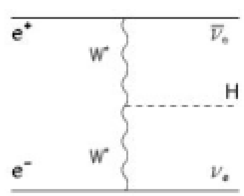



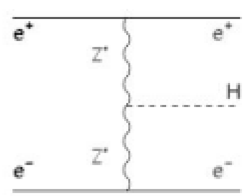




LEP2 $e^+e^-$ up to 209 GeV

(mostly bb and $\tau\tau$ decays)




**Excludes SM Higgs with mass below 114 GeV**

# Electroweak Precision Data and the Higgs Mass

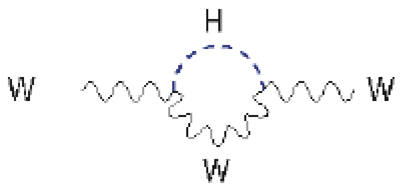
## *The famous blue band plot!*

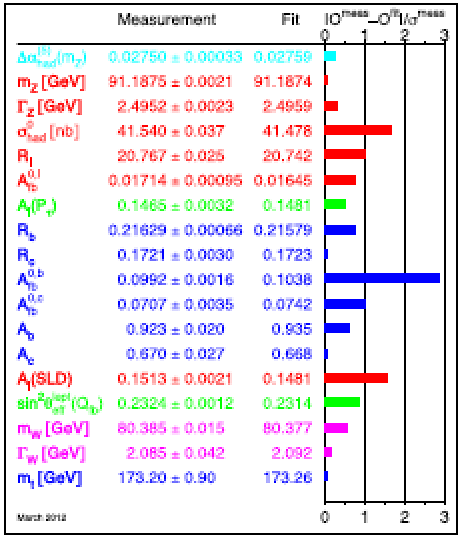
Fermi Constant $G_F = 1.166367(5) \times 10^{-5}\ \mathrm{GeV}^{-2}$ (muon lifetime)

Fine structure Constant $\alpha = 1/137.035999679(94)$ (quantum Hall effect)

Z mass $M_Z = 91.1876 \pm 0.0021\ \mathrm{GeV}$ (LEP)

$$G_F = \frac{\pi \alpha_{QED}}{\sqrt{2} m_W^2 (1 - m_W^2/m_Z^2)} (1 + \Delta r)$$



| | Measurement | Fit | $\lvert O^{meas} - O^{fit} \rvert / \sigma^{meas}$ |
|---|---|---|---|
| $\Delta\alpha_{had}^{(5)}(m_Z)$ | 0.02750 ± 0.00033 | 0.02759 | |
| $m_Z$ [GeV] | 91.1875 ± 0.0021 | 91.1874 | |
| $\Gamma_Z$ [GeV] | 2.4952 ± 0.0023 | 2.4959 | |
| $\sigma_{had}^0$ [nb] | 41.540 ± 0.037 | 41.478 | |
| $R_l$ | 20.767 ± 0.025 | 20.742 | |
| $A_{fb}^{0,l}$ | 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 | |
| $A_{fb}^{0,b}$ | 0.0992 ± 0.0016 | 0.1038 | |
| $A_{fb}^{0,c}$ | 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 | |
| $\sin^2\theta_{eff}^{lept}(Q_{fb})$ | 0.2324 ± 0.0012 | 0.2314 | |
| $m_W$ [GeV] | 80.385 ± 0.015 | 80.377 | |
| $\Gamma_W$ [GeV] | 2.085 ± 0.042 | 2.092 | |
| $m_t$ [GeV] | 173.20 ± 0.90 | 173.26 | |

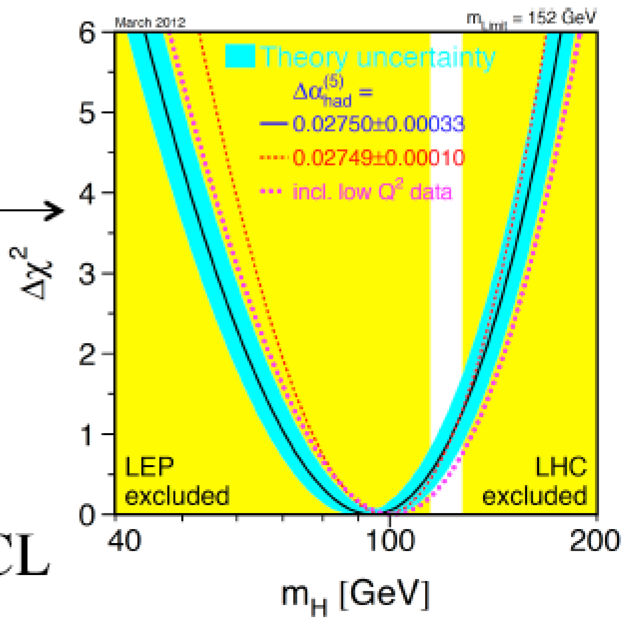


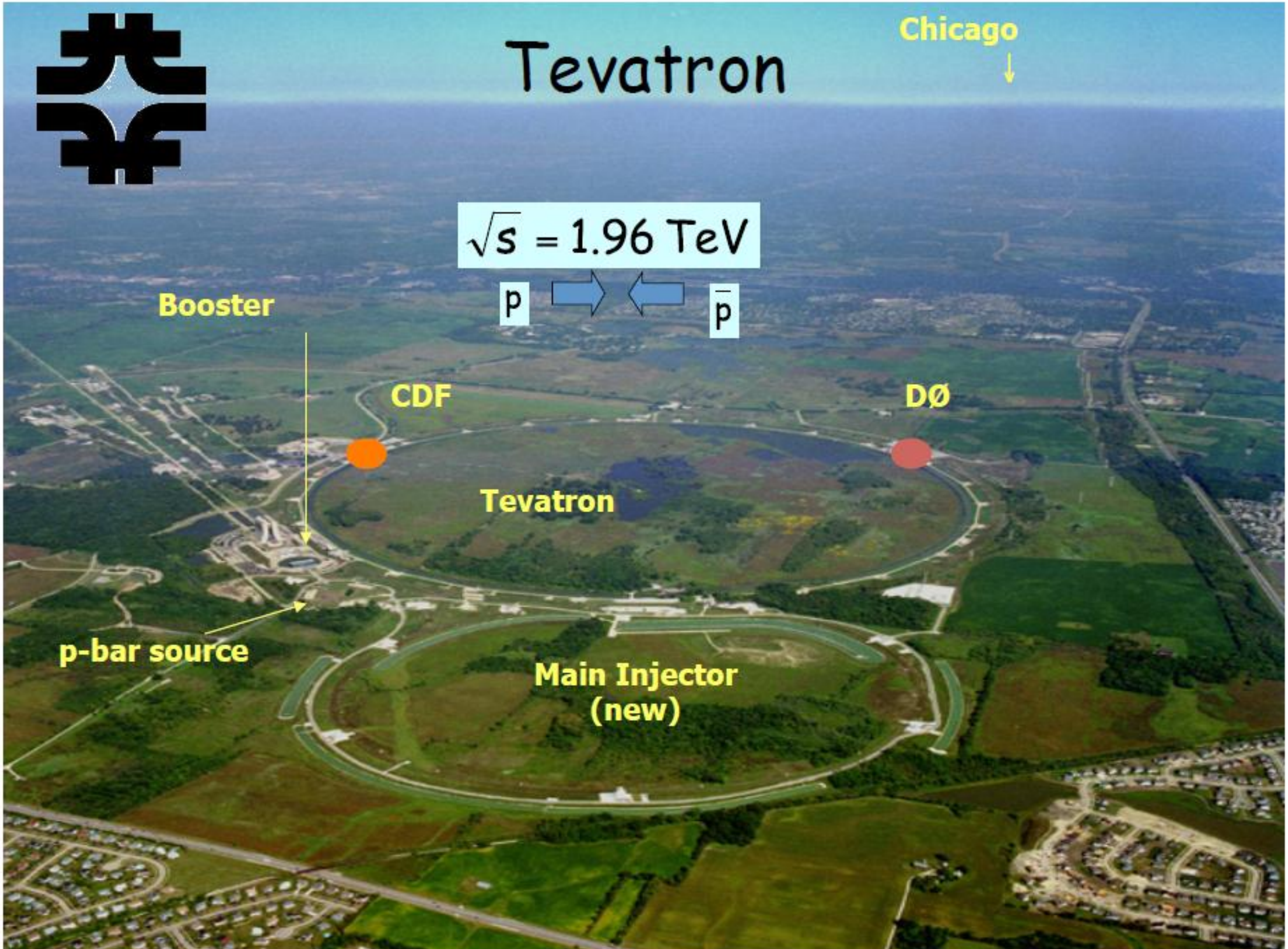
$$\Delta r \propto \log\left(\frac{m_H}{m_W}\right)$$

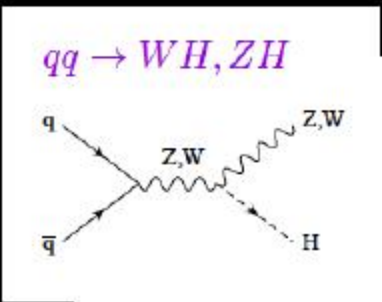
$$m_H = 94^{+29}_{-24}\ GeV$$

*Is there a Higgs?*

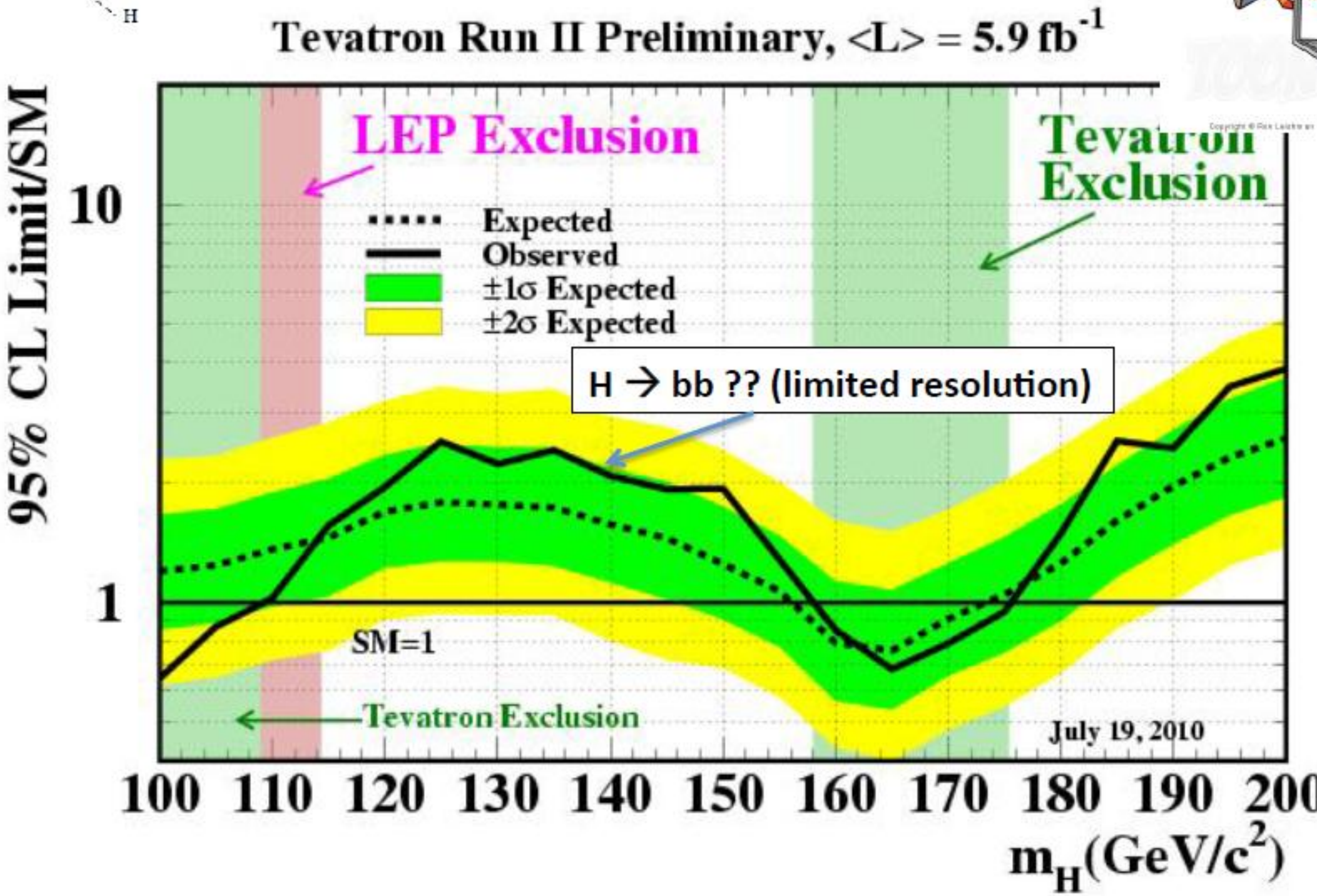
$$m_H < 152\ GeV \text{ at } 95\%\ \mathrm{CL}$$



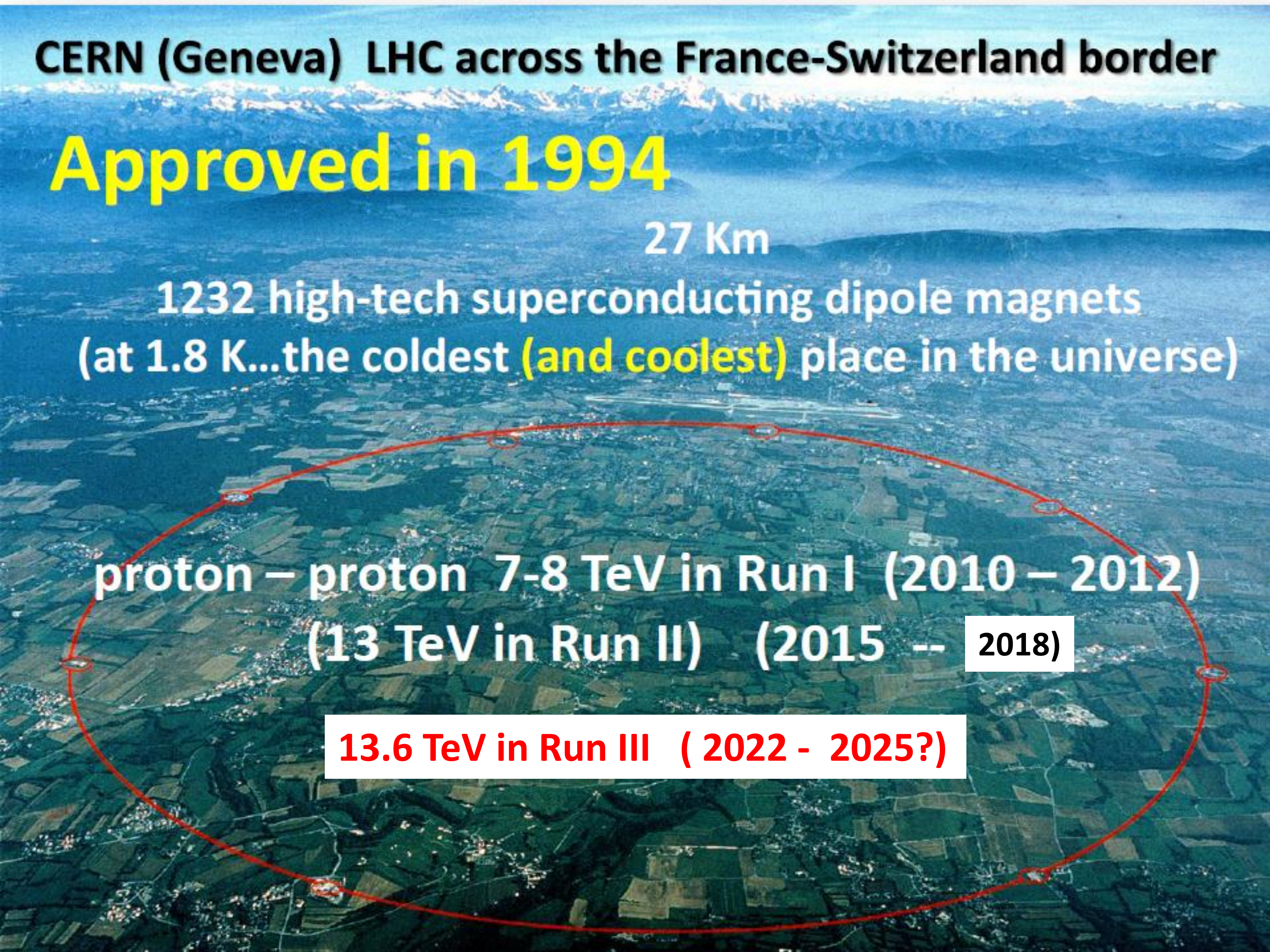

Tevatron
Chicago
$\sqrt{s} = 1.96$ TeV
p
$\bar{p}$
Booster
CDF
DØ
Tevatron
p-bar source
Main Injector
(new)




# Tevatron in July 2010

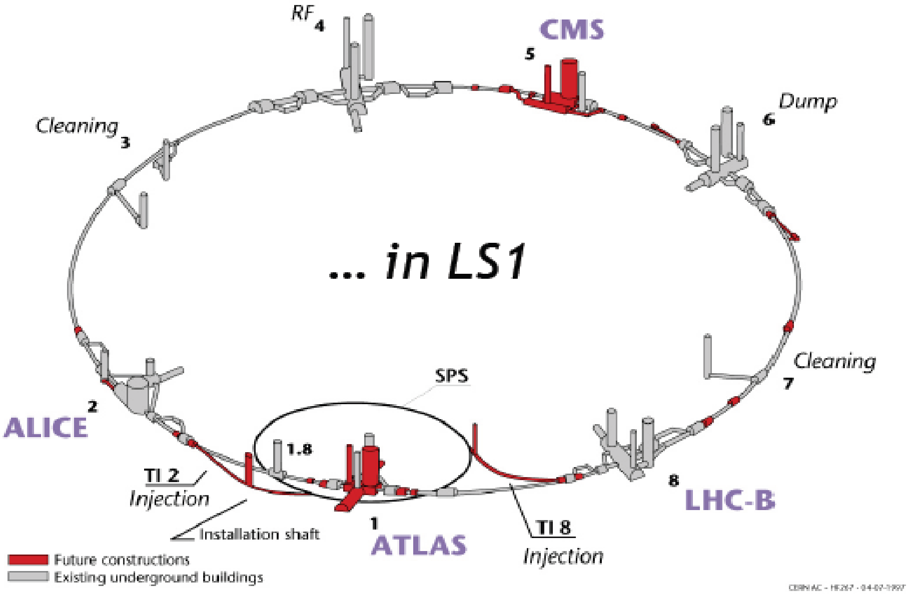



If goes below 1 you exclude the SM Higgs for a given mass


CERN (Geneva) LHC across the France-Switzerland border
Approved in 1994
27 Km
1232 high-tech superconducting dipole magnets
(at 1.8 K...the coldest (and coolest) place in the universe)
proton – proton 7-8 TeV in Run I (2010 – 2012)
(13 TeV in Run II) (2015 -- 2018)
13.6 TeV in Run III ( 2022 - 2025?)

# Shown here results based on Run I

## Energy frontier

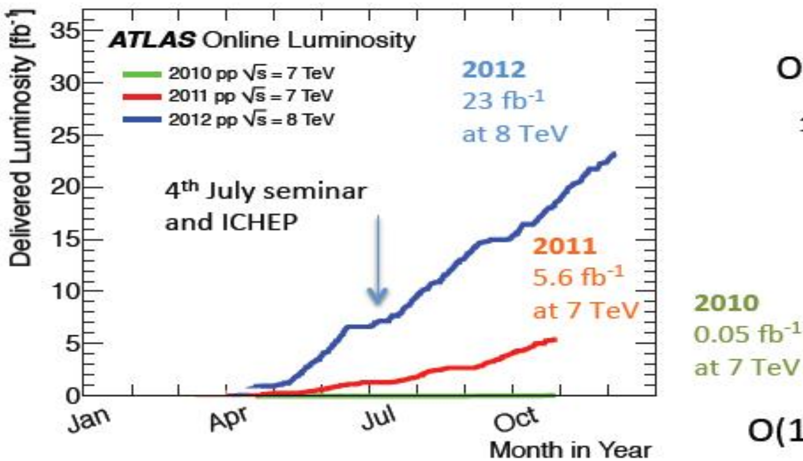


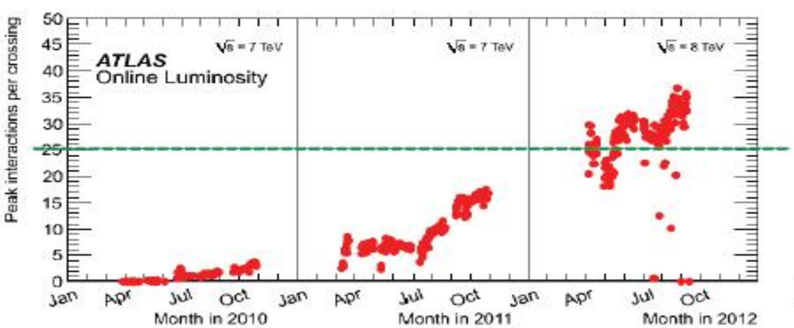

**The LHC**
- Circumference 27 km
- Up to 175 m underground
- Total number of magnets 9 553
- Number of dipoles 1 232
- Operation temperature 1.9 K (Superfluid He)

$$\mathcal{L} = \frac{N_p^2 k_b f_{rev} \gamma}{4\pi \beta^* \epsilon_n} F$$

| Parameter | 2010 | 2011 | 2012 | Nominal |
|---|---|---|---|---|
| C.O.M Energy | 7 TeV | 7 TeV | 8 TeV | 14 TeV |
| Bunch spacing / k | 150 ns / 368 | 50 ns / 1380 | 50 ns /1380 | 25 ns /2808 |
| ε (mm rad) | 2.4-4 | 1.9-2.3 | 2.5 | 3.75 |
| β* (m) | 3.5 | 1.5-1 | 0.6 | 0.55 |
| L ($cm^{-2}s^{-1}$) | $2x10^{32}$ | $3.3x10^{33}$ | $\sim7x10^{33}$ | $10^{34}$ |

# The first LHC run




Design value
(expected to be
reached at L=$10^{34}$ !)

