Half a Century of Higgs Boson Hunt

And its Recent Developments…

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GÖTTINGEN

Prerequistes

- General LHC detectors and physics (E. Richter-Was, M. Weber and R. Schmidt)
    - Introduction to the Machine
    - The detectors
    - The Experimental challenges of object reconstruction in high PU
    - The Main processes at the LHC
- Elements of QCD and toolbox (S. Schumann and A. Robson)
    - Difficulties to compute predictions
    - How to compute certain processes
    - Jets
- Statistics (G. d'Agostini)
    - How to compute a limit
    - What is the significance of an excess
- Electroweak Theory (V. Cavassini and B. Clement)
    - Construction of EW theory
    - Discovery of W and Z bosons at SPS

- In parallel to the top physics (S. Tokar)
- Introductory to SUSY and BSM (C. Clement)

How did we get here?

… On the NY Times front Page!

Let’s go Back one Step…

… when no one (or almost) new about the news…

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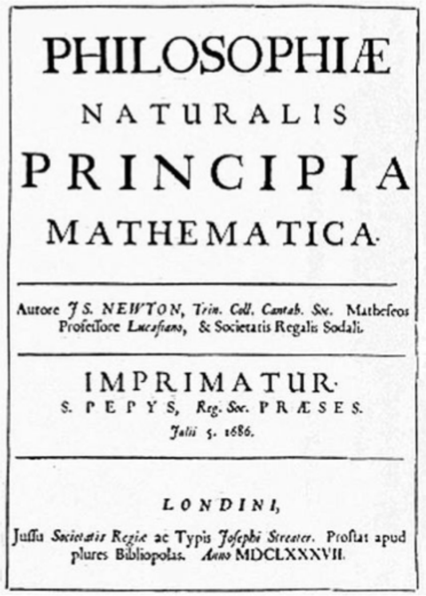


PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

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.

Digression on the origin of Mass

- Gallilean and Newtonian concept of mass :

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

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

- Einstein : Does the mass of a system depend 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 : binding energy ~2% of the mass
- Nucleus parton level : binding energy ~98% of the mass

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

- The insight of the Higgs mechanism :

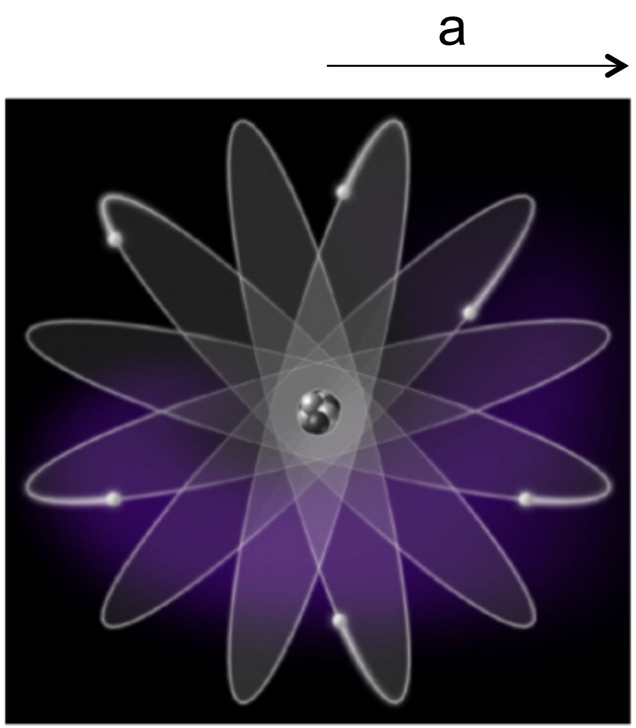
New element in trying to understand the origin of mass of gauge bosons and fermions

How Would it Be Without Elementary Particle Masses?

Electron mass (m_e = 511 keV)

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

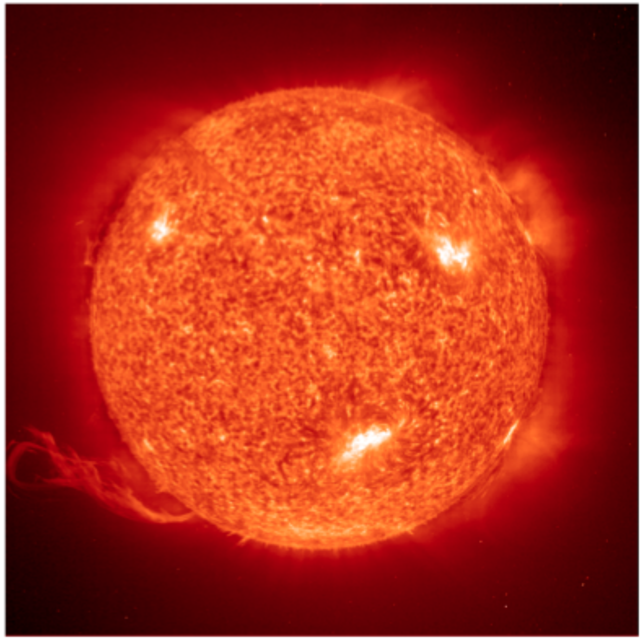
- if $m_e = 0$: Then no atomic binding
- if m_e ~ 100 MeV no pe reaction



W boson mass (m_W = 81 GeV)

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

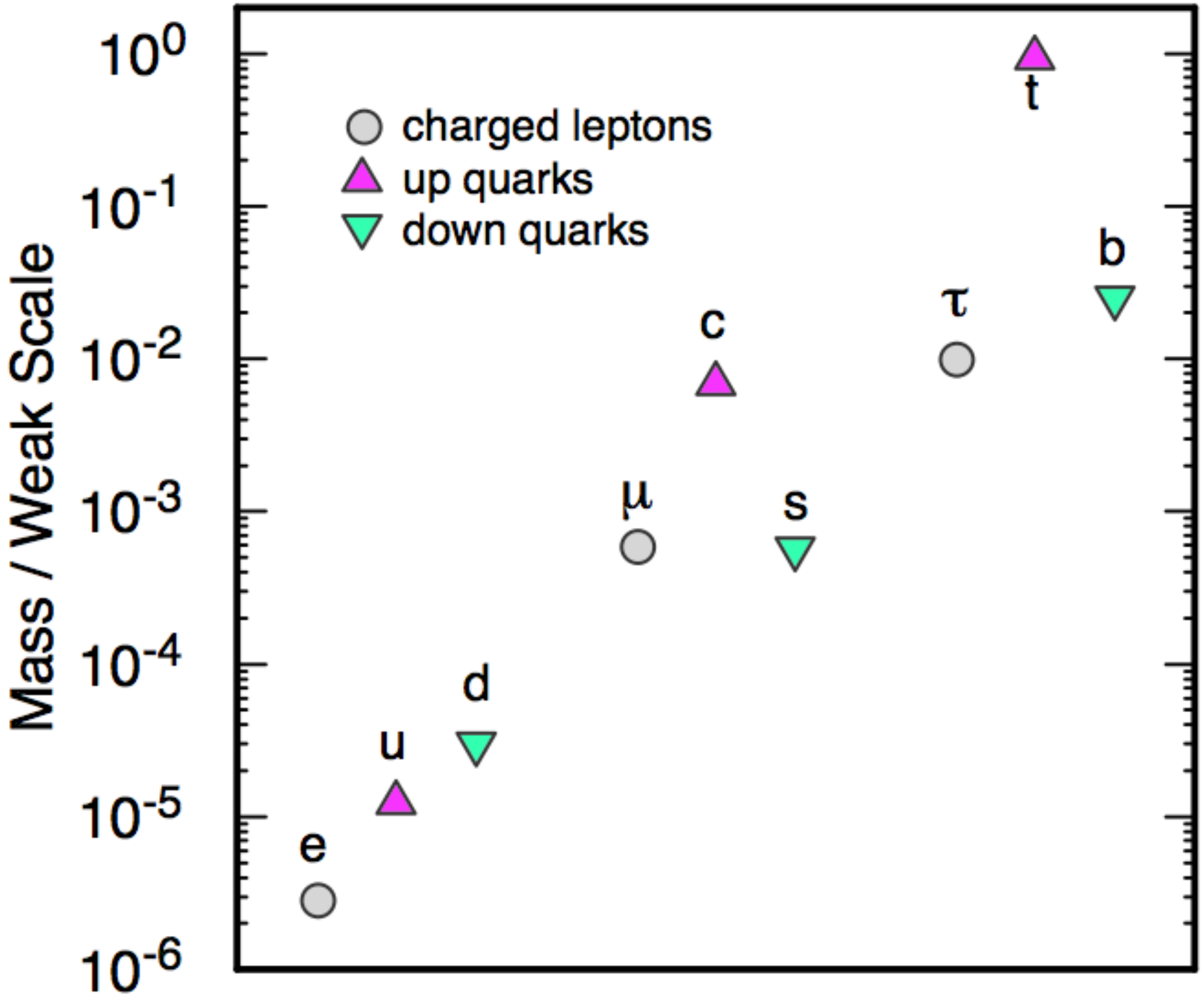
If no or lower W mass : shorter combustion time at lower temperature



Everything would be completely different!

The Flavor Hierarchy

Simple glance at the masses of Fermions



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 …

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

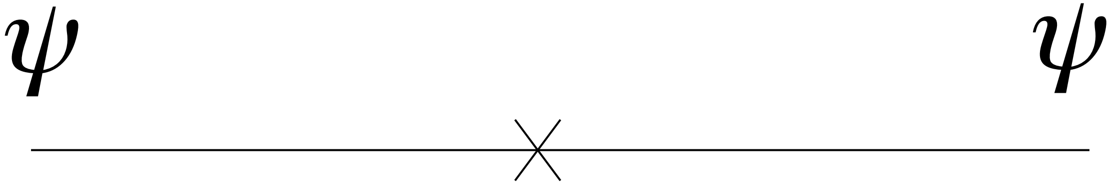
Caution, not unified in the sense of unified forces, only unique framework

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

How Does Mass Appear in a Lagrangian

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

In Terms of Feynman Diagram



Spontaneous Symmetry Breaking (SSB) - Global Symmetry

The Goldstone theorem is where it all began…

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)

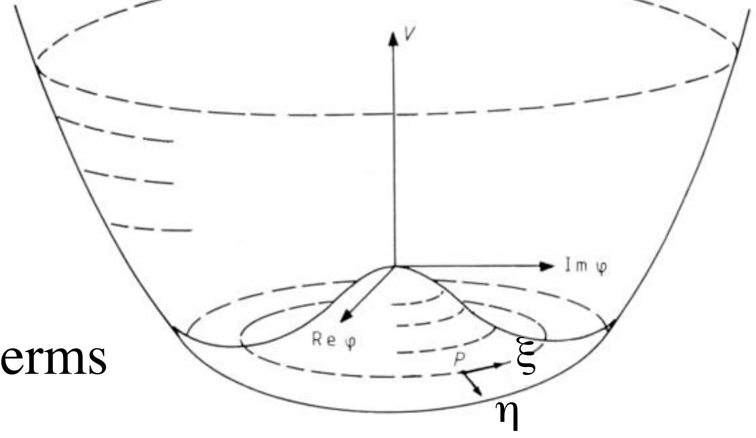
From a simple (complex) scalar theory with a U(1) symmetry

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

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

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

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.

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

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)

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

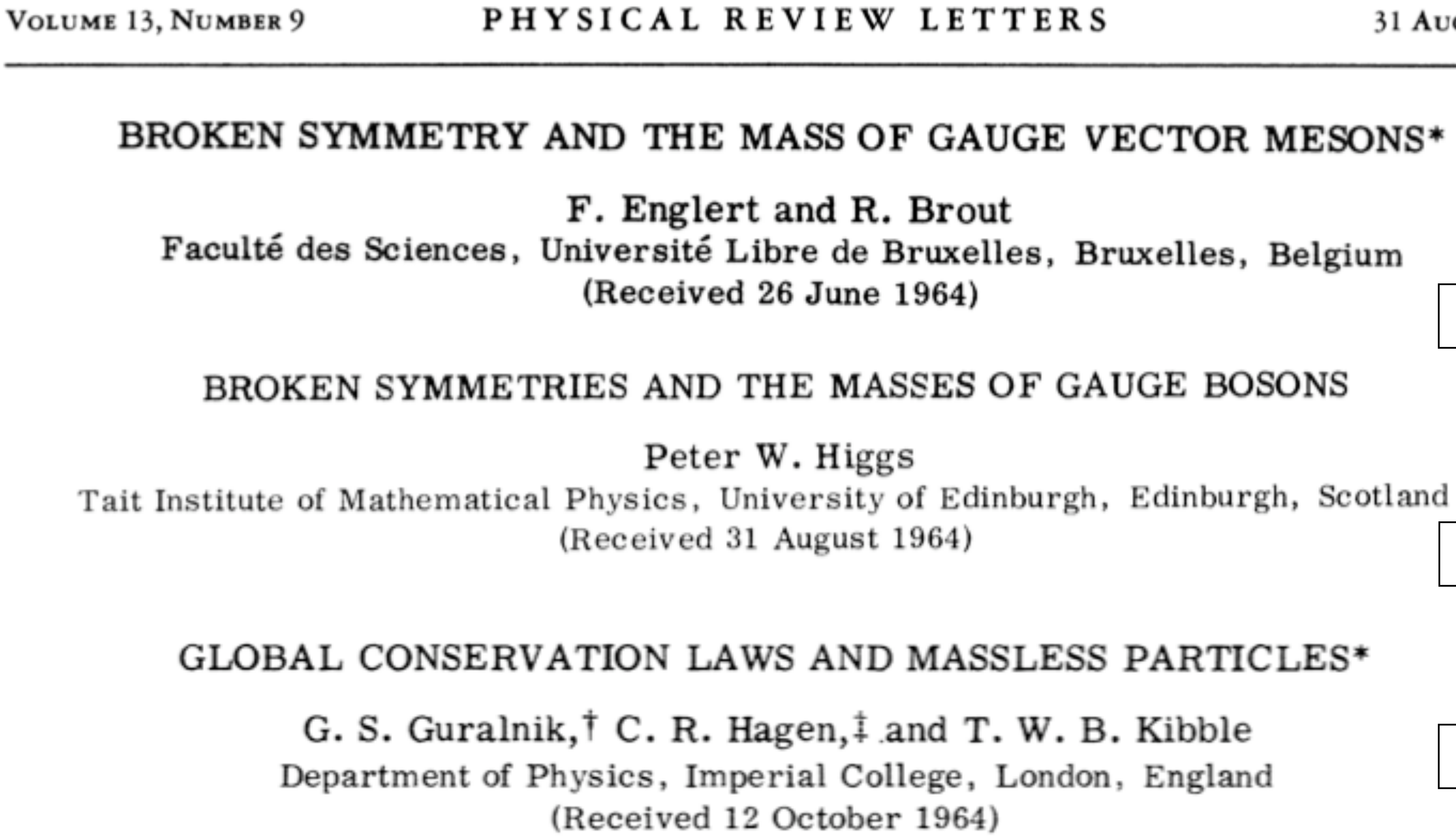
It is thus a Dynamical Symmetry Breaking where the pseudo-goldstone bosons are the π^+,π^0,π^- mesons

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

Spontaneous Symmetry Breaking (SSB) - Local Symmetry

All the players… in the same PRL issue



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

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

Mass term for the gauge field! But…

What about the field content?

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

Number of d.o.f. : 1 1 3

Number of initial d.o.f. : 4 Oooops… Problem!

But wait! Halzen & Martin p. 326 The term $evA_\mu\partial^\mu\xi$ is unphysical

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

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

Gauge fixed to absorb θ

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

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

Massive scalar : The Higgs boson

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

Massive gauge boson

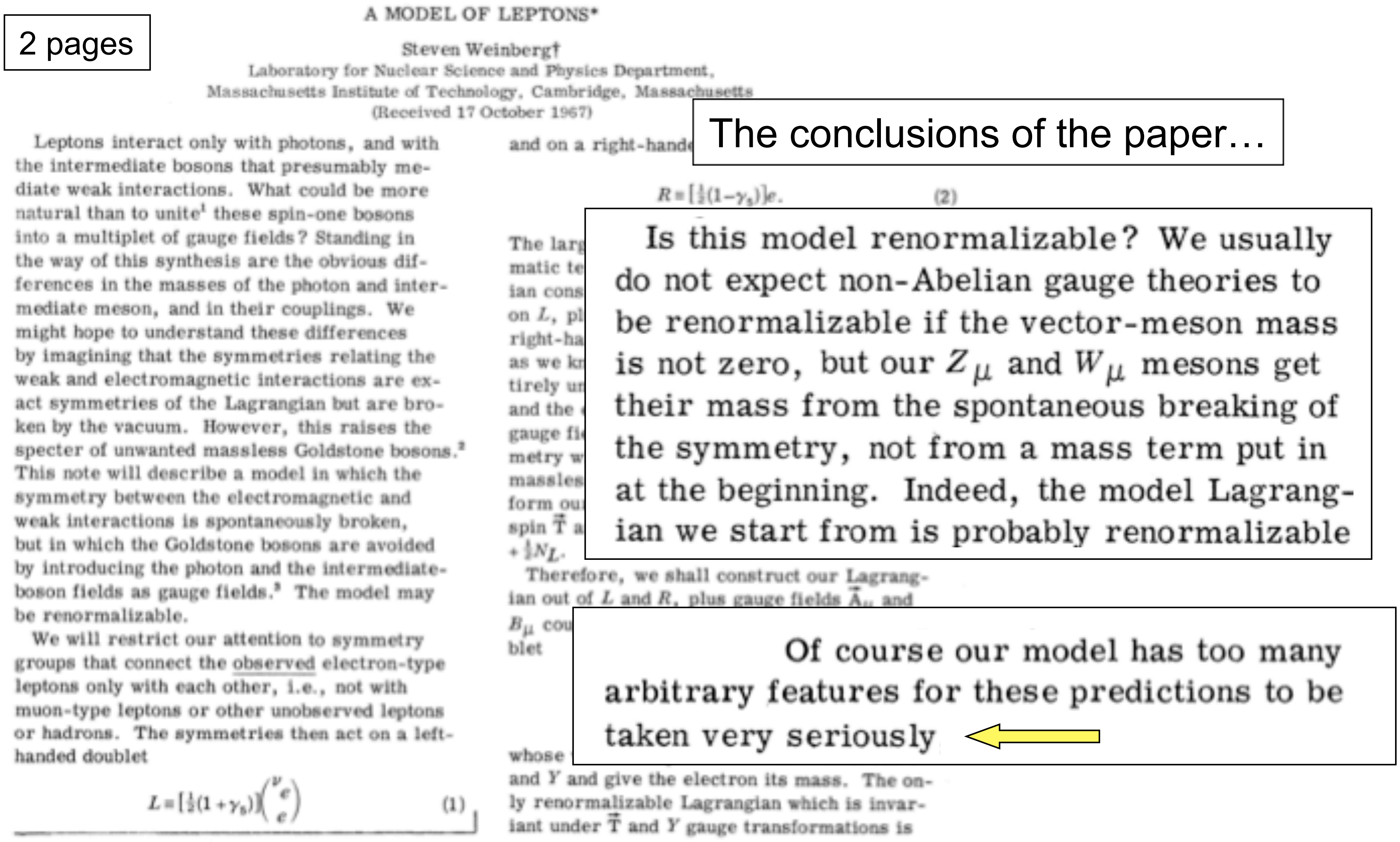
$$+(1/2)e^2A_\mu A^\mu h^2 + ve^2A_\mu A^\mu h$$

Gauge-Higgs interaction

The Goldstone boson does not appear anymore in the Lagrangian

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-hande

The conclusions of the paper…

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

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

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

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

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

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

Milestone PRL 1967

The Weinberg Salam model (classical)

Before applying the Higgs mechanism to the $SU(2)_L \times U(1)$ gauge symmetry

Why $SU(2)_L \times U(1)$? And not $SU(2)_L$ only?

In order to describe the weak and electromagnetic interactions with a unique gauge group, Q the photon should be among the three generators of $SU(2)_L$

… then the electric charges of the multiplets must add up to 0. Which is not the case for the simple electron-neutrino doublet.

The ways out are$_{\text{Cheng and Li p.341}}$:

(i) Add an additional U(1) thus introducing an additional gauge boson

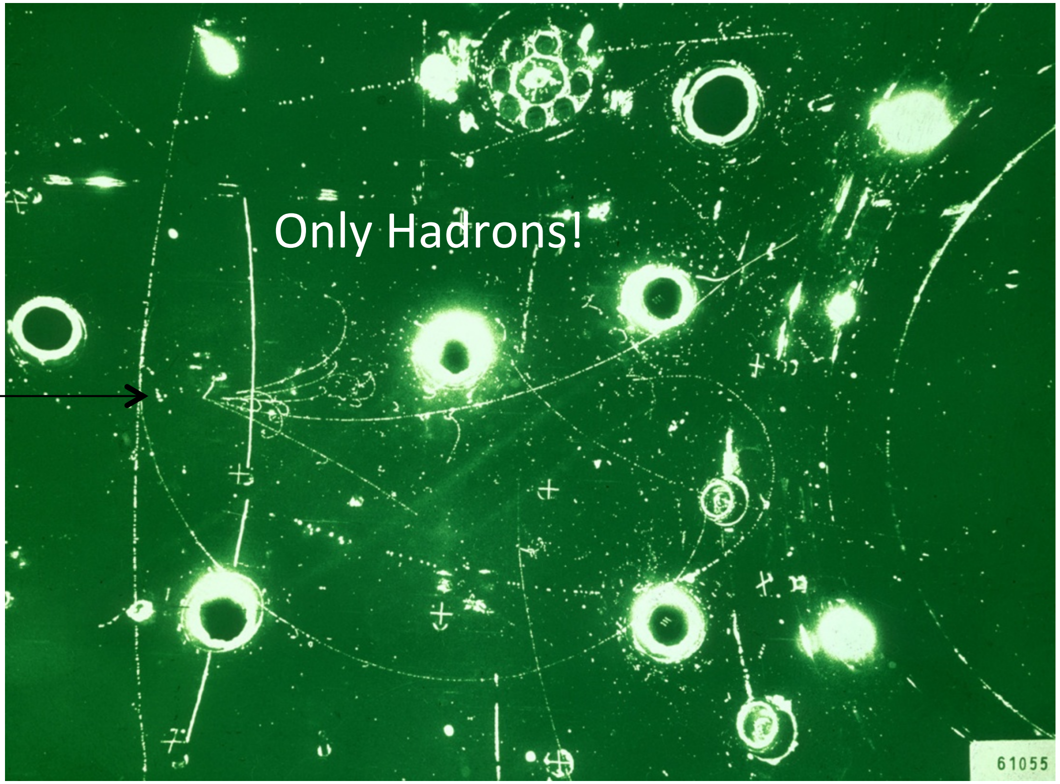
(ii) Add new fermions to form a triplet with charges adding up to 0

Georgi and Glashow followed (ii) in 1972 but their model was ruled out later in 1973 by a major discovery…

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)

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

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi^{+} \\ \phi^{o} \end{pmatrix}$$

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

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

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

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

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

In particular for a non charged vacuum

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

Then developing the covariant derivative for the Higgs field :

Just replacing the Pauli matrices :

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

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

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

For the mass terms only :

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

Explicit mixing of W^3 and B.

Finaly the full Lagrangian will then be written :

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

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

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)

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

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

The sector of Fermions (Fermionic neutral current)

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

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

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 : $g'Y_R = 2g'Y_L$

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 picture is now almost complete…

	Field	I_3	Y	Q	$SU(2)_L x U(1)_Y$	$SU(3)_C$
Leptons	(ν_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

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 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 :

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

Can be seen as giving mass to down type fermions…

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

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

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

... But not necessary.

The experimental crowning glory of the model

1974 - Discovery of the c quark

1975 - Discovery of the tau lepton

1977 - Discovery of the b quark

1979 - Discovery of the gluon

1983 - Discovery of the W and Z bosons

1990 - Determination of the number of light neutrino families

1991 - Precise tests of the internal coherence of the theory and top mass prediction

1993 - Top quark discovery

$$\rho = 1$$

Wilczek$_{\text{LEP celebration}}$: The Higgs mechanism is corroborated at 75%

And since :

1997 - Neutrino Oscillations

1998 – tau neutrino discovery

1975 - CP violation in B's

The Standard Model is experimentally crowned, except…

Where is the expected massive physical state ?

…and what is the (unmentioned) dark matter made of ?

Custodial Symmetry

Turning again to the chiral symmetry which is also a symmetry of the Higgs sector :

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

It is very interesting to note that under the $SU(2)_V$ symmetry, the weak gauge bosons (W^1,W^2,W^3) transform as a triplet

Meaning that after EWSB all W^i's are mass degenerate

This directly implies that $\rho=1$

Under this crucial condition does any Higgs sector work for this purpose?

For N iso-multiplets :

$$\rho = \frac{\sum_{k=1}^{N} v_k^2 [I^k(I^k+1) - (I_3^k)^2]}{\sum_{k=1}^{N} 2 v_k^2 (I_3^k)^2}$$

For the condition to be fulfilled any number of doublets is fine

Higher representations need to fine tune the vevs

Dynamical Symmetry Breaking and Technicolor

Turning yet once again to the chiral symmetry which is also a symmetry of the Higgs sector :

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

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

What have we learned?

Higgs mechanism

- Allows gauge bosons to acquire a mass
- Allows fermion masses
- Interpretation of EW interactions (not unification)
- Enables renormalizability of EW gauge theory

Legitimates $SU(2)_L xU(1)_Y$ as a gauge theory of electroweak interaction which is now known as the Standard Model

In practice : all known processes can be computed in this framework

$$\rho = 1$$

Open questions about the Standard Model

Does the Higgs boson exist?

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 ?

What is dark matter made of?

