HASCO Summer School 2017, University of Göttingen, 16-21 July 2017

Higgs Physics

Lecture 1

Aurelio Juste
ICREA/IFAE, Barcelona

“Higgsdependence Day”

Seminar at CERN, July 4, 2012

How did we get there??

(picture: courtesy of A. Hoecker]

PRESS COVERAGE

after July 4th seminars at CERN

CERN black board, Jul 2012

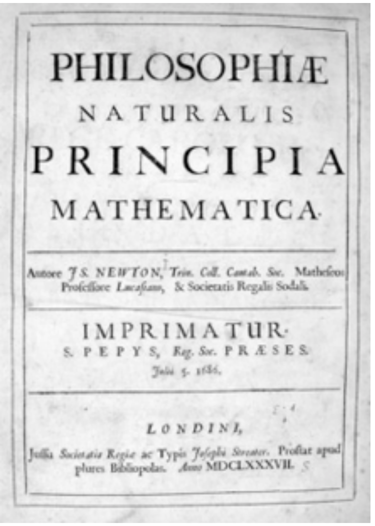
Not the origin of mass

- Galilean and Newtonian concept of mass:

$$\underbrace{\text{Inertial mass (F=ma)} \qquad \text{Gravitational mass (P=mg)}}$$

Single concept of mass

Conserved intrinsic property of matter where the total mass of a system is the sum of its constituents



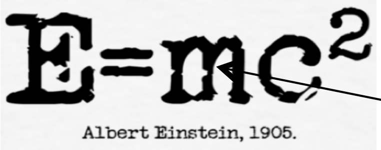
PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

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.

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



Rest mass

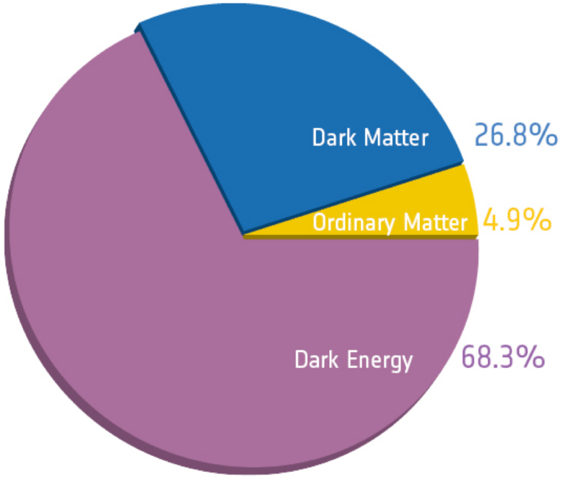
  - Atomic level: binding energy ~O(10 eV) ➔ ~10^{-8} of the mass
  - Nuclear level: binding energy ~O(4 MeV) ➔ ~1% of the mass
  - Nucleon level: binding energy ➔ ~98% of the mass!

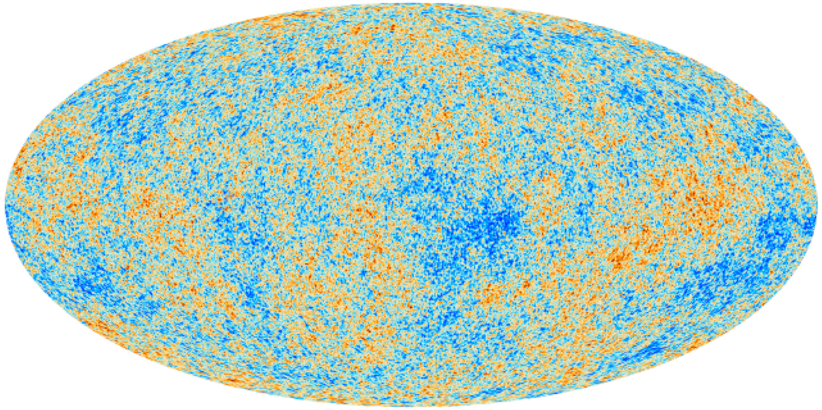
  ➔ Most of the (luminous) mass in the universe comes from QCD confinement energy

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

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.

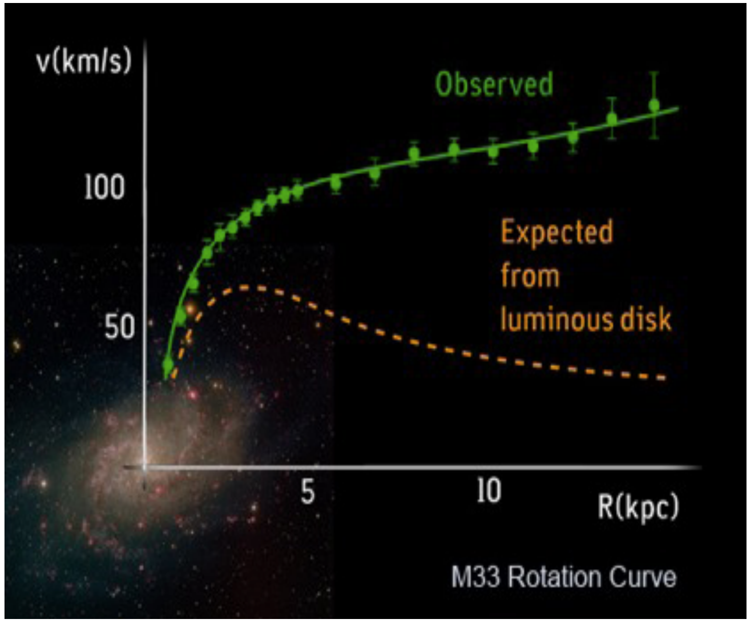




- So, only 5% of the universe is the stuff we know about. And we are trying to learn about the 2% contribution (non-QCD binding energy related) to that 5%???

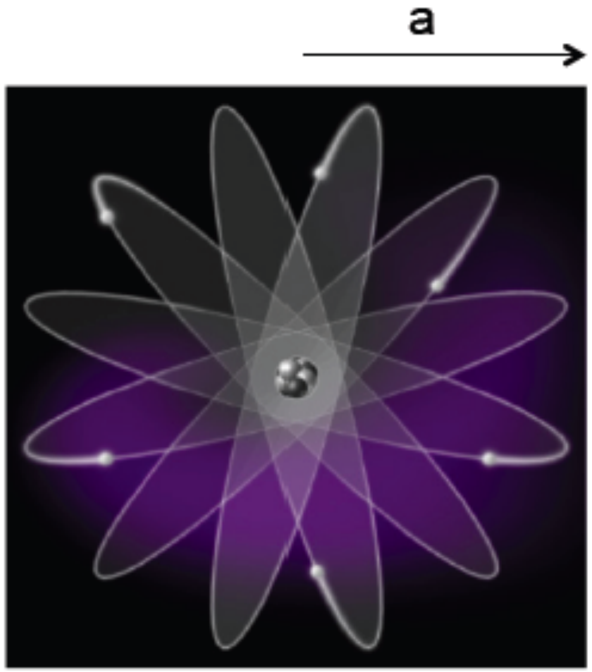
- Why should we care?

Dark matter effect on galaxy rotation curves

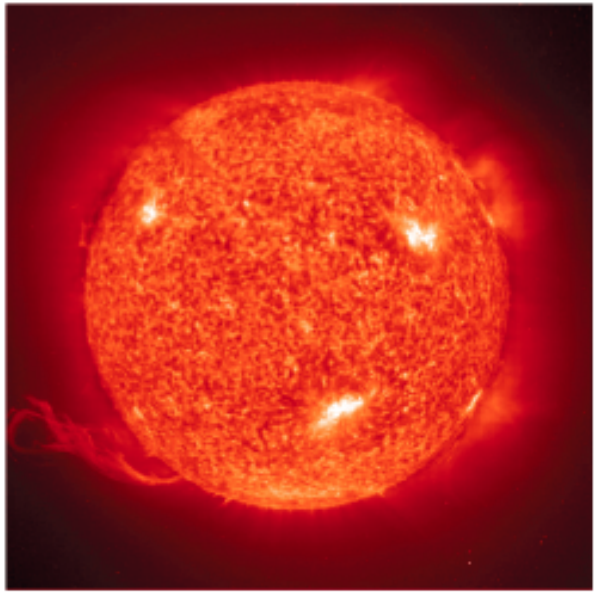


Why should we care?

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!

Historial 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

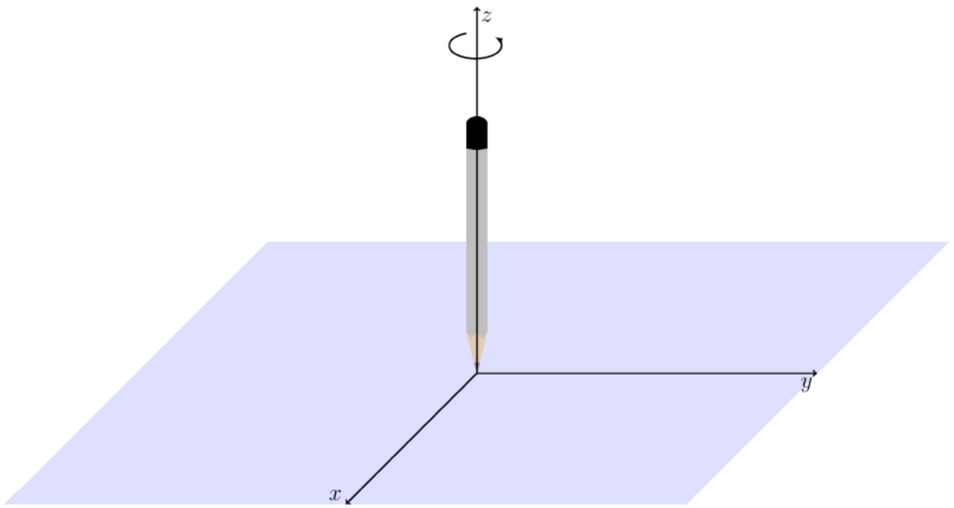
$$SU(2)_L \times U(1)_Y$$

gauge group.

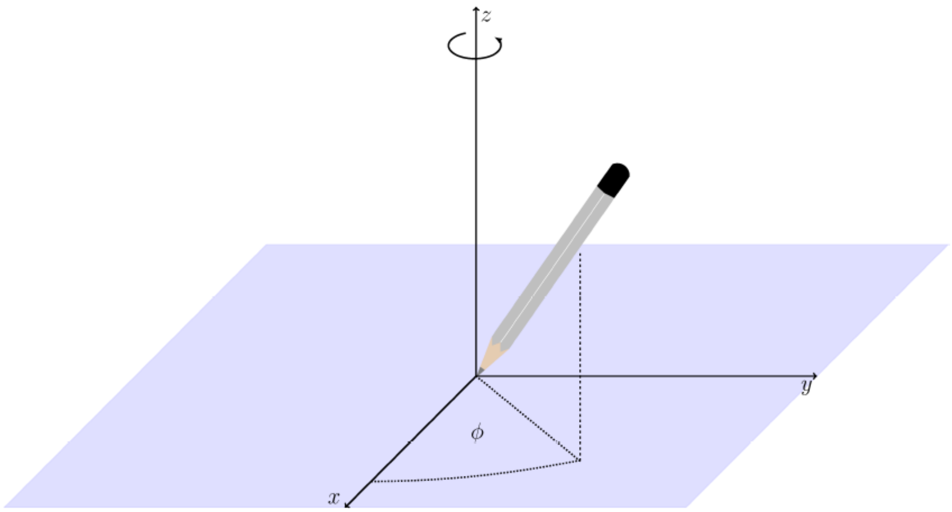
BUT, local gauge symmetry forbids gauge bosons and fermion masses!

Solution: spontaneous symmetry breaking (SSB)!

SSB visualized



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



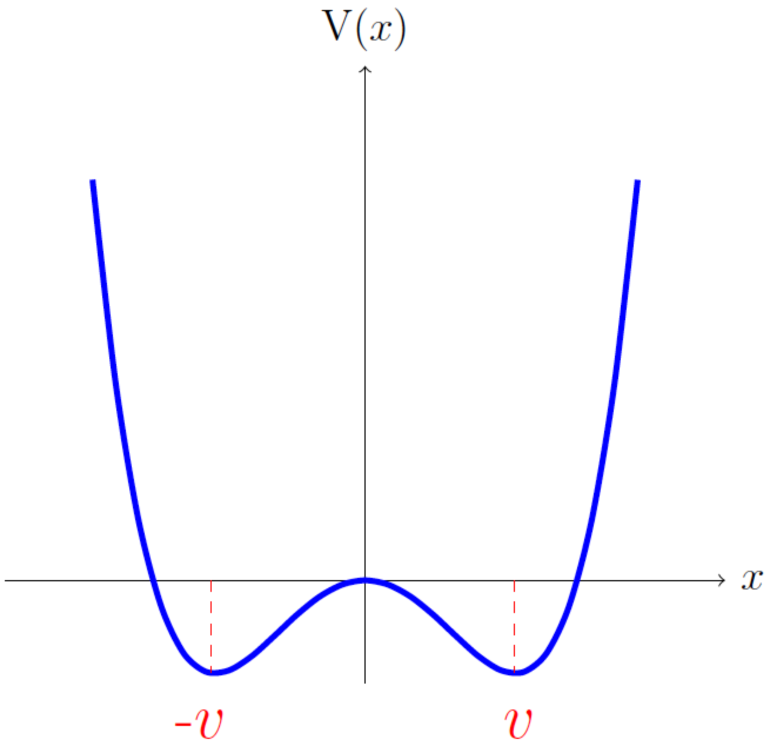
Pencil drops to one side (goes into ground state)
⇒ symmetry is spontaneously broken

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)

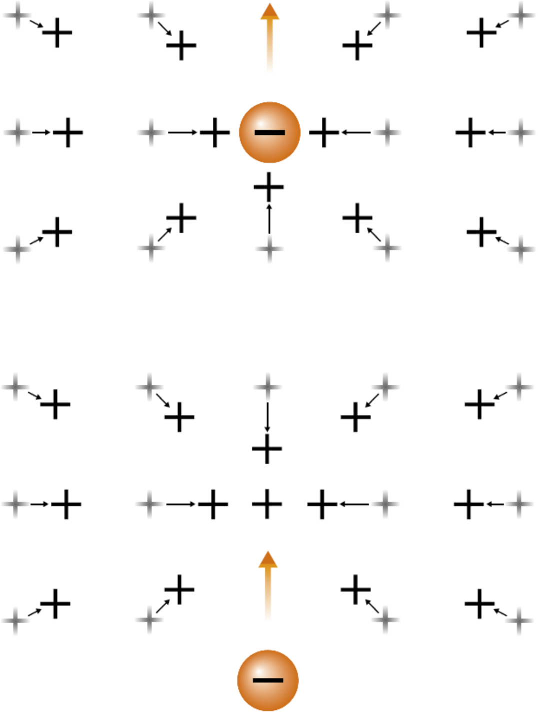
1950: Ginzburg & Landau

- 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)

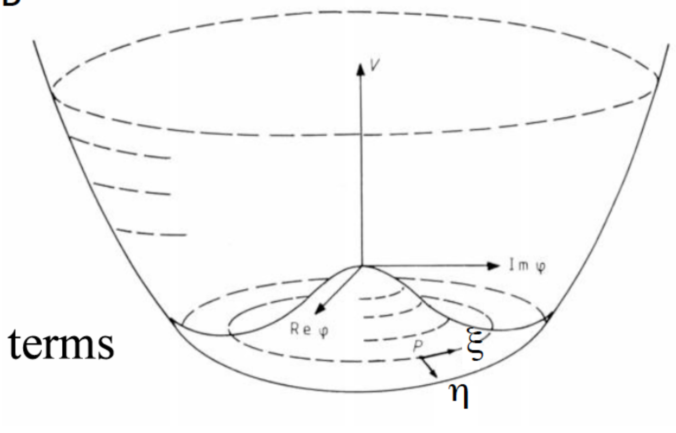
From a simple (complex) scalar theory with a U(1) symmetry

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

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

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

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.

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

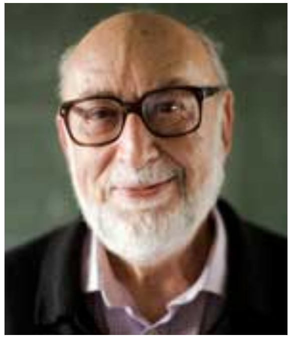
Problematic: a massless particle should have been found already!
➔ Need to find a way to eliminate it

A way out?

2010 Sakurai Prize for Theoretical Particle Physics:

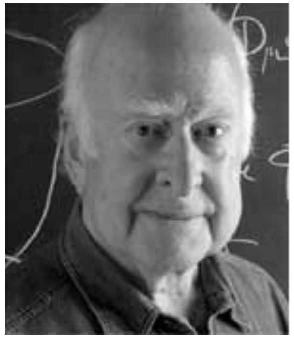
"For elucidation of the properties of spontaneous symmetry breaking in four-dimensional relativistic gauge theory and of the mechanism for the consistent generation of vector boson masses"

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?

All players in the same PRL issue…

Rober
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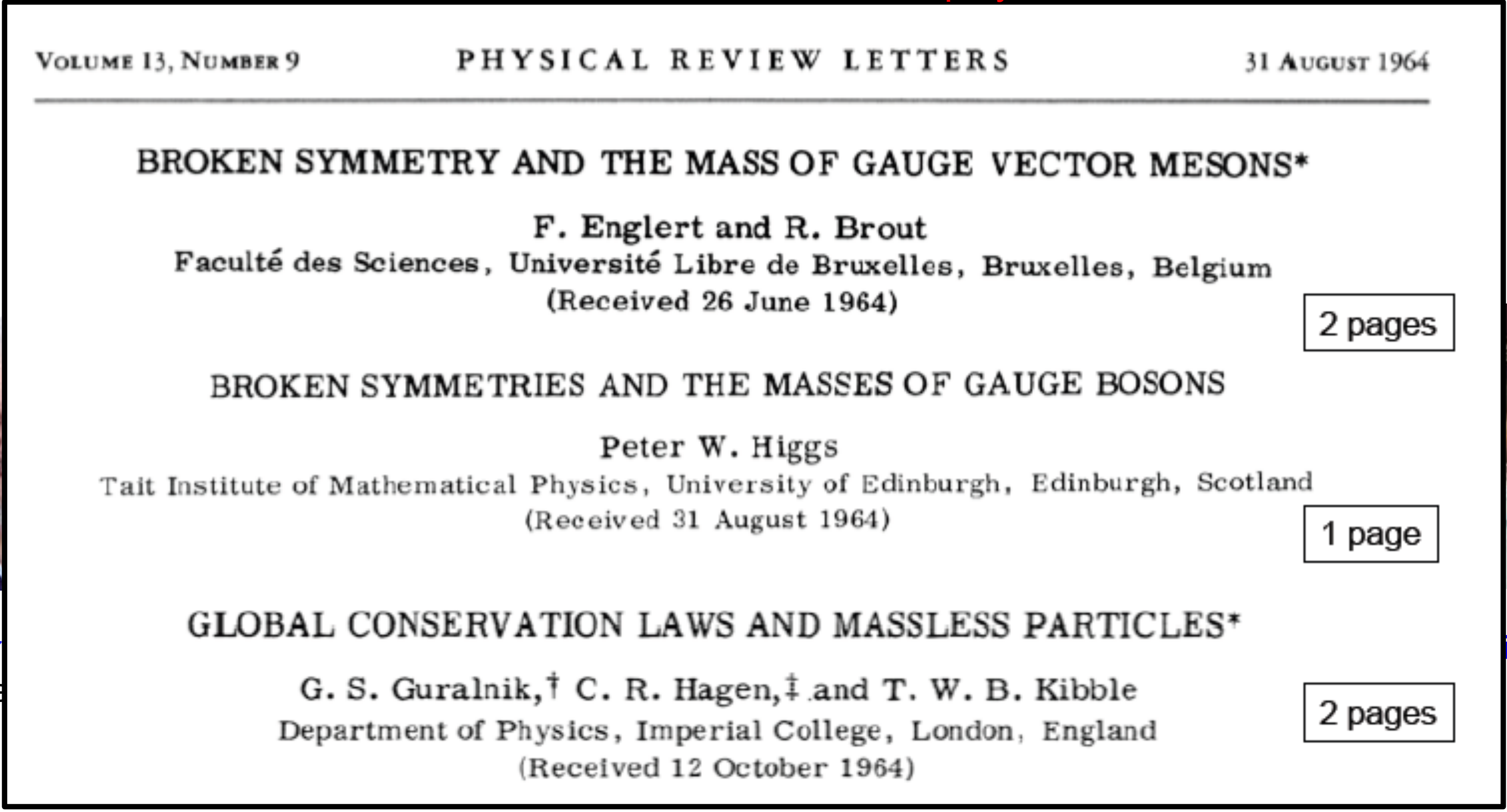

VOLUME 13, NUMBER 9 PHYSICAL REVIEW LETTERS 31 AUGUST 1964

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

2 pages

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

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

1 page

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

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

2 pages

ibble
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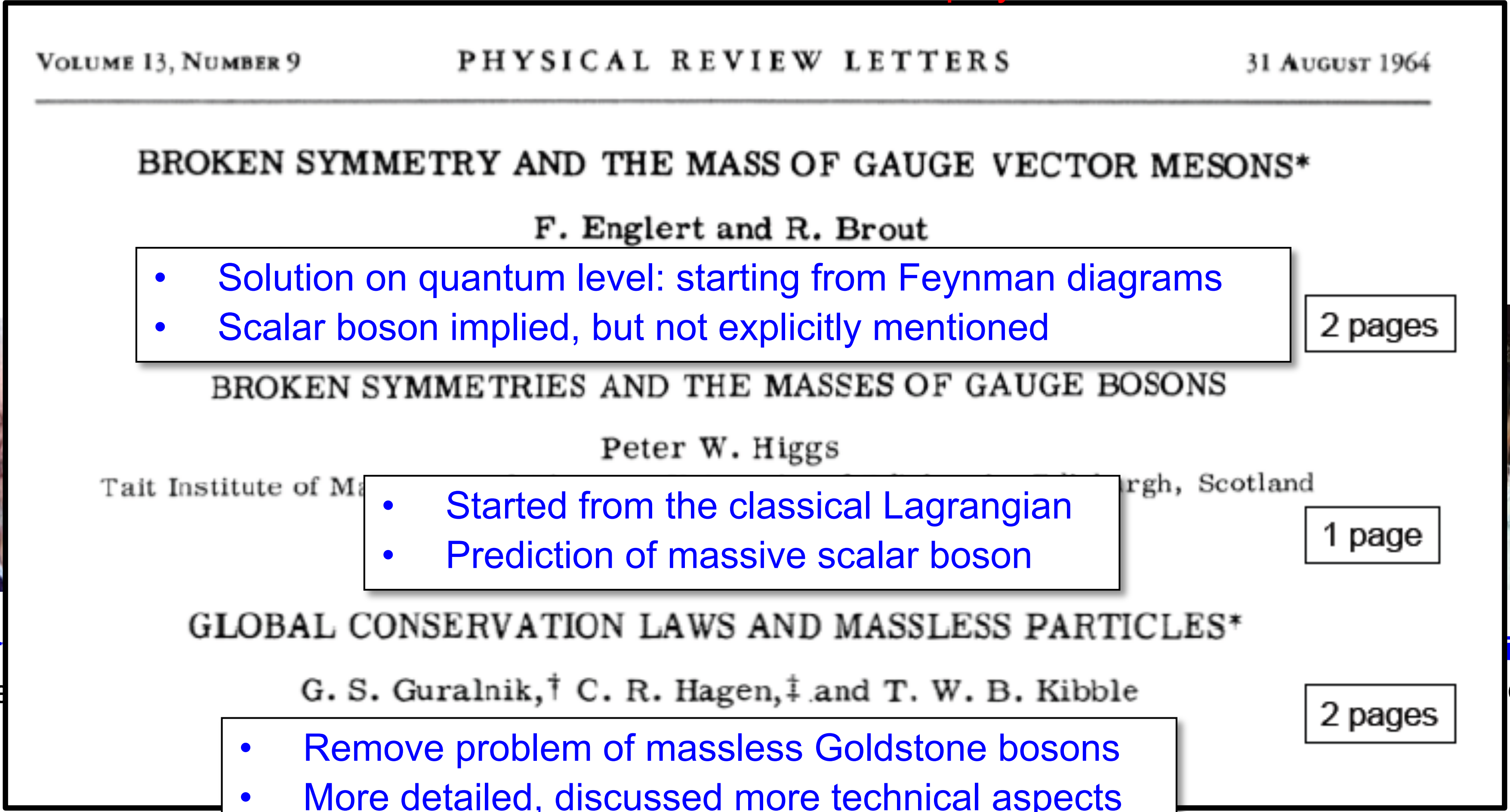
Disclosure: Though we often refer to the Higgs mechanism/boson, we're really discussing the BEGHHK mechanism/boson.

A way out?

All players in the same PRL issue…

Rober

Unive



VOLUME 13, NUMBER 9 PHYSICAL REVIEW LETTERS 31 AUGUST 1964

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout

- 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 of M… rgh, 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

2 pages

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

ibble

ollege

Disclosure: *Though we often refer to the Higgs mechanism/boson, we're really discussing the BEGHHK mechanism/boson.*

SSB – Local Symmetry

Let the aforementioned continuous symmetry U(1) be local : $\alpha(x)$ 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 : $\varphi = \dfrac{v + \eta + i\xi}{\sqrt{2}}$

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

Mass term for the gauge field! But…

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

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

Massive scalar : The Higgs boson

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

Massive gauge boson

$$+(1/2)e^2 A_\mu A^\mu h^2 + ve^2 A_\mu A^\mu h$$

Gauge-Higgs interaction

The Goldstone boson does not appear anymore in the Lagrangian

SSB – Local Symmetry

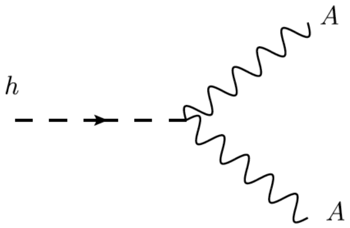
Before SSB

Not gauge invariant

$$mA_\mu A^\mu$$

Not existing vertex

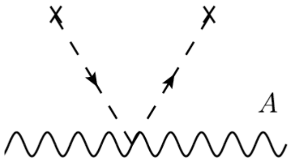
$$A_\mu A^\mu h$$



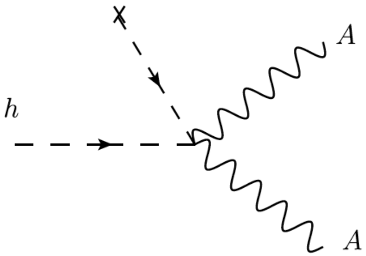
After SSB

Not only existing but also closely related!

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



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

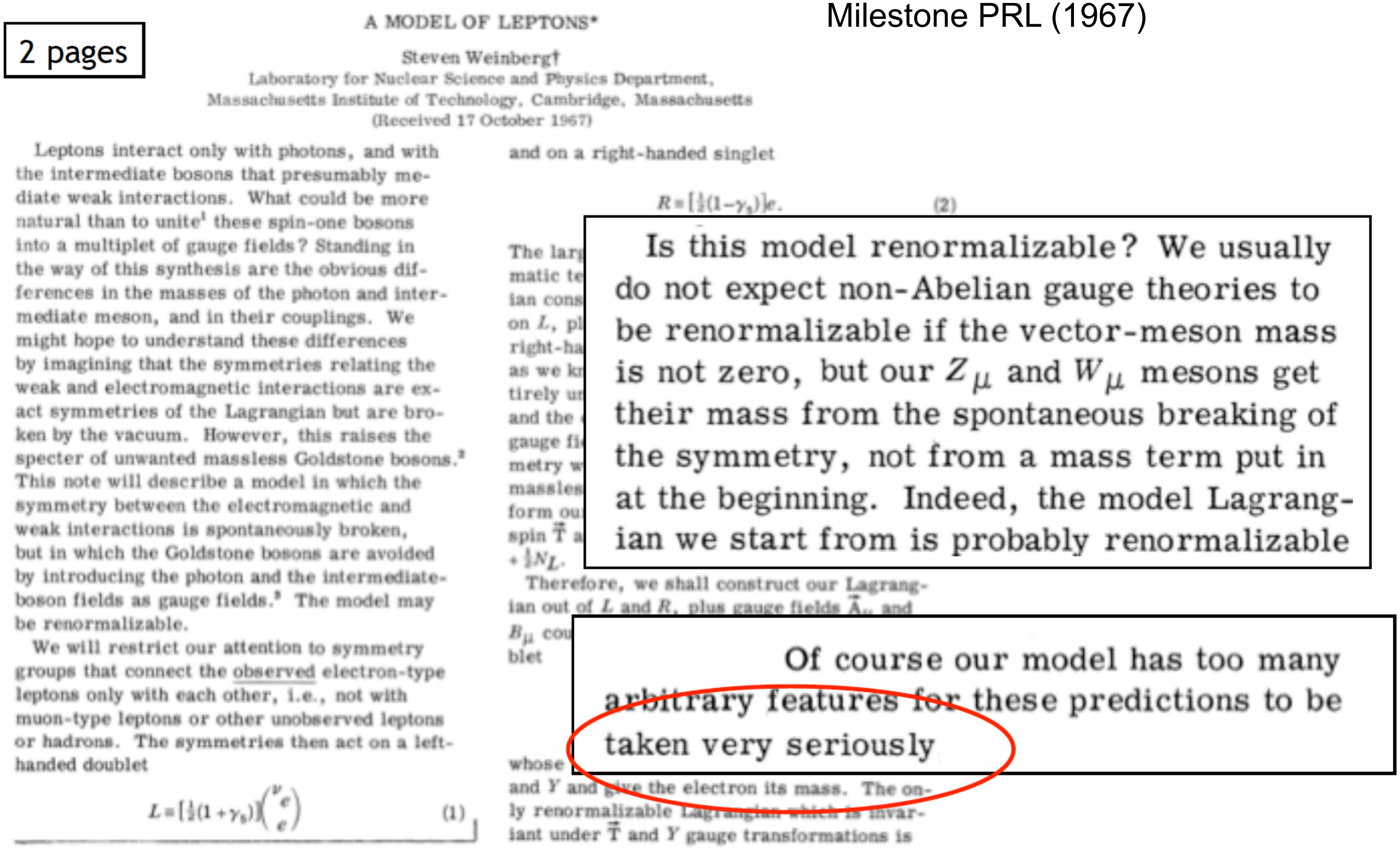


Proof of condensate !

The Glashow-Weinberg-Salam Model

Milestone PRL (1967)

2 pages



A MODEL OF LEPTONS*

Steven Weinberg†
Laboratory for Nuclear Science and Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts

(Received 17 October 1967)

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

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

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

and on a right-handed singlet

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

The larg
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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 $SU(2)_L x U(1)_Y$ 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 :

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

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)

Digression: Dynamical Symmetry Breaking

- In the massless quark approximation (valid for the lighter quark generations), $SU(2)_L x SU(2)_R$ is an (approximate) global symmetry of QCD.

- The chiral symmetry is broken dynamically by means of coherent states of quarks (analogous to the cooper pairs in the BCS theory for superconductivity).

$$SU(2)_L \times SU(2)_R \rightarrow SU(2)_V$$

  - Pseudo-goldstone bosons (approximately massless): $\pi^{\pm}$, π^0 (m~130 MeV)
  - Massive scalar: $f_0(500)$ or sigma (m~500 MeV)

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

Digression: Dynamical Symmetry Breaking

- Could the pions dynamically break the EW symmetry?

NO

  - They would disappear from the physical spectrum (become longitudinal components of the gauge bosons)
  - Insufficient mass generation (m_W~30 MeV) because the vev is too small (set for pion interactions).

- Technicolor-like models:
  - Generate correct gauge boson masses with a dynamical EWSB by fermion condensates (very appealing; recall theory of superconductivity).
  - Need:
    - Larger group describing a new strong interaction at the EW scale
    - Additional fermions

  - However, most simple models of technicolor are disfavored by EW precision data.

What about the fermions?

Another important consequence of the Weinberg Salam Model…

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

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

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

Fermion mass terms are forbidden

Not the case for Yukawa couplings to the Higgs doublet

Then after SSB one recovers :

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

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

Very important : The Higgs mechanism DOES NOT predict fermion masses

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

What about the fermions?

But wait…

The coupling to the Higgs fields is the following :

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

Can be seen as giving mass to down type fermions…

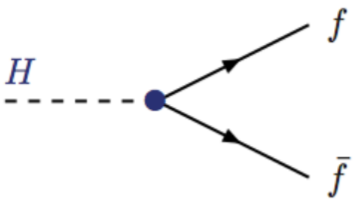
To give mass to up type fermions, need to use a slightly different coupling :

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

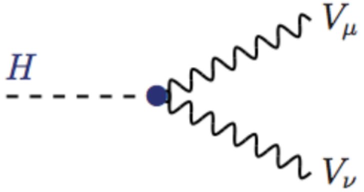
One doublet of complex scalar fields is sufficient to accommodate mass terms for gauge bosons and fermions !

... But not necessarily only one!

Higgs boson interactions

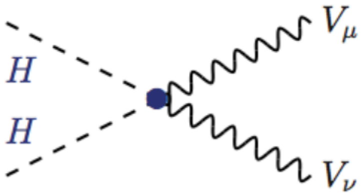


$$g_{Hff} = m_f/v$$



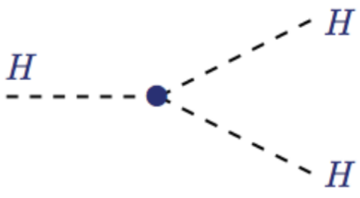
$$g_{HVV} = 2M_V^2/v$$

Proof of condensate !



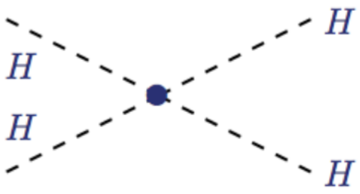
$$g_{HHVV} = 2M_V^2/v^2$$

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

1.- Two massive charged vector bosons :

Theory chosen to describe weak charged current interactions

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

Corresponding to the observed charged currents

Thus v = 246 GeV

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

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

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PREDICTED!

