

The Discovery of the Higgs Boson and Higgs Physics at LHC

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Outline

1.- Introduction and Context

2.- The « Bread and Butter » Discovery Channels, the detectors and the machine.

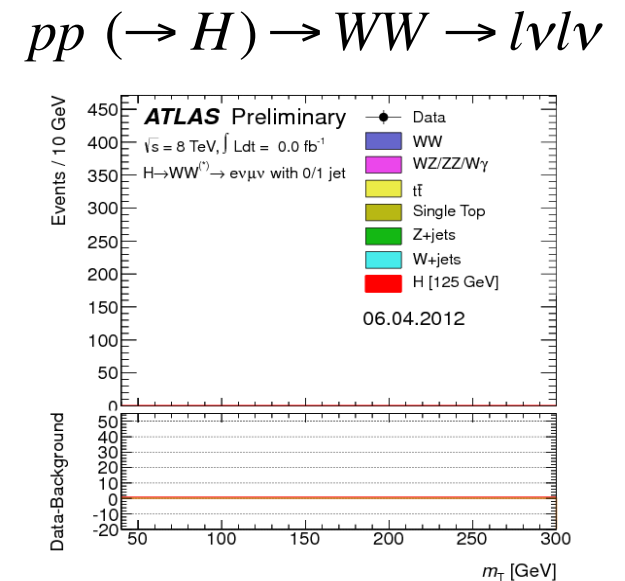
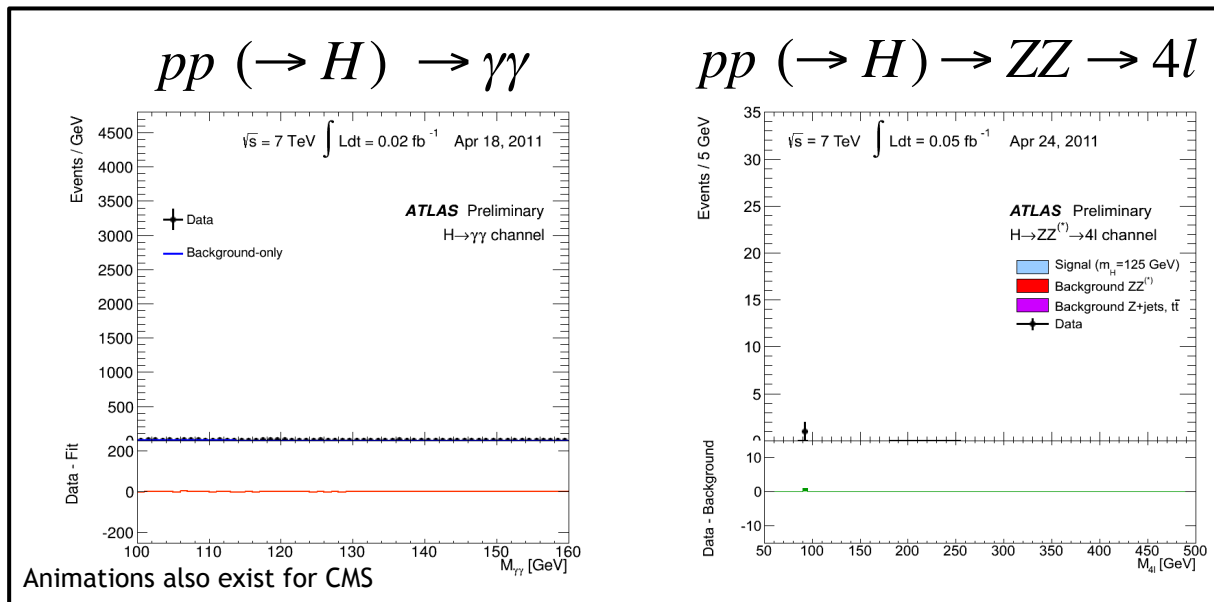
3.- Discovery channels beyond discovery

4.- Overview of post-discovery Higgs physics

5.- Glimpse at HL-LHC

(For other future projects see Michelangelo's Talk)

The Discovery Channels



« Bread and Butter » Mass peak signals

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.

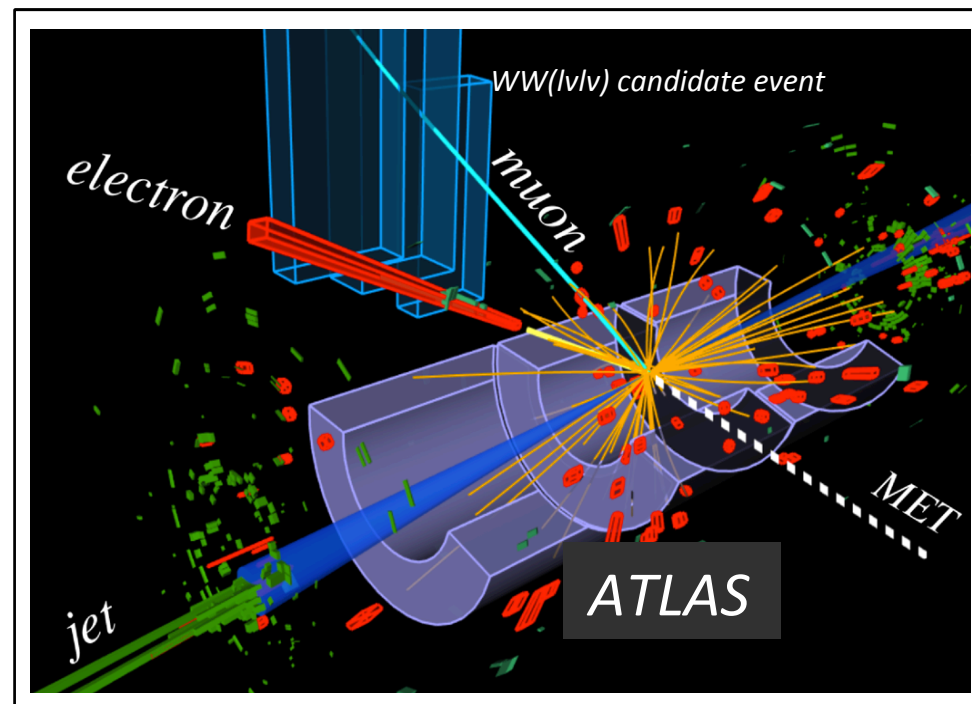
A report is given of studies of:
(a) $H \rightarrow \gamma\gamma$ (work done by C. Seez and T. Virdee)
(b) $WH \rightarrow \gamma\gamma$ (work done by L. DiLella, R. Kleiss, Z. Kunszt and W. J. Stirling)
for Higgs bosons in the intermediate mass range ($90 < m_H < 150 \text{ GeV}/c^2$).
The study of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

Introduction

A Standard Model neutral Higgs boson having a mass above the highest reach of LEP II (around $90 \text{ GeV}/c^2$) [1], and below about $2m_Z$ will be difficult to detect at a hadron collider. The most promising channels for detection are $H^0 \rightarrow \gamma\gamma$, or, for $m_H \geq 130 \text{ GeV}/c^2$, $H^0 \rightarrow ZZ^* \rightarrow e^+e^-e^+e^-$ [2]. As the decay width of the Higgs is about 5.5 MeV at $m_H = 100 \text{ GeV}/c^2$, and 8.3 MeV at $150 \text{ GeV}/c^2$, the width of the reconstructed mass distribution, and hence the signal/background ratio, will be limited by the detector, and in particular by the energy resolution of the electromagnetic calorimeter.

The decay channel $H^0 \rightarrow Z\gamma$ also appears to be potentially attractive, but, after requiring that the Z decay into electrons or muons, the combined branching fraction times cross-section is very small. The intrinsic background (i.e. the background with the same final state as the signal) is large and rules out the possibility of detecting the Higgs boson in this channel.

In this paper a detailed study of the possibility of detecting an intermediate mass Higgs boson in the di-photon channel is reported. Results from another study are also reported in which the same decay is considered but for a Higgs boson produced in association with an intermediate vector boson.



BEH Mechanism: Analogies and Origins

Universe ~ Superconductor

SC (BCS) Th

Particle Th

SC (BCS) Theory

BEH

1954 - Yang-Mills theories for non abelian gauge interactions

Cooper pair condensate

Higgs field

1950 - Landau and Ginzburg
JETP 20 (1950) 1064

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

Electrically charged ($2e$)

Weak charge

1957-59 - Schwinger, Bludman and Glashow: W bosons for the weak charged currents

Mass of the photon

Mass of the W and Z bosons

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

1960 - Nambu

1961 - Goldstone Theorem

The Higgs field is inserted by hand...

1962 - J. Schwinger

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

Condensate: the vacuum has a weak charge

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

1964 - W. Gilbert Phs. Rev. Lett 12 (1964) 713

Thought to be impossible in relativistic theories!

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

The Seminal Papers

SSB in local (Gauge) symmetries in RQFT

*Work supported in part by the U. S. Atomic Energy Commission and in part by the Graduate School from funds supplied by the Wisconsin Alumni Research Foundation.
 †F. Feynman and M. Gell-Mann, Phys. Rev. **109**, 19 (1955).
 ‡T. D. Lee and C. N. Yang, Phys. Rev. **110**, 1410 (1958); S. B. Treiman, Nuovo Cimento **13**, 918 (1959); S. Okubo and R. E. Marshak, Nuovo Cimento **23**, 56 (1963); Y. Nozawa, Nuovo Cimento **22**, 932 (1958).
 ††Estimates of the rate for $e^+e^- \rightarrow \mu^+\mu^-$ due to induced neutral currents have been calculated by several authors. For a list of previous references see Mirza and Baki *ibid.*, Phys. Rev. **139**, 148 (1961).
 †††M. Baker and S. Glashow, Nuovo Cimento **25**, 857 (1959).

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

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 (Received 26 June 1964)

It is of interest to inquire whether gauge vector mesons acquire mass through interaction[†]; by a gauge vector meson we mean a Yang-Mills field^{††} associated with the extension of a Lie group from global to local symmetry. The importance of this problem resides in the possibility that strong-interaction physics originates from massive and pseudovector gauge fields, a system of conserved currents.^{†††} In this note, we shall show that in certain cases vector mesons do indeed acquire mass when the vacuum is degenerate with respect to a compact Lie group.

Theories with degenerate vacuum (broken symmetry) have been the subject of intensive study since their inception by Nambu.^{†††} A characteristic feature of such theories is the possible existence of zero-mass bosons which tend to restore the symmetry.^{††††} We shall show that it is precisely these singularities which maintain the gauge invariance of the theory, despite the fact that the vector meson acquires mass.

We shall first treat the case where the original fields are a set of bosons ϕ_a which transform as a basis for a representation of a compact Lie group. This example should be considered as a rather general phenomenological model. As such, we shall not study the particular mechanism by which the symmetry is broken but simply assume that such a mechanism exists. A calculation performed in lowest order perturbation theory indicates that

(1962), they predict a branching ratio for decay mode (1) of $\sim 10^{-2}$.
 †N. P. Simon, Phys. Rev. **131**, 270 (1964).
 ††The best previously reported estimate comes from the limit on $K^0 \rightarrow \mu^+ \mu^- \nu$. The 90% confidence level is $4.6 \times 10^{-10} \text{ sec}^{-1}$. M. Haver, K. Lande, L. M. Lederman, and William Chinowsky, Ann. Phys. (N.Y.) **5**, 194 (1958). The absence of the decay mode $\mu^+ \rightarrow e^+ \nu_e \nu_\mu$ is not a good test for the existence of neutral currents since this decay mode may be absolutely forbidden by conservation of mass number. G. Feinberg and L. M. Lederman, Ann. Rev. Nucl. Sci., **13**, 465 (1963).
 †††S. Biswas and S. K. Bose, Phys. Rev. Letters **12**, 176 (1964).

these vector mesons which are coupled to currents that "ruinate" the original vacuum are the ones which acquire mass [see Eq. (6)].