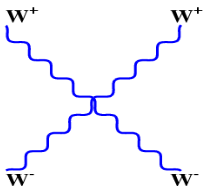
Theoretical Constraints on The Higgs Boson Mass

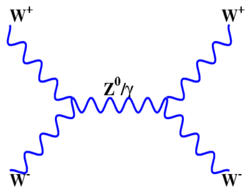
Self consistency arguments to derive lower and upper Higgs boson mass boundaries

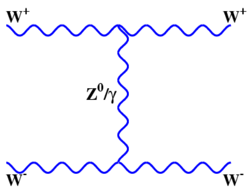
Unitarity or why a Higgs Boson is Highly Desirable

The cross section for the thought scattering process :

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







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 the electroweak interaction should become strong at the TeV scale and one would observe non perturbative effects such as multiple W production, WW resonances… (Technicolor…)

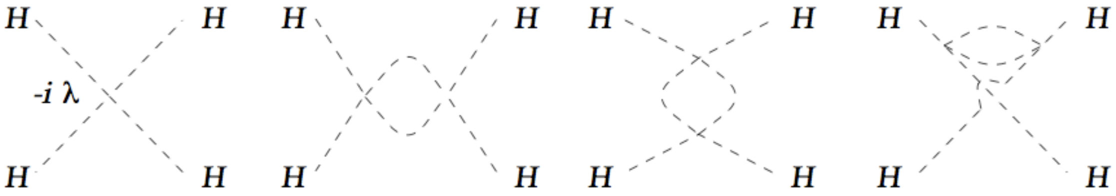
Running Quartic Coupling : Triviality

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

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

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

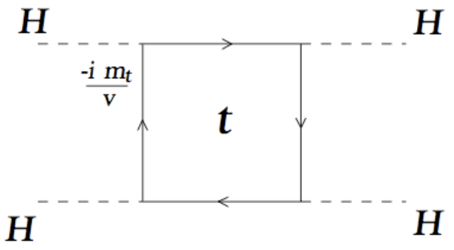
$$\boxed{M_H^2 < \frac{8\pi^2 v^2}{3\log\left(\frac{\Lambda^2}{v^2}\right)}}$$

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 :



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

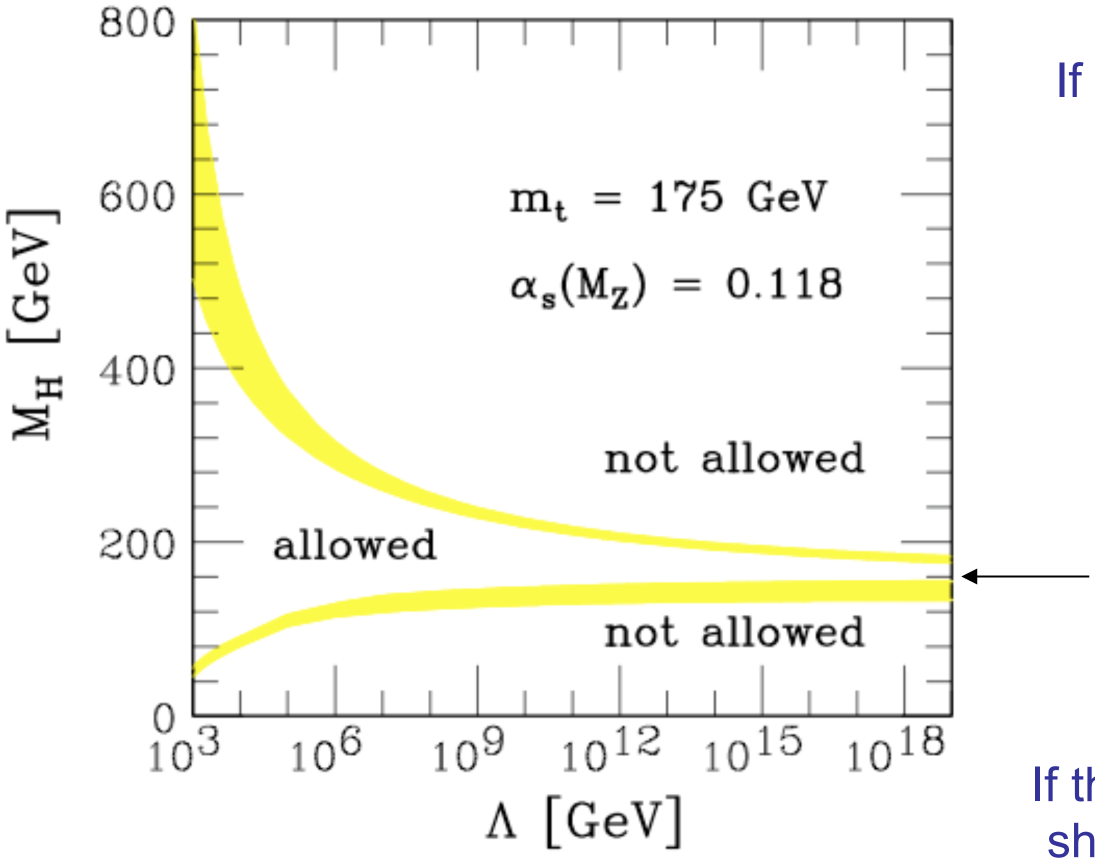
The equation is then very simply solved : $\lambda(\Lambda) = \lambda(v) - \frac{3}{4\pi^2} y_t^2 \log\left(\frac{\Lambda^2}{v^2}\right)$

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

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

Vacuum Stability and Triviality Constraints Summary

More acurate analysis yields :



What do we learn from these constraints?

If a Higgs boson exists it should be found at LHC!

If it is very heavy new physics should occur at a low scale

If the SM is valid at any scale the Higgs mass is quite precisely predicted

If the Higgs is rather light new physics should also be at a rather low energy

However it does not motivate the very existence of a Higgs boson…

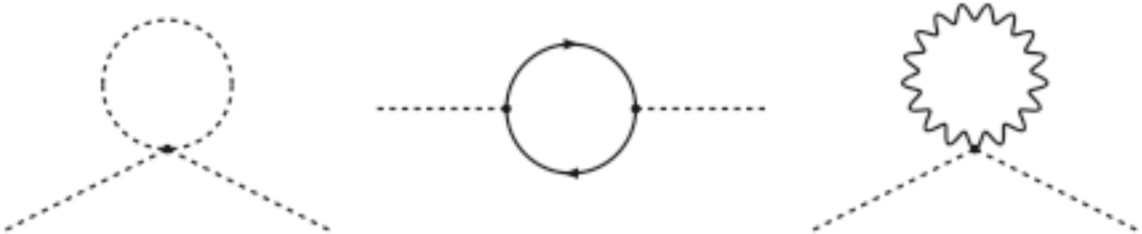
Gauge Hierarchy and Fine Tuning

How the Higgs boson may 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

$$m = m_0 + \Delta m + \ldots$$ Higher orders

…but if the Higgs boson exists it should have 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 :

$$\Delta m_H^2 \sim \frac{|\lambda_f|^2}{16\pi^2}(-2\Lambda^2 + 6m_f^2 \ln\frac{\Lambda}{m_f} + ...) \longrightarrow$$ Contribution of fermions

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

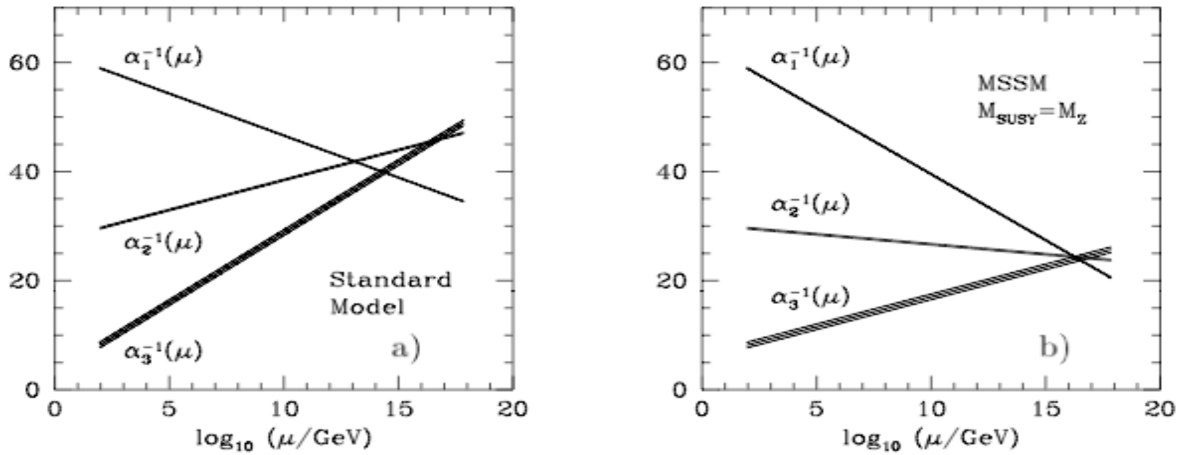
Implies that the m_{soft} should not exceed a few TeV

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 ~140 GeV/c^2 w/ rad. Corr.

The Higgs sector yields the strongest constraints on the MSSM

What have we learned

1.- A Higgs boson is highly desirable for the unitarity of the theory and should have a mass lower than about 1 TeV

2.- If it exists the running of the quartic coupling yields interesting bounds on its mass (triviality and vacuum stability)

3.- The existence of a Higgs boson is a key to investigate theories beyond the standard model (fine tuning)

4.- It highly motivates supersymmetry

5.- It even gives indication on the mass scale of SUSY particles

The Higgs mechanism is yielding way more than what it was initially introduced for

Electroweak Precision Data Indirect Constraints

The LEP and SLC legacies

Experimental Indirect Constraints : Electroweak Precision Data and the Higgs Mass

The standard model has 3 free parameters not counting the Higgs mass and the fermion masses and couplings.

Particularly useful set is :

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

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

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

Determined from muon lifetime

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

Measured from the Z lineshape scan at LEP

Experimental Constraint : Electroweak Precision Data and the Higgs Mass

Taking the hypothesis of a Minimal Standard Model, the radiative corrections to numerous observables can be computed in order to assess the impact of certain particles e.g. the Higgs boson

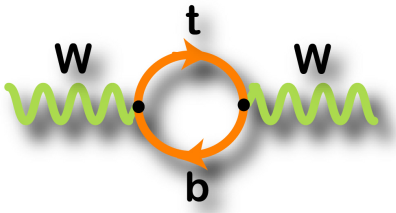
From the measurement of these observables a constraint is derived

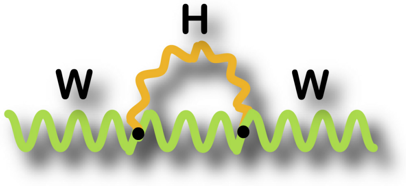
For example the corrections to the Fermi coupling constant can be written as :

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

With :

$$\begin{cases} \Delta r_t \propto m_t^2 \\ \underline{\Delta r_H \propto \log(m_H/m_W)} \end{cases}$$





Essential ingredients top, W and Z masses and α_{QED}

The Complete Data

Parameter	Input value	Free in fit	Results from global EW fits:		*Complete fit w/o exp. input in line*
			Standard fit	*Complete fit*	
M_Z [GeV]	91.1875 ± 0.0021	yes	91.1874 ± 0.0021	91.1878 ± 0.0021	$91.1951\,^{+0.0136}_{-0.0112}$
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4958 ± 0.0015	2.4955 ± 0.0014	2.4952 ± 0.0016
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	–	41.478 ± 0.014	$41.477\,^{+0.016}_{-0.013}$	41.470 ± 0.015
R^0_ℓ	20.767 ± 0.025	–	20.743 ± 0.018	20.741 ± 0.017	$20.717\,^{+0.027}_{-0.008}$
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	–	0.01637 ± 0.0002	$0.01627\,^{+0.0002}_{-0.0001}$	$0.01620\,^{+0.0002}_{-0.0001}$
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	–	$0.1477^{+0.0009}_{-0.0008}$	$0.1473^{+0.0008}_{-0.0006}$	–
A_c	0.670 ± 0.027	–	$0.6682\,^{+0.00042}_{-0.00035}$	$0.6680\,^{+0.00037}_{-0.00028}$	$0.6680\,^{+0.00034}_{-0.00030}$
A_b	0.923 ± 0.020	–	$0.93468\,^{+0.00008}_{-0.00007}$	$0.93463\,^{+0.00007}_{-0.00005}$	0.93466 ± 0.00005
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	–	$0.0740\,^{+0.0005}_{-0.0004}$	$0.0738\,^{+0.0005}_{-0.0003}$	0.0738 ± 0.0004
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	–	$0.1036\,^{+0.0007}_{-0.0006}$	$0.1032\,^{+0.0006}_{-0.0005}$	$0.1037\,^{+0.0003}_{-0.0005}$
R^0_c	0.1721 ± 0.0030	–	0.17223 ± 0.00006	0.17223 ± 0.00006	0.17223 ± 0.00006
R^0_b	0.21629 ± 0.00066	–	0.21474 ± 0.00003	0.21474 ± 0.00003	0.21474 ± 0.00003
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	–	$0.23144\,^{+0.00010}_{-0.00013}$	$0.23150\,^{+0.00008}_{-0.00011}$	$0.23145\,^{+0.00012}_{-0.00006}$
M_H [GeV] $^{(\circ)}$	95% CL limits	yes	$94^{+25[+59]}_{-22[-41]}$	–	$94^{+25[+59]}_{-22[-41]}$
M_W [GeV]	80.385 ± 0.015	–	$80.380\,^{+0.011}_{-0.012}$	$80.370\,^{+0.006}_{-0.007}$	$80.360\,^{+0.014}_{-0.012}$
Γ_W [GeV]	2.085 ± 0.042	–	2.092 ± 0.001	2.092 ± 0.001	2.092 ± 0.001
$\overline{m}_c$ [GeV]	$1.27\,^{+0.07}_{-0.11}$	yes	$1.27\,^{+0.07}_{-0.11}$	$1.27\,^{+0.07}_{-0.11}$	–
$\overline{m}_b$ [GeV]	$4.20\,^{+0.17}_{-0.07}$	yes	$4.20\,^{+0.17}_{-0.07}$	$4.20\,^{+0.17}_{-0.07}$	–
m_t [GeV]	173.2 ± 0.9	yes	173.2 ± 0.9	173.4 ± 0.8	$175.1\,^{+3.3}_{-2.4}$
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$ $^{(\dagger\triangle)}$	2757 ± 10	yes	2757 ± 11	2756 ± 11	2728^{+51}_{-50}
$\alpha_s(M_Z^2)$	–	yes	$0.1192\,^{+0.0028}_{-0.0027}$	0.1191 ± 0.0028	0.1191 ± 0.0028
$\delta_{\rm th} M_W$ [MeV]	$[-4, 4]_{\rm theo}$	yes	4	4	–
$\delta_{\rm th} \sin^2\theta^\ell_{\rm eff}$ $^{(\dagger)}$	$[-4.7, 4.7]_{\rm theo}$	yes	4.7	1.5	–

$^{(\star)}$Average of LEP ($A_\ell = 0.1465 \pm 0.0033$) and SLD ($A_\ell = 0.1513 \pm 0.0021$) measurements. The *complete fit* w/o the LEP (SLD) measurement gives $A_\ell = 0.1474\,^{+0.0006}_{-0.0007}$ ($A_\ell = 0.1469 \pm 0.0006$). $^{(\circ)}$In brackets the 2σ. $^{(\dagger)}$In units of 10^{-5}. $^{(\triangle)}$Rescaled due to α_s dependency.

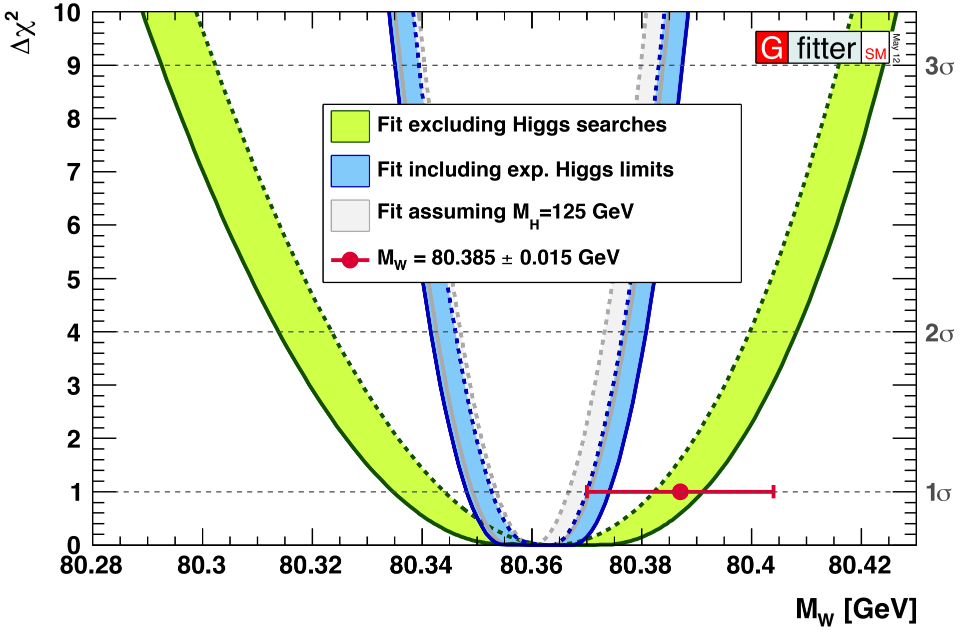
- Numerous observables O(40)

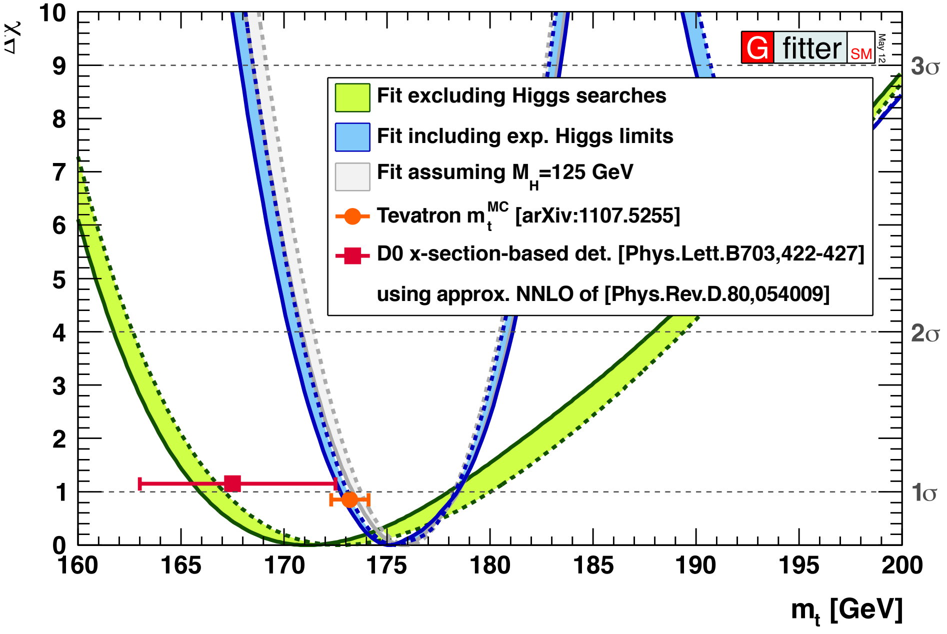
- Numerous experiments (with different systematics)

- Within experiments numerous analyses (with different systematics)

- Various theoretical inputs

W and Top quark mass measurements





Precision of ~0.02%

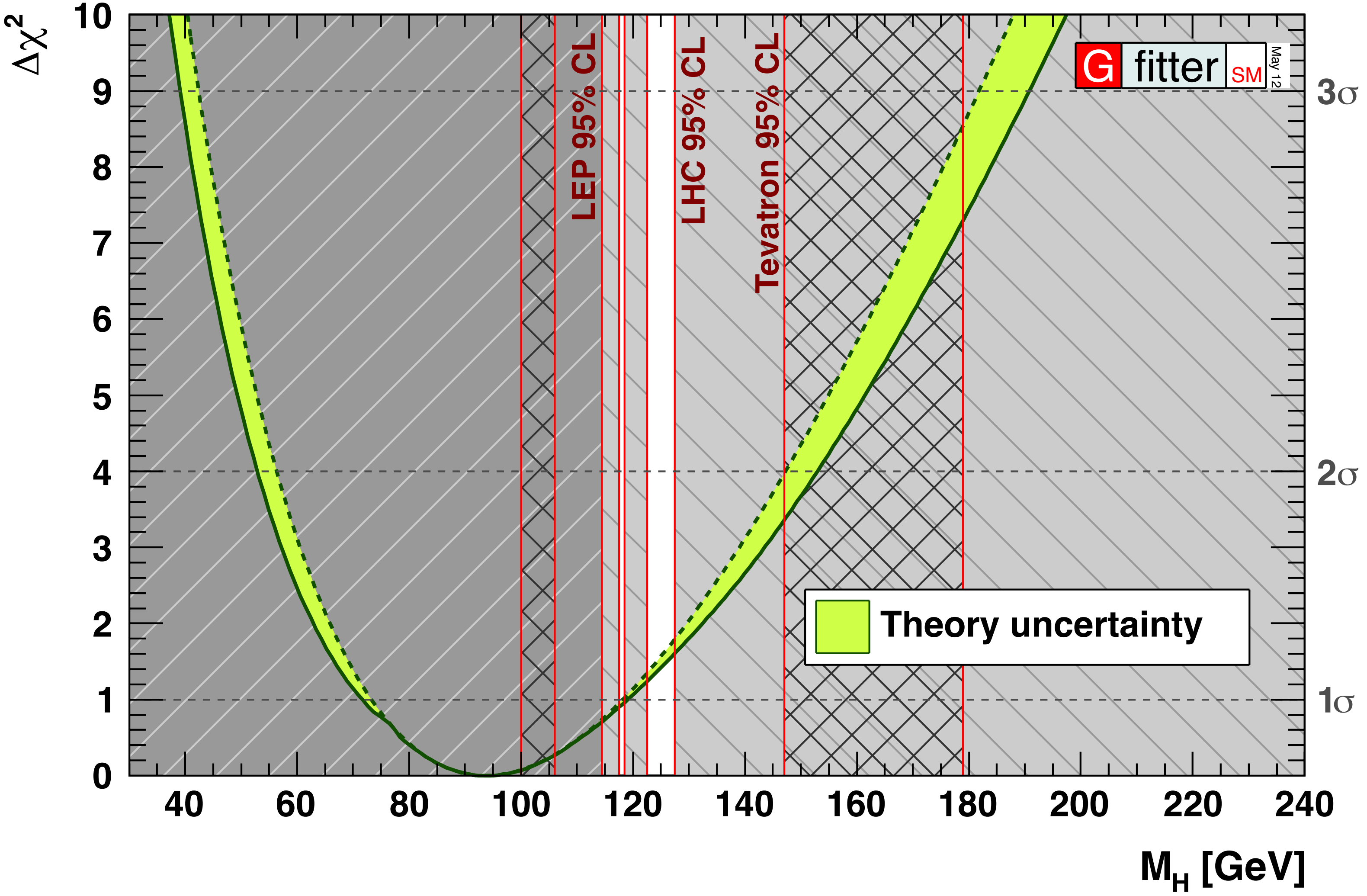
- TeVatron reached ~15 MeV
- LHC should reach ~15 MeV or better

Precision of ~0.8%

-TeVatron is aiming at ~ 0.9 GeV

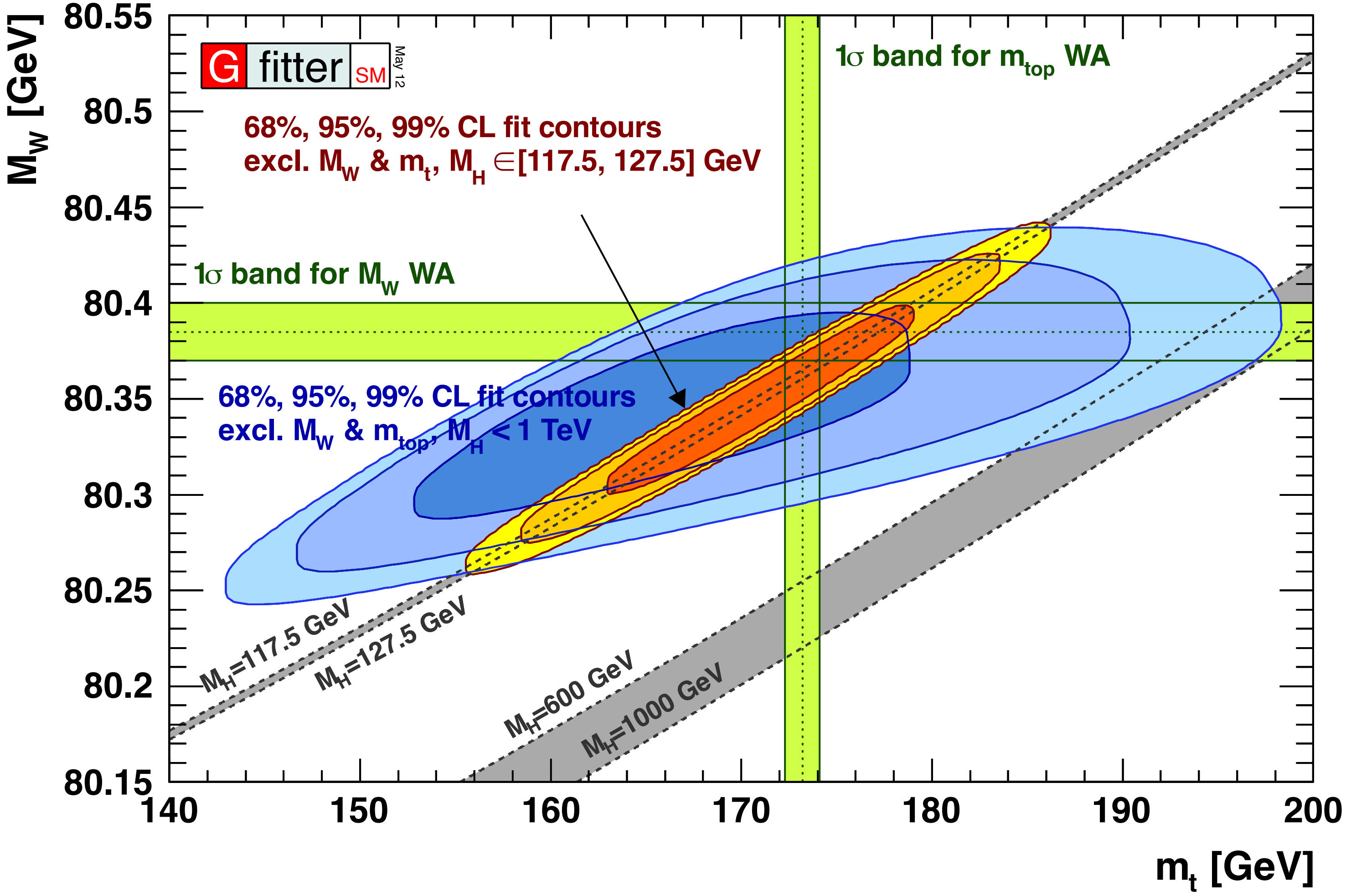
- Not so clear that LHC will be able to do much better.