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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 :

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

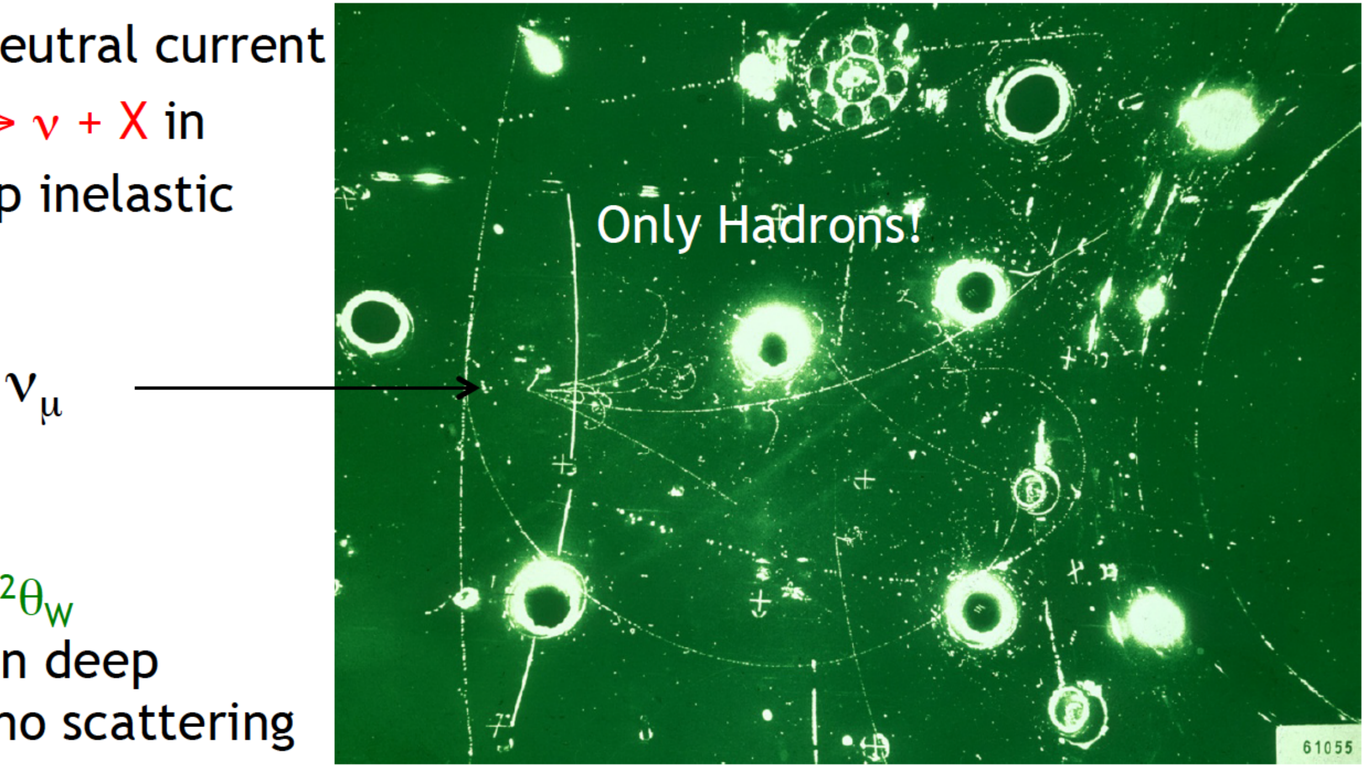
or

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

1973: Discovery of neutral weak currents

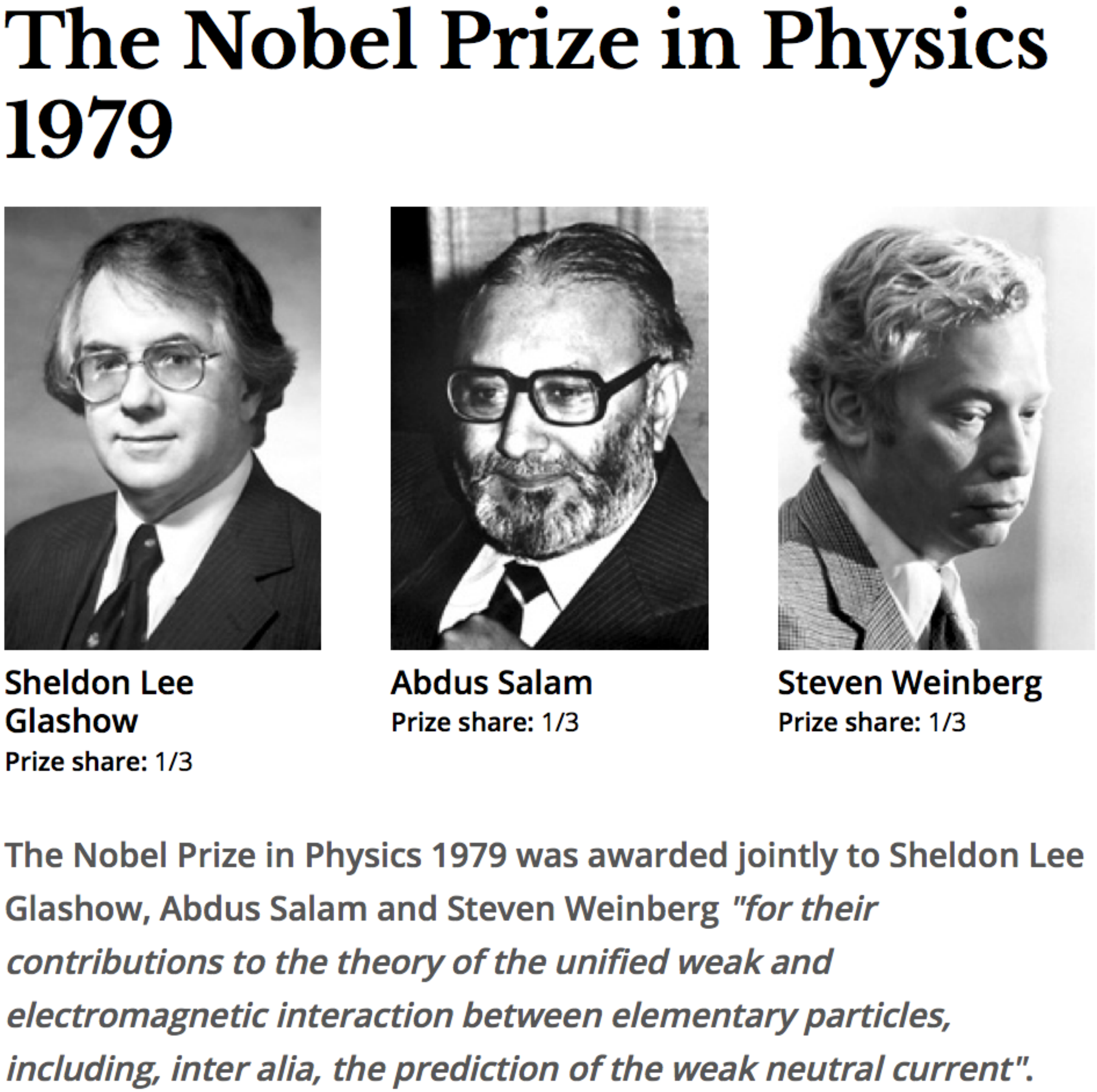
1973: neutral current discovery (Gargamelle experiment, CERN)

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

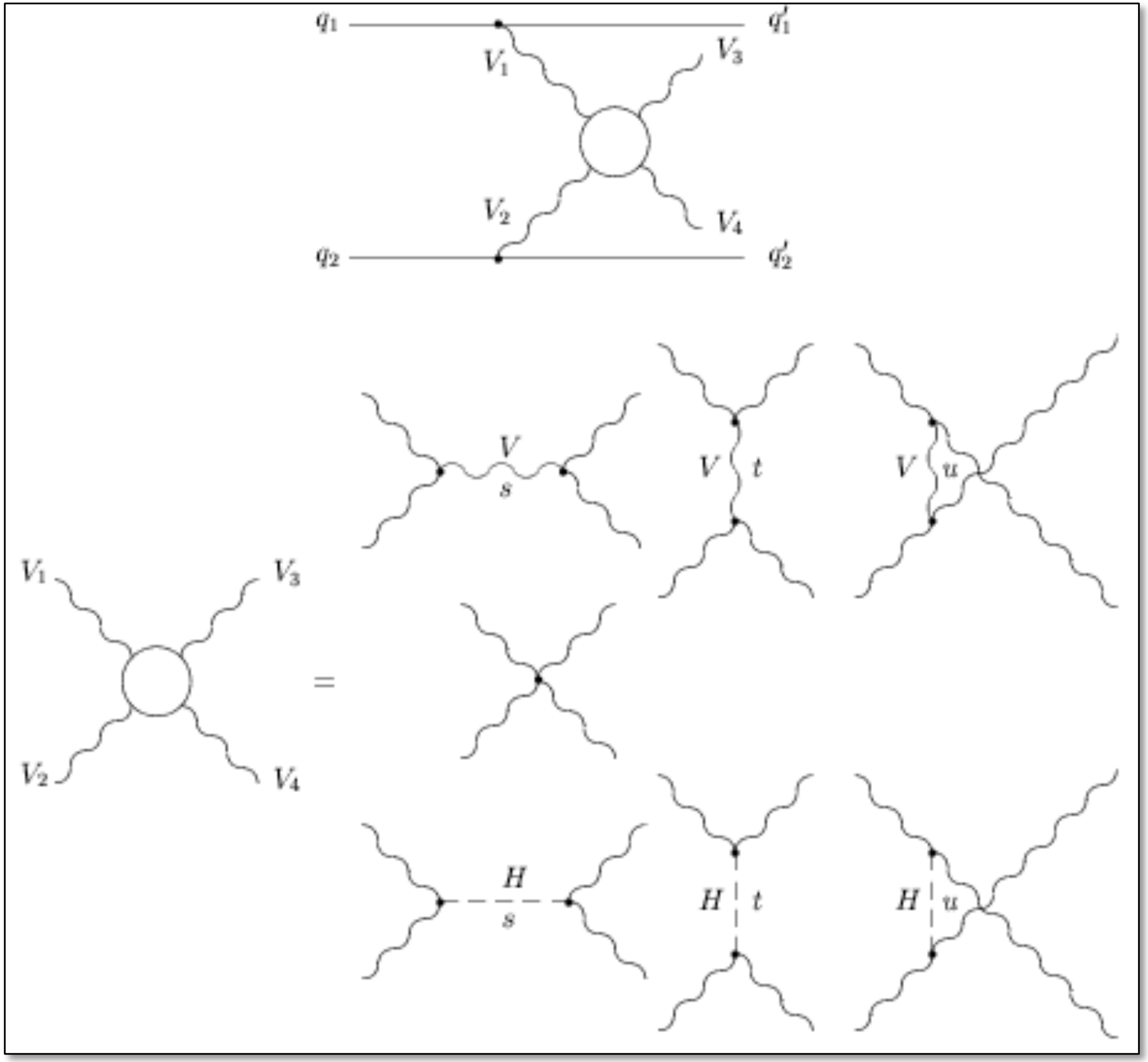
Sheldon Lee Glashow
Prize share: 1/3

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

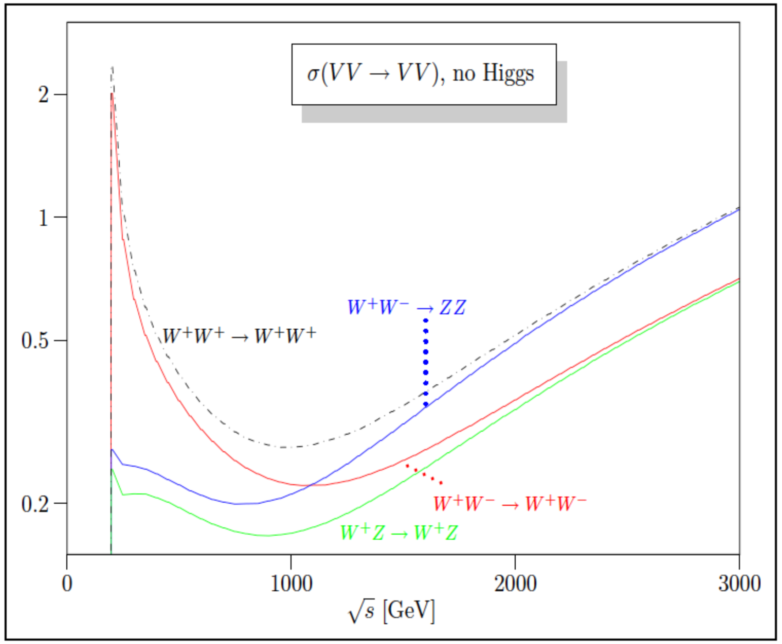
Quartic gauge couplings

Higgs-gauge boson couplings

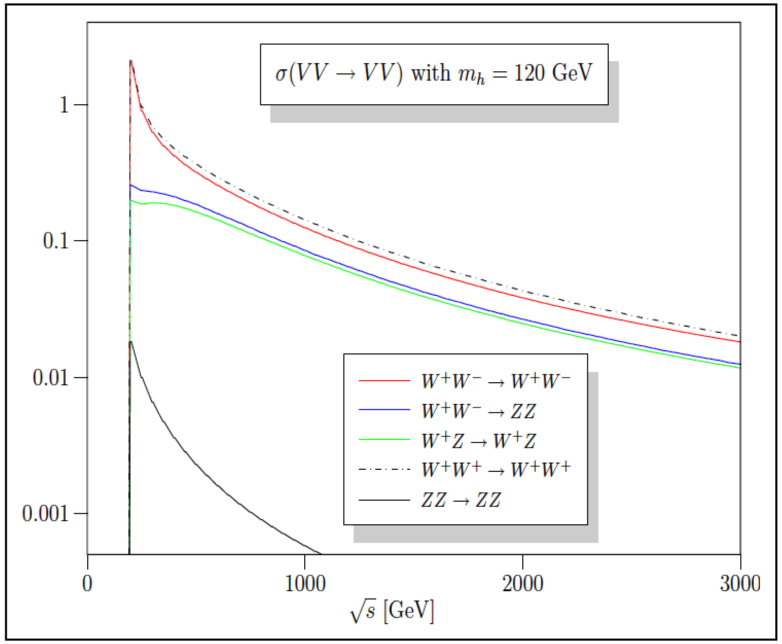
Vector boson scattering

- 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



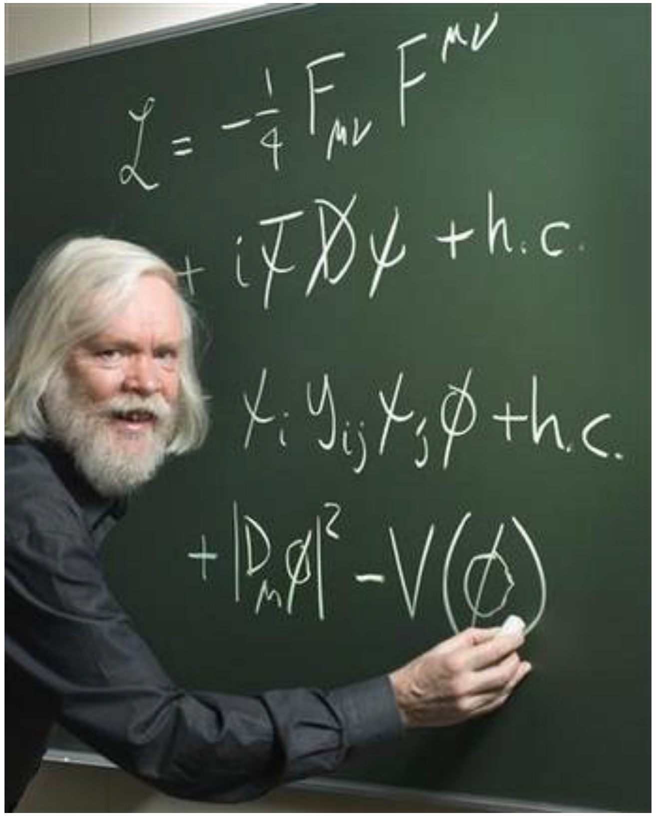
$$\sigma_{V_L V_L \to V_L V_L} \propto \left[-s - t - \frac{s^2}{s - m_{\mathrm{H}}^2} - \frac{t^2}{t - m_{\mathrm{H}}^2} \right]$$

Higgs boson contribution cancels increase at large √s

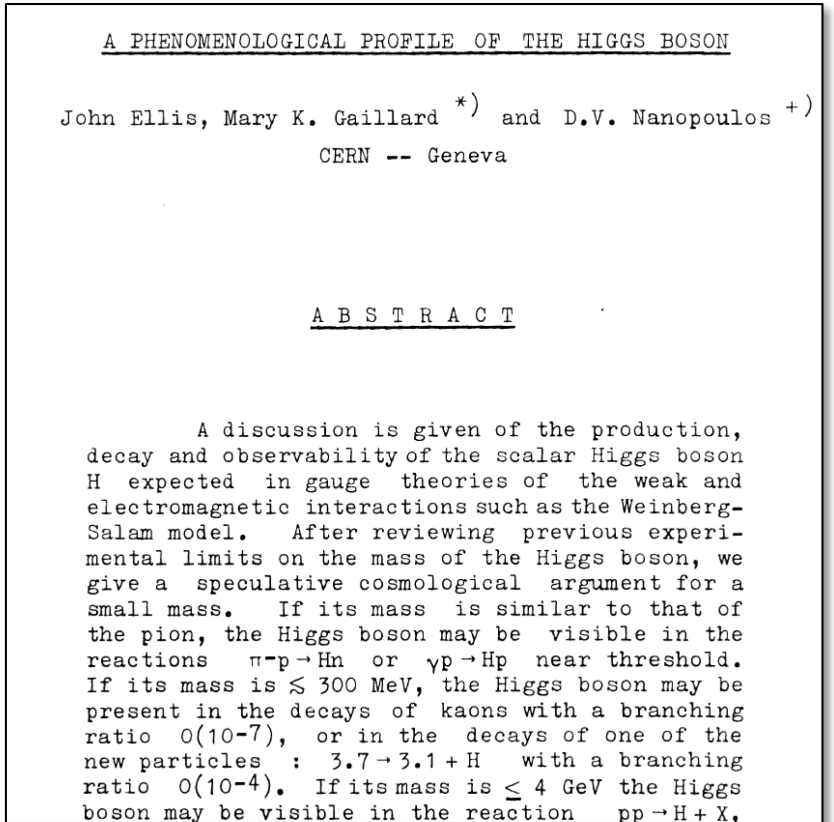
Not only a motivation for the Higgs mechanism but is also a strong constraint on its mass (if you believe in perturbative unitarity… otherwise, the weak force will become strong!)

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

1976: The birth of Higgs Physics



Nucl. Phys. B 106 (1976) 292



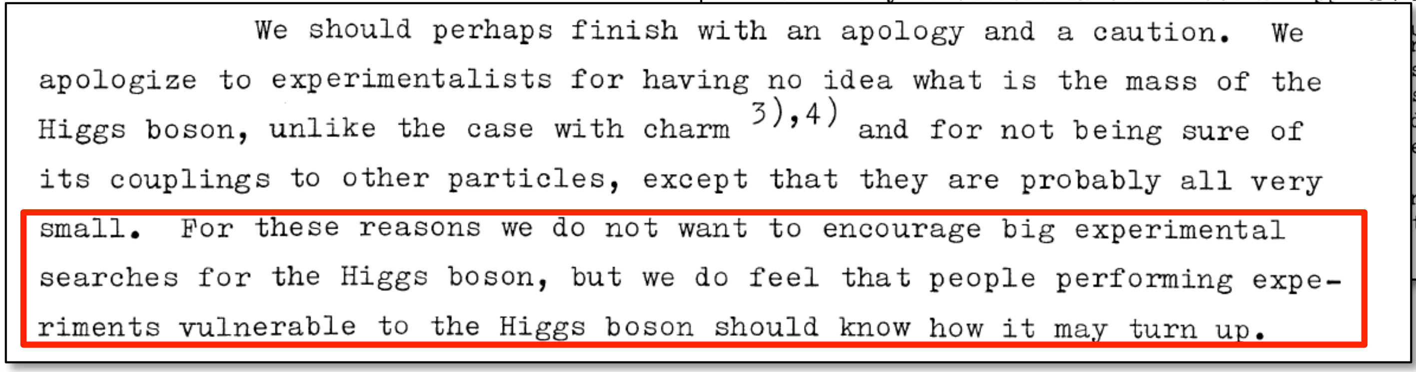
A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

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

CERN -- Geneva

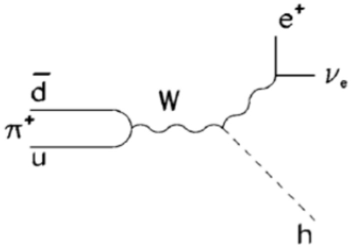
A B S T R A C T

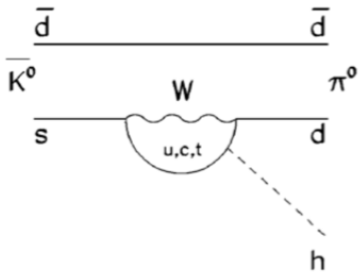
A discussion is given of the production, decay and observability of the scalar Higgs boson H expected in gauge theories of the weak and electromagnetic interactions such as the Weinberg-Salam model. After reviewing previous experimental limits on the mass of the Higgs boson, we give a speculative cosmological 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. If its mass is $\lesssim 300$ MeV, the Higgs boson may be present in the decays of kaons with a branching ratio $O(10^{-7})$, or in the decays of one of the new particles : $3.7 \to 3.1 + H$ with a branching ratio $O(10^{-4})$. If its mass is ≤ 4 GeV the Higgs boson may be visible in the reaction $pp \to H + X$,

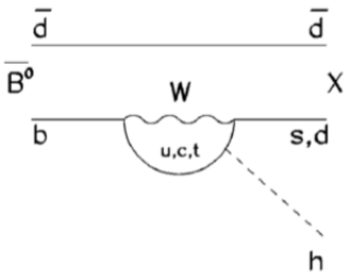


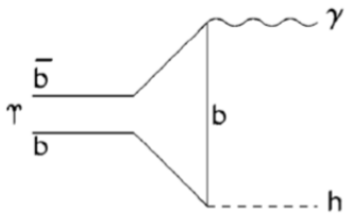
We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm 3),4) and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons 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







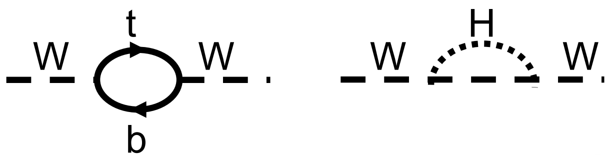


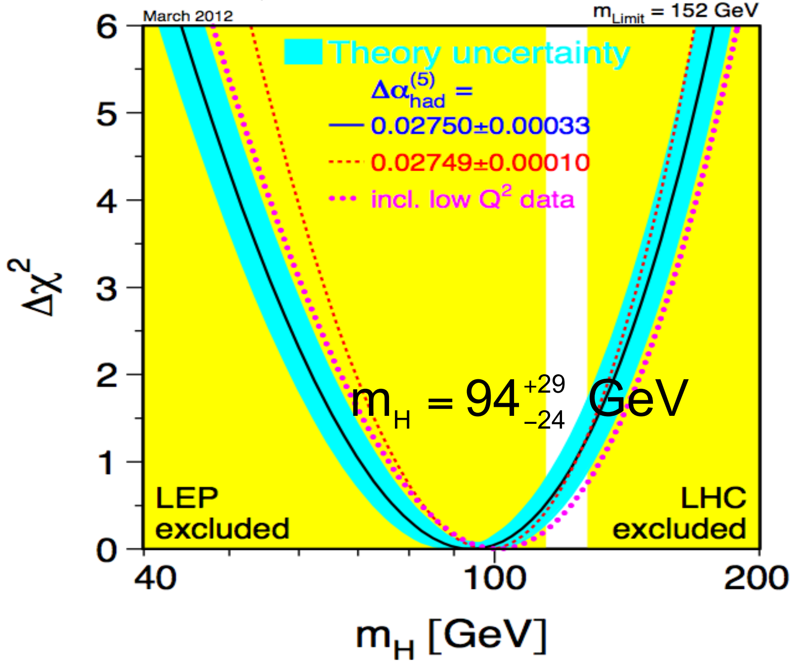
- SINDRUM Collaboration measured π to eν H (ee) Yielding a limit on very light Higgs
- CUSB Collaboration Υ to Hγ yielding limit of ~ 5-6 GeV (dependent on high order corrections)
- Jade and CLEO provided bounds on B to μμ+X
- CERN-Edimbrgh-Orsay-Mainz-Pisa-Siegen K to π H (ee) below ~50 MeV
- Electron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

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

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

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

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

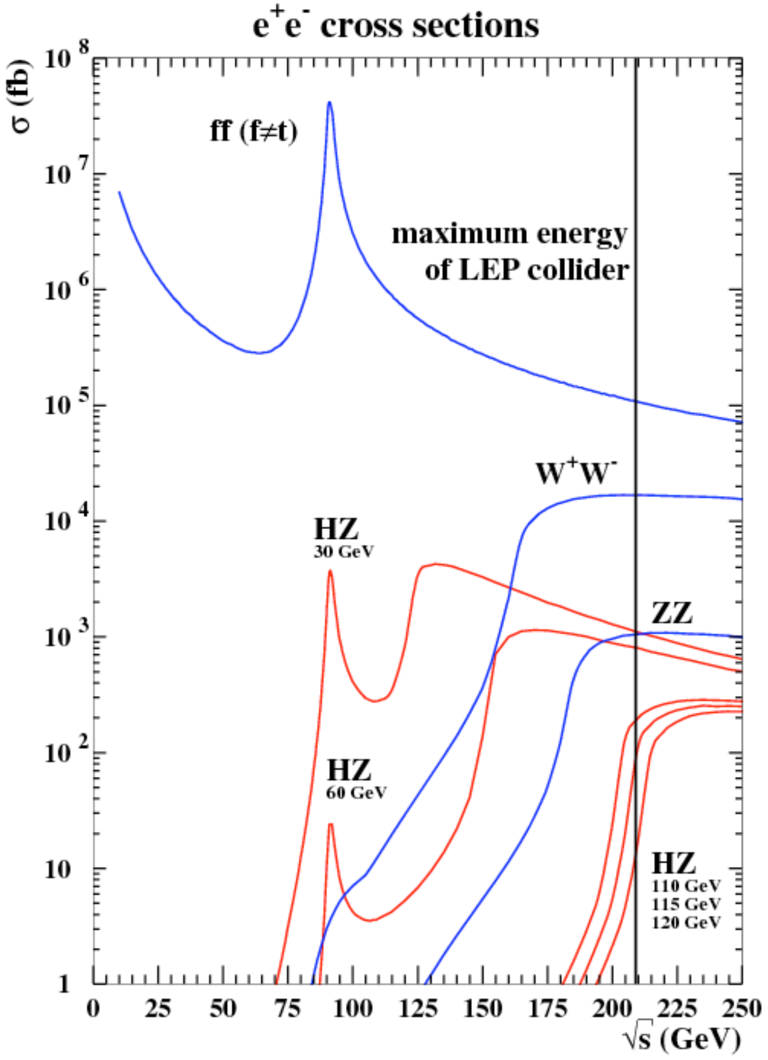
α= 1/137.035999679(94) (quantum hall effect)

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)

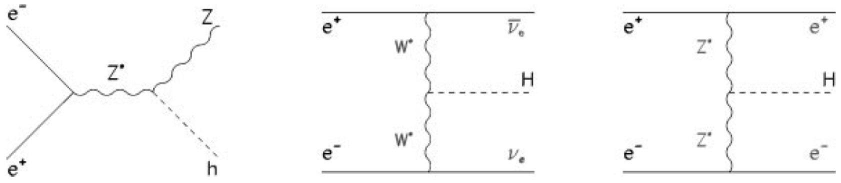
Stalking the Higgs Boson

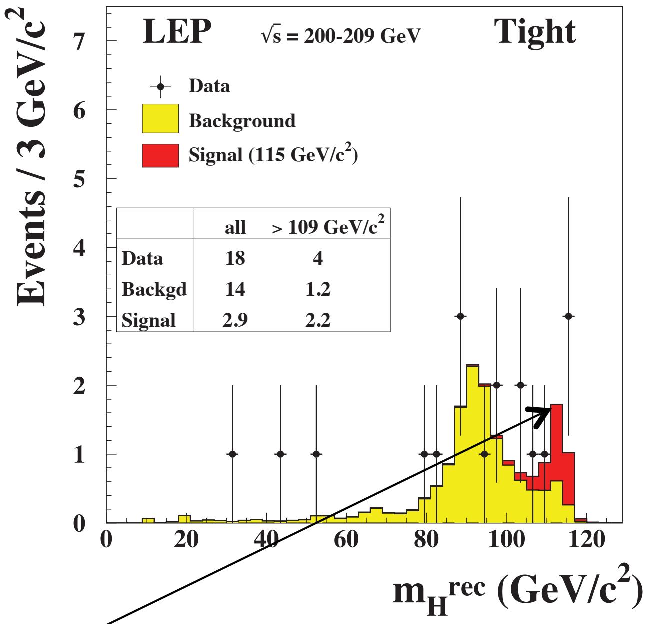


- Some hints (~1.7σ) of a SM-like Higgs boson with m_H~115 GeV. We know now it was just a statistical fluctuation.

Direct searches at LEP (1989-2000)

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





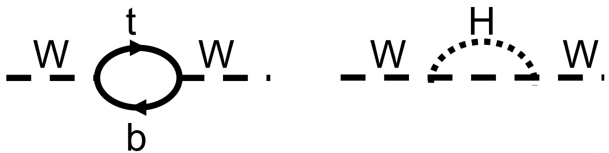
	all	> 109 GeV/c²
Data	18	4
Backgd	14	1.2
Signal	2.9	2.2

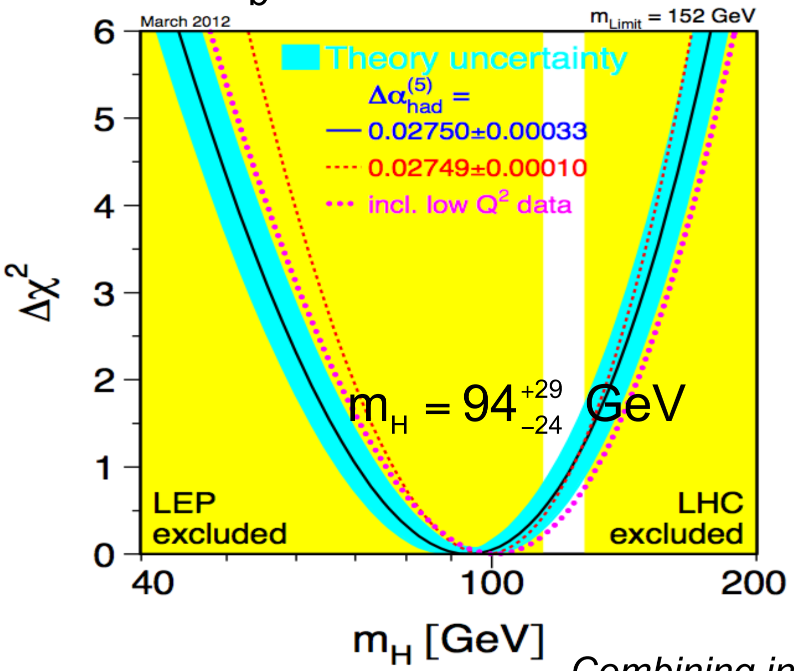
m_H> 114.4 GeV (95% CL)

Stalking the Higgs Boson

Indirect constraints

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





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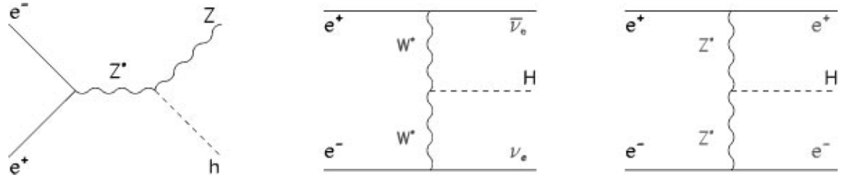

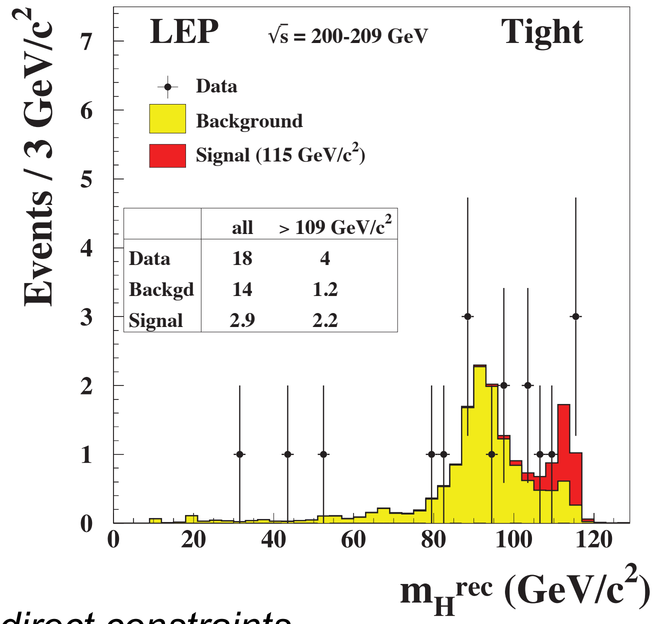

	all	> 109 GeV/c²
Data	18	4
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Signal	2.9	2.2

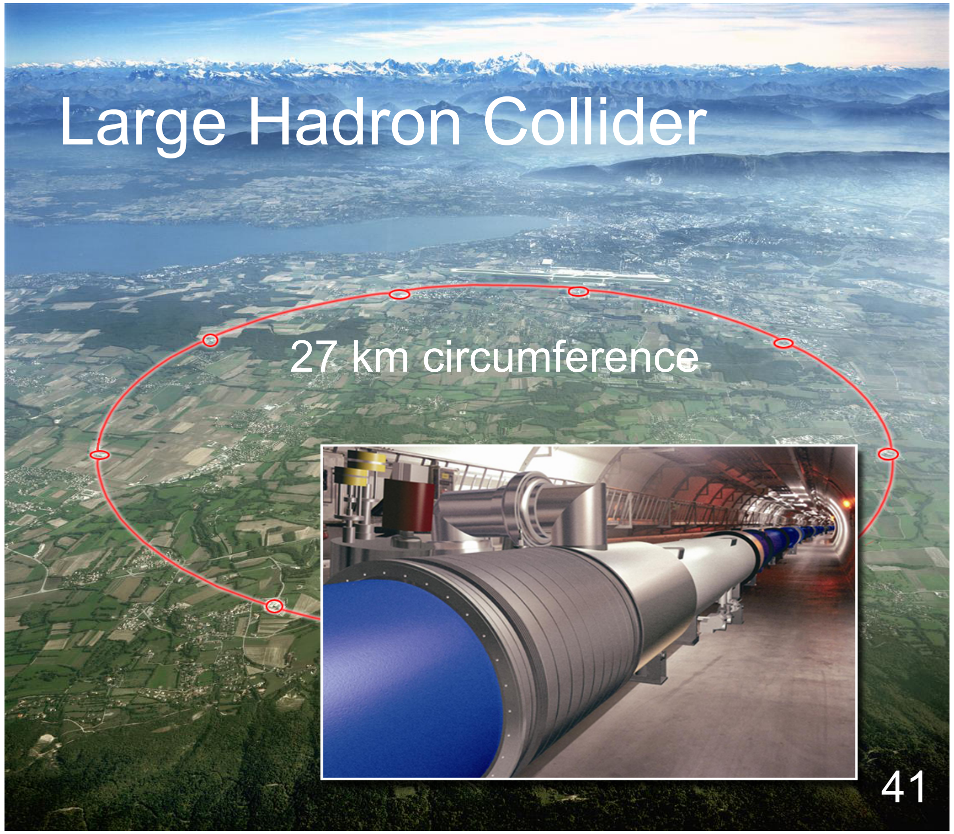
Combining indirect and direct constraints

m_H< 152 GeV (95% CL) m_H> 114.4 GeV (95% CL)

114.4 < m_H< 171 GeV (95% CL)

The hadron collider era

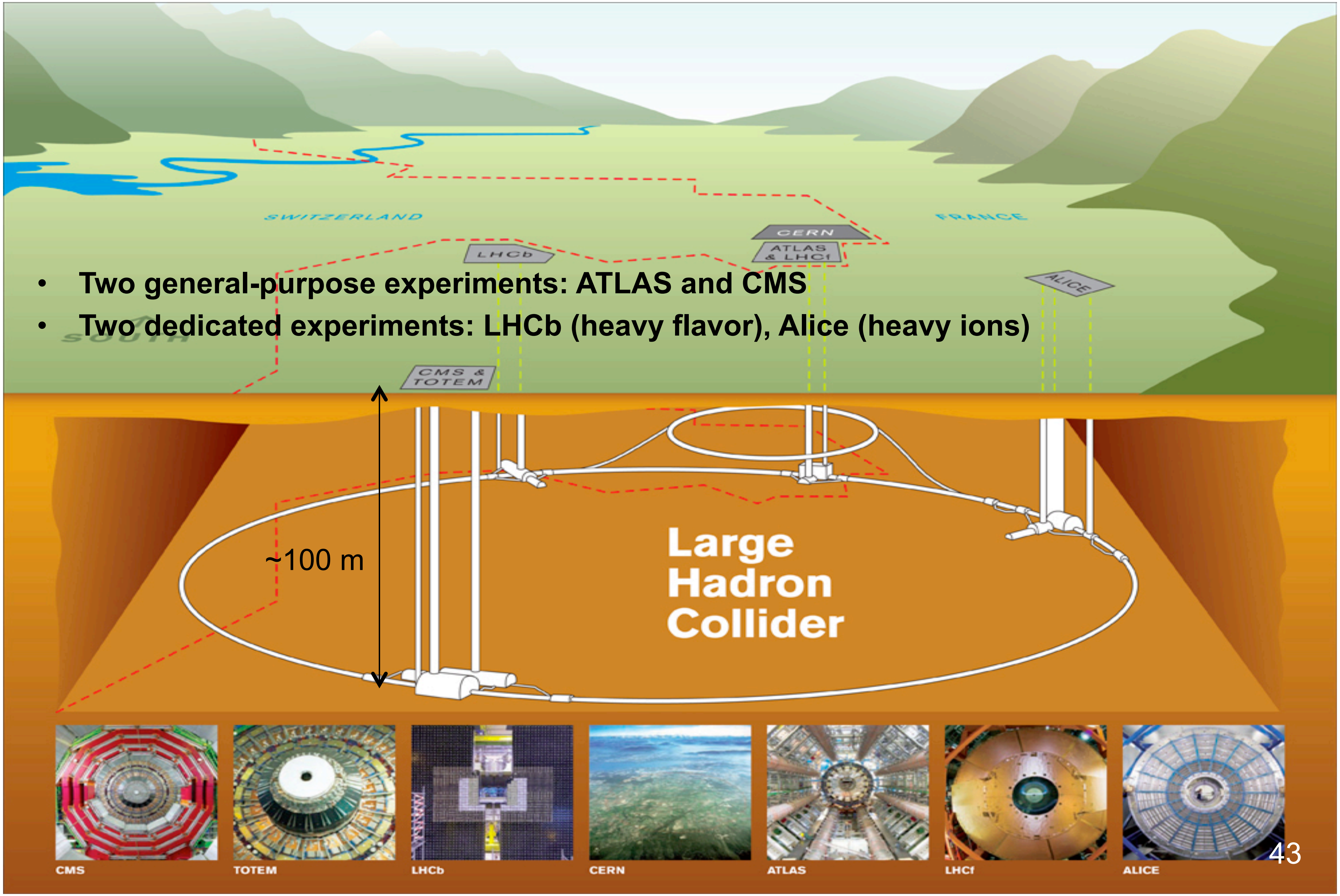
- SppS̄ Collider @ CERN: 1981-1984
  - pp̄ collisions at √s=400 GeV
- Tevatron Collider @ Fermilab:
  - pp̄ collisions at √s=1.8 TeV (Run 1: 1992-1996) and √s=1.96 TeV (Run 2: 2001-2011).
- Large Hadron Collider (LHC) @ CERN:
  - pp collisions up to √s=14 TeV. Construction approved in 1994.