We shall then examine a particular model based on chirality invariance^{††††} which may have a more fundamental significance. Here we begin with a chirality-invariant Lagrangian and introduce massive and pseudovector gauge fields, thereby guaranteeing invariance under both local phase and local γ_5 phase transformations. In this model the gauge fields themselves may break the γ_5 invariance leading to a mass for the original Fermi field. We shall show in this case that the pseudovector field acquires mass.

In the last paragraph we sketch a simple argument which renders these results reasonable.

(1) List the simplicity of the argument be shrouded in a cloud of indices, we first consider a one-parameter Abelian group, representing, for example, the phase transformation of a charged boson; we then present the generalization to an arbitrary compact Lie group.

The interaction between the ϕ and the A_μ fields is

$$i \int d^4x \phi^\dagger \partial_\mu \phi - e \phi^\dagger \gamma_5 \phi A_\mu, \quad (1)$$

where $\phi = (\phi_1, \phi_2)^T$. We shall break the symmetry by fixing $\langle \phi | \phi \rangle \neq 0$ in the vacuum, with the phase chosen for convenience such that $\langle \phi | \phi \rangle = \langle \phi_1 | \phi_1 \rangle$.

We shall assume that the application of the

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
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 (Received 10 August 1964)

In a recent note[†] it was shown that the Goldstone theorem,^{††} that Lorentz-covariant field theories in which spontaneous breakdown of symmetry under an internal Lie group occurs contain zero-mass particles, fails if and only if the conserved currents associated with the internal group are coupled to gauge fields. The purpose of the present note is to report that, as a consequence of this coupling, the spin-zero quanta of some of the gauge fields acquire mass; the longitudinal degrees of freedom of these particles (which would be absent if their mass were zero) go over into the Goldstone bosons when the coupling tends to zero. This phenomenon is just the relativistic analog of the plasmon phenomenon to which Anderson^{†††} has drawn attention: that the scalar zero-mass excitations of a superconducting neutral Fermi gas become longitudinal plasmon modes of finite mass when the gas is charged.

The simplest theory which exhibits this behavior is a gauge-invariant version of a model used by Goldstone^{††††} himself. Two real scalar fields ϕ_1, ϕ_2 and a real vector field A_μ interact through the Lagrangian density

$$L = \frac{1}{2} (\partial_\mu \phi_1)^2 - \frac{1}{2} (\partial_\mu \phi_2)^2 - \frac{1}{2} m^2 \phi_2^2 - \frac{1}{2} F_{\mu\nu}^2, \quad (1)$$

where

$$F_{\mu\nu} = \partial_\mu \nu_\nu - \partial_\nu \mu_\mu,$$

$$\nu_\mu = \phi_1 \partial_\mu \phi_2 - \phi_2 \partial_\mu \phi_1,$$

$$\mu_\mu = \phi_1 \partial_\mu \phi_1 - \phi_2 \partial_\mu \phi_2,$$

e is a dimensionless coupling constant, and the metric is taken as $g_{\mu\nu} = \delta_{\mu\nu}$. It is invariant under simultaneous gauge transformations of the first kind in ϕ_1, ϕ_2 and of the second kind on A_μ . Let us suppose that $\langle \phi_1 | \phi_1 \rangle \neq 0$, $\langle \phi_2 | \phi_2 \rangle = 0$; then spontaneous breakdown of (1) symmetry occurs. Consider the equations (derived from (1)) by treating ϕ_1, ϕ_2 and A_μ as small quantities^{†††††} governing the propagation of small oscillations

about the "vacuum" solution $\phi_1(x) = 0, \phi_2(x) = \nu_0$:

$$\partial^\mu \partial_\mu (\Delta_\mu \nu_1 - e \nu_2 A_\mu) = 0, \quad (2a)$$

$$[\partial^\mu \Delta_\mu \nu_2 + \nu_0^{-1} (\partial_\mu \nu_1)^2 - \Delta_\mu \nu_1] = 0, \quad (2b)$$

$$\partial_\mu \partial^\mu \nu_1 + e \nu_0^{-1} [\partial^\mu \nu_1 (\Delta_\mu \nu_1) - e \nu_2 \partial_\mu \nu_1]. \quad (2c)$$

Equation (2b) describes waves whose quanta have (bare) mass $(\Delta_\mu \nu_1)^2 / \nu_0$. Eqs. (2a) and (2c) may be transformed, by the introduction of new variables

$$B_\mu = A_\mu - (e \nu_0^{-1})^{-1/2} (\Delta_\mu \nu_1),$$

$$C_\mu = \nu_2 - B_\mu, \quad \nu_1 = \nu_0 + F_{\mu\nu}, \quad (3)$$

into the form

$$\partial_\mu \partial^\mu \nu_1 + \partial_\mu \partial^\mu \nu_2 - e^2 \nu_0^{-2} \nu_2^2 = 0, \quad (4)$$

Equation (4) describes vector waves whose quanta have (bare) mass $e \nu_0$. In the absence of the gauge field coupling ($e = 0$) the situation is quite different: Equations (2a) and (2c) describe zero-mass scalar and vector bosons, respectively. In passing, we note that the right-hand side of (2c) is just the linear approximation to the conserved current; it is linear in the vector potential, gauge invariance being maintained by the presence of the gradient term.[†]

When one considers theoretical models in which spontaneous breakdown of symmetry under a semisimple group occurs, one encounters a variety of possible situations corresponding to the various distinct irreducible representations to which the scalar fields may belong; the gauge field always belongs to the adjoint representation.^{††} The model of the most immediate interest is that in which the scalar fields form an octet under SU(3). Here one finds the possibility of two nonvanishing vacuum expectation values, which may be chosen to be the two $(0, 0, \frac{1}{2})$ or $(0, 0, -\frac{1}{2})$ states. There are two massive scalar bosons with just these quantum numbers; the remaining six components of the scalar octet combine with the corresponding components of the gauge-field octet to describe

from one or more compound states, probably in the 3P and 3S configurations.^{†††}
 ††The position of the hydrogen resonance on the energy scale is in very good agreement with theoretical predictions, which range from 9.5 to 9.5 eV.

Because of the difficulty of the present experiment the author had to seek advice on many aspects of the experiment. He is indebted to A. O. McCoubrey, R. F. C. Vesco, and F. Kaufman for advice on handling of atomic hydrogen; to B. R. McCaoy, J. L. Pack, and J. L. Moruzzi for advice on loan of high-power microwave equipment; to A. V. Phelps and P. J. Chantry for frequent discussions; and to W. J. Unlig, J. Kearney, and H. T. Garsika for technical assistance.

*This work was supported in part by the Advanced Research Projects Agency through the Office of Naval Research.

†P. G. Burke and H. M. Soby, Phys. Rev. **128**, 147 (1962). Their value for the energy at resonance is 9.43 eV, with a width of 0.109 eV. The state involved is the 3S state.

††P. G. Burke and K. Smith, in Atomic Collision Processes, edited by M. R. McDevitt (John Wiley & Sons, Inc., New York, 1964). They calculate the energy at resonance resulting from the $(1s2p)^1P$ state to be 9.78 eV, with 0.009 eV. They also calculate resonances resulting from $(1s1s)^1S$ and $(1s2p)^1P$ configurations at much lower energies.

†††M. Gell-Mann and D. Sharp, Proc. Phys. Soc. (London) **81**, 195 (1963).
 ††††G. J. Schulz, Phys. Rev. **138**, 4850 (1964).

†††††In addition to the usual problems encountered in calibrating energy scales, the charging of the glass and the existence of a residual plasma in the region in which the electron beam traverses the gas stream may play a role in establishing the potential in that region.

†††††The static cross section in both molecular and atomic hydrogen decreases with electron energy; thus the transmitted current as electron energy under our operating conditions is a steadily rising function. On such a curve it would be very difficult to observe such a curve if it were possible to alter the slope of the transmitted current as electron energy by adding various amounts of H_2 or He .

††††††A mixture of H_2 and He is difficult to establish the proper energy scale. It is a mixture of H_2 and He ; the rare gas serves both as a buffer gas for enhanced dissociation and as a calibrating gas.

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

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 (Received 12 October 1964)

In all of the fairly numerous attempts to date to formulate a consistent field theory possessing a broken symmetry, Goldstone's remarkable theorem^{††} has played an important role. This theorem, briefly stated, asserts that if there exists a conserved operator Q_i such that

$$[Q_i, \phi_j(x)] = -i \sum_k \delta_{jk} \phi_k(x),$$

and if it is possible consistently to take $\langle \phi_j | \phi_j \rangle \neq 0$, then $A_i(x)$ has a zero-mass particle. While this result might suggest a general procedure for the elimination of unwanted massless bosons, it will be seen that this has been accomplished by giving up the global conservation law usually

BRIEF COMMUNICATIONS
 †J. D. Schwinger, Rev. Mod. Phys. **35**, 916 (1963).
 ††It is possible to obtain an arbitrary ray of energy by taking a mixture of the two (1) representations for the above particles. This would require a non-conservation of the two (1) representations unless terms for the ϕ field theory.

BROKEN SYMMETRIES AND MASSLESS PARTICLES*

Robert Gilbert
 Jefferson Laboratories of Physics, Harvard University, Cambridge, Massachusetts
 (Received 19 March 1964)

In a recent note Kibble and Lee[†] have discussed the Goldstone theorem^{††} that any solution of a Lorentz-invariant theory that violates an internal symmetry operation of that theory will contain a massless scalar particle. They showed that this theorem does not necessarily apply in nonrelativistic theories and they pointed out that their work could apply to the original theorem. In this note they have examined the theorem also, treating as the non-relativistic case for reasons which will be explained in the next section.

