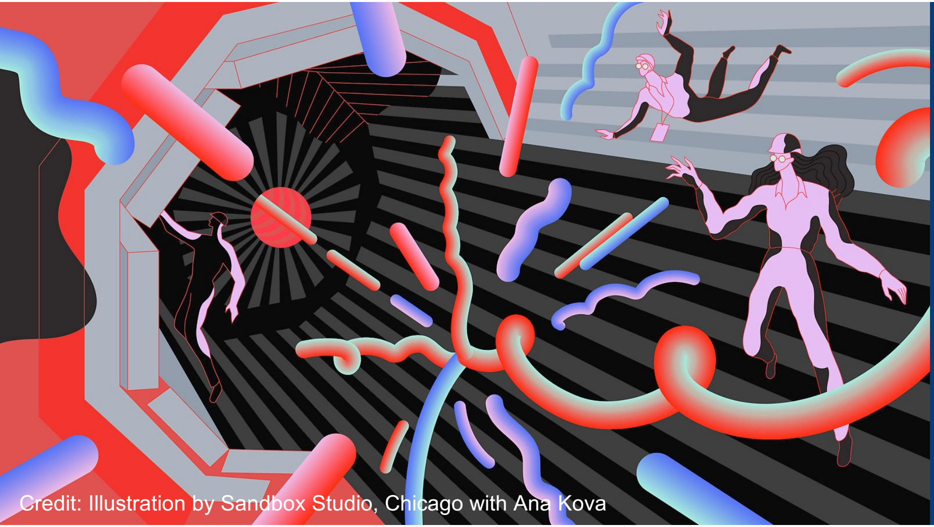
TAE 2023 – International Workshop on High Energy Physics
Benasque (Spain), 3-16 September 2023


Credit: Illustration by Sandbox Studio, Chicago with Ana Kova

Higgs Physics

(Lecture 1)

Aurelio Juste (ICREA/IFAE)

Institut de Física
d'Altes Energies

Outline

Lecture 1: Stalking the Higgs boson

- Preliminaries on Higgs physics
- Pre-LHC searches
- The discovery

Lecture 2: Studying the Higgs boson

- Overview of Run 1 studies
- Summary of recent Run 2 results
- Future prospects

July 4, 2012: “Higgsdependence Day”

Seminar at CERN, July 4, 2012

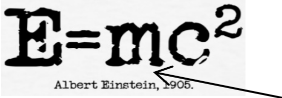
Not the origin of mass

- Galilean and Newtonian concept of mass:

$$\underbrace{\text{Inertial mass } (F=ma) \qquad\qquad \text{Gravitational mass } (P=mg)}_{\textbf{Single concept of mass}}$$

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 on its energy content?



$E=mc^2$

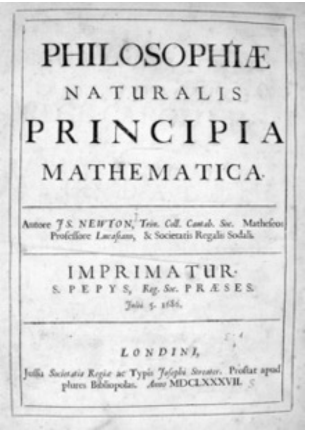
Albert Einstein, 1905.

Rest mass

- Atomic level: binding energy ~O(10 eV) ➔ ~10^{-8} of the mass
- Nuclear level: binding energy ~O(4 MeV) ➔ ~1% of the mass
- Nucleon level: binding energy ➔ ~98% of the mass!

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

- The Higgs mechanism: making the weak force weak (massive W and Z bosons) and allowing fermion masses in the theory.



PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

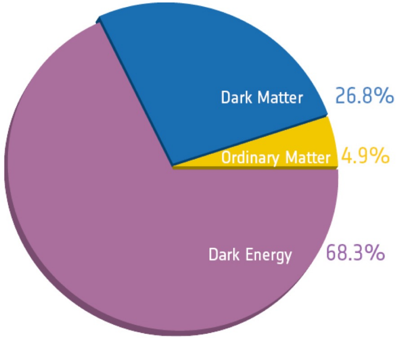
Autore J S. NEWTON, Trin. Coll. Cantab. Soc. Matheseos
Professore Lucasiano, & Societatis Regalis Sodali.

IMPRIMATUR.
S. PEPYS, Reg. Soc. PRÆSES.
Julii 5. 1686.

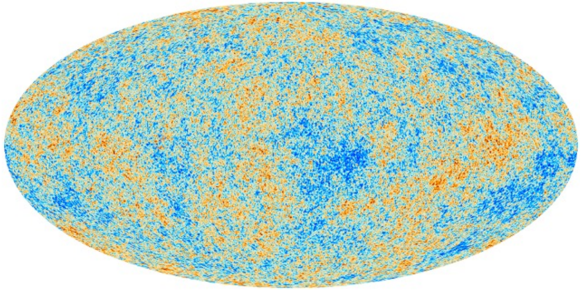
LONDINI,
Jussu Societatis Regiæ ac Typis Josephi Streater. Prostat apud
plures Bibliopolas. Anno MDCLXXXVII.

Not the only "massive problem" we have

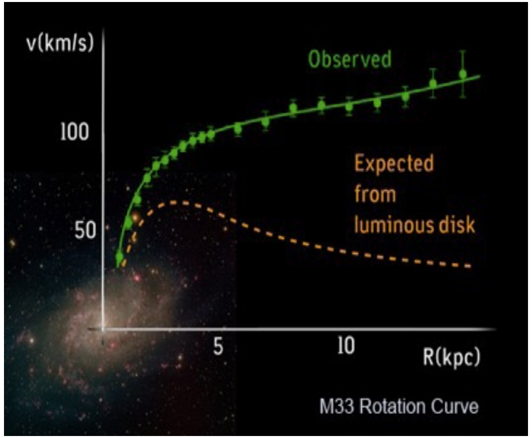
- Combination of Comic Microwave Background data with Hubble expansion data from Type Ia supernovae have taught us about the "dark side" of the universe we live in.



- So, only 5% of the universe is the stuff we know about. And we are trying to learn about the 2% contribution (non-QCD binding energy related) to that 5%???
- Why should we care?



Dark matter effect on galaxy rotation curves



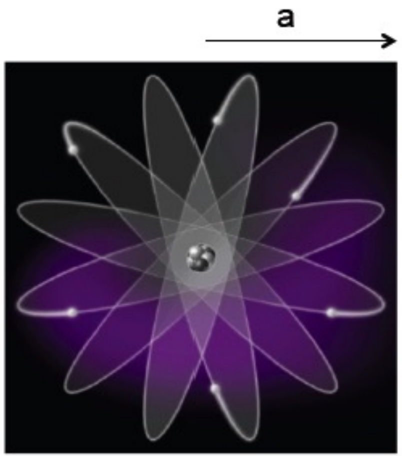
Not the only “massive problem” we have

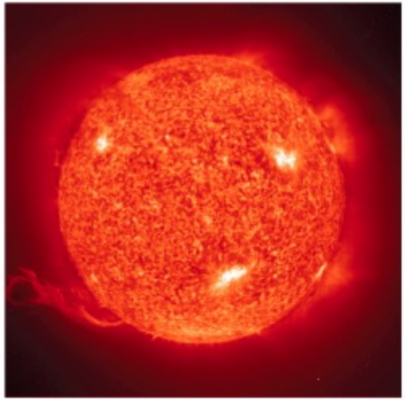
How would it be without elementary particle masses?

- Electron mass: m_e=511 keV
  Bohr radius: $a=1/(\alpha_{EM}\, m_e)$
  ➔ if m_e=0 then no atomic binding!!

- W boson mass: m_W=80 GeV
  Fermi constant: $G_F \sim 1/m_W^2$
  ➔ if no mass or lower mass then shorter combustion time at lower temperature!

Everything would be very different!





Historical context

1864-1958: Theory of Quantum Electrodynamics (QED) → abelian group

1933-1960: Fermi model of weak interactions → effective interaction

1954: Yang-Mills theories for gauge interactions → non-abelian group

1957-1959: Schwinger, Bludman and Glashow introduce W bosons to describe weak charged currents

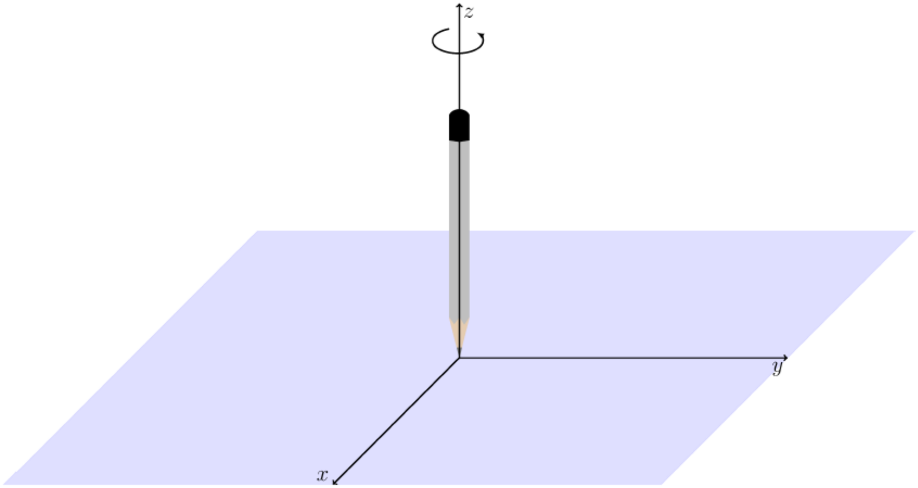
➔ Birth of the idea of a unified description of electromagnetic and weak interactions via the

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

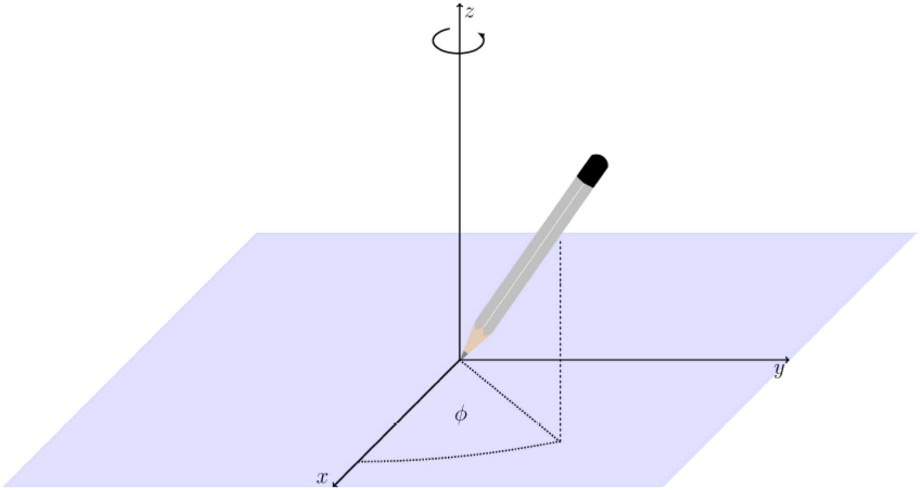
gauge group.

BUT, local gauge symmetry forbids gauge bosons and fermion masses!

SSB visualized



Pencil stands on its top, rotationally symmetric around z-axis.



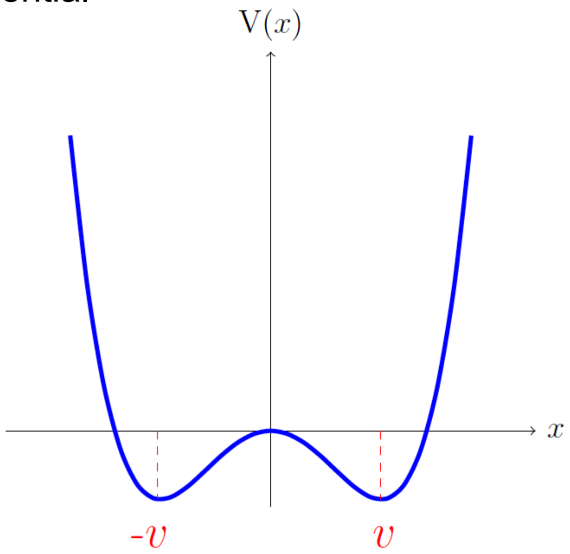
Pencil drops to one side (goes into ground state)
$\Rightarrow$ symmetry is spontaneously broken

State is rotationally invariant,
but highly unstable

System goes into stable ground state,
but symmetry is broken

SSB visualized

“Mexican-hat” potential



- Potential is rotationally invariant, V(0) is unstable
- Ground-state has non-vanishing vacuum expectation value *v*

Where does this play a role in physics?

The beginnings of SSB

1928: Werner Heisenberg

- First idea stems from condensed matter physics
- Heisenberg: theory of ferromagnetism

1947: Nicolay Bogoliubov

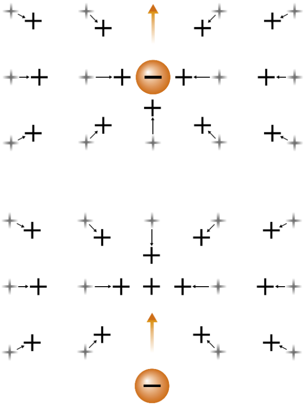
- Superfluidity (Bose-Einstein condensate)
- Phase transformation (U(1) symmetry)

1950: Ginzburg & Landau

- Explain superconductivity via charged Bose-Einstein condensate
- Full theory in 1957 by Bardeen, Cooper and Schrieffer (BCS Theory)

Analogy with superconductivity

- Below a certain critical temperature electrical resistance in some elements almost completely vanishes.
- Described in BCS theory (1957):
  - At very low T atomic movement quite low.
  - Electron attracts atom, lattice of positive ions gets polarized, second electron gets attracted by positive charge
    ➔ two electrons form (Cooper) pair



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…
- 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

SSB – Global Symmetry

- Goldstone Theorem: massless scalars (“Goldstone bosons”) occur in a theory with SSB (or more accurately where the continuous symmetry is not apparent in the ground state)

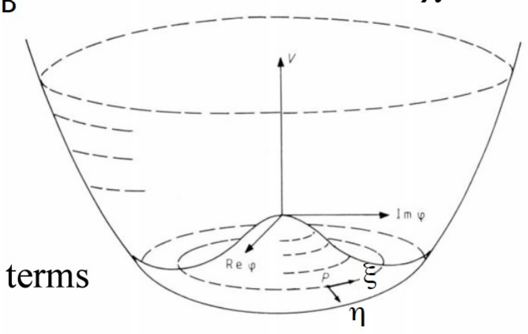
From a simple (complex) scalar theory with a U(1) symmetry

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

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

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

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 :

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

No loss in generality.

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

↑

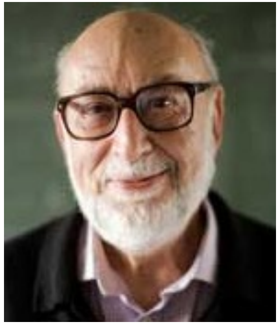
Problematic: a massless particle should have been found already! ➔ Need to find a way to eliminate it

A way out?

2010 Sakurai Prize for Theoretical Particle Physics:

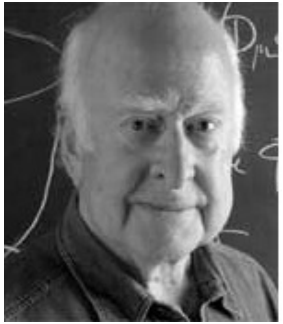
"For elucidation of the properties of spontaneous symmetry breaking in four-dimensional relativistic gauge theory and of the mechanism for the consistent generation of vector boson masses"

Robert Brout



Francois Englert

Universite Libre de Bruxelles



Peter W. Higgs

Univ. of Edinburgh

Gerald S. Guralnik

Brown University

Carl R. Hagen

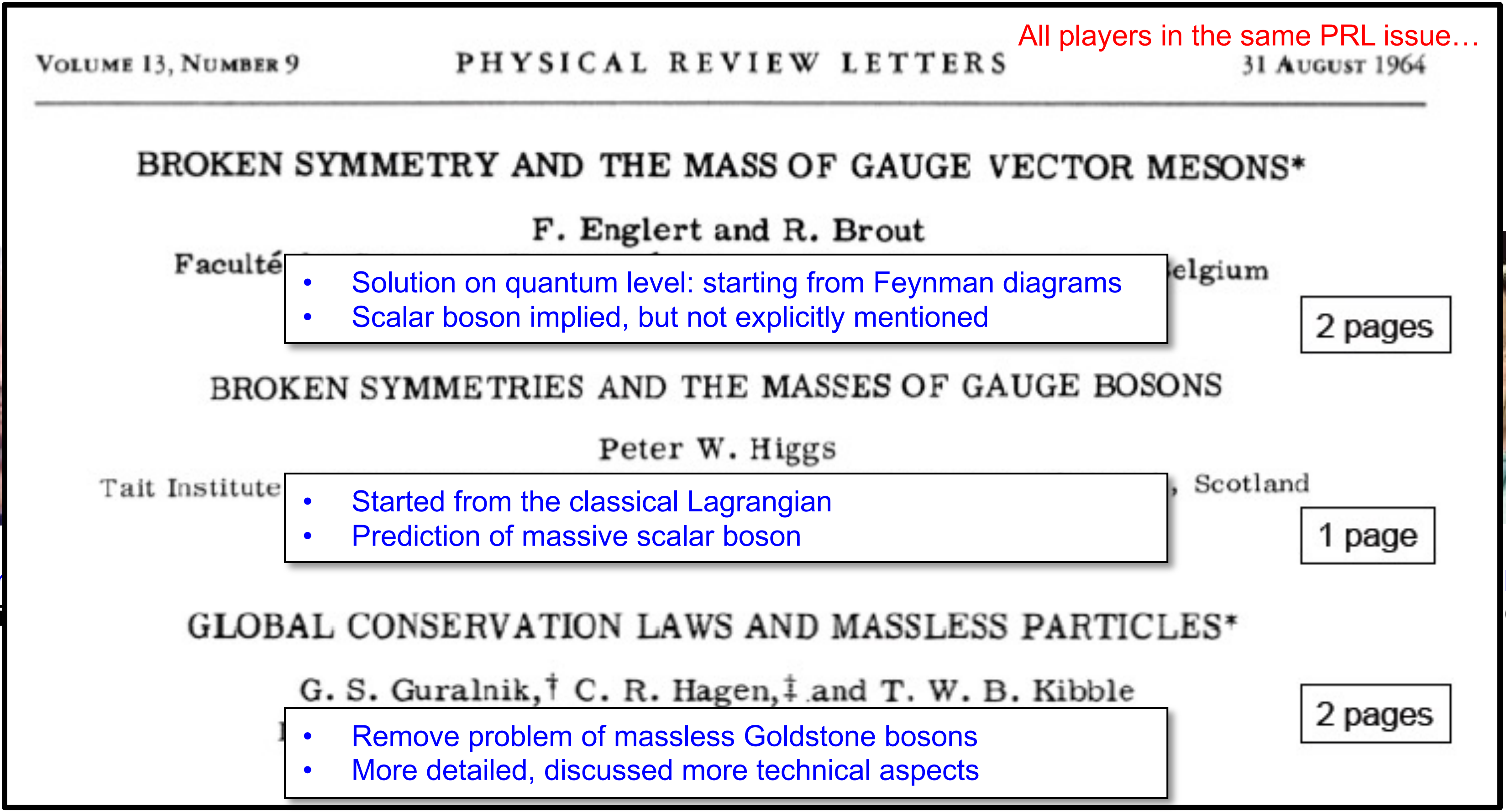
Univ. of Rochester

T.W.B. Kibble

Imperial College

A way out?