Large Hadron Collider

- Located at CERN, near Geneva (across France-Switzerland border)
- 27 km circumference, located in the old LEP tunnel
- 1232 high-tech superconducting dipole magnets at 1.8 K
- Proton-proton collisions at 7 TeV (2010-2011), 8 TeV (2012), 13/14 TeV (≥2015)
  - 10^{11} protons against 10^{11} protons every 25 ns
  - 600 million beam crossings per second!

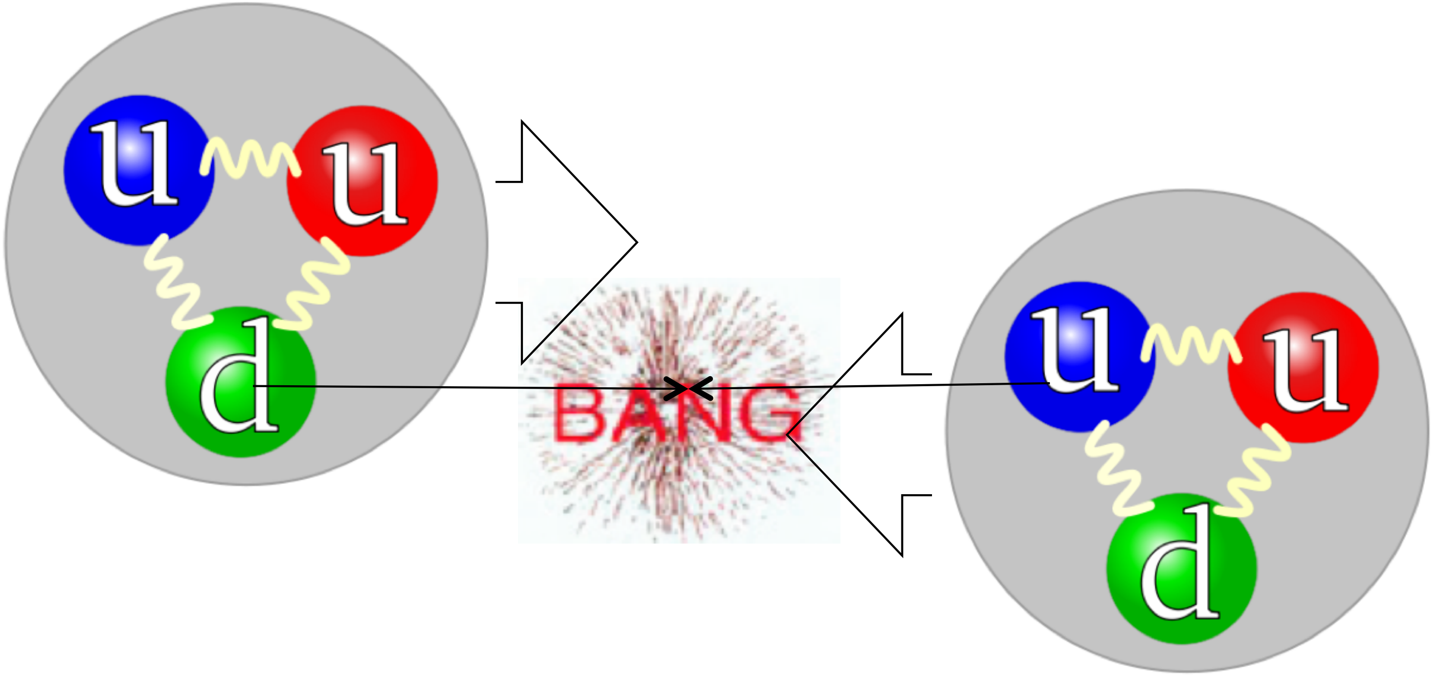
Large Hadron Collider



- **Two general-purpose experiments: ATLAS and CMS**
- **Two dedicated experiments: LHCb (heavy flavor), Alice (heavy ions)**

Hadron colliders as discovery machines

- Hadron colliders offer a “brute-force” approach to searches for New Physics:
  - Pro: Can reach higher energies in a cheaper way than lepton colliders.
  - Con: The proton has internal structure so only a fraction of proton energy is available for collision of its elementary constituents.



- “Doesn’t sound so bad…”
  - “Well, it’s a bit more complicated….”

Hadron colliders as discovery machines

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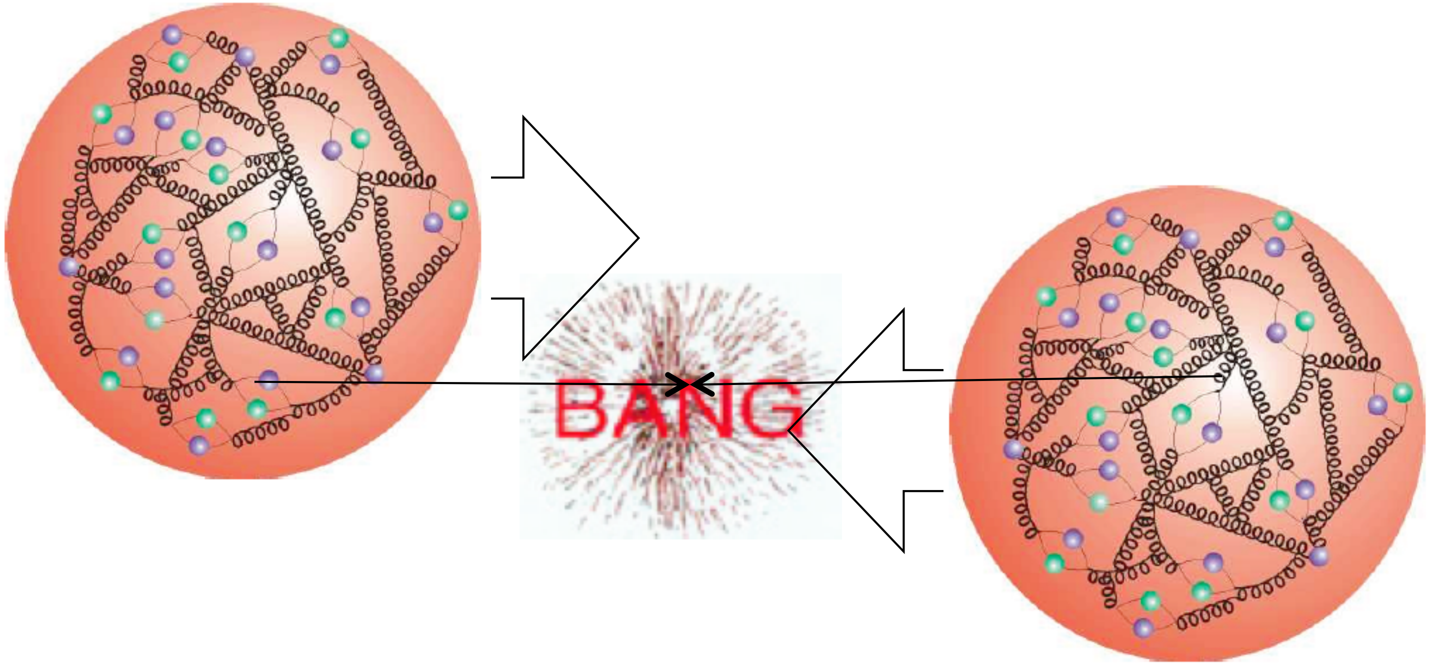

  - The proton is made up of the valence quarks (uud) but also a sea of quarks/antiquarks and gluons that come in and out of existence due to quantum fluctuations and which participate in the collision.
  - And everything is connected by the strong interaction, so it gets messy…

Hadron colliders as discovery machines

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  - Pro: Can reach higher energies in a cheaper way than lepton colliders.
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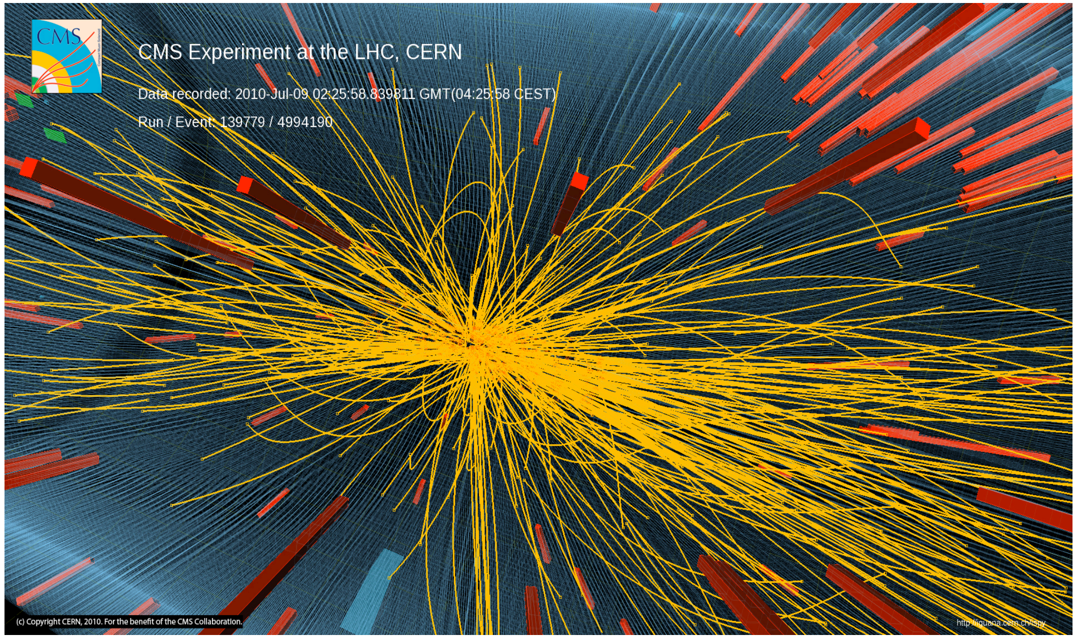
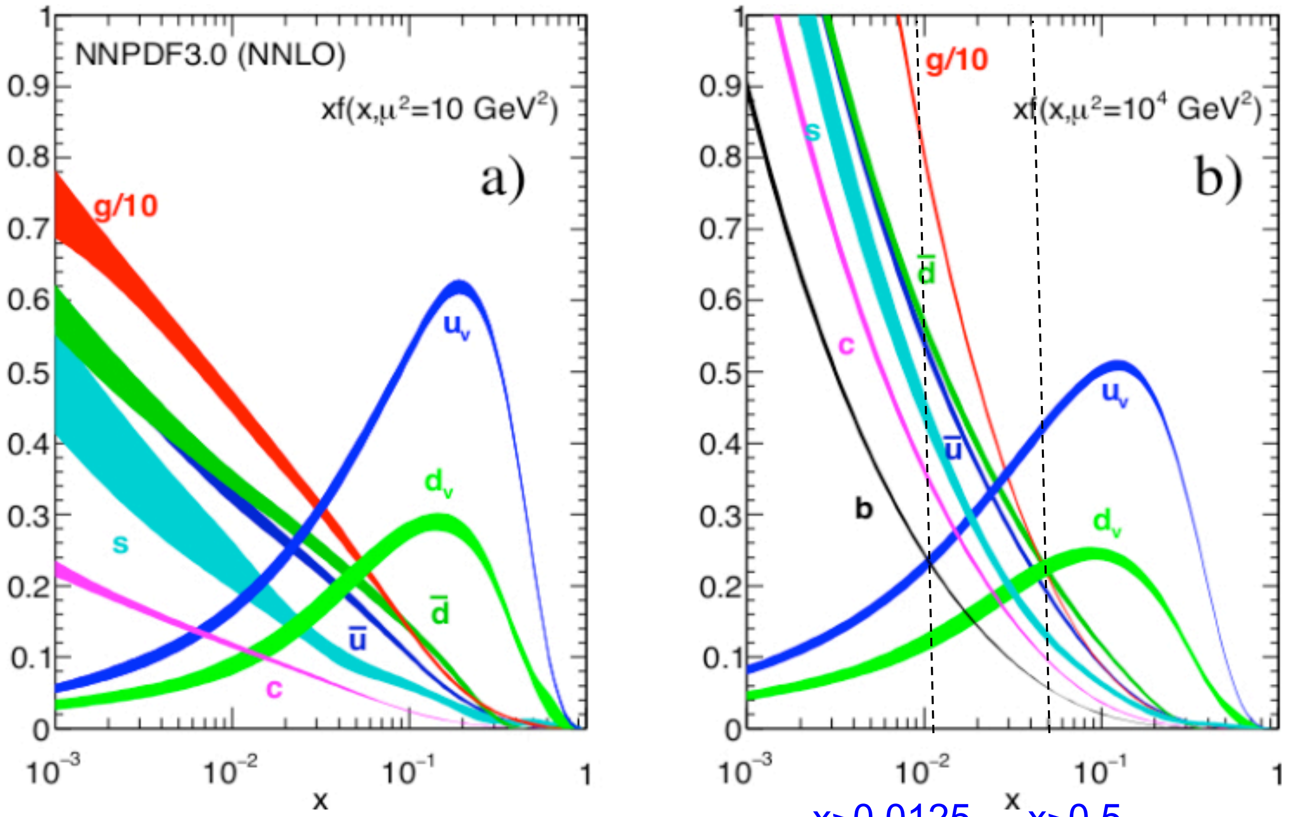


- Con: Much more complicated final state to study than at lepton colliders.

Hadron colliders as discovery machines

- Hadron colliders offer a “brute-force” approach to searches for New Physics:



x≥0.0125
LHC 8 TeV

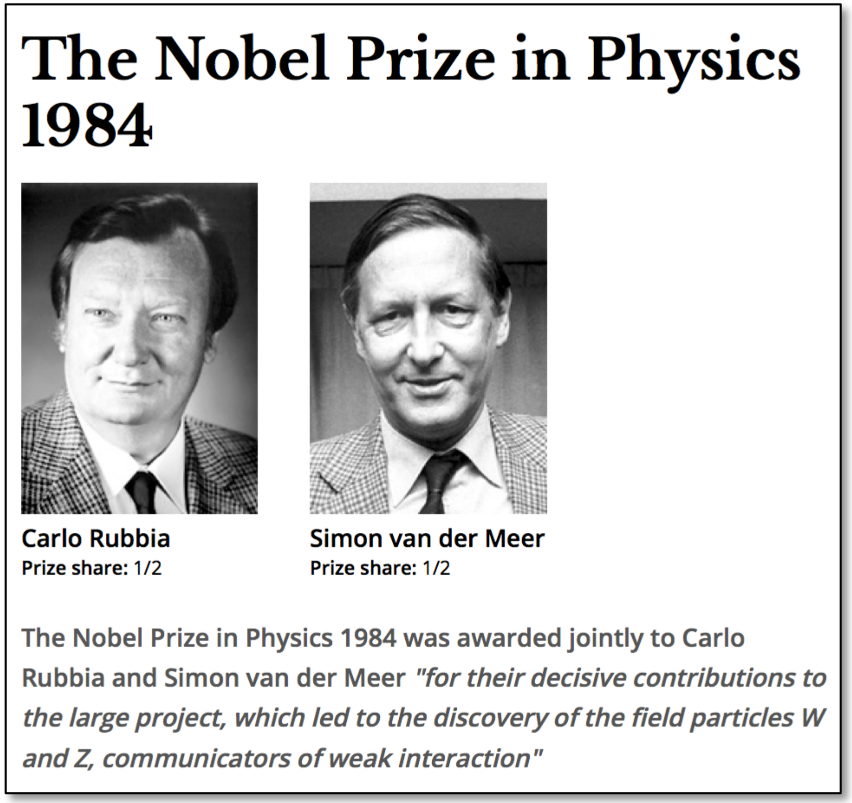
x≥0.5
Tevatron 2 TeV

- Pro: Have a broad spectrum of collision energies and colliding particles ($u\bar{u}$, $u\bar{d}$, ug, gg, $b\bar{b}$,….) which change event-by-event in an “uncontrolled way”, but with well-understood probabilities to occur.

Hadron colliders as discovery machines

Very successful!

- Sp$\bar{p}$S Collider @ CERN: 1981-1984
  - 1983: Discovery of the W and Z bosons
- Tevatron Collider @ Fermilab: 1992-2011
  - 1995: Discovery of the top quark
- Large Hadron Collider (LHC) @ CERN: 2010-
  - 2012: Discovery of the Higgs boson
  - ?



The Nobel Prize in Physics 1984

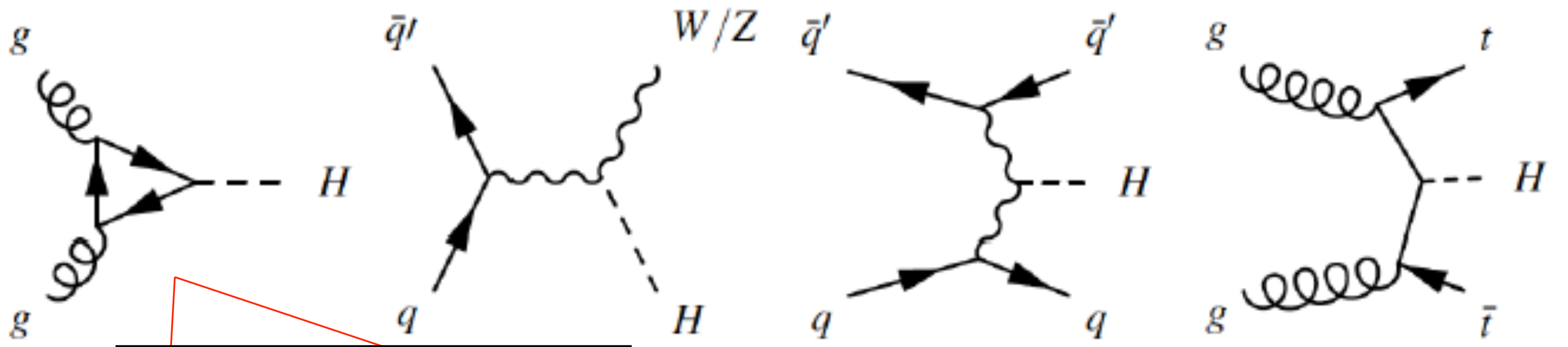
Carlo Rubbia
Prize share: 1/2

Simon van der Meer
Prize share: 1/2

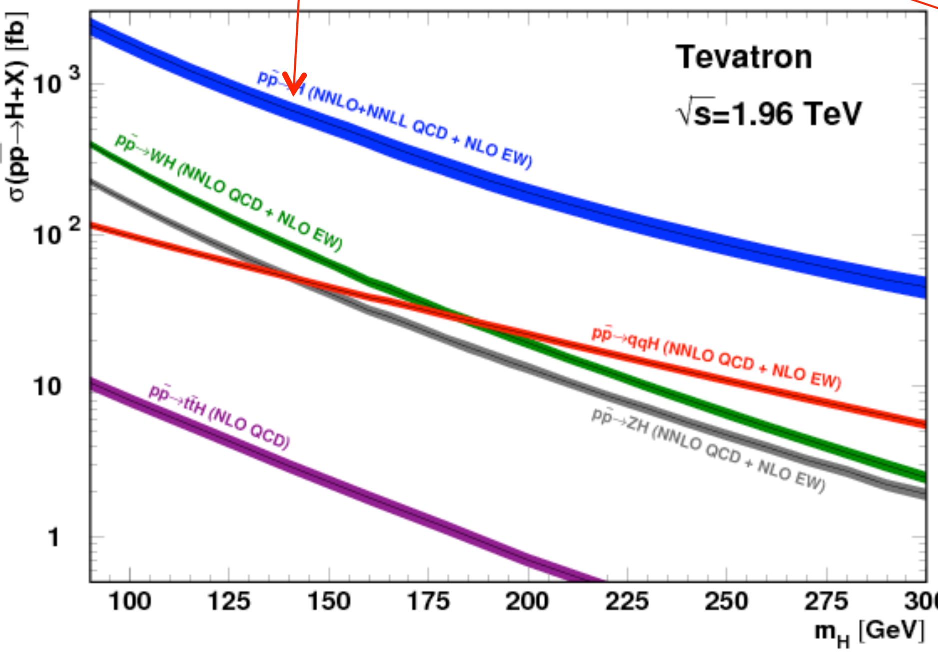
The Nobel Prize in Physics 1984 was awarded jointly to Carlo Rubbia and Simon van der Meer *"for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction"*

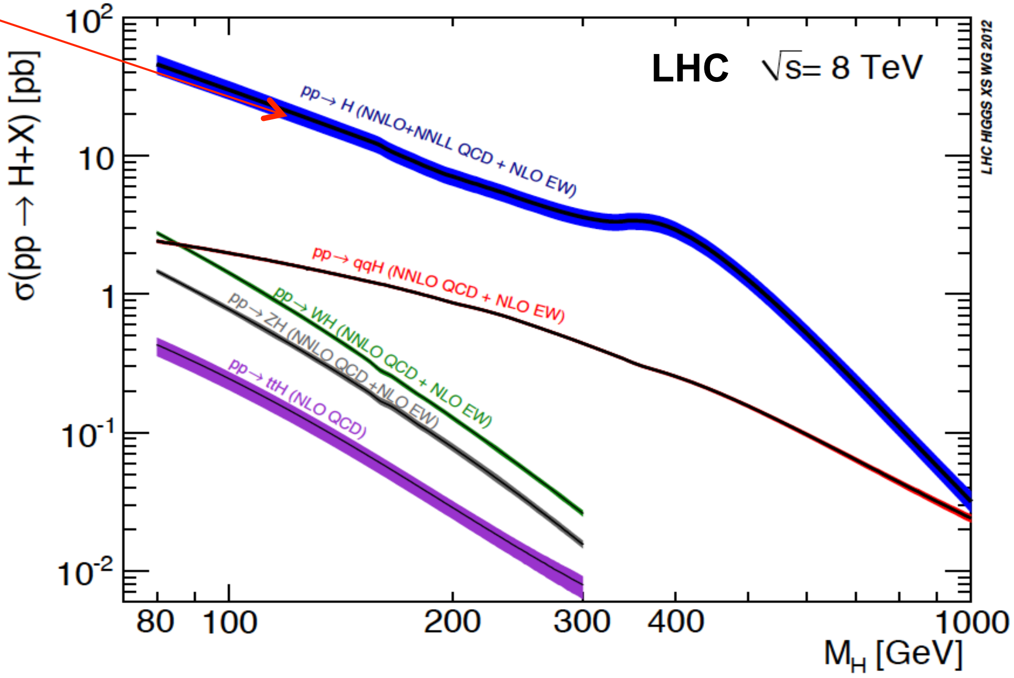
March 2nd,1995: First announcement of top quark discovery in a public seminar at Fermilab

SM Higgs production at hadron colliders

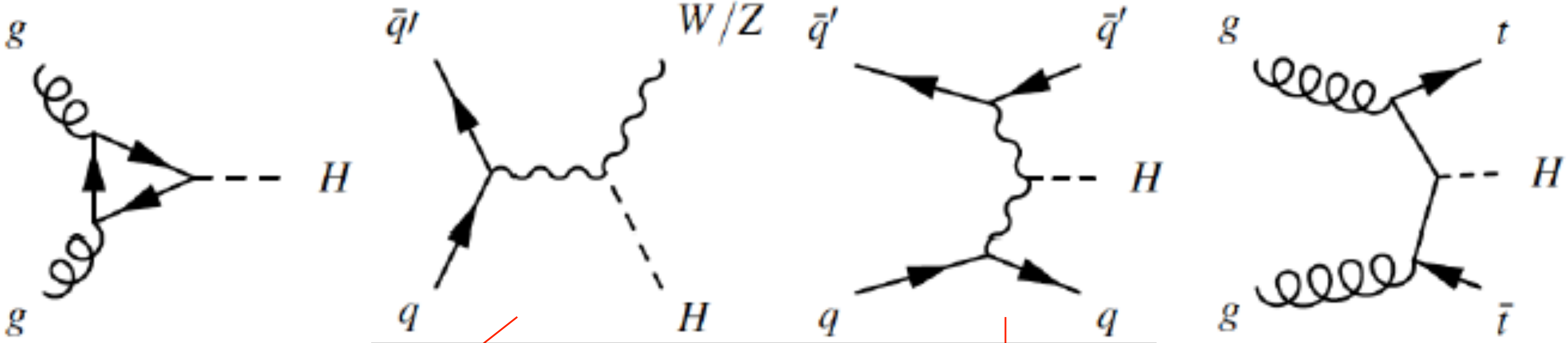


Main production mechanism

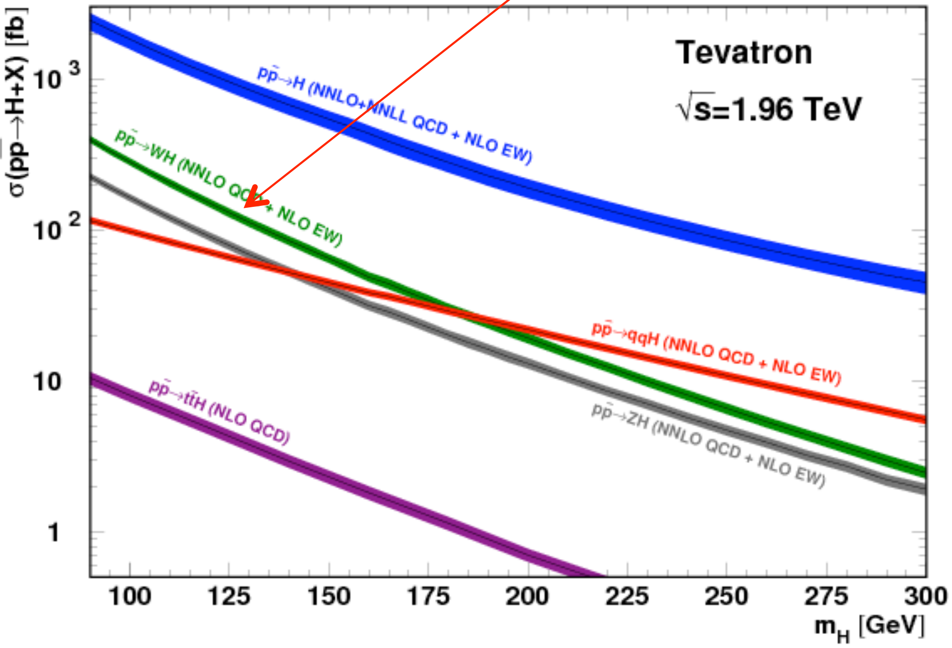


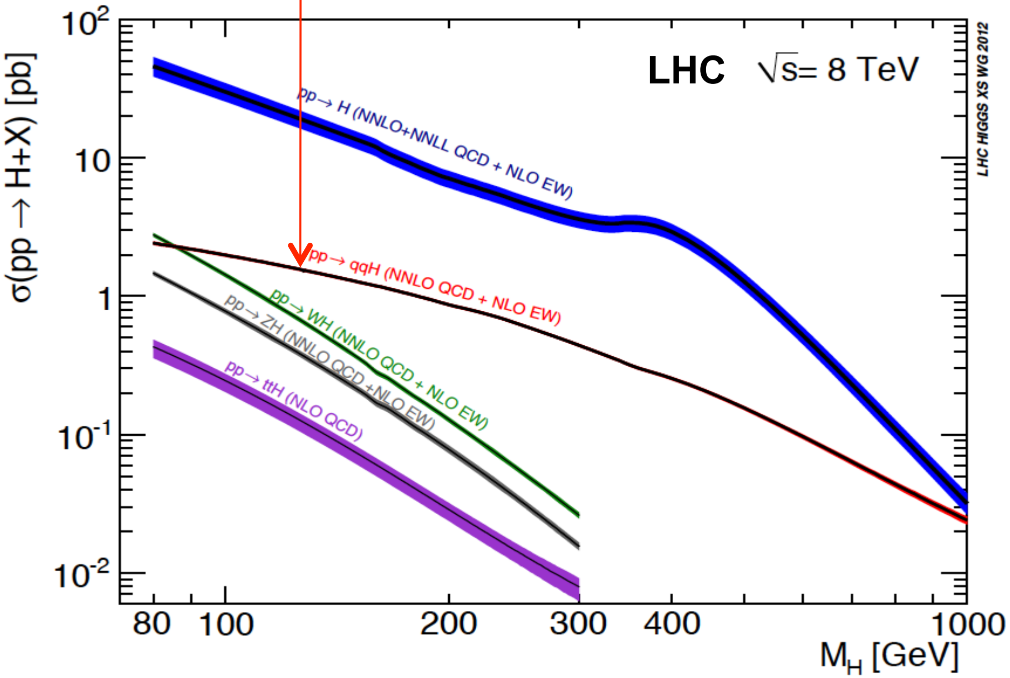


SM Higgs production at hadron colliders

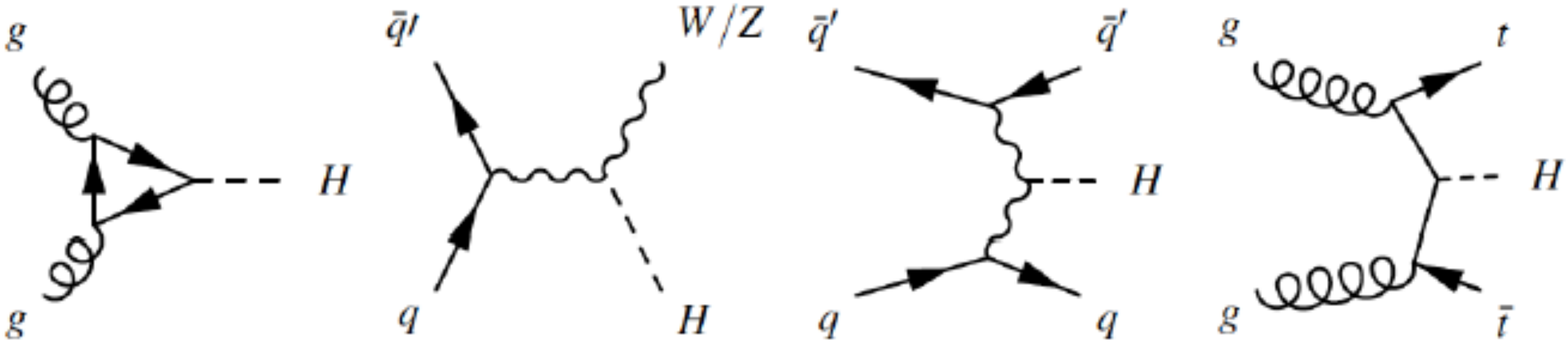


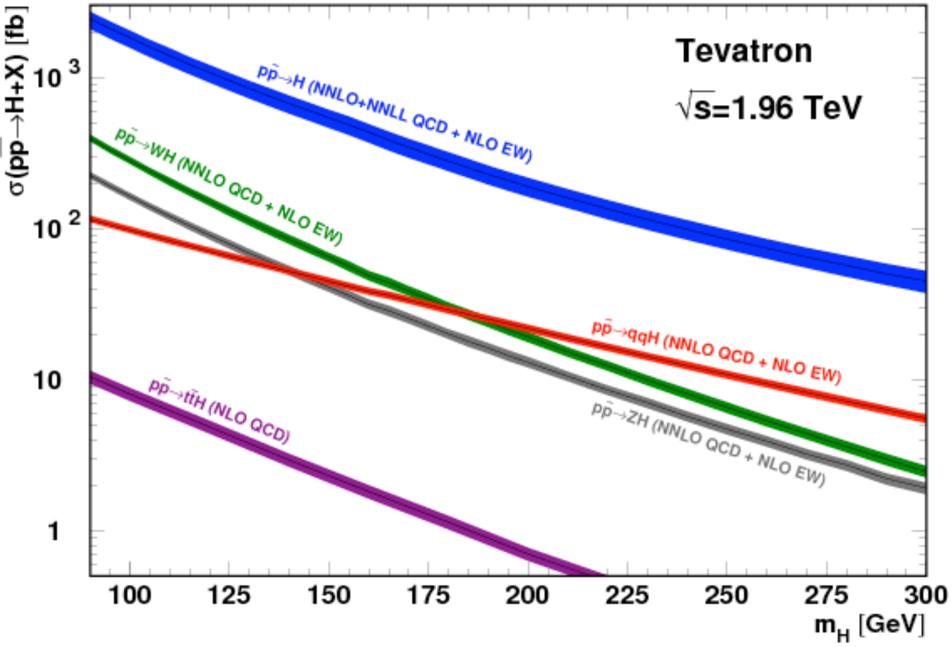
Next most important production mechanism





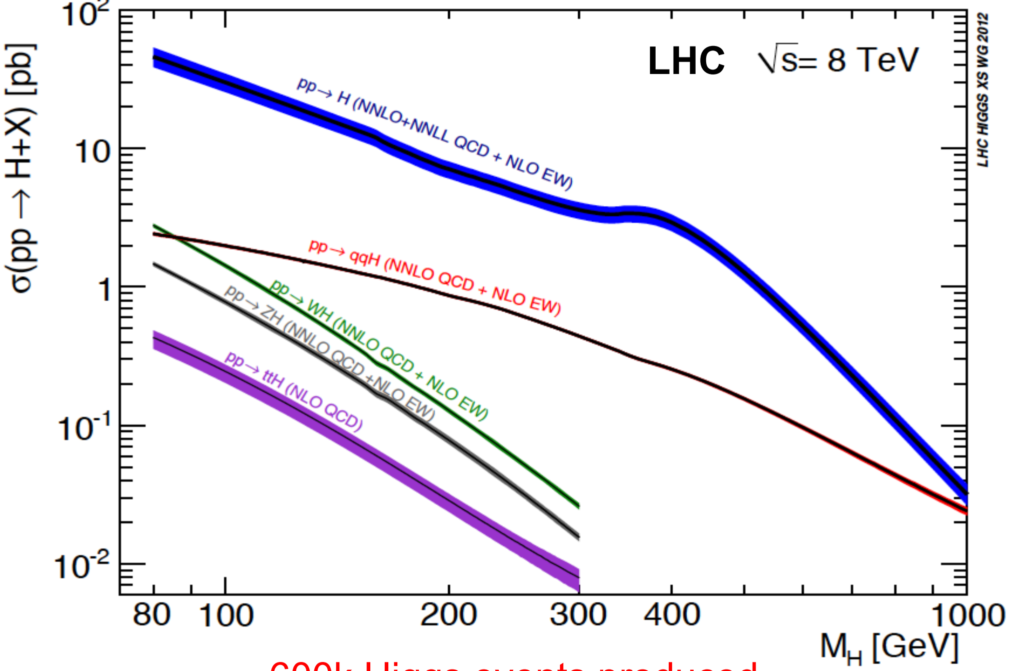
SM Higgs production at hadron colliders





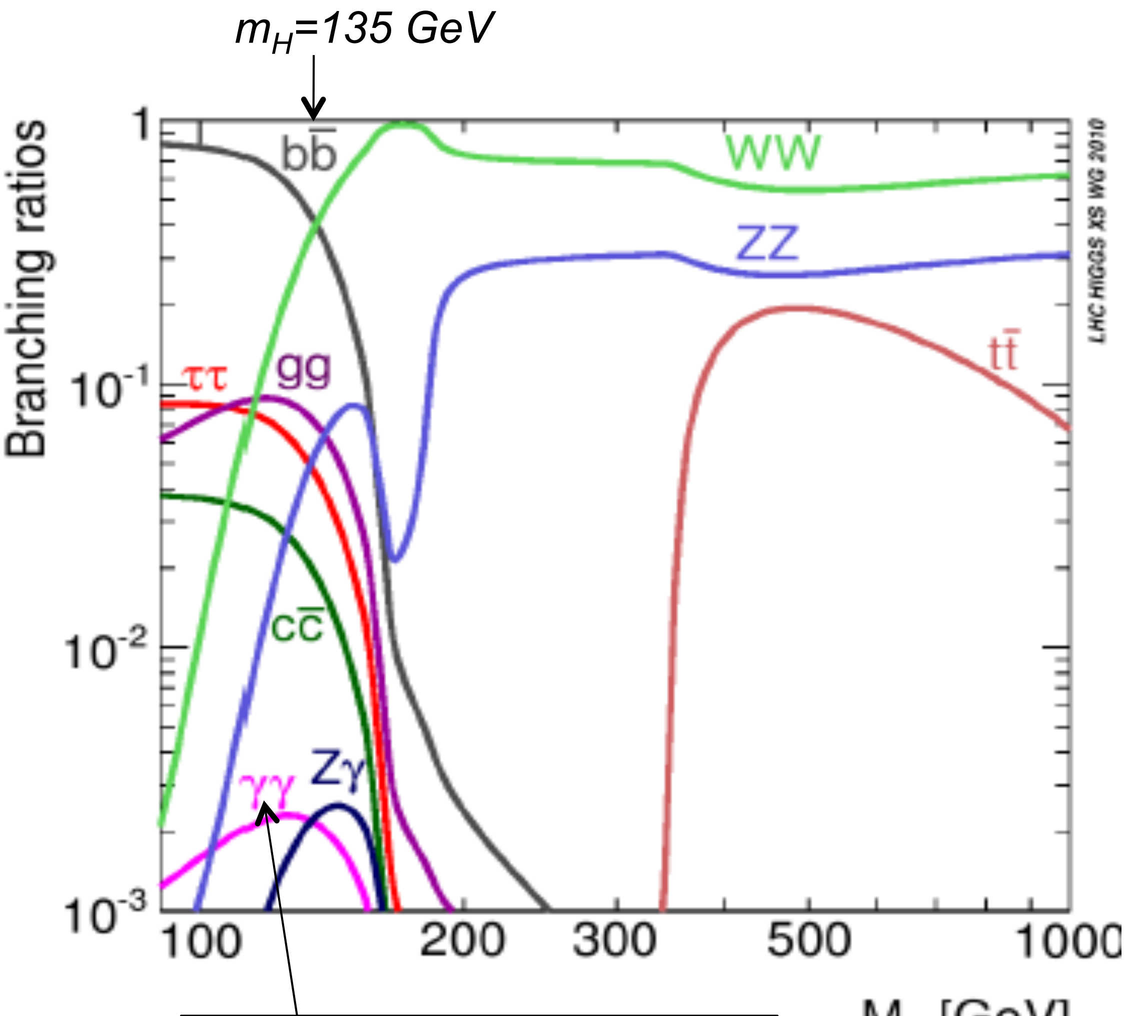
~20k Higgs events produced at CDF+D0 in the whole Run 2

A true Higgs factory!



