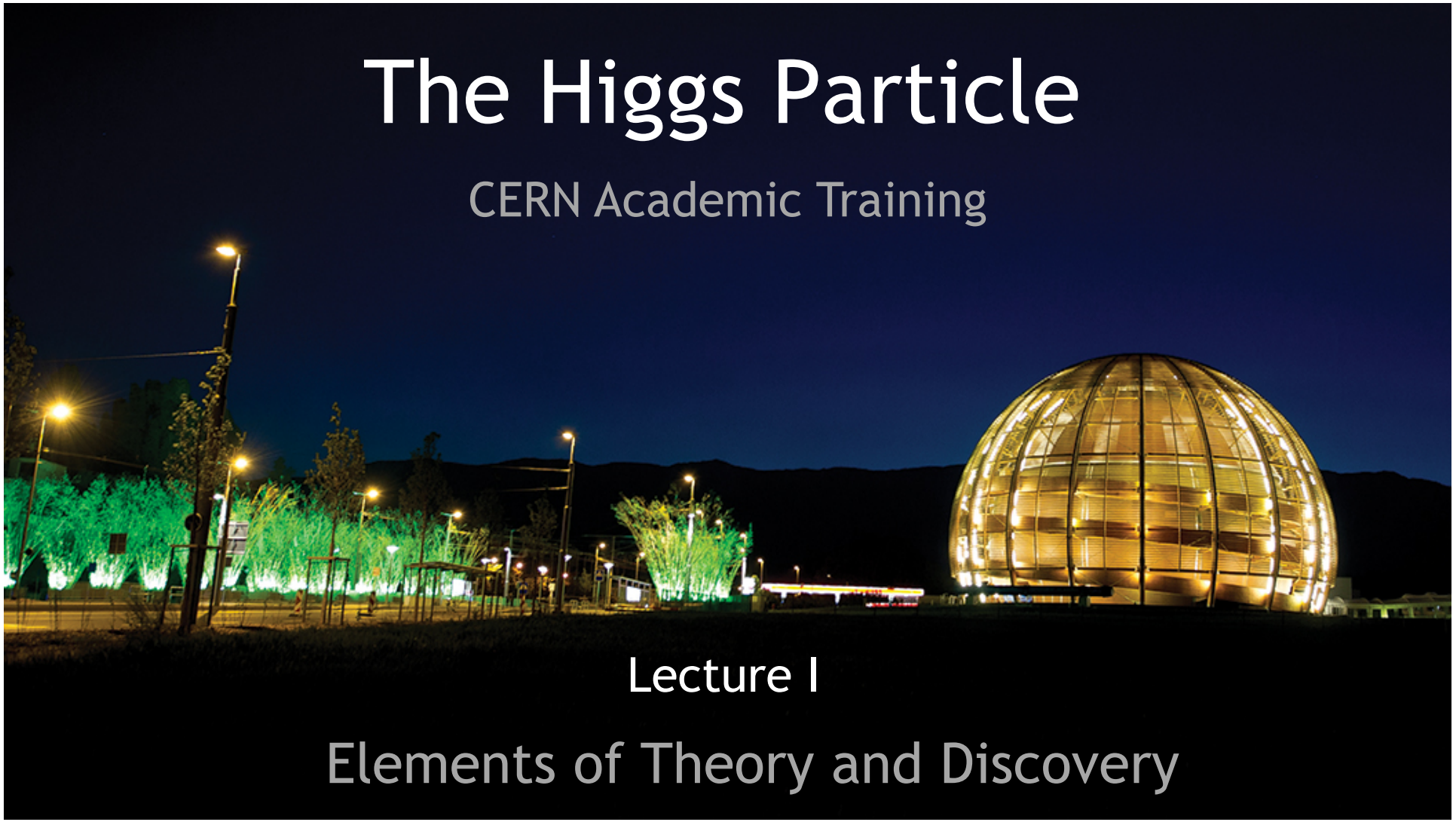
# The Higgs Particle

CERN Academic Training



## Lecture I

## Elements of Theory and Discovery

Marumi Kado

Laboratoire de l'Accélérateur Linéaire (LAL)

And CERN

# Outline

I.- The roadmap to the discovery (Lecture I)

1.- Review of basic theoretical foundations
2.- Historical context and perspective
3.- Statistical methods (Part I)
4.- The discovery

II.- An (early) experimental profile of the Higgs boson (Lecture II)

Measurements of the main properties of the Higgs boson

III.- Implications and future projects (Lecture III)

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

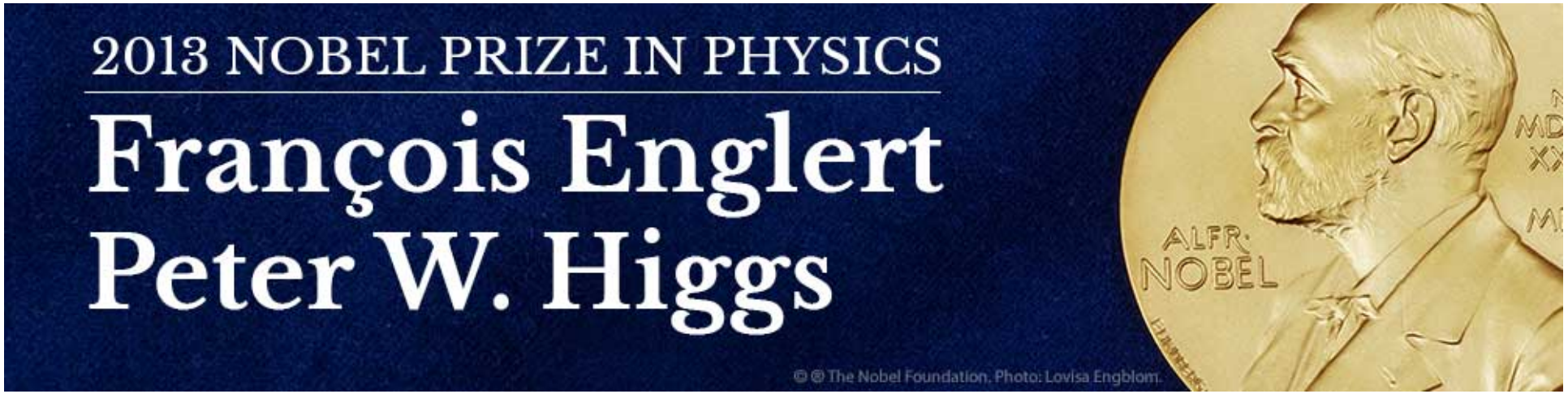
Disclaimer

# The Higgs boson

“The” refers to the one discovered


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

KUNGL. VETENSKAPS-AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES




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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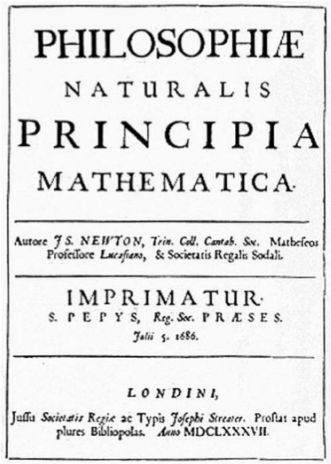
# Basic theoretical elements


PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

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

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

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

# Not the origin of Mass

- Gallilean and Newtonian concept of mass :

Inertial mass (F=ma) Gravitational mass (P=mg)

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

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

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

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

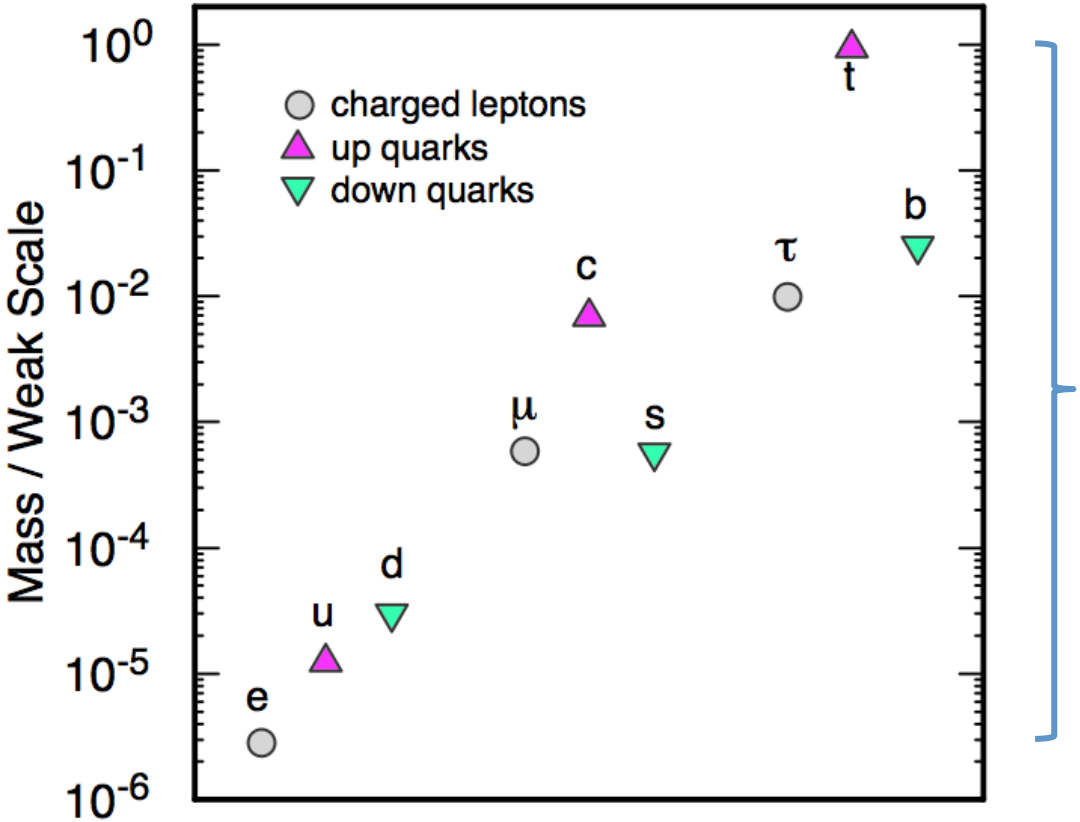
Most of the (luminous) mass in the universe comes from QCD confinement energy

**The insight(s) of the BEH mechanism :**

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

# Not explaining the flavor Hierarchy

## Replacing mass terms by Yukawa couplings




~6 orders of magnitude

Neutrinos are not even on the scale!

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

# 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 !

# Spontaneous Symmetry Breaking (SSB) in Particle Theory

## Nambu (1960) and Goldstone (1961)

Massless scalars occur in a theory with SSB

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

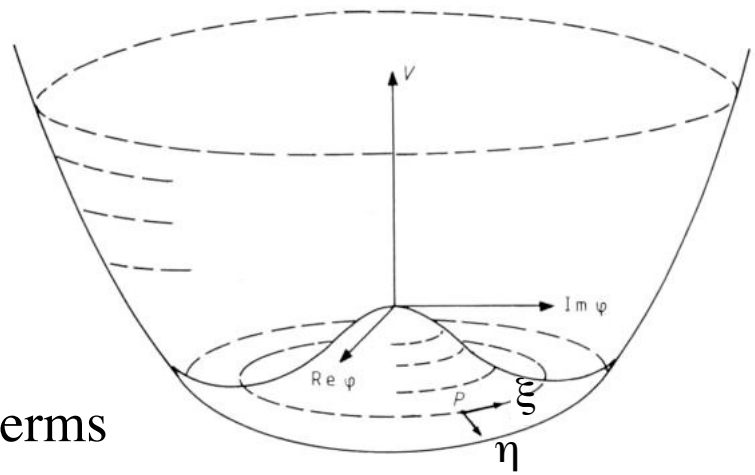
From a simple (complex) scalar theory with a U(1) symmetry

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

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

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

Shape of the potential if $\mu^2<0$ and $\lambda>0$ necessary for SSB and be bounded from below.




Change frame to local minimum frame :

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

No loss in generality.

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

# Digression on Chiral Symmetry

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

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

It is a Dynamical Symmetry Breaking where the pseudo-goldstone bosons are the $\pi^+,\pi^0,\pi^-$ 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

# Life before the Higgs

Historical review by J. Ellis (Higgs Hunting 2011)

Gauge theories require massless bosons: Yang-Mills theories irrelevant to describe weak interaction?

Nambu Goldstone global SSB implies massless scalar bosons

Can two wrongs make a right?

# The Seminal Papers 1964

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

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

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

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

Received 27 July 1964

Answering Gilbert's objection

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

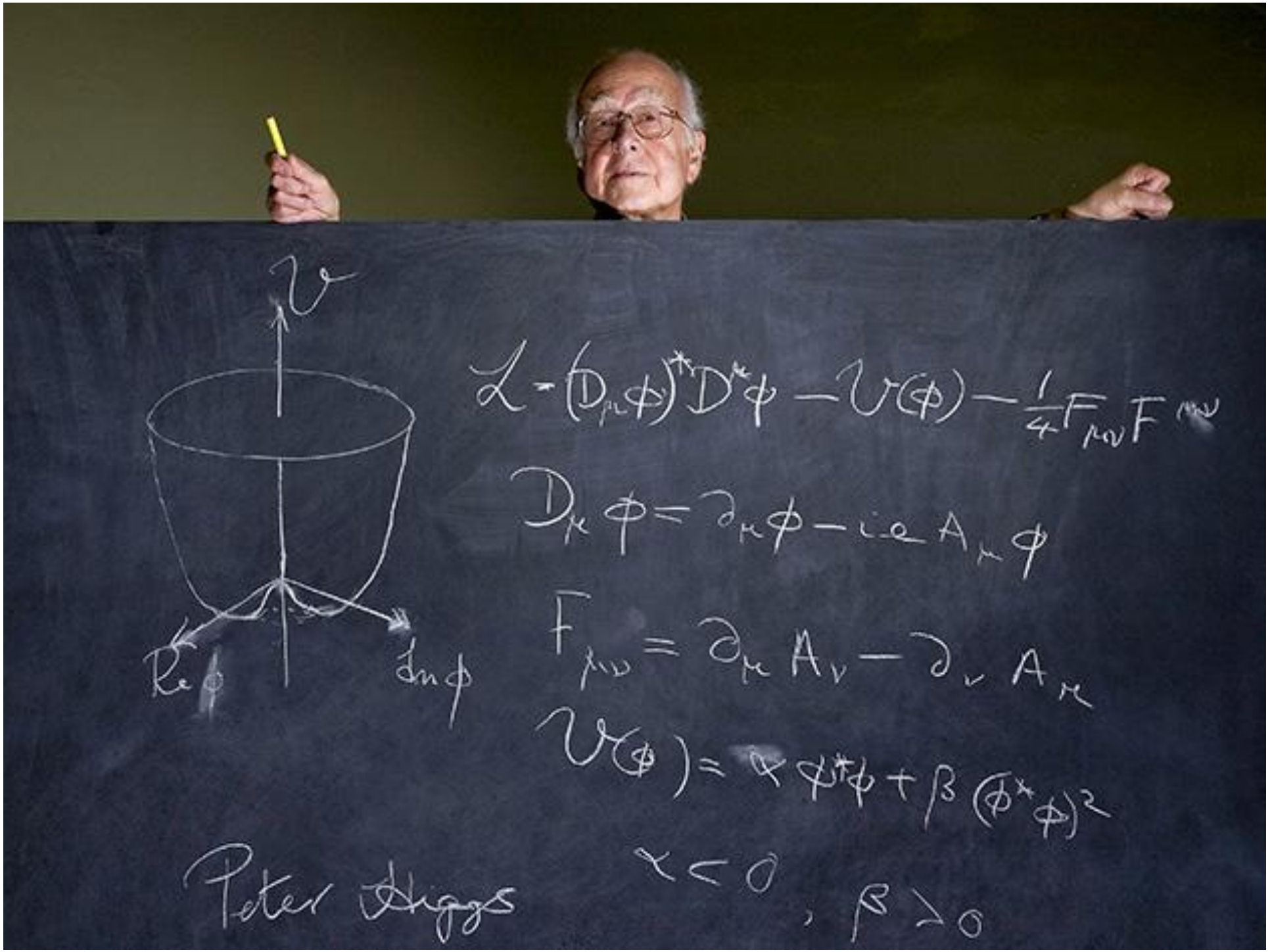
BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

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

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

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

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


$V$
$\mathrm{Re}\,\phi$
$\mathrm{Im}\,\phi$
$\mathcal{L} = (D_\mu \phi)^* D^\mu \phi - V(\phi) - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$D_\mu \phi = \partial_\mu \phi - ie A_\mu \phi$
$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$
$V(\phi) = \alpha \phi^* \phi + \beta (\phi^* \phi)^2$
$\alpha < 0, \ \beta > 0$
Peter Higgs

# Spontaneous Symmetry Breaking (SSB) with a Local Symmetry

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

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

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

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

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

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

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

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

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

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

Mass term for the gauge field! But…

What about the field content?

A massless Goldstone boson $\xi$, a massive scalar $\eta$ and a massive gauge boson!

| | | | |
|---|---|---|---|
| Number of d.o.f. : | 1 | 1 | 1 |
| Number of initial d.o.f. : | 2 | Oooops… Problem! | |

But wait! The term $evA_\mu \partial^\mu \xi$ is unphysical

The Lagrangian should be re-written using a more appropriate expression of the translated scalar field choosing a particular gauge where h(x) is real :

$$\varphi = (v + h(x))e^{i\frac{\theta(x)}{v}}$$

Gauge fixed to absorb $\theta$

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

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

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

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

The Goldstone boson does not appear anymore in the Lagrangian

# SSB and the Standard Model of EW interactions

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

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 largest group that leaves invariant the kinematic terms $-\bar{L}\gamma^\mu\partial_\mu L - \bar{R}\gamma^\mu\partial_\mu R$ of the Lagrangian consists of the electronic isospin $\vec{T}$ acting on $L$, plus the
right-handed el
as we know, tw
tirely unbroken
and the electro
gauge field cor
metry will have
massless particle coupled to $N_e$,* so we must form our gauge group out of the electronic isospin $\vec{T}$ and the electronic hyperchange $Y = N_R + \frac{1}{2}N_L$.

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

The only unequivocal new predictions made by this model have to do with the couplings of the neutral intermediate meson $Z_\mu$

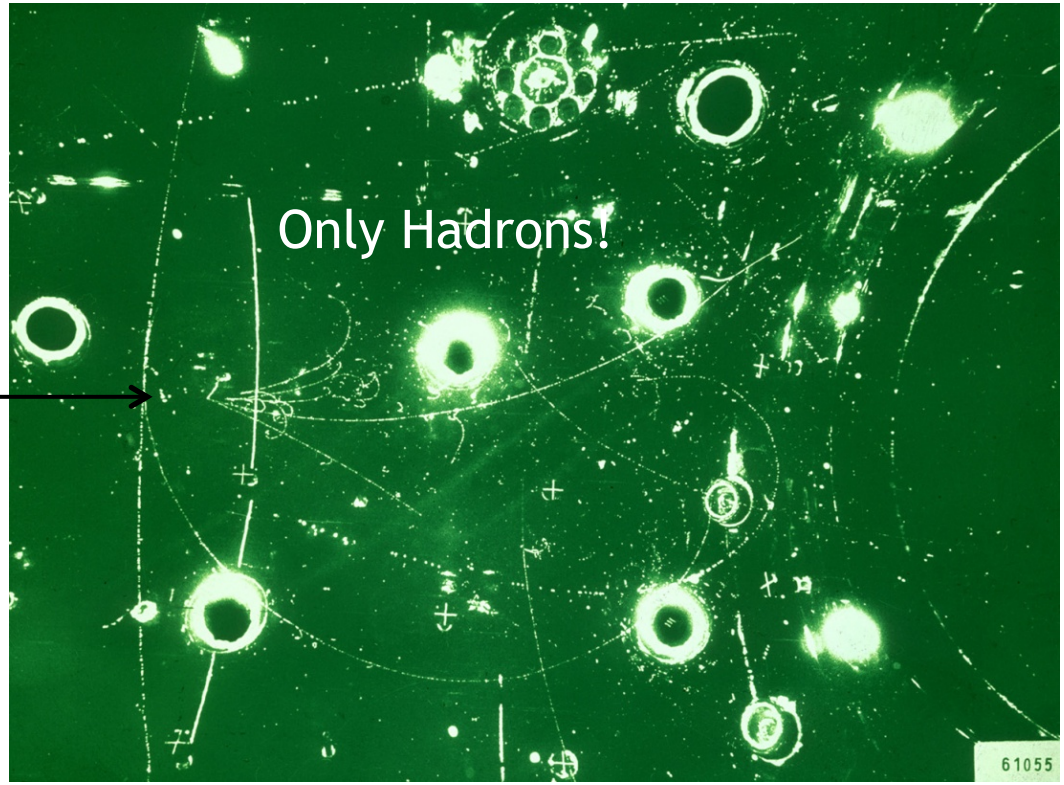
Of course our model has too many arbitrary features for these predictions to be taken very seriously

# The Neutral Currents

**1973:** neutral current discovery (Gargamelle experiment, CERN)

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

$\nu_\mu$




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

# Spontaneous Symmetry Breaking (SSB)

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

Introducing a double of complex scalar fields (4 d.o.f.) : $\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi^+ \\ \phi^o \end{pmatrix}$

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

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

The next step is to develop the Lagrangian near : $< \phi >= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$

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

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

Non electrically charged vacuum

Again choosing the gauge that will absorb the Goldstone bosons $\xi$...

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

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

Massive scalar : The Higgs boson

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

Massive gauge bosons

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

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

Gauge-Higgs interaction

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

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

Massive scalar : The Higgs boson

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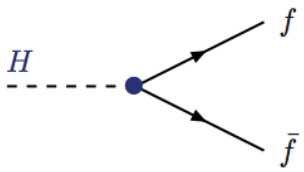
Massive gauge bosons

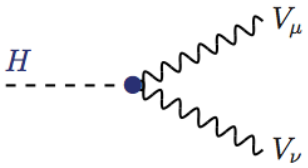
$$+ \frac{1}{v}\left[\frac{g'^2 v^2}{4} B_\mu B^\mu H - \frac{g g' v^2}{2} W^3_\mu B^\mu H + \frac{g^2 v^2}{4} \vec{W}_\mu . \vec{W}^\mu H\right]$$

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

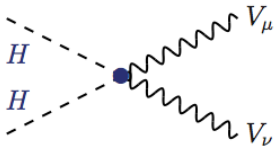
Gauge-Higgs interaction



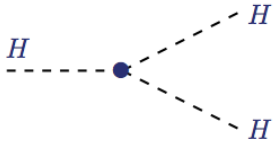

$$g_{Hff} = m_f/v$$



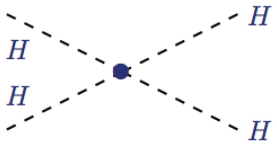

$$g_{HVV} = 2M_V^2/v$$




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




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




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

Keep this in mind for the next lectures…

# First important consequences of the mechanism : s

1.- Two massive charged vector bosons :

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

Corresponding to the then observed charged currents

Thus v = 246 GeV

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

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

3.- One massive neutral vector boson Z :

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

# The sector of Fermions

Another important consequence of the Weinberg Salam Model…

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

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

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

Not the case when using Yukawa couplings to the Higgs doublet

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

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

The Higgs mechanism DOES NOT predict fermion masses

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

# 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%

# Prediction of the Model

Beside the existence of the Z massive neutral gauge boson…

The existence of a massive scalar :

# The Higgs Particle

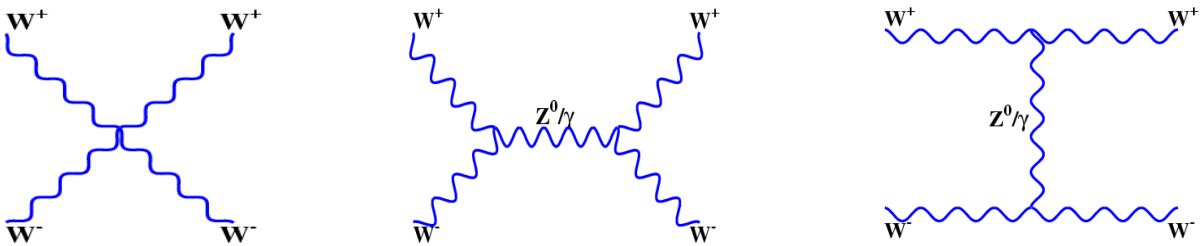
Whose mass (as $\lambda$) **<u>was</u>** an unknown parameter of the theory

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

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

# Very important additional virtue of the Higgs Particle

$$W^+W^- \to W^+W^-$$




Does not preserve perturbative unitarity.