*2010*

O(2) Pile-up events

150 ns inter-bunch spacing

*2011*

O(10) Pile-up events

50 ns inter-bunch spacing

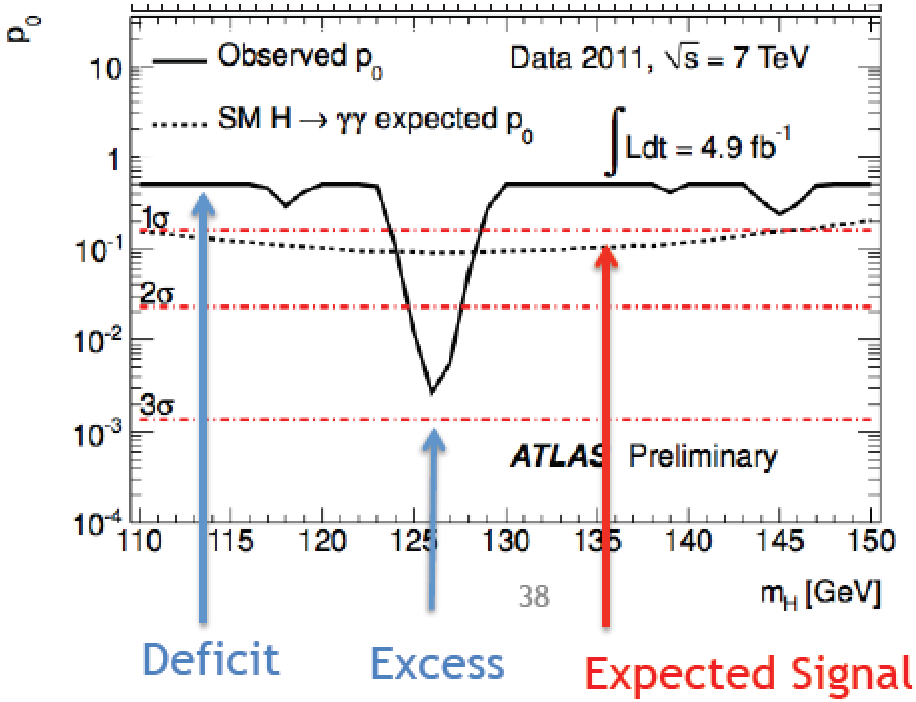
*2012*

O(20) Pile-up events

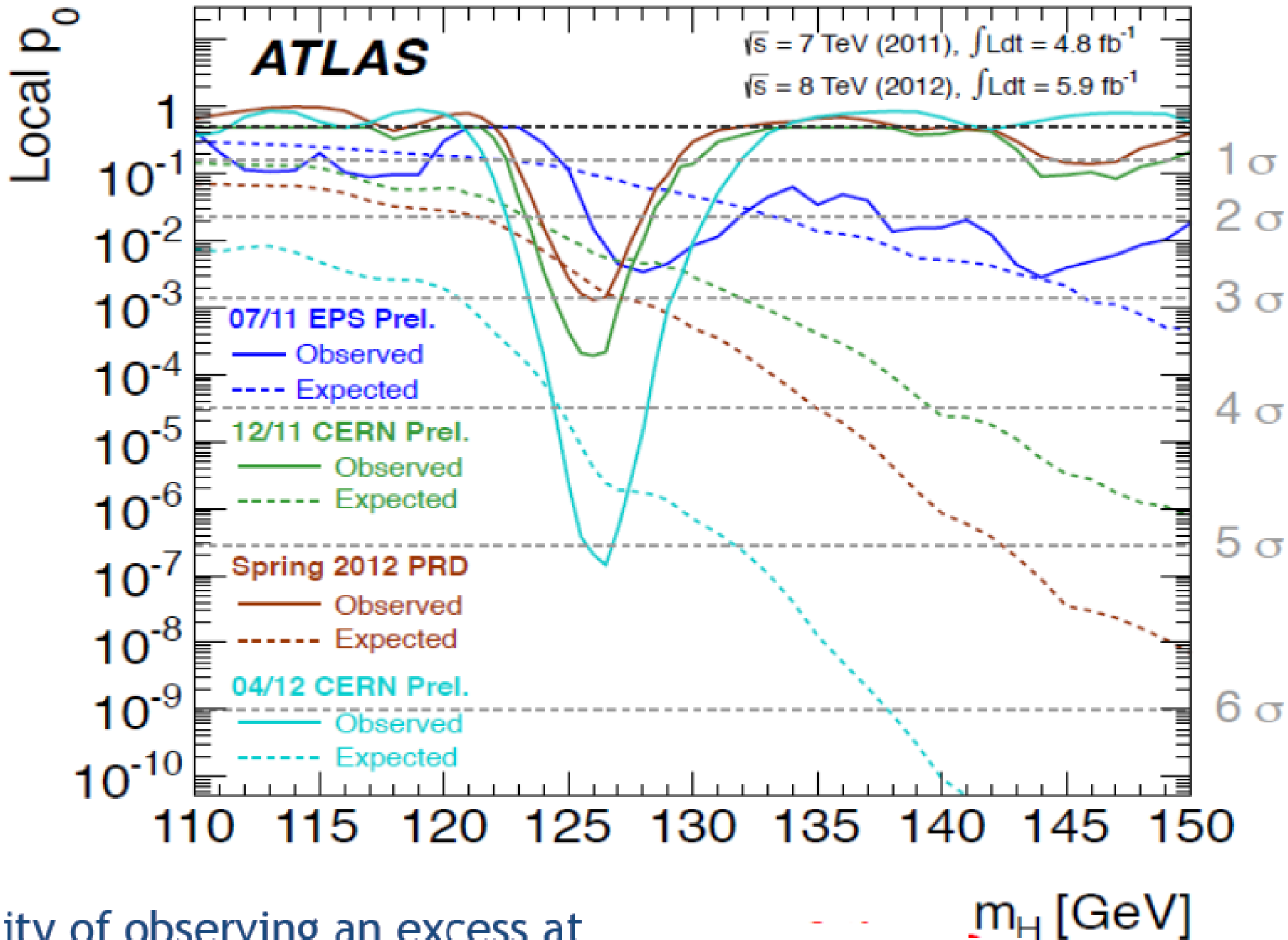
50 ns inter-bunch spacing

# Local $p_0$

Probability that the background can produce a fluctuation greater than or equal to the excess observed in data. Equivalent in terms of number of standard deviations is called local significance.



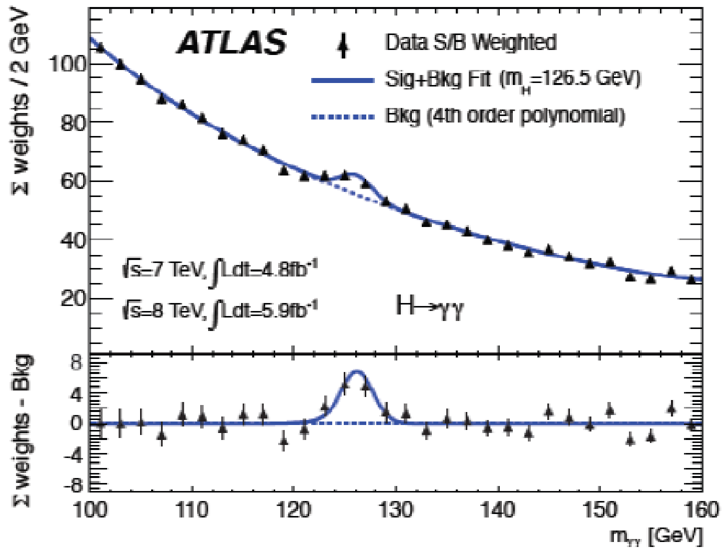
# Birth of a particle

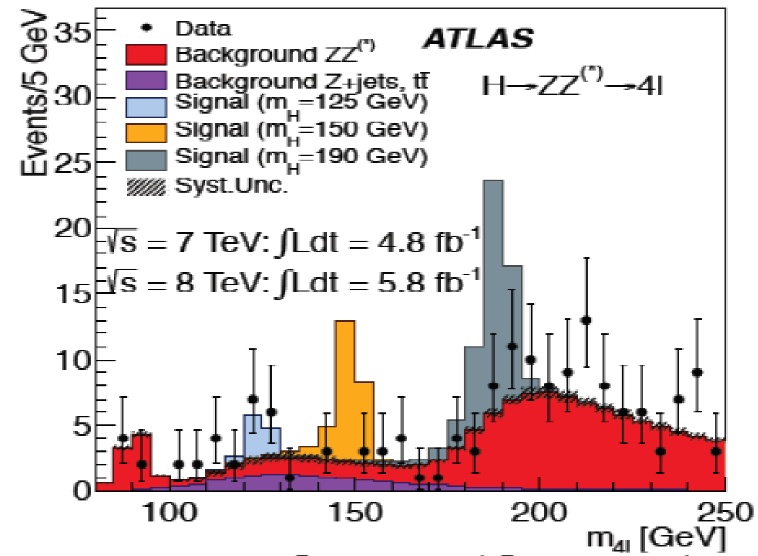



Probability of observing an excess at
one specific mass
(in absence of signal)…

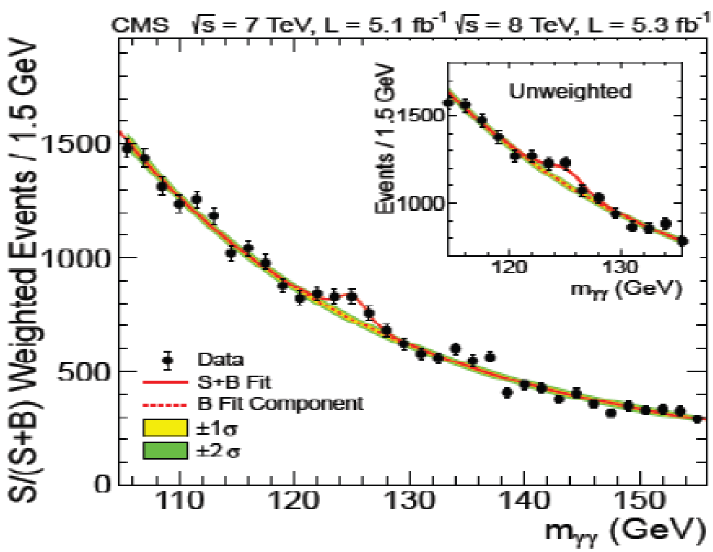
# Higgs-like particle – 4 July 2012

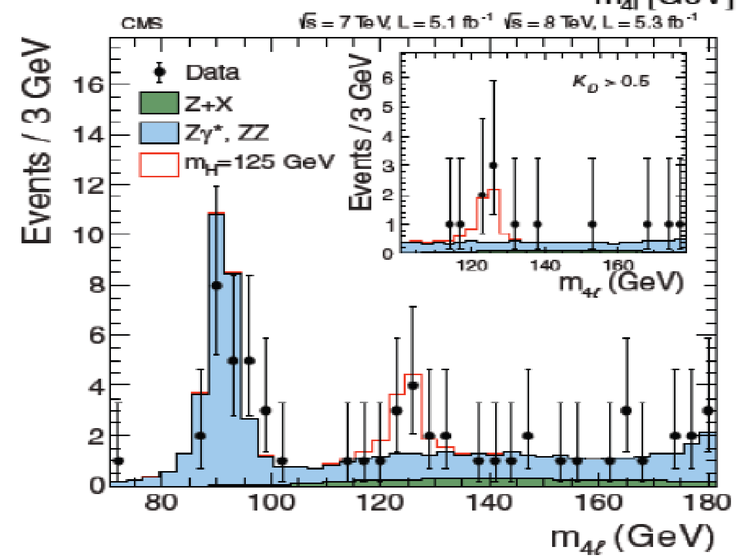
Phys.Lett. B716 (2012) 1-29



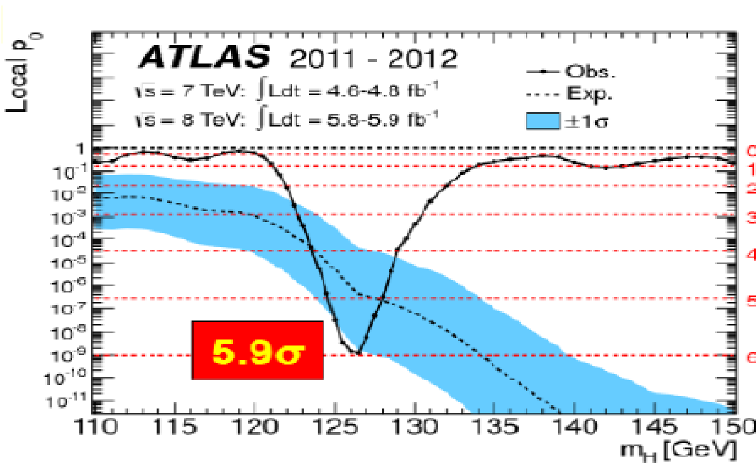

Phys.Lett. B716 (2012) 30-61

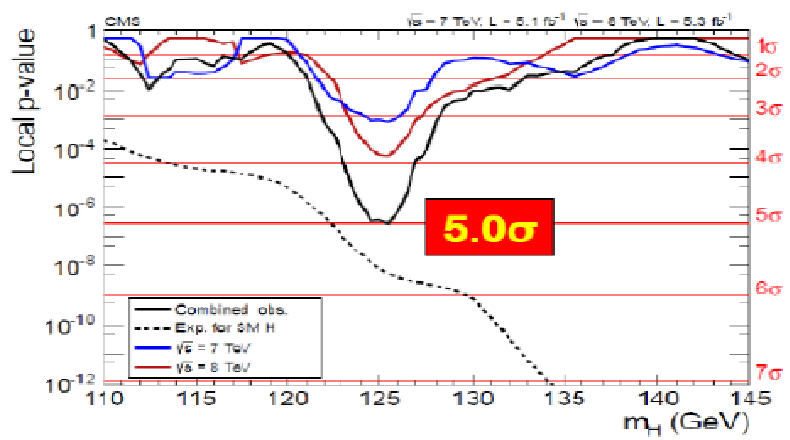


# Higgs-like particle – 4 July 2012

- We are living in a privileged moment in the history of High Energy Physics: **first fundamental scalar**
- The discovery came at half of the design energy, much more severe pile-up and one-third of integrated luminosity than was originally judged as




***ATLAS*** *PLB 716 (2012) 1-29, Sept 17 (2012)*

***Largest local excess:***
***5.9σ at $m_H$= 126.5 GeV***

H→γγ, bb, ττ, WW(lνlν, lνqq), ZZ(4l, llνν, llqq)

***CMS*** *PLB 716 (2012) 30-61, Sept 17 (2012)*

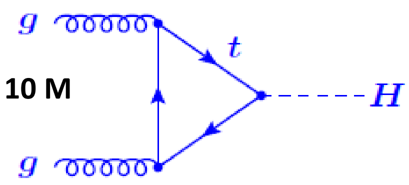
***Largest local excess:***
***5.0σ at $m_H$= 125.5 GeV***

H→γγ, bb, ττ, WW(lνlν), ZZ(4l, llττ, llνν, llqq)

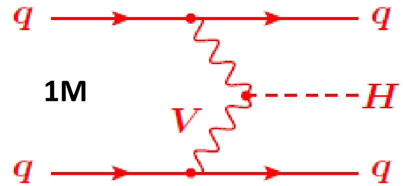
# The Higgs Boson at the LHC

## Production

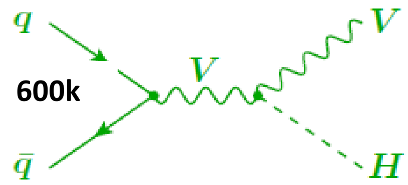
#Higgs produced at 13 TeV (2015-2017)



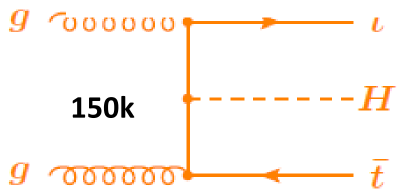

Main production channel




2 forward jets, little central hadronic activity

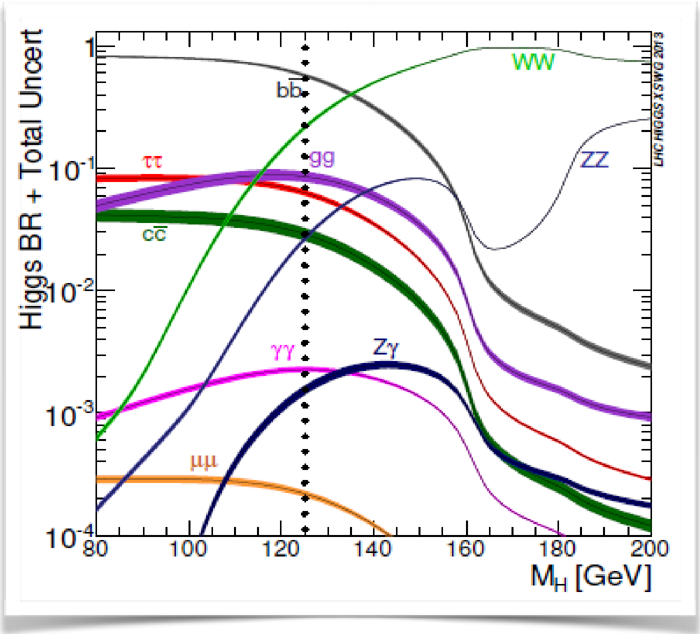



Tag W and Z decays




Tag 2 top quarks

## Decays

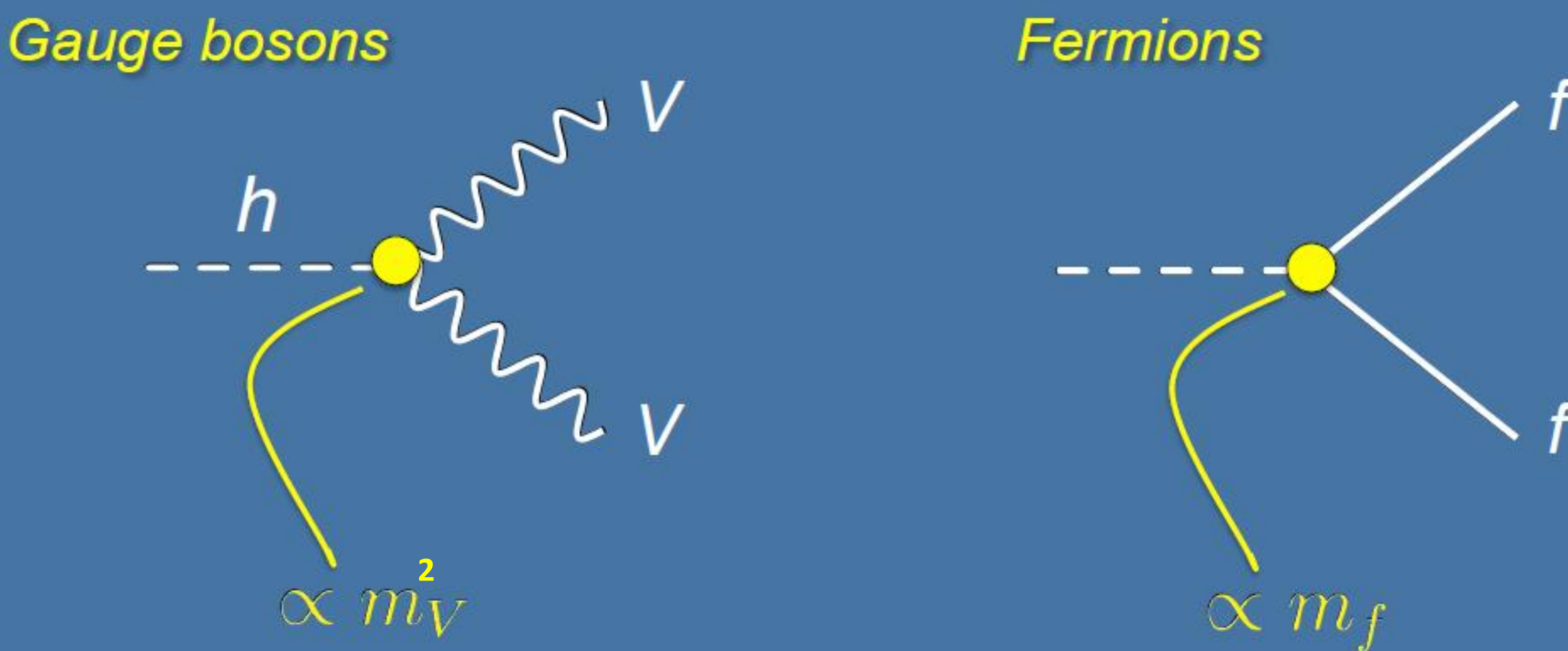



**5 main channels at the LHC**

Decay branching fractions for $m_H$ = 125 GeV

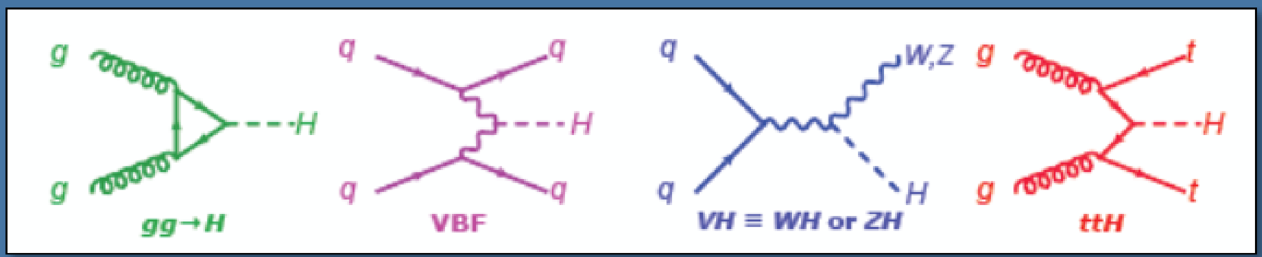
- $H \rightarrow bb$: 58 %
- $H \rightarrow WW^*$: 21%
- $H \rightarrow \tau^+\tau^-$: 6.3%
- $H \rightarrow ZZ^*$: 2.6%
- $H \rightarrow \gamma\gamma$: 0.2%