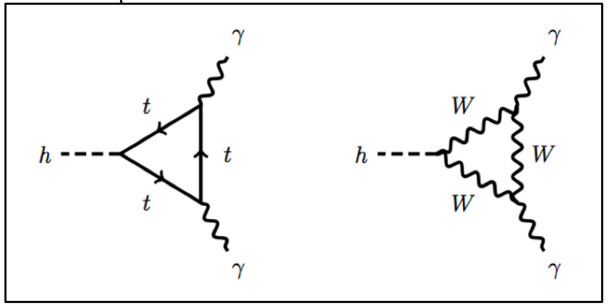
~600k Higgs events produced at each experiment in 2012!

SM Higgs decay modes



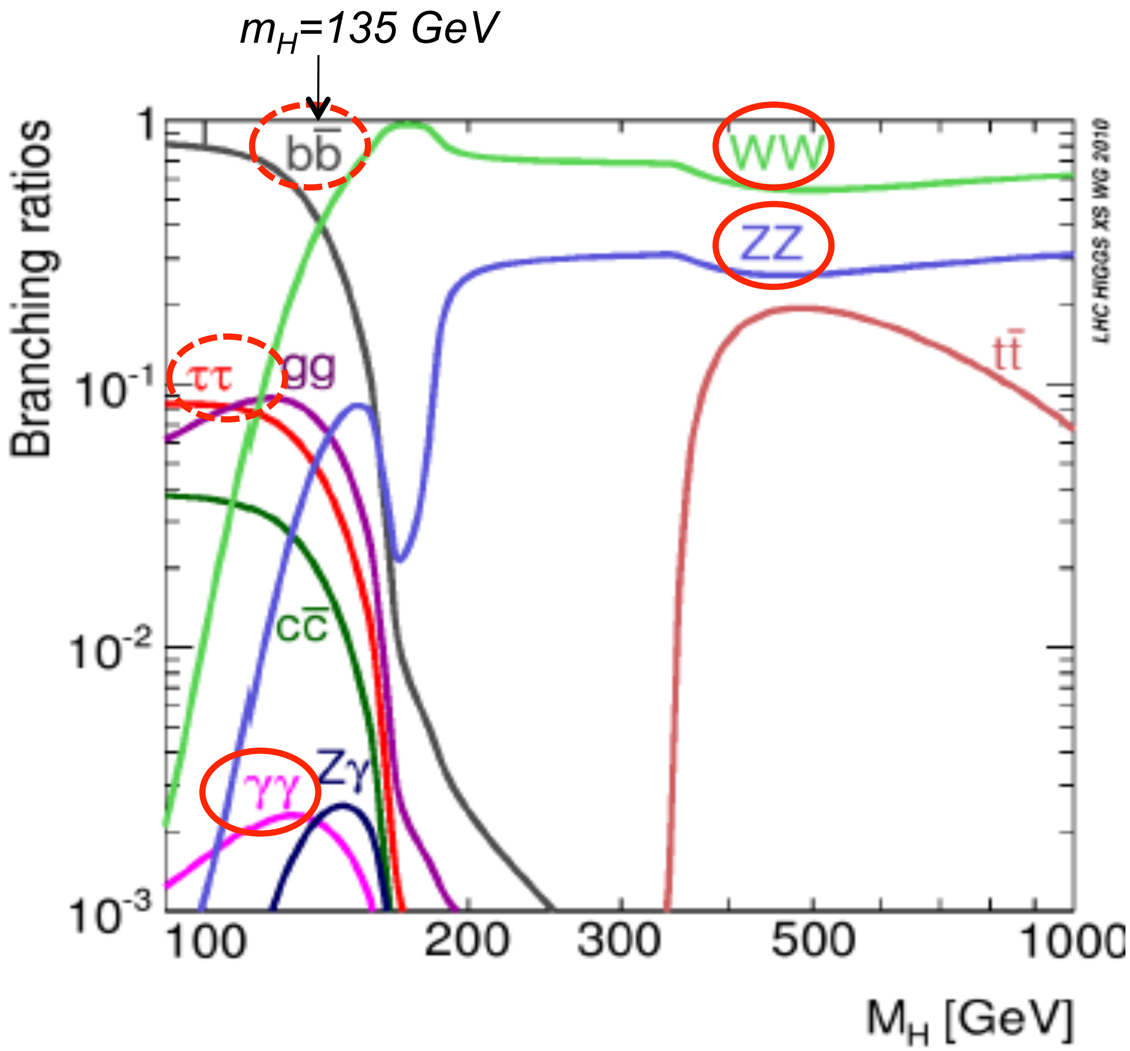
m_H<135 GeV: H→bb dominates

m_H>135 GeV: H→WW dominates



Via quantum fluctuations!
Very sensitive to New Physics!

SM Higgs decay modes



m_H<135 GeV: H→bb dominates

m_H>135 GeV: H→WW dominates

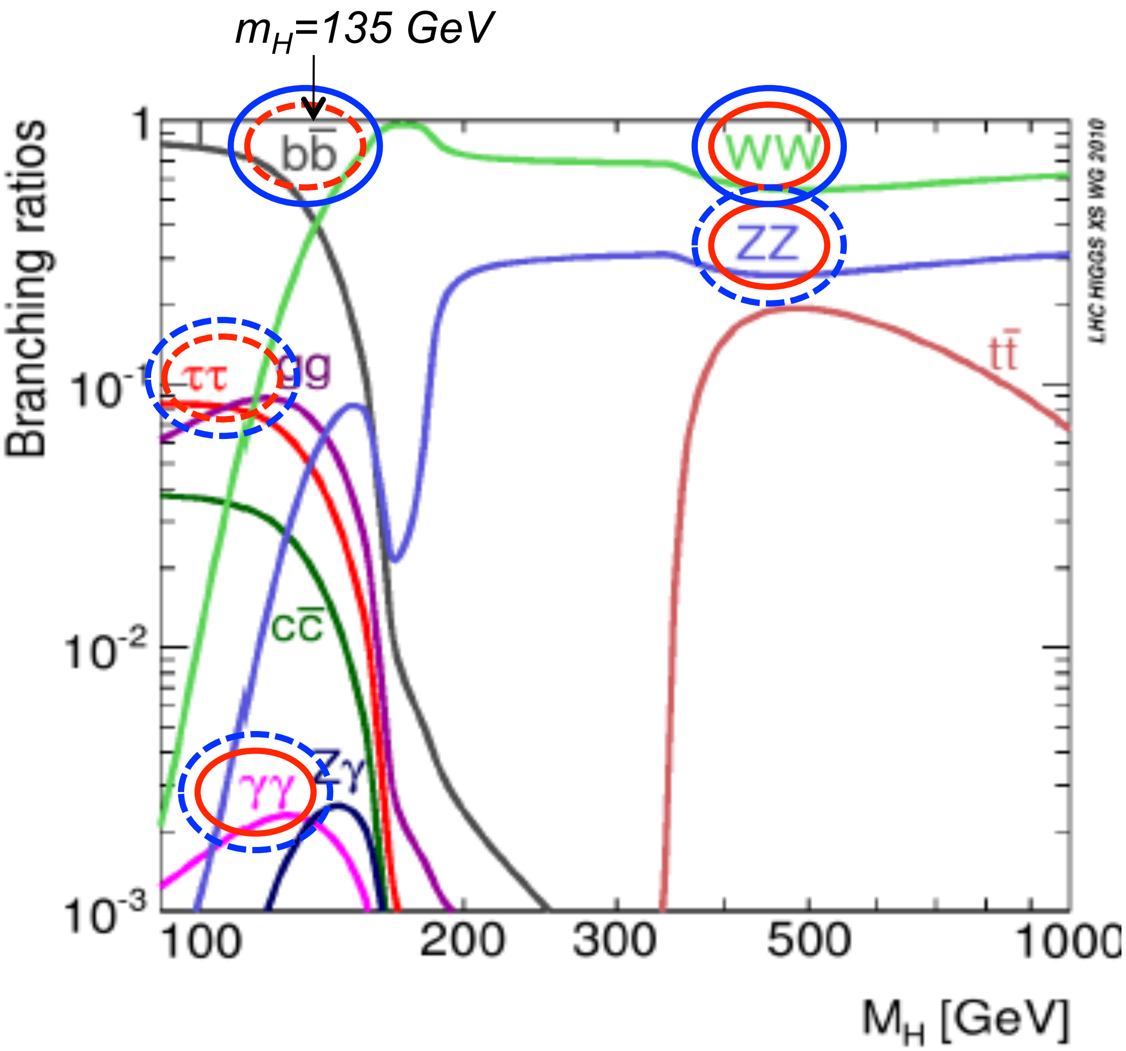
—— Main mode

----- Supporting mode

LHC

➔ Many decay modes being explored to increase the sensitivity of the search to the SM Higgs boson, but also to a non-SM one!

SM Higgs decay modes



m_H<135 GeV: H→bb dominates

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—	Main mode
-----	Supporting mode

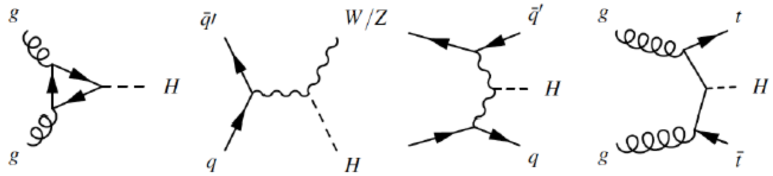
LHC

Tevatron

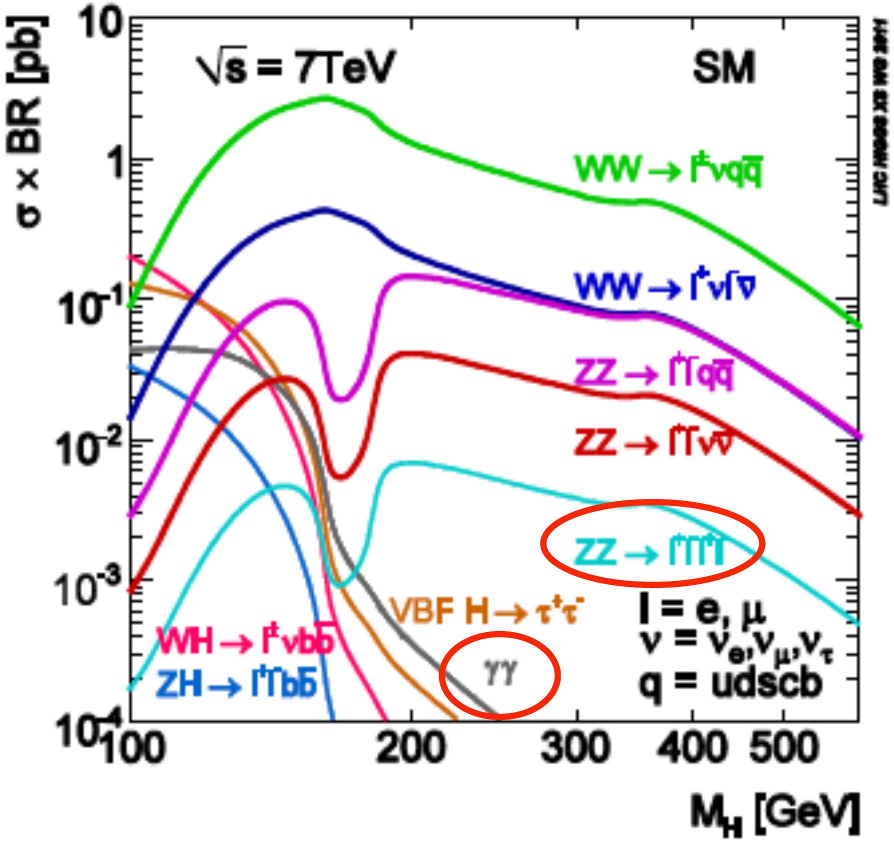
→ Many decay modes being explored to increase the sensitivity of the search to the SM Higgs boson, but also to a non-SM one!

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?

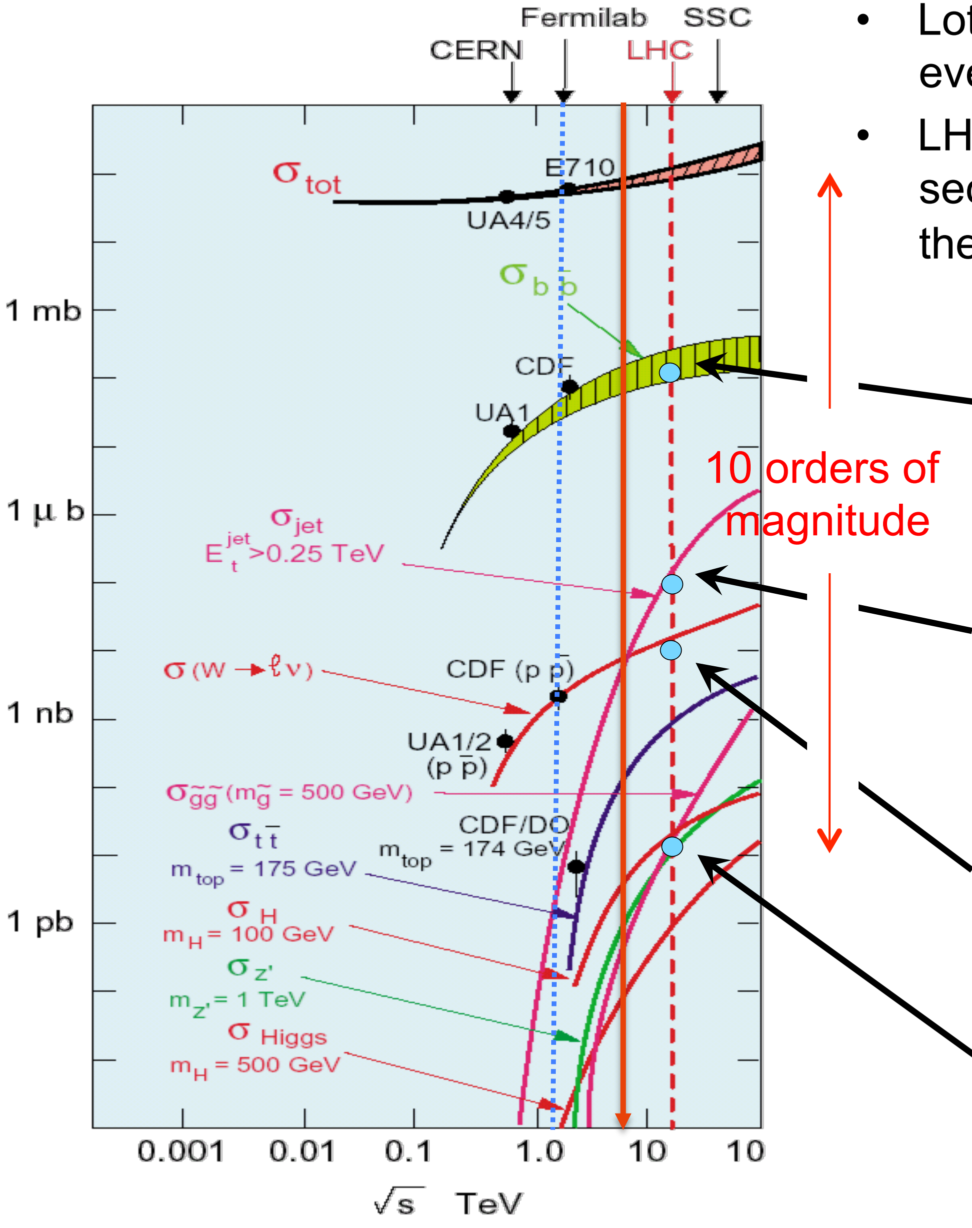


$H \rightarrow b\bar{b}$		♞		♝
$H \rightarrow \tau^+\tau^-$		♟	♞	
$H \rightarrow W^+W^-$	♜	♟	♟	
$H \rightarrow ZZ$	♜	♟	♟	
$H \rightarrow \gamma\gamma$	♛	♟	♝	

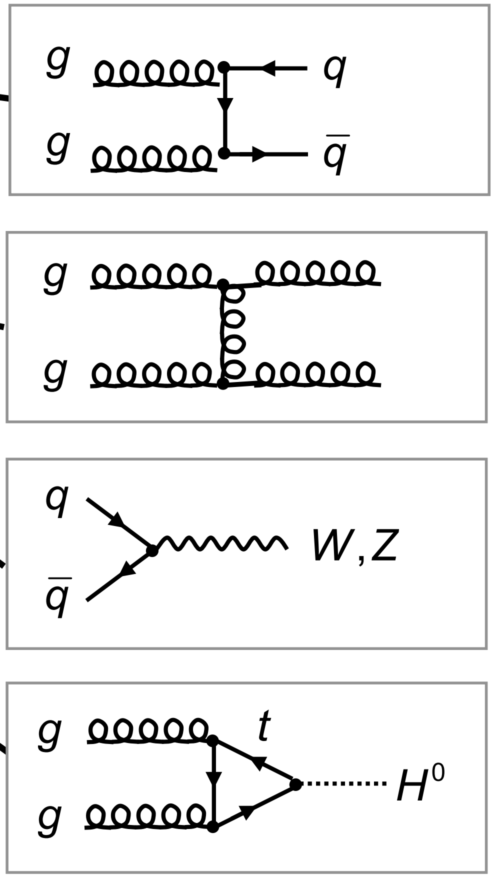


Physics backgrounds at hadron colliders

- Lots of signal events produced at the LHC, but even more background!
- LHC experiments need to be able to select every second the O(200) most interesting events out of the 10^9 collisions that took place!



10 orders of magnitude



b quark pair production

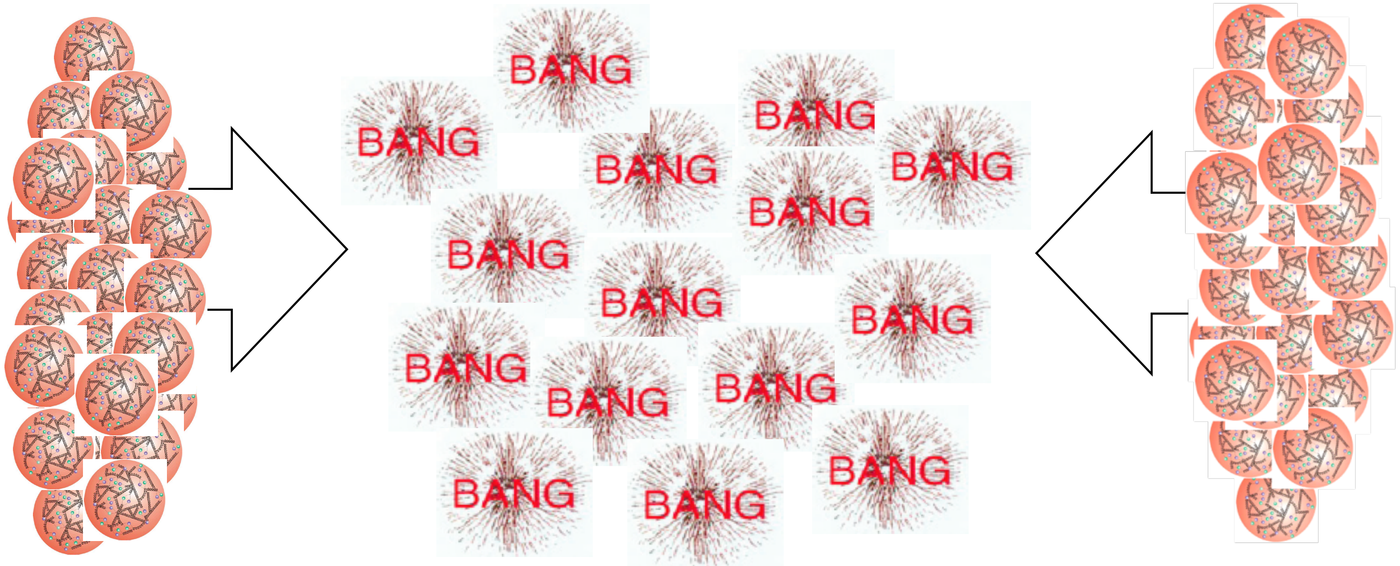
High-p_T dijets

W, *Z* production

gluon-to-Higgs fusion

At high luminosity it only gets harder

- Due to the huge number of protons per bunch, there is a high probability to have not just one, but multiple pp collisions in the same crossing!



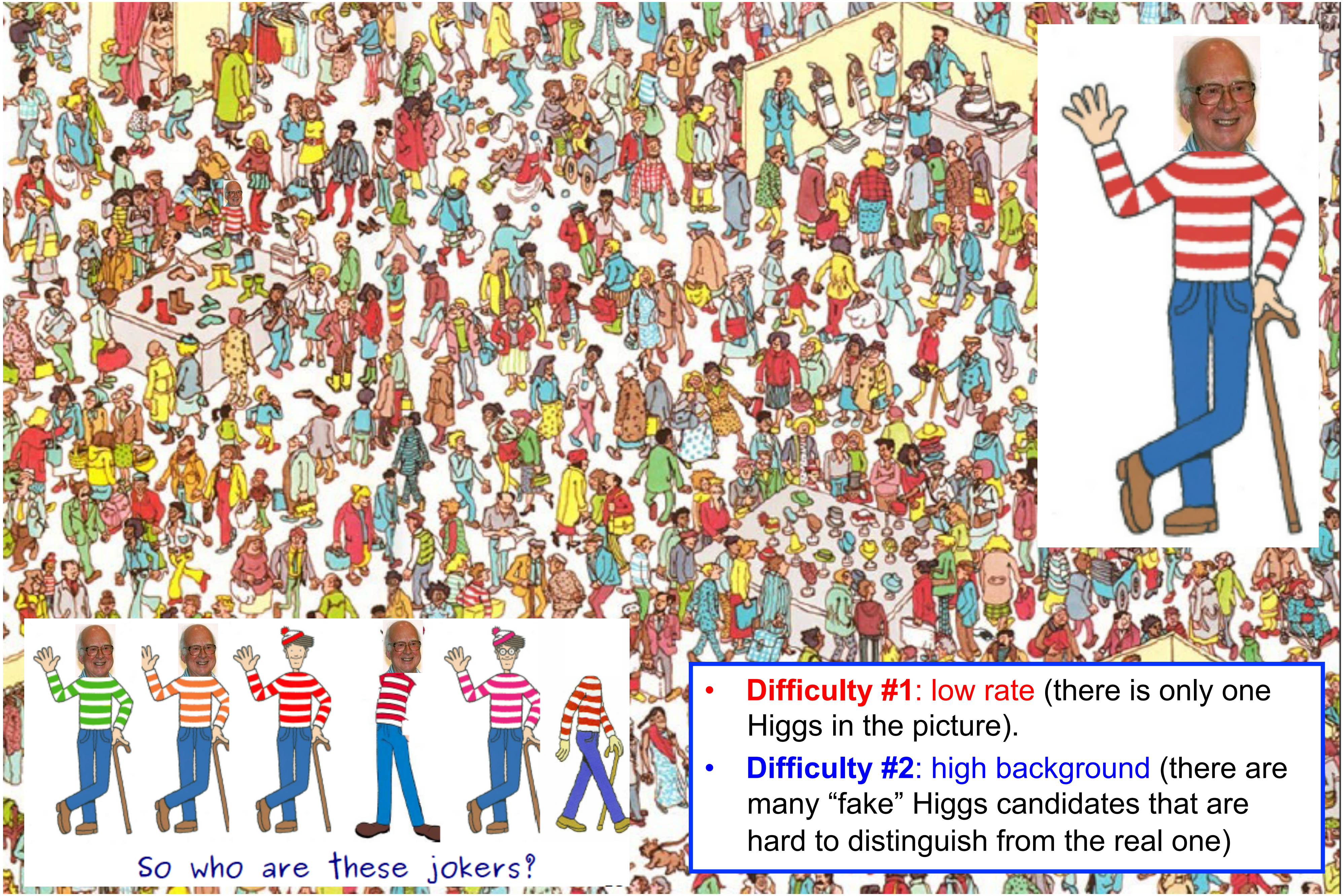
Bunch with 10^{11} protons

Bunch with 10^{11} protons

➔ Adds “confusion” in identifying the physical objects of interest

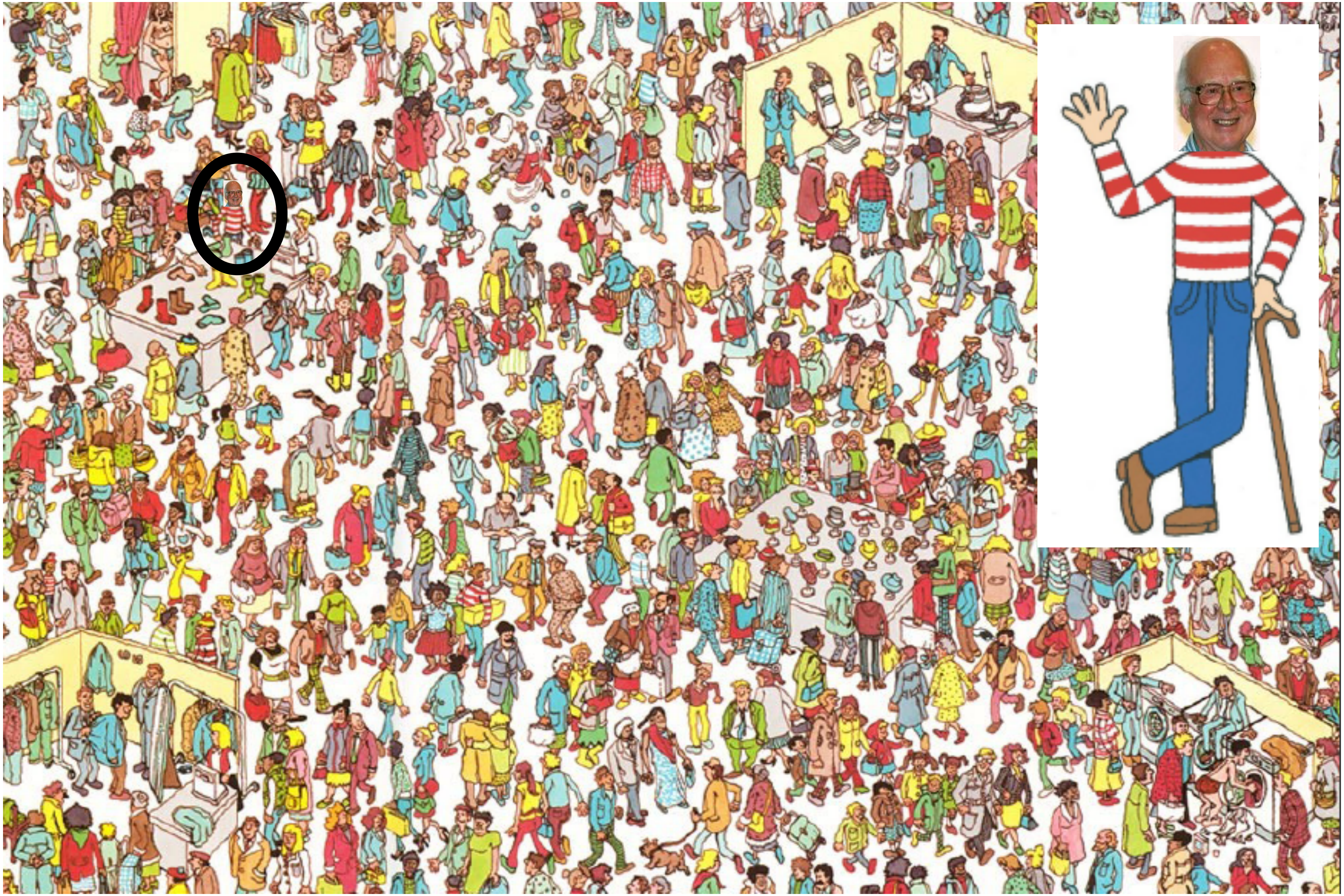
Bunch crossing with 25 pp collisions, out of which one is the Z→μμ event of interest

Searching for Higgs



- **Difficulty #1**: low rate (there is only one Higgs in the picture).
- **Difficulty #2**: high background (there are many “fake” Higgs candidates that are hard to distinguish from the real one)

Searching for Higgs



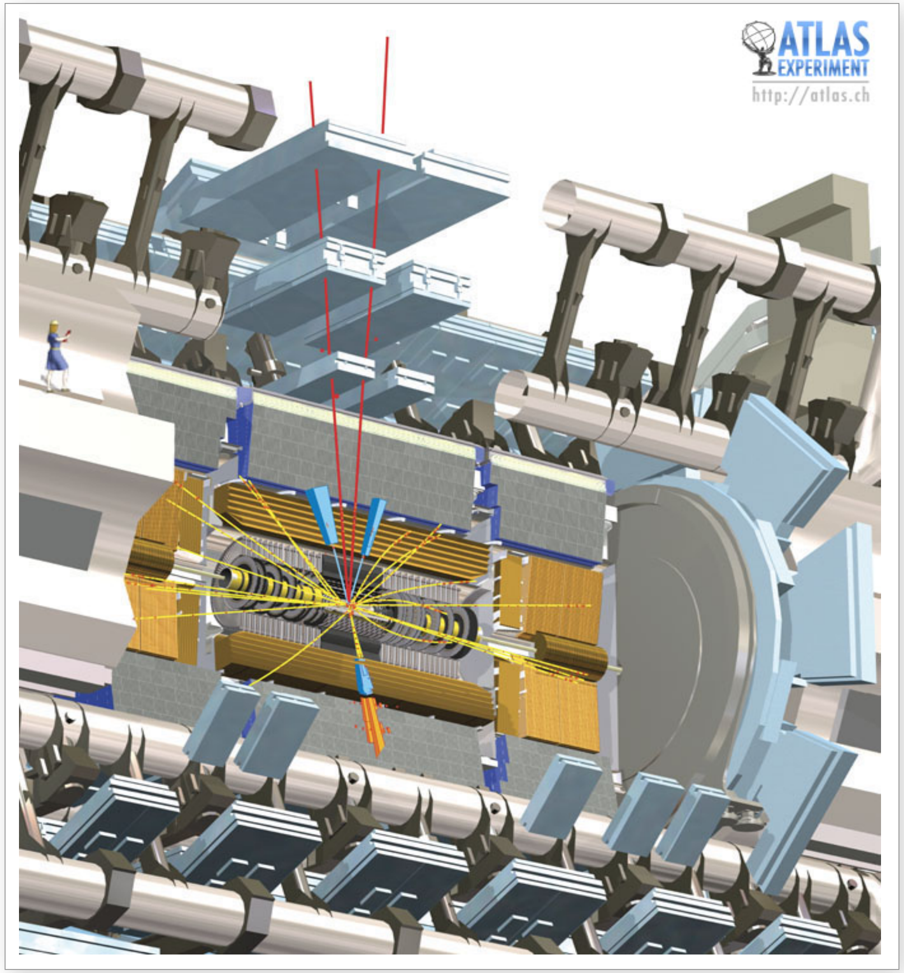
Searching for Higgs

Don’t be discouraged! This is still much easier than searching for the Higgs boson!

The Higgs search is possible because much more powerful instruments than the human eye are used.

Basic detector requirements

Signal signatures and backgrounds rates drive detector design!