Relativistic theories.—The Goldstone theorem can be derived from the behavior of the generator of the internal symmetry. Since this generator operator is related to a conserved Noether current, we can gain some information about the structure of the Fourier transform of a commutator of the conserved current with field quantities to prove the theorem. If the symmetry operation yields a conserved current, J_μ , such that

$$[J_\mu(x), \phi_j(y)] = i \delta_{\mu\nu} \phi_j(y) \quad (1)$$

is part of the structure of the symmetry operation, where ϕ_j and ψ_k are scalar or pseudoscalar quantities related from the field operators there is an appropriate relationship changing ϕ_j into ψ_k , and the violation of symmetry in the solution is that the vacuum expectation value of ϕ_j is not vanishing, then

$$i(f(\phi_j(x)), \psi_k(y)) = G_{jk}(x, y) \neq 0, \quad (2)$$

We may write the most general form for the structure of the Fourier transform of the vacuum expectation of the commutator of J_μ with ψ as

$$F(T) = i \int d^4x e^{ikx} (J_\mu(x), \psi(y)) \quad (3)$$

$$= i \int d^4x e^{ikx} (J_\mu(x), \psi(y)) \quad (3)$$

J_μ occurs because the commutator must be a δ -vector. In the structure (3), J_μ is actually

the total energy-momentum of the intermediate state that would arise in an expansion of the left-hand side. J_μ must be timelike. The conservation law, $\partial^\mu J_\mu = 0$, requires

$$\partial^\mu \langle \phi_j | J_\mu | \phi_j \rangle = 0 \quad \text{for all } \phi_j$$

and therefore

$$\partial_\mu \langle \phi_j | J_\mu | \phi_j \rangle = -C_{jk} p_\mu^2 \quad (4)$$

Thus, in the relativistic case, the Fourier transform of this commutator must be proportional to $\delta^4(k)$. Such a function arises only from a massless intermediate state. The broken symmetry condition (2) related to a conserved Noether current, we can gain some information about the structure of the Fourier transform of a commutator of the conserved current with field quantities to prove the theorem. If the symmetry operation yields a conserved current, J_μ , such that

$$[J_\mu(x), \phi_j(y)] = i \delta_{\mu\nu} \phi_j(y) \quad (1)$$

is part of the structure of the symmetry operation, where ϕ_j and ψ_k are scalar or pseudoscalar quantities related from the field operators there is an appropriate relationship changing ϕ_j into ψ_k , and the violation of symmetry in the solution is that the vacuum expectation value of ϕ_j is not vanishing, then

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J_μ occurs because the commutator must be a δ -vector. In the structure (3), J_μ is actually

introduced in order to define a renormalized gauge in which the vector gauge fields are well defined operators. Such theories are nevertheless Lorentz-covariant, as has been shown by Schwinger.[†] (This has, of course, long been known of the simplest such theory, quantum electrodynamics.) There seems to be no reason why the vector A_μ should not appear in the Fourier transform under consideration.

It is characteristic of gauge theories that the conservation laws hold in the strong sense, as a consequence of field equations of the form

$$\partial^\mu \phi_\mu = 0$$

$$F_{\mu\nu} = \partial_\mu \nu_\nu - \partial_\nu \mu_\mu \quad (5)$$

Except in the case of helicity gauges, the fields $A_\mu, F_{\mu\nu}$ are not simply the gauge field variables $A_\mu, F_{\mu\nu}$, but contain additional terms with coefficients that are structure constants of the gauge group. However, the structure of the Fourier transform of $(F_{\mu\nu}, \phi_\mu)$ must be given by eq. (5). Applying eq. (5) to this commutator gives us the Fourier transform of $(F_{\mu\nu}, \phi_\mu)$, $\psi_j(y)$ the simple term

$$i \int d^4x e^{ikx} (F_{\mu\nu}(x), \psi_j(y)) = i \delta_{\mu\nu} \psi_j(y) \quad (6)$$

both Goldstone's zero-mass bosons and the "topological" state ($\delta_{\mu\nu} = 0$) proposed by Klein and Lee.

In a subsequent note it will be shown, by considering some classical field theories which display broken symmetries, that the introduction of gauge fields may be shown to produce qualitative changes in the nature of the particles described by such theories after quantization.

References
 1. J. Schwinger, Nuovo Cimento **19** (1962) 542.
 2. J. Goldstone, A. Salam and S. Weinberg, Phys. Rev. **127** (1962) 965.
 3. A. Klein and B. W. Lee, Phys. Rev. Letters **12** (1964) 462.
 4. G. S. Guralnik, C. R. Hagen and T. W. B. Kibble, Phys. Rev. **139** (1962) 171.
 5. J. Schwinger, Phys. Rev. **127** (1962) 244.

It turns out, on applying eq. (1), that all three terms in eq. (4) can contribute to G_{jk} . Thus the Goldstone theorem fails if $\langle \phi_j | \phi_j \rangle \neq 0$. This is possible only if the other terms exist. Gilbert's remark that no special timelike vector ν_μ is available in a Lorentz-covariant theory appears to rule out this possibility in such a theory.

There is however a class of relativistic field theories in which a vector ν_μ does indeed play a part. This is the class of gauge theories, where an auxiliary unit timelike vector ν_μ must be introduced in order to define a renormalized gauge in which the vector gauge fields are well defined operators. Such theories are nevertheless Lorentz-covariant, as has been shown by Schwinger.[†] (This has, of course, long been known of the simplest such theory, quantum electrodynamics.) There seems to be no reason why the vector A_μ should not appear in the Fourier transform under consideration.

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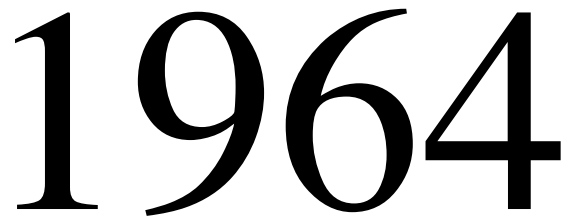
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References
 1. J. Schwinger, Nuovo Cimento **19** (1962) 542.
 2. J. Goldstone, A. Salam and S. Weinberg, Phys. Rev. **127** (1962) 965.
 3. A. Klein and B. W. Lee, Phys. Rev. Letters **12** (1964) 462.
 4. G. S. Guralnik, C. R. Hagen and T. W. B. Kibble, Phys. Rev. **139** (1962) 171.
 5. J. Schwinger, Phys. Rev. **127** (1962) 244.

Answering Gilbert's objection

Historical review in J. Iliopoulos (Higgs Hunting 2012)

<https://indico.lal.in2p3.fr/event/1747>



SSB and the Standard Model of EW interactions

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

1973: neutral current discovery
(Gargamelle experiment, CERN)

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

A MODEL OF LEPTONS*

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(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 unite¹ 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

$$L = \begin{bmatrix} \nu_e \\ e \end{bmatrix} \quad (1)$$

and on a right-handed singlet

$$R = \begin{bmatrix} \frac{1}{2}(1-\gamma_5)e \end{bmatrix} \quad (2)$$

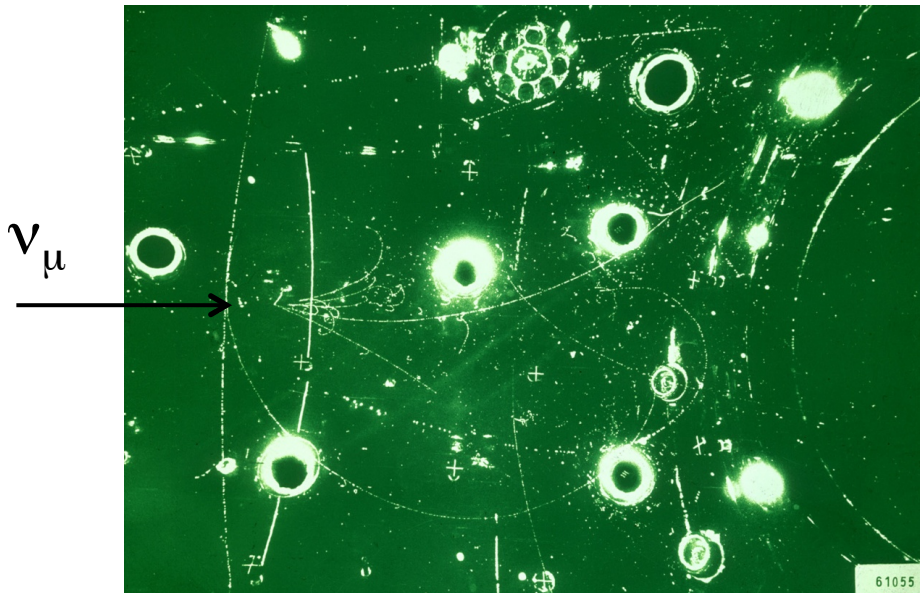
The largest group that leaves invariant the kinetic terms $-\bar{L}\gamma^\mu\partial_\mu L - \bar{R}\gamma^\mu\partial_\mu R$ of the Lagrangian consists of the electronic isospin \bar{T} acting on L , plus the numbers N_L , N_R of left- and right-handed electron-type leptons. As far as we know, two of these symmetries are entirely unbroken: the charge $Q = T_3 - N_R - \frac{1}{2}N_L$, and the electron number $N = N_R + N_L$. But the gauge field corresponding to an unbroken symmetry will have zero mass,⁴ and there is no massless particle coupled to N ,⁵ so we must form our gauge group out of the electronic isospin \bar{T} and the electronic hypercharge $Y = N_R + \frac{1}{2}N_L$.

Therefore, we shall construct our Lagrangian out of L and R , plus gauge fields \bar{A}_μ and B_μ coupled to \bar{T} and Y , plus a spin-zero doublet

$$\varphi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} \quad (3)$$

whose vacuum expectation value will break \bar{T} and Y and give the electron its mass. The only renormalizable Lagrangian which is invariant under \bar{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_μ



The Standard Model of EW Interactions

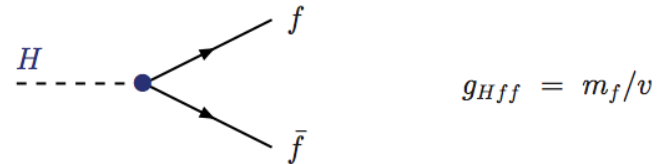
$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\Psi} \not{D} \Psi + h.c.$$

The elegant gauge sector

The least elegant Higgs sector

- Non universal interactions not governed by a symmetry
- Bares most of the free parameters of the SM

...but predictive!

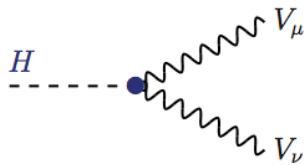


$$g_{Hff} = m_f/v$$

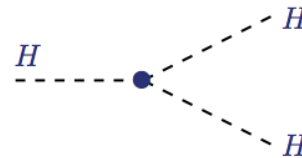
Not explaining the flavor Hierarchy

For neutrinos: introduction of a Dirac right handed neutrino is fine... but incredibly large hierarchy!
Majorana mass term possible and more natural

Gauge boson masses and couplings to the Higgs field



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



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

$$V(\varphi) = \mu^2 \varphi^* \varphi + \lambda (\varphi^* \varphi)^2 \quad v = -\frac{\mu^2}{\lambda}$$

First Bounds

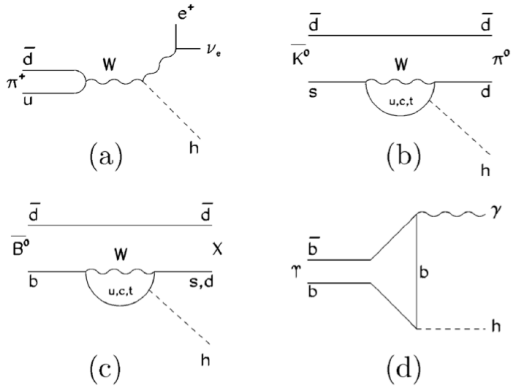
Astrophysical and Phenomenological

- Effect on Cosmic Microwave background ($0.1 \text{ eV} < m_H < 100 \text{ eV}$)
(Sato and Sato, 1975)
- Emission from stars: $m_H > 0.7 m_e$
(Sato and Sato, 1975)
- Neutron-electron scattering: $m_H > 0.7 \text{ MeV}$
(Rafelski, Muller, Soff and Greiner; Watson and Sundaresan, 1974)
- Neutron-electron scattering: $m_H > 0.7 \text{ MeV}$
(Adler, Dashen and Treiman; 1974)
- Neutron-nucleus scattering: $m_H > 13 \text{ MeV}$
(Barbieri and Ericson, 1975)
- Nuclear $^{16}\text{O}(6.05 \text{ MeV})$ to ground state ($0^+ - 0^+$) transitions (can occur through Higgs emission): $m_H > 18 \text{ MeV}$
(Kohler, Watson and Becker, 1974)

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

The situation with regard to Higgs bosons is unsatisfactory. First it should be stressed that they may well not exist. Higgs bosons

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.



