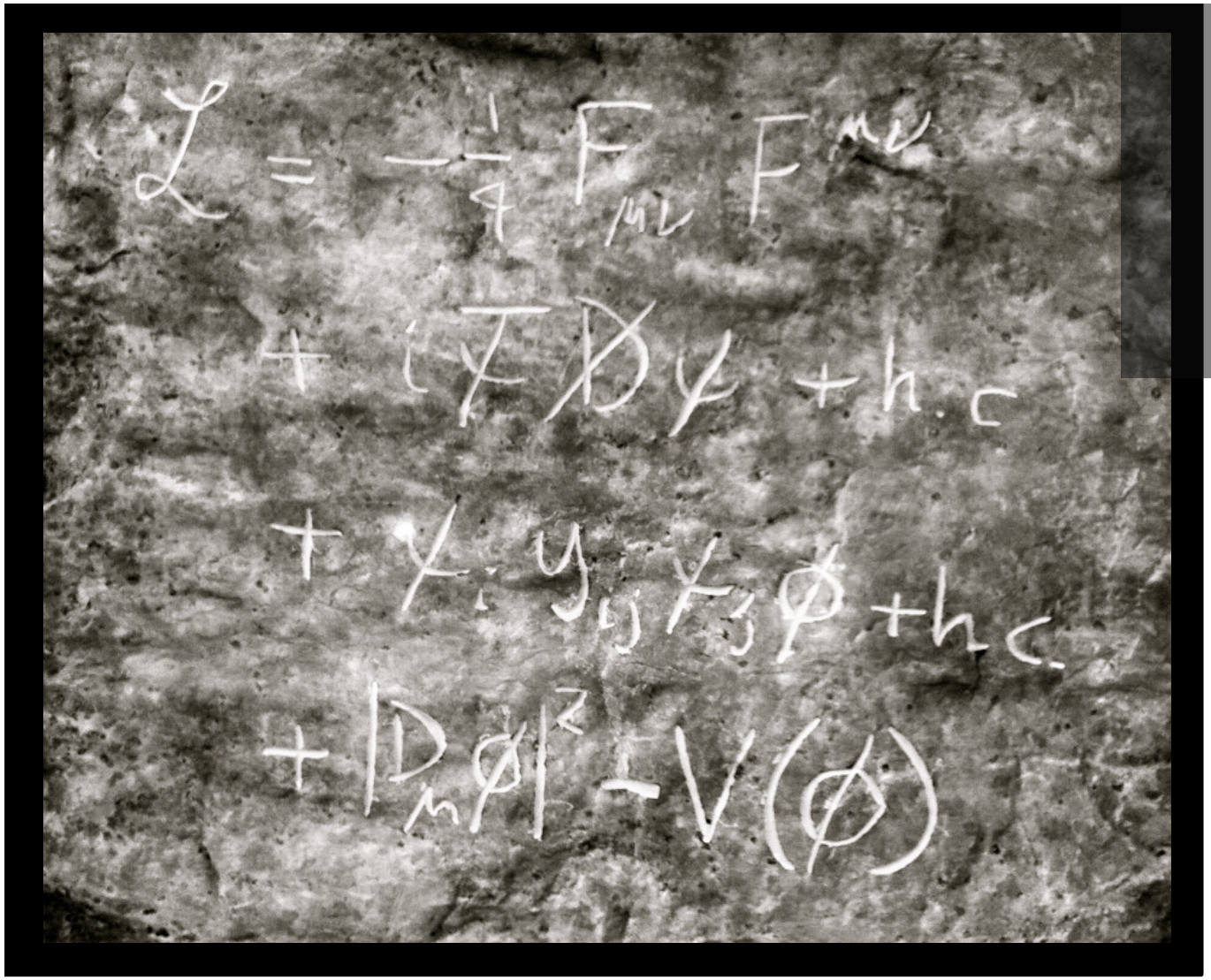


The Standard Model monolith @ CERN

Higgs Physics

HCP 2015

Nima Arkani Hamed

With the discovery of the Higgs, for the first time in our history, we have a self-consistent theory that can be extrapolated to exponentially higher energies.

Lecture I

Elements of History, Theory, Discovery and Implications

Marumi Kado
LAL and CERN

Email: Marumi.Kado@cern.ch
Office: 40-4-C01

Outline

Lecture I

- Introduction : Elements of history
- Elements of SM Higgs theory
- Precision EW tests
- The discovery of the Higgs boson
- An (early) experimental profile of the Higgs boson: The discovery channels

Lecture II

- An (early) experimental profile of the Higgs boson: Complex final states
- An (early) experimental profile of the Higgs boson: Combined measurements
- Rare decay modes
- Rare production modes
- The Higgs width

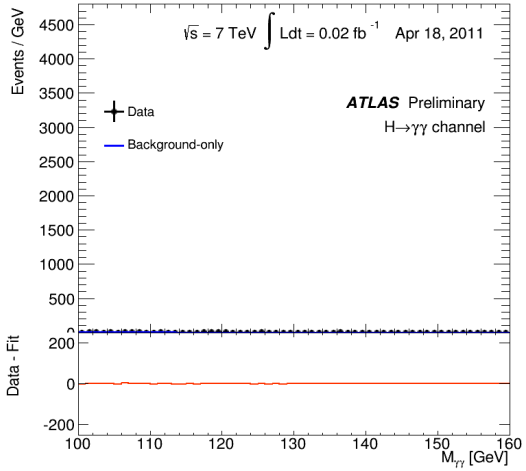
Lecture III

- Implications of the discovered state
- Search for BSM Higgs and extended sectors
- New trends
- Future Higgs programs

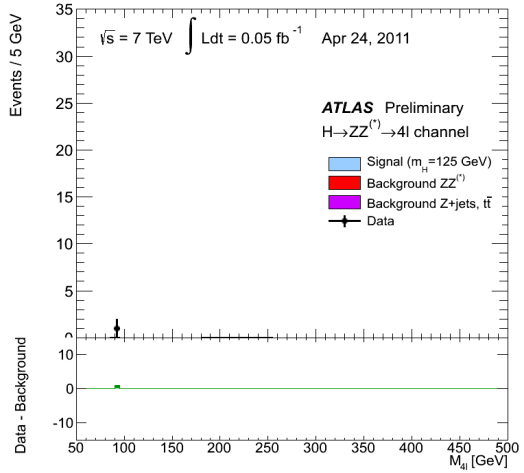
The Discovery

The Birth of a Particle…

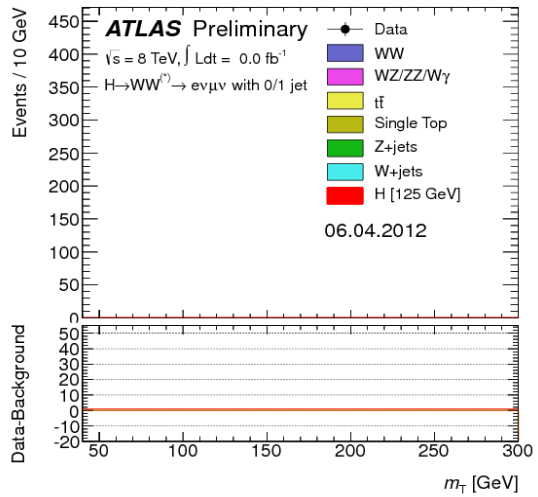
Diphoton



ZZ Four leptons



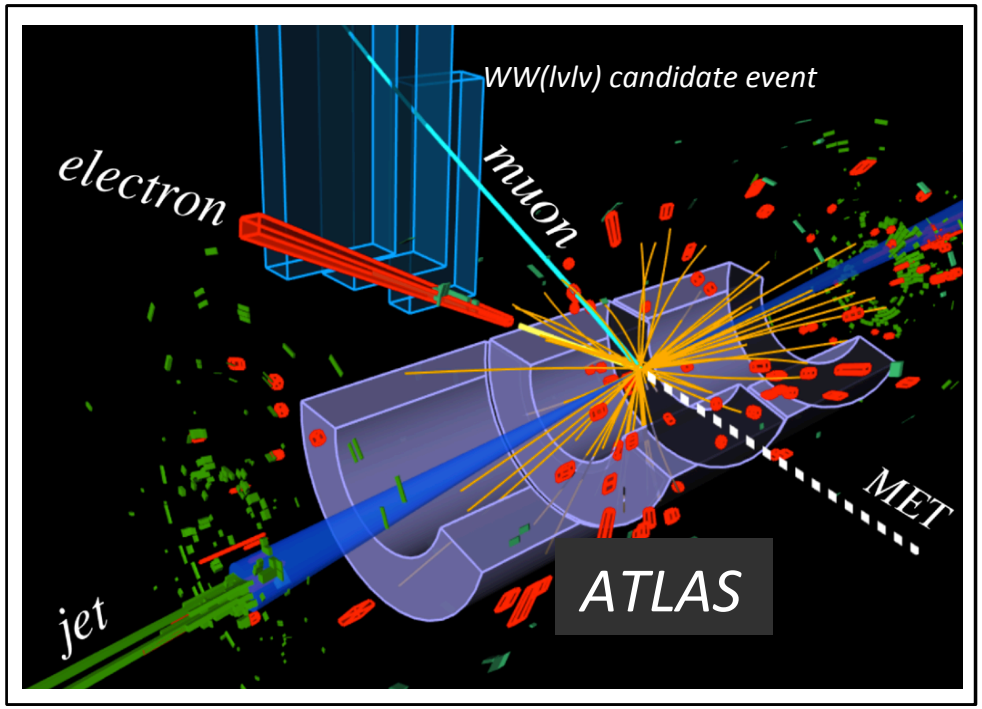
WW (lvlv)



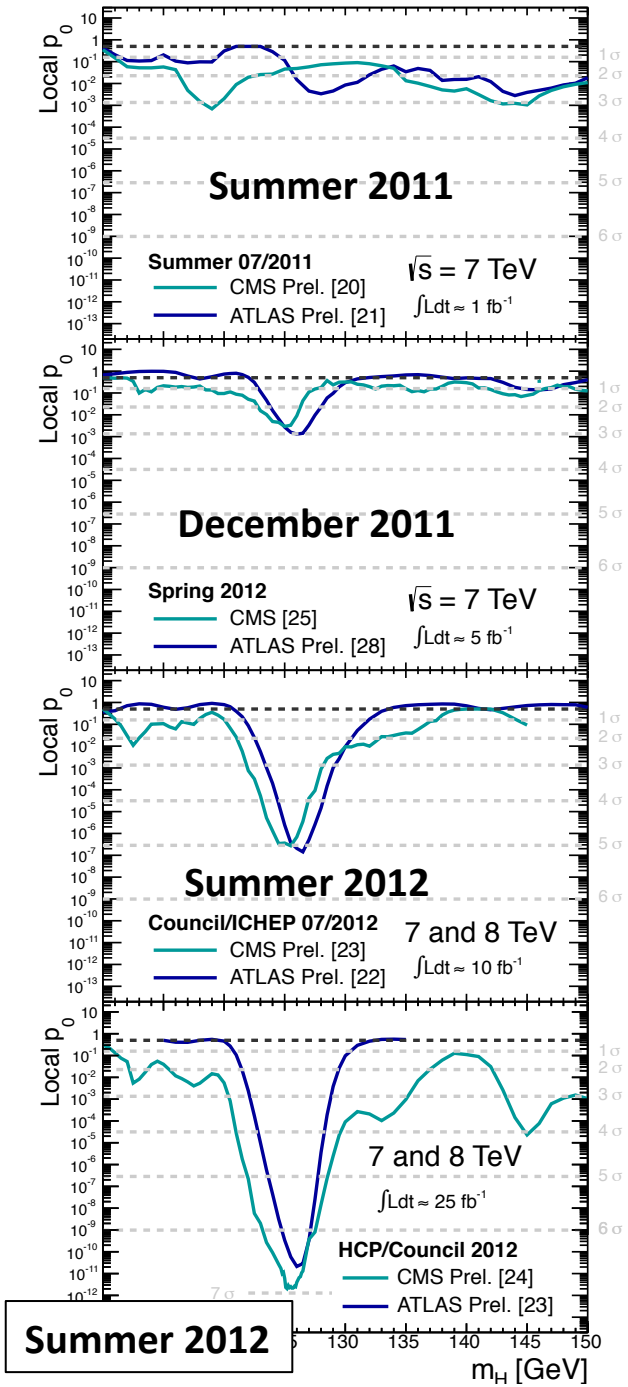
These animations also exist for CMS

A milestone which has reshaped the field of HEP…

It did not come as a complete surprise !



PDG, review of Particle Physics



Summer 2012

A Textbook and Timely Discovery

- Summer 2011: EPS and Lepton-Photon
  First (and last) focus on limits (scrutiny of the p_0)
- December 2011: CERN Council
  First hints
- Summer 2012: CERN Council and ICHEP
  Discovery!
- December 2012: CERN Council
  Begining of a new era

✓ Strongly Mostivated

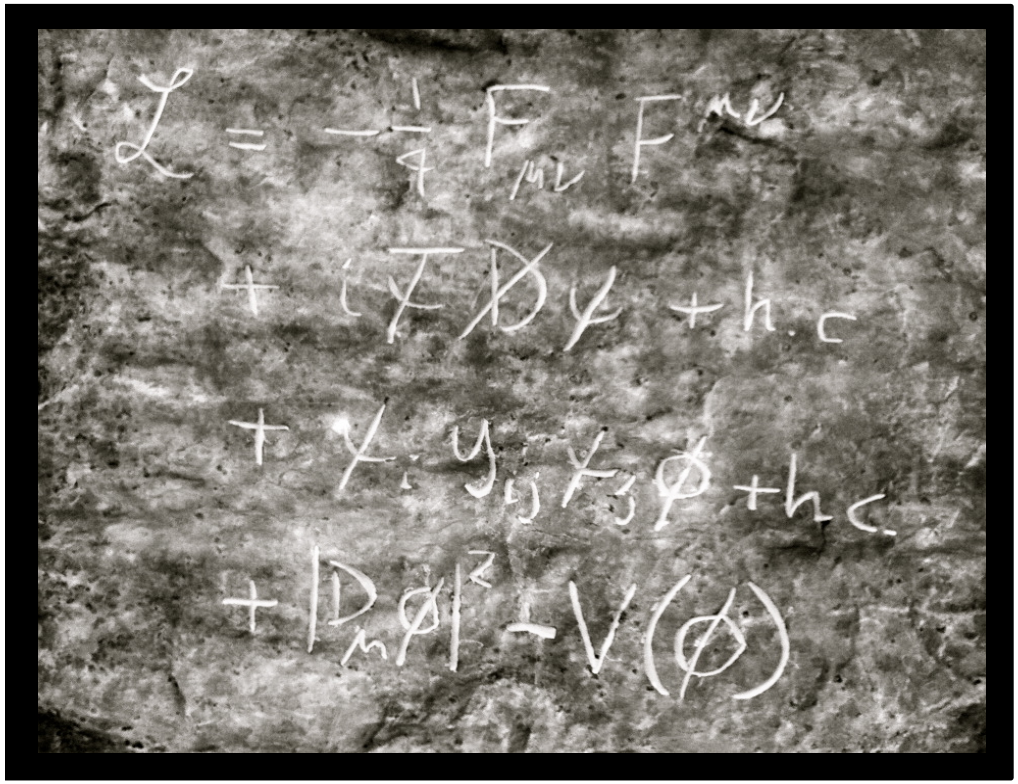
✓ Significance increased with luminosity to reach unambiguous levels

✓ Two experiments

✓ Several channels

The Standard Model

With one doublet of complex scalar field



The elegant gauge sector

The (less elegant) Higgs sector

- Non universal interactions not governed by a symmetry
- Bares most of the free parameters of the SM

+ *Dark matter ?*

+ *BSM ?*

… but testable!

The Origins

The Superconductor Analogy

SC (BCS) Theory	BEH Mechanism
Cooper pair condensate	Higgs field
Electrically charged (2e)	Weak charge
Mass of the photon	Mass of the W and Z bosons

- The Higgs field is inserted by hand…
- Condensate: the vacuum has a weak charge

Further reading : L. Dixon, “From superconductors to supercolliders” (http://www.slac.stanford.edu/pubs/beamline/26/1/26-1-dixon.pdf)

From SC to SSB in Particle Physics

SC (BCS) Theory

1950 – Landau and Ginzburg
JETP 20 (1950) 1064

1957 – Bardeen, Cooper and Schrieffer
Phys. Rev. 108 (1957) 1175

1958 – P. W. Anderson
Phys. Rev. 112 (1958) 1900
SC and gauge invariance

1963 – P. W. Anderson
Phys. Rev. 130 (1963) 439
Gauge field with mass (non relativistic)

Particle Theory

1954 - Yang-Mills theories for non abelian gauge interactions

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

… but local gauge symmetry forbids gauge bosons masses.

1962 – J. Schwinger
Phys. Rev. 125 (1962) 397
Gauge invariance and mass

1964 – W. Gilbert Phs. Rev. Lett 12 (1964) 713
Thought to be impossible in relativistic theories !

The Seminal Papers 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)

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

Answering Gilbert's objection

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

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

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)

Historical review also in J. Iliopoulos (Higgs Hunting 2012)

Spontaneous Symmetry Breaking (SSB) in Particle Theory

Nambu (1960) and Goldstone (1961)

Massless scalars occur in a theory with SSB

The symmetry is not apparent (hidden) in the ground state

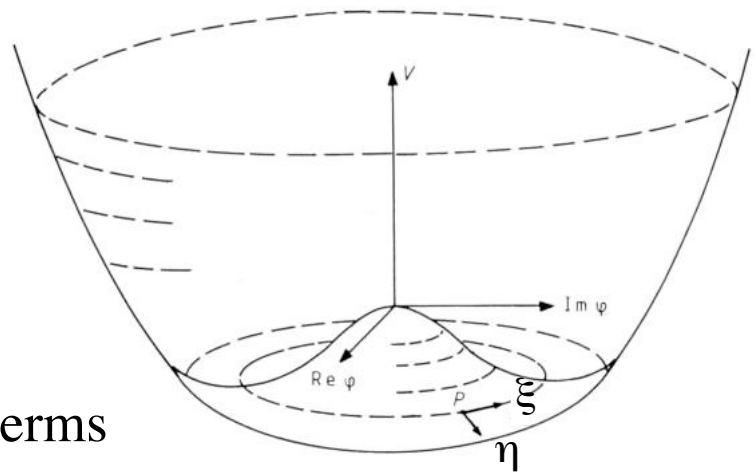
From a simple (complex) scalar theory with a U(1) symmetry

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

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.

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

Digression on Chiral Symmetry

In the massless quarks approximation : $SU(2)_L x SU(2)_R$ the chiral symmetry is an (approximate) global symmetry of QCD

The chiral symmetry is broken by means of coherent states of quarks (which play a role similar to the cooper pairs in the BCS superconductivity theory)

It is a Dynamical Symmetry Breaking where the pseudo-goldstone bosons are the π^+,π^0,π^- mesons

And the massive scalar is also there : the sigma!

This is the basis of the construction of an effective field theory ChPT allowing for strong interaction calculations at rather low energy

Spontaneous Symmetry Breaking (SSB) with a Local Symmetry

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

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

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

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

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

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! 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

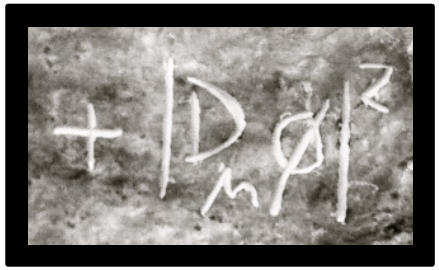
Then the gauge transformations are : $\varphi \rightarrow e^{-i\frac{\theta(x)}{v}}\varphi \qquad A_\mu \rightarrow A_\mu + \frac{1}{ev}\partial_\mu \theta$

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

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

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

The Goldstone boson does not appear anymore in the Lagrangian



EW Spontaneous Symmetry Breaking

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

Introducing a double of complex scalar fields (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 :

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

Non electrically 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.

After a few computational steps the Lagrangian will then be written :

$$\mathcal{L} = \frac{1}{2}\partial_\mu H \partial^\mu H - \frac{1}{2}\lambda v^2 H^2 - \lambda v H^3 - \frac{\lambda}{4} H^4$$

Massive scalar : The Higgs boson

$$+ \frac{1}{2}\left[\frac{g'^2 v^2}{4} B_\mu B^\mu - \frac{g g' v^2}{2} W^3_\mu B^\mu + \frac{g^2 v^2}{4} \vec{W}_\mu . \vec{W}^\mu\right]$$

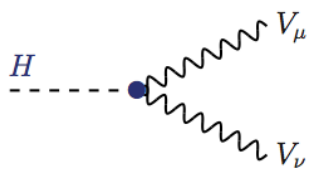
Massive gauge bosons

$$+ \frac{1}{v}\left[\frac{g'^2 v^2}{4} B_\mu B^\mu H - \frac{g g' v^2}{2} W^3_\mu B^\mu H + \frac{g^2 v^2}{4} \vec{W}_\mu . \vec{W}^\mu H\right]$$

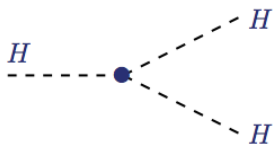
$$+ \frac{1}{2v^2}\left[\frac{g'^2 v^2}{4} B_\mu B^\mu H^2 - \frac{g g' v^2}{2} W^3_\mu B^\mu H^2 + \frac{g^2 v^2}{4} \vec{W}_\mu . \vec{W}^\mu H^2\right]$$

Gauge-Higgs interaction

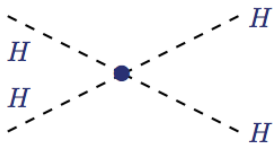
Higgs - Gauge main terms relevant for the LHC (and more)



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



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



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

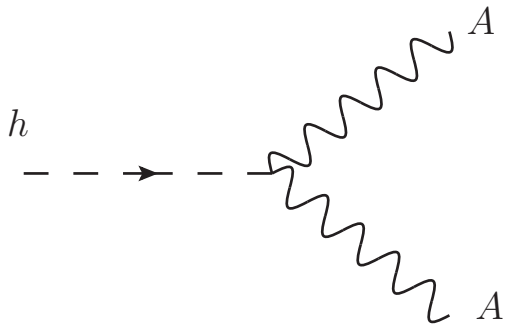
Without SSB

Not gauge invariant

$$m^2 A_\mu A^\mu$$

Not existing vertex
(Simple dimensional analysis)

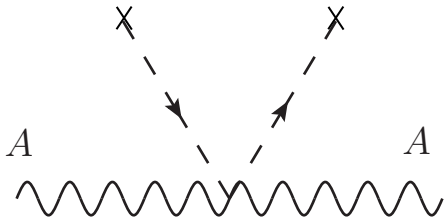
$$A_\mu A^\mu h$$



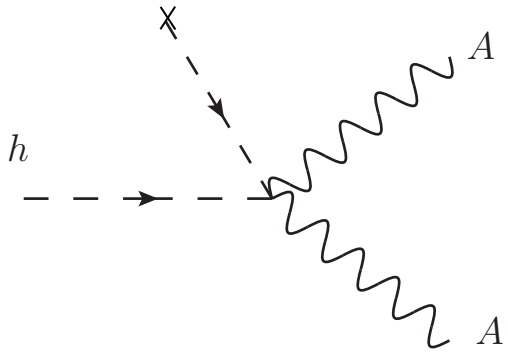
With the Higgs Mechanism (and after SSB)

Not only existing but also closely related!

$$(1/2)e^2 v^2 A_\mu A^\mu$$



$$v e^2 A_\mu A^\mu h$$



Proof of condensate !