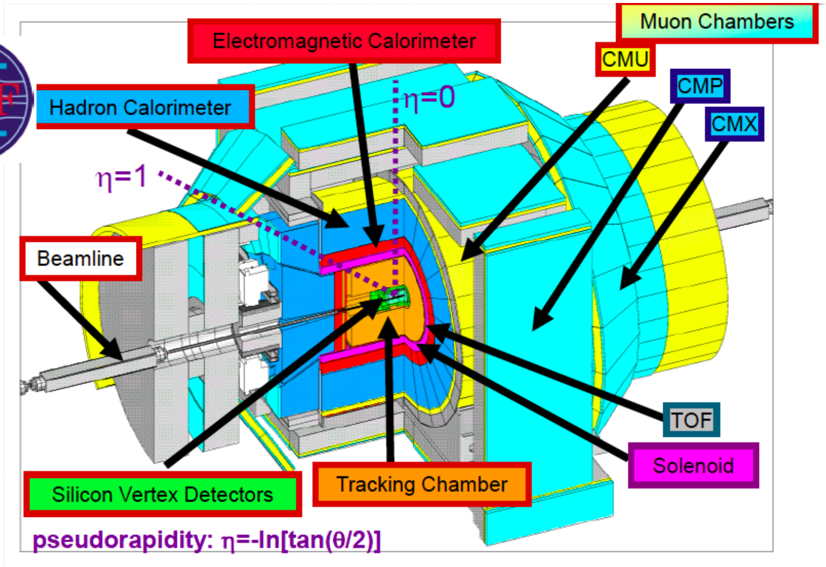
- Excellent identification and measurement of high-p_T muons, electrons and photons
- Excellent measurement of missing transverse energy (for W and τ final states) requiring energy measurement up to very forward region ($|\eta| \sim 5$)
- Jet tagging in forward direction (for weak-boson-fusion process)
- Efficient and pure *b*-tagging* and τ identification

*requiring silicon pixel detectors close to beam pipe

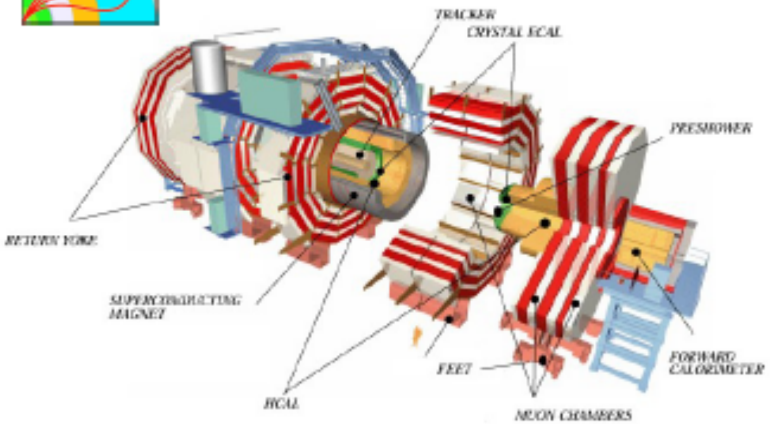
The tools of the hunt

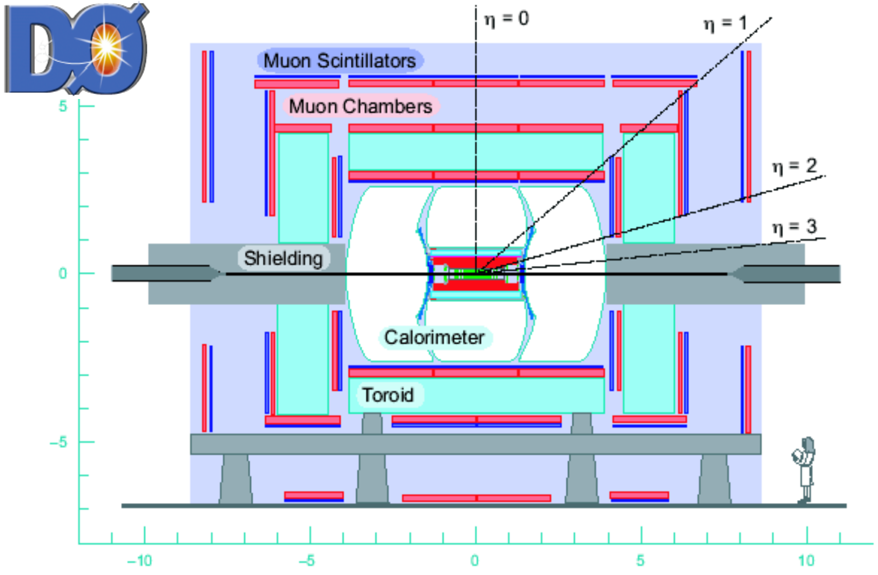
Tevatron experiments

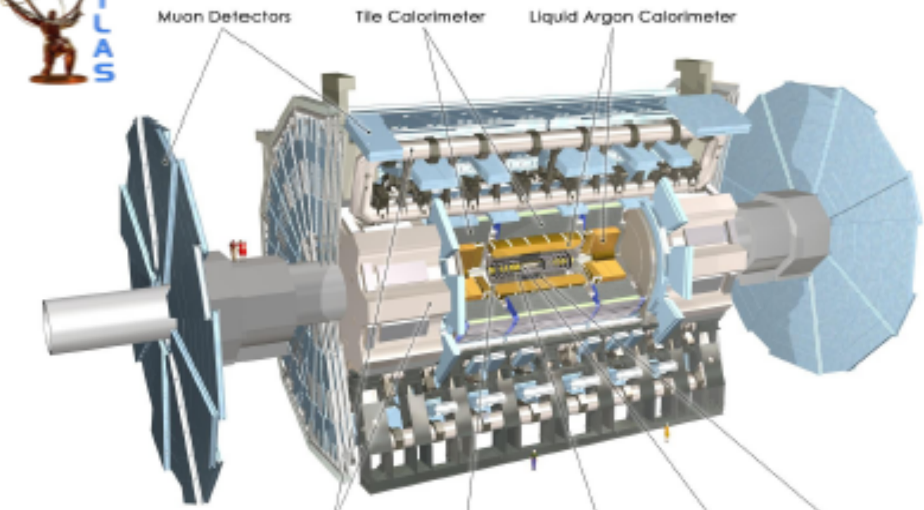
LHC experiments



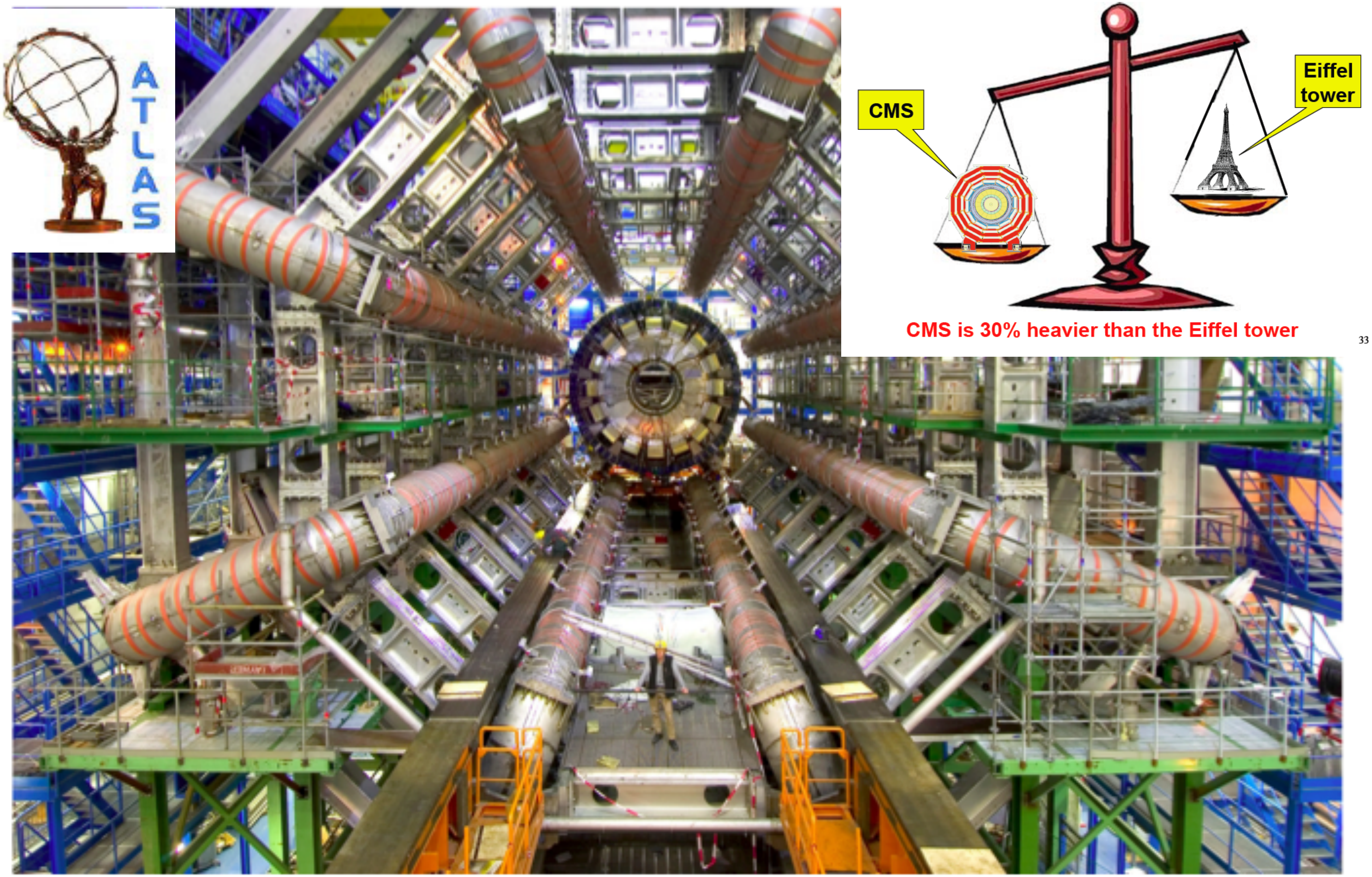
The CMS Experiment





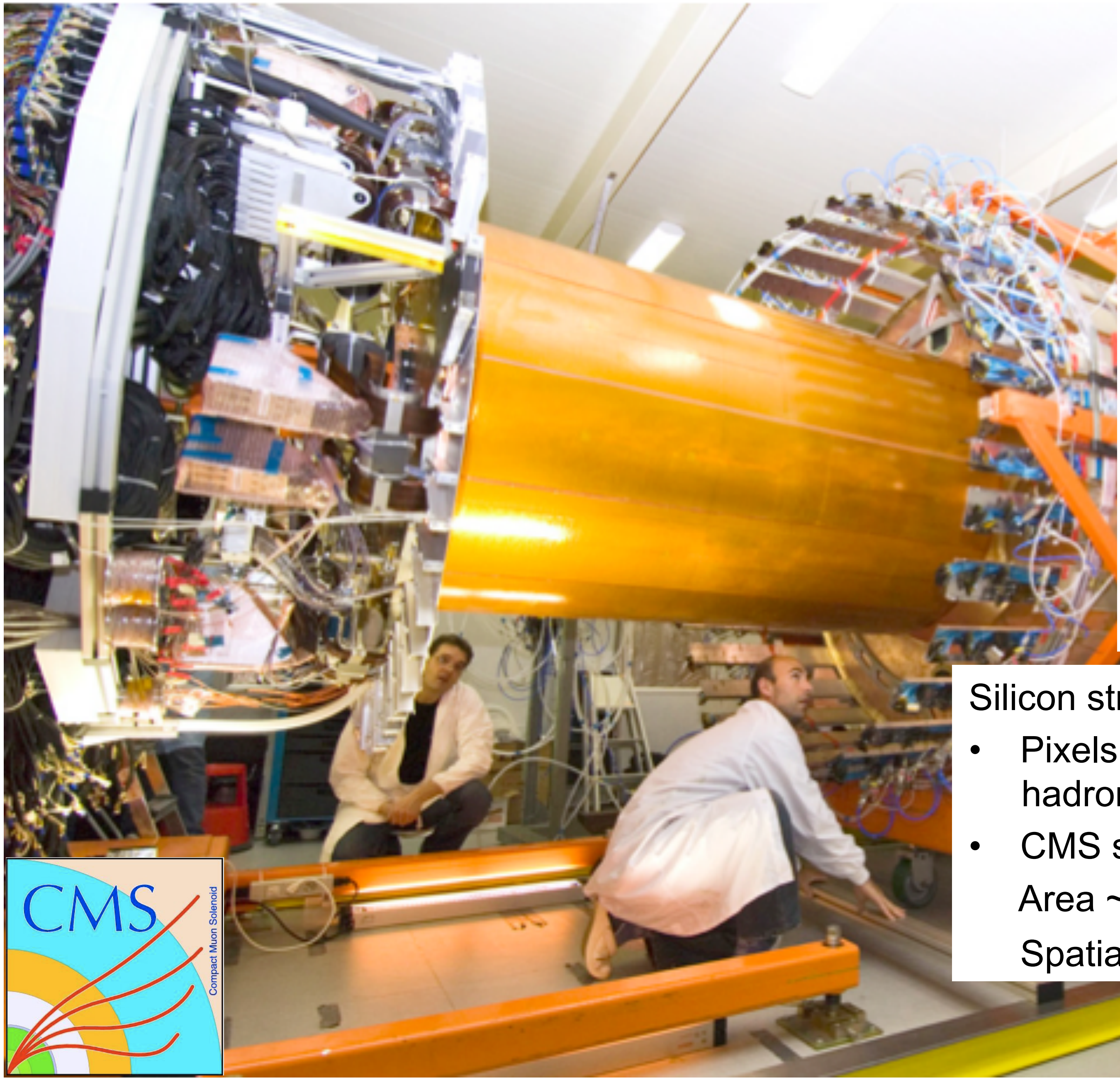


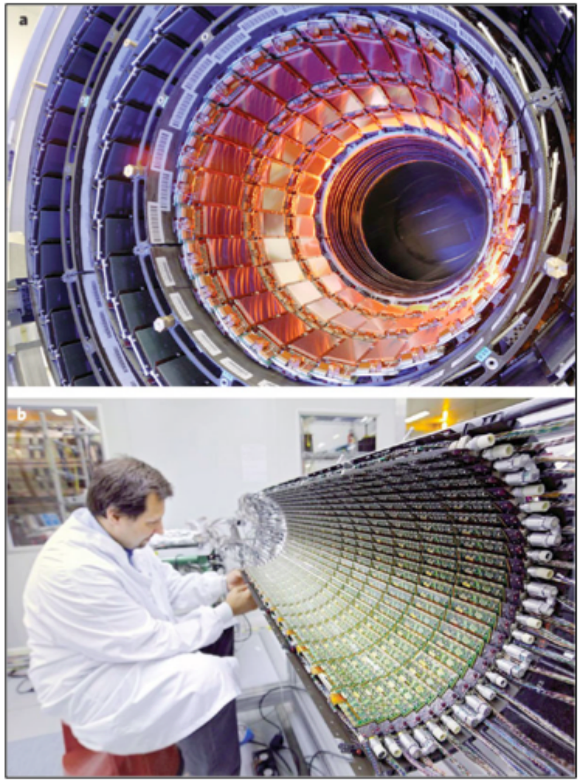
Really big…



CMS is 30% heavier than the Eiffel tower

…and precise tools





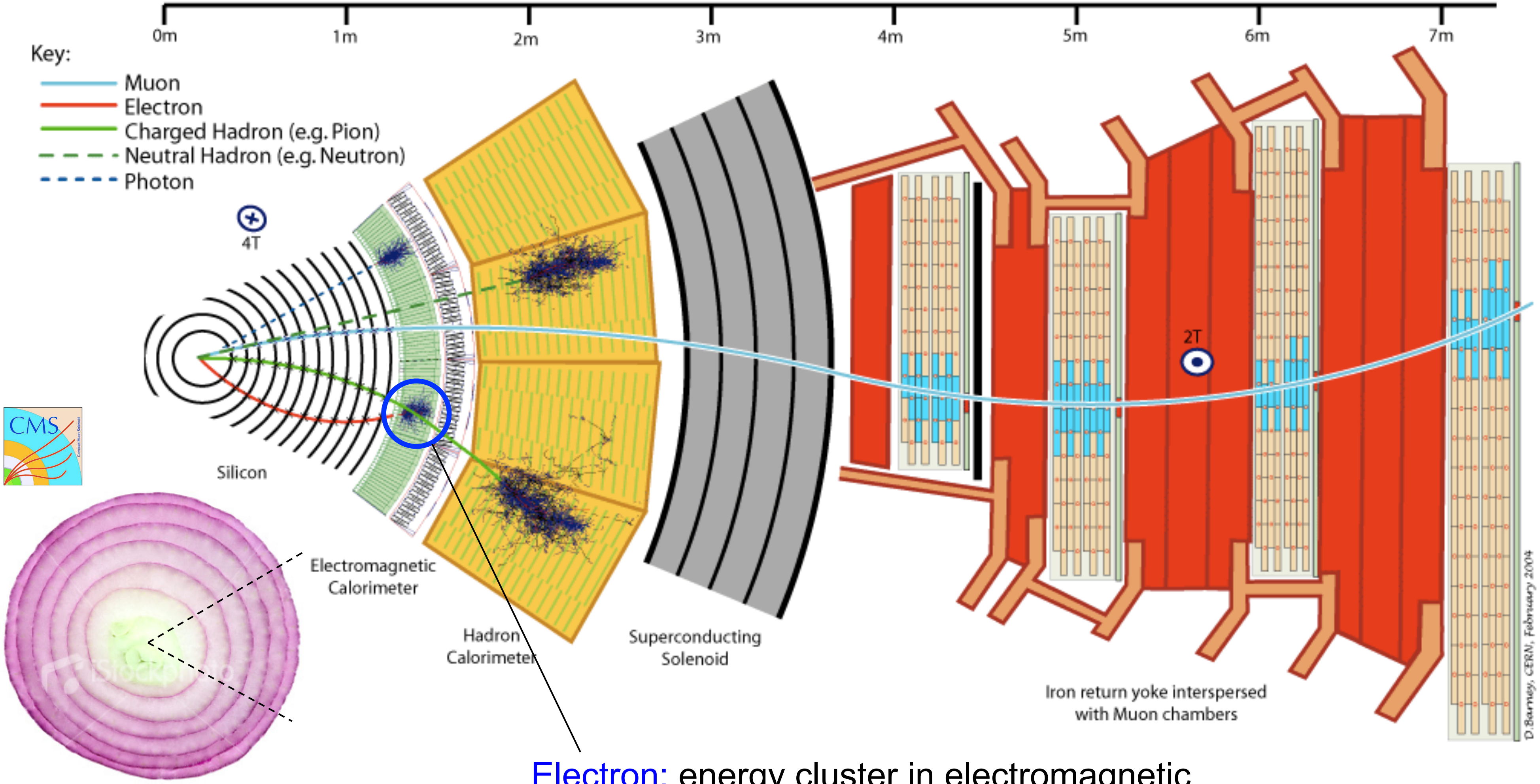
Silicon strip and pixel detectors

- Pixels used for the first time at a hadron collider
- CMS silicon tracker

  Area ~200 m^2

  Spatial resolution ~15 μm

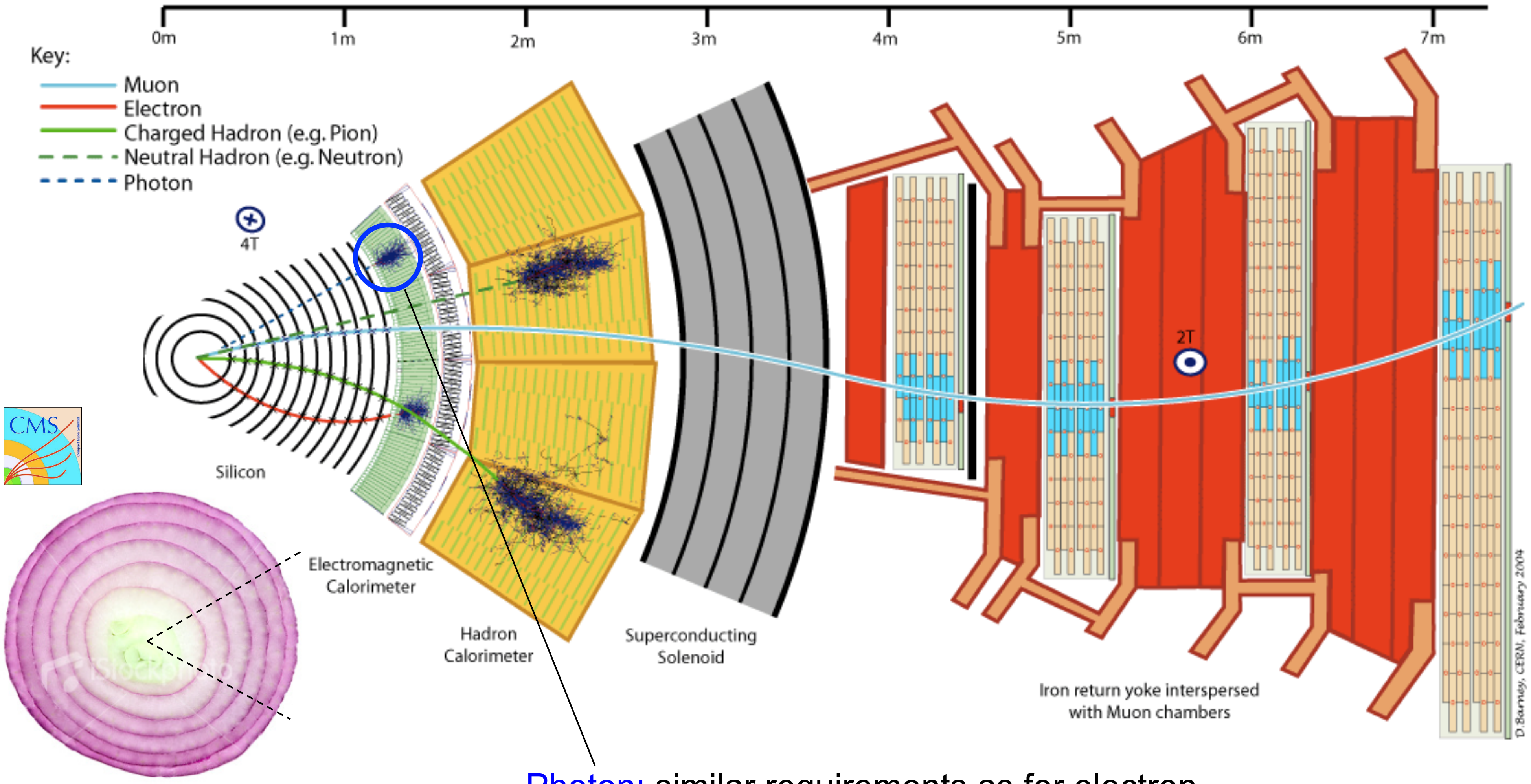
Particle identification basics



Transverse slice through CMS

Electron: energy cluster in electromagnetic calorimeter with e-like shower shape and with matching isolated track

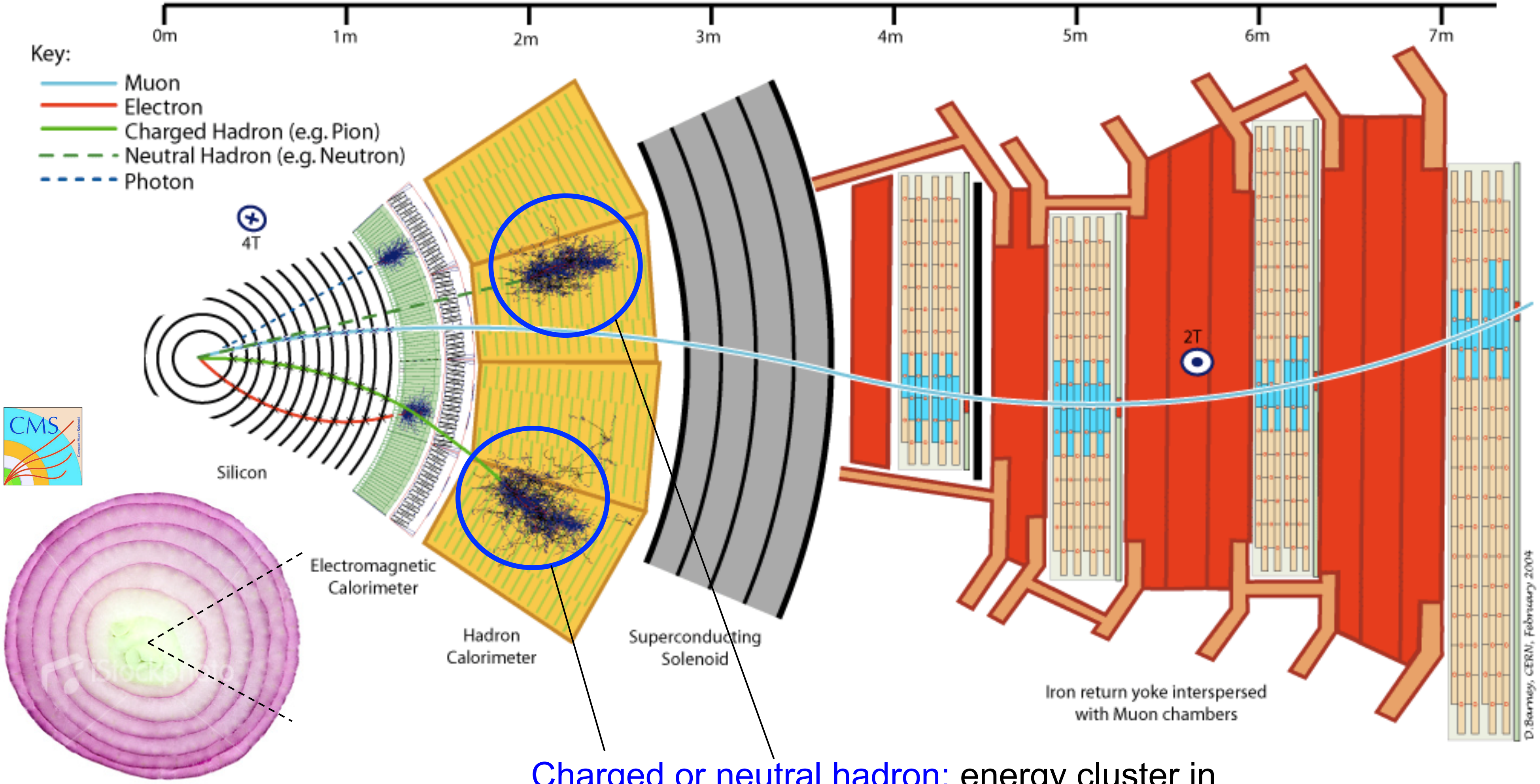
Particle identification basics



Transverse slice through CMS

Photon: similar requirements as for electron but with NO track pointing to it

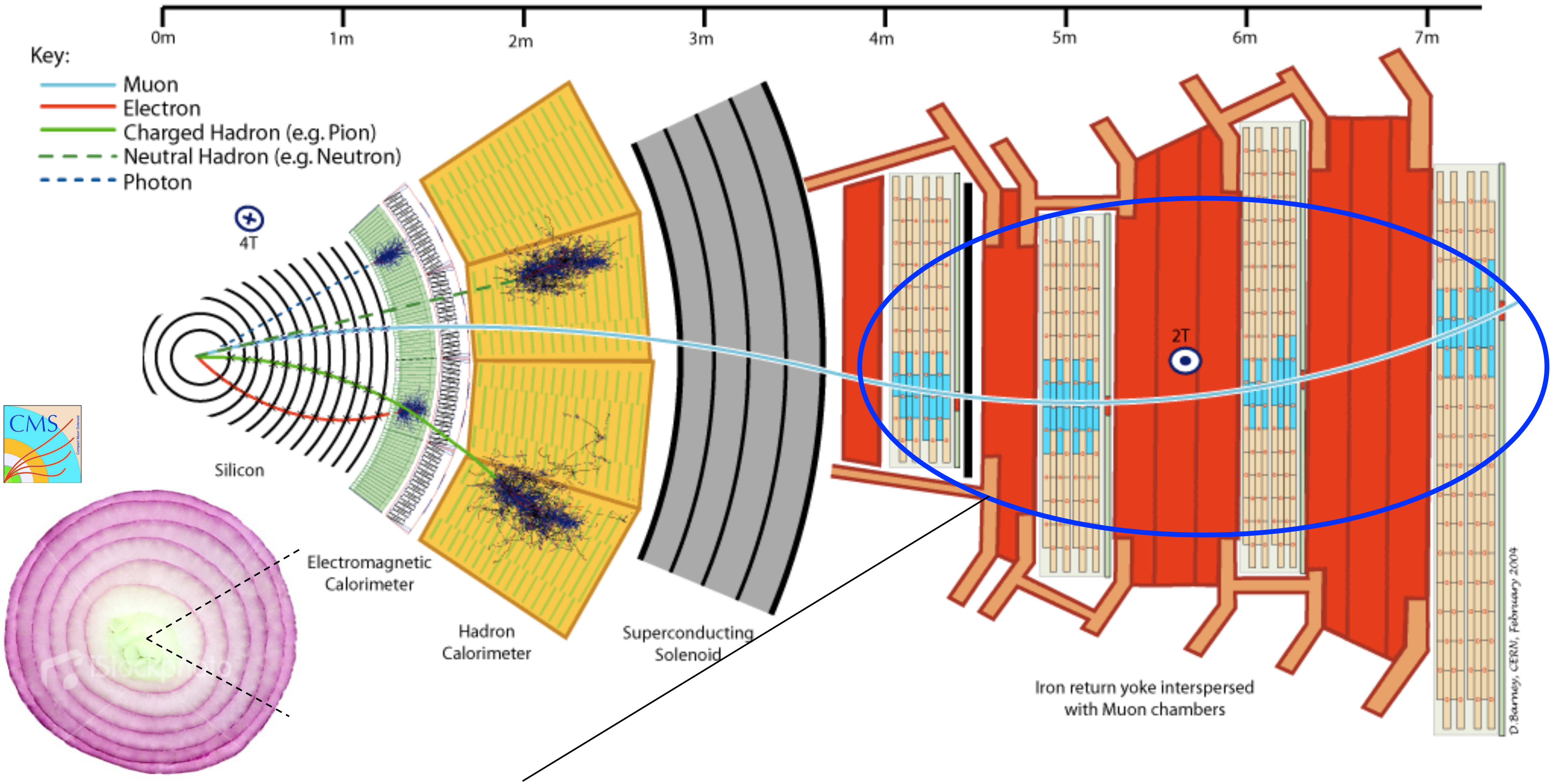
Particle identification basics



Transverse slice through CMS

Charged or neutral hadron: energy cluster in hadronic calorimeter w/ or w/o matching track

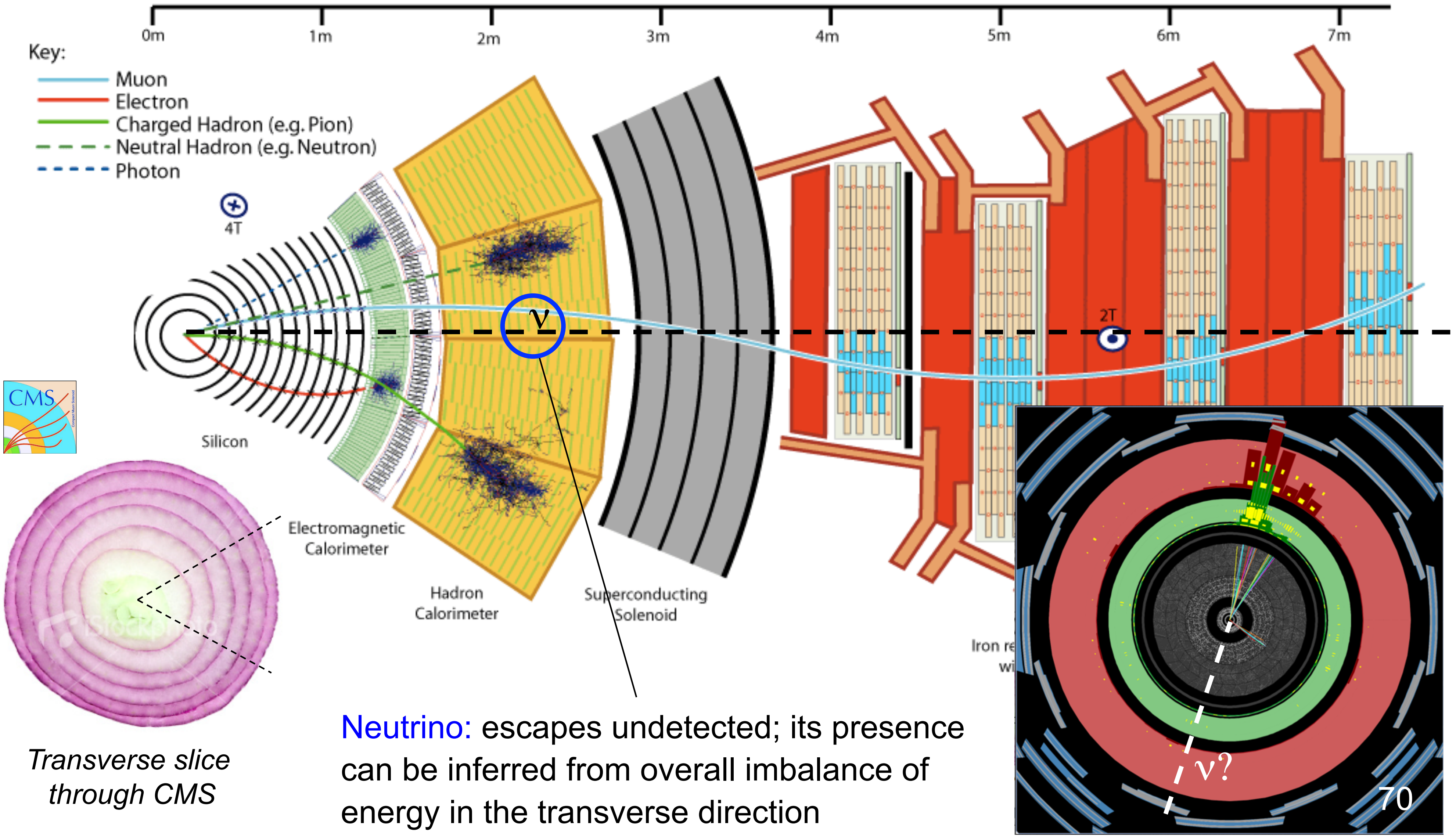
Particle identification basics



Transverse slice through CMS

Muon: central track matched to muon chamber track and small energy deposit in calorimeter

Particle identification basics

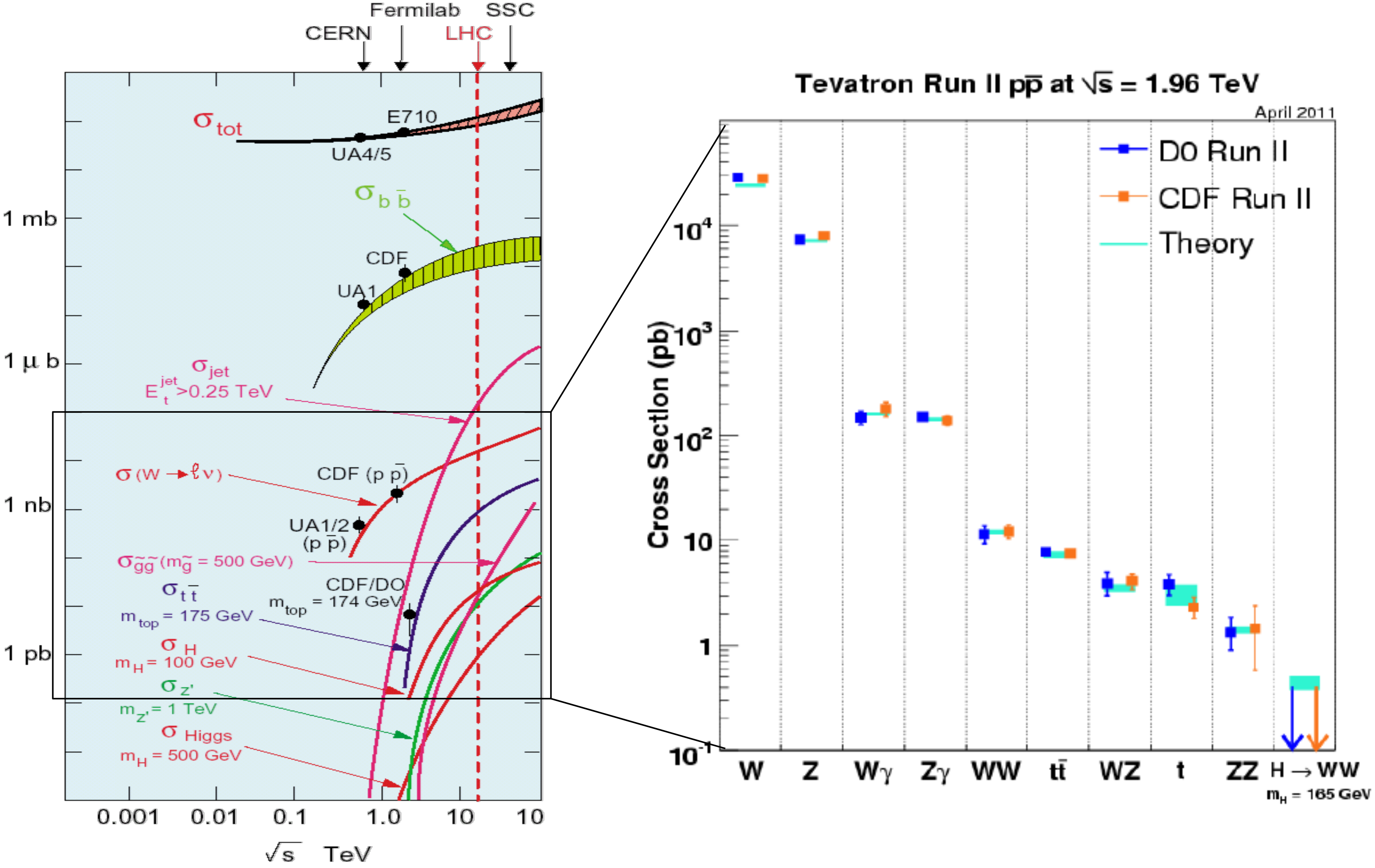


Transverse slice through CMS

Neutrino: escapes undetected; its presence can be inferred from overall imbalance of energy in the transverse direction

