The Higgs Particle

Higgs Physics (mostly) at LHC

Marumi Kado

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HASCO Hadron Collider Physcis School

GEORG-AUGUST-UNIVERSITÄT
GÖTTINGEN

HASCO 2013

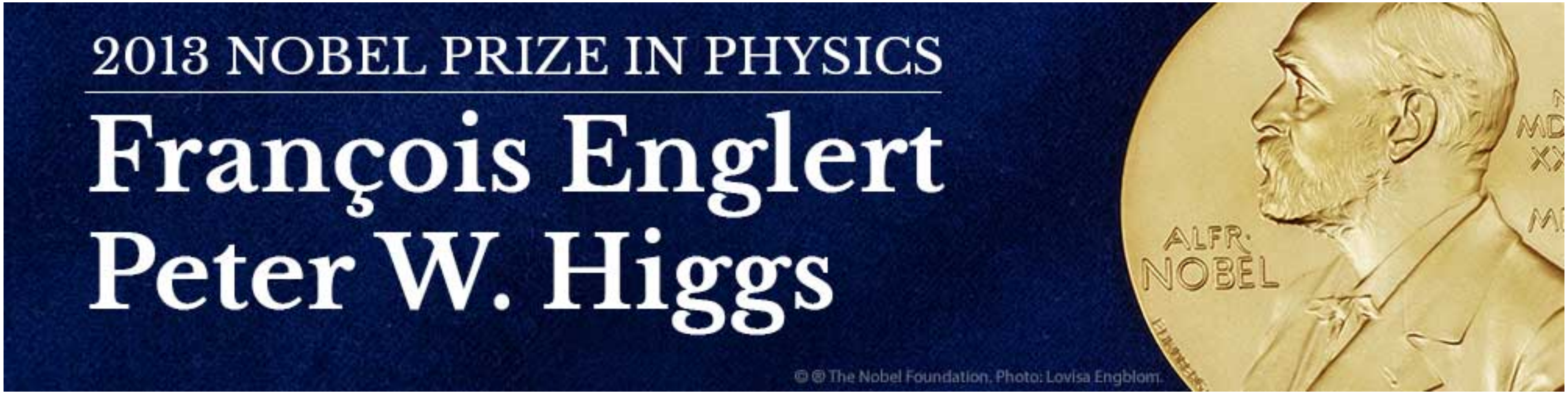
October 8, 2013…

?

Crowning of half a century of theoretical developments and Higgs Hunt ?

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

KUNGL.
VETENSKAPS-
AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES



2013 NOBEL PRIZE IN PHYSICS

François Englert
Peter W. Higgs

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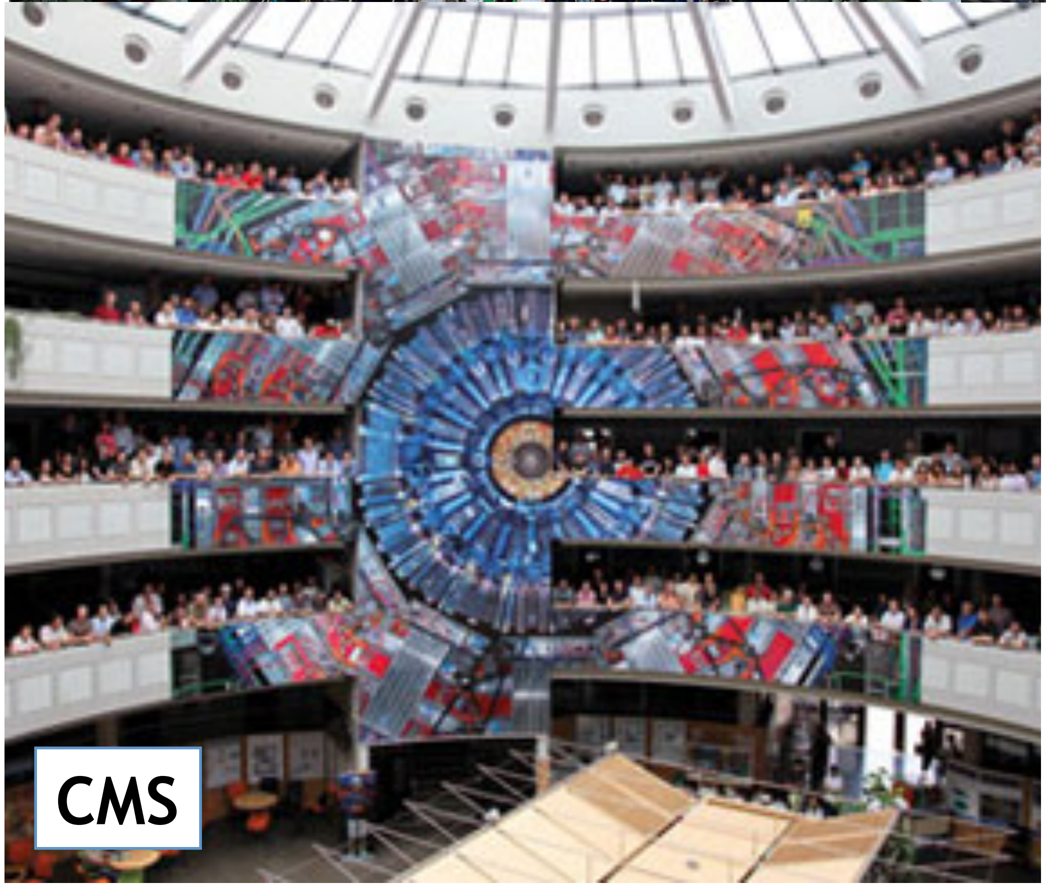
8 October 2013

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

François Englert and Peter Higgs

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



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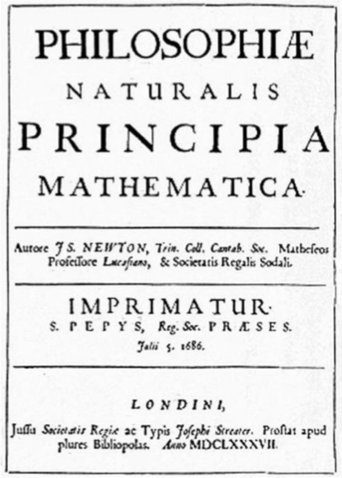
Not the origin of Mass



PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

Autore *JS. 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.

- Gallilean and Newtonian concept of mass :

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

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

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

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

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

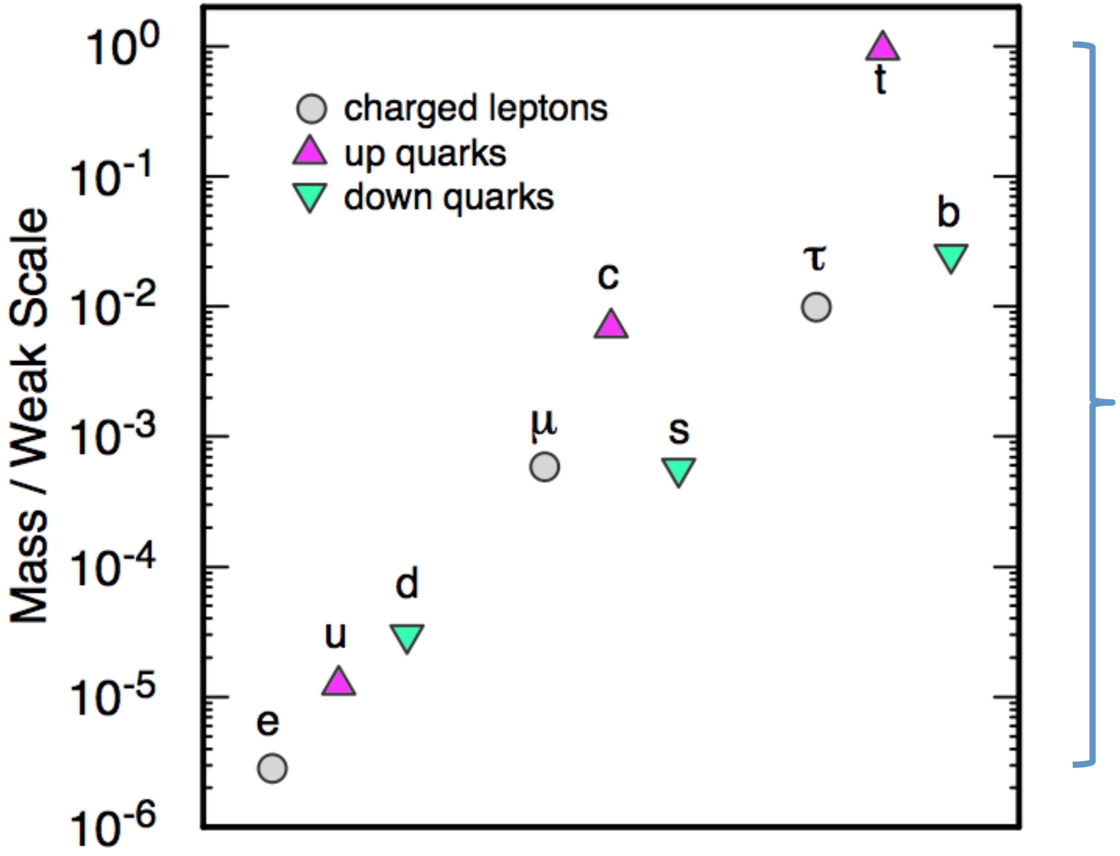
Most of the (luminous) mass in the universe comes from QCD confinement energy

The insight(s) of the BEH mechanism :

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

Not explaining the flavor Hierarchy

Replacing mass terms by Yukawa couplings

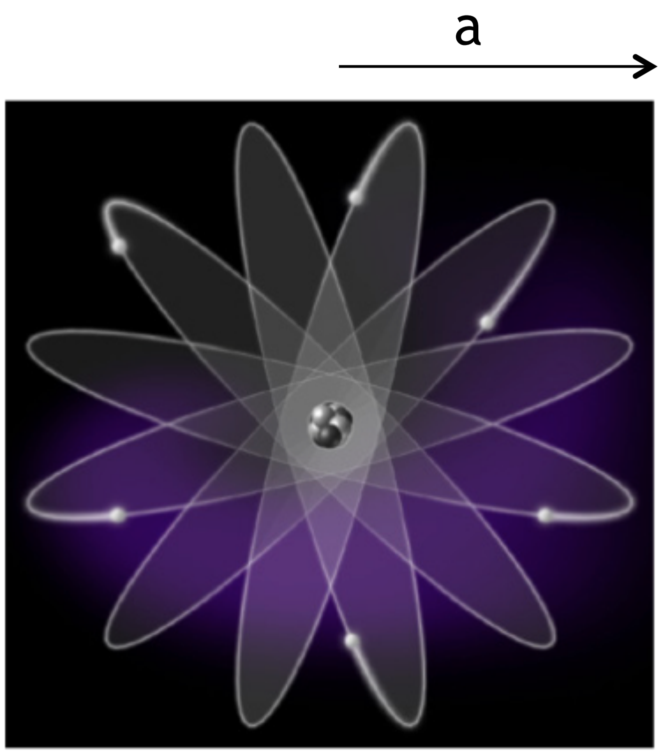


~6 orders of magnitude

Neutrinos are not even on the scale!

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

How Would it Be Without Elementary Particle Masses?



Electron mass (m_e = 511 keV)

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

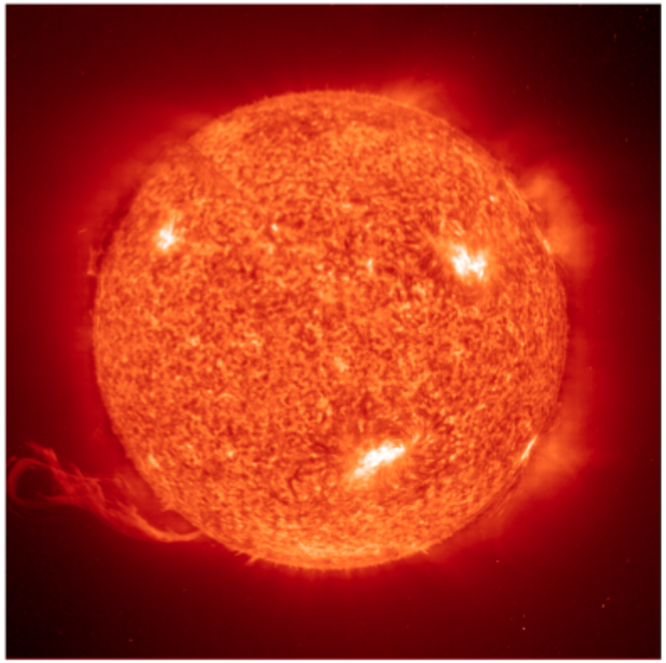
If $m_e = 0$: Then no atomic binding

W boson mass (m_W = 81 GeV)

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

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

Everything would be completely different!



Preamble

Historical context and roots of the Standard Model and Higgs Mechanism

1864-1958 - Abelian theory of quantum electrodynamics

1933-1960 - Fermi model of weak interactions

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

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

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

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

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

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

The Superconductor Analogy

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

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

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

From SC to SSB in Particle Physics

SC (BCS) Theory

1950 – Landau and Ginzburg
JETP 20 (1950) 1064

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

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

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

Particle Theory

1954 - Yang-Mills theories for non abelian gauge interactions

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

… but local gauge symmetry forbids gauge bosons masses.

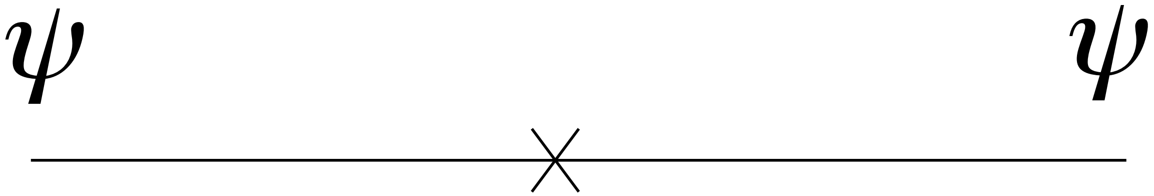
1962 – J. Schwinger
Phys. Rev. 125 (1962) 397
Gauge invariance and mass

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

How Does Mass Appear in a Lagrangian

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

In Terms of Feynman Diagram



1960

Spontaneous Symmetry Breaking (SSB) - Global Symmetry

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

Originates from the work of Landau (1937)

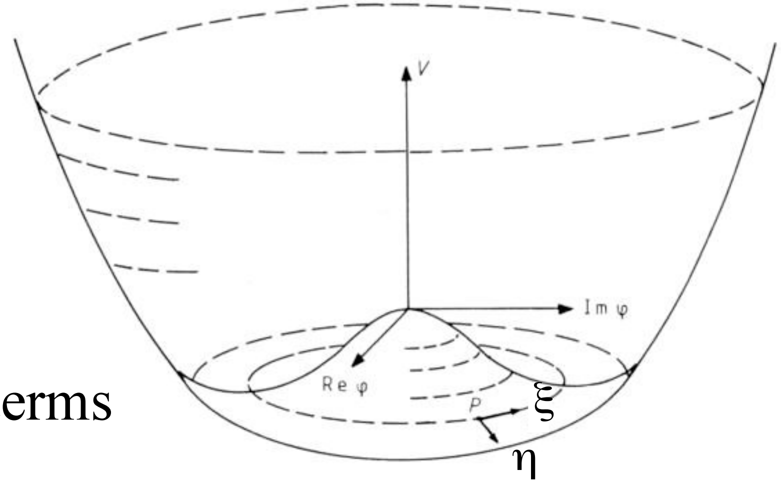
From a simple (complex) scalar theory with a U(1) symmetry

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

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

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

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.

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

Nice but what should we do with these massless salars?

Digression on Chiral Symmetry

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

While conserving the diagonal group $SU(2)_V$ symmetry, the chiral symmetry is broken by means of coherent states of quarks (which play a role similar to the cooper pairs in the BCS superconductivity theory)

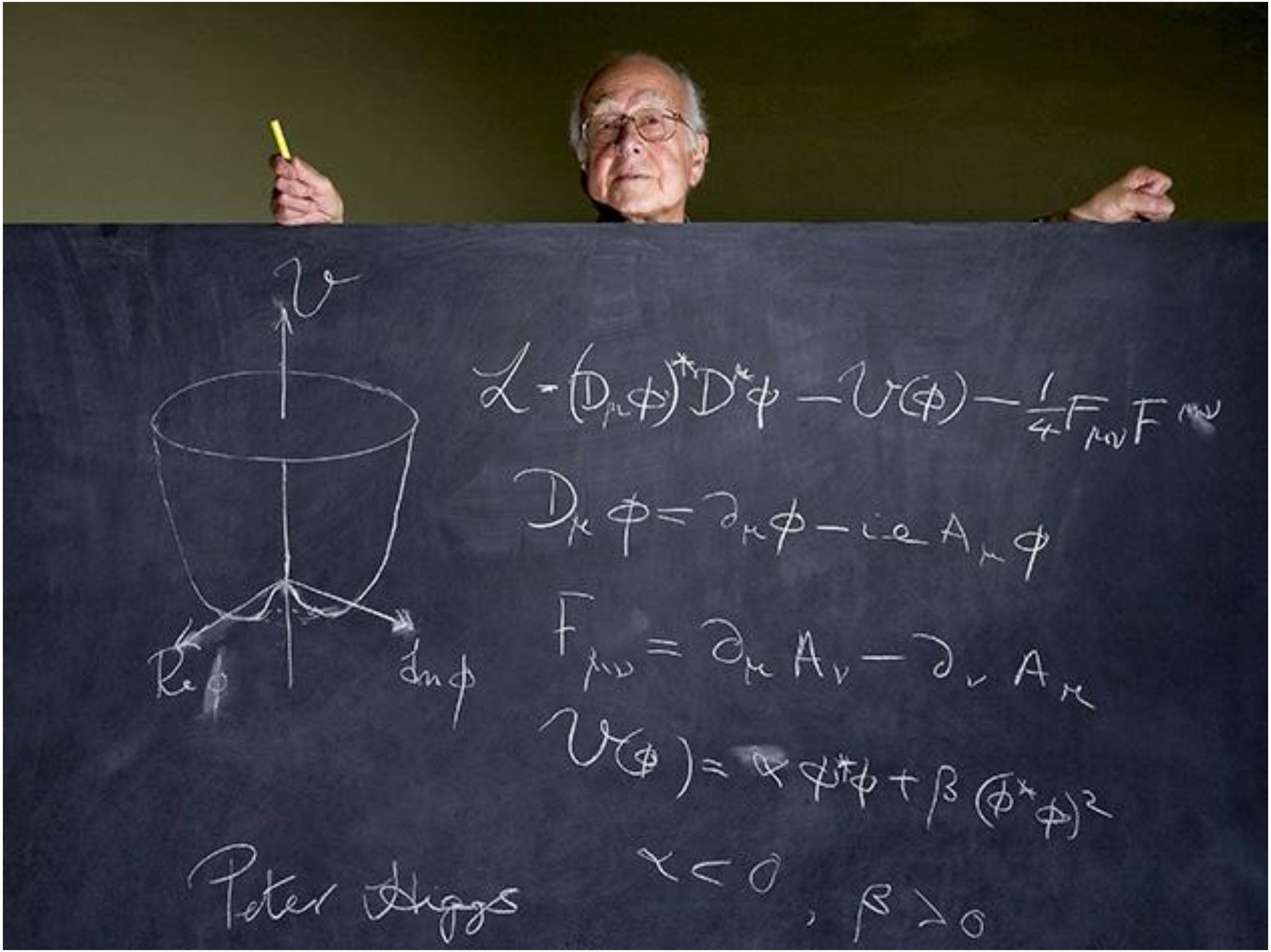
$$SU(2)_L \otimes SU(2)_R \rightarrow SU(2)_V$$

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

And the massive scalar is also there : the sigma!

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

1964



$$\mathcal{L} = (D_\mu \phi)^* D^\mu \phi - V(\phi) - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$D_\mu \phi = \partial_\mu \phi - ie A_\mu \phi$$

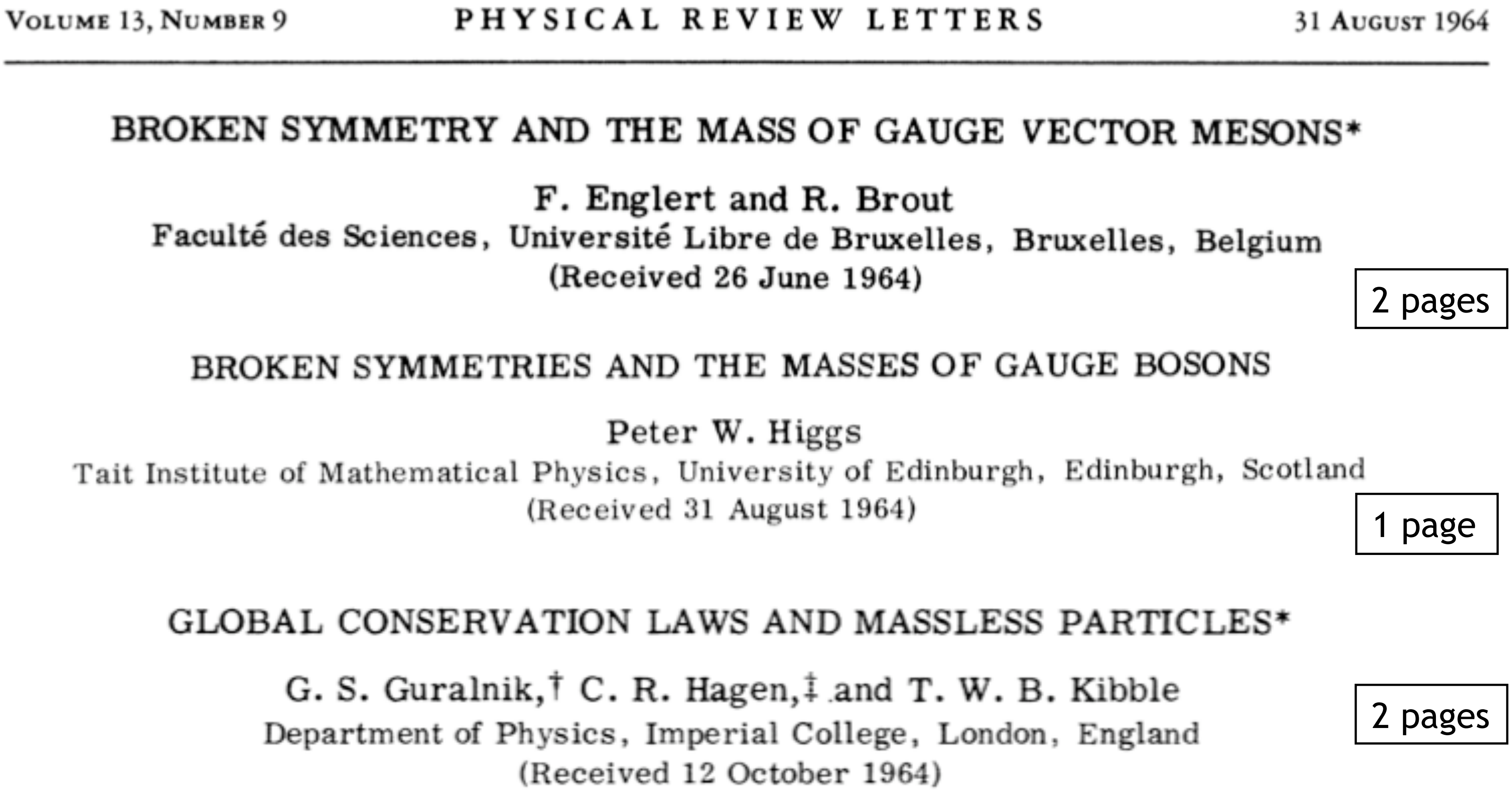
$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

$$V(\phi) = \alpha \phi^* \phi + \beta (\phi^* \phi)^2$$

$$\alpha < 0 \;, \quad \beta > 0$$

Spontaneous Symmetry Breaking (SSB) - Local Symmetry

All the players… in the same PRL issue



VOLUME 13, NUMBER 9 PHYSICAL REVIEW LETTERS 31 AUGUST 1964

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

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

2 pages

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

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

1 page

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

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

2 pages

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

Spontaneous Symmetry Breaking (SSB) Extended to Local Symmetry

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

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

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

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

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

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

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

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

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

Mass term for the gauge field! But…

What about the field content?

A massless Goldstone boson ξ, a massive scalar η and a massive gauge boson!

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

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

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

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

Massive scalar : The Higgs boson

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

Massive gauge boson

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

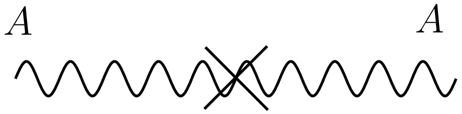
Gauge-Higgs interaction

The Goldstone boson does not appear anymore in the Lagrangian

Before SSB

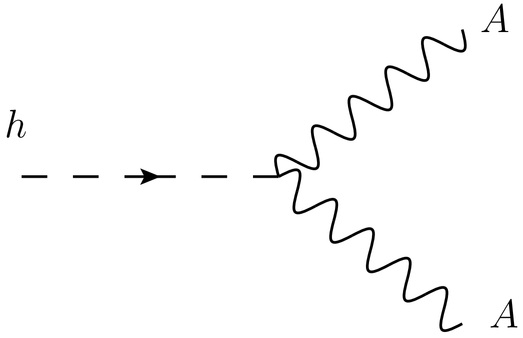
Not gauge invariant

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



Not existing vertex

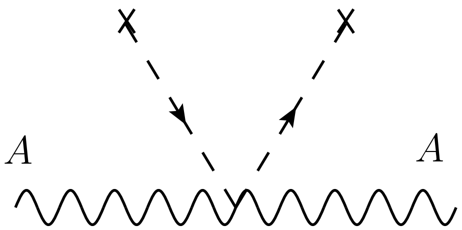
$$A_\mu A^\mu h$$

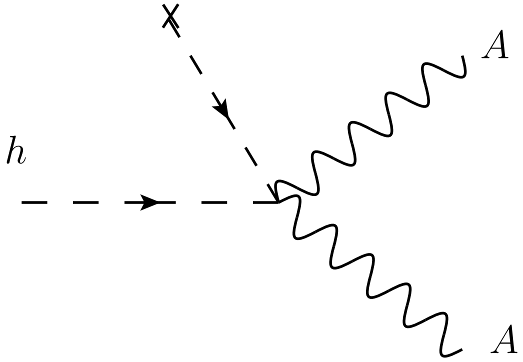


After SSB

Not only existing but also closely related!