LEP1 e⁺e⁻ at COM ~m_Z

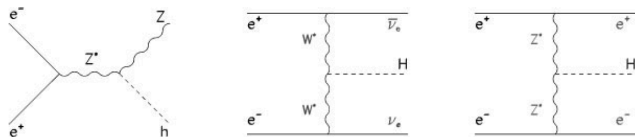
Various decays and topologies

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



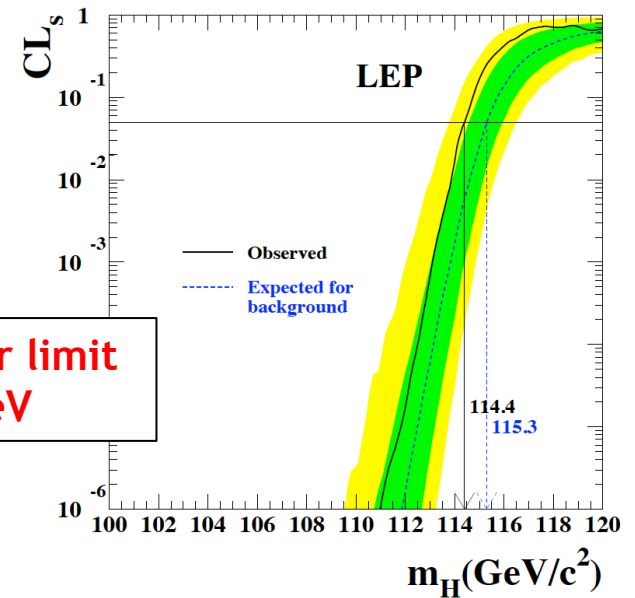
LEP2 e⁺e⁻ up to 209 GeV

(mostly bb and ττ decays)



Nano review of Pre-LHC Direct Constraints 1976 – 2010

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

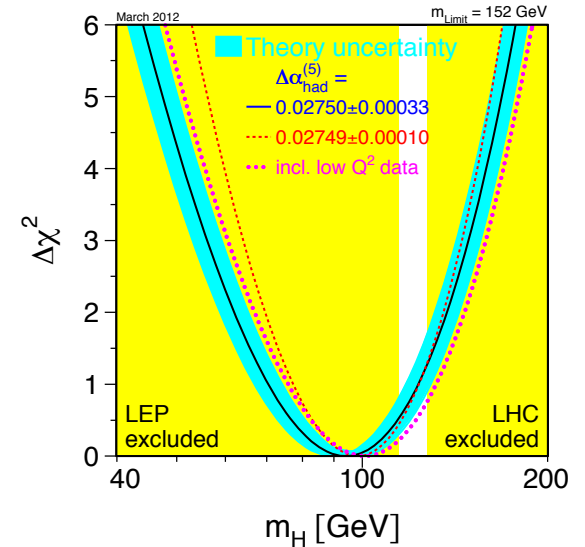
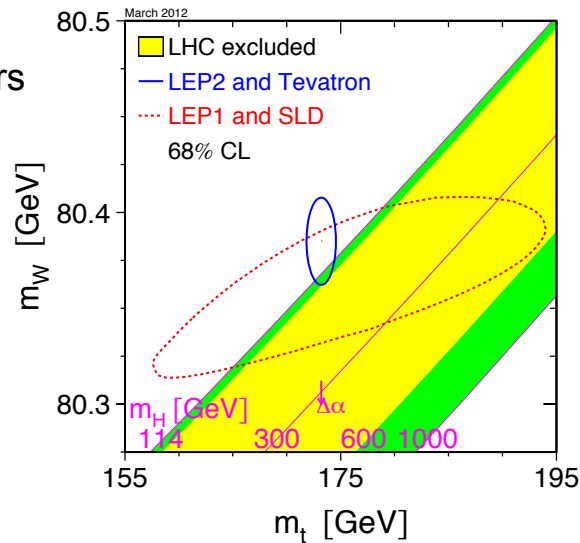
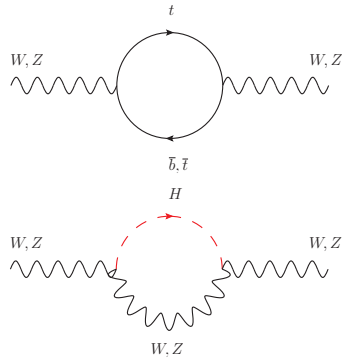


**Absoute lower limit
at 114 GeV**

Indirect Direct Constraints from Precision EW

At tree level, the gauge sector of the standard model has 3 free parameters not counting the Higgs mass and the fermion masses and couplings.

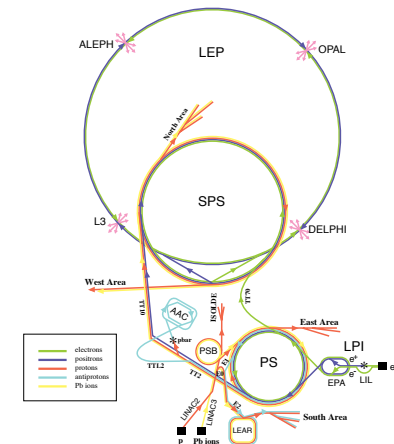
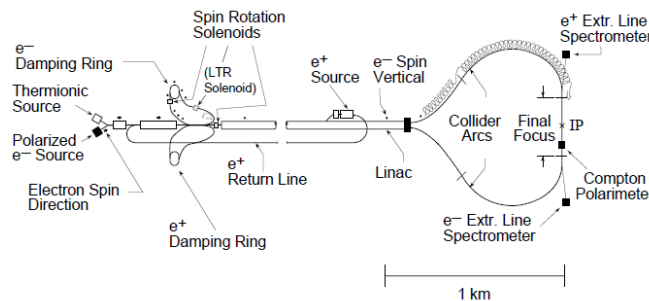
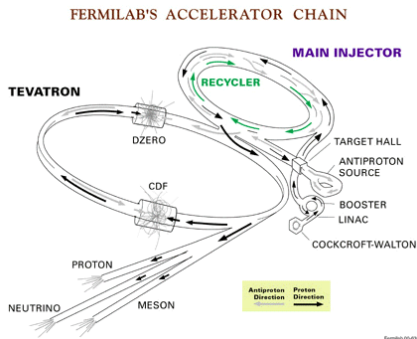
Precise measurement of EW parameters allow to constrain indirectly other parameters e.g. Higgs boson mass (or the top mass)



Tevatron 1987-2011
pp ~2TeV

SLC 1988-1998
e⁺e⁻ 91GeV

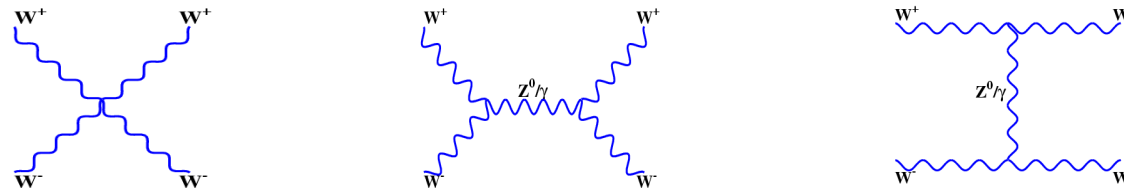
LEP 1989-2000
e⁺e⁻ 91GeV, 130-208GeV



The No Loose Theorem*

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 :

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

This is not only a motivation for the Higgs mechanism but is also a constraint on its mass... Otherwise strong interaction at the TeV scale.

Additional constraint on Higgs mass from the running of the quartic coupling (triviality similar upper limit) or vacuum stability (lower limit)

No Loose Theorem: Either a Higgs is found at the LHC (at a mass below 1 TeV) or interesting behavior of VBS scattering!