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

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

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

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

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

# Half a Century of Higgs Quest

*Pre-LHC Era*

# First Bounds

## Astrophysical and Phenomenological

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

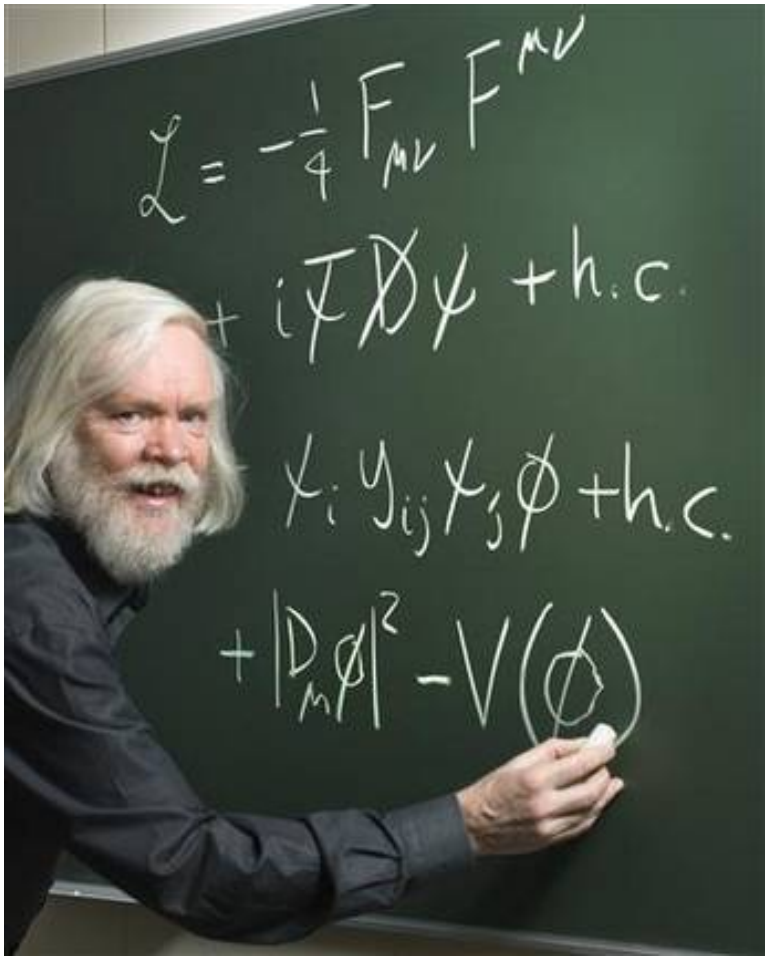
- Emission from stars: $m_H > 0.7\ m_e$
  (Sato and Sato, 1975)

- 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

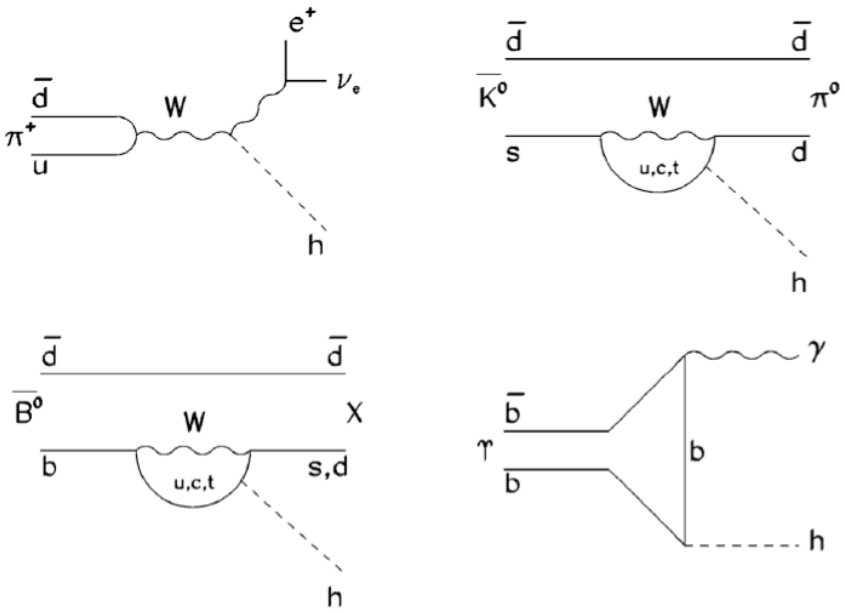
A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

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



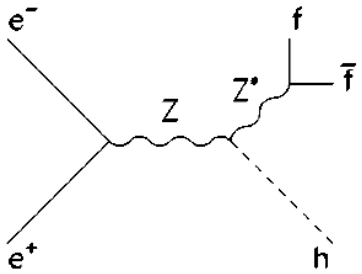

- SINDRUM Collaboration measured $\pi$ to ev H (ee) Yielding a limit on very light Higgs
- CUSB Collaboration $\Upsilon$ to H$\gamma$ yielding limit of ~ 5-6 GeV (dependent on high order corrections)
- Jade and CLEO provided bounds on B to $\mu\mu$+X
- CERN-Edimbrgh-Orsay-Mainz-Pisa-Siegen K to $\pi$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

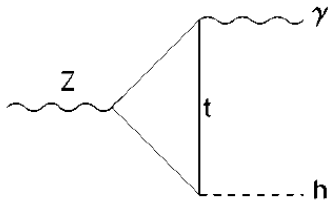
# Absolute Lower Limit on the Higgs Mass at LEP

LEP1 $e^+e^-$ at COM ~$m_Z$

Various decays and topologies

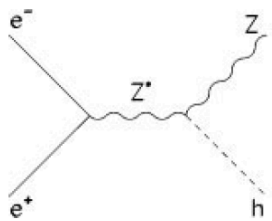
Limit down to below $2m_e$ using acoplanar lepton pairs (Higgs is long lived)

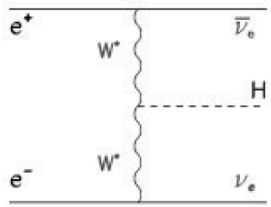


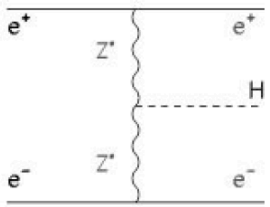



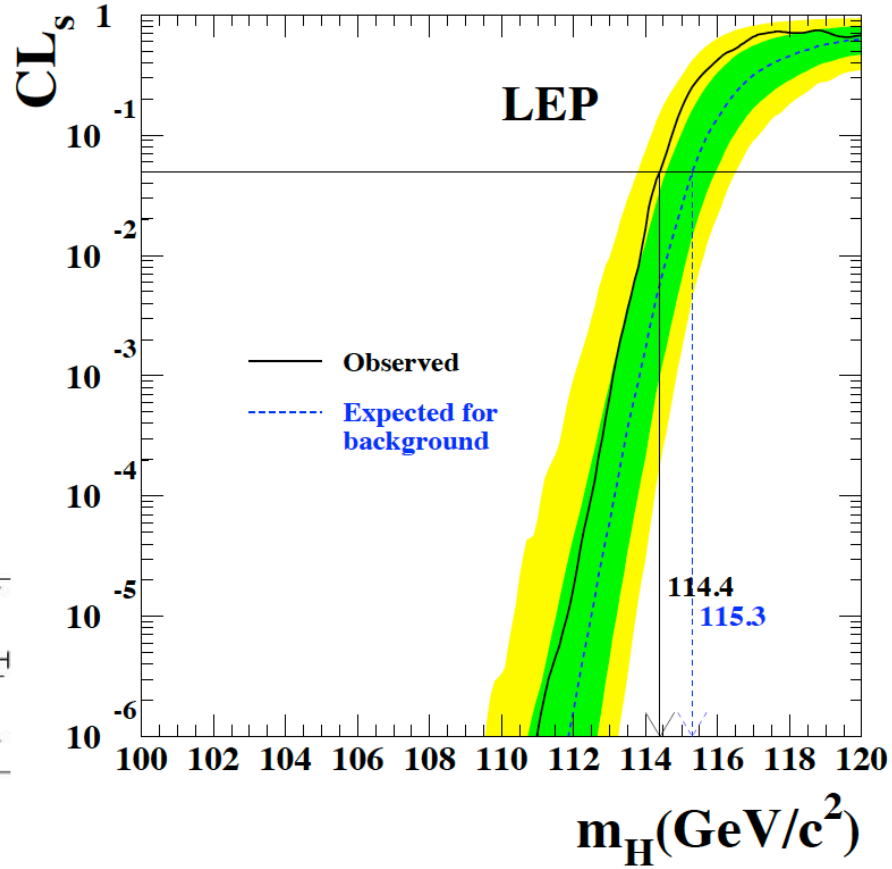

LEP2 $e^+e^-$ up to 209 GeV

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




**Excludes SM Higgs with mass below 114 GeV**

# Electroweak Precision Data and the Higgs Mass

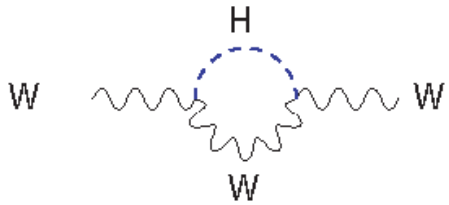
## *The famous blue band plot!*

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 | $\lvert O^{meas} - O^{fit} \rvert / \sigma^{meas}$ |
|---|---|---|---|
| $\Delta\alpha^{(5)}_{had}(m_Z)$ | 0.02750 ± 0.00033 | 0.02759 | |
| $m_Z$ [GeV] | 91.1875 ± 0.0021 | 91.1874 | |
| $\Gamma_Z$ [GeV] | 2.4952 ± 0.0023 | 2.4959 | |
| $\sigma^0_{had}$ [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 | |
| $\Gamma_W$ [GeV] | 2.085 ± 0.042 | 2.092 | |
| $m_t$ [GeV] | 173.20 ± 0.90 | 173.26 | |

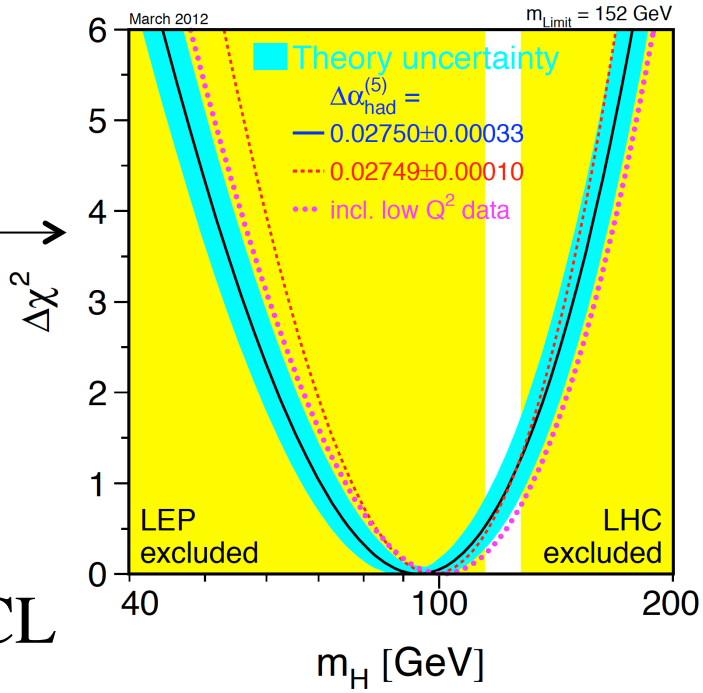
March 2012

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

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

*Is there a Higgs?*

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



# 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*

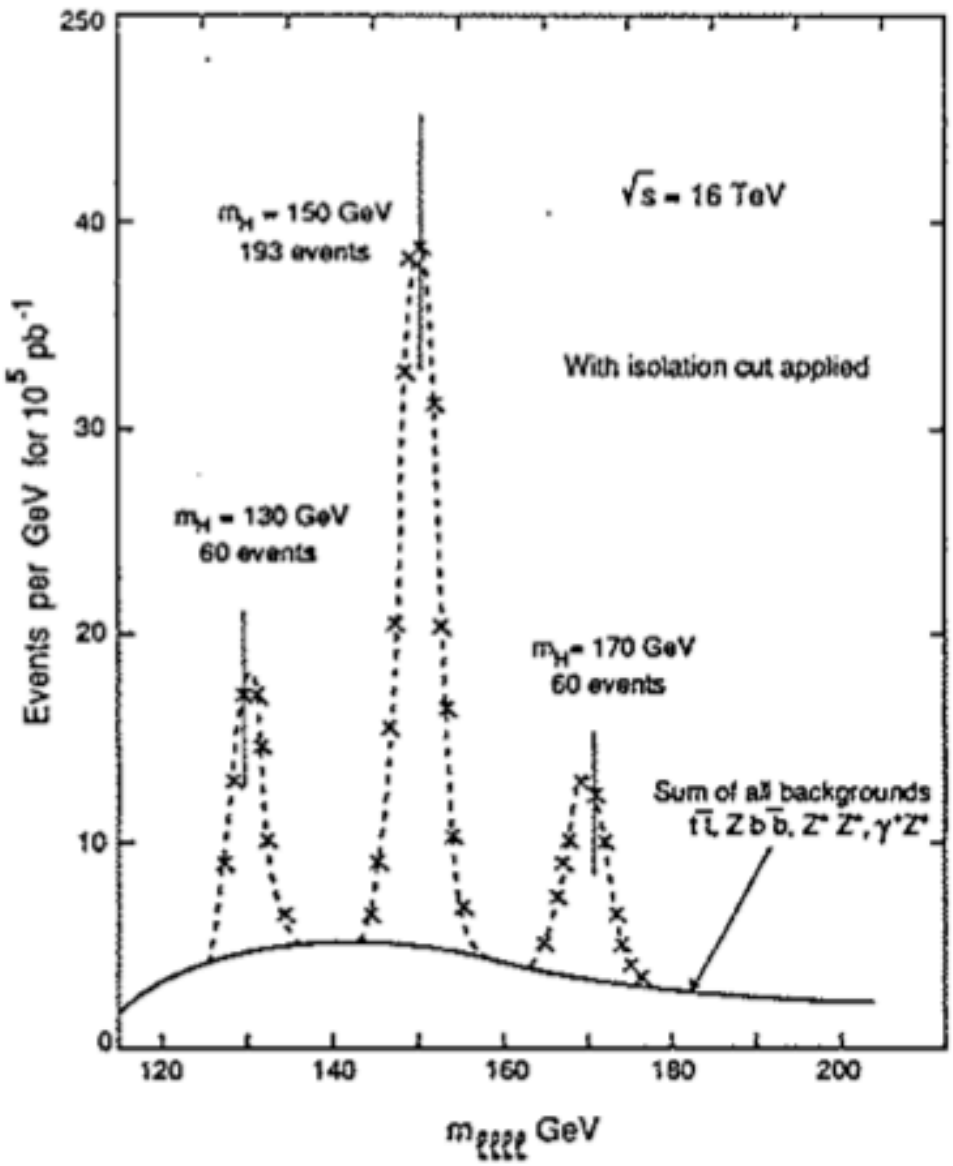
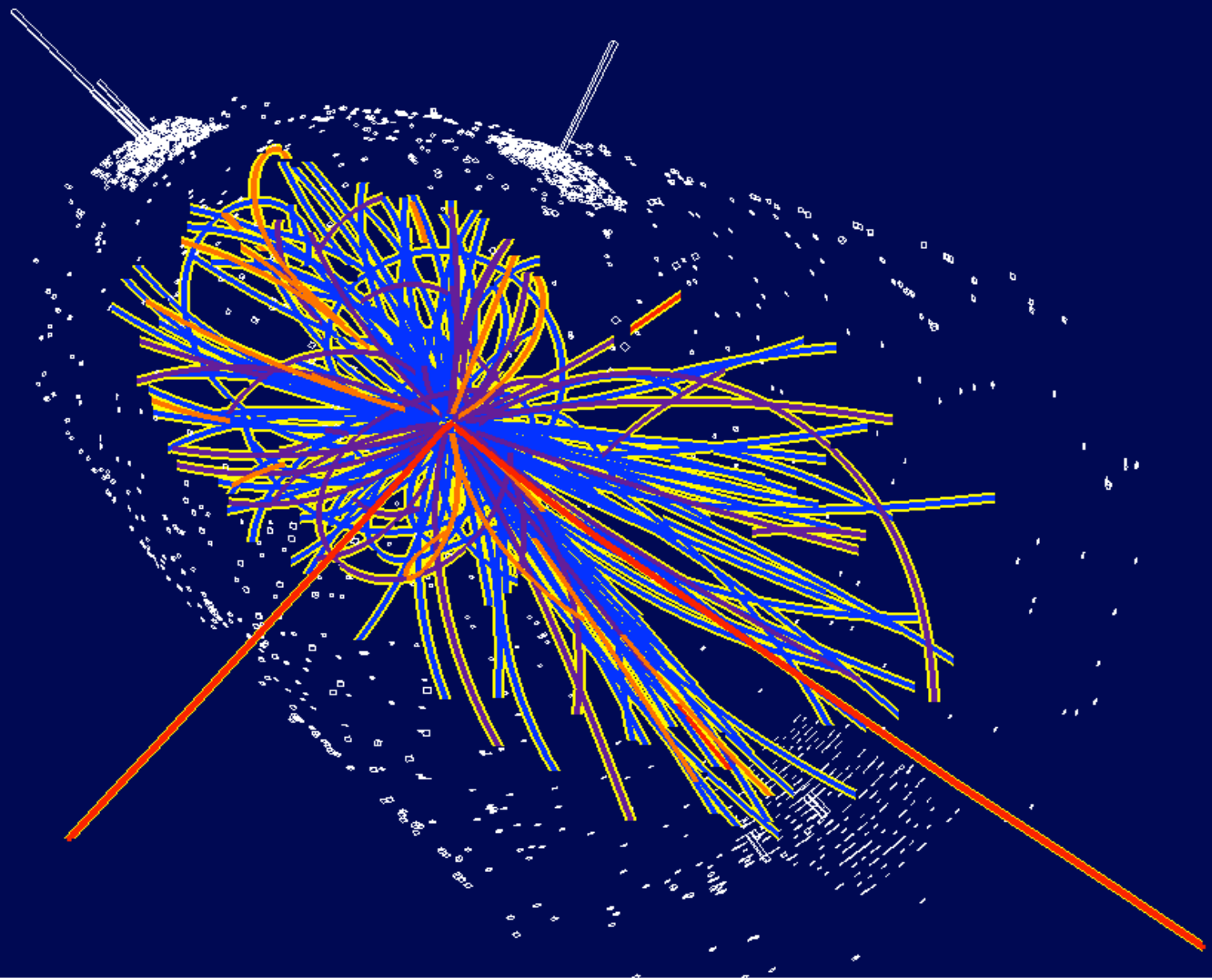



**Fig. 10**

# 1990

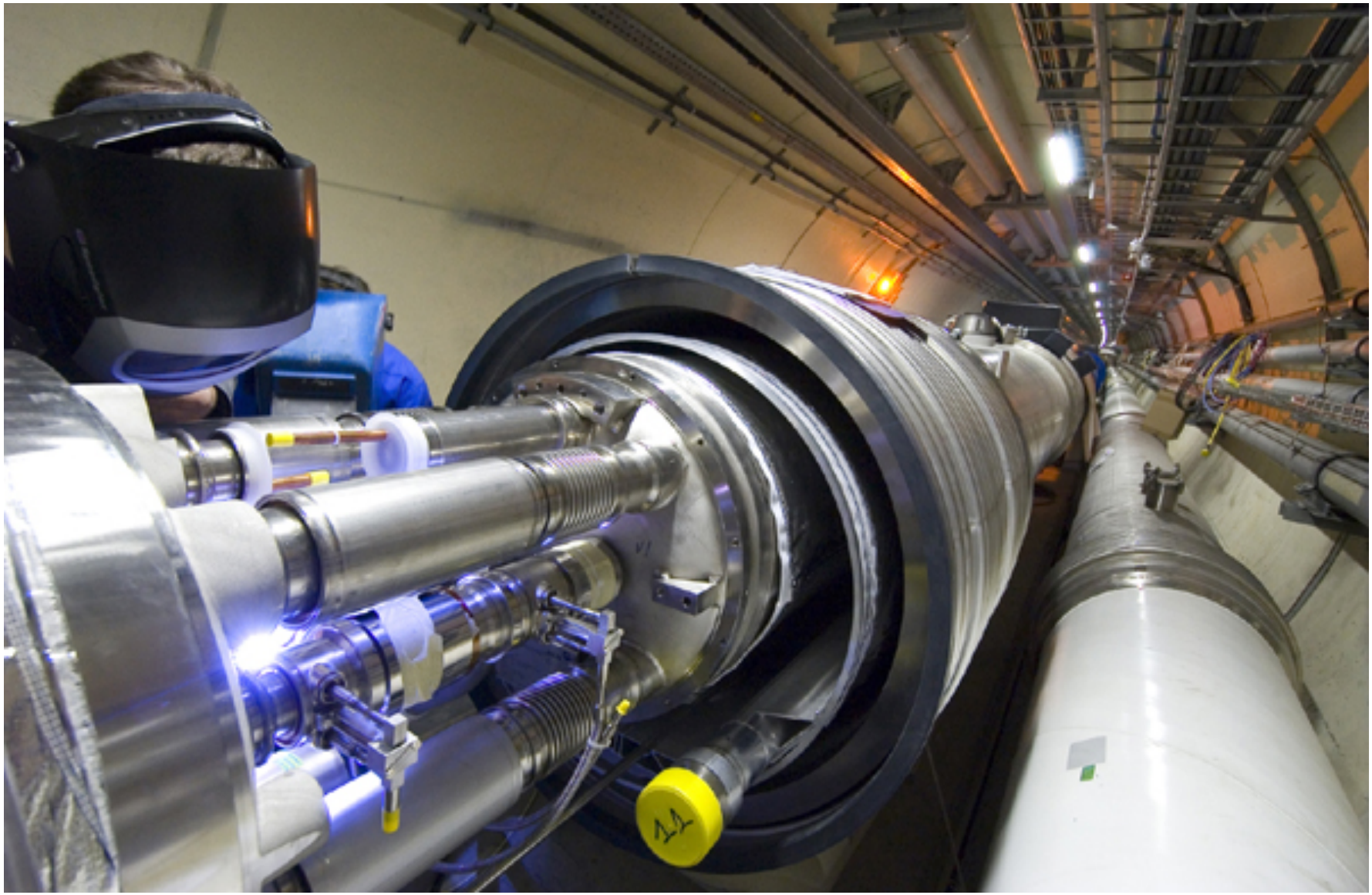
Proceedings of LHC Workshop
(Aachen, 1990):
$\sqrt{s}$ = 16 TeV, 100 fb$^{-1}$

# *20 Years, projecting, constructing and Simulating…*



# Years of Design, Construction and Commissioning of the LHC

# The largest cryogenic system on earth…



# The Machine Challenges in a Nutshell

- Unprecedented beam energy and luminosities (for a hadron machine)
- This results in the main LHC challenge : Stored beam energy two orders of magnitude higher than existing machines… 350 MJ (nominal)
- There is of course also the total stored energy in the magnets (11 GJ, enough to melt 15 tons of copper)

Risk of damage is the main concern :

- From the stored beam energy

(as an indication, a few cm groove in an SPS vacuum chamber from a beam 1% of nominal LHC beam, vacuum chamber ripped open)

Similar incident at LHC : 3 months stop.

- From the stored energy in the magnets

The November 19 2008 incident… (700 m damage area with 39 dipoles and 14 quadrupoles and beam vacuum affected over 2.7 km, 1 year repair)

# Years of Design, Construction and Commissioning of Experiments

D.Fournier 5-jan-90

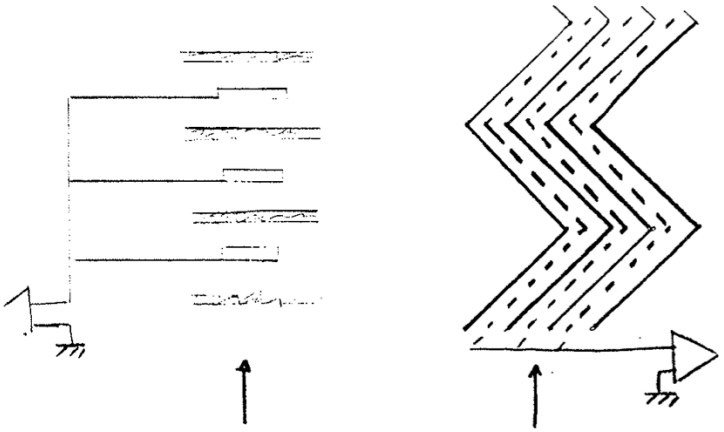
An approach to high granularity,fast Liq Ar calorimetry

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).



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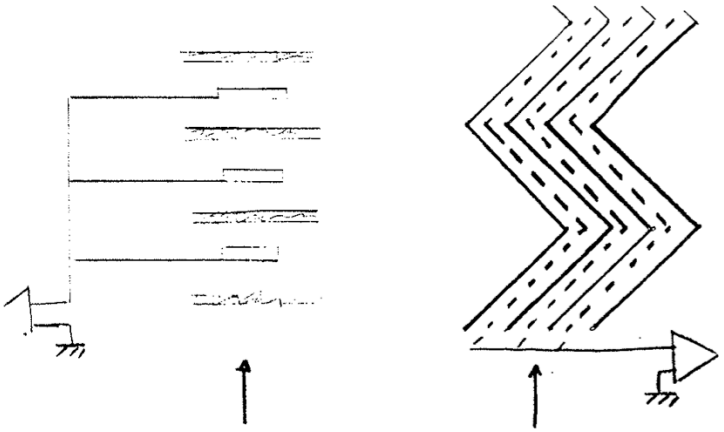
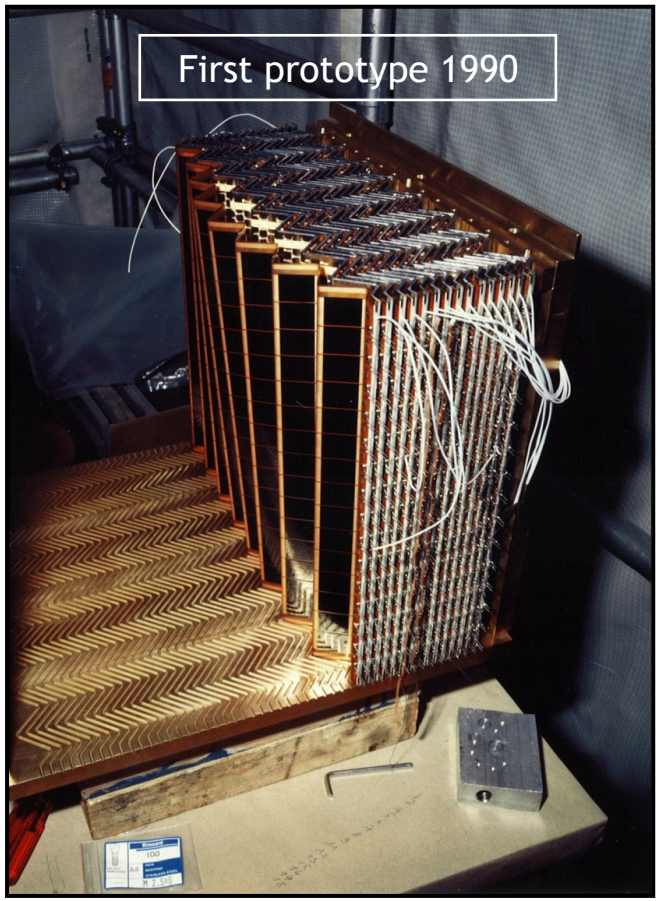


Classical "Accordeon"



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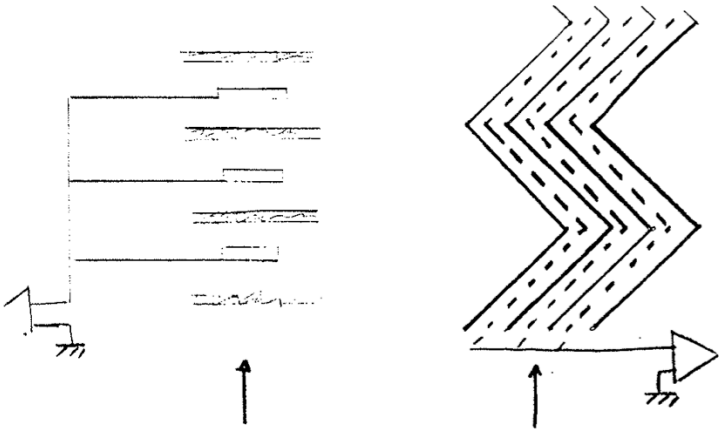