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



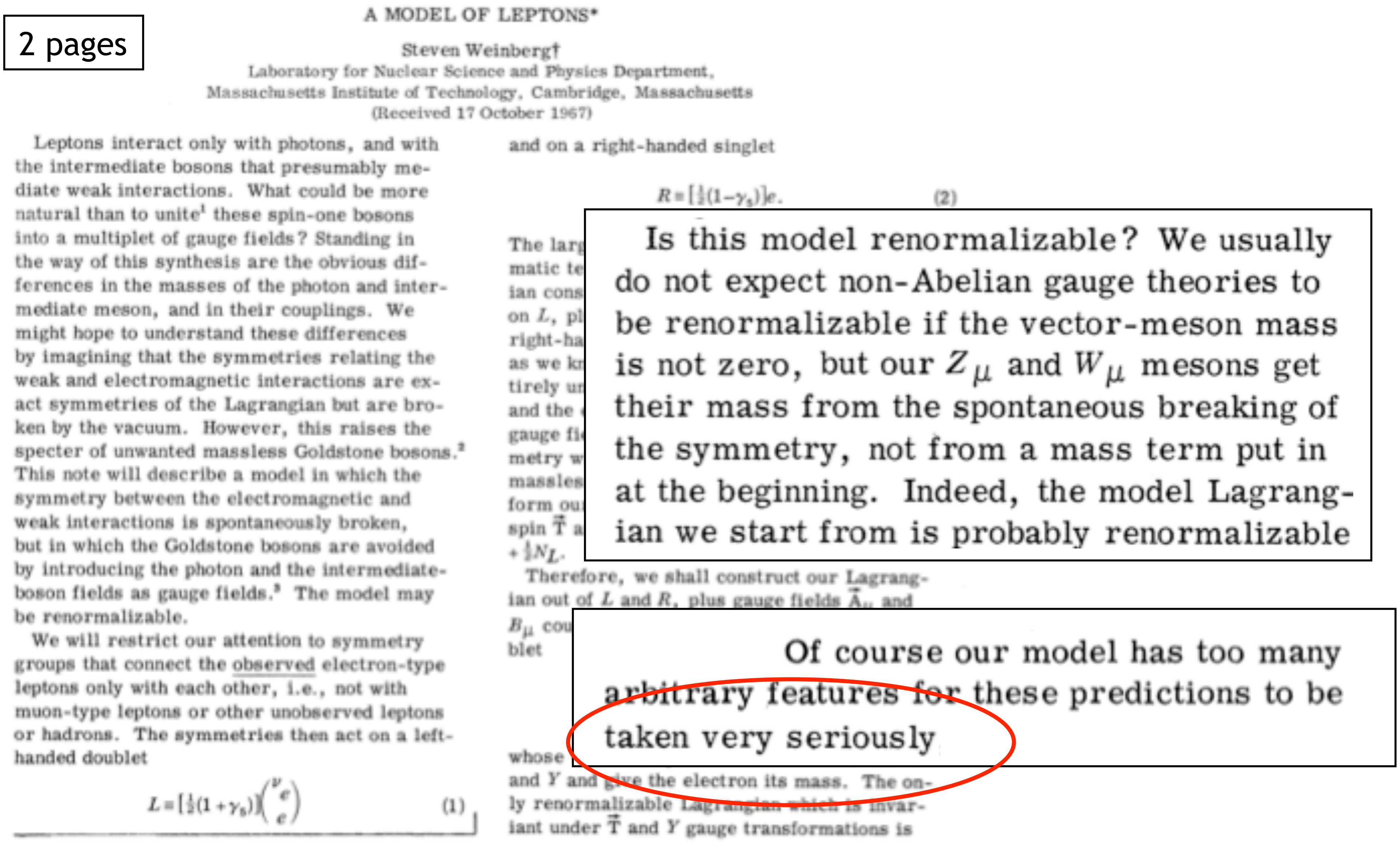


Proof of condensate !

1968

The turning point : Bolting pieces together !

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
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
$+\frac{1}{2}N_L$.

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

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

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

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

Milestone PRL 1967

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

$$\phi = \frac{1}{\sqrt{2}} \left(\begin{array}{c} \phi^+ \\ \phi^o \end{array} \right)$$

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

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

The next step is to develop the Lagrangian near : $$< \phi >= \frac{1}{\sqrt{2}} \left(\begin{array}{c} 0 \\ v \end{array} \right)$$

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

$$\phi = e^{-i\vec{\sigma}.\vec{\xi}} \frac{1}{\sqrt{2}} \left(\begin{array}{c} 0 \\ H + v \end{array} \right)$$

In particular for a non charged vacuum

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

Then developing the covariant derivative for the Higgs field :

Just replacing the Pauli matrices :

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

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

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

For the mass terms only :

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

Explicit mixing of W^3 and B.

Finaly the full Lagrangian will then be written :

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

Massive scalar : The Higgs boson

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

Massive gauge bosons

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

Gauge-Higgs interaction

In order to derive the mass eigenstates :

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

Where

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

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

Dynamical Symmetry Breaking and Technicolor

Could the pions dynamicaly break the EW symmetry?

Nice - Custodial symmetry protects $\rho = 1$

No
- Disappear from the physical spectrum (longitudinal components of gauge bosons)
- insufficient mass generaion e.g. : m_W = 30 MeV (vev too small, set for pion interactions)

In order to generate sufficiently high gauge boson masses with a dynamical EWSB, need :

Technicolor
- Additional fermions
- Larger group : strong interaction at EW scale

No fundamental scalars in the theory as the EWSB is dynamically done by fermion condensates… (very appealing)

Most simple models of technicolor are disfavored by EW precision data

The sector of Fermions (kinematic)

Another important consequence of the Weinberg Salam Model…

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

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

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

Fermion mass terms are forbidden

Not the case for Yukawa couplings to the Higgs doublet

Then after SSB one recovers :

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

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

Very important : The Higgs mechanism DOES NOT predict fermion masses

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

But wait…

The coupling to the Higgs fields is the following :

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

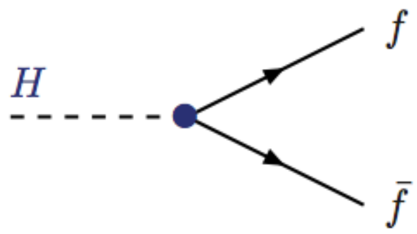
Can be seen as giving mass to down type fermions…

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

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

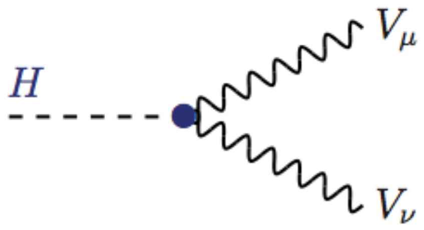
One doublet of complex scalar fields is sufficient to accommodate mass terms for gauge bosons and fermions !

... But not necessarily only one!



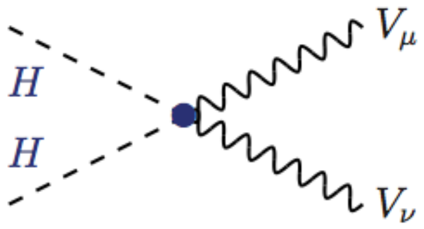
$$g_{Hff} = m_f/v$$

Gauge-Higgs and interactions



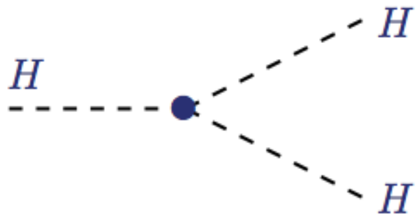
$$g_{HVV} = 2M_V^2/v$$

Proof of condensate !



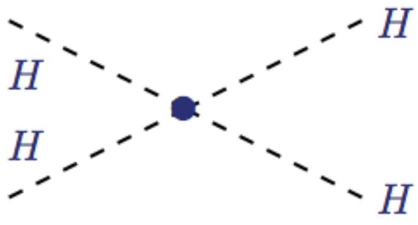
$$g_{HHVV} = 2M_V^2/v^2$$

Keep this in mind for the next lecture…



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

More directly testable relations!



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

Prediction of the Model

Beside the existence of the Z massive neutral gauge boson…

The existence of a massive scalar :

The Higgs Particle

Whose mass (as λ) **was** an unknown parameter of the theory

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

Historical review of including quantization and renormalization in
J. Zinn-Justin (Higgs Hunting 2010)

The first very important consequences of this mechanism :

1.- Two massive charged vector bosons :

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

Corresponding to the observed charged currents

Thus v = 246 GeV

Given the known W mass and g coupling

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

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

3.- One massive neutral vector boson Z :

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

4.- One massive scalar particle : The Higgs boson

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

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

Which of these consequences are actually predictions ?

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

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

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

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

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

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

or

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

Prediction of the Model

Beside the existence of the Z massive neutral gauge boson…

$$\rho = 1$$

Protected by cutsodial symmetry

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

F. Wilczek at the LEP Celebration :

The Higgs mechanism is corroborated at 75%

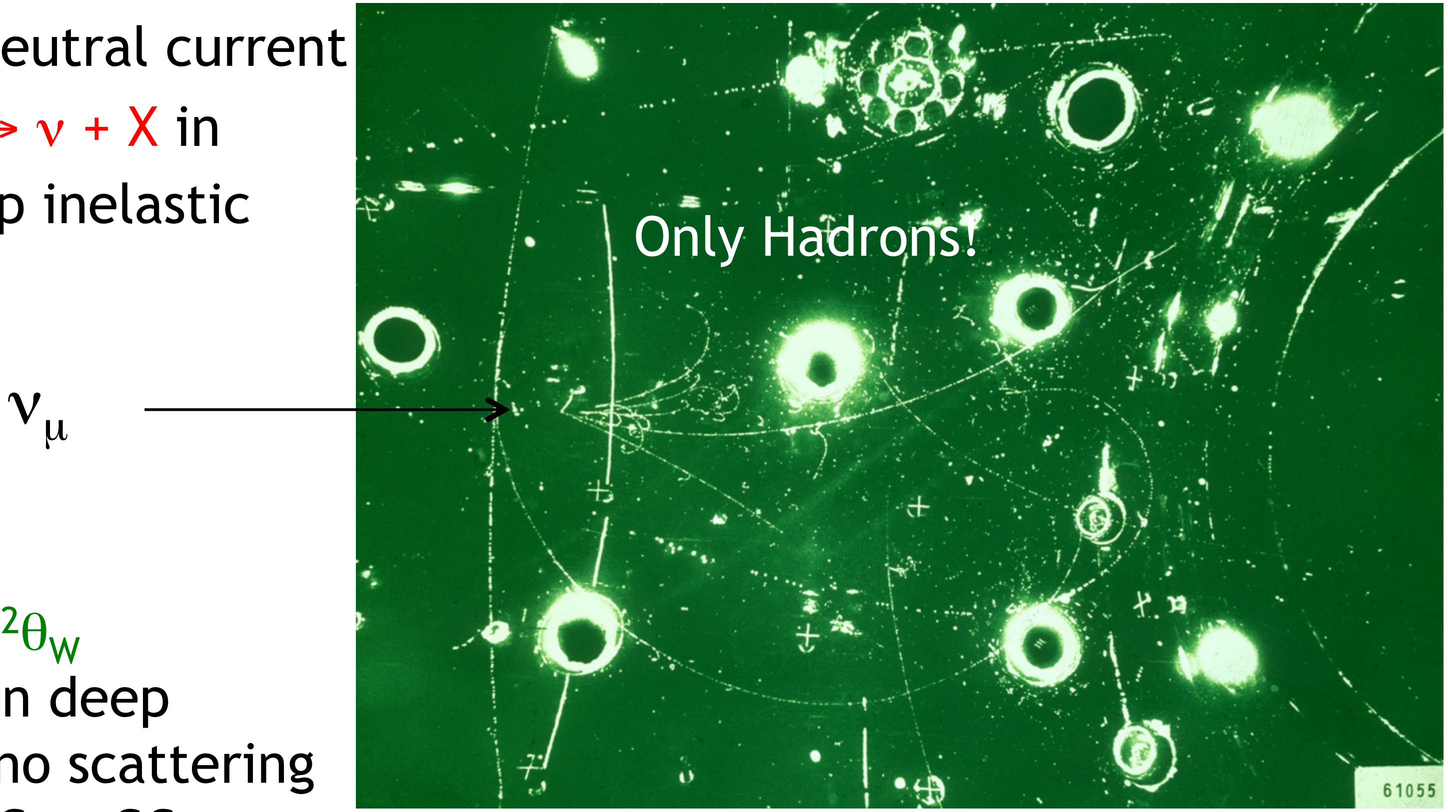
1973

Corroboration

The Neutral 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)

What about the Higgs? First Bounds

Astrophysical and Phenomenological

- Effect on Cosmic Microwave background ($0.1\ \text{eV} < m_H < 100\ \text{eV}$)
  (Sato and Sato, 1975)

- Emission from stars: $m_H > 0.7\ m_e$
  (Sato and Sato, 1975)

- Neutron-electron scattering: $m_H > 0.7$ MeV
  (Rafelski, Muller, Soff and Greiner; Watson and Sundaresan,1974)

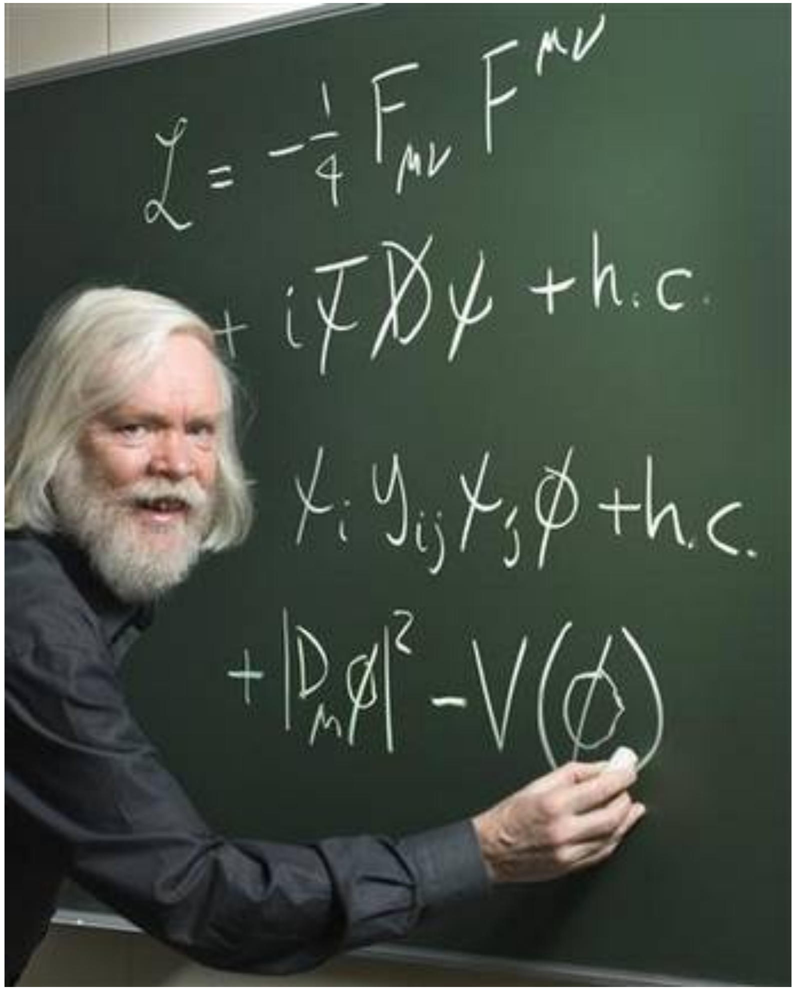
- Neutron-electron scattering: $m_H > 0.7$ MeV
  (Adler, Dashen and Treiman; 1974)

- Neutron-nucleus scattering: $m_H > 13$ MeV
  (Barbieri and Ericson, 1975)

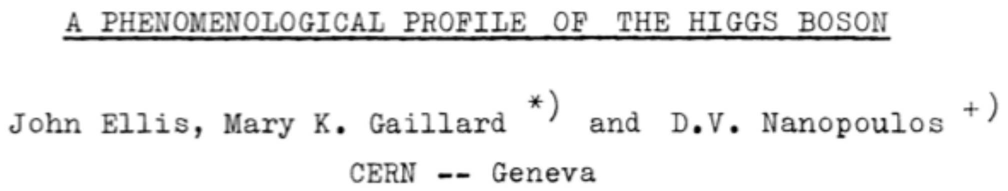
- Nuclear ^{16}O(6.05 MeV) to ground state ($0^+ – 0^+$) transitions (can occur through Higgs emission): $m_H > 18$ MeV
  (Kohler, Watson and Becker, 1974)

1976

The birth of Higgs physics



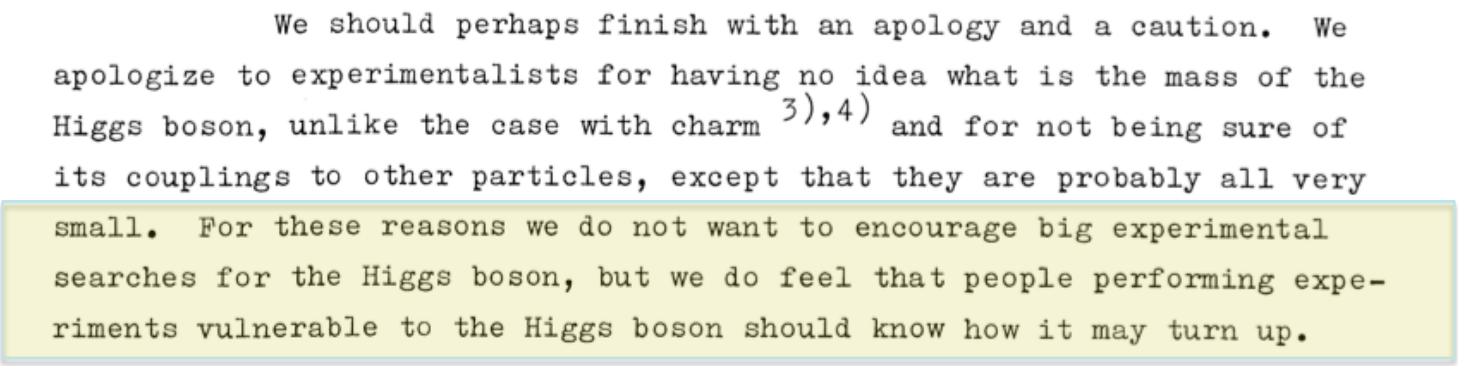
1976



A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

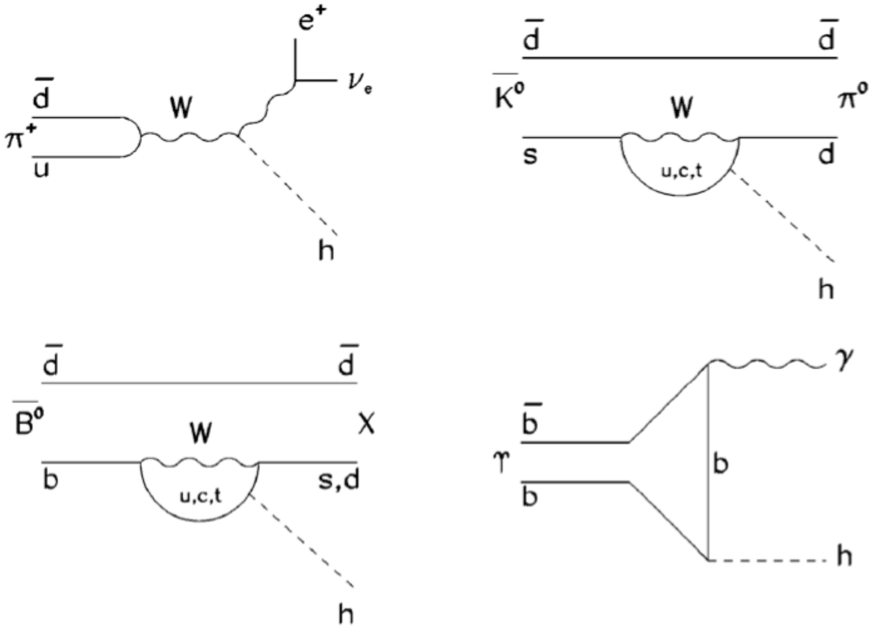
John Ellis, Mary K. Gaillard *) and D.V. Nanopoulos +)
CERN -- Geneva

The Roadmap



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

Pre-LEP Bounds



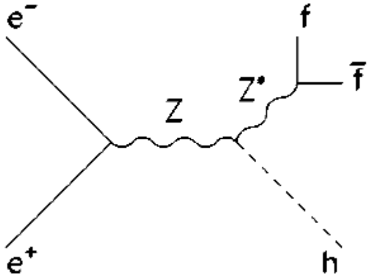
- SINDRUM Collaboration measured π to ev H (ee) Yielding a limit on very light Higgs
- CUSB Collaboration Υ to Hγ yielding limit of ~ 5-6 GeV (dependent on high order corrections)
- Jade and CLEO provided bounds on B to μμ+X
- CERN-Edimbrgh-Orsay-Mainz-Pisa-Siegen K to π H (ee) below ~50 MeV
- Electron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

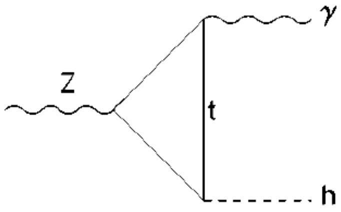
Absolute Lower Limit on the Higgs Mass at LEP

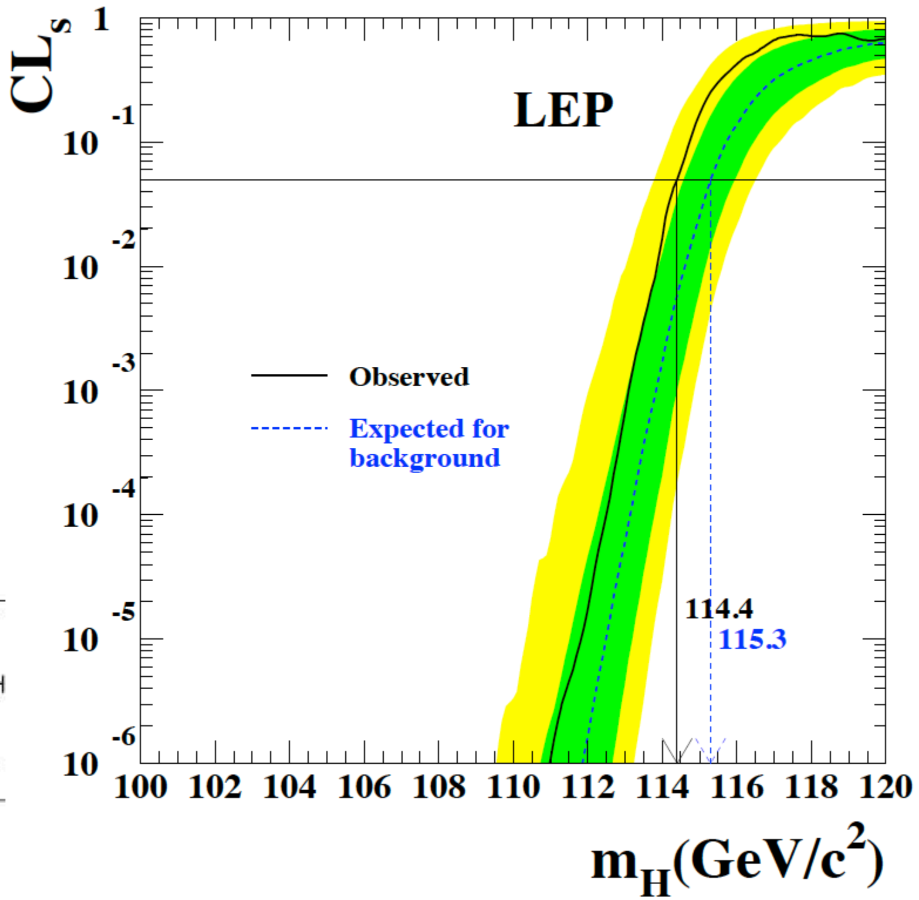
LEP1 e^+e^- at COM ~m_Z

Various decays and topologies

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

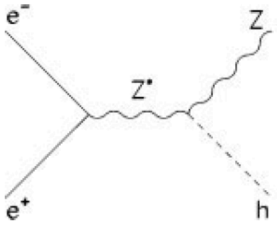


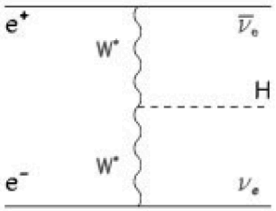


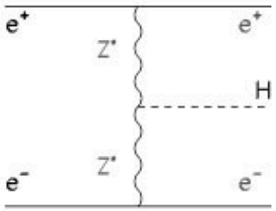


LEP2 e^+e^- up to 209 GeV

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







Excludes SM Higgs with mass below 114 GeV

Electroweak Precision Data and the Higgs Mass

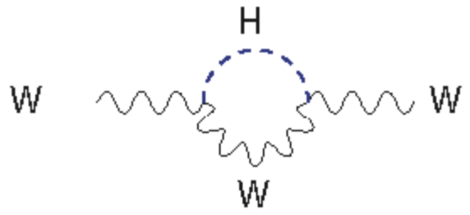
The famous blue band plot!