Rober
Uni



All 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 … elgium

- Solution on quantum level: starting from Feynman diagrams
- Scalar boson implied, but not explicitly mentioned

2 pages

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs

Tait Institute … , Scotland

- Started from the classical Lagrangian
- Prediction of massive scalar boson

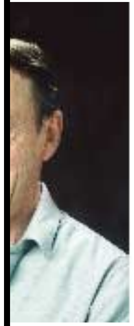
1 page

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble

- Remove problem of massless Goldstone bosons
- More detailed, discussed more technical aspects

2 pages

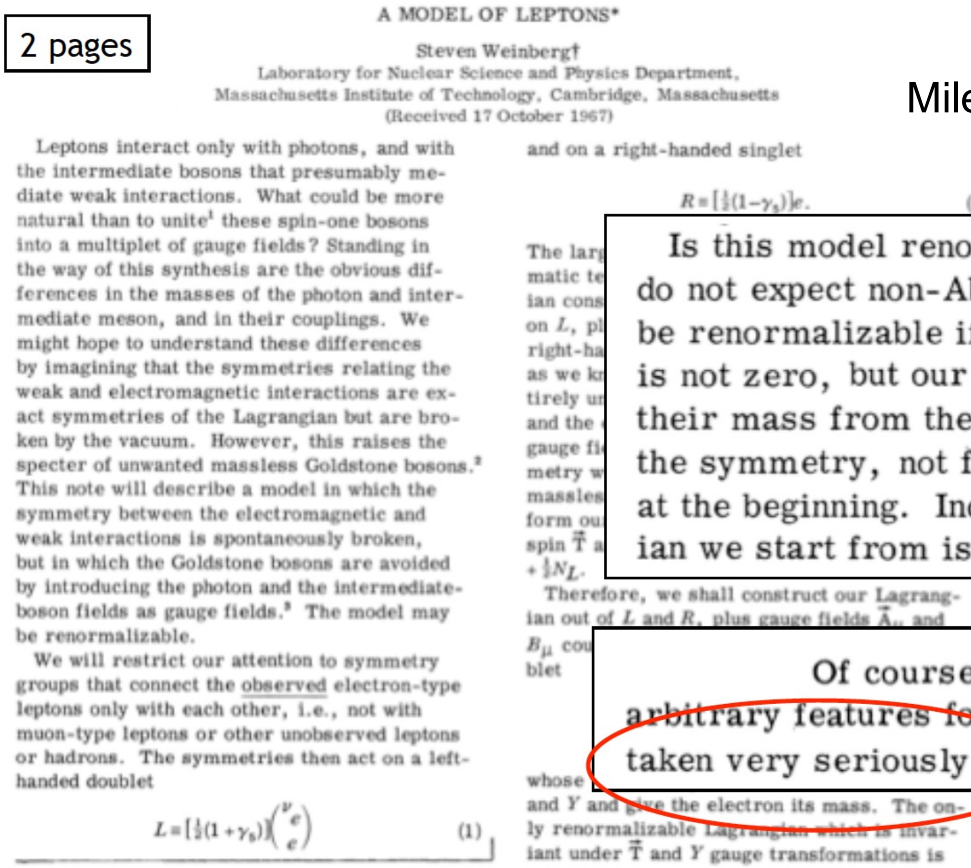


Kibble
College

The Glashow-Weinberg-Salam Model

2 pages

Milestone PRL (1967)



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 larg
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

The Glashow-Weinberg-Salam Model

- Data on electromagnetic and weak processes suggested that the interactions are invariant under weak isospin $SU(2)_L$ and weak hypercharge $U(1)_Y$ transformations ➔ start from $SU(2)_L xU(1)_Y$ invariant Lagrangian (3+1 generators → 3+1 gauge bosons)

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

The Glashow-Weinberg-Salam Model

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 :

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

Explicit mixing of W^3 and B.

The Glashow-Weinberg-Salam Model

Finaly the full Lagrangian will then be written :

$$
\begin{aligned}
\mathcal{L} \; = \; & \frac{1}{2}\partial_\mu H \partial^\mu H - \frac{1}{2}\lambda v^2 H^2 - \lambda v H^3 - \frac{\lambda}{4}H^4 \quad \text{Massive scalar : The Higgs boson} \\
& + \frac{1}{2}\left[\frac{g'^2 v^2}{4} B_\mu B^\mu - \frac{g g' v^2}{2} W^3_\mu B^\mu + \frac{g^2 v^2}{4} \vec{W}_\mu . \vec{W}^\mu\right] \quad \text{Massive gauge bosons} \\
& \left.\begin{aligned}
& + \frac{1}{v}\left[\frac{g'^2 v^2}{4} B_\mu B^\mu H - \frac{g g' v^2}{2} W^3_\mu B^\mu H + \frac{g^2 v^2}{4} \vec{W}_\mu . \vec{W}^\mu H\right] \\
& + \frac{1}{2v^2}\left[\frac{g'^2 v^2}{4} B_\mu B^\mu H^2 - \frac{g g' v^2}{2} W^3_\mu B^\mu H^2 + \frac{g^2 v^2}{4} \vec{W}_\mu . \vec{W}^\mu H^2\right]
\end{aligned}\right\} \text{Gauge-Higgs interaction}
\end{aligned}
$$

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)

What about the 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

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

What about the fermions?

But wait…

The coupling to the Higgs fields is the following :

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

Can be seen as giving mass to down type fermions…

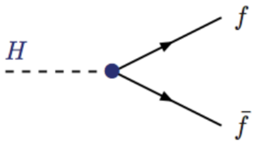
To give mass to up type fermions, need to use a slightly different coupling :

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

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

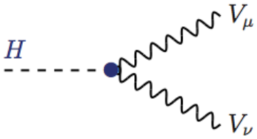
... But not necessarily only one!

Higgs-boson interactions



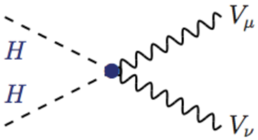
$$g_{Hff} = m_f/v$$

Gauge-Higgs and
interactions



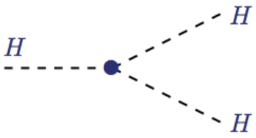
$$g_{HVV} = 2M_V^2/v$$

Proof of condensate !



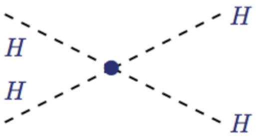
$$g_{HHVV} = 2M_V^2/v^2$$

Keep this in mind for
the next lecture…



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

More directly testable
relations!



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

Main consequences of the GWS model

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

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

Main consequences of the GWS model

Theory chosen to describe weak charged current interactions

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

Consequence of the choice of developing the Higgs field in the neutral and real part of the doublet

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

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

3.- One massive neutral vector boson Z :

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

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3.- One massive neutral vector boson Z :

PREDICTED!

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

4.- One massive scalar particle : The Higgs boson

PREDICTED!

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

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

Main consequences of the GWS 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 :

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

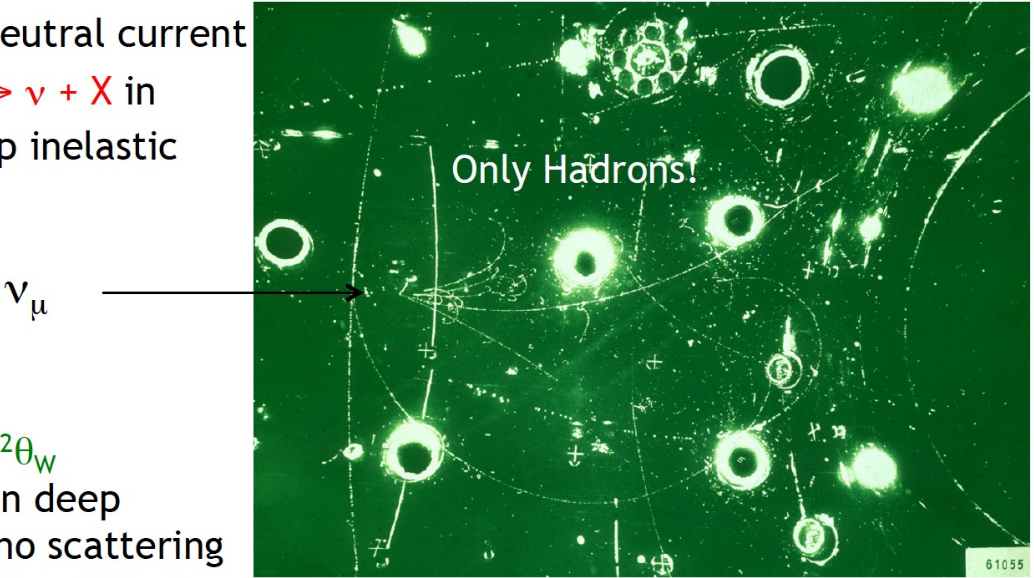
or

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

1973: Discovery of neutral weak currents

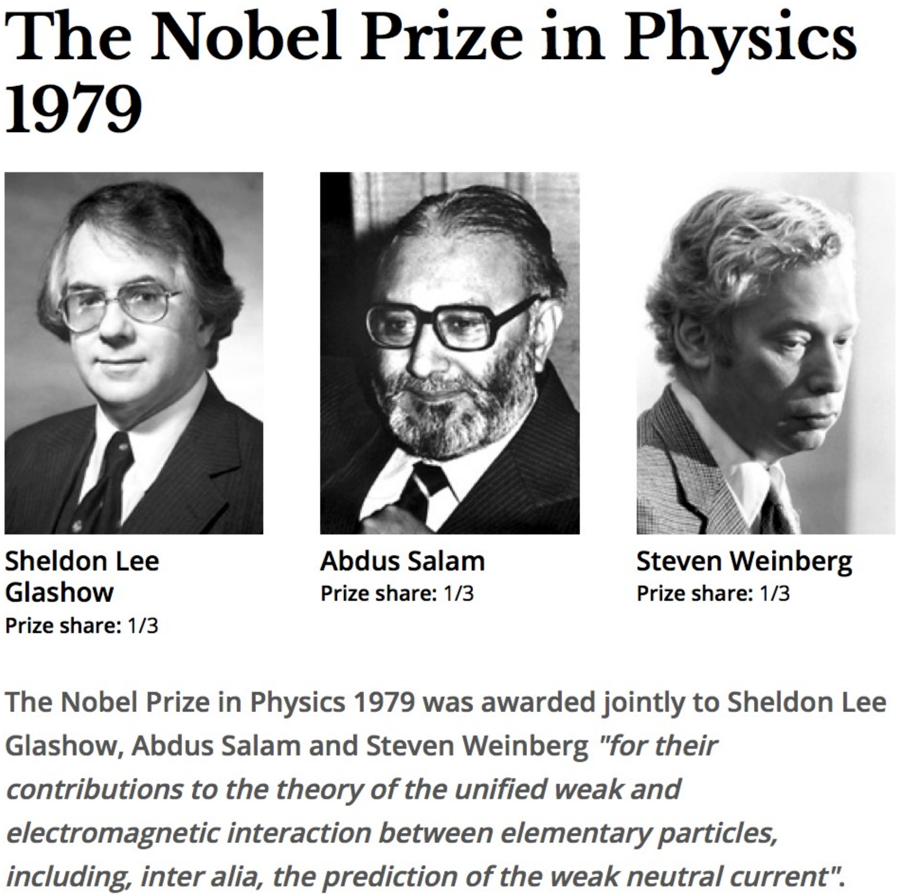
1973: neutral current discovery (Gargamelle experiment, CERN)

Evidence for neutral current events $\nu + N \rightarrow \nu + X$ in ν-nucleon deep inelastic scattering



1973-1982: $\sin^2\theta_W$ Measurements in deep inelastic neutrino scattering experiments (NC vs CC rates of νN events)

And The Prize arrived…



The Nobel Prize in Physics 1979

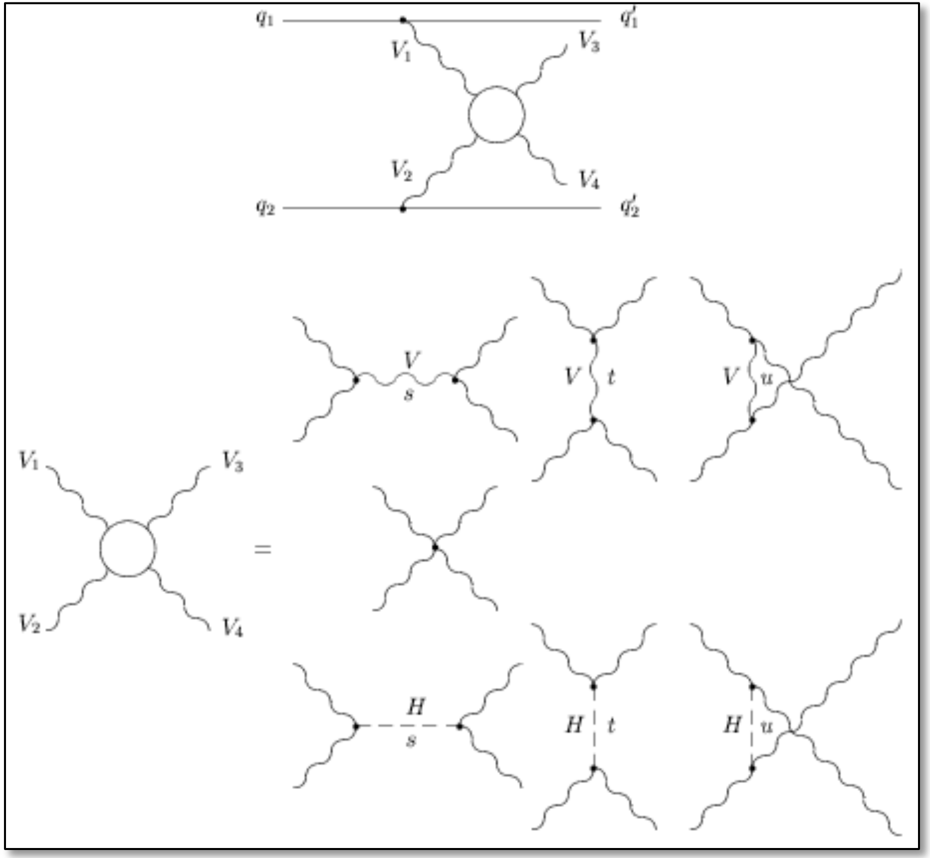
Sheldon Lee Glashow
Prize share: 1/3

Abdus Salam
Prize share: 1/3

Steven Weinberg
Prize share: 1/3

The Nobel Prize in Physics 1979 was awarded jointly to Sheldon Lee Glashow, Abdus Salam and Steven Weinberg *"for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, inter alia, the prediction of the weak neutral current"*.

Vector-boson scattering



Triple gauge couplings

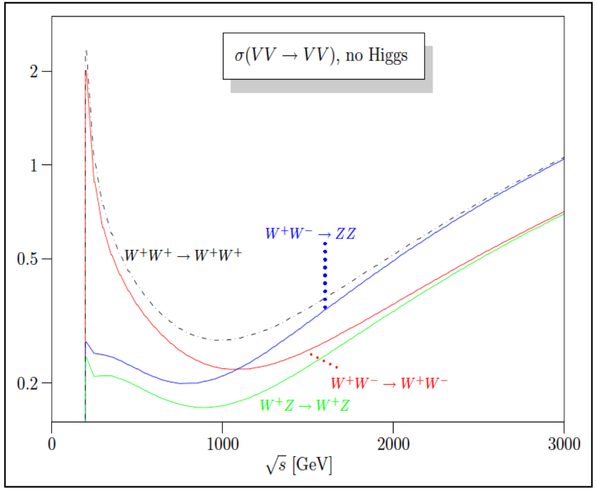
Quartic gauge couplings

Higgs-gauge boson couplings

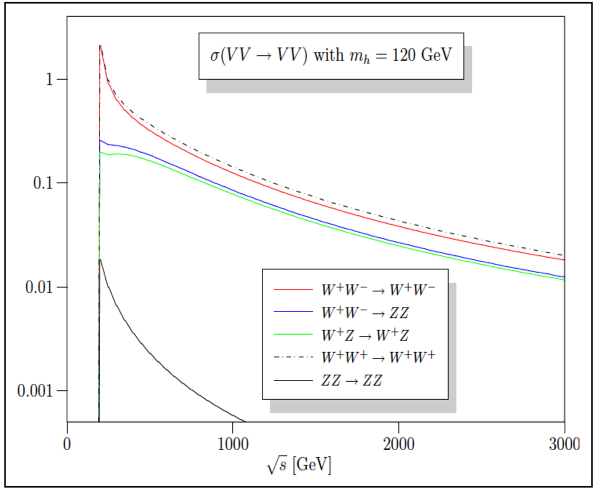
Vector-boson scattering

- Without a "light" Higgs boson (m_H<1 TeV) the vector boson scattering process would violate perturbative unitarity.

