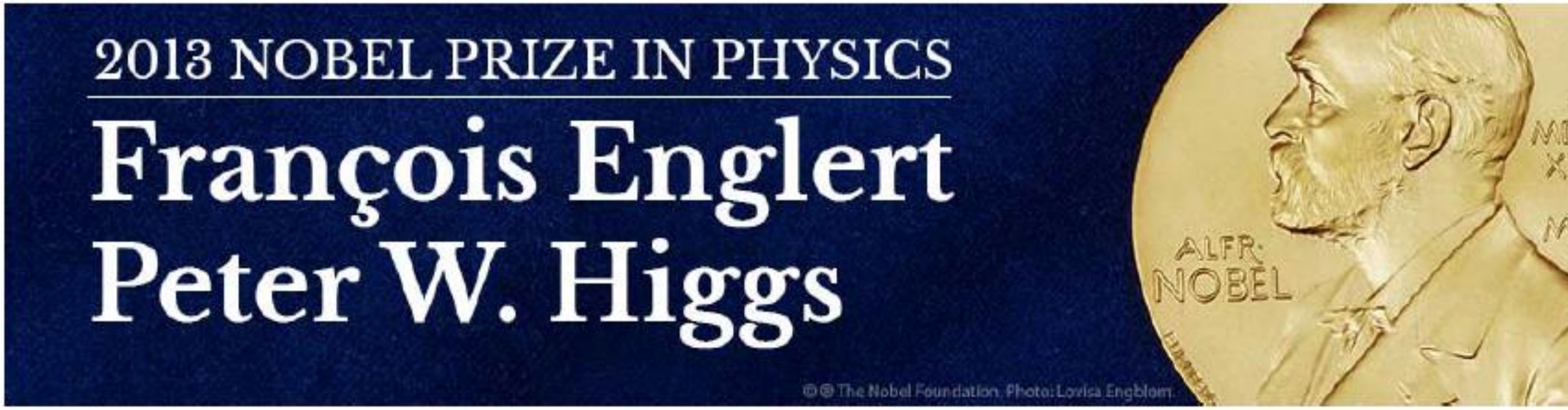
Elementary Particle Physics: theory and experiments

The Spontaneous Symmetry Breaking mechanism
The Higgs boson hunting at LEP and Tevatron
Discovery of the Higgs boson at LHC
Measurements: mass, spin, couplings

Follow the course/slides from M. A. Thomson lectures at Cambridge University and lectures by M. Kado and M. Martinez at HASCO schools.

Prof. dr hab. Elżbieta Richter-Wąs



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"

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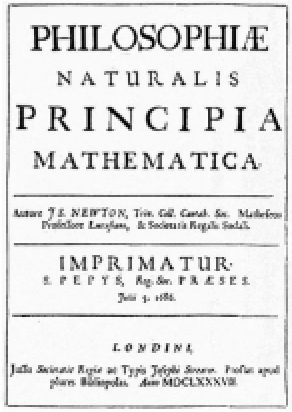

PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA

IMPRIMATUR

LONDINI,

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

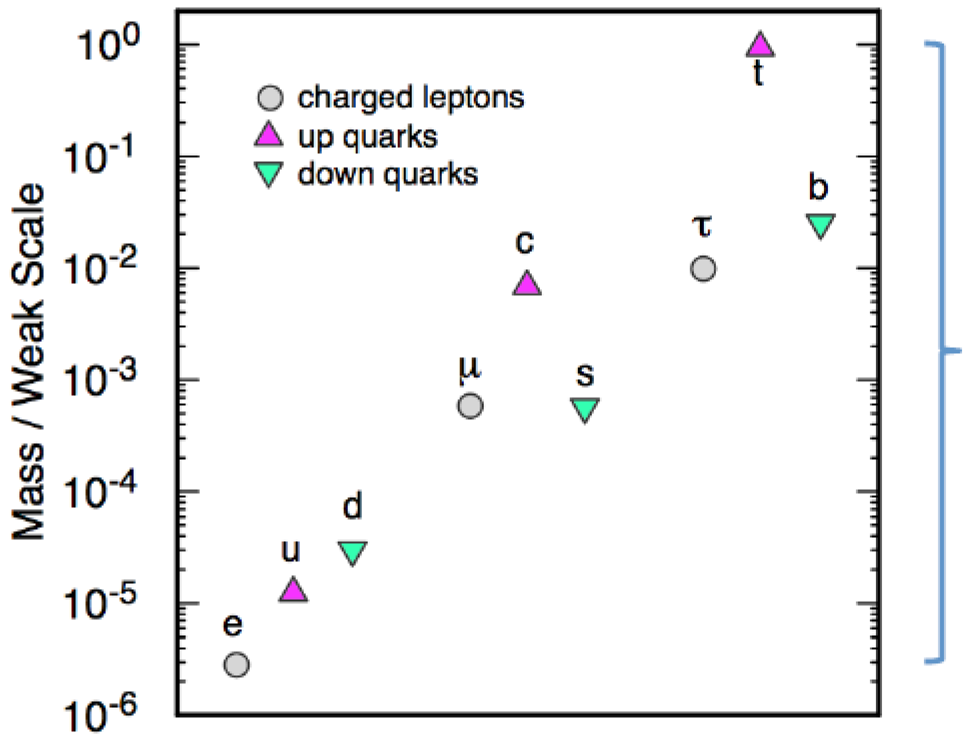
Most of the (luminous) mass in the universe comes from QCD confinement energy

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!

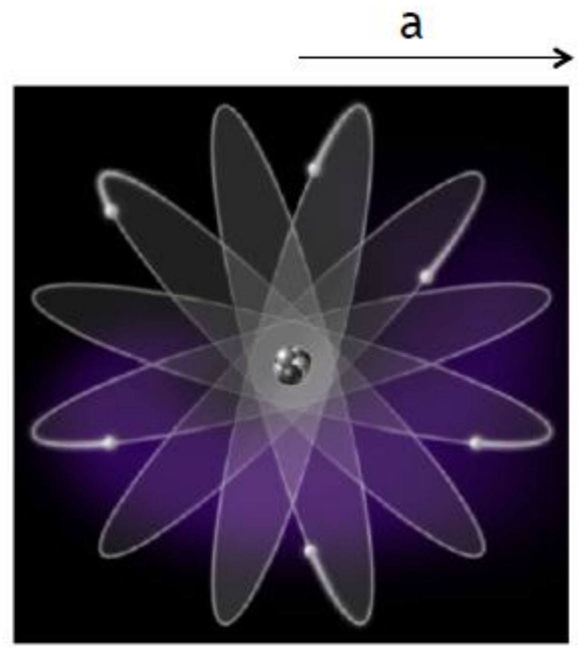
The BEH sector includes most of the free parameters of the Standard Model

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

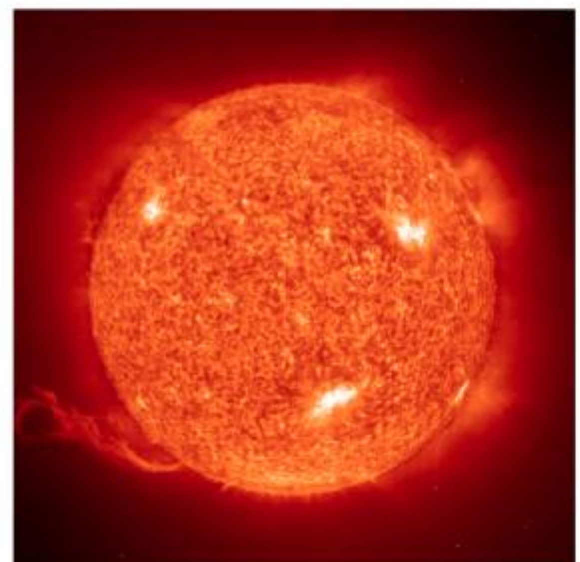


W boson mass (m_W = 81 GeV)

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

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

Everything would be completely different!



Preamble

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 …

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

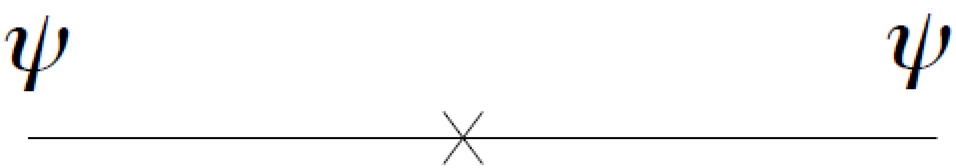
Caution, not unified in the sense of unified forces, only unique framework

… 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)

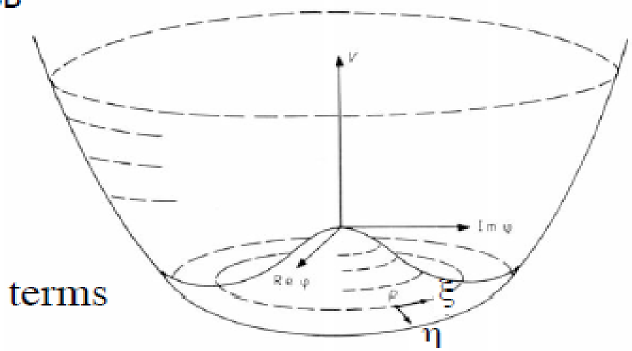
From a simple (complex) scalar theory with a U(1) symmetry

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

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.

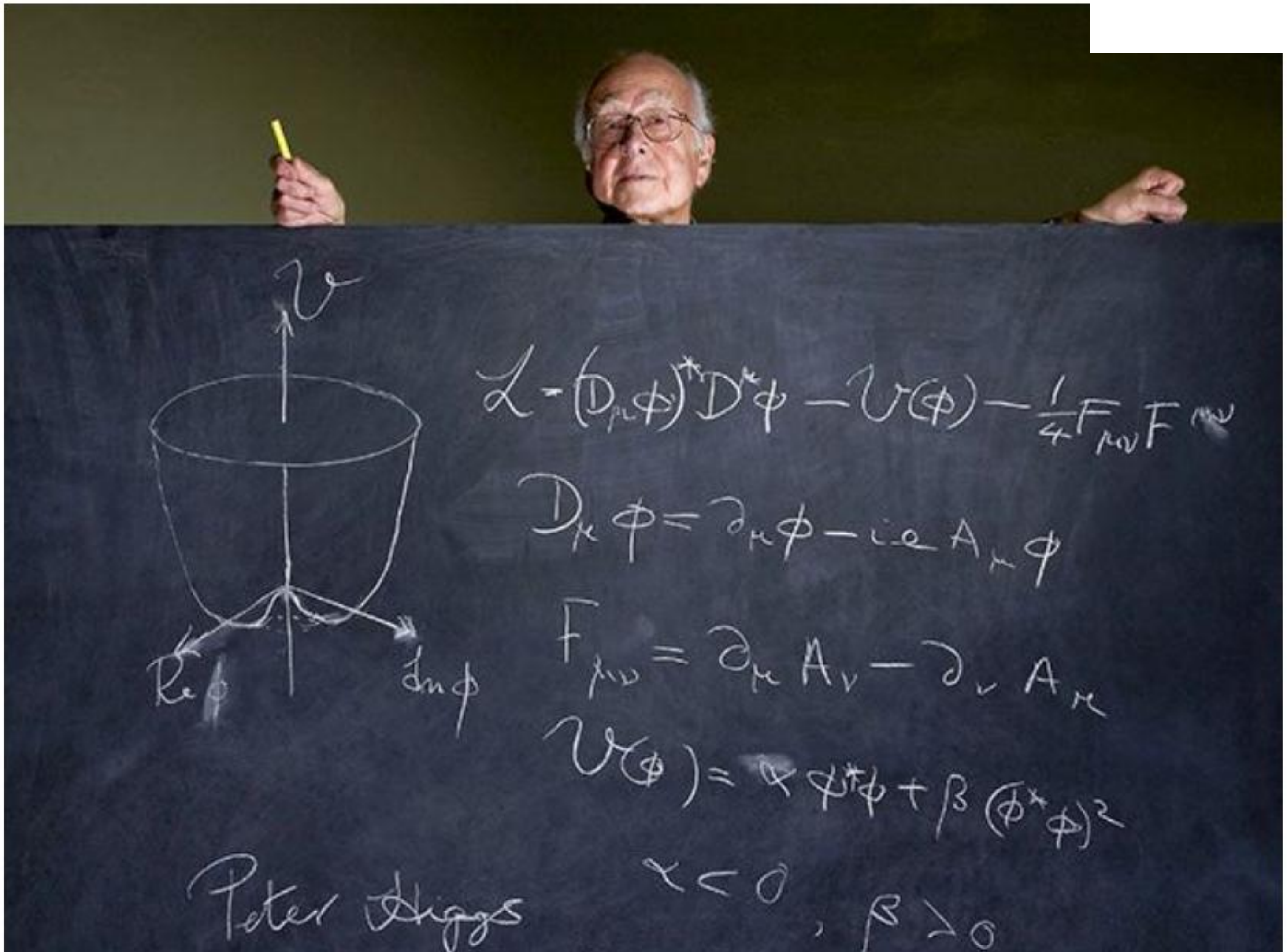
$$L = \frac{1}{2}\underbrace{\partial_\nu \xi \partial^\nu \xi}_{\text{Massless scalar}} + \frac{1}{2}\partial_\nu \eta \partial^\nu \eta + \underbrace{\mu^2 \eta^2}_{\text{Massive scalar}} + \text{interaction terms}$$

Massless scalar

Massive scalar

Nice but what should we do with these massless salars?

1964



V
$\mathcal{L} = (D_\mu\phi)^* D^\mu\phi - V(\phi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$
$D_\mu\phi = \partial_\mu\phi - ieA_\mu\phi$
$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$
$V(\phi) = \alpha\phi^*\phi + \beta(\phi^*\phi)^2$
$\alpha < 0, \beta > 0$
Re ϕ
Im ϕ
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 : $\varphi = \frac{v + \eta + i\xi}{\sqrt{2}}$

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

Mass term for the gauge field! But…

What about the field content?

A massless Goldstone boson ξ, a massive scalar η and a 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 θ

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

$$L = \frac{1}{2}\partial_\nu h \partial^\nu h - \lambda v^2 h^2 - \lambda v h^3 - \frac{1}{4}\lambda h^4$$ 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

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

The lar... matic te... ian cons... on L, pl... right-ha... as we kn... tirely un... and the ... gauge fi... metry w... massles... form ou... spin $\vec{T}$ a... $+\tfrac{1}{2}N_L$.

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

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

> 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_μ and W_μ 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

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

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 : $W_\mu^\pm = \dfrac{W_\mu^1 \mp iW_\mu^2}{\sqrt{2}}$

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

For the mass terms only :

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

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 $SU(2)_L xU(1)_Y$ 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 :

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

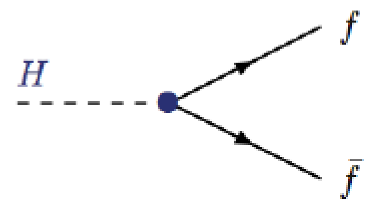
Can be seen as giving mass to down type fermions…

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

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

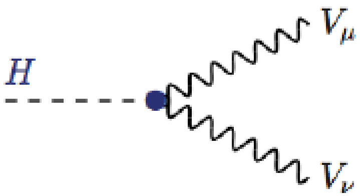
One doublet of complex scalar fields is sufficient to accommodate mass terms for gauge bosons and fermions !

... But not necessarily only one!

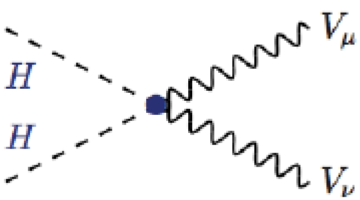


$$g_{Hff} = m_f/v$$

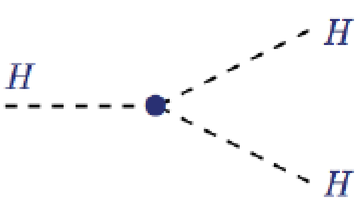
Gauge-Higgs and interactions



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

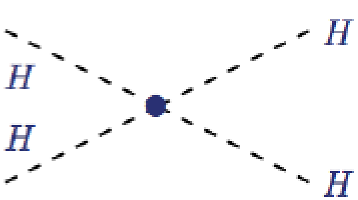


$$g_{HHVV} = 2M_V^2/v^2$$



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

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 λ) **was** an unknown parameter of the theory

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

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 :

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

or

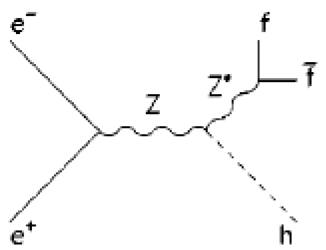
$$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = 1$$

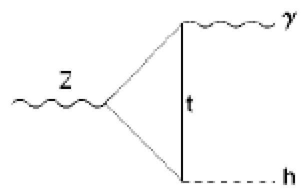
Absolute Lower Limit on the Higgs Mass at LEP

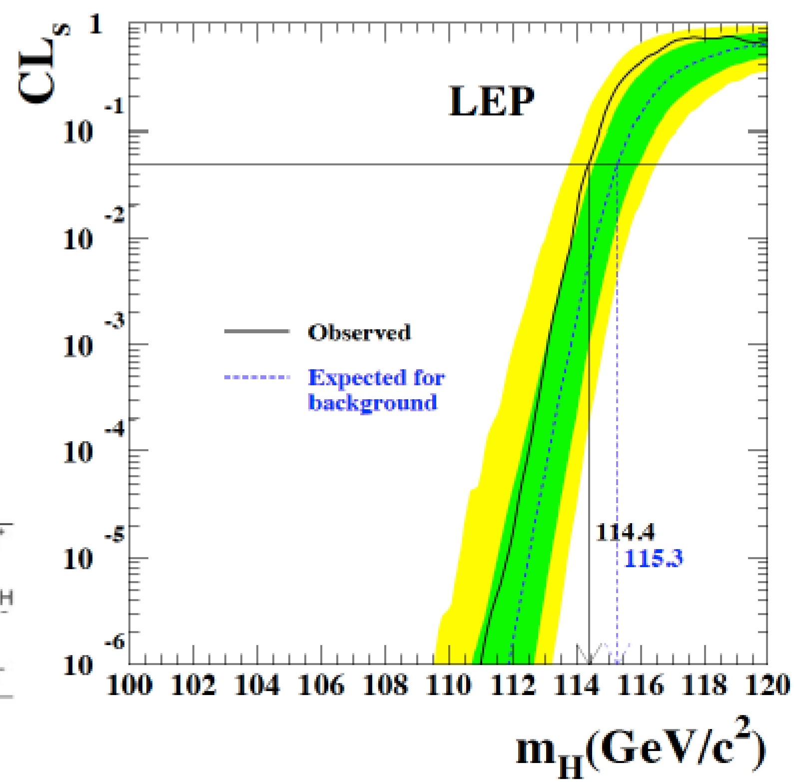
LEP1 e^+e^- at COM ~m_Z

Various decays and topologies

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

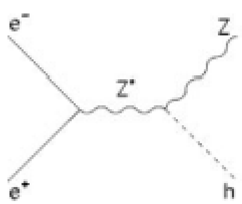


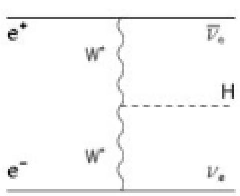


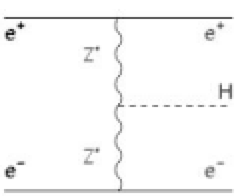


LEP2 e^+e^- up to 209 GeV

(mostly bb and ττ decays)







Excludes SM Higgs with mass below 114 GeV

Electroweak Precision Data and the Higgs Mass

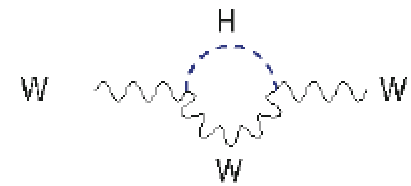
The famous blue band plot!

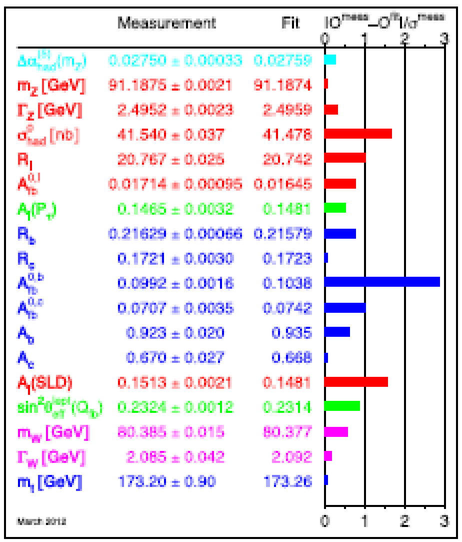
Fermi Constant $G_F = 1.166367(5) \times 10^{-5}\ \mathrm{GeV}^{-2}$ (muon lifetime)

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

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

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



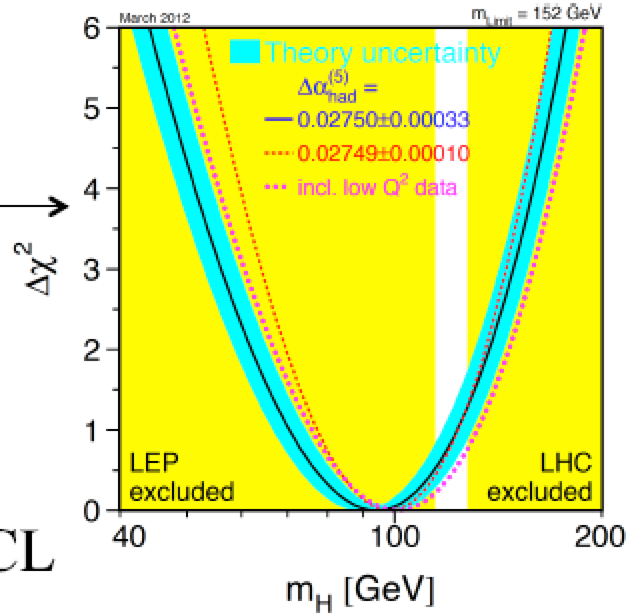


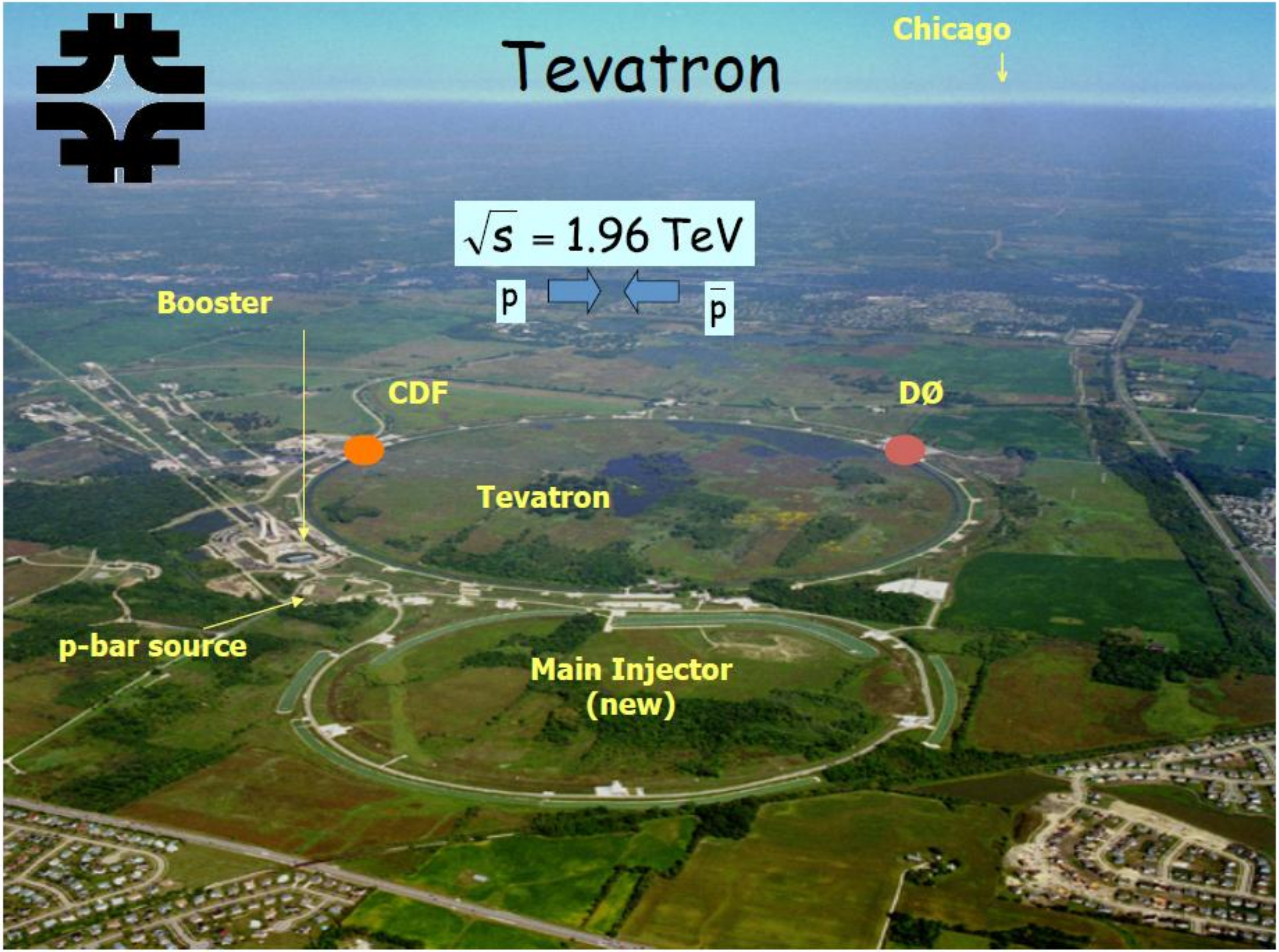
$$\Delta r \propto \log\left(\frac{m_H}{m_W}\right)$$

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

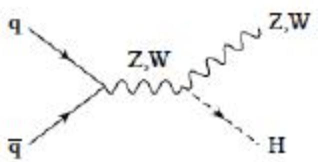
Is there a Higgs?