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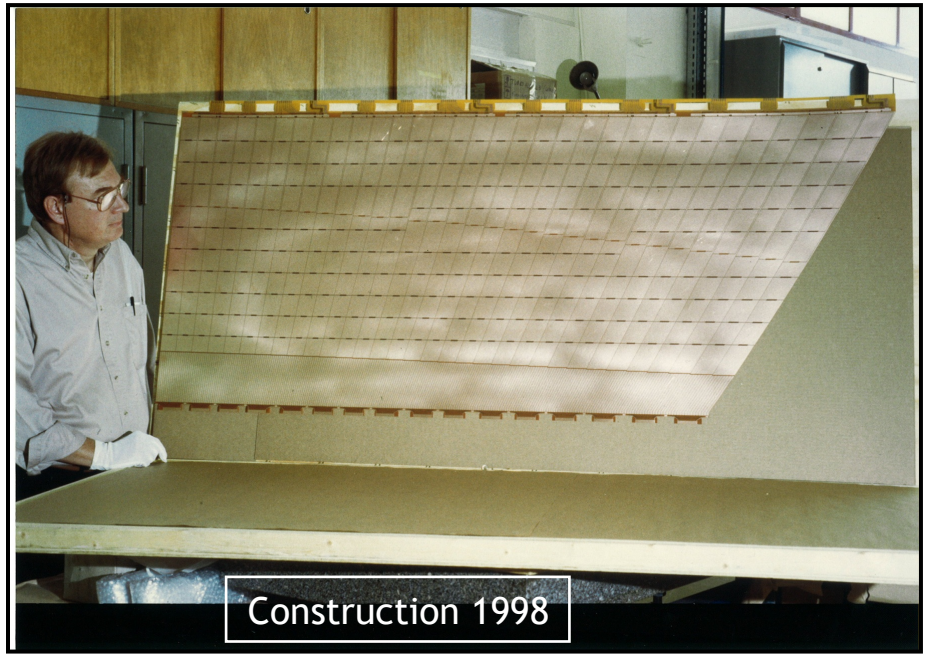
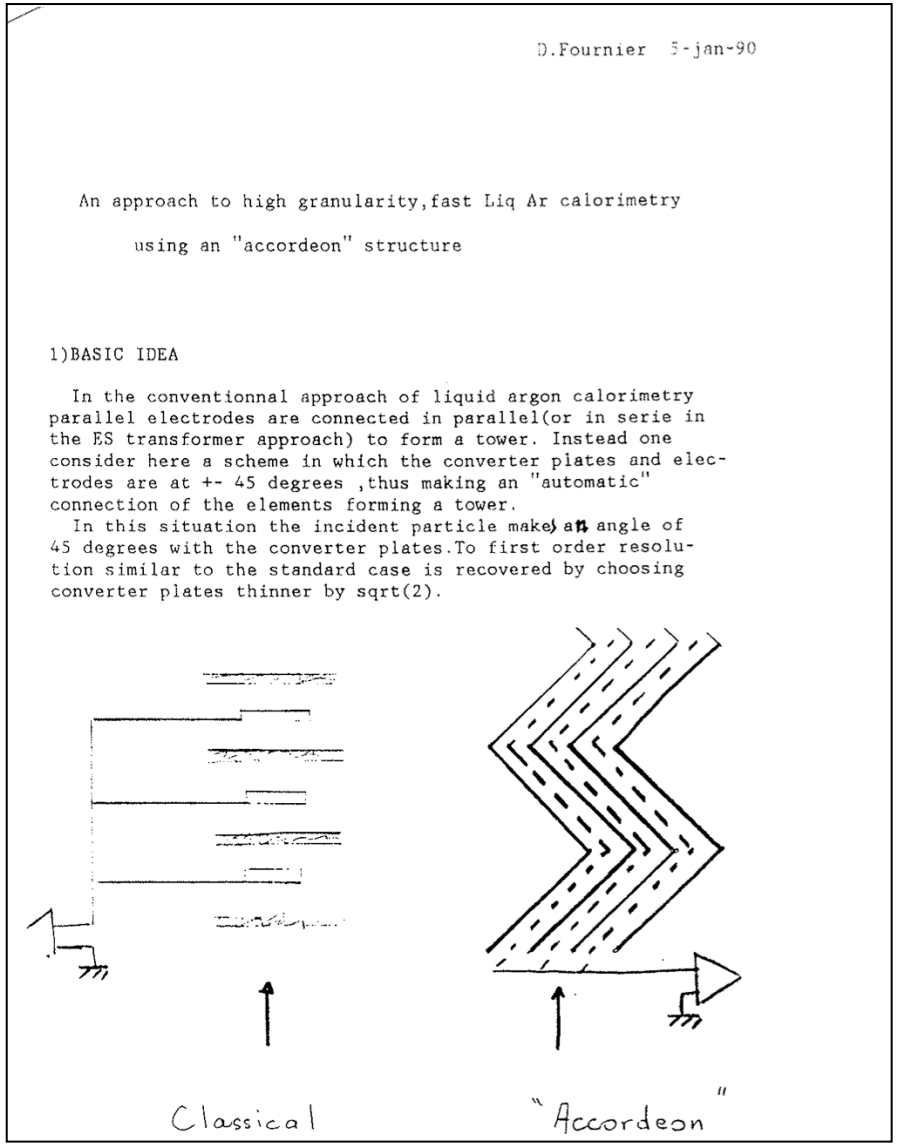


Construction 1998

# Years of Design, Construction and Commissioning of Experiments



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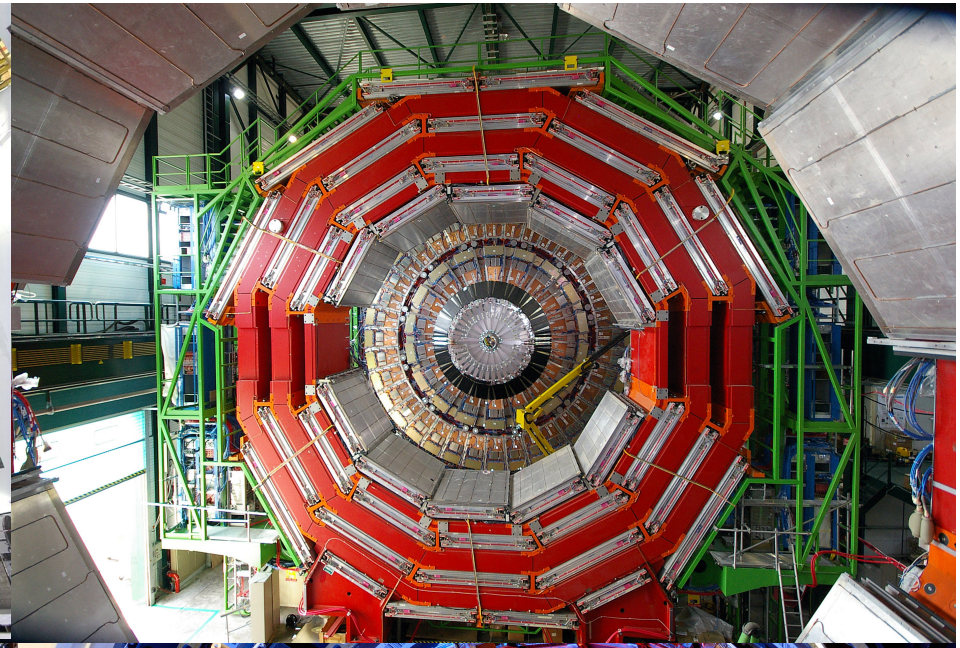
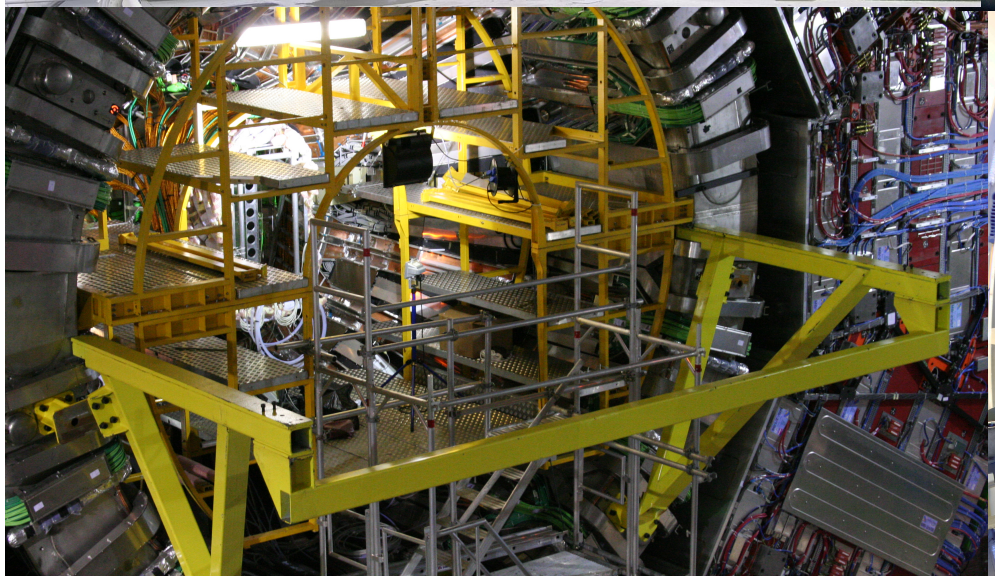
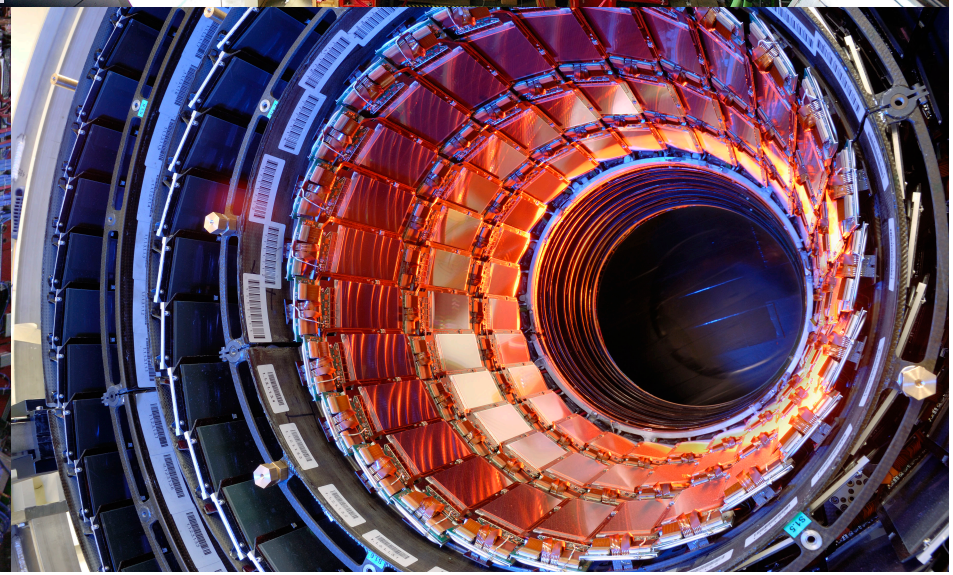
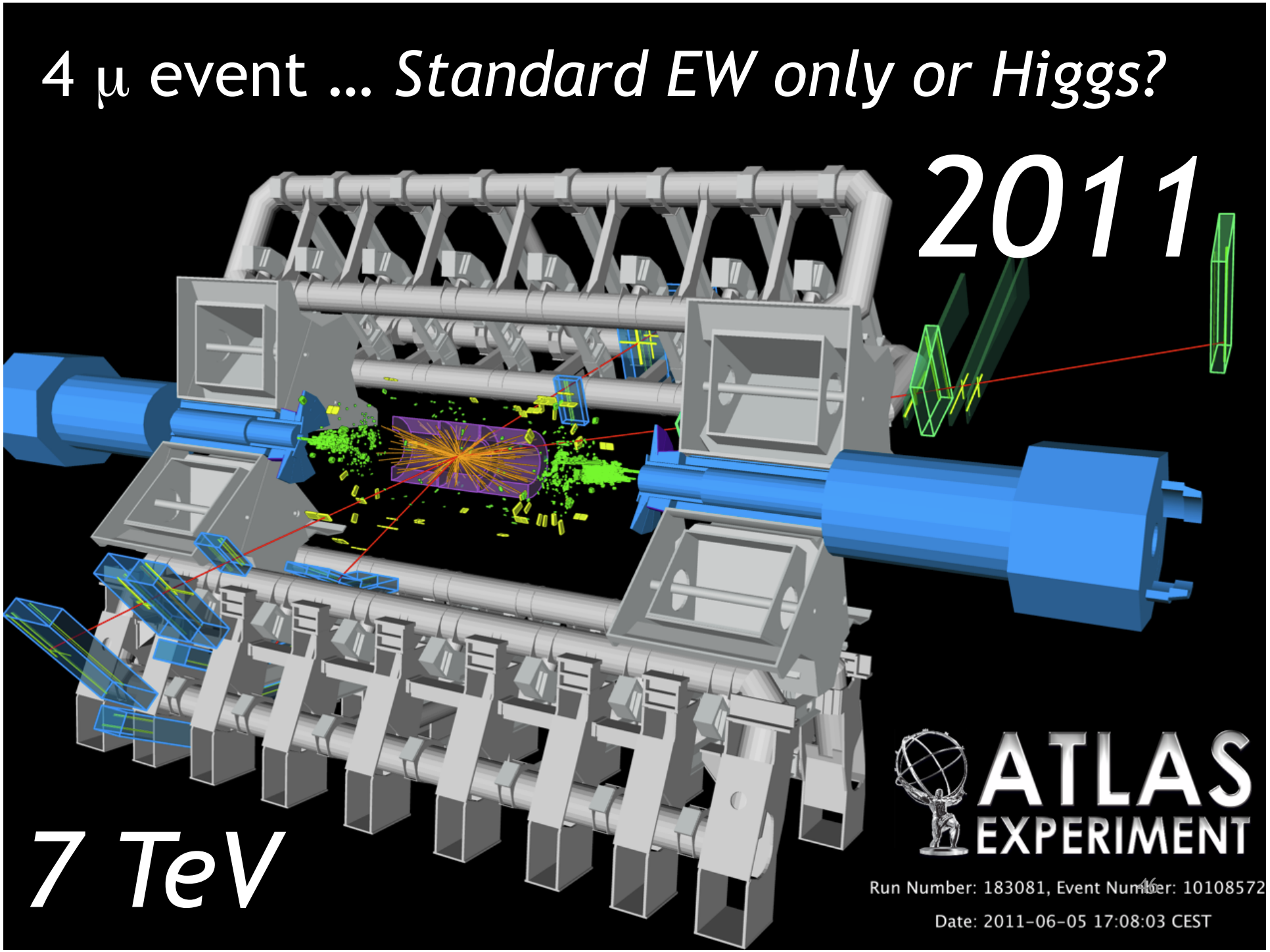
# Years of Design, Construction and Commissioning of Experiments





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



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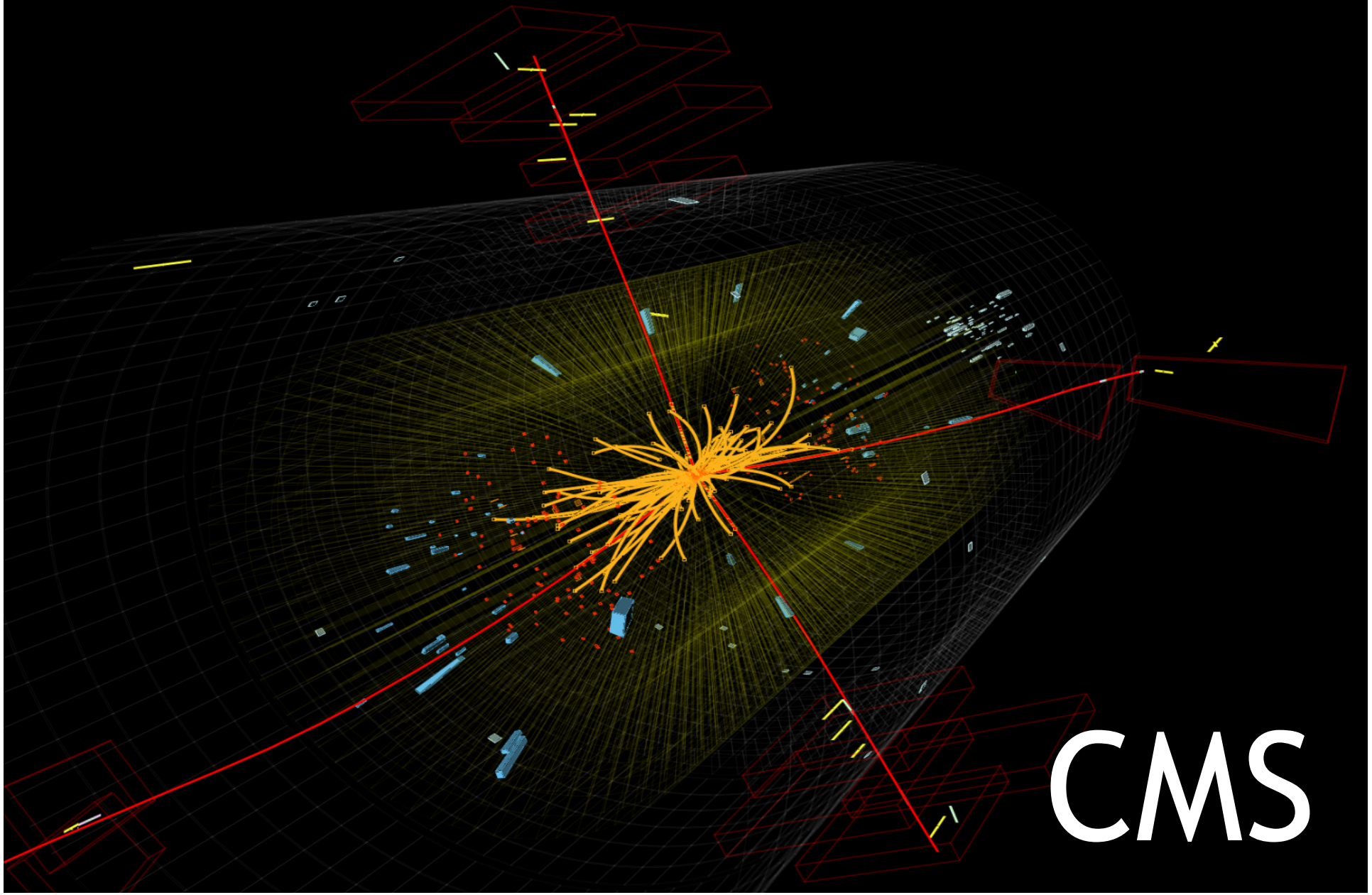
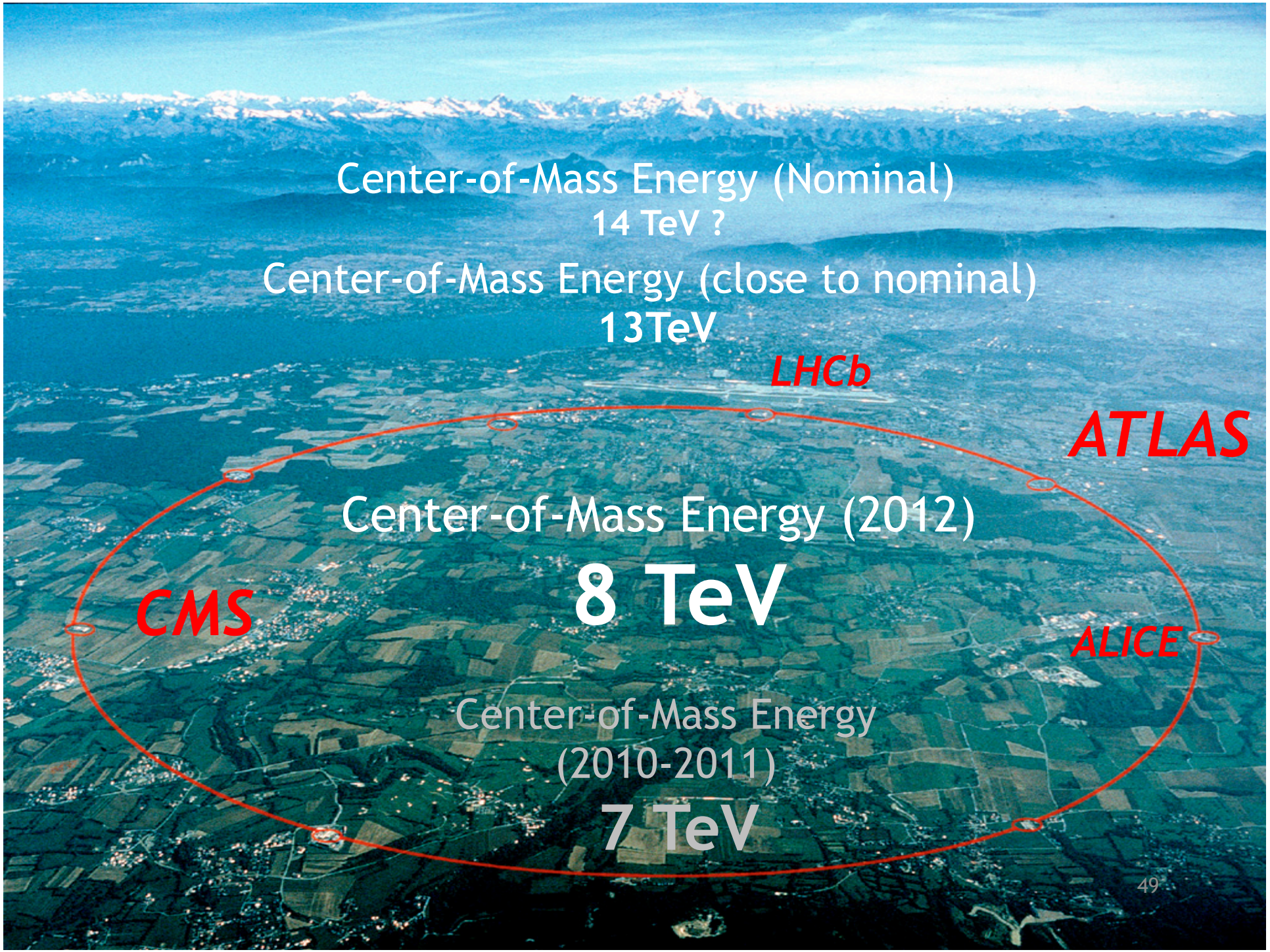
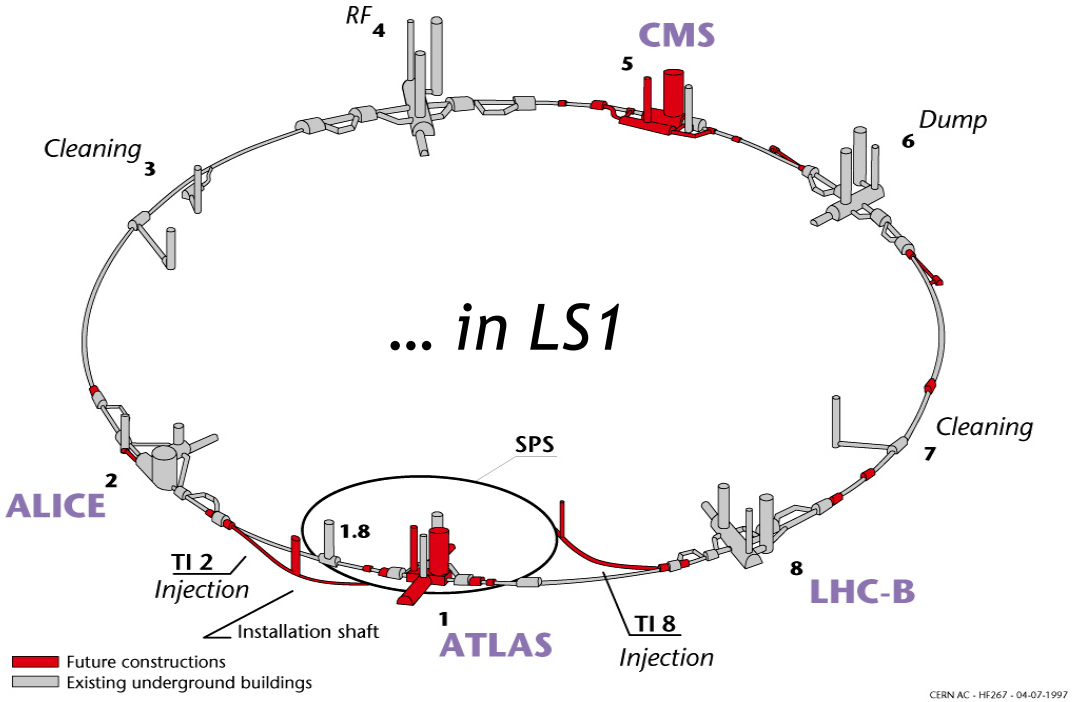



# Three Years at the Energy Frontier

*The Discovery !*


Center-of-Mass Energy (Nominal)
14 TeV ?
Center-of-Mass Energy (close to nominal)
13TeV
LHCb
ATLAS
Center-of-Mass Energy (2012)
8 TeV
CMS
ALICE
Center-of-Mass Energy
(2010-2011)
7 TeV

# Three Years of LHC operations at the Energy frontier



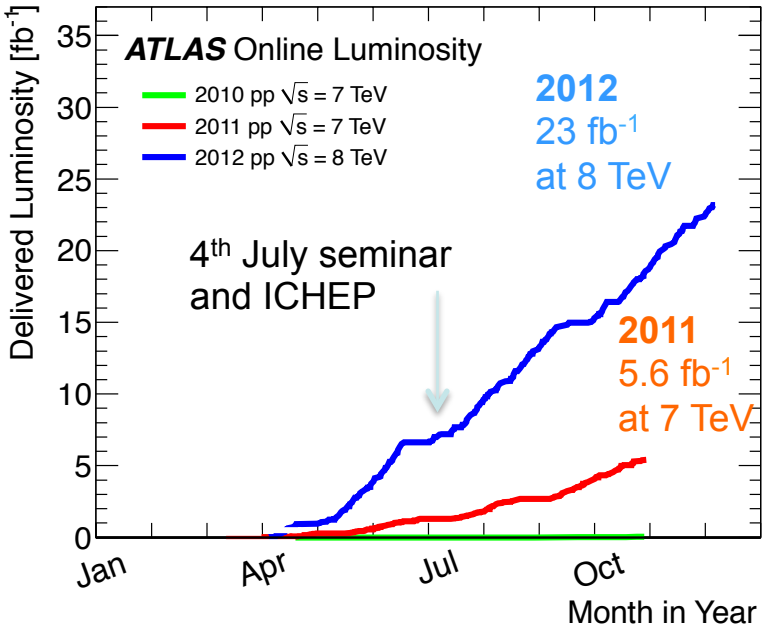

## The LHC

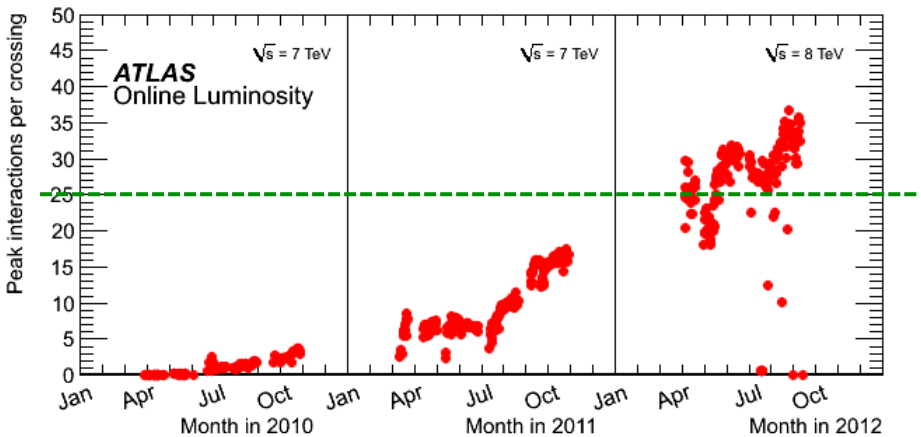
- Circumference 27 km
- Up to 175 m underground
- Total number of magnets 9 553
- Number of dipoles 1 232
- Operation temperature 1.9 K (Superfluid He)

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

| Parameter | 2010 | 2011 | 2012 | Nominal |
|---|---|---|---|---|
| C.O.M Energy | 7 TeV | 7 TeV | 8 TeV | 14 TeV |
| $N_p$ | $1.1\ 10^{11}$ | $1.4\ 10^{11}$ | $1.6\ 10^{11}$ | $1.15\ 10^{11}$ |
| Bunch spacing / k | 150 ns / 368 | 50 ns / 1380 | 50 ns /1380 | 25 ns /2808 |
| ε (mm rad) | 2.4-4 | 1.9-2.3 | 2.5 | 3.75 |
| β* (m) | 3.5 | 1.5-1 | 0.6 | 0.55 |
| L ($cm^{-2}s^{-1}$) | $2x10^{32}$ | $3.3x10^{33}$ | $\sim 7x10^{33}$ | $10^{34}$ |

# The first LHC run

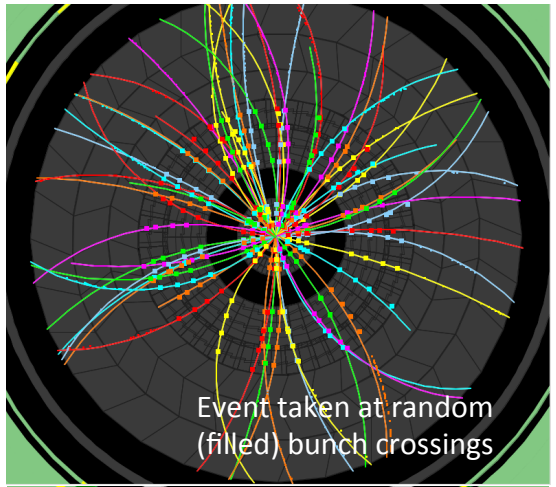



*2010*

O(2) Pile-up events

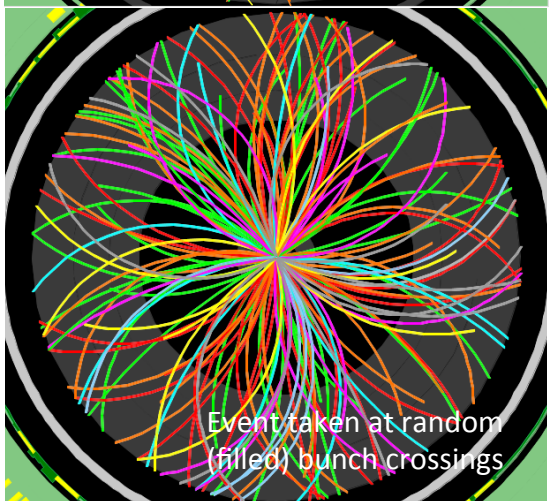
150 ns inter-bunch spacing




*2011*

O(10) Pile-up events

50 ns inter-bunch spacing



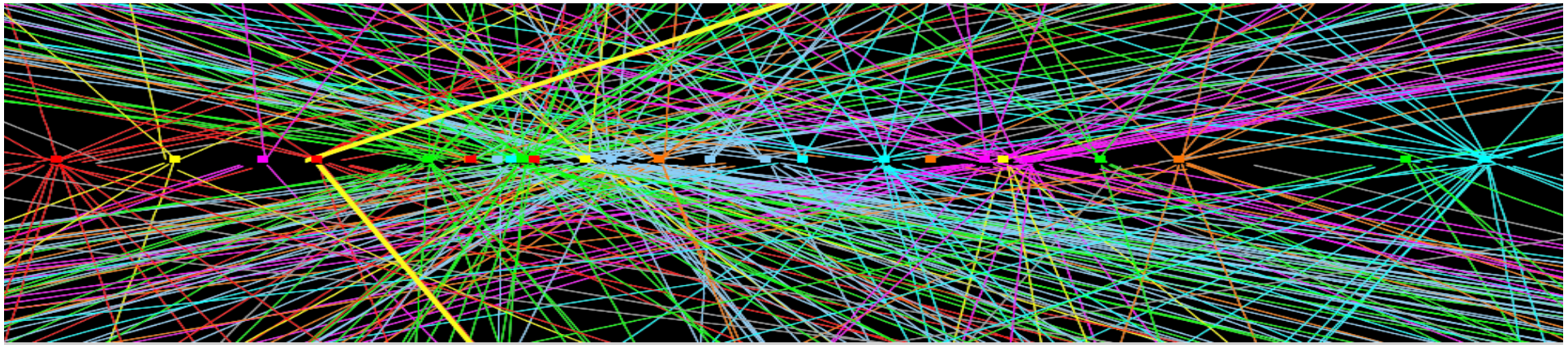

Design value (expected to be reached at $L=10^{34}$ !)