# Higgs boson couplings



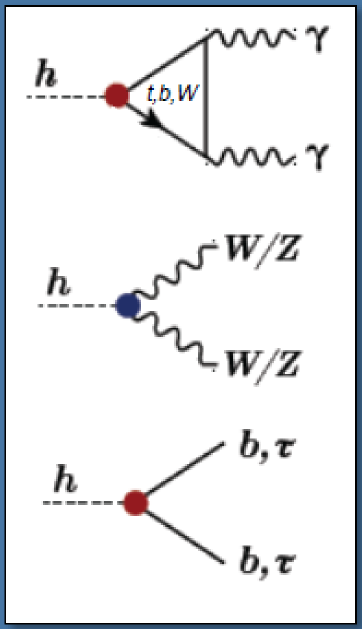

Higgs boson properties are fixed in the Standard Model ($m_h$)

# Higgs boson phenomenology

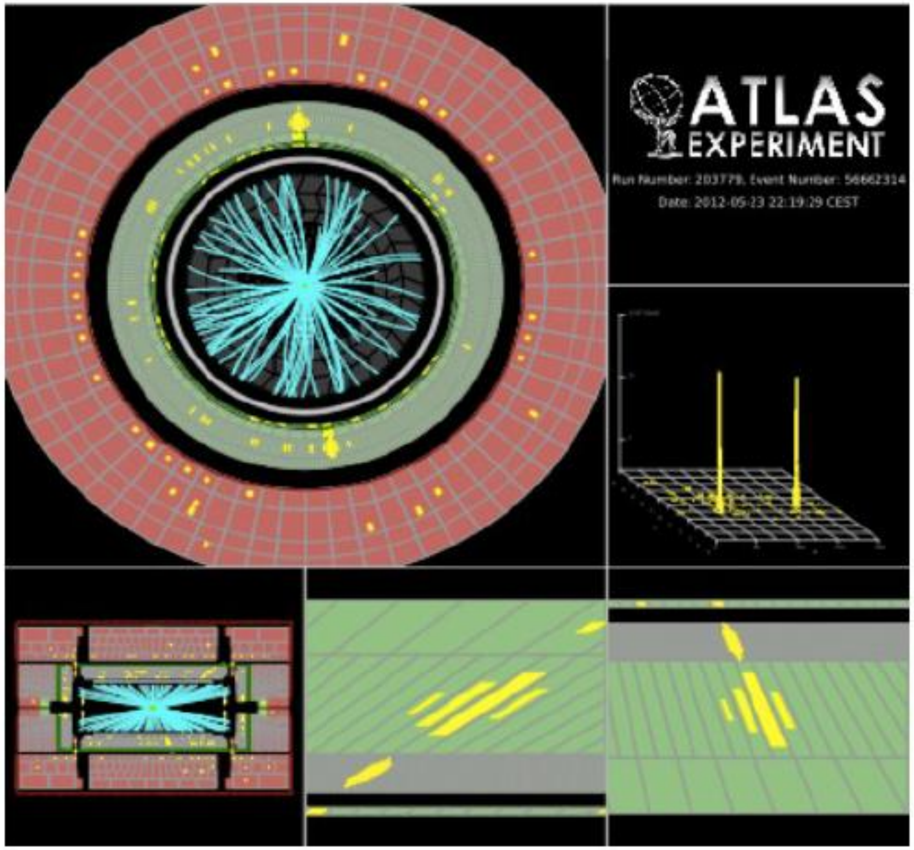



‘production & decay matrix’

sensitivity to different Higgs properties



# H->$\gamma\gamma$: events signature




***Simple event signature***

- **Two high pT photons**
  **$pT_1 > 40$ GeV and $pT_2 > 30$ GeV**
- **High trigger efficiency**
  **~99%**
- **High event selection efficiency despite high jet-jet & γ-jet production**
  **~40%**
- **High signal over background**
  **~3-10 % (depending on sub-category)**

**Invariant mass reconstruction $m_{\gamma\gamma}^2 = 2 * E_1 E_2 (1 - \cos \alpha)$**

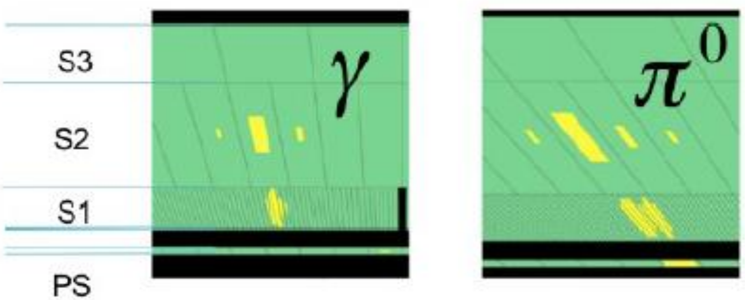
- **Good energy calibration**
- **Robust primary vertex reconstruction**

**→ Excellent invariant mass resolution ~1.6 GeV with 90% of events within ±2σ**

# Shower shapes and vertex reconstr.

## Photon ID 2 – Photon shower shapes and background rejection

$\pi^0$-$\gamma$ Rejection




- Photons shower shape distributions in LAr sampling layers - different for signal and background ($\pi^0$)

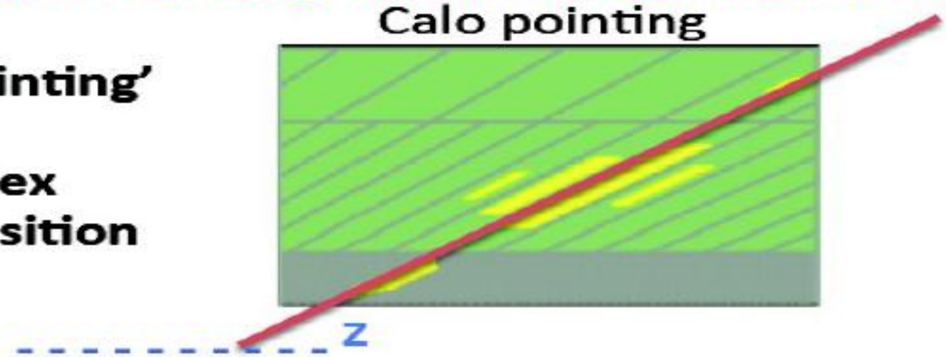
## Vertex Reconstruction

$$m_{\gamma\gamma}^2 = 2 * E_1 E_2 (1 - \cos\alpha)$$

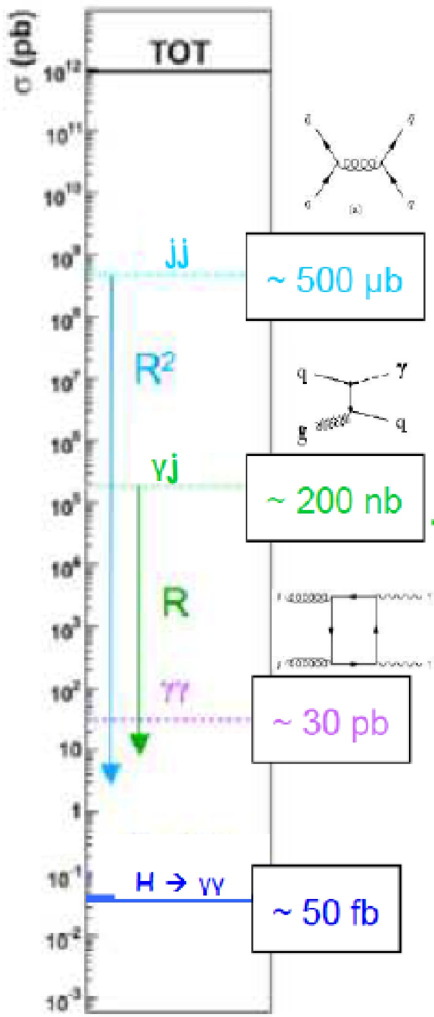
❑ Vertex reconstructed through likelihood combination

- Calorimeter 'pointing'
- $\Sigma$ tracks $pT^2$
- Conversion vertex
- Mean vertex position

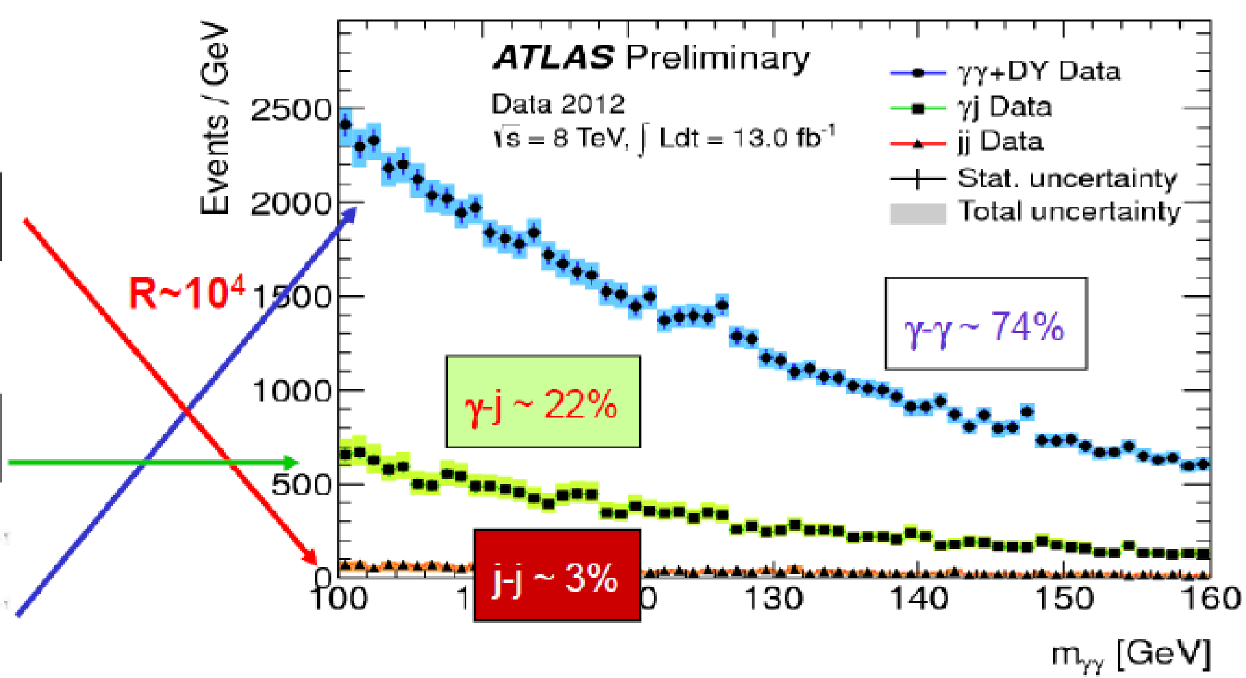
Calo pointing



# H->γγ: background rejection



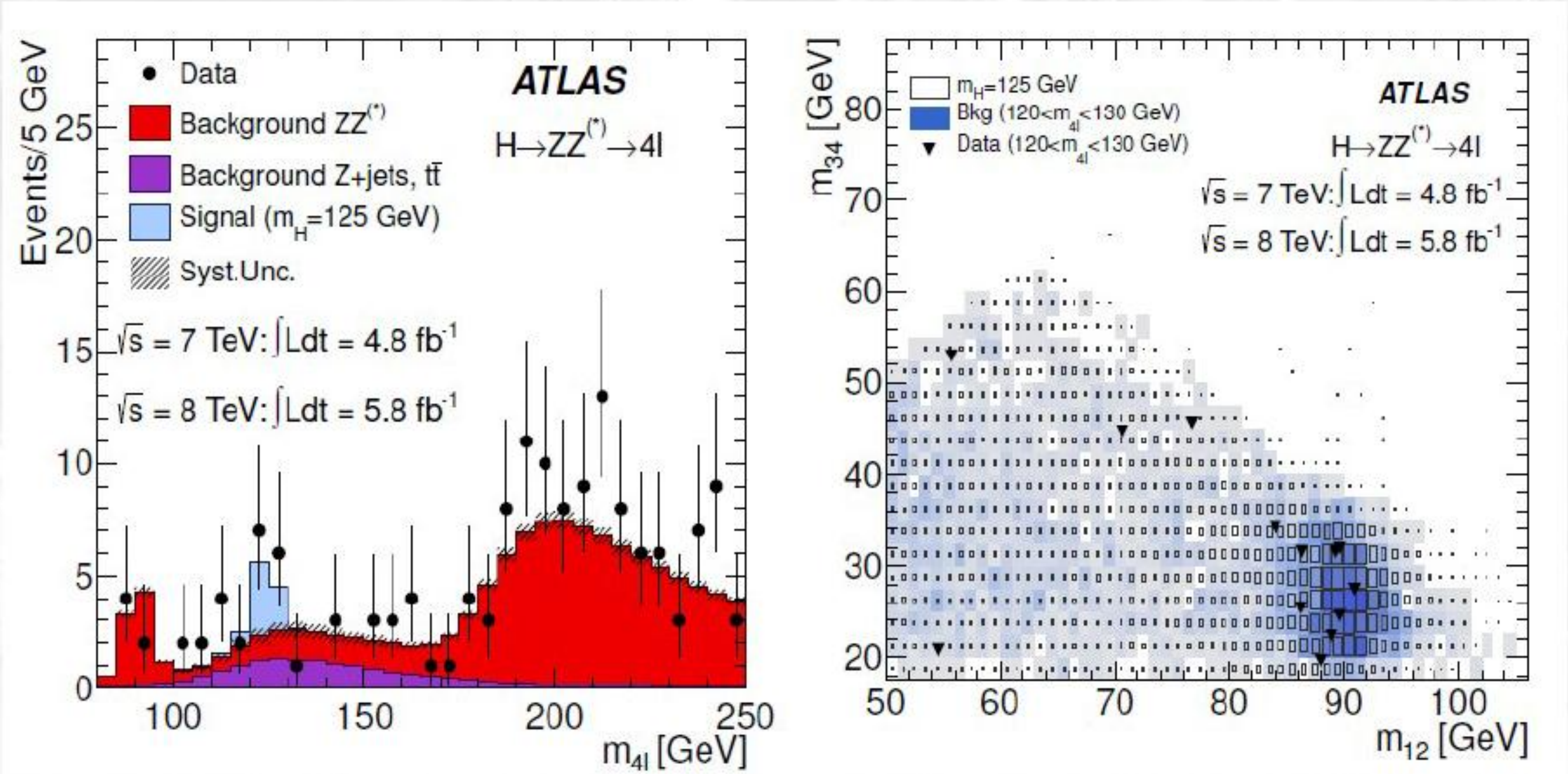

**Data-driven background decomposition**




➔ Reducible background γ-jet and jet-jet largely below irreducible background γ-γ

- Remark 1: this decomposition is not directly used in the Higgs search: the background is extrapolated from data sidebands
- Remark 2: Drell-Yan ~negligible for $m_{\gamma\gamma}$>100 GeV (~1%)

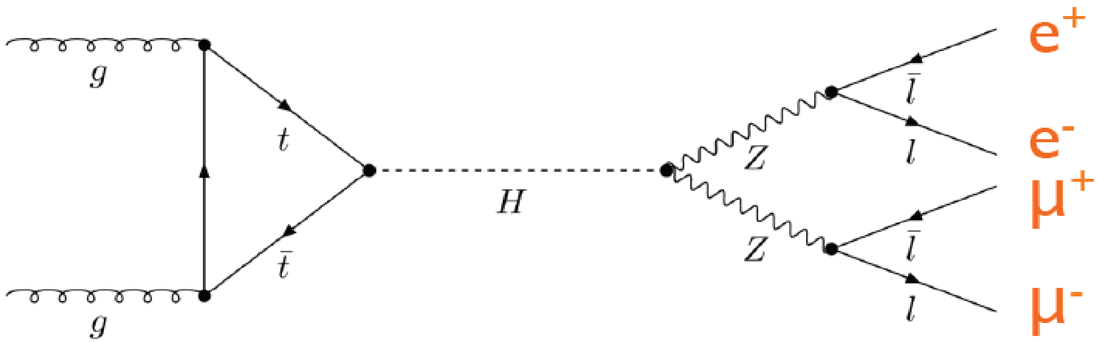
# The golden channel: H->ZZ, Z->ll




In a $m_{4\ell}$ window around 120-130 GeV:

| | Signal | $ZZ^{(*)}$ | $Z+$ jets, $t\bar{t}$ | Observed |
|---|---|---|---|---|
| $4\mu$ | 2.09±0.30 | 1.12±0.05 | 0.13±0.04 | 6 |
| $2e2\mu/2\mu2e$ | 2.29± 0.33 | 0.80±0.05 | 1.27±0.19 | 5 |
| $4e$ | 0.90±0.14 | 0.44±0.04 | 1.09±0.20 | 2 |

# Signal and background

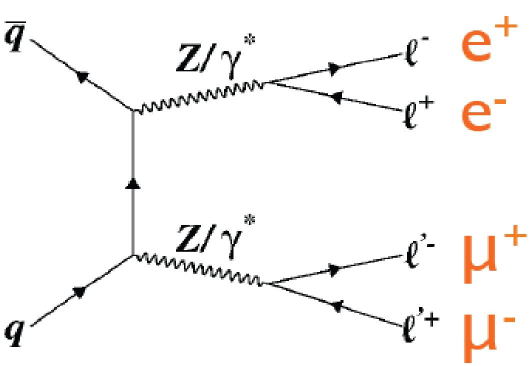


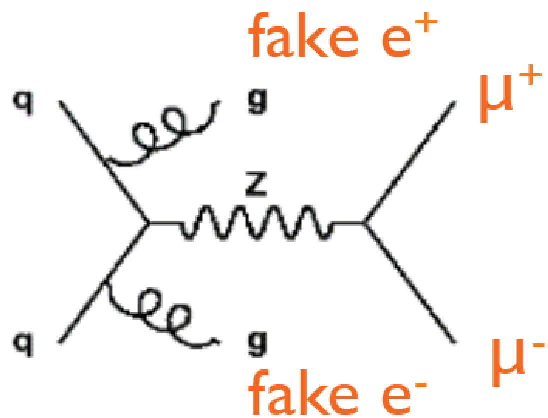

*Irreducible background*

The final state is exactly the same, but it does not come from the particle you are looking for

*Reducible background*

The final state looks like the same, but some f the particle fakes what you are looking for