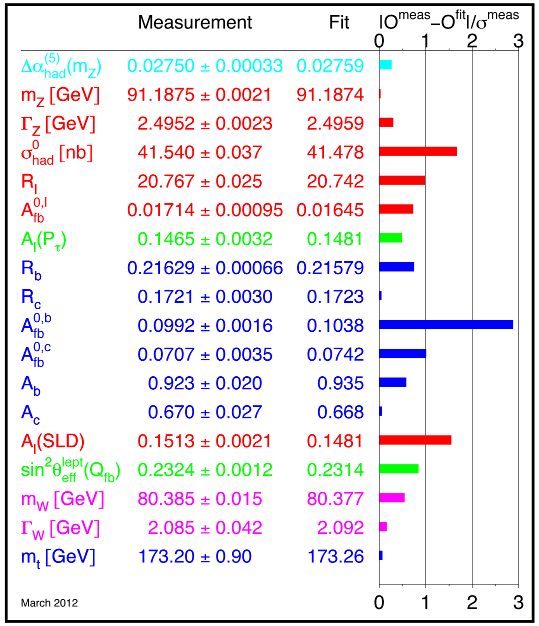
Fermi Constant $G_F = 1.166367(5) \times 10^{-5}\ \mathrm{GeV}^{-2}$ (muon lifetime)

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

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

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





	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ^0_{had} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.385 ± 0.015	80.377
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.26

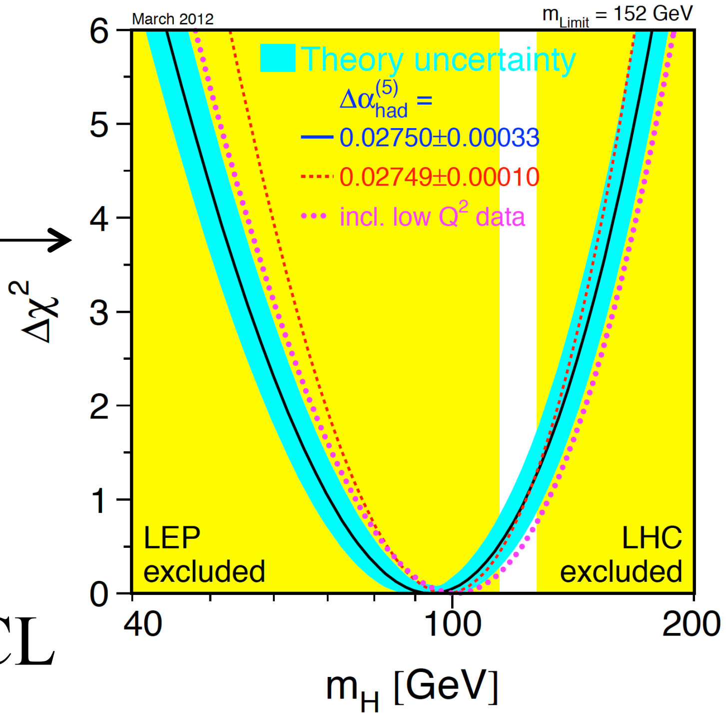
March 2012

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

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

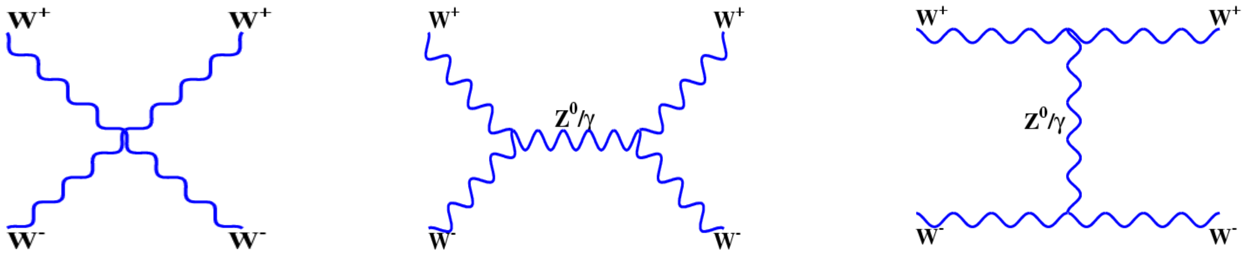
Is there a Higgs?

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



Very important additional virtue of the Higgs Particle

$$W^+W^- \rightarrow W^+W^-$$



Does not preserve perturbative unitarity.

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

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

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

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

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

The LHC Era

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

1993 December proposal of LHC with commissioning in 2002

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

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

From P. Jenni, Erice

1990

Birth of the LHC and… you!

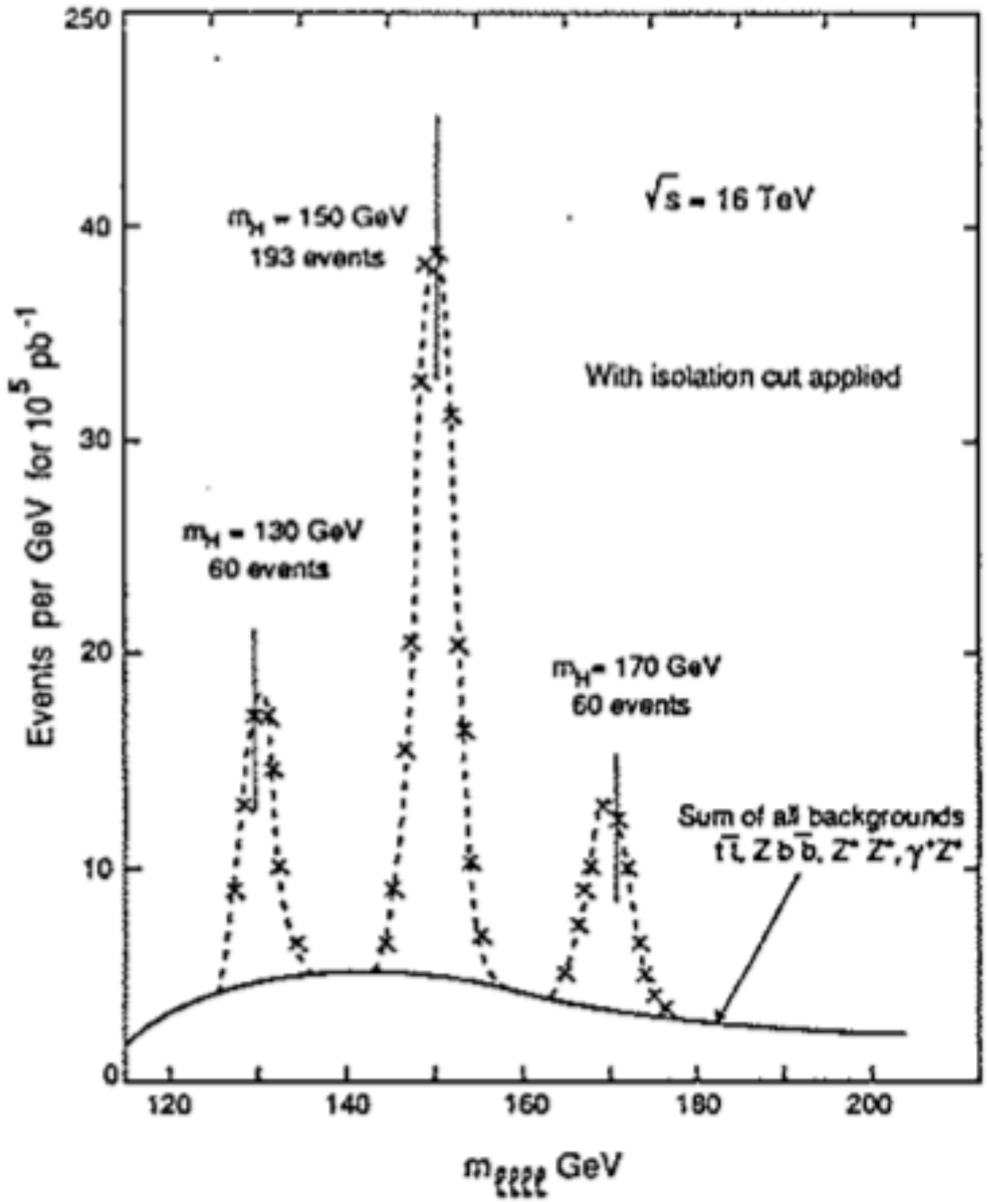
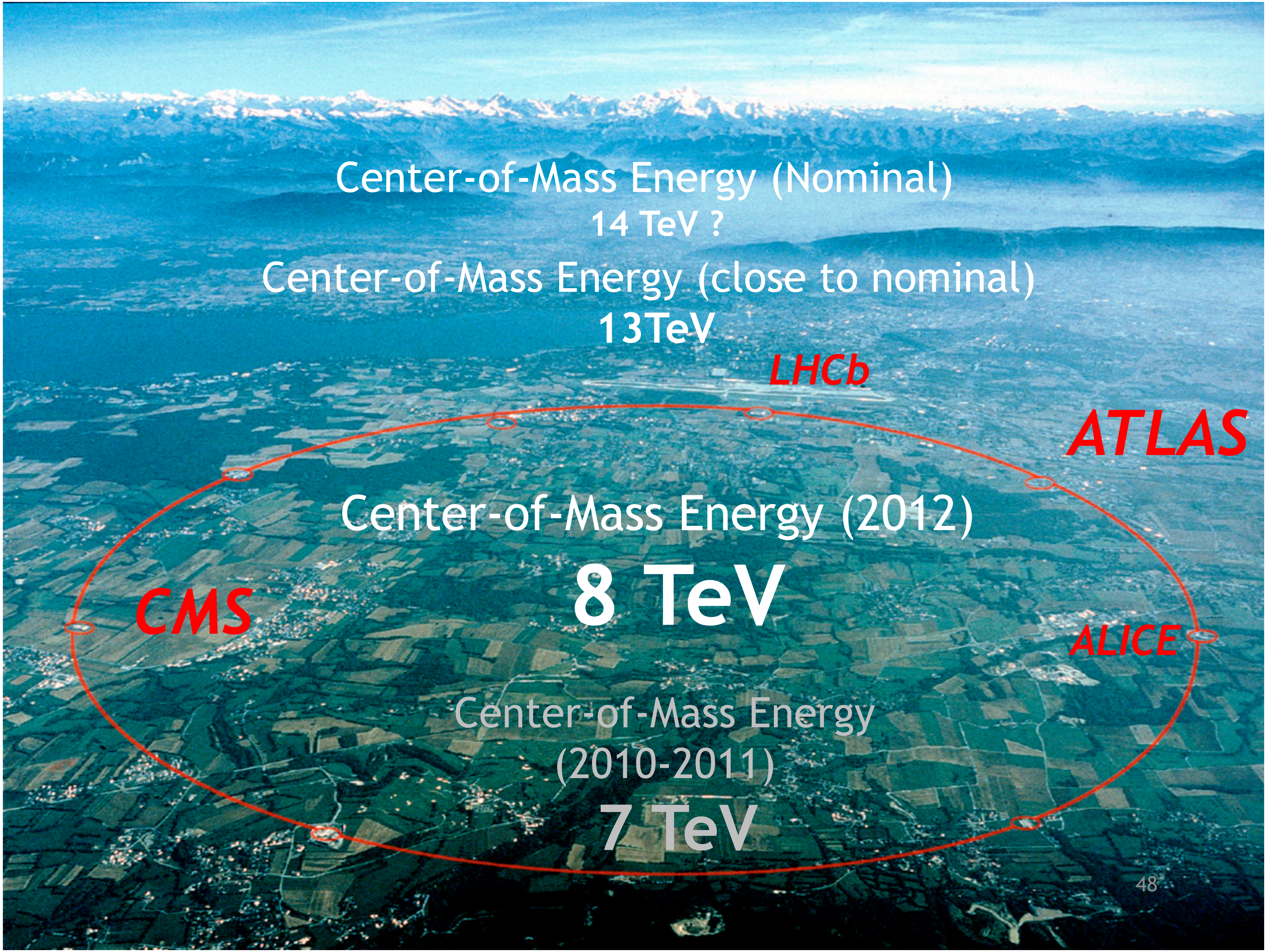


Fig. 10

1990

Proceedings of LHC Workshop
(Aachen, 1990):
$\sqrt{s}$ = 16 TeV, 100 fb^{-1}



Center-of-Mass Energy (Nominal)

14 TeV ?

Center-of-Mass Energy (close to nominal)

13TeV

Center-of-Mass Energy (2012)

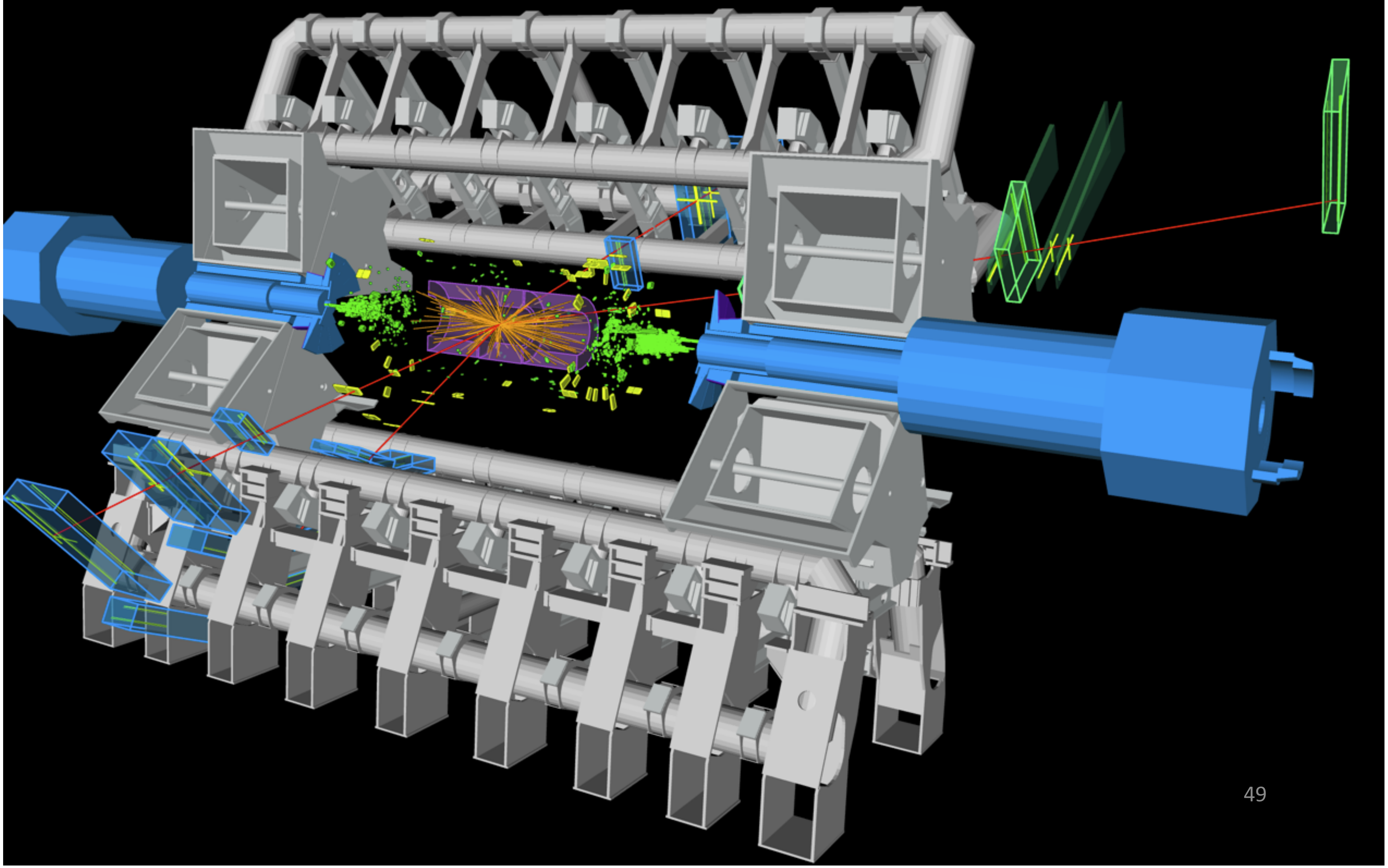
8 TeV

Center-of-Mass Energy

(2010-2011)

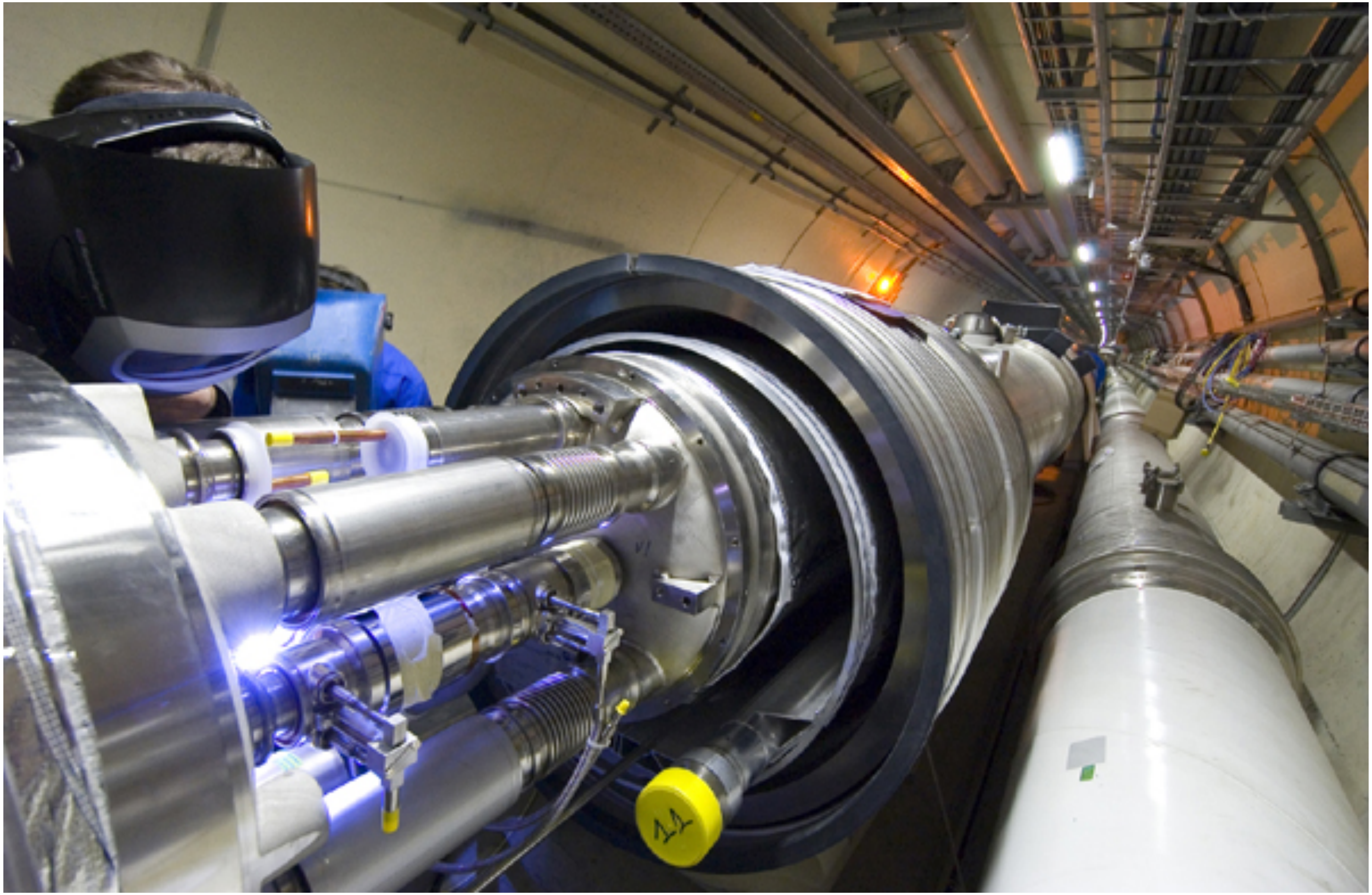
7 TeV

20 Years, projecting, constructing and Simulating…

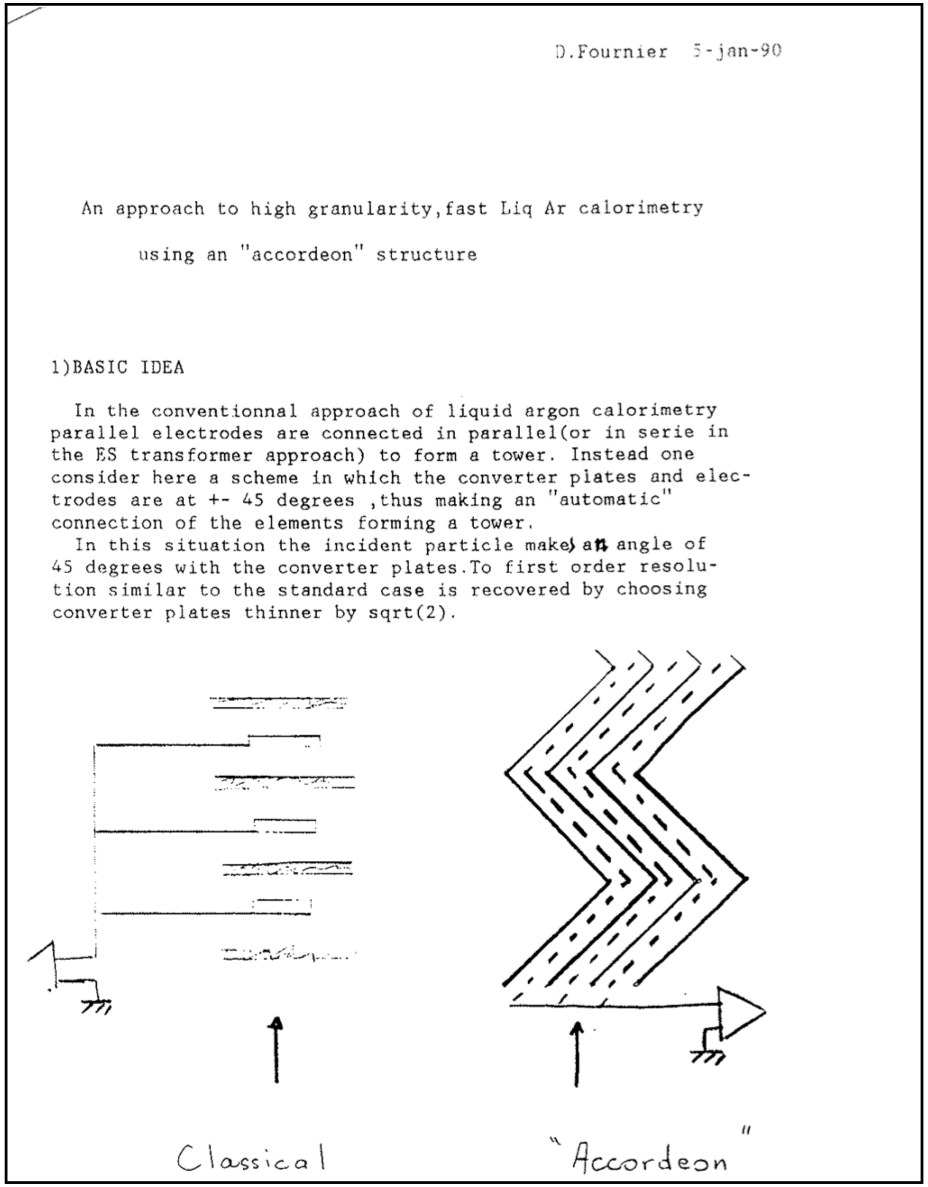


Years of Design, Construction and Commissioning of the LHC

The largest cryogenic system on earth…



Years of Design, Construction and Commissioning of Experiments



D.Fournier 5-jan-90

An approach to high granularity,fast Liq Ar calorimetry

using an "accordeon" structure

1)BASIC IDEA

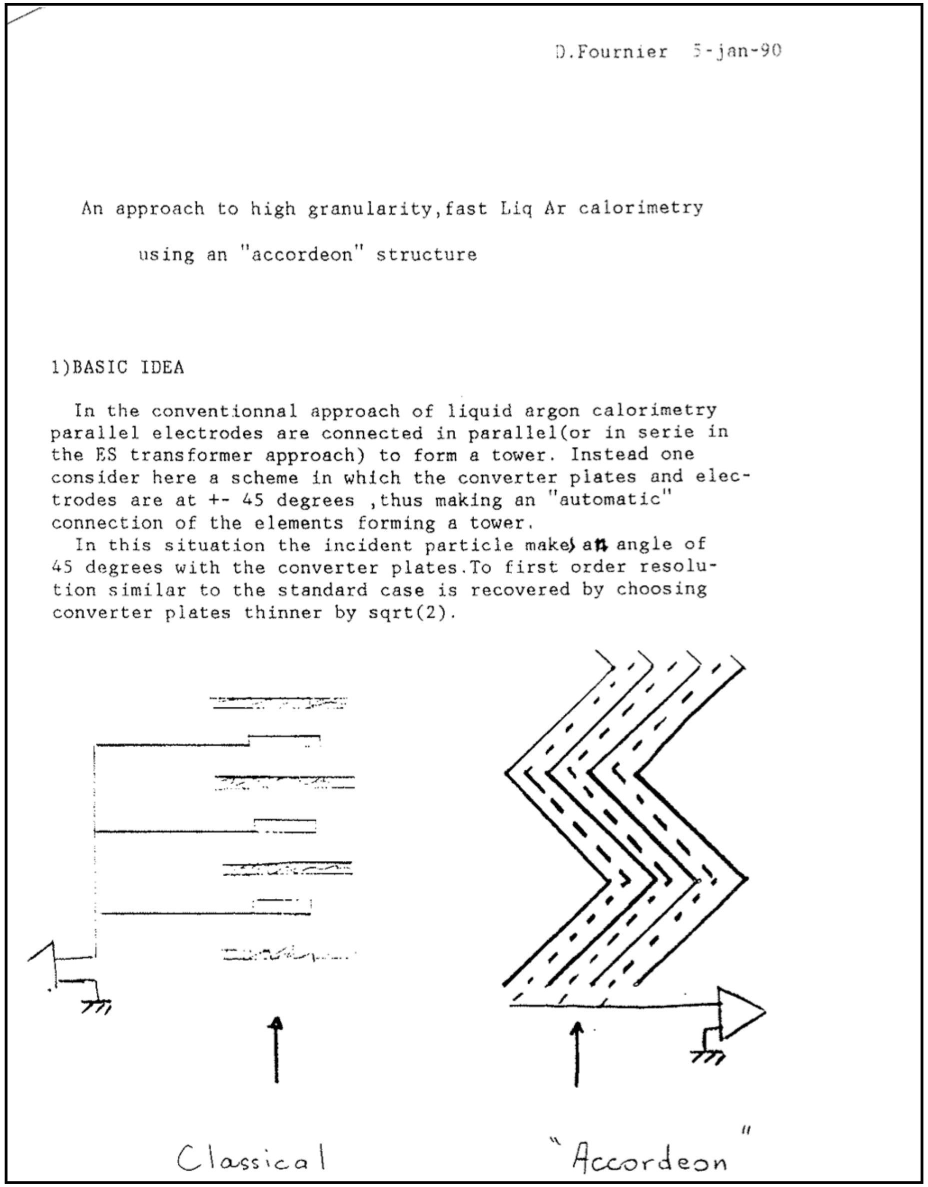
In the conventionnal approach of liquid argon calorimetry parallel electrodes are connected in parallel(or in serie in the ES transformer approach) to form a tower. Instead one consider here a scheme in which the converter plates and electrodes are at +- 45 degrees ,thus making an "automatic" connection of the elements forming a tower.