SM without a Higgs boson



SM with a 120 GeV Higgs boson



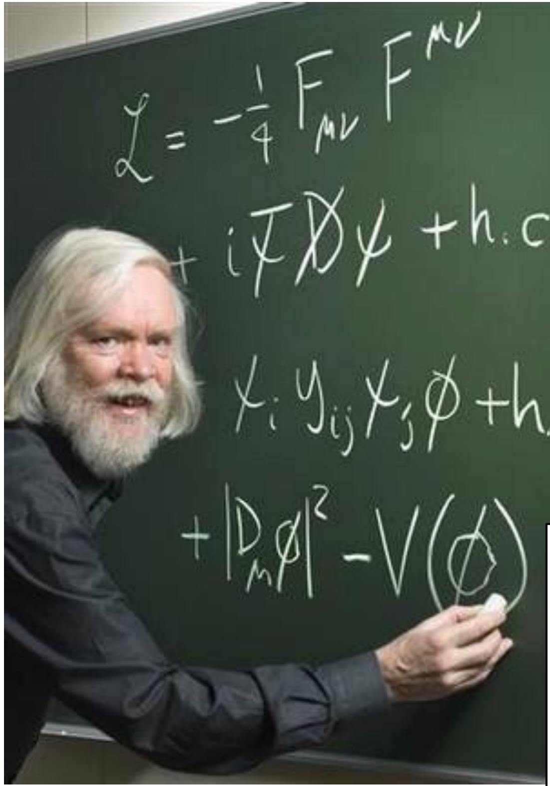
$$\sigma_{V_L V_L \to V_L V_L} \propto \left[-s - t - \frac{s^2}{s - m_{\mathrm{H}}^2} - \frac{t^2}{t - m_{\mathrm{H}}^2} \right]$$

Higgs boson contribution cancels increase at large √s

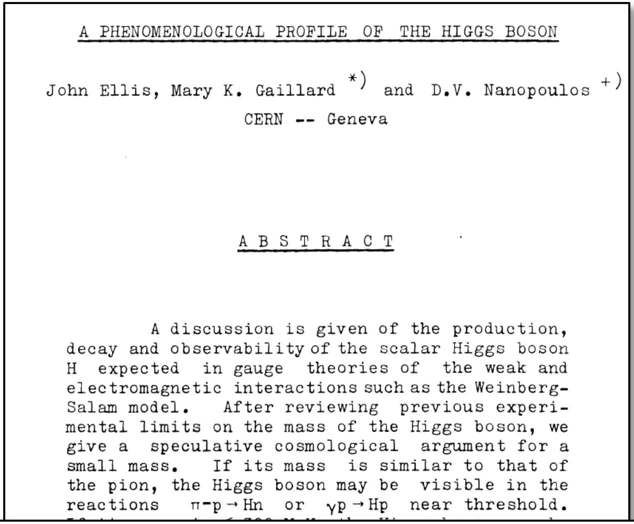
Not only a motivation for the Higgs mechanism but is also a strong constraint on its mass (if you believe in perturbative unitarity…otherwise, the weak force will become strong!)

One of the basis of the No Loose theorem at the LHC!

1976: The birth of Higgs Physics



Nucl. Phys. B 106 (1976) 292

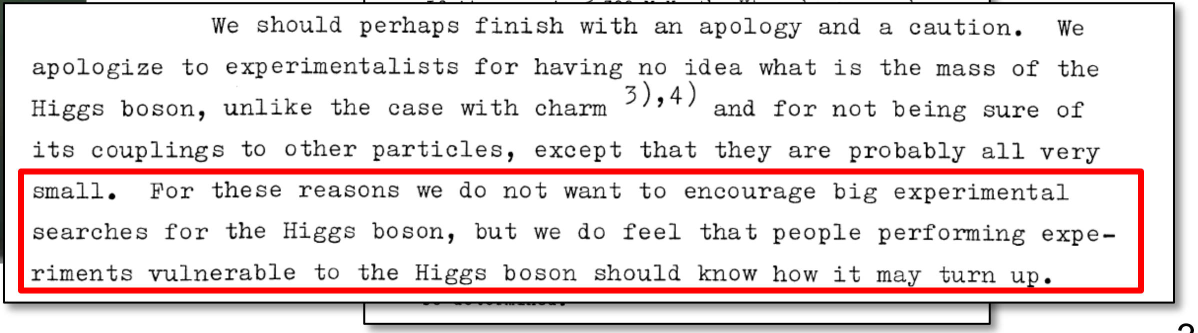


A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

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

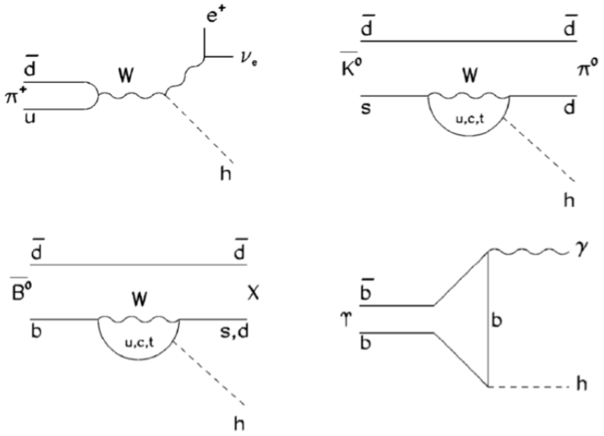
ABSTRACT

A discussion is given of the production, decay and observability of the scalar Higgs boson H expected in gauge theories of the weak and electromagnetic interactions such as the Weinberg-Salam model. After reviewing previous experimental limits on the mass of the Higgs boson, we give a speculative cosmological argument for a small mass. If its mass is similar to that of the pion, the Higgs boson may be visible in the reactions $\pi^- p \to Hn$ or $\gamma p \to Hp$ near threshold.



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 Higgs boson bounds

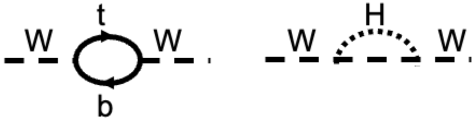


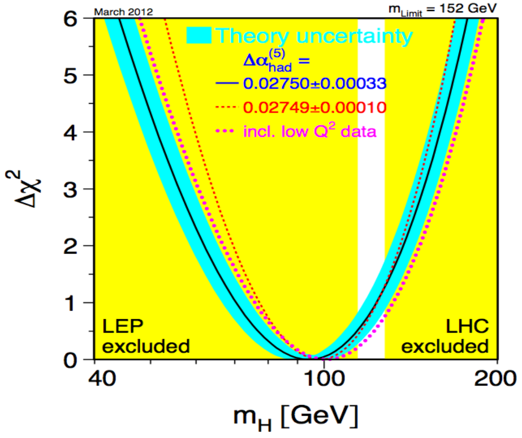
- SINDRUM Collaboration measured π to ev H (ee) Yielding a limit on very light Higgs
- CUSB Collaboration Υ to Hγ yielding limit of ~ 5-6 GeV (dependent on high order corrections)
- Jade and CLEO provided bounds on B to μμ+X
- CERN-Edimbrgh-Orsay-Mainz-Pisa-Siegen K to π H (ee) below ~50 MeV
- Electron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

Stalking the Higgs Boson

Indirect constraints

- Precision EW observables sensitive to the Higgs-boson mass via quantum corrections.





m_H< 152 GeV (95% CL)

$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r)$$

$$\Delta r_{\rm top}=-\frac{3\alpha}{16\pi}\frac{\cos^2\theta_W}{\sin^4\theta_W}\frac{m_t^2}{m_W^2}$$

$$\Delta r_{\rm Higgs}=+\frac{11\alpha}{48\pi\sin^2\theta_W}\log\frac{m_H^2}{m_W^2}$$

G_F=1.166367(5) x 10^{-5} GeV^{-2} (muon lifetime)

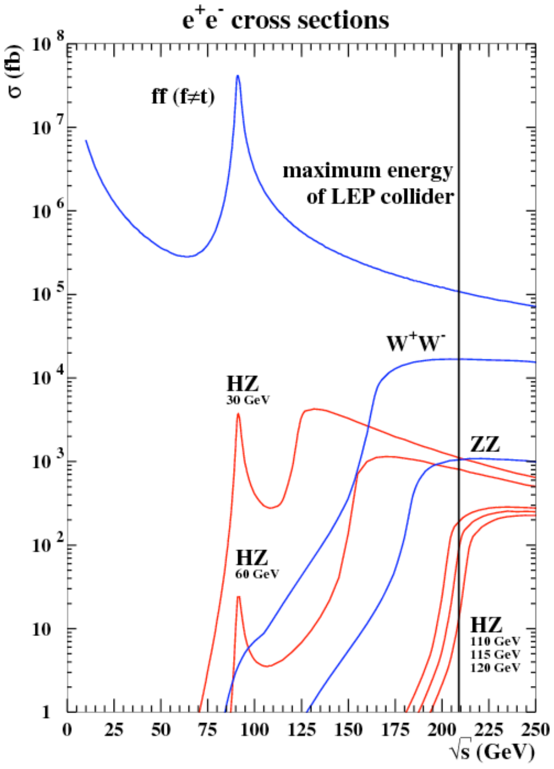
α= 1/137.035999679(94) (quantum hall effect)

m_Z = 91.1876 ± 0.0021 GeV (LEP1)

m_W = 80.385 ± 0.015 GeV (Tevatron+LEP2, as of March 2012)

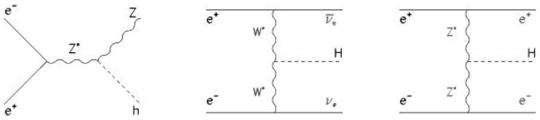
m_t = 173.2 ± 0.9 GeV (Tevatron, as of March 2012)

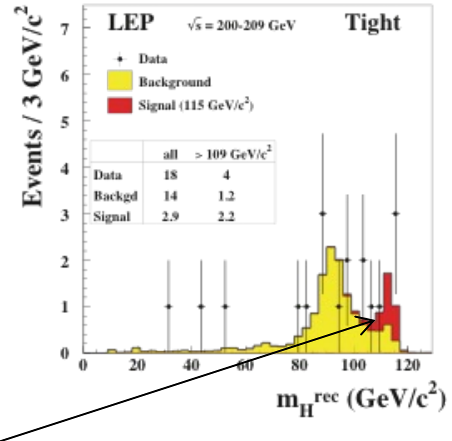
Stalking the Higgs Boson



Direct searches at LEP (1989-2000)

- In e^+e^- collisions up to $\sqrt{s}$=209 GeV. Mostly via h→bb, ττ decays.





	all	> 109 GeV/c²
Data	18	4
Backgd	14	1.2
Signal	2.9	2.2

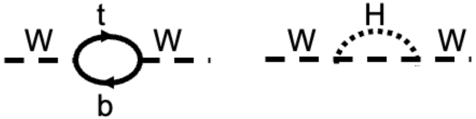
m_H> 114.4 GeV (95% CL)

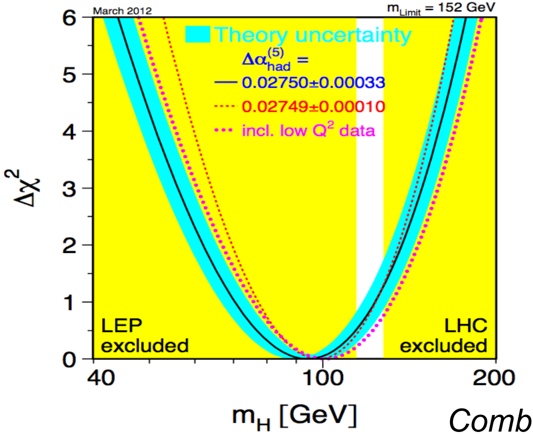
Some hints (~1.7σ) of a SM-like Higgs boson with m_H~115 GeV.
We know now it was just a statistical fluctuation.

Stalking the Higgs Boson

Indirect constraints

- Precision EW observables sensitive to the Higgs-boson mass via quantum corrections.





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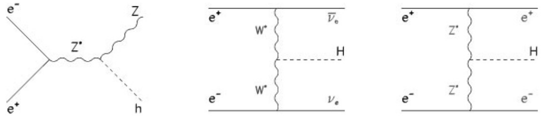
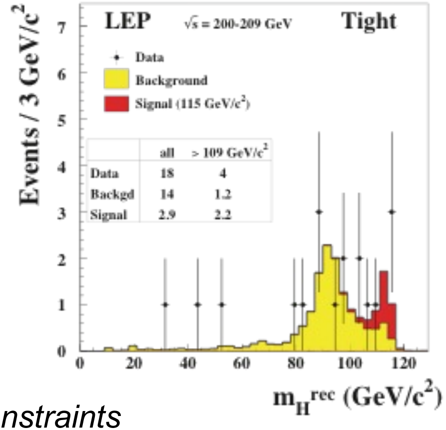




	all	> 109 GeV/c²
Data	18	4
Backgd	14	1.2
Signal	2.9	2.2

Combining indirect and direct constraints

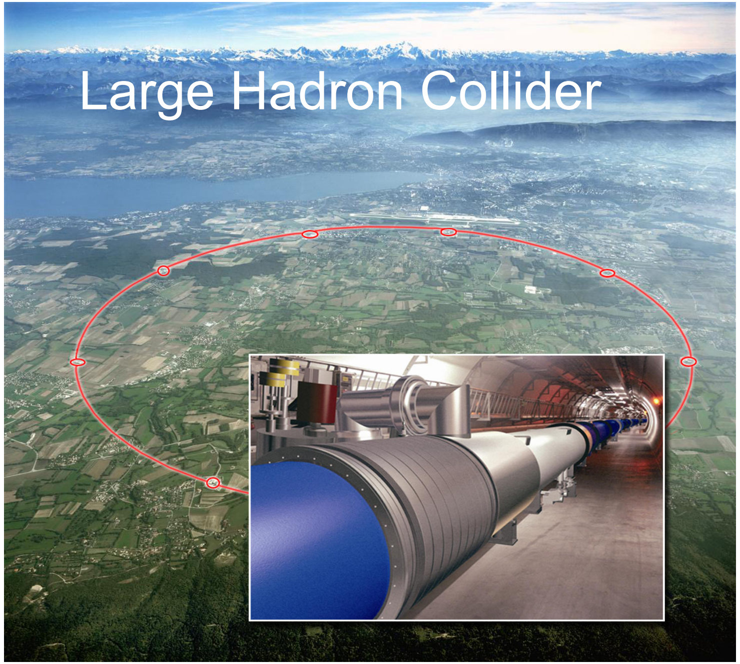
m_H< 152 GeV (95% CL)

m_H> 114.4 GeV (95% CL)

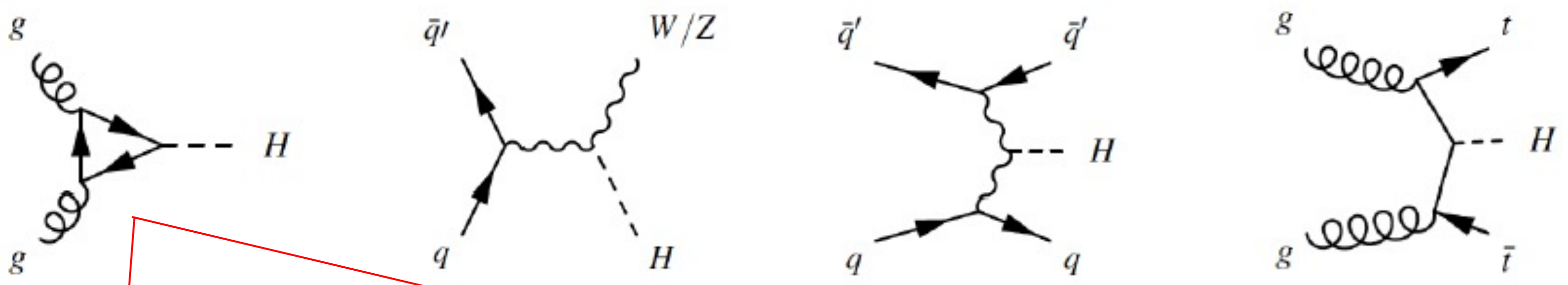
114.4 < m_H< 171 GeV (95% CL)

Hadron colliders take over

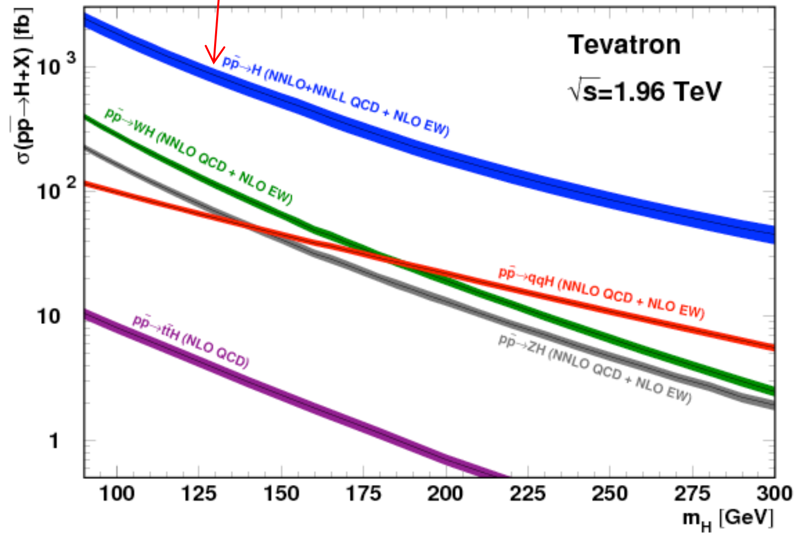
- SppS Collider @ CERN: 1981-1984
  - pp collisions at √s=400 GeV
- Tevatron Collider @ Fermilab: 10-year long Run II ended Sept. 30th, 2011.
  - pp collisions at √s=1.96 TeV.
- Large Hadron Collider (LHC) @ CERN: only hadron collider in operation today.
  - pp collisions at √s=7,8 TeV (2010-2011, 2012), 13 (2015-2018), 13.6 TeV (2022-).