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

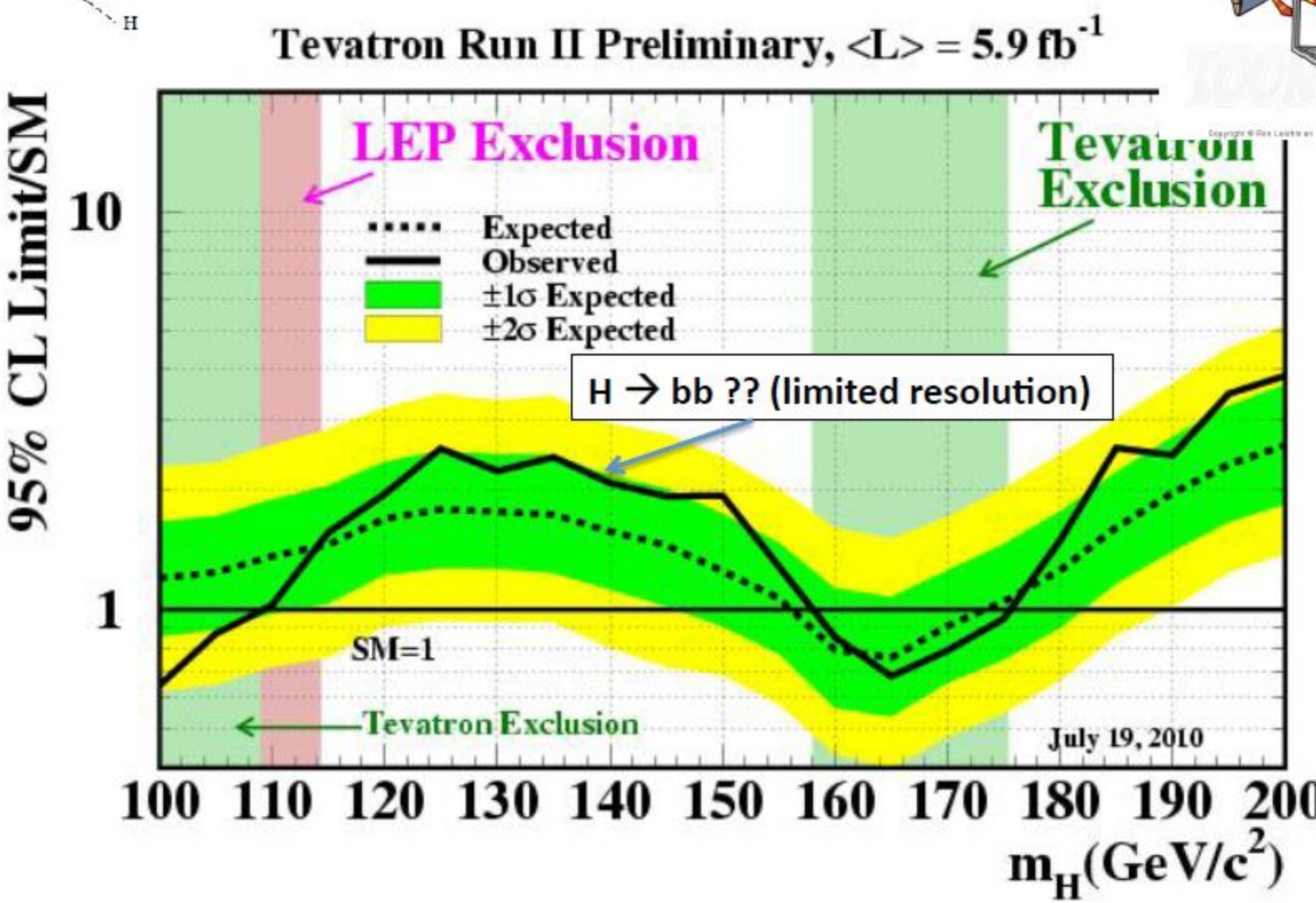



Tevatron
Chicago
$\sqrt{s} = 1.96$ TeV
p
$\bar{p}$
Booster
CDF
DØ
Tevatron
p-bar source
Main Injector
(new)

$qq \to WH, ZH$



Tevatron in July 2010



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

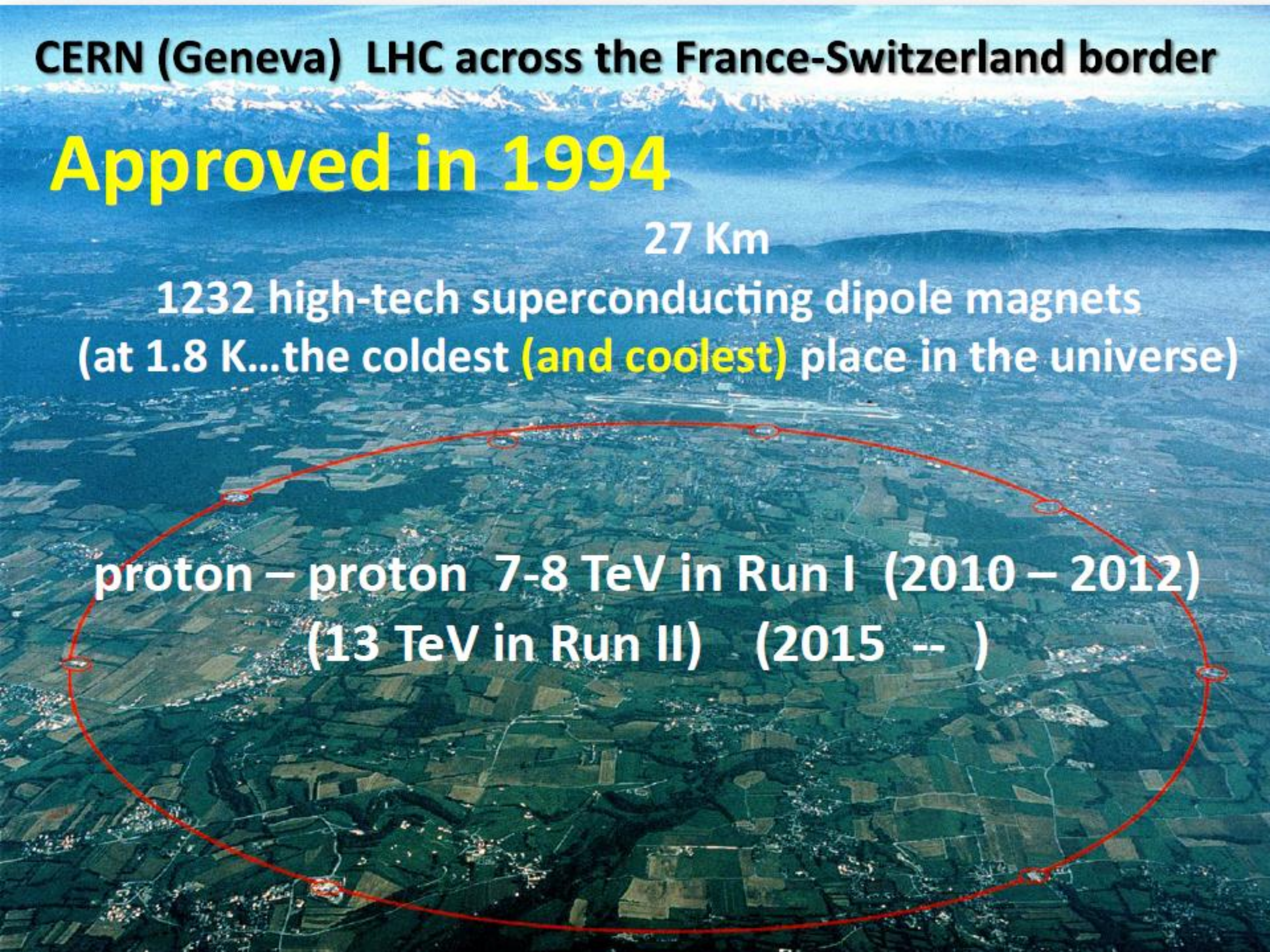
CERN (Geneva) LHC across the France-Switzerland border

Approved in 1994

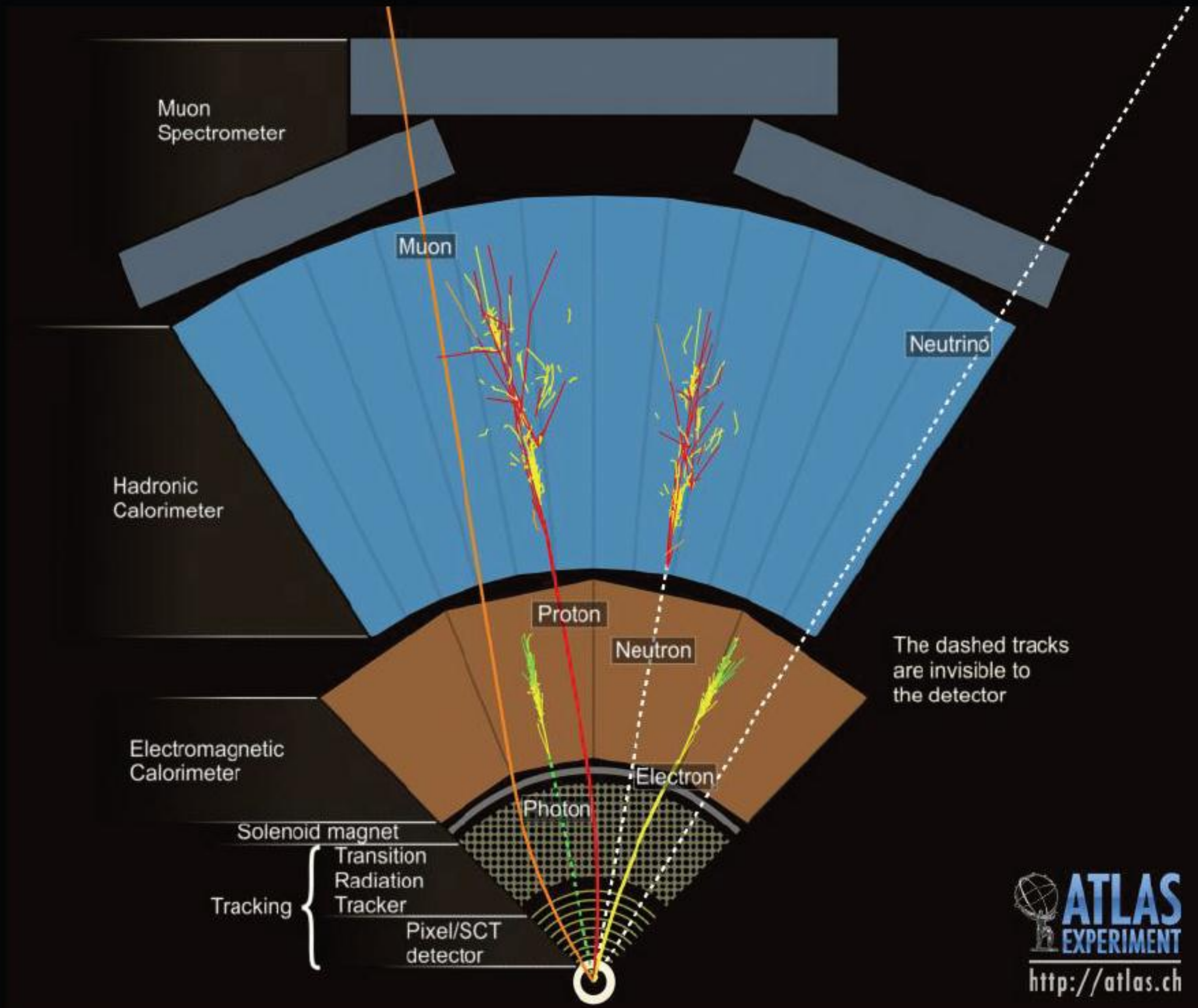
27 Km

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 --)



How do we "see" particles?

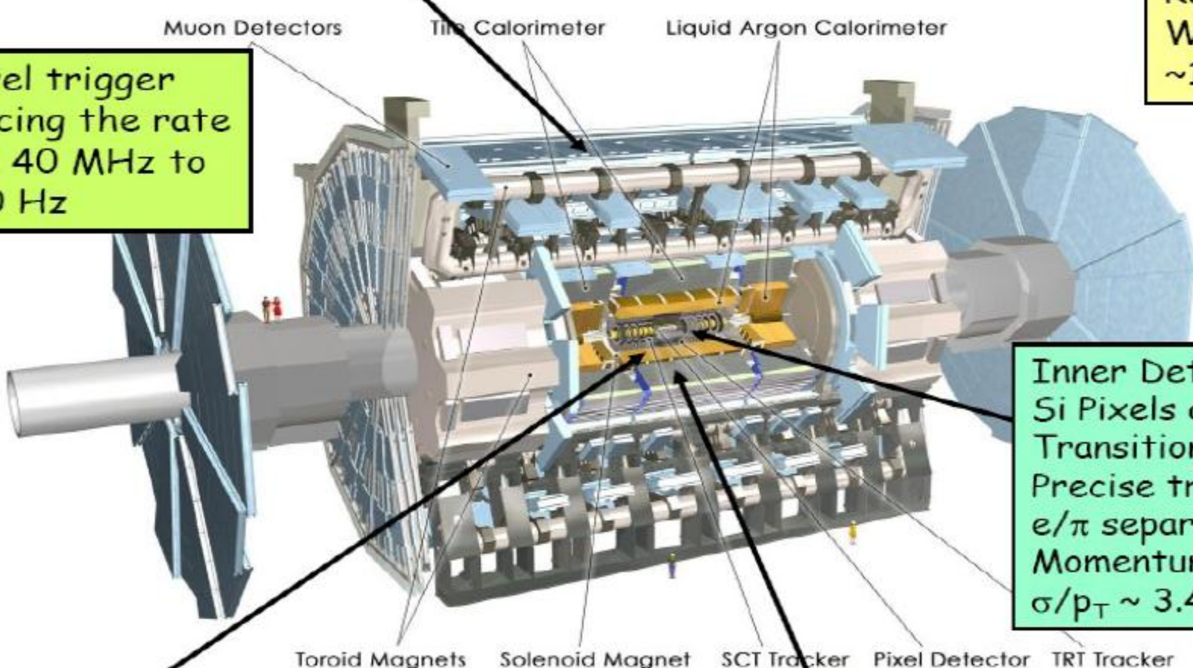


The ATLAS detector

Muon Spectrometer ($|\eta|<2.7$) : air-core toroids with gas-based chambers
Muon trigger and measurement with momentum resolution < 10% up to E_μ ~ TeV

Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~10^8 electronic channels

3-level trigger reducing the rate from 40 MHz to ~200 Hz

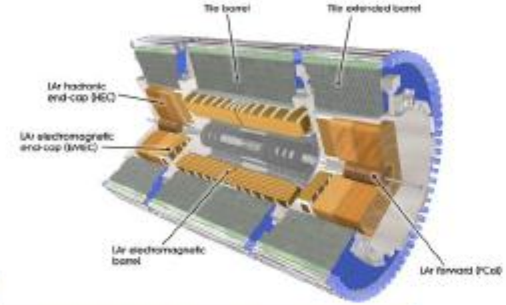


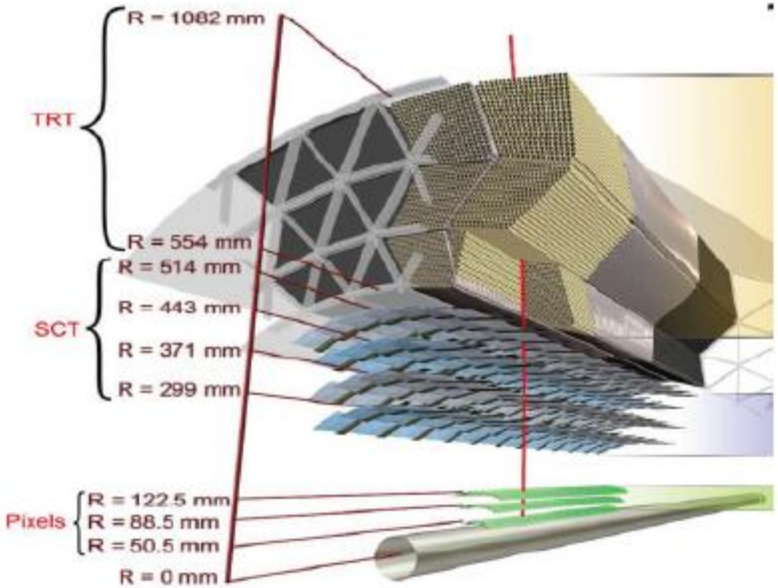
Inner Detector ($|\eta|<2.5$, B=2T):
Si Pixels and strips (SCT) +
Transition Radiation straws
Precise tracking and vertexing,
e/π separation (TRT).
Momentum resolution:
$\sigma/p_T \sim 3.4\times10^{-4}\ p_T(\mathrm{GeV}) \oplus 0.015$

EM calorimeter: Pb-LAr Accordion
e/γ trigger, identification and measurement
E-resolution: ~ 1% at 100 GeV, 0.5% at 1 TeV

HAD calorimetry ($|\eta|<5$): segmentation, hermeticity
Tilecal Fe/scintillator (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and missing E_T
E-resolution: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

ATLAS
(relevant to photon ID)



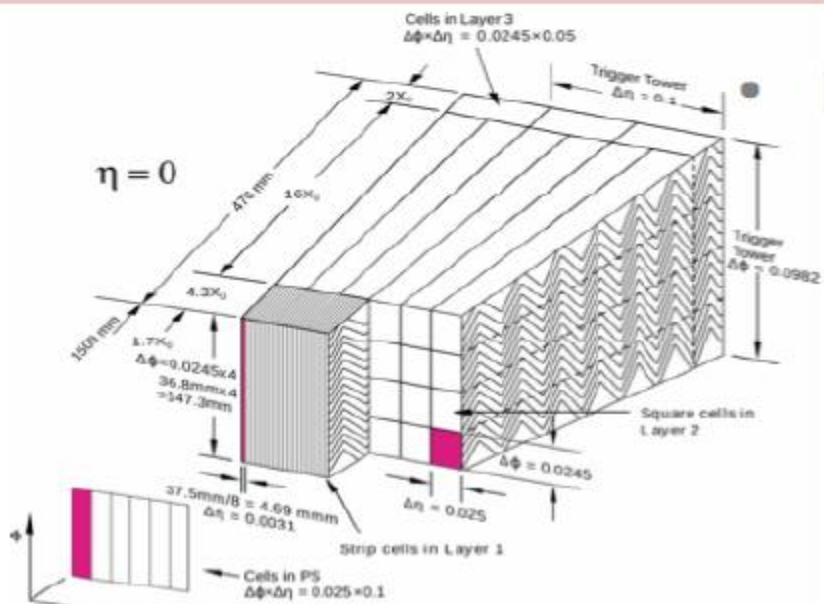


Inner Detector - Barrel (B)&End-cap (E) in 2T solenoidal magnetic field:

- Track reconstruction up to $|\eta|<2.47$;
- Conversion verticies reconstruction;
- e/γ and $e/\pi^{\pm}$ separation;
- Pixel: (B) 3 layers +(E) 2x3 disks $\sigma_{r\varphi}$~10 μm, σ_z~115 μm;
- Semi Conductor Tracker: (B) 4 layers +(E) 2x9 disks $\sigma_{r\varphi}$~17 μm, σ_z~580 μm;
- Transition Radiation Tracker: (B) 73 layers +(E) 2x160 layers σ_z~130 μm;

LAr lead sampling calorimeter with an 'accordion' geometry.

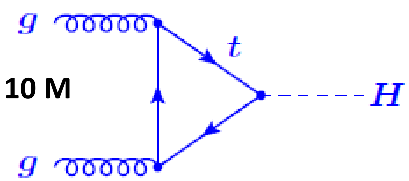
- 3 longitudinal layers with cell of $\Delta\eta \times \Delta\varphi$:
  - 1st layer (0.003÷0.006)x0.1;
  - 2nd layer 0.025x0.025;
  - 3rd layer 0.050x0.025.
- Presampler for $|\eta|<1.8$ $\Delta\eta\times\Delta\varphi$~0.025x0.1.
- Barrel-end-cap crack $|\eta|$=1.37÷1.52.
- $\sigma(E)/E=(10\text{-}17\%)(\eta)/\sqrt{E(GeV)} \oplus (1.2\div1.8\%)$.

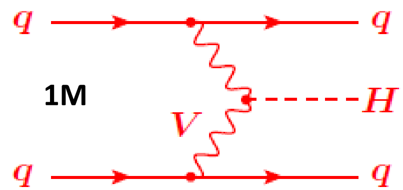


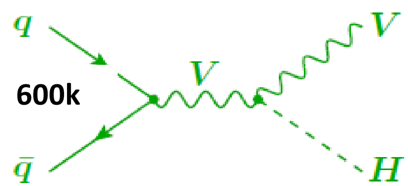
The Higgs Boson at the LHC

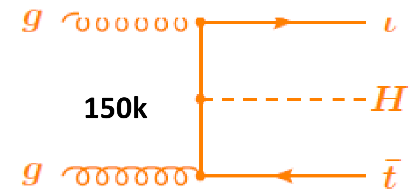
Production

#Higgs produced at 13 TeV **(2015-2017)**









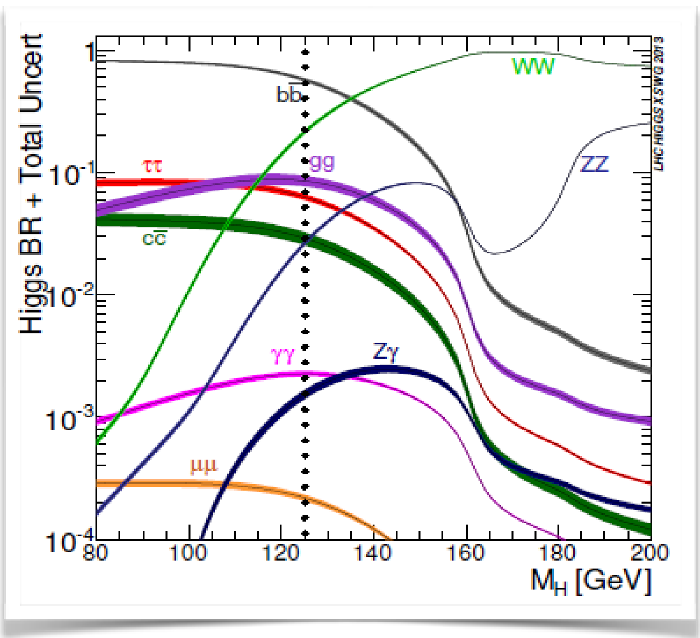
Main production channel

2 forward jets, little central hadronic activity

Tag W and Z decays

Tag 2 top quarks

Decays



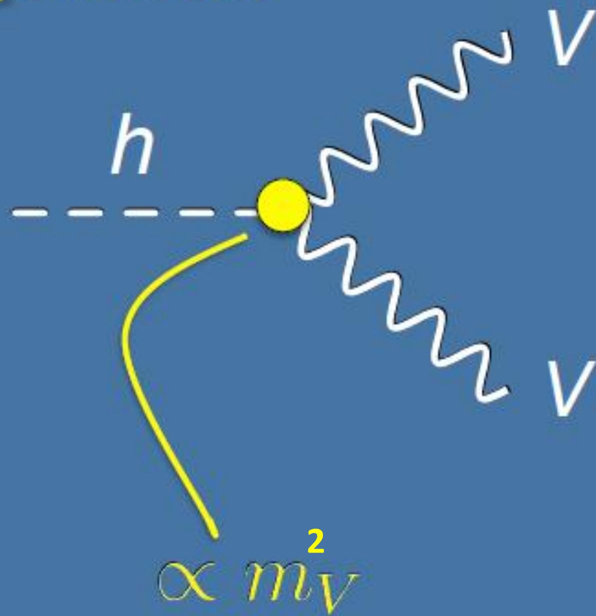
5 main channels at the LHC

Decay branching fractions for m_H = 125 GeV

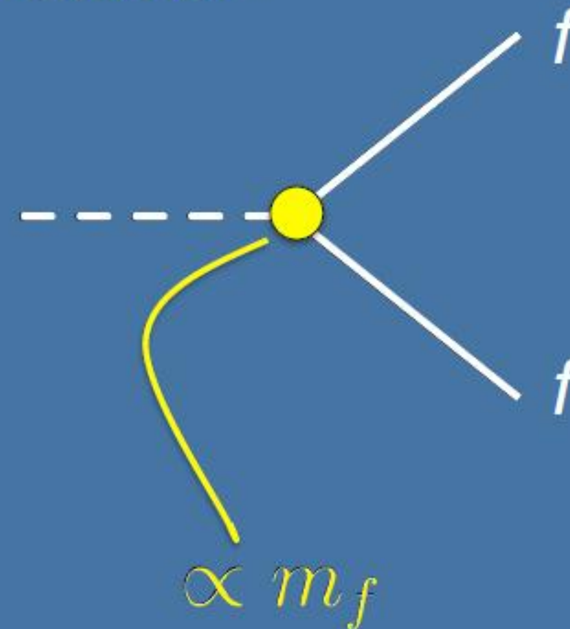
- H→bb: 58 %
- H→WW*: 21%
- H→τ⁺τ⁻: 6.3%
- H→ZZ*: 2.6%
- H→γγ: 0.2%

Higgs boson couplings

Gauge bosons

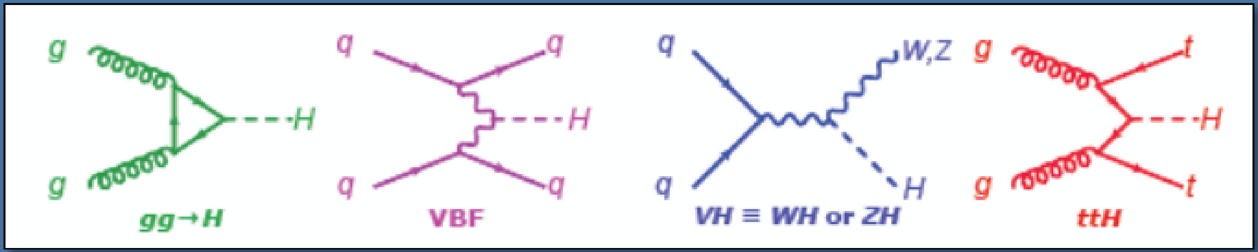


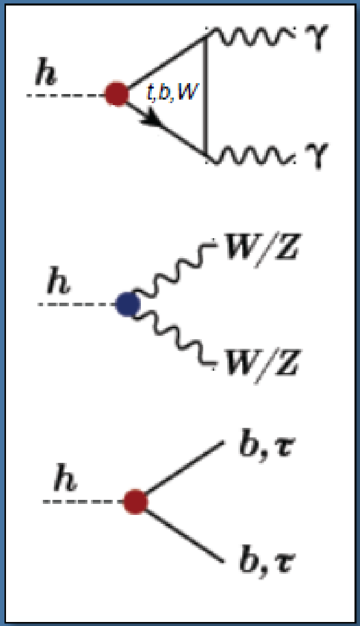
Fermions



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

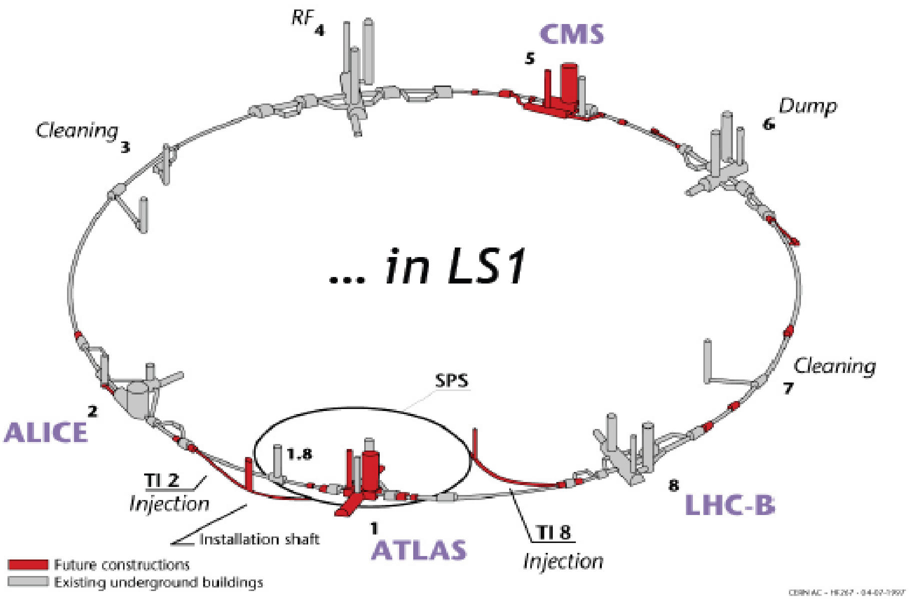
Higgs boson phenomenology





Shown here results based on Run I

Energy frontier



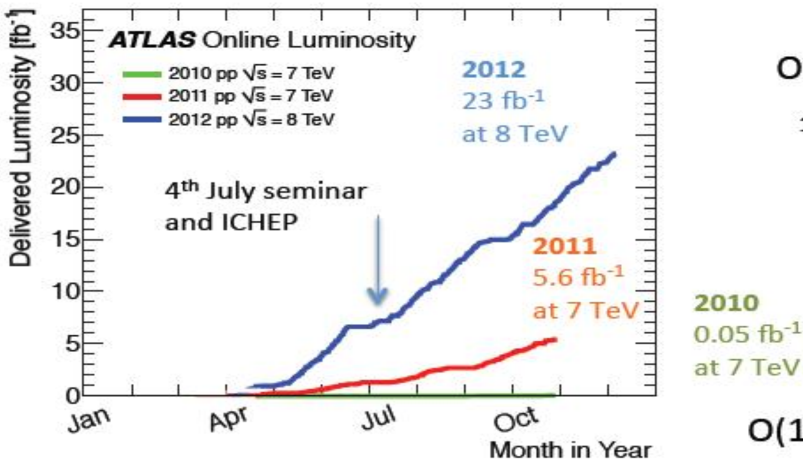
The LHC

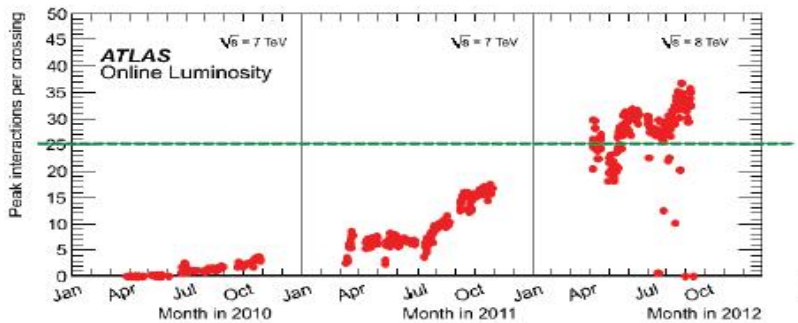
- Circumference 27 km
- Up to 175 m underground
- Total number of magnets 9 553
- Number of dipoles 1 232
- Operation temperature 1.9 K (Superfluid He)