Consequences of the mechanism :

1.- Two massive charged vector bosons :

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

Corresponding to the then observed charged currents

Thus v = 246 GeV

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

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

3.- One massive neutral vector boson Z :

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

Prediction of the Model

Beside the existence of the Z massive neutral gauge boson…

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

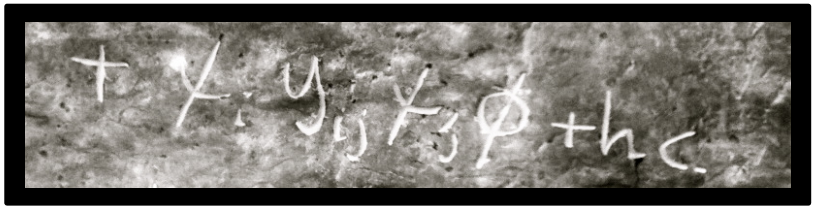
$$\rho = 1$$

Protected by cutsodial symmetry

$$m_t^2 + m_b^2 - 2(m_t^2 m_b^2)\ \log(m_t^2/m_b^2)/(m_t^2 - m_b^2)$$

F. Wilczek at the LEP Celebration :

The Higgs mechanism is corroborated at 75%



The sector of Fermions

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

Not the case when using Yukawa couplings to the Higgs doublet

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

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

The Higgs mechanism DOES NOT predict fermion masses

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

Wait…

The coupling to the Higgs fields is the following :

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

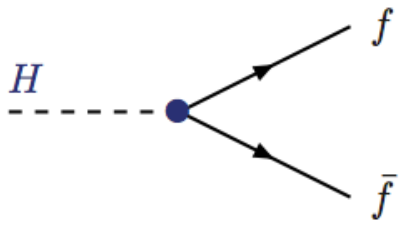
Can be seen as giving mass to down type fermions…

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

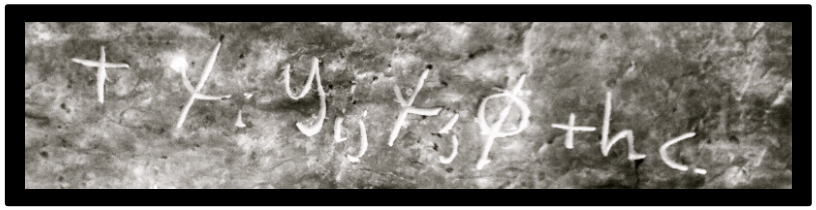
$$\phi^C = i\sigma_2 \phi^* \qquad \lambda_u Q_L \ \phi^C \ \bar{u}_R = \lambda_u (\bar{u}_L, \bar{d}_L) \begin{pmatrix} v + h \\ 0 \end{pmatrix} d_R + H.C.$$

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

… But not necessary.



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



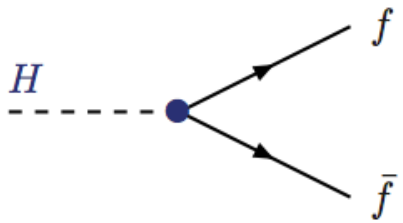
(and masses of fermions)

Not explaining the flavor Hierarchy

Replacing mass terms by Yukawa couplings

For neutrino masses: introduction of a Dirac right handed neutrino is fine… but how to explain the incredibly large hierarchy?

Majorana mass term possible and more natural



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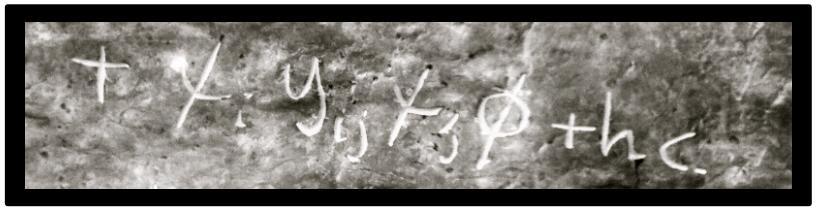
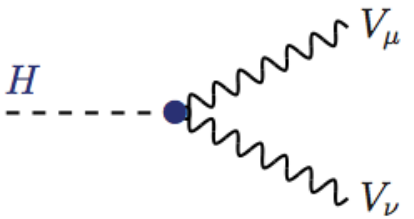


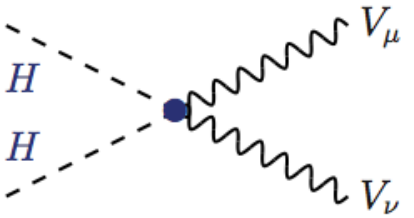
(and masses of fermions)



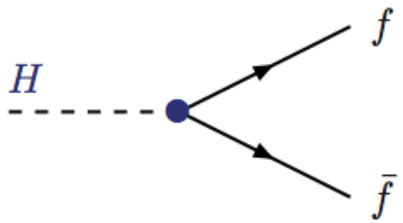
$$g_{HVV} = 2M_V^2/v$$

Proof of condensate !

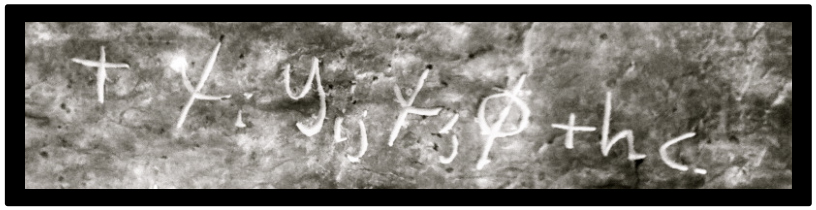
(and masses of gauge bosons)



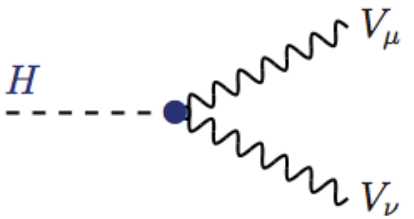
$$g_{HHVV} = 2M_V^2/v^2$$



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

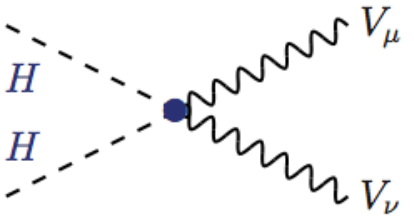


(and masses of fermions)



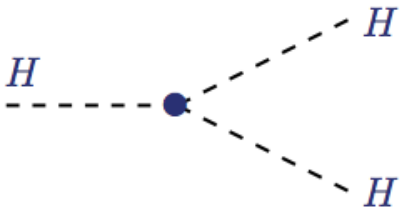
$$g_{HVV} = 2M_V^2/v$$

Proof of condensate !



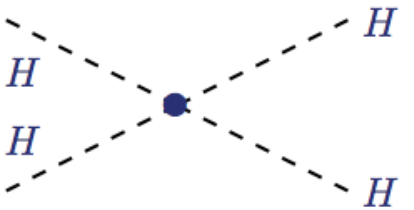
$$g_{HHVV} = 2M_V^2/v^2$$

(and masses of gauge bosons)



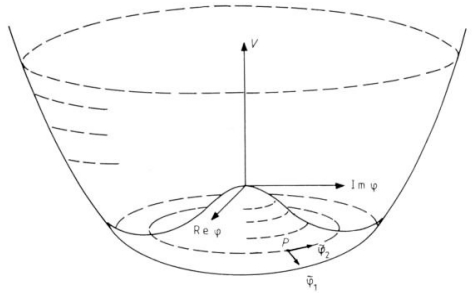
$$g_{HHH} = 3M_H^2/v$$

$$V(\varphi) = \mu^2 \varphi^* \varphi + \lambda (\varphi^* \varphi)^2$$



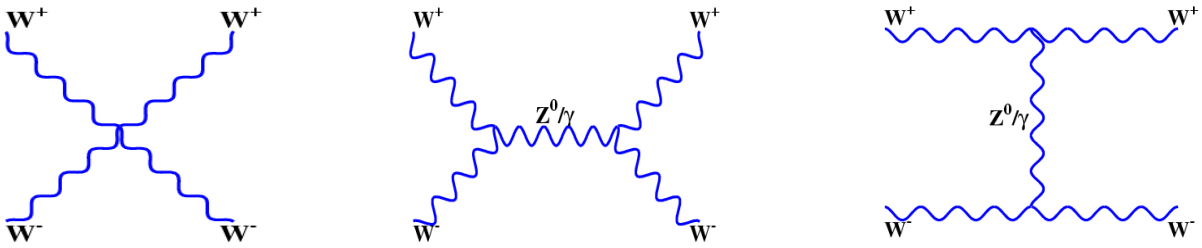
$$g_{HHHH} = 3M_H^2/v^2$$

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



Very important additional virtue of the Higgs Particle

$$W_L^+ W_L^- \to W_L^+ W_L^-$$



Does not preserve perturbative unitarity.

Introducing a Higgs boson ensures the unitarity of this process <u>PROVIDED</u> that its mass be smaller than :

$$\sqrt{4\pi\sqrt{2}/3G_F}$$ v.i.z. approximately 1 TeV

This is not only a motivation for the Higgs mechanism but is also a strong experimental constraint on its mass (if you believe in perturbative unitarity)

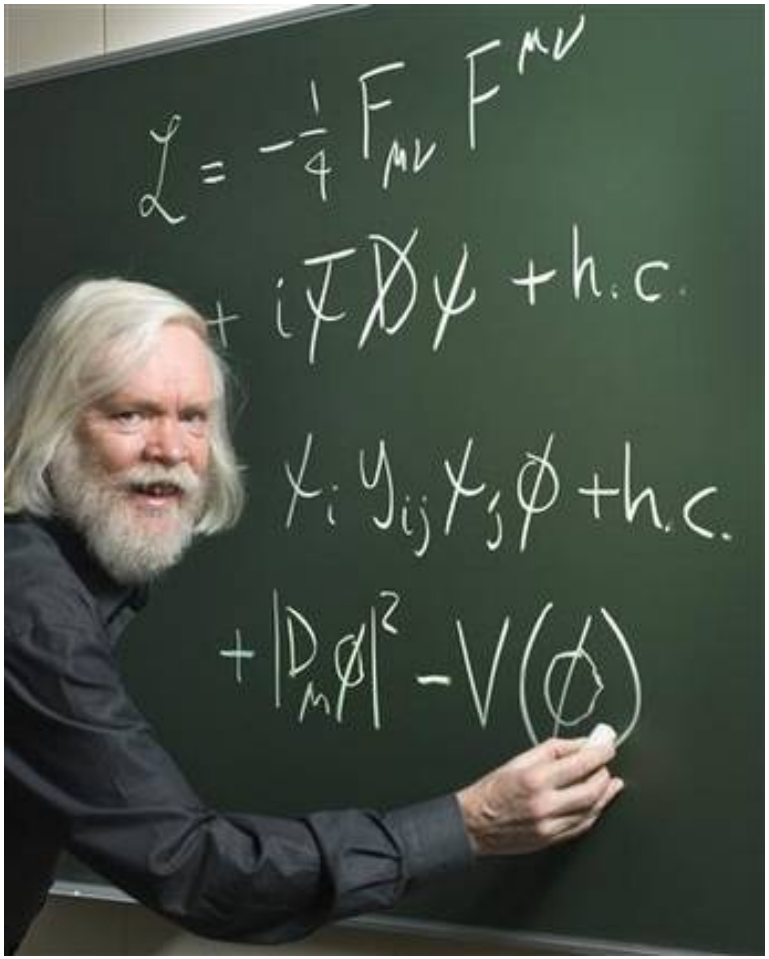
…If you don't, weak force will become strong !

The origin of the No Loose theorem* at the LHC

**Approximate*

The Pre LHC Era:

Searches and Importance of Precision



1976

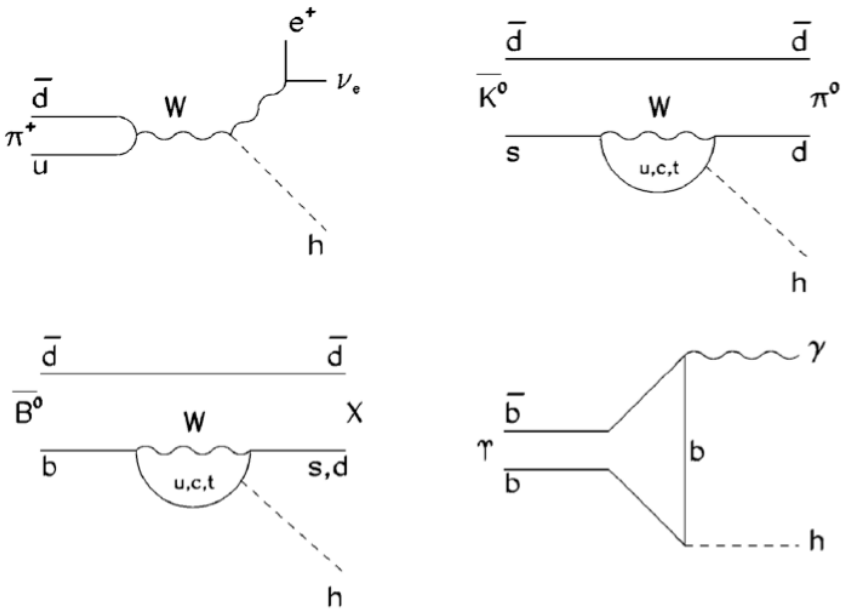
A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John Ellis, Mary K. Gaillard *) and D.V. Nanopoulos +)
CERN -- Geneva

The Roadmap

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3),4)] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

Pre-LEP Bounds



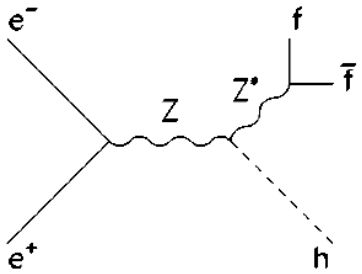
- SINDRUM Collaboration measured π to ev H (ee) Yielding a limit on very light Higgs
- CUSB Collaboration Υ to Hγ yielding limit of ~ 5-6 GeV (dependent on high order corrections)
- Jade and CLEO provided bounds on B to $\mu\mu$+X
- CERN-Edimbrgh-Orsay-Mainz-Pisa-Siegen K to π H (ee) below ~50 MeV
- Electron beam dump e to eH (ee) excluded 1.2 MeV to 52 MeV (TH uncertainties free)

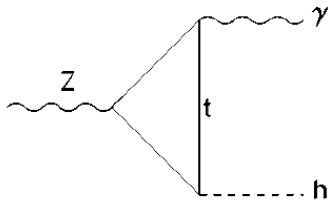
Absolute Lower Limit on the Higgs Mass at LEP

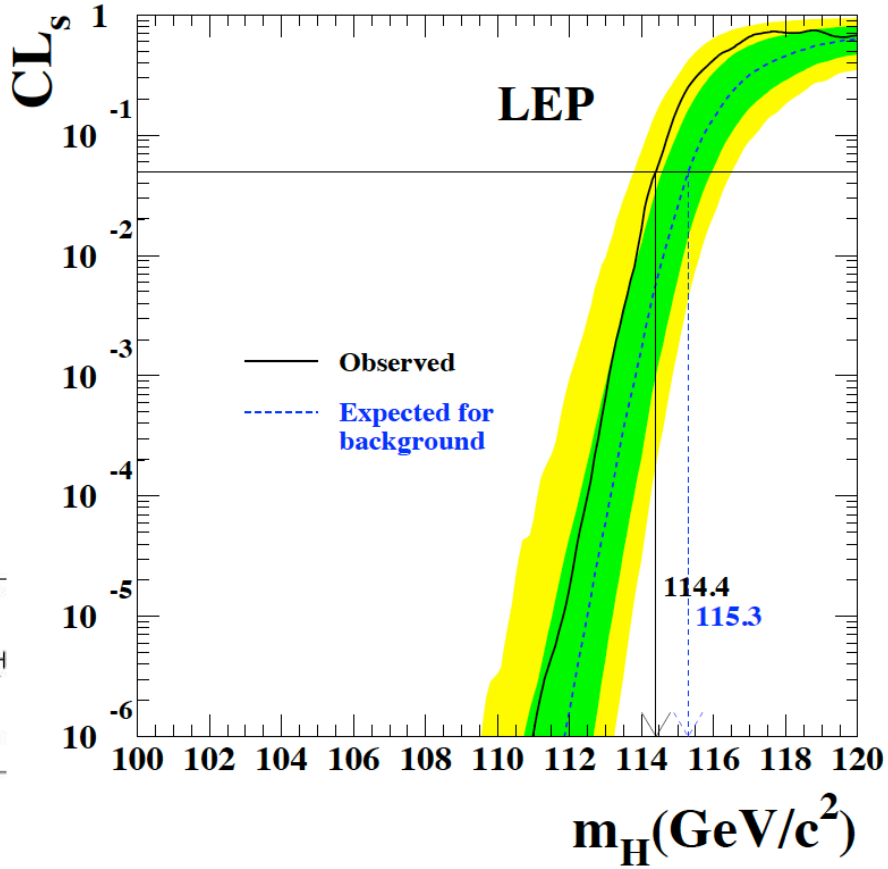
LEP1 e^+e^- at COM ~m_Z

Various decays and topologies

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

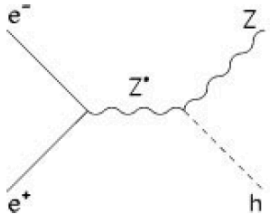


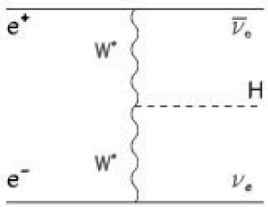


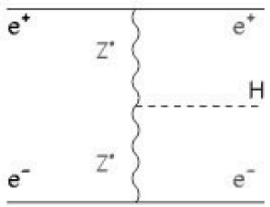


LEP2 e^+e^- up to 209 GeV

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







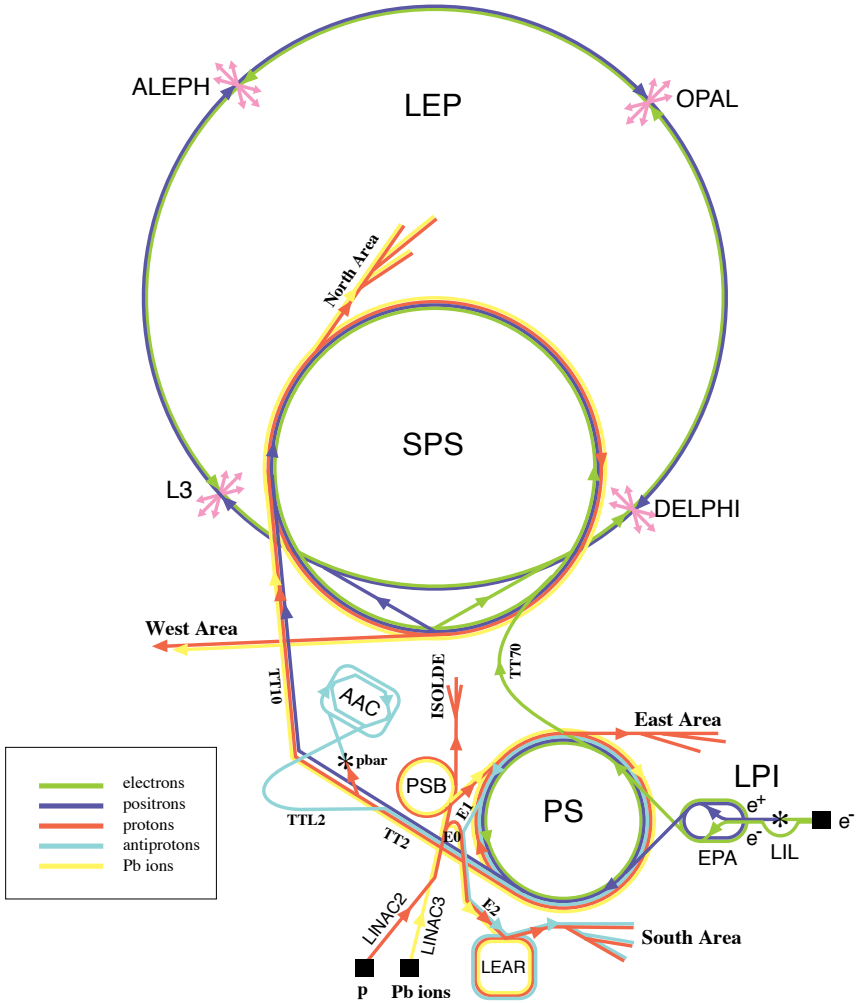
Excludes SM Higgs with mass below 114 GeV

Precision EW Measurements

e^+e^- and hadron collider complementarity

Three Machines in three years…

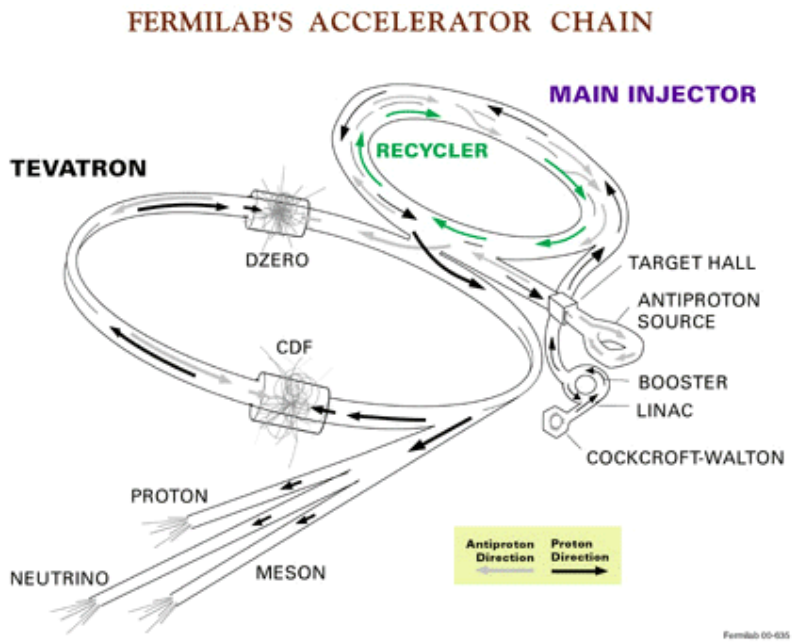
LEP 1989-2000 e^+e^- 91Gev,130-208GeV



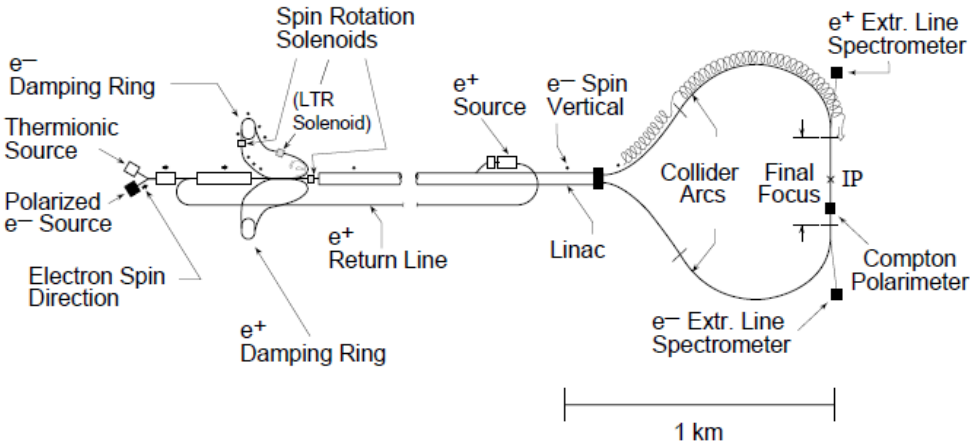
LEP: Large Electron Positron collider
SPS: Super Proton Synchrotron
AAC: Antiproton Accumulator Complex
ISOLDE: Isotope Separator OnLine DEvice
PSB: Proton Synchrotron Booster
PS: Proton Synchrotron

LPI: Lep Pre-Injector
EPA: Electron Positron Accumulator
LIL: Lep Injector Linac
LINAC: LINear ACcelerator
LEAR: Low Energy Antiproton Ring

Tevatron 1987-2011 pp ~2TeV



SLC 1988-1998 e^+e^- 91GeV



Experimental Constraint : Electroweak Precision Data and the Higgs Mass

At tree level, the gauge sector of the standard model has 3 free parameters not counting the Higgs mass and the fermion masses and couplings.