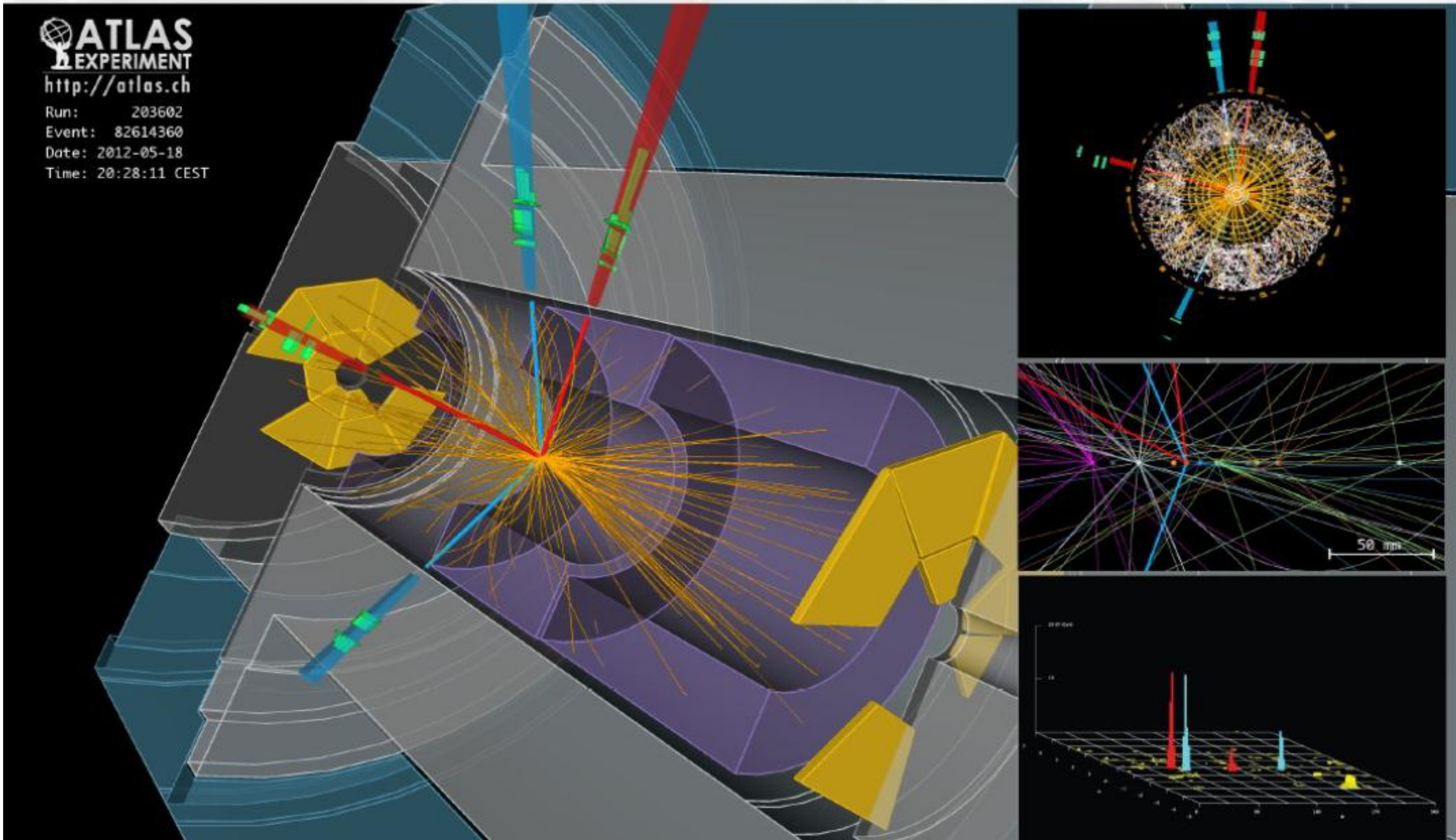


$4e$ candidate. $m_{4\ell} = 124.6$ GeV, $m_{12} = 70.6$ GeV, $m_{34} = 44.7$ GeV.

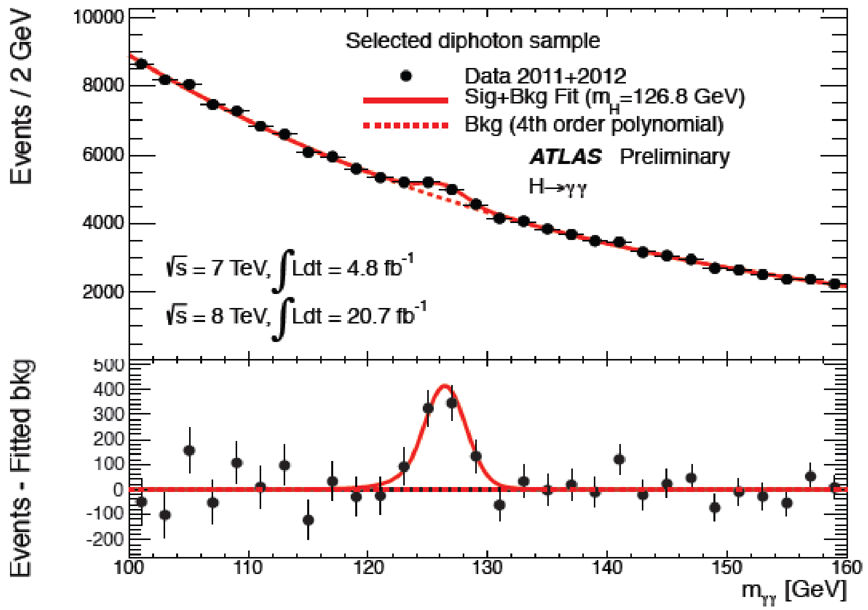
$e_1$: $P_T = 24.9$ GeV, $\eta = -0.33$, $\phi = 1.98$ $e_2$: $P_T = 53.9$ GeV, $\eta = -0.40$, $\phi = 1.69$

$e_3$: $P_T = 61.9$ GeV, $\eta = -0.12$, $\phi = 1.45$ $e_4$: $P_T = 17.8$ GeV, $\eta = -0.51$, $\phi = 2.84$



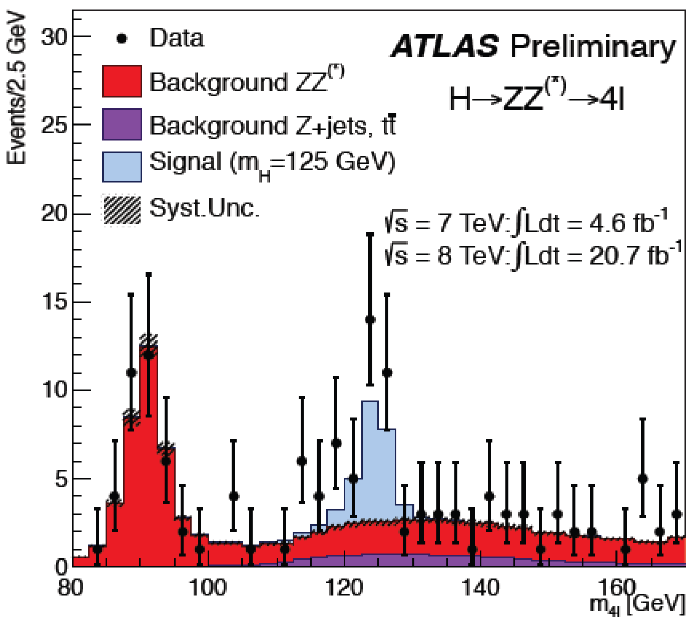
# Higgs like signal with 7 TeV and 8 TeV data

**H→γγ**



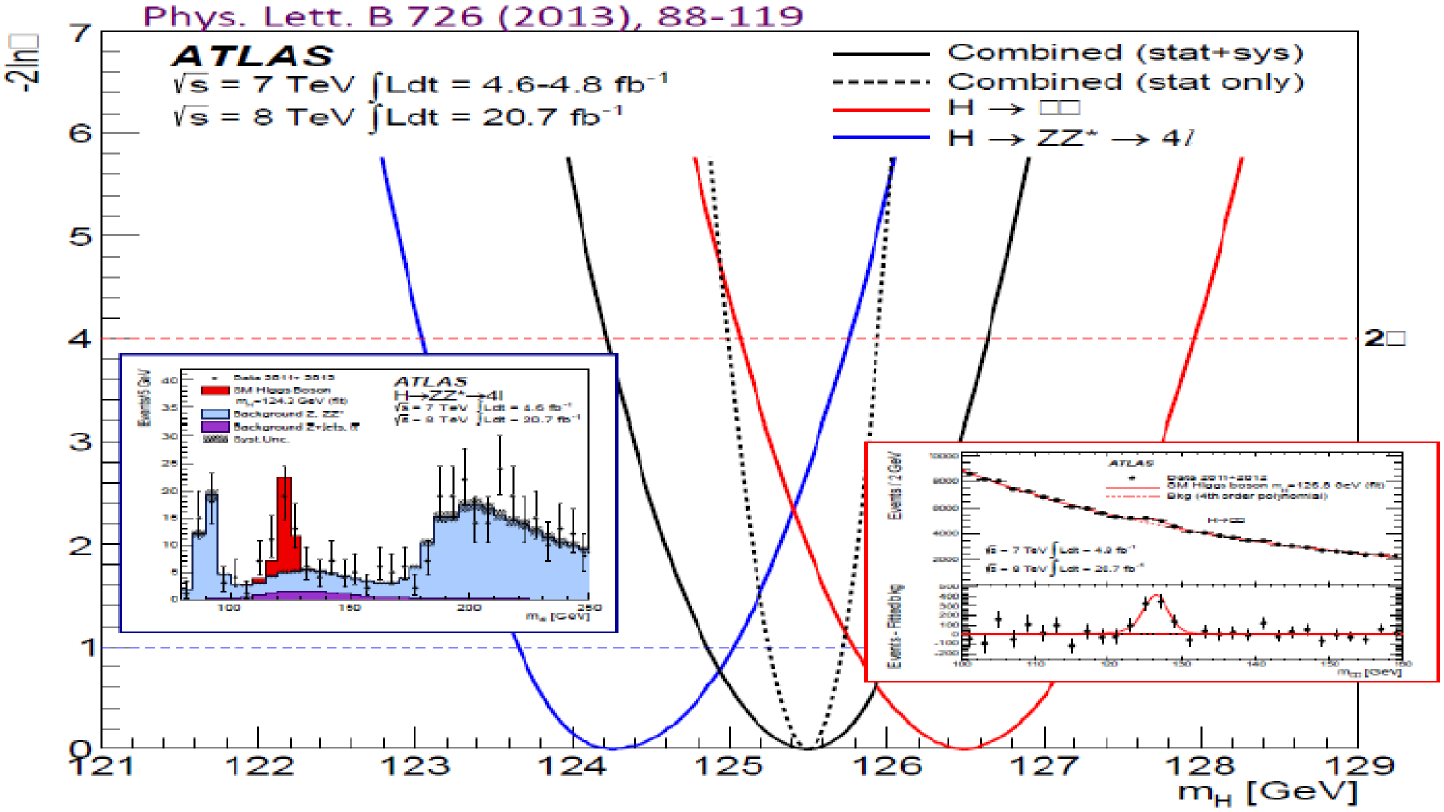

- Signal significance = $7.4\ \sigma$
- $m_H$ = $126.8 \pm 0.2$ (stat) $\pm 0.7$ (syst) GeV
- $\mu$ = $1.65 \pm 0.34$ (deviation w.r.t. SM at $2.3\sigma$)

**H→4l**




- Signal significance = $6.6\ \sigma$
- $m_H$ = $124.3\ ^{+0.6}_{-0.5}$ (stat) $^{+0.6}_{-0.3}$ (syst) GeV
- $\mu$ = $1.7 \pm 0.34$

# Mass measurement




4ℓ: $M_H = 124.3 \pm \mathbf{0.6}_{stat} \pm 0.4_{sys}$ GeV

γγ: $M_H = 126.8 \pm 0.2_{stat} \pm \mathbf{0.7}_{sys}$ GeV

Combined: $M_H = 125.5 \pm 0.2_{stat} \pm 0.6_{sys}$ GeV

# And since then ….

## Panorama of ATLAS Higgs (125) Analyses

| channel | ggF | VBF | VH | ttH | Yield | S/B (%) | Res. (GeV/c²) |
|---|---|---|---|---|---|---|---|
| $\gamma\gamma$ | ✓ | ✓ | ✓ | ✓ | ~ 450 | 1 - 20% | ~ 1.6 |
| $ZZ \rightarrow 4l$ | ✓ | | | | ~ 16 | 1 | ~ 2.2 |
| $WW \rightarrow l\nu l\nu$ | ✓ | ✓ | ✓ | | ~ 250 | 10% | Poor |
| $\tau\tau$ | ✓ | ✓ | ✓ | | ~ 330 | 0.3 – 30% | ~ 20 |
| VH(bb) | | | ✓ | | ~ 50 | 1 - 10% | ~ 15 |
| ttH(bb) | | | | ✓ | ~20 | Up to ~5% | Poor (combinatorial) |
| $\mu\mu$ | Inclusive | | | | ~ 40 | ~ 0.2 % | ~ 2.5 |
| Invisible | (✓) | | ✓ | | ~ 30 | ~ 0.2 | Poor |
| $Z\gamma$ | Inclusive | | | | ~ 15 | ~ 0.5% | ~ 1.8 |

# Which Higgs boson we have discovered?

Higgs boson was discovered in $ZZ^*$, $\gamma\gamma$ and $WW^*$ decays

- Higgs boson mass is ~125.6 GeV

  Measured in $H \rightarrow ZZ^* \rightarrow 4l$ and $H \rightarrow \gamma\gamma$

  ATLAS: $m_H = 125.5 \pm 0.2$ (stat) $\pm 0.6$ (syst) GeV

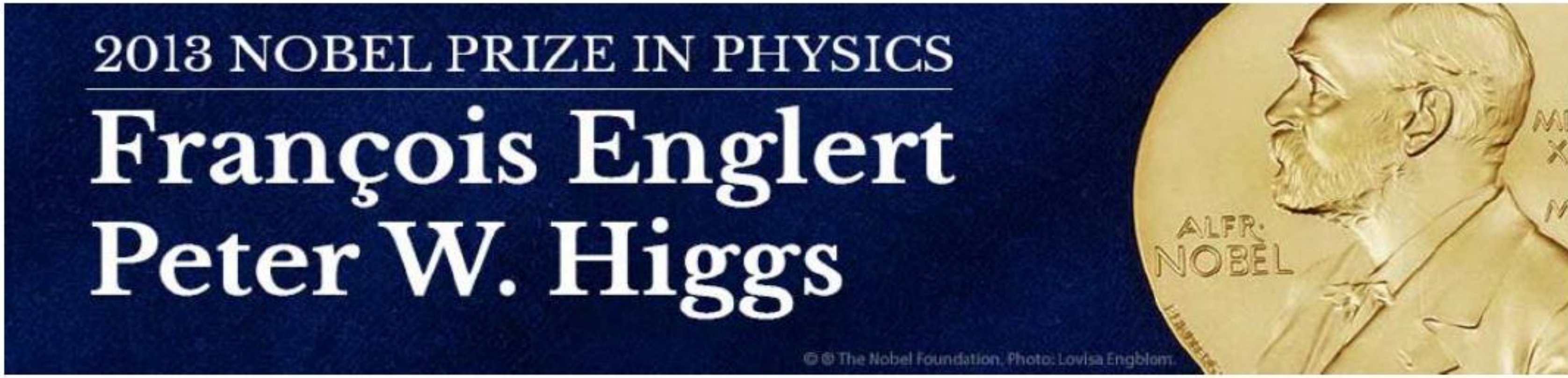
  CMS: $m_H = 125.7 \pm 0.3$(stat) $\pm 0.3$ (syst) GeV

- ATLAS and CMS data strongly favour $J^P = 0^+$ SM quantum numbers; alternative models excluded at 95% CL.
- Signal strength $\mu = \sigma/\sigma_{SM}$ consistent with 1

**Summer 2013:**

All measured properties are compatible with SM hypothesis.

# Nobel price for predicting Higgs particle




THE BEH-MECHANISM, INTERACTIONS WITH SHORT RANGE FORCES AND SCALAR PARTICLES

8 October 2013

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2013 to

François Englert and Peter Higgs

*"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

# Entrance of the Higgs into PDG

**2013**

## Higgs Bosons — $H^0$ and $H^{\pm}$

A REVIEW GOES HERE – Check our WWW List of Reviews

NODE=S055
NODE=S055

**CONTENTS:**

NODE=S055CNT
NODE=S055CNT



NODE=S055CNT

### $H^0$ (Higgs Boson)

NODE=S055210

The observed signal is called a Higgs Boson in the following, although its detailed properties and in particular the role that the new particle plays in the context of electroweak symmetry breaking need to be further clarified. The signal was discovered in searches for a Standard Model (SM)-like Higgs. See the following section for mass limits obtained from those searches.

NODE=S055210

### $H^0$ MASS

NODE=S055HBM
NODE=S055HBM

| VALUE (GeV) | DOCUMENT ID | TECN | COMMENT |
|---|---|---|---|
| **125.9±0.4 OUR AVERAGE** | | | |
| 125.8±0.4±0.4 | [1] CHATRCHYAN 13J | CMS | $pp$, 7 and 8 TeV |
| 126.0±0.4±0.4 | [2] AAD 12AI | ATLS | $pp$, 7 and 8 TeV |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | |
| 126.2±0.6±0.2 | [3] CHATRCHYAN 13J | CMS | $pp$, 7 and 8 TeV |
| 125.3±0.4±0.5 | [4] CHATRCHYAN 12N | CMS | $pp$, 7 and 8 TeV |

OCCUR=2

[1] Combined value from $ZZ$ and $\gamma\gamma$ final states.
[2] AAD 12AI obtain results based on 4.6–4.8 $fb^{-1}$ of $pp$ collisions at $E_{cm}$ = 7 TeV and 5.8–5.9 $fb^{-1}$ at $E_{cm}$ = 8 TeV. An excess of events over background with a local significance of 5.9 $\sigma$ is observed at $m_{H^0}$ = 126 GeV. See also AAD 12DA.
[3] Result based on $ZZ \to 4\ell$ final states in 5.1 $fb^{-1}$ of $pp$ collisions at $E_{cm}$ = 7 TeV and 12.2 $fb^{-1}$ at $E_{cm}$ = 8 TeV.
[4] CHATRCHYAN 12N obtain results based on 4.9–5.1 $fb^{-1}$ of $pp$ collisions at $E_{cm}$ = 7 TeV and 5.1–5.3 $fb^{-1}$ at $E_{cm}$ = 8 TeV. An excess of events over background with a local significance of 5.0 $\sigma$ is observed at about $m_{H^0}$ = 125 GeV. See also CHATRCHYAN 12BY.