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

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 ($cm^{-2}s^{-1}$)	$2x10^{32}$	$3.3x10^{33}$	$\sim 7x10^{33}$	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

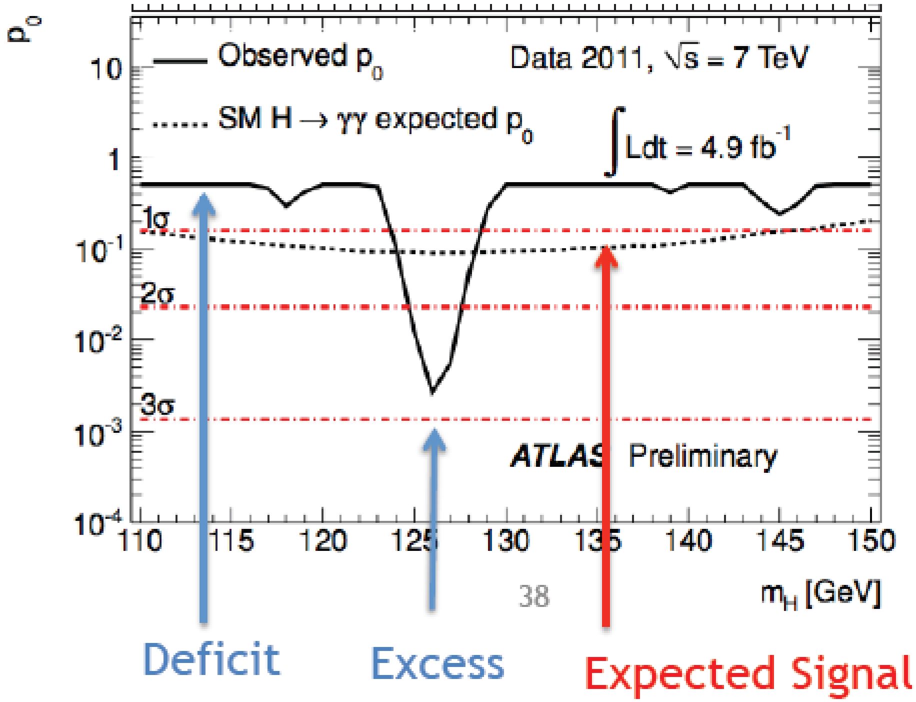
2012

O(20) Pile-up events

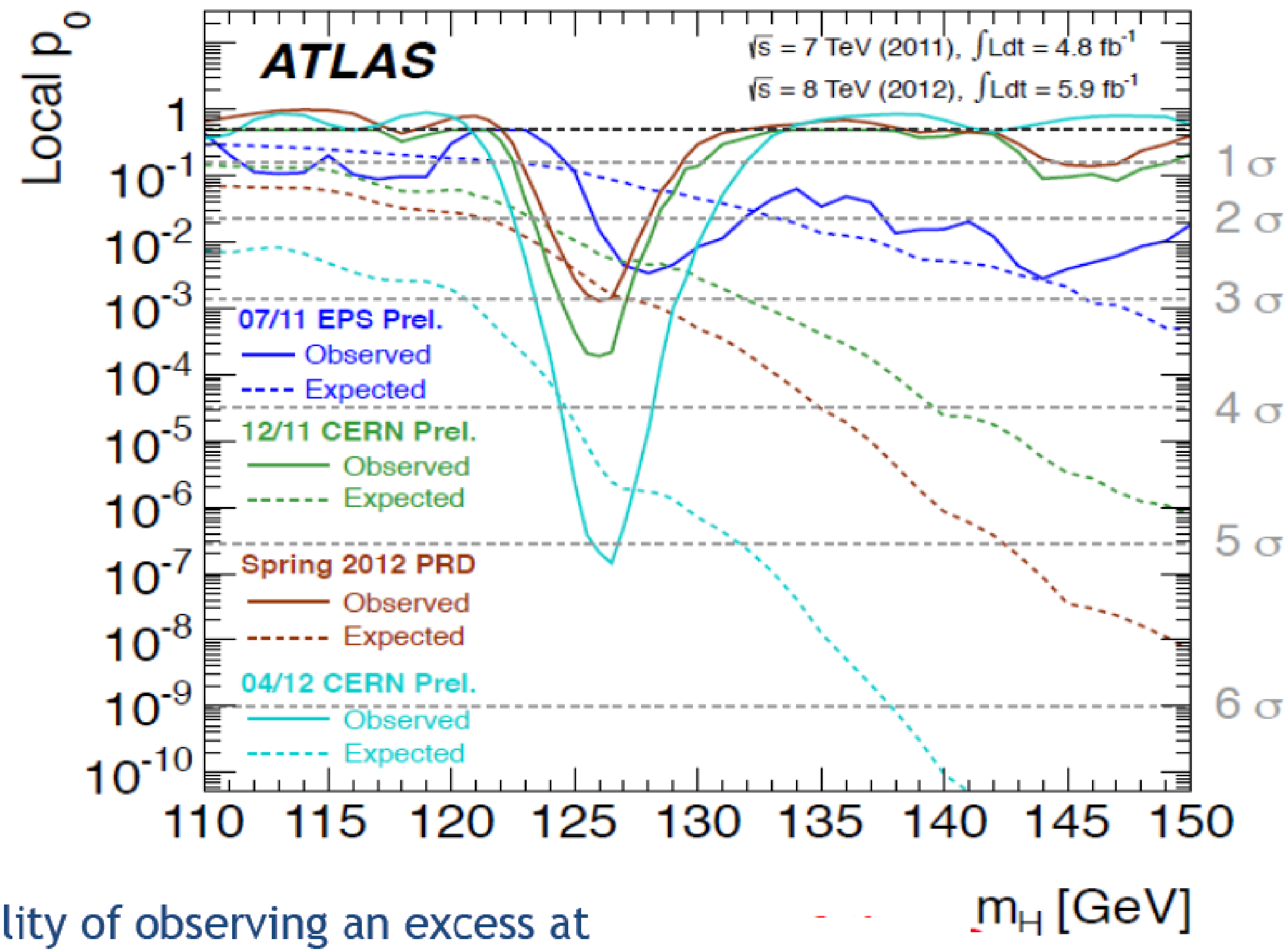
50 ns inter-bunch spacing

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.



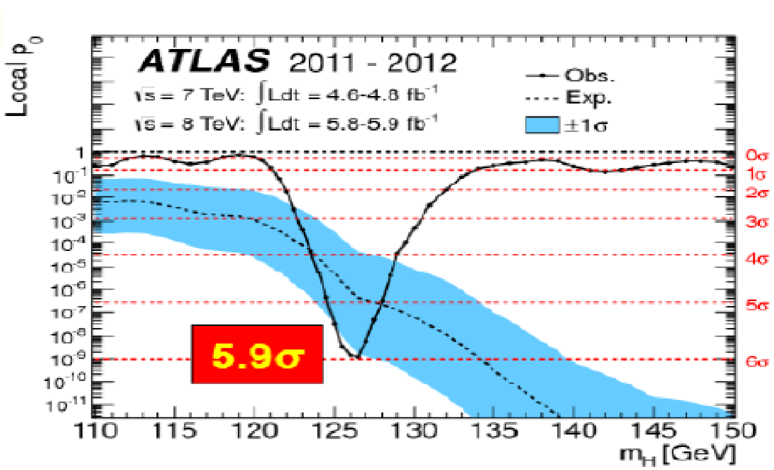
Birth of a particle

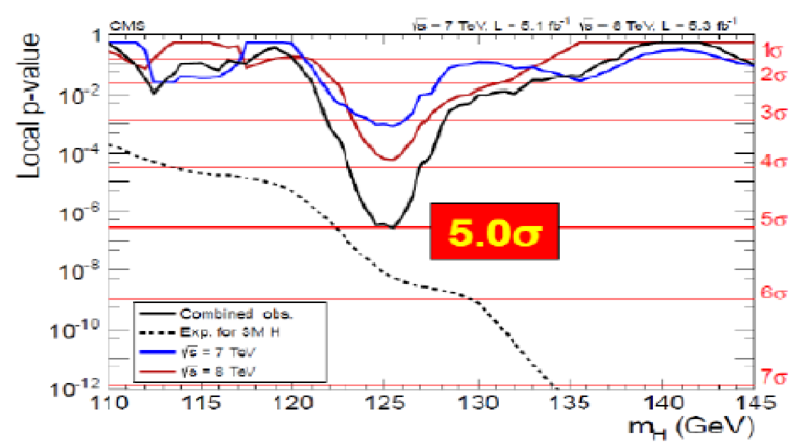


Probability of observing an excess at
one specific mass
(in absence of signal)...

Higgs-like particle – 4 July 2012

- 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)

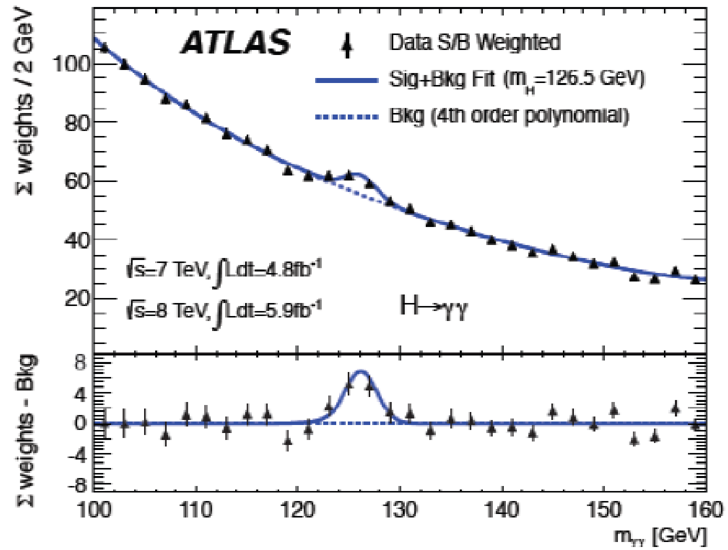
CMS PLB 716 (2012) 30-61, *Sept 17 (2012)*

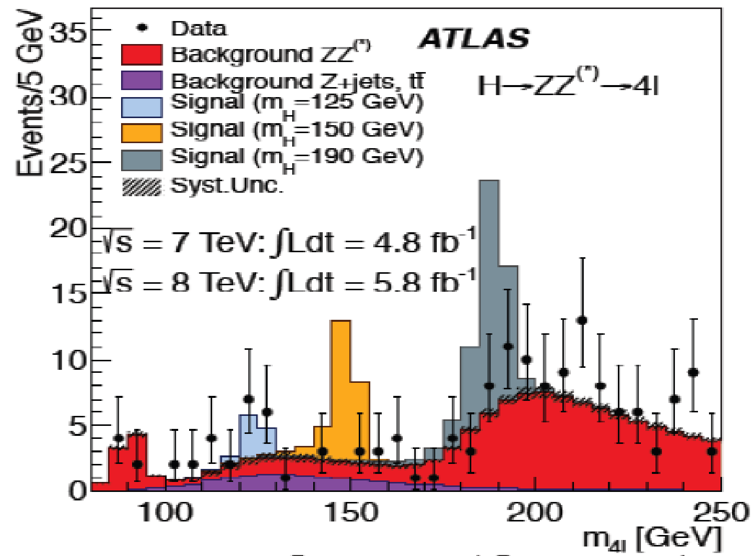
Largest local excess:
5.0σ at m_H= 125.5 GeV

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

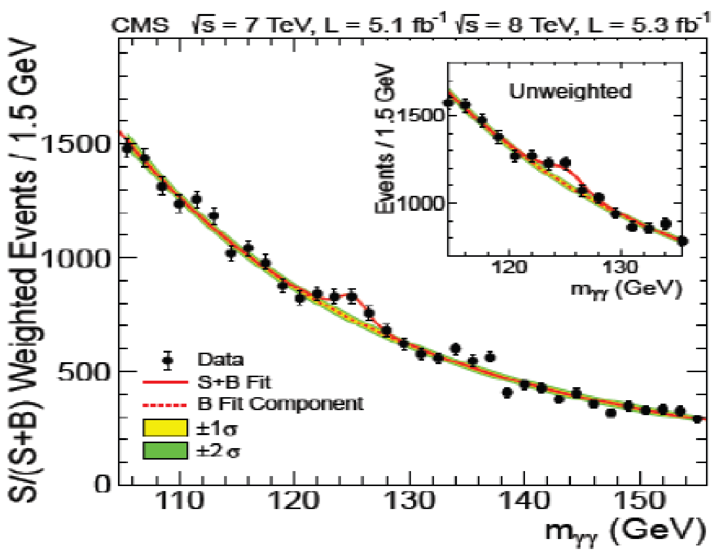
Higgs-like particle – 4 July 2012

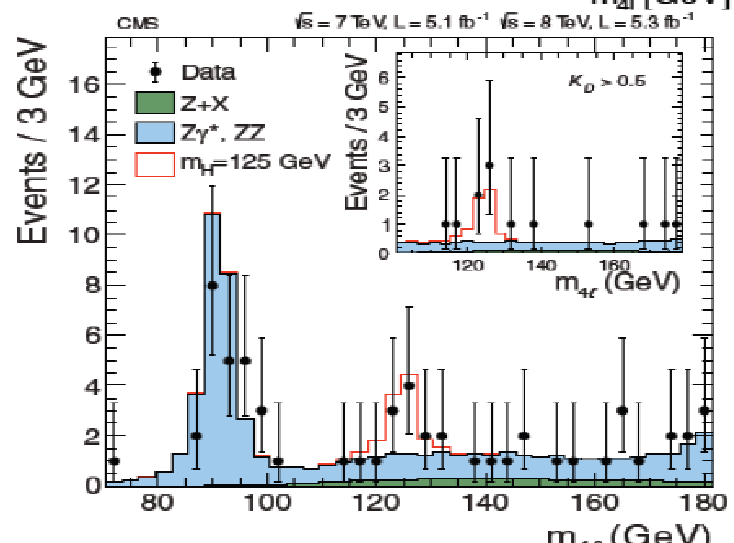
Phys.Lett. B716 (2012) 1-29



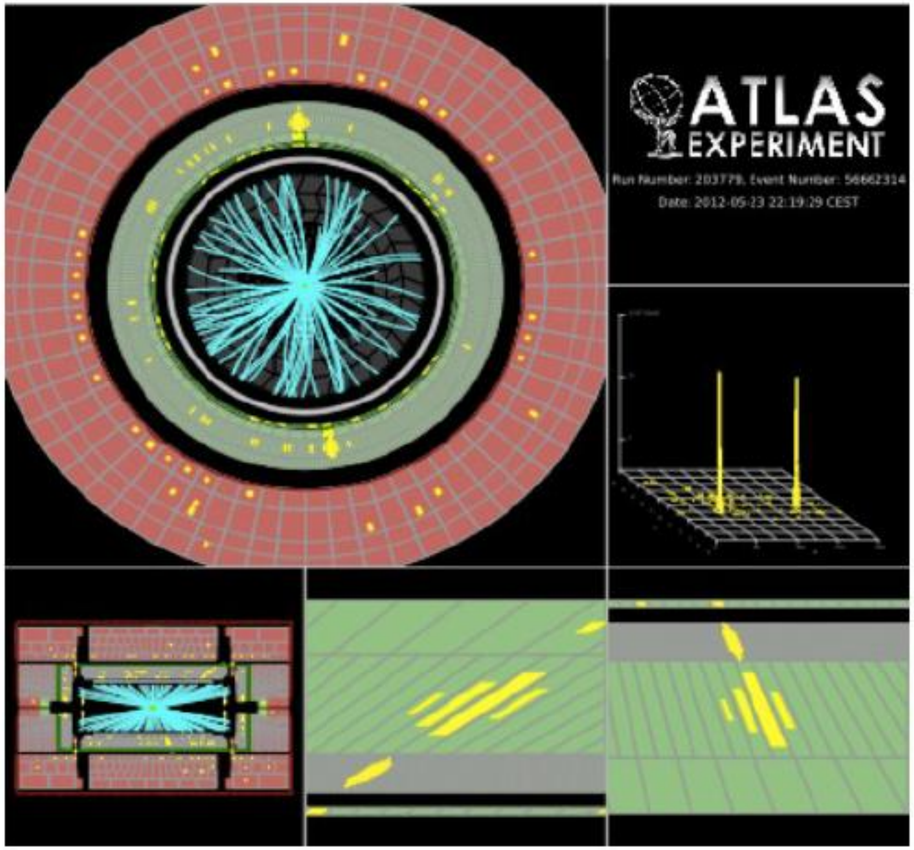


Phys.Lett. B716 (2012) 30-61





H->γγ: 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)

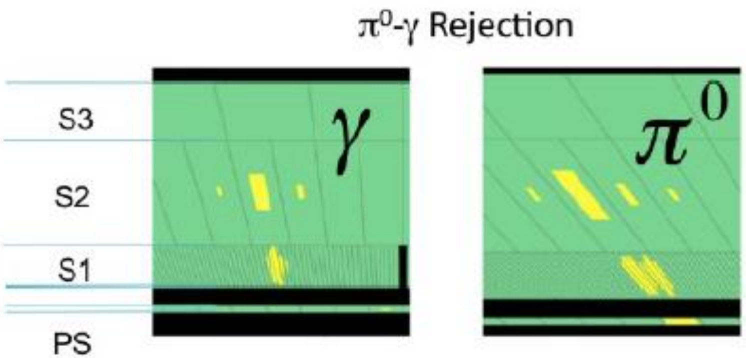
Invariant mass reconstruction $m_{\gamma\gamma}^2 = 2 * E_1 E_2 (1 - \cos \alpha)$

- ❑ 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



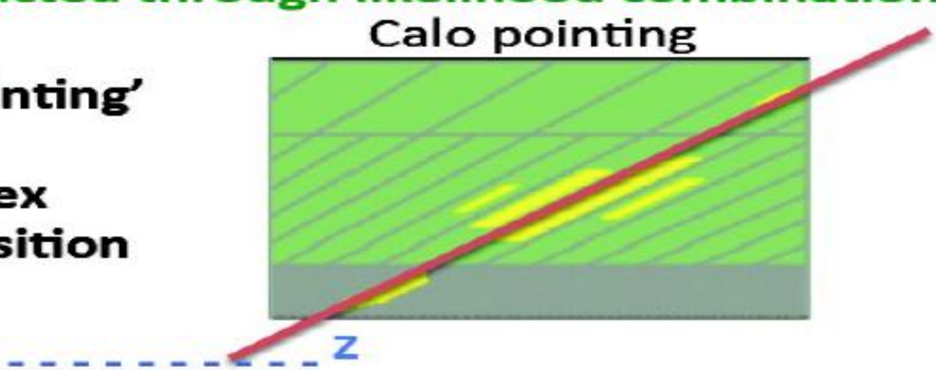
- Photons shower shape distributions in LAr sampling layers - different for signal and background (π^0)

Vertex Reconstruction

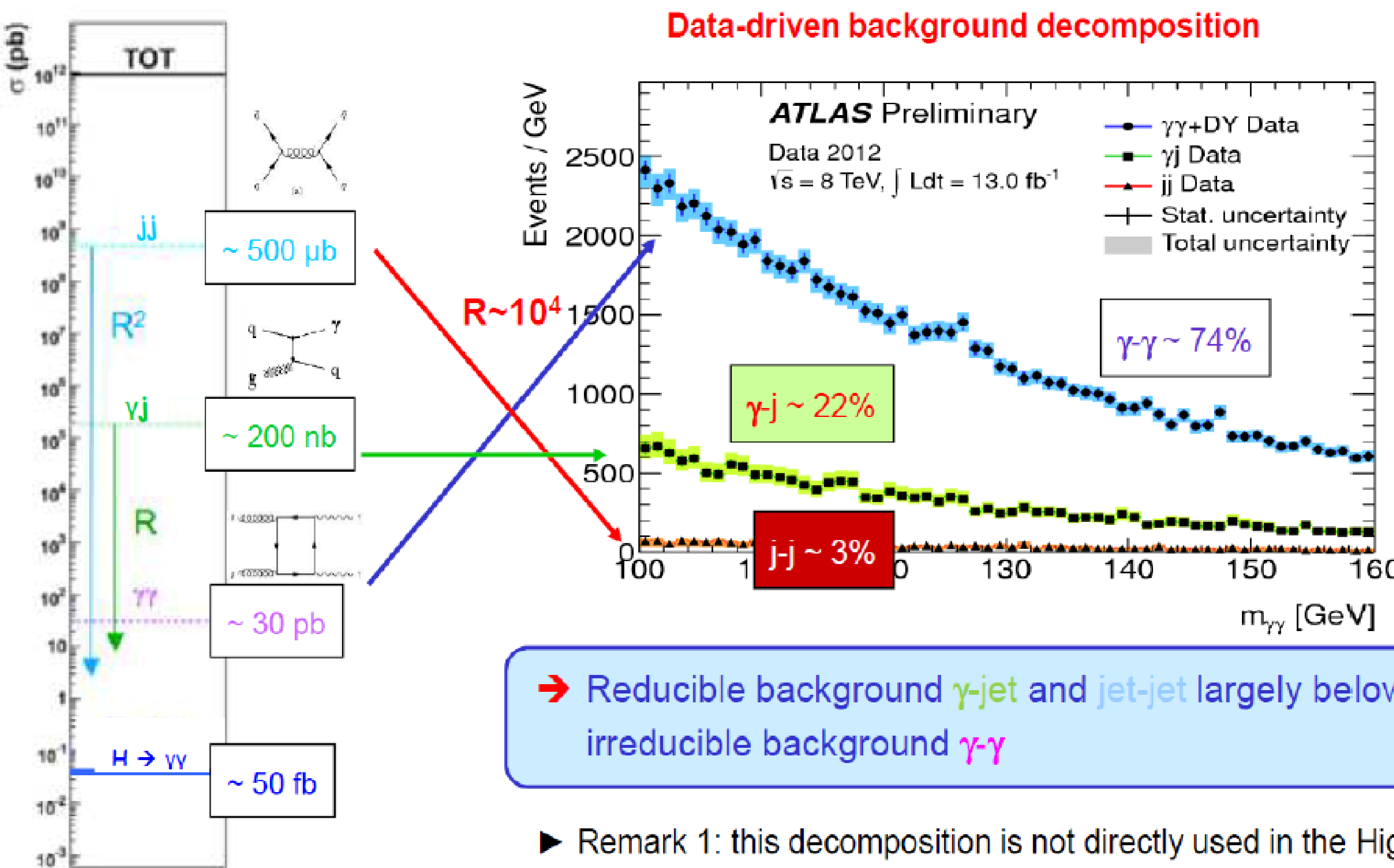
$$m_{\gamma\gamma}^2 = 2 * E_1 E_2 (1 - \cos\alpha)$$

❑ Vertex reconstructed through likelihood combination

- **Calorimeter 'pointing'**
- **Σ tracks pT^2**
- **Conversion vertex**
- **Mean vertex position**



H->γγ: background rejection

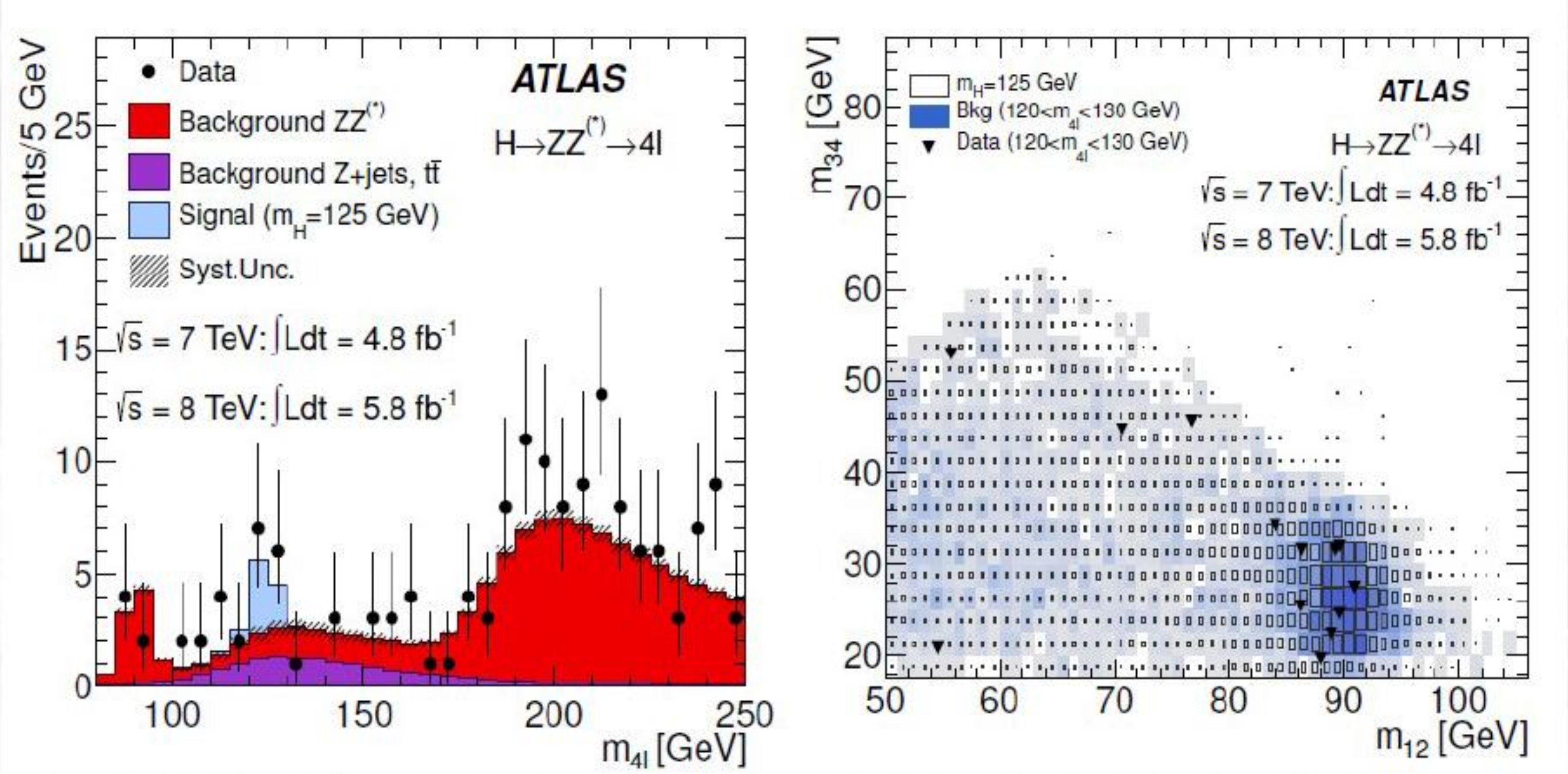


➔ Reducible background γ-jet and jet-jet largely below irreducible background γ-γ

▶ 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%)

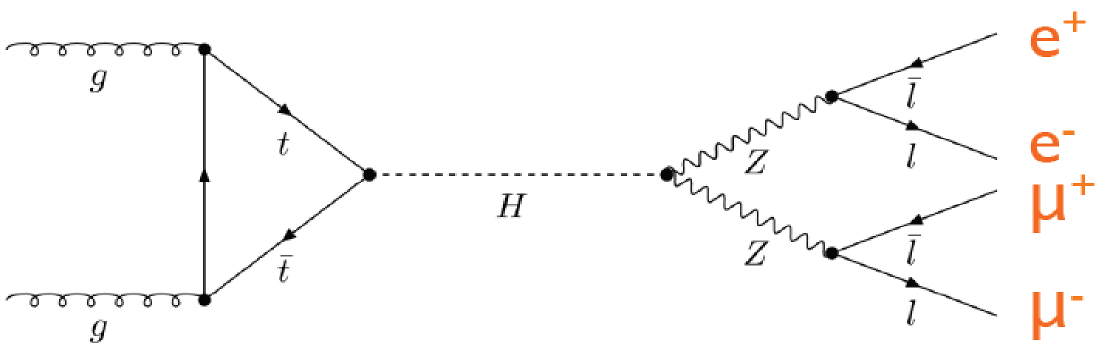
The golden channel: H->ZZ, Z->ll



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

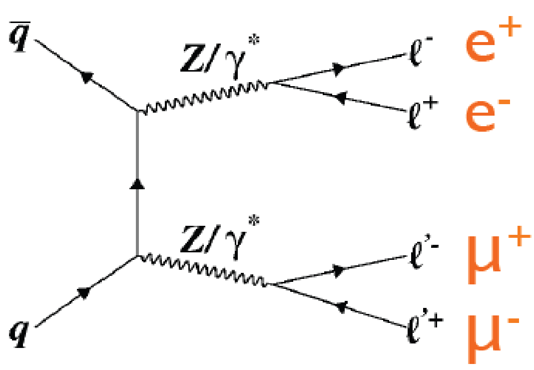
	Signal	$ZZ^{(*)}$	$Z+$ jets, $t\bar{t}$	Observed
4μ	2.09±0.30	1.12±0.05	0.13±0.04	6
$2e2\mu/2\mu 2e$	2.29± 0.33	0.80±0.05	1.27±0.19	5
$4e$	0.90±0.14	0.44±0.04	1.09±0.20	2