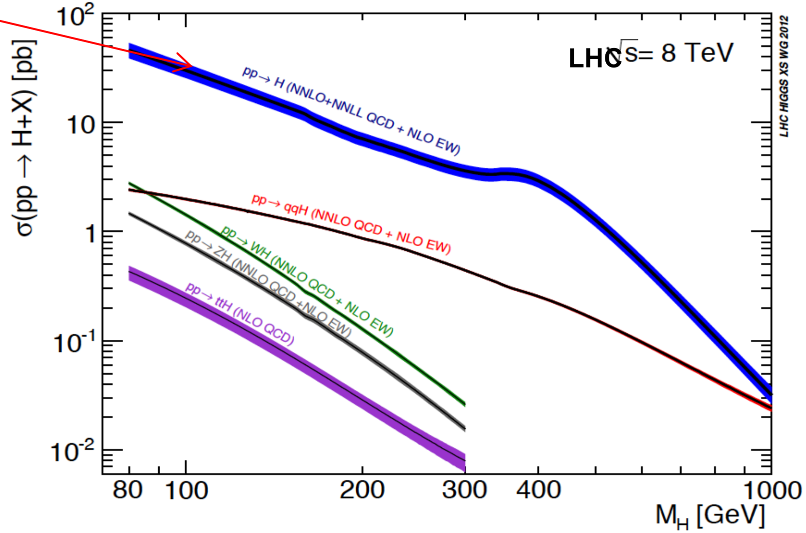


SM Higgs production at hadron colliders

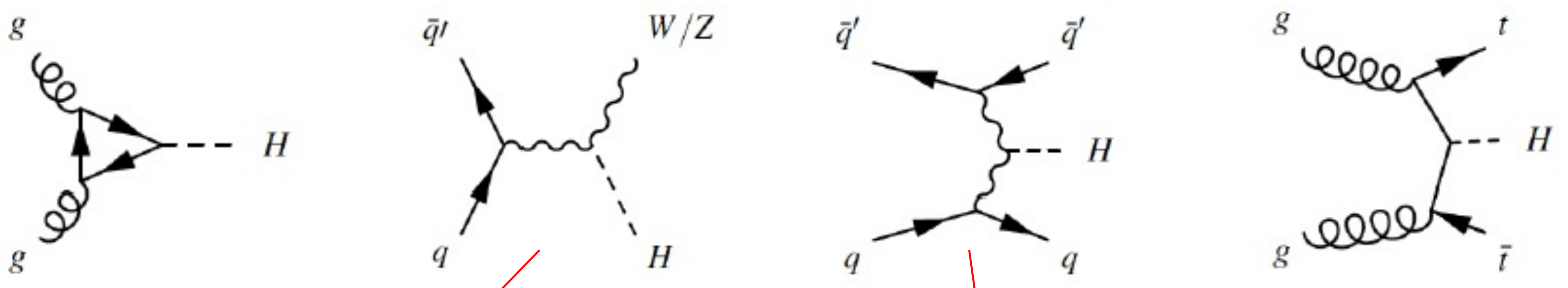


Main production mechanism

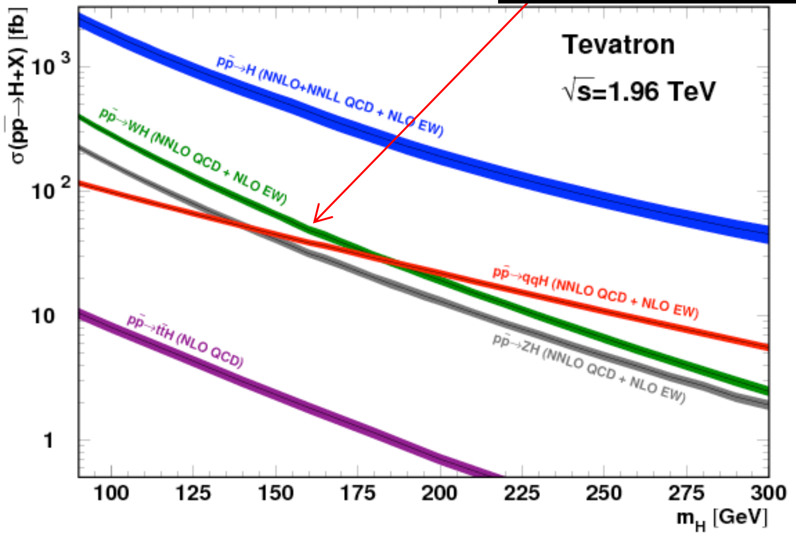


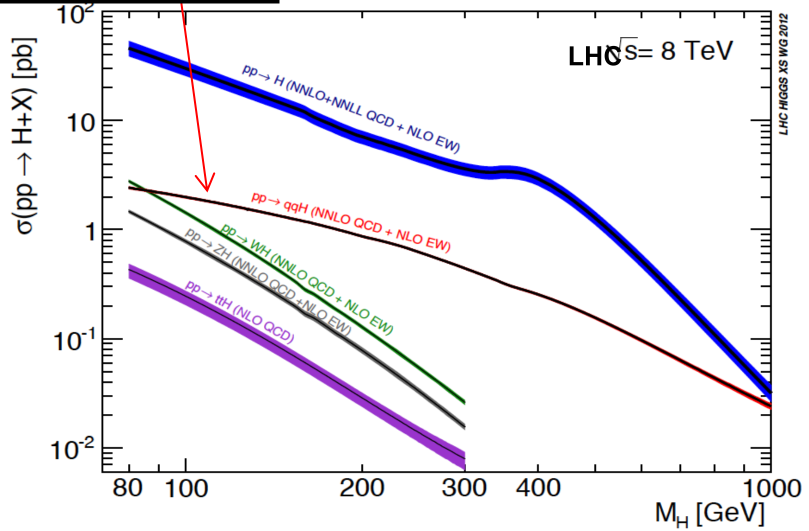


SM Higgs production at hadron colliders

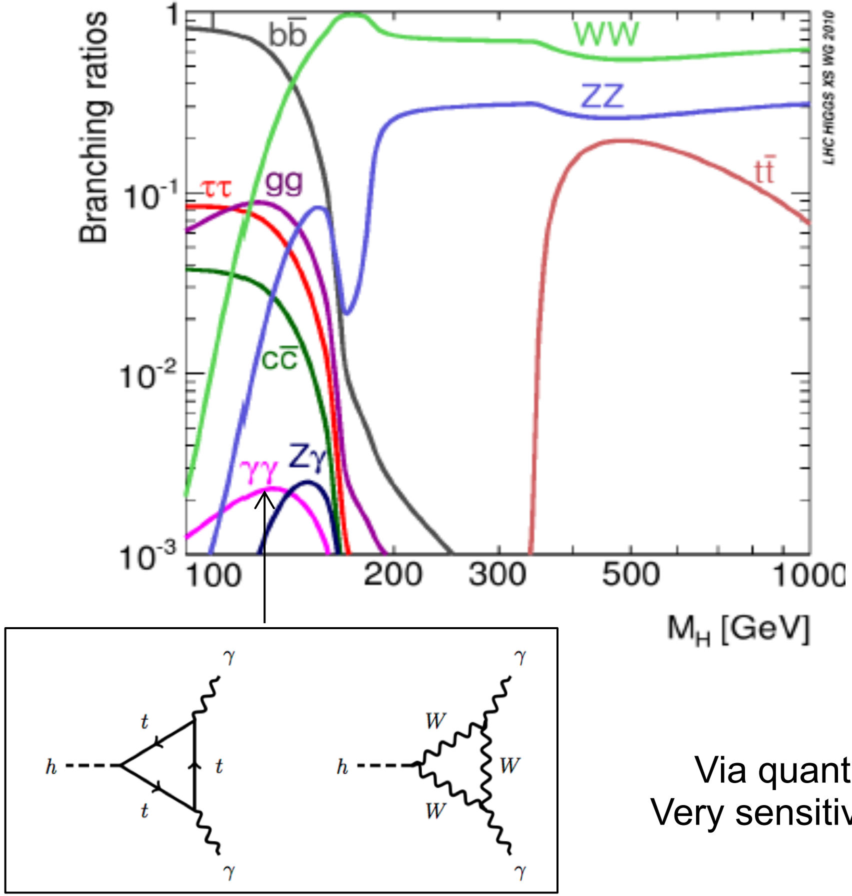


Next most important production mechanism





SM Higgs decay modes



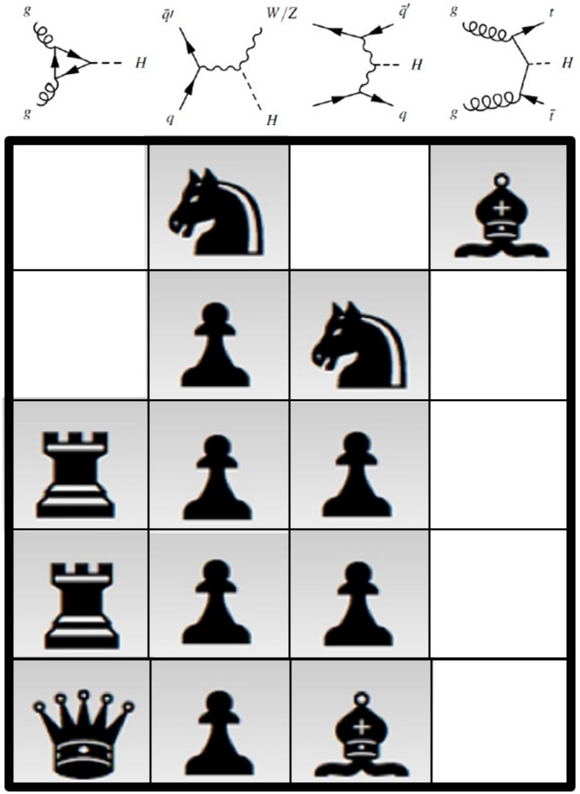
m$_H$<135 GeV: H→bb dominates

m$_H$>135 GeV: H→WW dominates

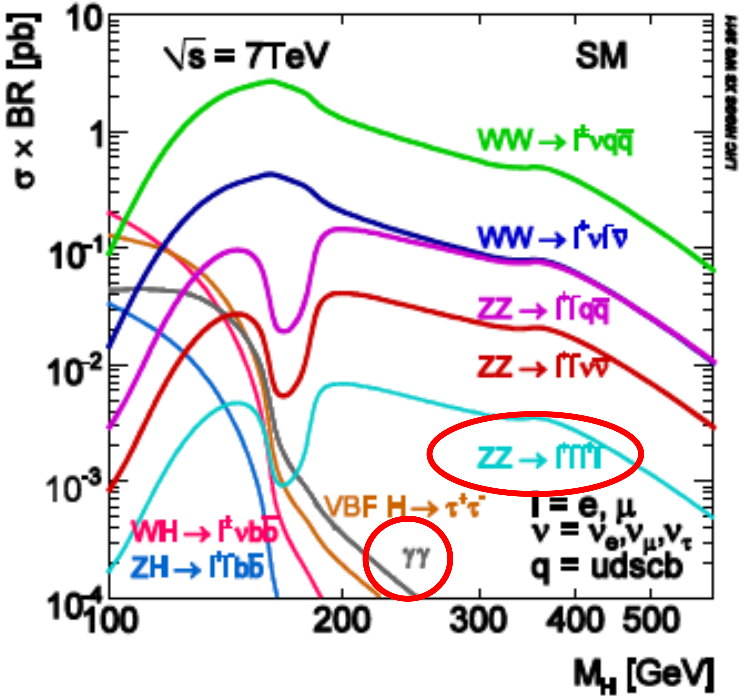
Via quantum fluctuations!
Very sensitive to New Physics!

Search strategies

- Defined by a combination of theoretical and experimental considerations, e.g. is the expected rate high enough?, can we isolate the signal events?



H→bb		♞		♝
$H\rightarrow\tau^+\tau^-$		♟	♞	
$H\rightarrow W^+W^-$	♜	♟	♟	
H→ZZ	♜	♟	♟	
$H\rightarrow\gamma\gamma$	♛	♟	♝	



H→$\gamma\gamma$

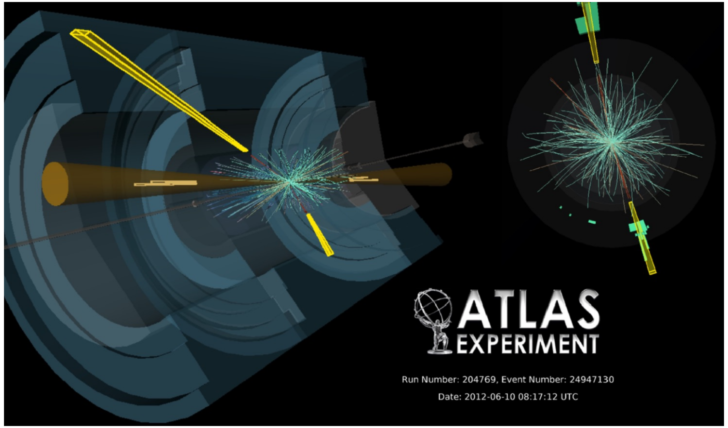
Searching for H→$\gamma\gamma$

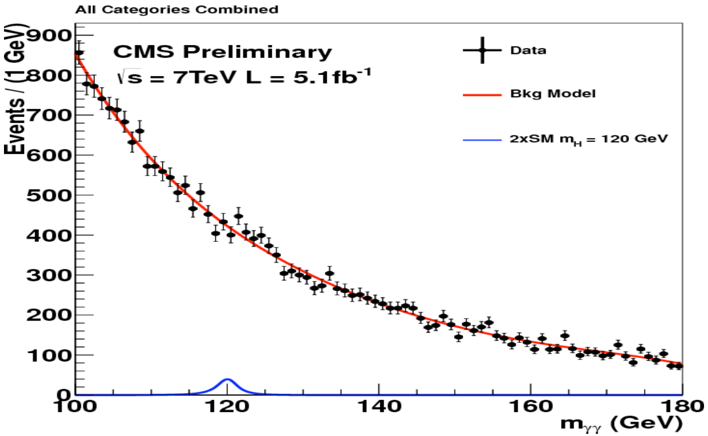
- A rare Higgs decay mode but most sensitive search at m_H<125 GeV!

  Prob(H→$\gamma\gamma$)~0.2%

- Simple strategy:
  - Identify two energetic photons
  - Compute their invariant mass
  - Search for a bump on top of a smoothly-declining background

- So need:
  - Good photon identification capabilities
  - Good photon energy resolution
  - Categorization of events depending on their intrinsic sensitivity (e.g. better measured events, or with characteristics that are rare in background, etc)

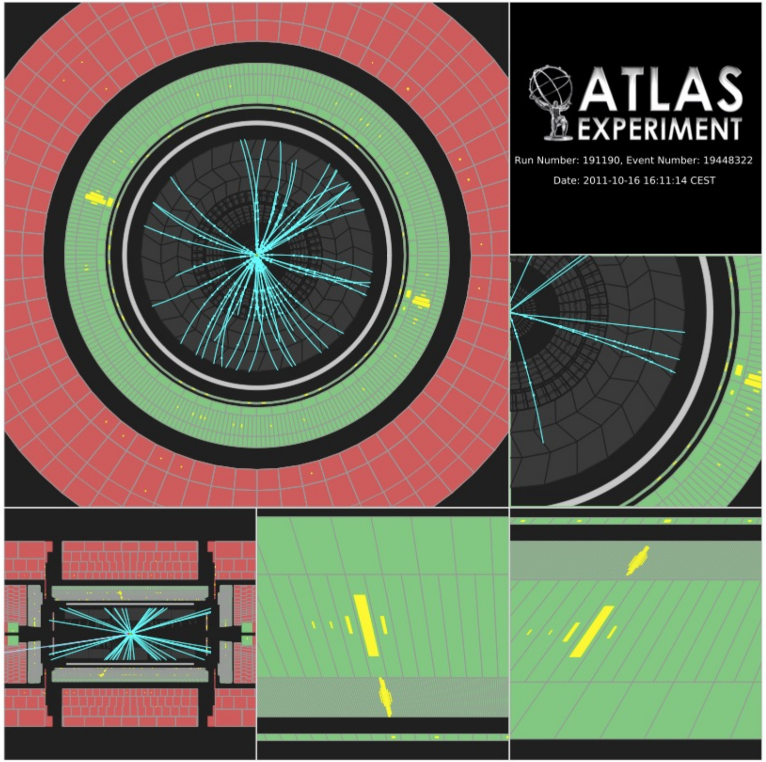




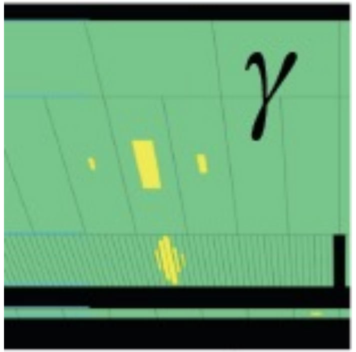
Searching for $H\rightarrow\gamma\gamma$