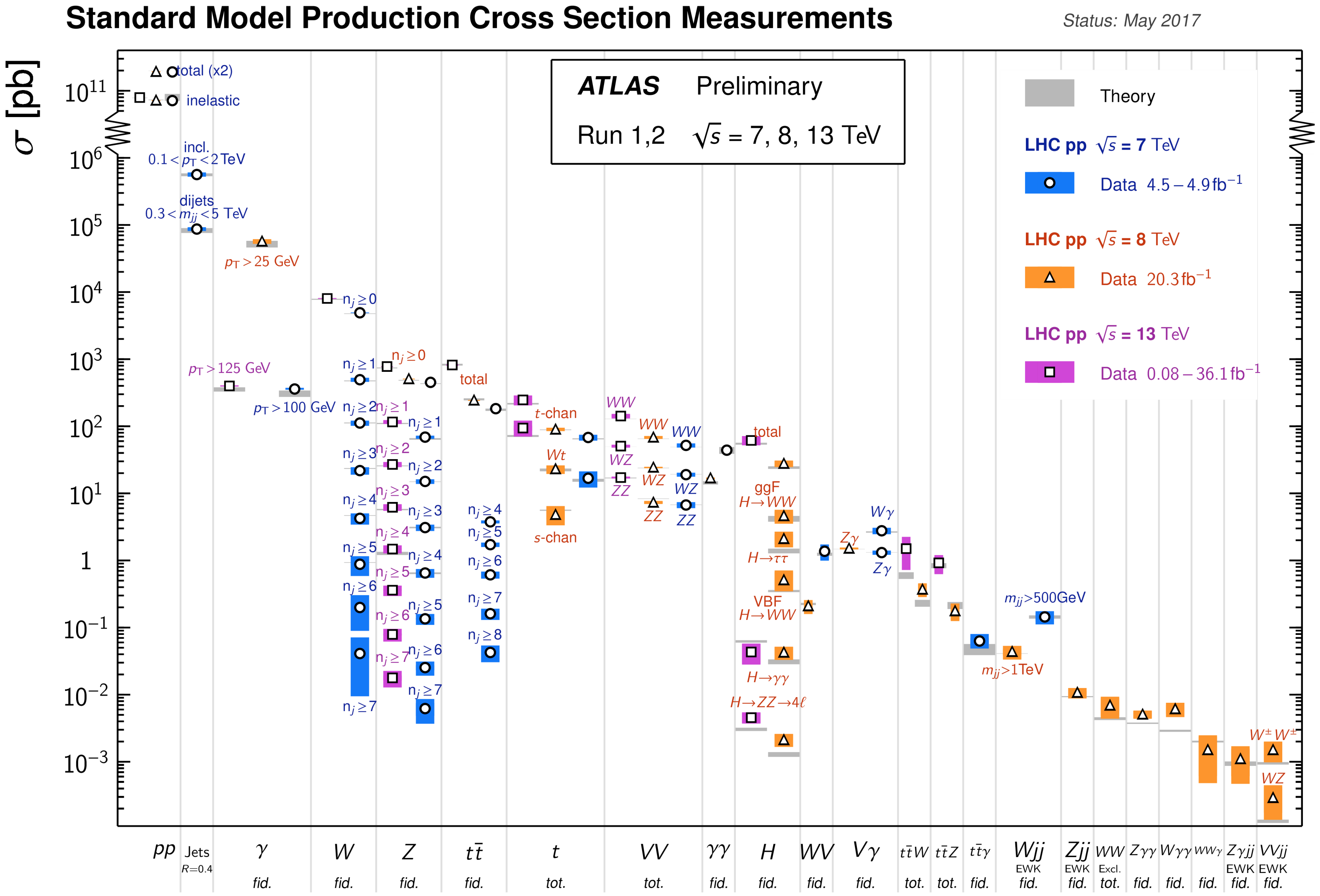
The stairway to the Higgs

Experiments have established a solid foundation to search for the Higgs boson through precise measurements of SM processes



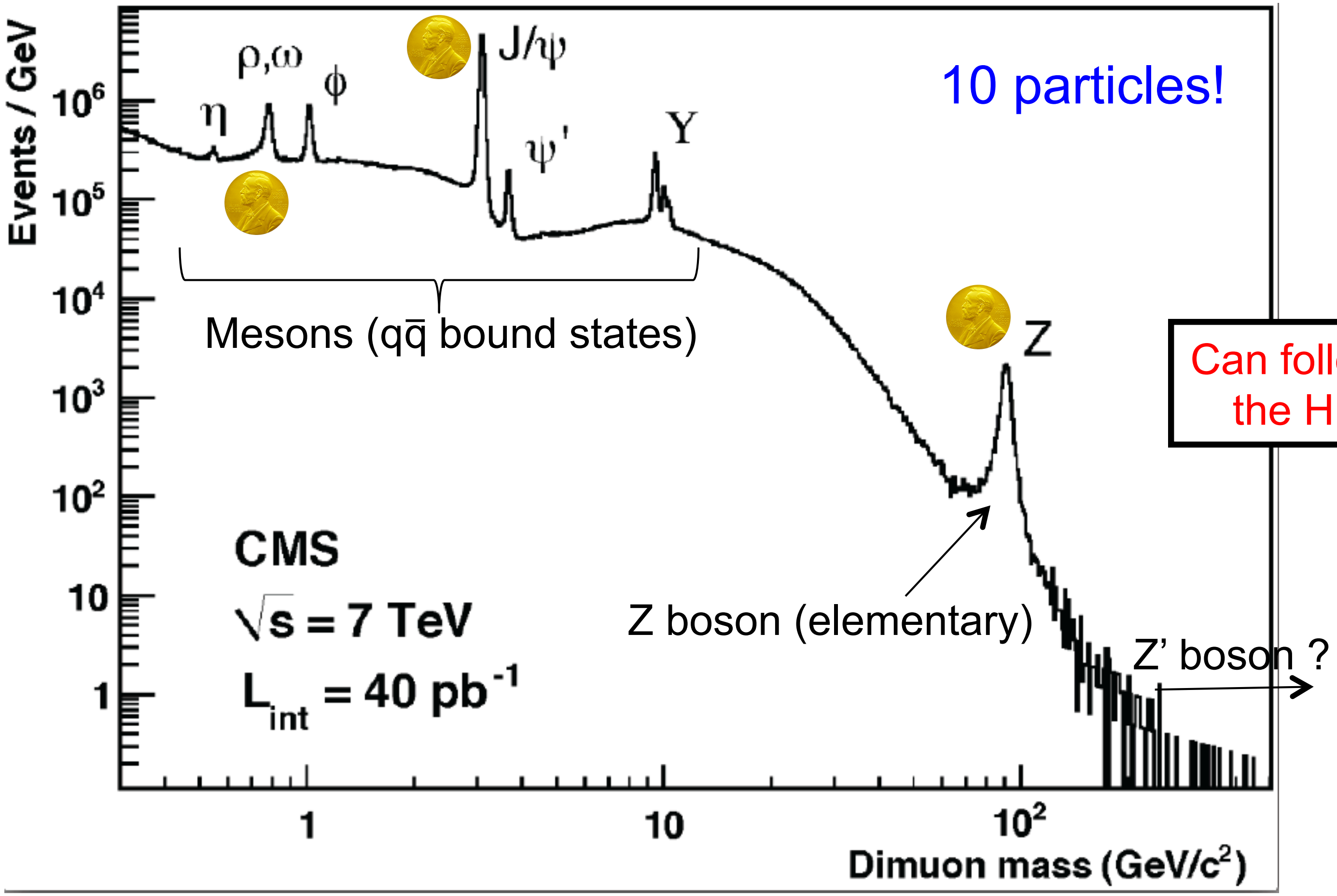
The stairway to the Higgs

Experiments have established a solid foundation to search for the Higgs boson through precise measurements of SM processes



"Fast track" to Nobel Prize: bump hunting

- Most particles that are not inside atoms are unstable and quickly decay into other particles.
- If it is possible to identify those decay products and measure their kinematics, one can reconstruct the mass of the original particle, which would show up as a "bump" in the distribution of invariant mass of the decay products.
- Example: resonances decaying into a $\mu^+\mu^-$ pair

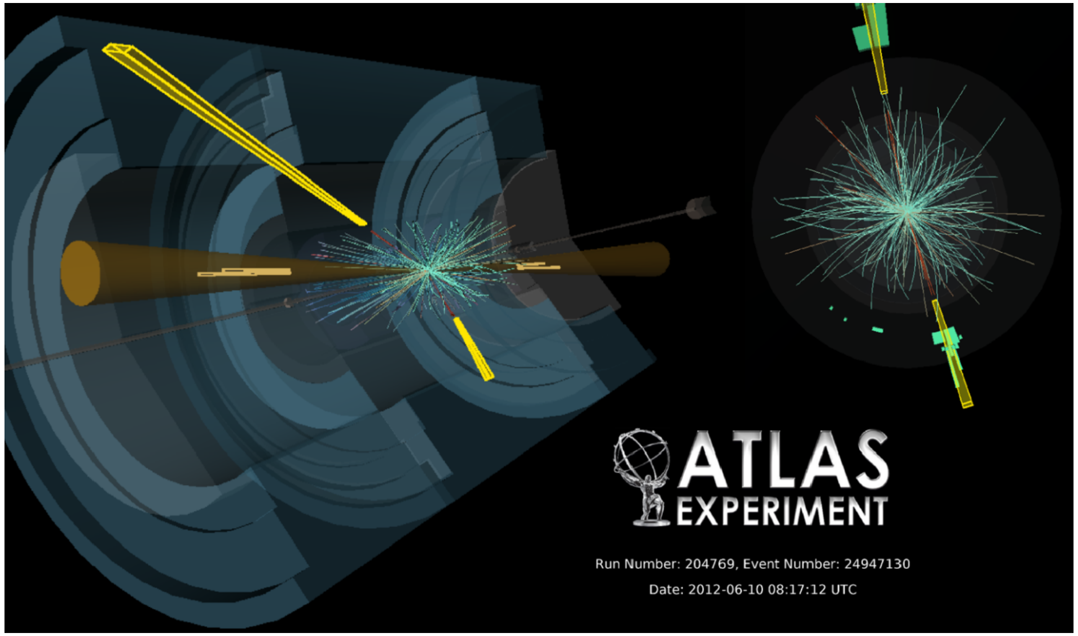


Can follow same strategy for the Higgs boson search!

$H \rightarrow \gamma\gamma$

Searching for H→γγ

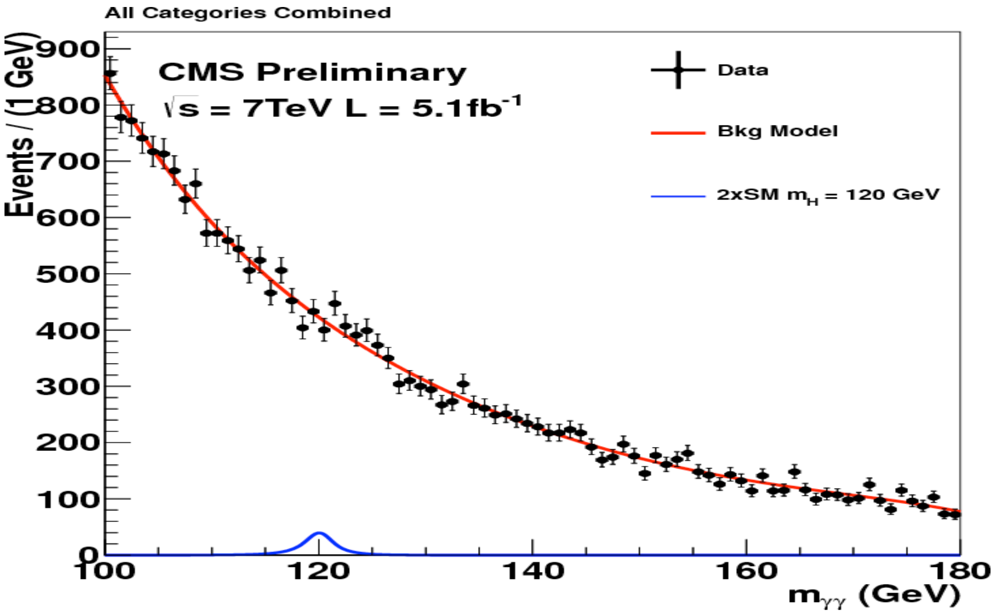
- A rare Higgs decay mode but most sensitive search at m_H<125 GeV!
  Prob(H→γγ)~0.2%



Run Number: 204769, Event Number: 24947130
Date: 2012-06-10 08:17:12 UTC

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

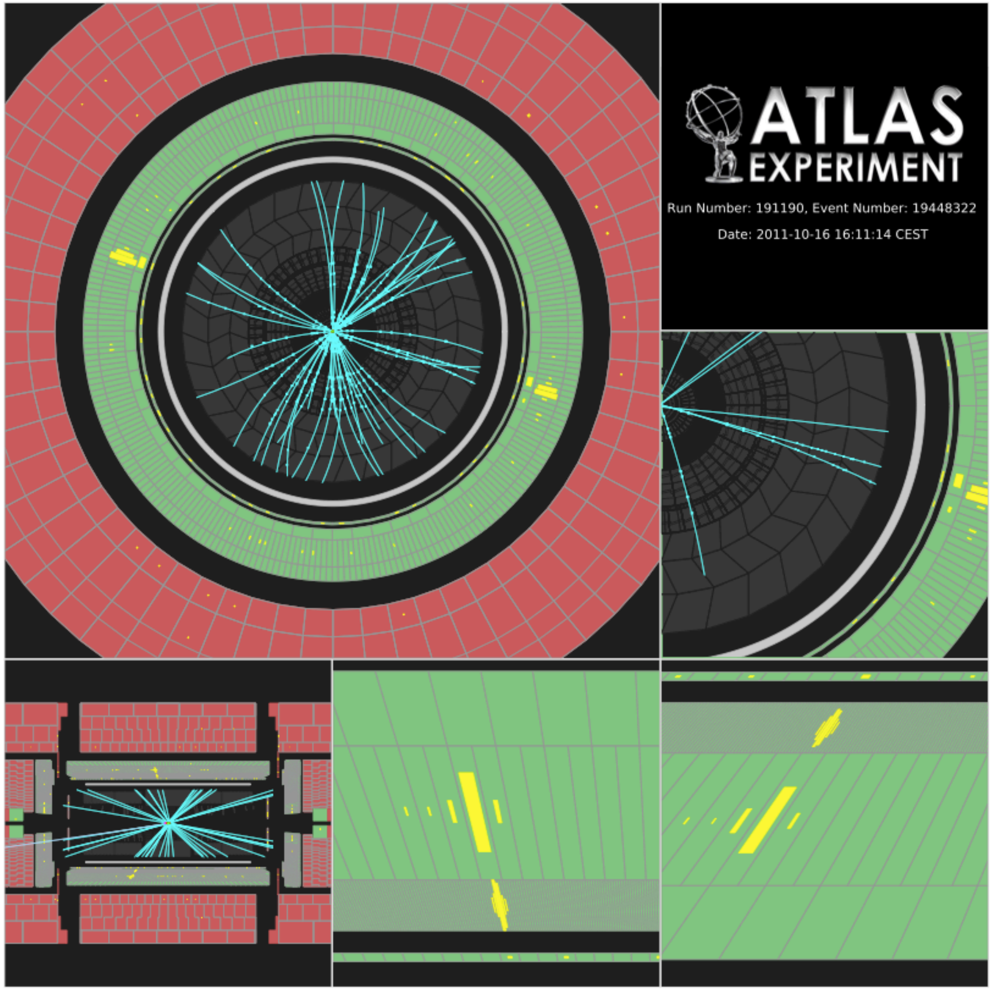
- So need:
  - Good photon identification capabilities
  - Good photon energy resolution
  - Categorization of events depending on their intrinsic sensitivity (e.g. better measured events, or with characteristics that are rare in background, etc)



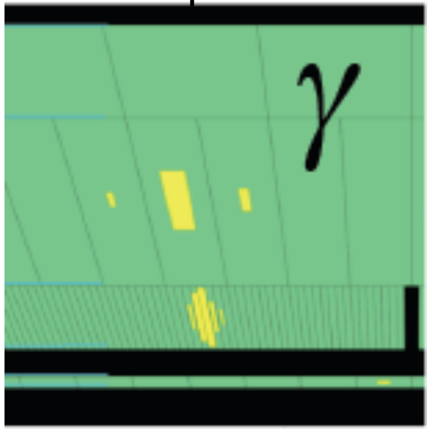
Searching for H→γγ

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

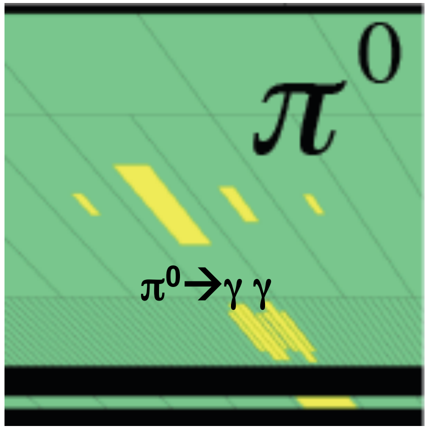
    ➔ requires finely segmented calorimeters!



Real photon



“Fake” photon



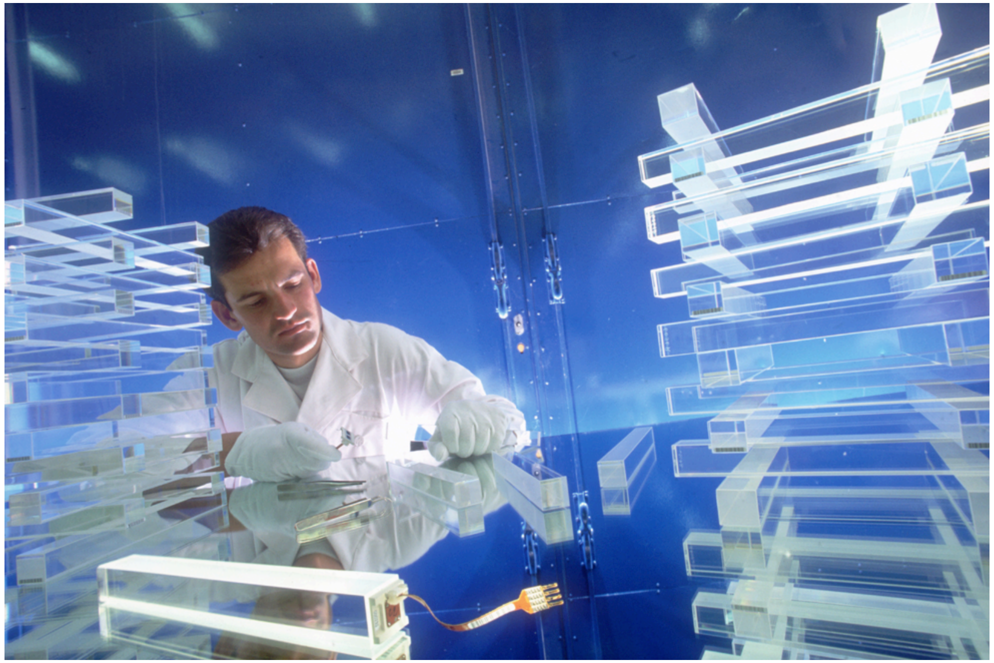
Only 1 in 10^5 jets fakes a photon

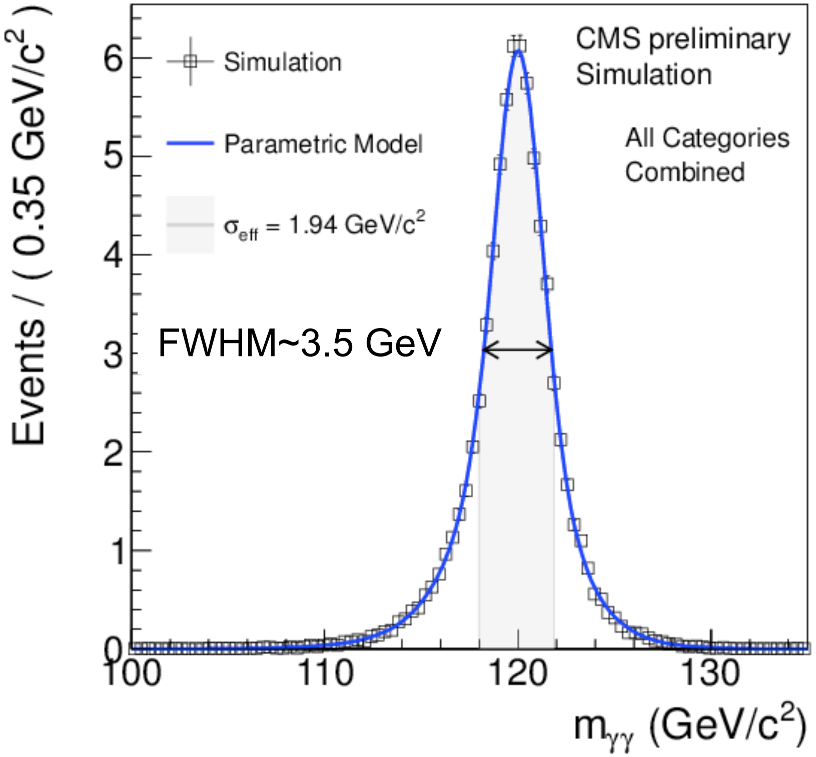
Searching for H→γγ

- 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





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  - Efficient photon identification with excellent background rejection from jets misidentified as photons
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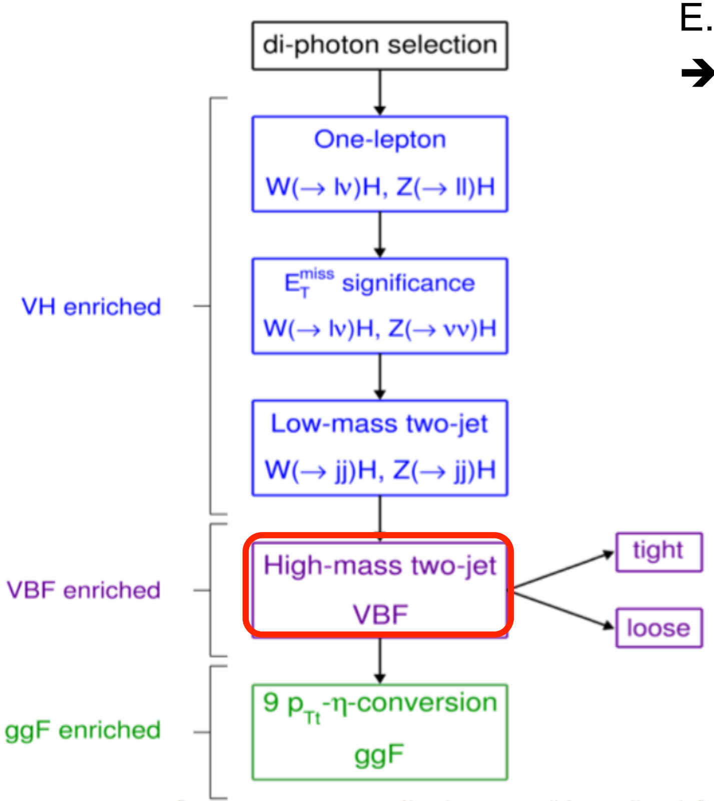
  - Event categorization to fully profit from distinctive features.
    - Improve overall sensitivity by keeping high/low S/B categories separate.



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

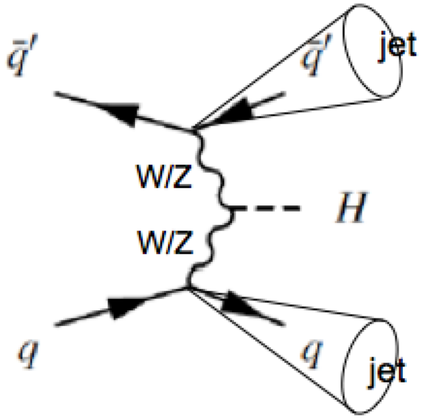
ggF enriched

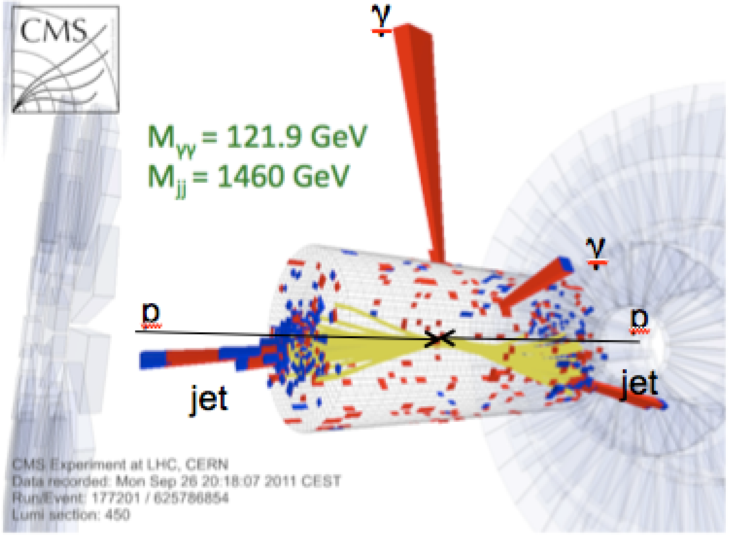
9 p_{Tt}-η-conversion
ggF

[$p_{Tt} = p_T^{\gamma\gamma}$ 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

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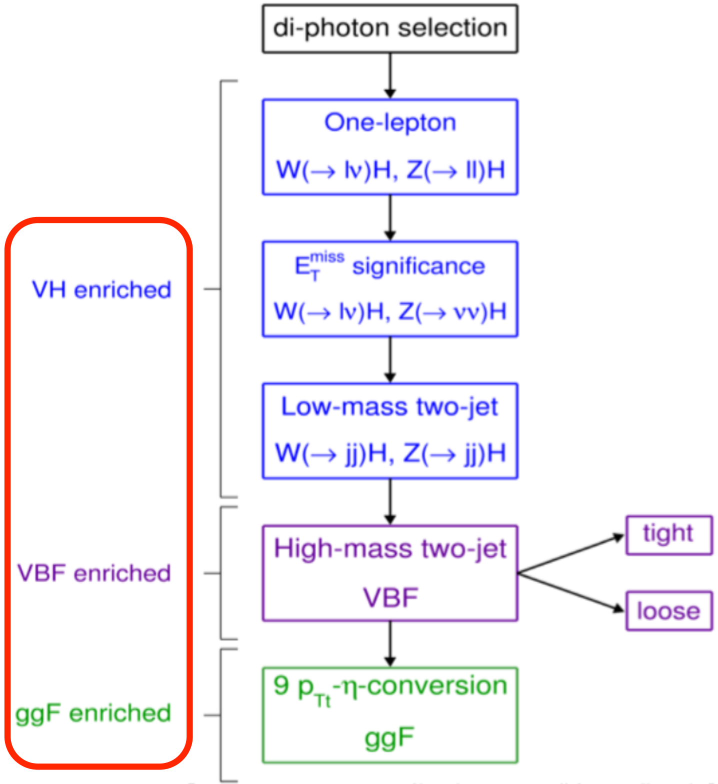
  - Efficient photon identification with excellent background rejection from jets misidentified as photons
  - Excellent diphoton mass resolution: ~1.2%-6%
  - Event categorization to fully profit from distinctive features.
    - Improve overall sensitivity by keeping high/low S/B categories separate.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



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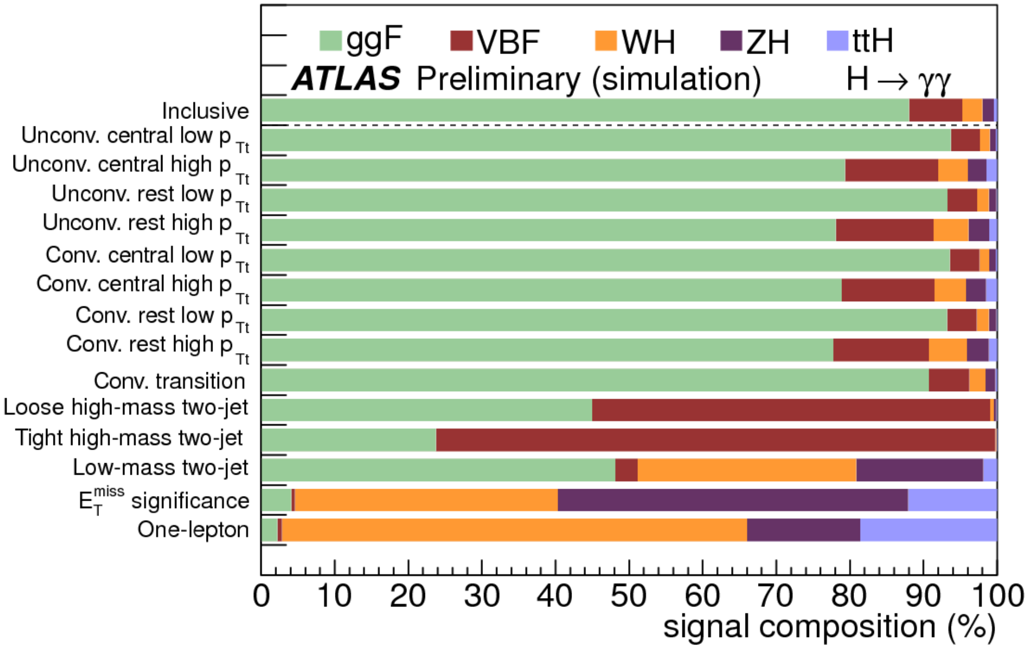
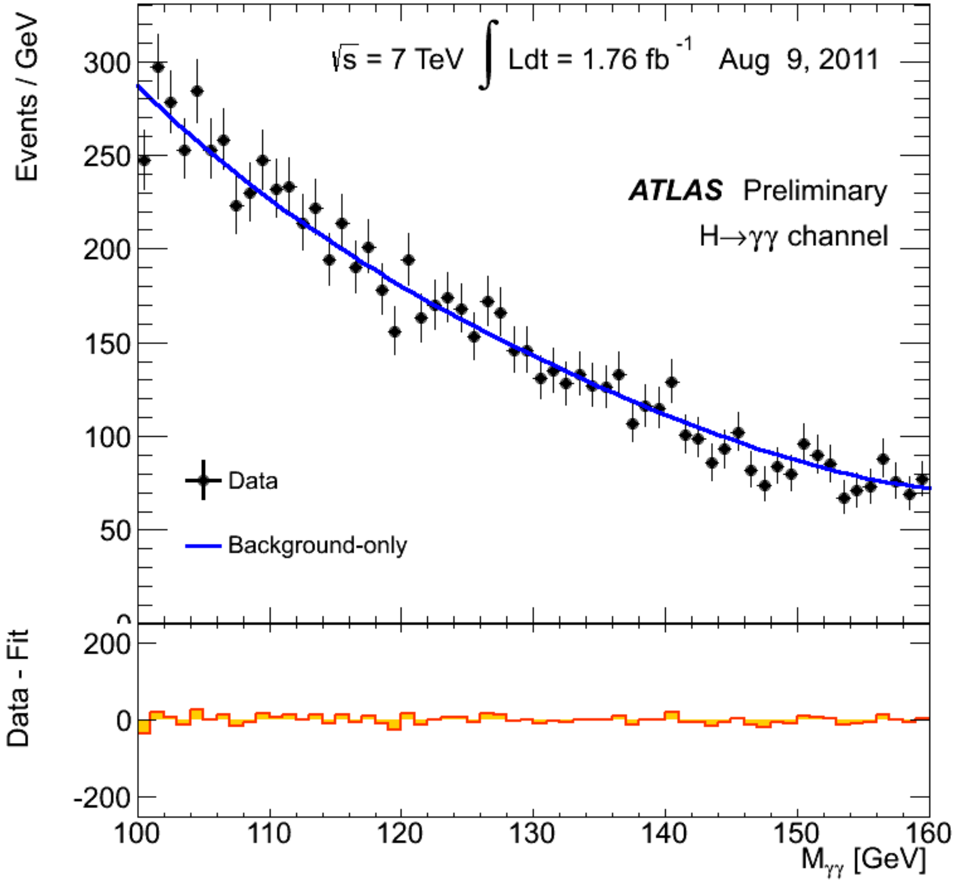


The birth of a particle



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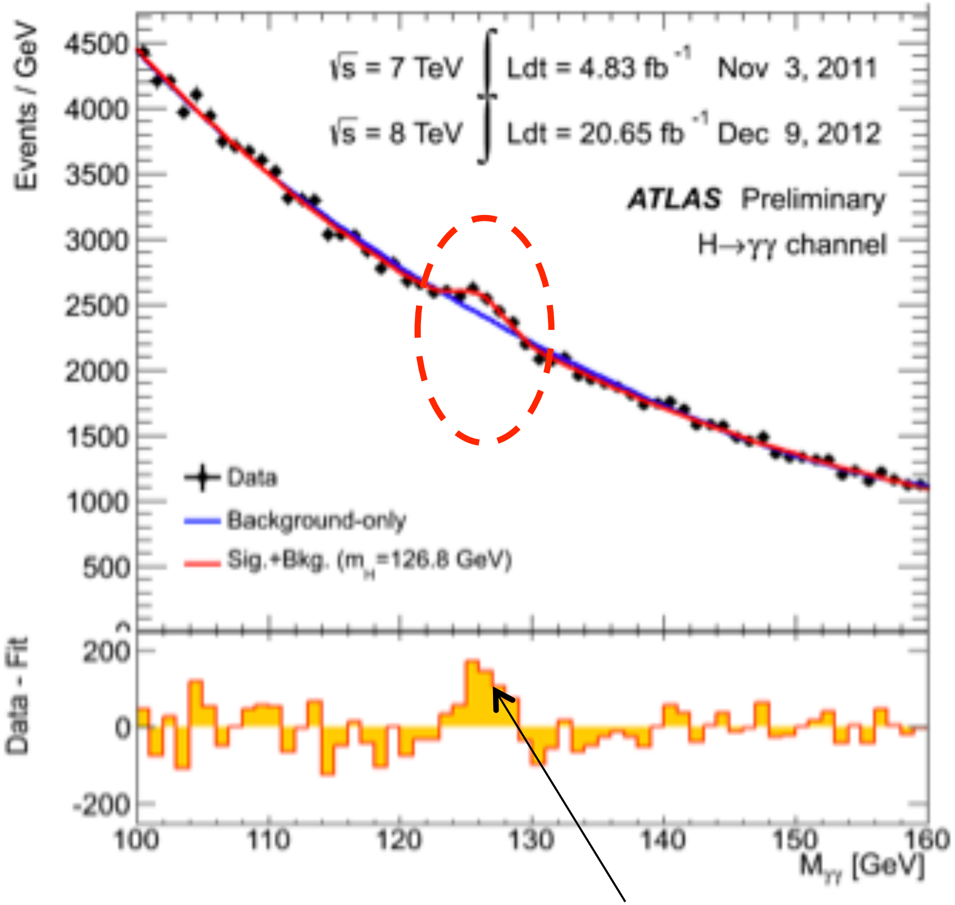
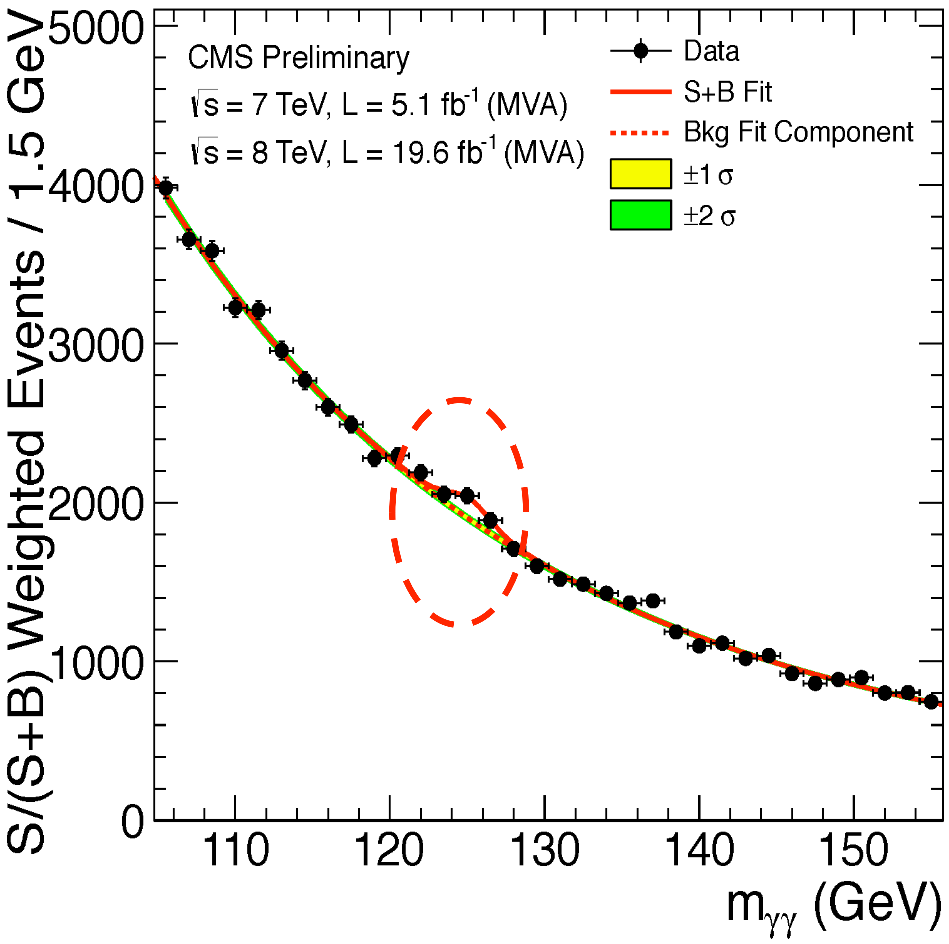
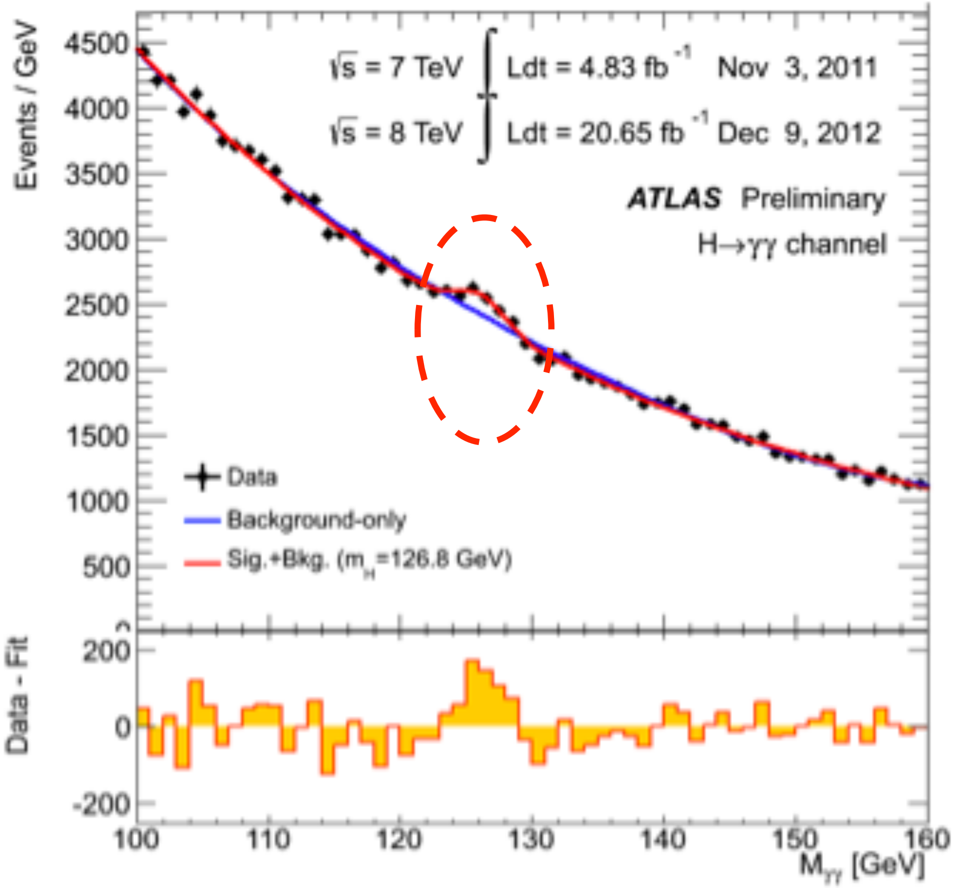