Particularly useful set to start is :

1.- The fine structure constant : $\alpha = 1/137.035999679(94)$ 10^{-9}

Determined at low energy by electron anomalous magnetic moment and quantum Hall effect

2.- The Fermi constant : $G_F = 1.166367(5) \times 10^{-5}\ \mathrm{GeV}^{-2}$ 10^{-5}

Determined from muon lifetime

3.- The Z mass : $M_Z = 91.1876 \pm 0.0021\ \mathrm{GeV}$ 10^{-5}

Measured from the Z lineshape scan at LEP

Parameter	Input value
M_H [GeV]$^{(\circ)}$	125.14 ± 0.24
M_W [GeV]	80.385 ± 0.015
Γ_W [GeV]	2.085 ± 0.042
M_Z [GeV]	91.1875 ± 0.0021
Γ_Z [GeV]	2.4952 ± 0.0023
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037
R^0_ℓ	20.767 ± 0.025
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010
A_ℓ $^{(\star)}$	0.1499 ± 0.0018
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012
A_c	0.670 ± 0.027
A_b	0.923 ± 0.020
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016
R^0_c	0.1721 ± 0.0030
R^0_b	0.21629 ± 0.00066
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$
m_t [GeV]	173.34 ± 0.76
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)^{(\dagger\triangle)}$	2757 ± 10
$\alpha_s(M_Z^2)$	–

There is many more !!

- Numerous observables O(40)
- Numerous experiments (with different systematics)
- Within experiments numerous analyses (with different systematics)
- Various theoretical inputs

For the weak mixing angle

Forward-backward asymmetry: asymmetry of the Z decay product angular distribution (for all fermions)

$$A^{0,f}_{FB} \equiv \frac{n(\theta^*<90°)-n(\theta^*>90°)}{n(\theta^*<90°)+n(\theta^*>90°)}$$

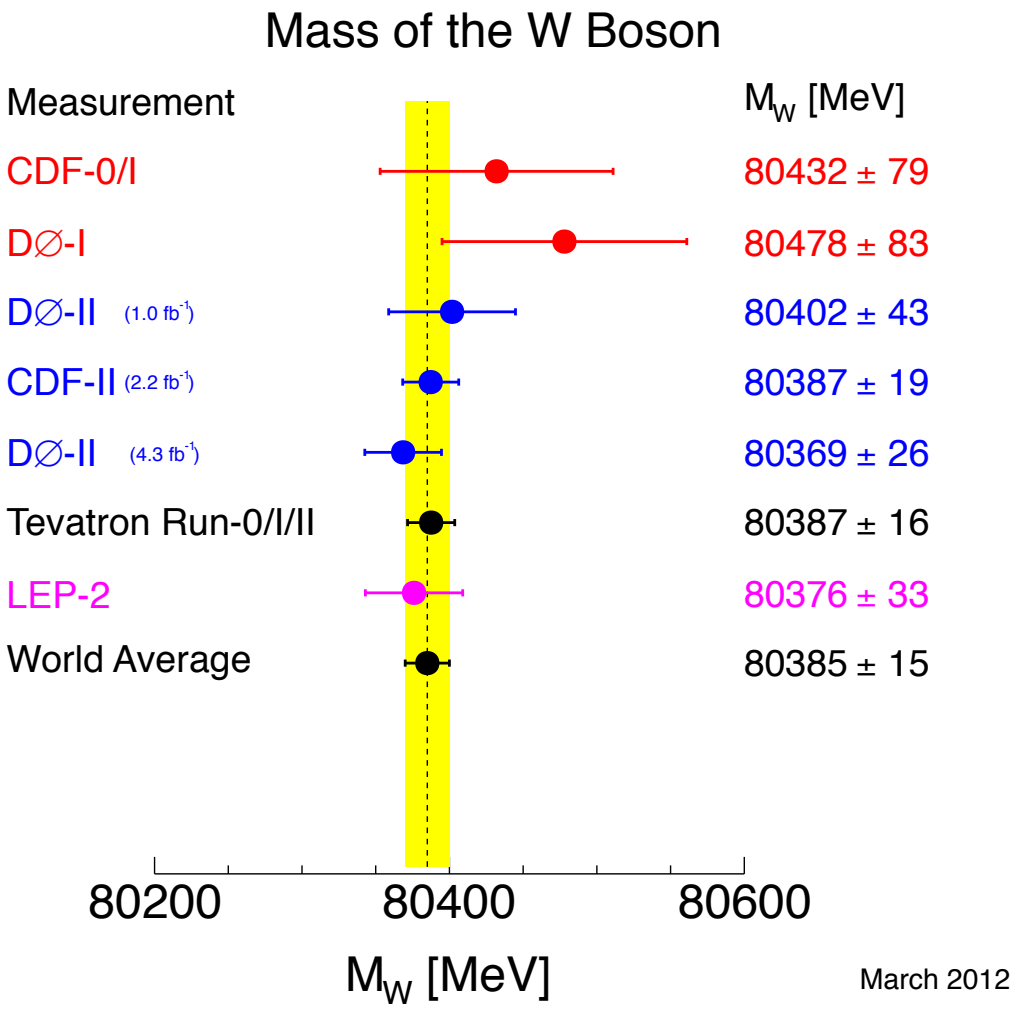
Polarisation asymmetry: asymmetry of the rates of the Z decay polarised final-states (can be measured only for τ's)

$$P^\tau_- \equiv \frac{n(\tau_R)-n(\tau_L)}{n(\tau_R)+n(\tau_L)} = -A_\tau$$

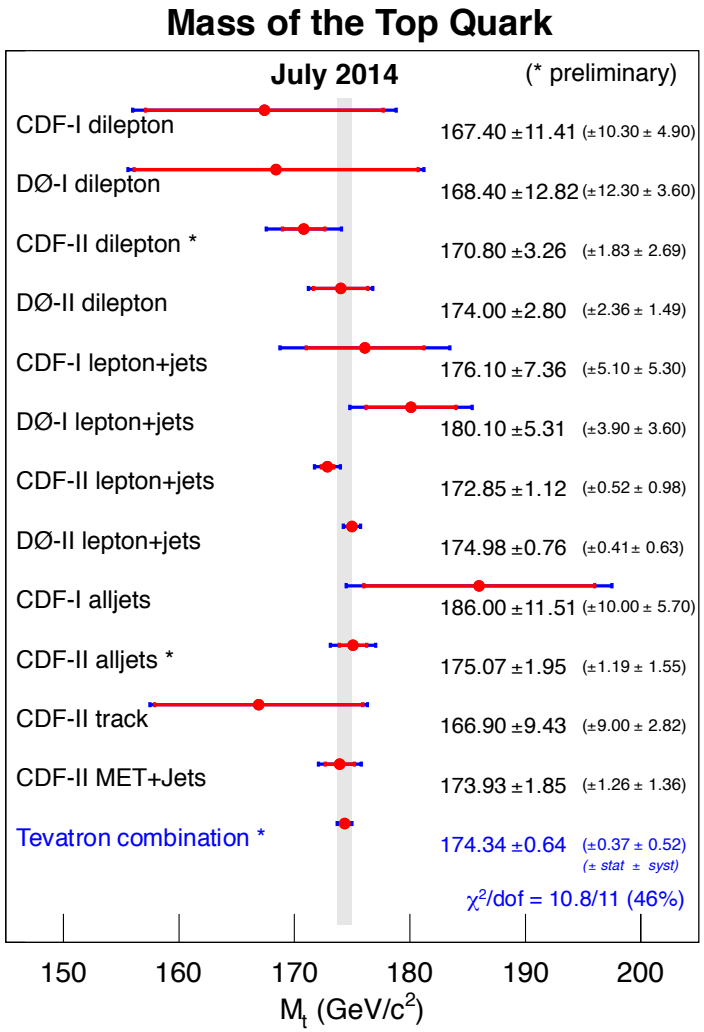
Left-right asymmetry: asymmetry of the cross-sections with incident polarized electron beam

$$A_{LR} \equiv \frac{\sigma(e_L)-\sigma(e_R)}{\sigma(e_L)+\sigma(e_R)} = A_e$$

W and Top quark mass measurements



Precision of ~0.02%



Precision of ~0.4%

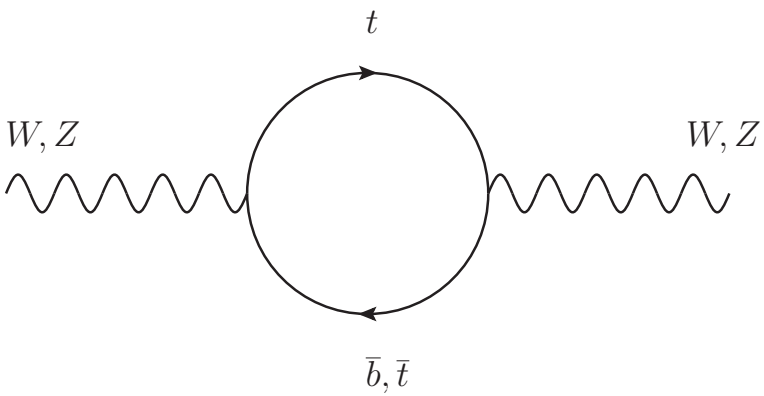
Superb Legacy of Tevatron

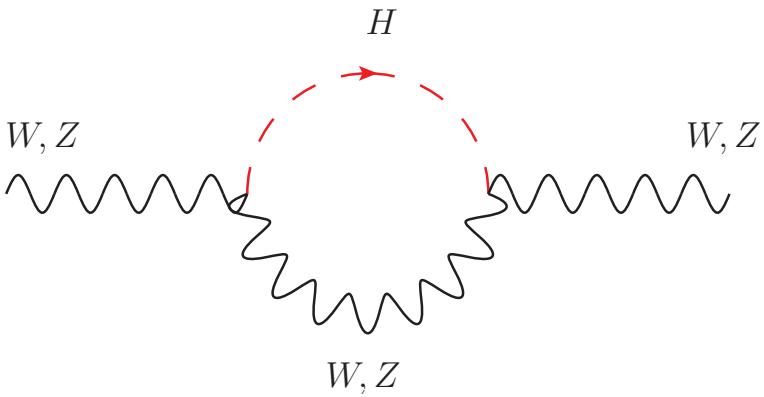
Key: Beyond Tree Level

Taking the hypothesis of a Minimal Standard Model, small weak radiative corrections (few percent level) to numerous observables can be computed in order to assess the impact of crucial parameters e.g. Higgs and top quark mass

For example the mass of the W boson:

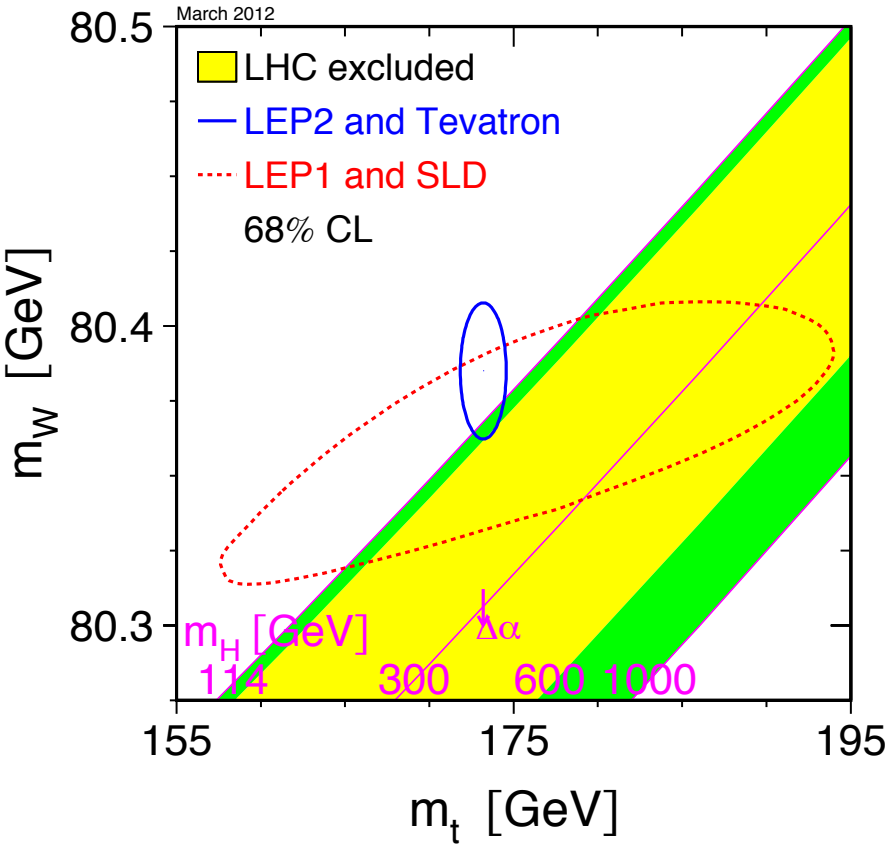
$$M_W = \frac{M_Z}{\sqrt{2}}\left[1+\sqrt{1-\frac{4\pi\alpha}{\sqrt{2}G_F M_z^2(1-\Delta r)}}\right]^{\frac{1}{2}}$$

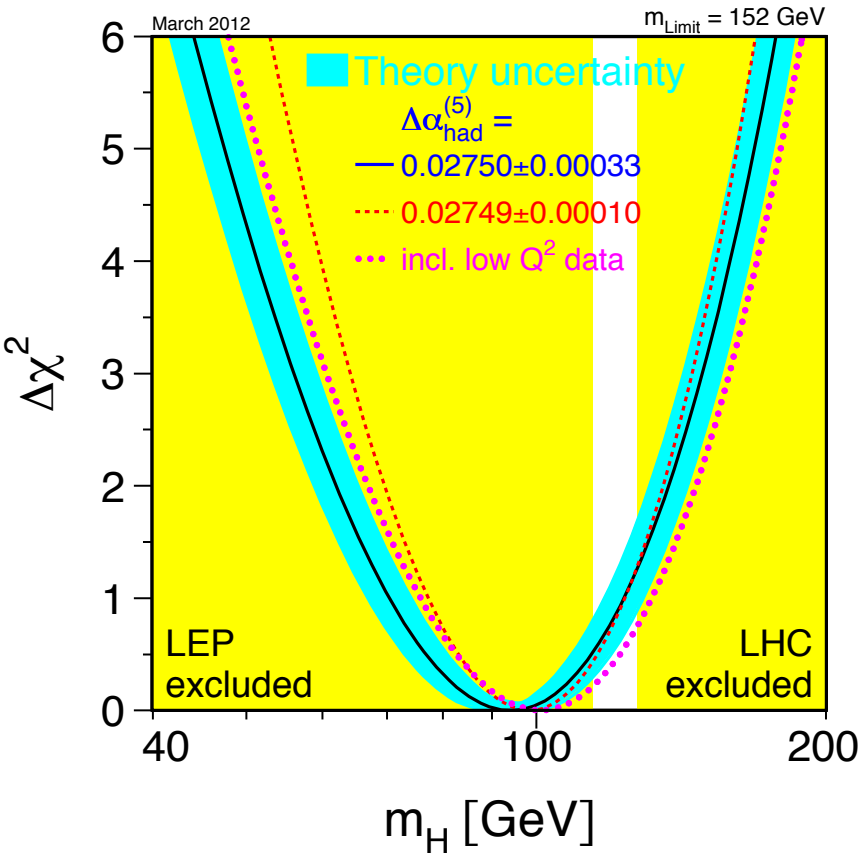




$$\Delta r \propto m_{top}^2, Log\frac{M_H}{M_W}$$

Indirect Predictions of the EW precision





Predicts the top mass as well as the Higgs boson mass

The fit yields : $94^{+29}_{-24}\,GeV$

The Electromagnetic Coupling Constant

$$\alpha_{QED}(m_Z^2) = \frac{\alpha(0)}{1 - \Delta\alpha_\ell(m_Z^2) - \Delta\alpha_{had}(m_Z^2) - \Delta\alpha_{top}(m_Z^2)}$$

As mentionned above $\alpha(0)$ measured with ~10^{-9} precision

The probem is how to evaluate : $\Delta\alpha_{had}(m_Z^2)$

The origin of one of the most important uncertainties on the Higgs mass prediction :

The famous blue band plot is named after this contribution

Summary of Pre LHC Era

- No loose theorem: There should be something allowing to either preserve perturbative unitarity or strongly coupled new physics below 1 TeV (approximate no-loose).

- The Higgs boson is a key missing piece of the SM if it exists it should have a mass below 1 TeV approximately.

- If it exists its mass can be indirectly measured to be relatively low of $94^{+29}_{-24} GeV$

The LHC Era

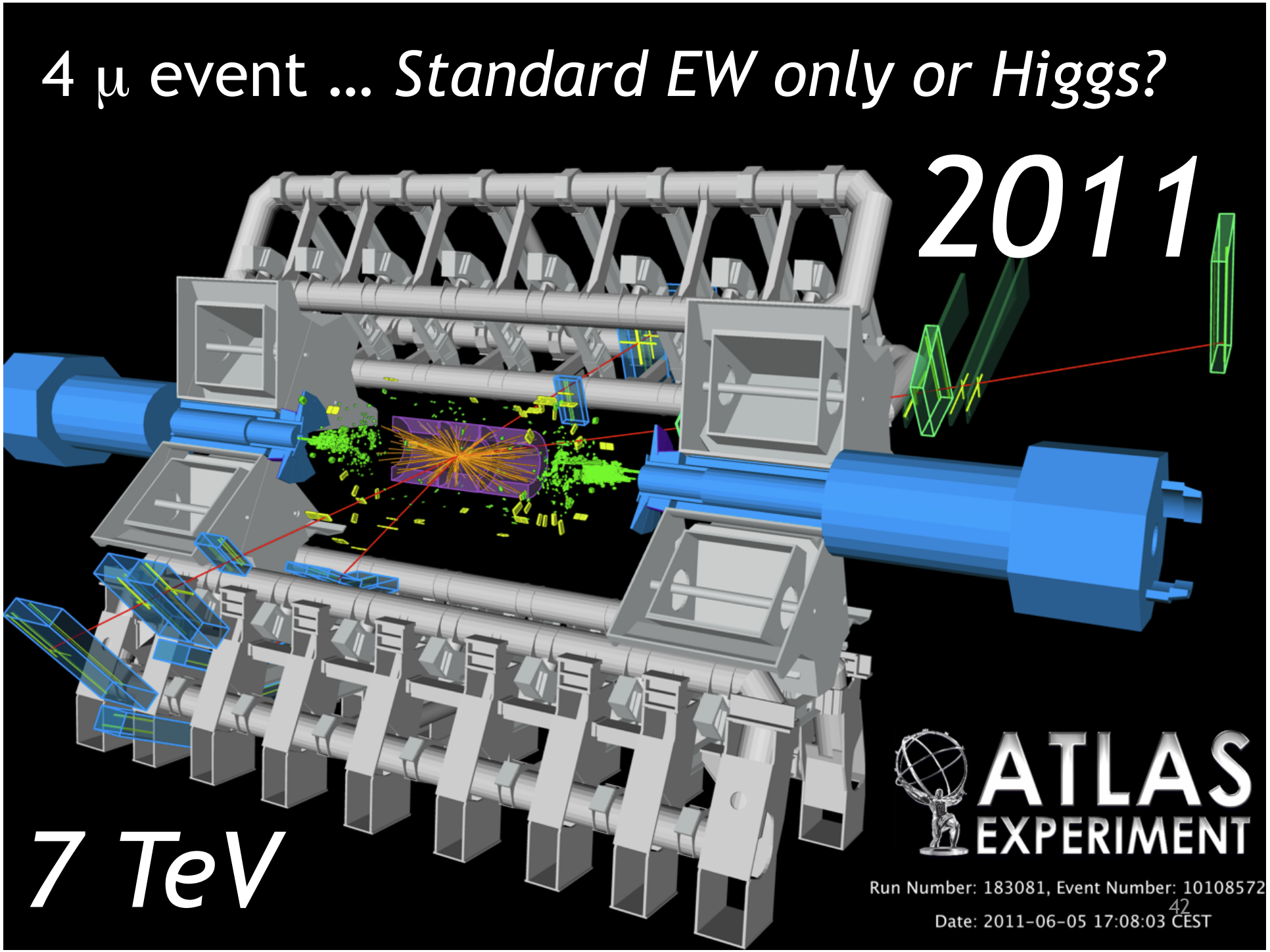
1991 December CERN Council: ‘LHC is the right machine for advance of the subject and the future of CERN’ (thanks to the great push by DG C Rubbia)