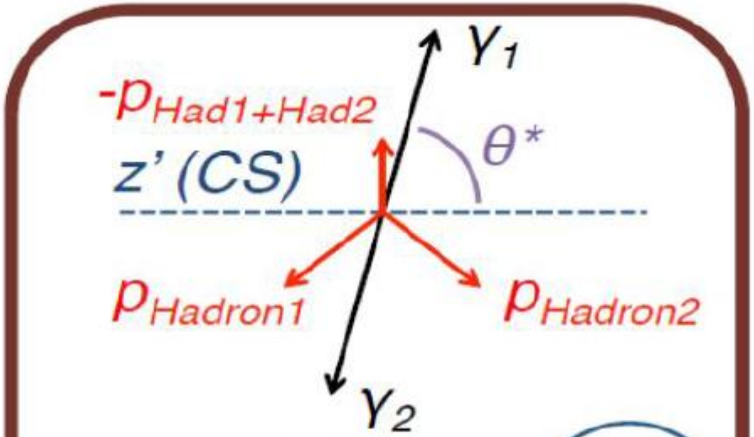
NODE=S055HBM;LINKAGE=CA
NODE=S055HBM;LINKAGE=AA
NODE=S055HBM;LINKAGE=CT
NODE=S055HBM;LINKAGE=CH

Inaugural entrance of the Higgs boson in the PDG particle listing !

$$H^0$$

# Spin observables for H->γγ

**Separate 0⁺ and 2⁺ spin hypotheses using the angular correlation of the two photons**



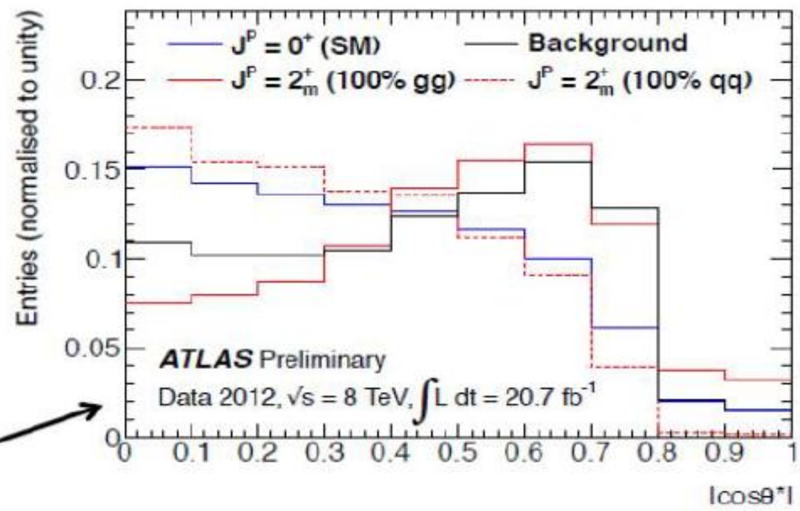

$$\left|\cos\theta^*_{CS}\right| = \frac{\left|\sinh\left(\Delta\eta^{\gamma\gamma}\right)\right|}{\sqrt{1+\left(p_T^{\gamma\gamma}/m_{\gamma\gamma}\right)^2}}\,\frac{2p_T^{\gamma 1}p_T^{\gamma 2}}{m_{\gamma\gamma}^2}$$

**Relative $p_T$ cuts on the photons remove most correlation with $m_{\gamma\gamma}$**

$qq \rightarrow 2^+$ very similar to SM $gg \rightarrow 0^+$

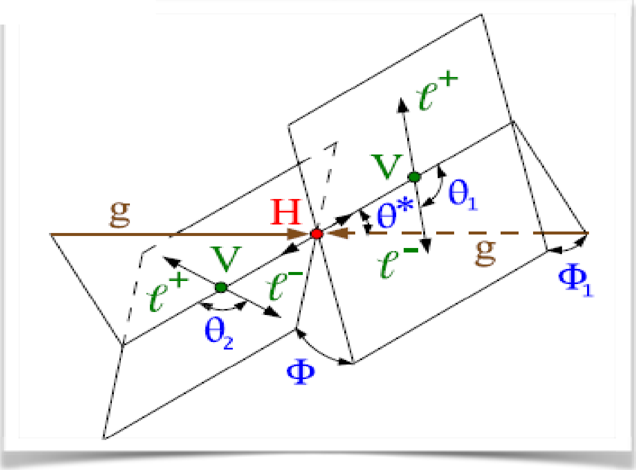
**Collins-Soper frame used to get reference axis z' for cos(θ*)**

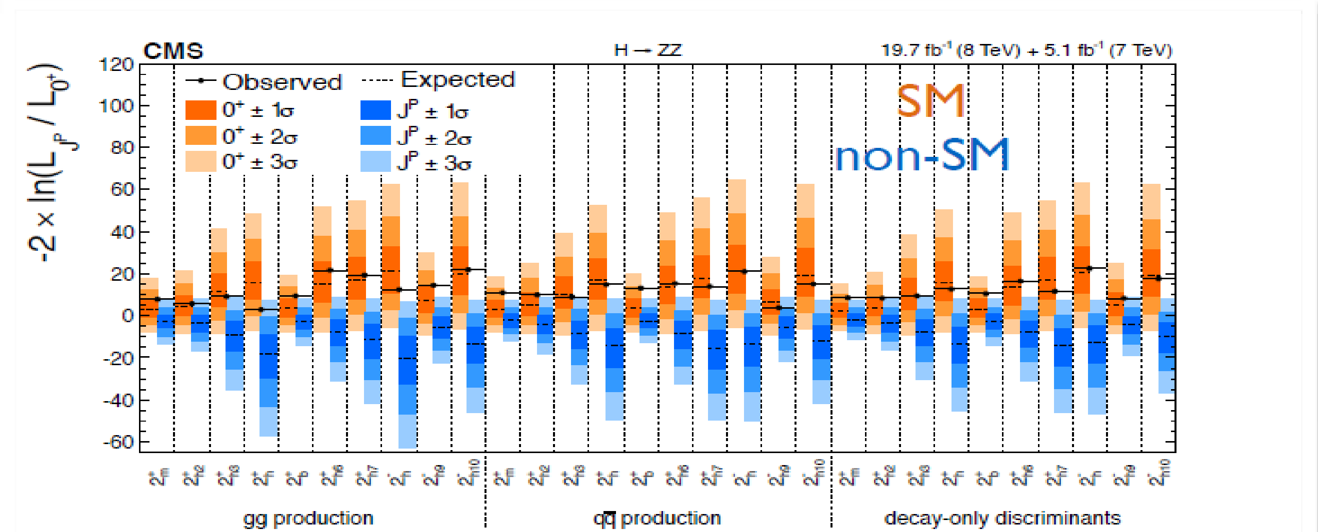
- z-axis bisects angle between the momenta of colliding hadrons
- Minimizes impact of ISR
- Better 0⁺ / 2⁺ discrimination



# Spin study with H->4l

- SM predicts $J^{PC} = 0^{++}$
- Angular distributions sensitive to JP
- Wide range of alternative quantum numbers excluded at >99% CL
- All observations consistent with expectations for the SM Higgs boson




PRD 92 (2015) 012004

Tests of alternative $J^P$ hypotheses in ZZ

# Higgs boson decay width

$m_h$= 125 GeV → $\Gamma_h$= 4.07 MeV

$\tau_h = 1.62\ 10^{-22}$ [s]

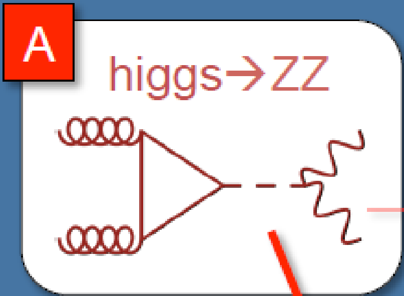
A deviation would imply a decay to non-SM particles

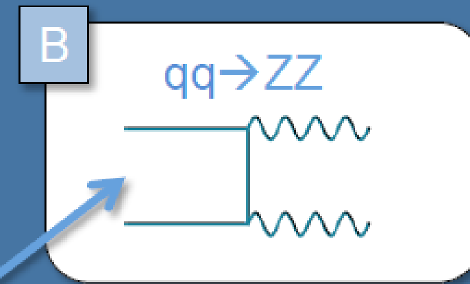
Differential Higgs production cross-section

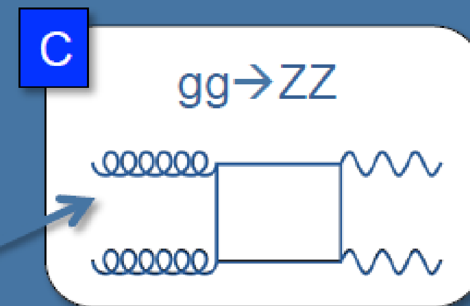
$$\frac{d\sigma_{gg\to H\to ZZ}}{dm^2_{ZZ}} \sim \frac{g^2_{ggH}g^2_{HZZ}}{(m^2_{ZZ}-m^2_H)^2+m^2_H\Gamma^2_H},$$

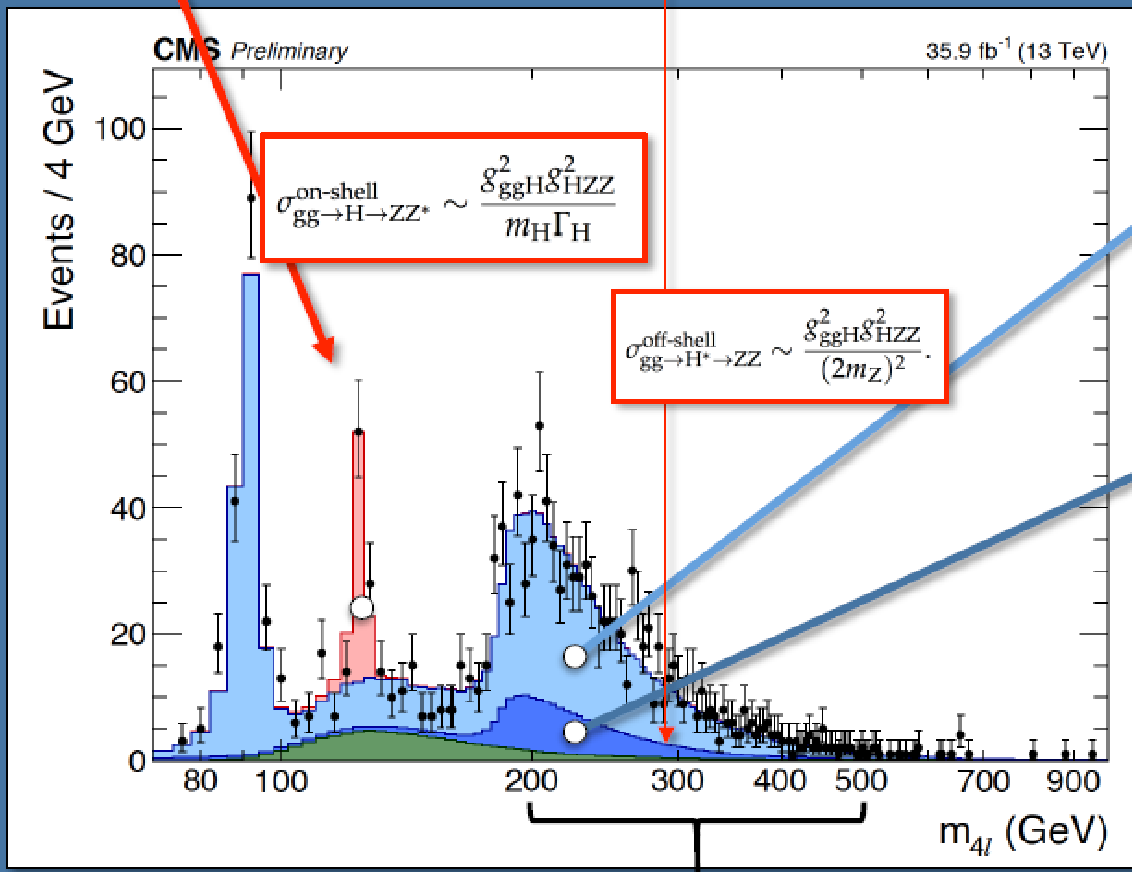
$\Gamma_h$ cannot be accessed directly (experimental resolution ~ 1-2 GeV)

# Indirect measurement



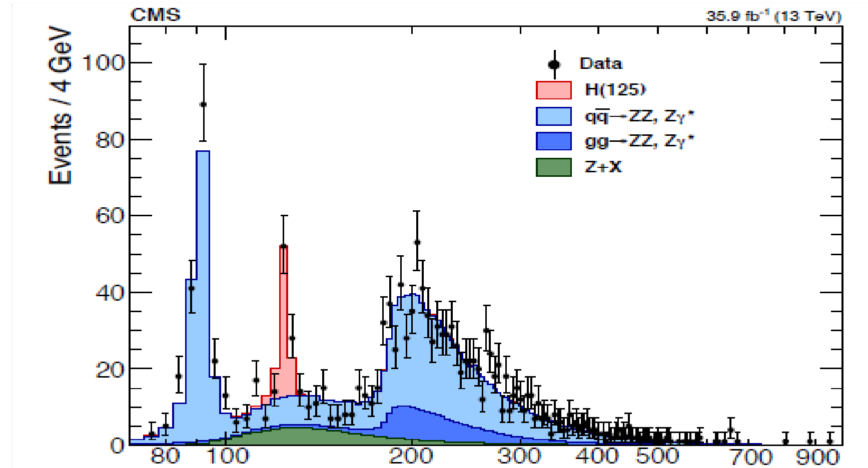

Interference between A and C : $(A+C)^2 = A^2 + C^2 + 2AC$

***tiny*** ← → ***accessible***

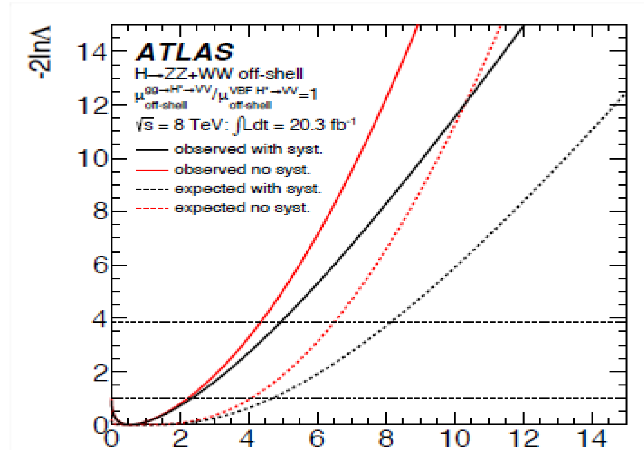
# Higgs boson decay width

## Total width

- Lower bound on total width from decay measurements
- Direct experimental measurements probe 3 orders of magnitude larger than SM width (Γ=4 MeV)
- Indirect constraint* on the width via measurement of ratio of off-peak to on-peak cross-section
  - CMS: Γ < 13 MeV
  - ATLAS: Γ < 22 MeV



accepted by JHEP



EPJC (2015) 75:335

*N. Kauer and G. Passarino, JHEP (2012) 2012: 116
*F. Caola and K. Melnikov, PRD88 (2013) 054024

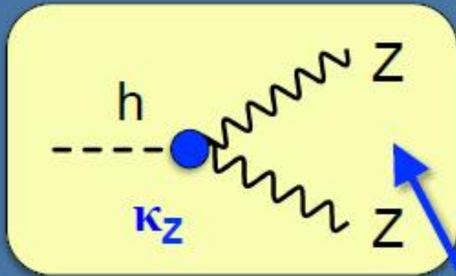
# Couplings: kappa-framework

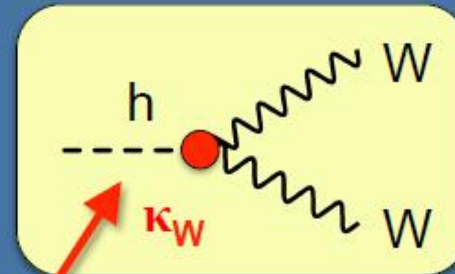
Scale factor for each (fundamental) coupling:

$$\sigma(i \to h \to f) = \kappa_i^2 \sigma_i^{SM} \frac{\kappa_f^2 \Gamma_f^{SM}}{\kappa_h^2 \Gamma_h^{SM}}$$

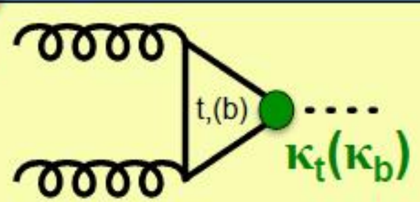
$$\begin{aligned}\mathcal{L} = \;& \kappa_3 \frac{m_H^2}{2v} H^3 + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu H + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H \\ & + \kappa_g \frac{\alpha_s}{12\pi v} G_{\mu\nu}^a G^{a\mu\nu} H + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \kappa_{Z\gamma} \frac{\alpha}{\pi v} A_{\mu\nu} Z^{\mu\nu} H \\ & - \left( \kappa_t \sum_{f=u,c,t} \frac{m_f}{v} f\bar{f} + \kappa_b \sum_{f=d,s,b} \frac{m_f}{v} f\bar{f} + \kappa_\tau \sum_{f=e,\mu,\tau} \frac{m_f}{v} f\bar{f} \right) H\end{aligned}$$

Scale Higgs boson couplings (wrt SM): production & decay

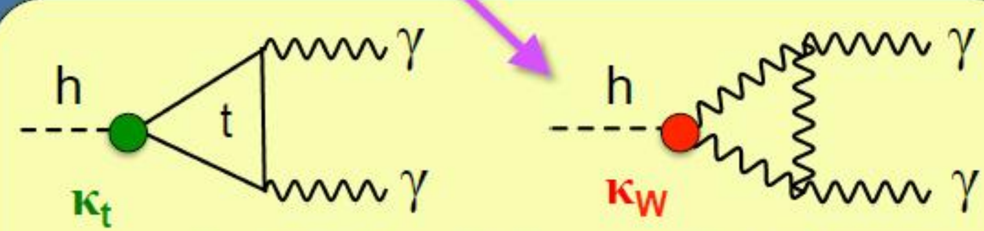



$$\mathcal{L} = \kappa_3 \frac{m_H^2}{2v} H^3 + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu H + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H$$
$$+ \kappa_g \frac{\alpha_s}{12\pi v} G_{\mu\nu}^a G^{a\mu\nu} H + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \kappa_{Z\gamma} \frac{\alpha}{\pi v} A_{\mu\nu} Z^{\mu\nu} H$$
$$- \left( \kappa_t \sum_{f=u,c,t} \frac{m_f}{v} f\bar{f} + \kappa_b \sum_{f=d,s,b} \frac{m_f}{v} f\bar{f} + \kappa_\tau \sum_{f=e,\mu,\tau} \frac{m_f}{v} f\bar{f} \right) H$$




$$\kappa_g^2 \propto 1.06\kappa_t^2 - 0.07\kappa_t\kappa_b + 0.01\kappa_b^2$$




$$\kappa_\gamma^2 \propto 1.59\kappa_W^2 - 0.66\kappa_W\kappa_t + 0.07\kappa_t^2$$

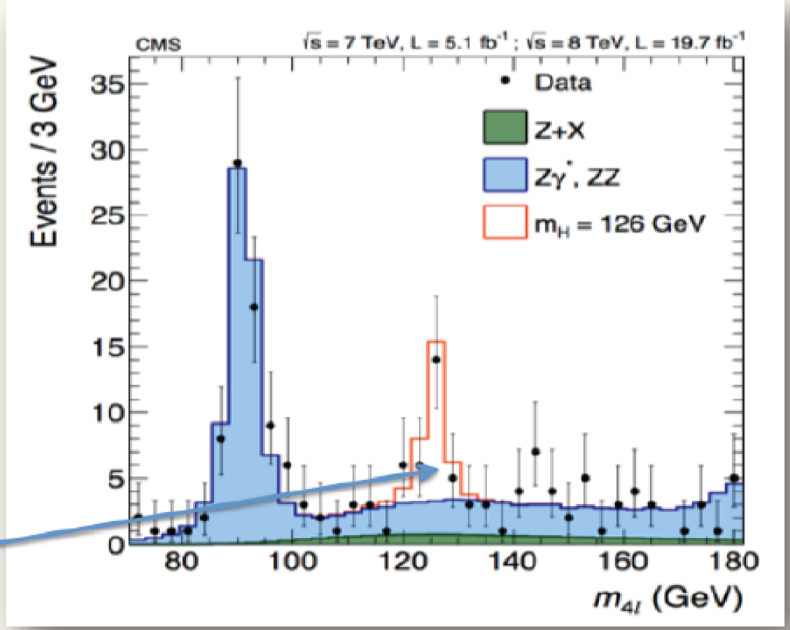
# What do we measure?