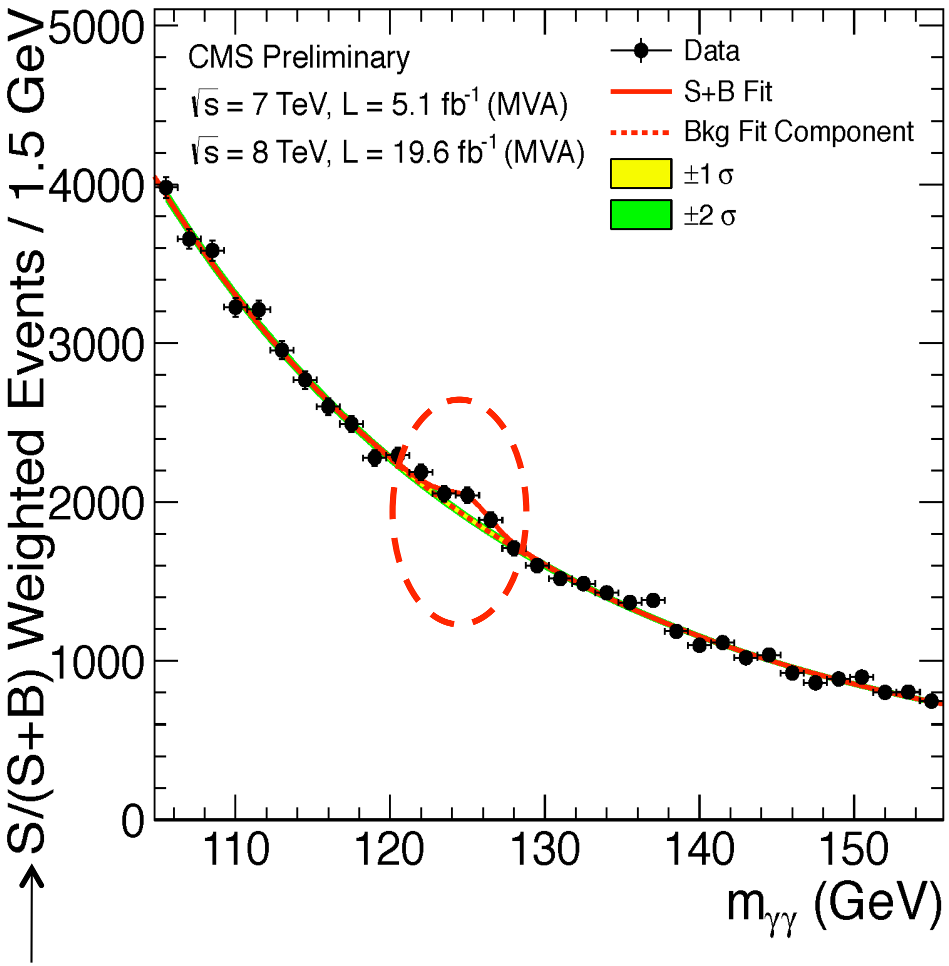
~200 signal events



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

$H \rightarrow ZZ \rightarrow 4l$

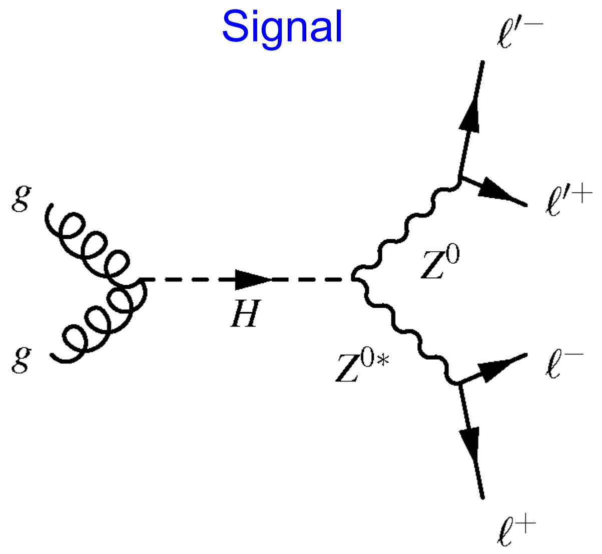
Searching for H→ZZ$^{(*)}$→4l

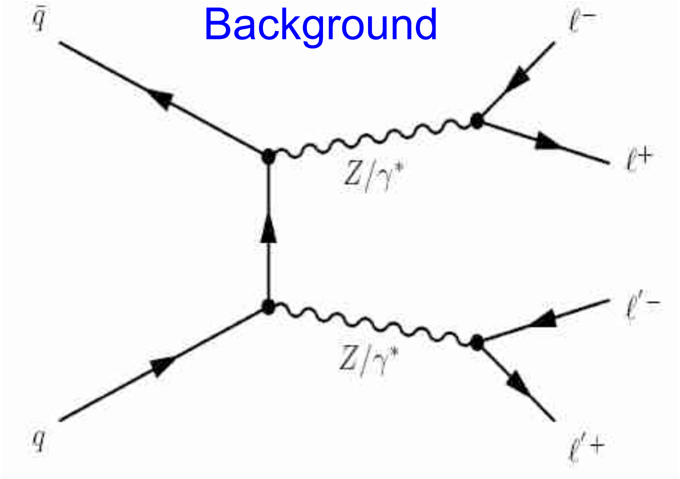
- An even rarer Higgs decay mode if both Z bosons are required to decay into electrons or muons!

  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

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

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  Prob($H \rightarrow ZZ \rightarrow 4e$, 4μ or $2e2\mu$)~0.01%

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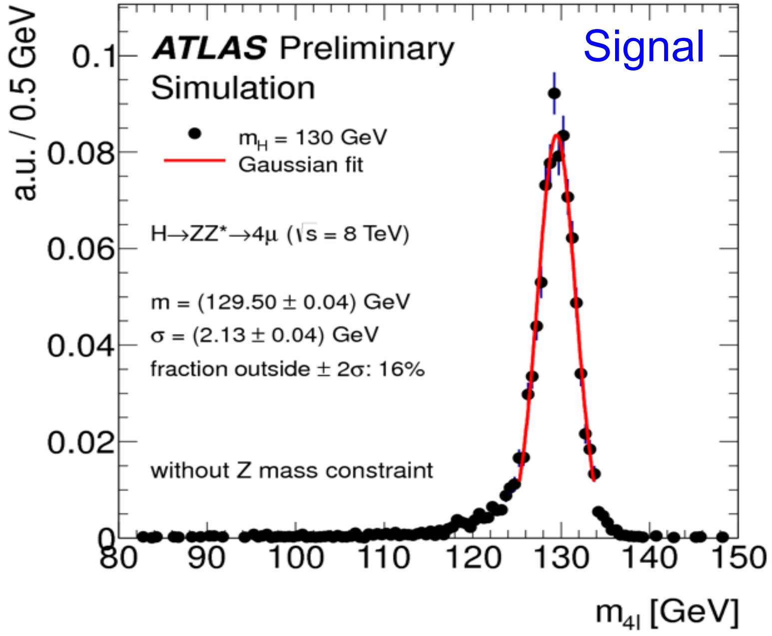
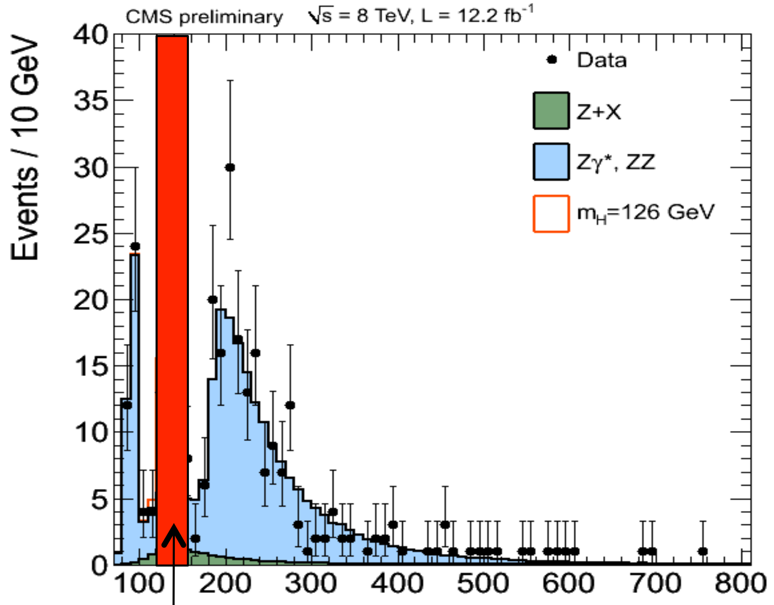


Signal



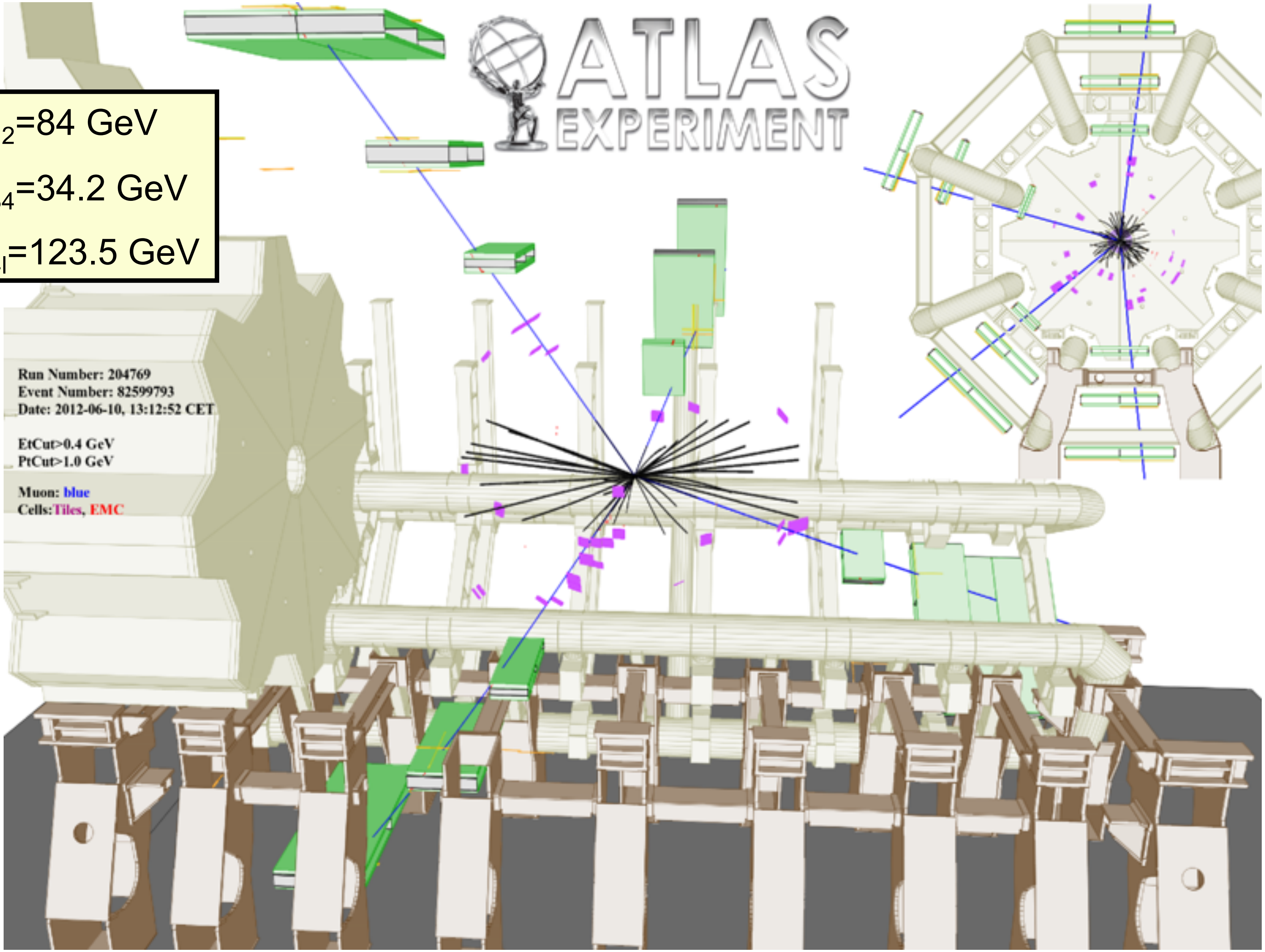
“Blinded”

H→ZZ→4μ Candidate Event

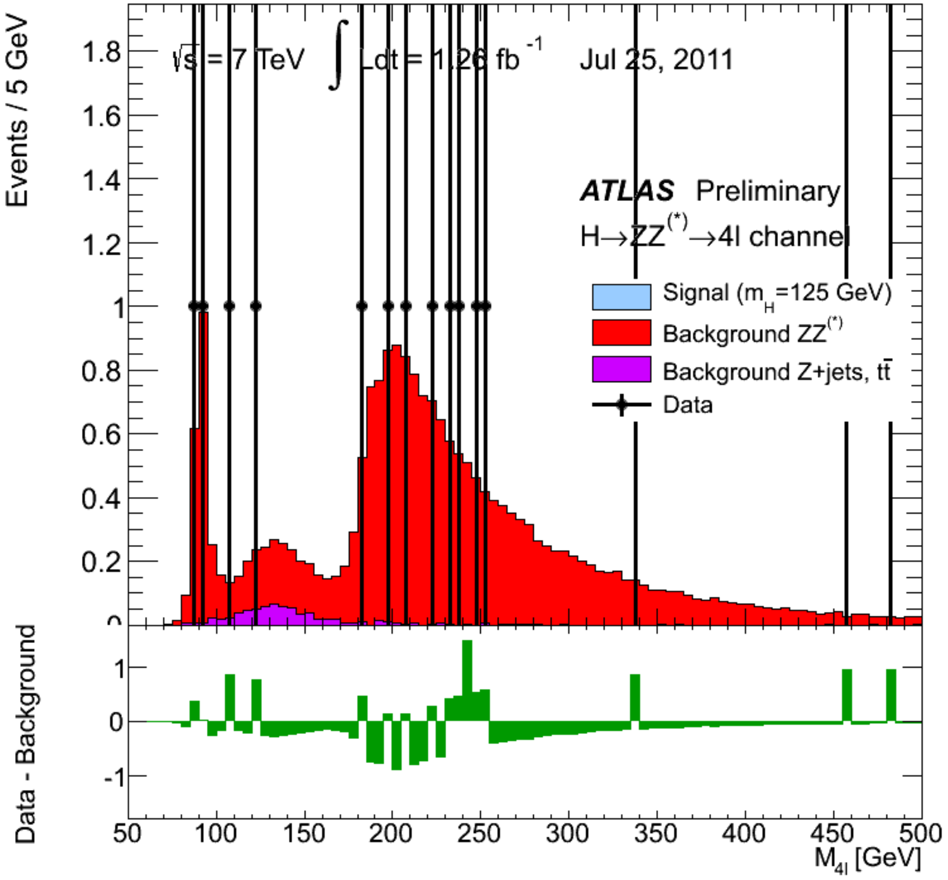
m_{12}=84 GeV

m_{34}=34.2 GeV

m_{4l}=123.5 GeV



The birth of a particle



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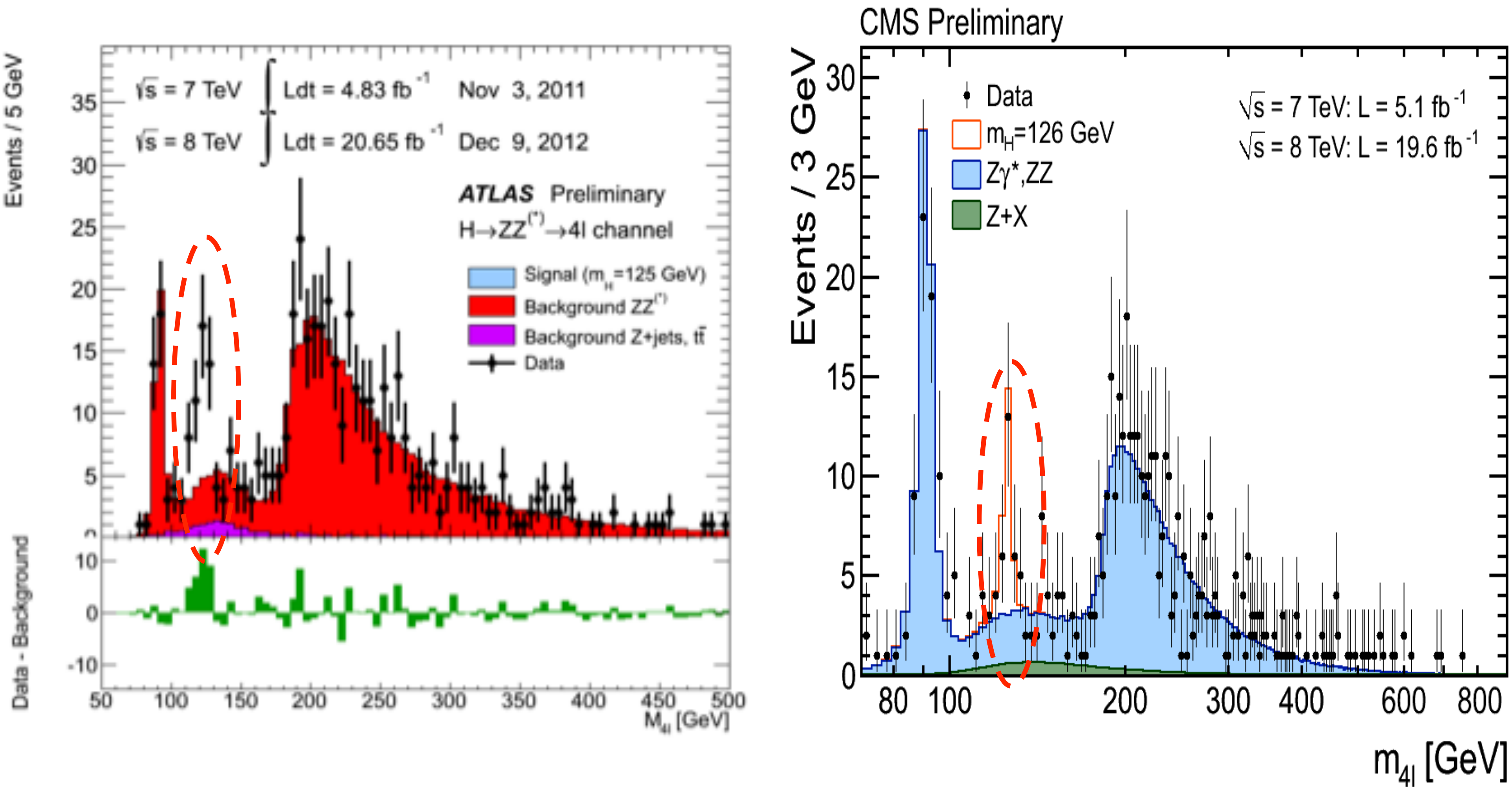


ATLAS and CMS observe signal-like excesses at the same mass (~125 GeV)

Statistical methods

Statistical interpretation

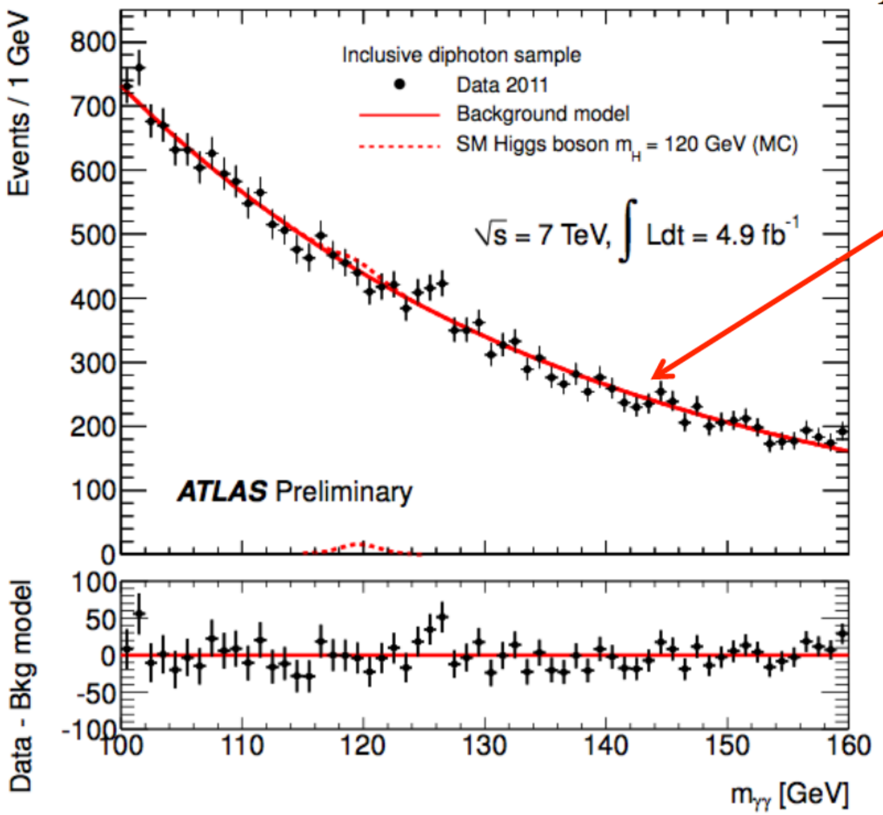
Hypothesis testing using the

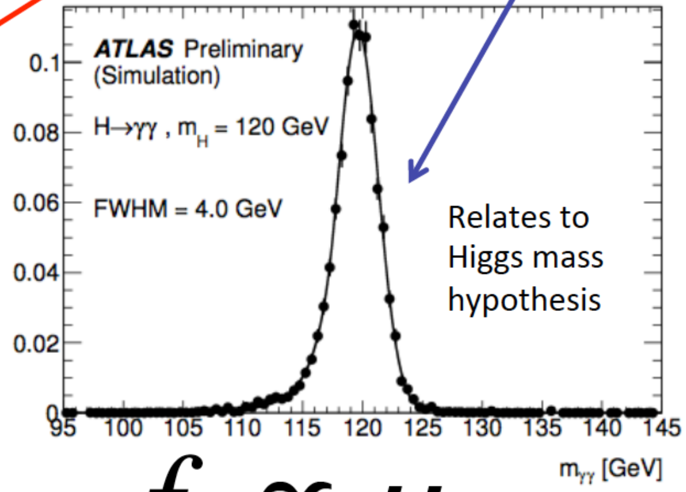
Profile likelihood ratio…

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

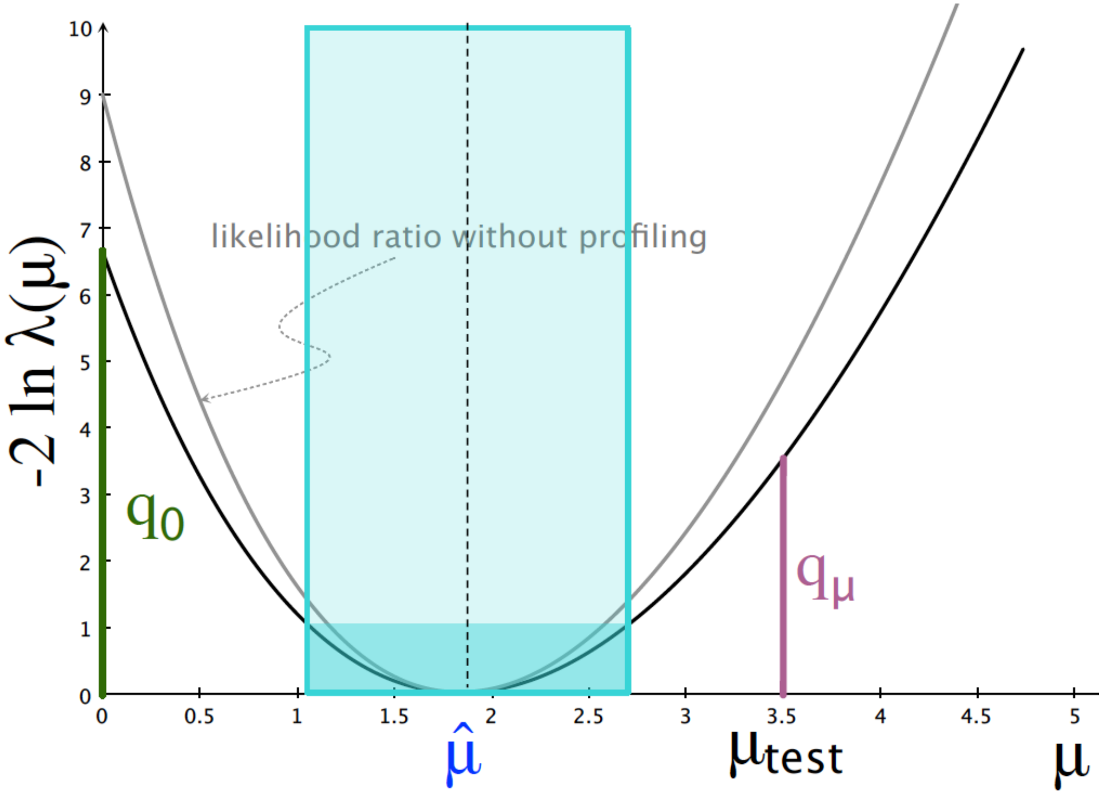
$$n_s = \mu\sigma BrL\varepsilon$$

Profile likelihood ratio

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

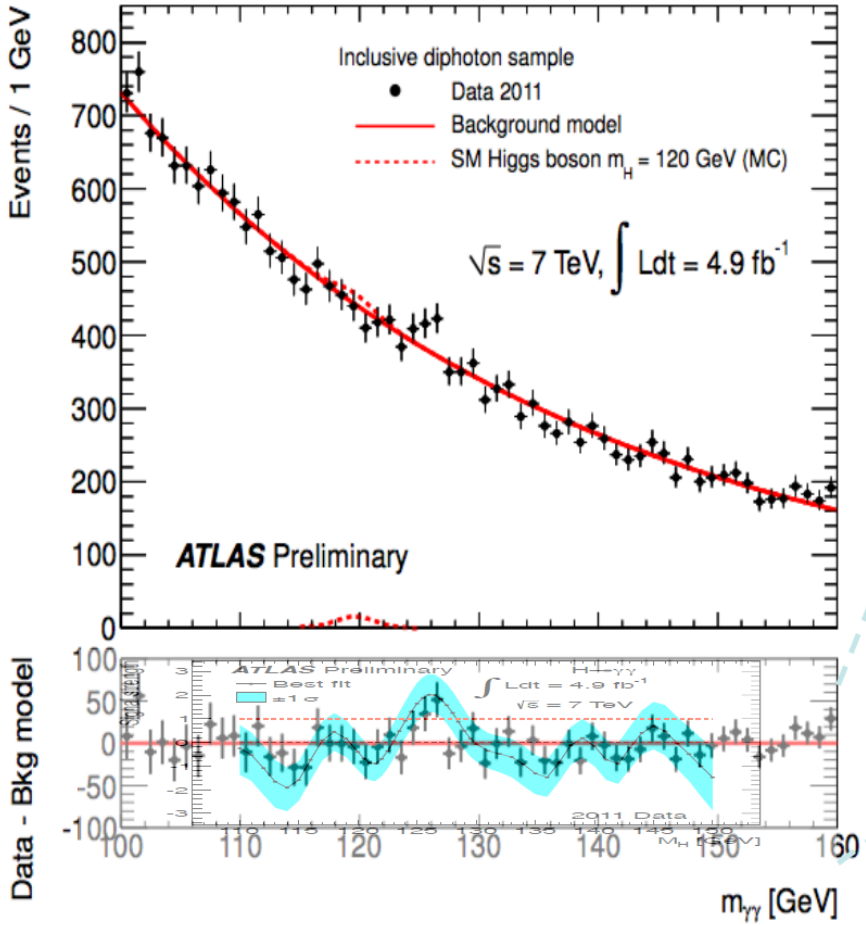
$\mu =$ signal strength

$\theta =$ nuisance parameters parameterizing impact of uncertainties



Fitting signal strength

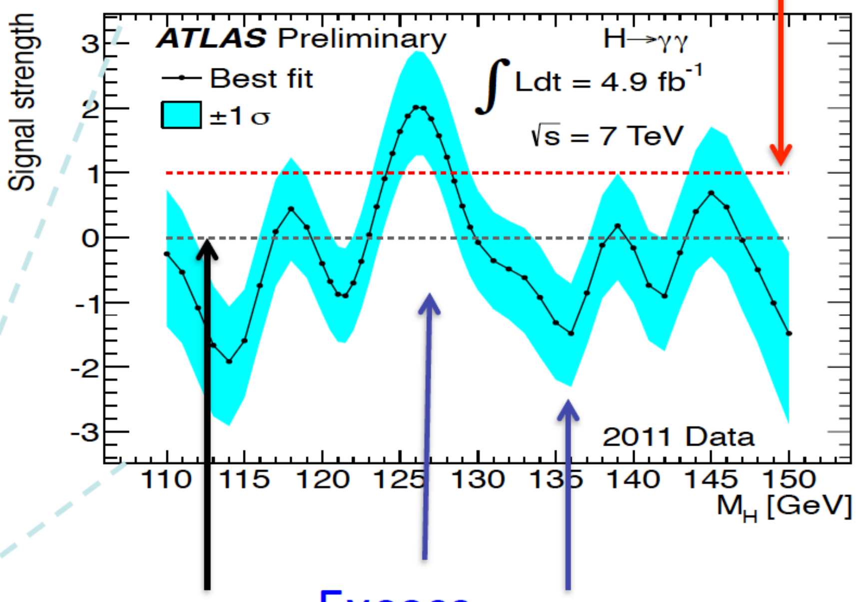
Hypothesis testing using the Profile likelihood ratio…



$\hat{\mu}$

Relate to Higgs mass hypothesis

Expected Signal

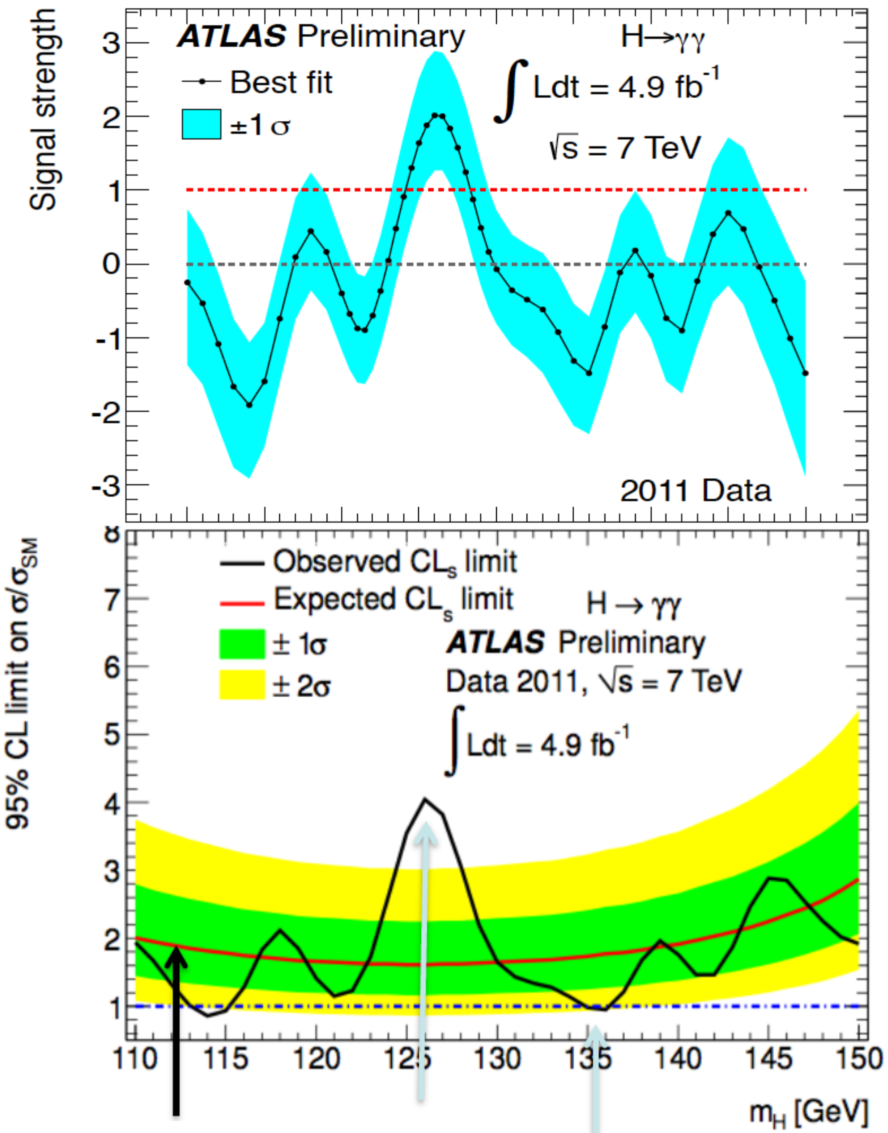


Expected Background

Excess

Deficit

Excluding a signal hypothesis



Median expected limit
(b-only hypothesis)