1993 December proposal of LHC with commissioning in 2002

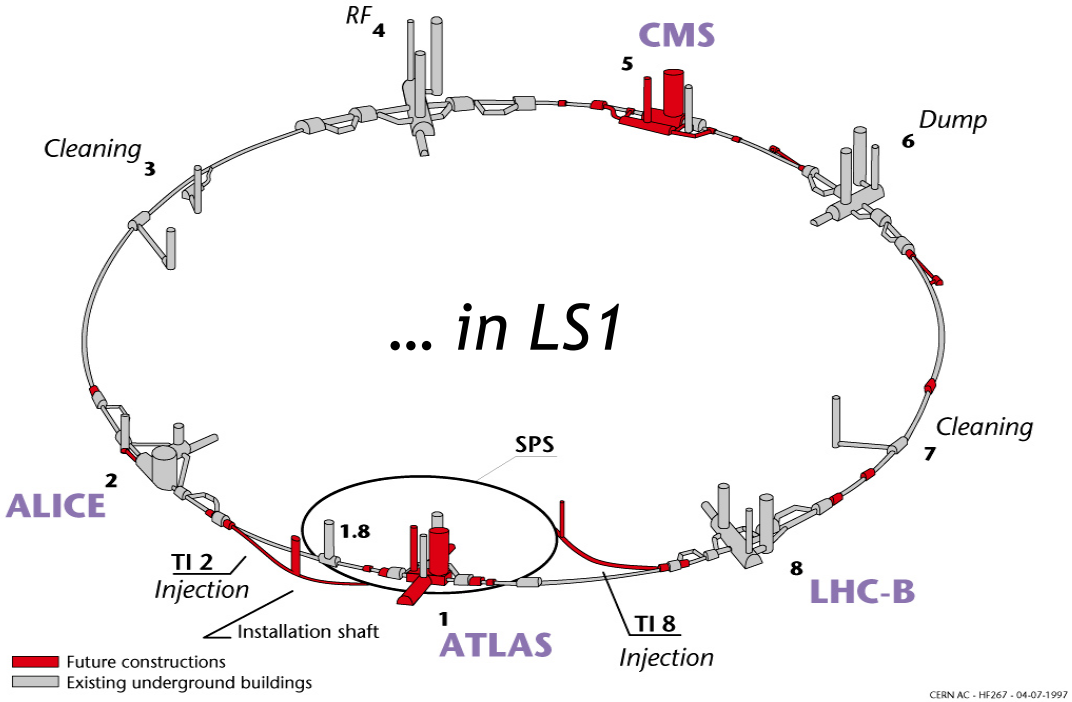
1994 June Council:
Staged construction was proposed by DG Chris Llewellyn Smith, but some countries could not yet agree, so the Council session vote was suspended until

16 December 1994 Council:
(Two-stage) construction of LHC was approved

4 μ event … *Standard EW only or Higgs?*



Three Years of LHC operations at the Energy frontier (in a nutshell)



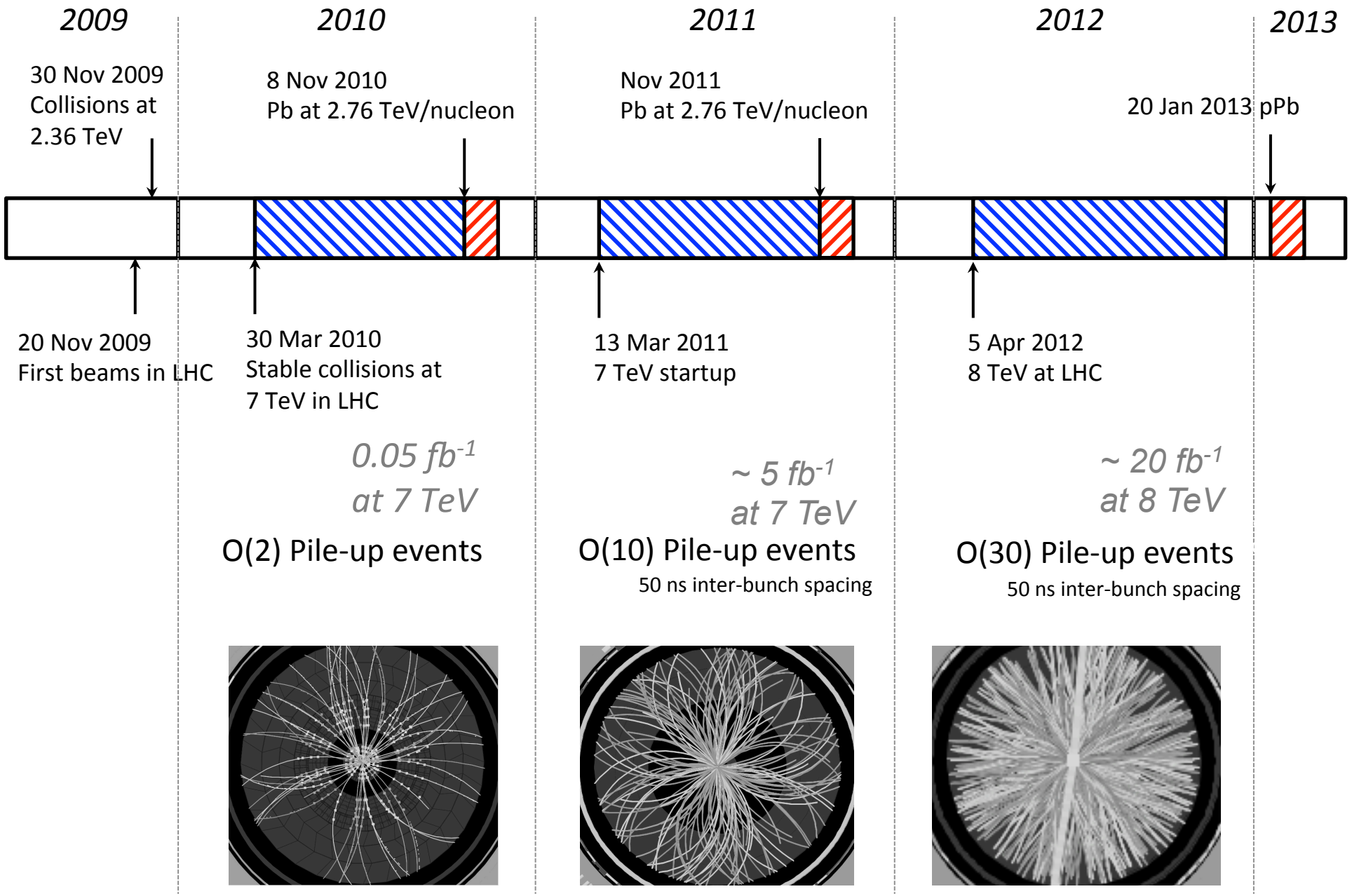
The LHC

- 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)

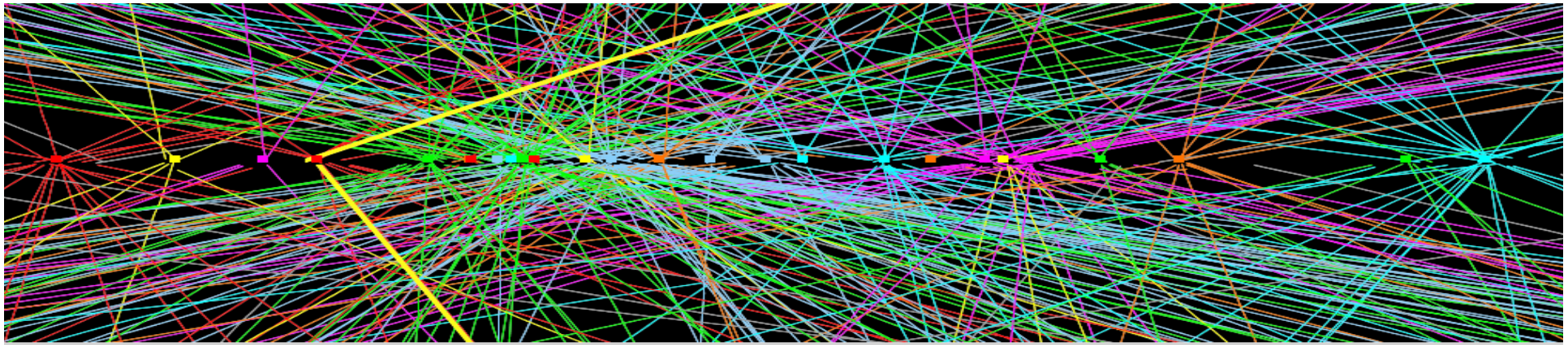
$$\mathcal{L} = \frac{N_p^2 k_b f_{rev} \gamma}{4\pi \beta^* \epsilon_n} F$$

Parameter	2010	2011	2012	Nominal
C.O.M Energy	7 TeV	7 TeV	8 TeV	14 TeV
N_p	$1.1\ 10^{11}$	$1.4\ 10^{11}$	$1.6\ 10^{11}$	$1.15\ 10^{11}$
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 LHC Run 1


2009
2010
2011
2012
2013
30 Nov 2009
Collisions at
2.36 TeV
8 Nov 2010
Pb at 2.76 TeV/nucleon
Nov 2011
Pb at 2.76 TeV/nucleon
20 Jan 2013 pPb
20 Nov 2009
First beams in LHC
30 Mar 2010
Stable collisions at
7 TeV in LHC
13 Mar 2011
7 TeV startup
5 Apr 2012
8 TeV at LHC
0.05 fb-1
at 7 TeV
O(2) Pile-up events
~ 5 fb-1
at 7 TeV
O(10) Pile-up events
50 ns inter-bunch spacing
~ 20 fb-1
at 8 TeV
O(30) Pile-up events
50 ns inter-bunch spacing

Detector Challenges (Highlights)

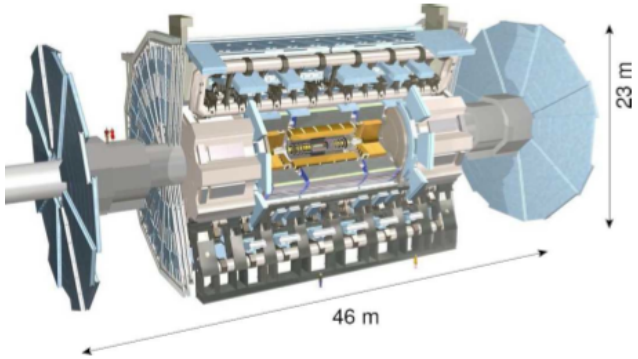
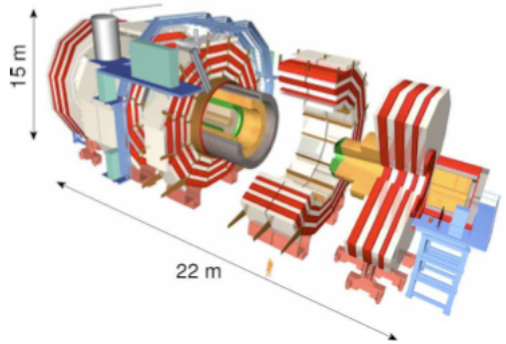


- Trigger Challenge : How to select 400 out of 20M events per second while keeping the interesting (including unknown) physics

- Computing Challenge : How to reconstruct, store and distribute 400 increasingly complex events per second (over 100 PB per experiment)

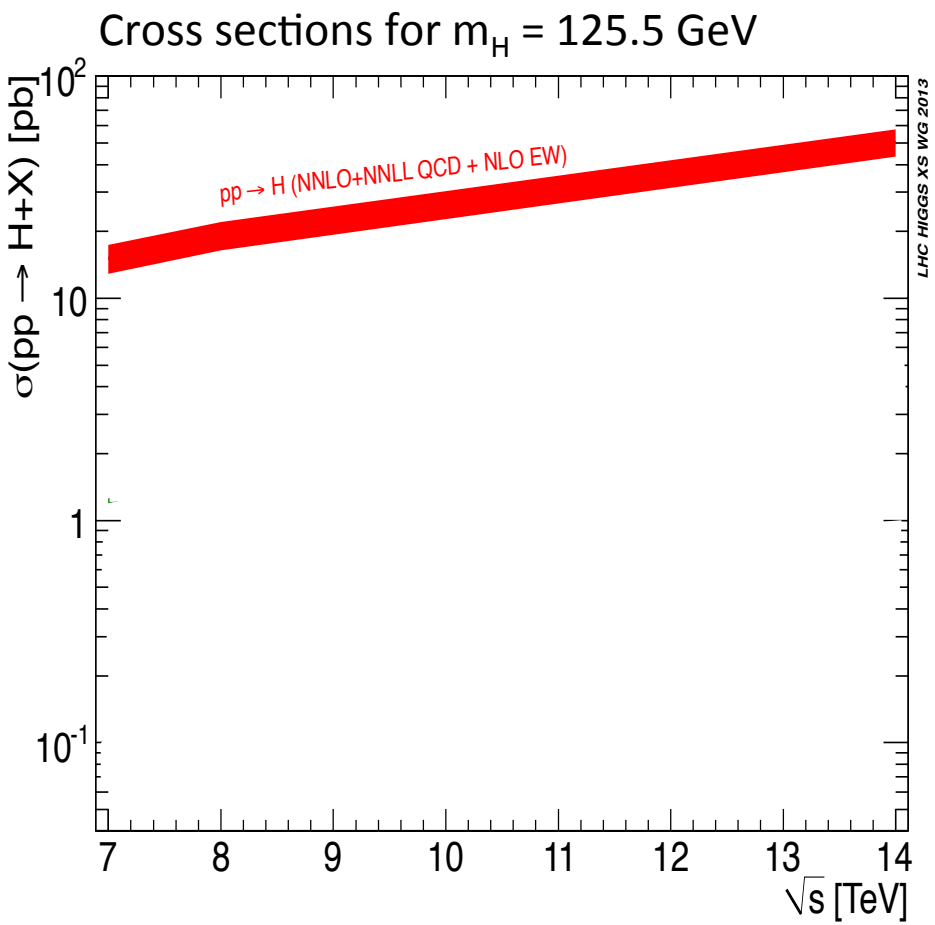
- Analysis Challenge : Maintain high (and as much as possible stable) reconstruction and identification efficiency for physics objects (e, μ, τ, jets, E^T_{mis}, b-jets) up to the highest pile-up

Preamble I: The ATLAS and CMS Detectors In a Nutshell

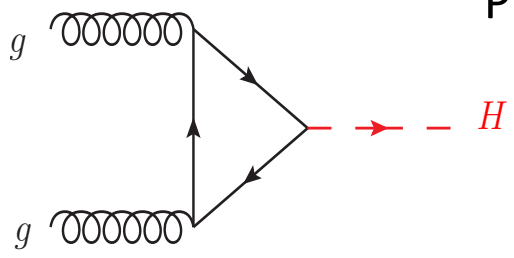
Sub System	ATLAS	CMS
Design		
Magnet(s)	Solenoid (within EM Calo) 2T 3 Air-core Toroids	Solenoid 3.8T Calorimeters Inside
Inner Tracking	Pixels, Si-strips, TRT PID w/ TRT and dE/dx $\sigma_{p_T}/p_T \sim 5 \times 10^{-4} p_T \oplus 0.01$	Pixels and Si-strips PID w/ dE/dx $\sigma_{p_T}/p_T \sim 1.5 \times 10^{-4} p_T \oplus 0.005$
EM Calorimeter	Lead-Larg Sampling w/ longitudinal segmentation $\sigma_E/E \sim 10\%/\sqrt{E} \oplus 0.007$	Lead-Tungstate Crys. Homogeneous w/o longitudinal segmentation $\sigma_E/E \sim 3\%/\sqrt{E} \oplus 0.5\%$
Hadronic Calorimeter	Fe-Scint. & Cu-Larg (fwd) $\gtrsim 11\lambda_0$ $\sigma_E/E \sim 50\%/\sqrt{E} \oplus 0.03$	Brass-scint. $\gtrsim 7\lambda_0$ Tail Catcher $\sigma_E/E \sim 100\%/\sqrt{E} \oplus 0.05$
Muon Spectrometer System Acc. ATLAS 2.7 & CMS 2.4	Instrumented Air Core (std. alone) $\sigma_{p_T}/p_T \sim 4\,\%$ (at 50 GeV) $\sim 11\,\%$ (at 1 TeV)	Instrumented Iron return yoke $\sigma_{p_T}/p_T \sim 1\%$ (at 50 GeV) $\sim 10\%$ (at 1 TeV)

Higgs Production at the LHC and Decay

Production modes at the LHC



Process



Gluon fusion

~0.4 M evts produced at LHC Run 1

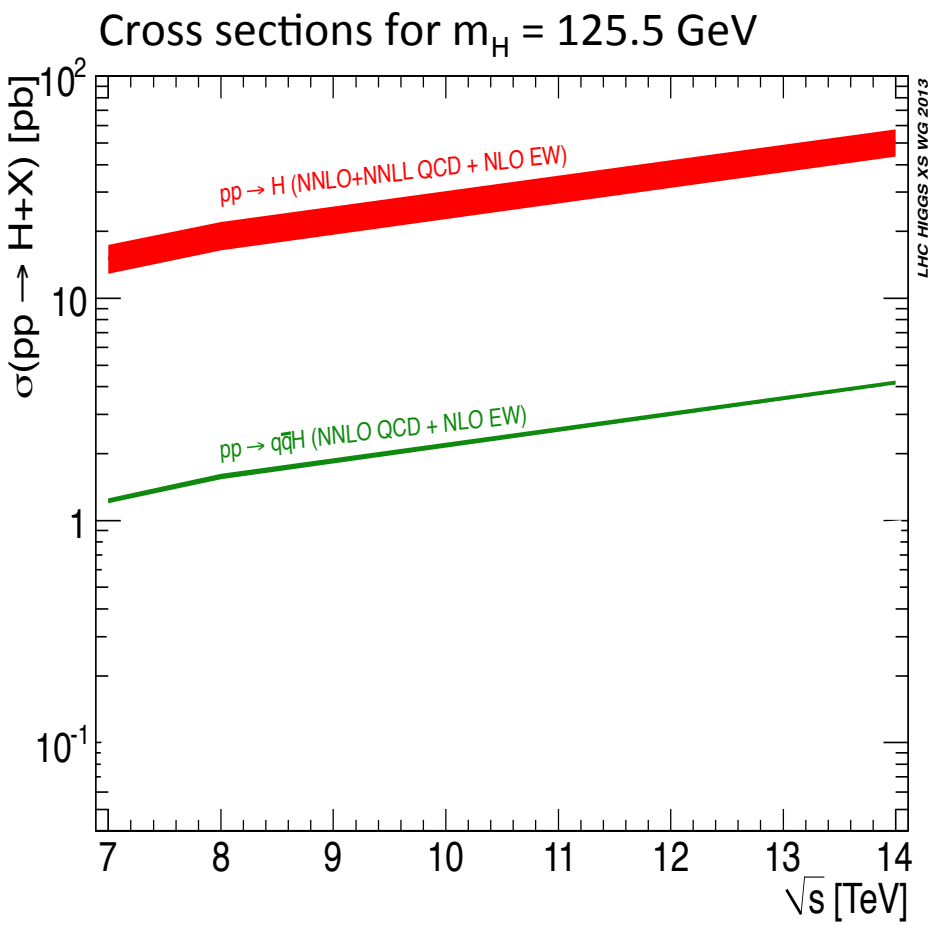
Properties

- Coupling absent at tree level
- Process dominated by a top quark in the loop

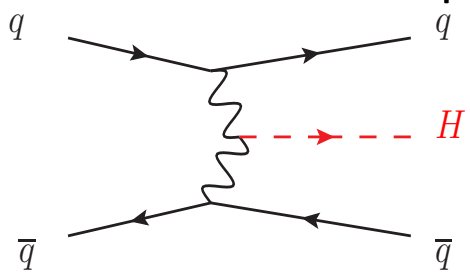
$$\kappa_g^2 \propto 1.\times 06\kappa_t^2 - 0.07\times\kappa_t\kappa_b + 0.01\times\kappa_b^2$$

- Indirectly measures the Yukawa coupling to the top

Production modes at the LHC



Process



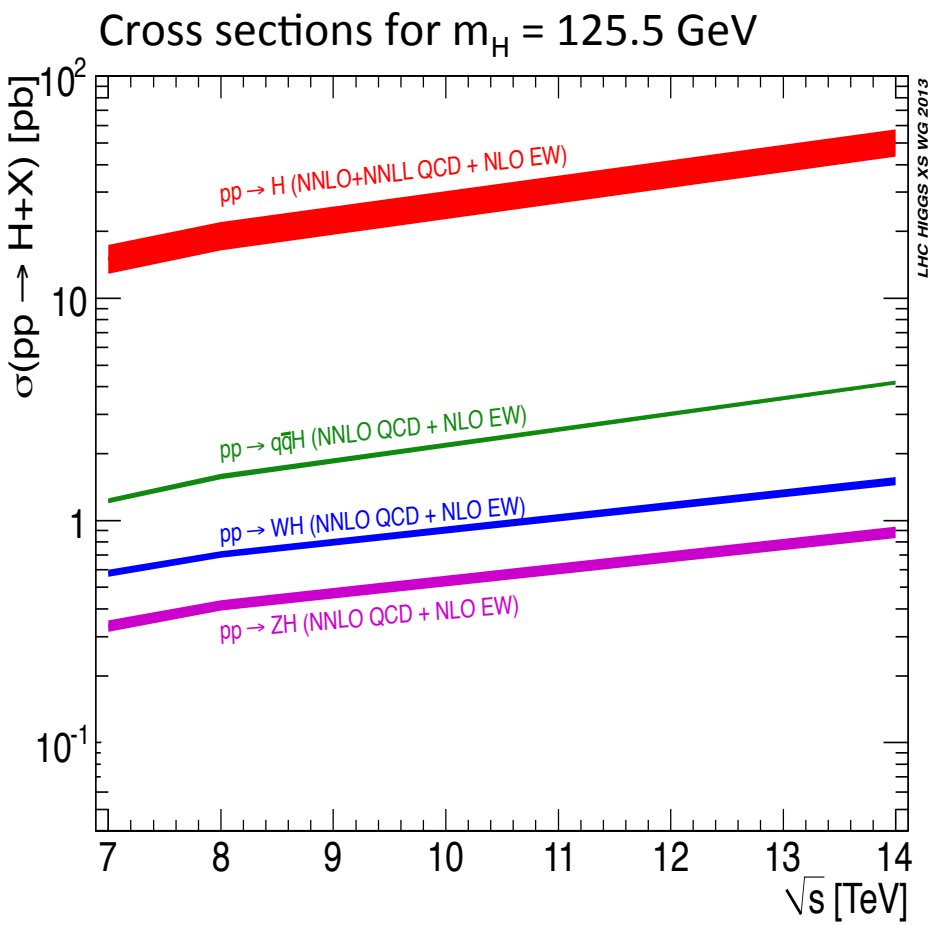
Vector boson fusion

~40 k evts produced at LHC Run 1

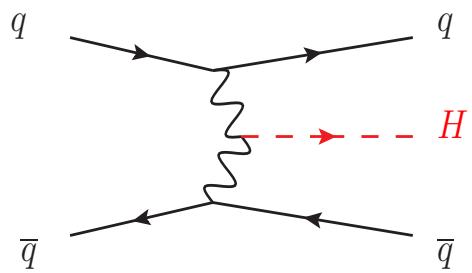
Properties

- Tree level coupling to the gauge bosons
- Distinctive and challenging topology
- Two forward jets and rapidity gap