Indirect Measurement of Higgs Boson Mass



M_H [GeV] $^{(\circ)}$	95% CL limits	yes	$94^{+25[+59]}_{-22[-41]}$	–	$94^{+25[+59]}_{-22[-41]}$

Indirect Measurement of Higgs Boson Mass



M_H [GeV] $^{(\circ)}$	95% CL limits	yes	$94^{+25[+59]}_{-22[-41]}$	–	$94^{+25[+59]}_{-22[-41]}$

The Economist

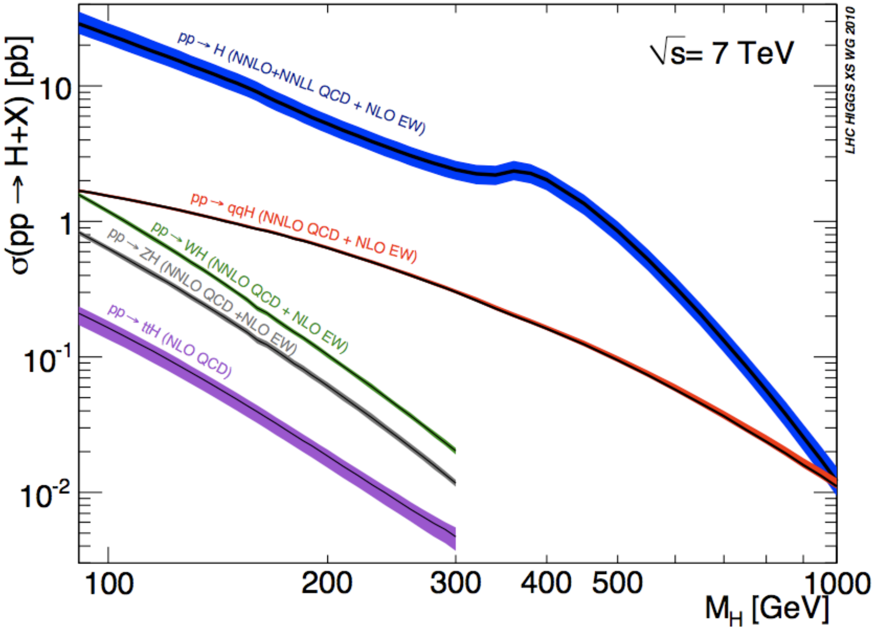
The Discovery!

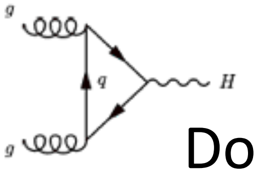
A Giant Leap For Science!

NASA/masterfile

The Main Production Modes at the LHC

Data driven background estimates legitimate use of NNLO cross sections!

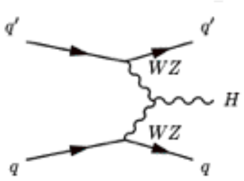




- Gluon fusion process :

Dominant process known at

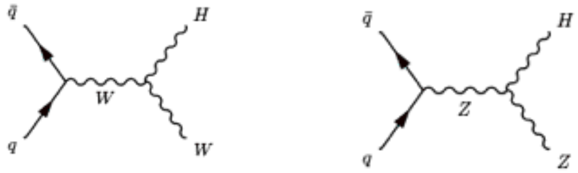
~200 kEvts produced at 125 GeV



- Vector Boson Fusion :

known at NLO TH uncertainty ~O(5%)

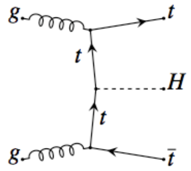
Rather distinctive features w/ two conspicuous forward jets and a rapidity gap



- Associated Production with W and Z :

known at NNLO TH uncertainty ~O(5%)

Very distinctive feature with a Z or W decaying leptonically



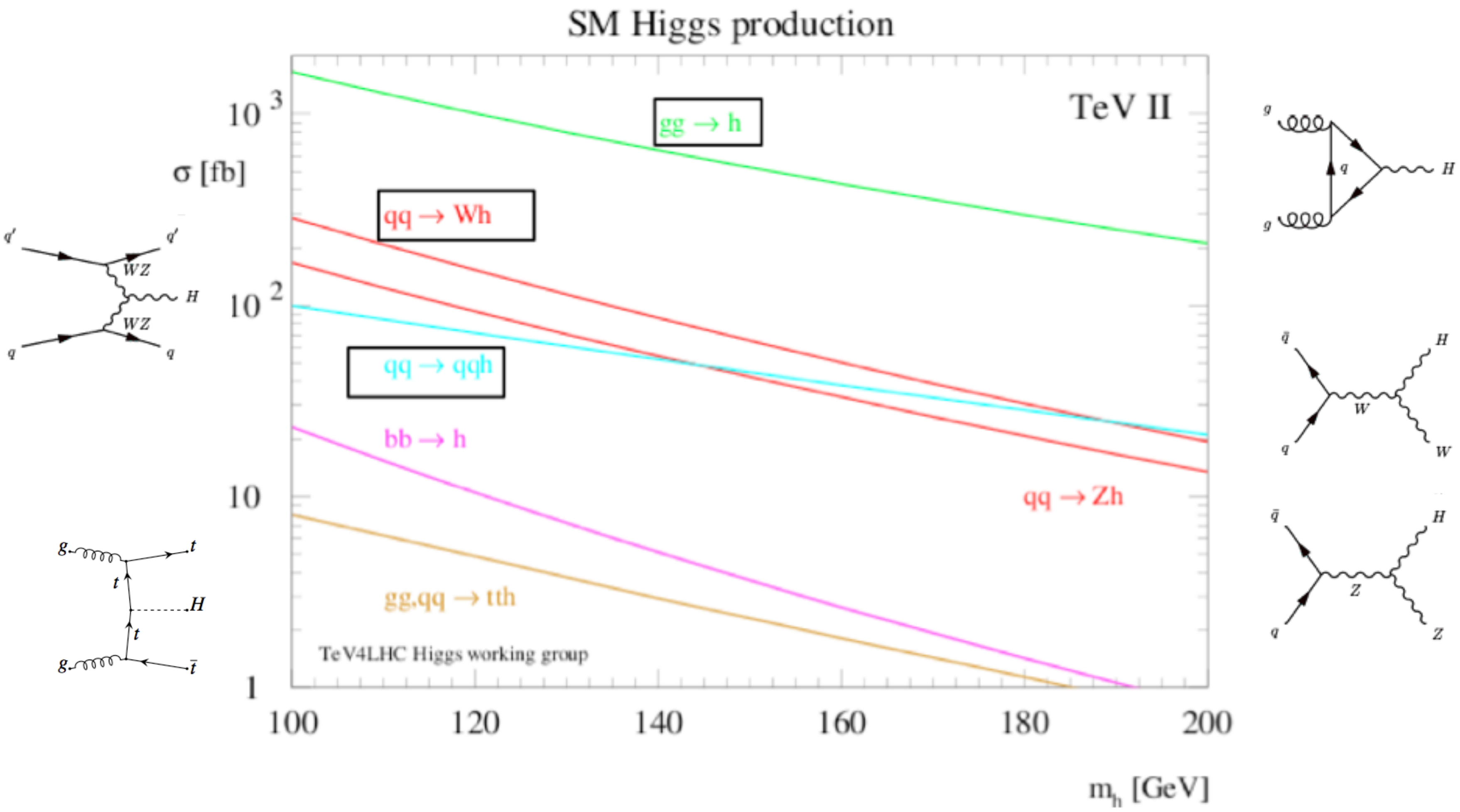
- Associated Production with top pair :

known at NLO TH uncertainty ~O(15%)

Quite distinctive but also quite crowded

* TH uncertainty mostly from scale variation and PDFs, $\delta\sigma_{\text{PDF-}\alpha s}$~8-10% and $\delta\sigma_{\text{Scale}\sim}$ 7-8%

The Main Production Modes at TeVatron



~factor 10 less gluon fusion than at LHC
VH production is second production process, better S/B than at LHC (ppbar vs pp)

Decay Modes

Exclusive Modes Cross Sections

- The dominant b-decay channel

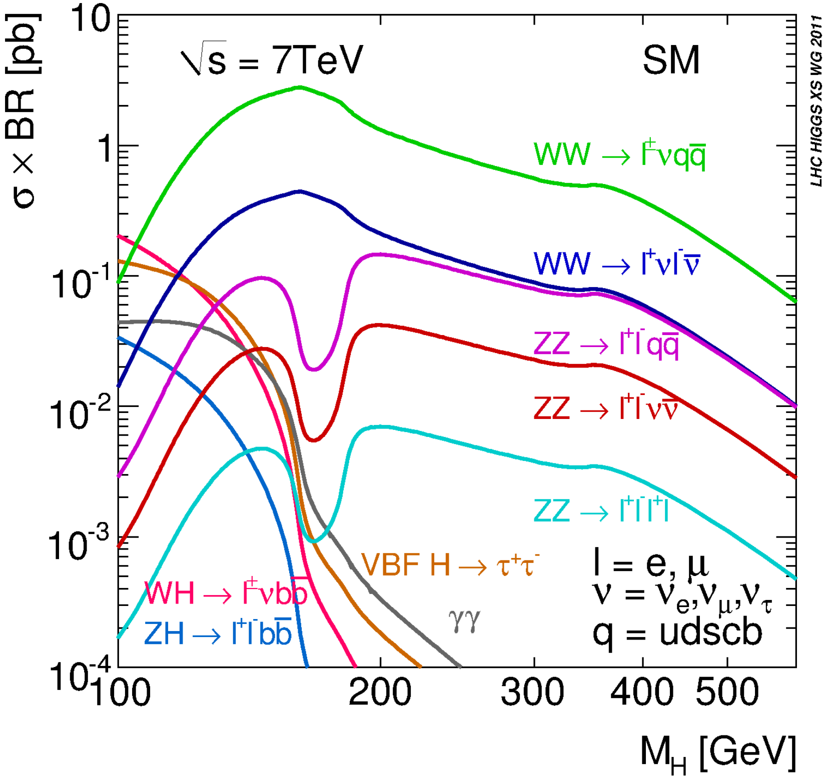
Huge backgrounds, needs distinctive features at production level and beyond… Associate production W,Z H and Boost!

- The ττ channel

Also needs distinctive production features, typically VBF or VH. Hopes from NEW MASS RECOSTRUCTION techniques

- The γγ channel

Dominant Channel in the very low mass range. Small branching but sizable yield. Very distinctive signature on its own.



- The WW Channels

- Dilepton (lnln) channel is dominant in the low mass (very poor mass resolution, essentially counting experiment)
- Semi leptonic (lnqq) largest event yield effective at large mass where the background is smaller.

- The ZZ Channels

- 4-leptons : "Golden mode" smallest event yield but large s/b ratio
- semi-leptonic (llqq) larger event yield but also much larger background (make use of the large branching Z in bb)
- 2-leptons 2-neutrinos (llnn) : Best compromise yield/purity. Dominant channel at high mass

Production Modes and Decay Channels at LHC

Channel		ggF	VBF	W,Z H	ttH	Range (GeV)
γγ		✓	✓	✓	✓	110-150
ττ		✓	✓			110-140
W,Z H (bb)				✓		110-130
ZZ (llll)		✓	✓			110-130
WW (lνlν)	0-jet	✓				110-600
	1-jet	✓	✓			110-600
	VBF	✓	✓			110-600
	WH*	✓		✓		110-200
WW** (lνqq)	0-jet	✓	✓			300-600
	1-jet	✓	✓			300-600
	VBF		✓			300-600
ZZ (llνν)		✓	✓			110-600
ZZ (llττ)*		✓	✓			200-600
ZZ (llqq)		✓	✓			130*-600

* CMS only / ** ATLAS only

Low Mass : Challenging Range

110 -150 GeV/c^2

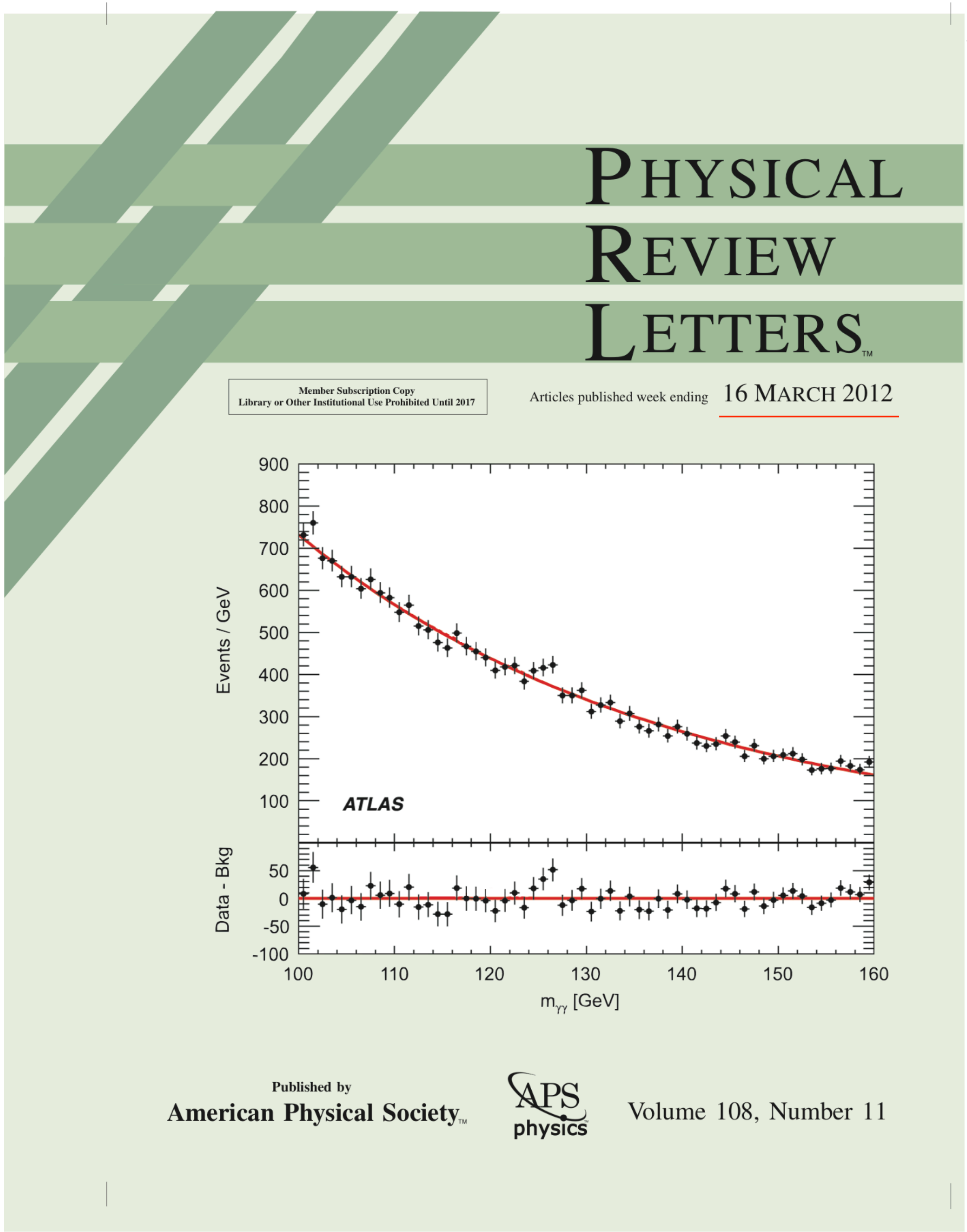
Intermediate : Wide Range

110 - 600 GeV/c^2

High Mass : Larger contribution from VBF

200 - 600 GeV/c^2

Not theory difficulties above 500 GeV/c^2



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Volume 108, Number 11

How to read Higgs Search Plots…

Starting from PRL Cover Plot

Statistical Interpretation

How to read Higgs Search Plots

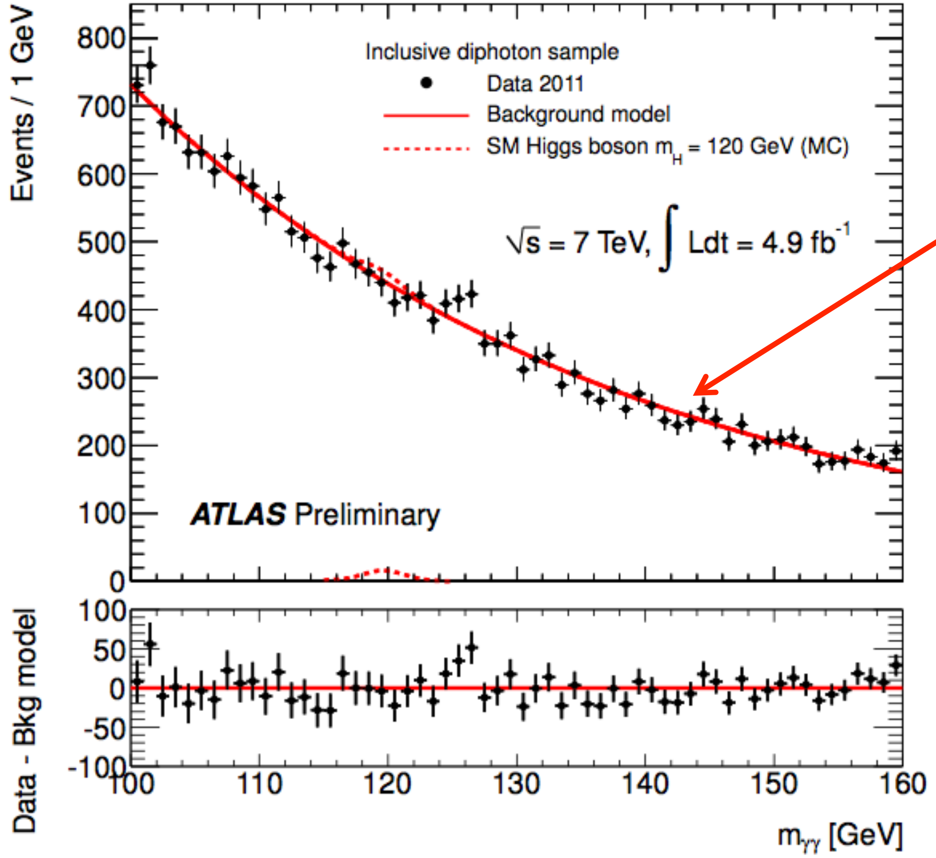
Hypothesis testing using the

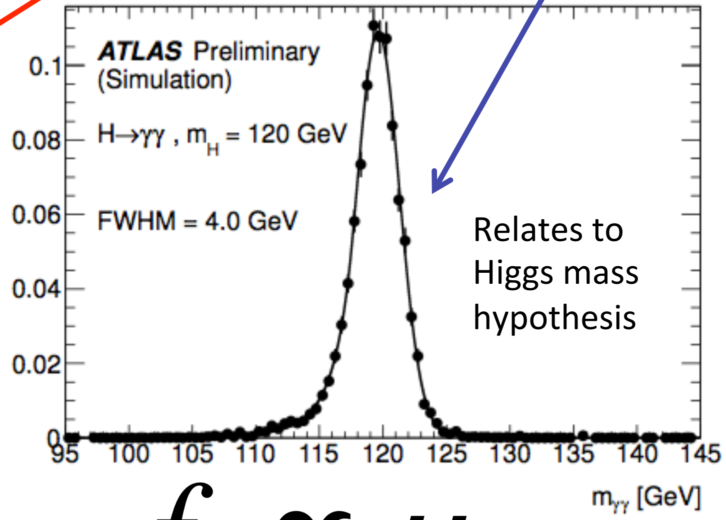
Profile likelihood ratio…

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

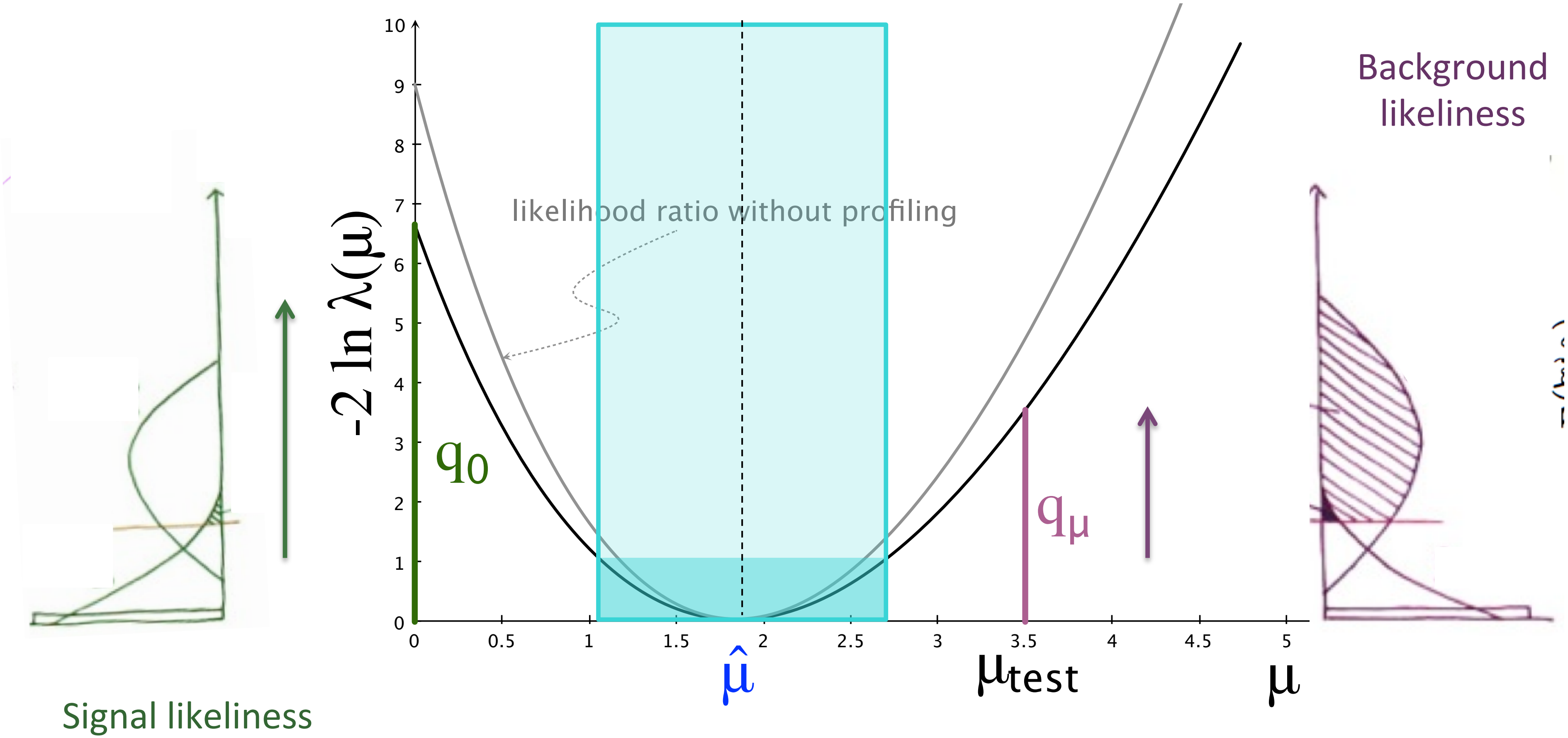
$$f_s \propto \mu$$

Global coherent factor

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

How to Read Higgs Exclusion Limits Plots

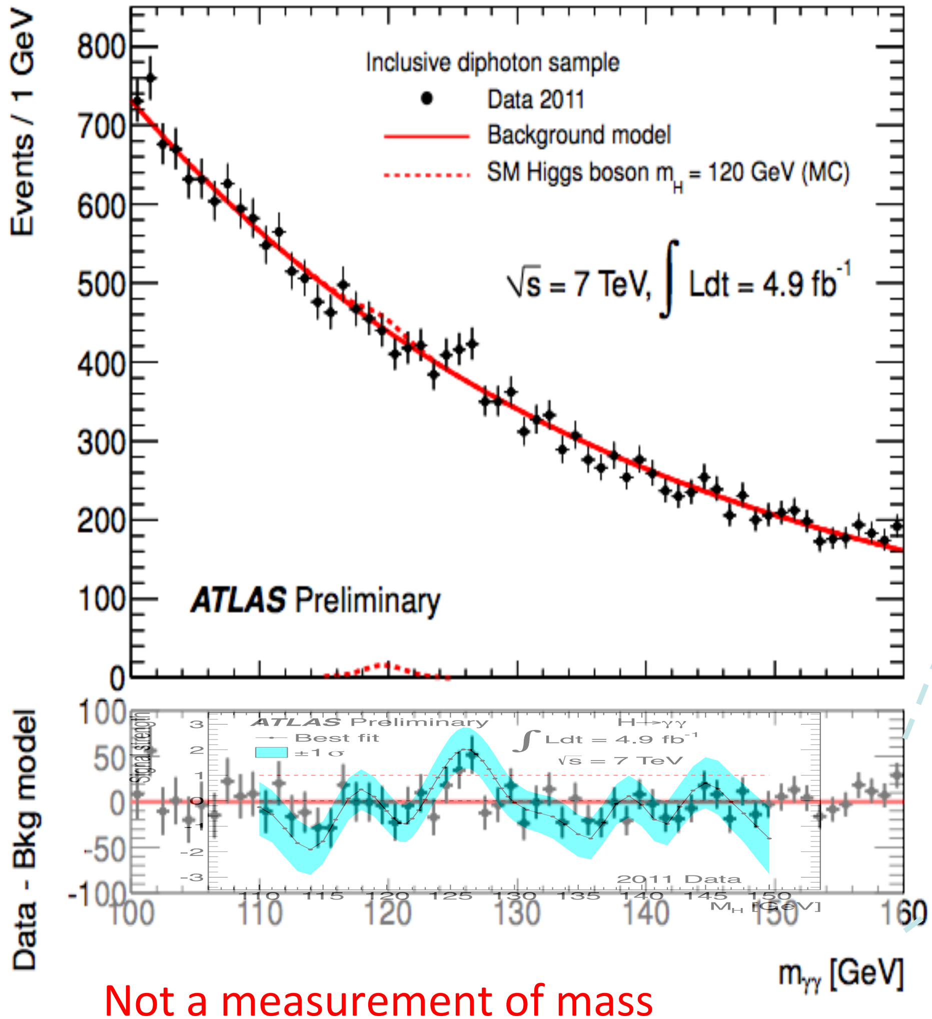
$$\lambda_\mu = \lambda(\mu,\theta) = \frac{L(\mu,\hat{\hat{\theta}}(\mu))}{L(\hat{\mu},\hat{\theta})} \qquad q_\mu = -2\ln\lambda_\mu$$