In this situation the incident particle makes an angle of 45 degrees with the converter plates.To first order resolution similar to the standard case is recovered by choosing converter plates thinner by sqrt(2).

Classical

"Accordeon"

Years of Design, Construction and Commissioning of Experiments



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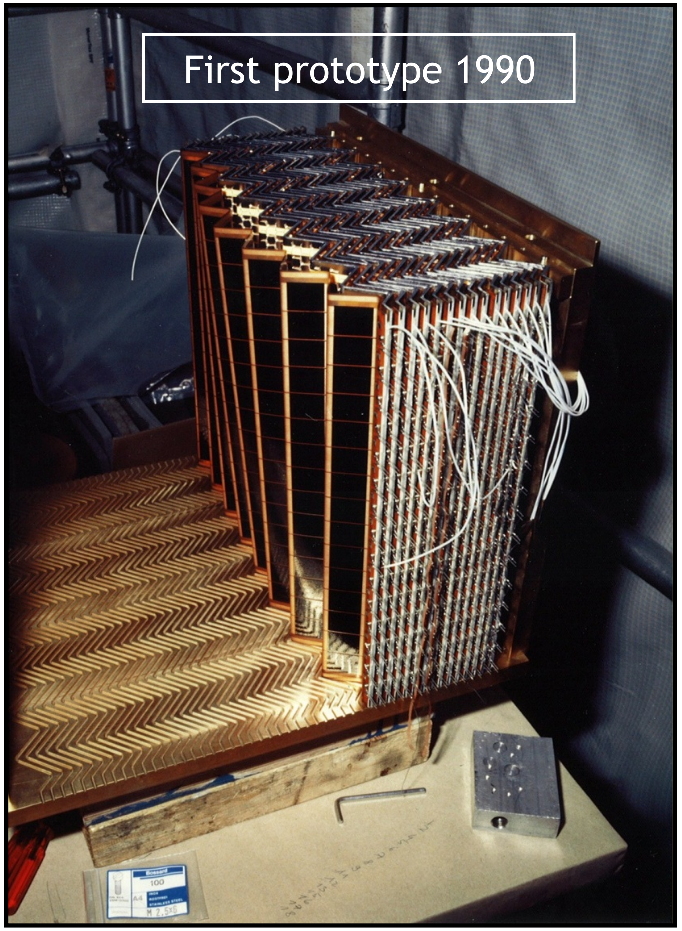
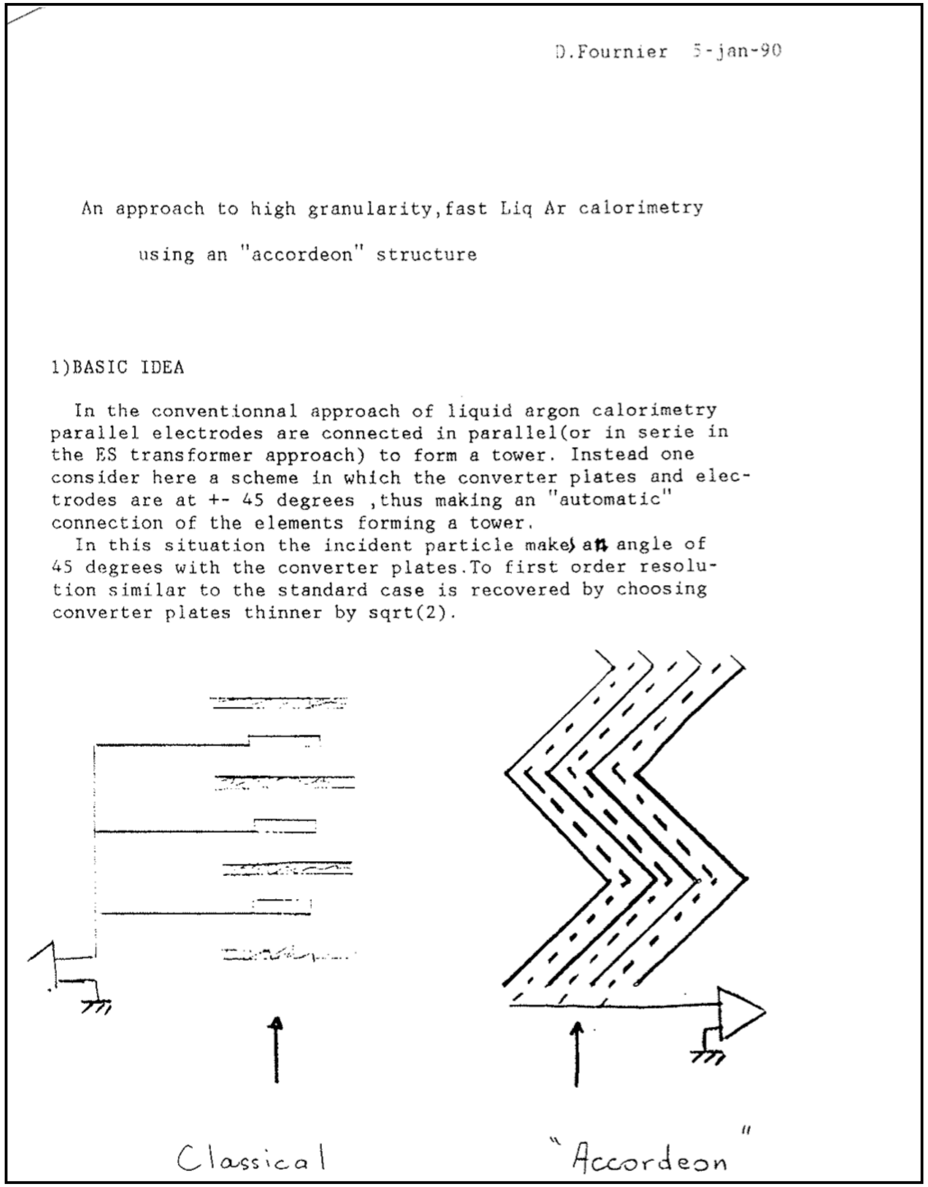


First prototype 1990

Years of Design, Construction and Commissioning of Experiments



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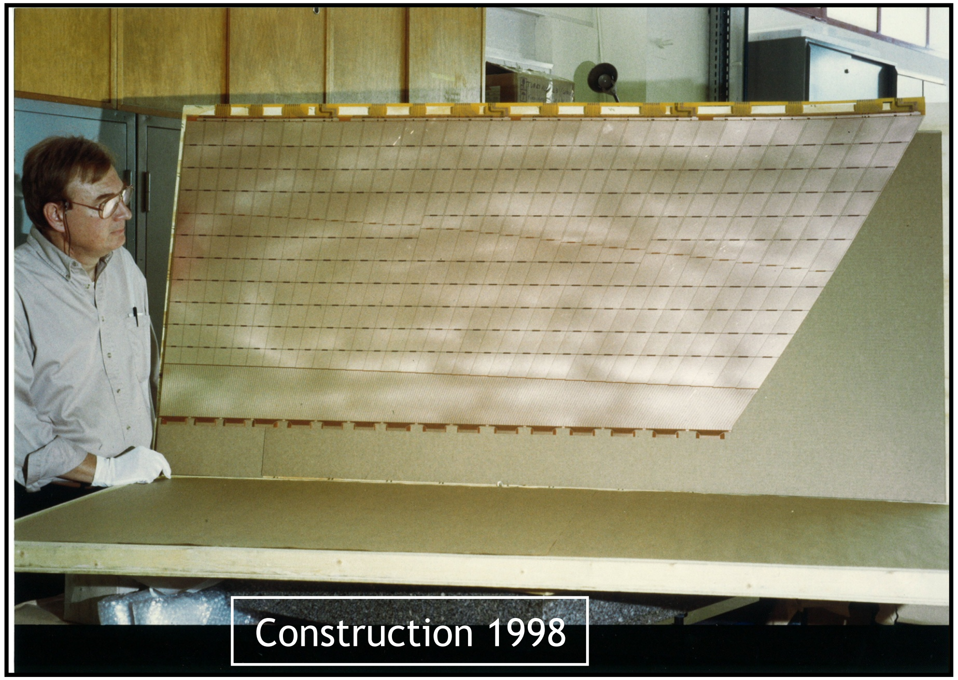
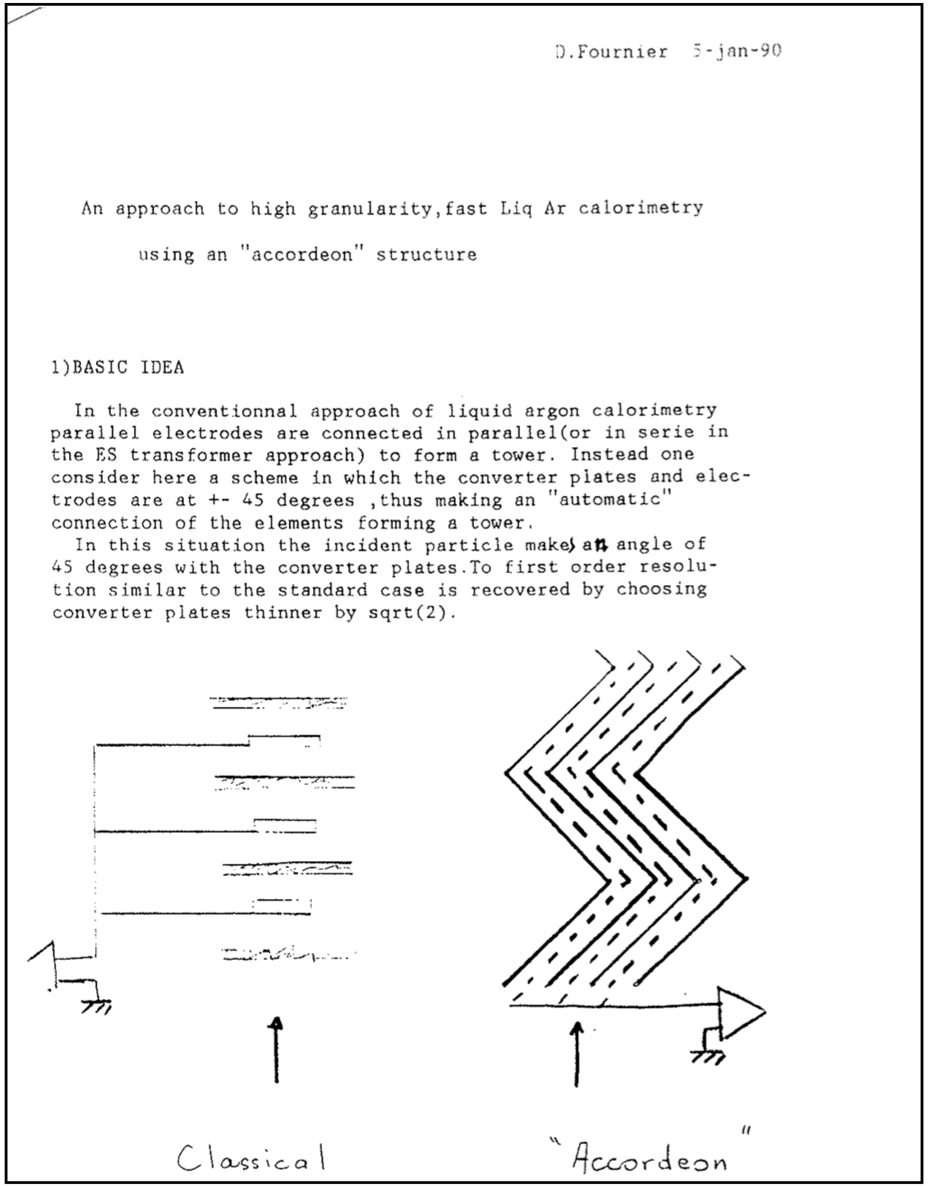


Construction 1998

Years of Design, Construction and Commissioning of Experiments



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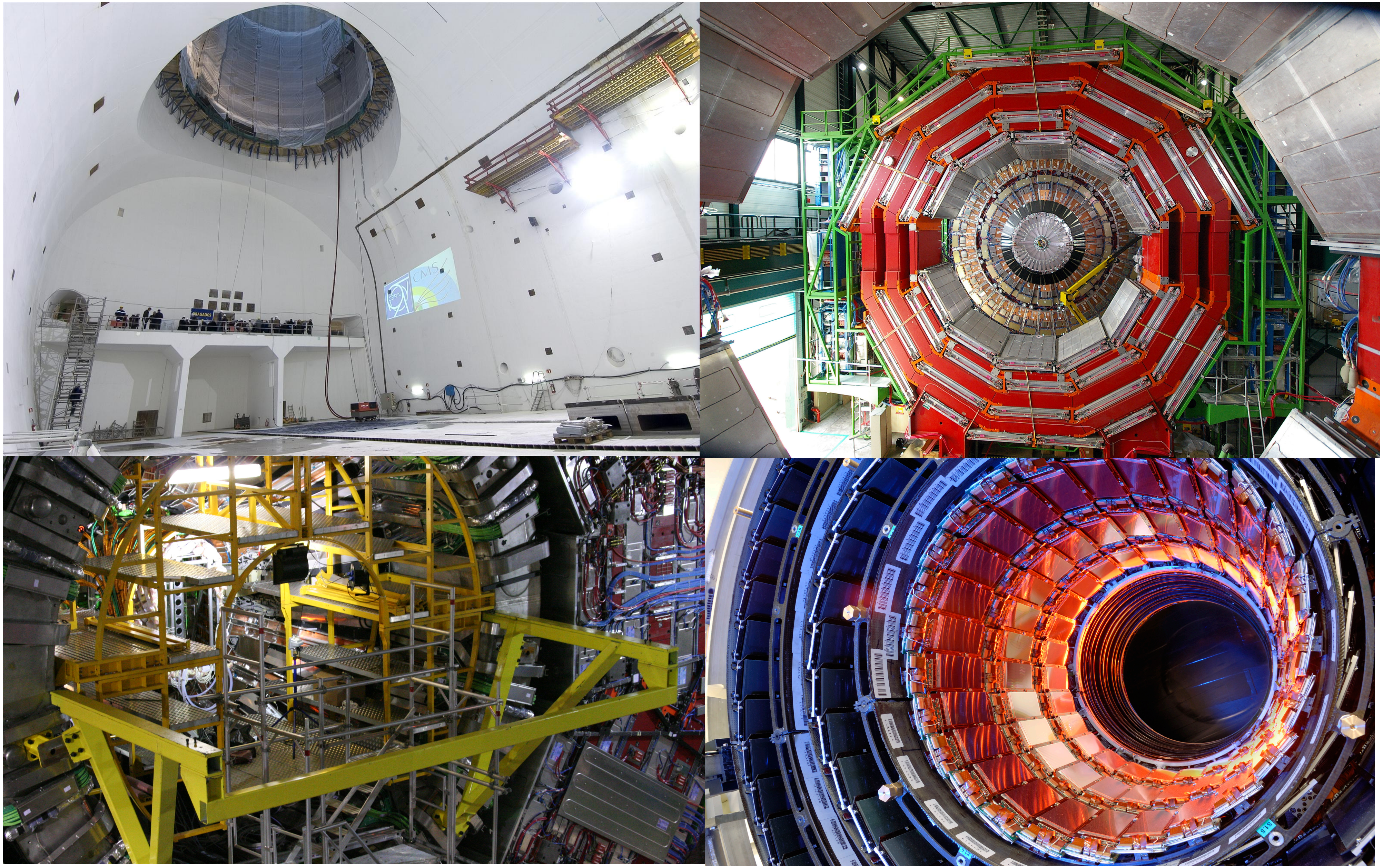
Classical

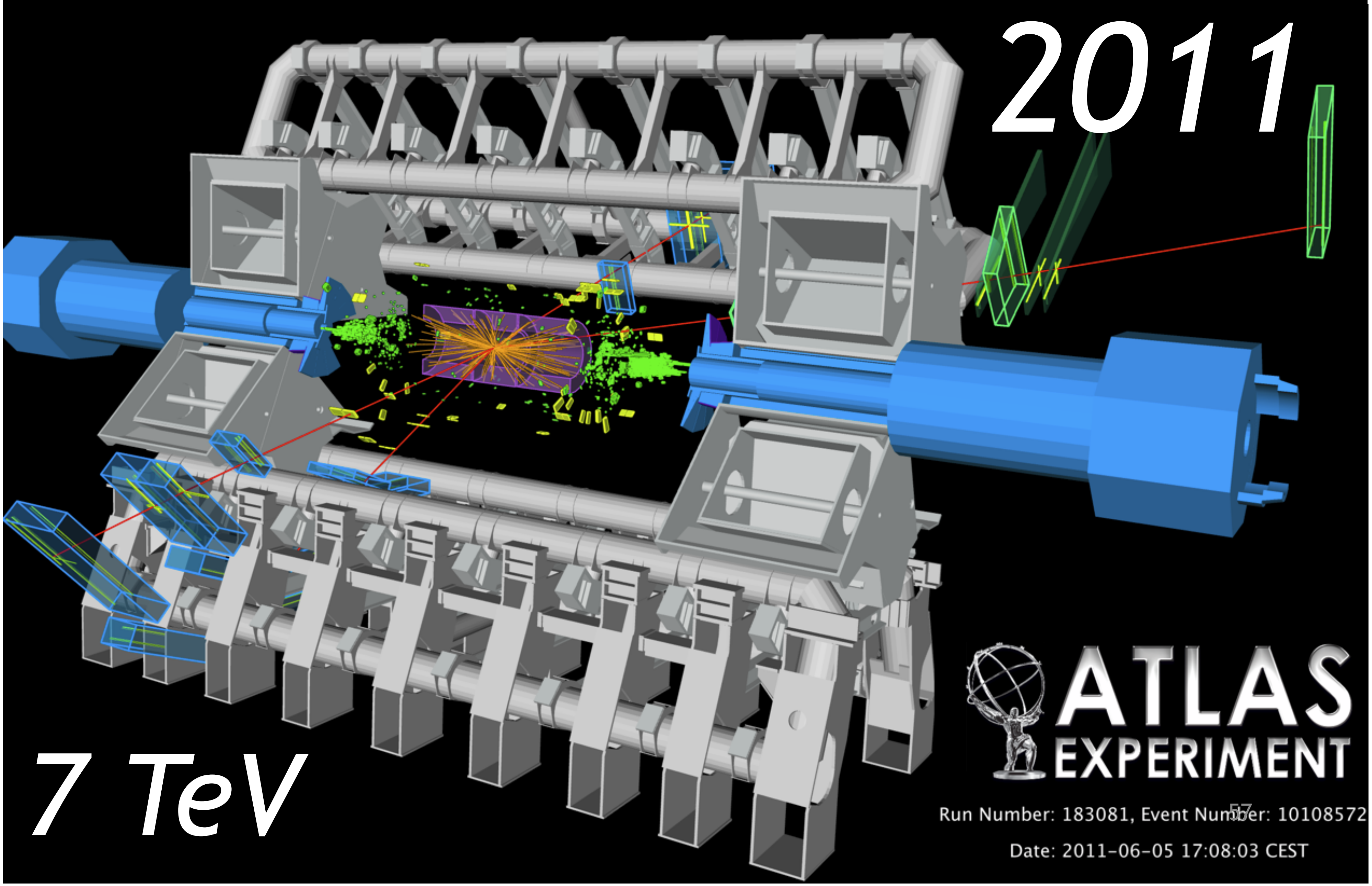
"Accordeon"

Installation 2004

Years of Design, Construction and Commissioning of Experiments



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



2011

7 TeV

Run Number: 183081, Event Number: 10108572

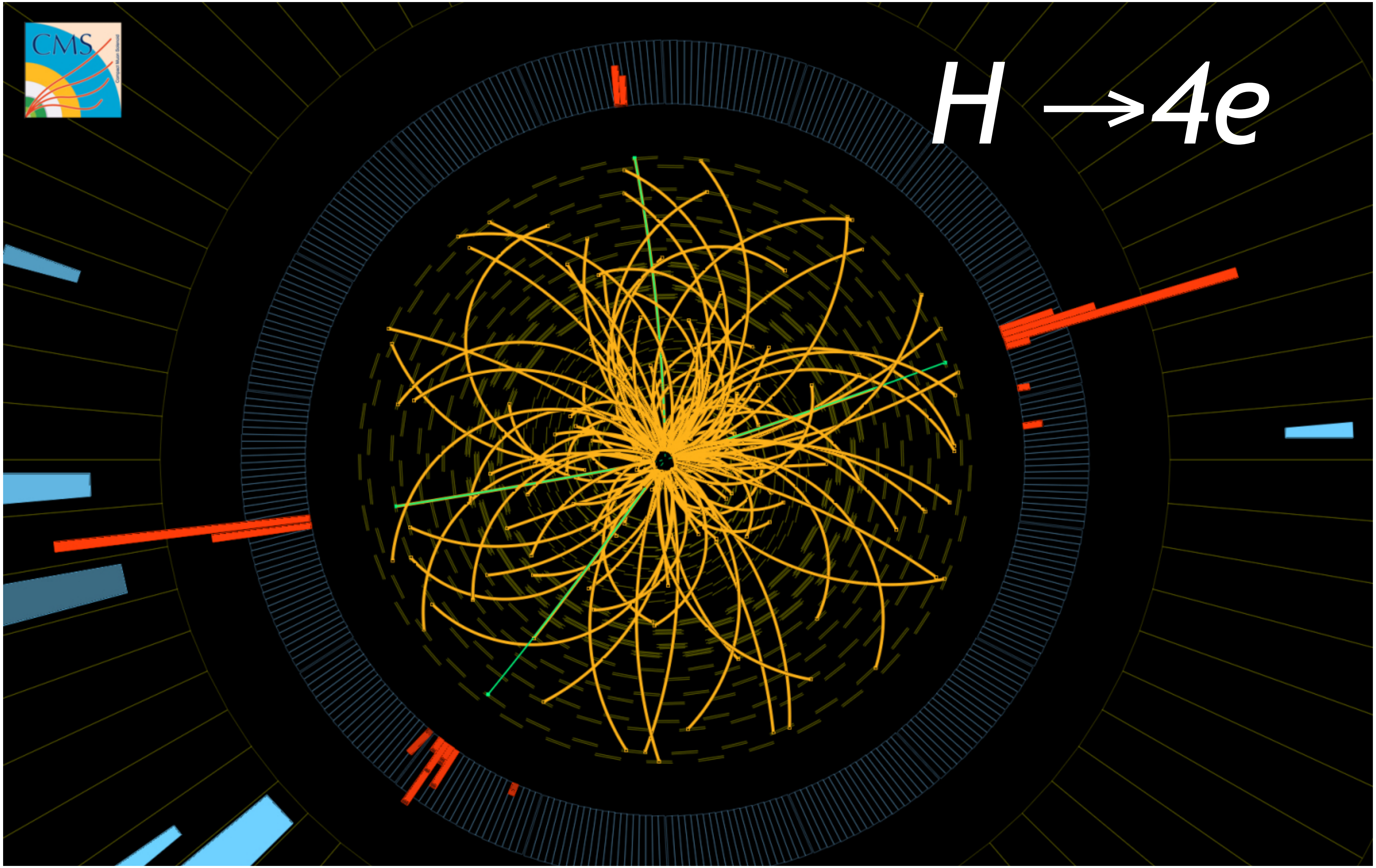
Date: 2011-06-05 17:08:03 CEST

2012

The turning point : Bolting pieces together !