*2012*

O(20) Pile-up events

50 ns inter-bunch spacing

# Detector Challenges (Highlights)

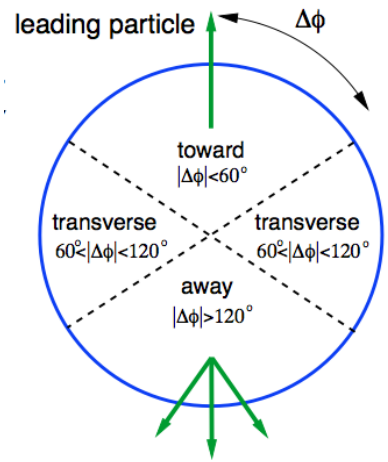


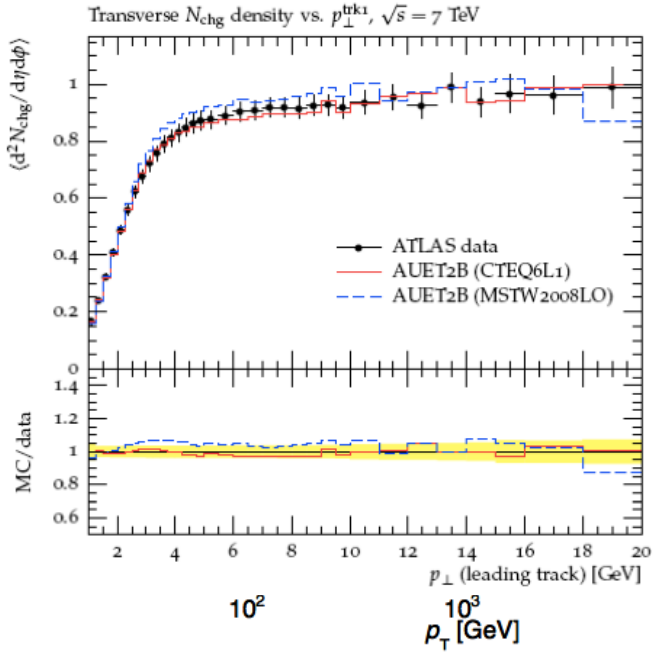
- Trigger Challenge : How to select 400 out of 20M events per second while keeping the interesting (including unknown) physics

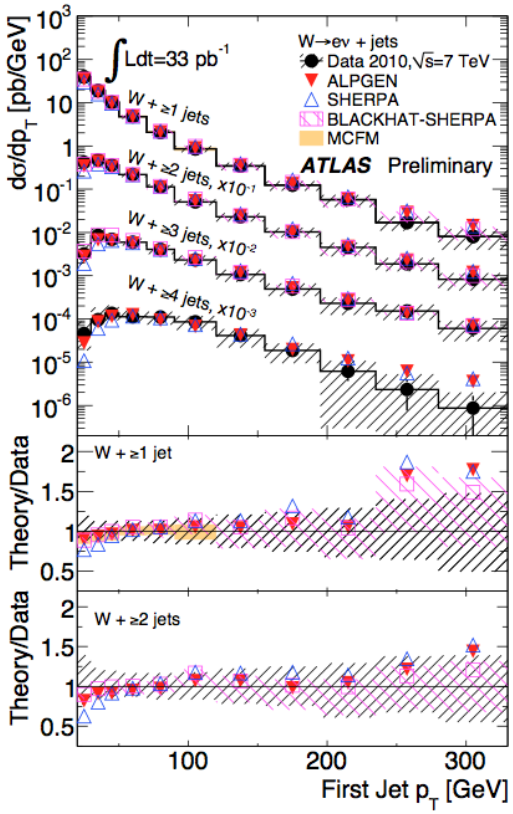
- Computing Challenge : How to reconstruct, store and distribute 400 increasingly complex events per second (over 100 PB per experiment)

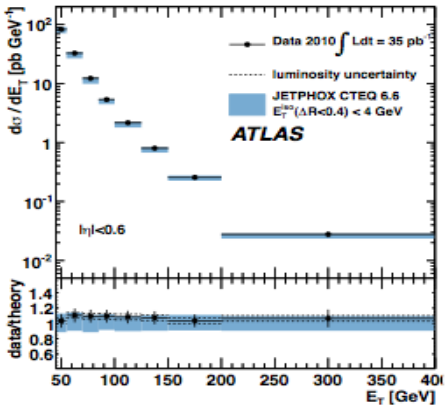
- Analysis Challenge : Maintain high (and as much as possible stable) reconstruction and identification efficiency for physics objects (e, $\mu$, $\tau$, jets, $E^T_{mis}$, b-jets) up to the highest pile-up

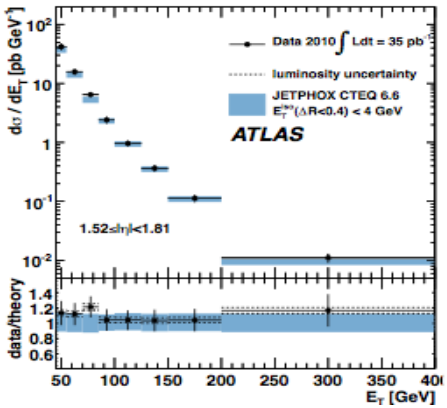
# QCD

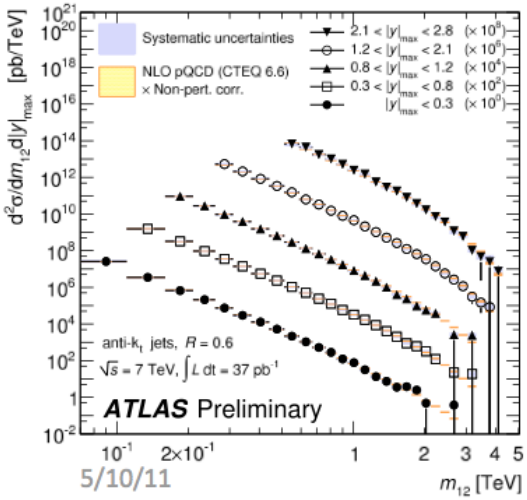

leading particle
Δφ
toward
|Δφ|<60°
transverse
60°<|Δφ|<120°
transverse
60°<|Δφ|<120°
away
|Δφ|>120°

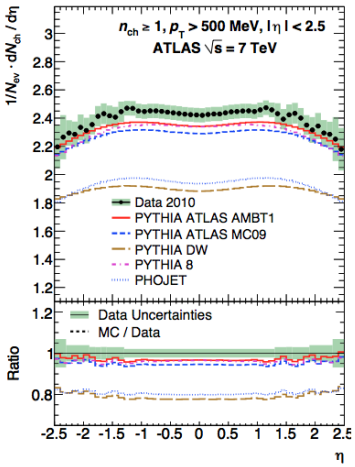

Transverse $N_{chg}$ density vs. $p_\perp^{trk1}$, $\sqrt{s} = 7$ TeV
$\langle d^2N_{chg}/d\eta d\phi \rangle$
ATLAS data
AUET2B (CTEQ6L1)
AUET2B (MSTW2008LO)
MC/data
$p_\perp$ (leading track) [GeV]
$10^2$
$10^3$
$p_T$ [GeV]

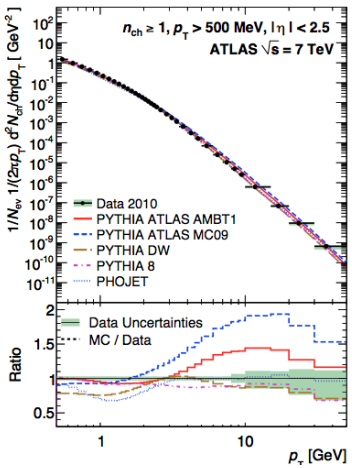

$\int$Ldt=33 pb$^{-1}$
W→eν + jets
Data 2010, √s=7 TeV
ALPGEN
SHERPA
BLACKHAT-SHERPA
MCFM
ATLAS Preliminary
W + ≥1 jets
W + ≥2 jets, x10$^{-1}$
W + ≥3 jets, x10$^{-2}$
W + ≥4 jets, x10$^{-3}$
dσ/dp$_T$ [pb/GeV]
W + ≥1 jet
W + ≥2 jets
Theory/Data
First Jet p$_T$ [GeV]


Data 2010 $\int$ Ldt = 35 pb$^{-1}$
luminosity uncertainty
JETPHOX CTEQ 6.6
ATLAS
|η|<0.6
dσ / dE$_T$ [pb GeV$^{-1}$]
data/theory
E$_T$ [GeV]


Data 2010 $\int$ Ldt = 35 pb$^{-1}$
luminosity uncertainty
JETPHOX CTEQ 6.6
ATLAS
1.52<|η|<1.81
dσ / dE$_T$ [pb GeV$^{-1}$]
data/theory
E$_T$ [GeV]


Systematic uncertainties
NLO pQCD (CTEQ 6.6)
× Non-pert. corr.
anti-k$_t$ jets, R = 0.6
√s = 7 TeV, $\int$L dt = 37 pb$^{-1}$
ATLAS Preliminary
$d^2\sigma/dm_{12}d|y|_{max}$ [pb/TeV]
$m_{12}$ [TeV]

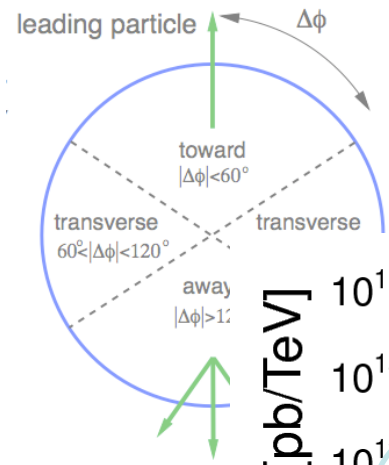

$n_{ch} \geq 1$, $p_T > 500$ MeV, |η| < 2.5
ATLAS √s = 7 TeV
Data 2010
PYTHIA ATLAS AMBT1
PYTHIA ATLAS MC09
PYTHIA DW
PYTHIA 8
PHOJET
Data Uncertainties
MC / Data
Ratio
η

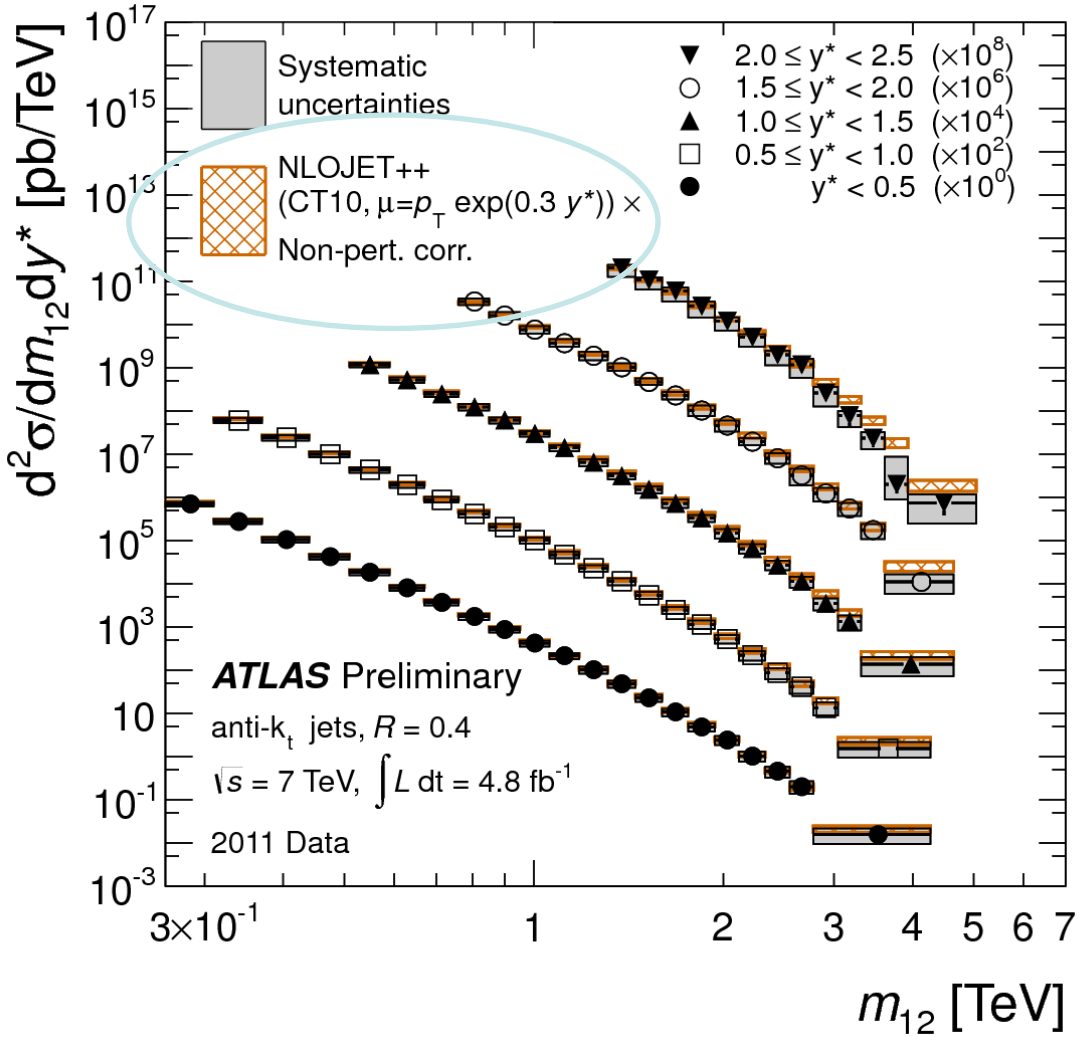

$n_{ch} \geq 1$, $p_T > 500$ MeV, |η| < 2.5
ATLAS √s = 7 TeV
Data 2010
PYTHIA ATLAS AMBT1
PYTHIA ATLAS MC09
PYTHIA DW
PYTHIA 8
PHOJET
Data Uncertainties
MC / Data
Ratio
$p_T$ [GeV]

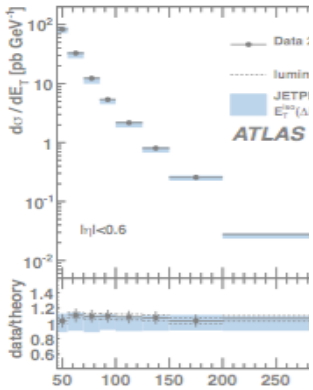
5/10/11

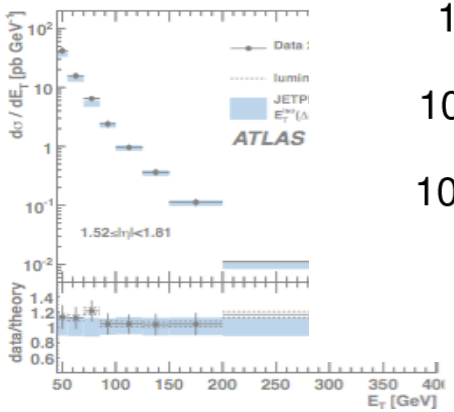
# QCD

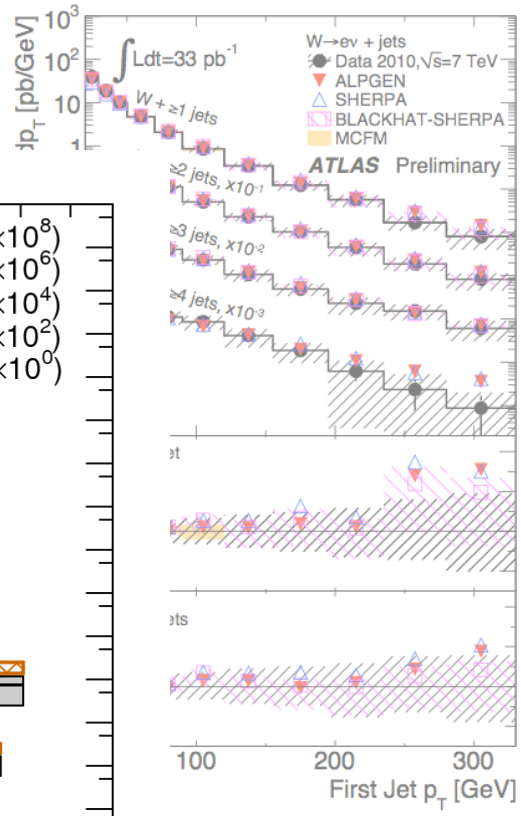
## Testing predictions over 8 orders of magnitude !

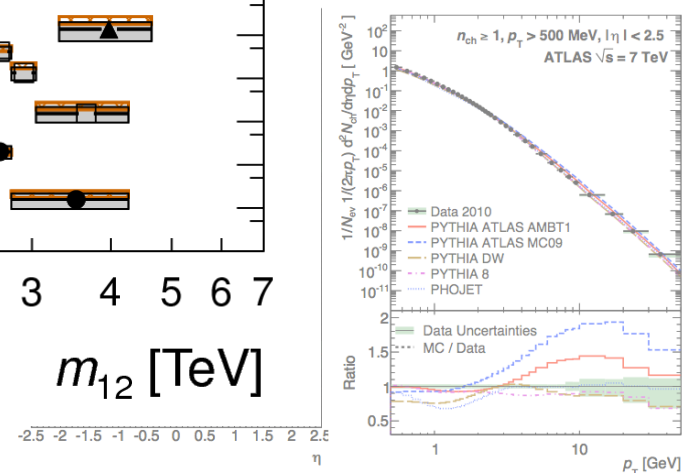


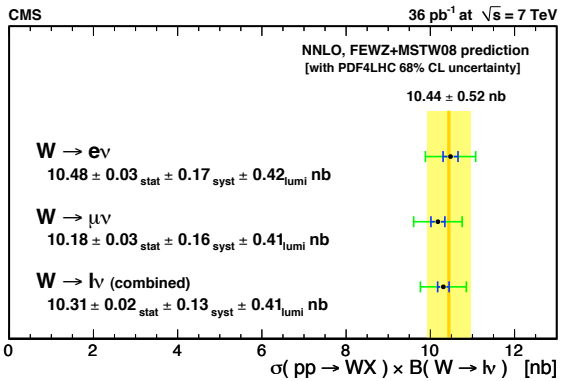



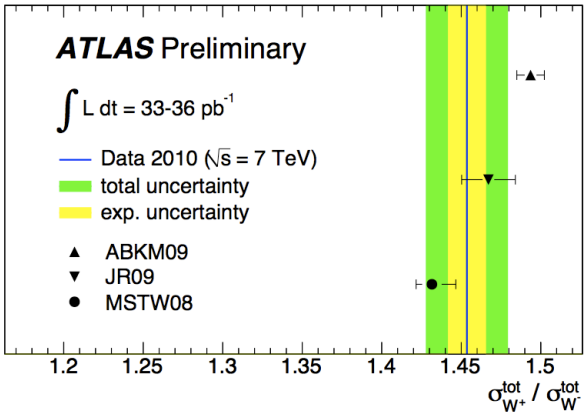



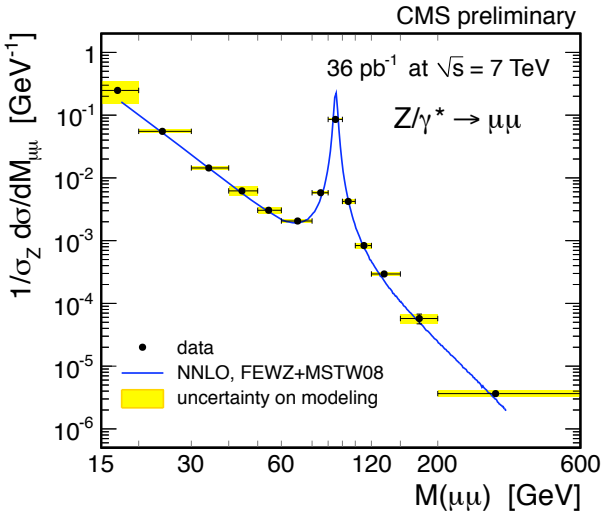



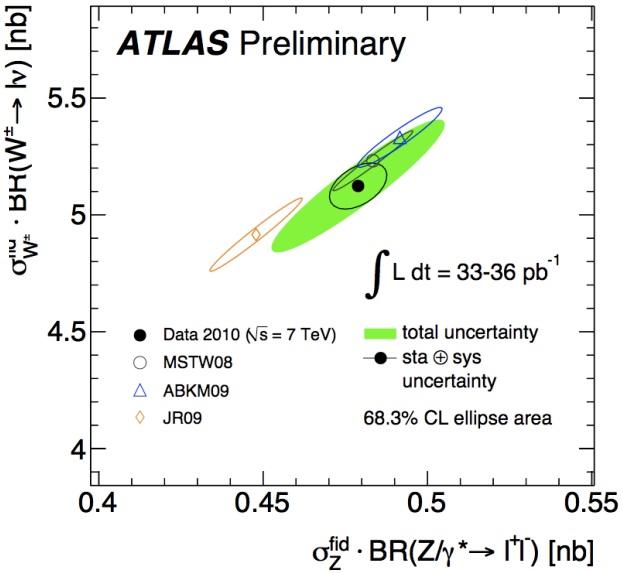



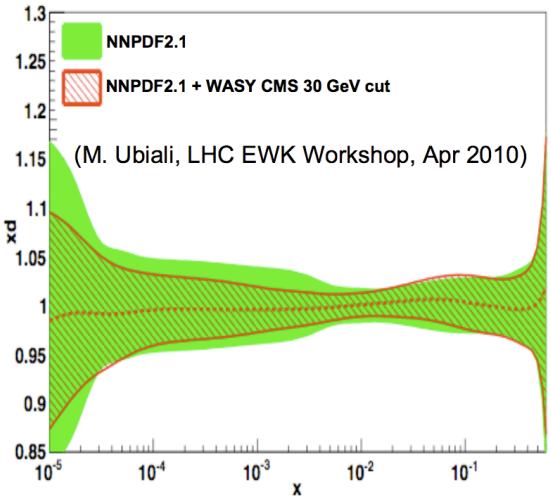
# EW

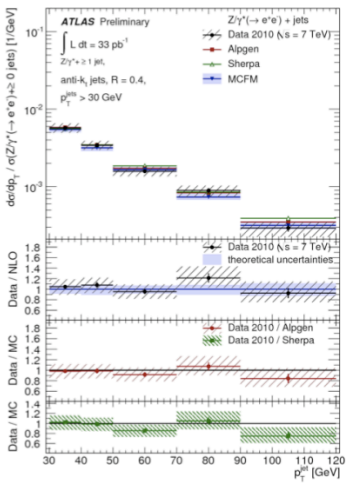

CMS
36 pb$^{-1}$ at $\sqrt{s}$ = 7 TeV
NNLO, FEWZ+MSTW08 prediction
[with PDF4LHC 68% CL uncertainty]
10.44 ± 0.52 nb
W → eν
10.48 ± 0.03 stat ± 0.17 syst ± 0.42 lumi nb
W → μν
10.18 ± 0.03 stat ± 0.16 syst ± 0.41 lumi nb
W → lν (combined)
10.31 ± 0.02 stat ± 0.13 syst ± 0.41 lumi nb
σ( pp → WX ) × B( W → lν ) [nb]

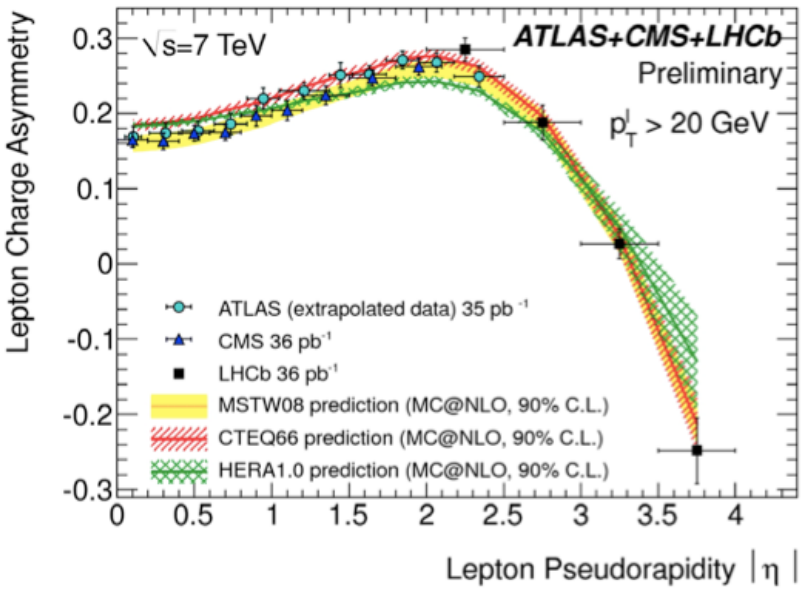

ATLAS Preliminary
∫ L dt = 33-36 pb$^{-1}$
Data 2010 (√s = 7 TeV)
total uncertainty
exp. uncertainty
ABKM09
JR09
MSTW08
$\sigma^{tot}_{W^+} / \sigma^{tot}_{W^-}$