Outline

1.- Introduction and Context

2.- The « Bread and Butter » Discovery Channels, the detectors and the machine

3.- Discovery channels beyond discovery

4.- Overview of post-discovery Higgs physics

5.- Glimpse at HL-LHC

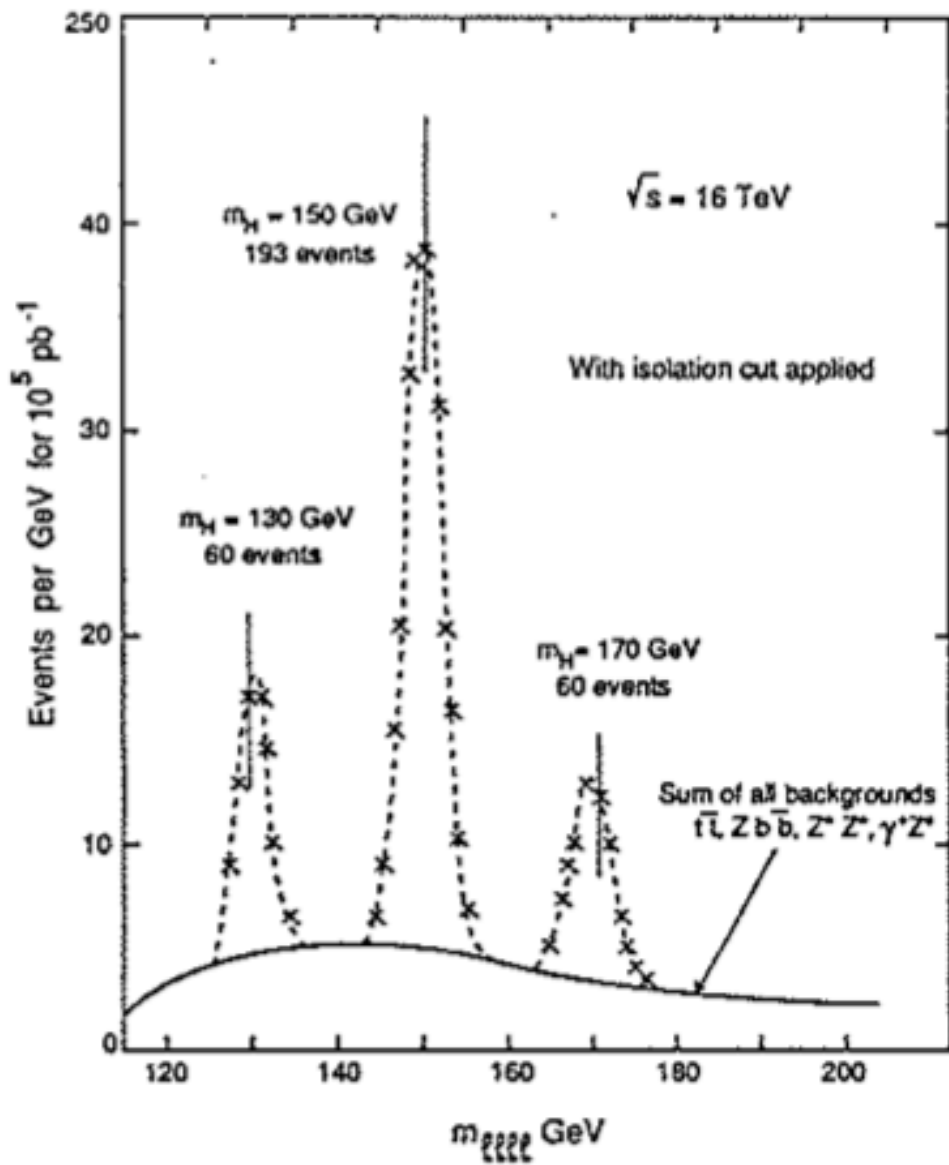
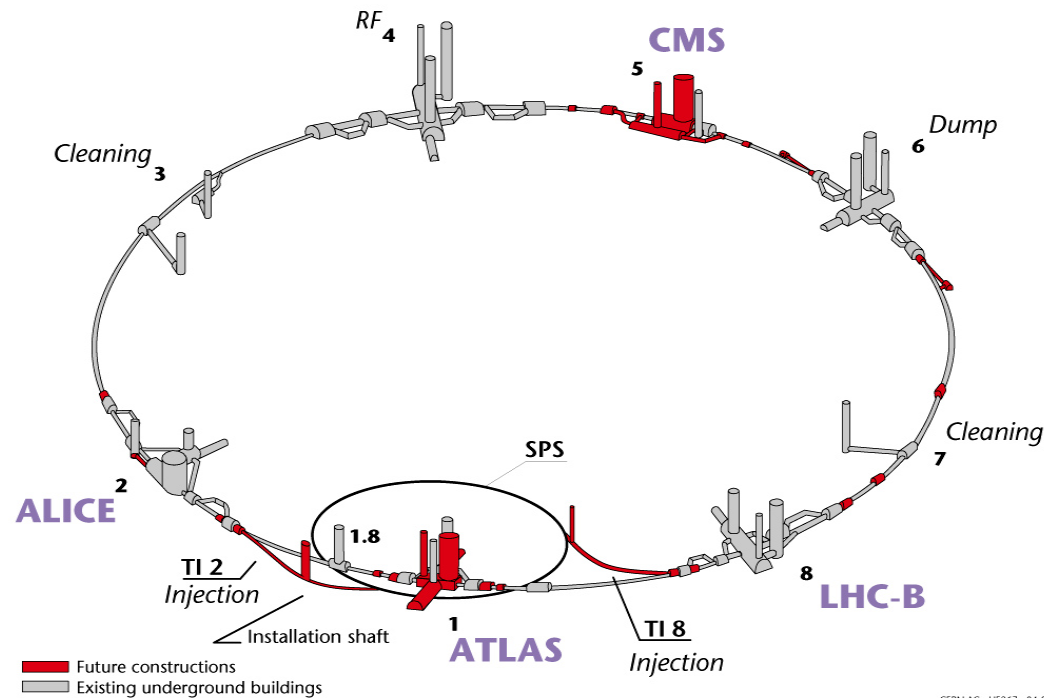


Fig. 10

1990

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

Projected Nominal Specifications of the LHC



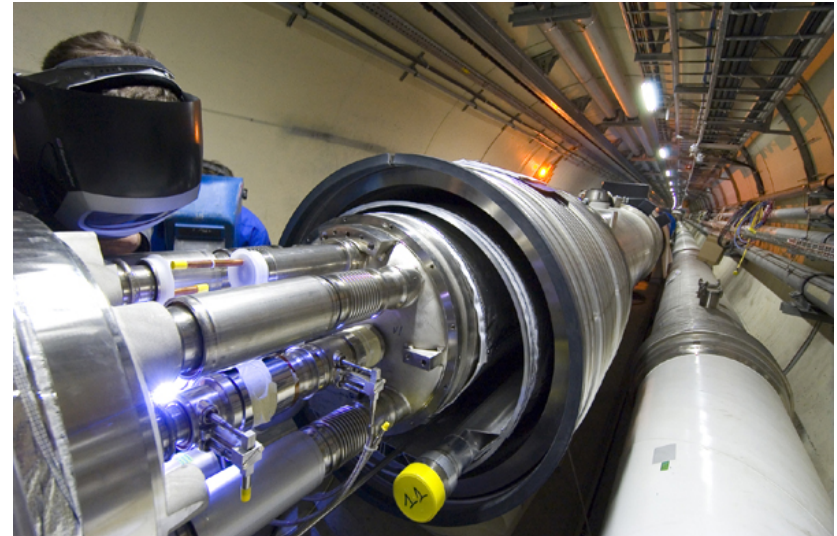
Main Numbers

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

Parameter	Nominal
C.O.M Energy	14 TeV
N_p	$1.15 \cdot 10^{11}$
Bunch spacing / k	25 ns / 2808
ϵ (mm rad)	3.75
β^* (m)	0.55
L ($\text{cm}^{-2}\text{s}^{-1}$)	10^{34}

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

Design, Construction and Commissioning of the LHC



Operation challenge: Unprecedented beam energy and luminosities (for a hadron machine)

- Main challenge : Stored beam energy 2 orders of magnitude higher than existing machines... 350 MJ
- Total stored energy in the magnets (11 GJ, enough to melt 15 tons of copper)

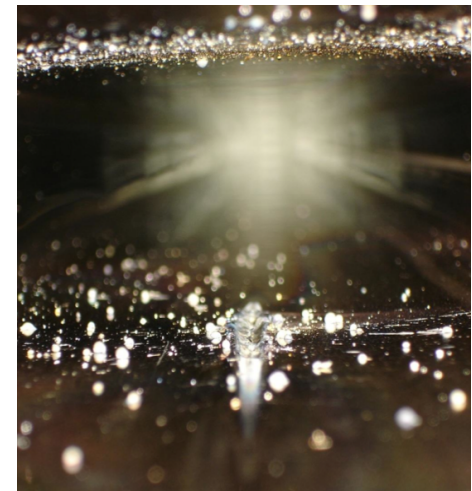
Risk of damage is the main concern :

- **From the stored beam energy**

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

- **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

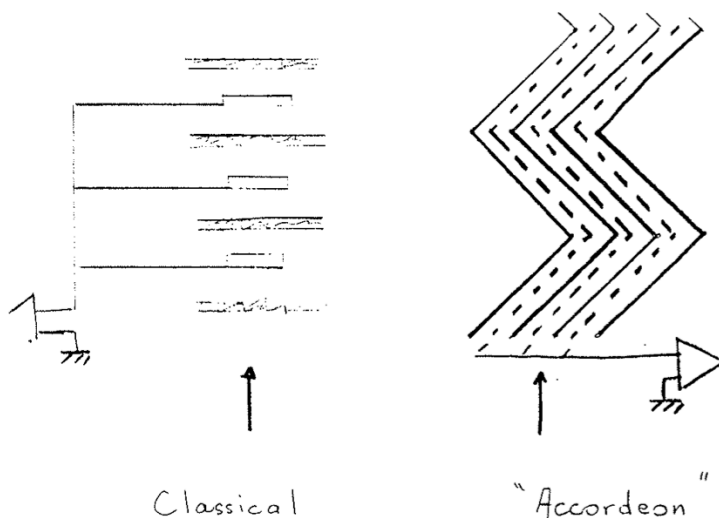
D.Fournier 5-jan-90

An approach to high granularity, fast Liq Ar calorimetry
using an "accordeon" structure

1) BASIC IDEA

In the conventional 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 make a 45 angle with the converter plates. To first order resolution similar to the standard case is recovered by choosing converter plates thinner by $\sqrt{2}$.