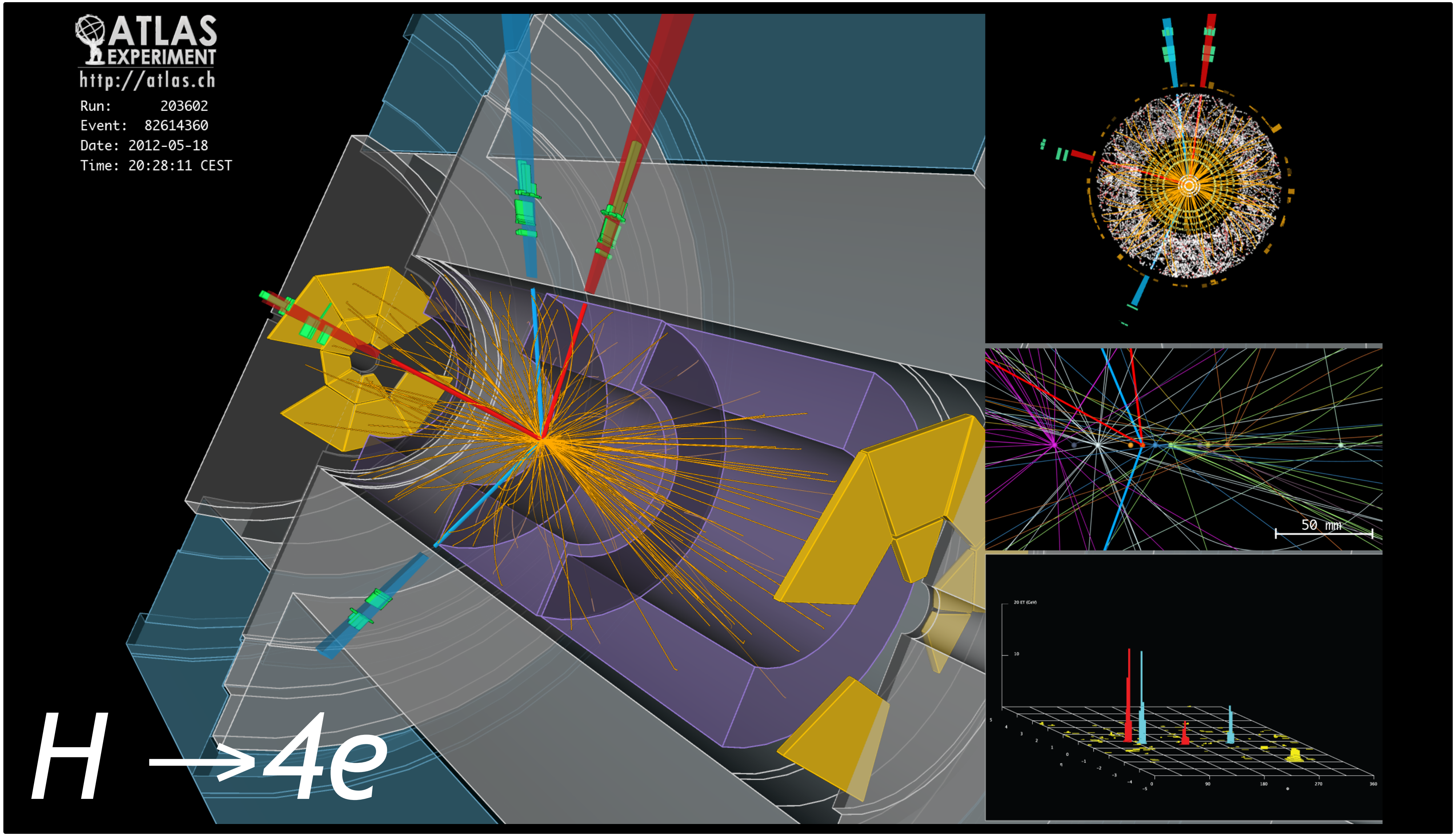
And of course…

The Discovery !



4l channel basic facts :

- Ns ~ O(15-20) per experiment
- Signal purity > 1.5



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Signal purity > 1.5

The ZZ Channel Historical Prospective

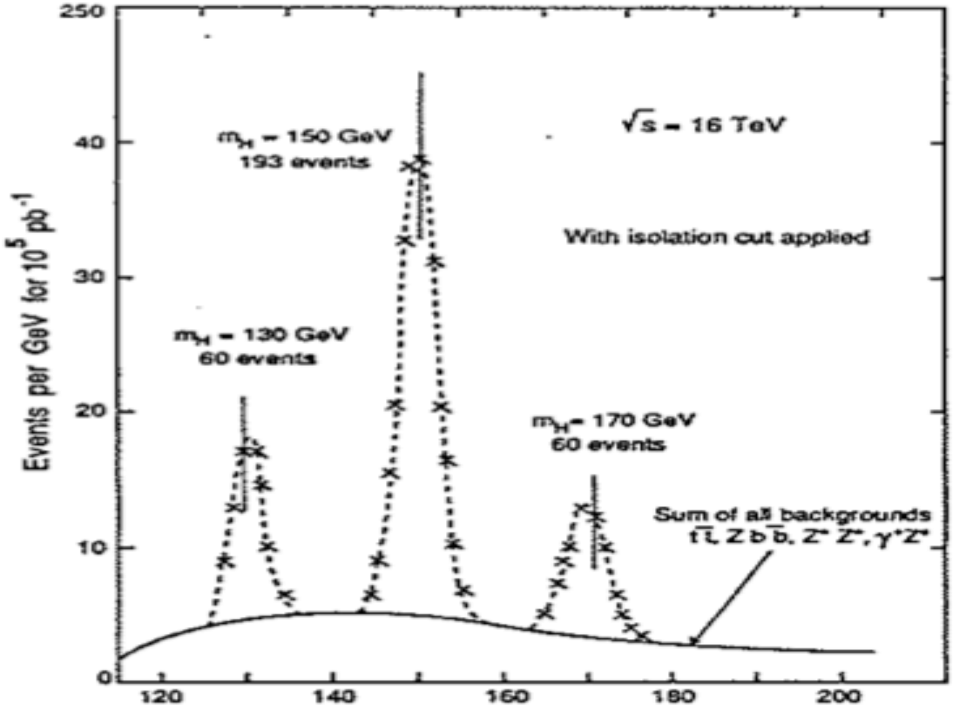


Fig. 10

The ZZ Channel Historical Prospective

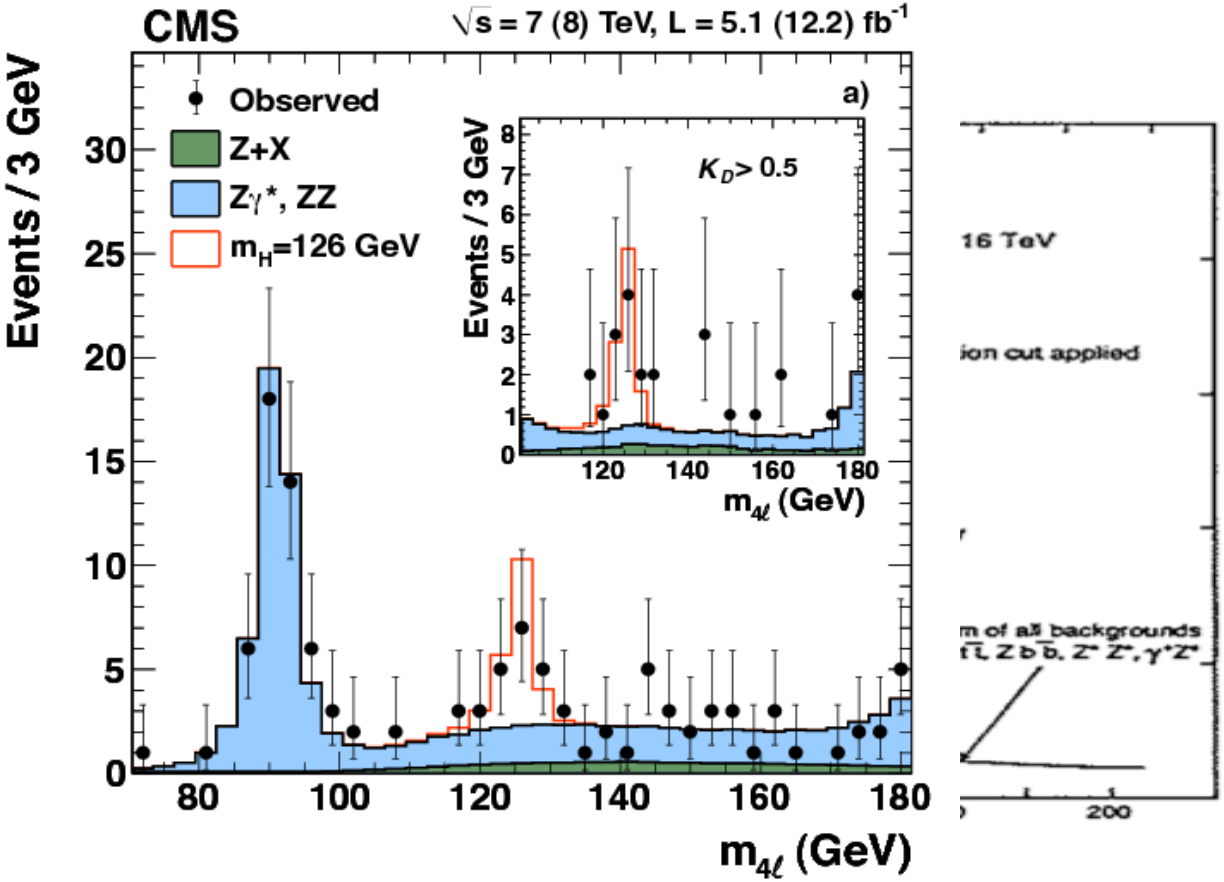
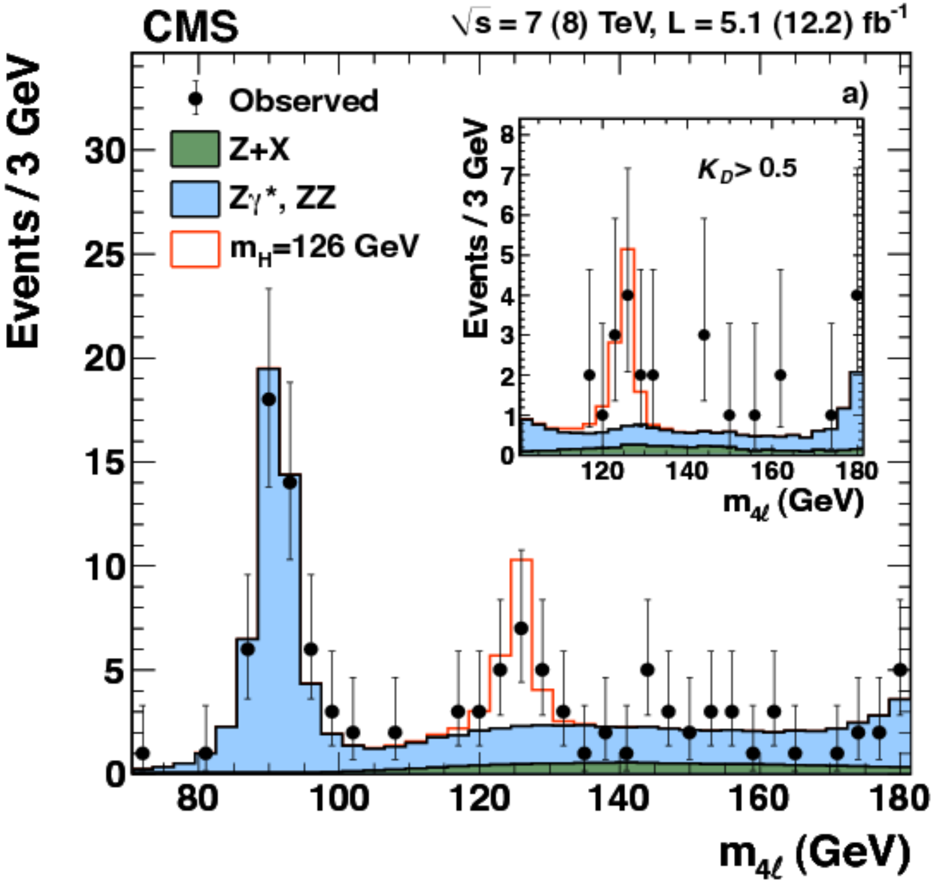


Fig. 10

The ZZ Channel Historical Prospective



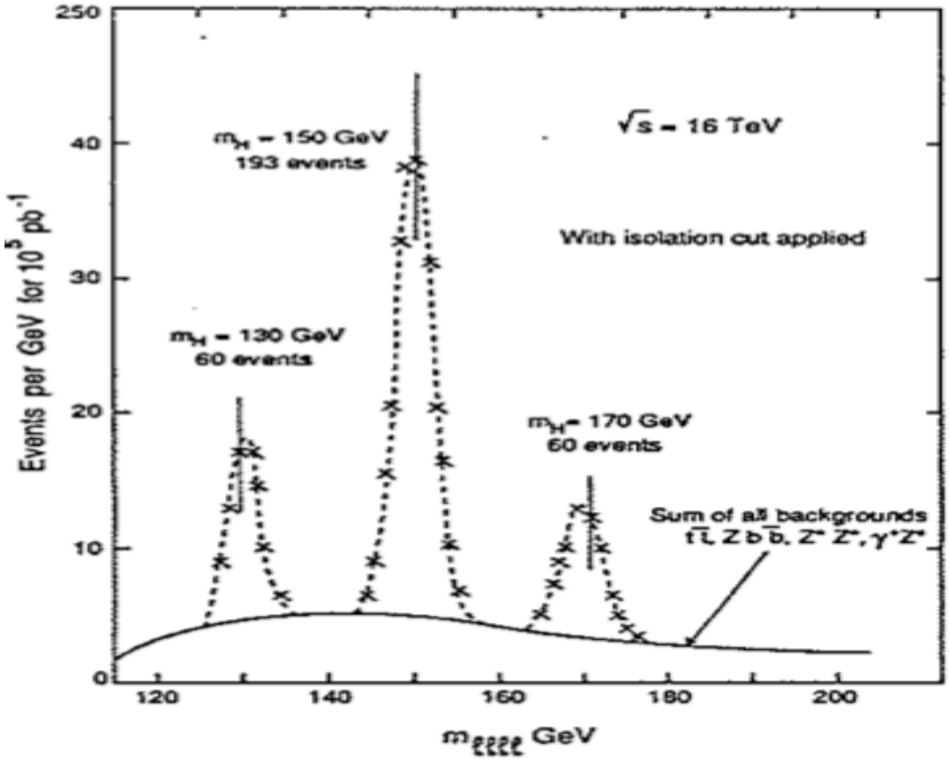


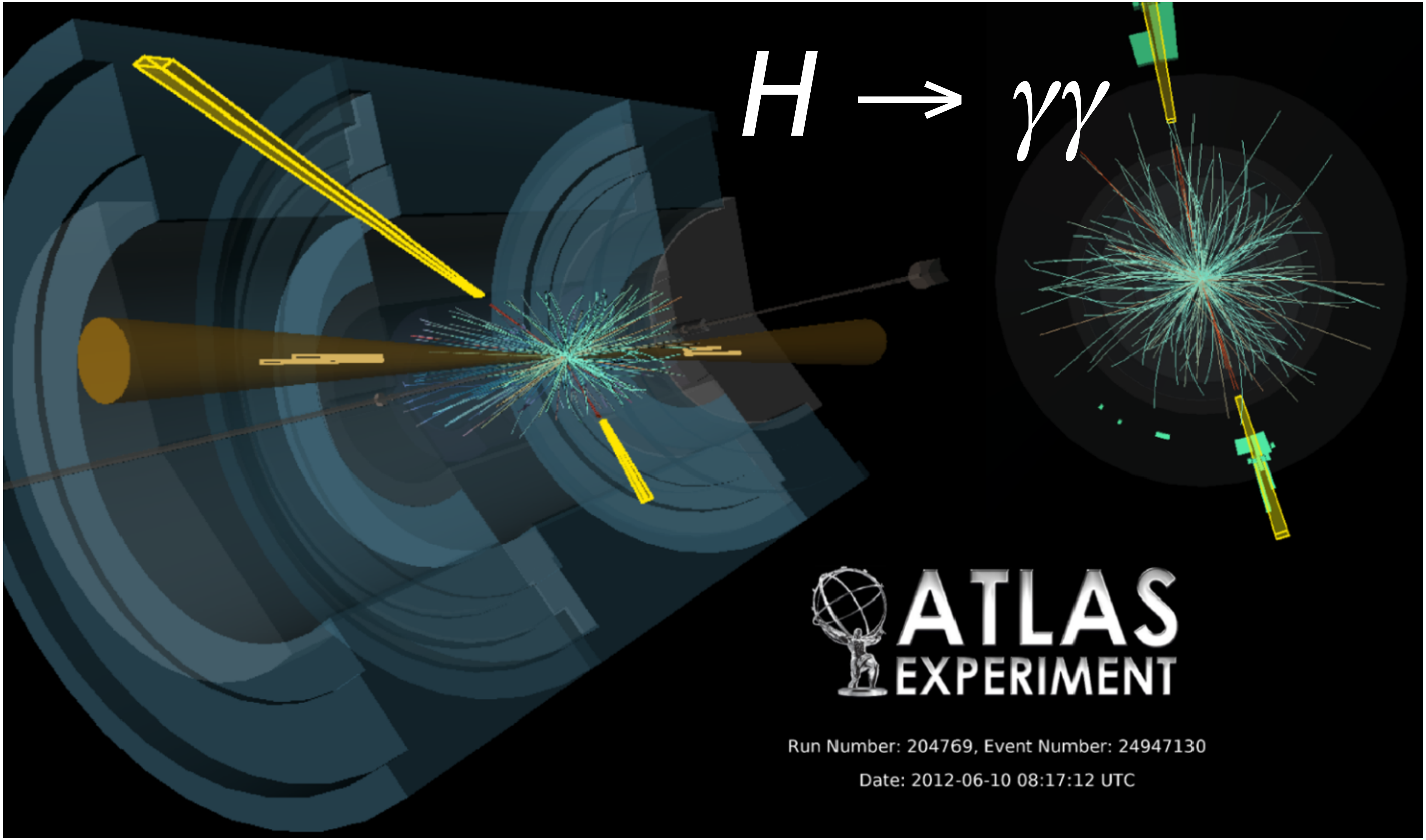
Fig. 10

7 - 8 TeV, ~25 fb^{-1}

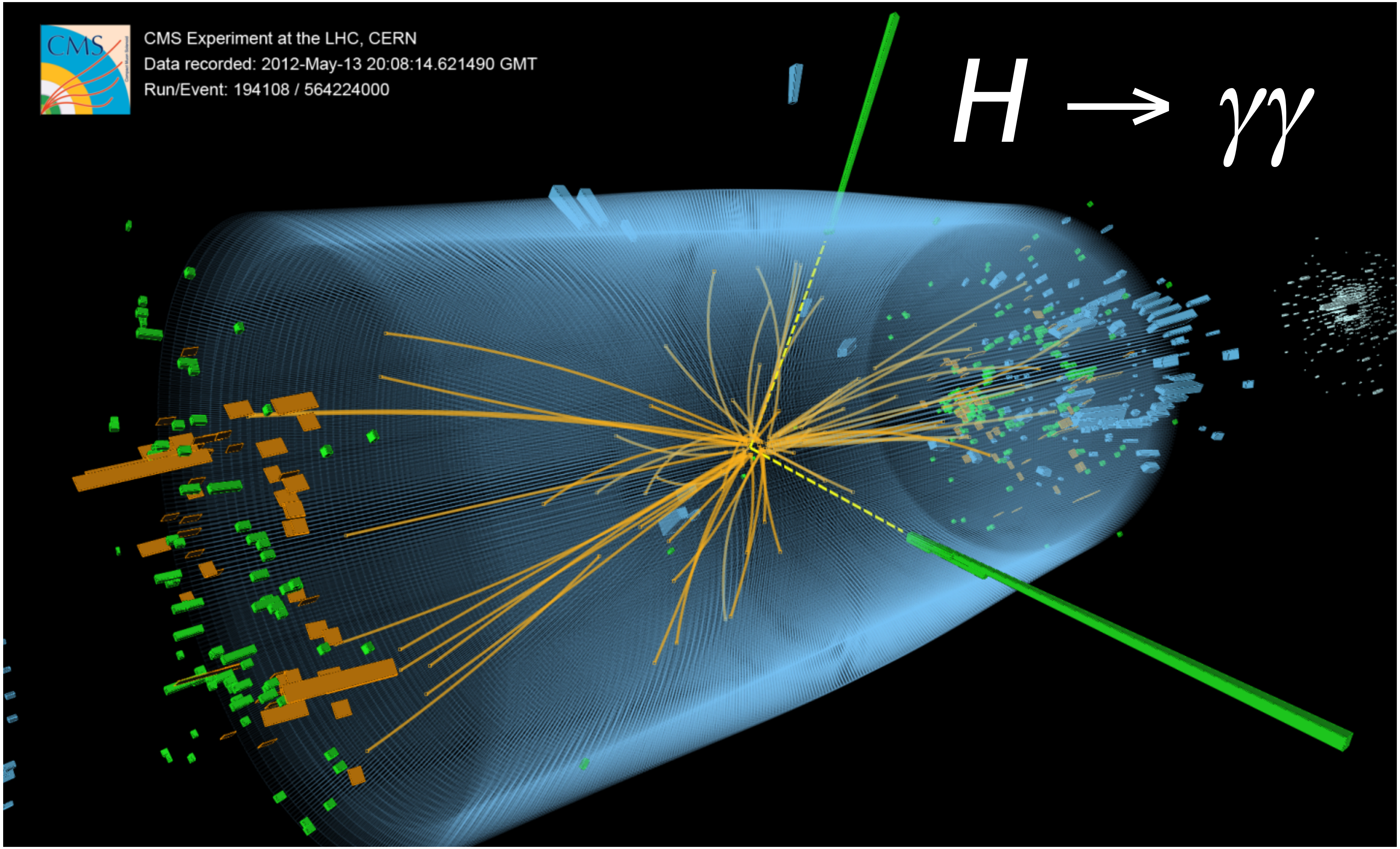
16 TeV, 100 fb^{-1}

Significance ~7 σ

Significance ~6 σ



$\gamma\gamma$ channel basic facts :
$\left\{\begin{array}{l}\text{Ns} \sim \text{O}(500) \text{ per experiment} \\ \text{Signal purity} \sim 2\% - 60\%\end{array}\right.$



γγ channel basic facts :

- Ns ~ O(500) per experiment
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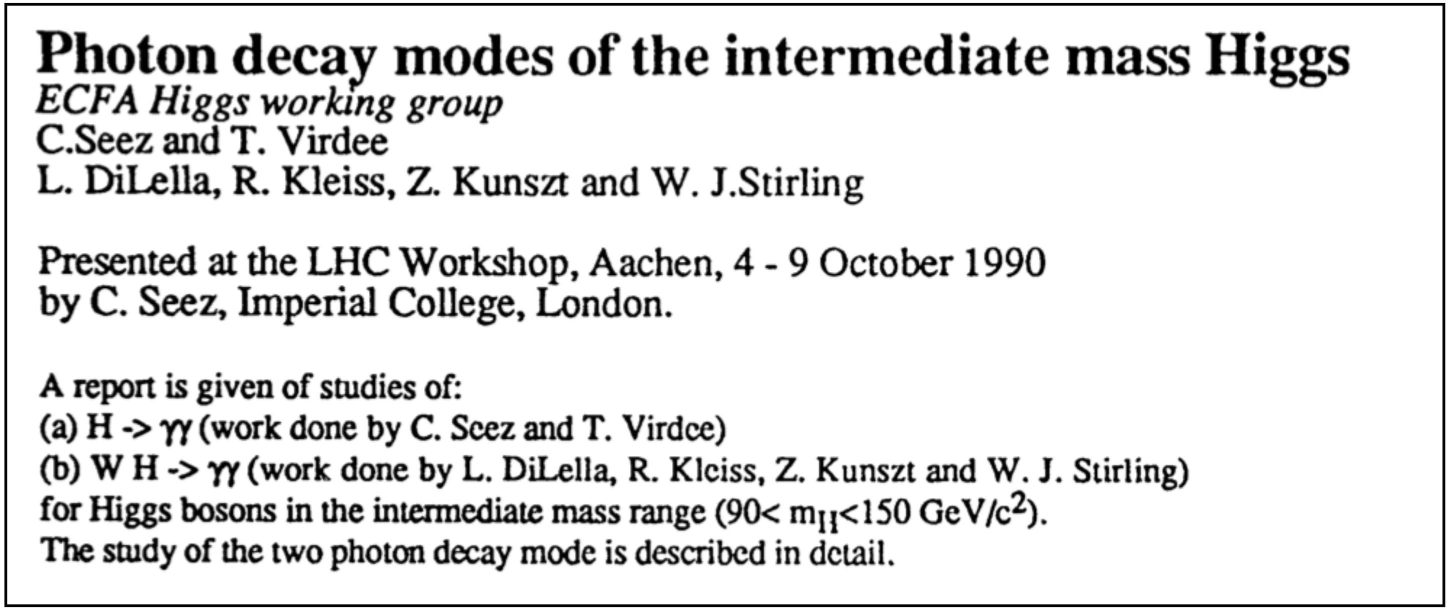
The Di-Photon Channel Historical Prospective

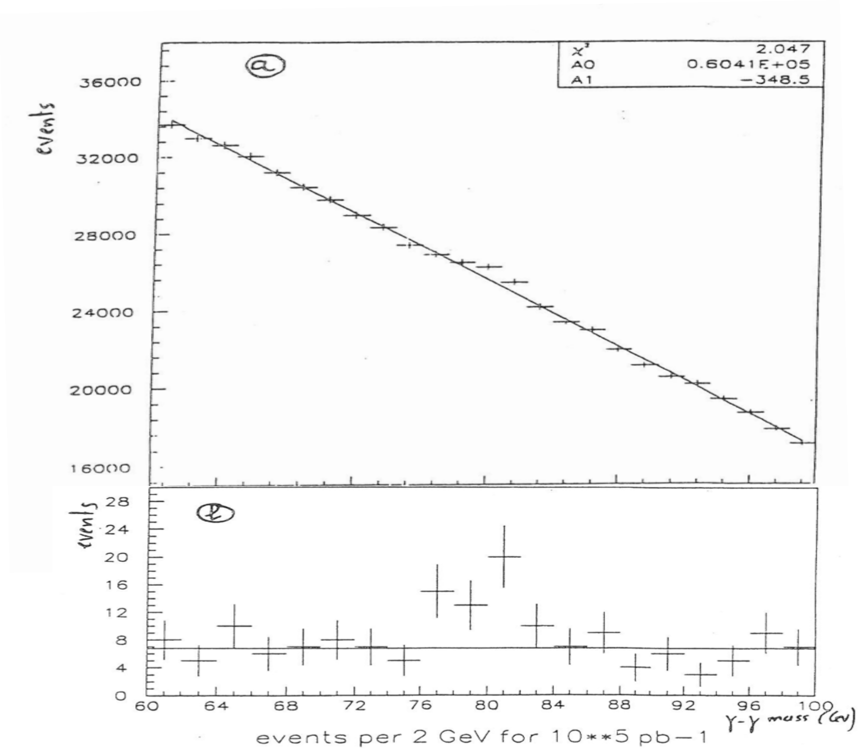


Photon decay modes of the intermediate mass Higgs
ECFA Higgs working group
C.Seez and T. Virdee
L. DiLella, R. Kleiss, Z. Kunszt and W. J.Stirling

Presented at the LHC Workshop, Aachen, 4 - 9 October 1990
by C. Seez, Imperial College, London.