CMS preliminary
36 pb$^{-1}$ at $\sqrt{s}$ = 7 TeV
Z/γ* → μμ
data
NNLO, FEWZ+MSTW08
uncertainty on modeling
$1/\sigma_Z\ d\sigma/dM_{\mu\mu}$ [GeV$^{-1}$]
M(μμ) [GeV]


ATLAS Preliminary
∫ L dt = 33-36 pb$^{-1}$
Data 2010 (√s = 7 TeV)
MSTW08
ABKM09
JR09
total uncertainty
sta ⊕ sys uncertainty
68.3% CL ellipse area
$\sigma^{fid}_{W^\pm} \cdot BR(W^\pm \to l\nu)$ [nb]
$\sigma^{fid}_{Z} \cdot BR(Z/\gamma^* \to l^+l^-)$ [nb]


NNPDF2.1
NNPDF2.1 + WASY CMS 30 GeV cut
(M. Ubiali, LHC EWK Workshop, Apr 2010)
xd
x


ATLAS Preliminary
Alpgen
Sherpa
MCFM
Data / NLO
Data / MC

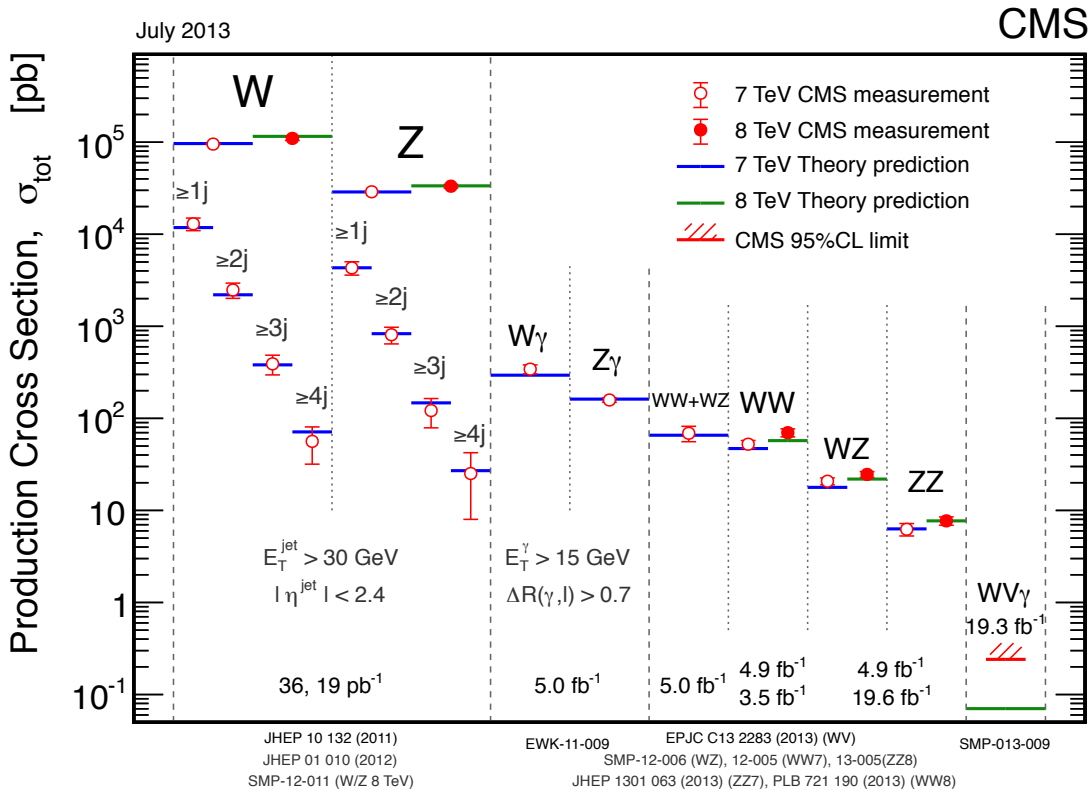

√s=7 TeV
ATLAS+CMS+LHCb
Preliminary
$p^l_T$ > 20 GeV
ATLAS (extrapolated data) 35 pb$^{-1}$
CMS 36 pb$^{-1}$
LHCb 36 pb$^{-1}$
MSTW08 prediction (MC@NLO, 90% C.L.)
CTEQ66 prediction (MC@NLO, 90% C.L.)
HERA1.0 prediction (MC@NLO, 90% C.L.)
Lepton Charge Asymmetry
Lepton Pseudorapidity |η|

# Overview of Cross Sections

## Expected Standard Model and Higgs Productions

Theory and simulation “Next-to…” revolution :

- NNLO PDFs sets
- Calculations at unprecedented order in perturbation theory
- Parton Shower (and Matrix Element matching) improvements



# Overview of Cross Sections

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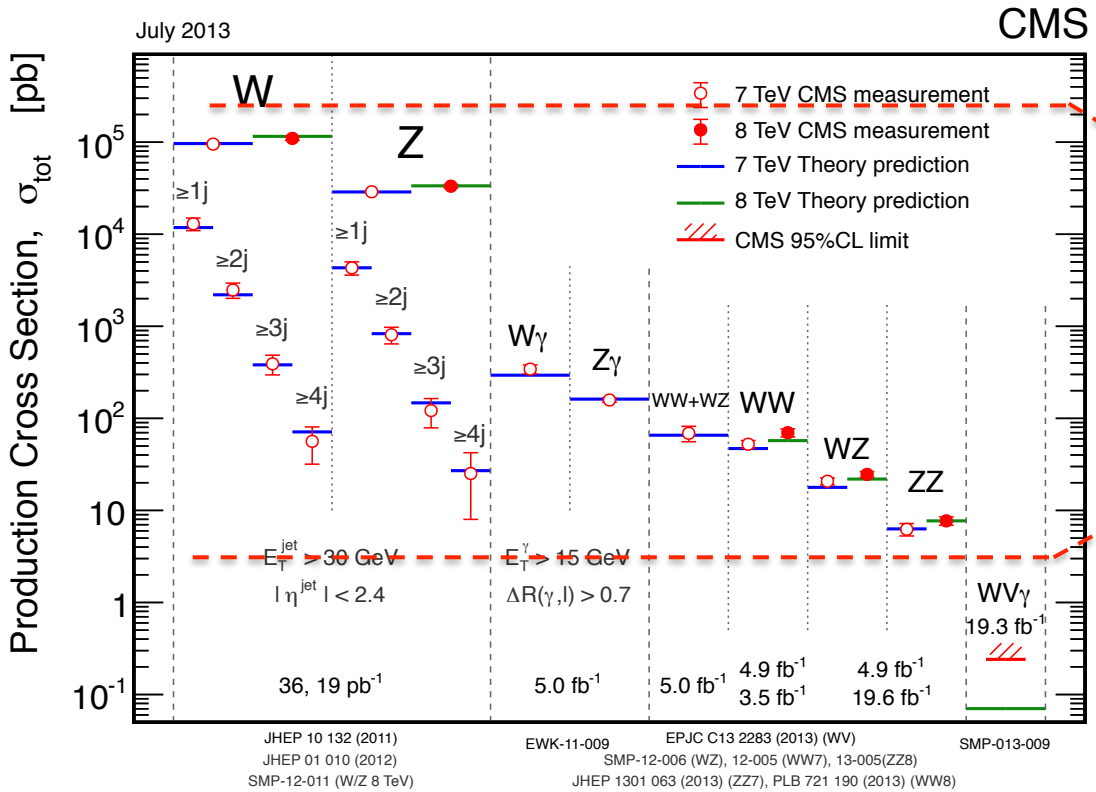
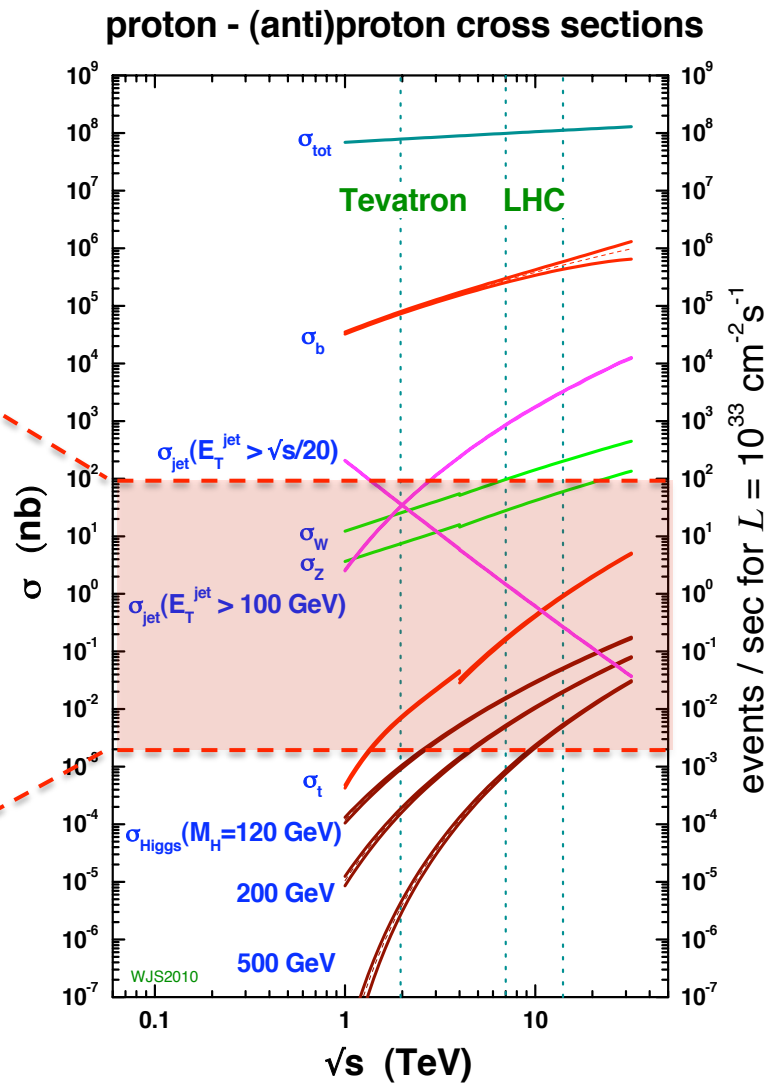
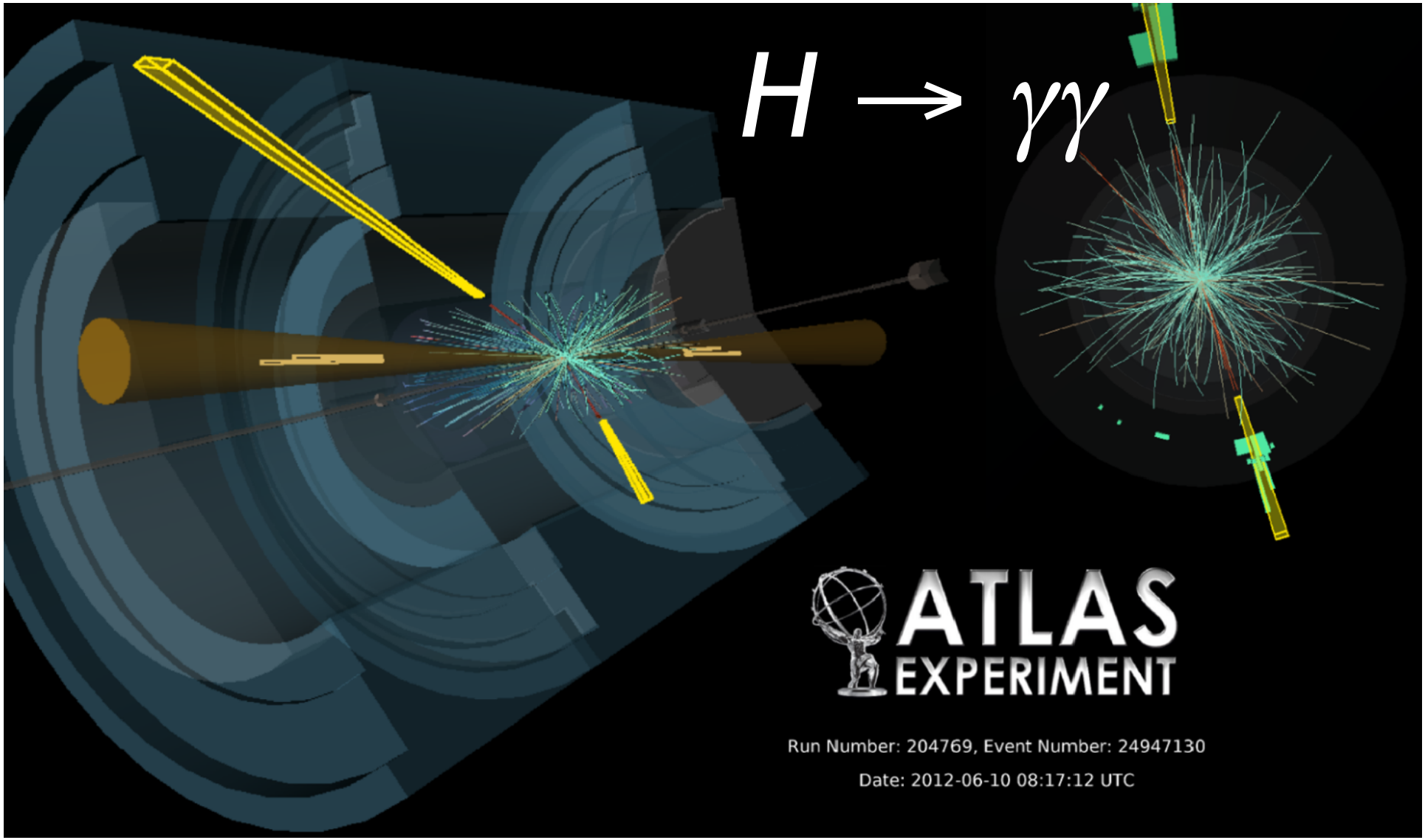
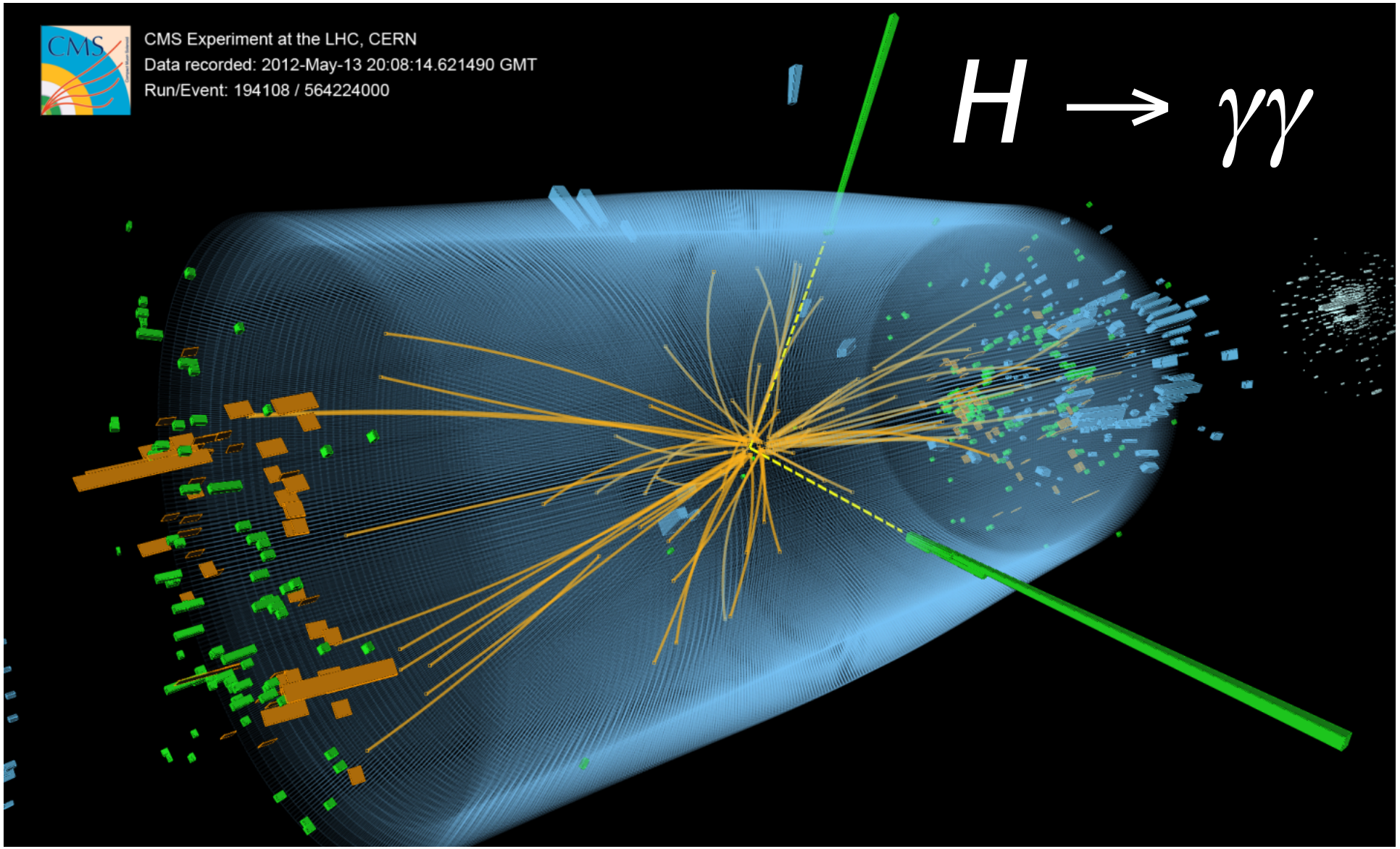





$\gamma\gamma$ channel basic facts :

- Ns ~ O(500) per experiment
- Signal purity ~ 2% - 60%




$\gamma\gamma$ channel basic facts :

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

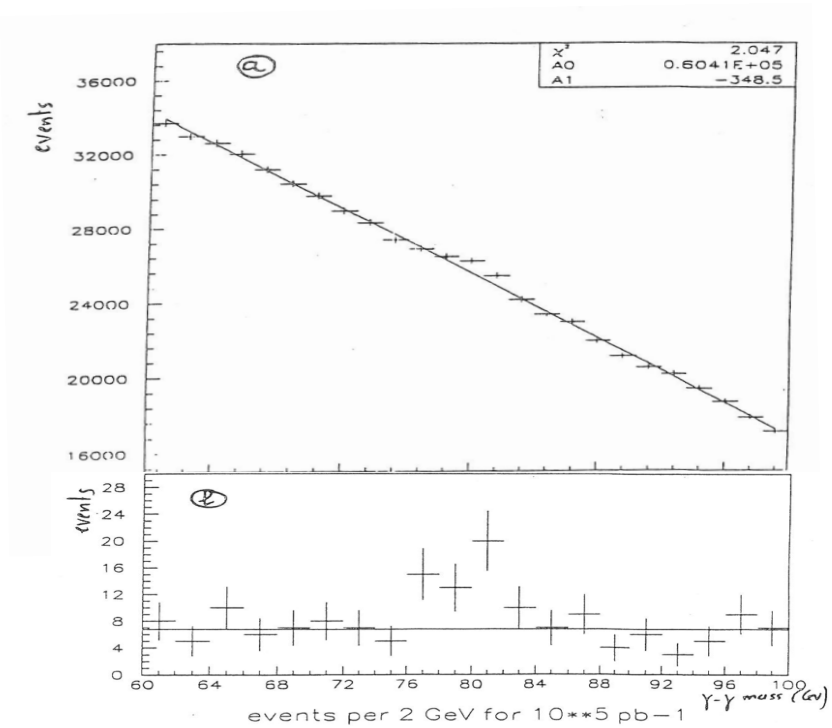
**Photon decay modes of the intermediate mass Higgs**

*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

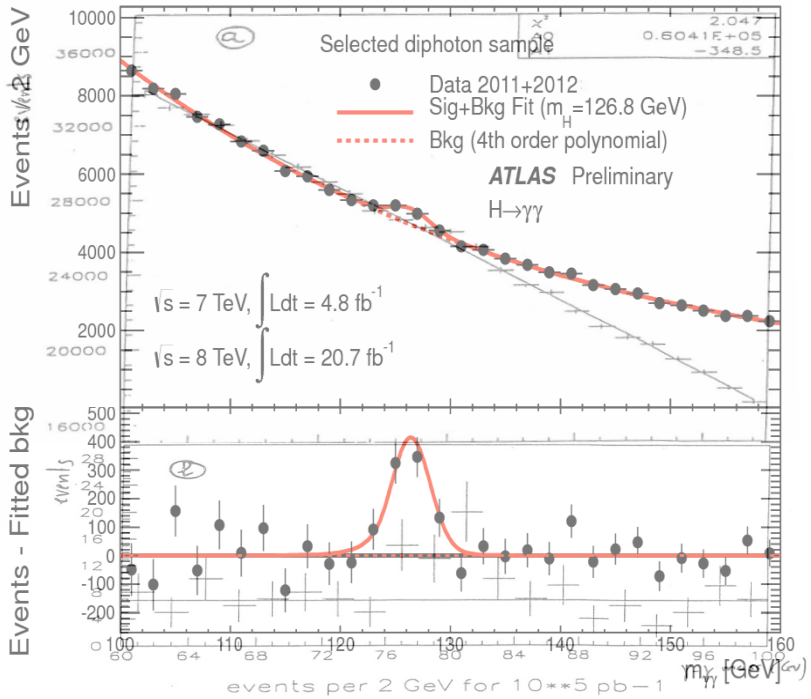



## 1991 Analysis

First EAGLE (ATLAS) note

diphoton channel

# The Di-Photon Channel Historical Prospective

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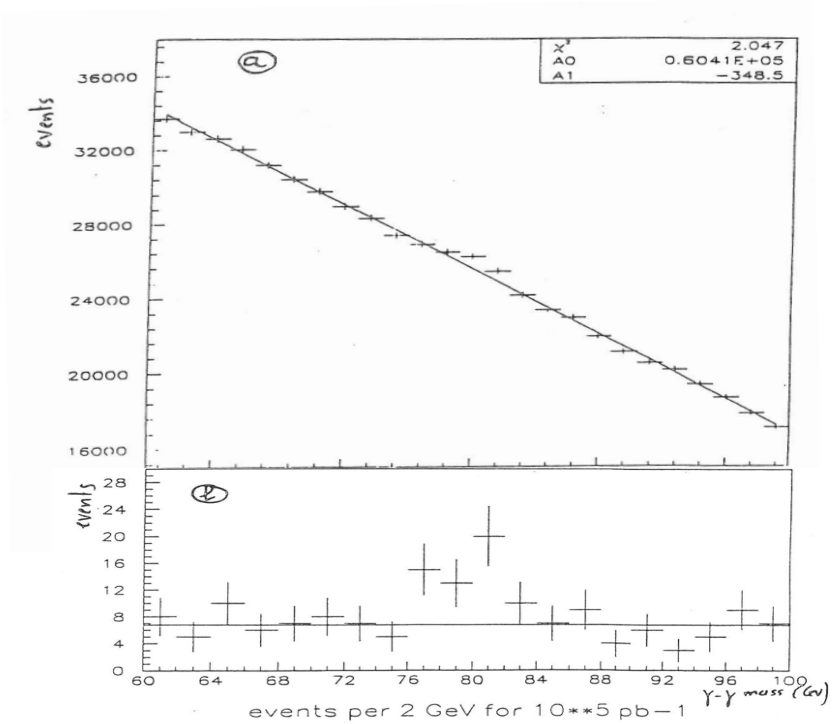
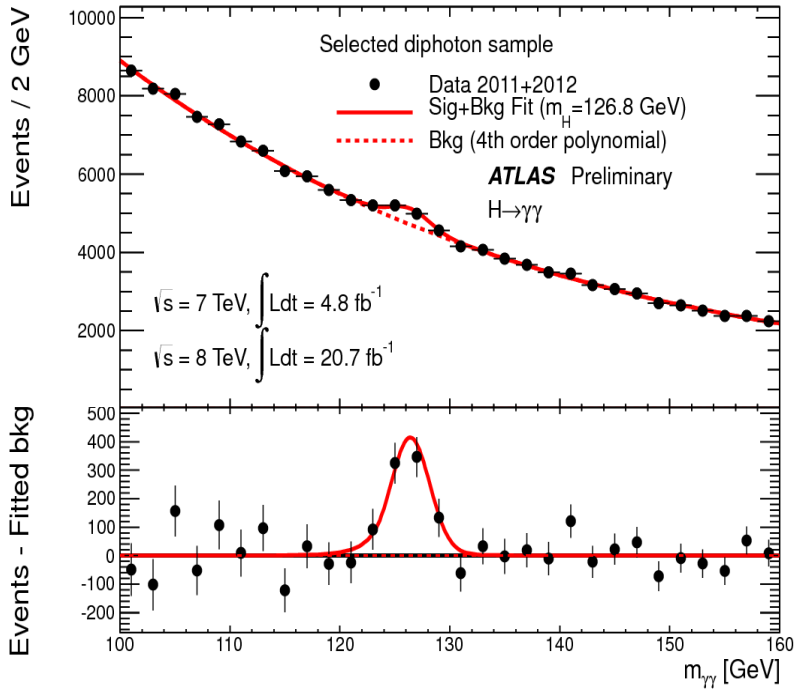
# The Di-Photon Channel Historical Prospective




## 1991 Analysis

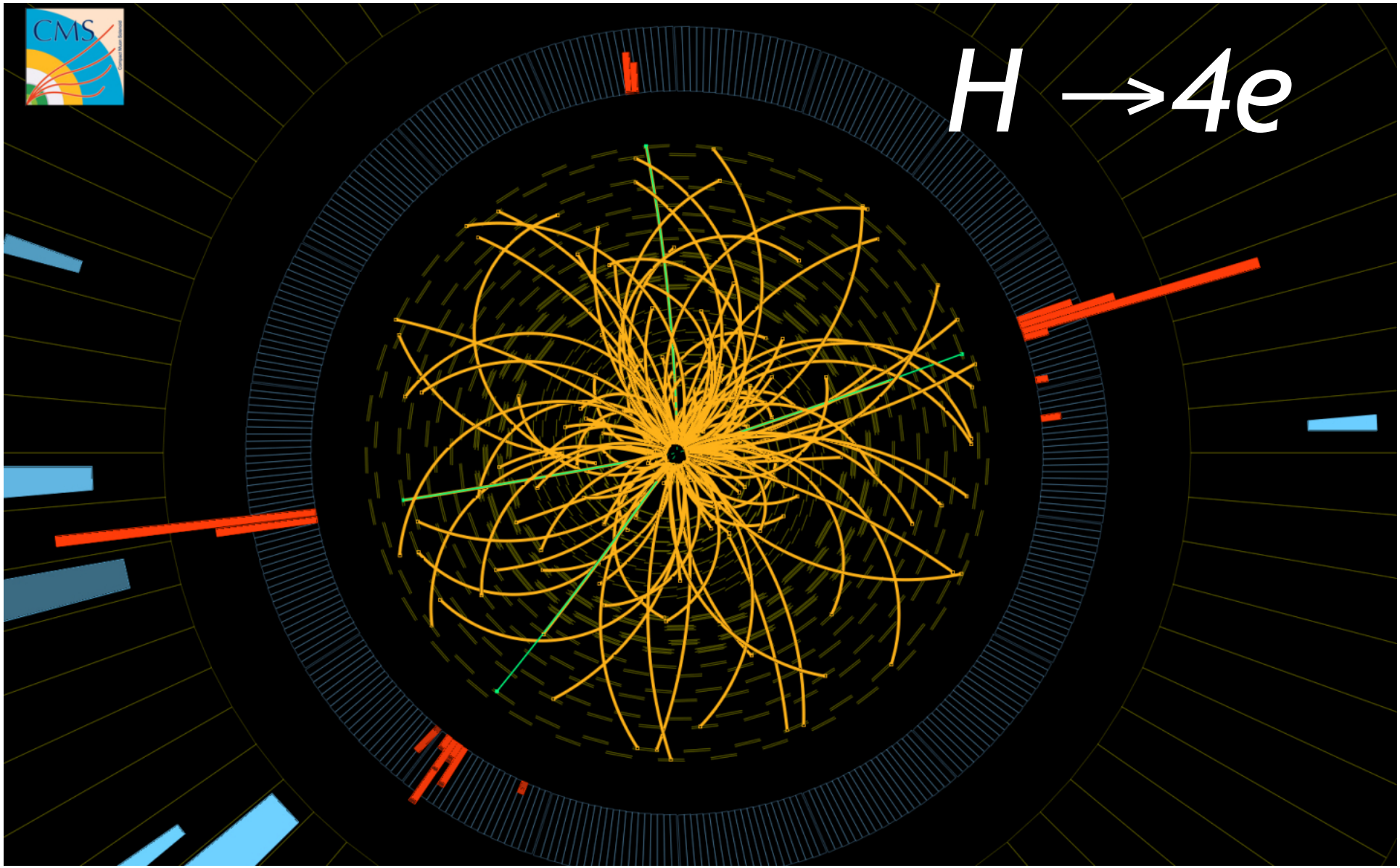
First EAGLE (ATLAS) note
diphoton channel