Production modes at the LHC



Process



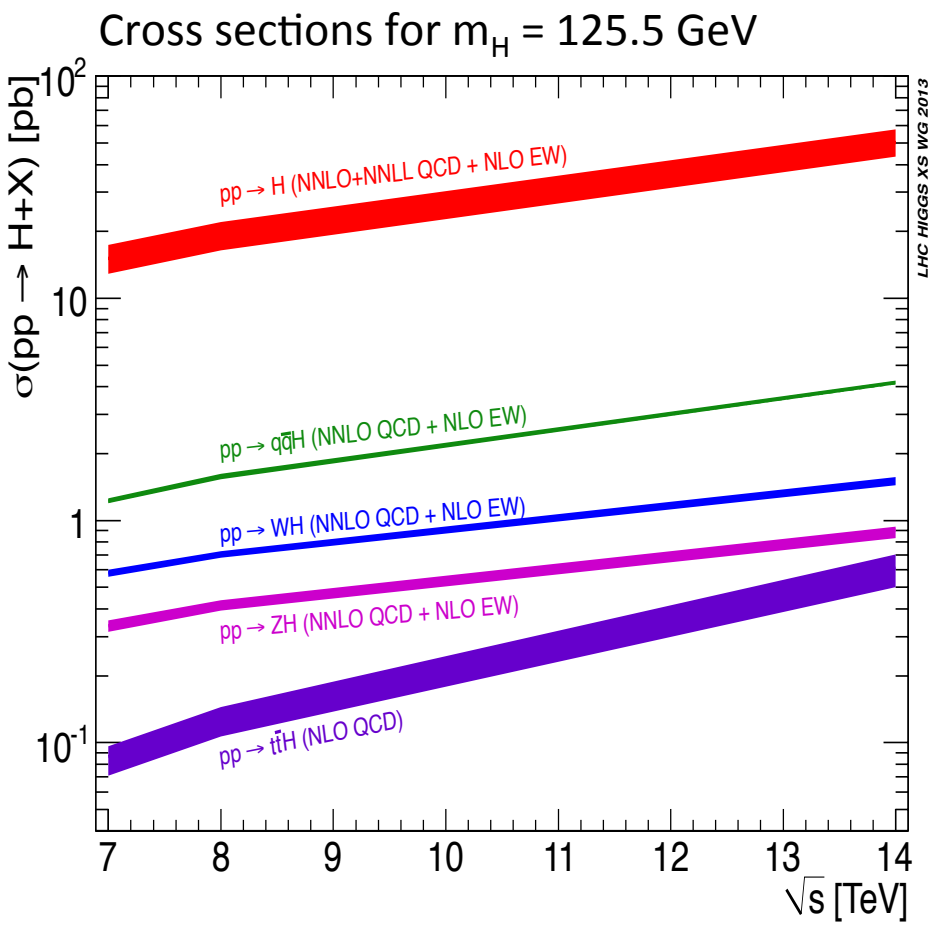
Vector boson fusion

~40 k evts produced at LHC Run 1

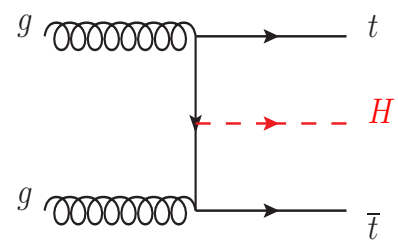
Properties

- Tree level coupling to gauge bosons
- Distinctive topology
- Multiple choices for the decay of the W and the Z boson

Production modes at the LHC



Process



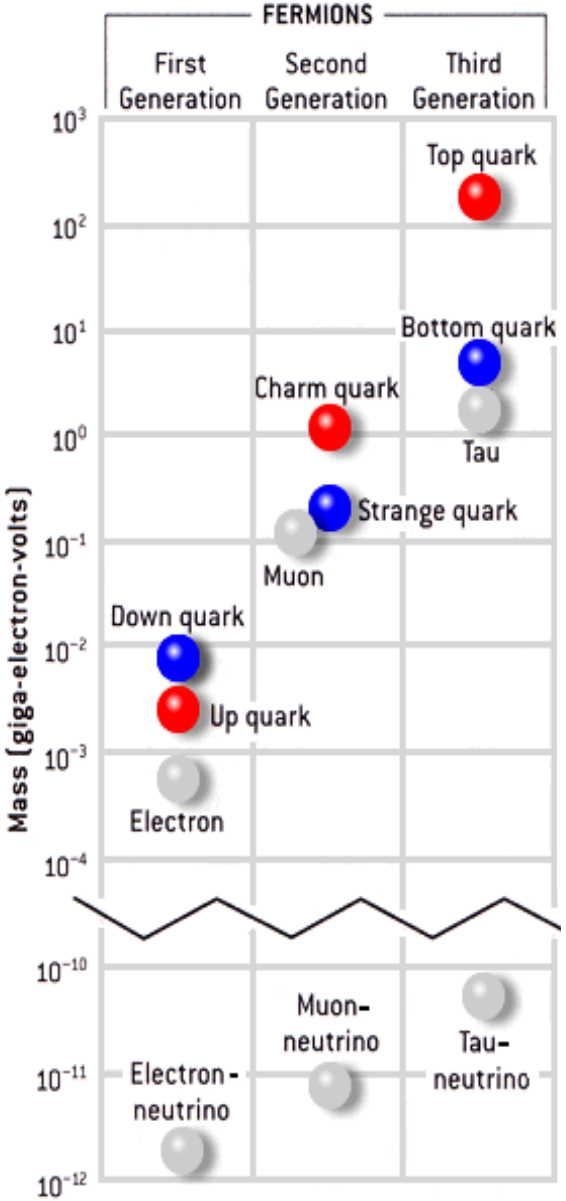
. Top associated production

~3 k evts produced at LHC Run 1

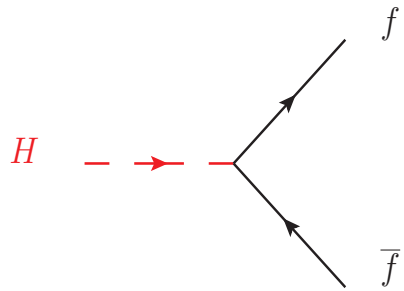
Properties

- Tree level coupling to top quark
- Complex topology with two top quarks in the final states
- Many possible decay modes, relativelylow stats

Non Universal Higgs Couplings and Decay Channels



Yukawa coupling to fermions

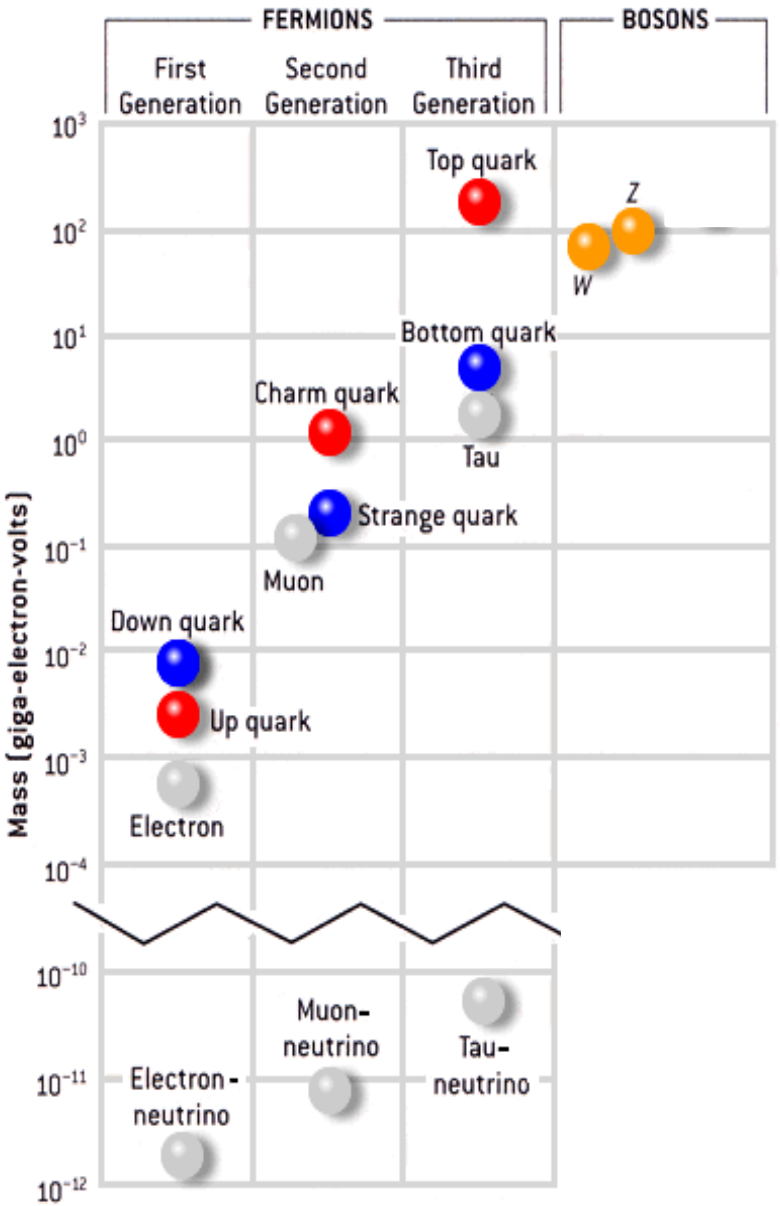


$$\propto \frac{m_f}{v}$$

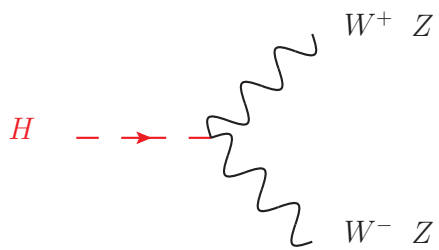
Main channels

- Dominant: bb (57%)
- Most sensitive ττ (6.3%)
- Incredibly difficult (3%)
- Low stat but eventually… μμ (0.02%)

Non Universal Higgs Couplings and Decay Channels



Coupling to Gauge bosons



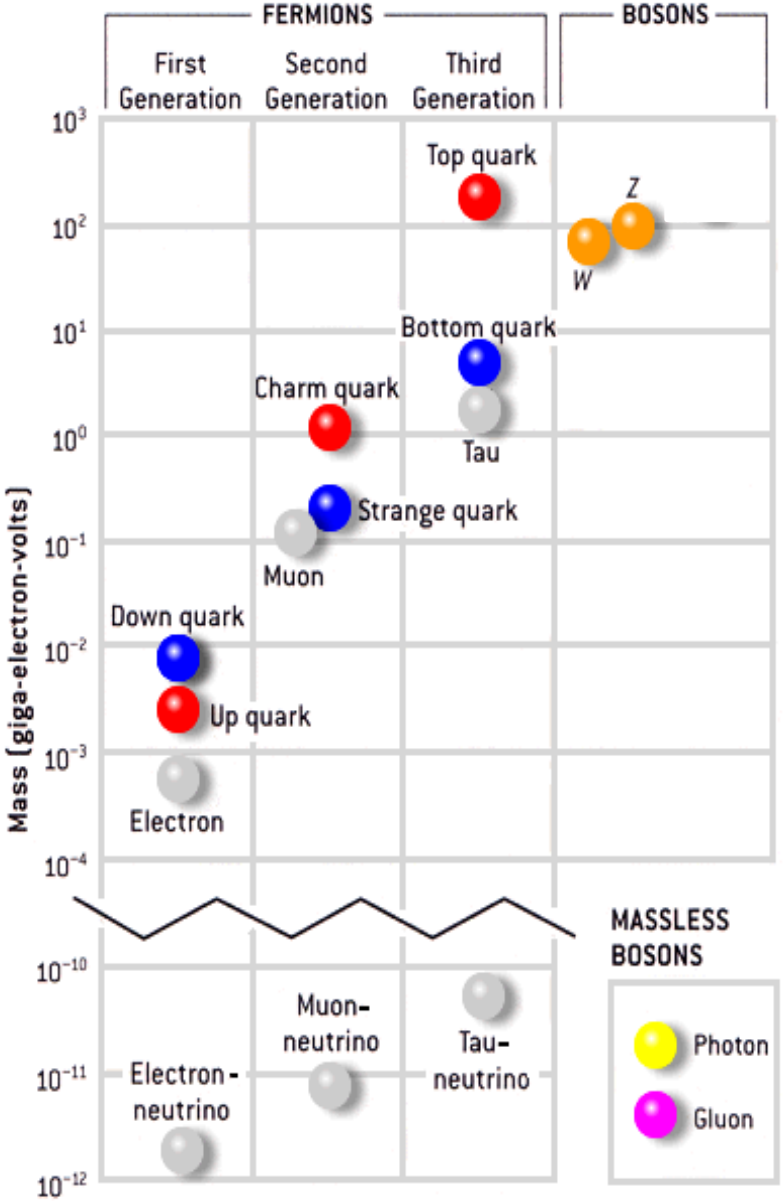
$$\propto \frac{2m_V^2}{v}$$

Main channels

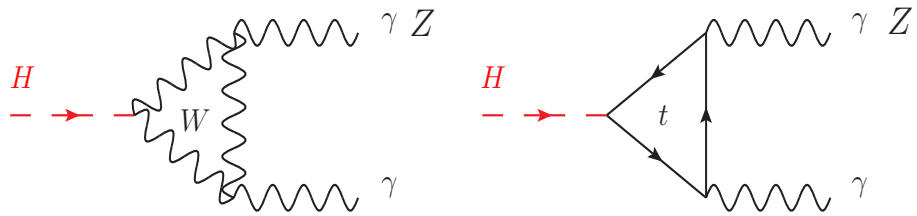
- The ZZ channel (3%)
- The WW channel (22%)

W and Z decay channels typically to leptons

Non Universal Higgs Couplings and Decay Channels



Coupling to photons (and Z and γ)



No coupling at tree level

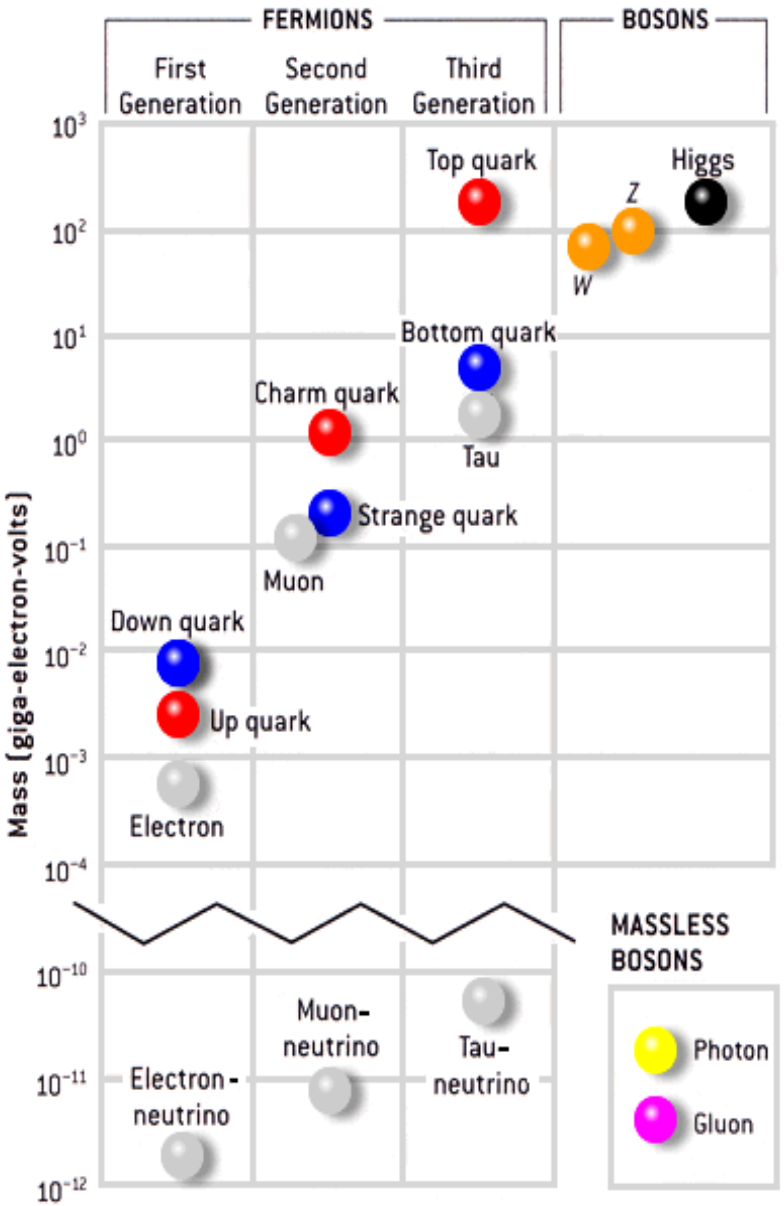
- The γγ channel (0.2%)

$$\kappa_\gamma \propto 1.6 \times \kappa_W^2 - 0.7 \times \kappa_t \kappa_W + 0.1 \times \kappa_t^2$$

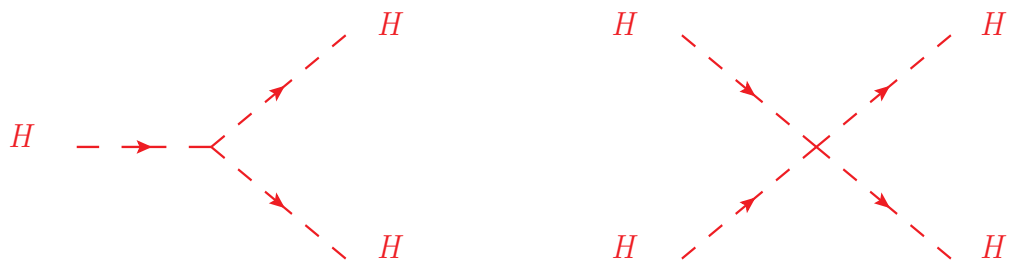
- The Zγ channel (0.2%)

$$\kappa_{Z\gamma} \propto 1.12 \times \kappa_W^2 - 0.15 \times \kappa_t \kappa_W + 0.03 \times \kappa_t^2$$

Non Universal Higgs Couplings and Decay Channels



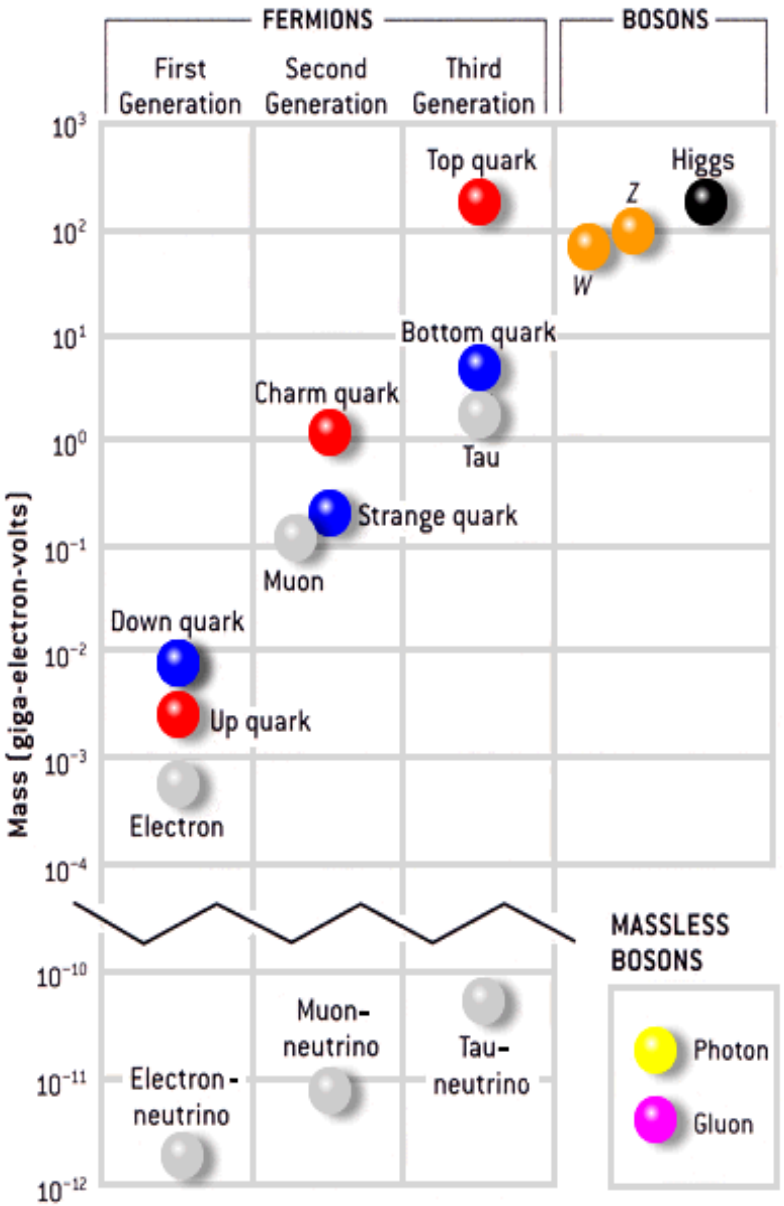
Self couplings



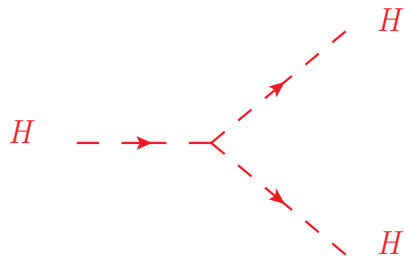
$$\propto \frac{3m_H^2}{v} \qquad \propto \frac{3m_H^2}{v^2}$$

Extremely difficult channels requiring at least one Higgs boson off mass shell

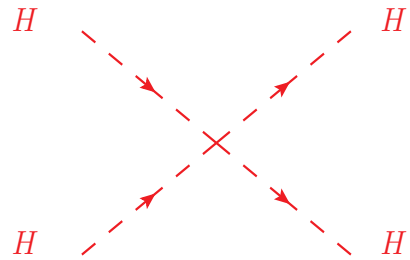
Non Universal Higgs Couplings and Decay Channels



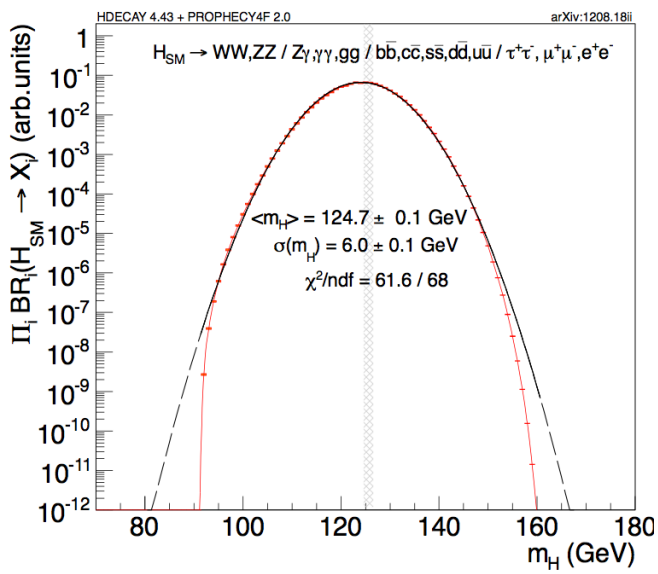
Self couplings



$$\propto \frac{3m_H^2}{v}$$



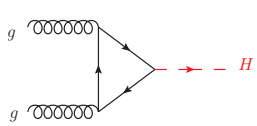
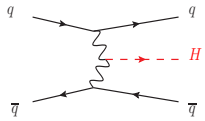
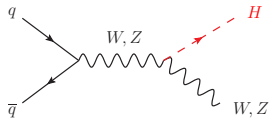
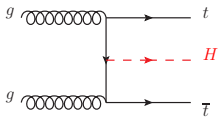
$$\propto \frac{3m_H^2}{v^2}$$