A report is given of studies of:
(a) H -> $\gamma\gamma$ (work done by C. Seez and T. Virdee)
(b) W H -> $\gamma\gamma$ (work done by L. DiLella, R. Kleiss, Z. Kunszt and W. J. Stirling)
for Higgs bosons in the intermediate mass range ($90 < m_H < 150$ GeV/c^2).
The study of the two photon decay mode is described in detail.

The Di-Photon Channel Historical Prospective

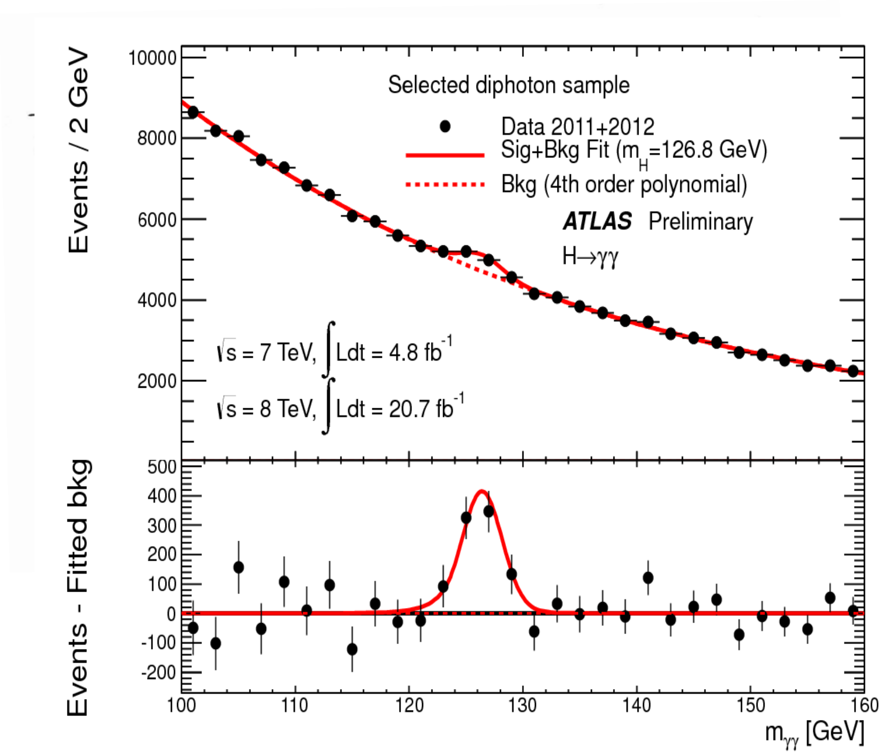


1991 Analysis

First EAGLE (ATLAS) note

diphoton channel

The Di-Photon Channel Historical Prospective



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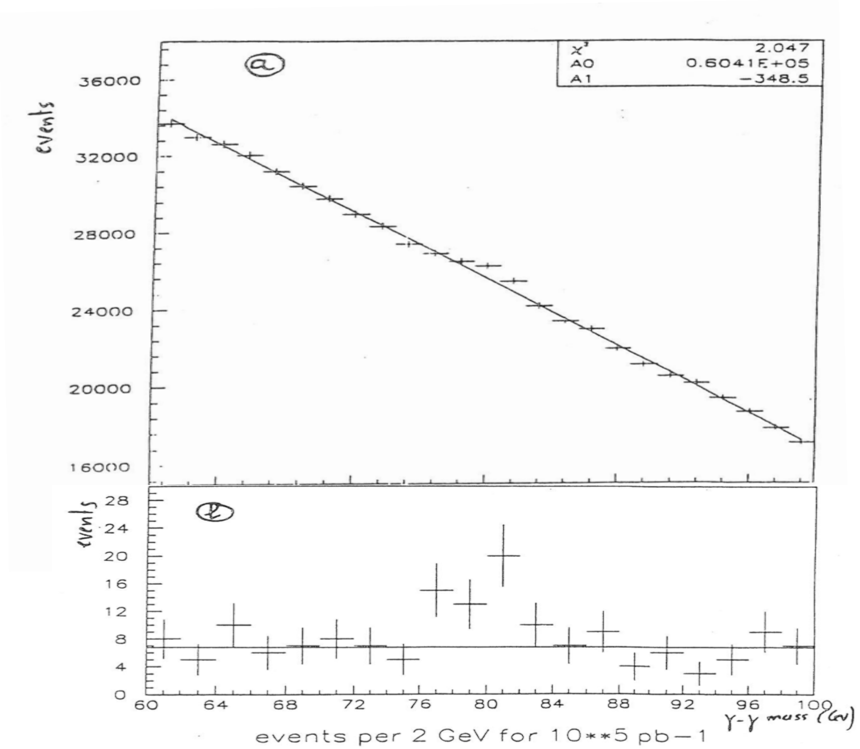
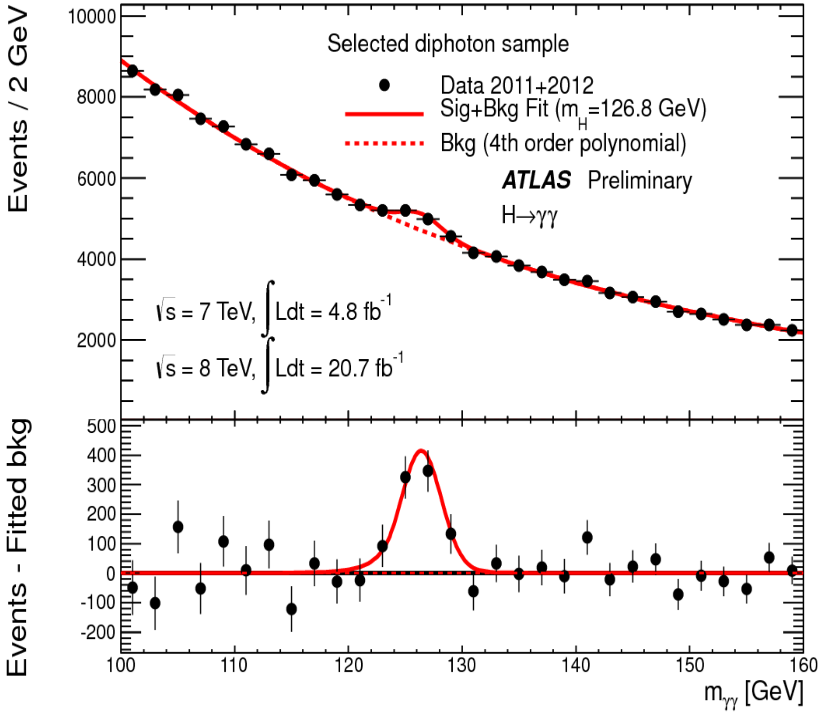
diphoton channel

The Di-Photon Channel Historical Prospective





1991 Analysis

First EAGLE (ATLAS) note
diphoton channel

16 TeV, 100 fb^{-1}

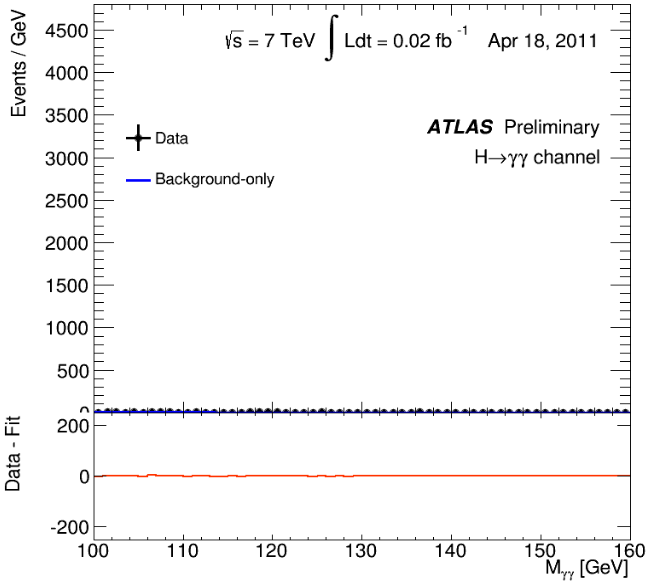
Moriond 2013 Analysis

ATLAS diphoton channel

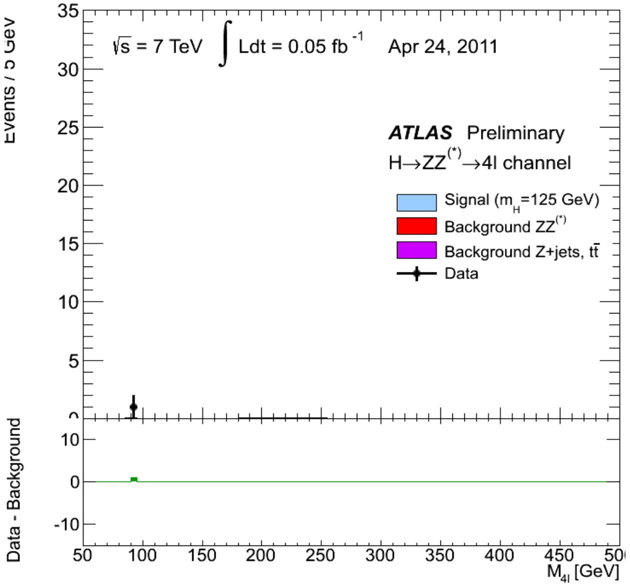
7 - 8 TeV, ~25 fb^{-1}

The Birth of a Particle

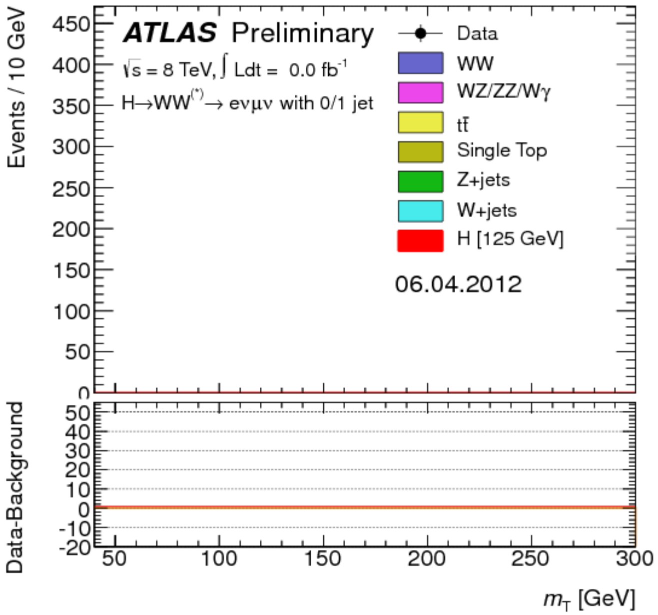
Diphoton



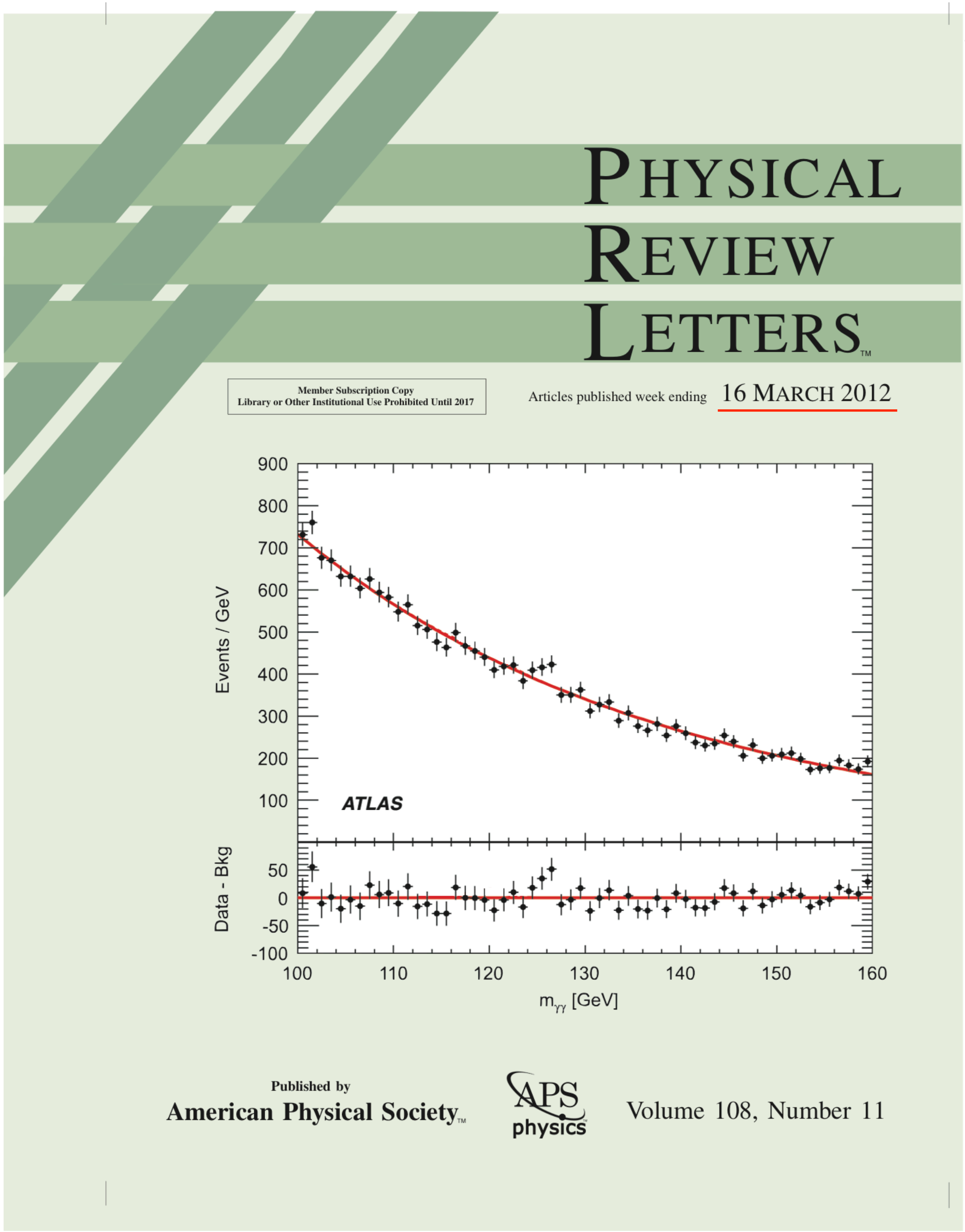
ZZ Four leptons



WW (lvlv)



Clear excesses in these three channels



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Statistical Methods Digression

How to Quantify the significance of an excess ?

Starting from PRL
Cover Plot

Statistical Interpretation

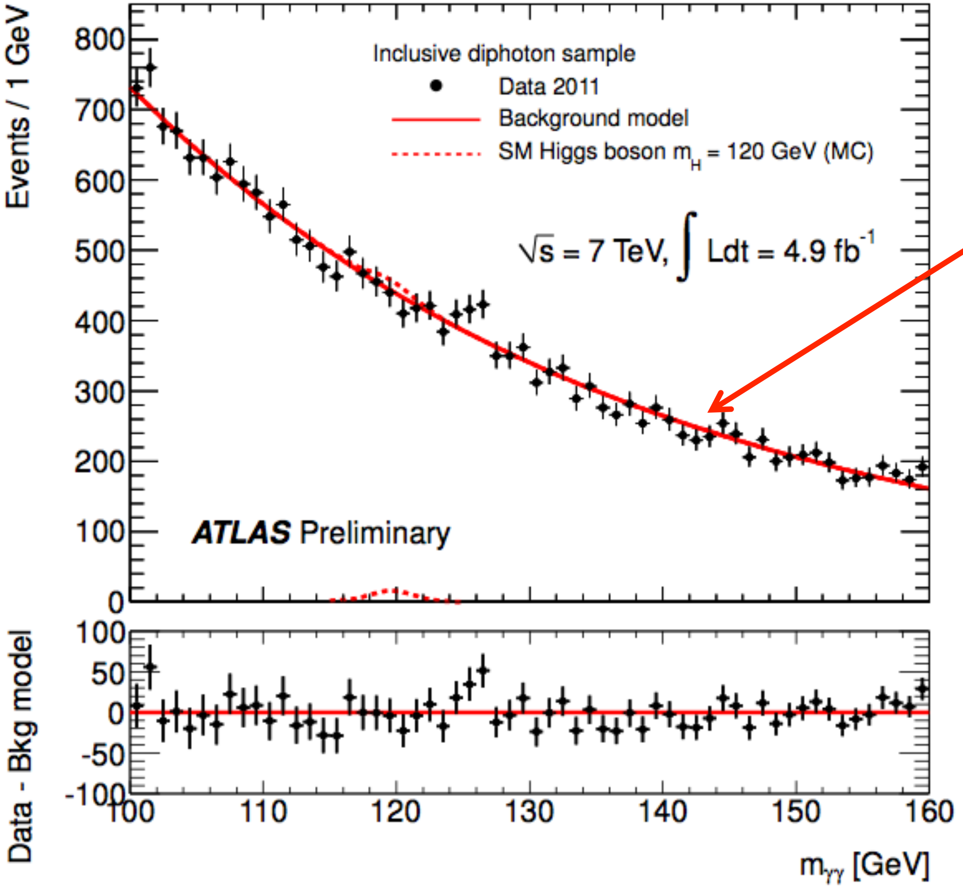
How to read Higgs Search Plots

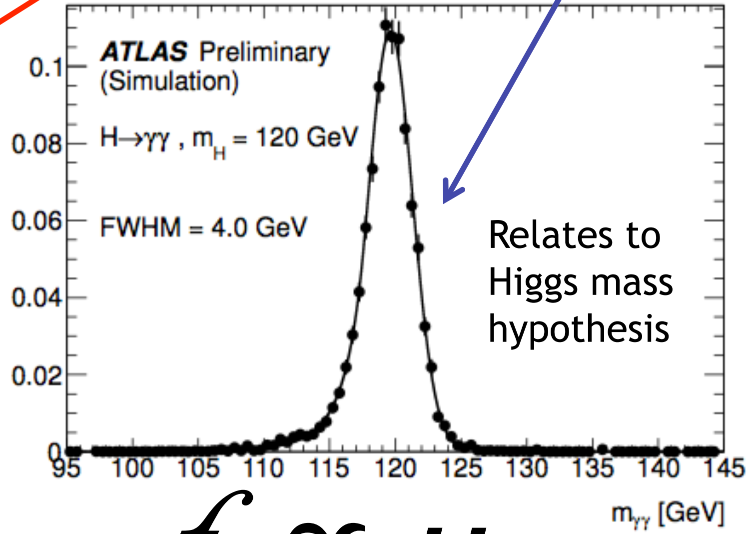
Hypothesis testing using the Profile likelihood ratio…

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

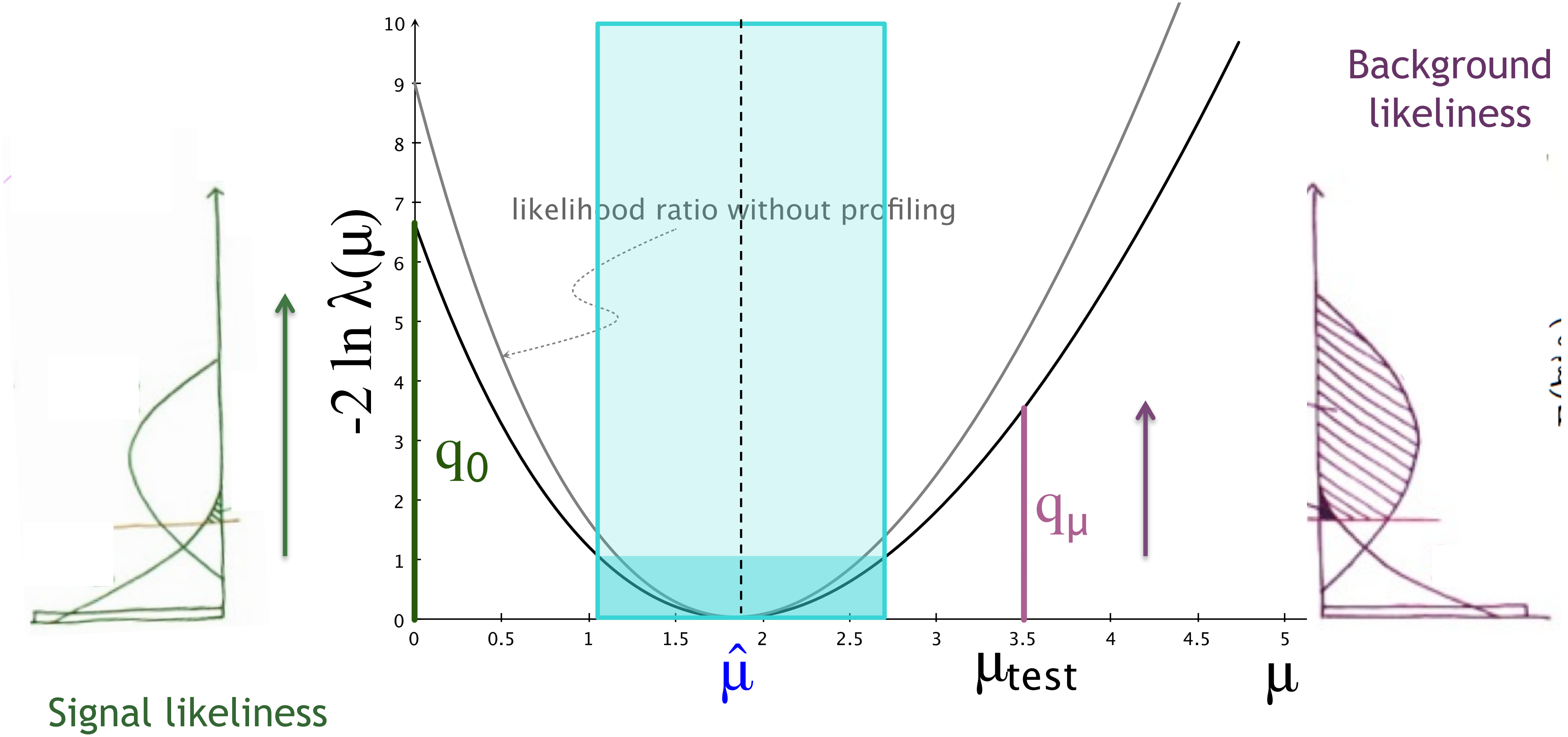
$$f_s \propto \mu$$

Global coherent factor

$$n_s = \mu\sigma Br L\varepsilon$$

Definition of the Test Statistic

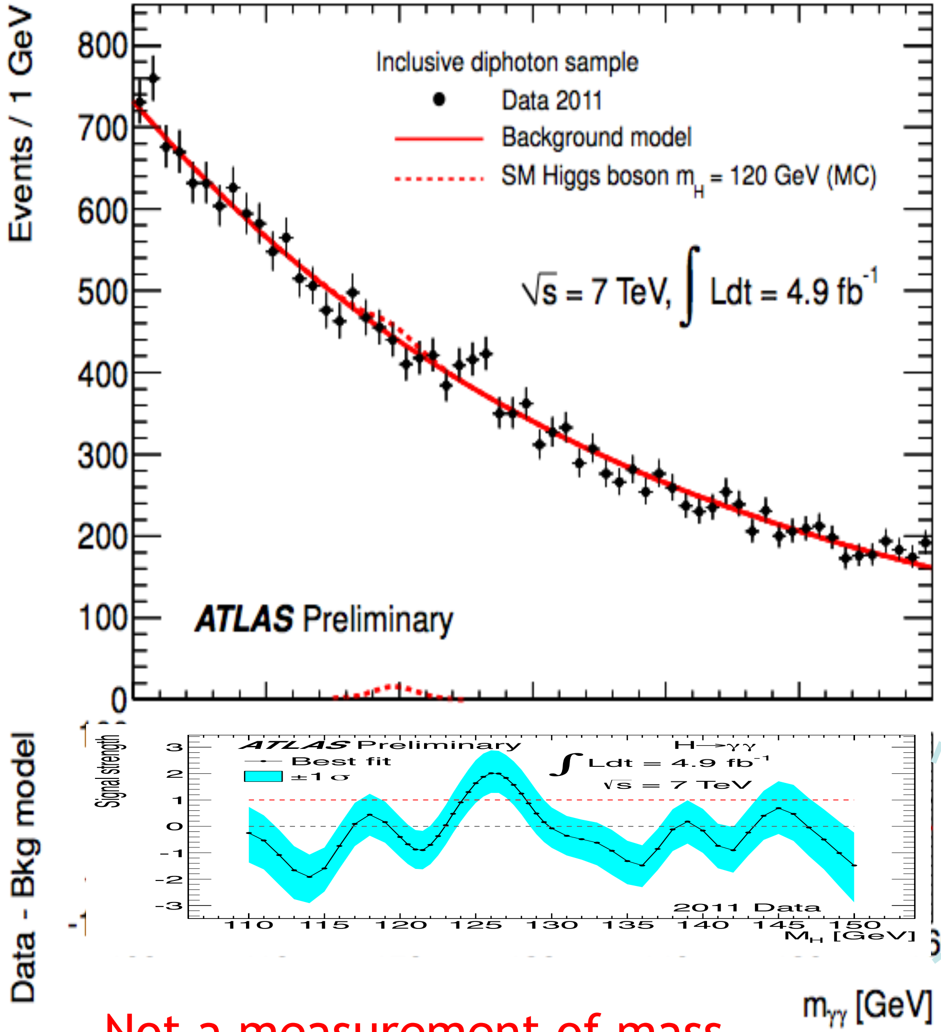
$$\lambda_\mu = \lambda(\mu,\theta) = \frac{L(\mu,\hat{\hat{\theta}}(\mu))}{L(\hat{\mu},\hat{\theta})} \qquad q_\mu = -2\ln\lambda_\mu$$