Statistical Interpretation

How to read Higgs Search Plots

Hypothesis testing using the Profile likelihood ratio…



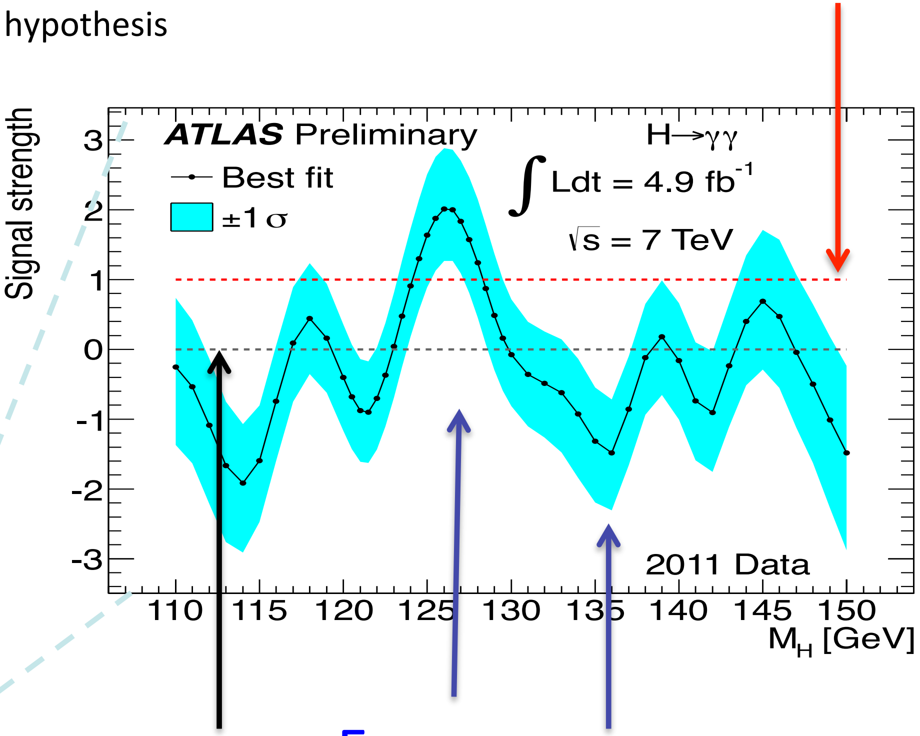
Not a measurement of mass

Not a measurement of cross section

$$\hat{\mu}$$

Relate to Higgs mass hypothesis

Expected Signal

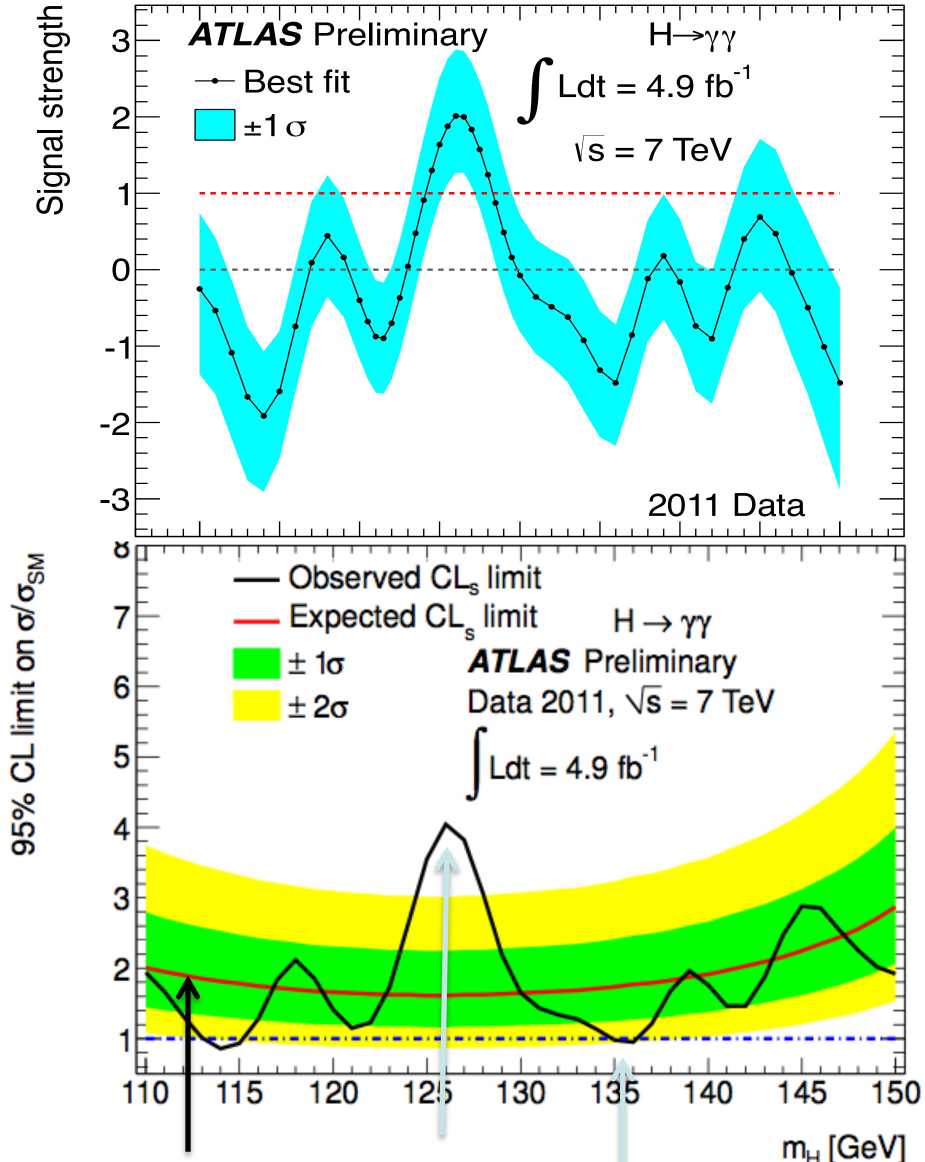


Expected Background

Excess

Deficit

How to Read Higgs Exclusion Limits Plots



Expected
Backgroun

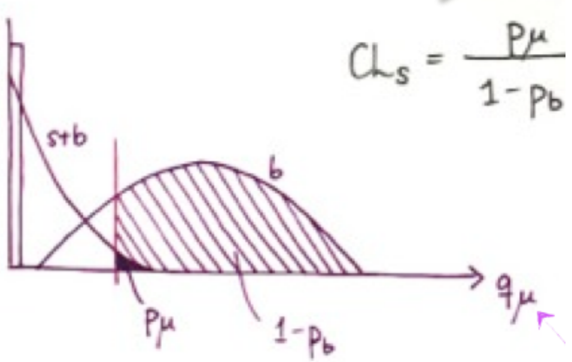
Excess

Deficit

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

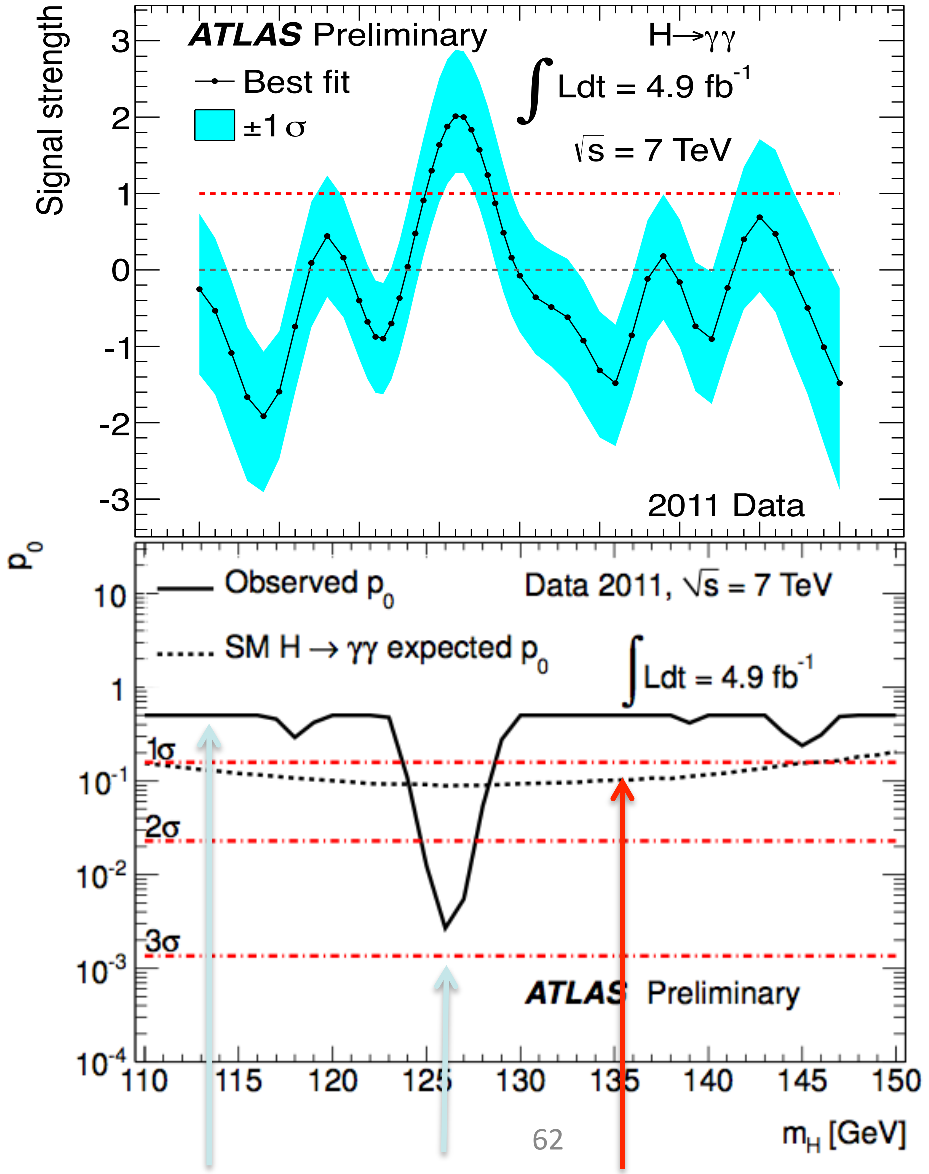
$$q_\mu = -2\ln\lambda_\mu$$

Background likeliness →



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

How to Read Higgs Observation Estimates



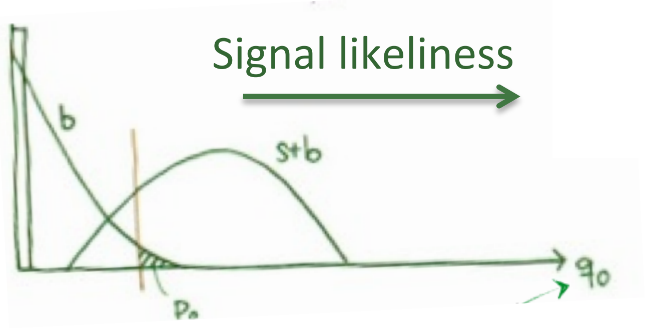
Deficit

Excess

Expected Signal

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

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

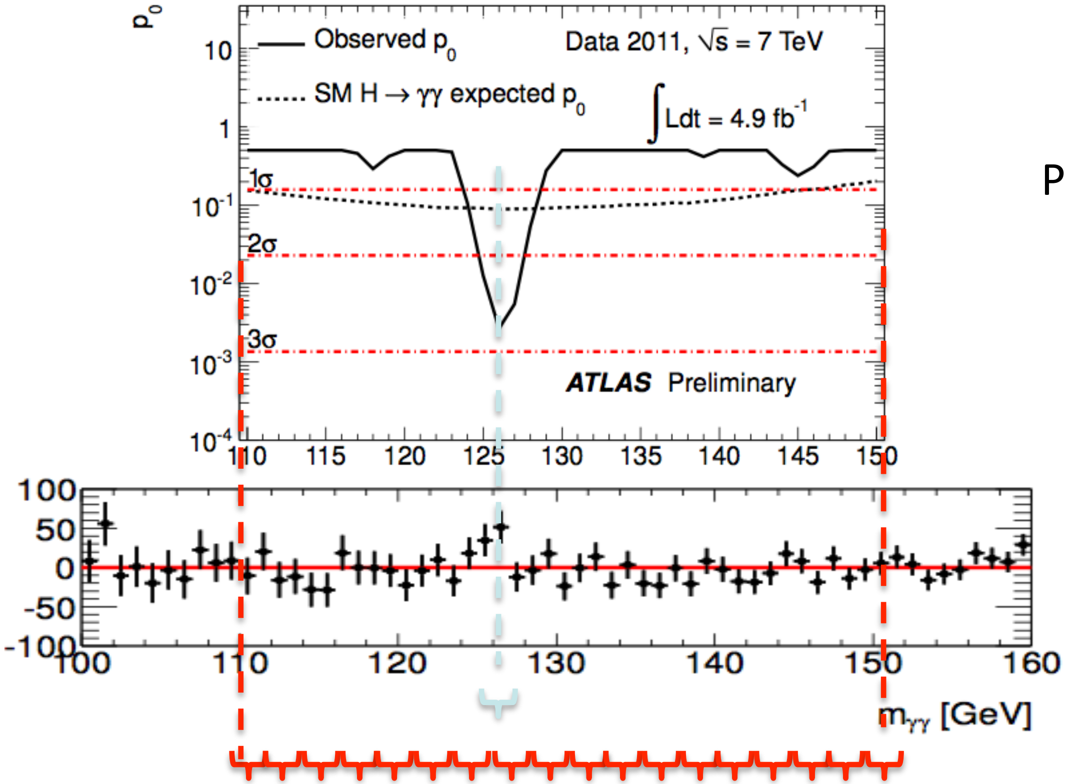


p_0 Probability that a background only experiment be more signal like than observed

Local vs. Global Probability

Look Elswhere Effect

(over)Simplified View



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

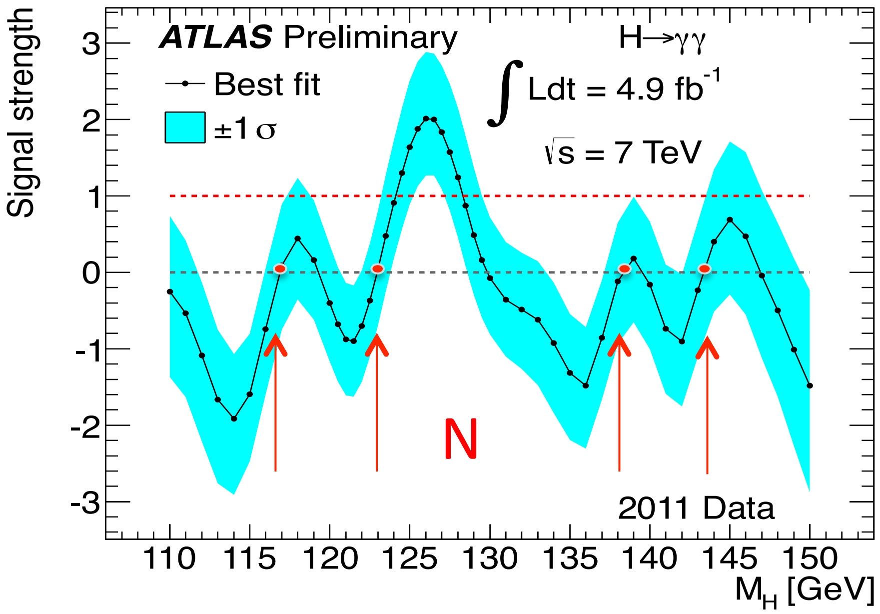
What is the probability of observing an excess at least as large as observed within a mass range ?

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)

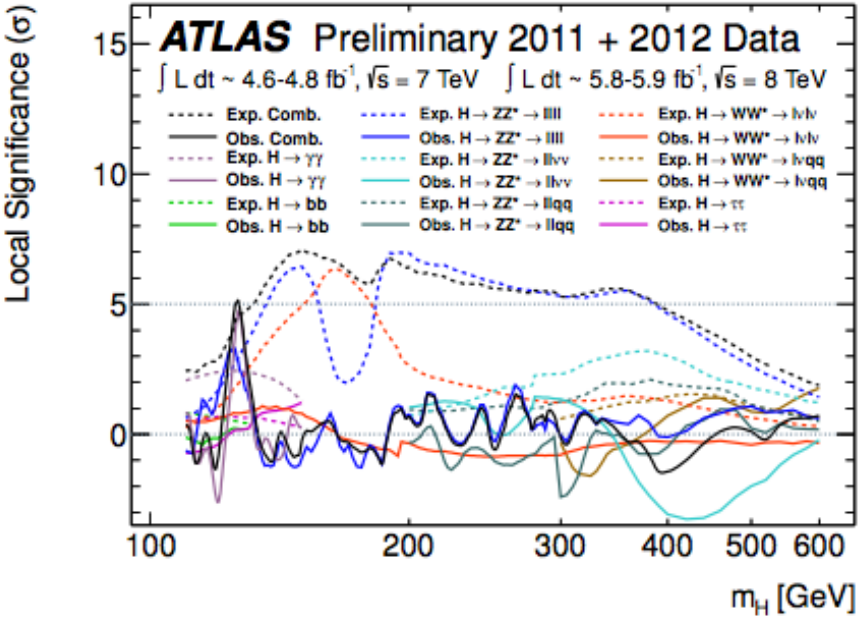
$$p_{global} = p_{local} + N \times e^{-\frac{Z^2}{2}}$$

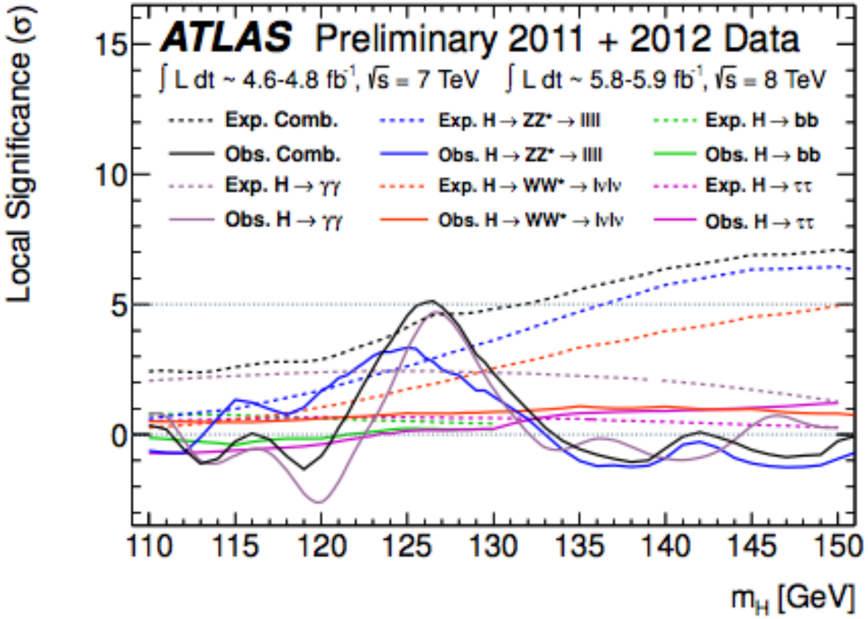
Trial factor ~ Here the dependence is explicit…

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

All Channels at the LHC

Selected Topics…





$$H \to \gamma\gamma$$

Most sensitive Channel in [115-125] GeV Mass range

ATLAS 4.8 – 5.9 fb^{-1}

CMS 4.8 – 5.3 fb^{-1}

Signal yield after cuts (low mass) ~O(200)

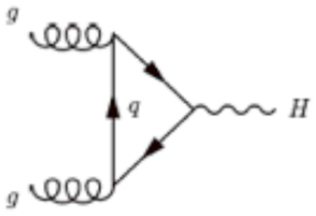
s/b ~ 1.5% to O(15)% depending on category

DiPhoton Channel

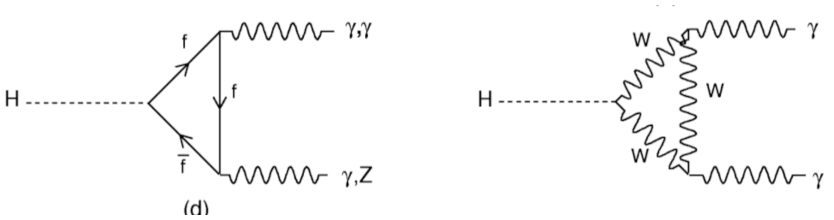
Common Misconceptions and Basic Facts

- Small branching… but amongst largest yields (Dominant Channel in the very low mass range 110-125 GeV)

- Main production and decay processes occur through loops :



A priori potentially large enhancement…



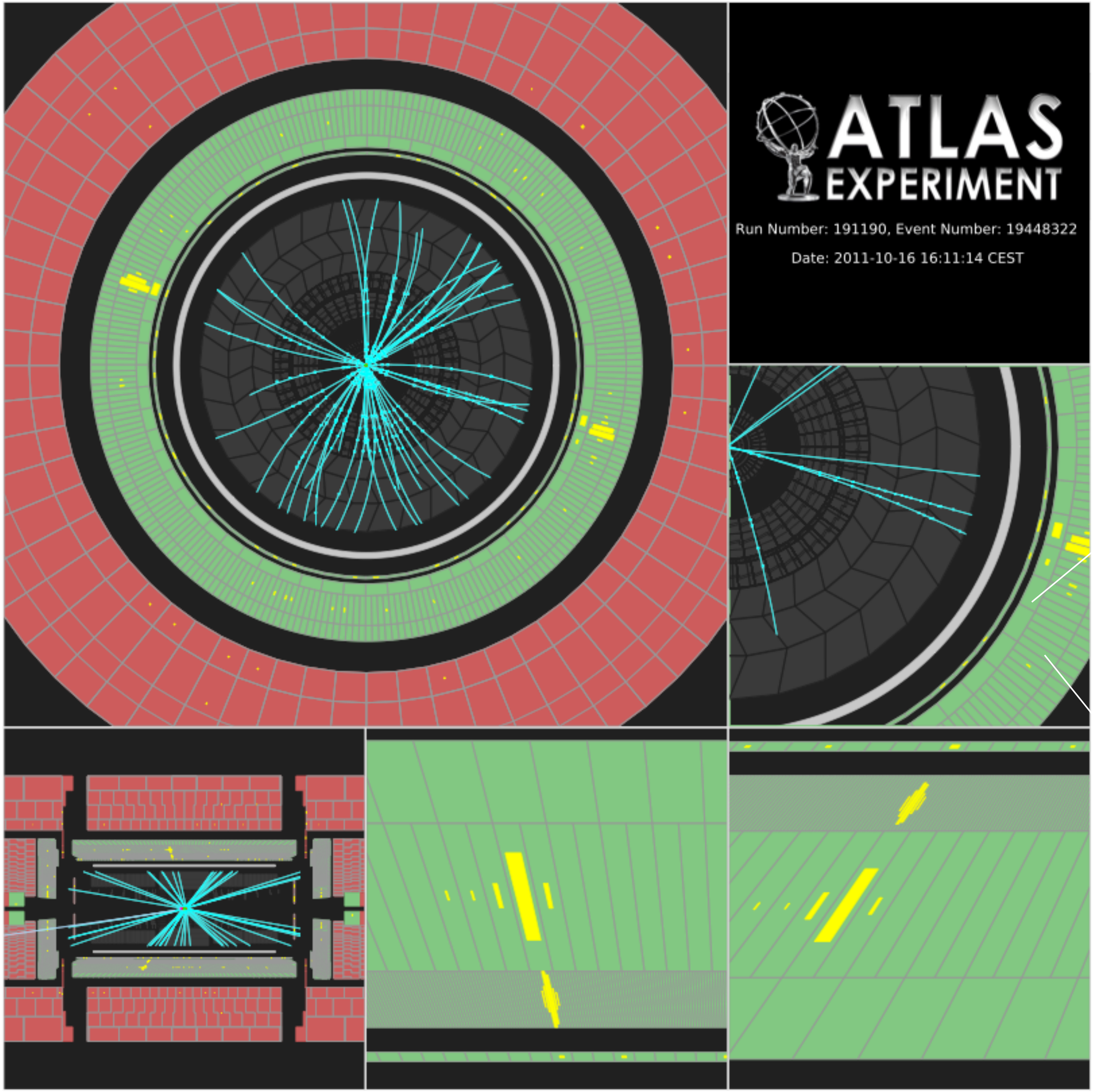
… Not so obviously enhanced (e.g. SUSY, SM4)

Still e.g. NMMSSM (U. Ellwanger Phys.Lett. ***B 698****, 293-296,2011) up to x6 at low masses, Fermiophobia…*

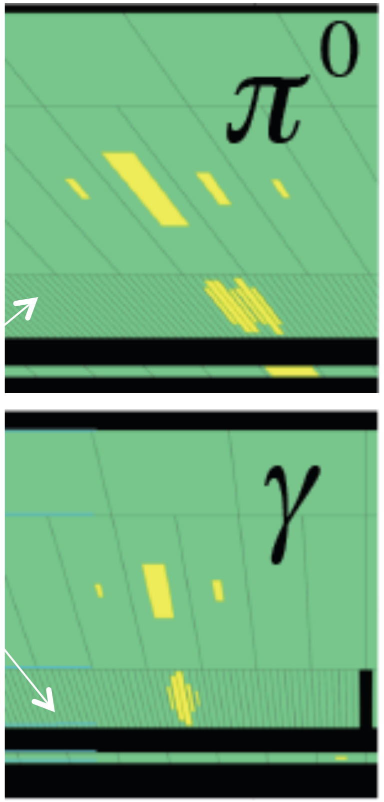
- If observed implies that it does not originate from spin 1 : Landau-Yang theorem