16 TeV, 100 $fb^{-1}$

## Moriond 2013 Analysis

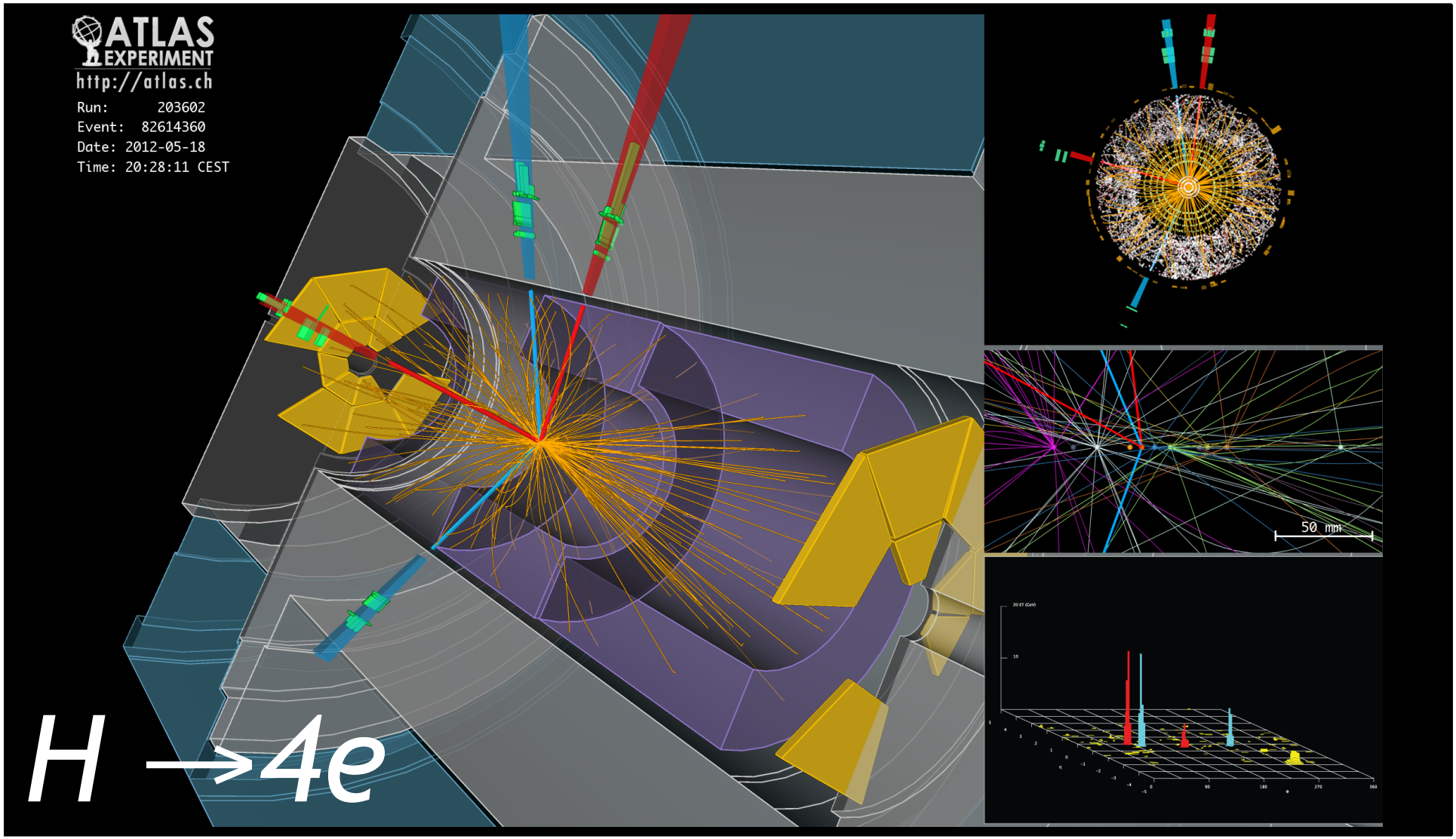
ATLAS diphoton channel

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




4l channel basic facts :

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




4l channel basic facts :

- Ns ~ O(15-20) per experiment
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# The ZZ Channel Historical Prospective

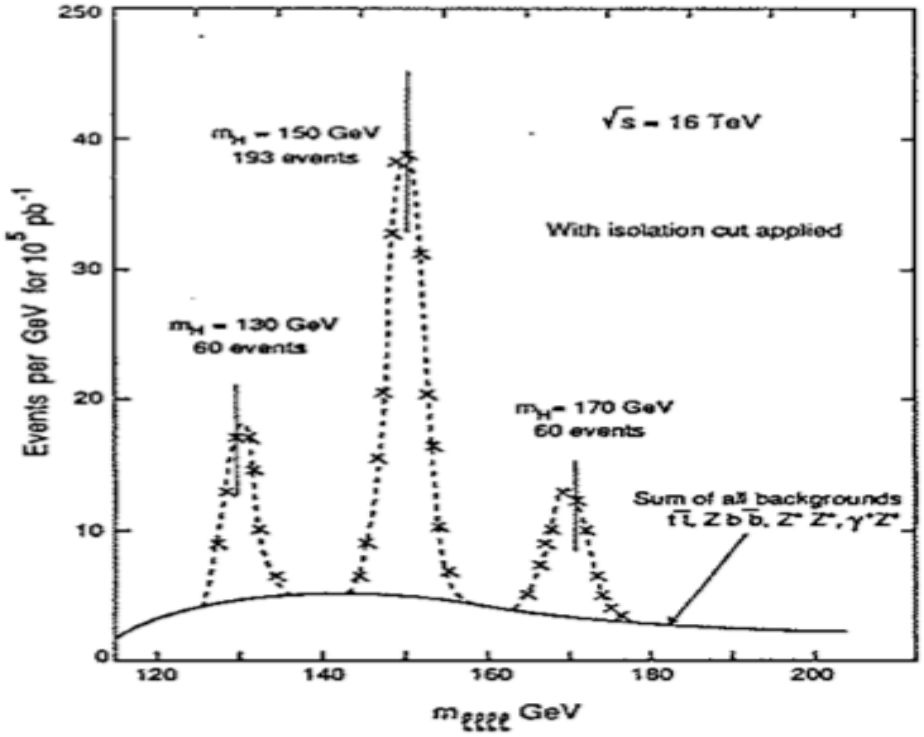



**Fig. 10**

# The ZZ Channel Historical Prospective

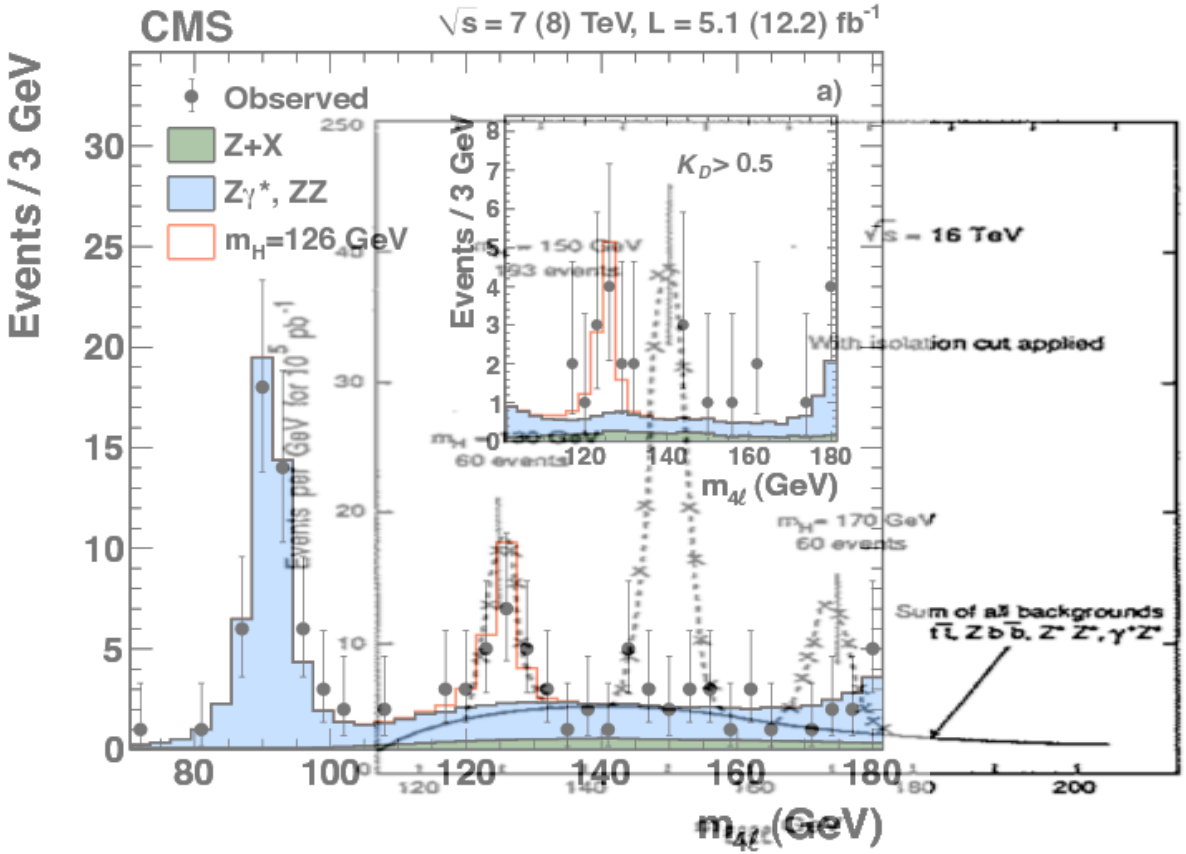
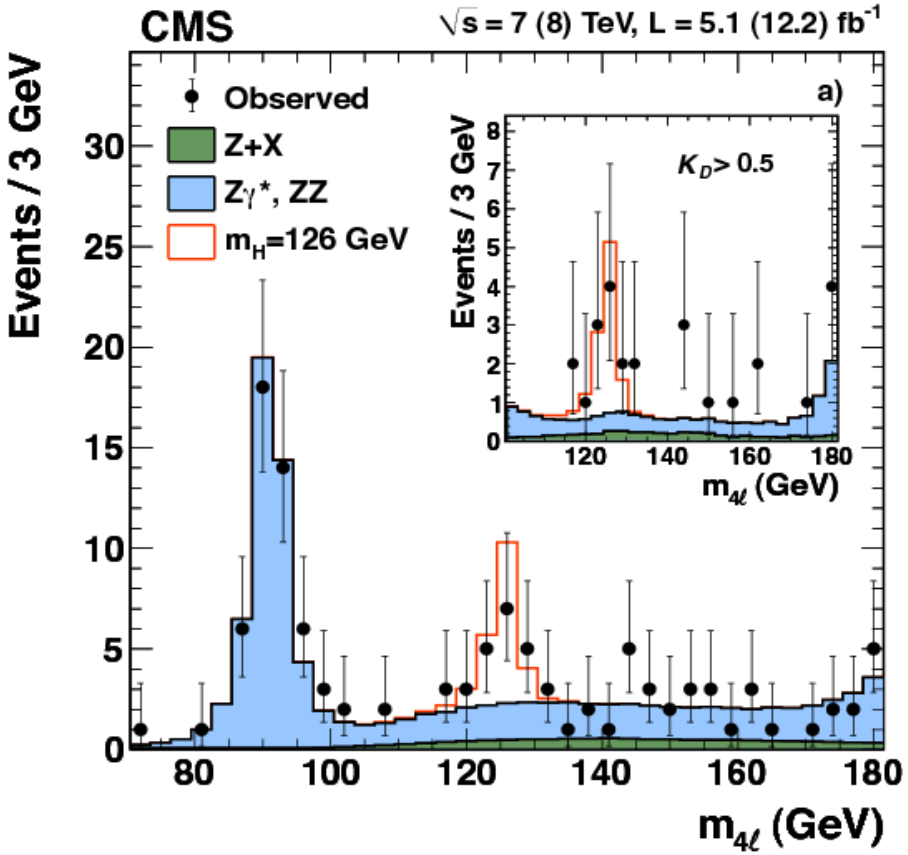



Fig. 10

# The ZZ Channel Historical Prospective



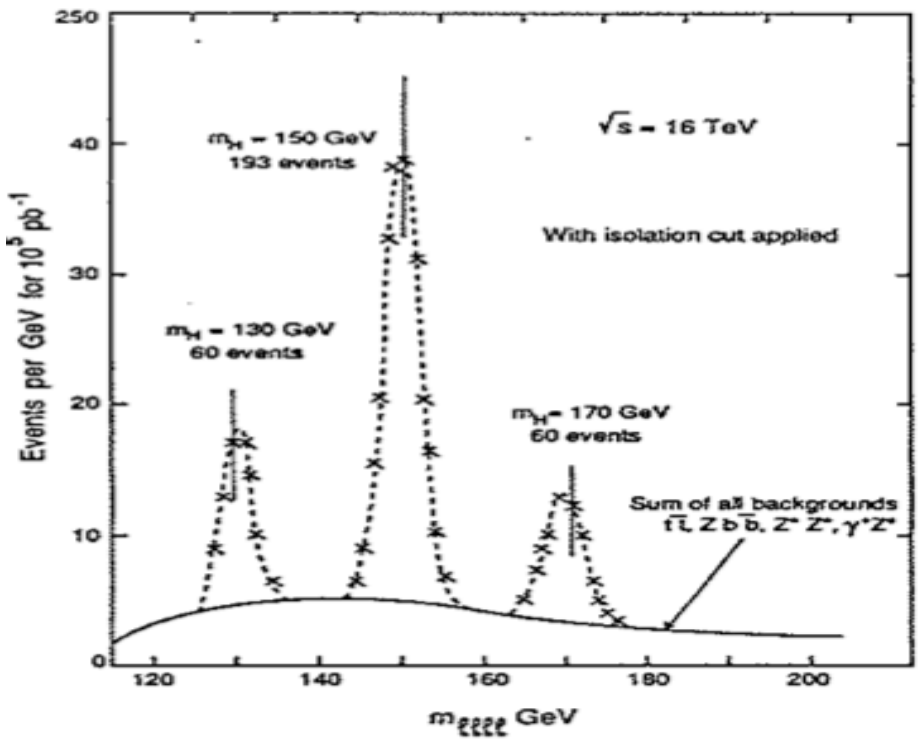



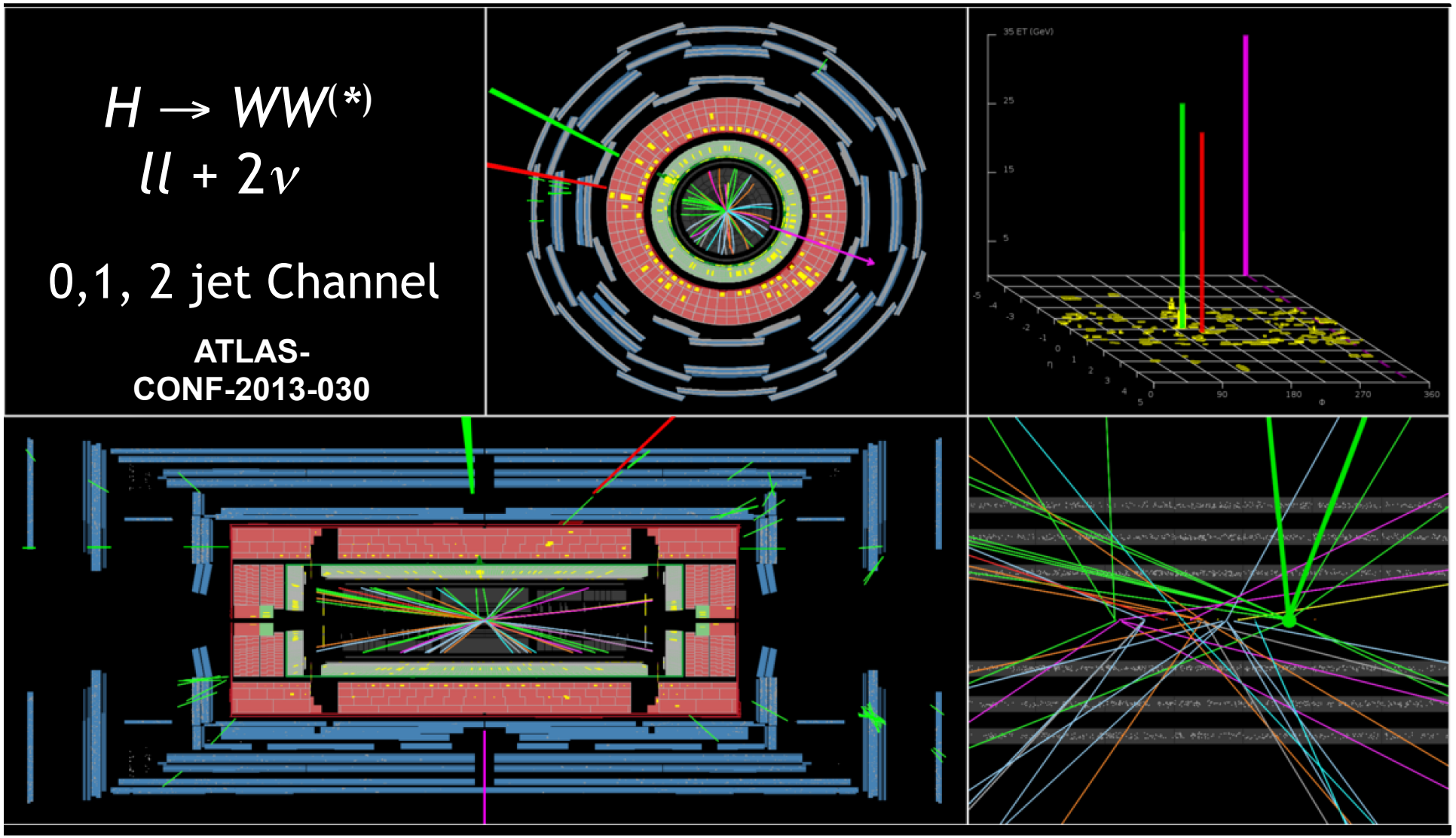

Fig. 10

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

Significance ~7 $\sigma$

16 TeV, 100 $fb^{-1}$

Significance ~6 $\sigma$

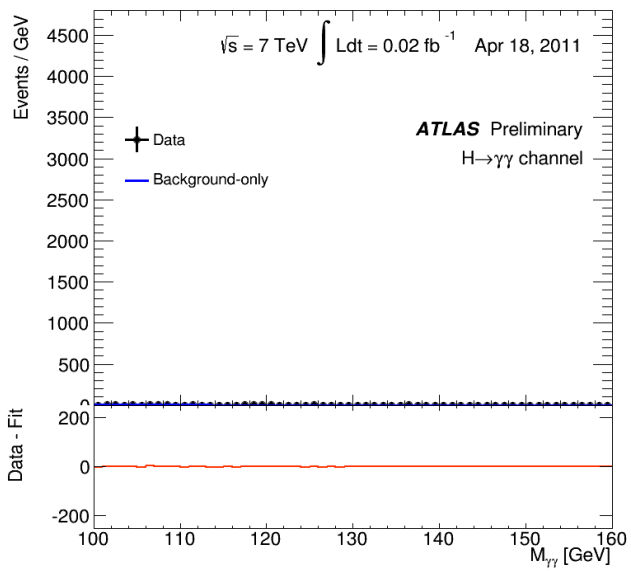



lvlv channel basic facts :

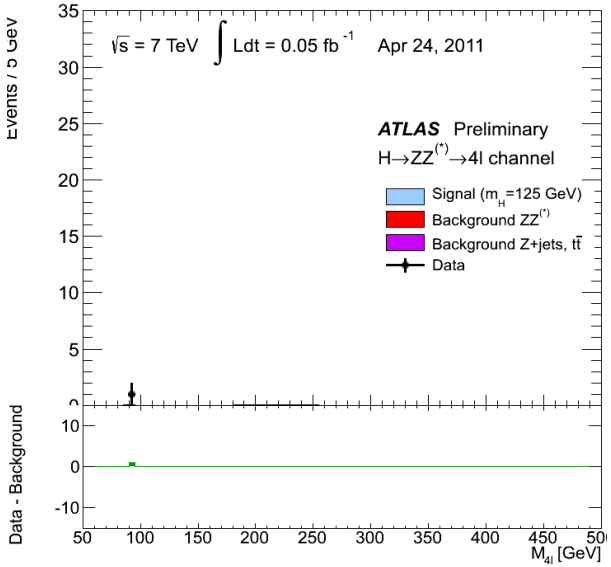
- Ns ~ O(300) per experiment
- Signal purity ~ 5% and 40%

# The Birth of a Particle

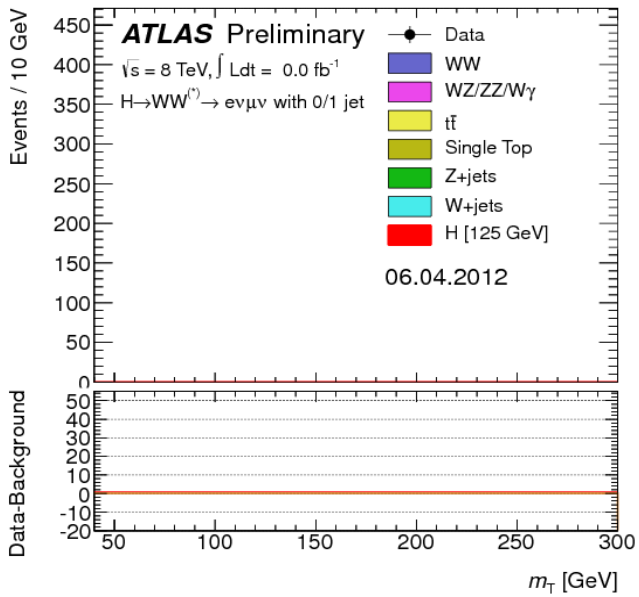
## Diphoton



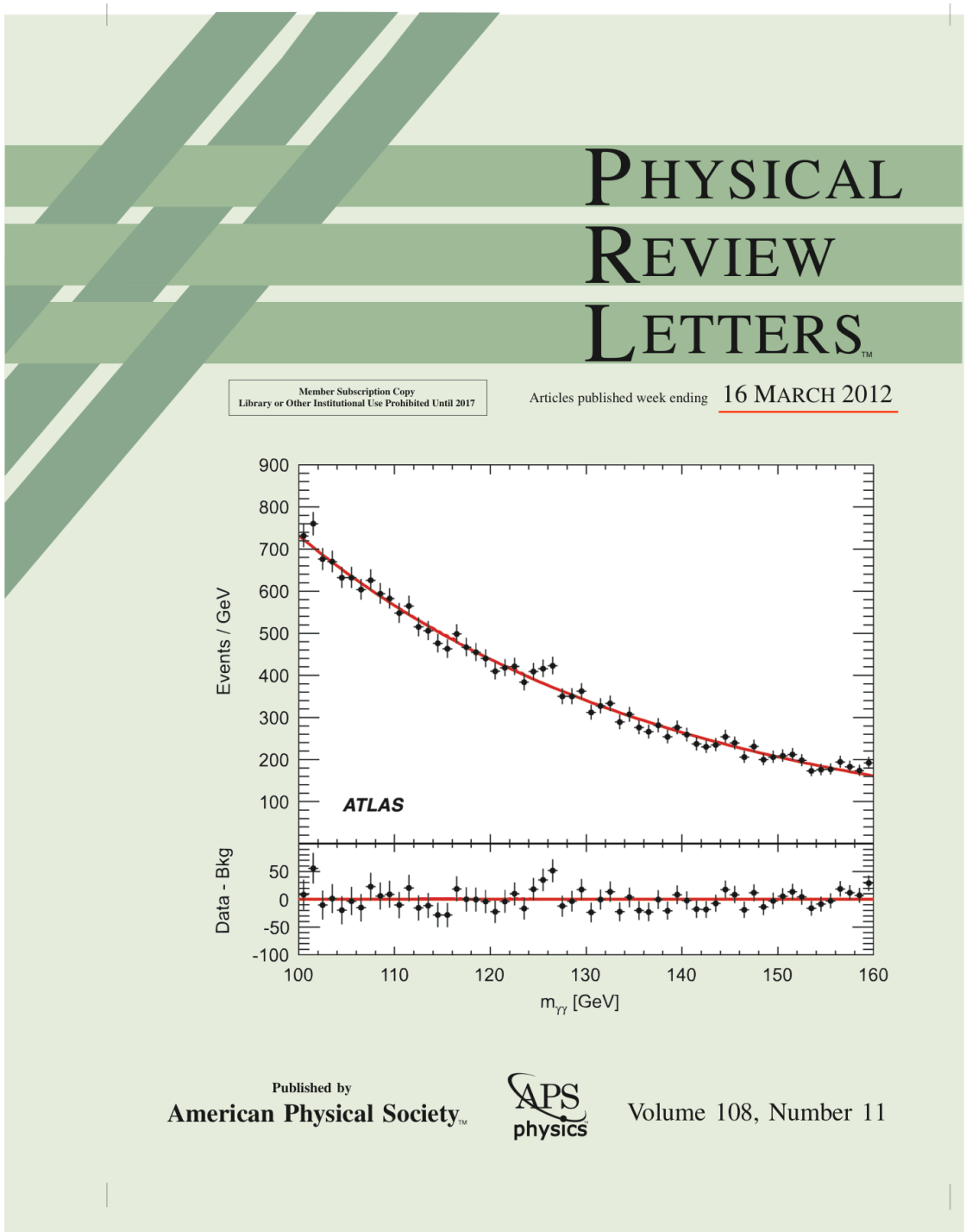

## ZZ Four leptons




## WW (lvlv)




Clear excesses in these three channels
How to quantify these excesses?




# Statistical Methods Part I

How to Quantify the significance of an excess ?