Statistical Interpretation

How to read Higgs Search Plots

Hypothesis testing using the Profile likelihood ratio…



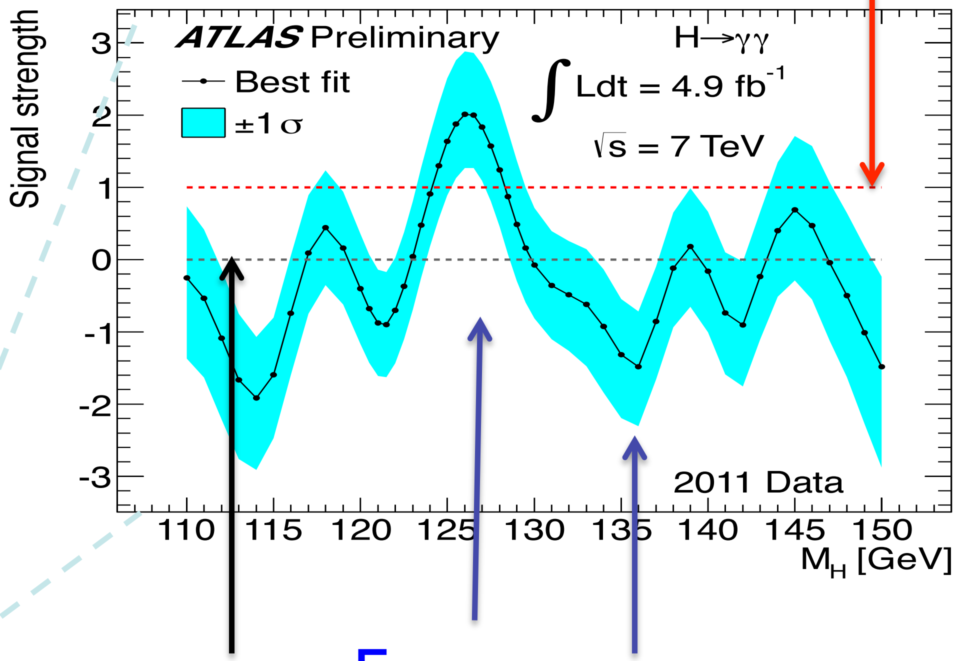
Not a measurement of mass

Not a measurement of cross section

$$\hat{\mu}$$

Relate to Higgs mass hypothesis

Expected Signal

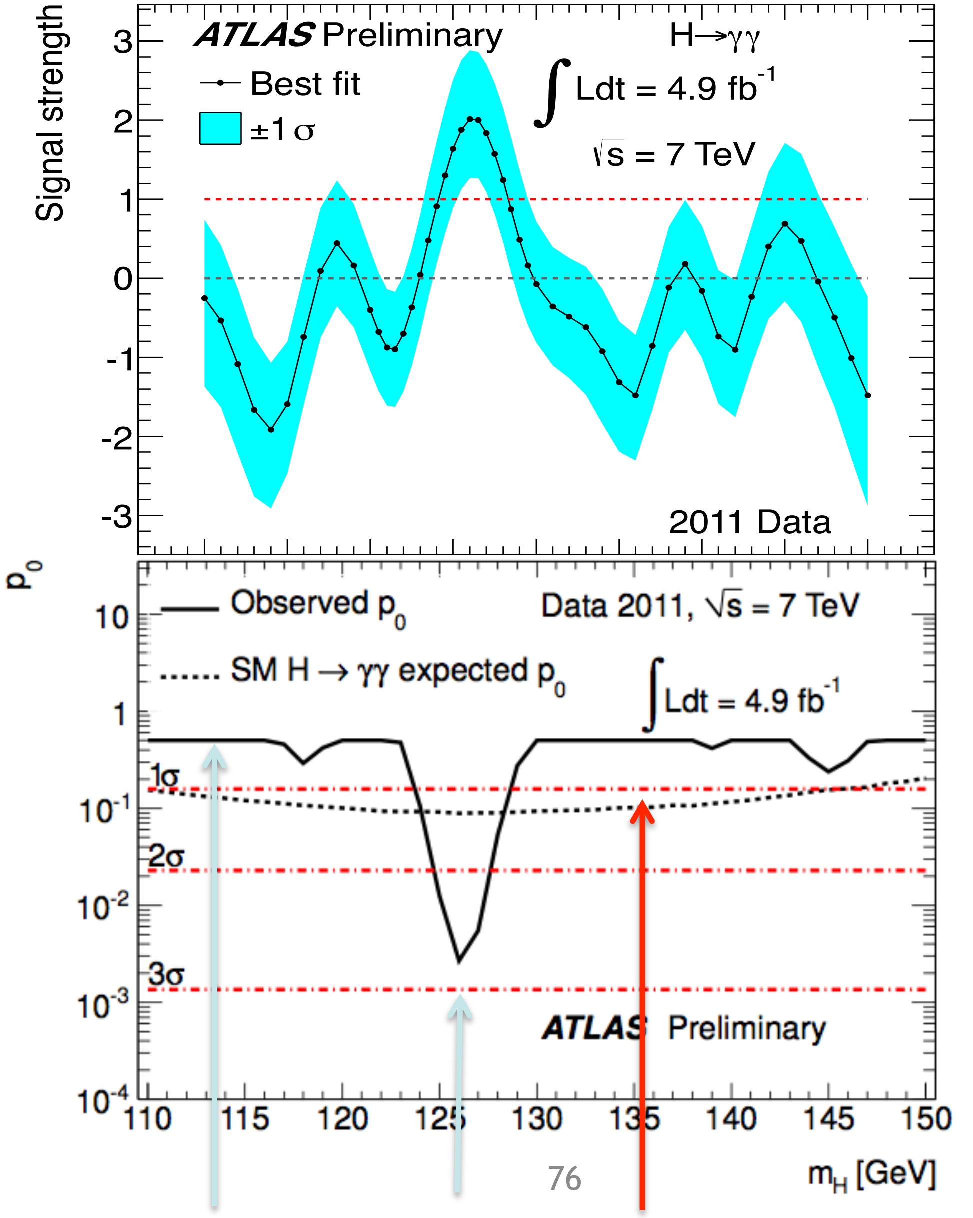


Expected Background

Excess

Deficit

How to Read Higgs Observation Estimates



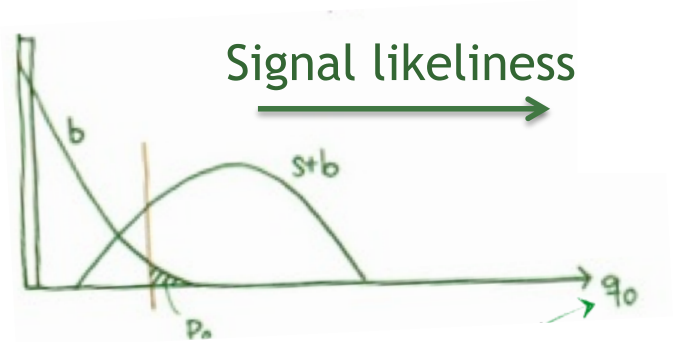
Deficit

Excess

Expected Signal

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

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



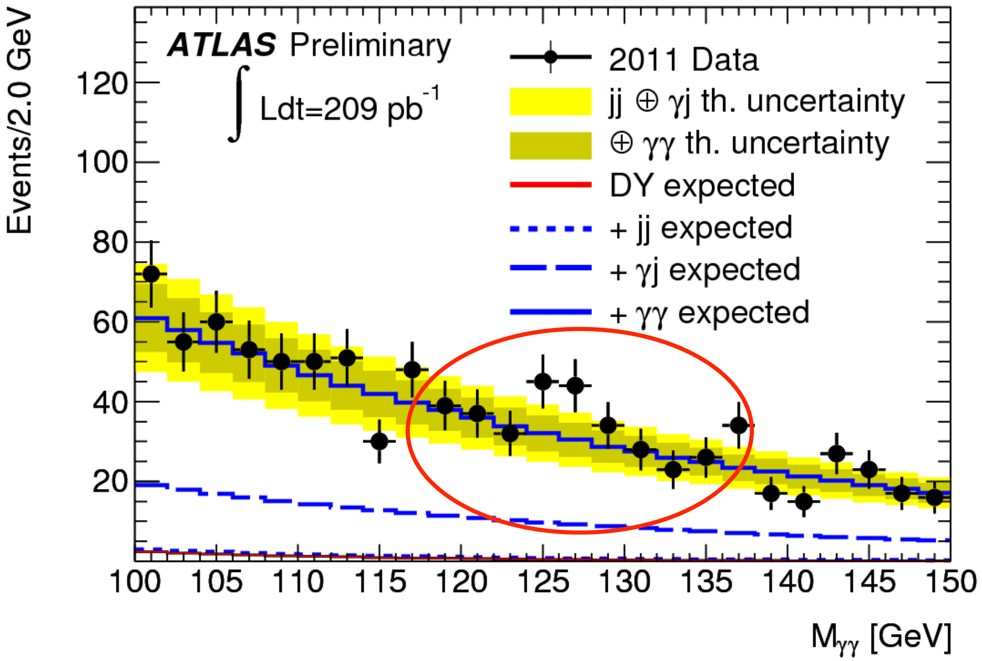
Signal likeliness

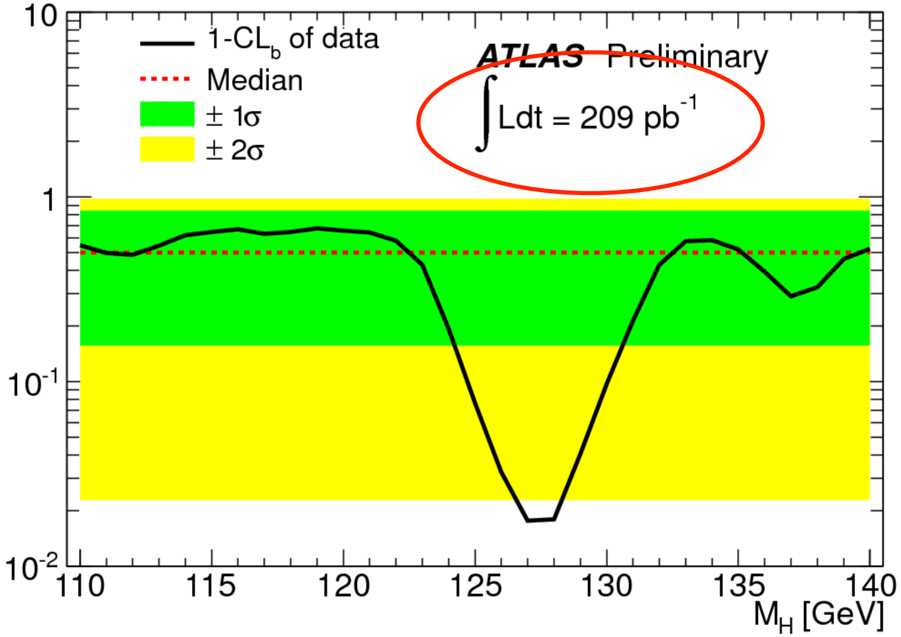
p_0 Probability that a background only experiment be more signal like than observed

The beginning of the p_0 Era

For the PLHC 2011 Perugia Conference in spring 2011

ATLAS-CONF-2011-071



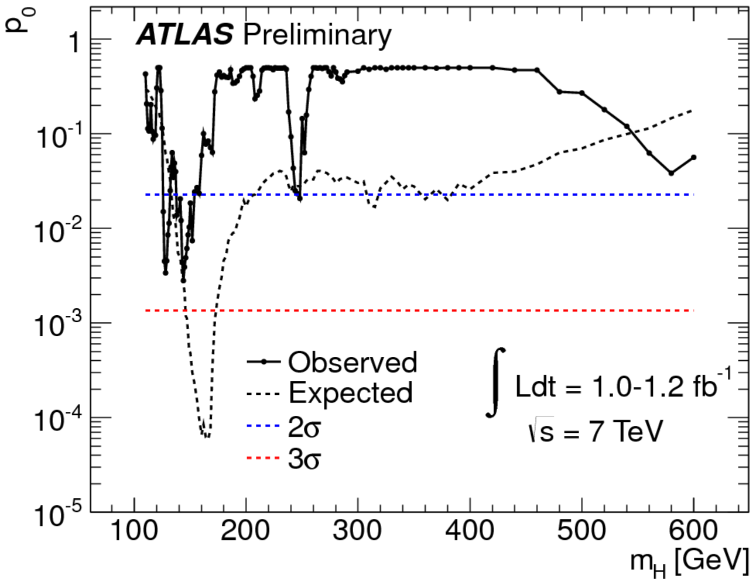


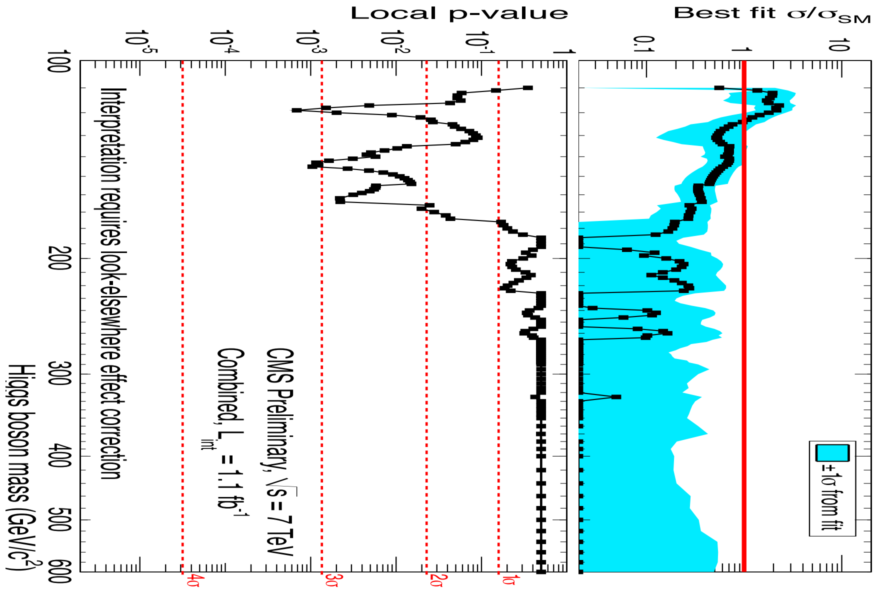
Discussion of the p_0 with LEE on data… at 127 GeV!

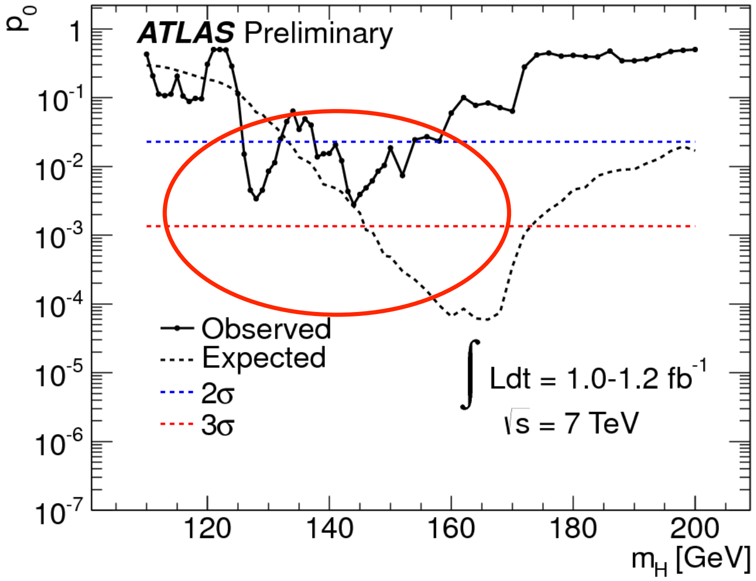
No attention paid… of course it was a fluctuation!

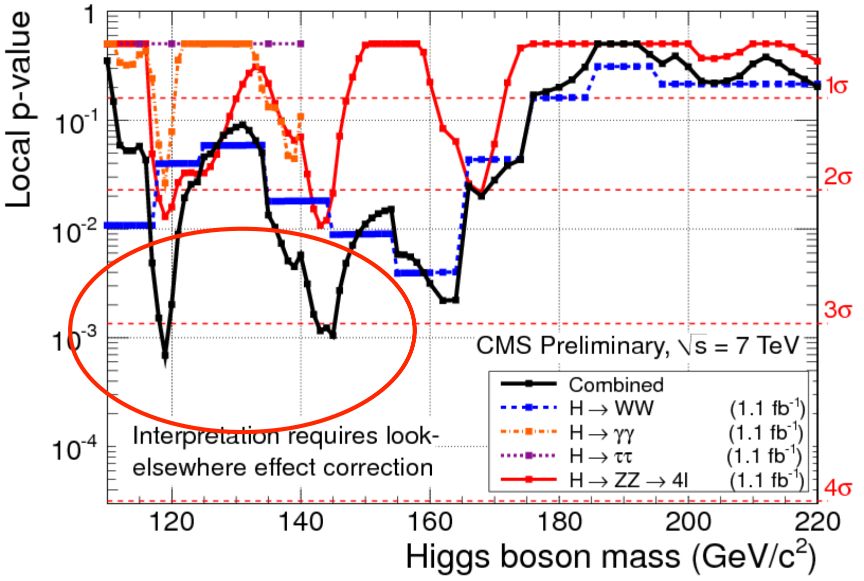
The First fb^{-1} in the p_0 Era

EPS-HEP Grenoble 2011



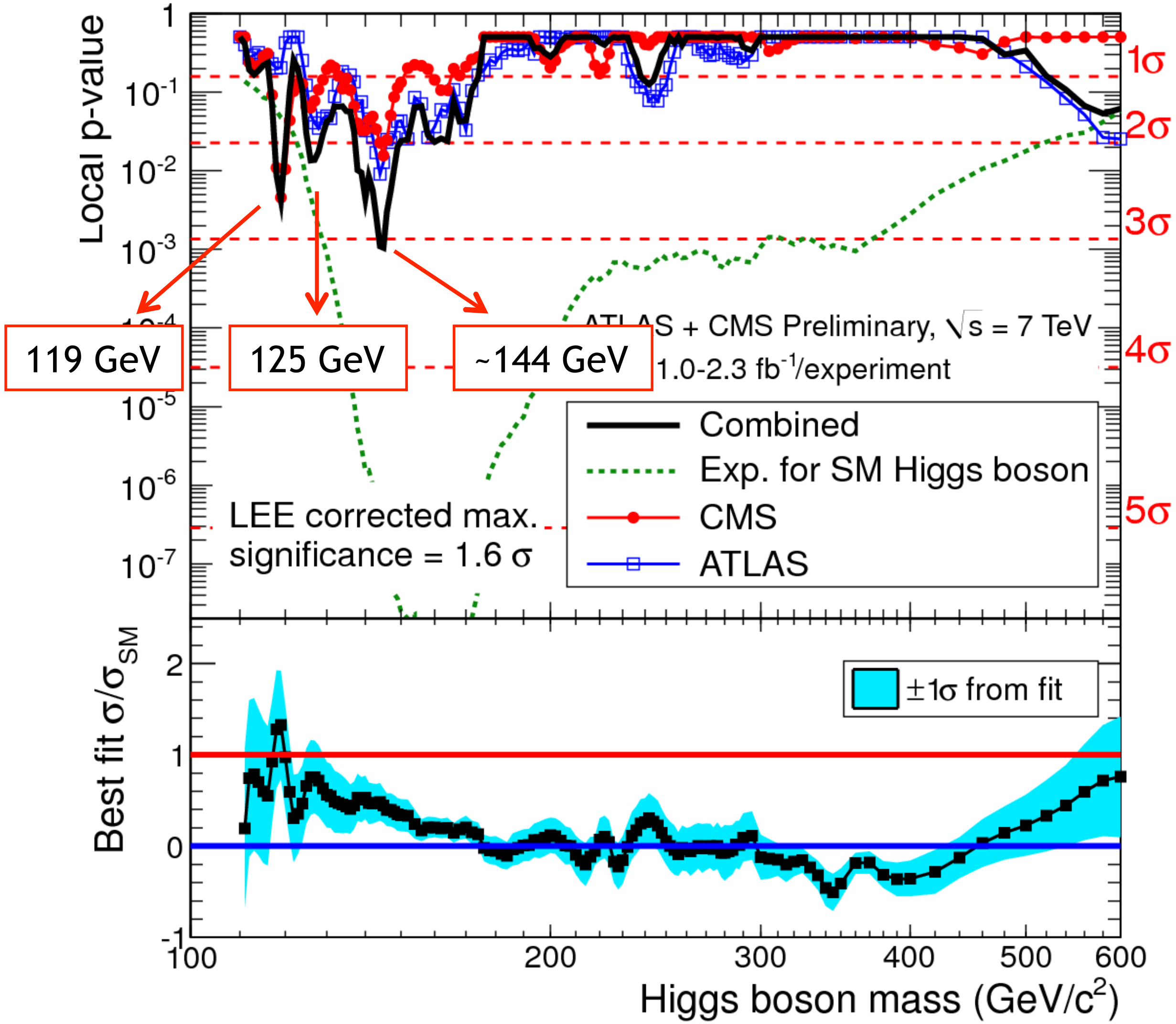






The First LHC Combination

HCP - Paris 2011



119 GeV

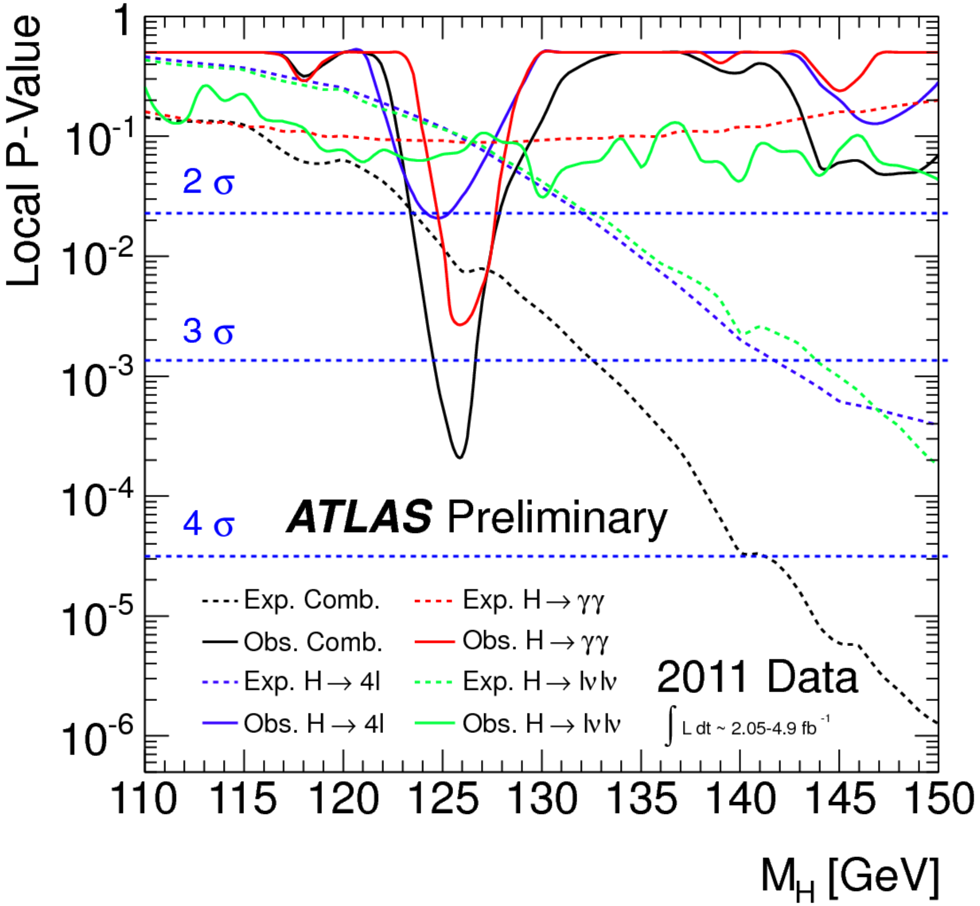
125 GeV

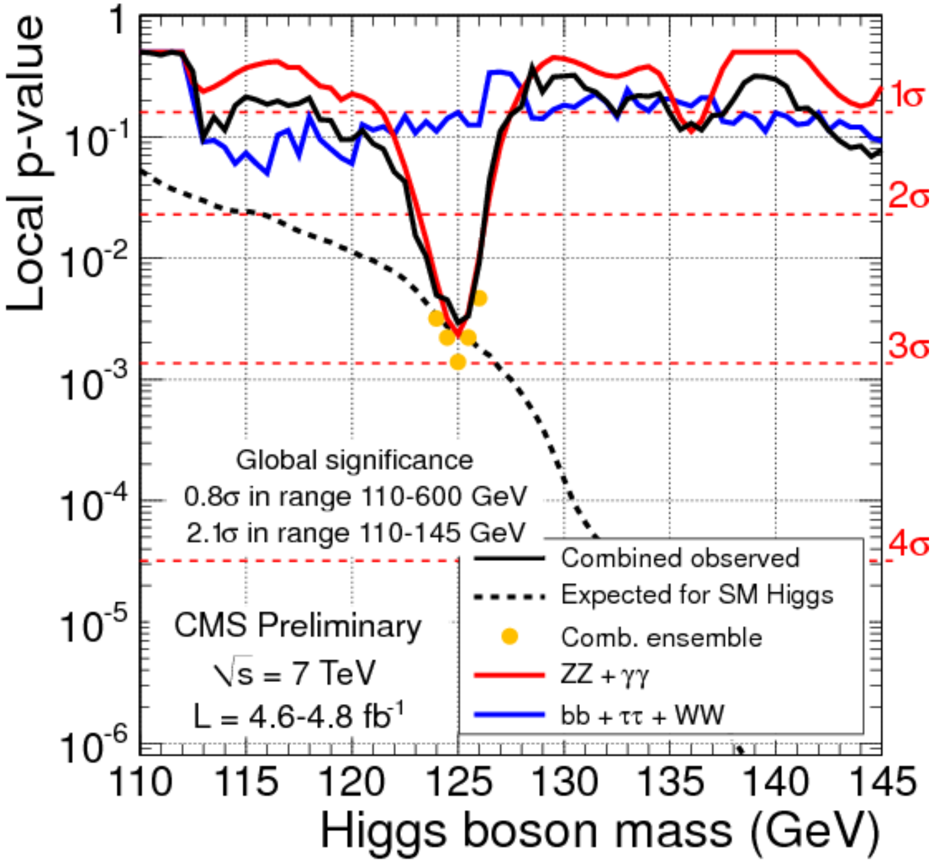
~144 GeV

No other combinations to follow in order to ensure independence!