Years of Design, Construction and Commissioning of Experiments

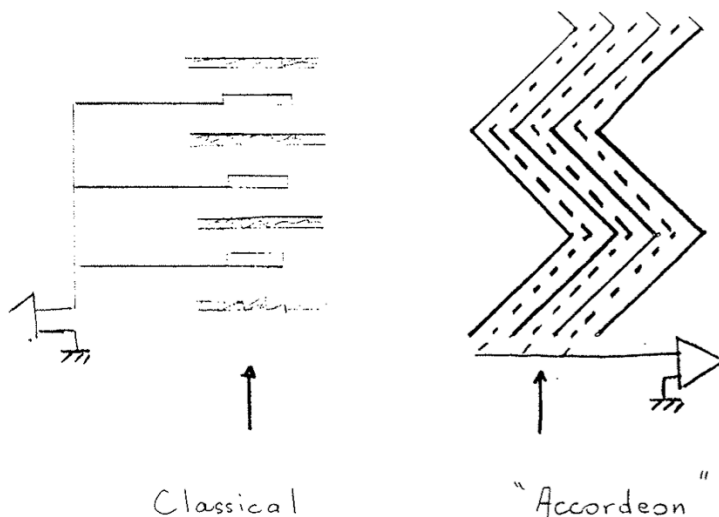
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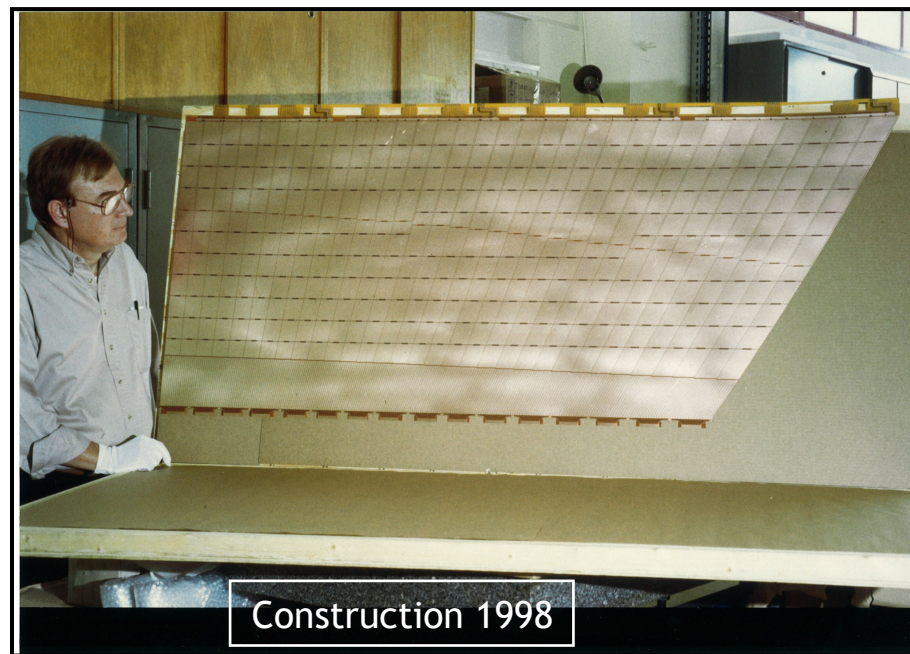
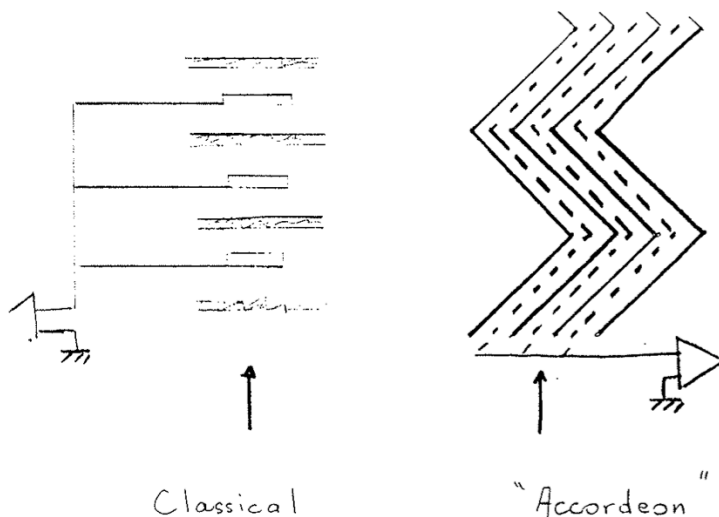
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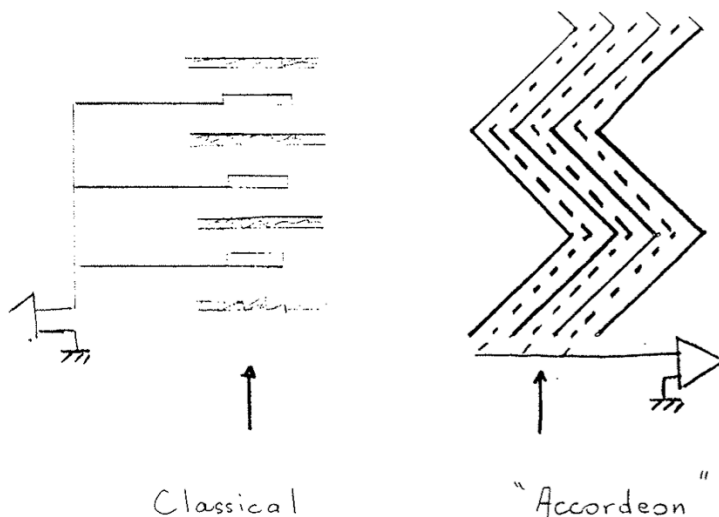
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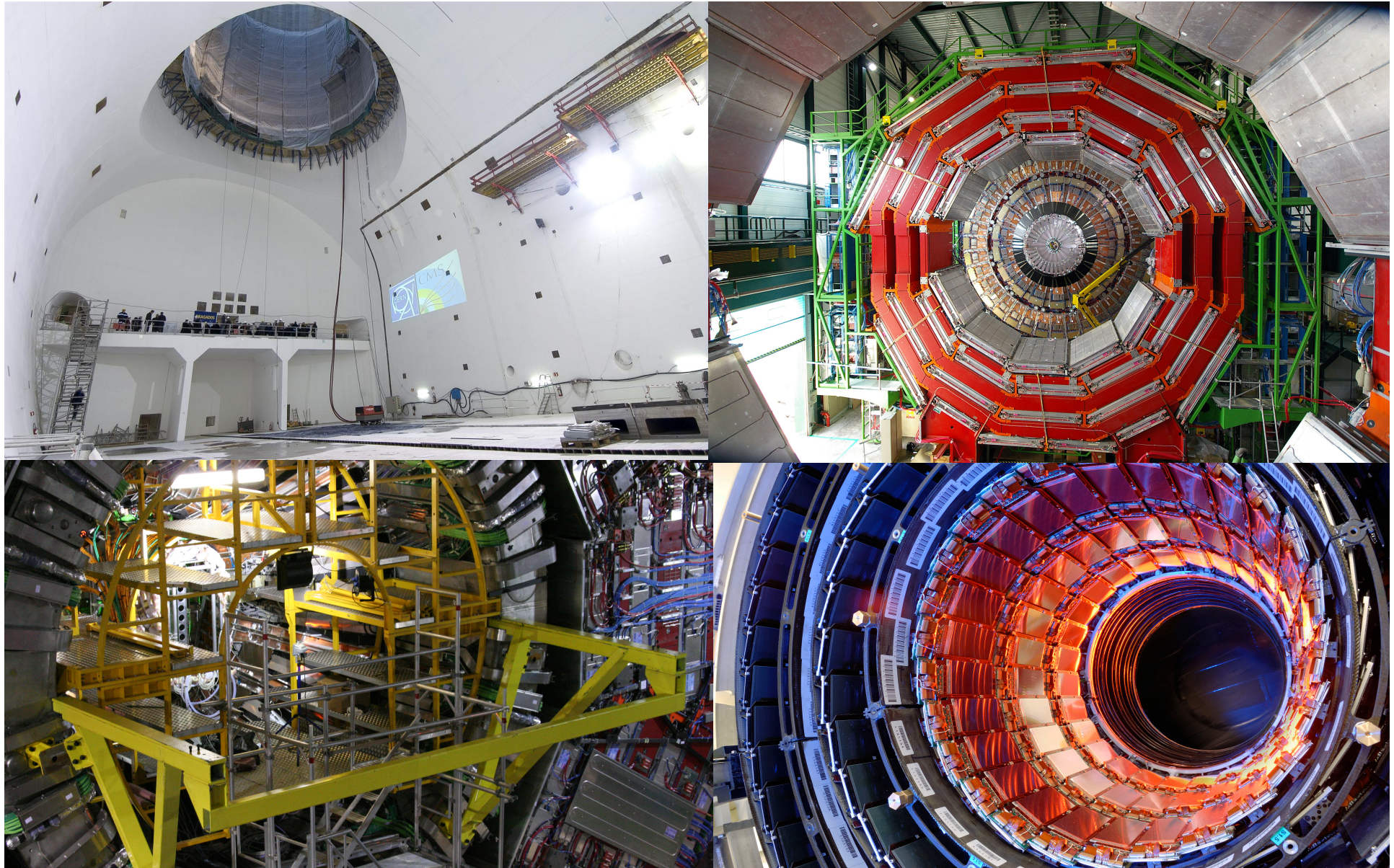
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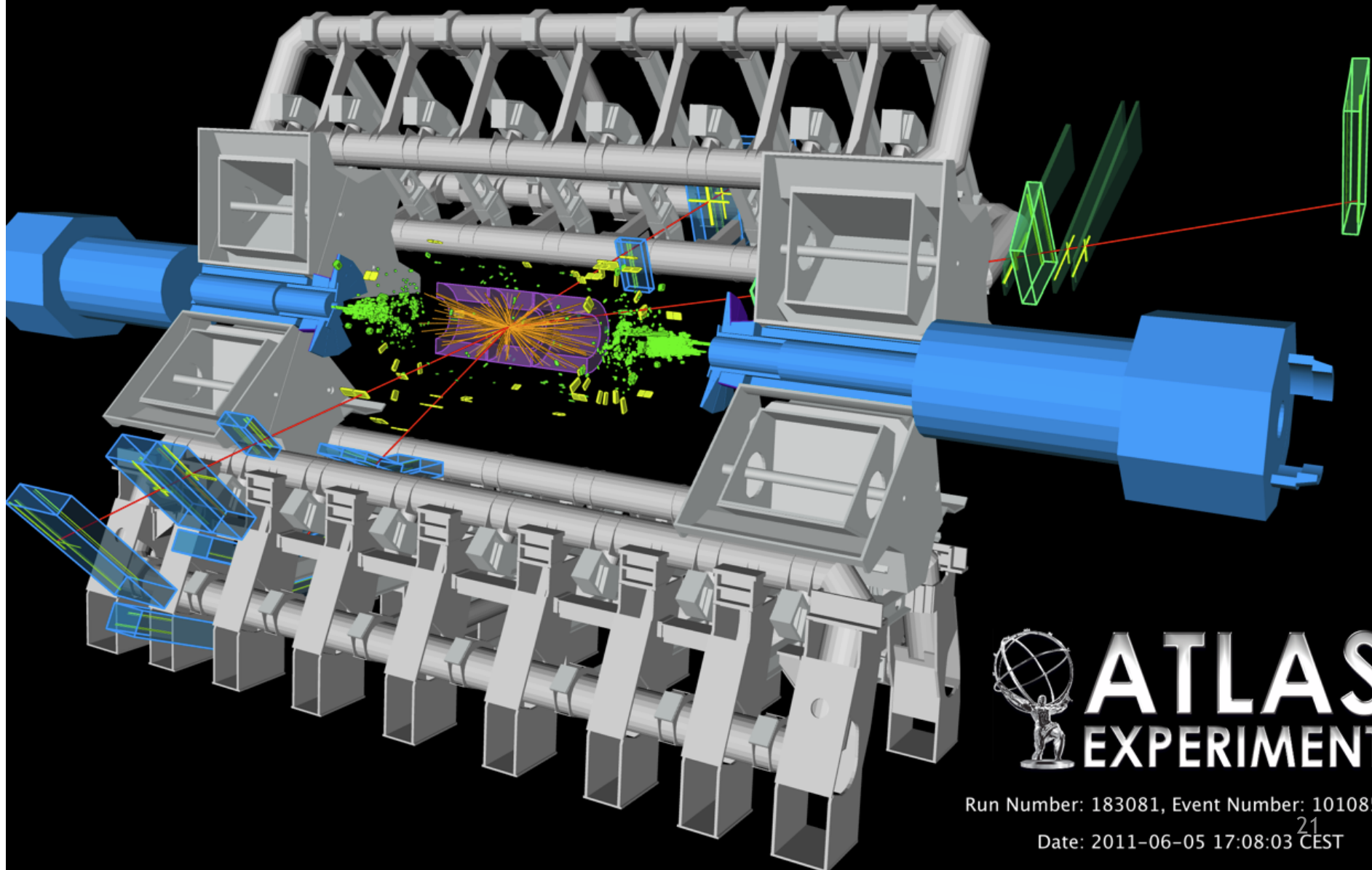