Signal and background



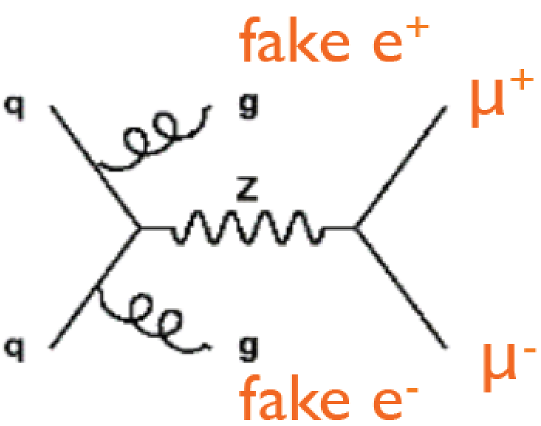
Irreducible background

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



Reducible background

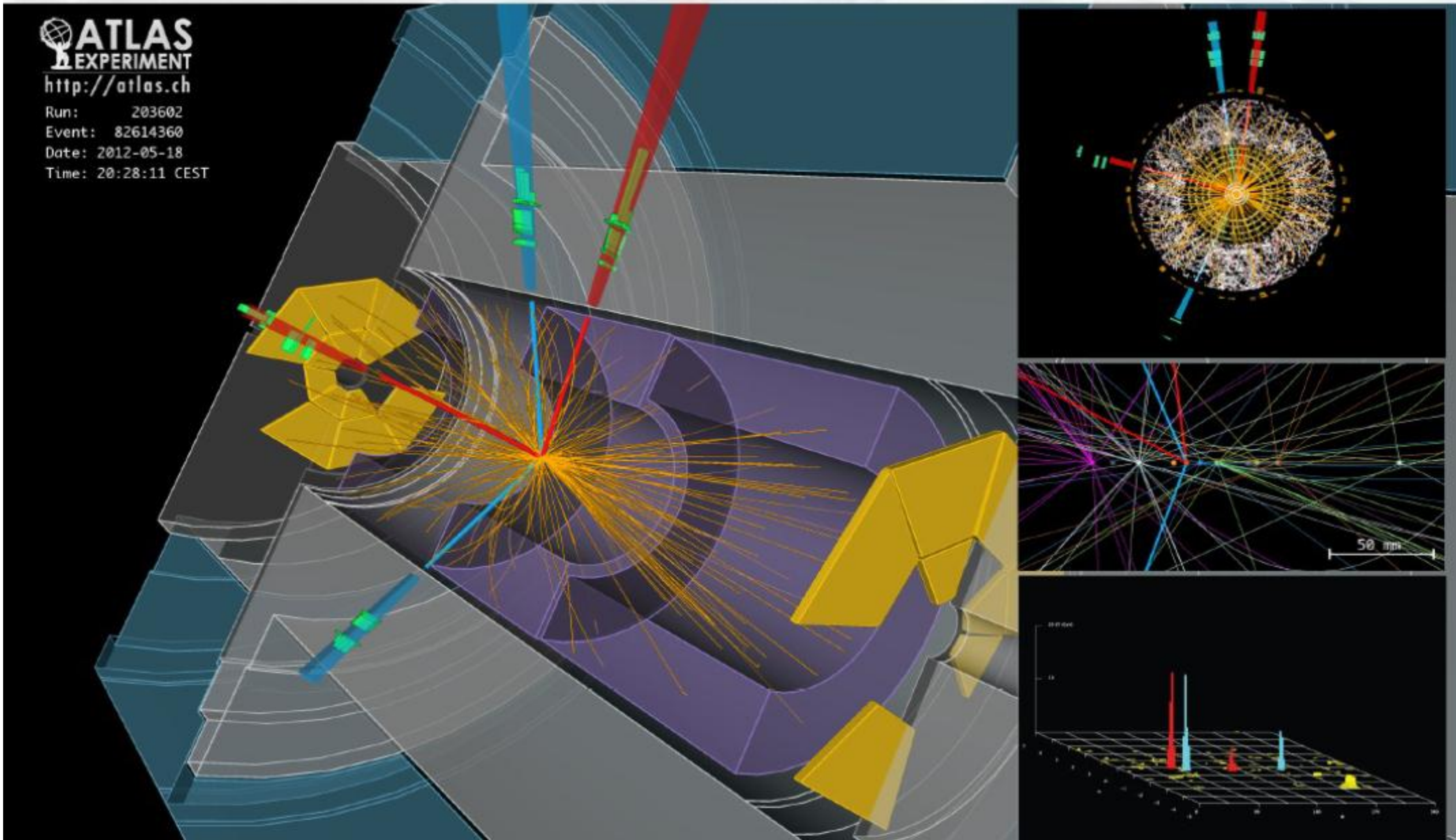
The final state looks like the same, but some f the particle fakes what you are looking for



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

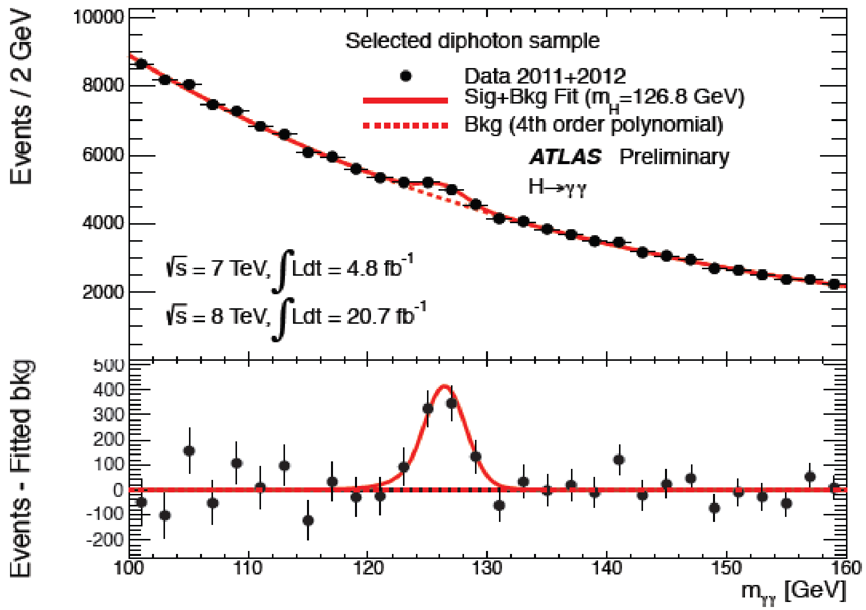
e_1: $P_T = 24.9$ GeV, $\eta = -0.33$, $\phi = 1.98$ e_2: $P_T = 53.9$ GeV, $\eta = -0.40$, $\phi = 1.69$

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



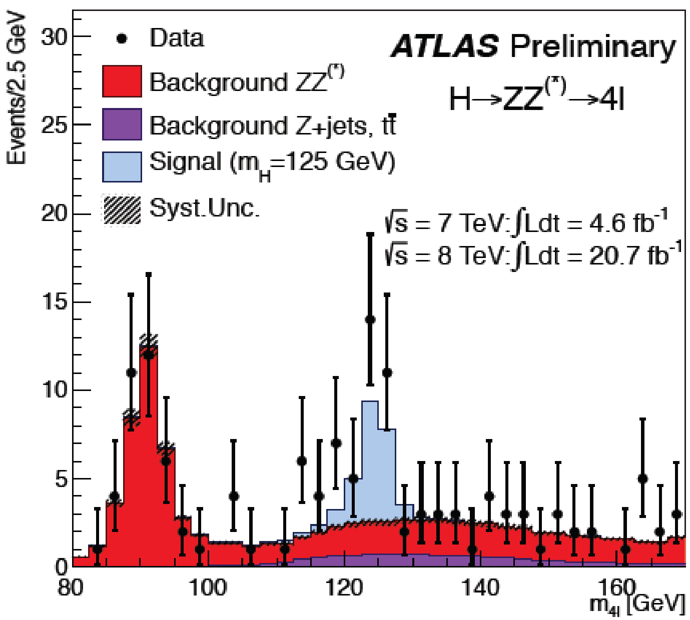
Higgs like signal with 7 TeV and 8 TeV data

H→γγ



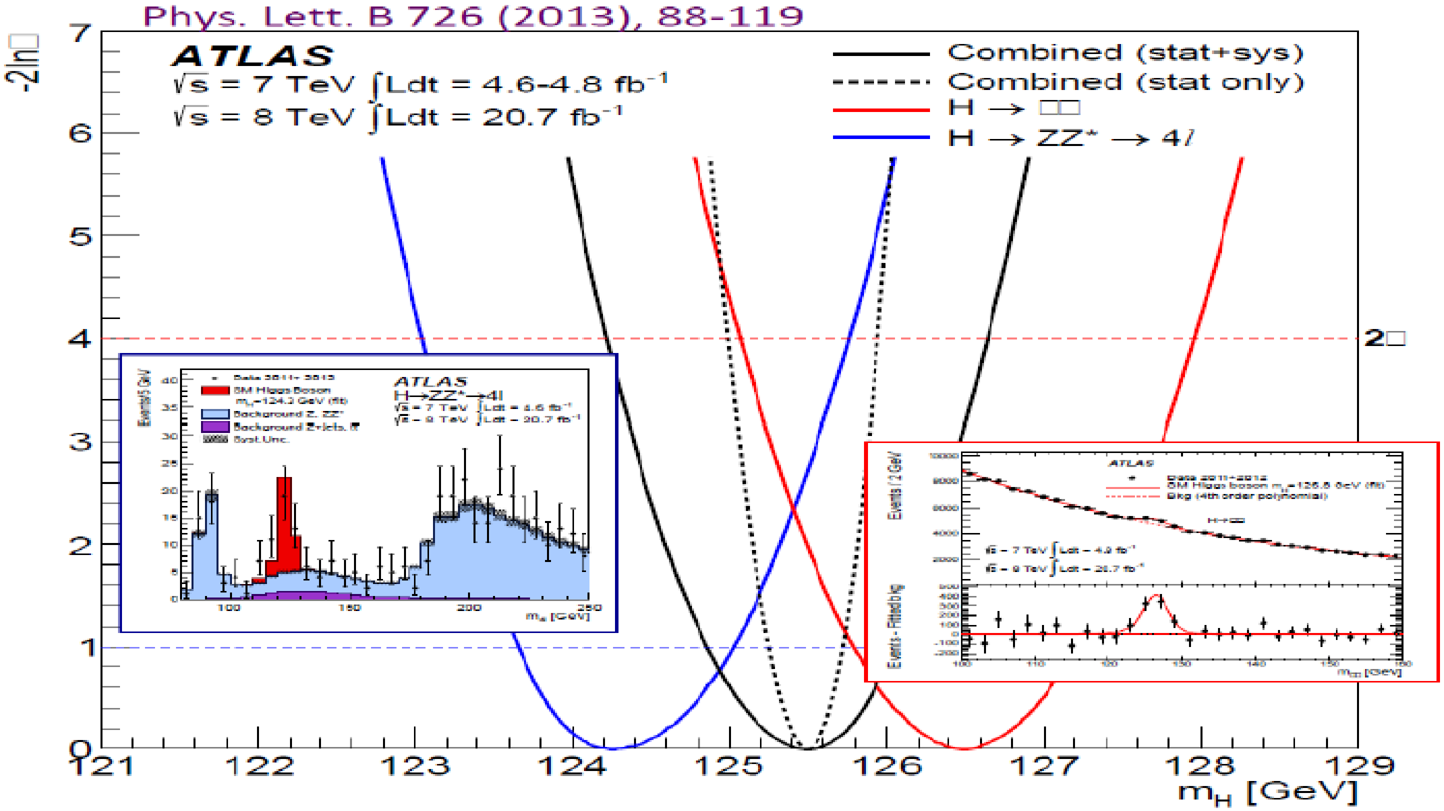
- Signal significance = 7.4 σ
- m_H = 126.8 ± 0.2 (stat) ± 0.7 (syst) GeV
- μ = 1.65 ± 0.34 (deviation w.r.t. SM at 2.3σ)

H→4l



- Signal significance = 6.6 σ
- m_H = 124.3 $^{+0.6}_{-0.5}$ (stat) $^{+0.6}_{-0.3}$ (syst) GeV
- μ = 1.7 ± 0.34

Mass measurement



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

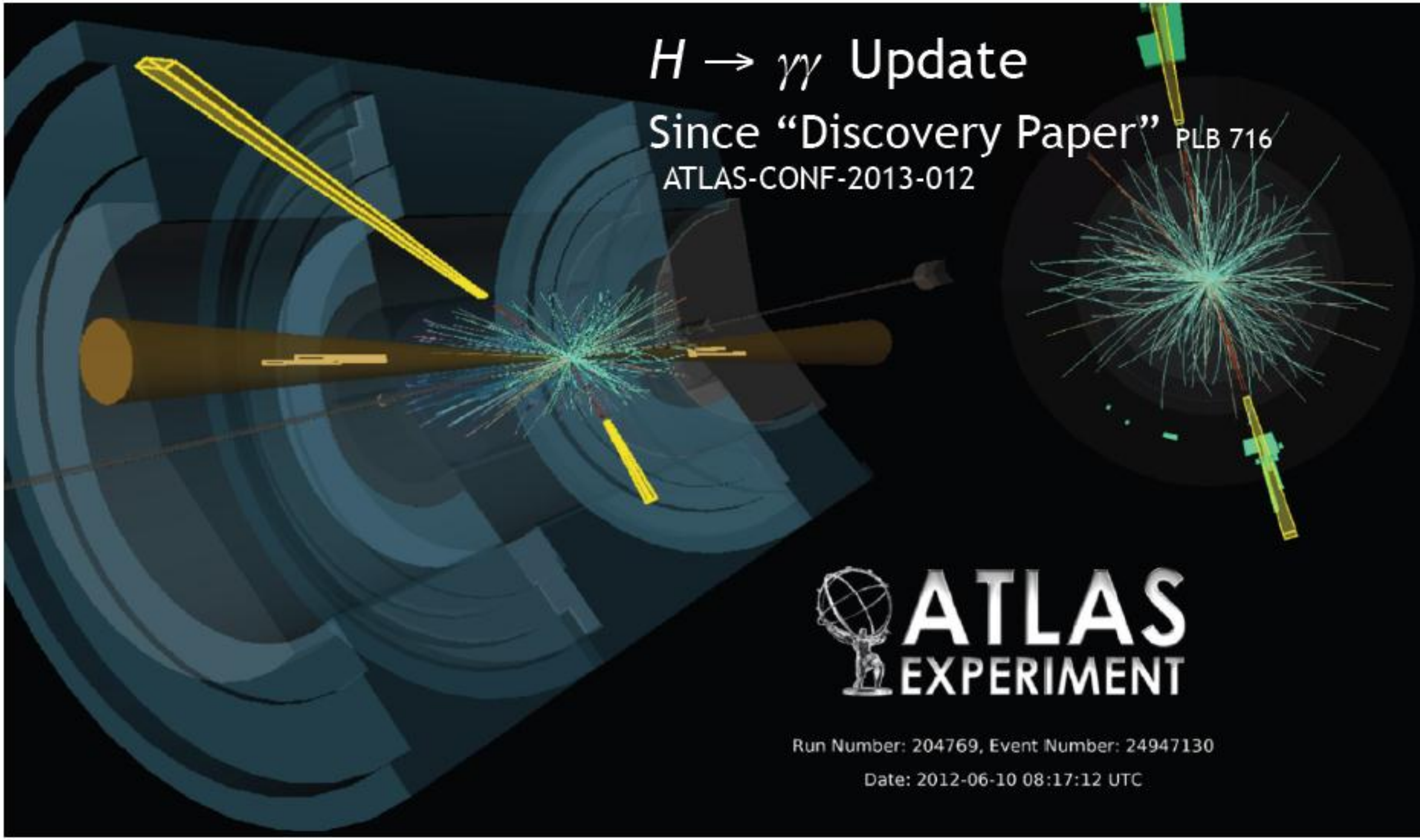
γγ: $M_H = 126.8 \pm 0.2_{stat} \pm \mathbf{0.7}_{sys}$ GeV

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

And since then ....

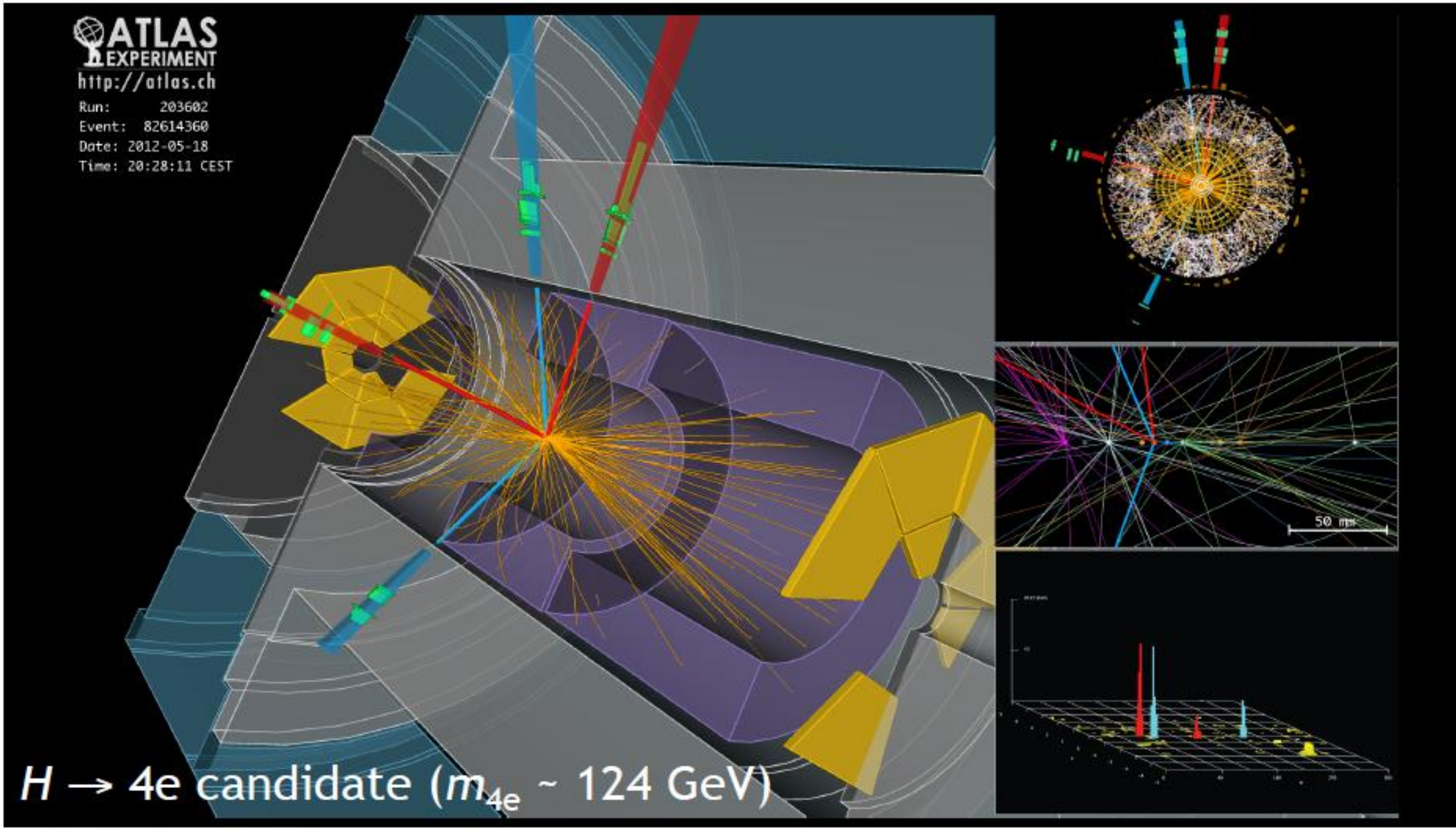
Panorama of ATLAS Higgs (125) Analyses

channel	ggF	VBF	VH	ttH	Yield	S/B (%)	Res. (GeV/c^2)
$\gamma\gamma$	✓	✓	✓	✓	~ 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



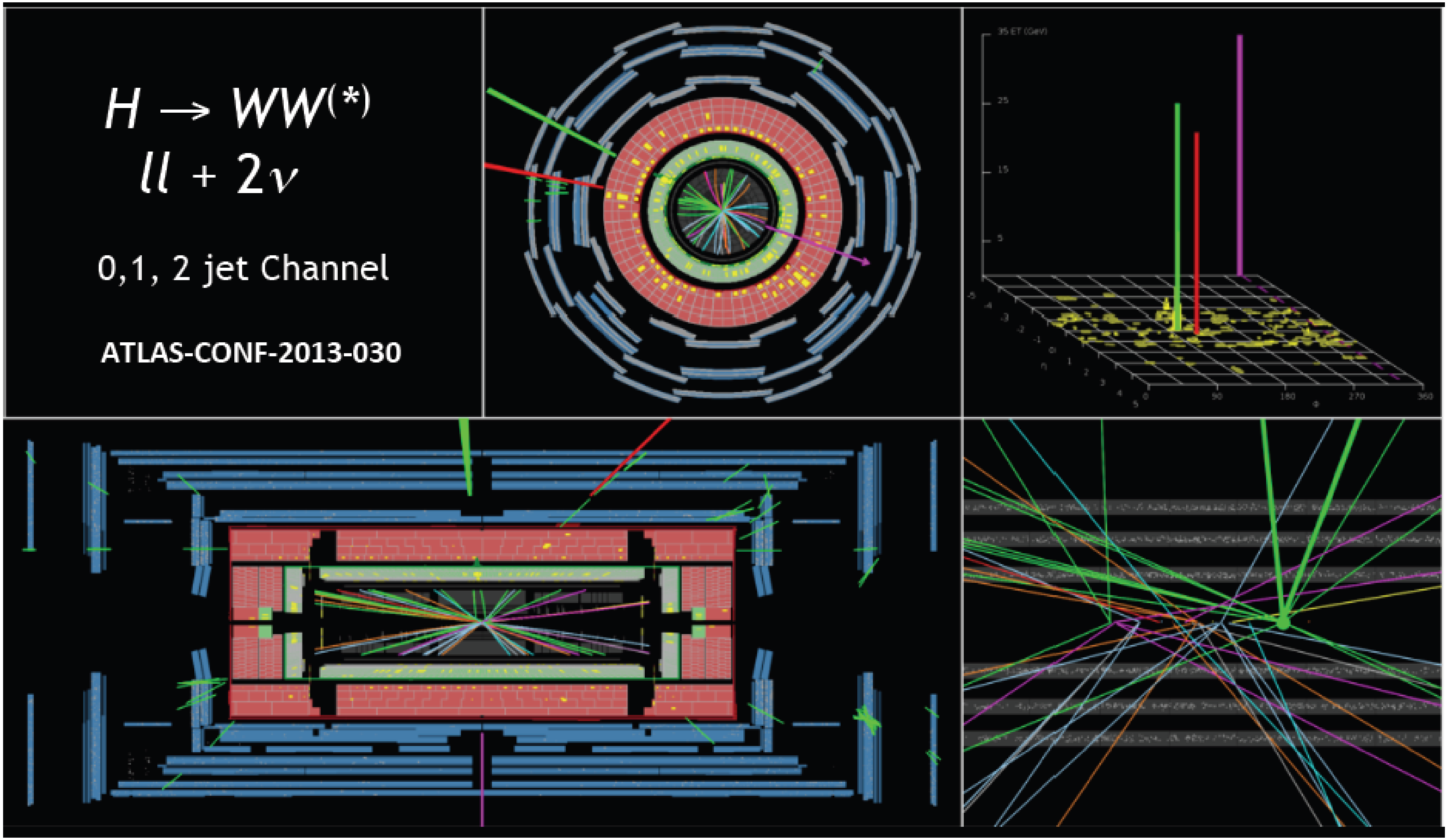
γγ channel basic facts sheet :

Signal ($SM_{126\ GeV}$)	Signal purity s/b	Main backgrounds	Production	7 & 8 TeV $\int L dt$
~450	2% - 60%	γγ,γj and jj	Hgg, VBF, VH	4.9 & 20.7 fb^{-1}



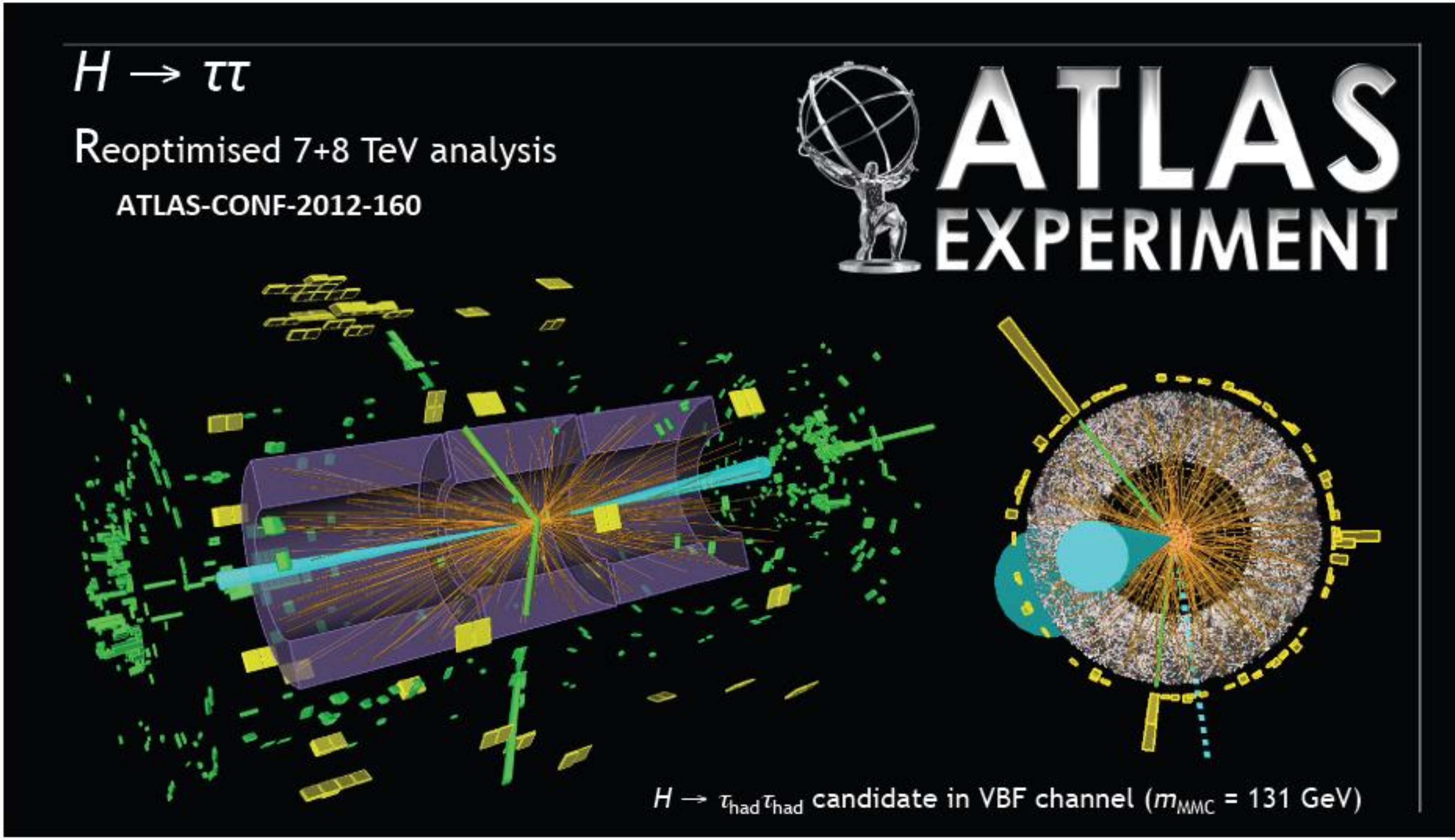
4l channel basic facts sheet :