"A Gift of Nature"

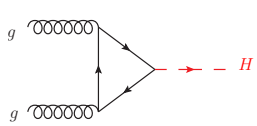
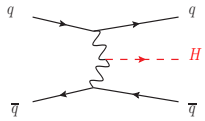
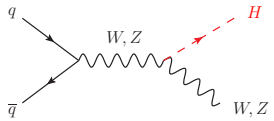
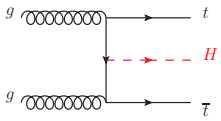
Fabiola Gianotti
(July 4, 2012 CERN)

Panorama of Main Higgs Analyses

Channel categories	ggF 	VBF 	VH 	ttH 
γγ	✓	✓	✓	✓
ZZ (llll)	✓	✓	✓	✓
WW (lνlν)	✓	✓	✓	✓
ττ	✓	✓	✓	✓
bb		✓	✓	✓
Zγ and γγ*	✓	✓		
μμ and ee	✓	✓		
Invisible	✓ (monojet)	✓	✓	

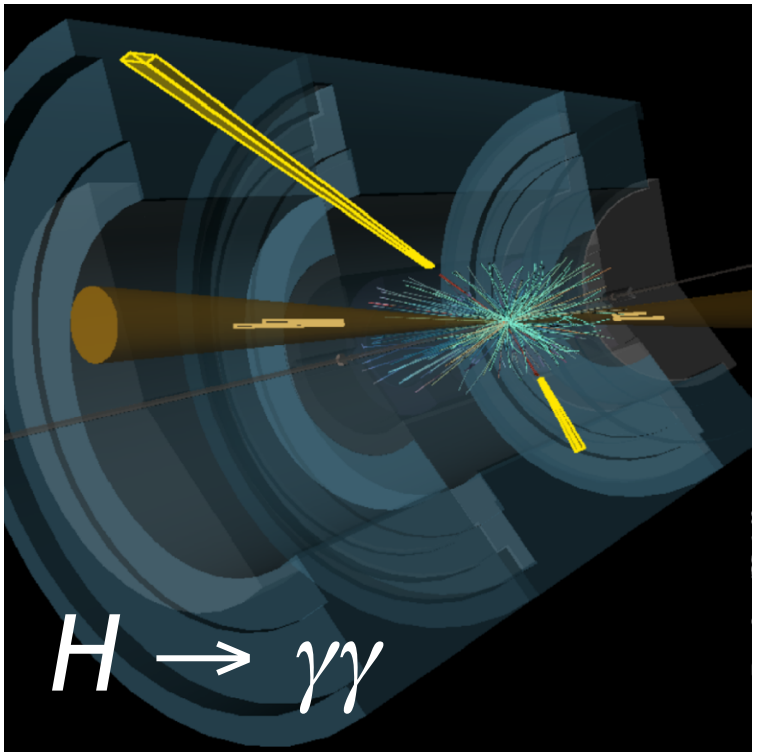
The Discovery Channels

Panorama of Main Higgs Analyses

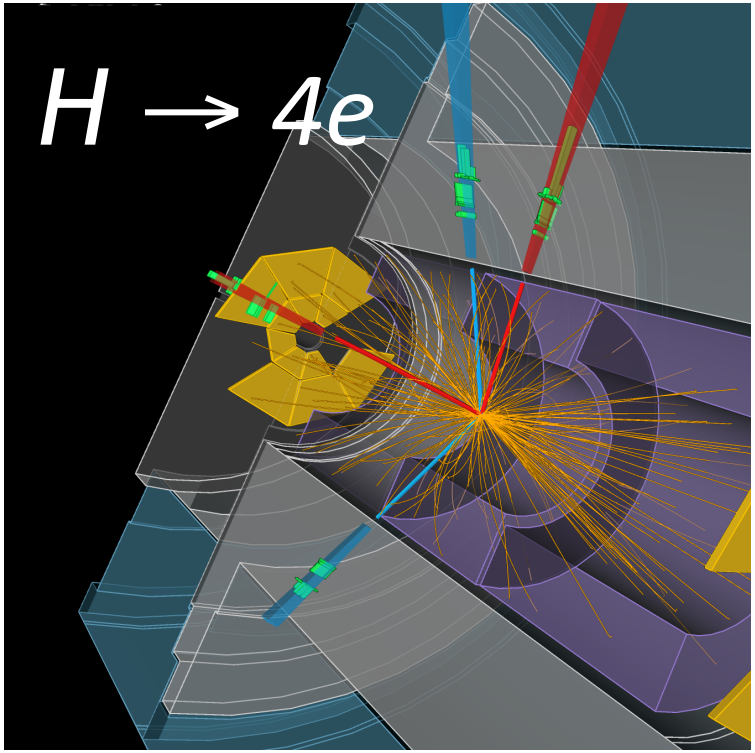
Channel categories	ggF 	VBF 	VH 	ttH 
γγ	✓	✓	✓	✓
ZZ (llll)	✓	✓	✓	✓
WW (lνlν)	✓	✓	✓	✓
ττ	✓	✓	✓	✓
bb		✓	✓	✓
Zγ and γγ*	✓	✓		
μμ and ee	✓	✓		
Invisible	✓ (monojet)	✓	✓	

The two Main discovery Chanels

An excellent chanel for a Higgs boson near 125 GeV



The Golden chanel over a large range in mass



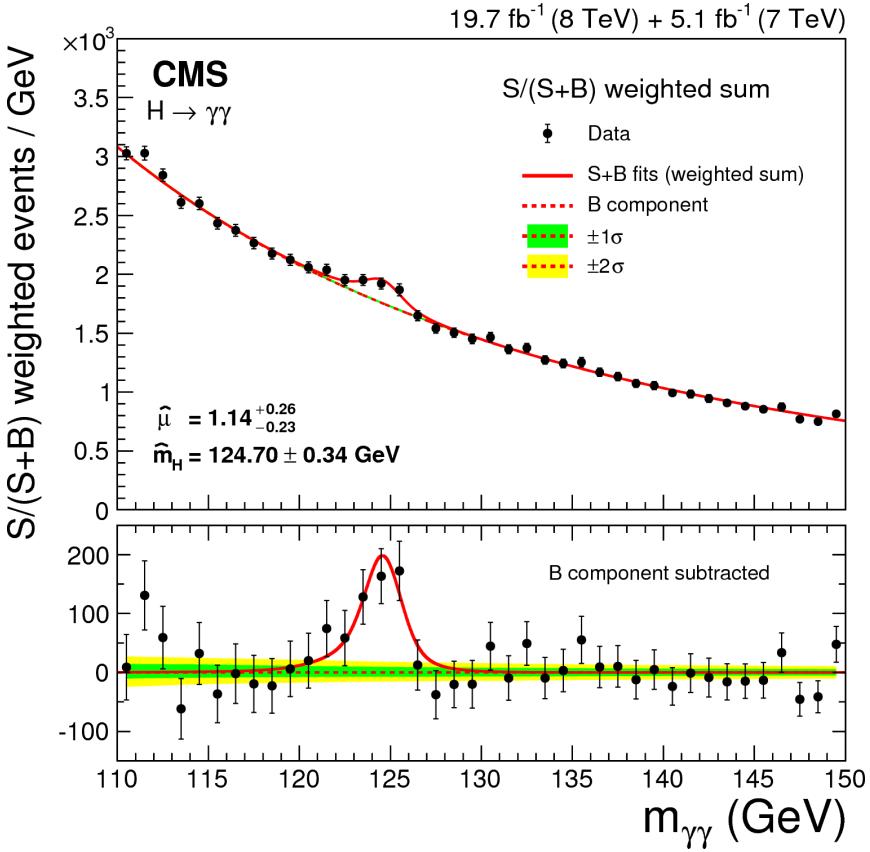
Inclusive approximate number of selected signal events

$$n_s \sim 500$$

$$n_s \sim 20 - 30$$

Very simple channels, with excellent mass resolution (unambiguous signatures)

The Discovery and the Measurement are fully lead by two channels



ATLAS

$$m_H = 125.4 \pm 0.27$$

$$Z = 5.2\ (4.6)\ \sigma$$

$$\mu = 1.18 \pm 0.27$$

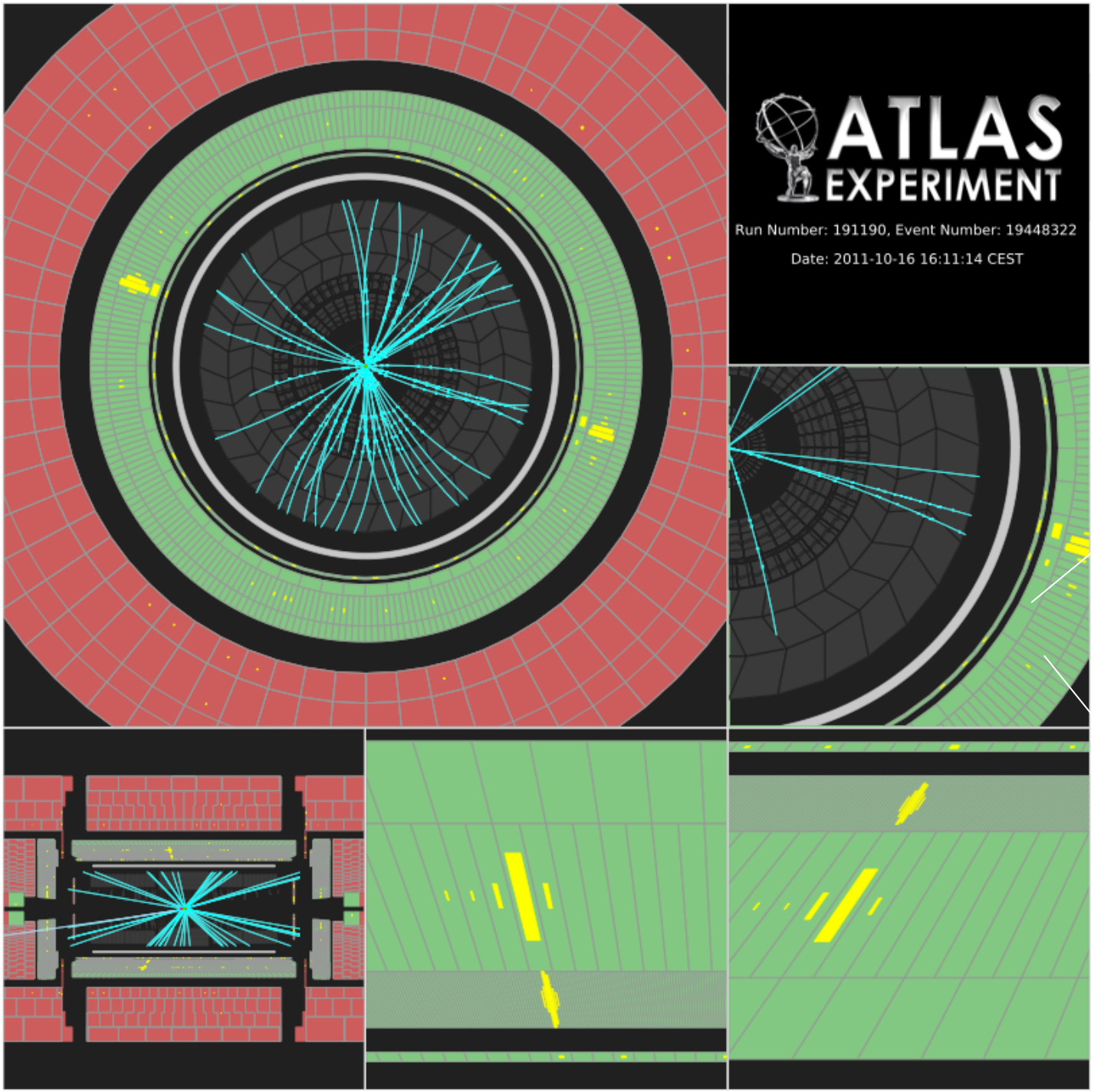
CMS

$$m_H = 124.7 \pm 0.34$$

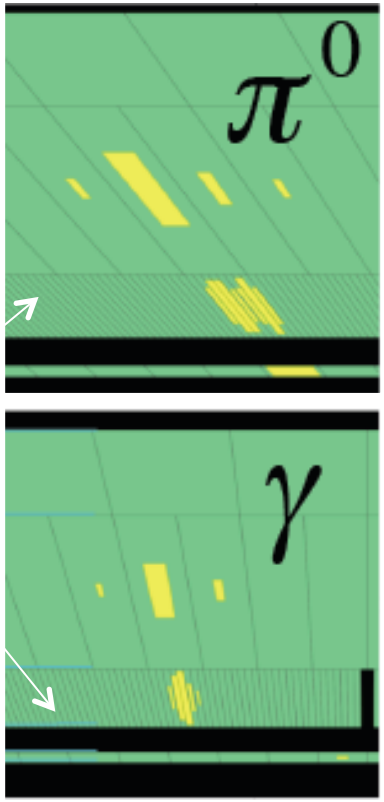
$$Z = 5.7\ (5.2)\ \sigma$$

$$\mu = 1.14 \pm 0.26$$

- s/b ratio ranging from few % to approximately 30%
- Uses exclusive production (VBF,VH and ttH) not for the mass measurement
- Uses Higgs pT as discriminating variable

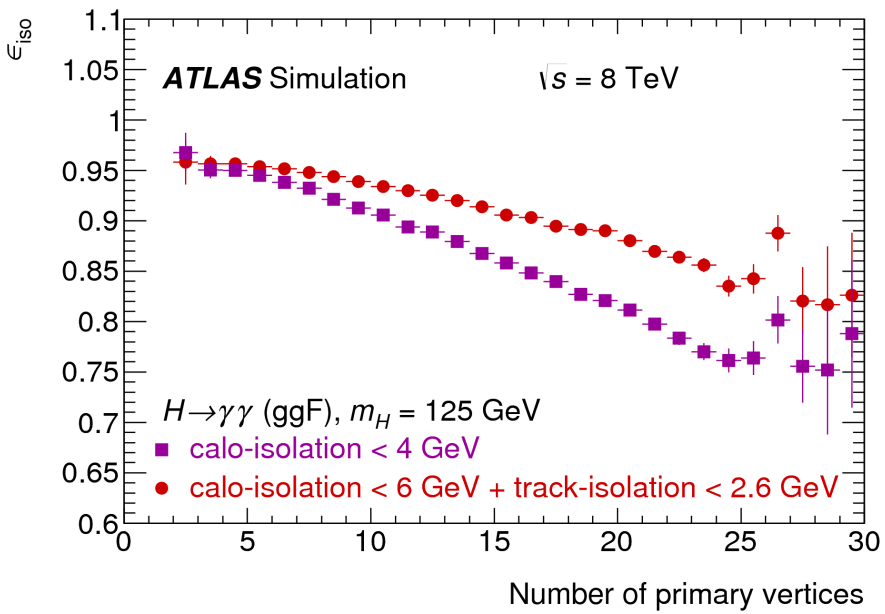


Background
From jets

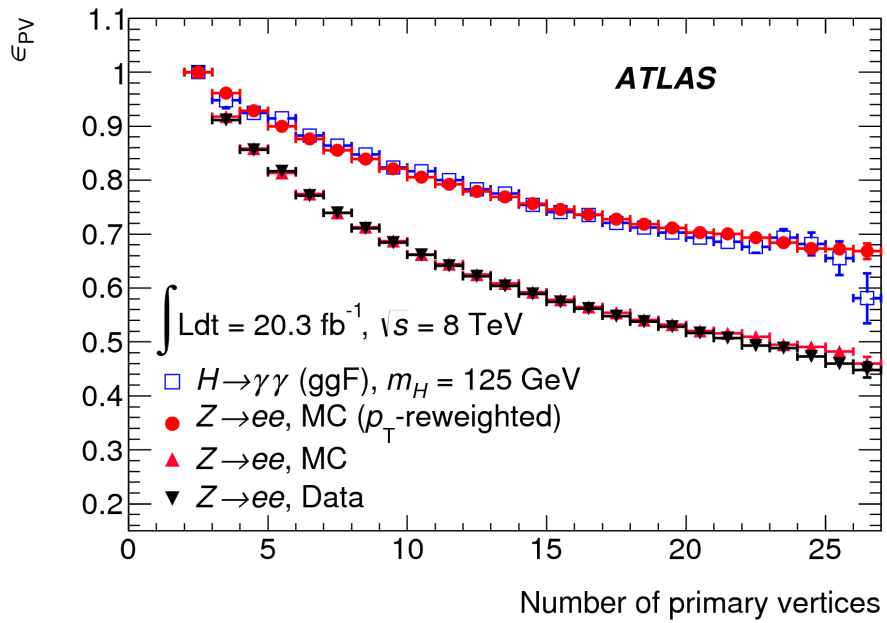


Signal

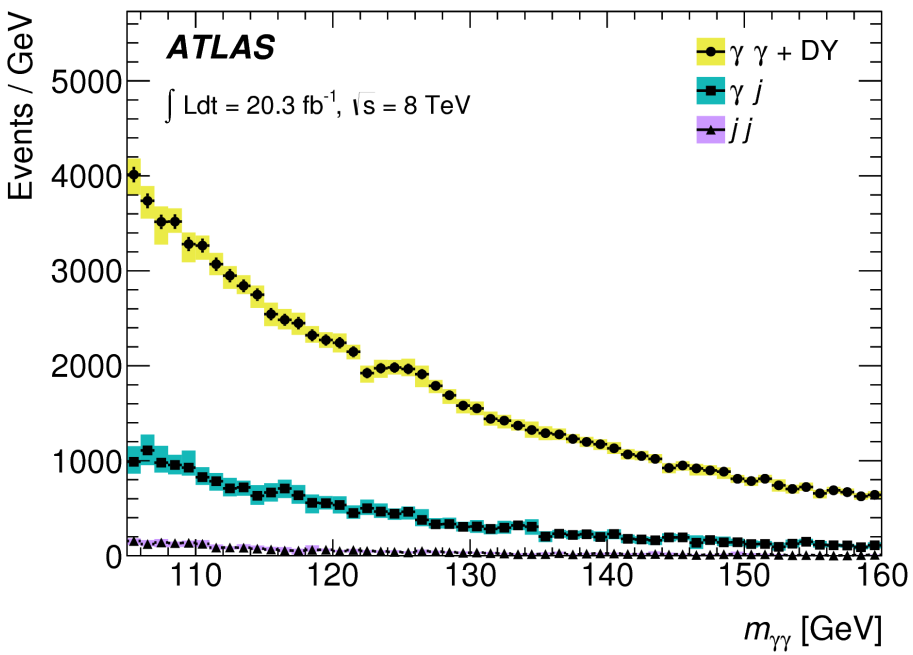
Isolated Photon Identification

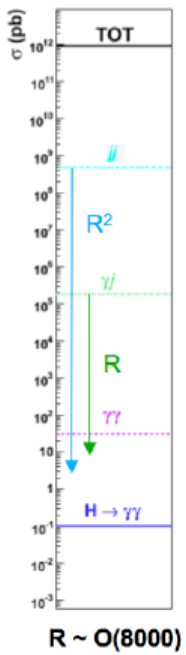


PV reconstruction



Bkg rejection

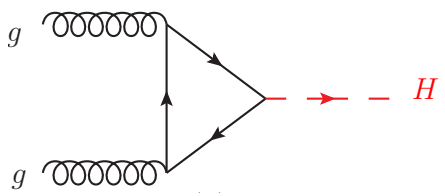


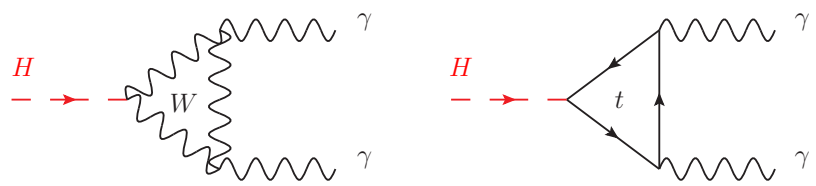


Interesting Facts about the γγ Channel

- Main production and decay processes occur through loops :

Excellent probe for new physics !





A priori potentially large possible enhancement…

$$1.6 \times A_W^2 - 0.7 \times A_t A_W + 0.1 \times A_t^2$$

… Not so obviously enhanced (e.g. SM4)

Seldom larger yields : e.g. NMSSM (U. Ellwanger et al.) up to x6, large stau mixing (M. Carena et al.), Fermiophobia…

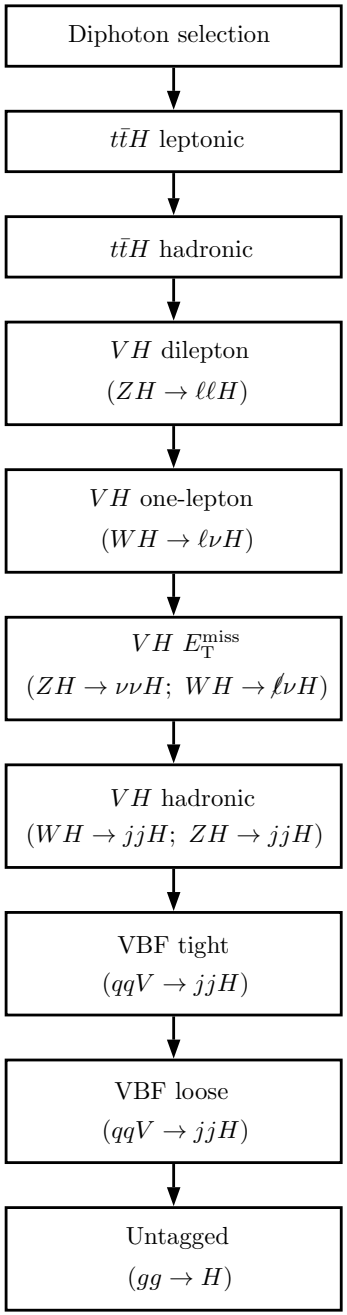
- High mass resolution channel

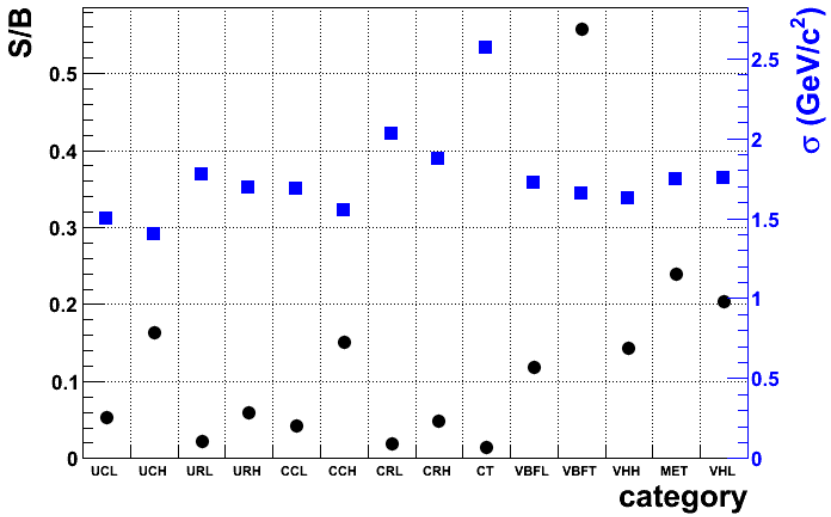
- If observed implies that it does not originate from spin 1 : Landau-Yang theorem

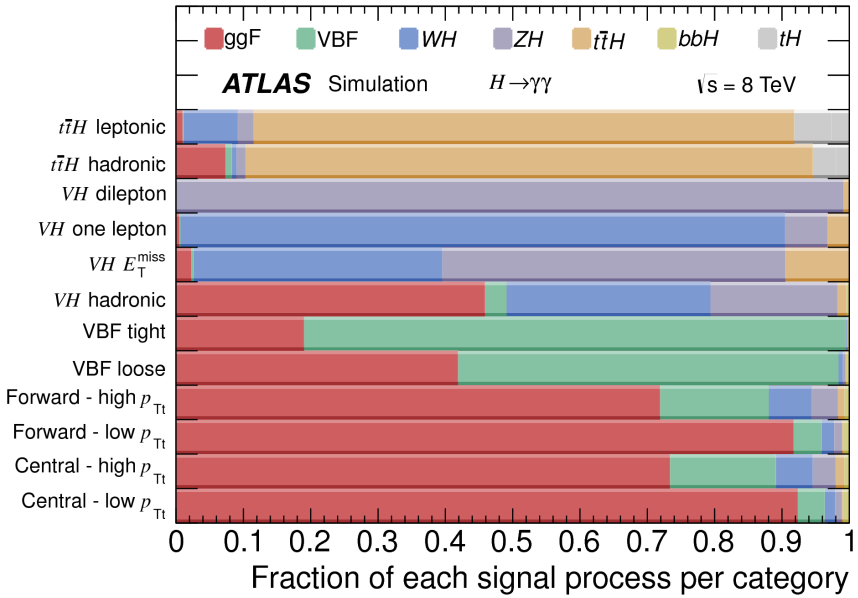
- If observed implies that its Charge Conjugation is +1 (assuming C and P separately conserved)

Improving Sensitivity and Probing Production Modes

Performing analysis with *categories*







Why Categories?