We measure event yields

We want to derive couplings and signal strengths

The first thing we want to measure is the the "signal strength" per channel

The analysis is using discriminators (usually reconstructed mass related) to increase S/B



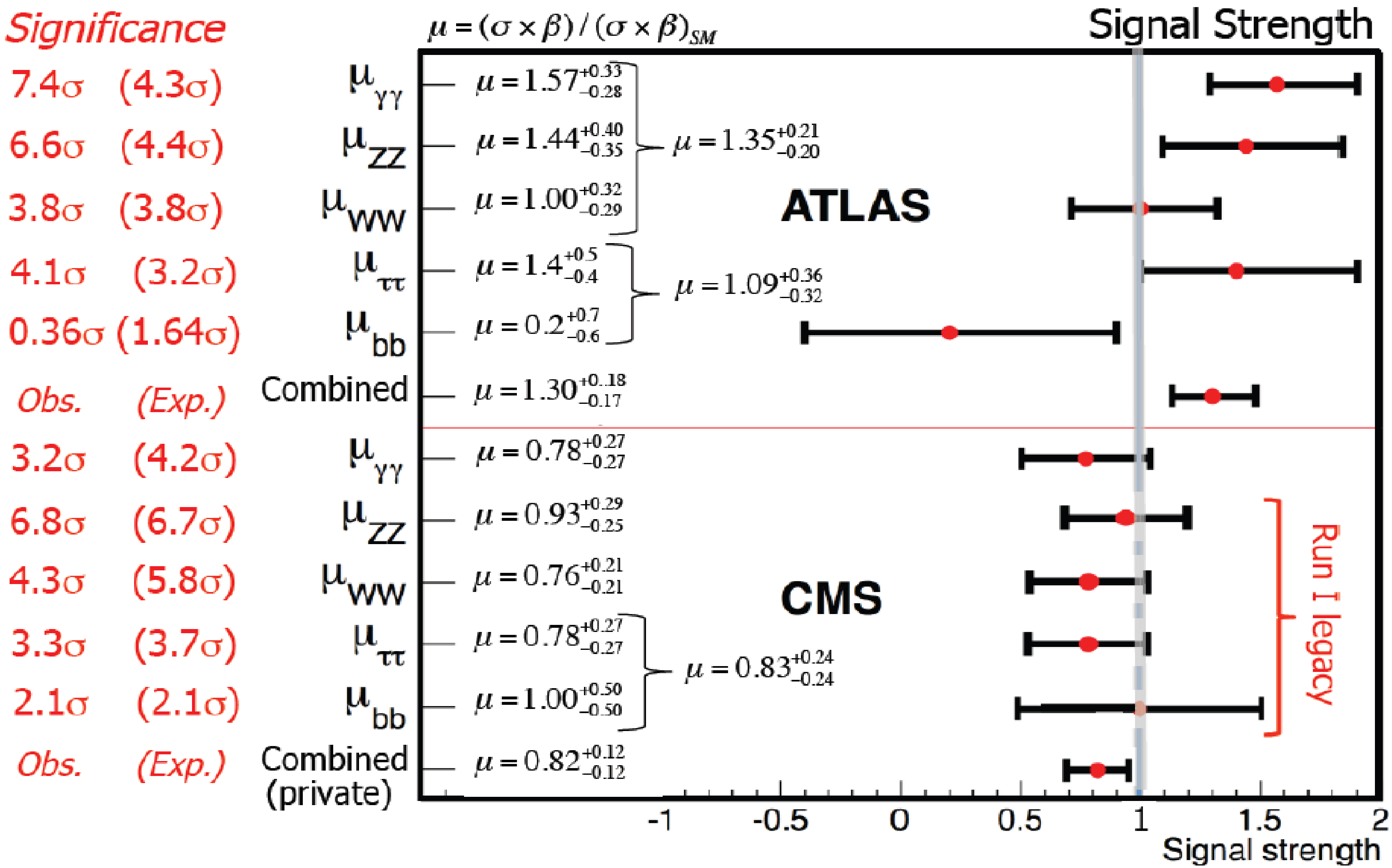

$$n_s^i = \mu^i \times \sum_p (\sigma^p \times Br^i)_{SM} \times A_p^i \times \varepsilon_p^i \times Lumi$$

$$p \in (ggF, VBF, VH, ttH) \quad i \in (\gamma\gamma, ZZ, WW, bb, \tau\tau)$$

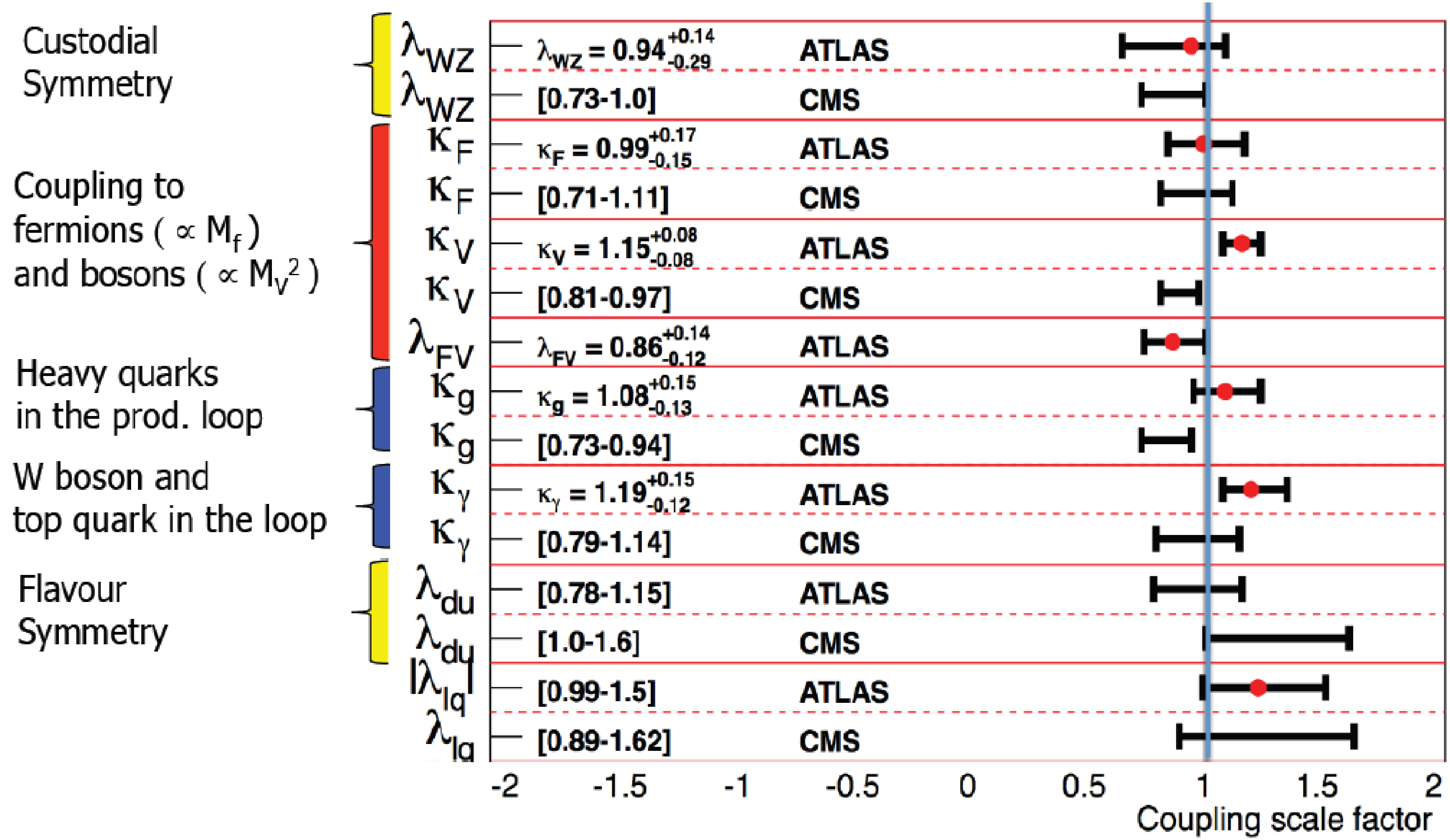
$\mu^{ZZ}$(@125.5 GeV) = 1.44 $^{+0.40}_{-0.35}$ 6.6σ (4.4 exp) ATLAS

$\mu^{ZZ}$(@125.6 GeV) = 0.93 $^{+0.26+0.13}_{-0.23-0.09}$ 6.8σ (6.7 exp) CMS

# Higgs boson decay channels

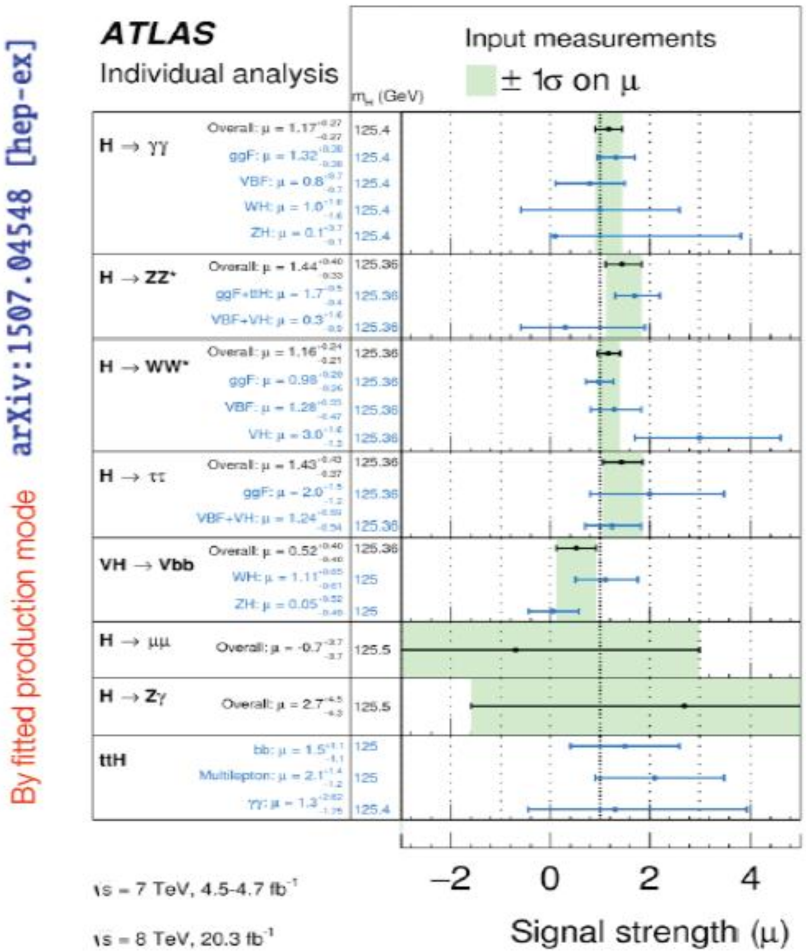


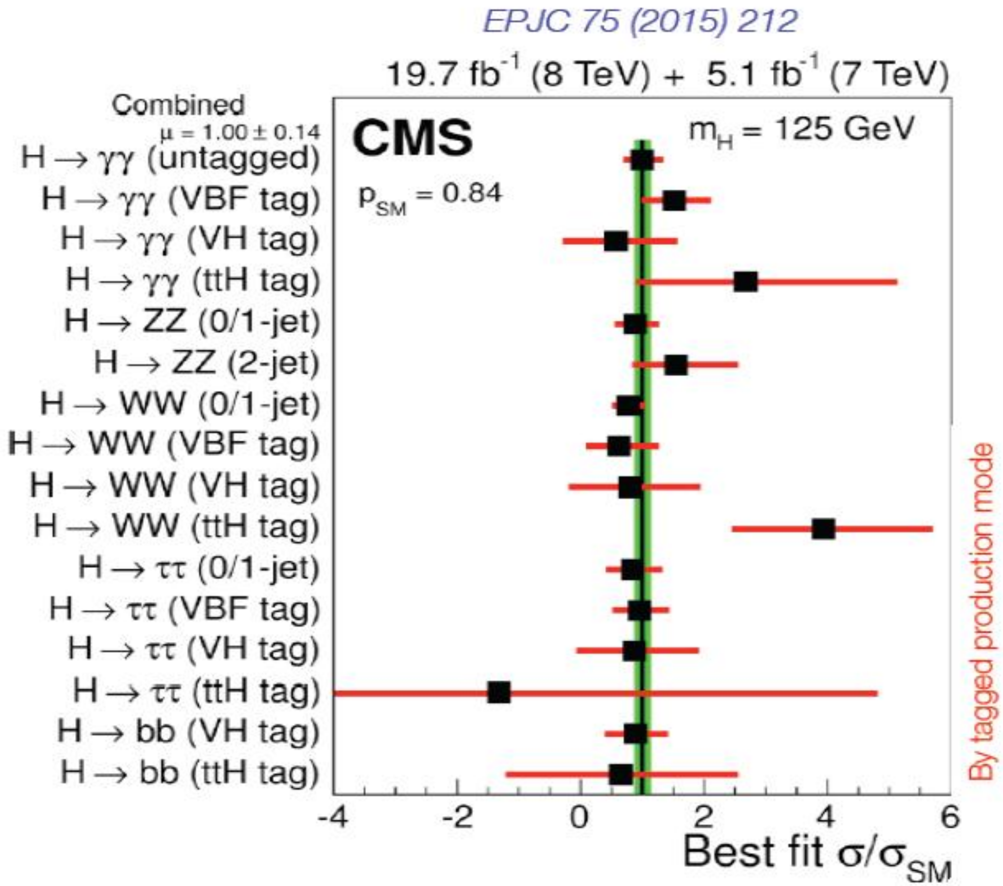
# Overall comparison of all couplings results



# Combination of two experiments

## (ATLAS-CONF-2015-044, CMS-PAS-HIG-15-002)



# The global signal strength

- Assuming SM ratios of production cross-sections and decay rates

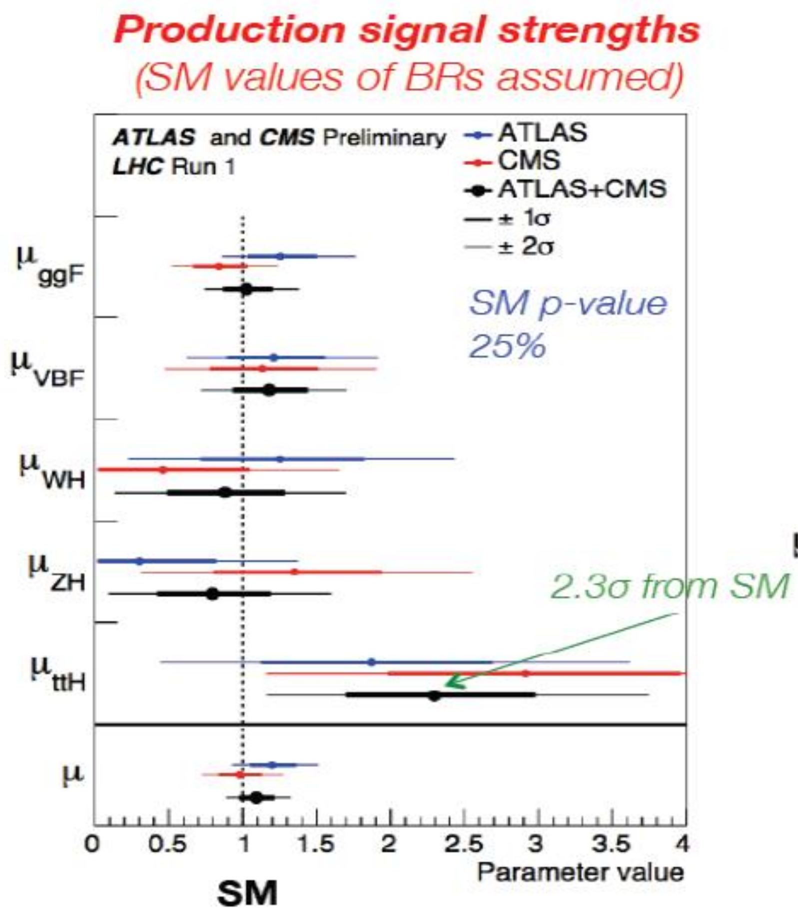
$$\mu = 1.09^{+0.11}_{-0.10}$$

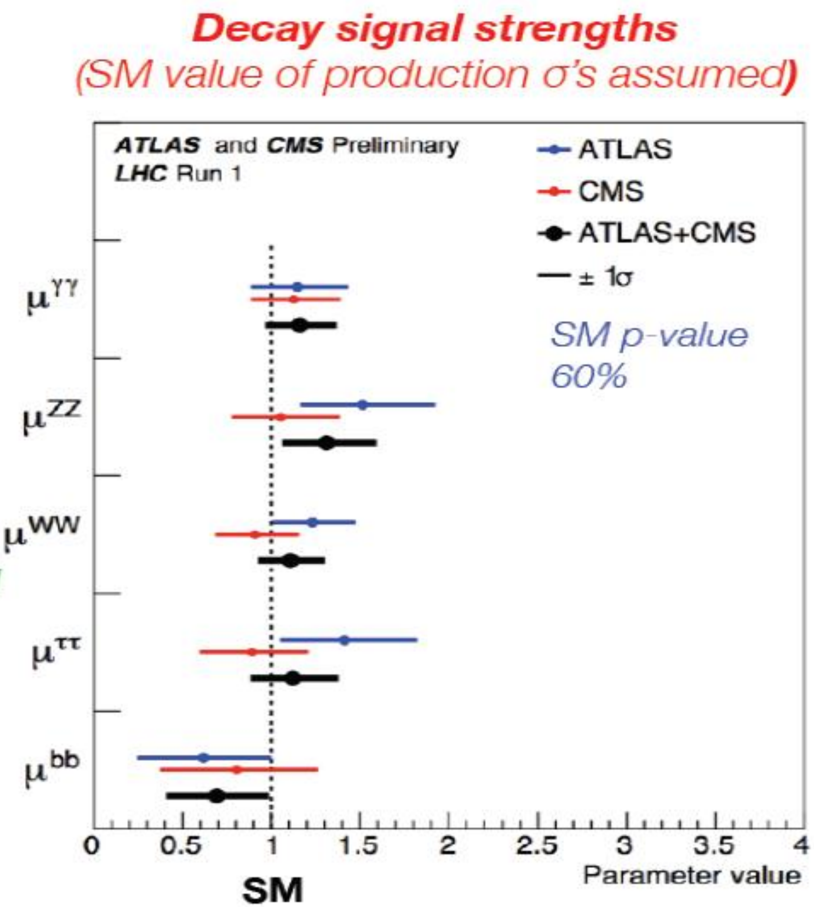
*Most precise result at the expense of the largest assumptions*

$$= 1.09^{+0.07}_{-0.07}\,(\text{stat})\;^{+0.04}_{-0.04}\,(\text{expt})\;^{+0.03}_{-0.03}\,(\text{thbgd})^{+0.07}_{-0.06}\,(\text{thsig})$$

*Stat and Th.Sig of comparable size*
*(Th.Sig dominated by ggF cross-section uncertainty)*

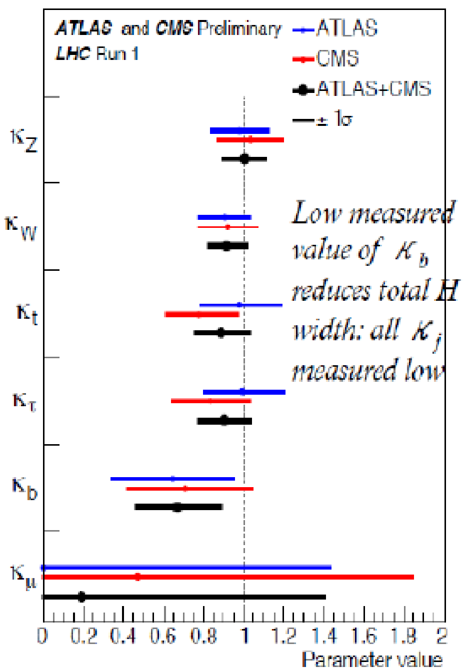
# Signal strength by production and decay mode

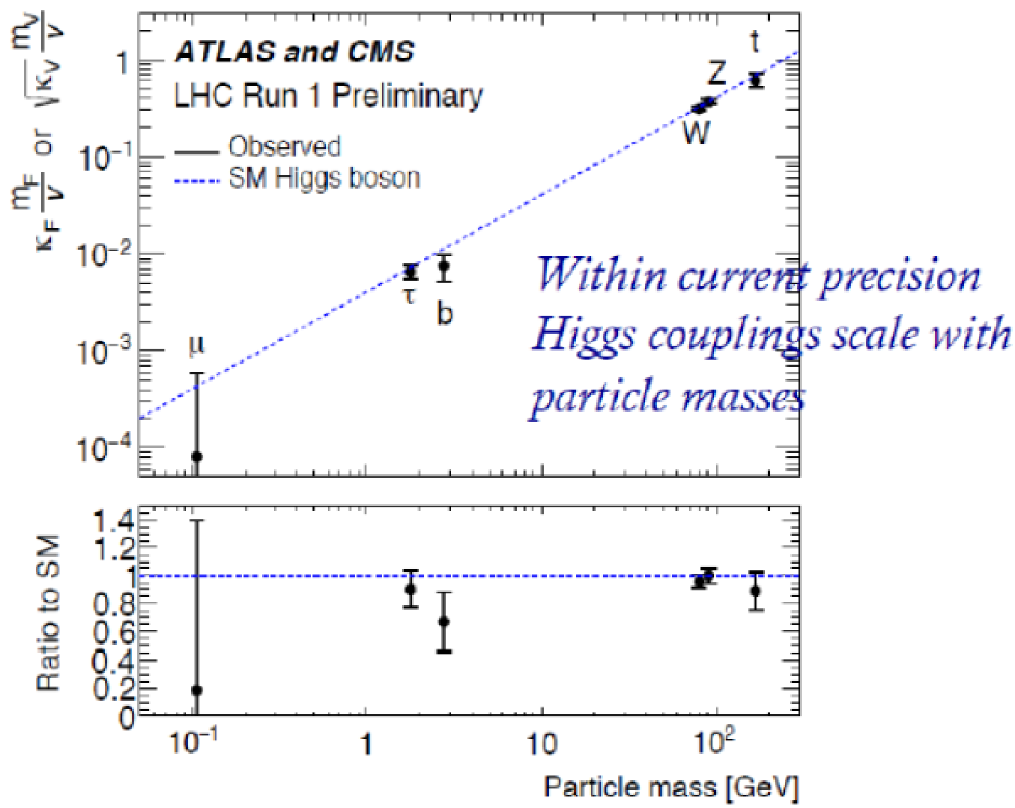


# Constrains on three-level Higgs couplings

- Assume only SM physics in loops, no invisible or unseen BSM Higgs decays
- Fit for scaling parameters for Higgs couplings to W, Z, b, t, τ, μ