Signal	Signal Purity s/b	Main backgrounds	Production	7 & 8 TeV $\int L\,dt$
~16	~1.5	ZZ, Z+jets, top	ggH, VBF & VH	4.9 & 20.7 fb^{-1}



WW channel basic facts sheet :

Signal	Sig. Purity s/b	Main backgrounds	Production	7 & 8 TeV $\int L\,dt$
~250	~5%-40%	WW, W+jets, top, etc...	ggH & VBF	25fb^{-1}

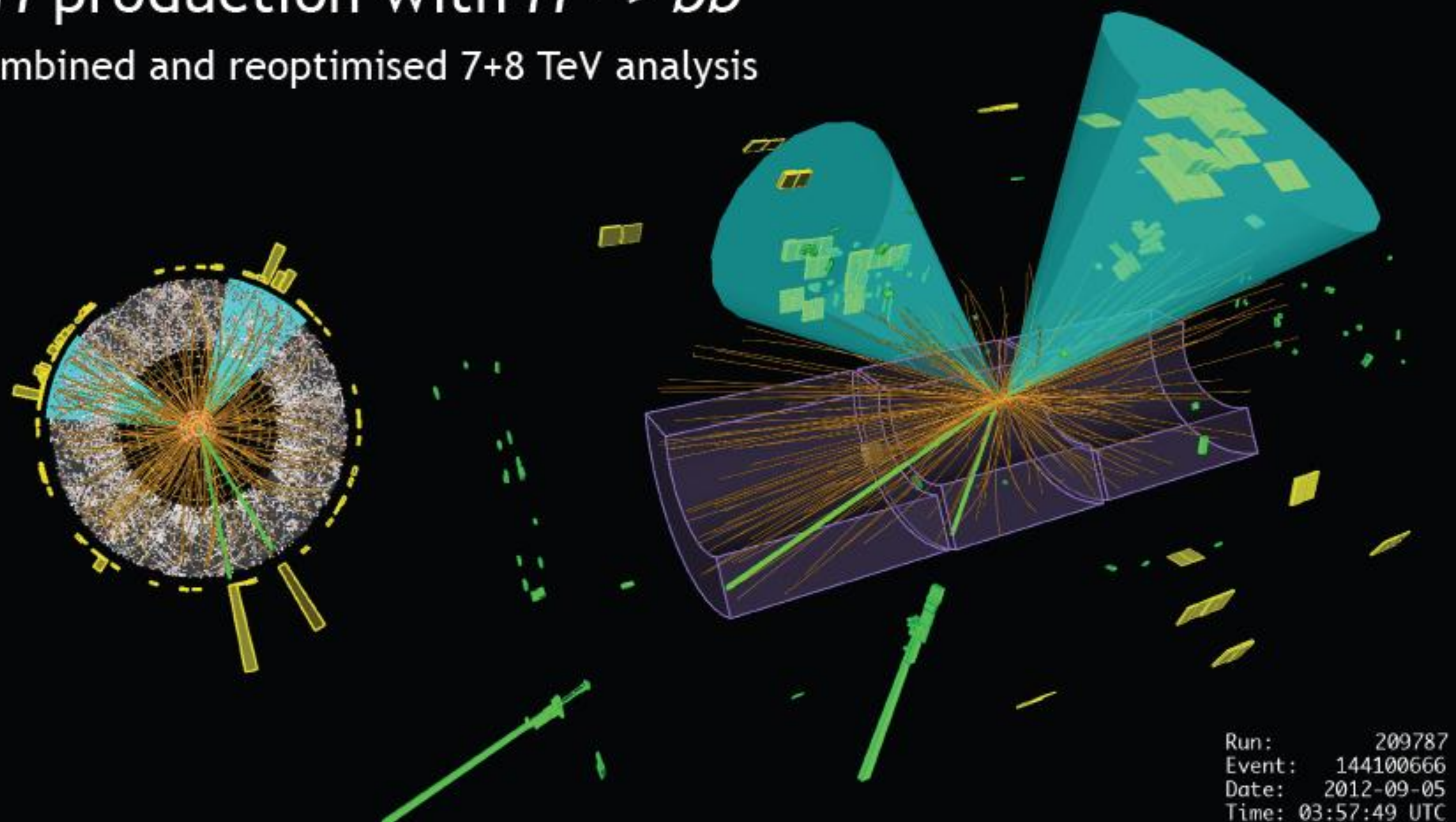


ττ channel basic facts sheet :

Signal (SM)	Signal purity s/b	Main backgrounds	Production	7 & 8 TeV $\int L dt$
~330	0.3% - 30%	ZZ, Z+jets, top	VBF, Hgg, VH	4.9 & 13 fb^{-1}

VH production with $H \rightarrow bb$

Combined and reoptimised 7+8 TeV analysis



VH(bb) channel basic facts sheet :

Signal (SM)	Signal purity s/b	Main backgrounds	Production	7 & 8 TeV $\int L\,dt$
~50	~1% - 10%	Wbb,Zbb, top, etc...	VH	4.9 & 13 fb^{-1}

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 $H \to ZZ^* \to 4l$ and $H \to \gamma\gamma$

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

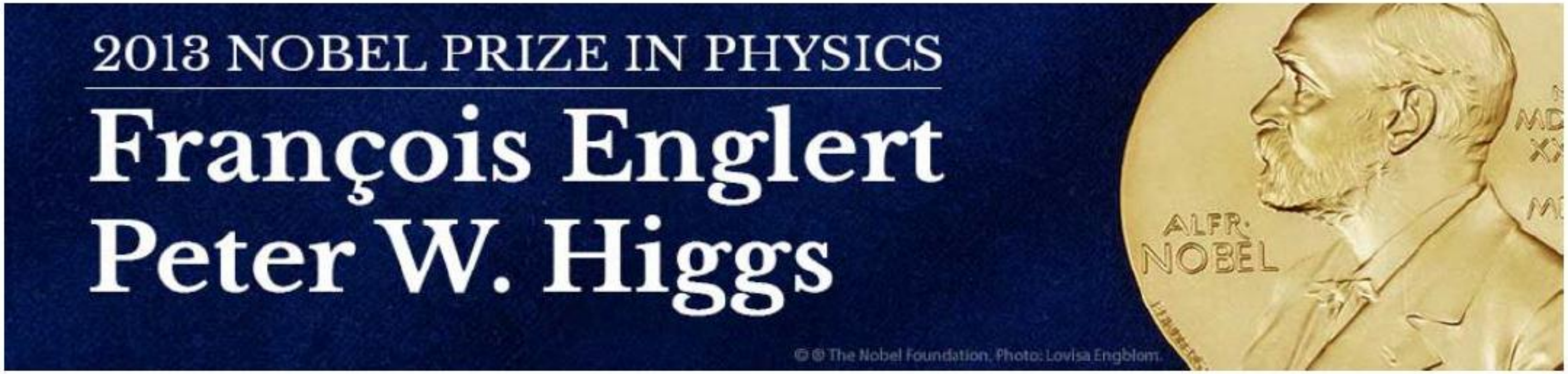
  CMS: $m_H = 125.7 \pm 0.3$(stat) ± 0.3 (syst) GeV

- 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

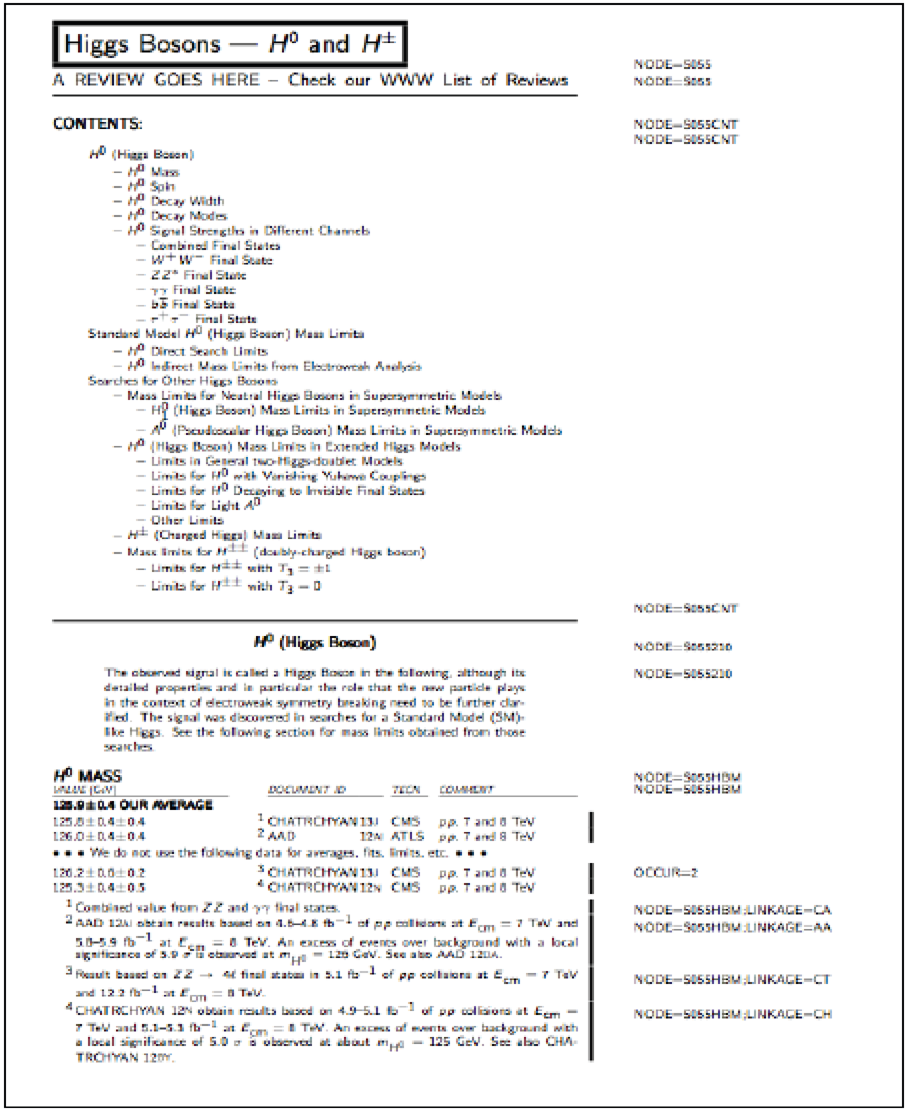
The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2013 to

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

H^0 (Higgs Boson)
- H^0 Mass
- H^0 Spin
- H^0 Decay Width
- H^0 Decay Modes
- H^0 Signal Strengths in Different Channels
  - Combined Final States
  - W^+W^- Final State
  - ZZ^* Final State
  - $\gamma\gamma$ Final State
  - $b\bar{b}$ Final State
  - $\tau^+\tau^-$ Final State

Standard Model H^0 (Higgs Boson) Mass Limits
- H^0 Direct Search Limits
- H^0 Indirect Mass Limits from Electroweak Analysis

Searches for Other Higgs Bosons
- Mass Limits for Neutral Higgs Bosons in Supersymmetric Models
  - H_1^0 (Higgs Boson) Mass Limits in Supersymmetric Models
  - A^0 (Pseudoscalar Higgs Boson) Mass Limits in Supersymmetric Models
- H^0 (Higgs Boson) Mass Limits in Extended Higgs Models
  - Limits in General two-Higgs-doublet Models
  - Limits for H^0 with Vanishing Yukawa Couplings
  - Limits for H^0 Decaying to Invisible Final States
  - Limits for Light A^0
  - Other Limits
- $H^\pm$ (Charged Higgs) Mass Limits
- Mass limits for $H^{\pm\pm}$ (doubly-charged Higgs boson)
  - Limits for $H^{\pm\pm}$ with $T_3 = \pm1$
  - Limits for $H^{\pm\pm}$ with $T_3 = 0$

NODE=S055CNT

H^0 (Higgs Boson)

NODE=S055210
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.

H^0 MASS

NODE=S055HBM
NODE=S055HBM

VALUE (GeV)	DOCUMENT ID		TECN	COMMENT
125.9±0.4 OUR AVERAGE				
$125.8\pm0.4\pm0.4$	[1] CHATRCHYAN	13J	CMS	pp, 7 and 8 TeV
$126.0\pm0.4\pm0.4$	[2] AAD	12AI	ATLS	pp, 7 and 8 TeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$126.2\pm0.6\pm0.2$	[3] CHATRCHYAN	13J	CMS	pp, 7 and 8 TeV
$125.3\pm0.4\pm0.5$	[4] CHATRCHYAN	12N	CMS	pp, 7 and 8 TeV

OCCUR=2

[1] Combined value from ZZ and $\gamma\gamma$ final states.

NODE=S055HBM;LINKAGE=CA

[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 σ is observed at $m_{H^0} = 126$ GeV. See also AAD 12DA.

NODE=S055HBM;LINKAGE=AA

[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.

NODE=S055HBM;LINKAGE=CT

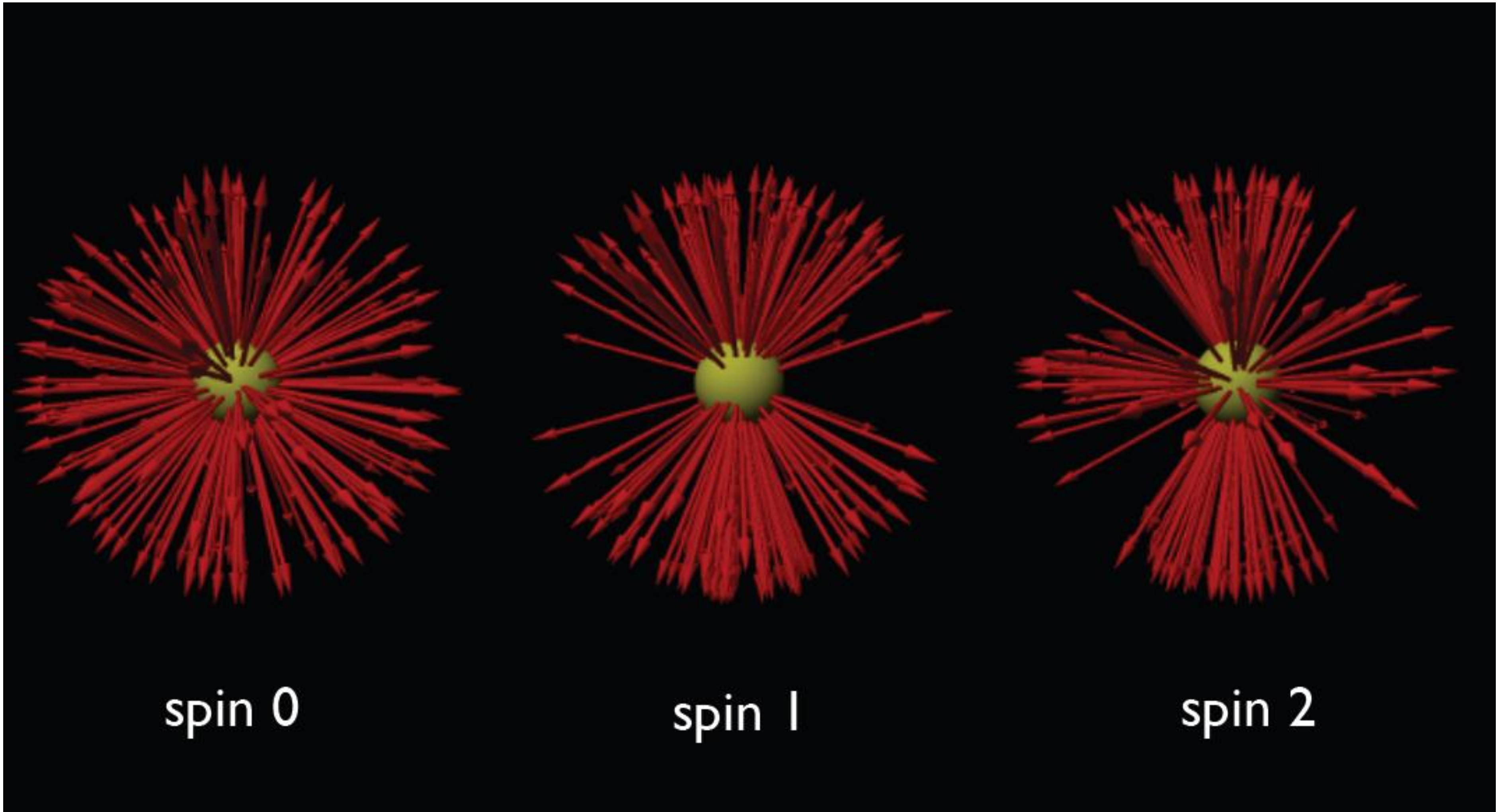
[4] CHATRCHYAN 12N obtain results based on 4.9–5.1 fb^{-1} of pp collisions at $E_{cm} = 7$ TeV and 5.1–5.3 fb^{-1} at $E_{cm} = 8$ TeV. An excess of events over background with a local significance of 5.0 σ is observed at about $m_{H^0} = 125$ GeV. See also CHATRCHYAN 12BY.

NODE=S055HBM;LINKAGE=CH

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

$$H^0$$

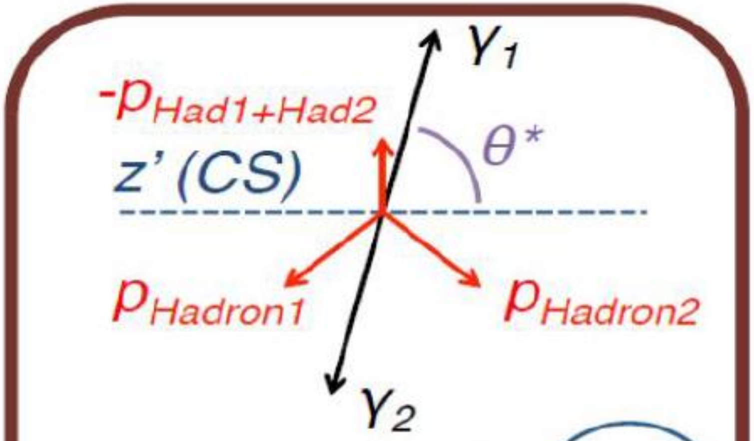
How we can recognize spin?



Spin-0 decays in all directions with equal probability; spin-1 prefers decaying toward or away from the direction of spin; spin-2 prefers the poles and the equator to the region in between. These pictures exaggerate the real distributions for clarity.

Spin observables for H->γγ

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



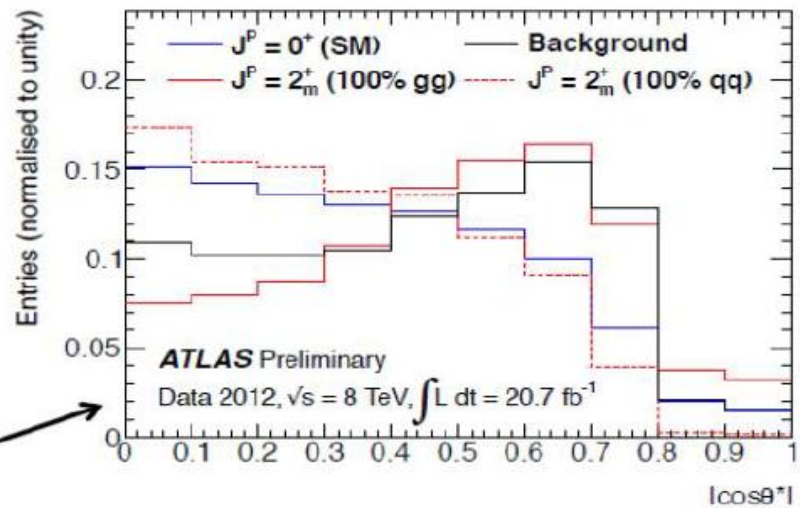
$$\left|\cos\theta^*_{CS}\right| = \frac{\left|\sinh\left(\Delta\eta^{\gamma\gamma}\right)\right|}{\sqrt{1+\left(p_T^{\gamma\gamma}/m_{\gamma\gamma}\right)^2}}\frac{2p_T^{\gamma1}p_T^{\gamma2}}{m_{\gamma\gamma}^2}$$

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

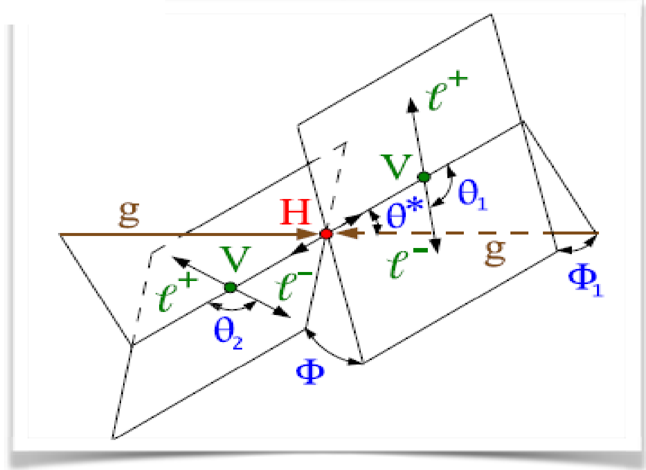
Relative p_T cuts on the photons remove most correlation with $m_{\gamma\gamma}$

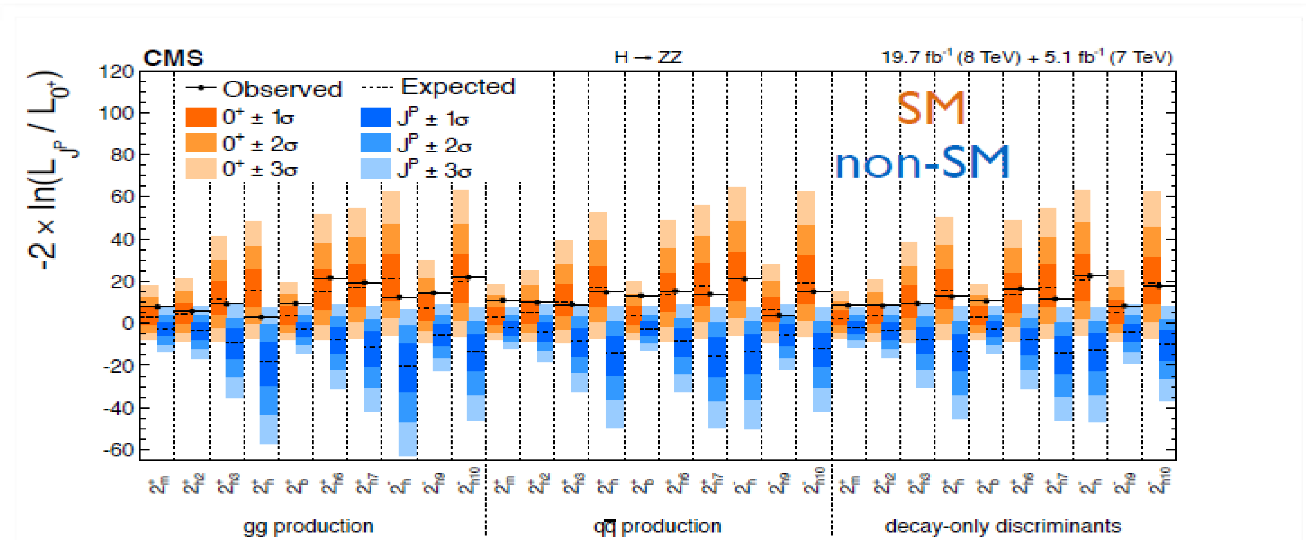
$qq \rightarrow 2^+$ very similar to SM $gg \rightarrow 0^+$



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]

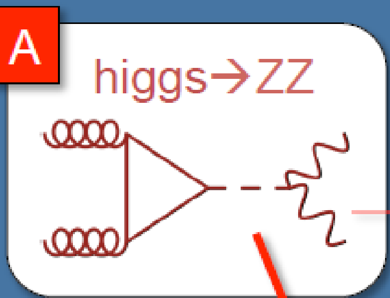
A deviation would imply a decay to non-SM particles

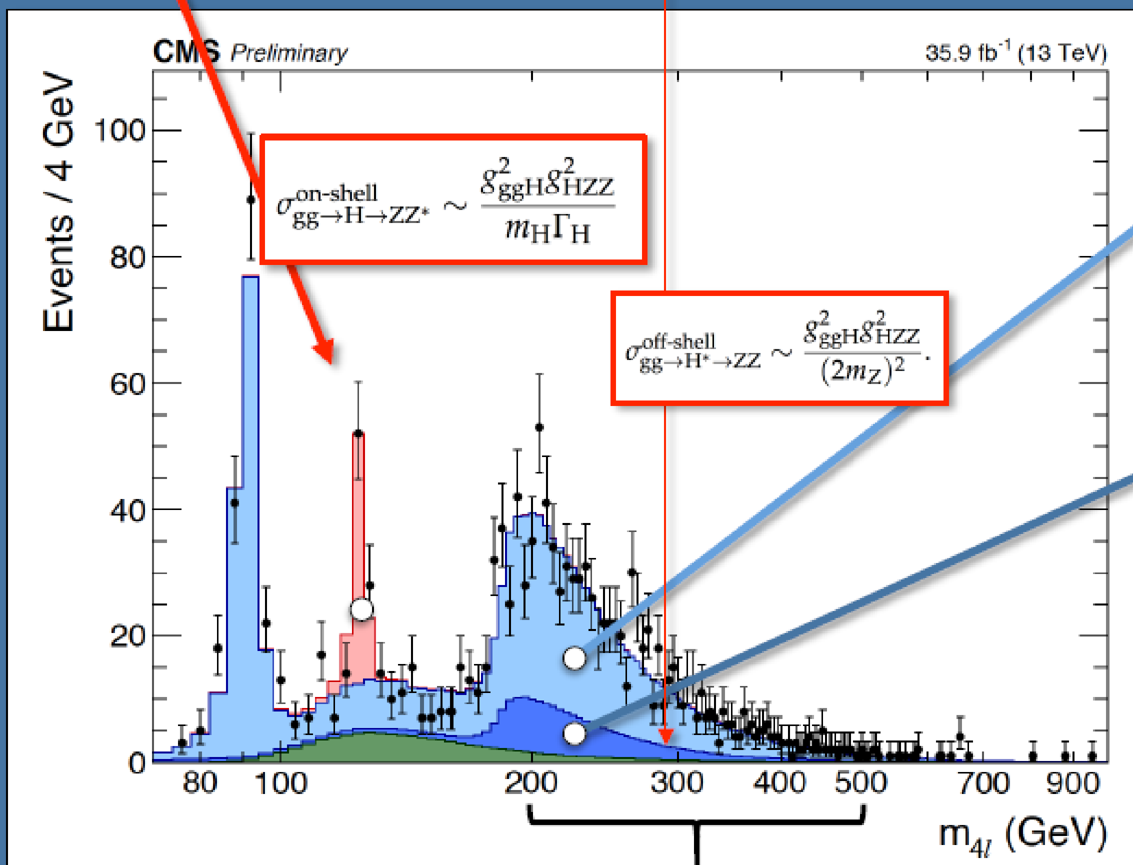
Differential Higgs production cross-section

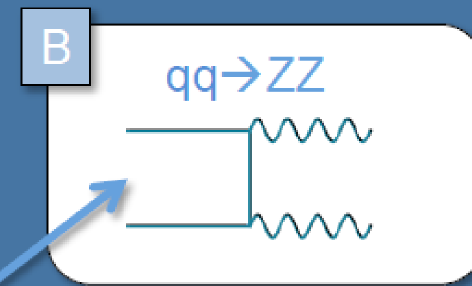
$$\frac{d\sigma_{gg\to H\to ZZ}}{dm^2_{ZZ}} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(m^2_{ZZ} - m^2_H)^2 + m^2_H \Gamma^2_H},$$

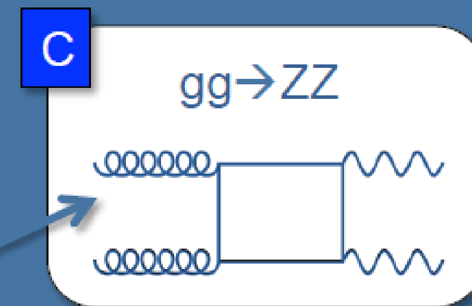
Γ_h cannot be accessed directly (experimental resolution ~ 1-2 GeV)