Let's take a simple example with two categories:

- C1: s=12 and b=60
- C2: s=18 and b=40

Inclusively we have a significance of 3

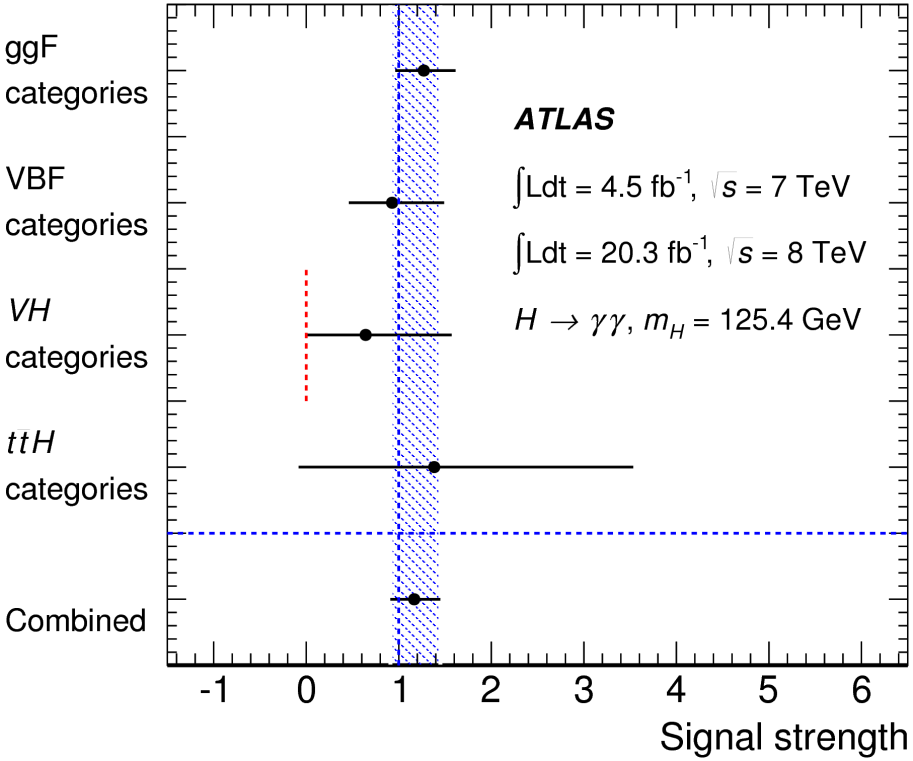
Separating in two categories:

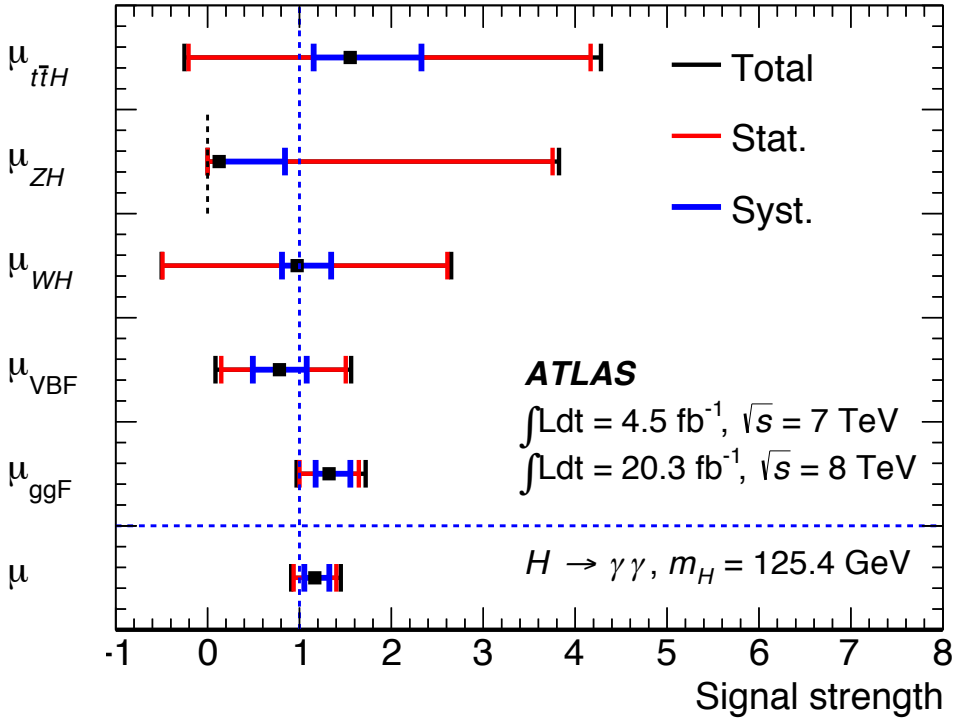
- C1 2.85 σ
- C2 1.55 σ

Combined significance: 3.24

Analyses in Categories

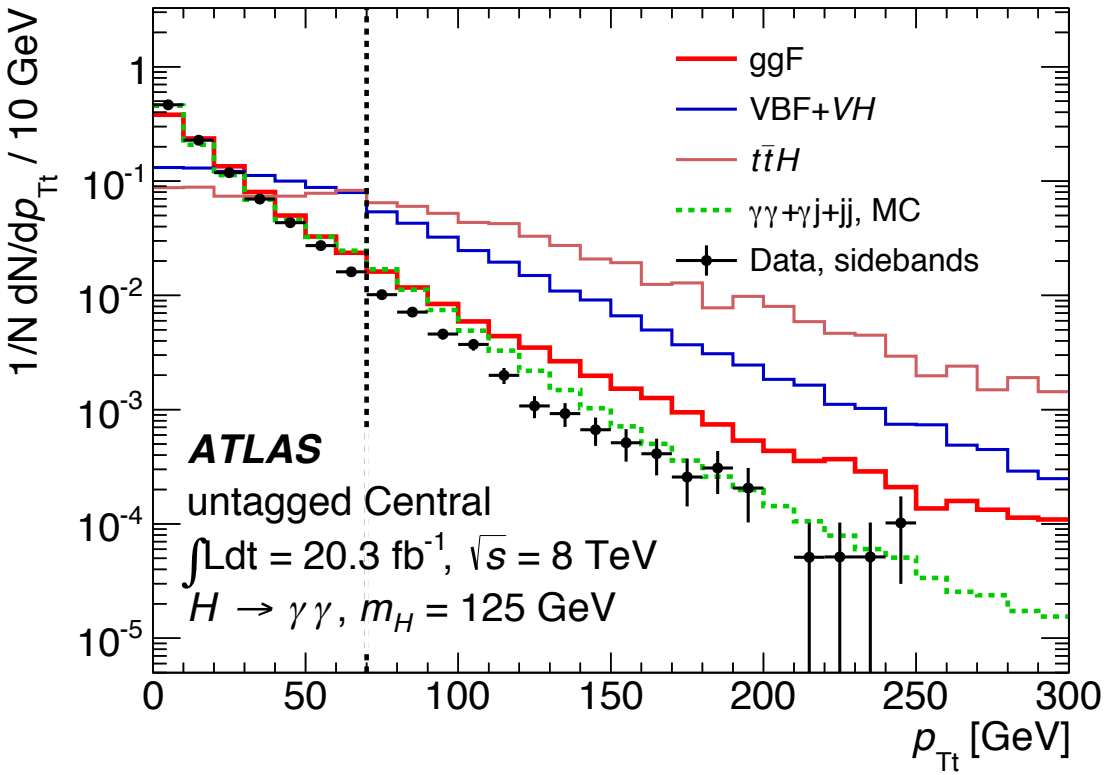
Resolving an over-constrained linear system of N(>5) equations and 5 unknowns



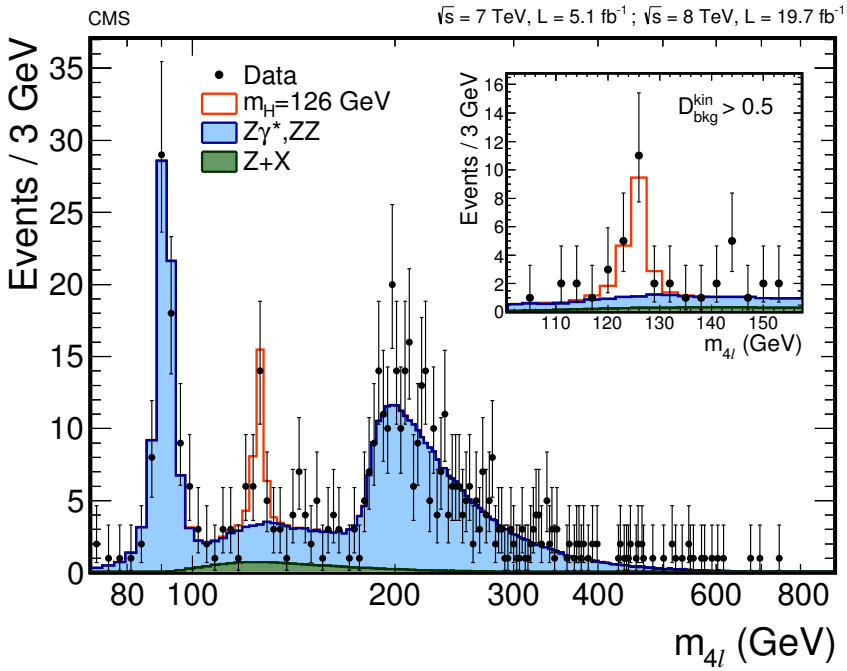


$$\begin{pmatrix} n_s^1 \\ \vdots \\ n_s^N \end{pmatrix} = \begin{pmatrix} \varepsilon_{ggF}^1 A_{ggF}^1 L^1 & \varepsilon_{VBF}^1 A_{VBF}^1 L^1 & \varepsilon_{VH}^1 A_{VH}^1 L^1 & \varepsilon_{ttH}^1 A_{ttH}^1 L^1 \\ \vdots & \vdots & \vdots & \vdots \\ \varepsilon_{ggF}^N A_{ggF}^N L^N & \varepsilon_{VBF}^N A_{VBF}^N L^N & \varepsilon_{VH}^N A_{VH}^N L^N & \varepsilon_{ttH}^N A_{ttH}^N L^N \end{pmatrix} \begin{pmatrix} \mu_{ggF}\sigma_{ggF}^{SM} \\ \mu_{VBF}\sigma_{VBF}^{SM} \\ \mu_{VH}\sigma_{VH}^{SM} \\ \mu_{ttH}\sigma_{ttH}^{SM} \end{pmatrix} B_{\gamma\gamma}^{SM}$$

The Importance of the Higgs Boson Transverse Momentum



The Discovery and the Measurement are fully lead by two channels



ATLAS

$$m_H = 125.4 \pm 0.27$$

$$Z = 8.1\ (6.2)\ \sigma$$

$$\mu = 1.66^{+0.44}_{-0.37}$$

CMS

$$m_H = 125.6 \pm 0.45$$

$$Z = 6.8\ (6.7)\ \sigma$$

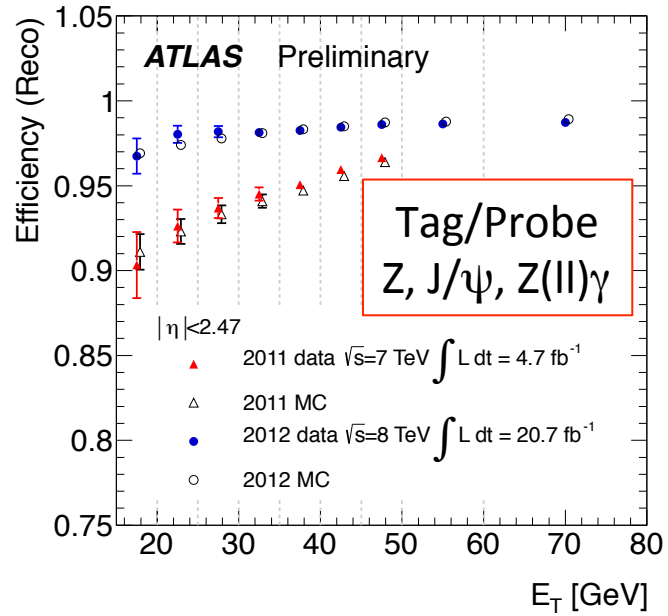
$$\mu = 0.93 \pm 0.29$$

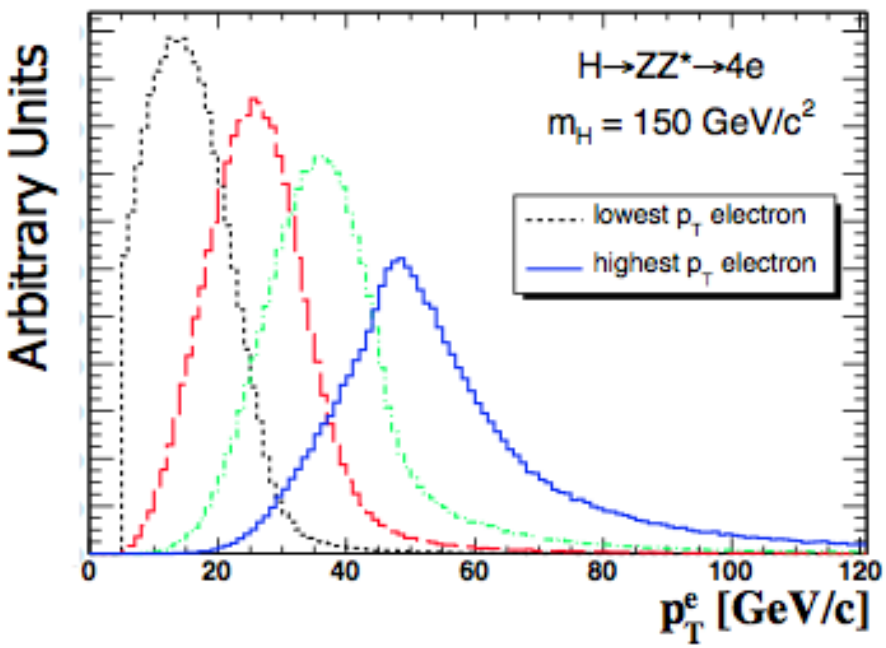
- High s/b ratio from approximately 1.5 up to more than 10
- Uses exclusive production (VBF,VH and ttH)
- Uses Higgs pT as discriminating variable
- Uses angular variables to discriminate background

Key features

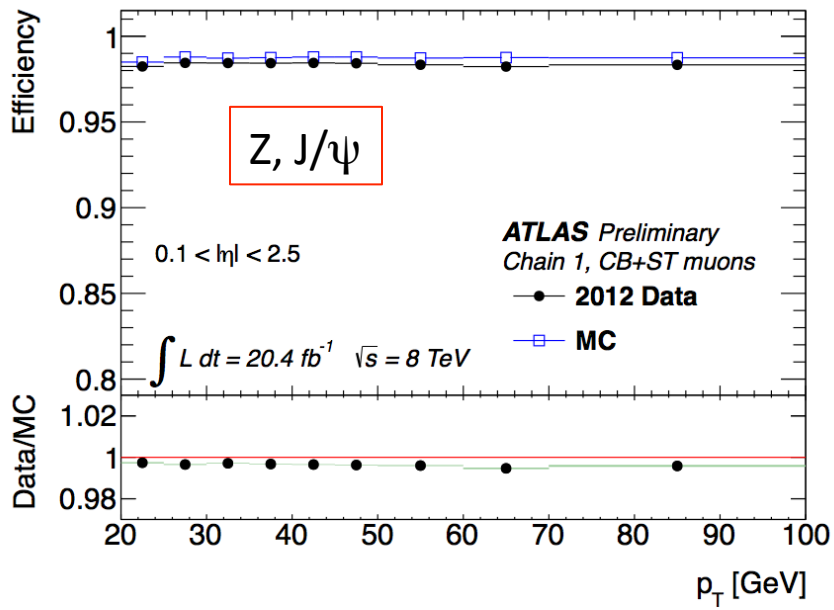
- One Z allowed to be off-mass shell (m_H < 180 GeV)
- low p_T lepton reconstruction very important
- Invariant mass selections also important to optimize low mass selection
- Main Background ZZ from Monte Carlo or from high mass data
- Other backgrounds (Zbb and top) data driven (small)

Electrons





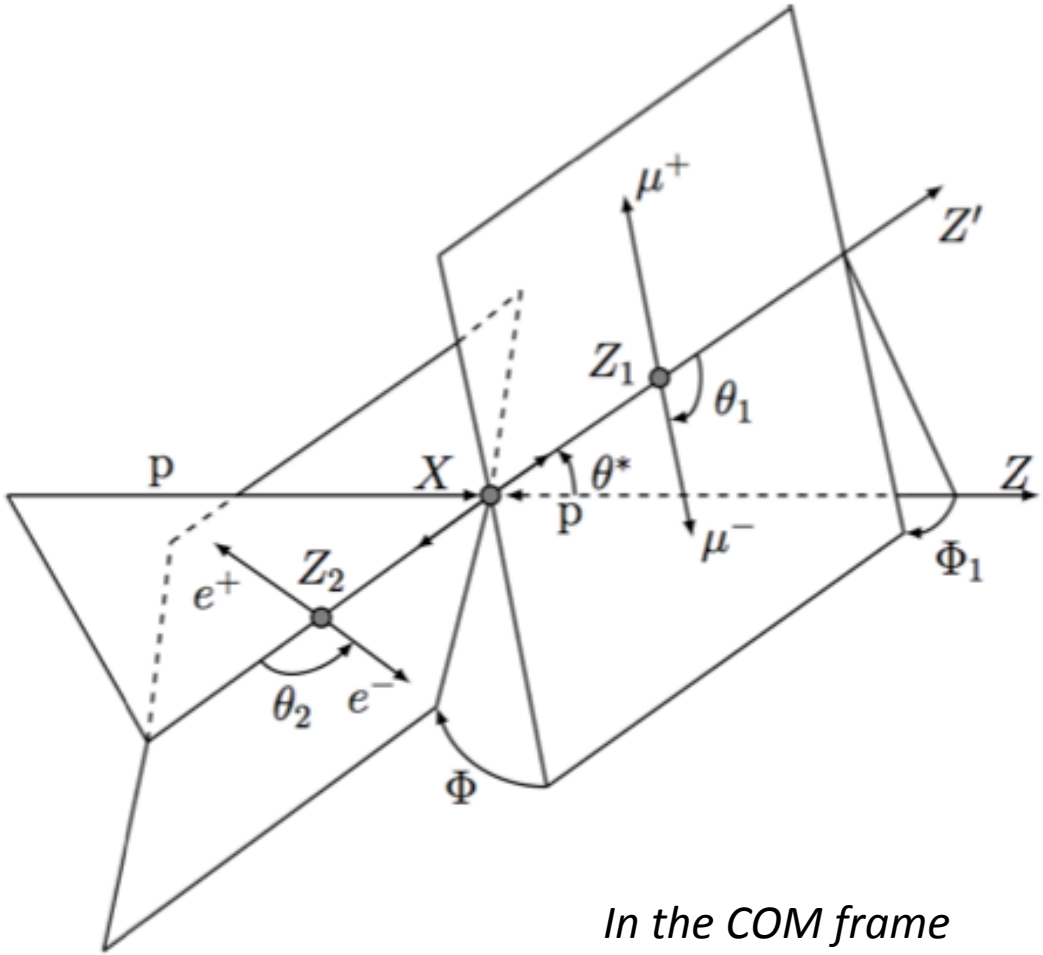
Muon



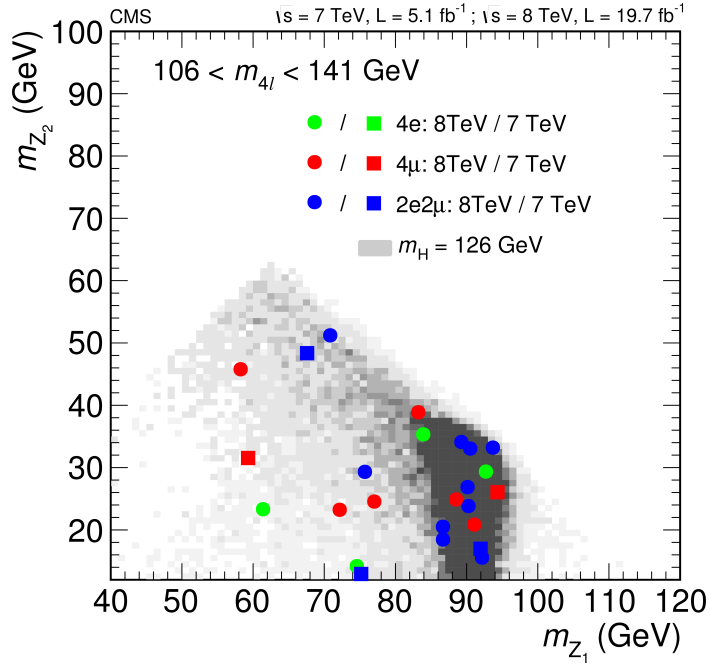
Analysis of in the $H \rightarrow 4l$ Channel