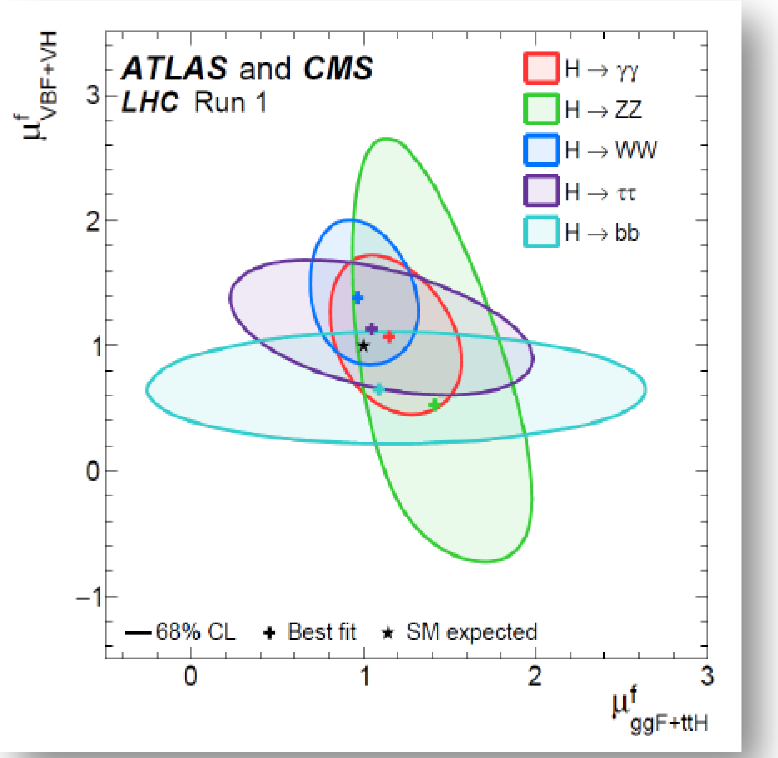
# Concluding Higgs couplings measurements

ATLAS and CMS Higgs boson coupling results have been combined, **sensitivity on signal strength improved by almost $\sqrt{2}$**

- **Higgs to $\tau\tau$ and VBF production established at more than $5\sigma$ level**
- The most precise results on Higgs production and decay and constraints on its couplings have been obtained at O(10%) precision.
- Different parametrisations have been studied, all consistent with the SM predictions within uncertainties
- **SM p-value of all combined fits in range of 10%-88%**

# What did we know from Run I

- **Discovery of a new neutral scalar boson, first in diboson, then in di-fermion decays**
- **Observations:**
  - **H→γγ, H →ZZ →4l**
  - **H →WW →2l2ν**
  - **H →ττ**
  - **gg-fusion and VBF production**
  - **Evidence for VH and ttH processes**




- **Individual and combined ATLAS and CMS measurements include**
  - **Mass and width**
  - **Production rate (@10% accuracy)**
  - **Decays**
  - **Spin, parity** $J^{PC} = 0^{++}$

- **Initial compatibility with the Standard Model Higgs**

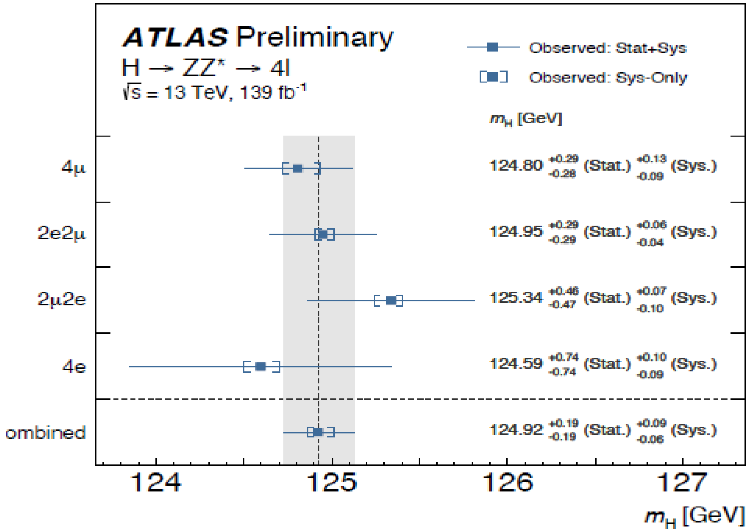
JHEP08 (2016) 045 | PRL114 (2015)191803 | EPJC75(2015) 212 | PLB726 (2013) 120

# Lepton-Photon 2021 (January 2022)

## Higgs mass:

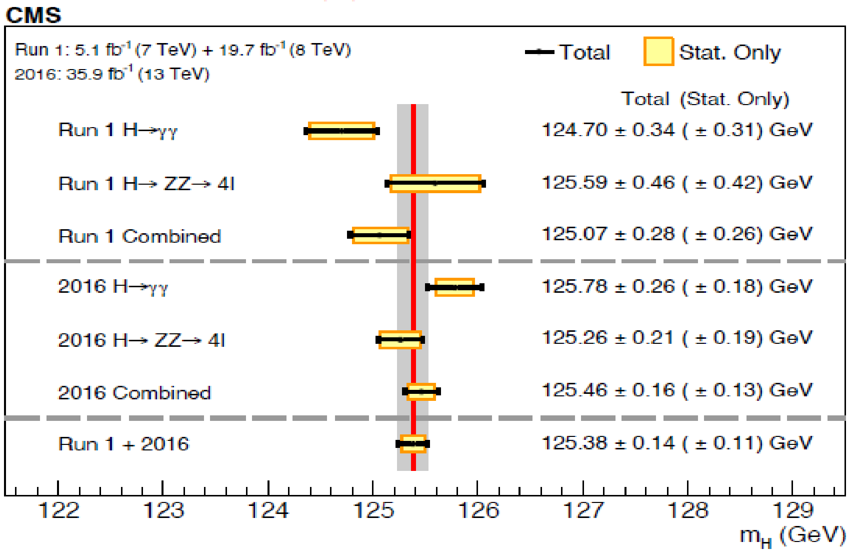
- Measurement done in H→4ℓ and H→γγ only
- precision dominated by statistics and experimental systematics

$H \to ZZ^* \to 4\ell$




$m_H = 124.92 \pm 0.19\ (\text{stat})\ {}^{+0.09}_{-0.06}\ (\text{syst})\ \text{GeV}$

$H \to \gamma\gamma, ZZ^* \to 4\ell$

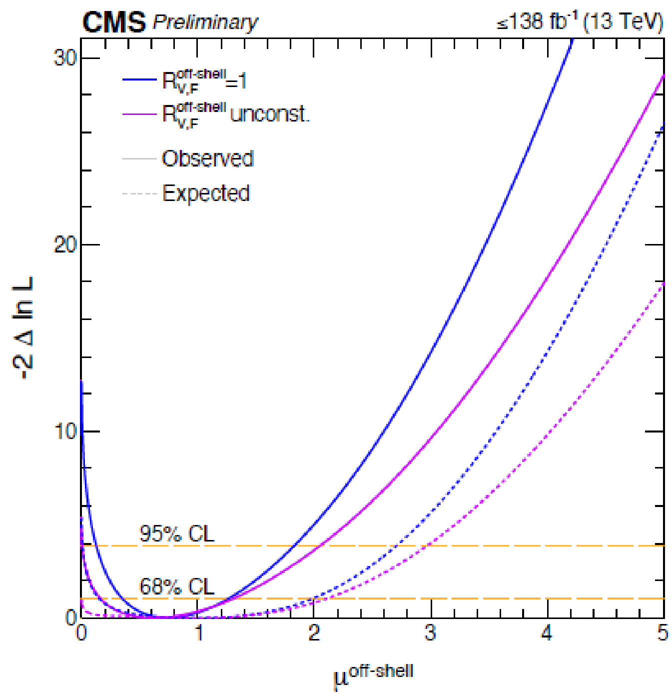



$m_H = 125.38 \pm 0.14\ (\pm 0.11)\ \text{GeV}$

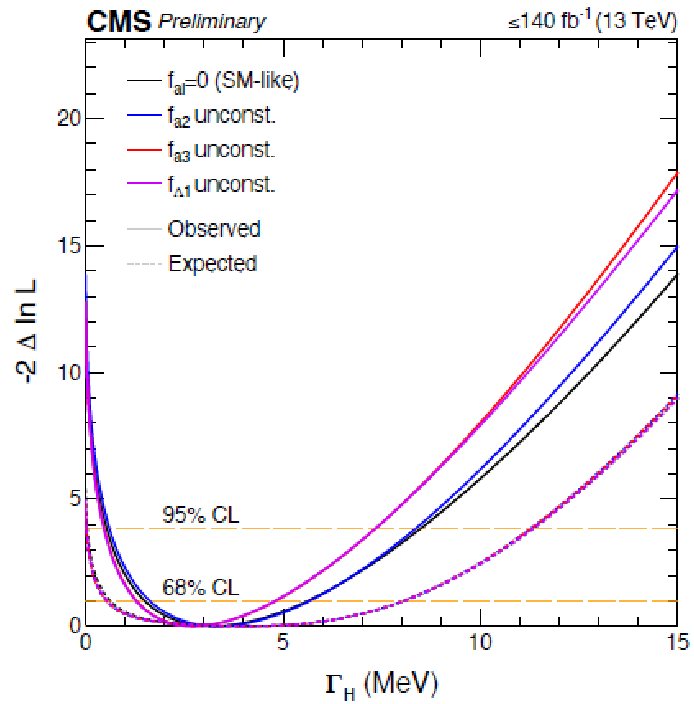
**precision on $m_H$: 140 MeV ≈ 0.1%**

# Lepton-Photon 2021 (January 2022)

- Combination of $H \to 4\ell$, $H \to 2\ell 2\nu$ analysis of full Run2 data CMS-PAS-HIG-21-013
  - $H \to 4\ell$ analysis on full Run2, using on-shell + off-shell events
  - $H \to 2\ell 2\nu$ analysis on full Run2, with $\ell = e, \mu$ final states and categorized in jet multiplicity




**first evidence** for off-shell Higgs production at **3.6σ**



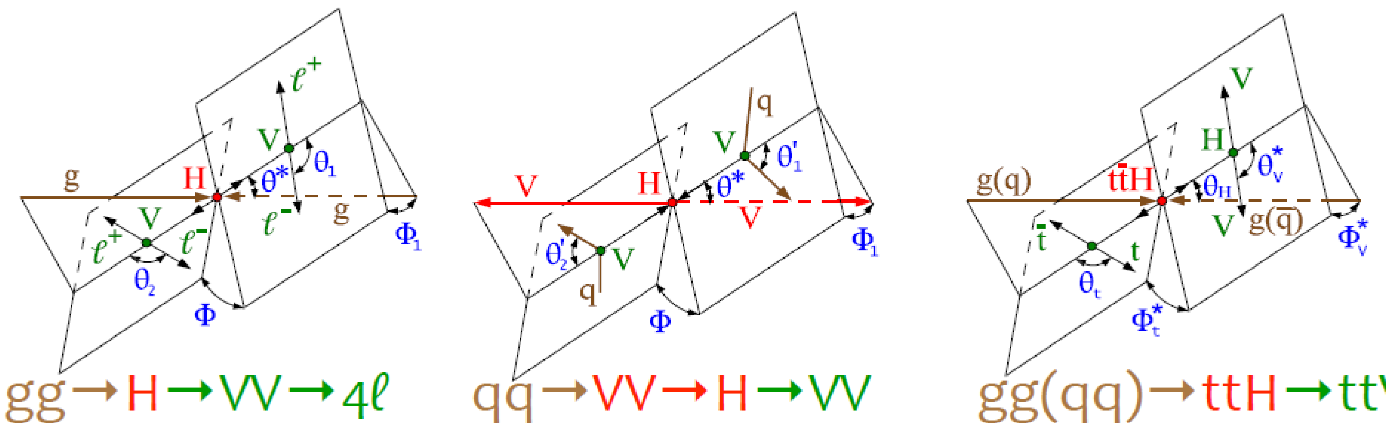

$\Gamma_H = 3.2\,^{+2.4}_{-1.7}$ MeV

$\sigma(\Gamma_H) \sim 50\,\%$ : most precise measurement up to now

# Higgs CP and anomalous couplings:

- After Run1 excluded spin-1 and spin-2 hypotheses, analyses with full Run2 investigate CP structure in a vast program of measurements
- HVV couplings tested with $H \rightarrow 4\ell$ using production and decay
  - production categories: untagged, boosted, VBF 1/2 jets, VH H hadronic/ leptonic

Phys. Rev D 104 (2021) 052004




$$A(HV_1V_2) = \frac{1}{v}\left[a_1^{VV} + \frac{\kappa_1^{VV} q_{V1}^2 + \kappa_2^{VV} q_{V2}^2}{(\Lambda_1^{VV})^2} + \frac{\kappa_3^{VV}(q_{V1}+q_{V2})^2}{(\Lambda_Q^{VV})^2}\right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + \frac{1}{v} a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + \frac{1}{v} a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu},$$

$a_1$: SM

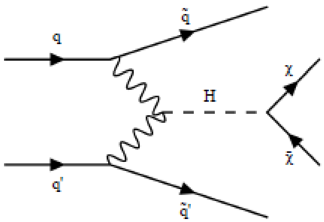
$a_2$: CP even anomalous coupling

$a_3$: CP odd anomalous coupling

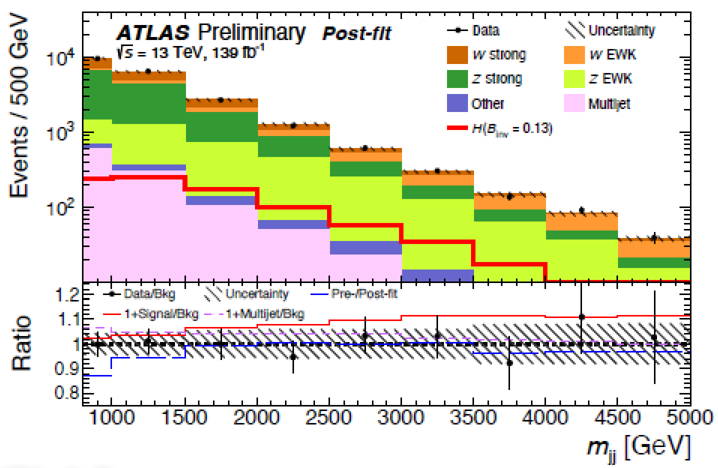
# Lepton-Photon 2021 (January 2022)

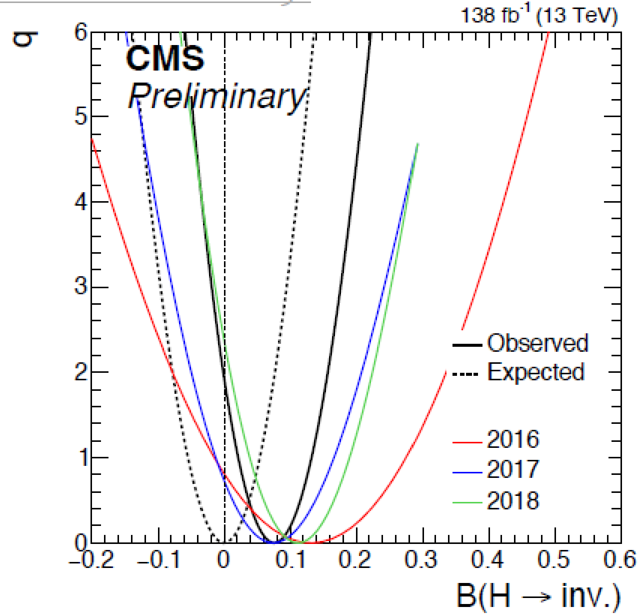
## VBF Higgs, H->invisible:

- Part of Higgs width could be due to decays to not detectable particles: searches can be interpreted within Dark Matter models
- CMS: Search of 2 forward jets with high $M_{jj}$ and high $|\Delta\eta_{jj}|$ + MET
  - Dominant backgrounds: $W \to \ell\nu$ and $Z \to \nu\nu$ +jets
  - systematically dominated by V+jets modelling
- ATLAS: VBF combined to VH production
  - $V = Z \to \ell\ell;\ V = (W, Z) \to \text{had}$



ATLAS-CONF-2020-008
HIGG-2018-26
CMS-PAS-HIG-20-003
ATLAS-CONF-2020-052



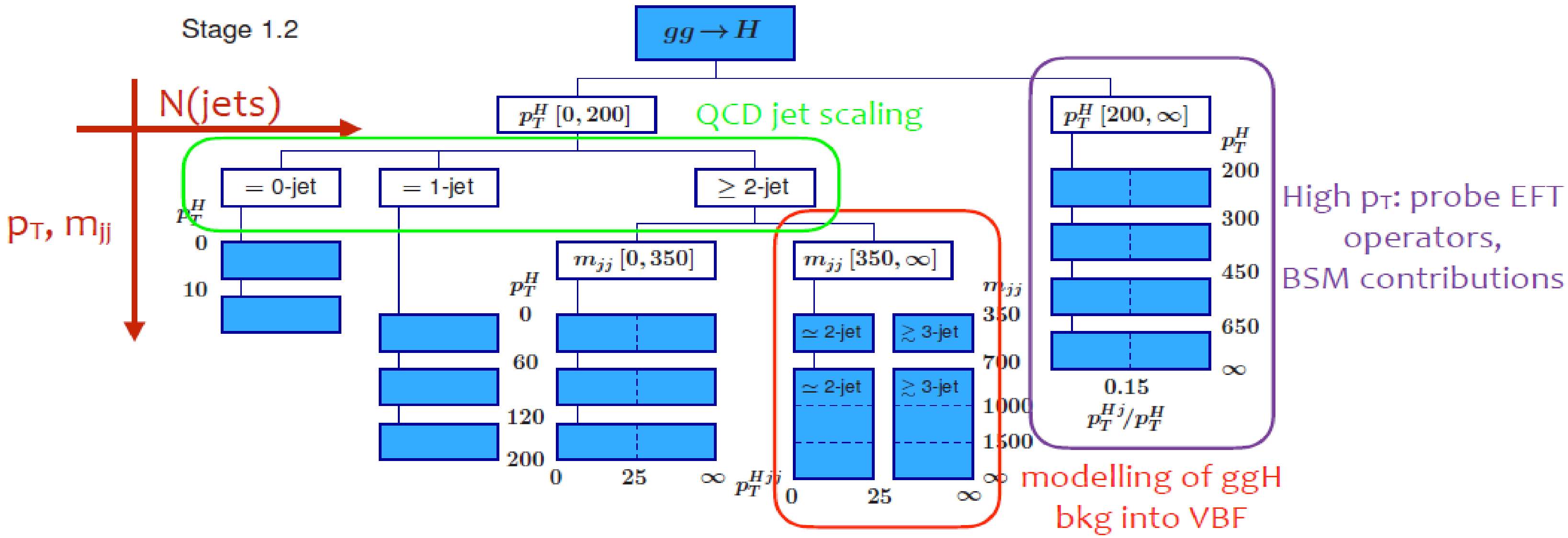

ATLAS: BR($H \to$ inv) < 0.11 (exp 0.11)

CMS: BR($H \to$ inv) < 0.17 (exp 0.11)

# Lepton-Photon 2021 (January 2022)

## STSX cross-section measurement:

- Approach devoted to minimize simultaneously experimental and theoretical uncertainties on Higgs cross section measurements
- Split Higgs production modes in gen-level bins in $p_T$, N(jets), $m_{jj}$
  - Assume within each bin acceptance is only weakly depending on SM kinematics, used in STXS measurements as proxy for true properties
  - Allow re-interpretation of results in different models
  - Look for BSM in extreme bins of the phase space



# Lepton-Photon 2021 (January 2022)

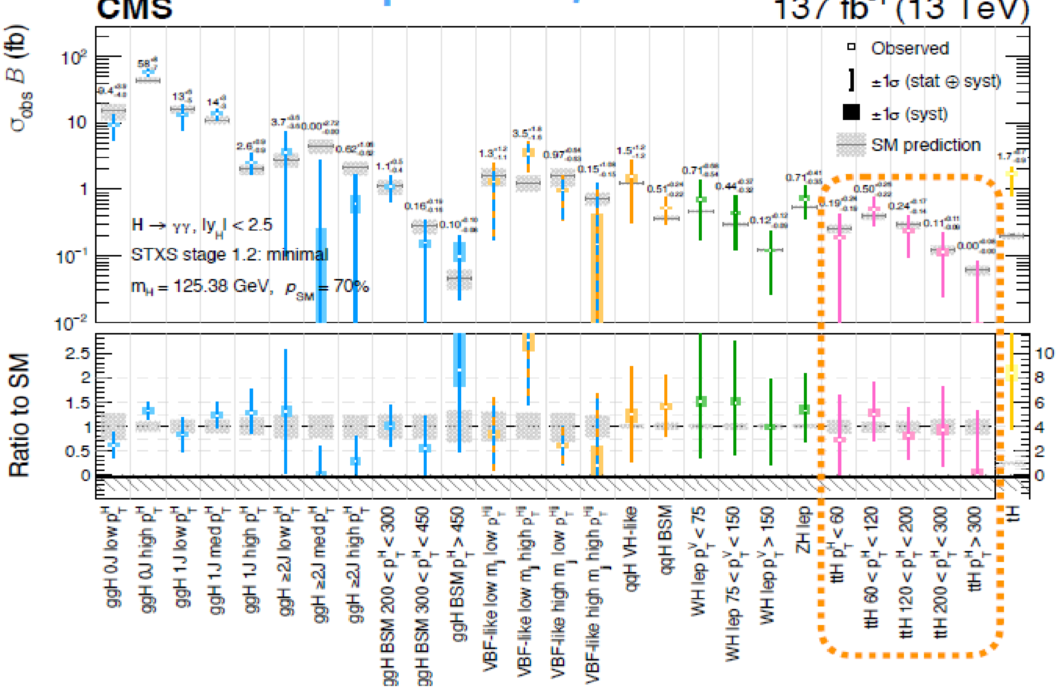
## STSX cross-section measurement:

- $H \rightarrow \gamma\gamma$ channel well suited for STXS measurement:
  - high yields, efficiency and S/B across whole phase space
  - robust background estimation from m(γγ)
  - **reaching first ttH differential measurements**

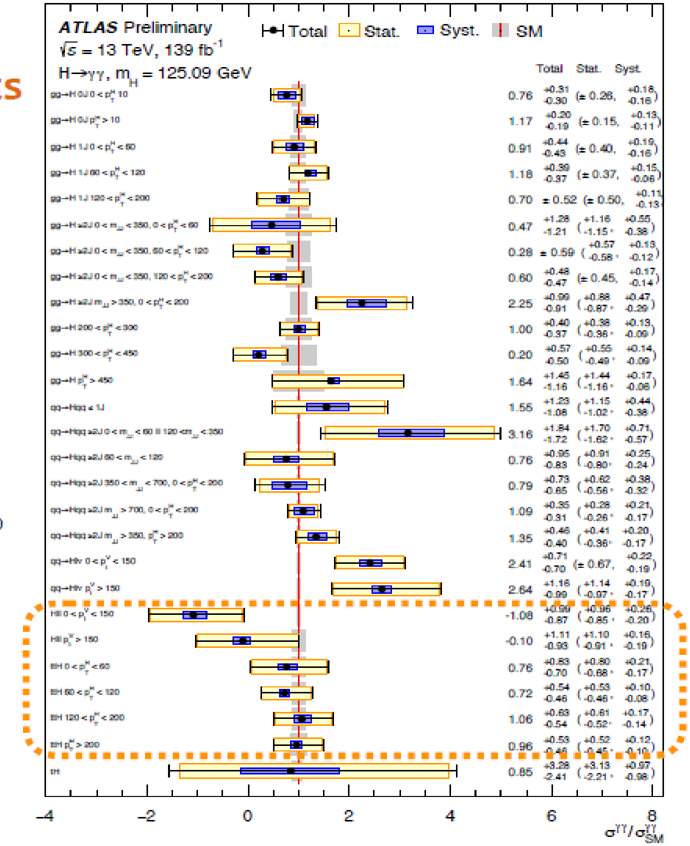
JHEP 07 (2021) 027

ATLAS-CONF-2020-026

CMS p-value = 70%




ATLAS p-value = 60%

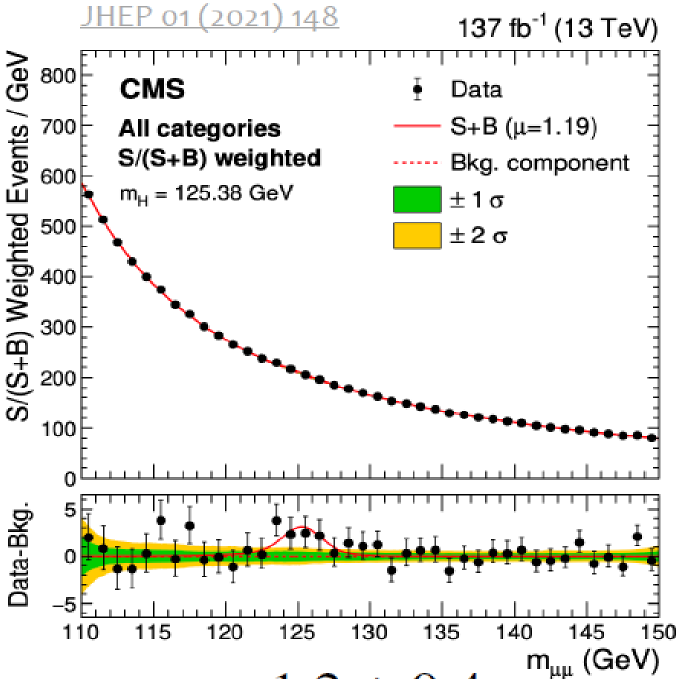


# Lepton-Photon 2021 (January 2022)

## Rare decays:

- Rare decay: $BR(H \to \mu\mu) \approx 2 \times 10^{-4}$, with large non-resonant background from $DY \to \mu\mu$
  - all production modes used: ggF, VBF, VH, ttH, categorized to improve sensitivity

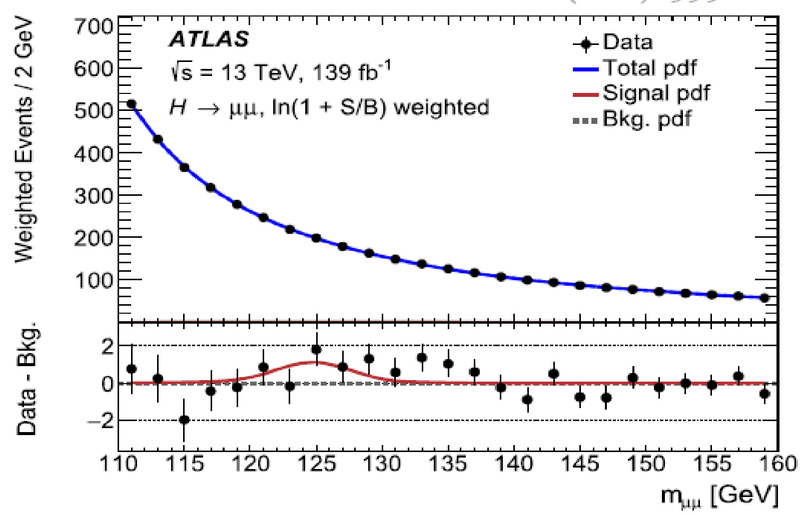
JHEP 01 (2021) 148




$\mu = 1.2 \pm 0.4$

significance: $3.0\sigma$ ($2.5\sigma$ exp.)

PLB 812(2021) 135980




$\mu = 1.2 \pm 0.6$

significance: $2.0\sigma$ ($1.7\sigma$ exp.)

# Lepton-Photon 2021 (January 2022)

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- Rare decay: $BR(H \to \mu\mu) \approx 2 \times 10^{-4}$, with large non-resonant background from $DY \to \mu\mu$
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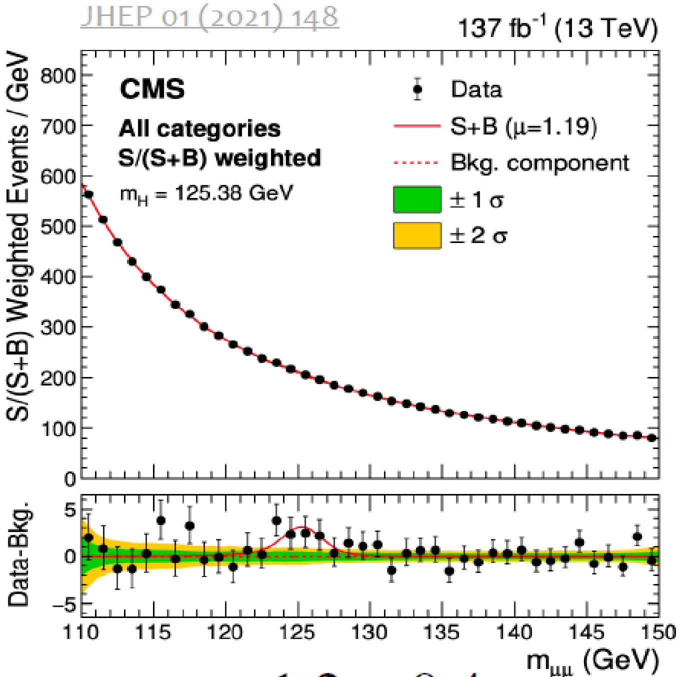
JHEP 01 (2021) 148

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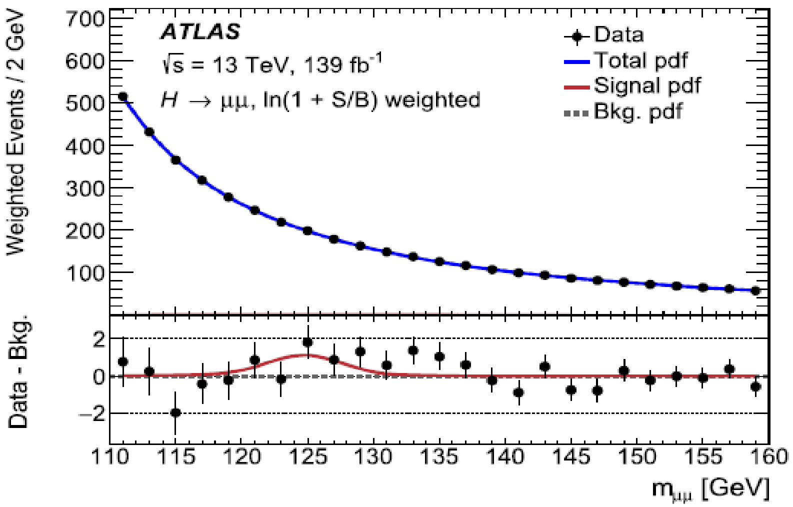
PLB 812(2021) 135980




$\mu = 1.2 \pm 0.6$

significance: $2.0\sigma$ ($1.7\sigma$ exp.)

# Lepton-Photon 2021 (January 2022)

## H-> μμ challenges:

- S/B ~ 0.1% for inclusive events at 125 GeV
- Strategies to increase sensitivity:
  - improve $\sigma(m_{\mu\mu})$ with FSR recovery, constrain tracks to beam line
  - use dedicated DNN/BDT in each category
  - very accurate DY bkg modelling

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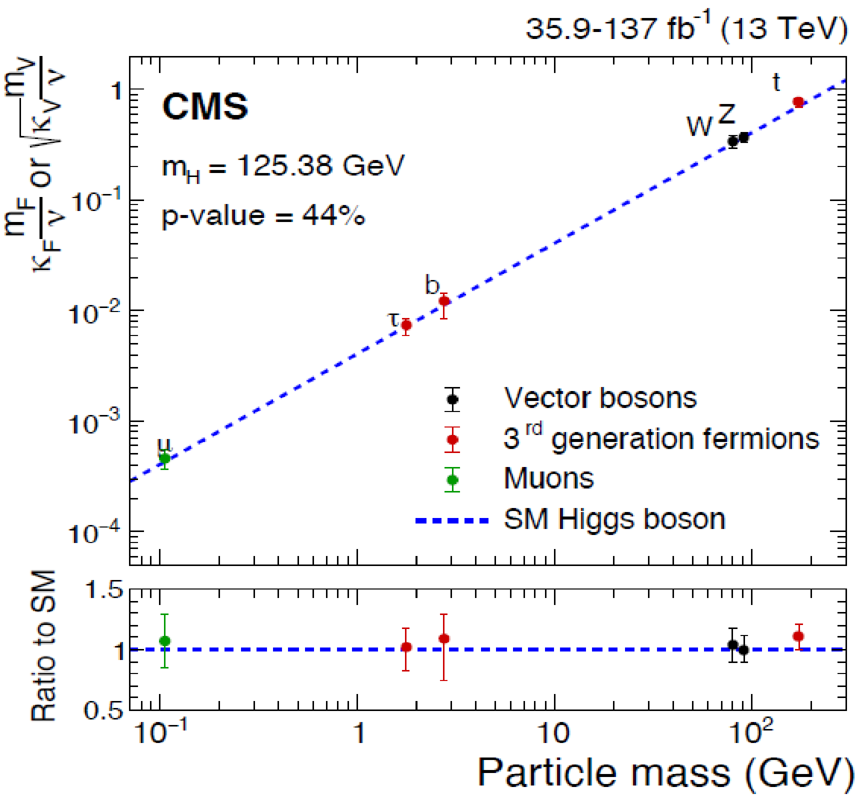
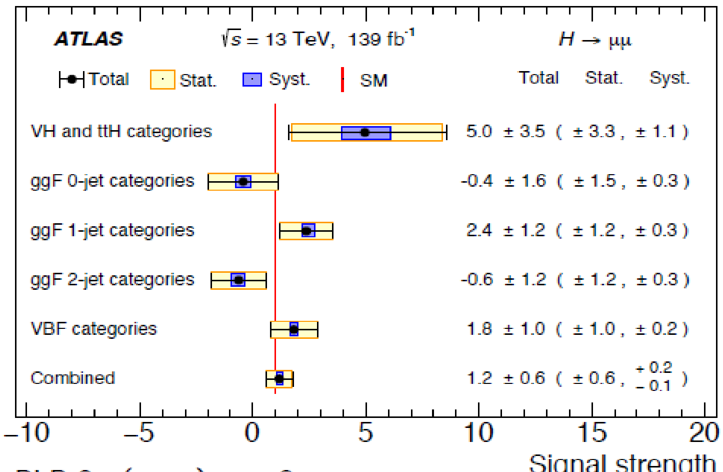



PLB 812(2021) 135980

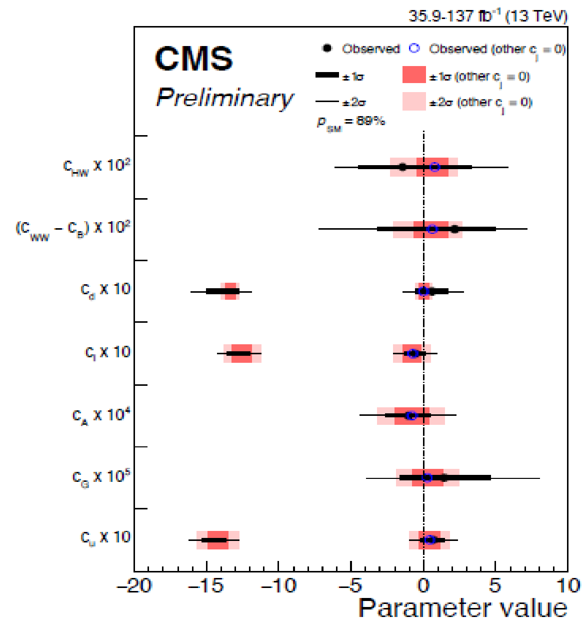
# Lepton-Photon 2021 (January 2022)

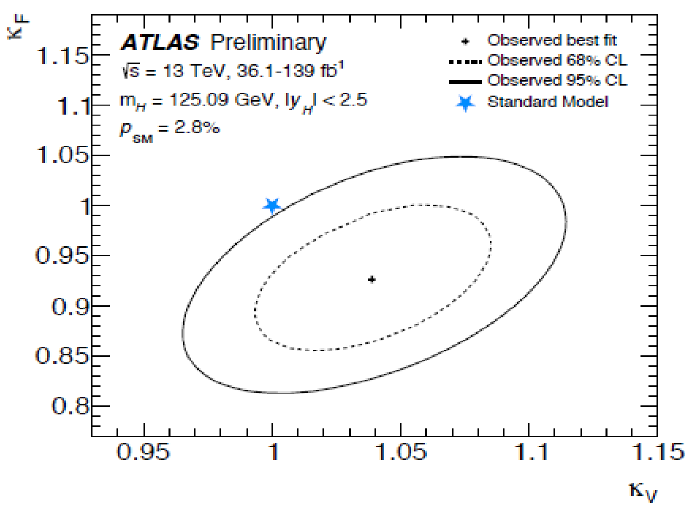
## Run II combination κ and EFT:

- Combination also for in the $\kappa$-**framework** for the coupling modifiers
  - assuming decays to SM-only particles

$$\kappa_j^2 = \Gamma_j / \Gamma_J^{SM}$$

  - e.g. universal vector-boson couplings $\kappa_V = \kappa_W = \kappa_Z$ and universal fermion couplings $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_\mu$




- **Or EFT for BSM at a scale $\Lambda \gg \mathrm{VEV^H}$:** constraints of Wilson coefficients of the higher-order operators derived from STXS signal strengths $\mu_i$ in each bin-$i$:

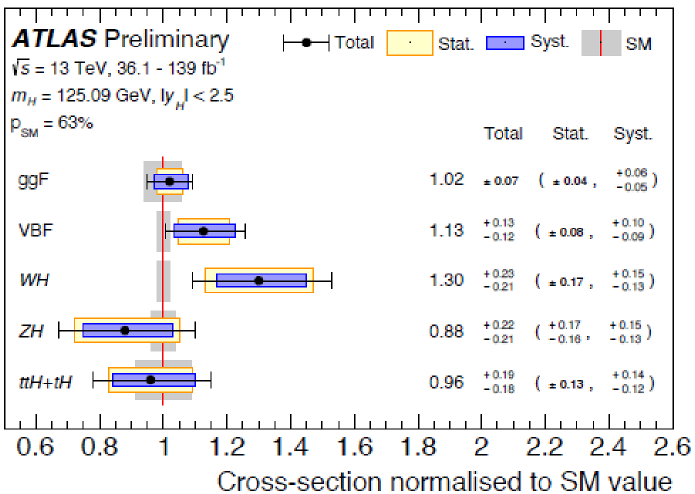
$$\mu_i(c_j) = \frac{\sigma_i^{\mathrm{EFT}}}{\sigma_i^{\mathrm{SM}}}$$

ATLAS-CONF-2021-05
CMS-PAS-HIG-19-005

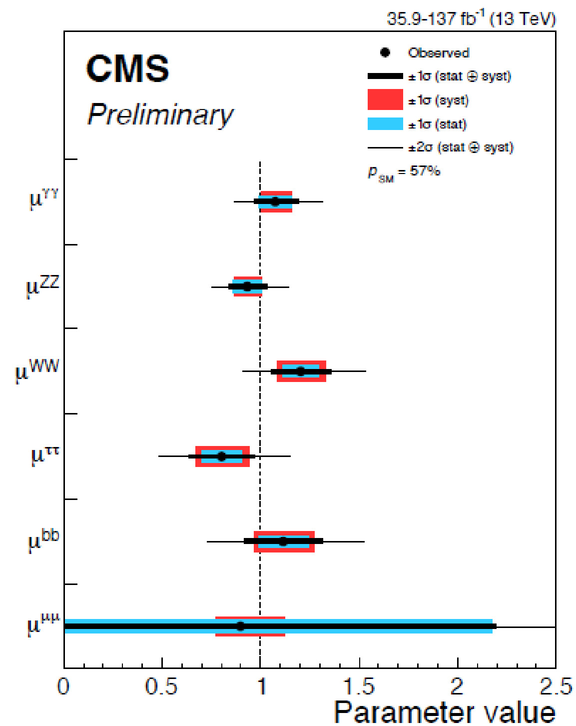
# Run II combination $\mu$:

- Higgs physics in the **era of precision (6% on $\mu$)**:
  - **ATLAS**: $\mu = 1.06 \pm 0.06 = 1.06 \pm 0.03(\mathrm{stat.}) \pm 0.03(\mathrm{exp.}) \pm 0.04(\mathrm{sig.th.}) \pm 0.02(\mathrm{bkg.th.})$
  - **CMS**: $\mu = 1.02^{+0.07}_{-0.06} = 1.02 \pm 0.04(\mathrm{stat.}) \pm 0.04(\mathrm{exp.}) \pm (\mathrm{th.})$

ATLAS-CONF-2021-053
CMS-PAS-HIG-19-005




$\sigma^H/\sigma^H_{SM}$ **in production**




$\sigma^H/\sigma^H_{SM}$ **in decay**

# Lepton-Photon 2021 (January 2022)

## Conclusions:

- The LHC Run2 provided data for a lot of results from ATLAS and CMS characterizing the Higgs boson
  - mass measured with 0.1% precision, and width measured for the first time with 50% precision
  - the production cross section are now measured differentially in many STXS bins, in several production modes
  - fiducial cross sections and coupling modifiers measured at 10% level, allowing interesting EFT interpretations
  - couplings to 2nd generation established with $H \to \mu^+\mu^-$, next challenge is $H \to c\bar{c}$
  - CP violation studied in many channels, including rare ttH
  - searches for HH production for H self-couplings impressive
- **The LHC is going to have new collisions in Spring 2022** with $\sqrt{s}$=13.6 TeV and **500 $fb^{-1}$ is expected per experiment in Run3**
  - a unique opportunity to continue characterizing the Higgs potential: entering the precision era for the Higgs field