- LHC detectors were designed having this search in mind!
  - Efficient photon identification with excellent background rejection from jets misidentified as photons

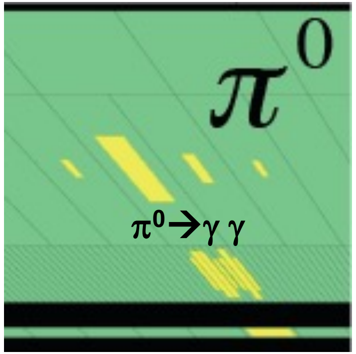
    ➔ Requires finely segmented calorimeters



Real photon



“Fake” photon

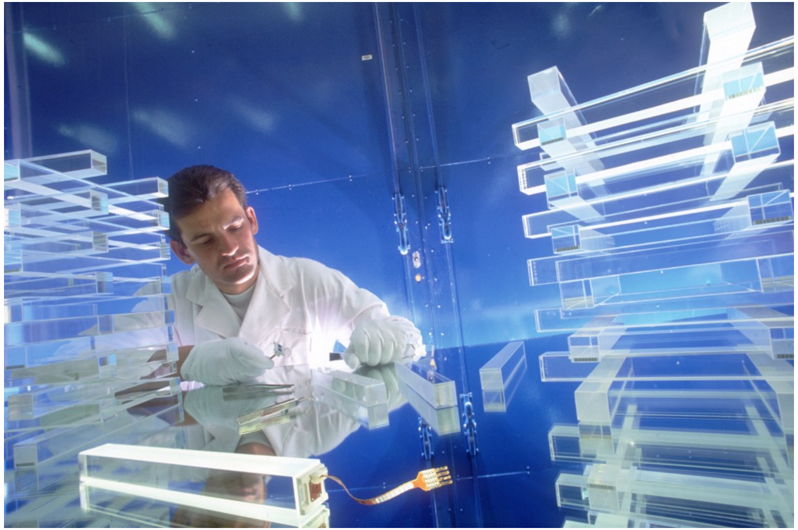


Only 1 in 10^5 jets fakes a photon

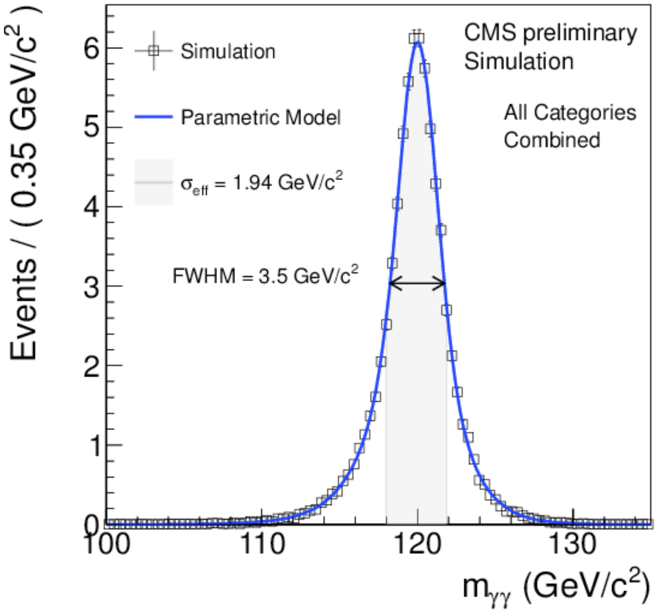
Searching for H→γγ

- LHC detectors were designed having this search in mind!
  - Efficient photon identification with excellent background rejection from jets misidentified as photons
  - Excellent diphoton mass resolution: ~1.2%-6%

    ➔ Requires best possible energy resolution from electromagnetic calorimeter (also corrections for material upstream the calorimeter, etc)



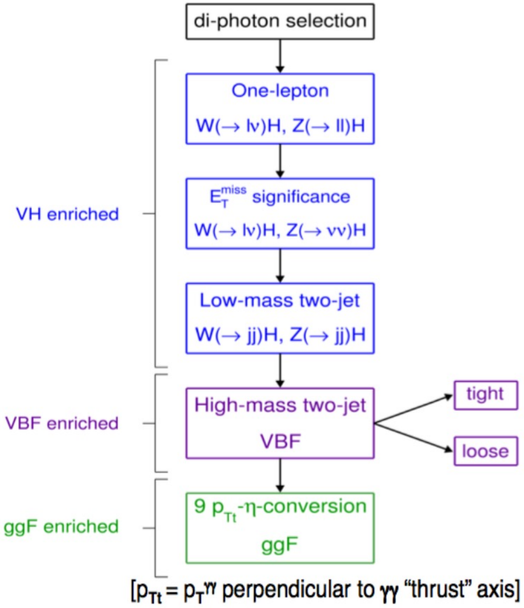
CMS electromagnetic calorimeter built from crystals of lead tungstate ($PbWO_4$)
➔ an extremely dense but optically clear material



Searching for H→γγ

- LHC detectors were designed having this search in mind!
  - Efficient photon identification with excellent background rejection from jets misidentified as photons
  - Excellent diphoton mass resolution: ~1.2%-6%
  - Event categorization to fully profit from distinctive features.

    ➔ Improve overall sensitivity by keeping high/low S/B categories separate.



di-photon selection

VH enriched

One-lepton
$W(\to l\nu)H$, $Z(\to ll)H$

E_T^{miss} significance
$W(\to l\nu)H$, $Z(\to \nu\nu)H$

Low-mass two-jet
$W(\to jj)H$, $Z(\to jj)H$

VBF enriched

High-mass two-jet
VBF
tight
loose

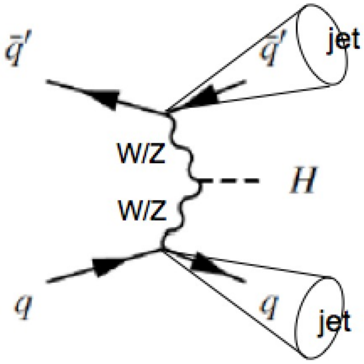
ggF enriched

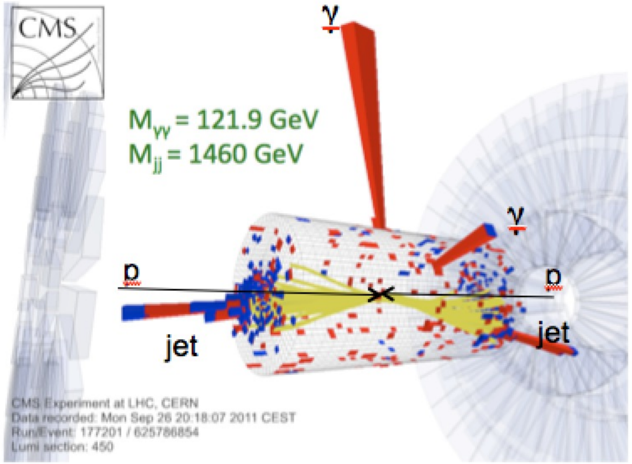
9 p_{Tt}-η-conversion
ggF

[$p_{Tt} = p_T^{\gamma\gamma}$ perpendicular to γγ "thrust" axis]

E.g. vector-boson fusion-like events are purest

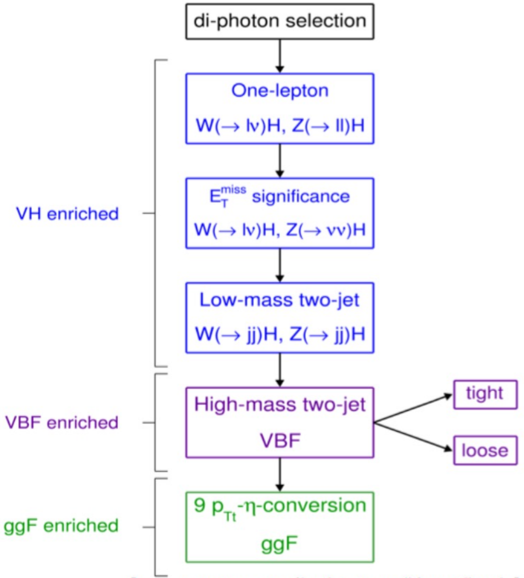
➔ Requires being able to identify jets very close to the beam pipe



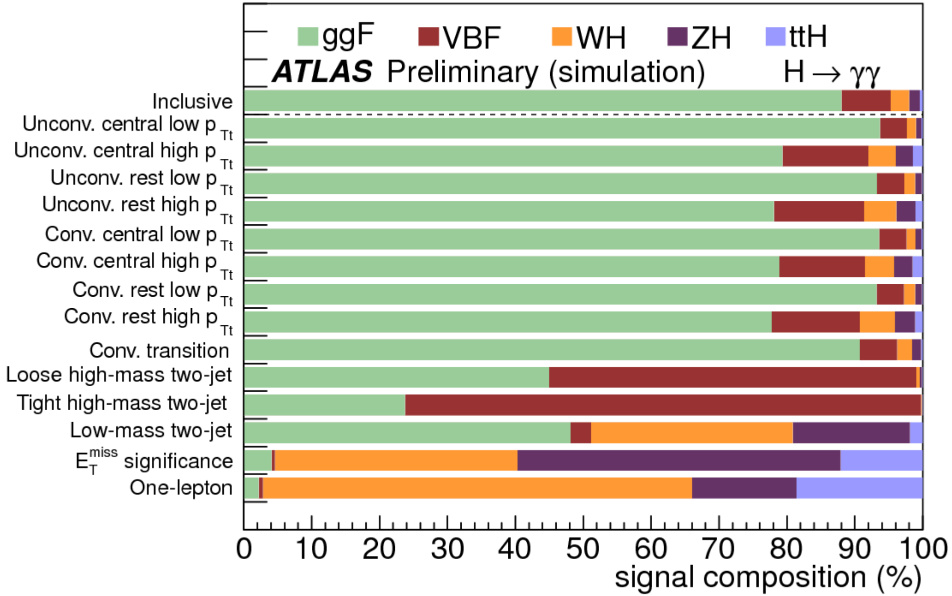


Searching for H→γγ

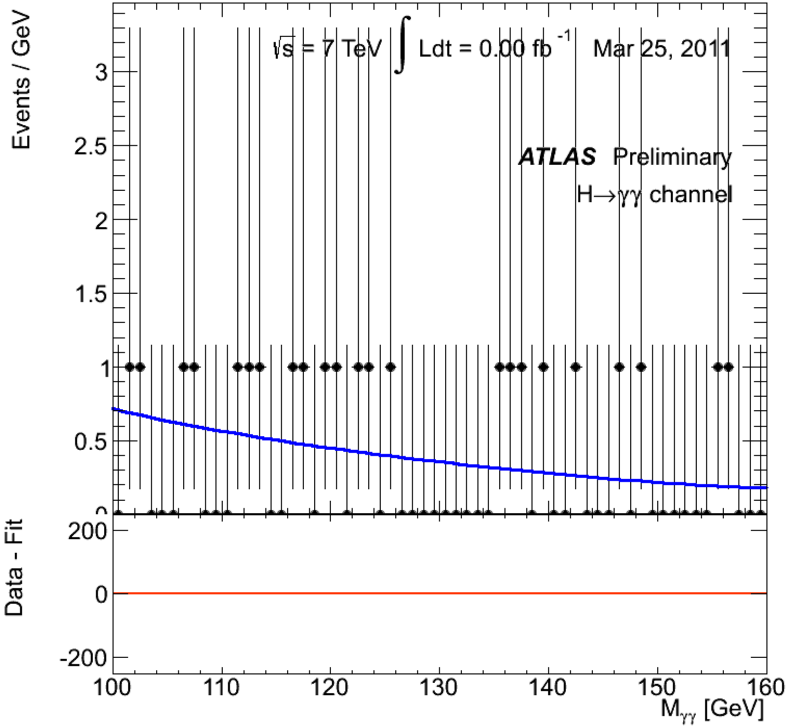
- LHC detectors were designed having this search in mind!
  - Efficient photon identification with excellent background rejection from jets misidentified as photons
  - Excellent diphoton mass resolution: ~1.2%-6%
  - Event categorization to fully profit from distinctive features.
    - ➔ Improve overall sensitivity by keeping high/low S/B categories separate.
    - ➔ Increase sensitivity to different production modes



[$p_{Tt} = p_T^{\gamma\gamma}$ perpendicular to γγ "thrust" axis]



The birth of a particle



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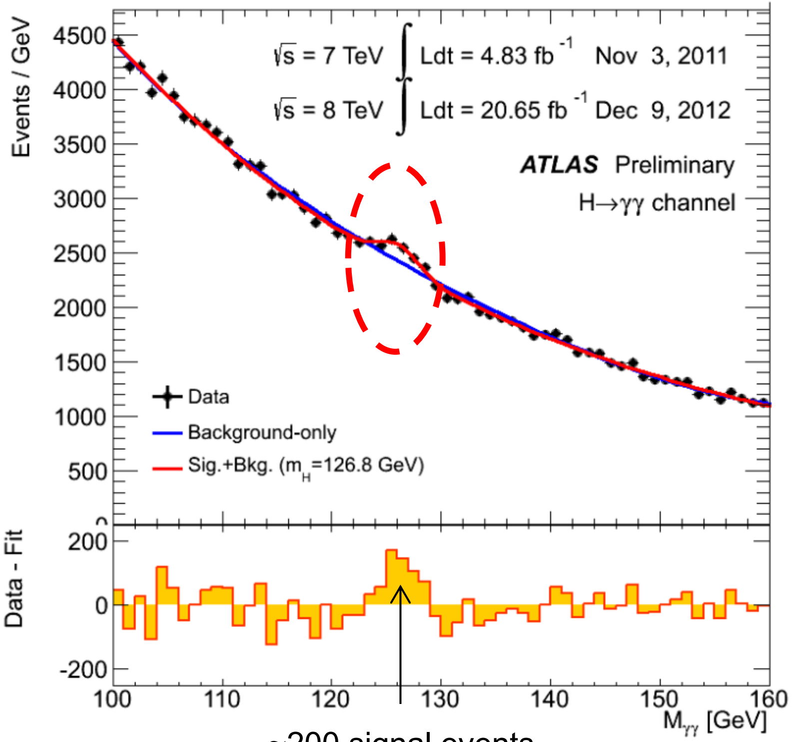
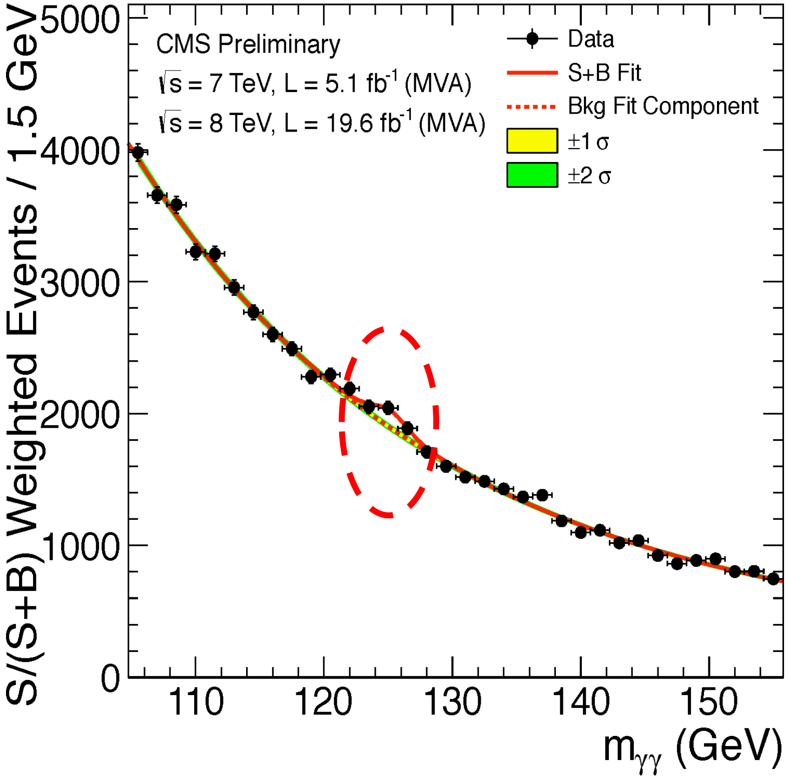
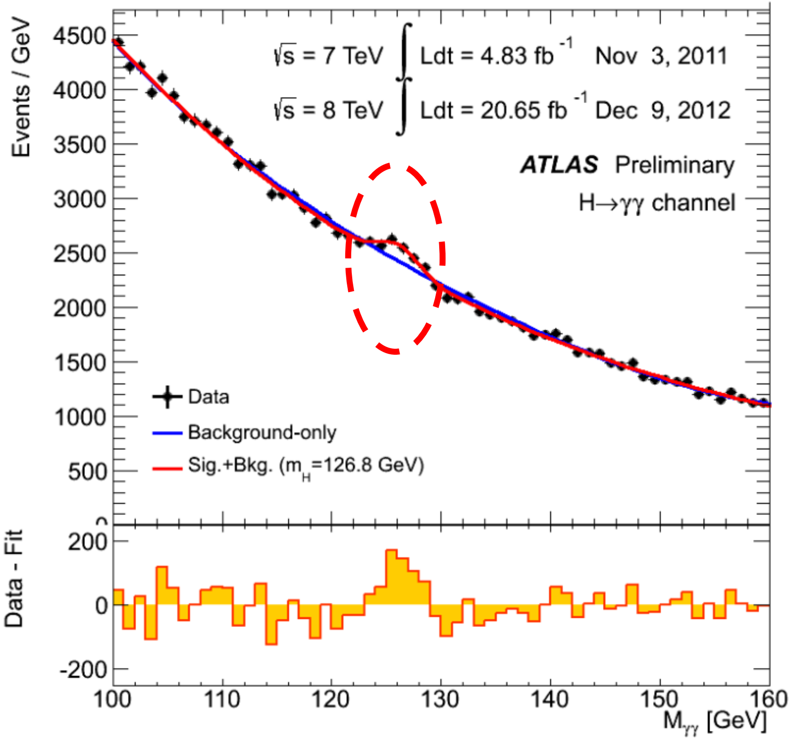