Indirect measurement









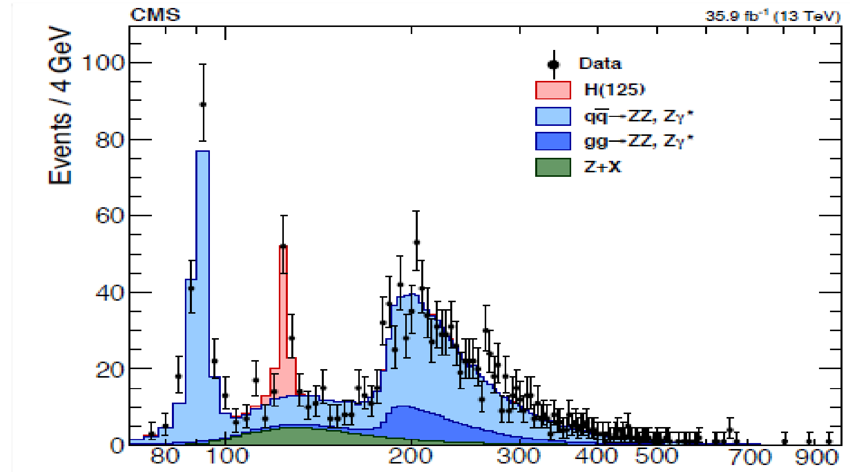
Interference between A and C : $(A+C)^2 = A^2 + C^2 + 2AC$

tiny ←┘ └──→ ***accessible***

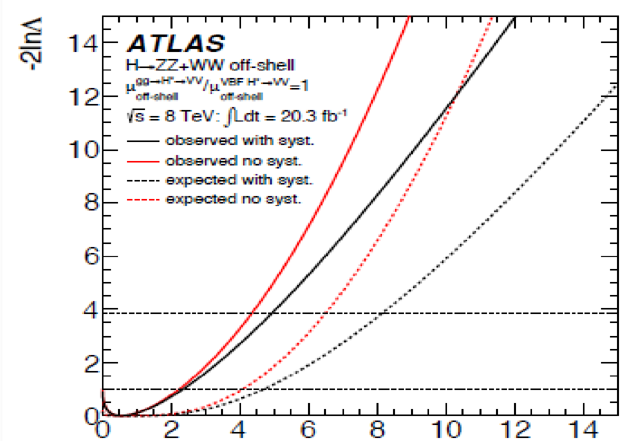
Higgs boson decay width

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

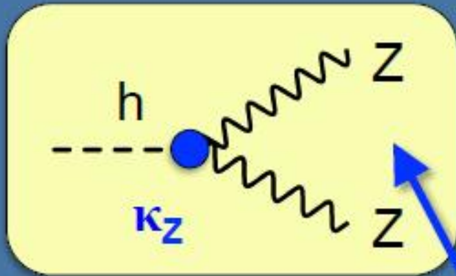
Couplings: kappa-framework

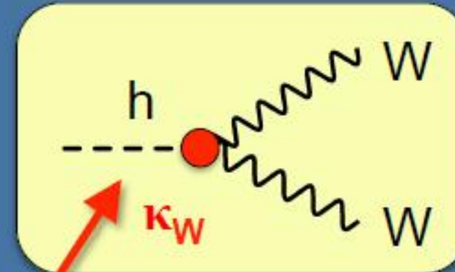
Scale factor for each (fundamental) coupling:

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

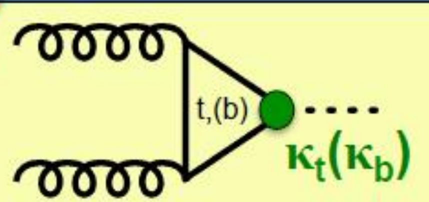
$$\mathcal{L} = \kappa_3 \frac{m_H^2}{2v} H^3 + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu H + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H$$
$$+ \kappa_g \frac{\alpha_s}{12\pi v} G_{\mu\nu}^a G^{a\mu\nu} H + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \kappa_{Z\gamma} \frac{\alpha}{\pi v}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

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

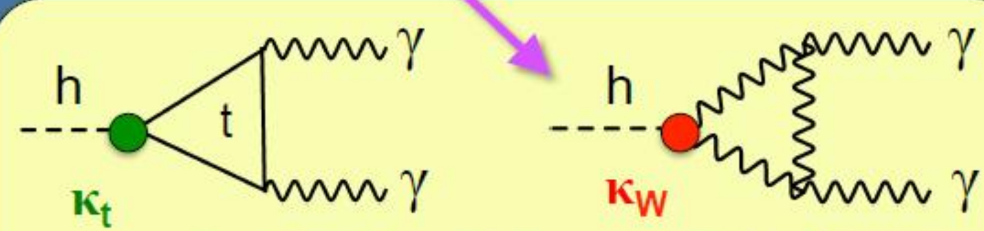




$$\mathcal{L} = \kappa_3 \frac{m_H^2}{2v} H^3 + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu H + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H$$
$$+ \kappa_g \frac{\alpha_s}{12\pi v} G_{\mu\nu}^a G^{a\mu\nu} H + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \kappa_{Z\gamma} \frac{\alpha}{\pi v}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



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



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

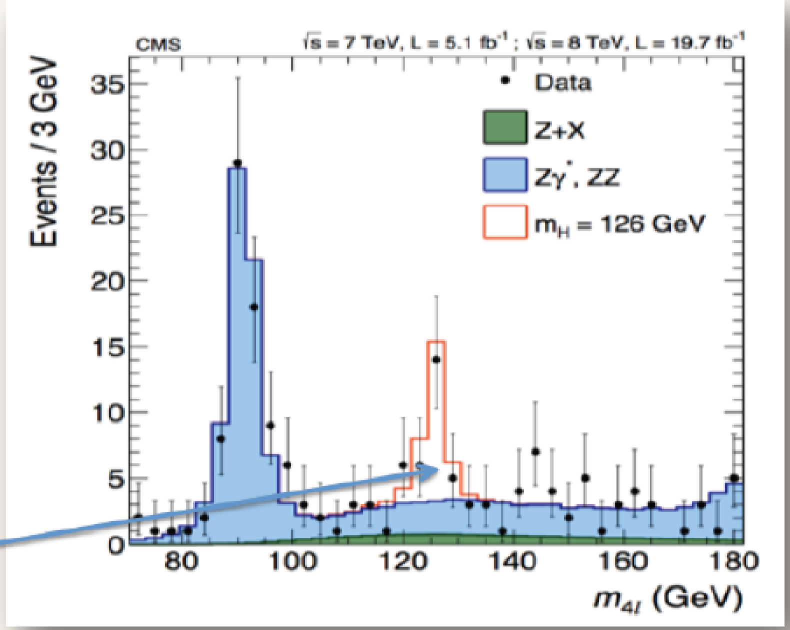
What do we measure?

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



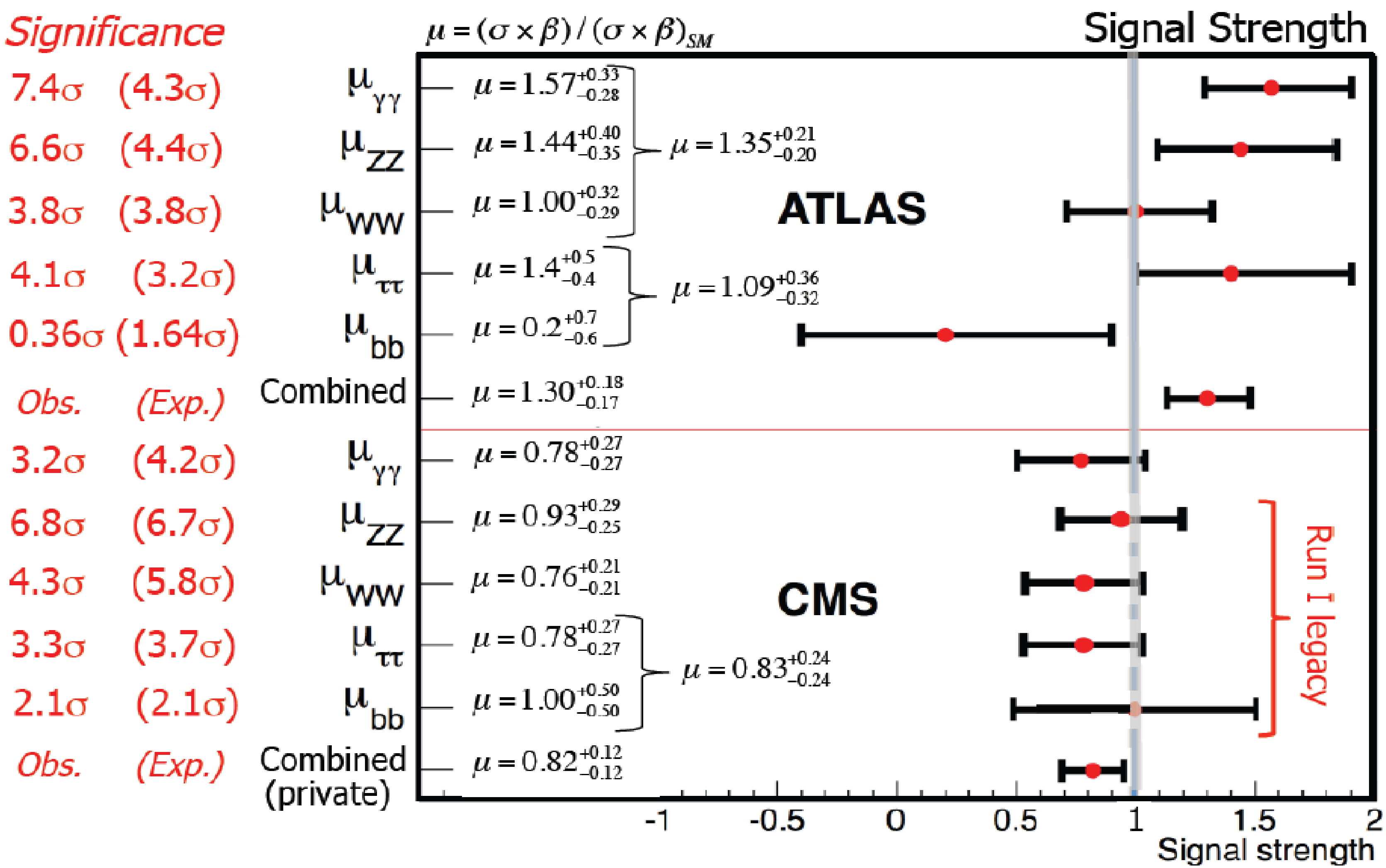
$$n_s^i = \mu^i \times \sum_p (\sigma^p \times Br^i)_{SM} \times A_p^i \times \varepsilon_p^i \times Lumi$$

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

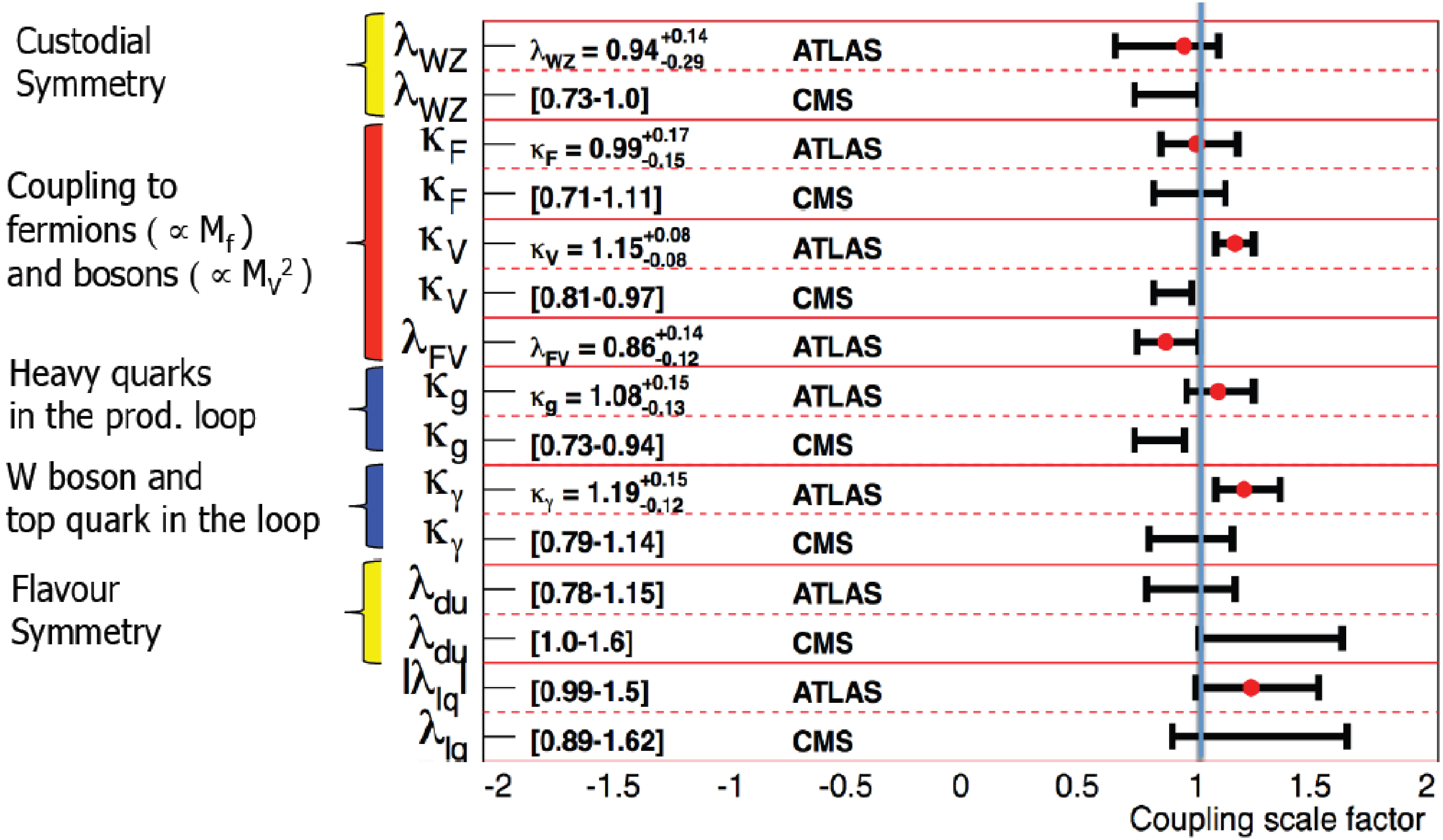
μ^{ZZ}(@125.5 GeV) = 1.44 $^{+0.40}_{-0.35}$ 6.6σ (4.4 exp) ATLAS

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

Higgs boson decay channels

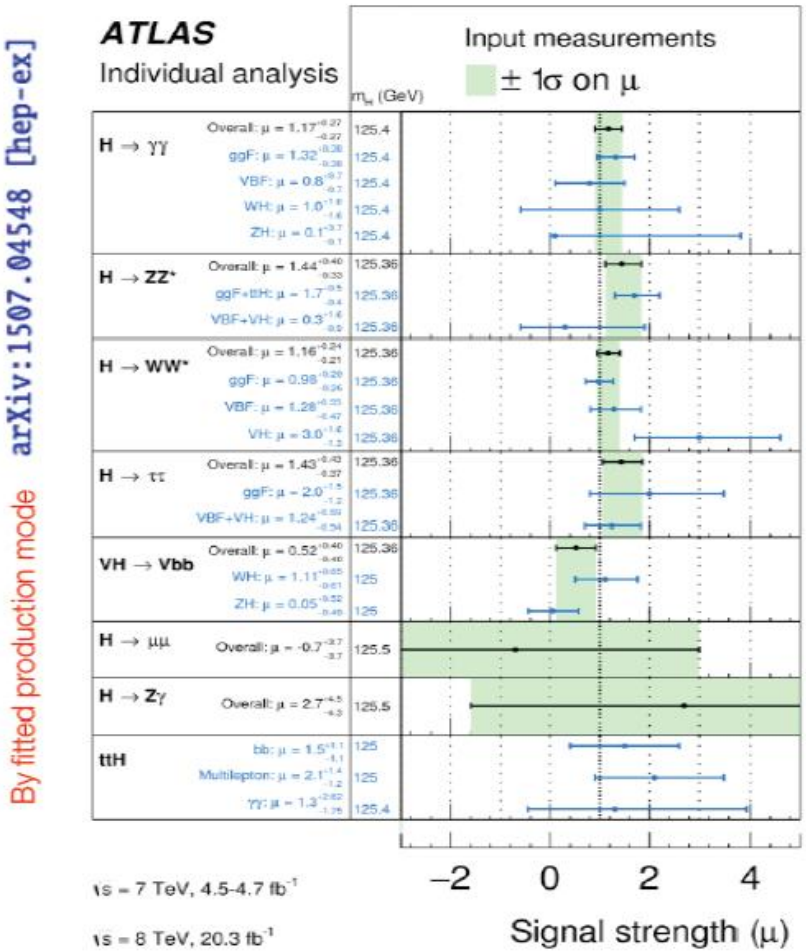


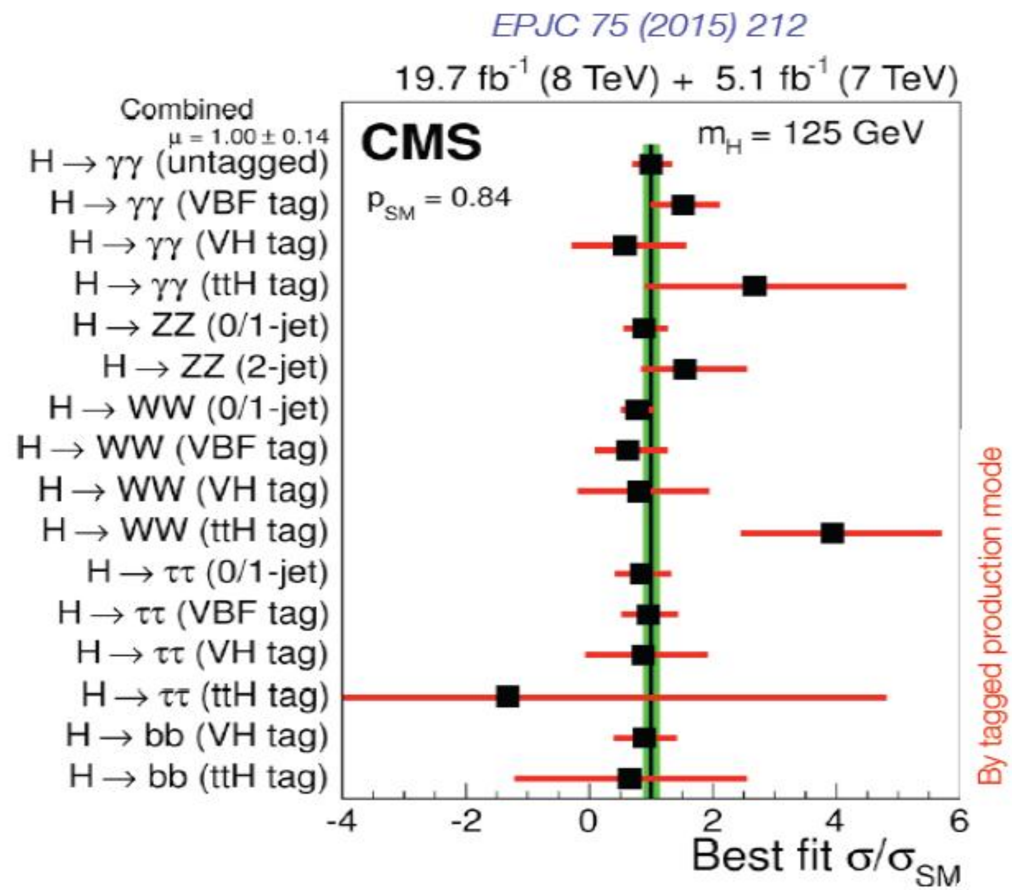
Overall comparison of all couplings results



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

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

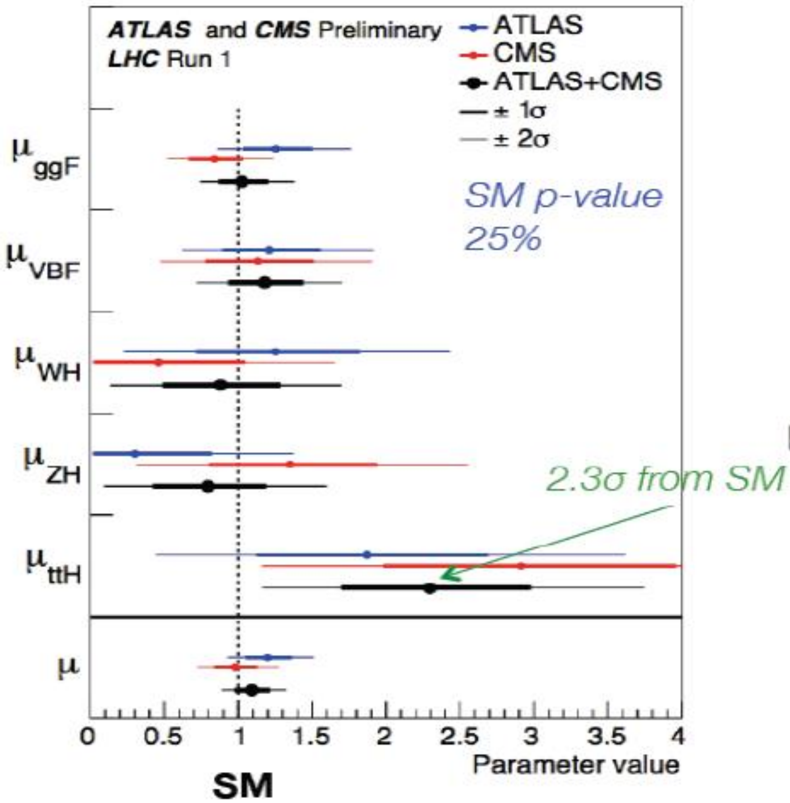
Most precise result at the expense of the largest assumptions

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

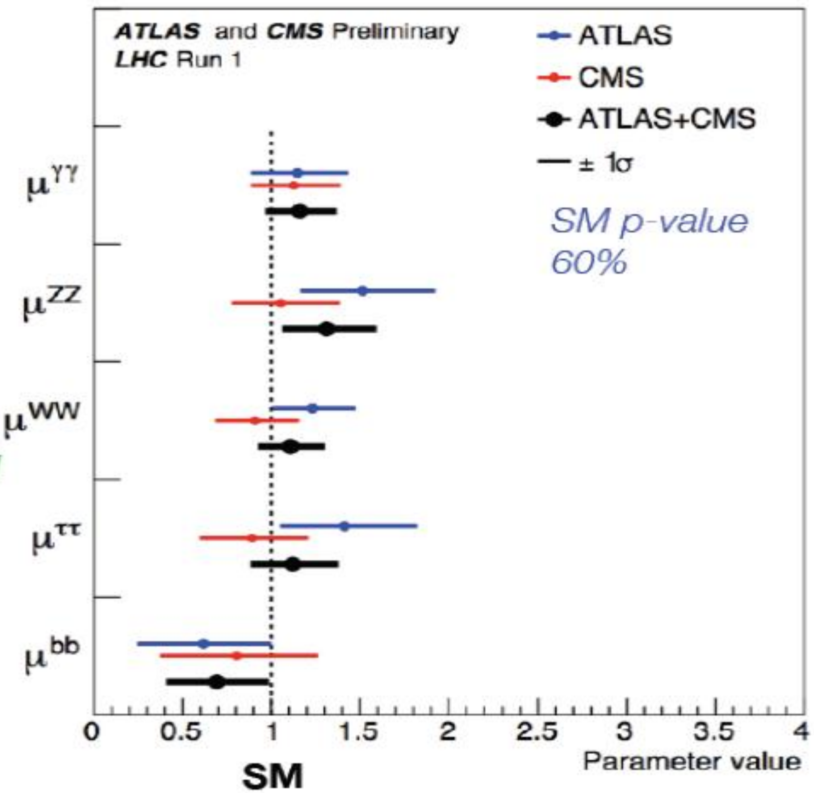
Stat and Th.Sig of comparable size
(Th.Sig dominated by ggF cross-section uncertainty)

Signal strength by production and decay mode

Production signal strengths
(SM values of BRs assumed)

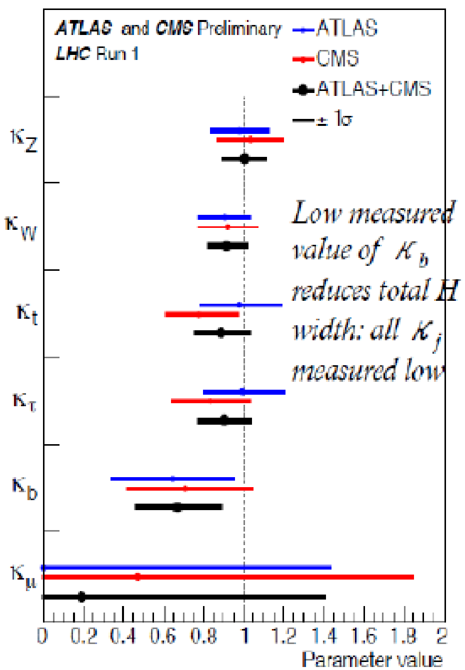


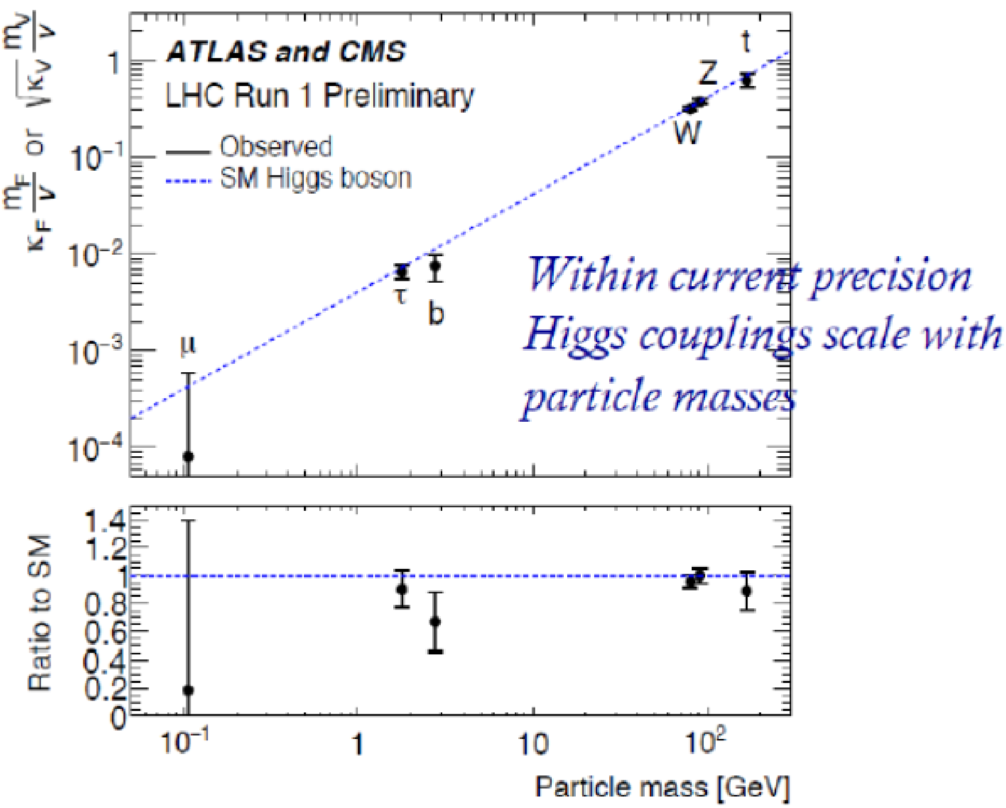
Decay signal strengths
(SM value of production σ's assumed)