Installation 2004

Years of Design, Construction and Commissioning of Experiments

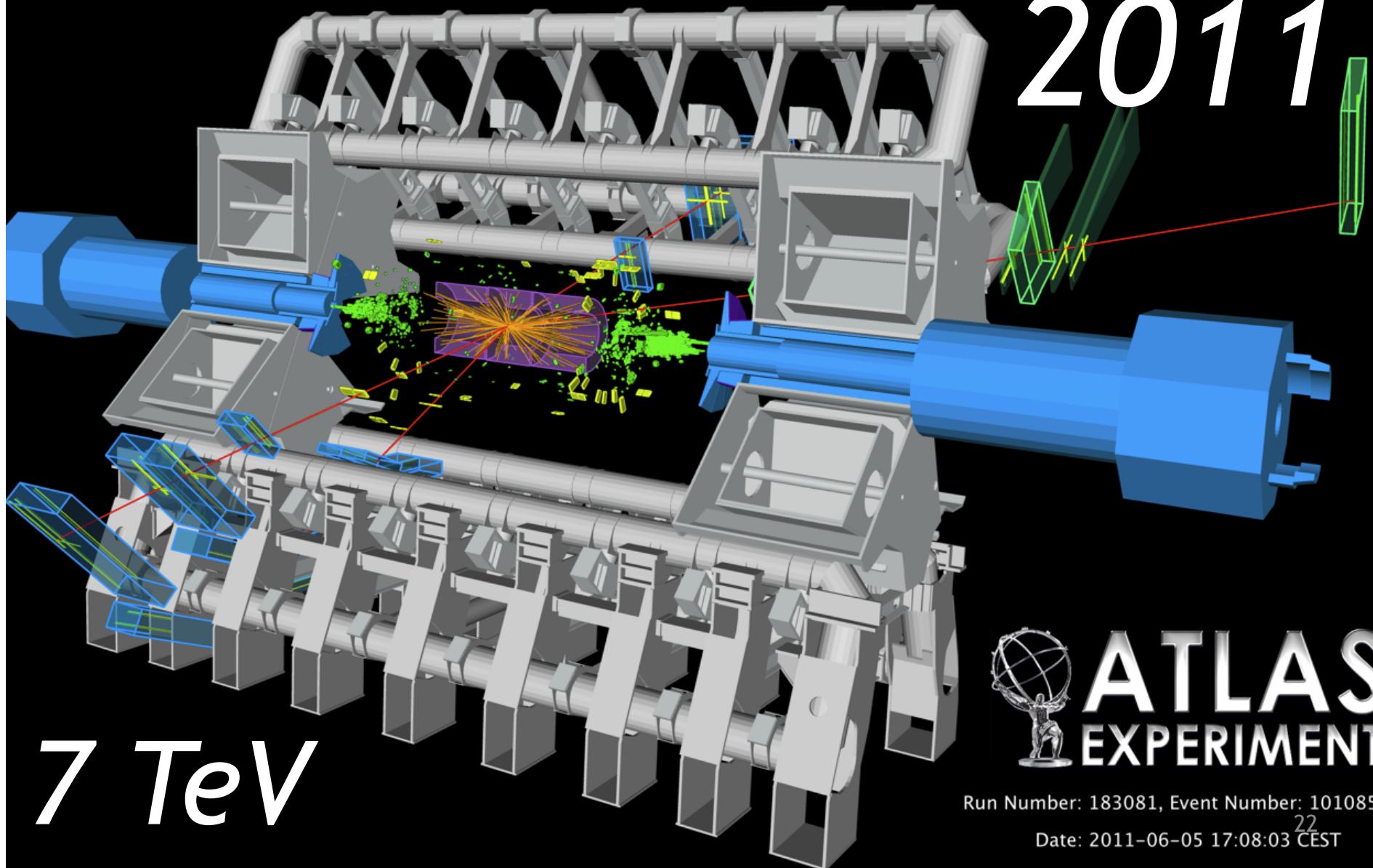


4 μ event ... *Standard EW only or Higgs?*



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

2011



7 TeV

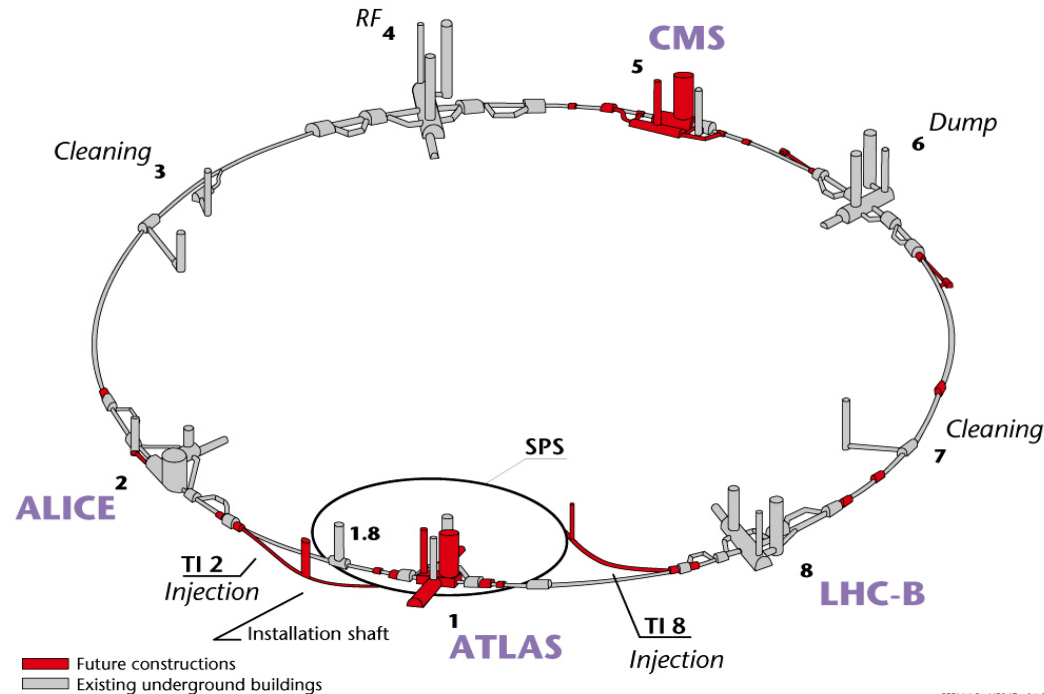


ATLAS
EXPERIMENT

Run Number: 183081, Event Number: 10108572

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

Three Years of LHC operations



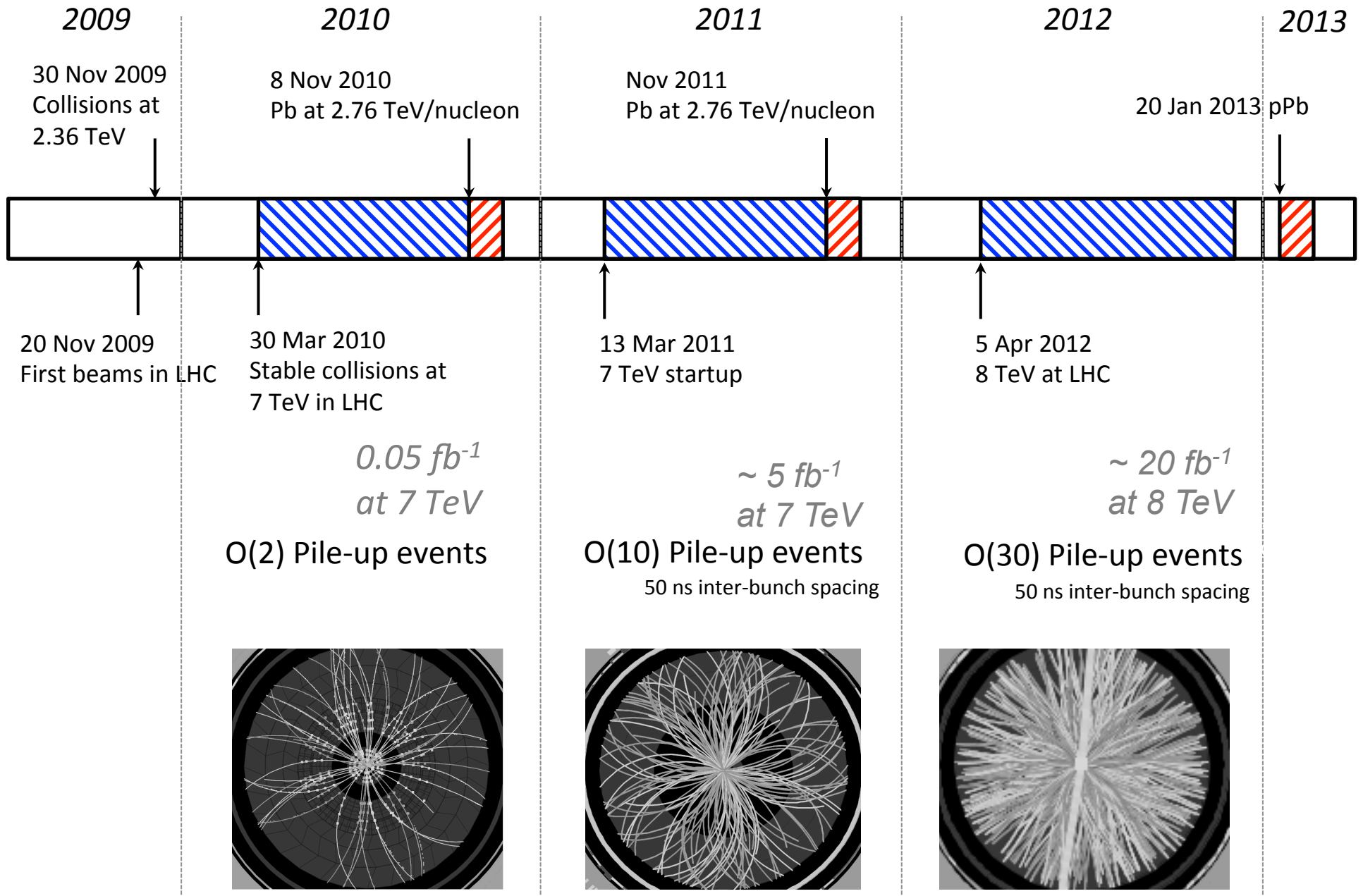
The LHC

- 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)

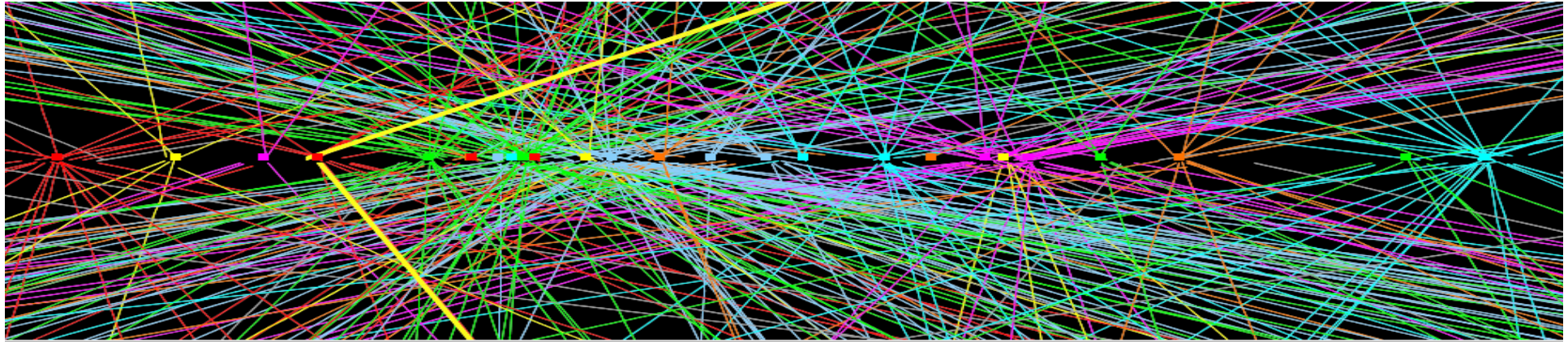
$$\mathcal{L} = \frac{N_p^2 k_b f_{rev} \gamma}{4\pi \beta^* \epsilon_n} F$$

Parameter	2010	2011	2012	Nominal
C.O.M Energy	7 TeV	7 TeV	8 TeV	14 TeV
N_p	$1.1 \cdot 10^{11}$	$1.4 \cdot 10^{11}$	$1.6 \cdot 10^{11}$	$1.15 \cdot 10^{11}$
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 ($\text{cm}^{-2}\text{s}^{-1}$)	$2 \cdot 10^{32}$	$3.3 \cdot 10^{33}$	$\sim 7 \cdot 10^{33}$	10^{34}