The CERN december 2011 Council Meeting

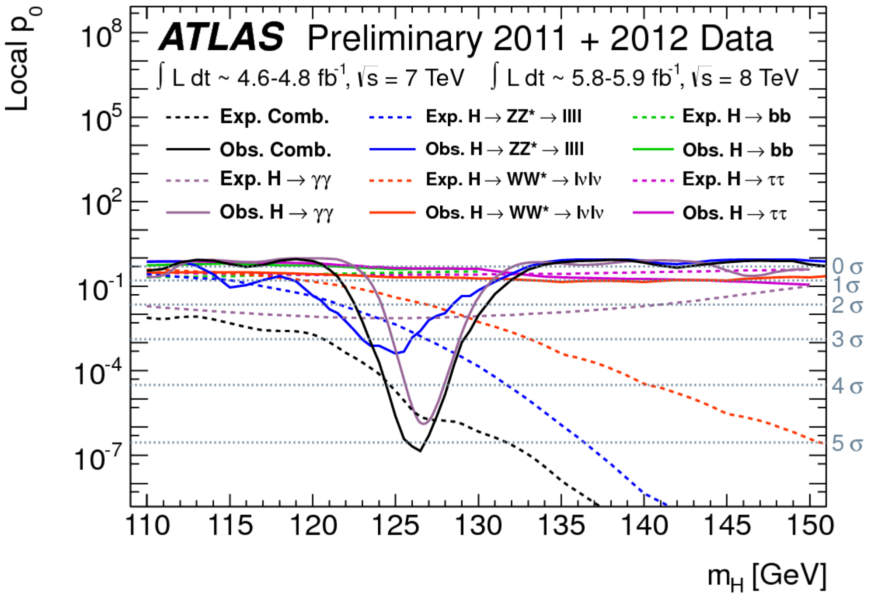
The first evidence



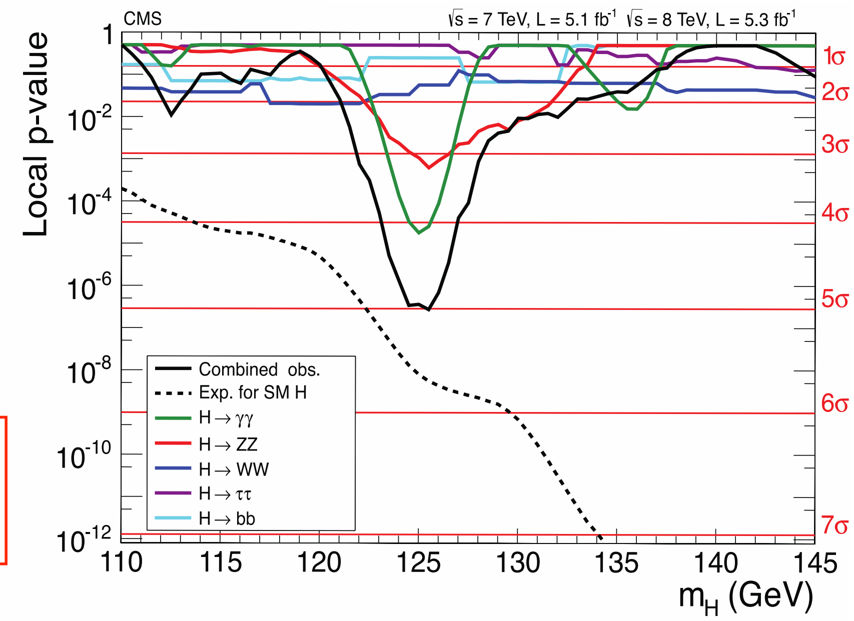


Council Meeting July 4, 2012 and ICHEP - Melbourne 2012

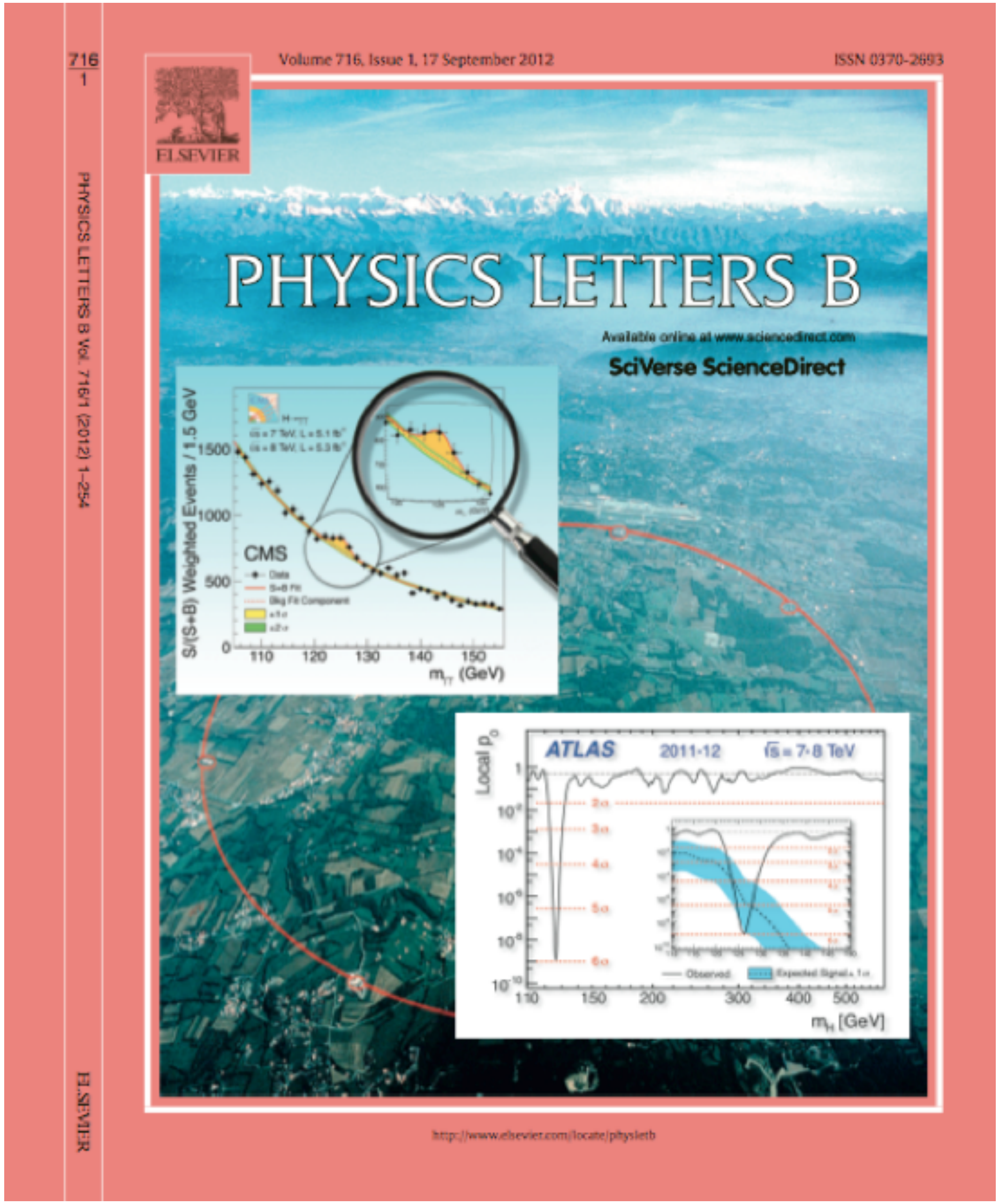
As a Layman : We have it!



5σ



PLB 716



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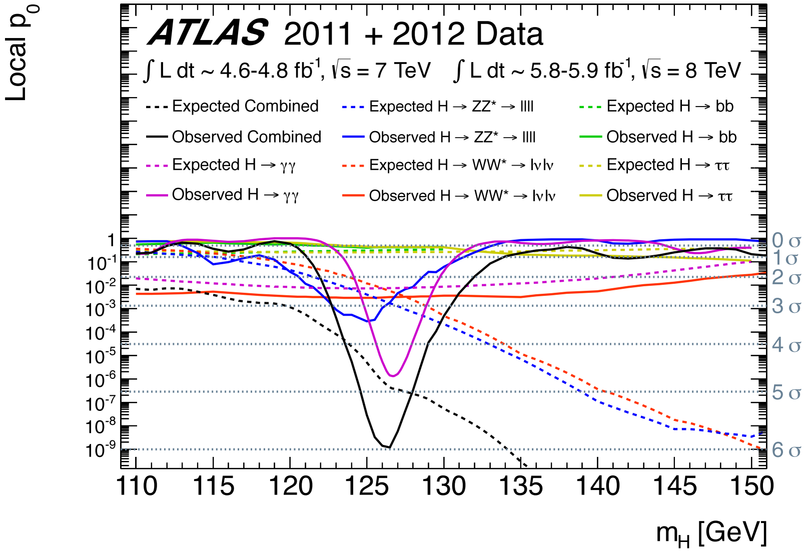
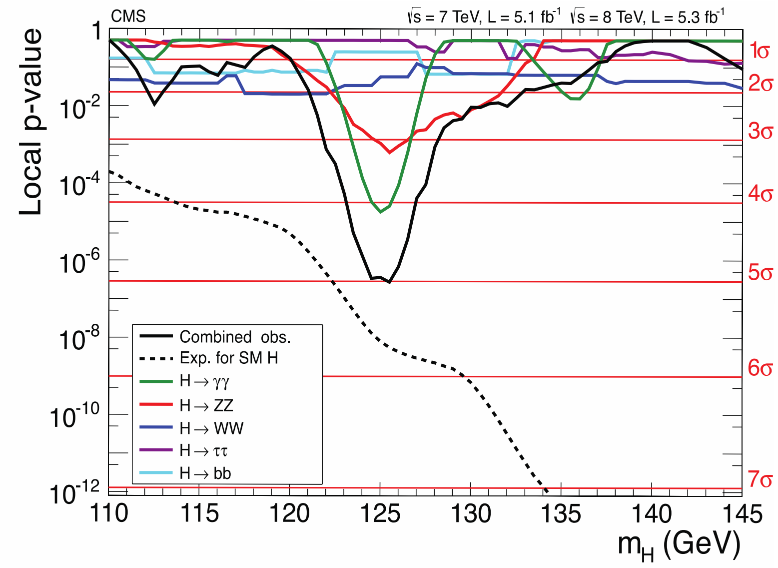
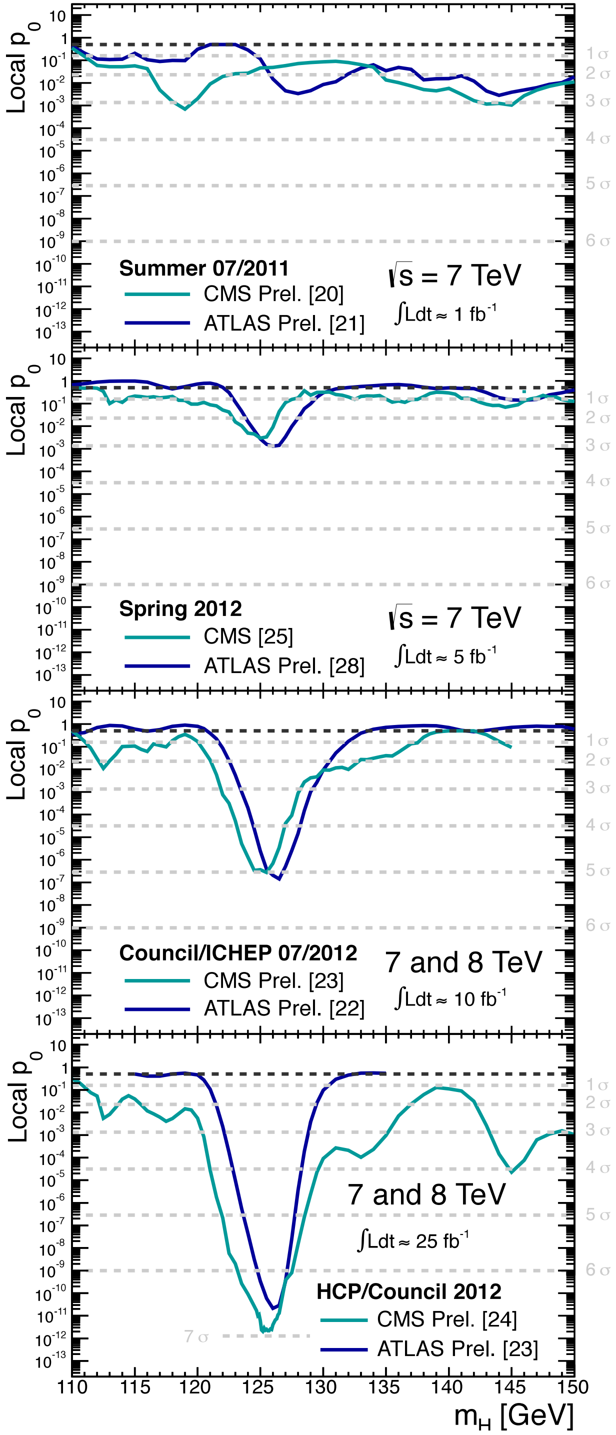






PDG, review of Particle Physics

A Textbook and Timely Discovery

- Summer 2011: EPS and Lepton-Photon

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

- December 2011: CERN Council

  First hints

- Summer 2012: CERN Council and ICHEP

  Discovery!

- December 2012: CERN Council

  Begining of a new era

What have we learned?

Standard Model now fully corroborated

The Higgs sector somehow is the least elegant sector of the Standard Theory

- It accounts for most of the unknown parameters (fermion masses)
- There is no underlying gauge principle

Open questions

Is it the Higgs boson of the Standard Model?

Is it composite or elementary?

Is there a reason why is μ^2 should be negative?

What could explain the flavor mass hierarchy?

Is the mechanism responsible for the mass of gauge boson also responsible for fermion masses ?

Is the Higgs sector minimal?

What is dark matter made of?

…and wait!

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

Knowing the Higgs mass…

$$\lambda = 0.126$$

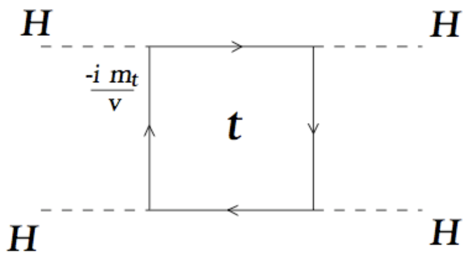
So?

Running Quartic Coupling : Vacuum stability

Looking closer into the limit where the Higgs boson mass is small :

$$32\pi^2\frac{d\lambda}{dt} = 24\lambda^2 - (3g'^2 + 9g^2 - 24y_t^2)\lambda + \frac{3}{8}g'^4 + \frac{3}{4}g'^2 g^2 + \frac{9}{8}g^4 - \boxed{24y_t^4} + \cdots$$

The last term of the equation is dominant and due to diagrams such as :



$$\sim \frac{m_t^4}{v^4}$$

The equation is then very simply solved : $\lambda(\Lambda) = \lambda(v) - \frac{3}{4\pi^2} y_t^2 \log\left(\frac{\Lambda^2}{v^2}\right)$

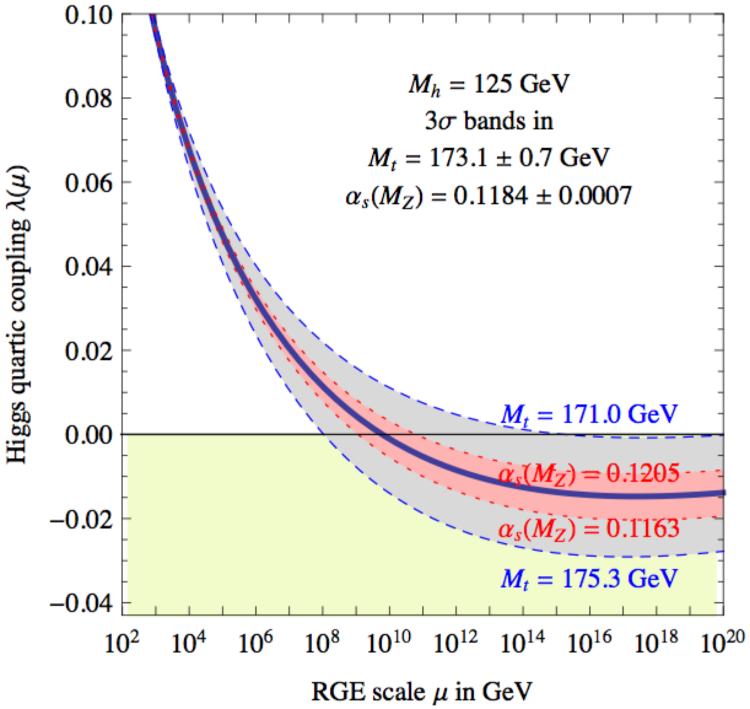
Requiring that the solutions are stable (non-negative quartic coupling) :

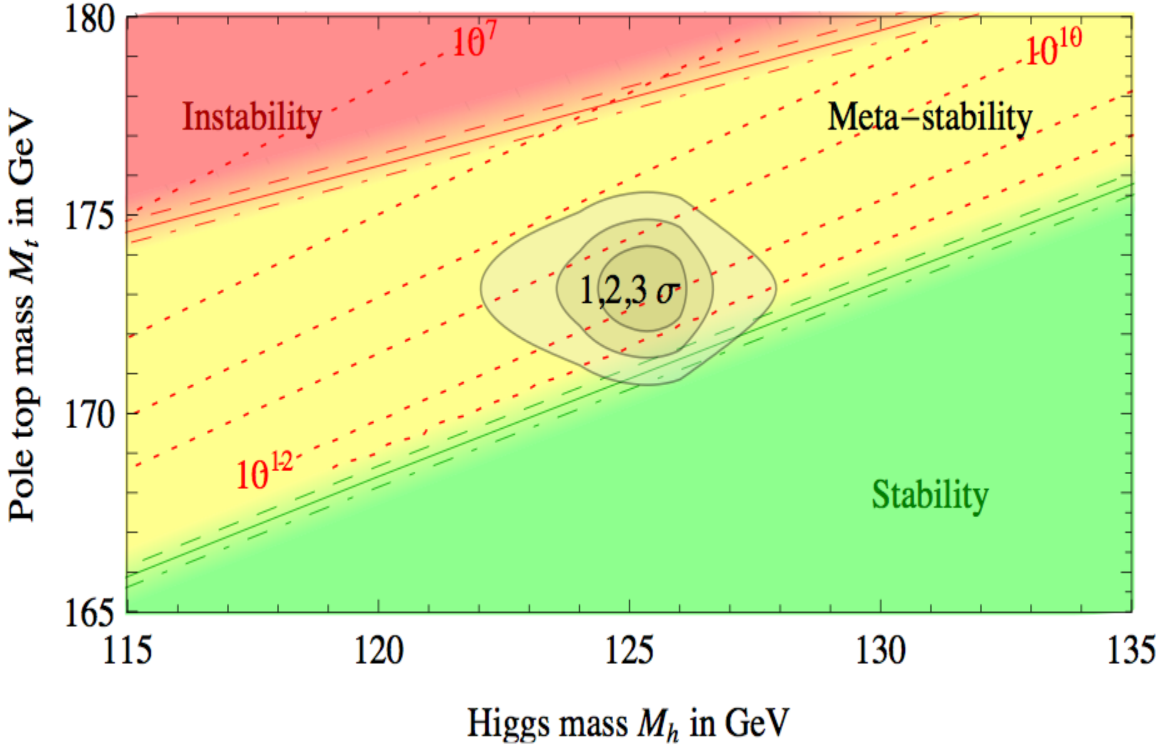
$\lambda(\Lambda) > 0$ then $\boxed{M_H^2 > \frac{3v^2}{2\pi^2} y_t^2 \log\left(\frac{\Lambda^2}{v^2}\right)}$

Running of the Quartic Coupling

Metastability

Guiding Principle?





$\lambda \sim 0$
(at the high scale)

Large dependence on top mass and of course Higgs boson mass

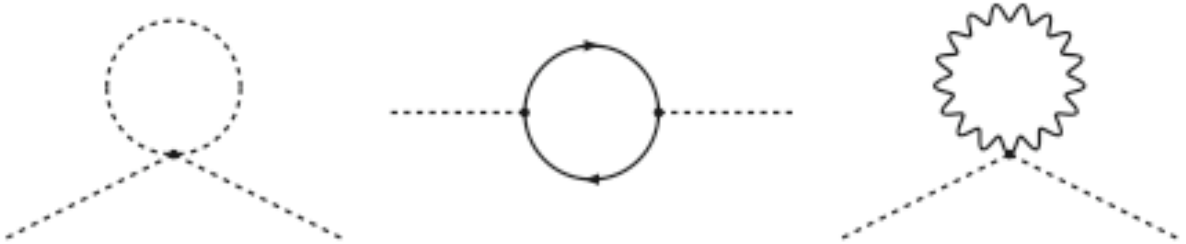
Hierarchy, Fine Tuning and Naturalness

How the Higgs boson does not only SOLVE problems

The Hierarchy Problem

The Higgs potential is fully renormalizable, but…

Loop corrections to the Higgs boson mass…



…are quadratically divergent : $\Delta m^2 \propto \int^{\Lambda} \frac{d^4k}{(2\pi)^4} \frac{1}{k^2} \sim \frac{\Lambda^2}{16\pi^2}$

If the scale at which the standard model breaks down is large, the Higgs natural mass should be of the order of the cut-off. e.g. the Planck scale

$$m_H = m_0 + \Delta m + \ldots$$

Higher orders

…but the Higgs boson has a low mass!

This can be achieved by fine tuning our theory… Inelegant…

(note that technicolor models are not concerned by this problem)

Supersymmetry

The Hierarchy problem is not only a problem of esthetics : If the difference is imposed at tree level, the radiative corrections will still mix the scales and destabilize the theory.

One may note that :

$$\Delta m_H^2 \sim \frac{|\lambda_f|^2}{16\pi^2}\left(-2\Lambda^2 + 6m_f^2 \ln\frac{\Lambda}{m_f} + \ldots\right)$$

→ Contribution of fermions

$$\Delta m_H^2 \sim \frac{\lambda_s}{16\pi^2}\left(\Lambda^2 + 2m_f^2 \ln\frac{\Lambda}{m_s} + \ldots\right)$$

→ Contribution of scalars

Therefore in a theory where for each fermion there are two scalar fields with

$$\lambda_s = |\lambda_f|^2$$

(which is fulfilled if the scalars have the same couplings as the fermions) quadratic divergencies will cancel

The field content of the standard model is not sufficient to fulfill this condition

A solution is given by supersymmetry where each fermionic degree of freedom has a symmetrical bosonic correspondence

In supersymmetry the quadratic divergences naturally disappear but…

Immediately a problem occurs : Supersymmetry imposes $m_{boson} = m_{fermion}$

Supersymmetry must be broken!

But in the case of SUSY a SSB mechanism is far more complex than for the EWSB and no satisfactory SSB solution exists at this time…

…However an explicit breaking "by hand" is possible provided that it is softly done in order to preserves the SUSY good UV behavior…

$$\Delta m_H^2 \propto m_{soft}^2 (\ln \frac{\Lambda}{m_{soft}} + ...)$$

Interestingly similar relation to that of the general fine tuning one

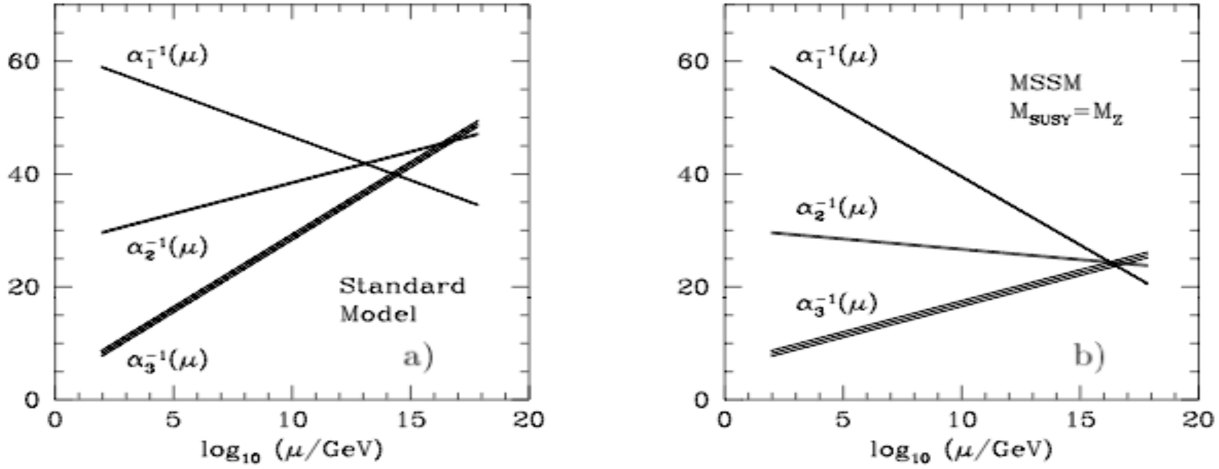
Implies that the m_{soft} should not exceed a few TeV

The Minimal Supersymmetric Standard Model's Higgs Sector

In a tiny nut shell

Additional motivations for supersymmetry :

- Allows the unification of couplings
- Local SUSY: spin 3/2 gravitino (essential ingredient in strings)
- Natural candidate for Dark Matter



The Higgs Sector : Two doubets with opposite hypercharges are needed to cancel anomalies (and to give masses independently to different isospin fermions)

- MSSM : 5 Higgs bosons
- Lightest mass < m_z at tree level and smaller than ~130 GeV/c^2 w/ rad. Corr.

The discovery of the Higgs boson has opened new and fundamental horizons

Tomorrow: Discuss how we have started the exploration at the LHC!