L. Landau, Dokl. Akad. Nauk. , USSR **60**, 207 (1948) and C. N. Yang, Phys. Rev. **77**, 242 (1950).

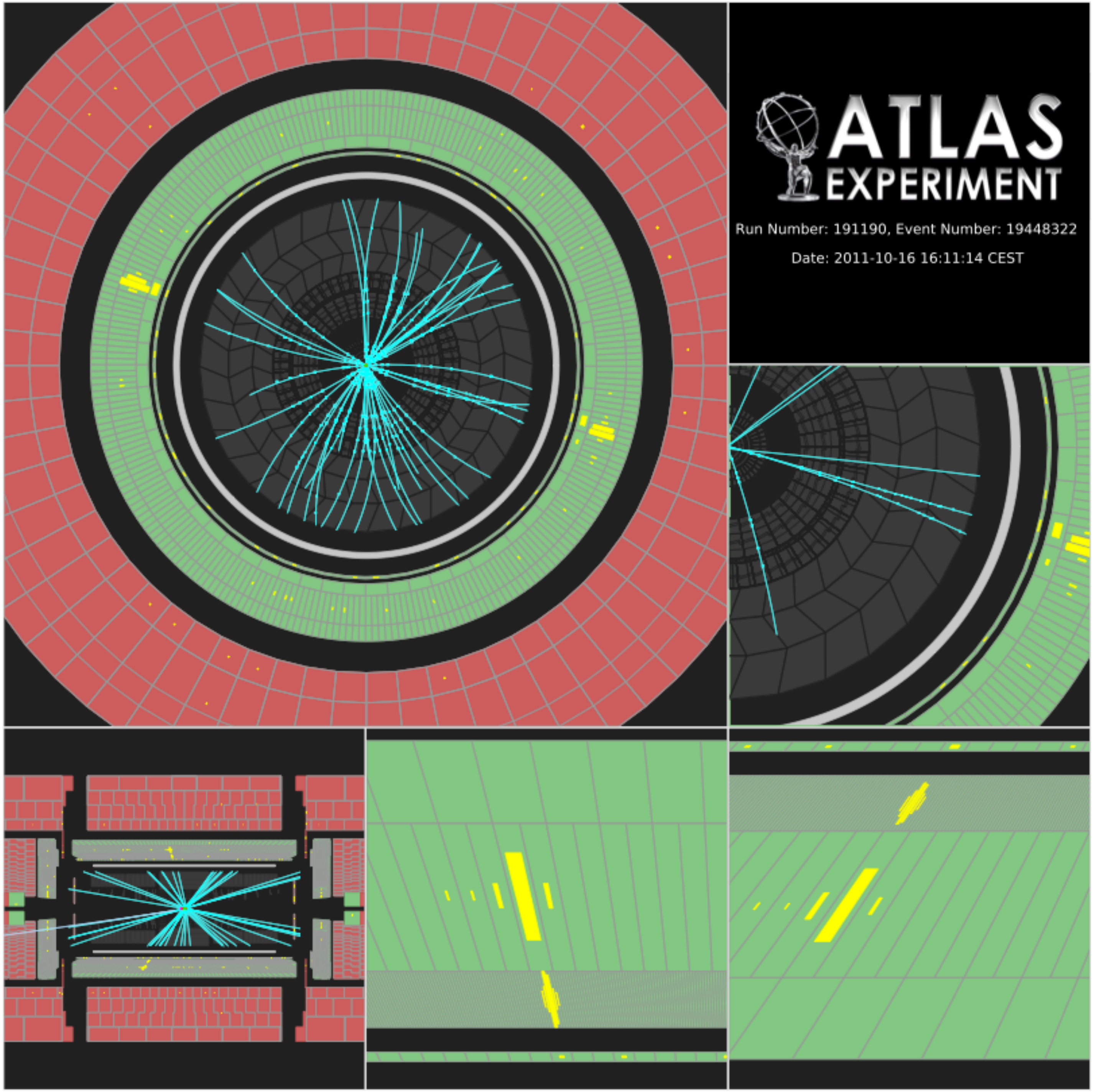
- Extremely simple event selection : two photons 25/40 GeV (ATLAS) and M-dependent cut (CMS)

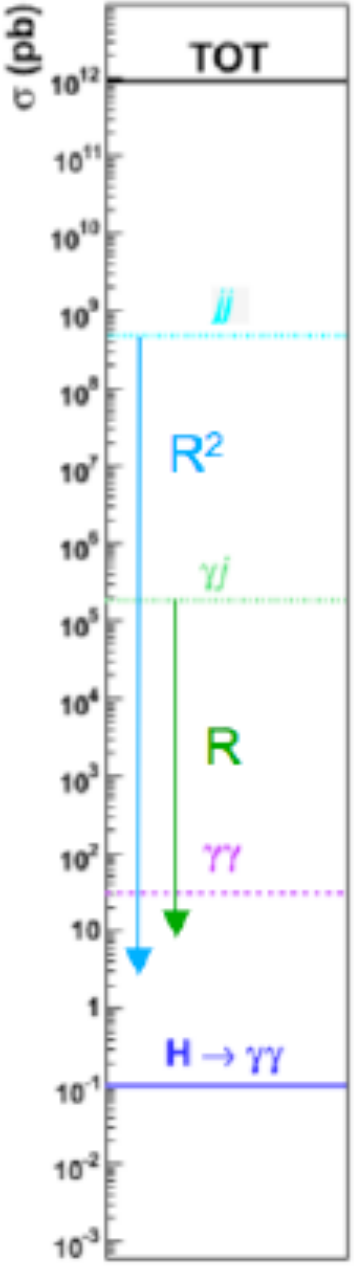


Background
From jets



Signal


ATLAS EXPERIMENT
Run Number: 191190, Event Number: 19448322
Date: 2011-10-16 16:11:14 CEST


σ (pb)
TOT
jj
R^2
γj
R
$\gamma\gamma$
$H \to \gamma\gamma$
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10
1
10^{-1}
10^{-2}
10^{-3}

R ~ O(8000)

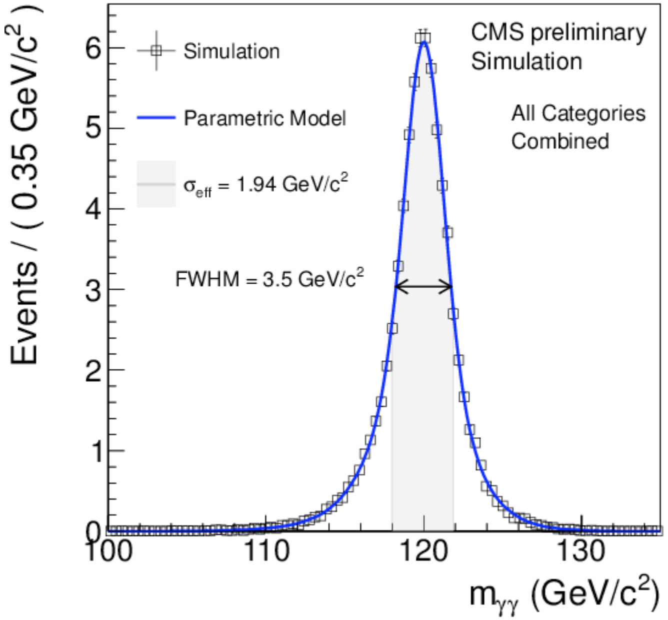
Key features :

- Background rejection… but also…
- Invariant mass resolution
  - Energy response
  - Interaction vertex position

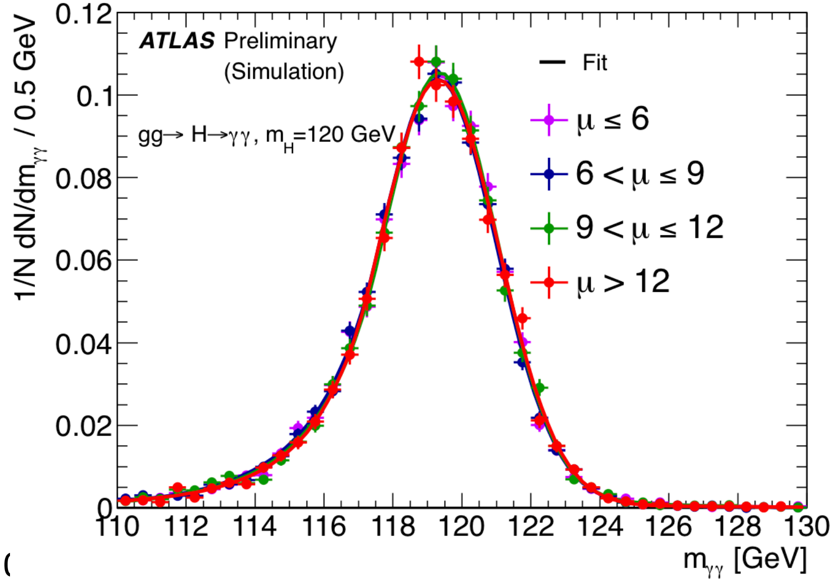
(IP spread of 5.6 cm, assuming (0,0,0) adds ~1.4 GeV in mass resolution)

$FWHM \sim 3.5\ \mathrm{GeV}$

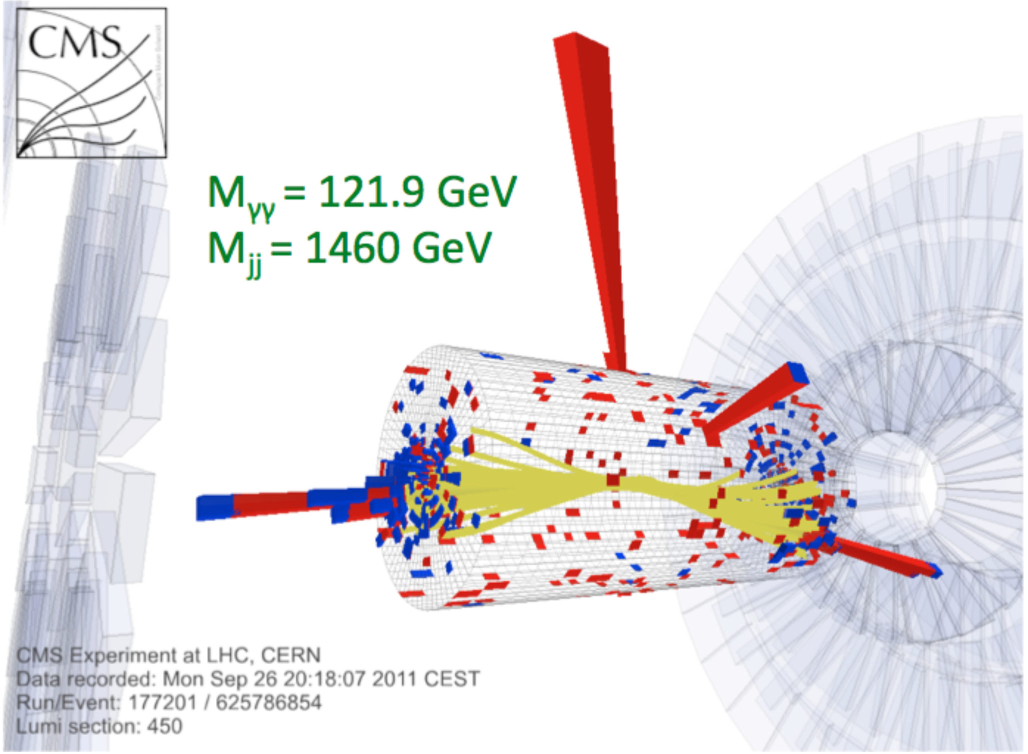
$FWHM \sim 4.0\ \mathrm{GeV}$



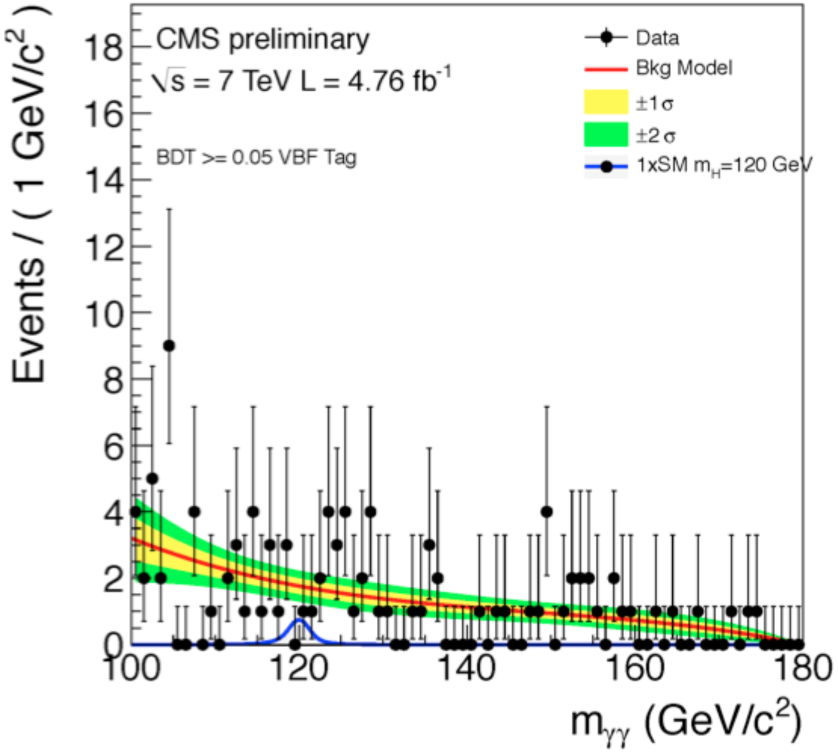
ninar (



Event Categrization to fully profit from distinctive features



Dijet tag selection has high s/b, ~1/3



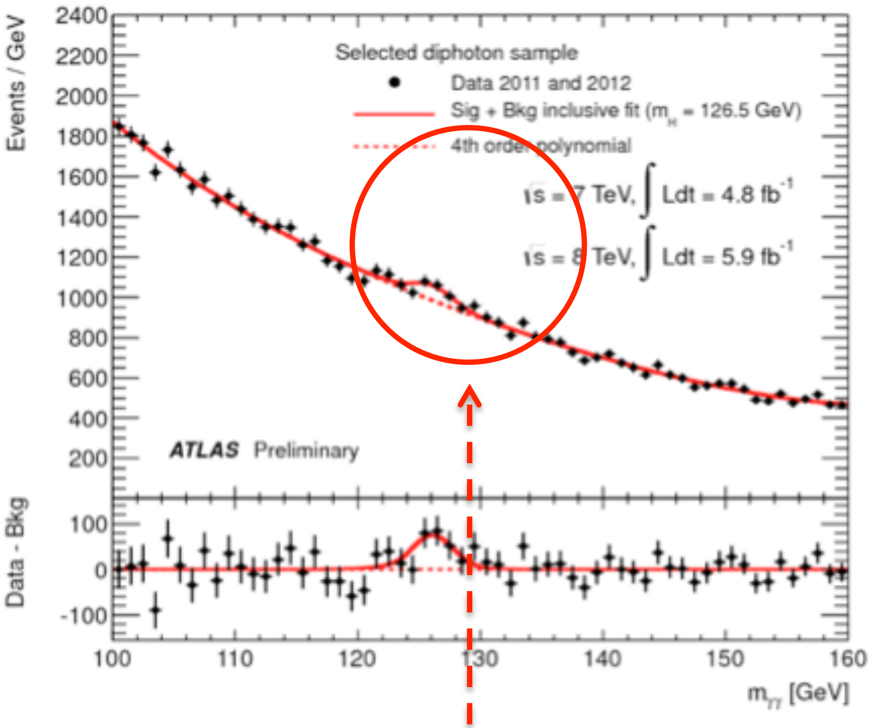
ATLAS (9 Categories) :

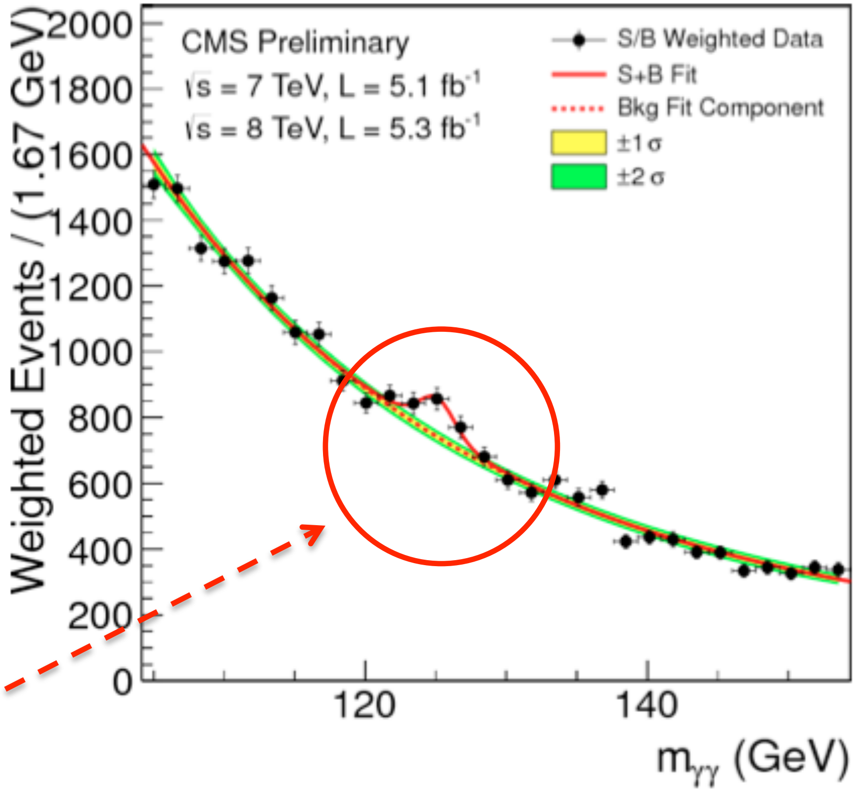
- Pseudo-rapidity
- Conversion status (tracks)
- Transverse momentum w.r.t. thrust axis
- VBF Category

CMS (4 Categories) :

- MVA Analysis (4)
  - Kinematics
  - Conversion status
  - Resolution
- VBF Category (1)

Inclusive/Weighted Mass Spectra





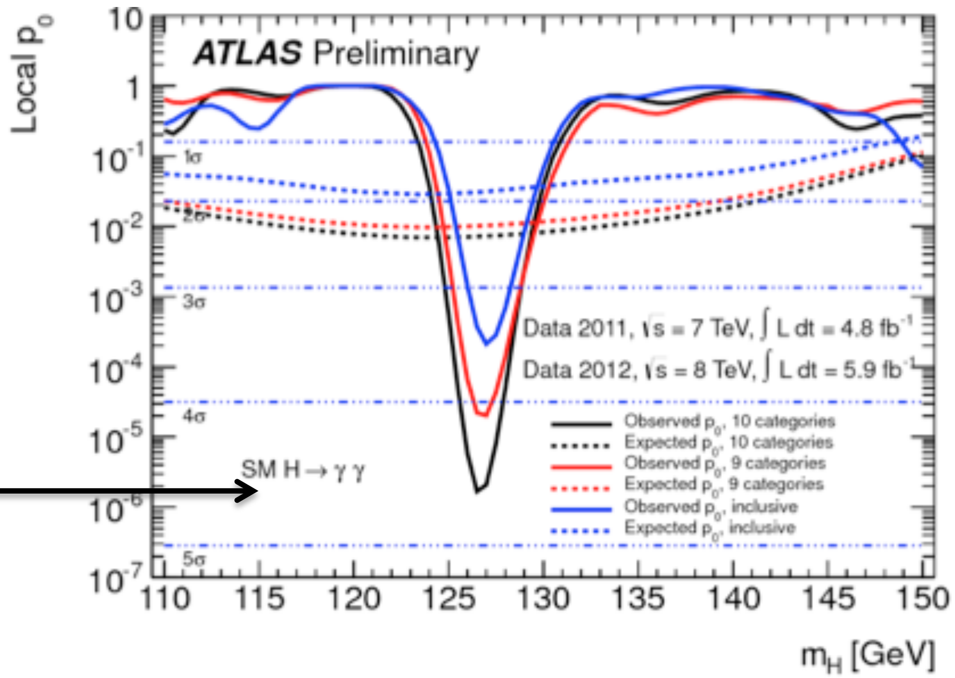
CMS has a slightly wider fit range

Excesses visible in the inclusive mass spectra

ATLAS

Excess of

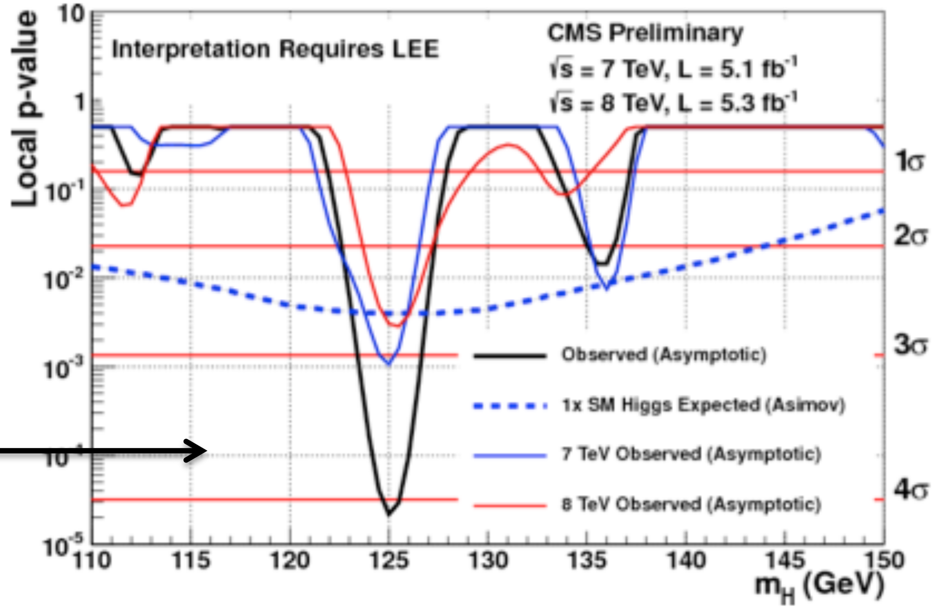
4.5σ



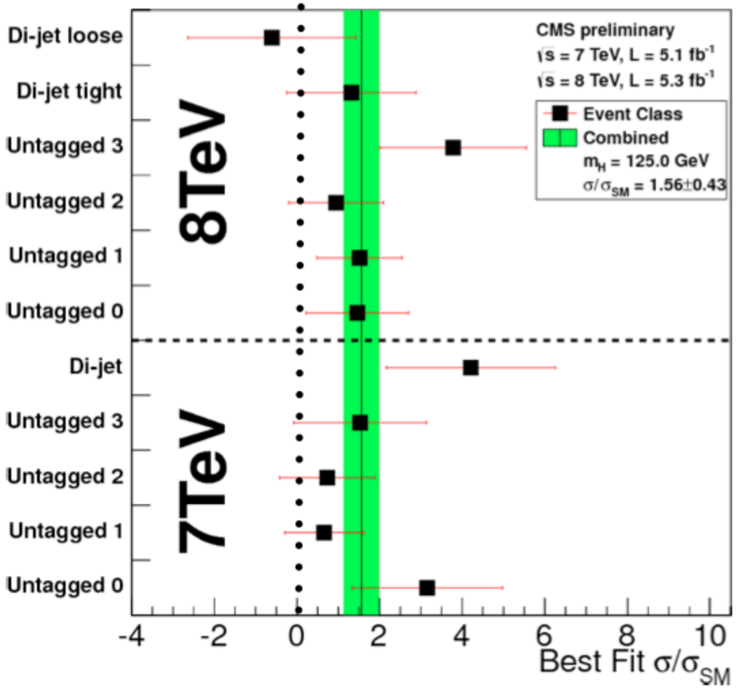
CMS

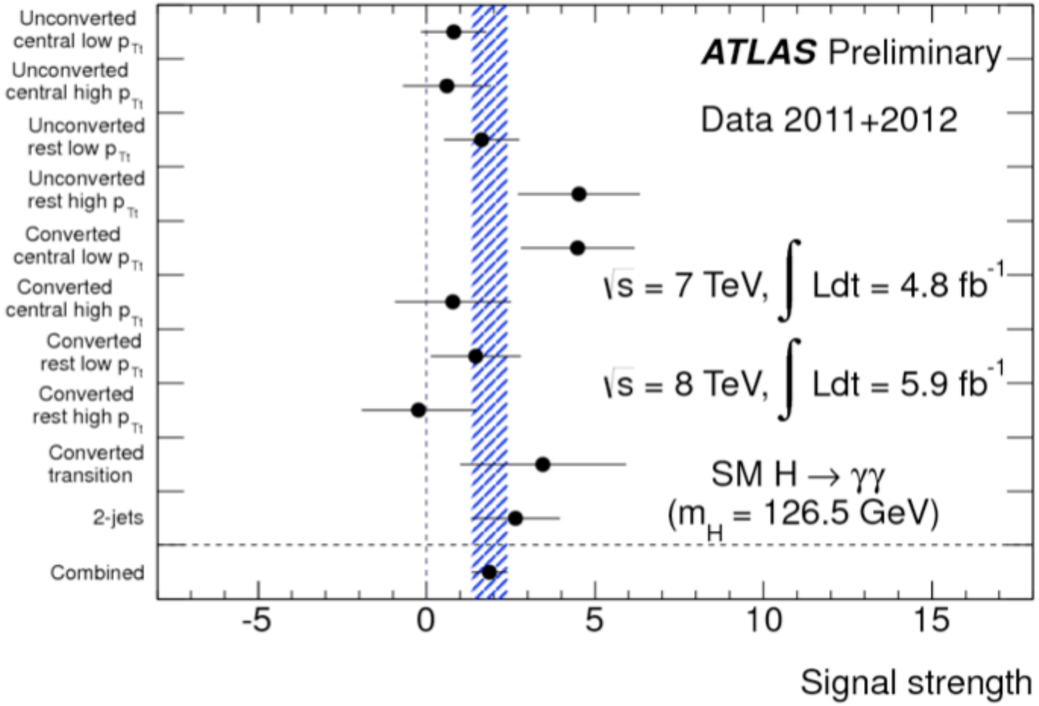
Excess of

4.1σ



Compatibility Across Categories





$$H \rightarrow ZZ \rightarrow \ell\ell\ell\ell$$

The « Golden » Channel

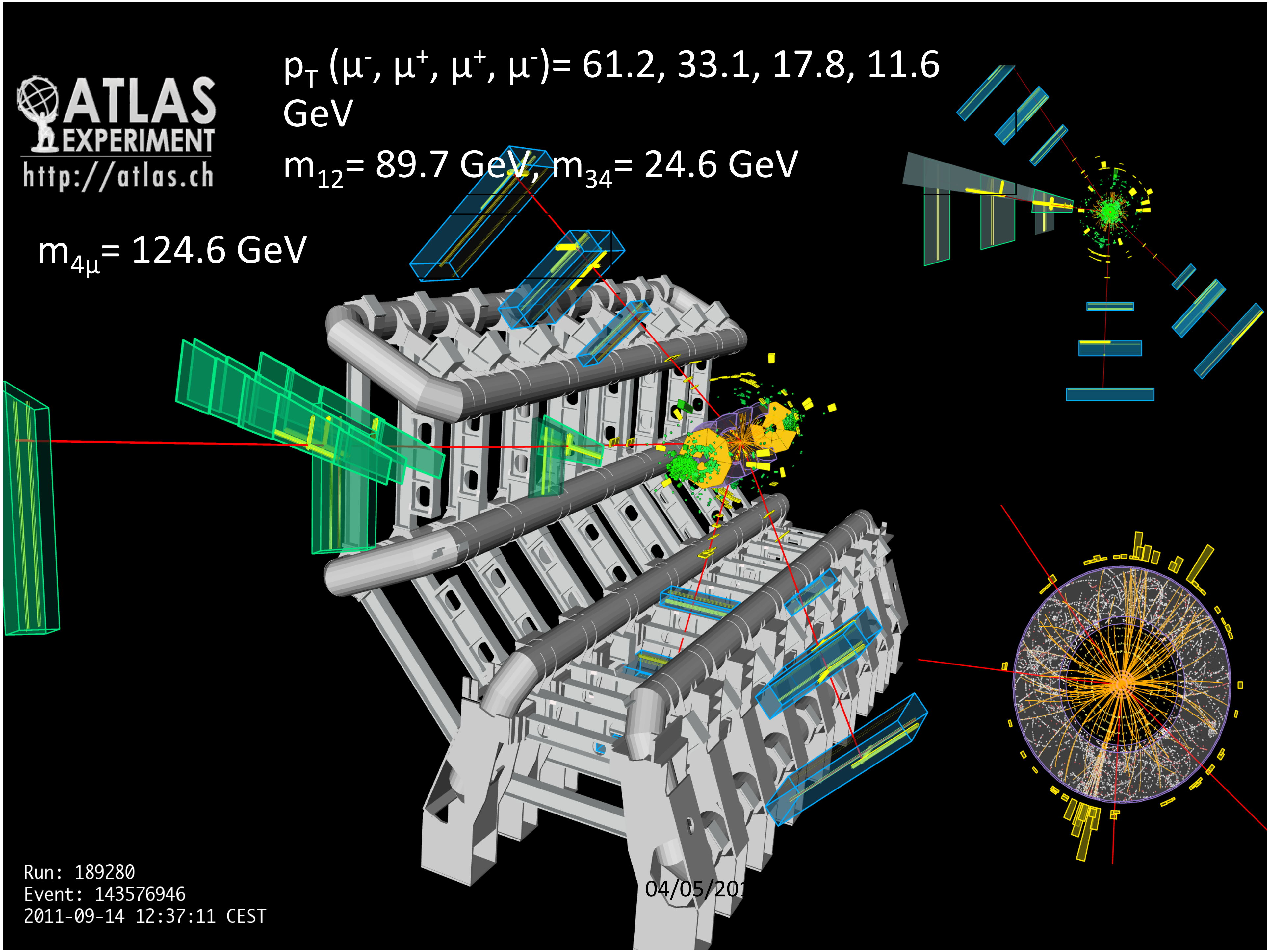
Most sensitive Channel in [180-250] GeV Mass range