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





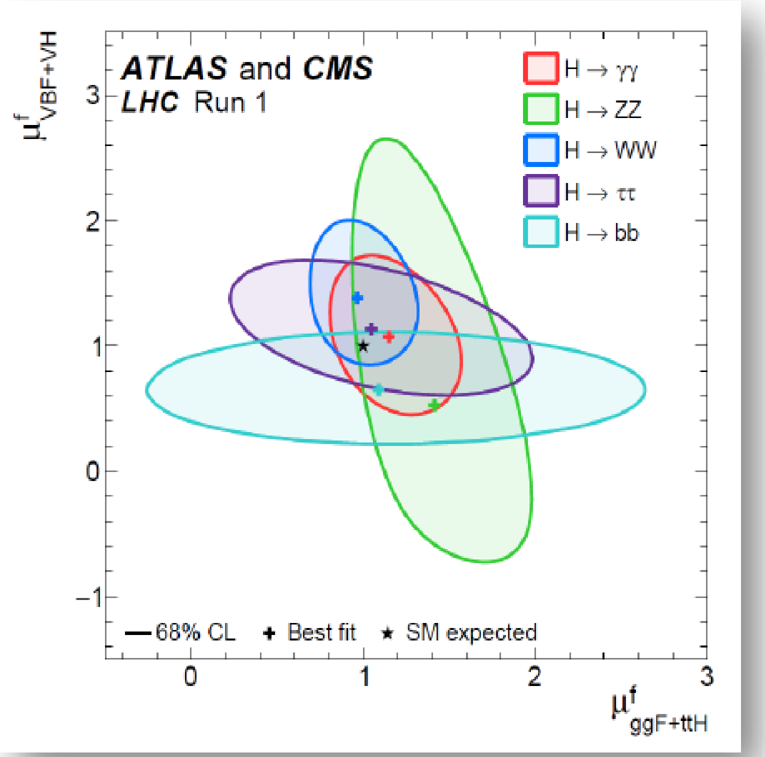
Concluding Higgs couplings measurements

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 5σ 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 do we know from Run I

- Discovery of a new neutral scalar boson, first in diboson, then in di-fermion decays
- Observations:
  - $H \to \gamma\gamma$, $H \to ZZ \to 4l$
  - $H \to WW \to 2l2\nu$
  - $H \to \tau\tau$
  - 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 $J^{PC} = 0^{++}$

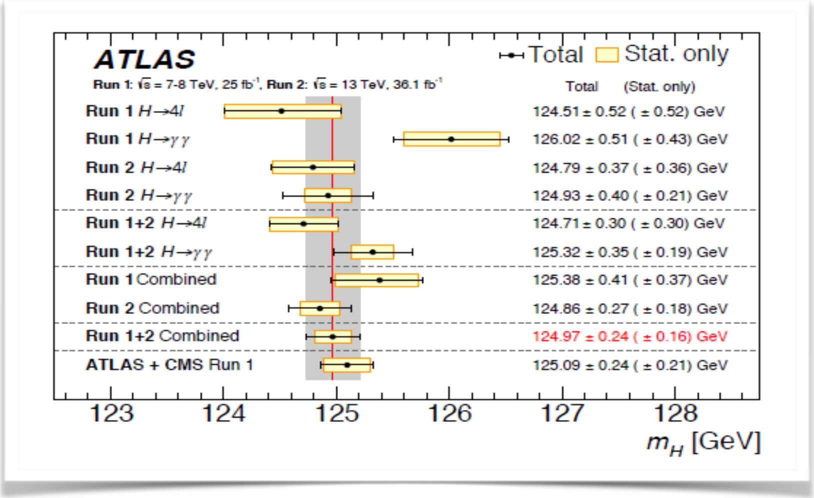
- Initial compatibility with the Standard Model Higgs

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

Run II : Higgs boson mass

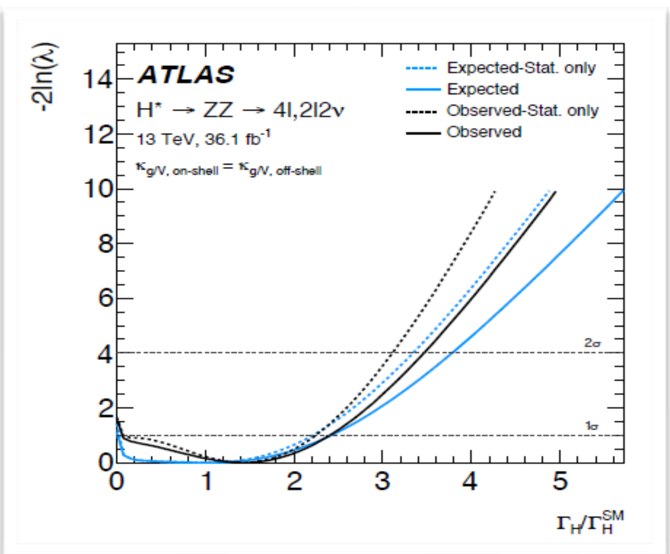
Higgs Properties

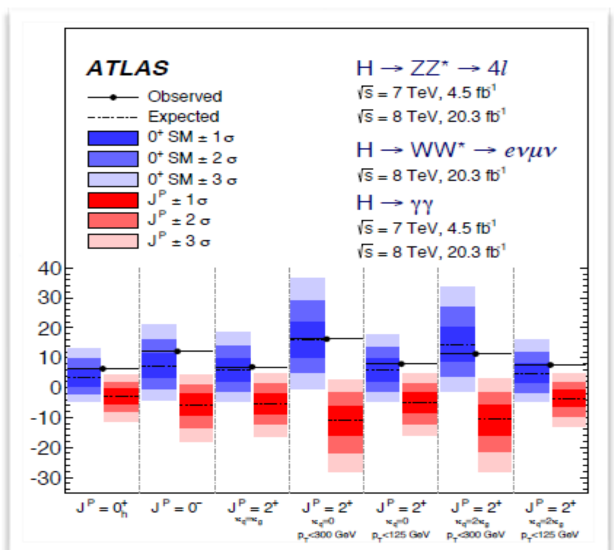
- Mass: 124.97 ± 0.24 GeV
- (Indirect) width: < 14.4 MeV
  - (15.2 MeV)
- Spin and parity $J^{PC} = 0^{++}$
- Couplings



PLB784 (2018) 345

PLB786 (2018) 223





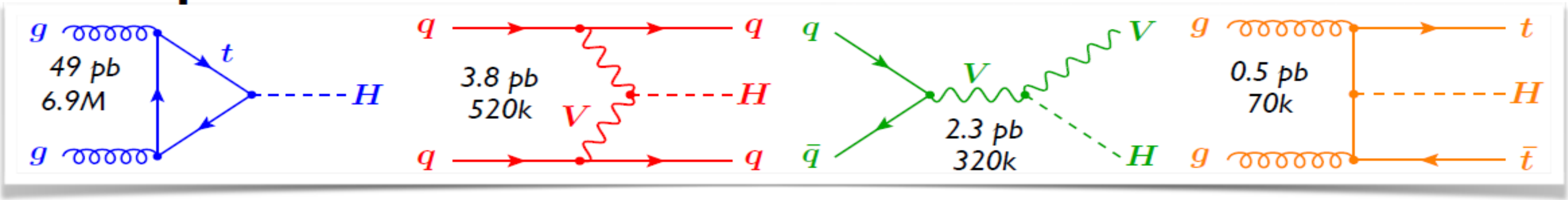
EPJC75 (2015) 476

Run II : Higgs boson couplings

Probing Higgs Couplings at the LHC

σ [pb]
#Higgs produced during Run-2

4 main production modes

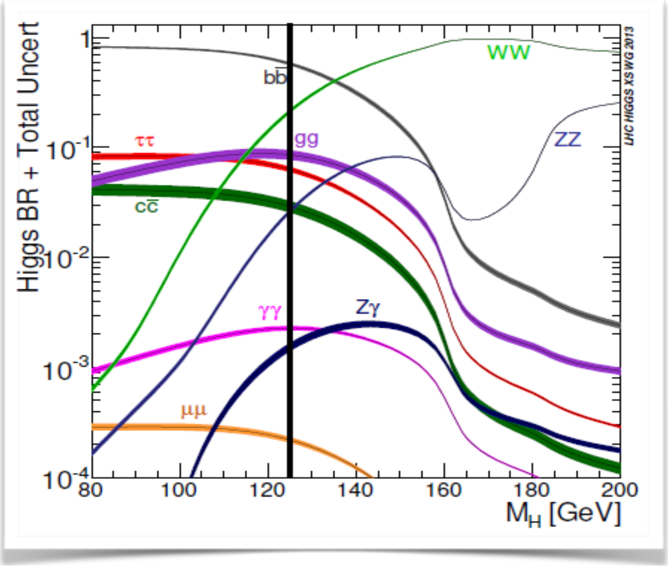


Main production channel: gluon-gluon fusion

2 forward jets, little central hadronic activity

Tag W and Z decays

Tag 2 top quarks



5 key decay channels

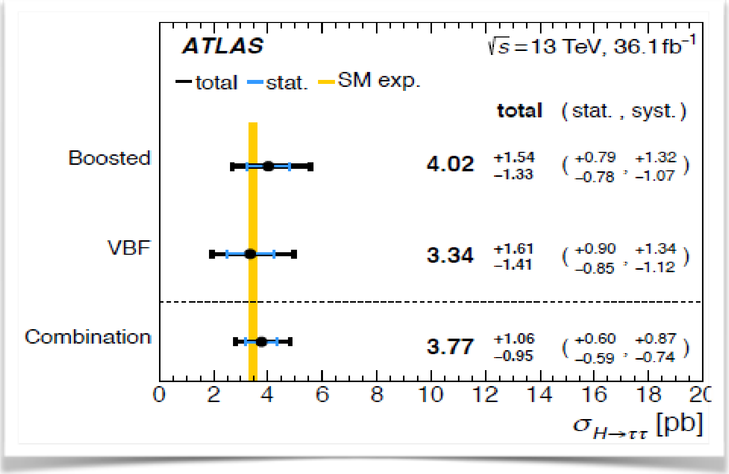
- H→bb: 58 %
- H→WW*: 21%
- H→$\tau^+\tau^-$: 6.3%
- H→ZZ*: 2.6%
- H→γγ: 0.23%

Decay branching fractions for m_H = 125 GeV

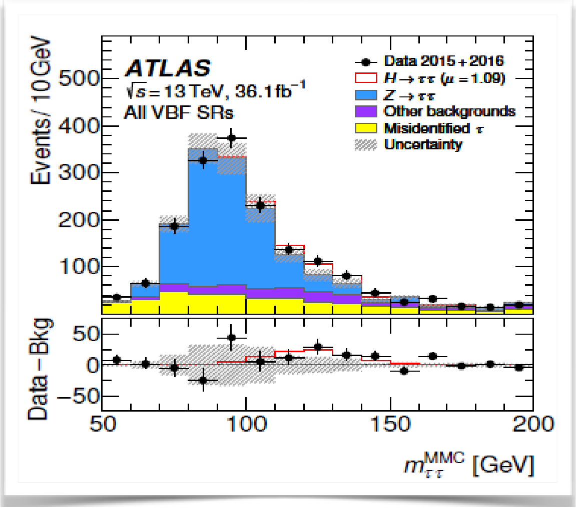
Run II : Higgs boson couplings to fermions

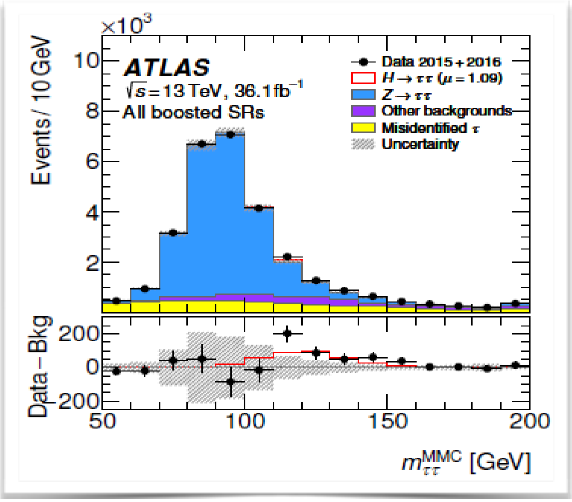
Observation of coupling to τ-leptons

- 5.5 (5.0)σ for H→ττ (ATLAS/CMS Run-1)
- 6.4 (5.4)σ from ATLAS (7-13 TeV results)
- Sensitive decay channel for VBF production
  - ggF: 3.1 ± 0.1 (stat) $^{+0.1.6}_{-1.3}$ (syst.) pb
    - (SM: 3.05 ± 0.13 pb)
  - VBF:0.28 ± 0.09 (stat)$^{+0.11}_{-0.9}$ (syst.) pb
    - (SM: 0.237 ± 0.006 pb)



JHEP08(2016)045, arXiv:1811.08856

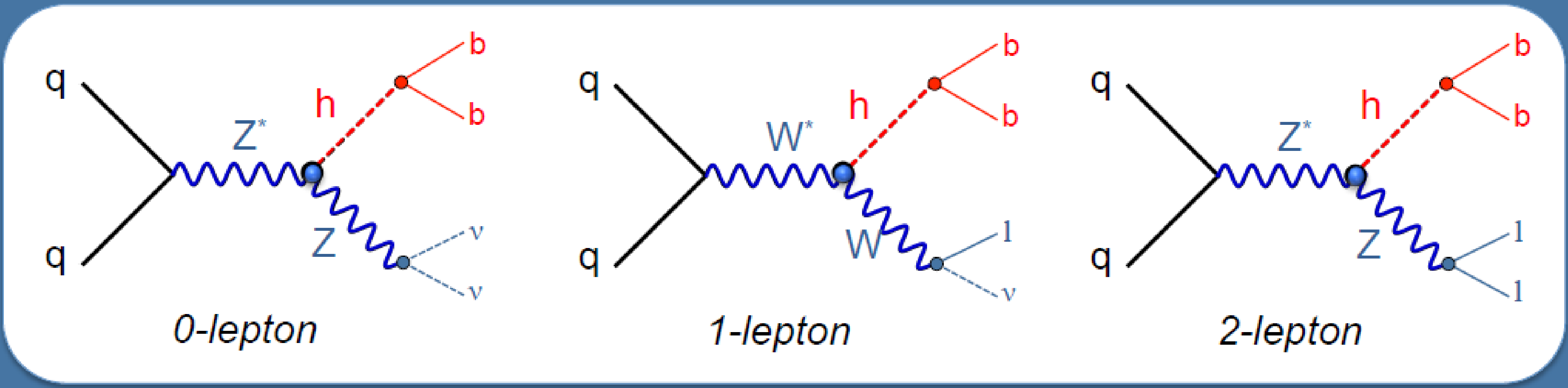




Higgs decay to b-quarks

$Br(h \rightarrow bb) = 0.577$

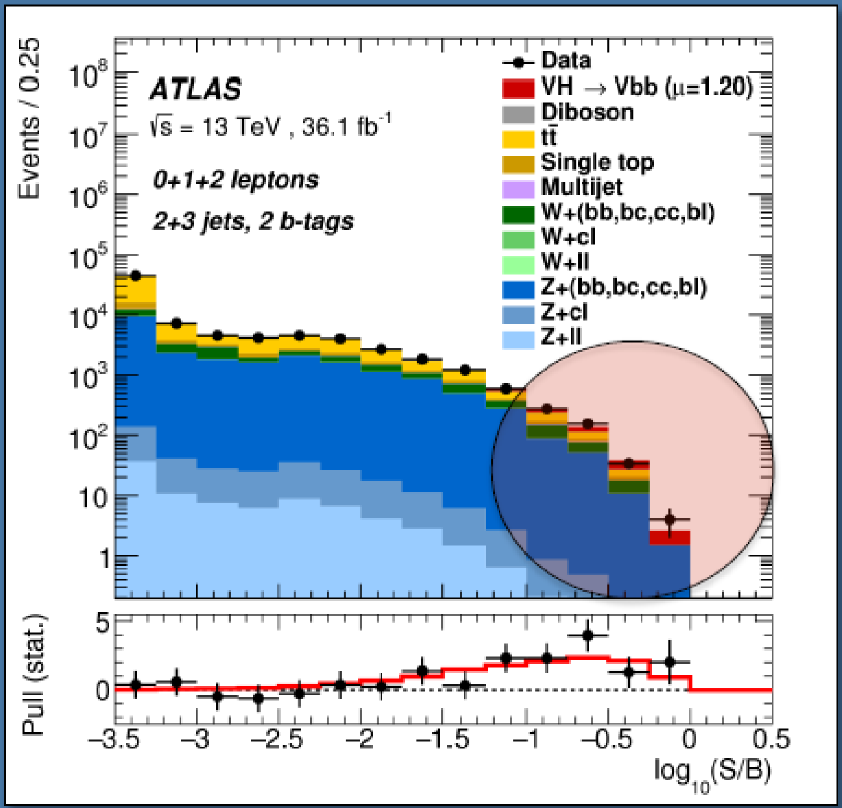
Enormous QCD bb background. Highest sensitivity in the VBF channel.



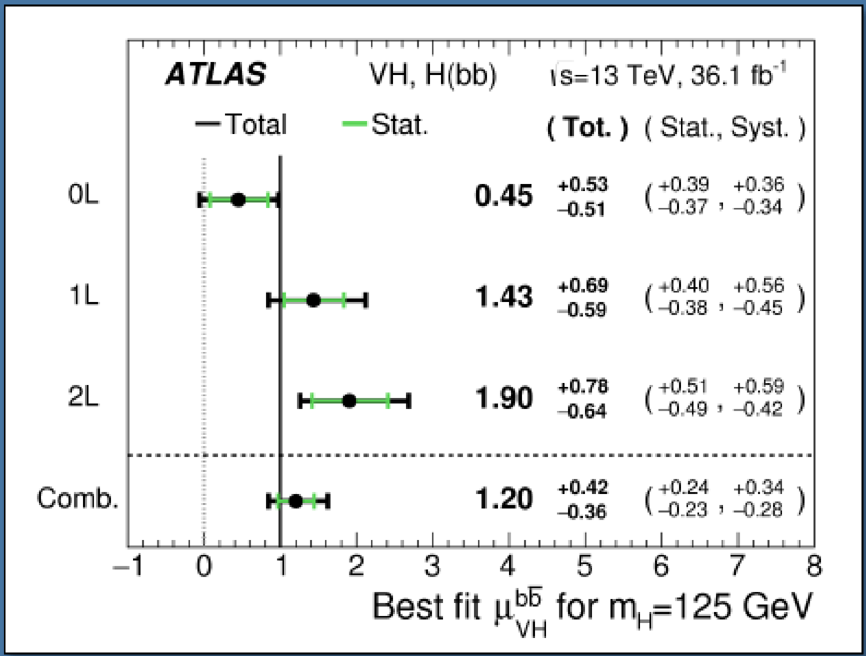
- Categories: jet multiplicity & transverse momentum vector boson (dedicated boosted decision tree for each category)
- Validation using VV channels ($\sigma_{VV(bb)} \sim 9x\sigma_{VH(bb)}$)

h→bb: analysis for √s=13 TeV

Combined BDT(S/B) ranking

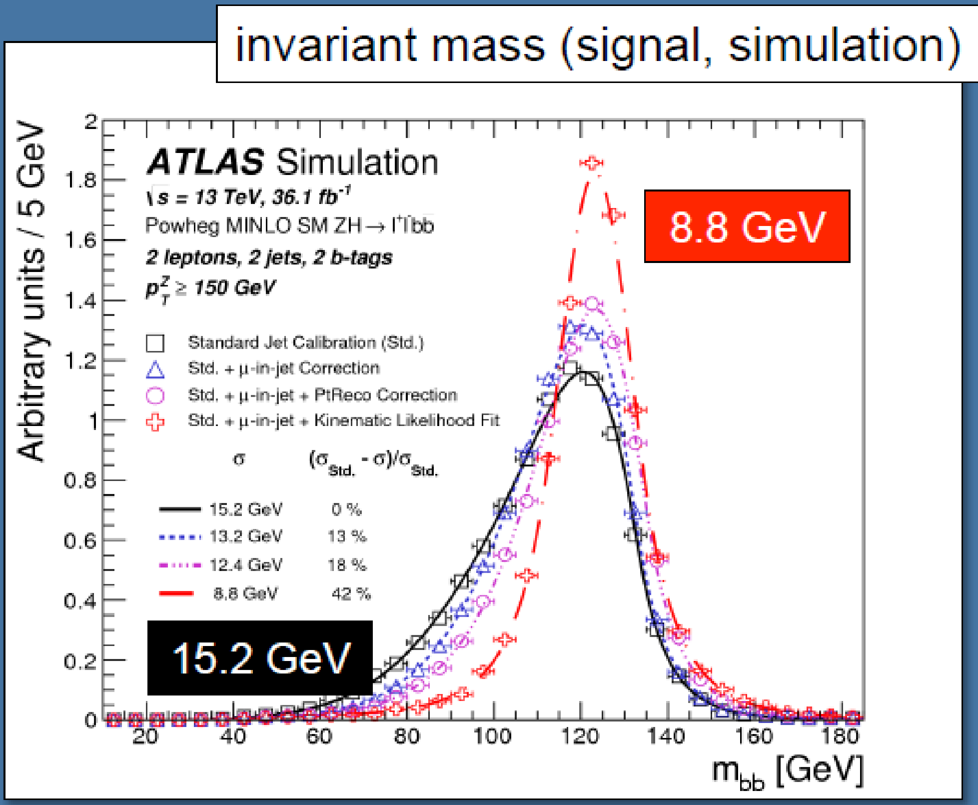


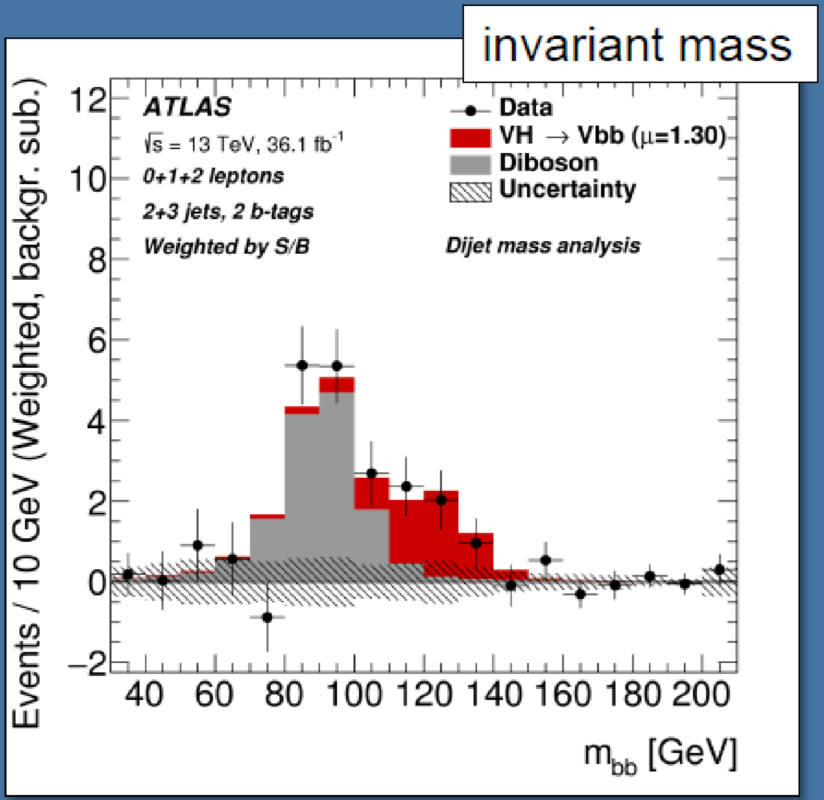
Production rates topology: 0l, 1l, 2l



$$\mu = 1.20^{+0.24}_{-0.23}(stat.)^{+0.34}_{-0.28}(syst.)$$

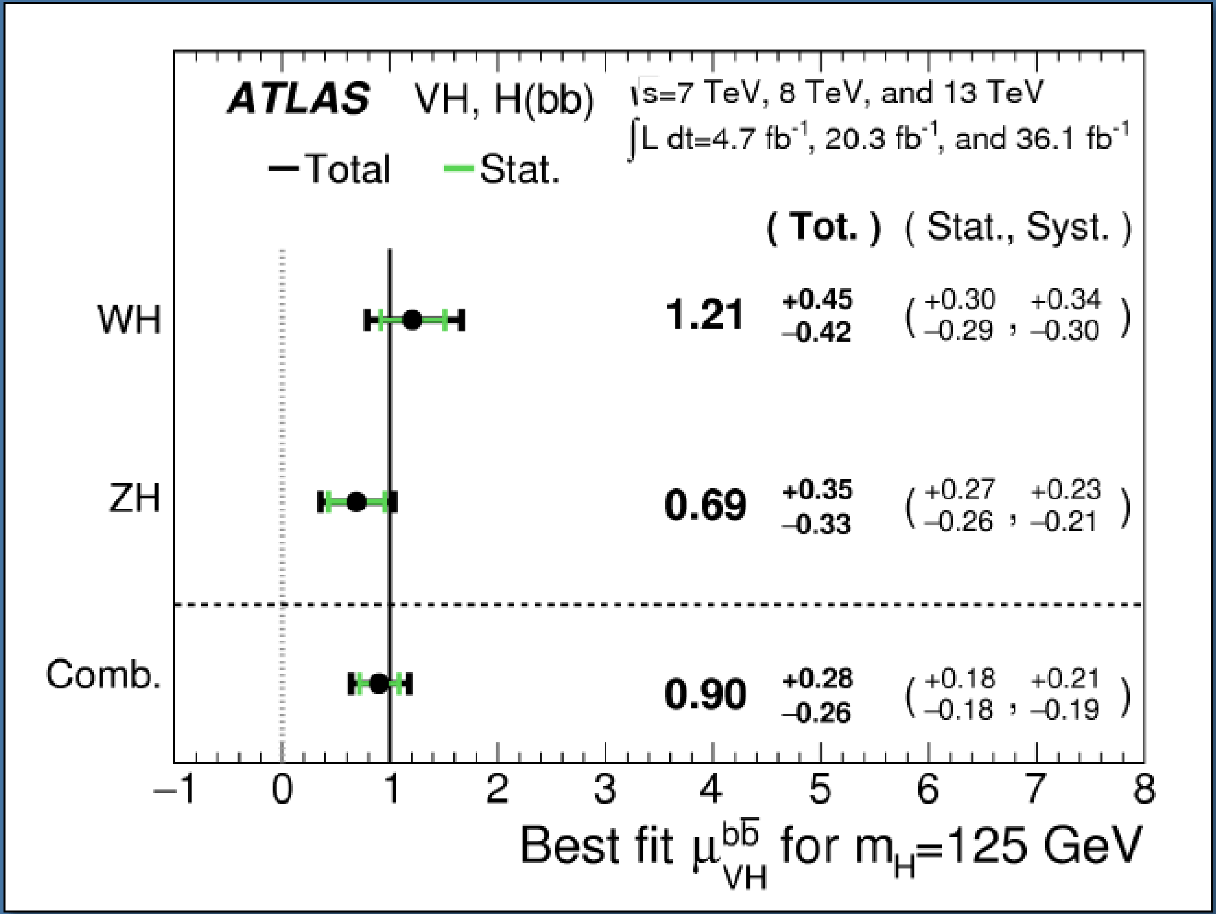
H→bb: invariant mass distribution





Resolution improvement in channel:
2 leptons, 2 jets, 2 b-tags, $P_T^V \geq 150$ GeV

H→bb: RUN1 & RUN2 combination

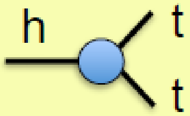


3.6 sigma excess ←

$$\mu = 0.90 \pm 0.18(stat.)^{+0.21}_{-0.19}(syst.)$$

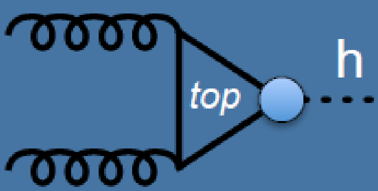
Top Yukawa coupling

Top-Yukawa



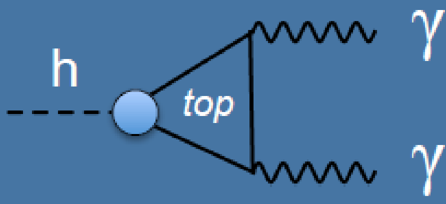
$$\lambda_t = \frac{m_t\sqrt{2}}{V} = 0.996$$