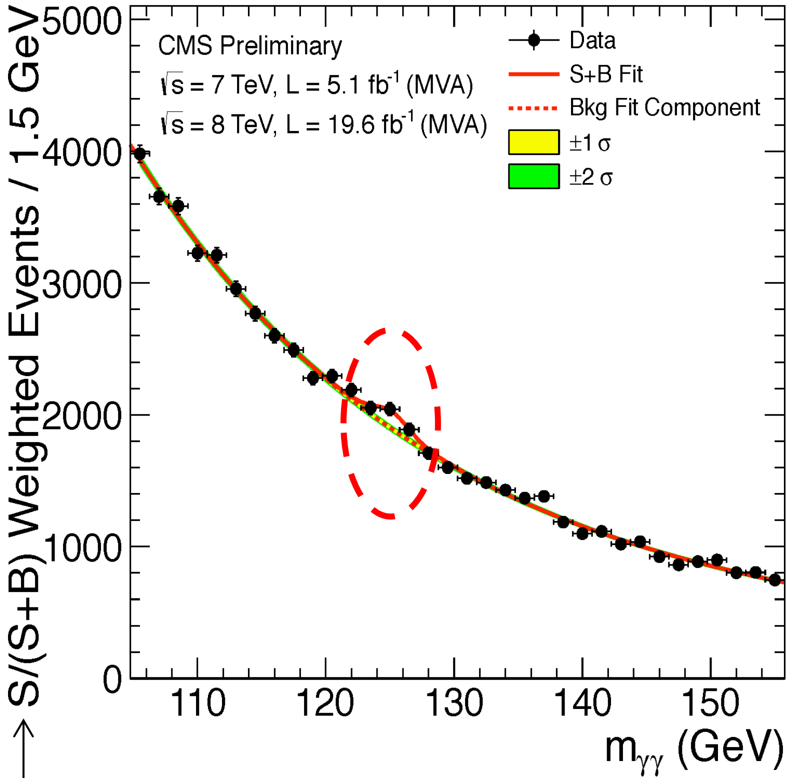
~200 signal events



ATLAS and CMS observe signal-like excesses at the same mass (~125 GeV)

The birth of a particle





Many different event categories considered, so hard to visualize a possible signal

➔ plot all events in same histogram with different event categories weighted by their expected purity

$H \rightarrow ZZ^{(*)} \rightarrow 4l$

Searching for H→ZZ$^{(*)}$→4l

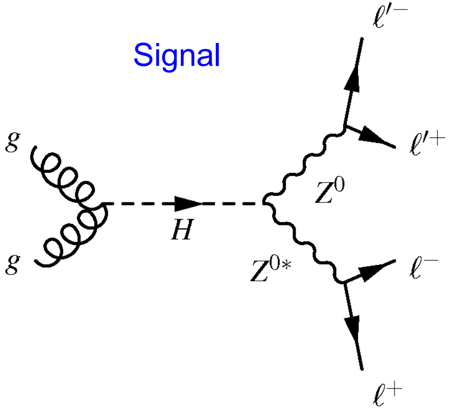
- An even rarer Higgs decay mode if both Z bosons are required to decay into electrons or muons!

  Prob(H→ZZ→4e, 4μ or 2e2μ)~0.01%

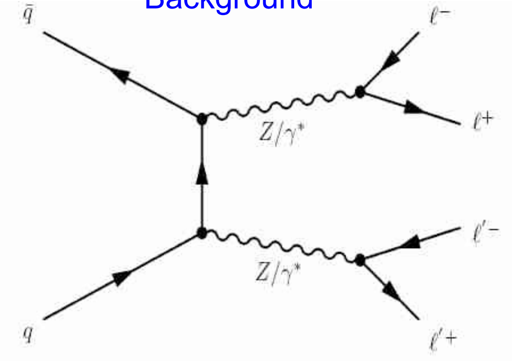
- But it makes this channel a golden discovery mode over most of the mass range:
  - Clean signature with very small background (mainly non-resonant ZZ production)
  - Can reconstruct Higgs mass with good resolution ➔ again, bump hunt!
  - Main limitation is that it requires high statistics (but eventually this won't be a problem!)

- So need:
  - Efficient lepton identification down to low energies
  - Good lepton energy resolution

Signal



Background



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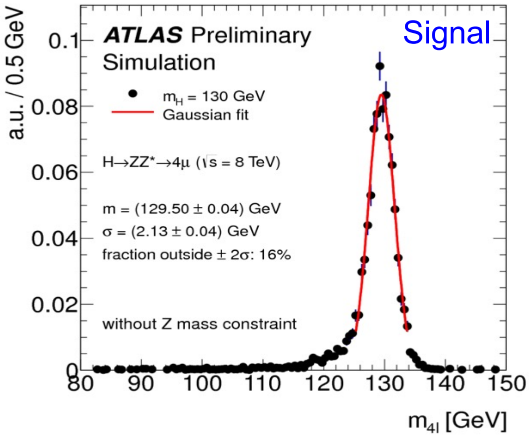
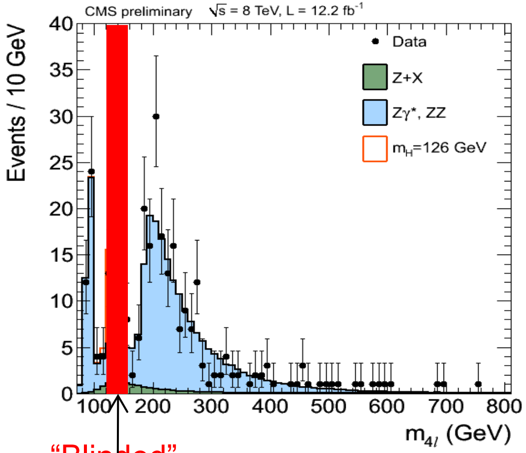
  - Good lepton energy resolution





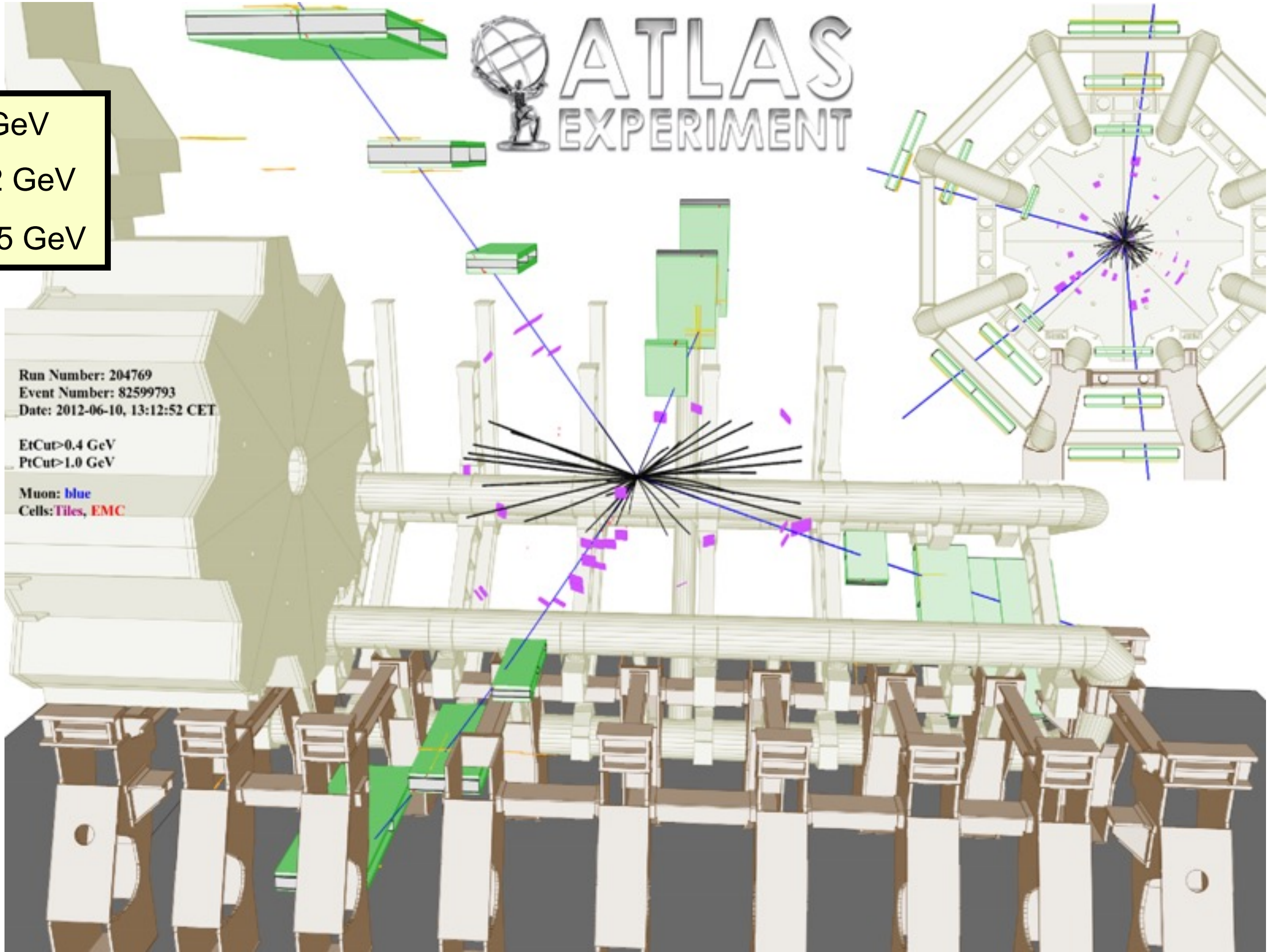
"Blinded"

$H \rightarrow ZZ^{(*)} \rightarrow 4\mu$ candidate event

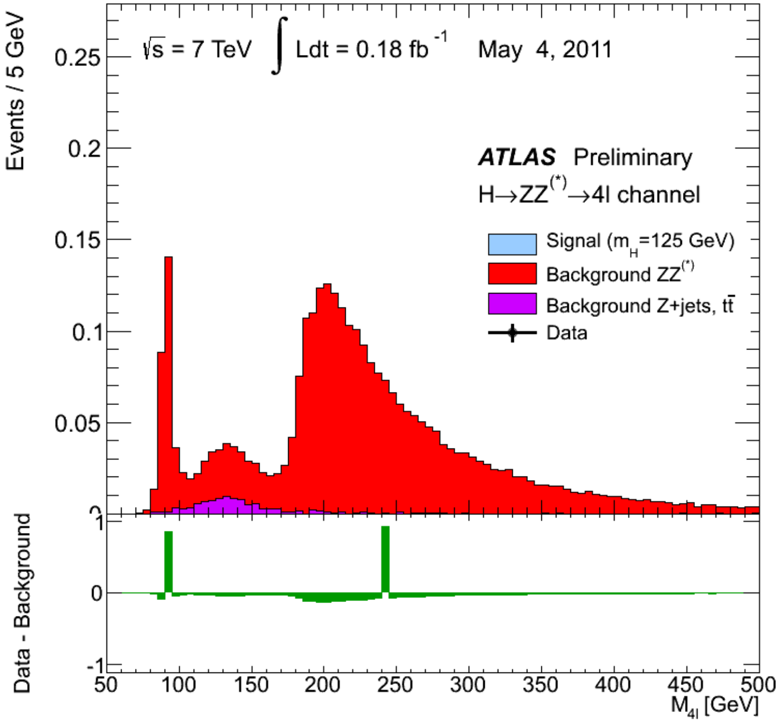
m_{12}=84 GeV

m_{34}=34.2 GeV

m_{4l}=123.5 GeV

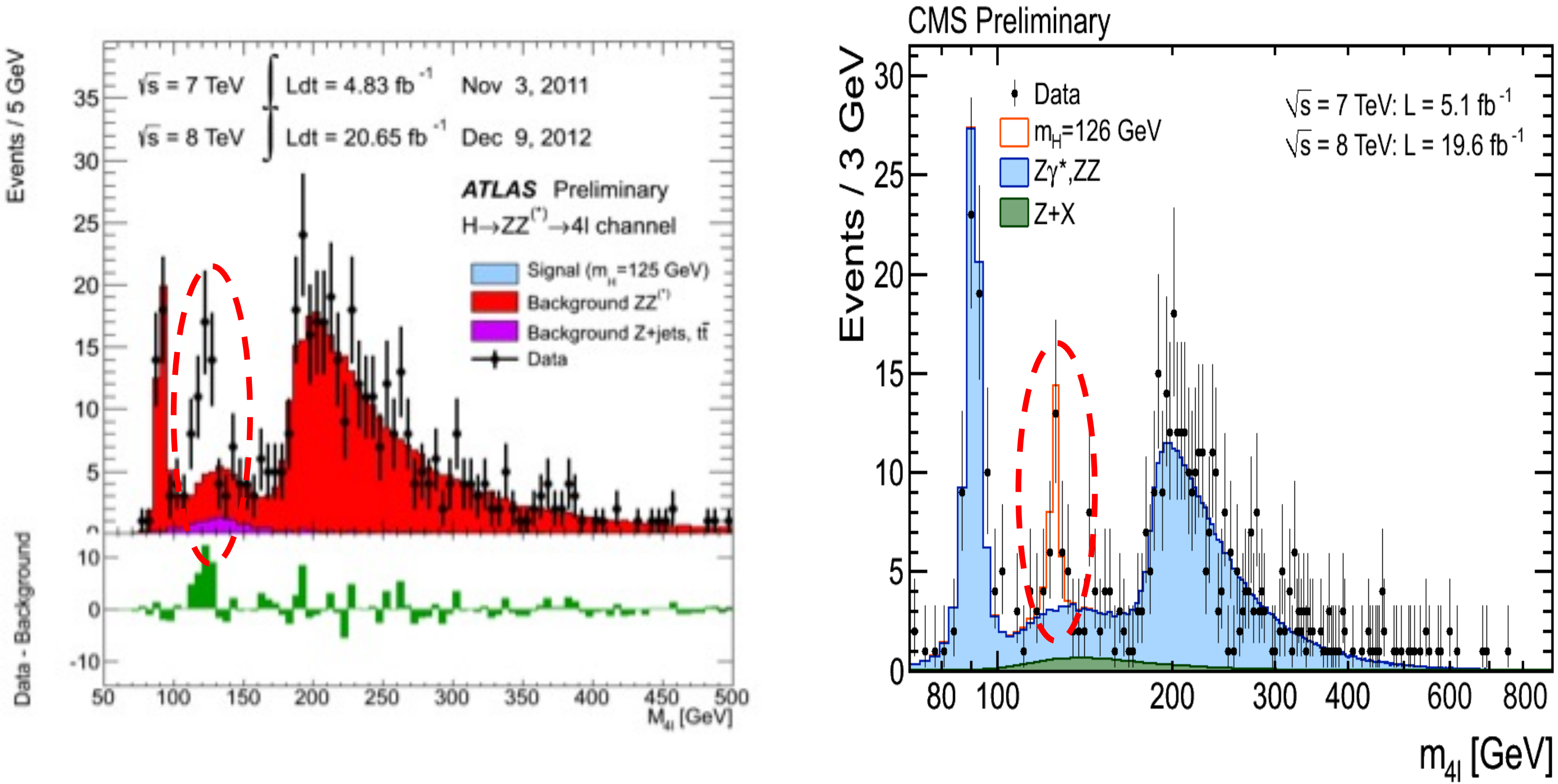


The birth of a particle



ATLAS and CMS observe signal-like excesses at the same mass (~125 GeV)

The birth of a particle



ATLAS and CMS observe signal-like excesses at the same mass (~125 GeV)

Statistical methods

Statistical interpretation

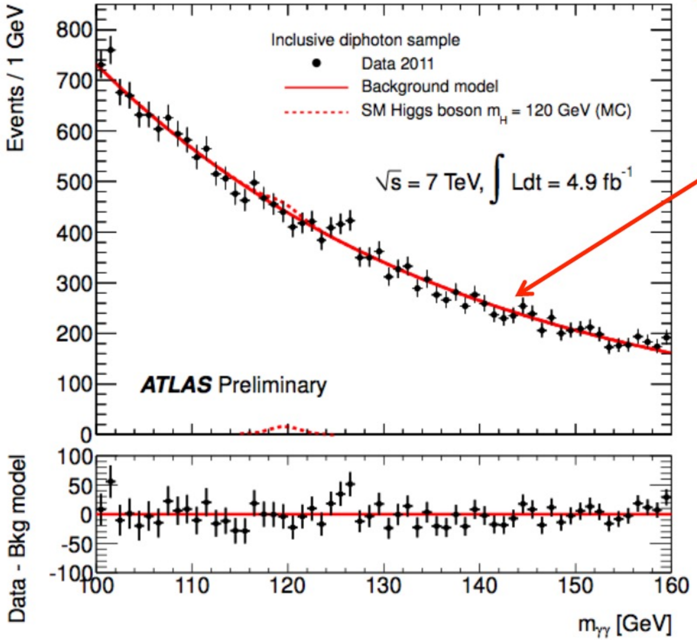
Hypothesis testing using the

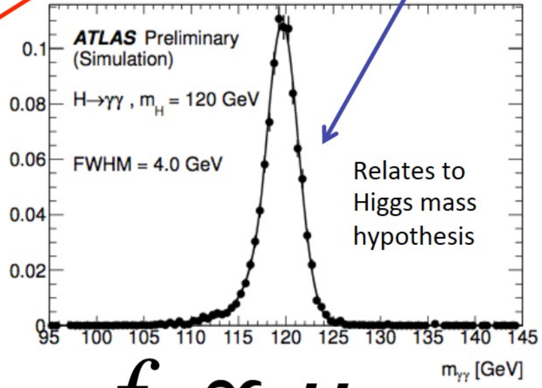
Profile likelihood ratio…

Likelihood Definition:

Simplified

$$L(\mu,\theta) = f_b\psi_b(M_{\gamma\gamma}) + f_s\psi_s(M_{\gamma\gamma})$$





Relates to
Higgs mass
hypothesis

$$f_s \propto \mu$$

Global coherent factor

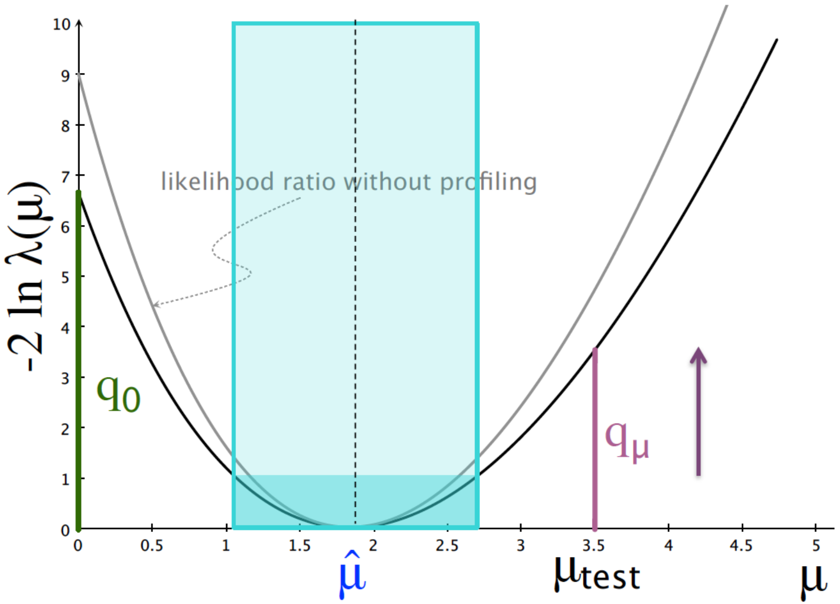
$$n_s = \mu\sigma BrL\varepsilon$$

Profile likelihood ratio

$$\lambda_\mu = \lambda(\mu,\theta) = \frac{L(\mu,\hat{\hat{\theta}}(\mu))}{L(\hat{\mu},\hat{\theta})} \qquad q_\mu = -2\ln\lambda_\mu$$

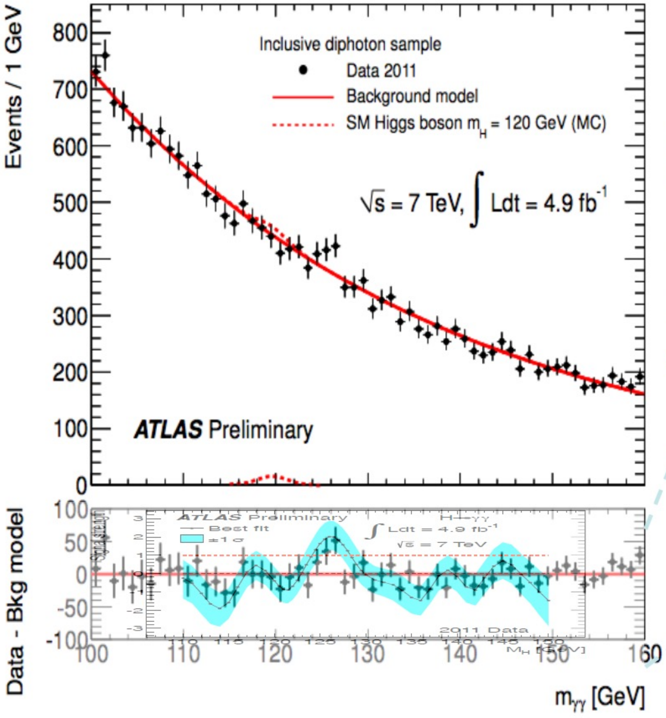
μ : signal strength

θ: nuisance parameters parameterizing impact of uncertainties



Fitting the signal strength

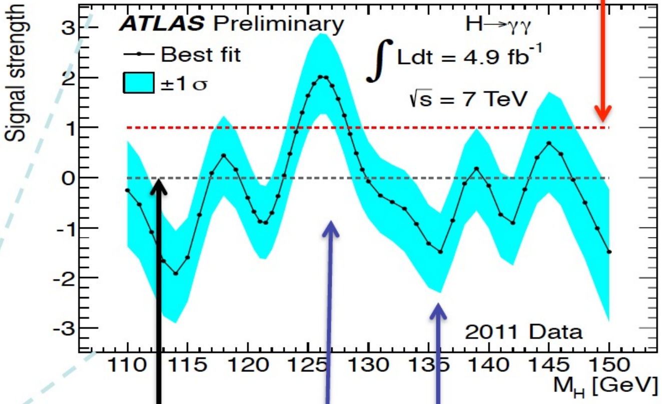
Hypothesis testing using the Profile likelihood ratio…



$$\hat{\mu}$$

Relate to Higgs mass hypothesis

Expected Signal

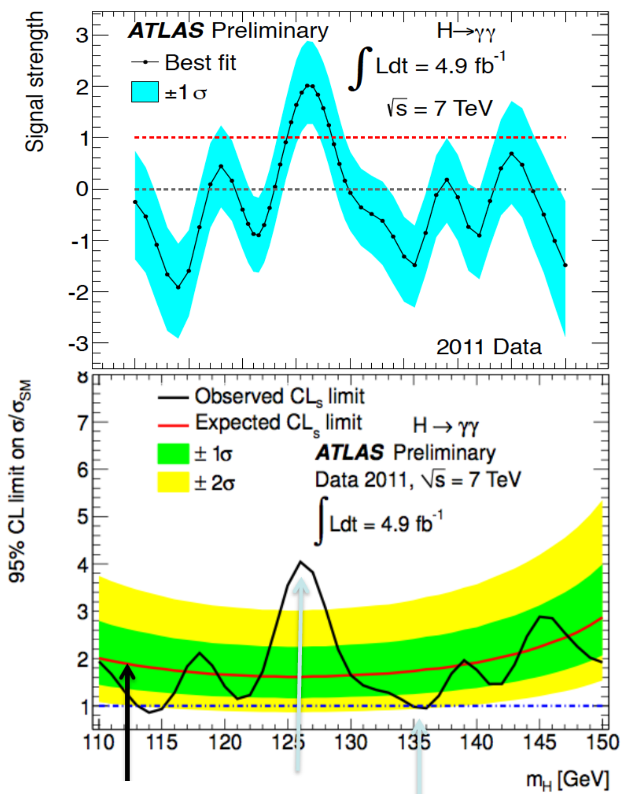


Expected Background

Excess

Deficit

Excluding a signal hypothesis



Median expected limit
(b-only hypothesis)

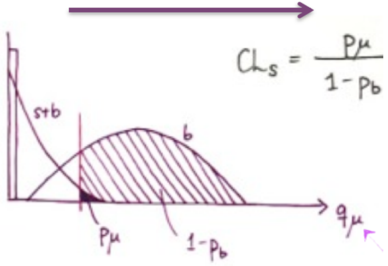
Excess

Deficit

$$\lambda_\mu = \lambda(\mu,\theta) = \frac{L(\mu,\hat{\hat{\theta}}(\mu))}{L(\hat{\mu},\hat{\theta})}$$

$$q_\mu = -2\ln\lambda_\mu$$

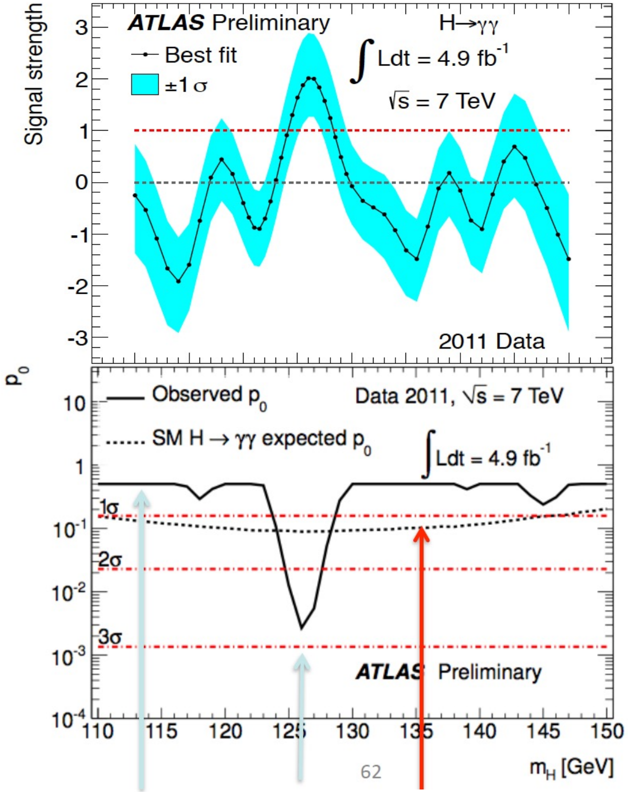
Background likeliness



CL_{s+b} Probability that a signal-plus-background experiment be more background-like than observed

Exclude at 95% CL values of μ for which $CL_s<0.05$

Local significance of an excess



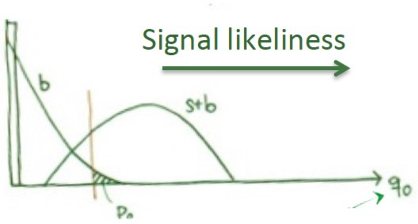
Deficit

Excess

Median expected significance
(s+b hypothesis)

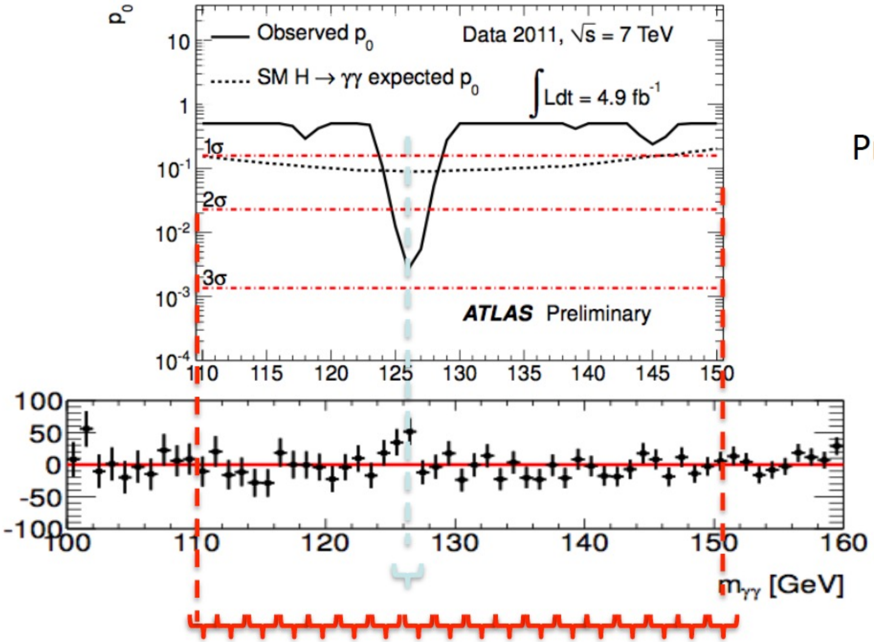
$$\lambda_0 = \lambda(0,\theta) = \frac{L(0,\hat{\hat{\theta}}(0))}{L(\hat{\mu},\hat{\theta})}$$

$$q_0 = -2\ln\lambda_0$$



p_0 Probability that a background only experiment be more signal like than observed

Local vs global significance



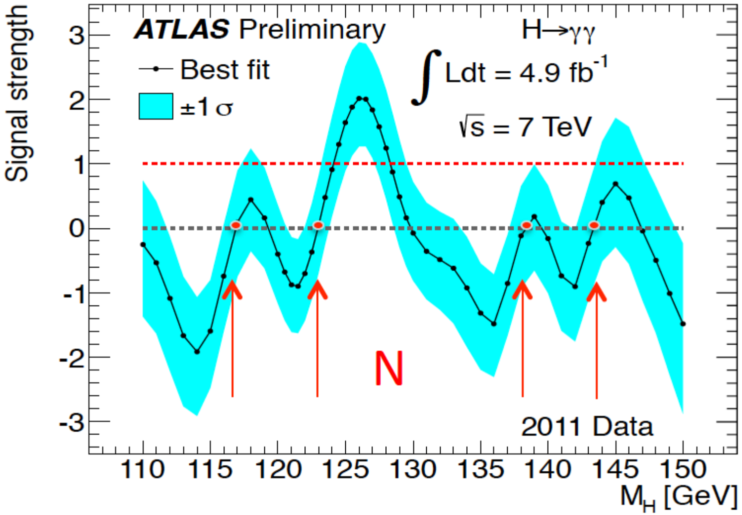
Probability of observing an excess at one specific mass
(in absence of signal)...

What is the probability of observing an excess at least as large as observed within a mass range ?

Trial factor ~ Number of possible independent outcomes within a mass range... (dependence on the significance)

Local vs global significance

Approximate formula



Based on counting the numbers of up-crossings

Then applying the very simple following formula (Z is the local significance)

$$p_{global} = p_{local} + N \times e^{-\frac{Z^2}{2}}$$

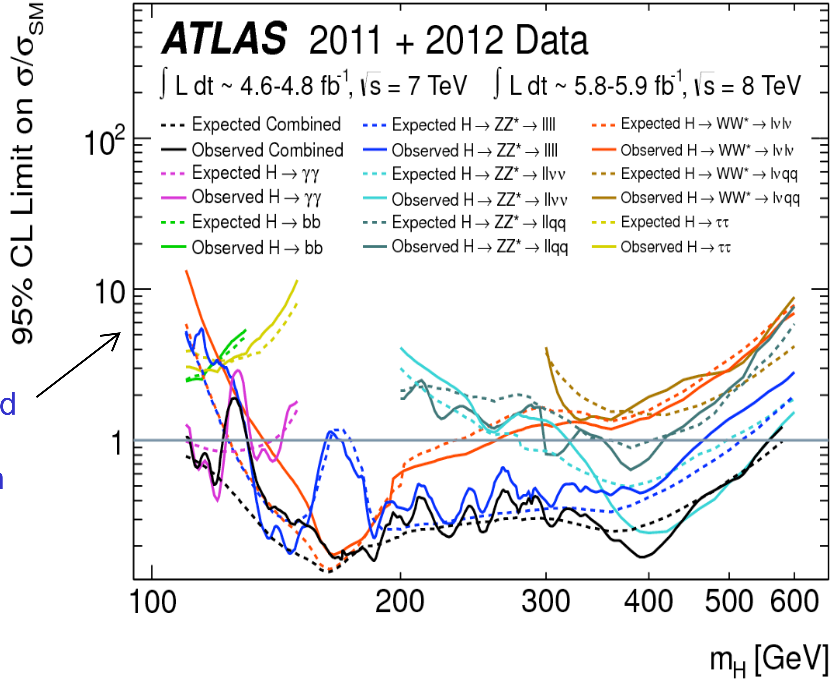
For more details:

E. Gross and O. Vitells, *Trial factors for the look elsewhere effect in high energy physics*, Eur. Phys. J. **C70** (2010) 525–530.

Summing it all up

Combination of results

- Today we just discussed about the search modes with best mass resolution, but searches were performed in many other modes (H→W^+W^-, H→bb, H→$\tau^+\tau^-$, etc).
- Combination of multiple search channels yields the greatest sensitivity!