ATLAS 4.8 – 5.9 fb^{-1}

CMS 4.7 – 5.3 fb^{-1}

Signal yield after cuts (low mass) ~ O(20)

s/b ~ O(1) locally at 125 GeV

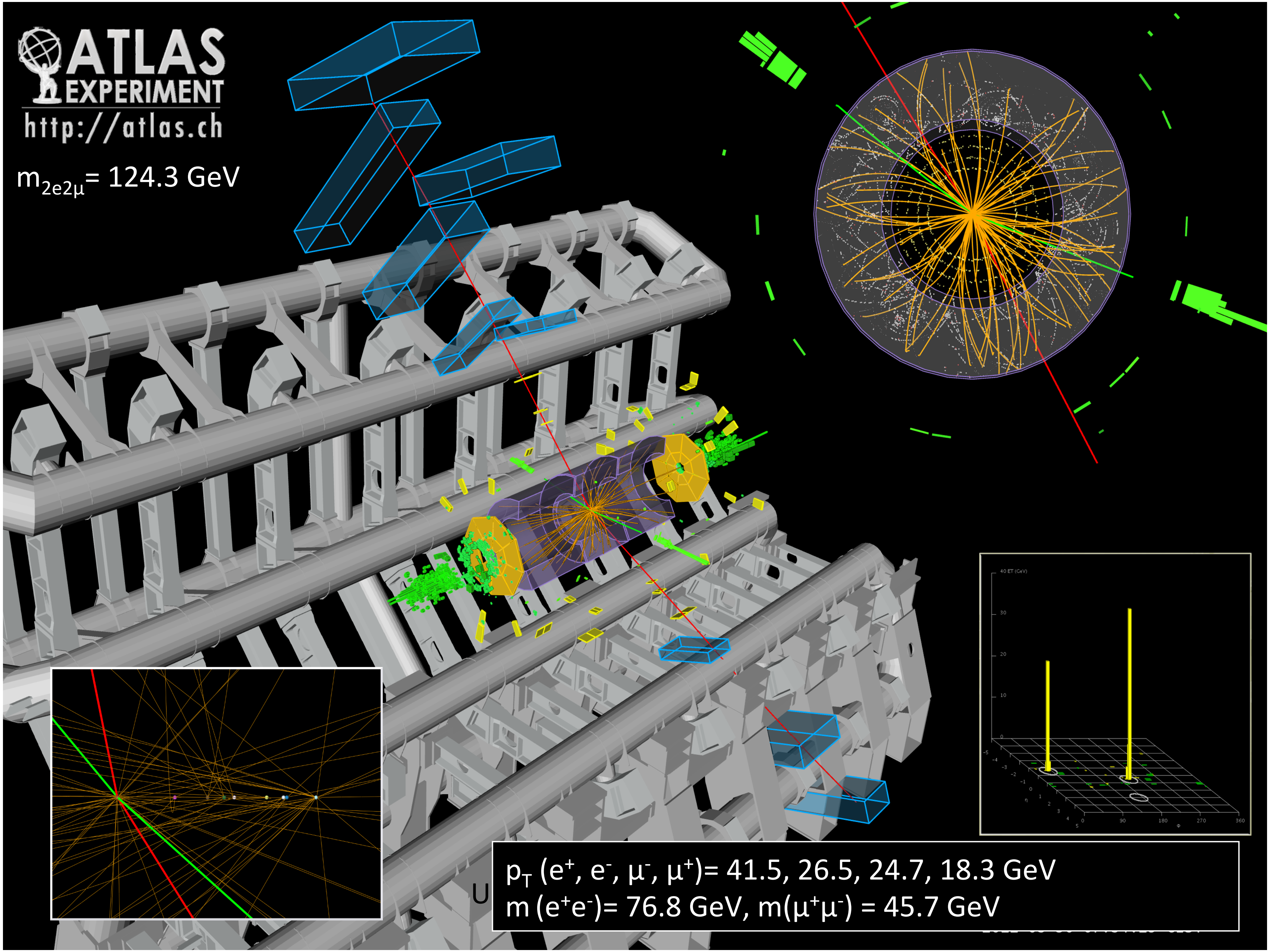


$p_T(\mu^-, \mu^+, \mu^+, \mu^-)$= 61.2, 33.1, 17.8, 11.6 GeV

m_{12}= 89.7 GeV, m_{34}= 24.6 GeV

$m_{4\mu}$= 124.6 GeV

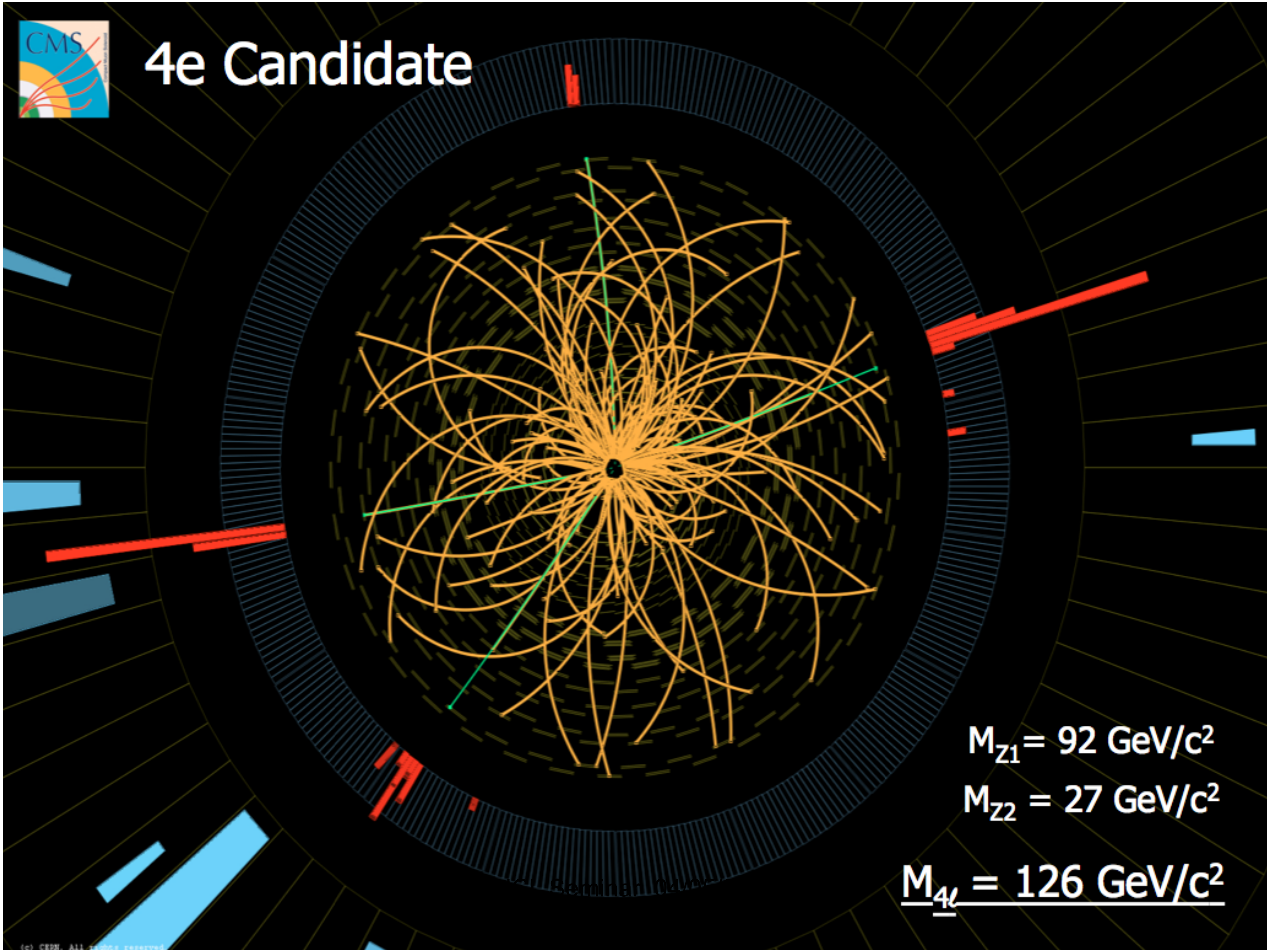
Run: 189280
Event: 143576946
2011-09-14 12:37:11 CEST



$m_{2e2\mu}$= 124.3 GeV

p_T (e^+, e^-, μ^-, μ^+)= 41.5, 26.5, 24.7, 18.3 GeV
m (e^+e^-)= 76.8 GeV, m($\mu^+\mu^-$) = 45.7 GeV

4e Candidate

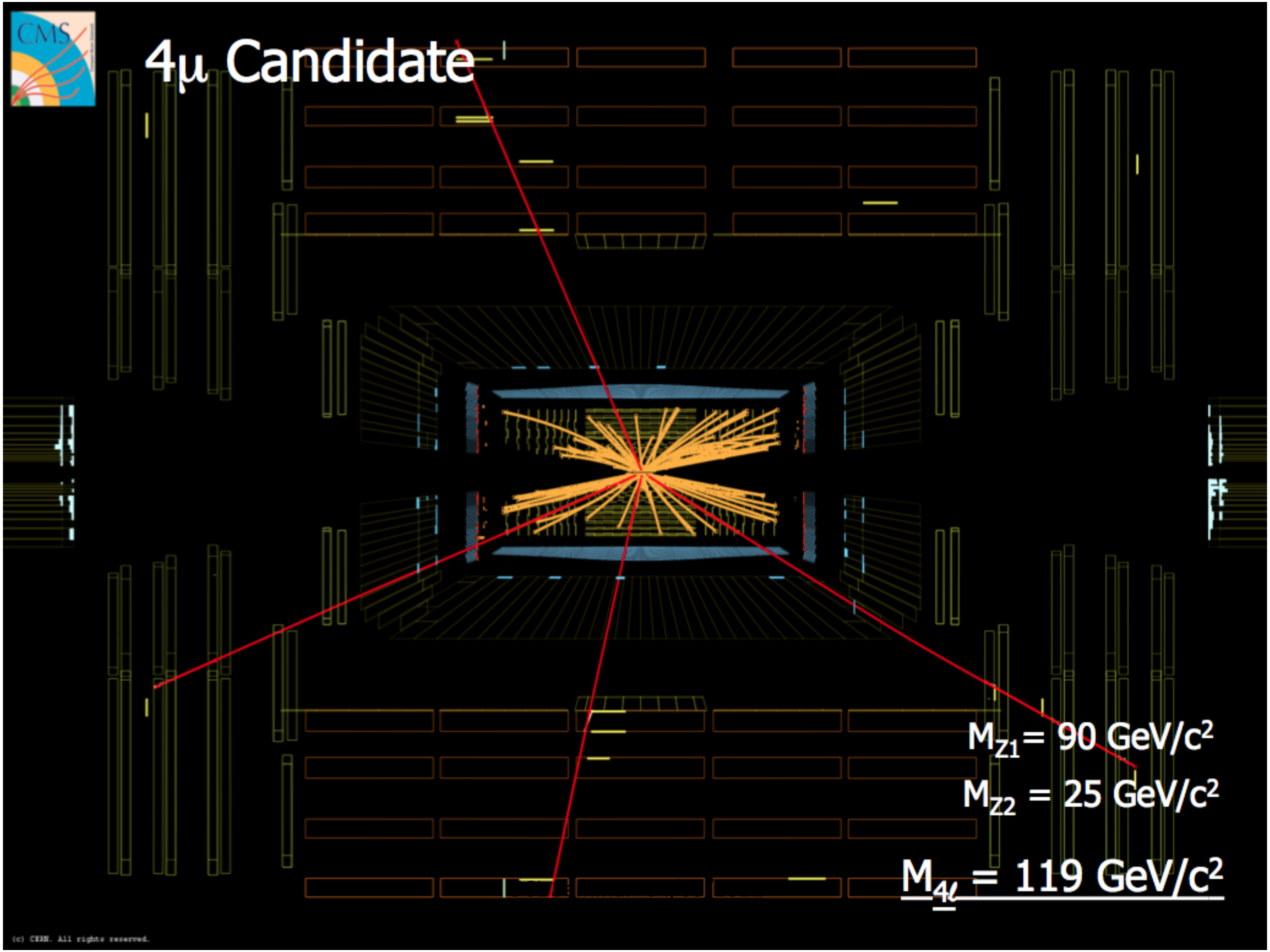


$M_{Z1} = 92\ \mathrm{GeV/c^2}$

$M_{Z2} = 27\ \mathrm{GeV/c^2}$

$\underline{M_{4\ell} = 126\ \mathrm{GeV/c^2}}$

4μ Candidate



$M_{Z1} = 90\ \mathrm{GeV}/c^2$

$M_{Z2} = 25\ \mathrm{GeV}/c^2$

$\underline{M_{4\ell} = 119\ \mathrm{GeV}/c^2}$

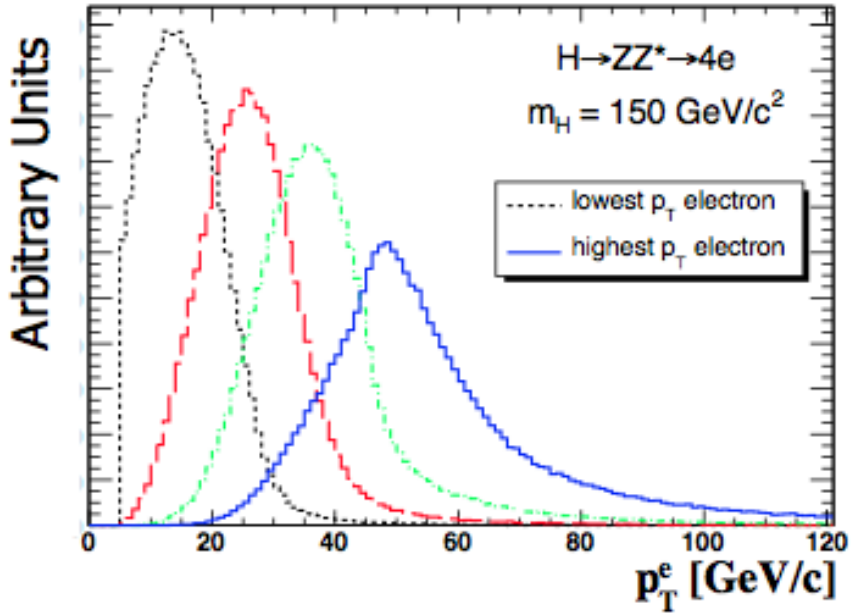
Higgs Boson Search in the $ZZ^{(*)}\rightarrow 4l$

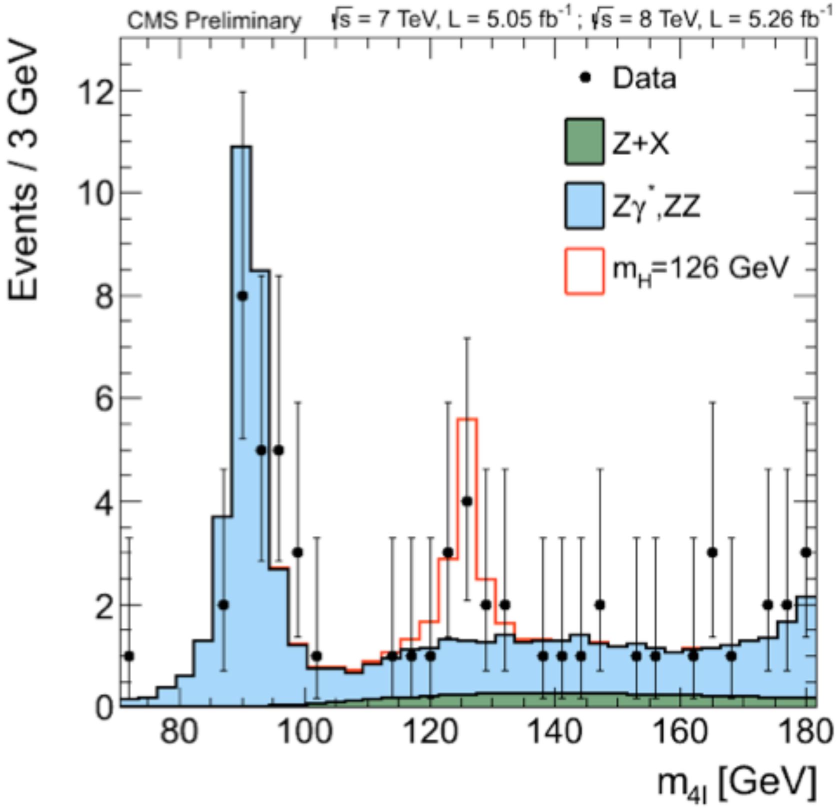
Key features

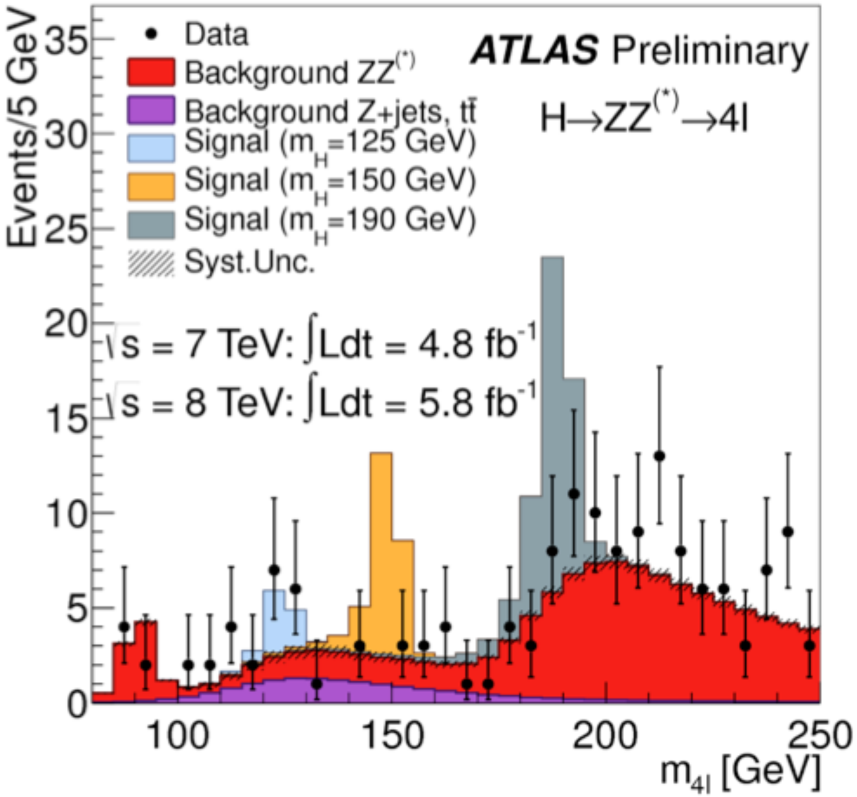
- One Z allowed to be off-mass shell (m_H < 180 GeV)
- low p_T lepton reconstruction very important
- Invariant mass selections also important to optimize low mass selection

Low Background

- Main Background ZZ from Monte Carlo (ATLAS) and derived from Z (CMS)
- Other backgrounds (Zbb and top) data driven (but small)







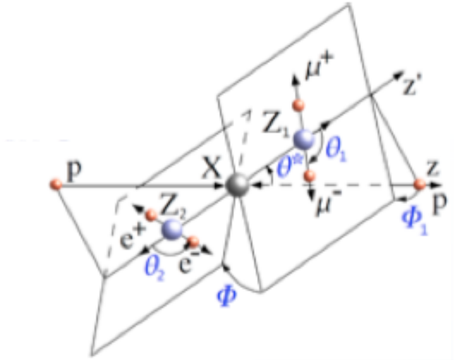
Somewhat better S/B in CMS

(for instance lower reducible background)

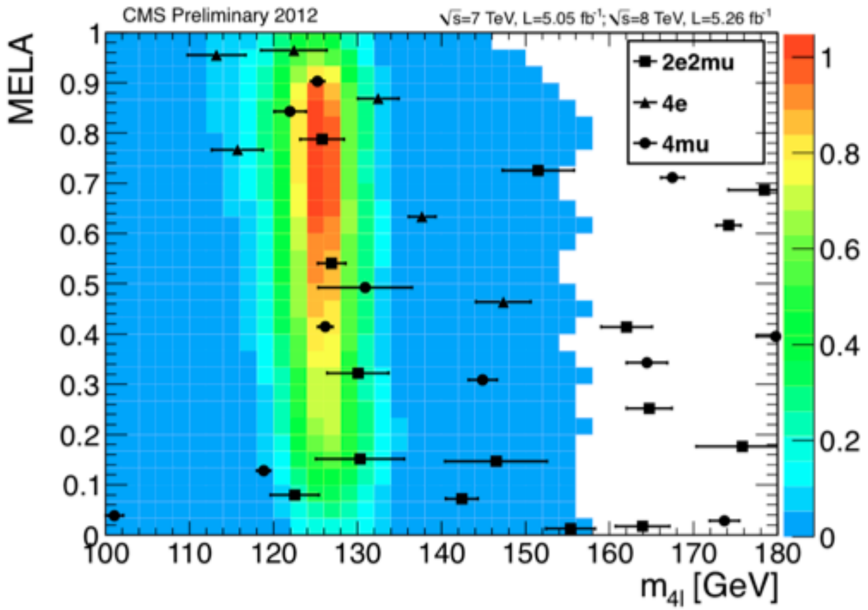
(also 7 TeV ATLAS analysis does not have latest improvements in electron reconstruction)

Improving S/B using angular distributions

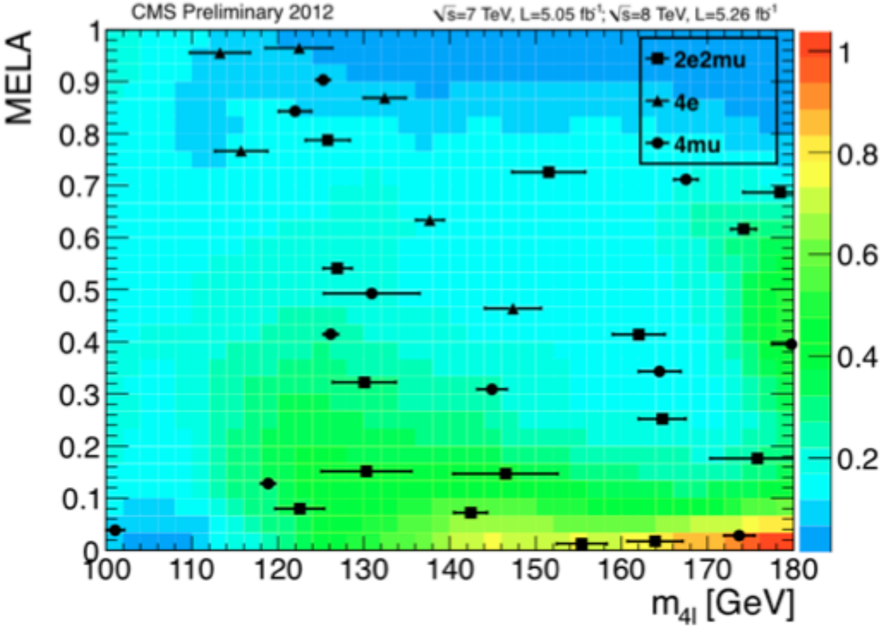
MELA = P(sig)/(P(sig)+P(bkg))
P = Matrix element(5 angles, M1,M2)