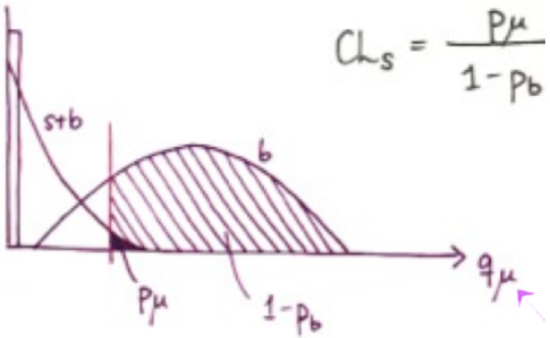
Excess

Deficit

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

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

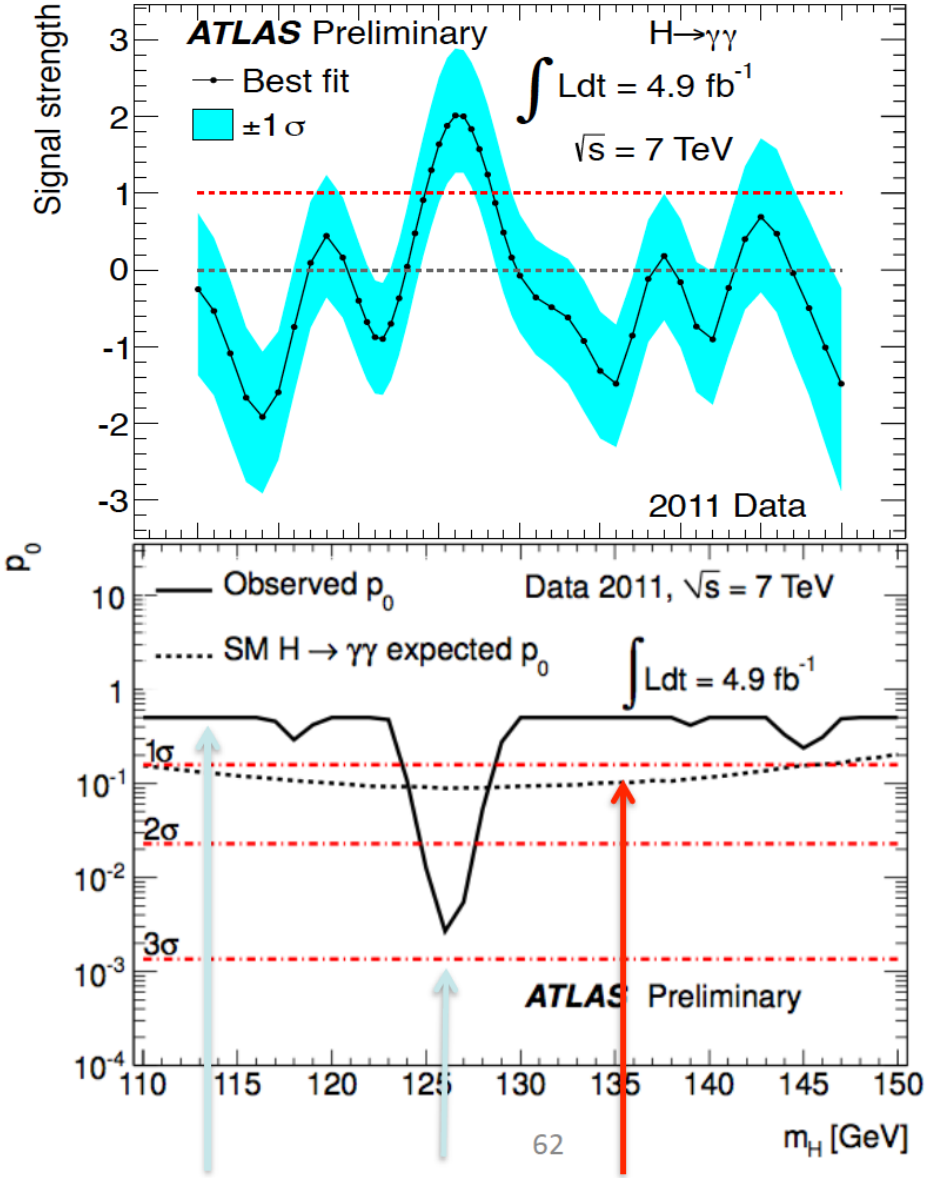
Background likeliness



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 $CL_s<0.05$

Quantifying (local) significance of an excess



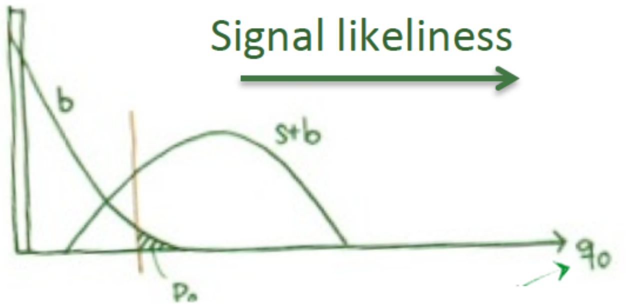
Deficit

Excess

Median expected significance
(s+b hypothesis)

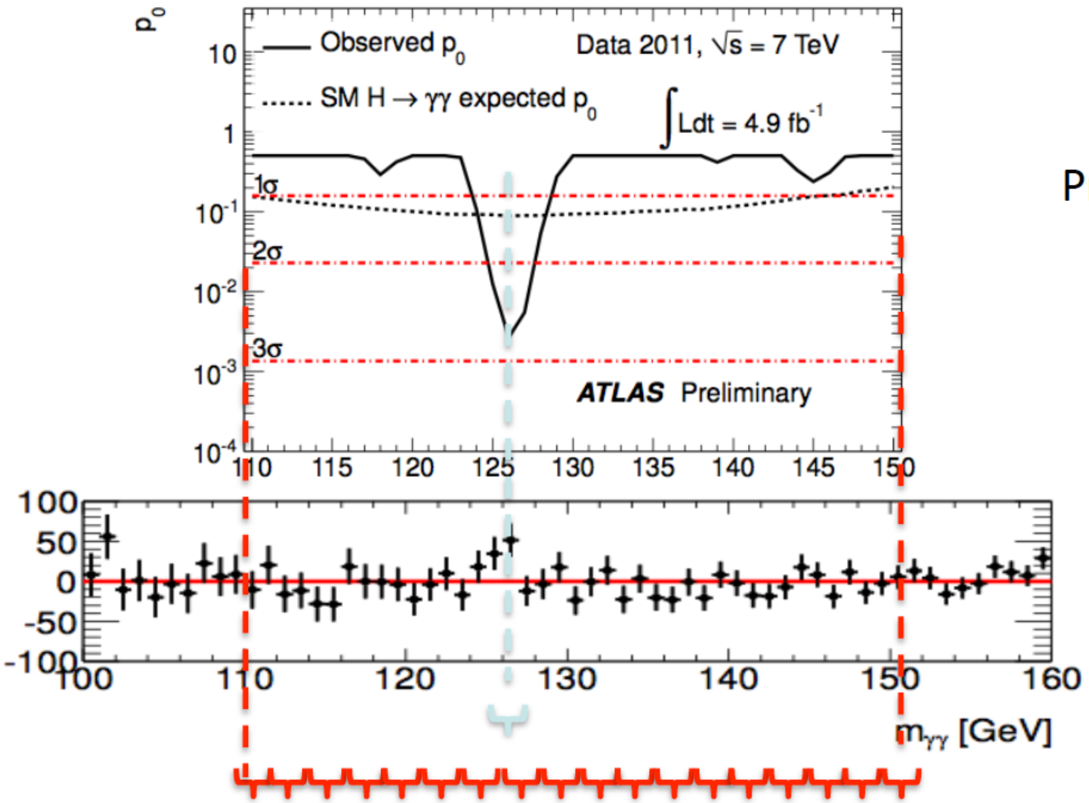
$$\lambda_0 = \lambda(0,\theta) = \frac{L(0,\hat{\hat{\theta}}(0))}{L(\hat{\mu},\hat{\theta})}$$

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



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)…

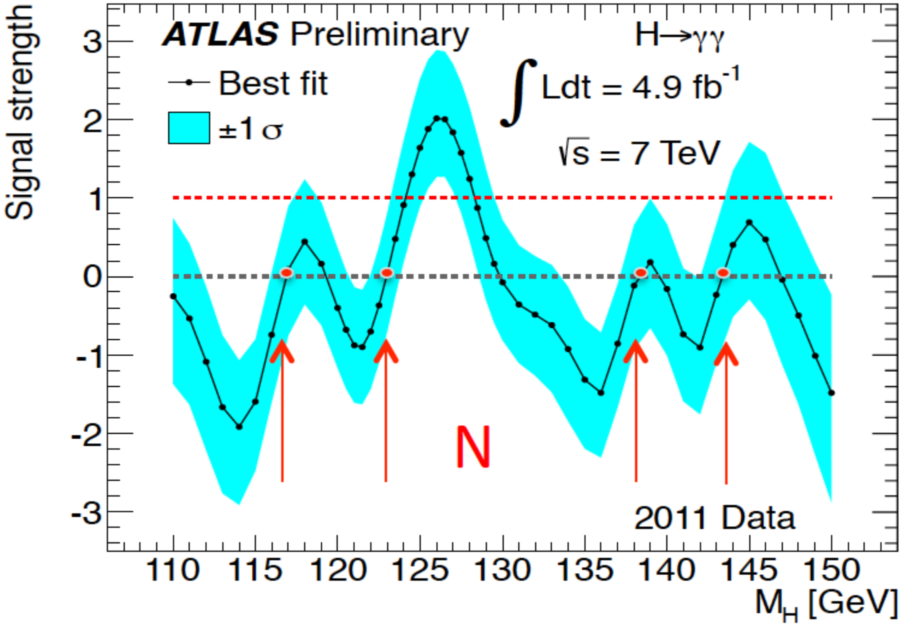
What is the probability of observing an excess at least as large as observed within a mass range ?

a.k.a. "look elsewhere effect"

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)

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

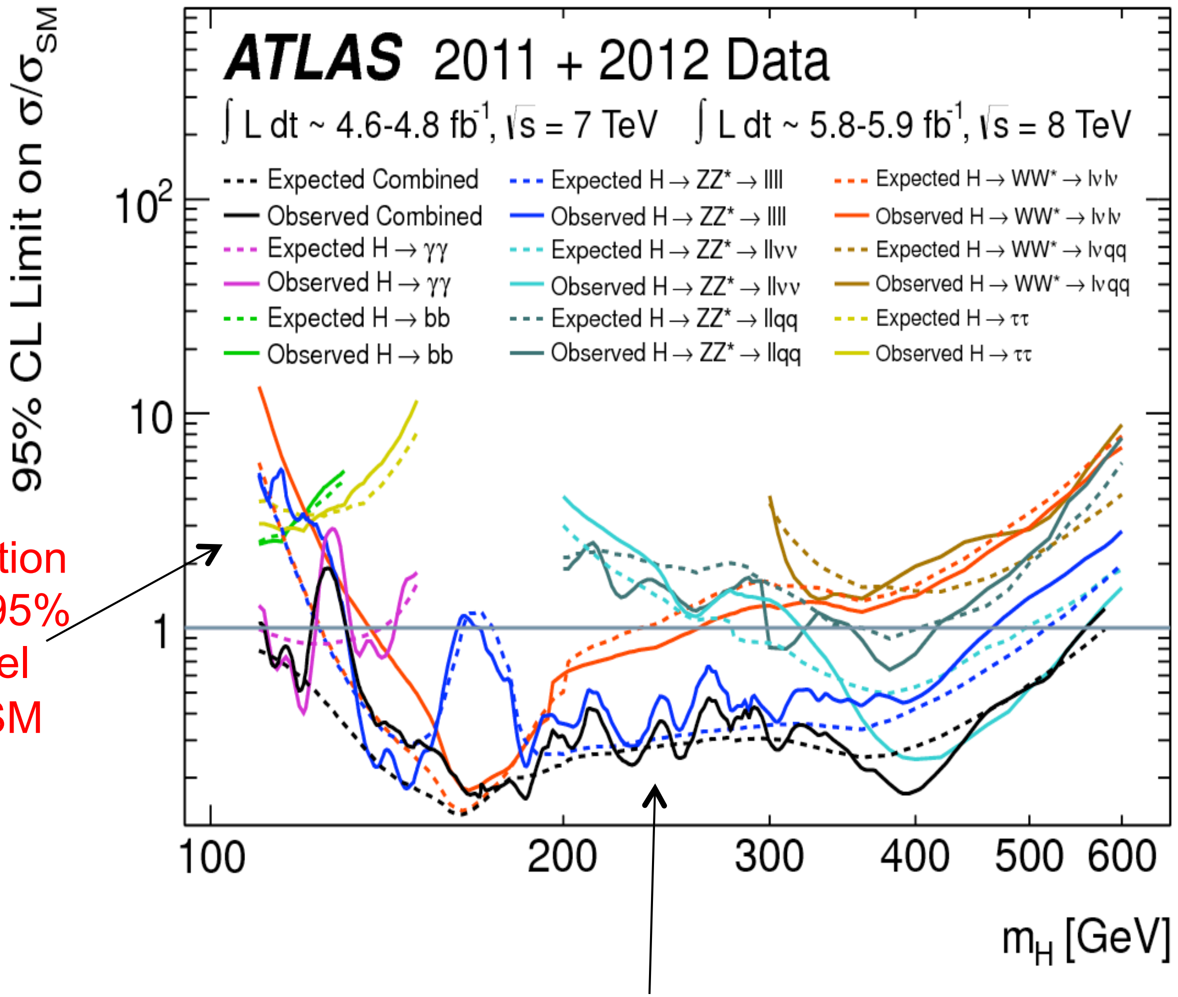
For more details:

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 ($H\rightarrow b\bar{b}$, $H\rightarrow W^+W^-$, $H\rightarrow \tau^+\tau^-$, etc).
- Combination of multiple search channels yields the greatest sensitivity!

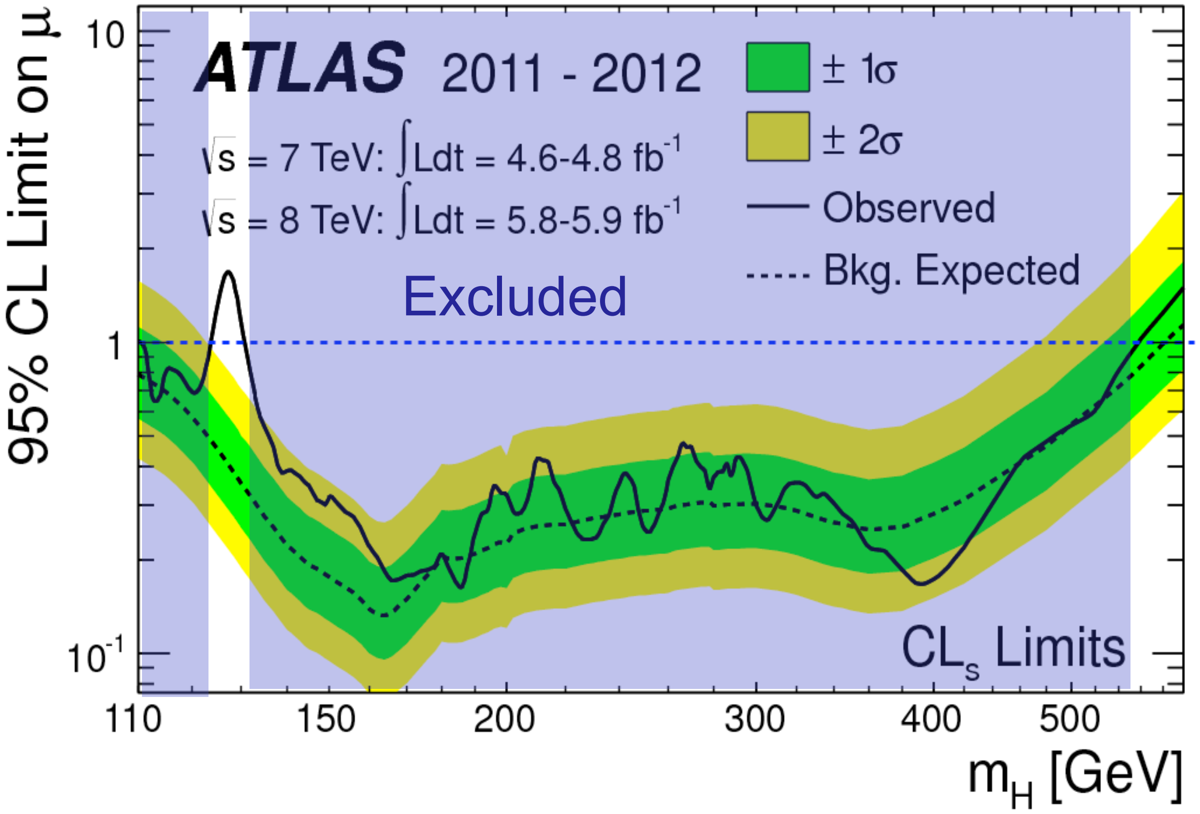


Signal cross section excluded at the 95% confidence level relative to the SM prediction

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

Upper limits on Higgs boson production

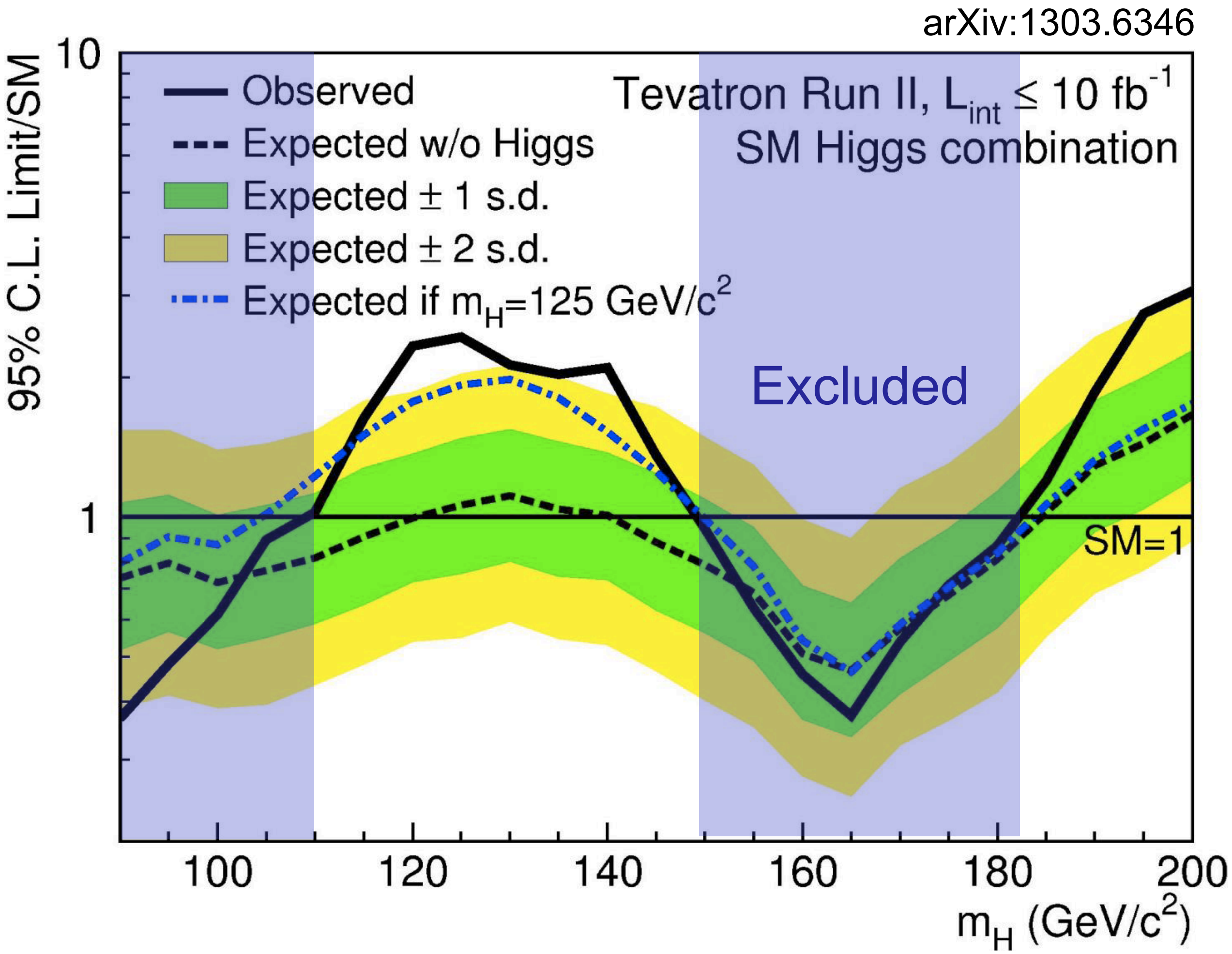


- The ATLAS data is inconsistent with the presence of a SM Higgs boson over a wide range of possible masses!

  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 results



- Expected exclusion: $90 < m_H < 120$ GeV, $140 < m_H < 184$ GeV

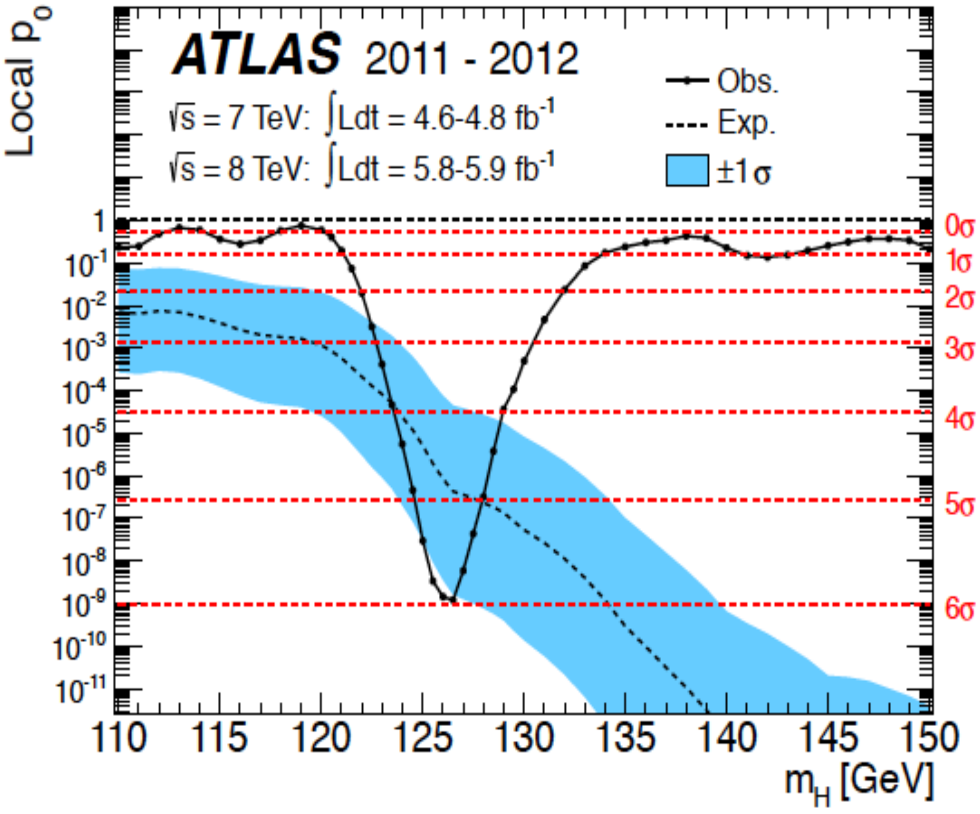
  Observed exclusion: $90 < m_H < 109$ GeV, $149 < m_H < 182$ GeV
- 95% CL limit at m_H=125 GeV: 1.06xSM (expected), 2.44xSM (observed)

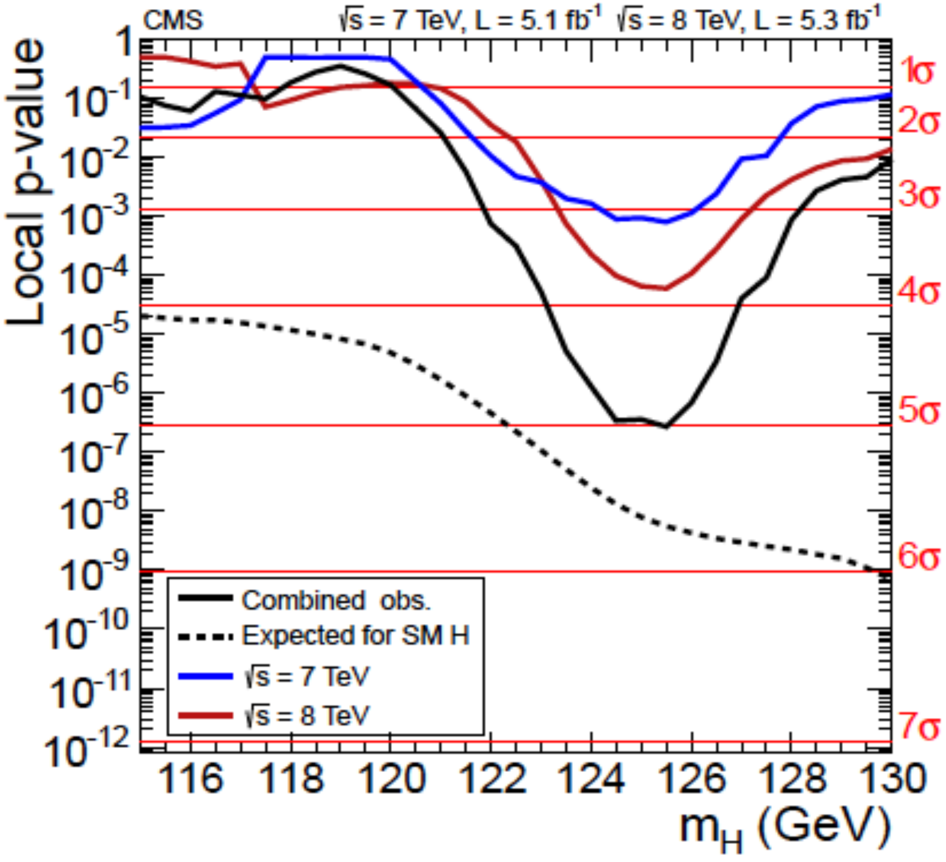
Significance of the results

- 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)





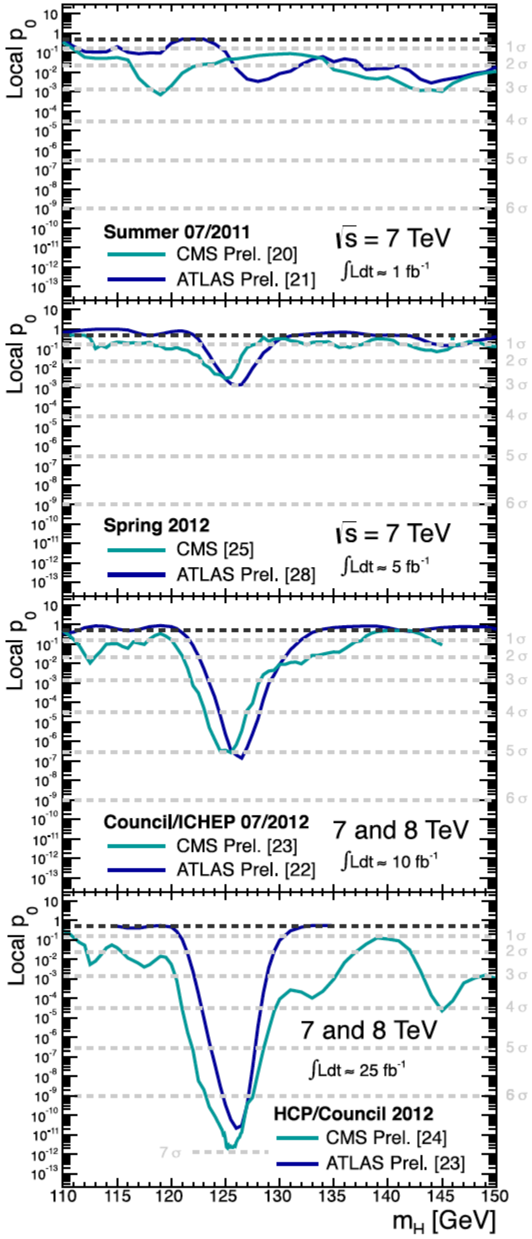
5.9 s.d. at m_H=126.5 GeV

5.0 s.d. at m_H=125.5 GeV

(The analysis of more data since July 4, 2012 has further strengthened the significance)

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

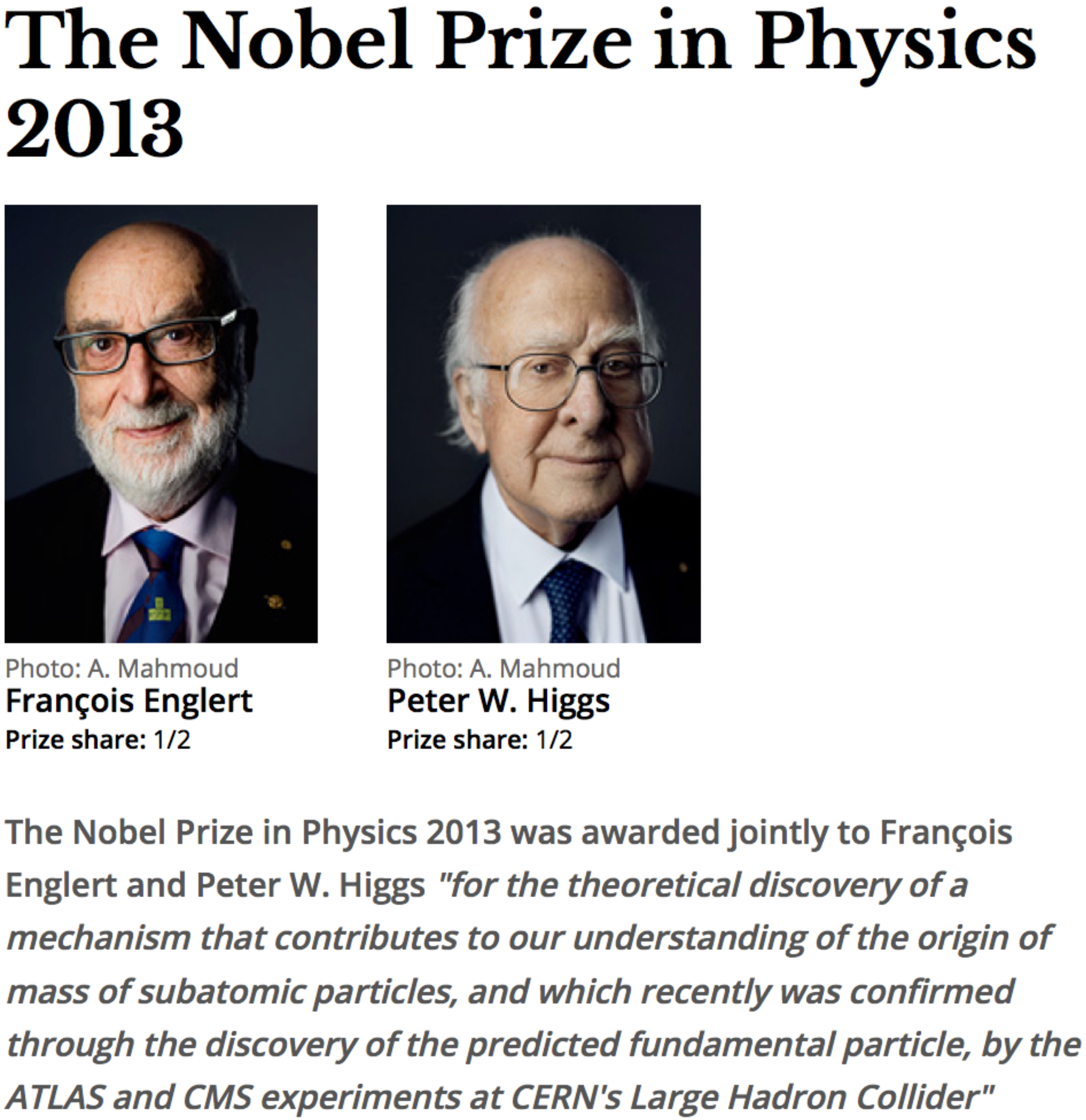
First hints

Summer 2012: CERN Council and ICHEP

Discovery!


Rolf-Dieter Heuer (Director General of CERN)

One year later…



The Nobel Prize in Physics 2013

Photo: A. Mahmoud

François Englert

Prize share: 1/2

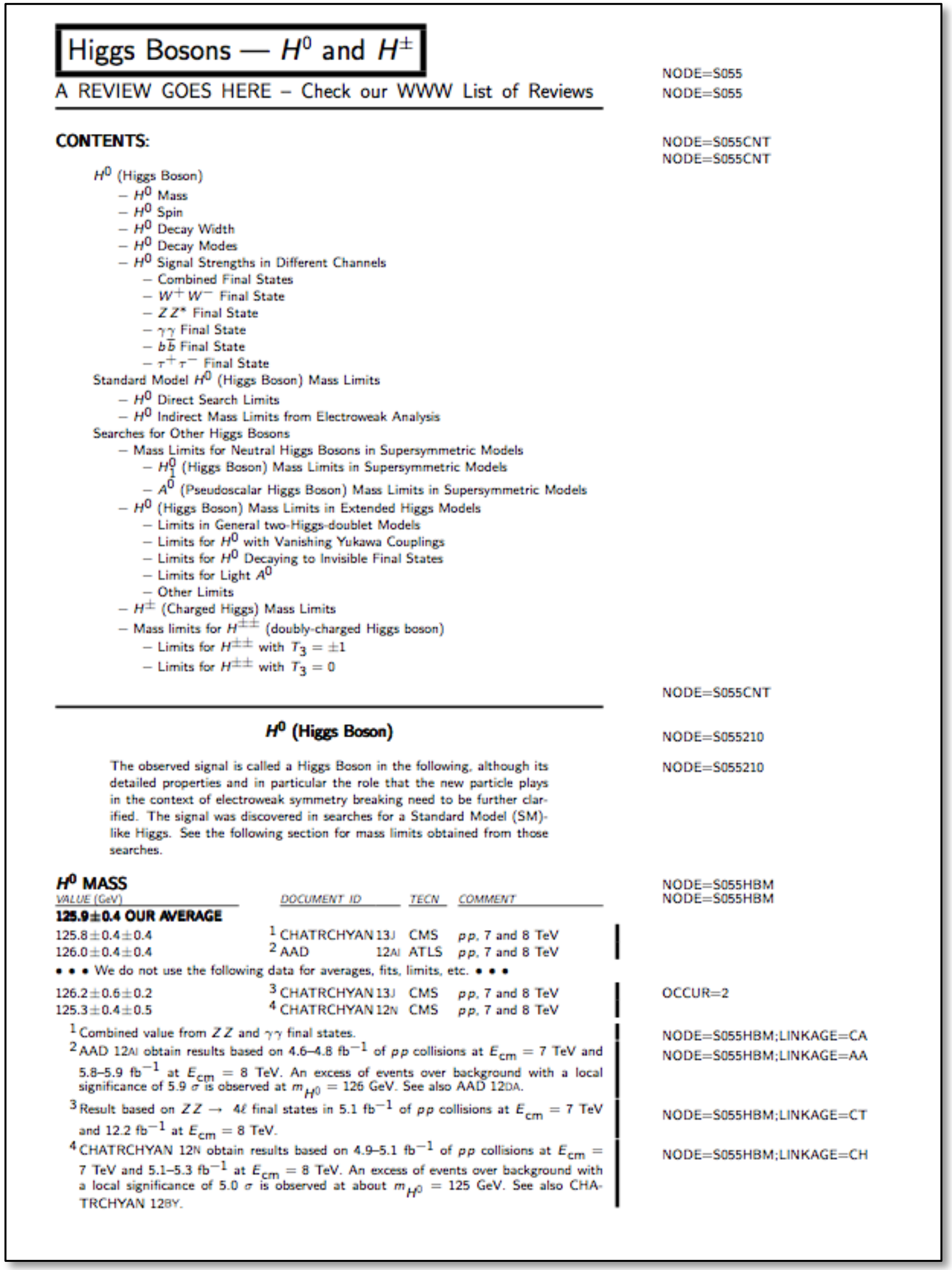
Photo: A. Mahmoud

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

NODE=S055CNT

H^0 (Higgs Boson)

NODE=S055210

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

NODE=S055210

H^0 MASS

NODE=S055HBM
NODE=S055HBM

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

OCCUR=2

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

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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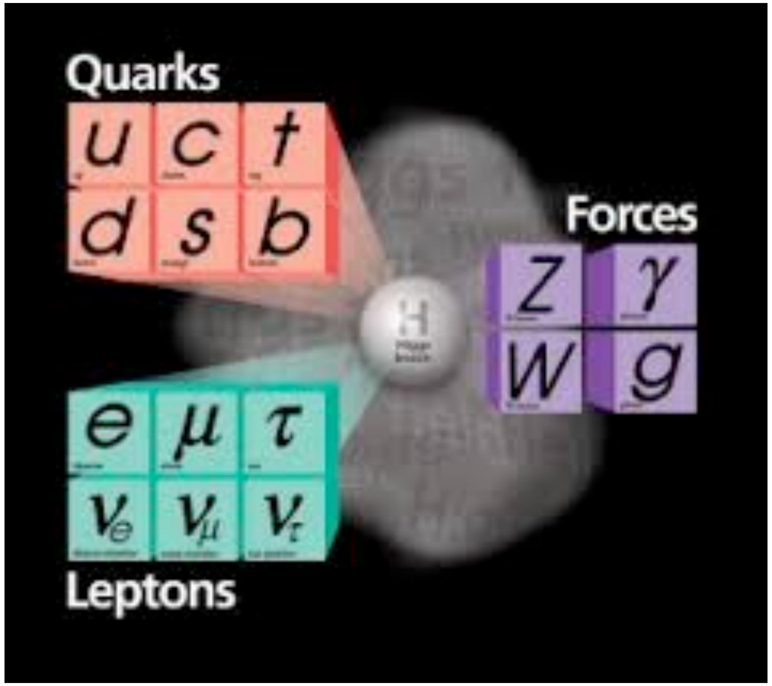
$$H^0$$

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?