Starting from PRL Cover Plot

# Statistical Interpretation

## How to read Higgs Search Plots

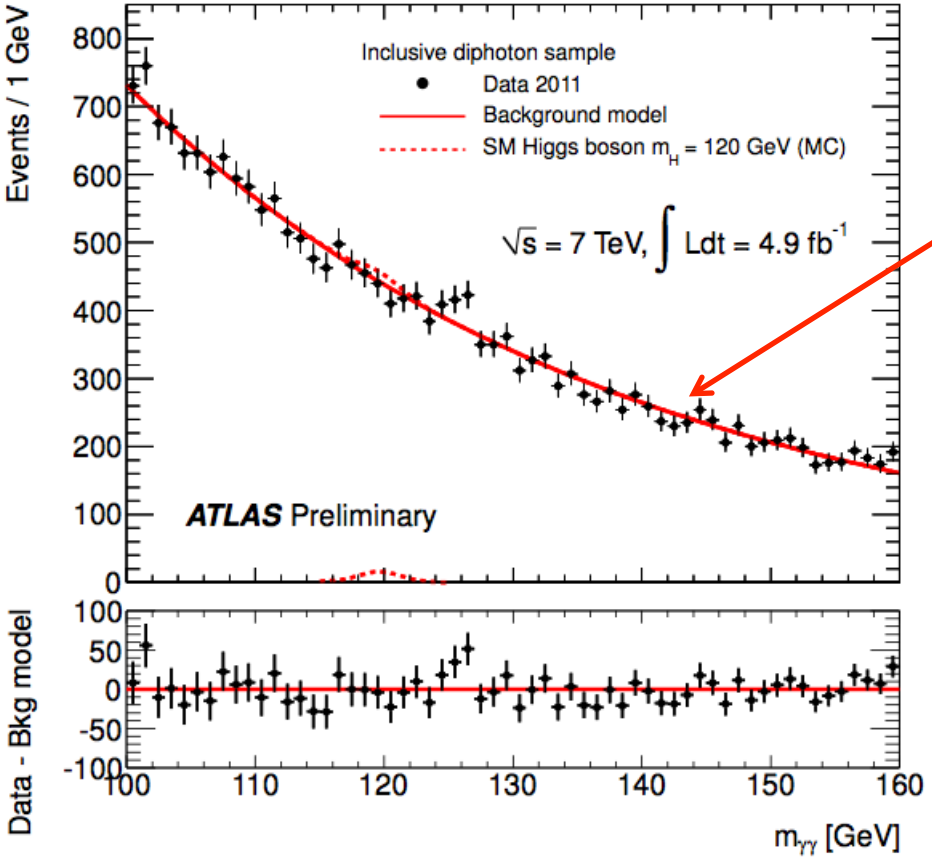
Hypothesis testing using the

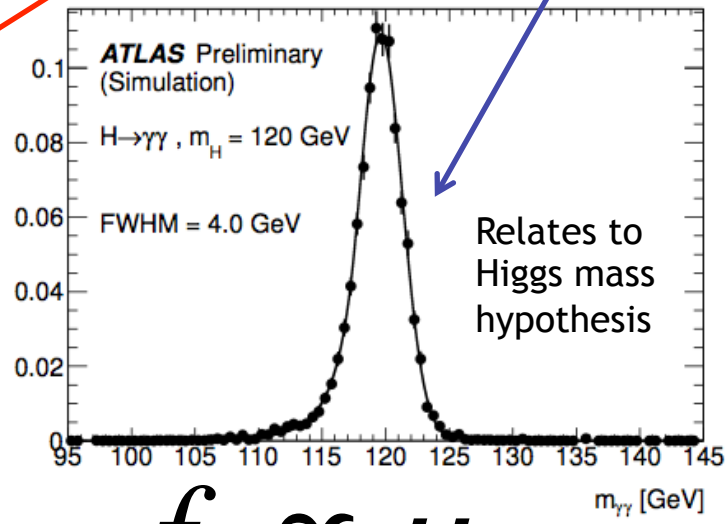
Profile likelihood ratio…

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

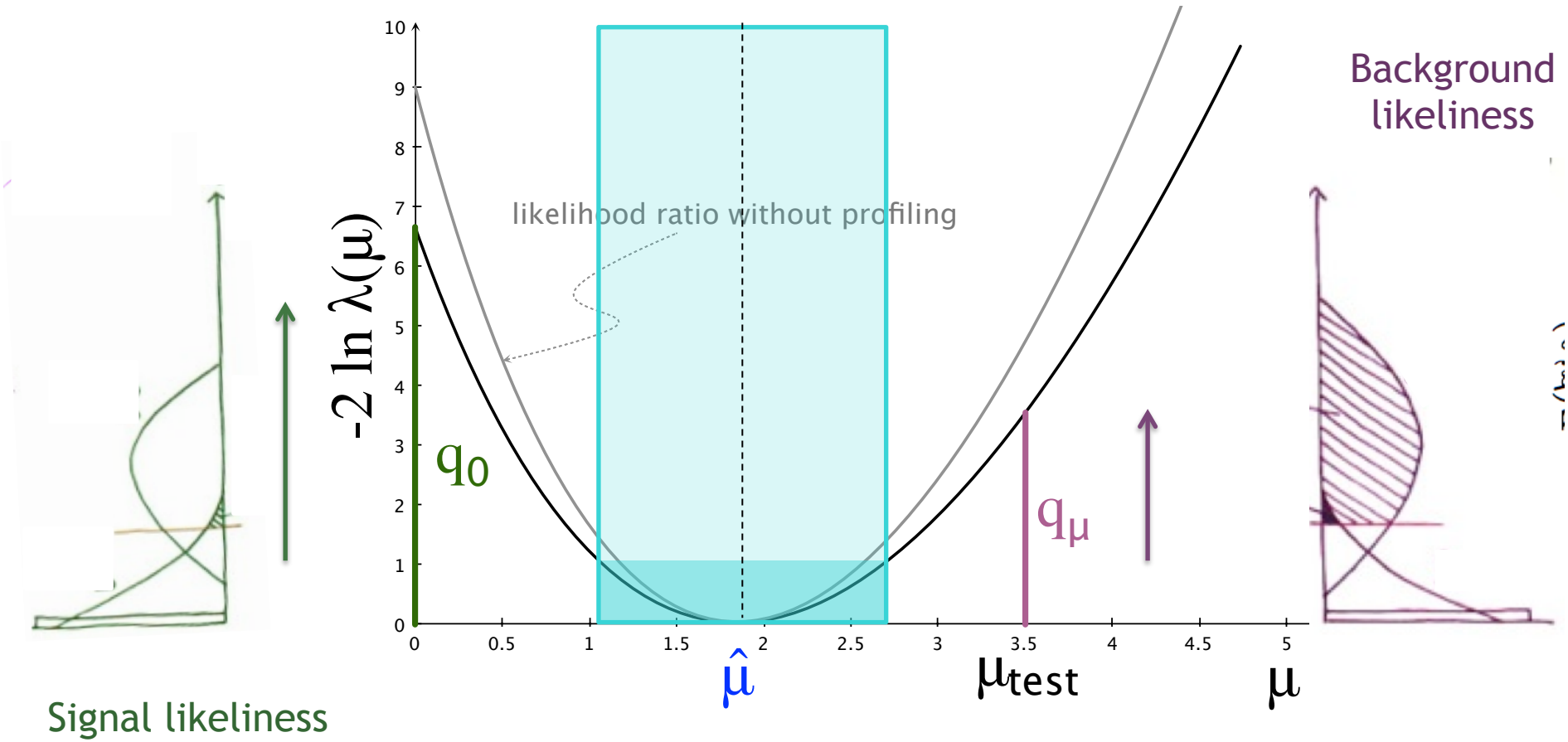
$$f_s \propto \mu$$

Global coherent factor

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

# Definition of the Test Statistic

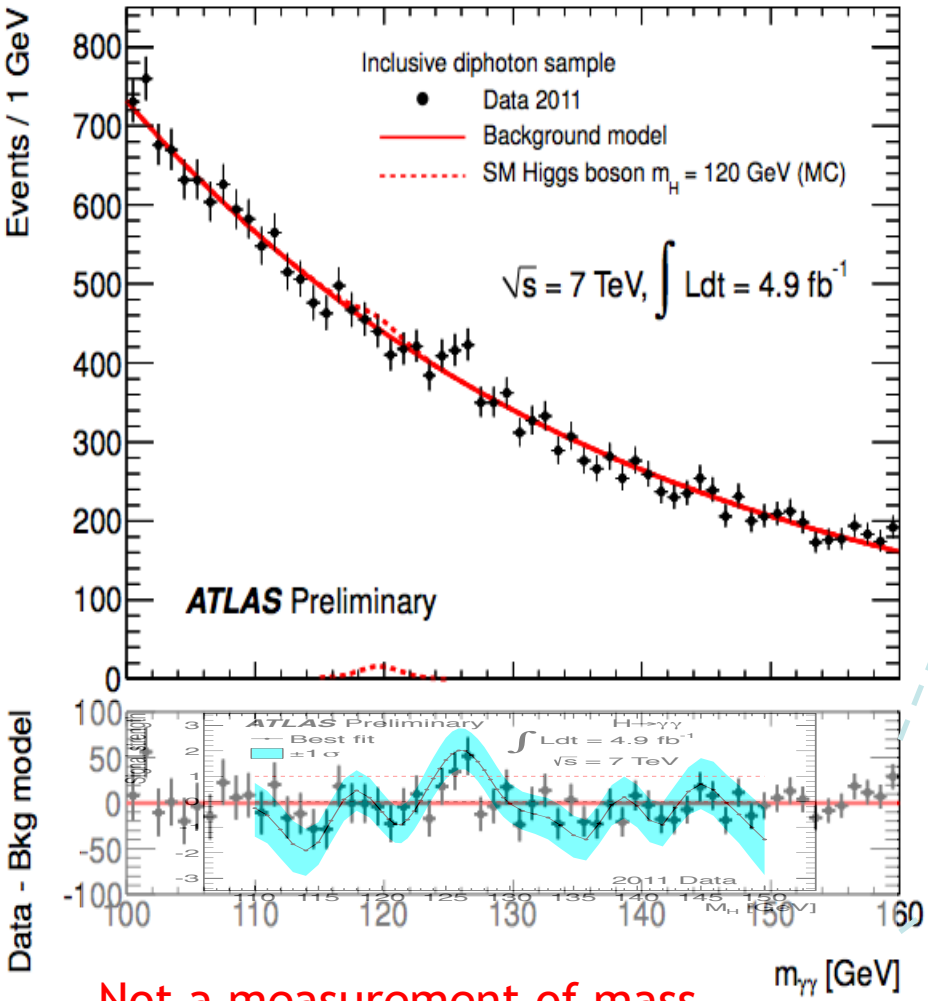
$$\lambda_\mu = \lambda(\mu,\theta) = \frac{L(\mu,\hat{\hat{\theta}}(\mu))}{L(\hat{\mu},\hat{\theta})} \qquad q_\mu = -2\ln\lambda_\mu$$



# Statistical Interpretation

## How to read Higgs Search Plots

Hypothesis testing using the Profile likelihood ratio…



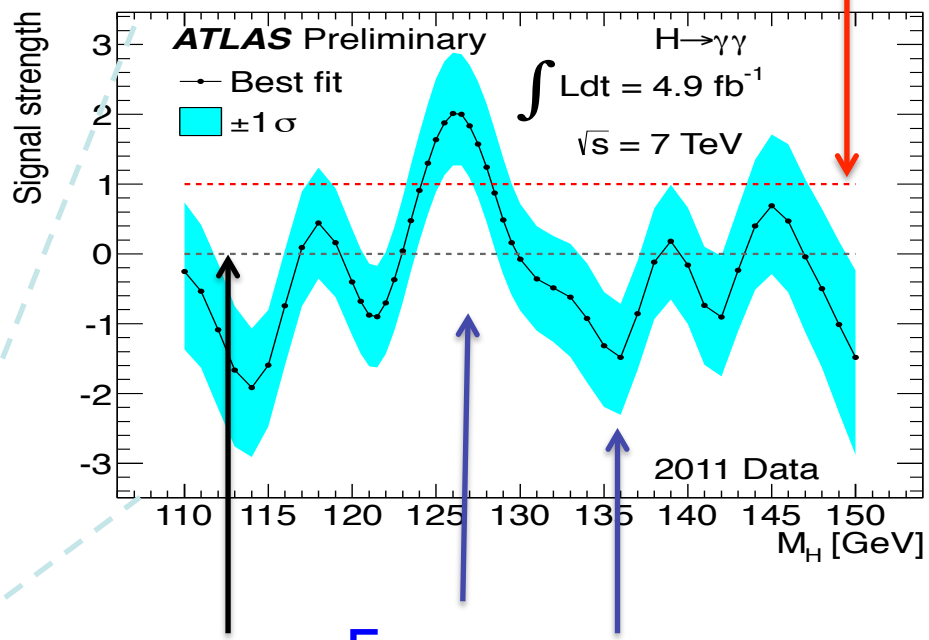

Not a measurement of mass

Not a measurement of cross section

$\hat{\mu}$

Relate to Higgs mass hypothesis

Expected Signal

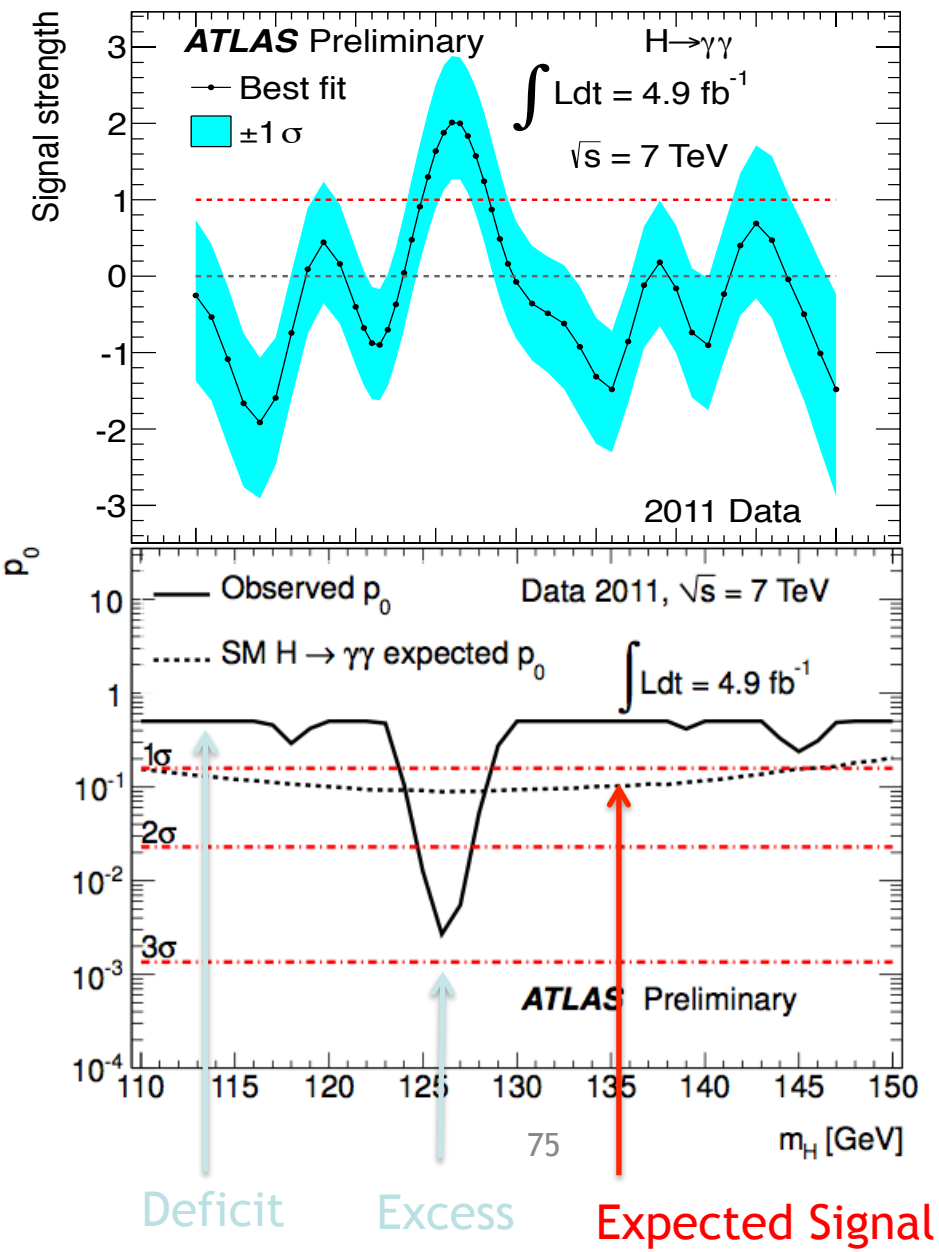



Expected Background

Excess

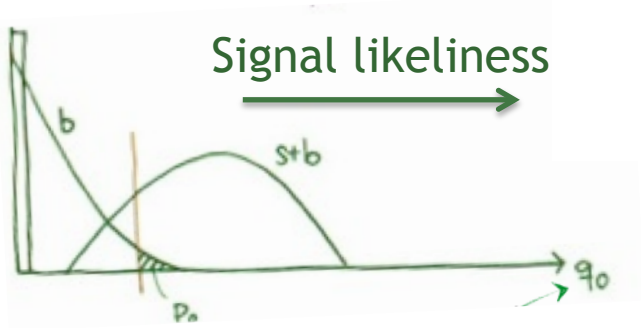
Deficit

# How to Read Higgs Observation Estimates




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

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

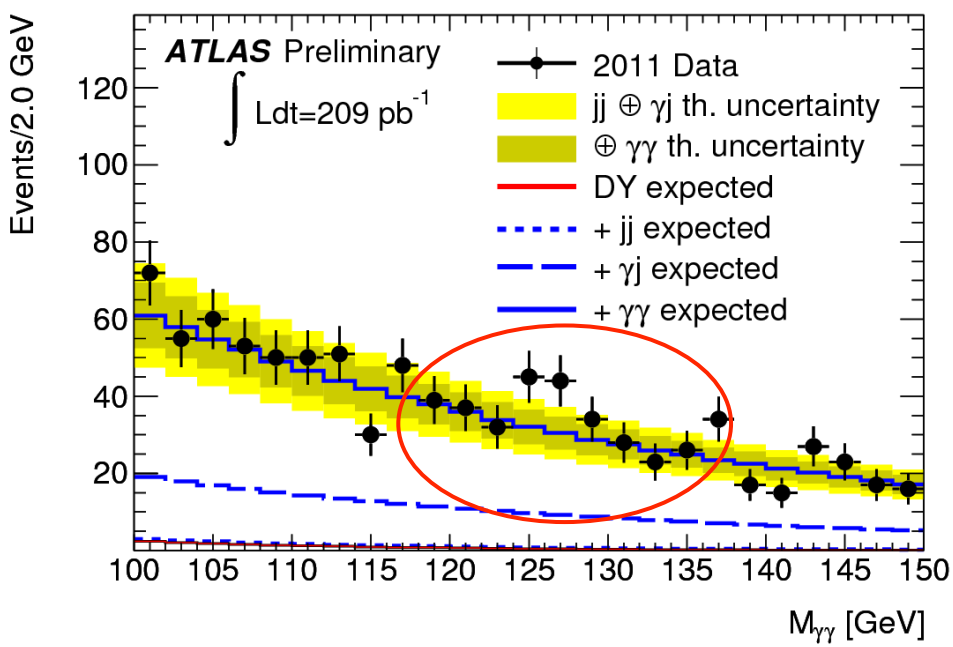


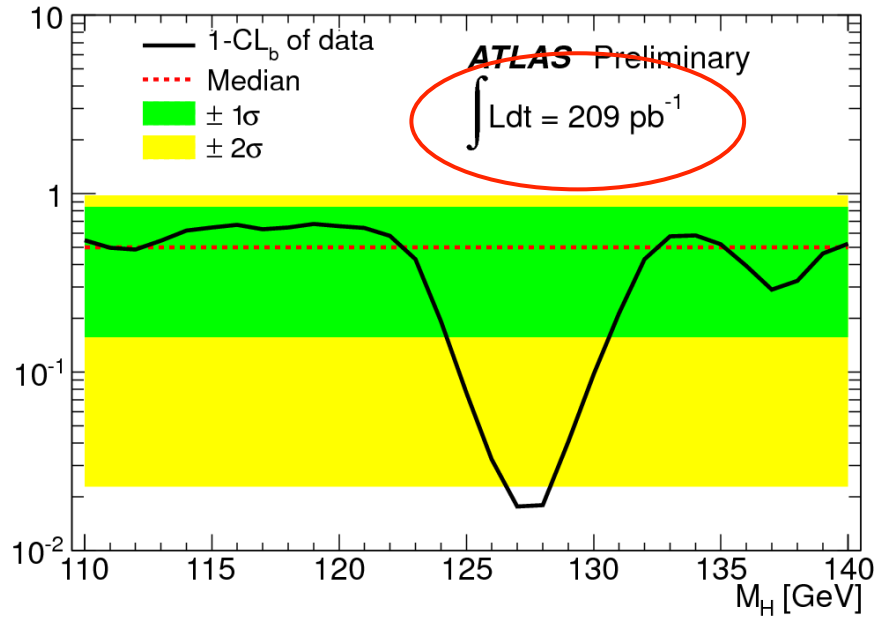

$p_0$ Probability that a background only experiment be more signal like than observed

# The beginning of the $p_0$ Era

For the PLHC 2011 Perugia Conference in spring 2011

ATLAS-CONF-2011-071



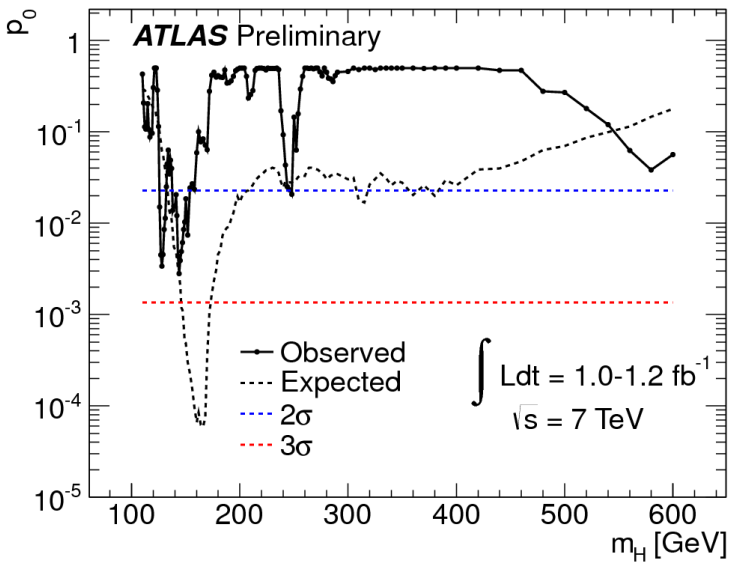



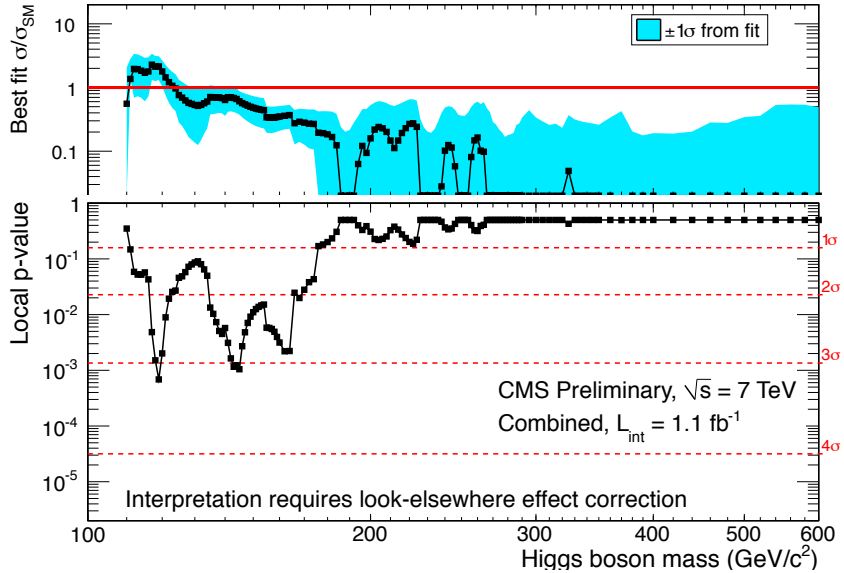

Discussion of the $p_0$ with LEE on data… at 127 GeV!

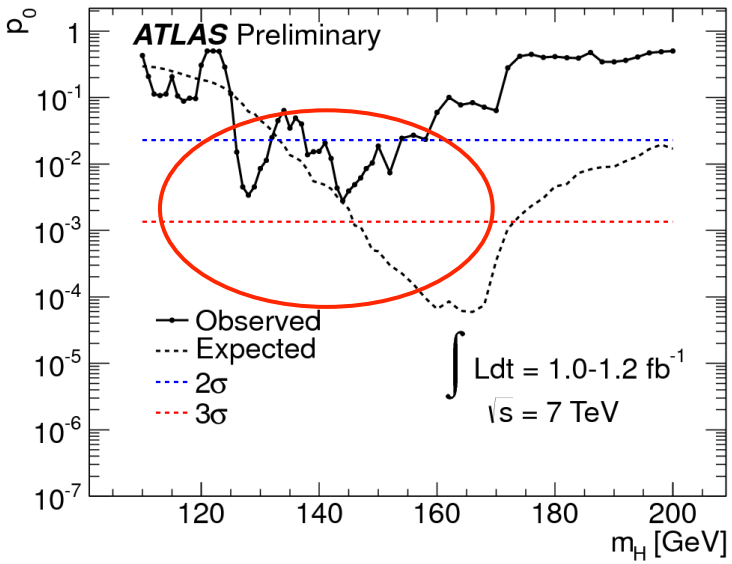
No attention paid… of course it was a fluctuation!