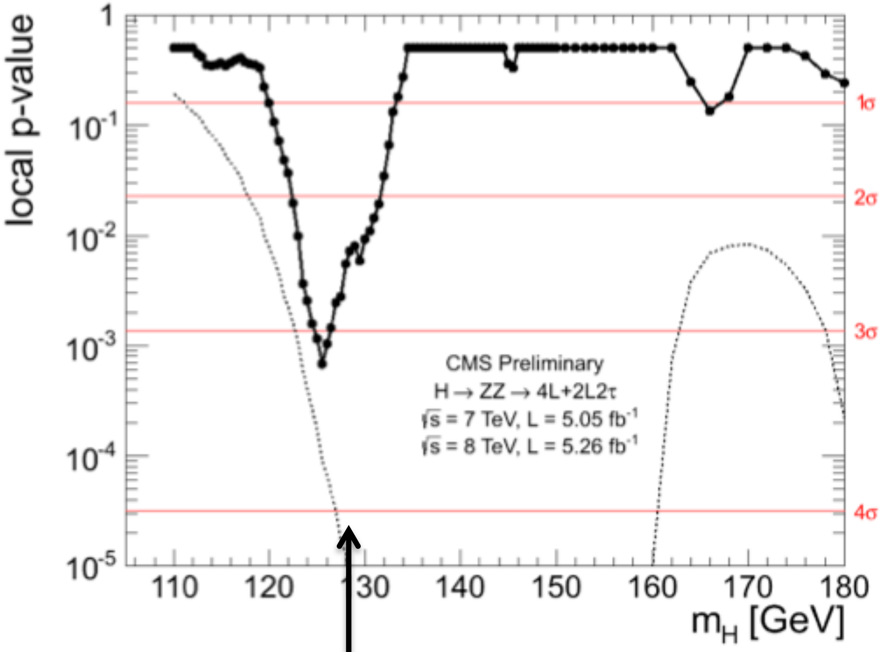
Data vs Signal

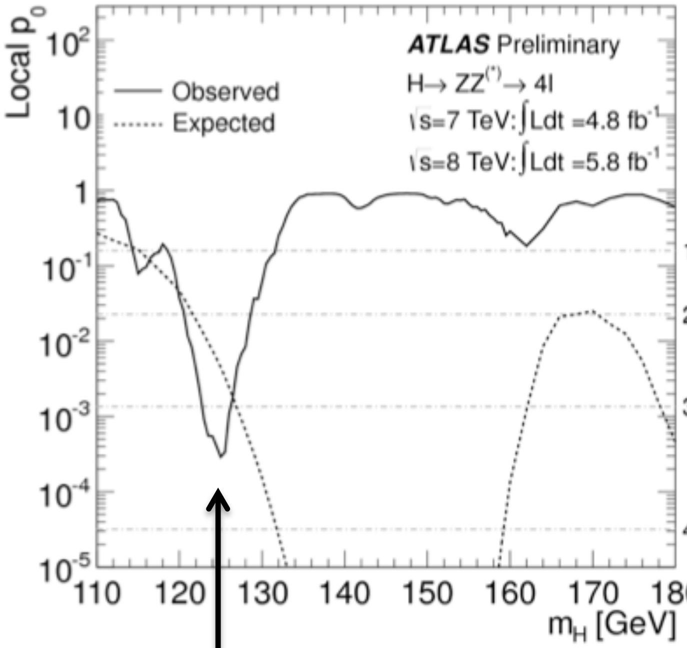


Data vs Bkg



CMS better sensitivity from use of angular variables (20%) + better S/B at low mass (~20%)





CMS
Excess of
3.2σ

ATLAS
Excess of
3.4σ

$$H \rightarrow W^{+}W^{-} \rightarrow \ell\upsilon\ell\upsilon$$

Most sensitive Channel in [125-180] GeV Mass range

ATLAS 4.7 – 5.9 fb^{-1}

CMS 4.6 - 5.3 fb^{-1}

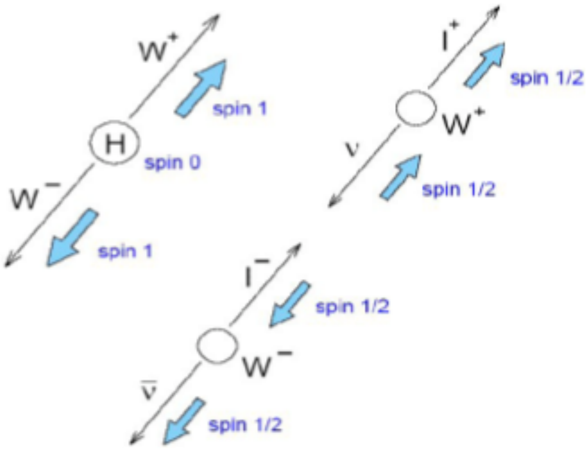
Signal yield after cuts (low mass) ~O(60)

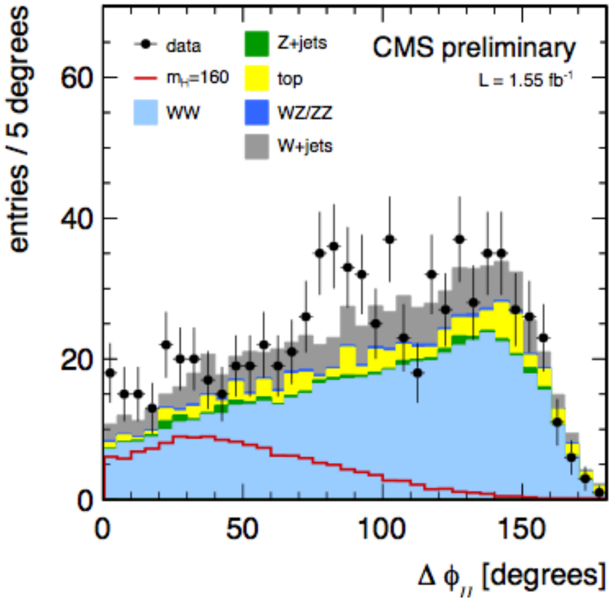
s/b ~ O(15)%

Higgs Boson Search in the $WW\rightarrow l\nu l\nu$

Key features :

- Neutrinos: Poor resolution in mass (requires in particular a good control of MET)
- Search carried out in 0, 1-jet and VBF topologies
- ATLAS cut based only / CMS cut based and MVA
- Good control of the WW and top backgrounds is essential!
- Use of spin correlations is essential for the analysis and to define control regions… CMS also use a BDT (kinematic variables)





Higgs Boson Search in the WW→lνlν

Key features :

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- Search carried out in 0, 1-jet and VBF topologies
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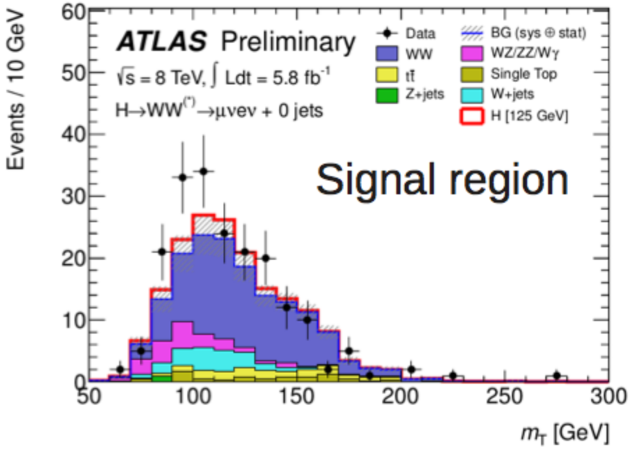
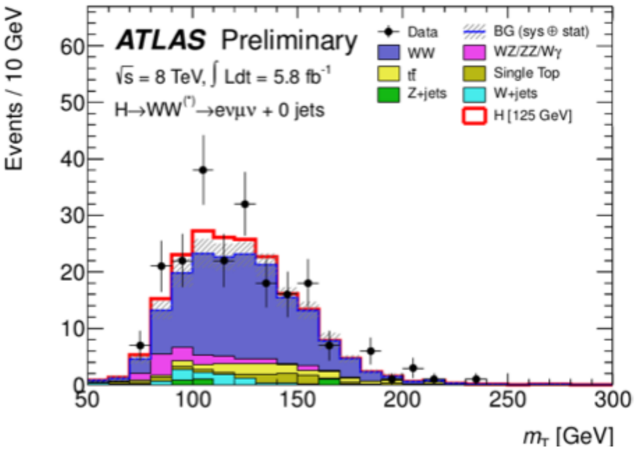
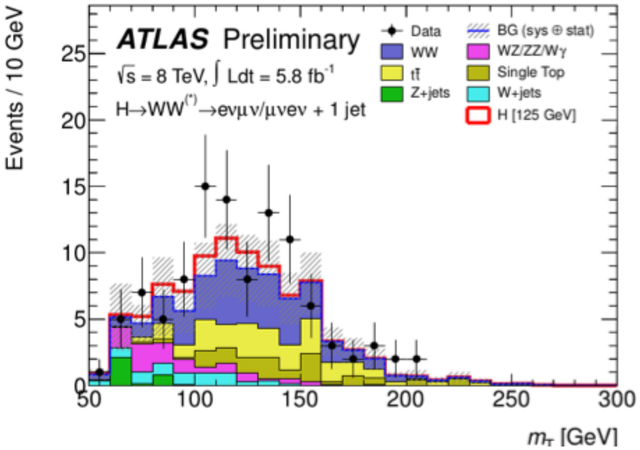
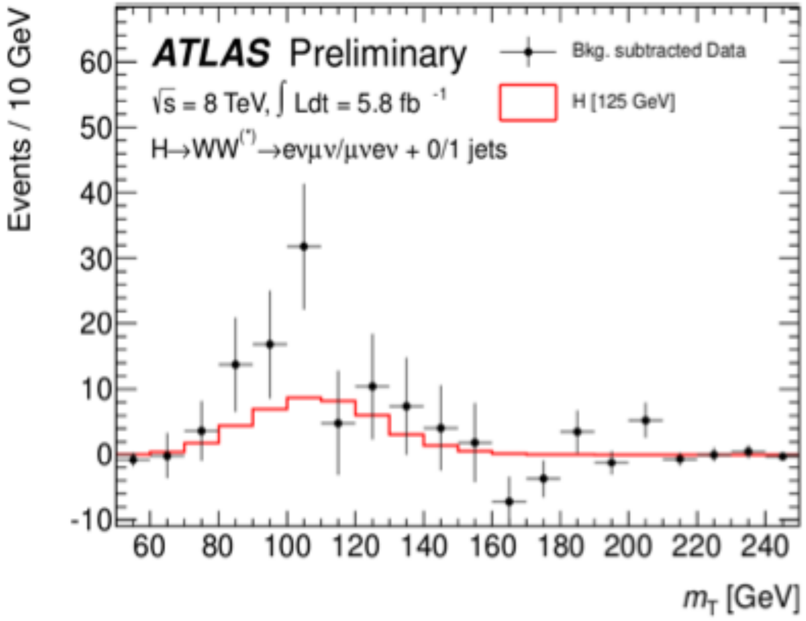
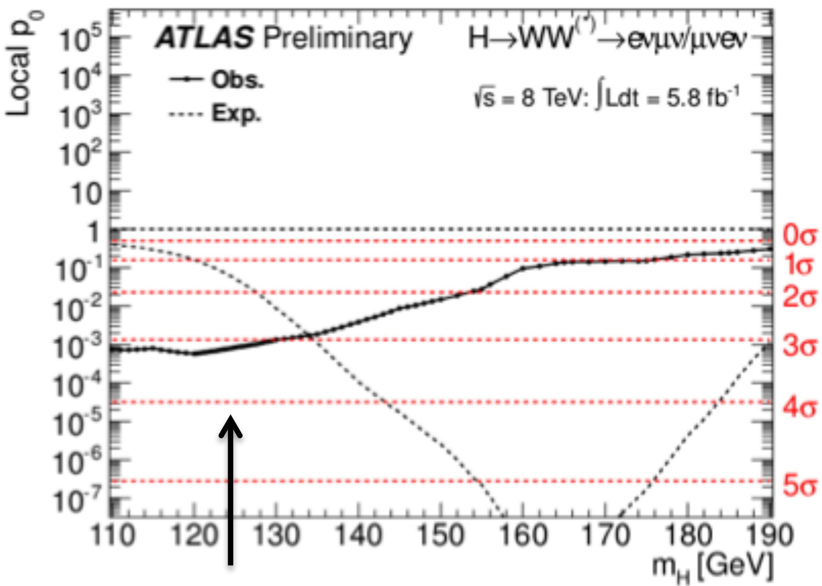








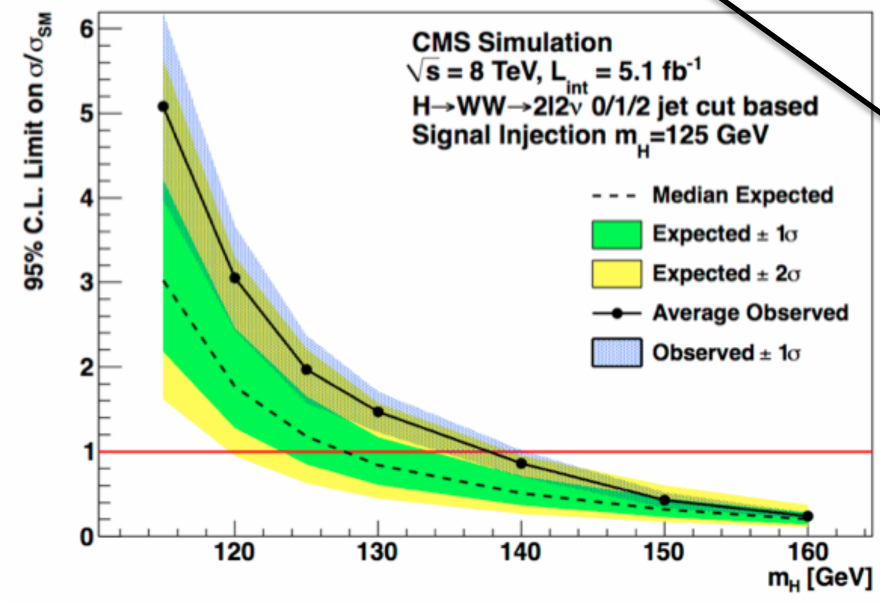


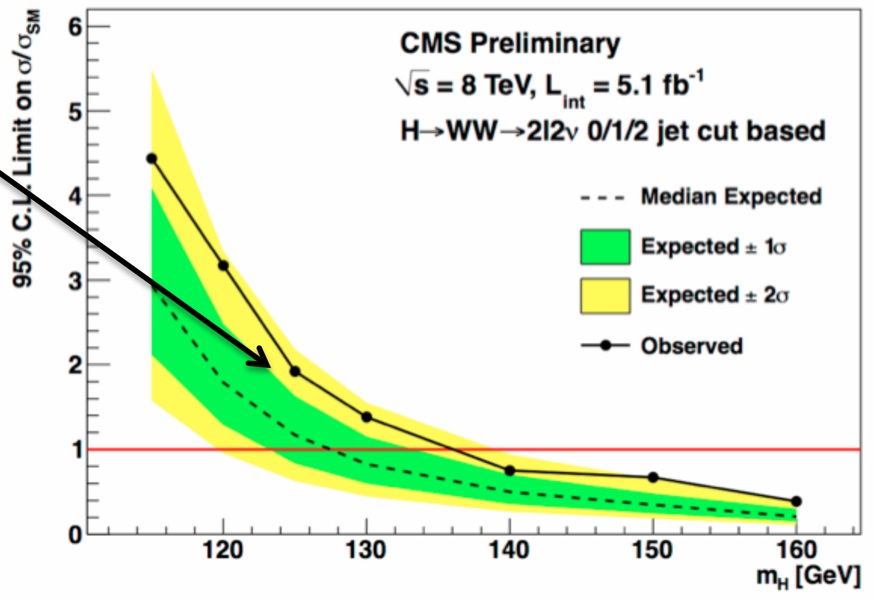
CMS

Excess of
~2σ

ATLAS

Excess of
3.1σ



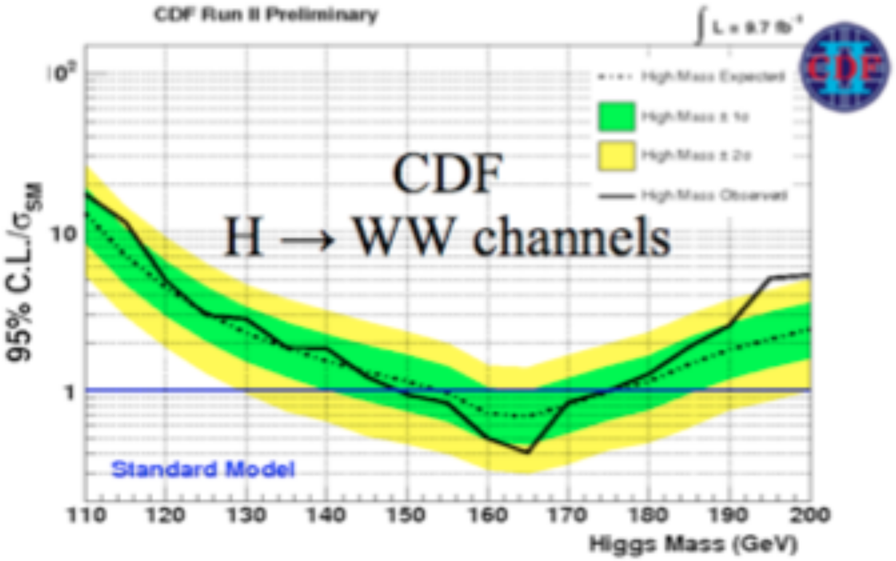


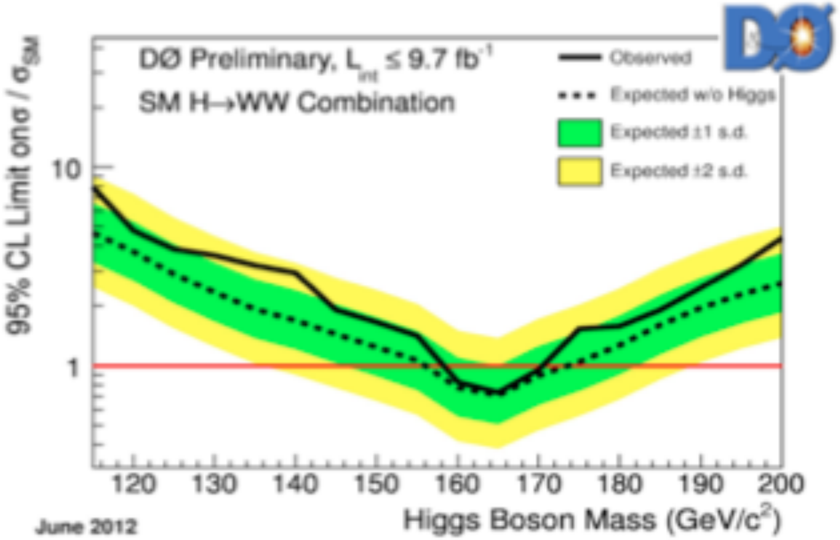
The WW→lνlν Channel at the Tevatron

At the Tevatron

Split analysis in many categories according to purity, ...
Use MVA to separate S and B (kinematics, event topology,..)
Validate measuring WW cross-section with same methods