INDIRECT

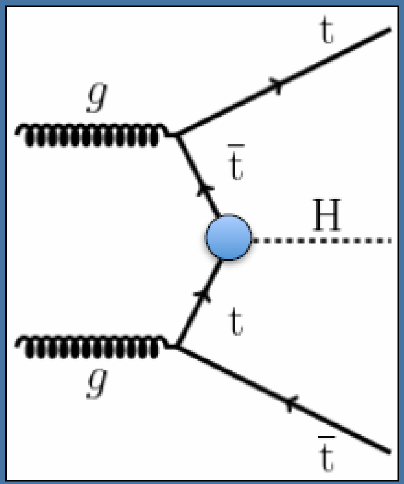


Production:
gluon fusion

Decay:
gluon fusion



DIRECT



b-jet + qq/lν

bb
4l
γγ

b-jet + qq/lν

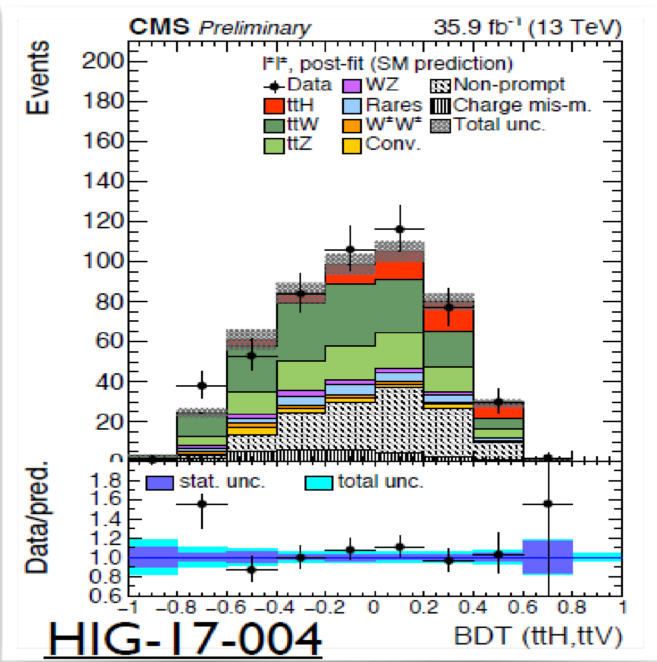
- 1% of gluon-fusion process
- (many) complex final states
  … very very difficult

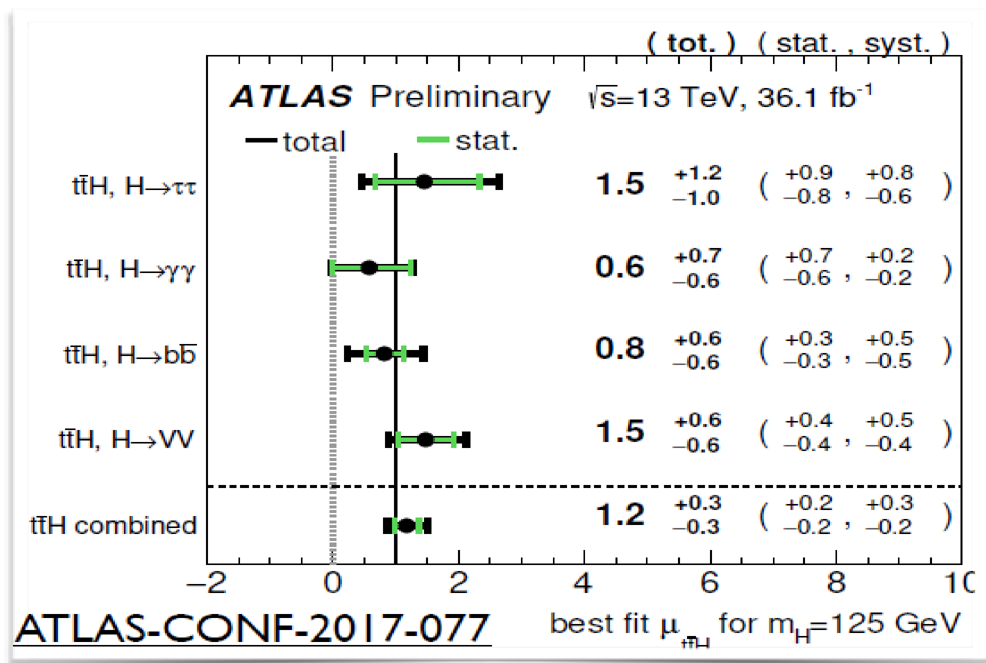
RUN1 ATLAS: $\mu = 1.9 \pm 0.8$

Higgs boson couplings to top quarks

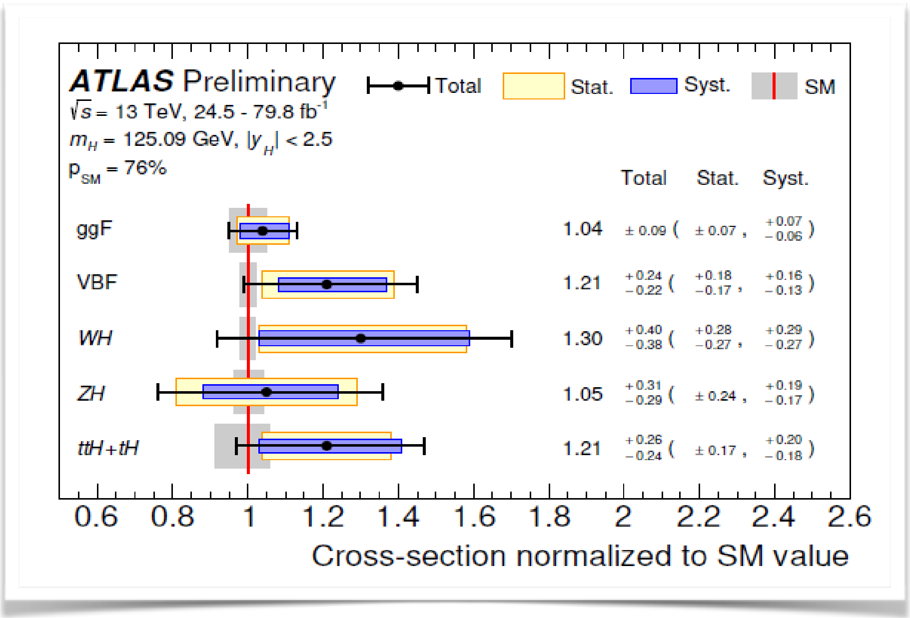
Direct evidence for coupling to top quarks

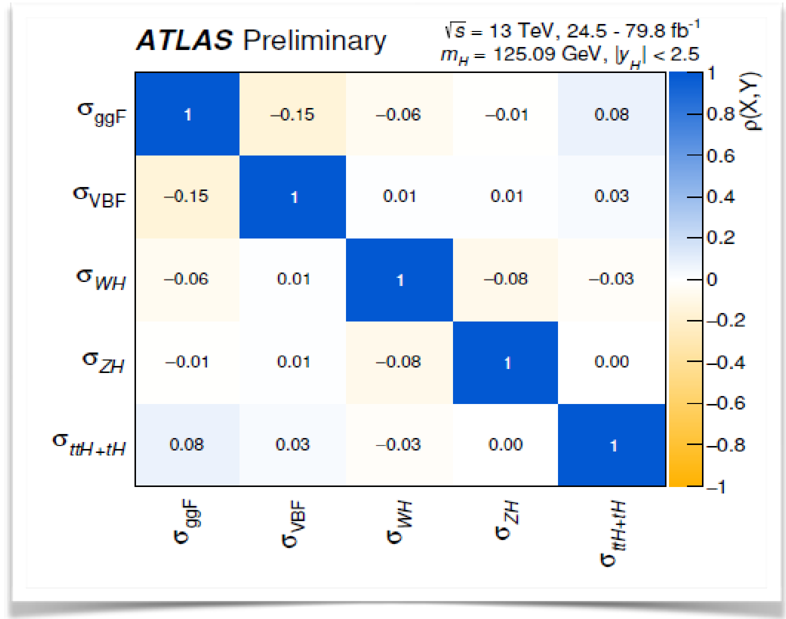
- ttH production provides a probe of the direct coupling of the Higgs boson to top quarks
- 3.3σ evidence for ttH production from CMS using leptonic final states
- 4.2σ evidence from ATLAS from combination of five major decay modes





Higgs boson production modes





- Significances above 5σ are obtained for ggF, VBF (6.5σ), VH (5.3σ) and ttH (5.8σ) production modes when assuming SM branching ratios
- Low correlations between production modes
- Results are consistent with predictions from the Standard Model

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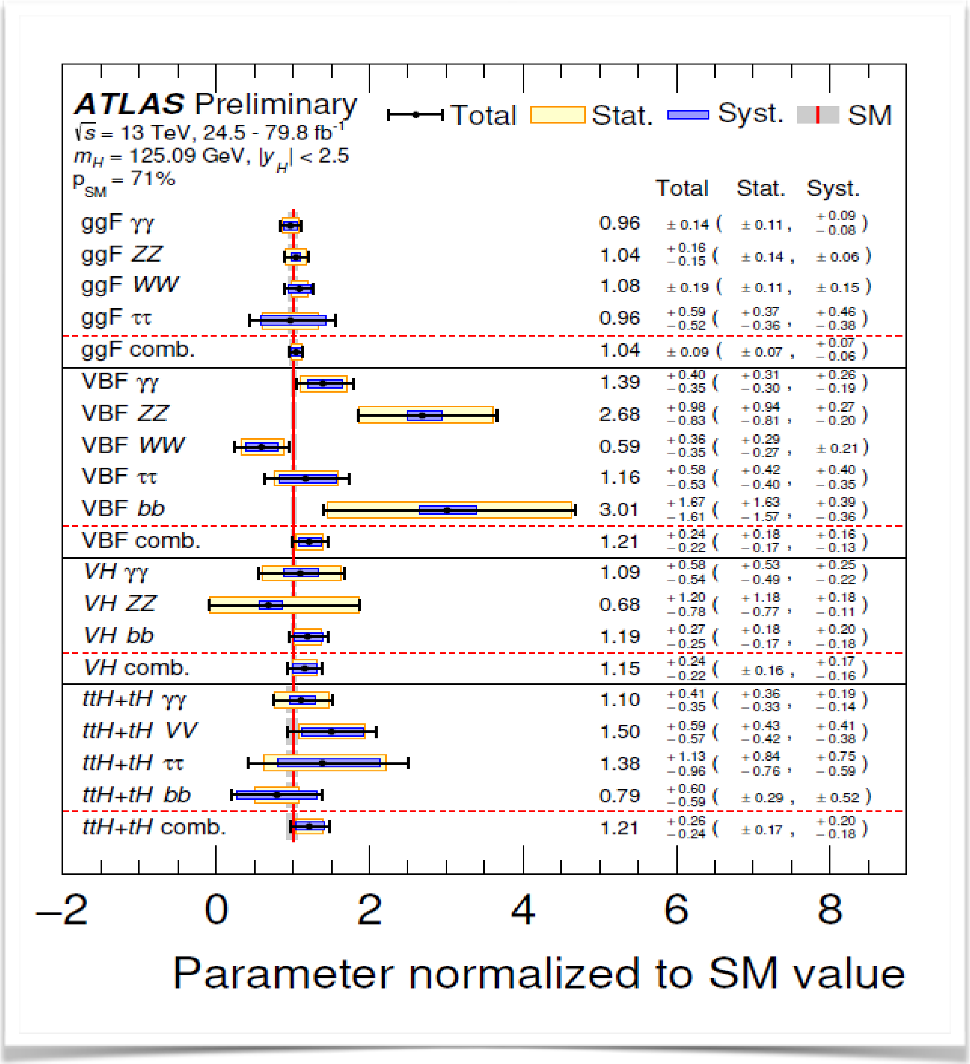
Production and decay modes



Fix production/decays with low sensitivity to SM values

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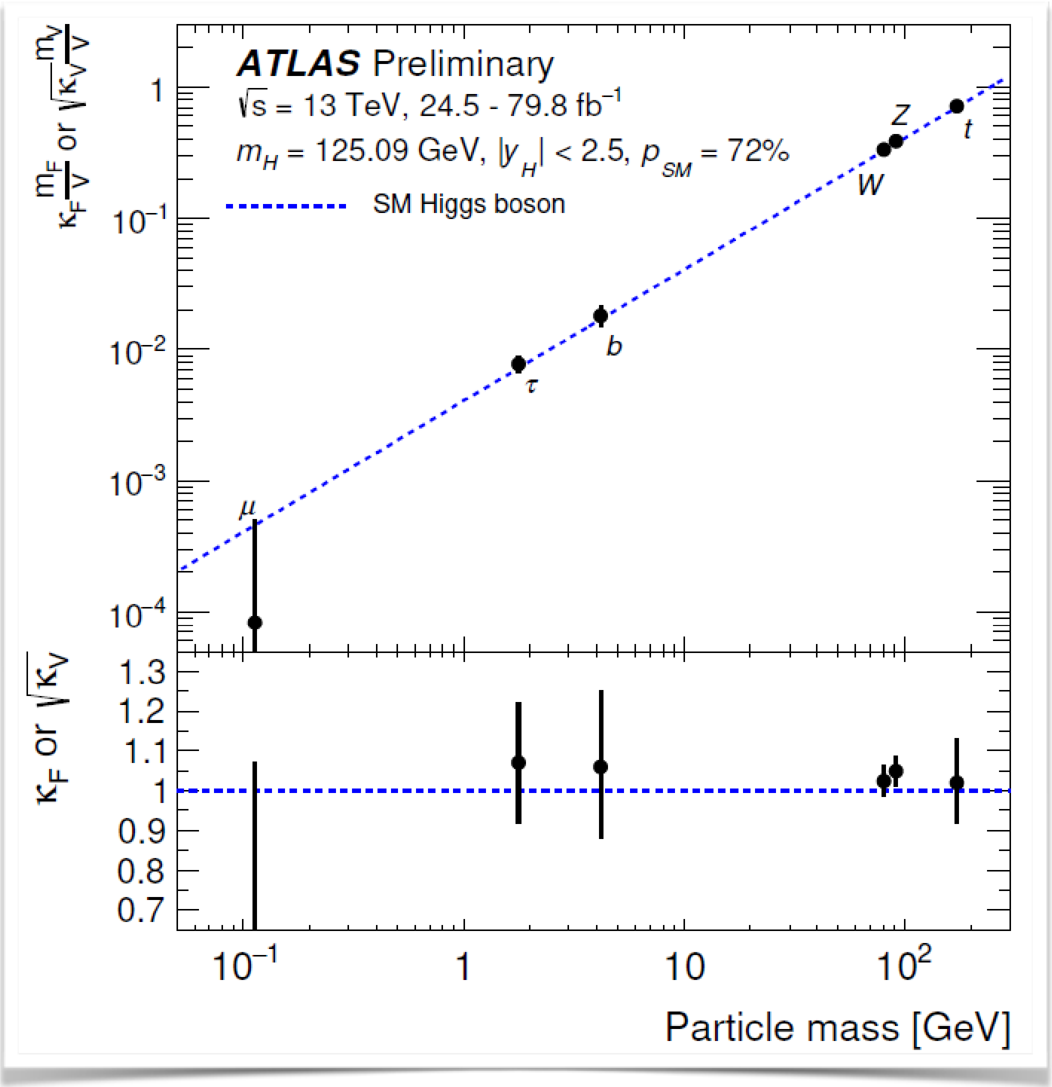
Couplings vs mass



Interpret the results in the κ framework as a function of the particle mass assuming no BSM contributions to the total width

$$\kappa_j^2 = \frac{\sigma_j}{\sigma_j^{\mathrm{SM}}} \quad \text{or} \quad \kappa_j^2 = \frac{\Gamma^j}{\Gamma^j_{\mathrm{SM}}}$$

ATLAS-CONF-2019-005

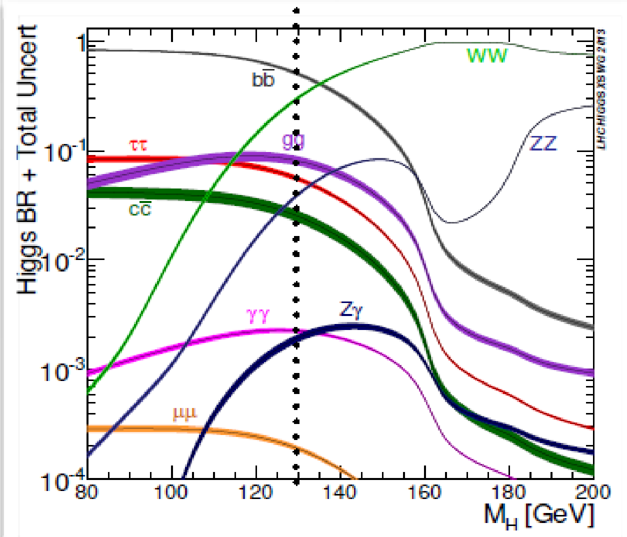
ATLAS combination

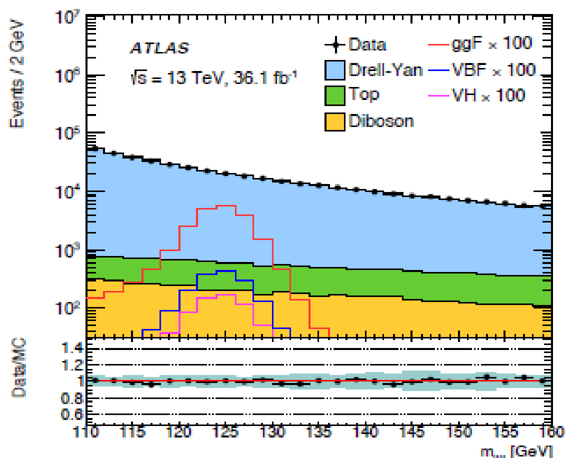
	$H\to\gamma\gamma$	$H\to ZZ^*$	$H\to WW^*$	$H\to\tau\tau$	$H\to b\bar{b}$
$t\bar{t}H$	$t\bar{t}H$ leptonic (3 categories) $t\bar{t}H$ hadronic (4 categories)	$t\bar{t}H$ multilepton 1 ℓ + 2 τ_{had} $t\bar{t}H$ multilepton 2 opposite-sign ℓ + 1 τ_{had} $t\bar{t}H$ multilepton 2 same-sign ℓ (categories for 0 or 1 τ_{had}) $t\bar{t}H$ multilepton 3 ℓ (categories for 0 or 1 τ_{had}) $t\bar{t}H$ multilepton 4 ℓ (except $H\to ZZ^*\to 4\ell$) $t\bar{t}H$ leptonic, $H\to ZZ^*\to 4\ell$ $t\bar{t}H$ hadronic, $H\to ZZ^*\to 4\ell$			$t\bar{t}H$ 1 ℓ, boosted $t\bar{t}H$ 1 ℓ, resolved (11 categories) $t\bar{t}H$ 2 ℓ (7 categories)
VH	VH 2 ℓ VH 1 ℓ, $p_T^{\ell+E_T^{\mathrm{miss}}} \geq 150$ GeV VH 1 ℓ, $p_T^{\ell+E_T^{\mathrm{miss}}} <150$ GeV VH E_T^{miss}, $E_T^{\mathrm{miss}} \geq 150$ GeV VH E_T^{miss}, $E_T^{\mathrm{miss}} <150$ GeV VH+VBF $p_T^{j1} \geq 200$ GeV VH hadronic (2 categories)	VH leptonic 0-jet, $p_T^{4\ell} \geq 100$ GeV 2-jet, $m_{jj} < 120$ GeV			2 ℓ, $75 \leq p_T^V < 150$ GeV, $N_{\mathrm{jets}} = 2$ 2 ℓ, $75 \leq p_T^V < 150$ GeV, $N_{\mathrm{jets}} \geq 3$ 2 ℓ, $p_T^V \geq 150$ GeV, $N_{\mathrm{jets}} = 2$ 2 ℓ, $p_T^V \geq 150$ GeV, $N_{\mathrm{jets}} \geq 3$ 1 ℓ $p_T^V \geq 150$ GeV, $N_{\mathrm{jets}} = 2$ 1 ℓ $p_T^V \geq 150$ GeV, $N_{\mathrm{jets}} = 3$ 0 ℓ, $p_T^V \geq 150$ GeV, $N_{\mathrm{jets}} = 2$ 0 ℓ, $p_T^V \geq 150$ GeV, $N_{\mathrm{jets}} = 3$
VBF	VBF, $p_T^{\gamma\gamma jj} \geq 25$ GeV (2 categories) VBF, $p_T^{\gamma\gamma jj} <25$ GeV (2 categories)	2-jet VBF, $p_T^{j1} \geq 200$ GeV 2-jet VBF, $p_T^{j1} <200$ GeV	2-jet VBF	VBF $p_T^{\tau\tau} > 140$ GeV ($\tau_{\mathrm{had}}\tau_{\mathrm{had}}$ only) VBF high-m_{jj} VBF low-m_{jj}	VBF, two central jets VBF, four central jets VBF +γ
ggF	2-jet, $p_T^{\gamma\gamma} \geq 200$ GeV 2-jet, 120 GeV $\leq p_T^{\gamma\gamma}$¡200 GeV 2-jet, 60 GeV $\leq p_T^{\gamma\gamma}$¡120 GeV 2-jet, $p_T^{\gamma\gamma} < 60$ GeV 1-jet, $p_T^{\gamma\gamma} \geq 200$ GeV 1-jet, 120 GeV $\leq p_T^{\gamma\gamma}$¡200 GeV 1-jet, 60 GeV $\leq p_T^{\gamma\gamma}$¡120 GeV 1-jet, $p_T^{\gamma\gamma} < 60$ GeV 0-jet (2 categories)	1-jet, $p_T^{4\ell} \geq 120$ GeV 1-jet, 60 GeV$\leq p_T^{4\ell}$¡120 GeV 1-jet, $p_T^{4\ell} < 60$ GeV 0-jet, $p_T^{4\ell} < 100$ GeV	1-jet, $m_{\ell\ell} < 30$ GeV, $p_T^{\ell 2} < 20$ GeV 1-jet, $m_{\ell\ell} < 30$ GeV, $p_T^{\ell 2} \geq 20$ GeV 1-jet, $m_{\ell\ell} \geq 30$ GeV, $p_T^{\ell 2} < 20$ GeV 1-jet, $m_{\ell\ell} \geq 30$ GeV, $p_T^{\ell 2} \geq 20$ GeV 0-jet, $m_{\ell\ell} < 30$ GeV, $p_T^{\ell 2} < 20$ GeV 0-jet, $m_{\ell\ell} < 30$ GeV, $p_T^{\ell 2} \geq 20$ GeV 0-jet, $m_{\ell\ell} \geq 30$ GeV, $p_T^{\ell 2} < 20$ GeV 0-jet, $m_{\ell\ell} \geq 30$ GeV, $p_T^{\ell 2} \geq 20$ GeV	Boosted, $p_T^{\tau\tau} > 140$ GeV Boosted, $p_T^{\tau\tau} \leq 140$ GeV	

$$\mu = 1.11^{+0.09}_{-0.08} = 1.11 \pm 0.05\,(\text{stat.})\,^{+0.05}_{-0.04}\,(\text{exp.})\,^{+0.05}_{-0.04}\,(\text{sig. th.})\,^{+0.03}_{-0.03}\,(\text{bkg. th.})$$

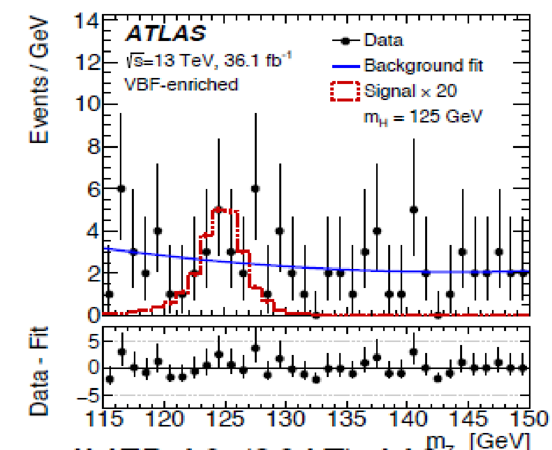
Probing rare Higgs decays

- Exploit growing LHC dataset to explore further decay channels
  - H→μμ: 2.8 x SM
  - H→Zγ: 6.6 x SM
  - H→cc:
    - 110 x SM (ZH(cc))
    - 200 x SM (J/ψγ)
  - H→φγ: 200 x SM
  - H→ργ: 50 x SM

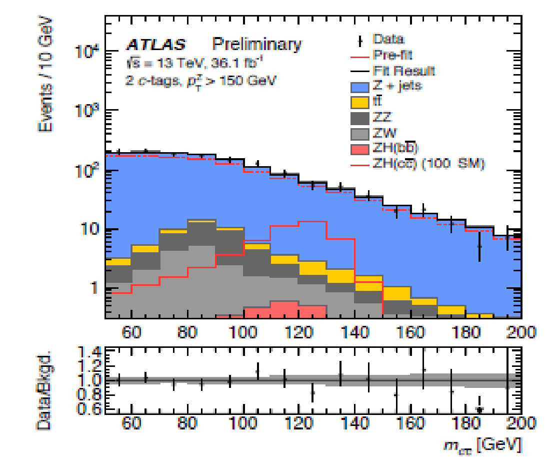




PRL 119 (2017) 05182



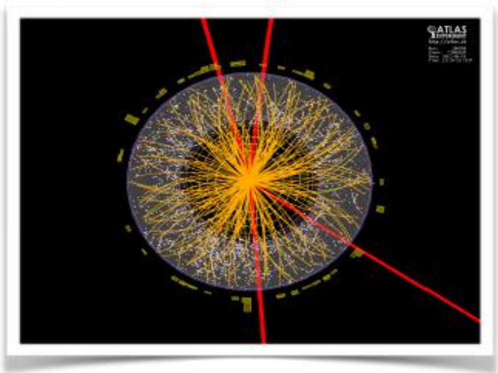
JHEP 10 (2017) 112



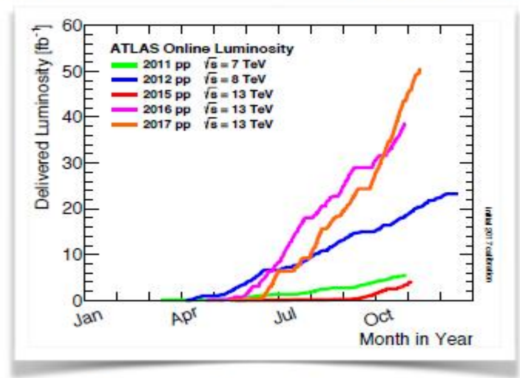
ATLAS-CONF-2017-078

The Higgs and the LHC

First beam in ATLAS
(2009)



Higgs discovery
(2012)

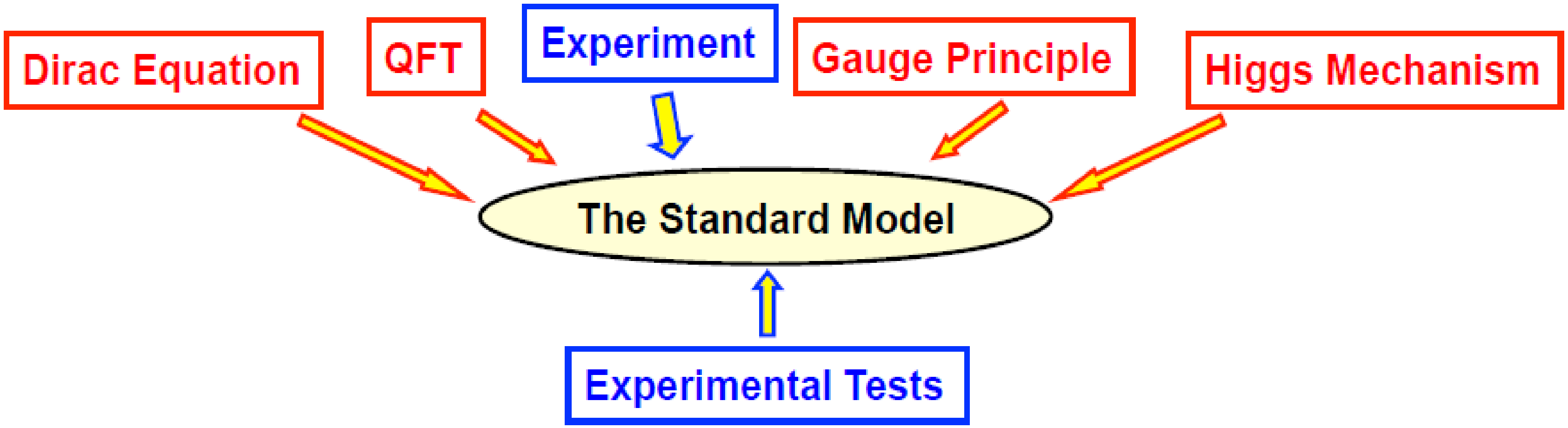


Only ~5% of total
expected data

Summary

★ The Standard Model of Particle Physics is one of the great scientific triumphs of the late 20^{th} century

★ Developed through close interplay of experiment and theory



★ Modern experimental particle physics provides many precise measurements. and the **Standard Model** successfully describes all current data !

★ Despite its great success, we should not forget that it is just a model; a collection of beautiful theoretical ideas cobbled together to fit with experimental data.

★ There are many issues / open questions…