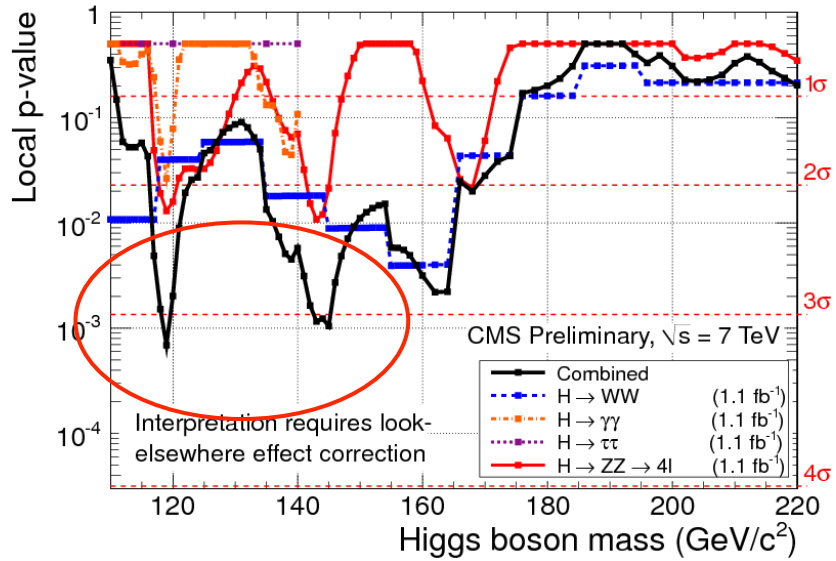
# The First $fb^{-1}$ in the $p_0$ Era

## EPS-HEP Grenoble 2011



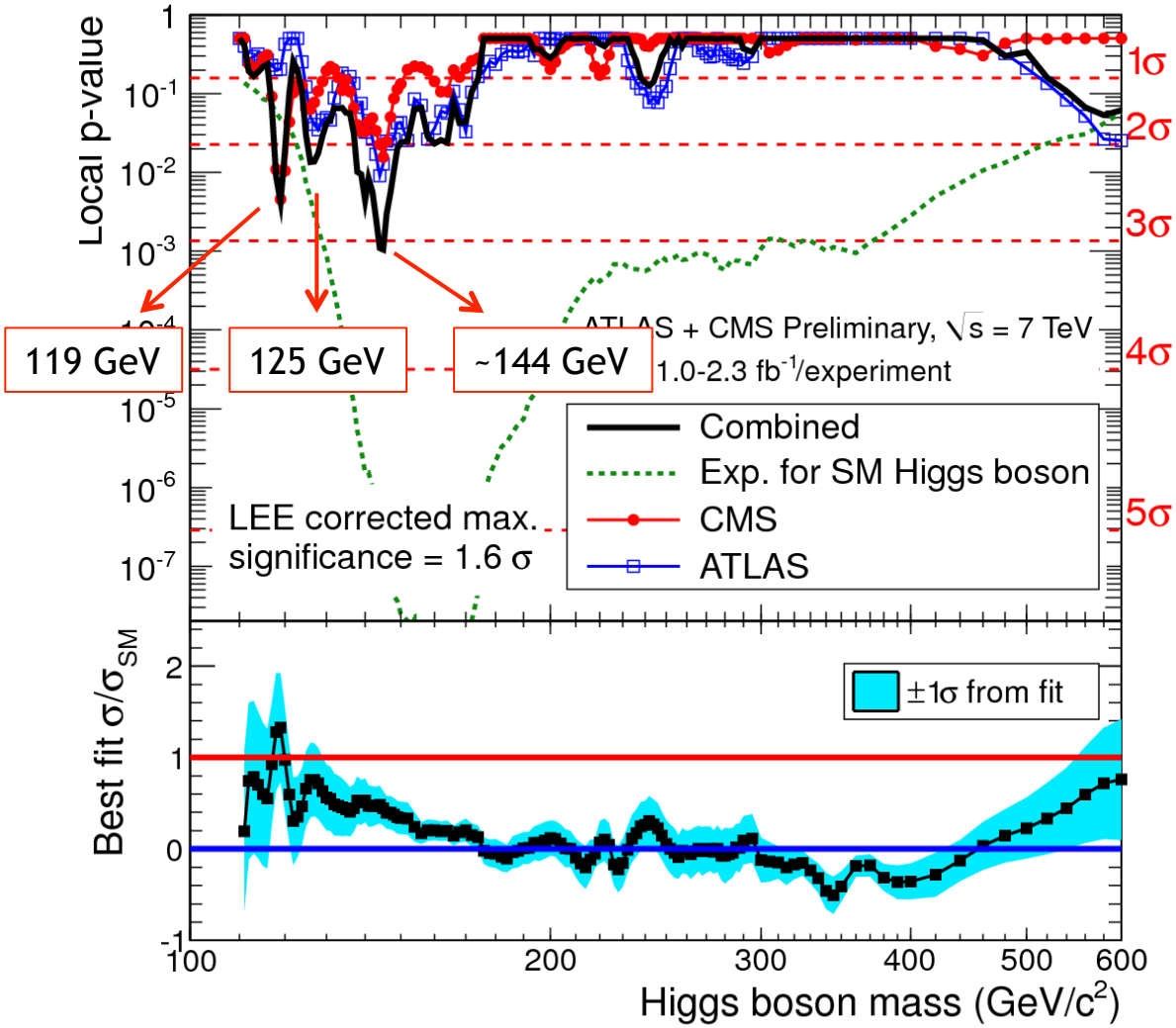



# The First LHC Combination

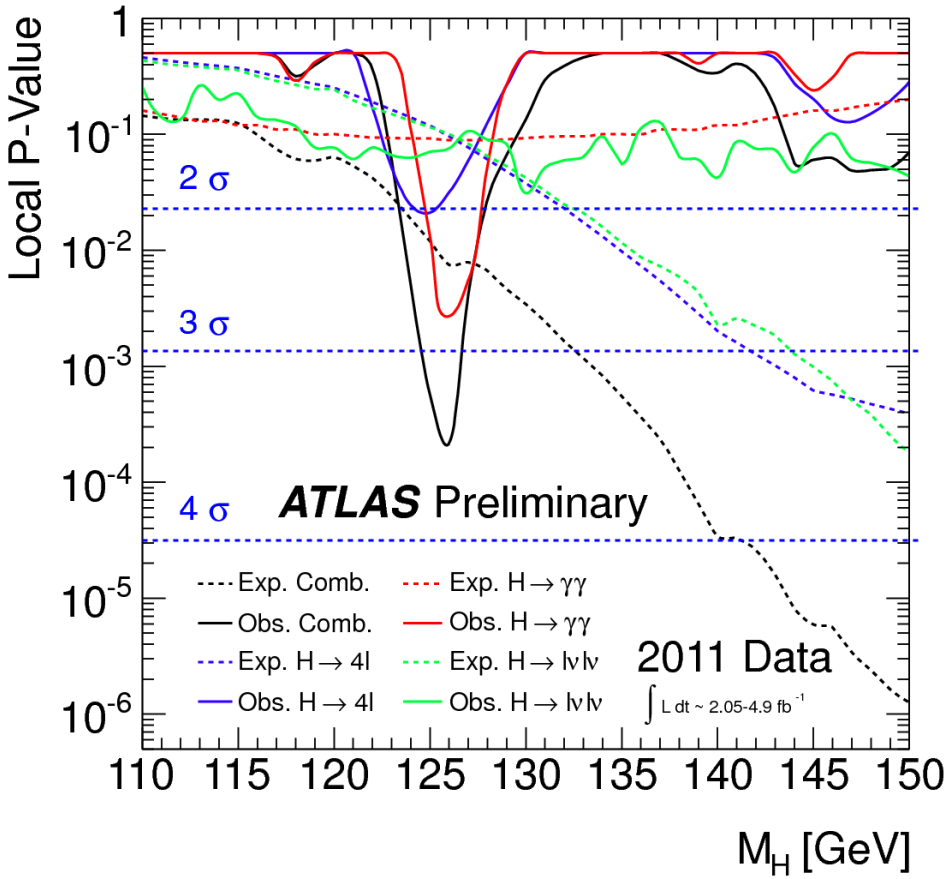
## HCP - Paris 2011

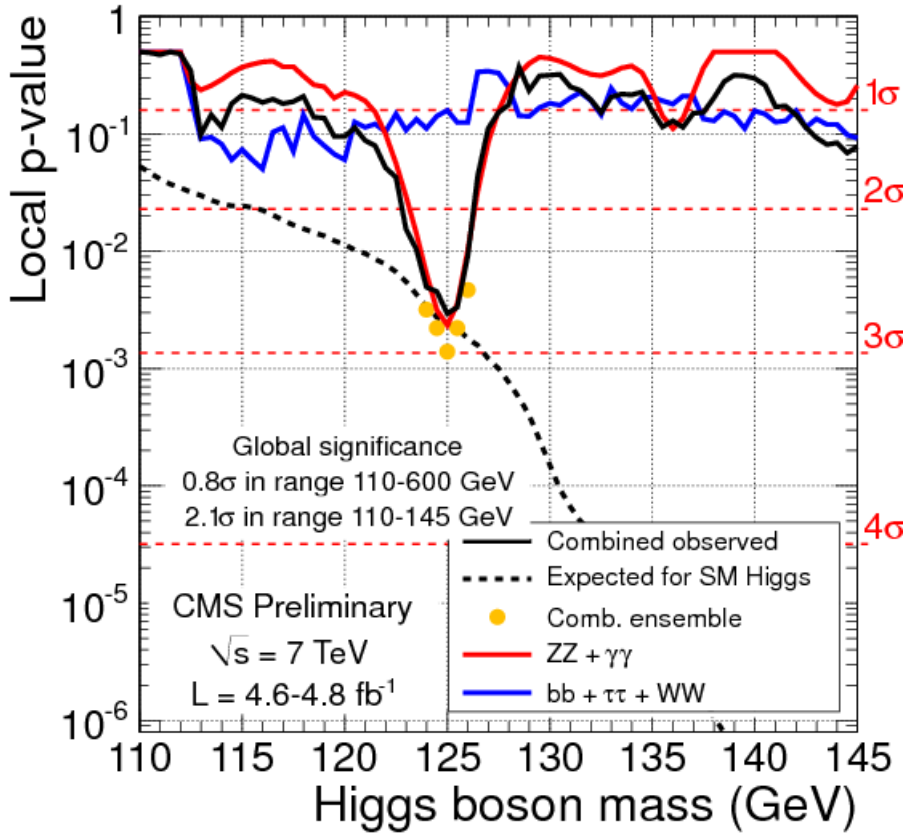



No other combinations to follow in order to ensure independence!

# The CERN december 2011 Council Meeting

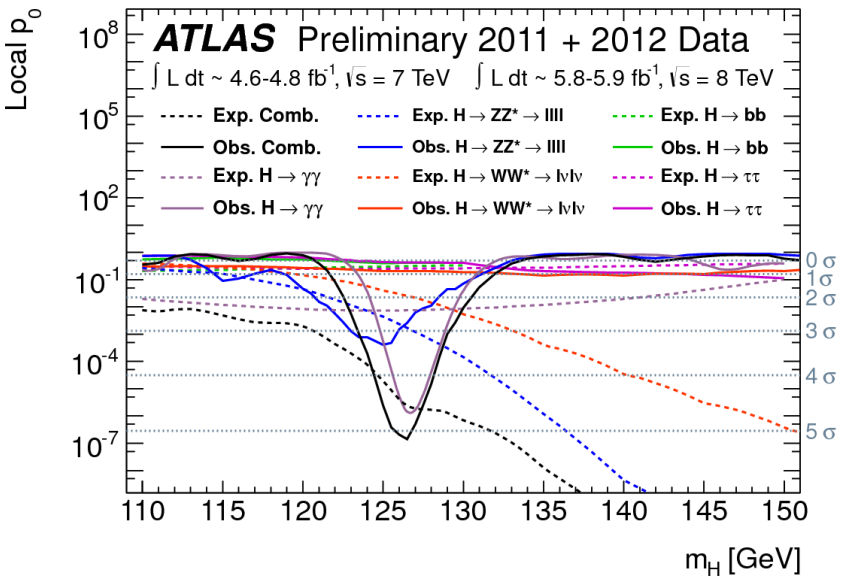
## The first evidence



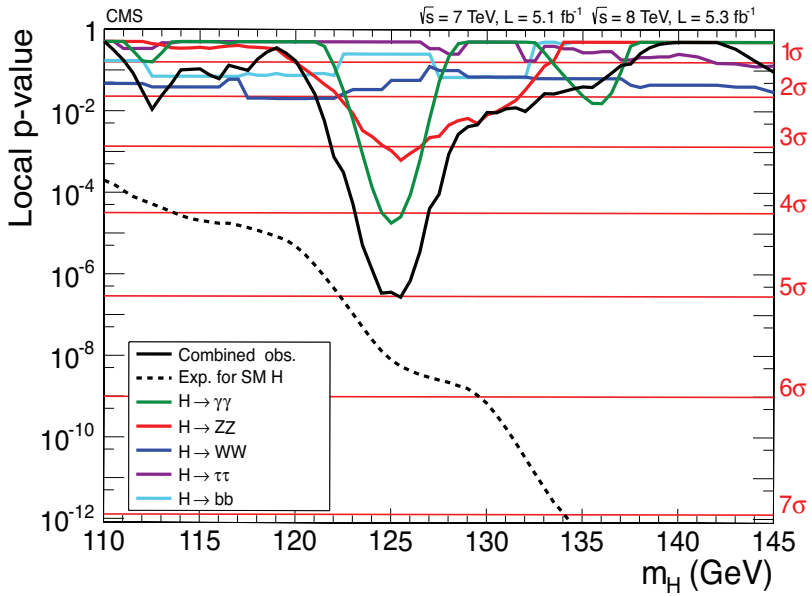



Council Meeting July 4, 2012 and ICHEP - Melbourne 2012

# As a Layman : We have it!

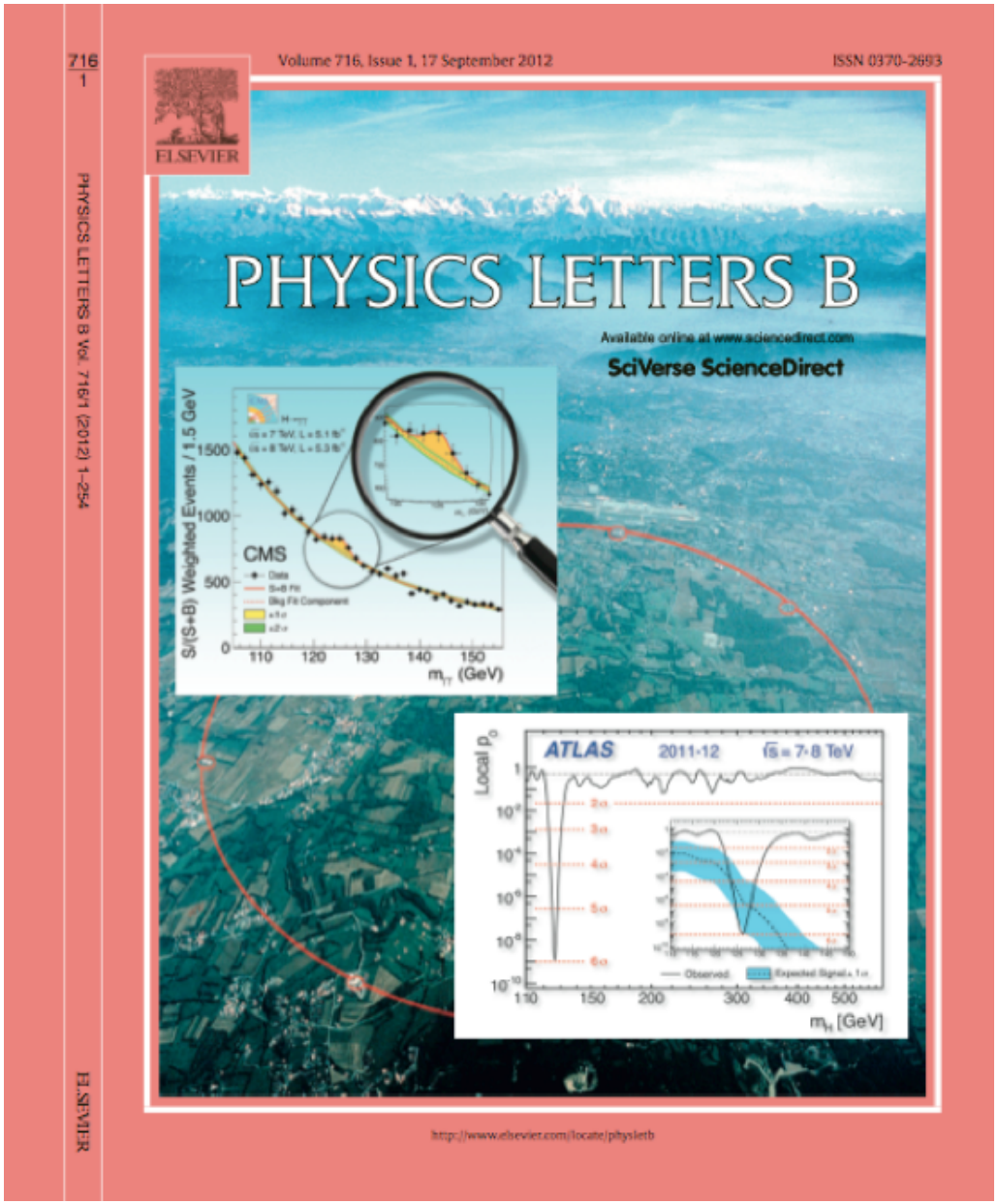



5σ




# Discovery Announced

# PLB 716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Volume 716, Issue 1, 17 September 2012
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PHYSICS LETTERS B
Available online at www.sciencedirect.com
SciVerse ScienceDirect
CMS
ATLAS
2011-12
√s = 7-8 TeV
Local p0
mH [GeV]
PHYSICS LETTERS B Vol. 716/1 (2012) 1–254
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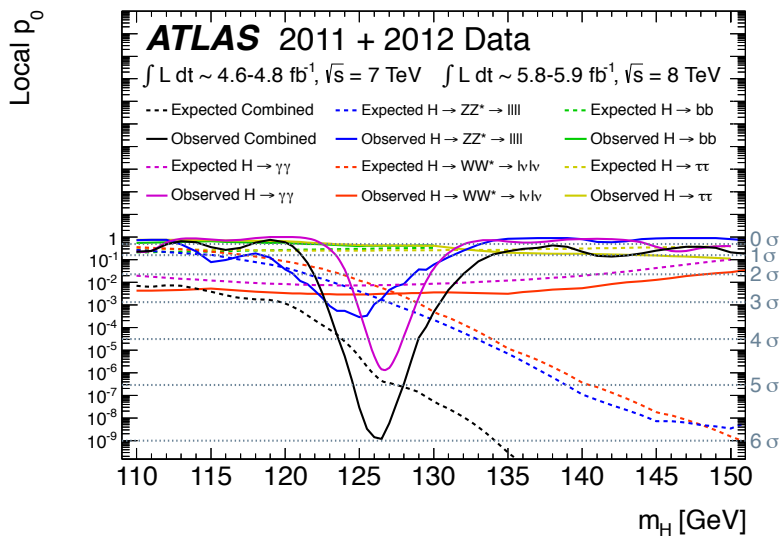
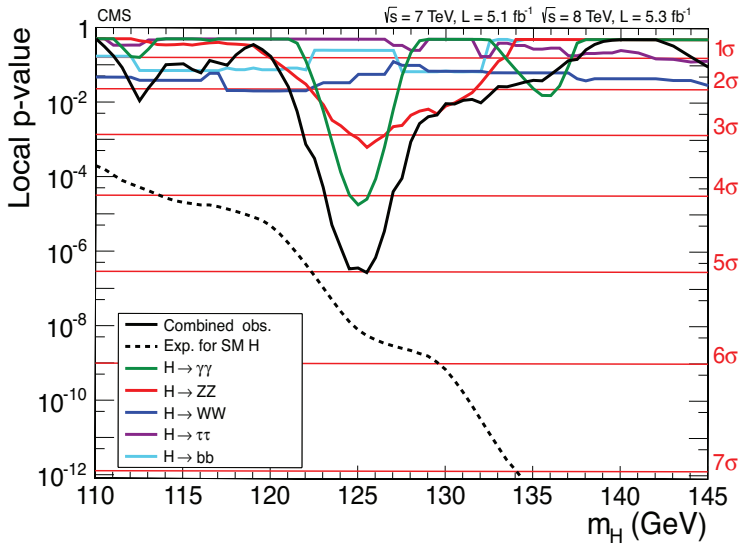

ATLAS 2011 + 2012 Data
∫ L dt ~ 4.6-4.8 fb-1, √s = 7 TeV ∫ L dt ~ 5.8-5.9 fb-1, √s = 8 TeV
Expected Combined
Observed Combined
Expected H → γγ
Observed H → γγ
Expected H → ZZ* → llll
Observed H → ZZ* → llll
Expected H → WW* → lνlν
Observed H → WW* → lνlν
Expected H → bb
Observed H → bb
Expected H → ττ
Observed H → ττ
Local p0
mH [GeV]


CMS
√s = 7 TeV, L = 5.1 fb-1 √s = 8 TeV, L = 5.3 fb-1
Combined obs.
Exp. for SM H
H → γγ
H → ZZ
H → WW
H → ττ
H → bb
Local p-value
mH (GeV)

# Additional Material

# The sector of Fermions (Fermionic neutral current)

Taking a closer look at the neutral current interaction part of the Lagrangian :

$$L_L = -\frac{1}{2}\overline{\psi}_L \gamma_\mu \begin{pmatrix} gW_3^\mu + g'Y_L B^\mu & 0 \\ 0 & -gW_3^\mu + g'Y_L B^\mu \end{pmatrix} \psi_L \qquad L_R = -\frac{1}{2}\overline{\psi}_R \gamma_\mu \begin{pmatrix} g'Y_R B^\mu & 0 \\ 0 & 0 \end{pmatrix} \psi_R$$

In the lepton sector :

$$\begin{aligned} -2L_{NC}^{leptons} &= \overline{\nu}_L \gamma_\mu \left[ (c_W g - s_W g' Y_L) Z^\mu + (s_W g + c_W g' Y_L) A^\mu \right] \nu_L \\ &+ \overline{e}_L \left[ (-c_W g - s_W g' Y_L) Z^\mu + (-s_W g + c_W g' Y_L) A^\mu \right] e_L \\ &+ \overline{e}_R \gamma_\mu \left[ -s_W g' Y_R Z^\mu + c_W g' Y_R A^\mu \right] e_R \end{aligned}$$

1.- Eliminate neutrino coupling to the photon : $g \sin\theta_W = -g' Y_L \cos\theta_W$

2.- Same coupling $e_R$ and $e_L$ to the photon : $g' Y_R = 2 g' Y_L$

3.- Link to the EM coupling constant *e* : $g \sin\theta_W = e$

Y the hypercharge is chosen to verify the Gell-Mann Nishijima formula :

$$Q = I_3 + \frac{Y}{2}$$

# The sector of Fermions (kinematic)

Another important consequence of the Weinberg Salam Model…

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

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

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

Fermion mass terms are forbidden

Not the case when using 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 necessary.

The picture is now almost complete…

| | Field | $I_3$ | Y | Q | $SU(2)_L x U(1)_Y$ | $SU(3)_C$ |
|---|---|---|---|---|---|---|
| Leptons | $(\nu_L, e_L)$ | (1/2,-1/2) | -1 | (0,-1) | (2,-1) | 1 |
| | $e_R$ | 0 | -2 | -1 | (1,-2) | 1 |
| Quarks | $(u_L, d_L)$ | (1/2,-1/2) | -1 | (2/3,-1/3) | (2,1/3) | 3 |
| | $u_R$ | 0 | 4/3 | 2/3 | (1,4/3) | $\bar{3}$ |
| | $d_R$ | 0 | -2/3 | -1/3 | (1,-2/3) | $\bar{3}$ |
| IVB | B | 0 | 0 | - | (1,0) | 1 |
| | W | (1,0,-1) | 0 | - | (3,0) | 1 |
| | g | 0 | 0 | - | (1,0) | 8 |
| Higgs | H | (1/2,-1/2) | 1 | - | (2,1) | 1 |

The Minimal Standard Model

Jean Iliopoulos

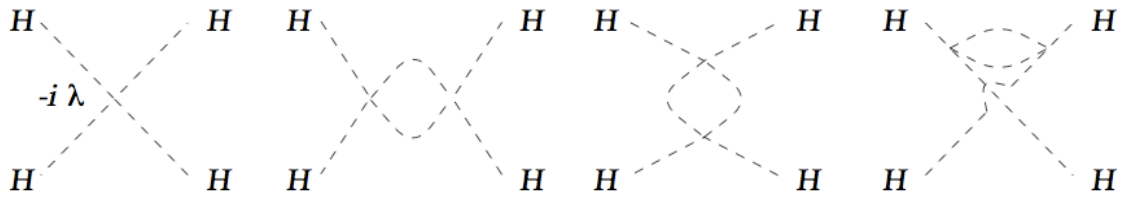
# Running Quartic Coupling : Triviality

The (non exhaustive though rather complete) evolution of the quartic coupling :

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

In the case where the Higgs mass is large (large λ) : $M_H^2 = 2\lambda v^2$

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




$$\frac{d\lambda(Q^2)}{dt} = \frac{3}{4\pi^2}\lambda^2(Q^2) \longrightarrow \frac{1}{\lambda(Q^2)} = \frac{1}{\lambda(Q_0^2)} - \frac{3}{4\pi^2}\ln\left(\frac{Q^2}{Q_0^2}\right)$$

If Q can be high at will eventually lead to Landau pole

Triviality condition to avoid such pole : $1/\lambda(Q) > 0$

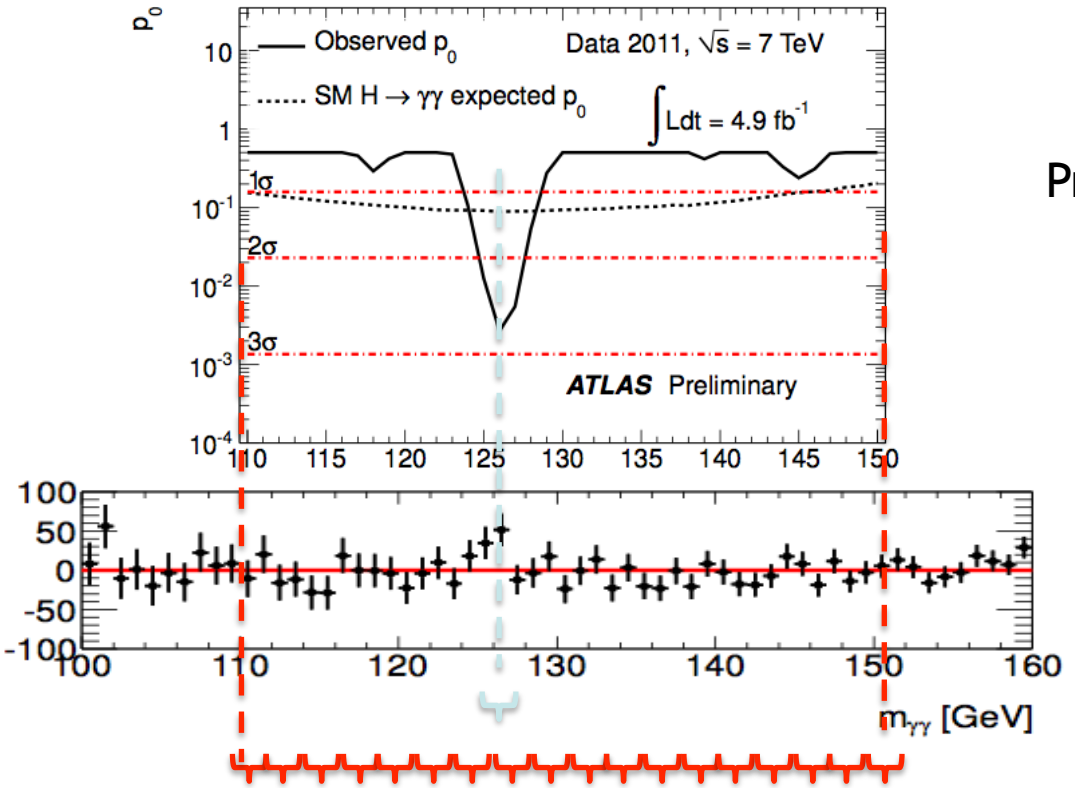
Then

$$\boxed{M_H^2 < \frac{8\pi^2 v^2}{3\log\left(\frac{\Lambda^2}{v^2}\right)}}$$

# Local vs. Global Probability

Look Elswhere Effect

(over)Simplified View




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

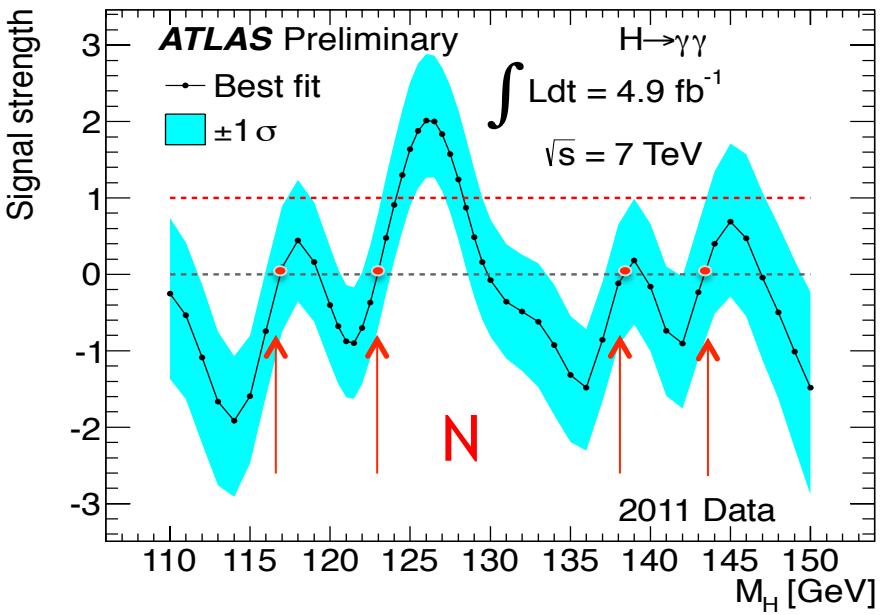
What is the probability of observing an excess at least as large as observed within a mass range ?

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

# Local vs. Global Probability

Look Elswhere Effect

Approximate Formula




Based on counting the numbers of up-crossings

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

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

Trial factor ~ Here the dependence is explicit…

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