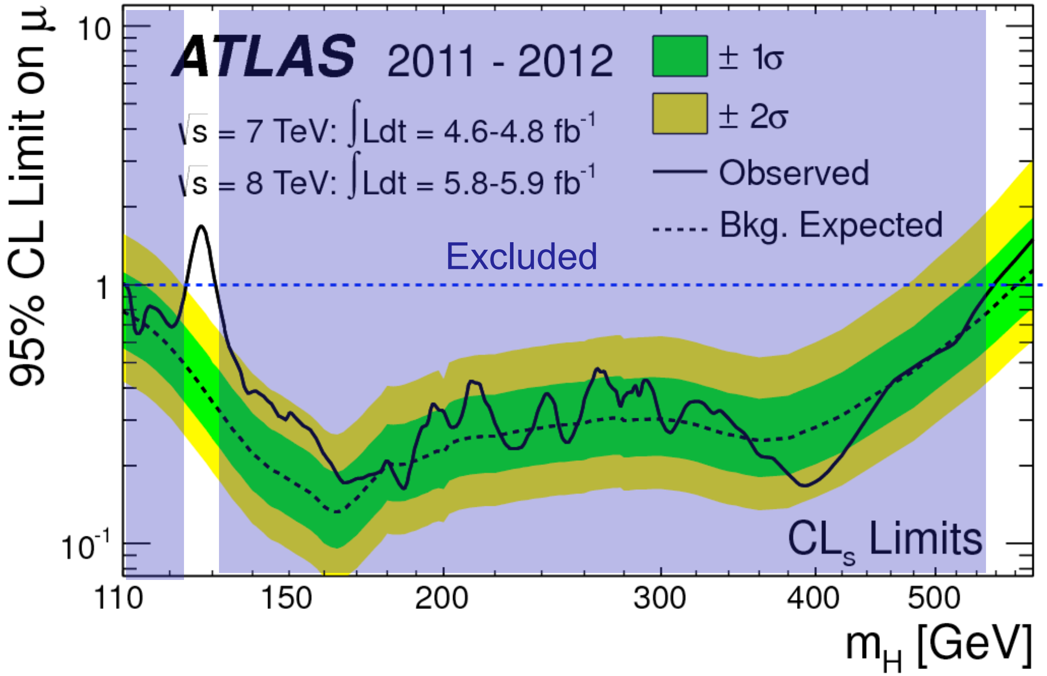


Signal cross section excluded at the 95% confidence level relative to the SM prediction

Remember, a-priori we don't know the mass so need to look everywhere…

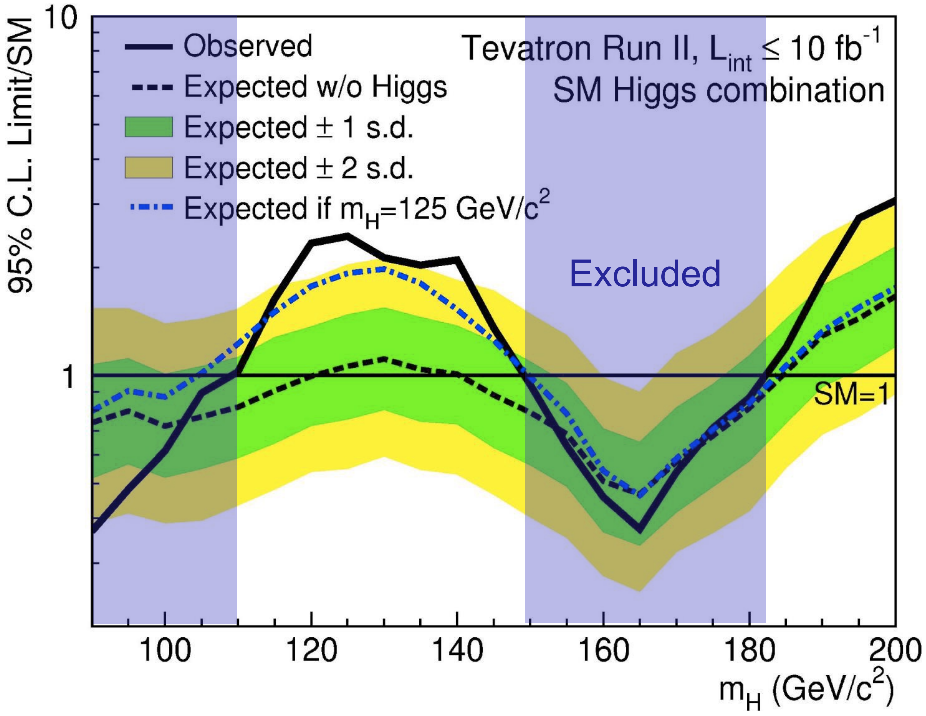
m_H values for which limit on σ/σ_{SM} is <1, are excluded at 95% CL

LHC combined limits



- The ATLAS data is inconsistent with the presence of a SM Higgs boson over a wide mass range! Excluded at 95% CL: 111 < m_H < 122 GeV, 131 < m_H < 559 GeV
  A narrow region remains unexcluded, because there is a signal-like excess!
- Similar conclusions achieved by the CMS experiment!

Tevatron combined limits



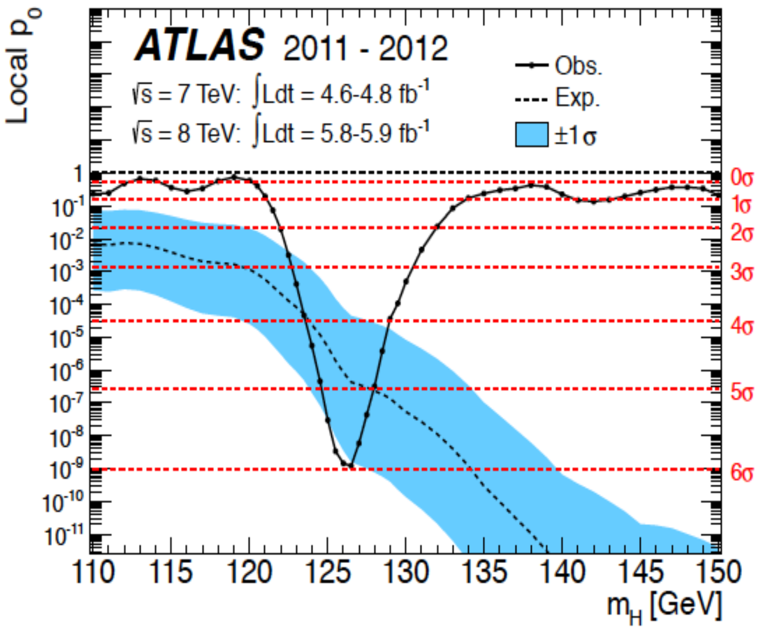
- Expected exclusion: 90 < m_H < 120 GeV, 140< m_H < 184 GeV
  Observed exclusion: 90 < m_H < 109 GeV, 149 < m_H < 182 GeV
- 95% CL limit at m_H=125 GeV: 1.06xSM (expected), 2.44xSM (observed)

Significance of the results

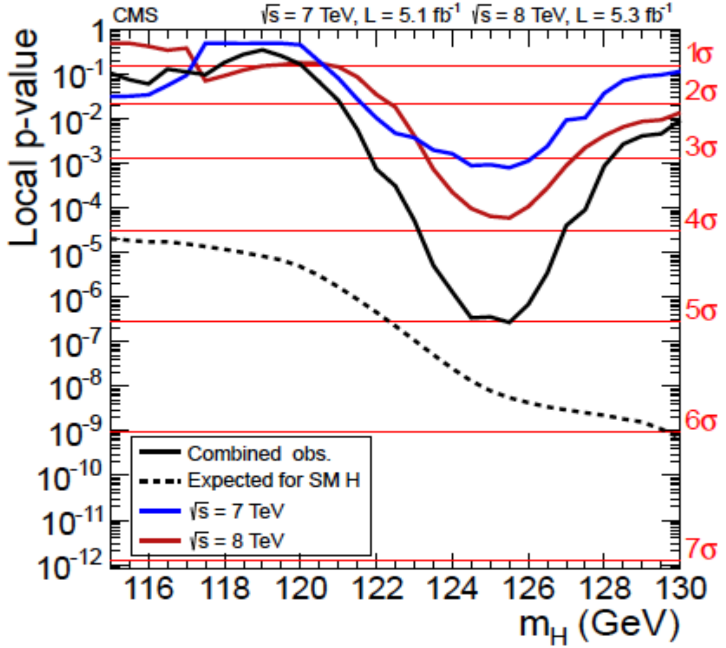
- p_0: probability that the data could come from a model with no Higgs boson.
- Very high standards:

  Evidence benchmark ➔ $p_0 = 0.00135$ (3 Gaussian standard deviations)

  Discovery benchmark ➔ $p_0 = 2.6 \times 10^{-7}$ (5 Gaussian standard deviations)



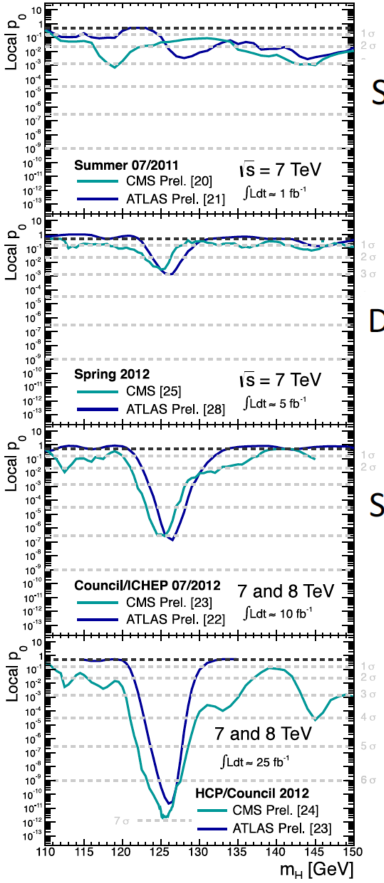
5.9σ at m_H=126.5 GeV



5.0σ at m_H=125.5 GeV

A textbook discovery

PDG, review of Particle Physics



Summer 2011: EPS and Lepton-Photon

First (and last) focus on limits (scrutiny of the p_0)

December 2011: CERN Council

First hints

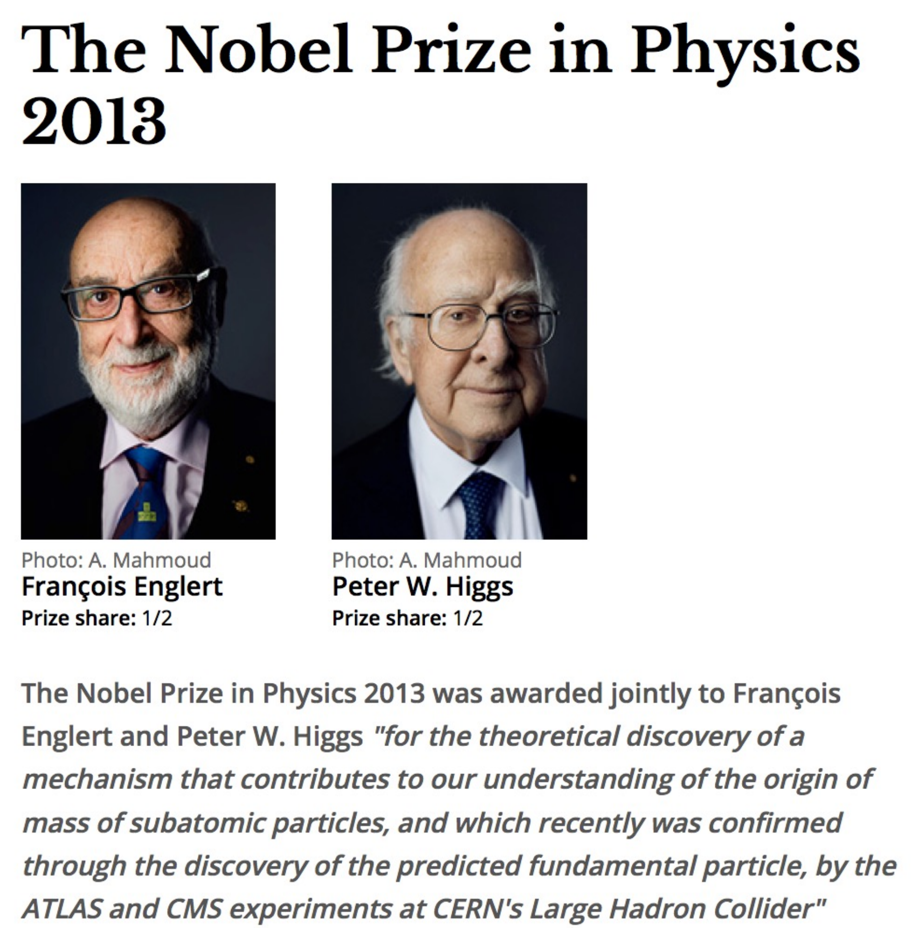
Summer 2012: CERN Council and ICHEP

Discovery!

Rolf-Dieter Heuer (Director General of CERN)

As a Layman: We have it!

One year later…



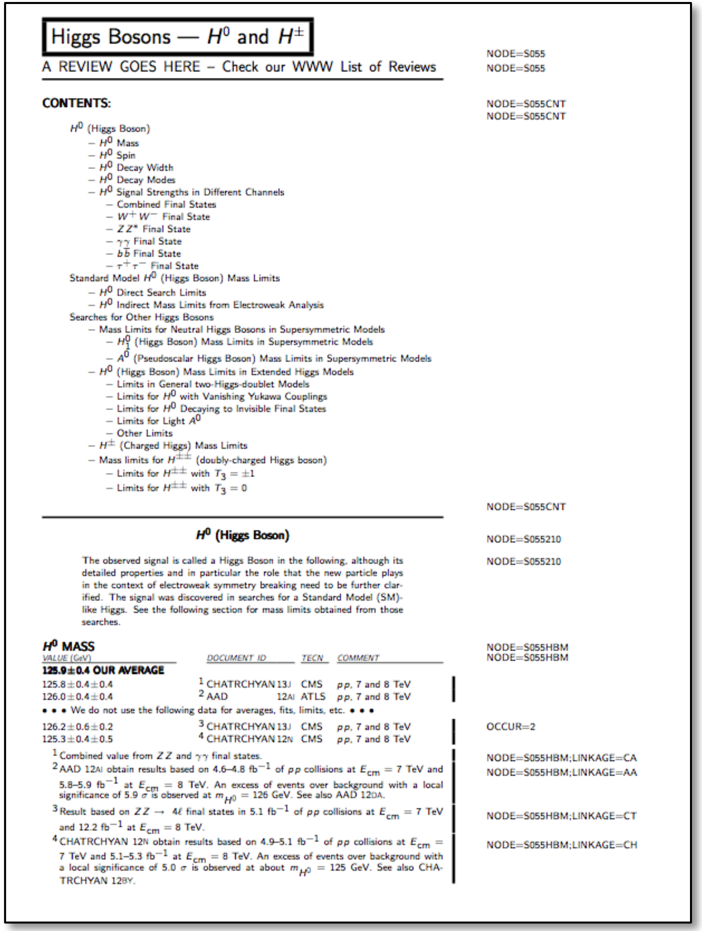
The Nobel Prize in Physics 2013

Photo: A. Mahmoud
François Englert
Prize share: 1/2

Photo: A. Mahmoud
Peter W. Higgs
Prize share: 1/2

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. 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"*

One year later…



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
    – $b\overline{b}$ 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±0.4±0.4	[1] CHATRCHYAN 13J	CMS	pp, 7 and 8 TeV
126.0±0.4±0.4	[2] AAD 12AI	ATLS	pp, 7 and 8 TeV
• • • We do not use the following data for averages, fits, limits, etc. • • •			
126.2±0.6±0.2	[3] CHATRCHYAN 13J	CMS	pp, 7 and 8 TeV
125.3±0.4±0.5	[4] CHATRCHYAN 12N	CMS	pp, 7 and 8 TeV

OCCUR=2

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

NODE=S055HBM;LINKAGE=CA

[2] AAD 12AI obtain results based on 4.6–4.8 fb^{-1} of pp collisions at $E_{\text{cm}} = 7$ TeV and 5.8–5.9 fb^{-1} at $E_{\text{cm}} = 8$ 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 $ZZ \rightarrow 4\ell$ final states in 5.1 fb^{-1} of pp collisions at $E_{\text{cm}} = 7$ TeV and 12.2 fb^{-1} at $E_{\text{cm}} = 8$ TeV.

NODE=S055HBM;LINKAGE=CT

[4] CHATRCHYAN 12N obtain results based on 4.9–5.1 fb^{-1} of pp collisions at $E_{\text{cm}} = 7$ TeV and 5.1–5.3 fb^{-1} at $E_{\text{cm}} = 8$ 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.

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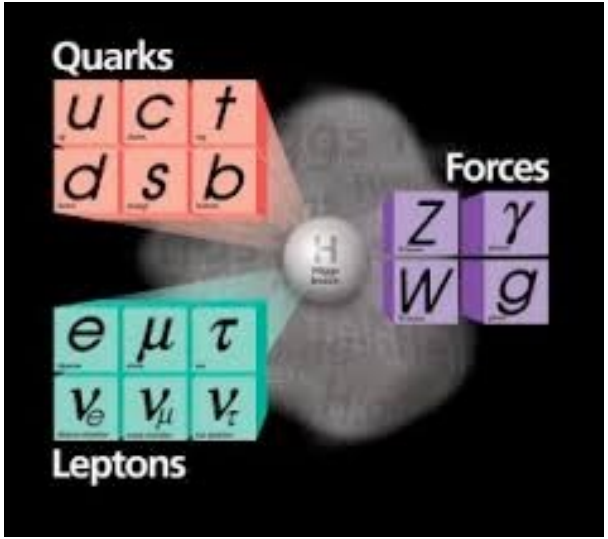
$$H^0$$

The Higgs boson enters the Particle Data Group listing!

What have we learned?

- With the discovery of the Higgs boson the Standard Model is “complete”.



- However, the Higgs sector is somehow the least elegant sector of the Standard Model:
  - It accounts for most unknown parameters (masses and mixing angles).
  - There is no underlying gauge principle.

Open questions

- Is it the Higgs boson of the Standard Model?
- Is it elementary or composite?
- What makes μ^2 negative?
- What’s the explanation for the flavor mass hierarchy?
- Is the mechanism responsible for the mass of gauge boson also responsible for fermion masses?
- Is the Higgs sector minimal?
- Is there a connection between the Higgs sector and dark matter?

Next lecture

Lecture 1: Stalking the Higgs boson
- Preliminaries on Higgs physics
- Pre-LHC searches
- The discovery

Lecture 2: Studying the Higgs boson
- Overview of Run 1 studies
- Summary of recent Run 2 results
- Future prospects

Backup

SSB – Local Symmetry

Let the aforementioned continuous symmetry U(1) be local : α(x) now depends on the space-time x.

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

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 : $A_\mu \to A_\mu + \frac{1}{e}\partial_\mu\alpha$

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…

SSB – Local Symmetry

What about the field content?

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

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

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

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

SSB – Local Symmetry

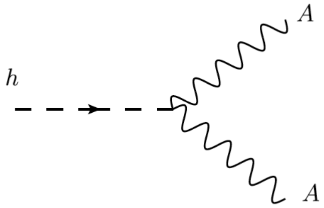
Before SSB

Not gauge invariant

$$mA_\mu A^\mu$$

Not existing vertex

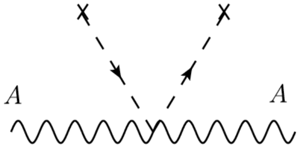
$$A_\mu A^\mu h$$



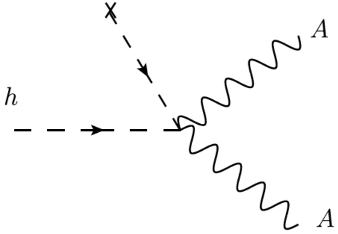
After SSB

Not only existing but also closely related!

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



$$ve^2 A_\mu A^\mu h$$



Proof of condensate !