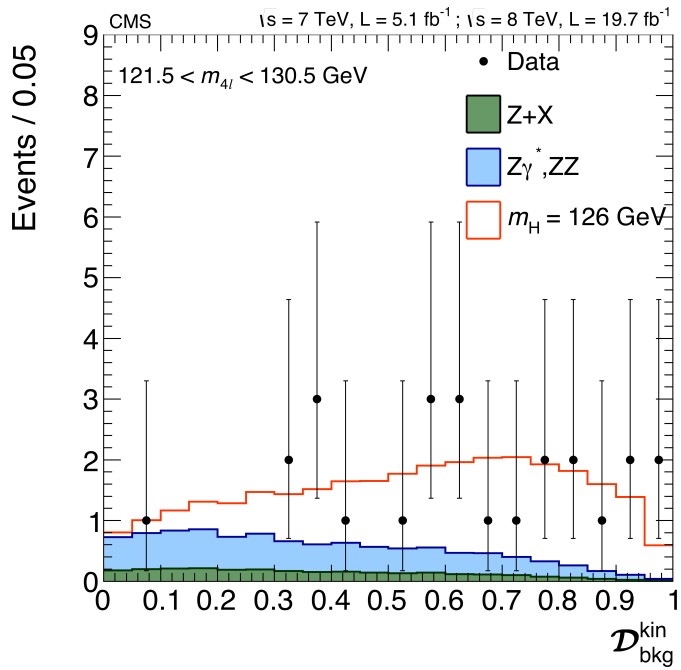
- Use distributions of 2 production and 3 decay angles
- … and the Z_1 and Z_2 masses

Combination of this information through LO Matrix Element based event probabilities or MVA



In the COM frame

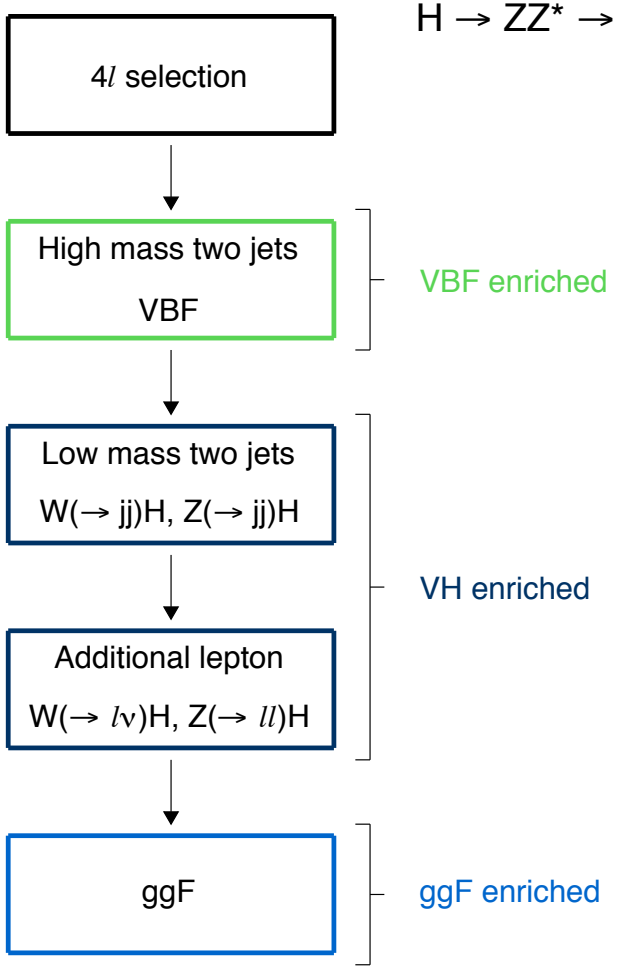


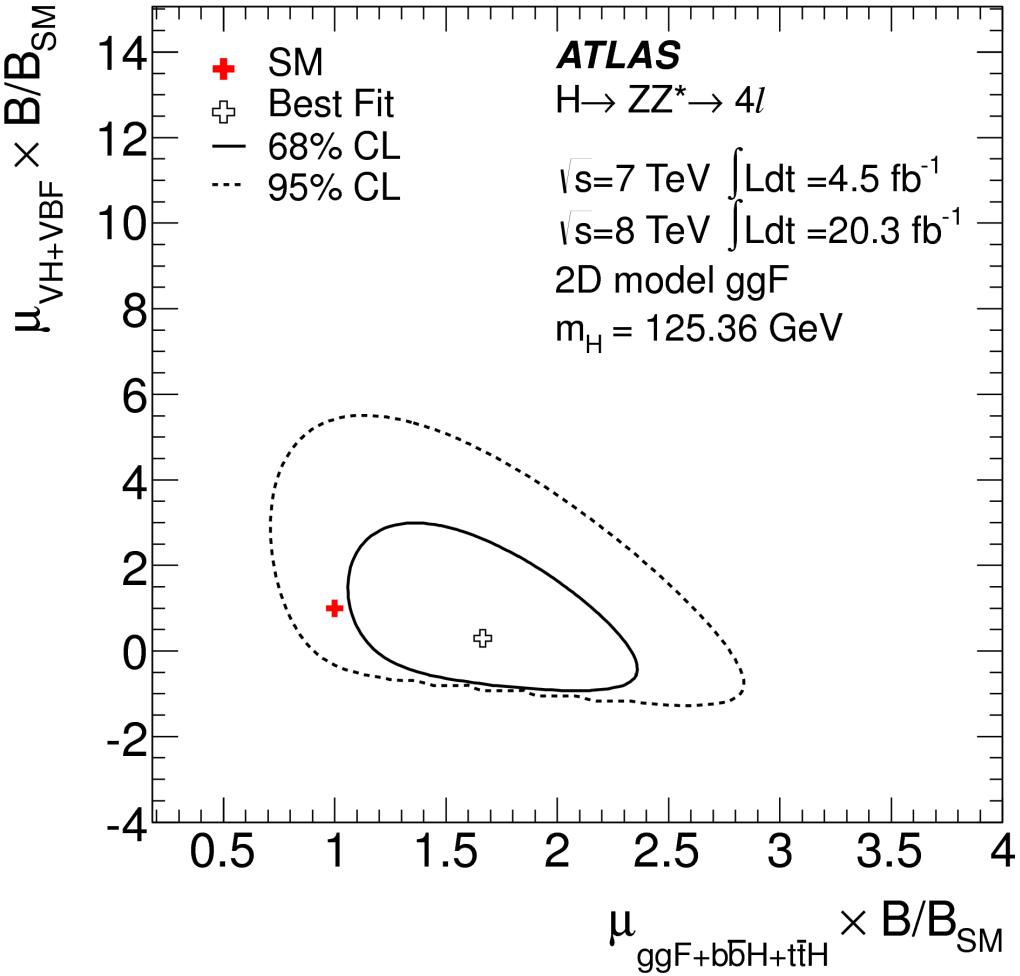


Analyses in Categories

Less sensitive in low statistics categories…

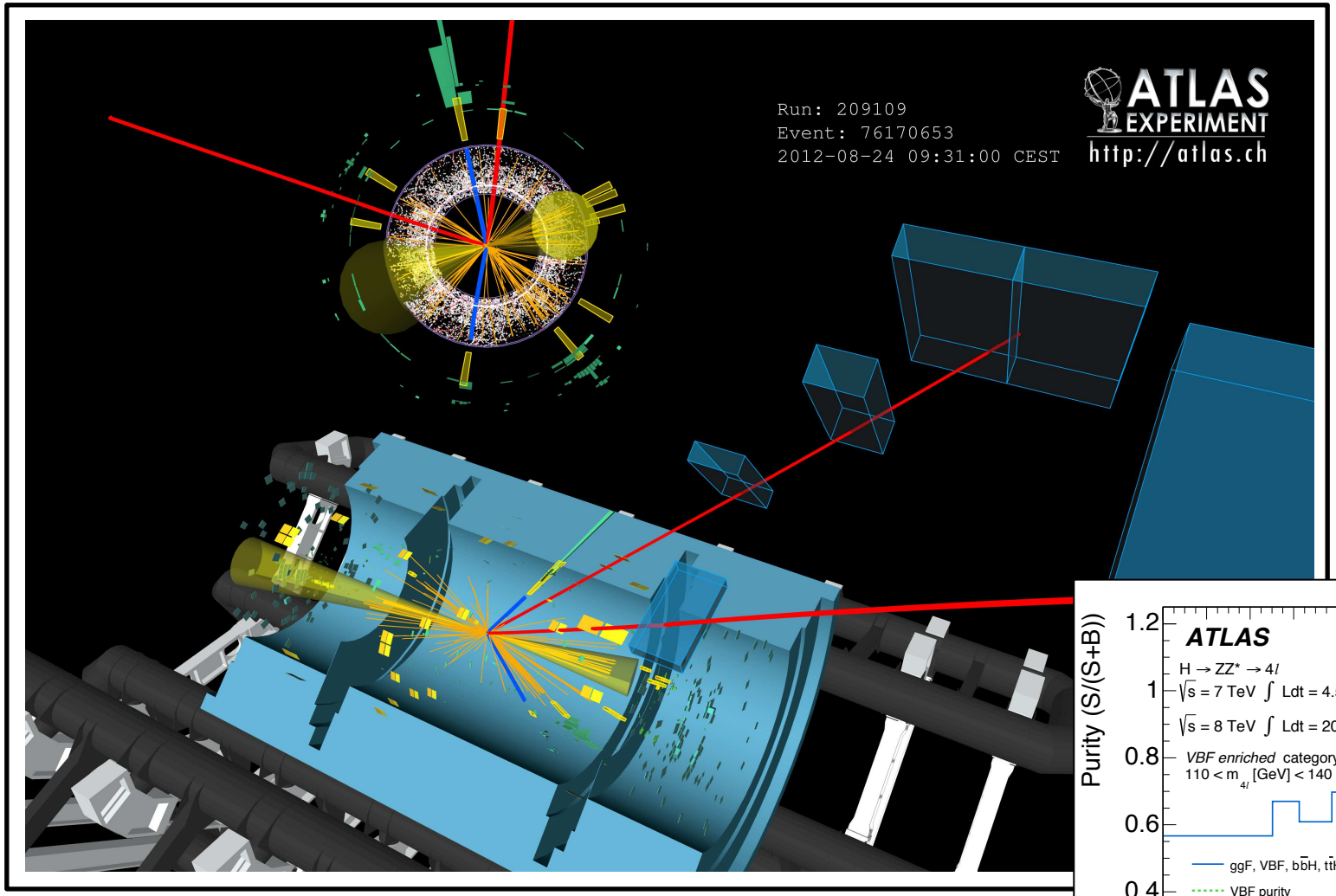
$H \rightarrow ZZ^* \rightarrow 4l$

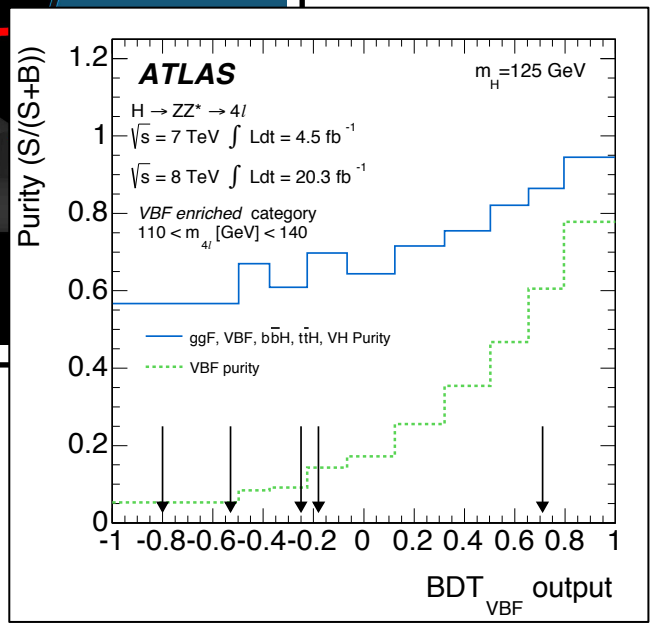




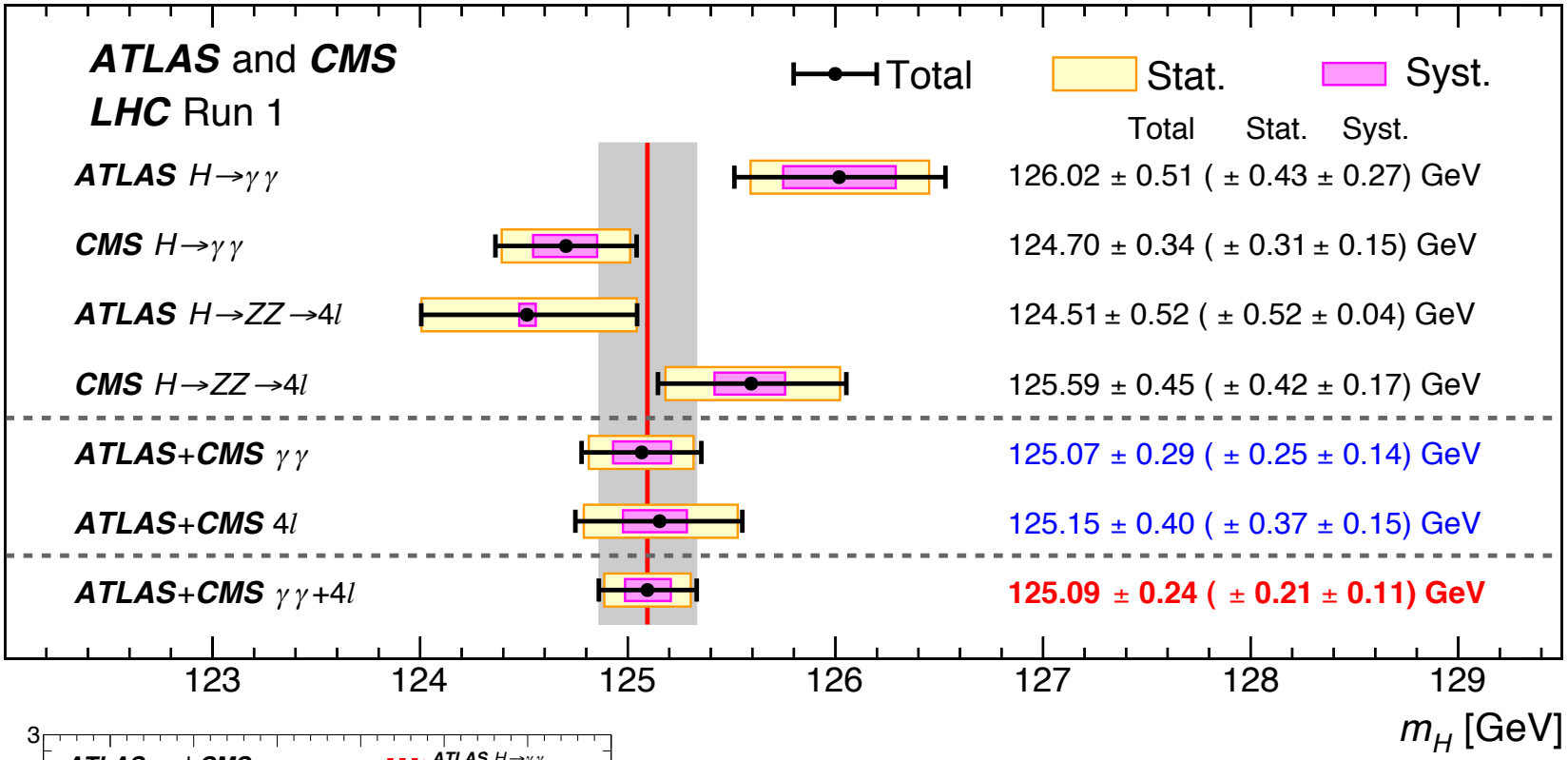
… will improve rapidly

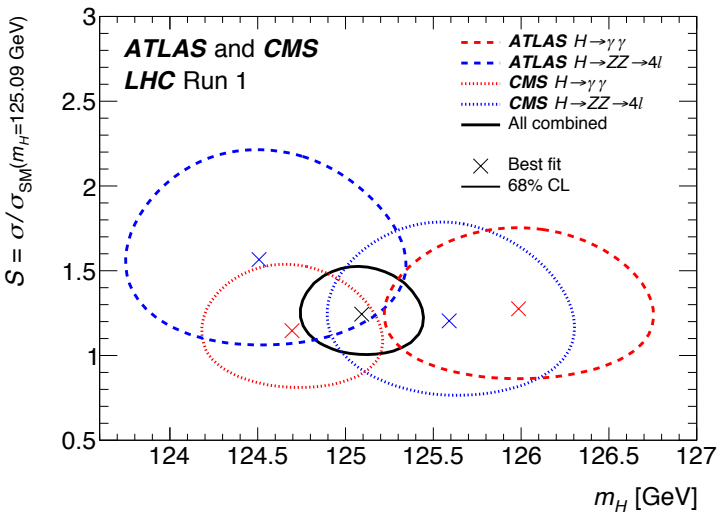
Bright Future for Higgs analyses at Run 2





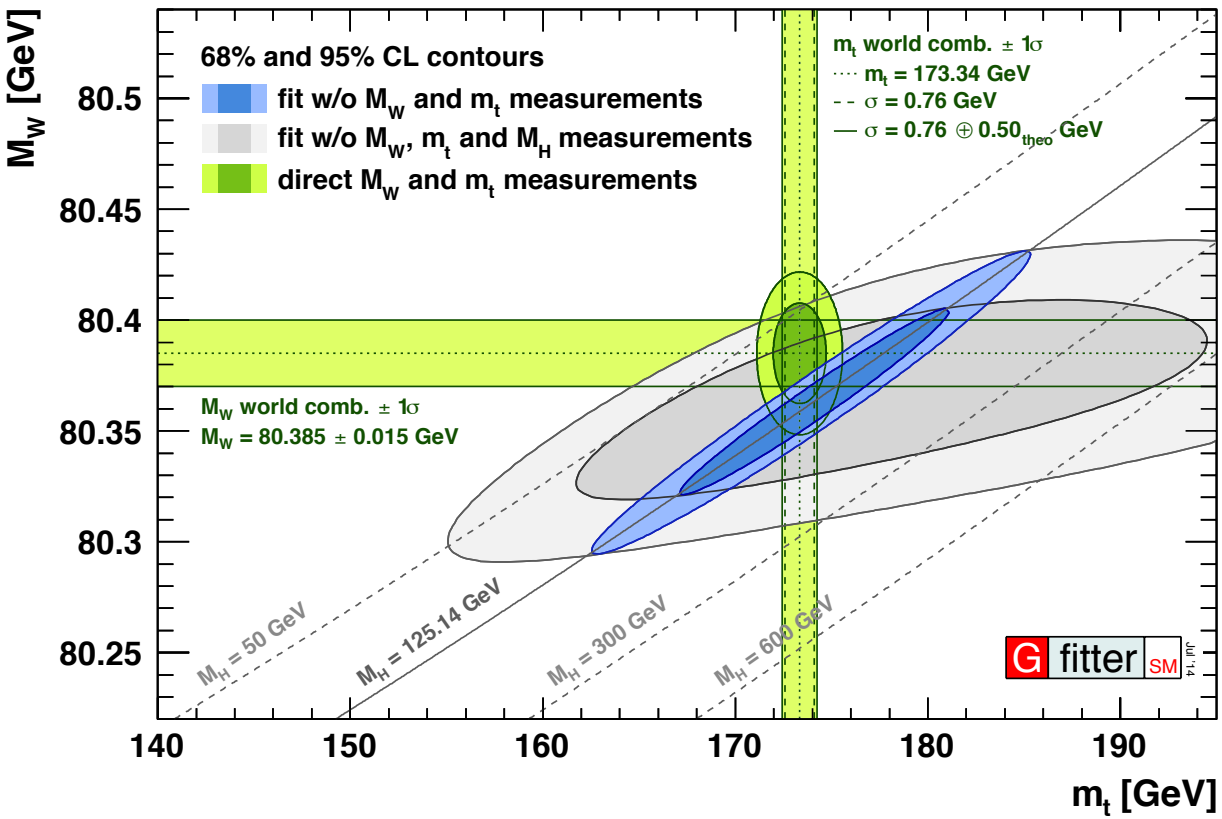
The Most Precise Measurement at Run I !!





- Statistics dominated Measurement
- Systematic uncertainties completely dominated by calibration uncertainties
- Compatibility of the four measurements masses O(10%)
- Tension between ATLAS 4l and γγ ~2σ

EW Precision Fit after the discovery



Important to have the Higgs mass, the current uncertainty is irrelevant in the fit

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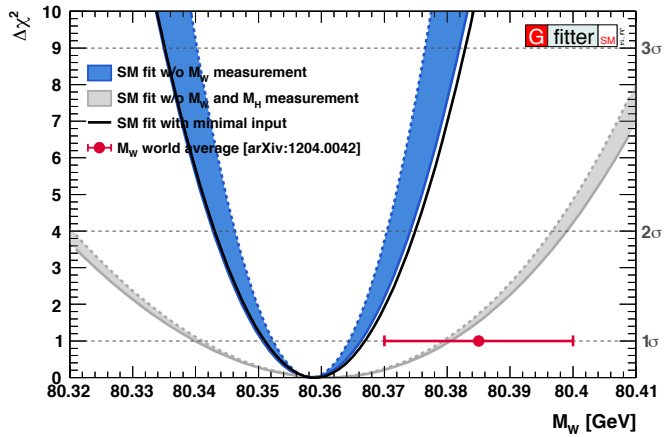

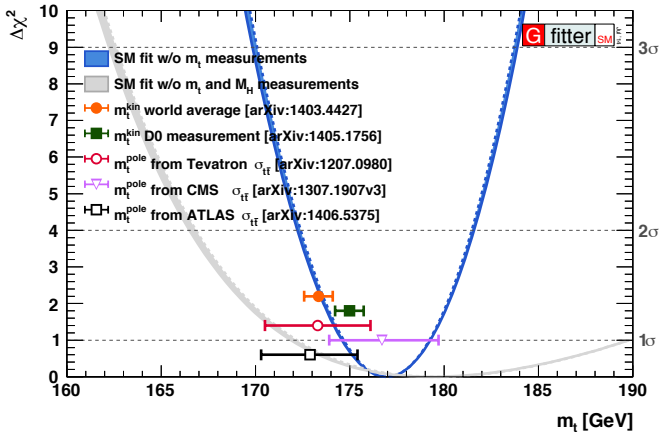

Summary

- Key phenomenological and TH aspects on the role of the Higgs boson in the SM

- Reviewed basics of discovery channels

  - Production and decays in the $\gamma\gamma$ and ZZ channels are compatible with the expectation from SM Higgs boson
  - Clear evidence of coupling to vector bosons W and Z through the decays
  - Strong indirect evidence of the coupling to fermions (top) through the production
  - Already strong indications of the VBF production
  - Already extremely precise measurements

- Interplay between direct measurements and EW precision data