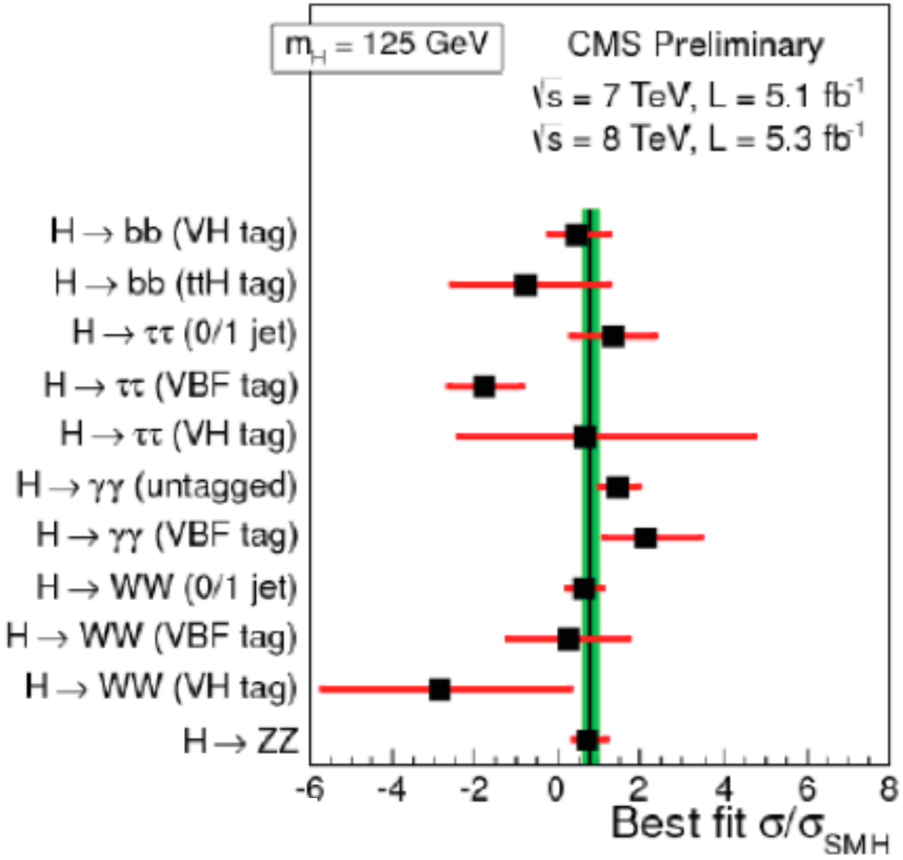
B.Tuchming

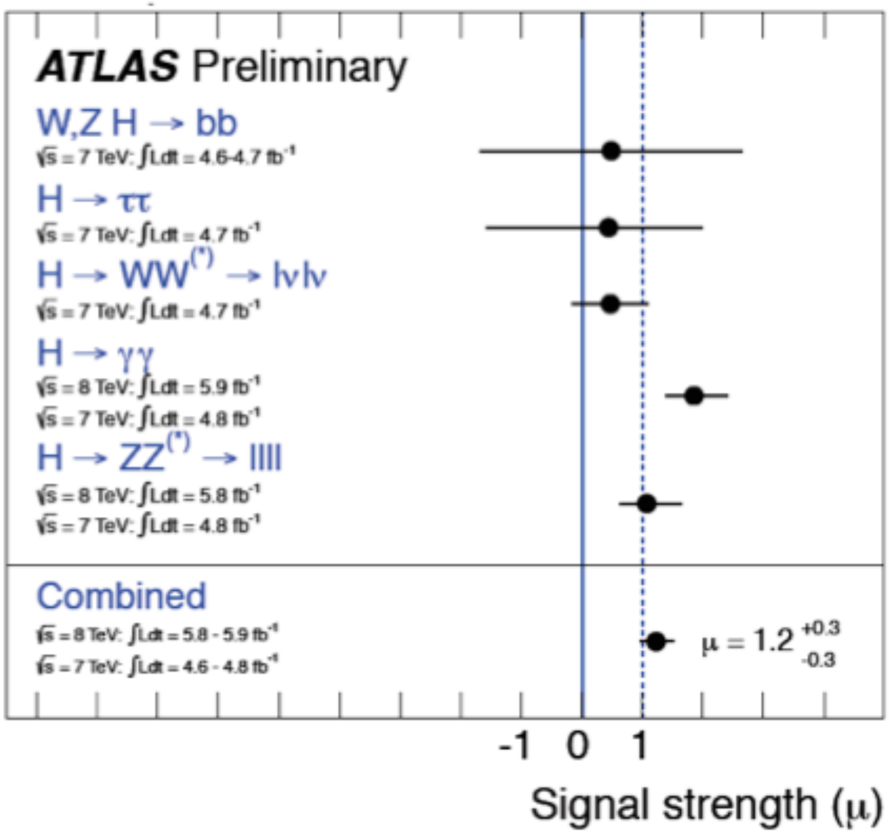




Consistent with B only and S(125 GeV)+B, ~1 sigma excess in D0

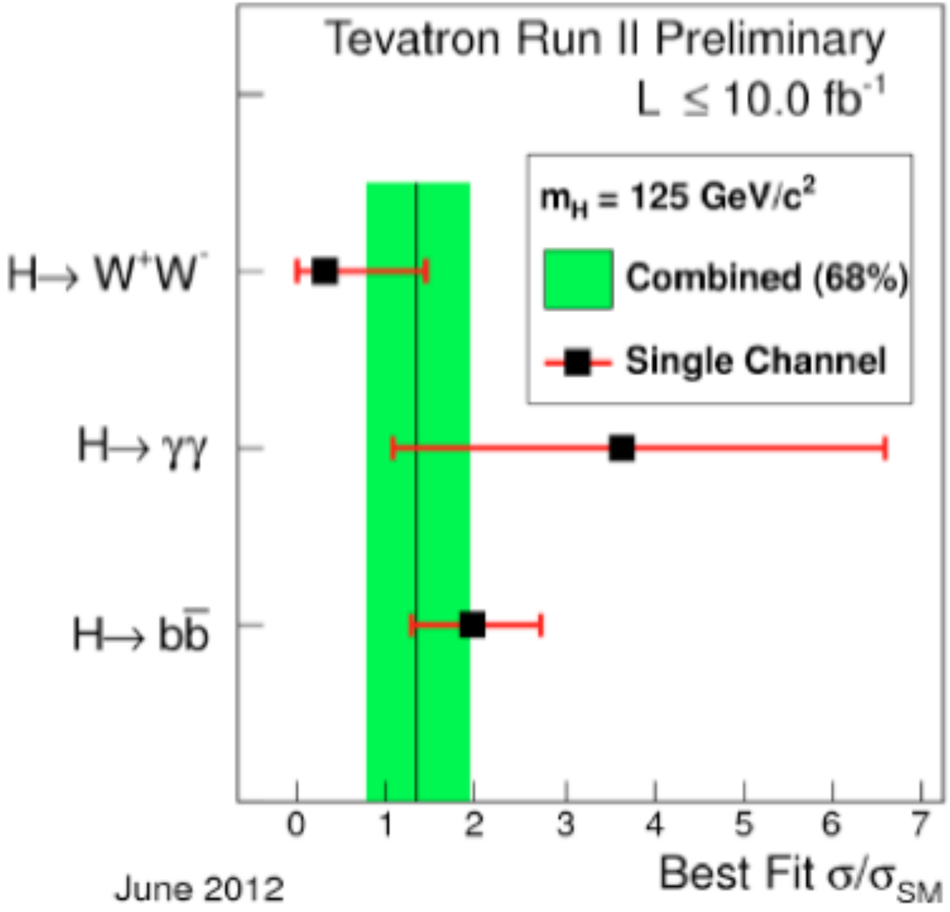
Other Channels In A Nutshell





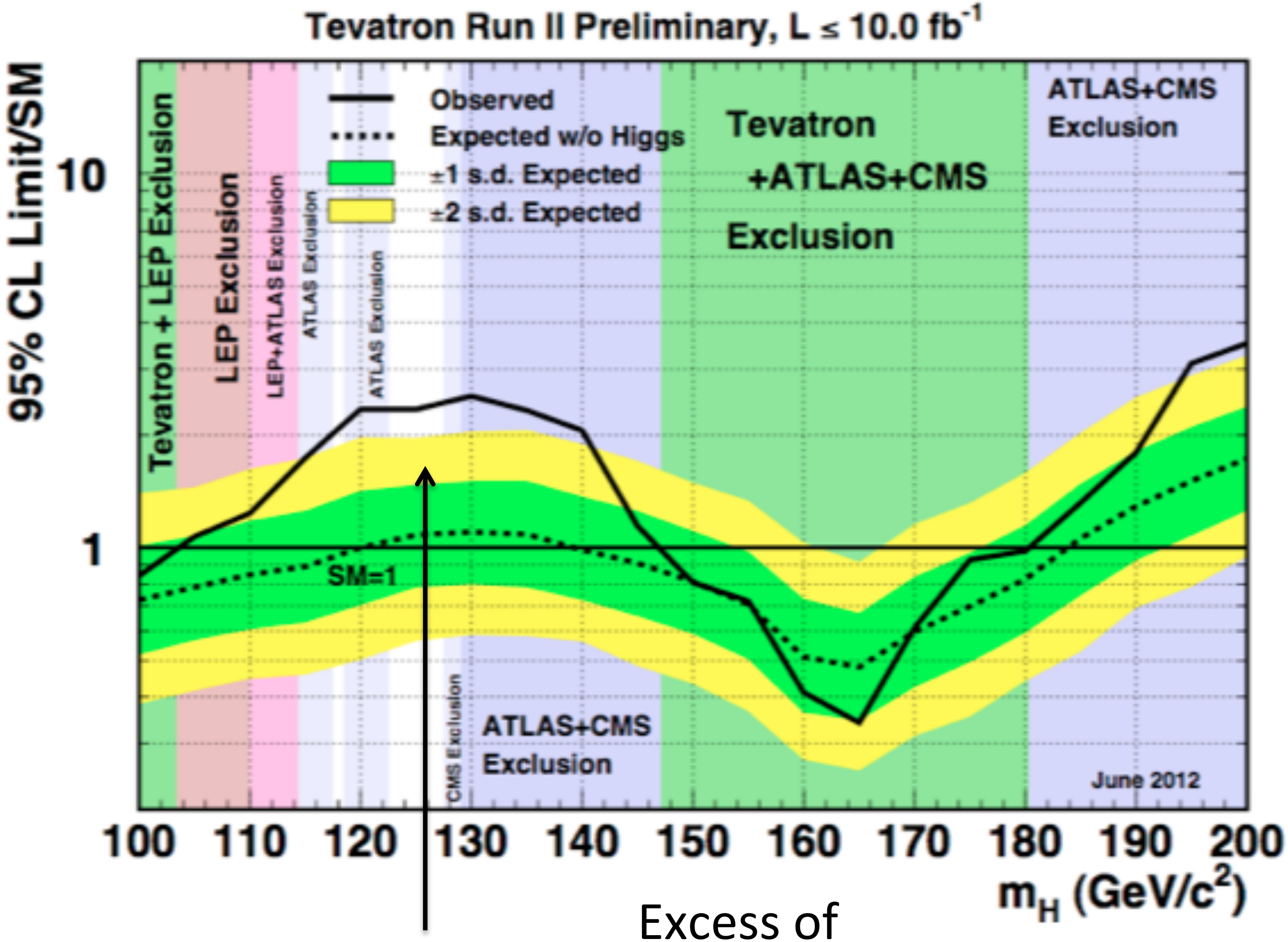
Impressively consistent picture possible slight tension : CMS ττ

… and the TeVatron bb Channel



Even more Impressively consistent picture
possible slight tension : CMS $\tau\tau$

Combination(s)

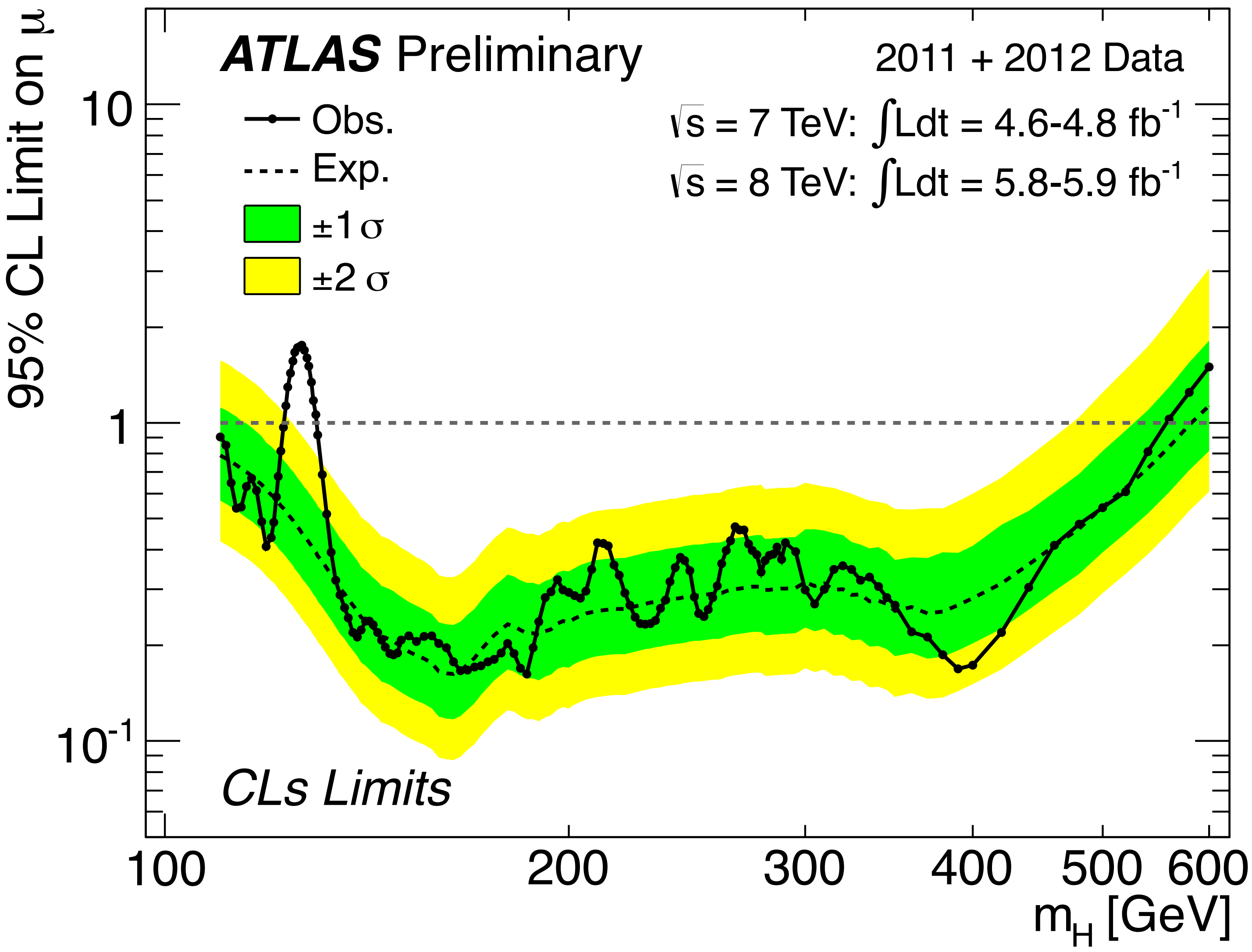


TeVatron

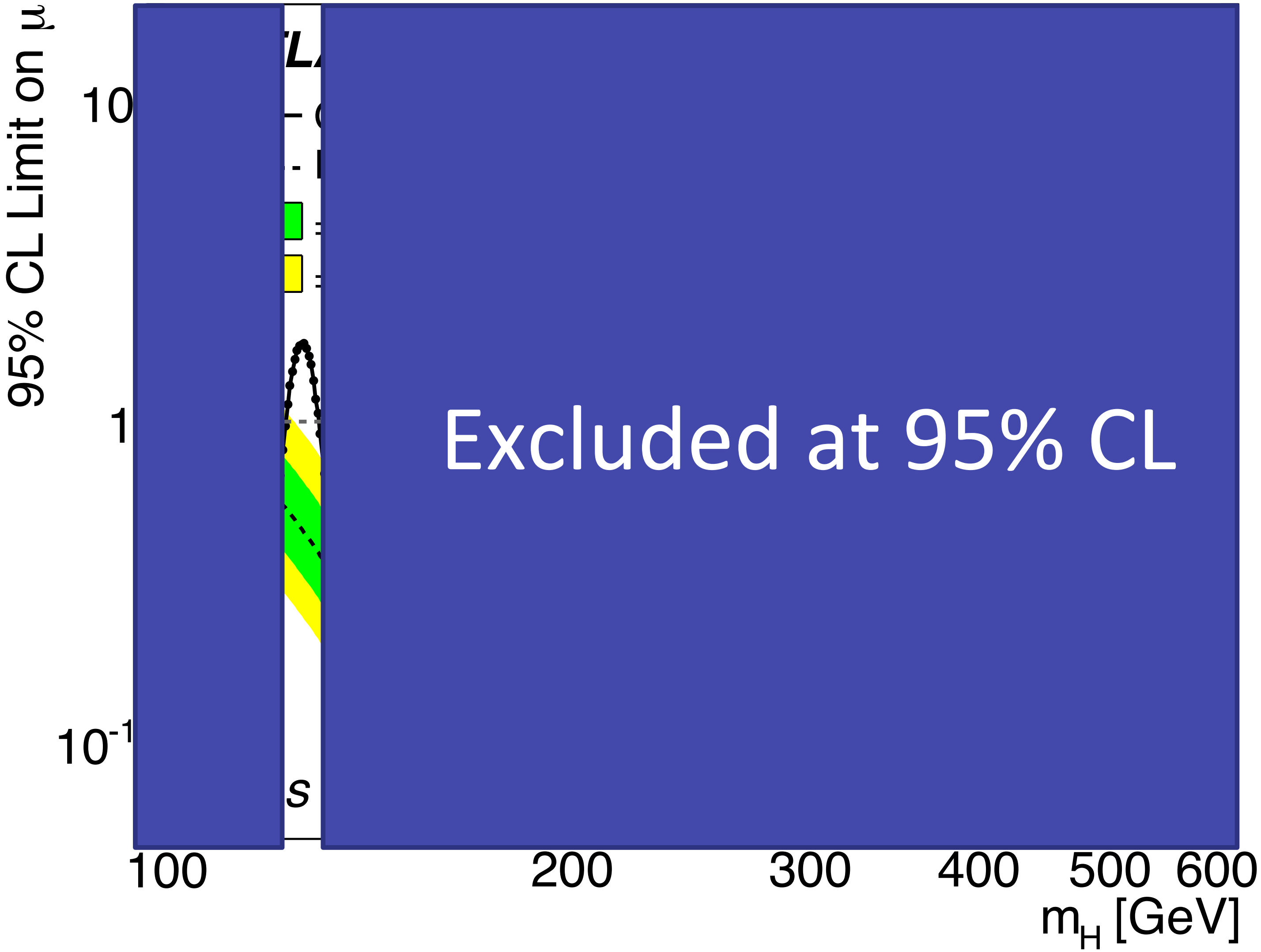
Excess of

3.0σ

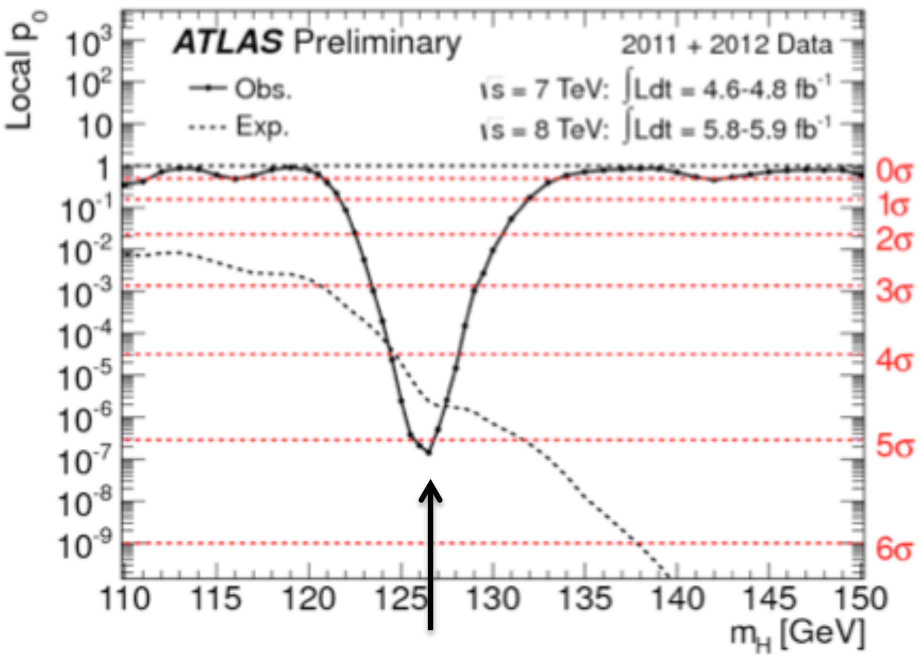
Impressive Exclusion Range for both ATLAS and CMS



Impressive Exclusion Range for both ATLAS and CMS



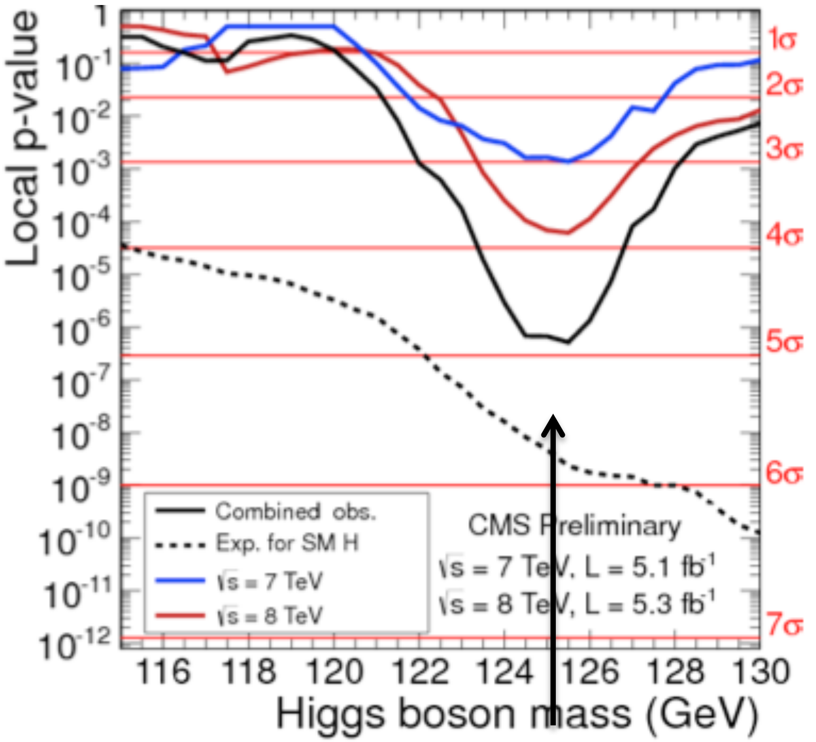
Combination(s)



ATLAS

Excess of

5.0σ



ATLAS

Excess of

4.9σ

As a Layman : We have it!

Outlook

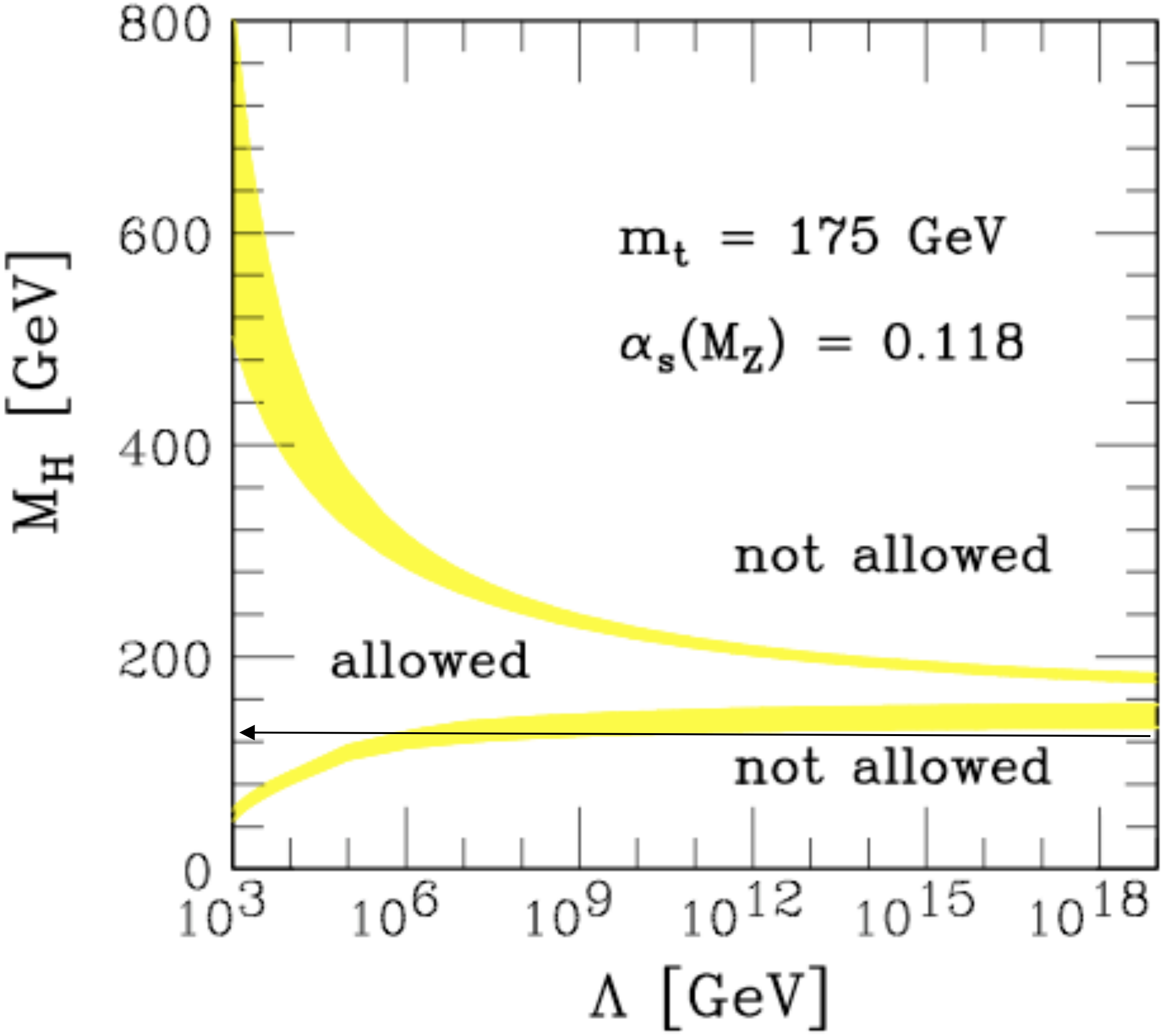
Michael Peskin at Higgs hunting last week

Without further apologies I will call it the Higgs Boson !

$\gamma\gamma$ decay mode	✓
ZZ decay mode	✓
WW decay mode	✓
bb decay mode	Tevatron only
$\tau\tau$ decay mode	? deficit at CMS
spin-parity	preliminary evidence
gg production mode	✓
VBF production mode	marginal
Higgsstrahlung mode	Tevatron only

All of these issues could be settled with the full 2012 LHC data set.

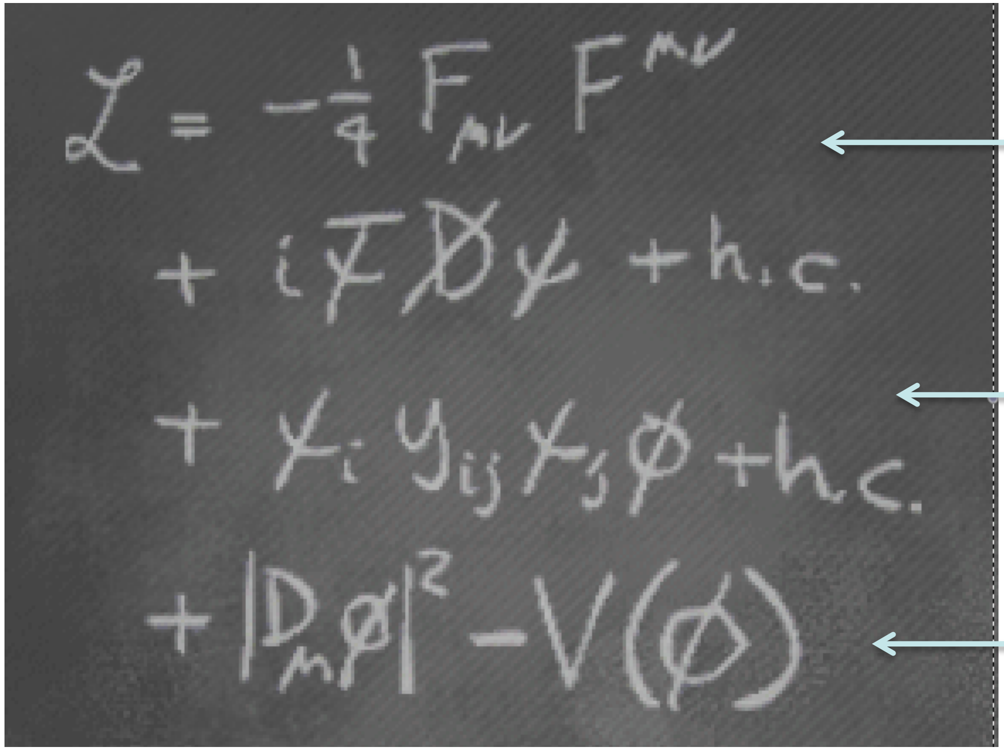
Back to Vacuum Stability and Triviality Constraints Summary



For a 125 GeV Higgs boson no triviality problem, but what about vacuum stability?

Still Many Open questions

Famous J. Ellis blackboard



$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + h.c. + \psi_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

+ Dark Matter

+ Dark Energy

Directly searched for at the LHC

The Gauge Sector

Ongoing revolution in QCD, and calculation of new processes. LHC has its word to say on this question!

The Fermion/Yukawa Sector

Great progress in recent measurement of θ_{13} not at LHC!
Many flavor questions to be addressed… at the LHC.

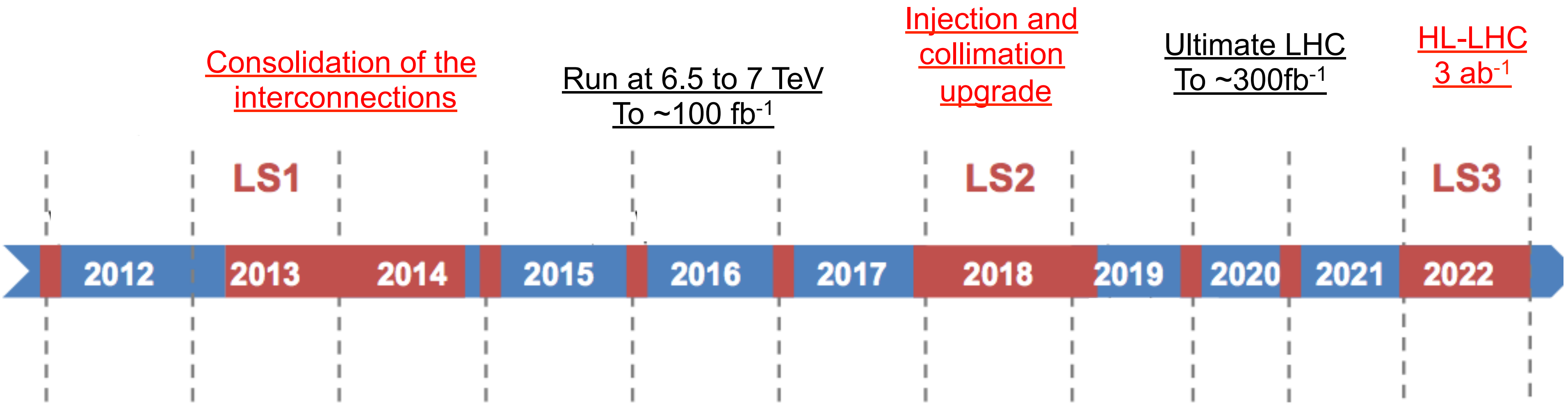
The Higgs Sector

A milestone, what now :

- Quantum numbers J^{PC}
- Couplings
- Elementary?
- Natural?

Still Many Open questions

The LHC Time schedule :



Consolidation of the interconnections

Run at 6.5 to 7 TeV
To ~100 fb^{-1}

Injection and collimation upgrade

Ultimate LHC
To ~300fb^{-1}

HL-LHC
3 ab^{-1}

Possible future projects at the energy frontier :

- Linear e^+e^- collider
- New circular e^+e^- collider (LEP III)
- HL-LHC
- HE-LHC
- muon collider

Unforgettable July 4

Unforgettable July 4