The LHC Run 1

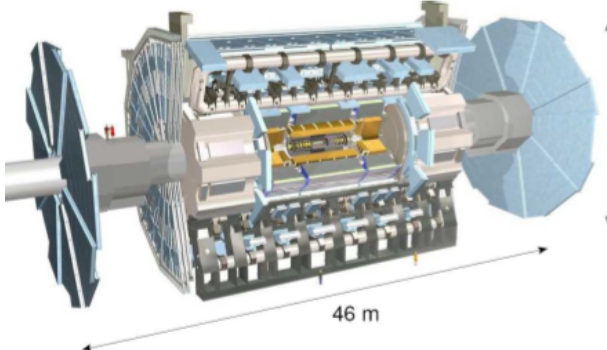
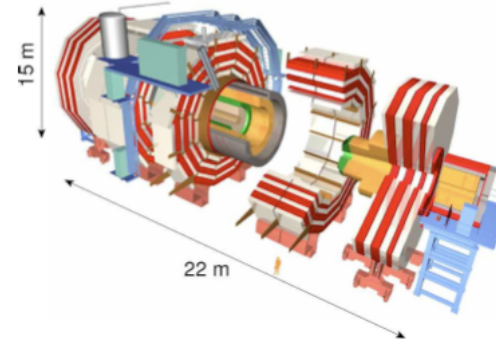


Detector Challenges



- **Trigger Challenge** : How to select typically 400-1000 out of 20M events per second while keeping the interesting (including unknown) physics
- **Computing Challenge** : How to reconstruct, store and distribute 1000 increasingly complex events per second and the very large amount of simulation (over 100 PB per experiment)
- **Analysis Challenge** : Maintain high (and as much as possible stable) reconstruction and identification efficiency for physics objects (e, μ , τ , jets, E_{mis}^T , b-jets) up to the highest pile-up

The ATLAS and CMS Performance In a Nutshell

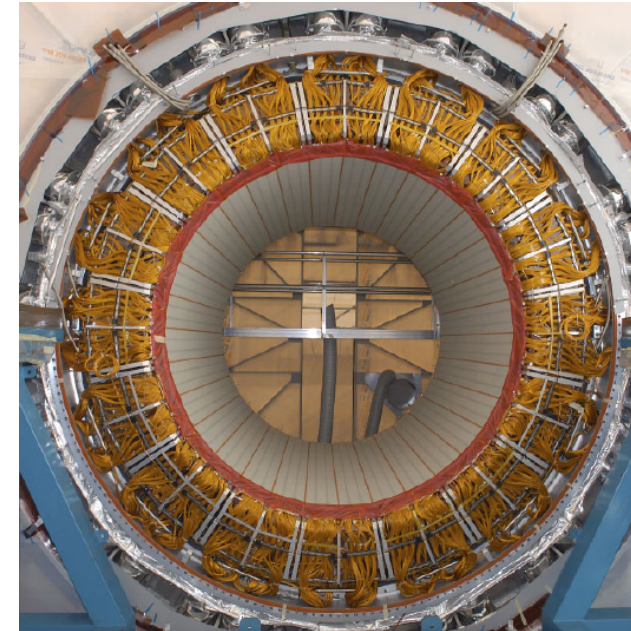
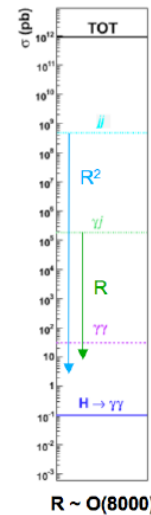
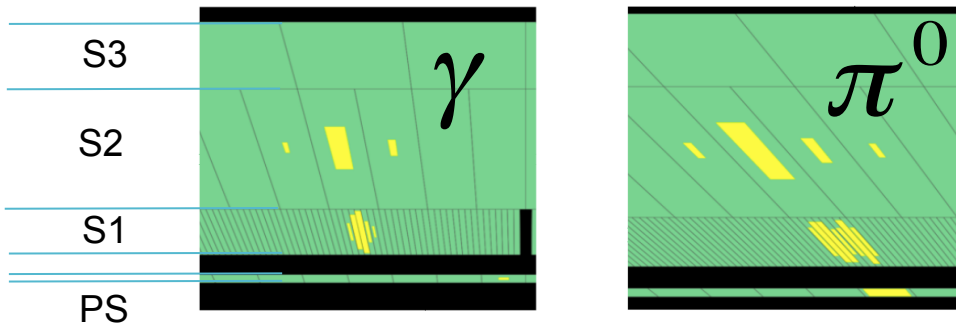
Sub System	ATLAS	CMS
Design		
Magnet(s)	Solenoid (within EM Calo) 2T 3 Air-core Toroids	Solenoid 3.8T Calorimeters Inside
Inner Tracking	Pixels, Si-strips, TRT PID w/ TRT and dE/dx $\sigma_{p_T}/p_T \sim 5 \times 10^{-4} p_T \oplus 0.01$	Pixels and Si-strips PID w/ dE/dx $\sigma_{p_T}/p_T \sim 1.5 \times 10^{-4} p_T \oplus 0.005$
EM Calorimeter	Lead-Larg Sampling w/ longitudinal segmentation $\sigma_E/E \sim 10\%/\sqrt{E} \oplus 0.007$	Lead-Tungstate Crys. Homogeneous w/o longitudinal segmentation $\sigma_E/E \sim 3\%/\sqrt{E} \oplus 0.5\%$
Hadronic Calorimeter	Fe-Scint. & Cu-Larg (fwd) $\gtrsim 11\lambda_0$ $\sigma_E/E \sim 50\%/\sqrt{E} \oplus 0.03$	Brass-scint. $\gtrsim 7\lambda_0$ Tail Catcher $\sigma_E/E \sim 100\%/\sqrt{E} \oplus 0.05$
Muon Spectrometer System Acc. ATLAS 2.7 & CMS 2.4	Instrumented Air Core (std. alone) $\sigma_{p_T}/p_T \sim 4\%$ (at 50 GeV) $\sim 11\%$ (at 1 TeV)	Instrumented Iron return yoke $\sigma_{p_T}/p_T \sim 1\%$ (at 50 GeV) $\sim 10\%$ (at 1 TeV)

The ATLAS Electromagnetic Calorimeter Granular and Uniform by Construction!

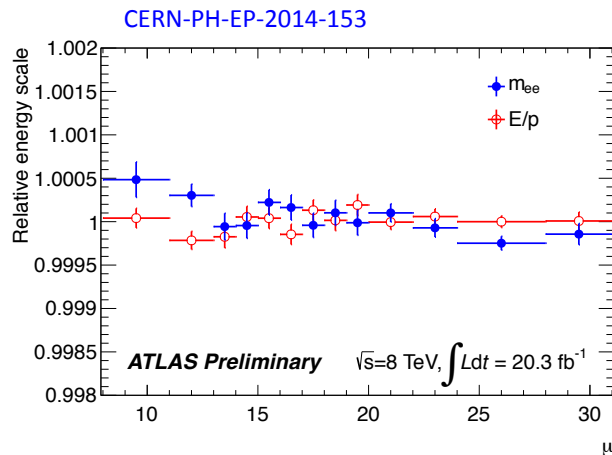
Both longitudinal and transverse granularity:

- Photon – Pion discrimination
- Pointing direction reconstruction

π^0 - γ Rejection



Crack-less Accordion geometry



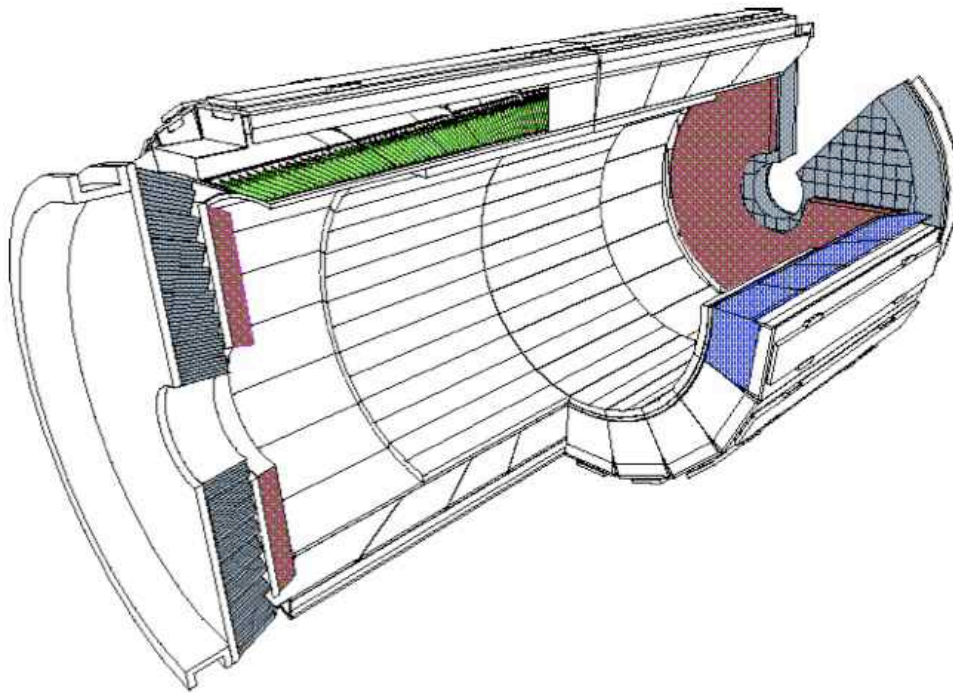
A.- Stability in time within: 0.05%

B.- Stability in PU within: 0.05%

The CMS Crystal Calorimeter

Homogeneous, Compact, Hermetic, Granular PbWO_4 Crystal calorimeter

- Barrel up to eta of 1.48 (61200 Crystals 2.2 x 2.2 x 23 cm)
- Endcap up to eta 3 (14648 Crystals 2.6 x 2.6 x 22 cm)

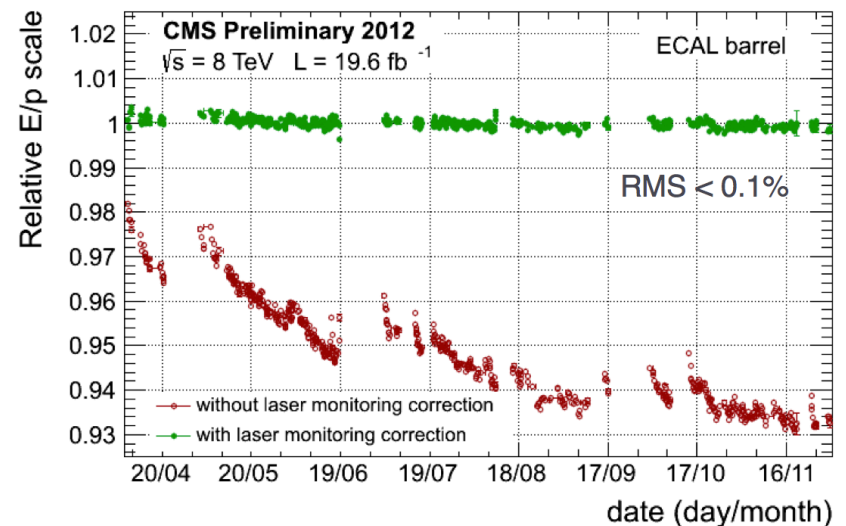


Intercalibration and transparency corrections

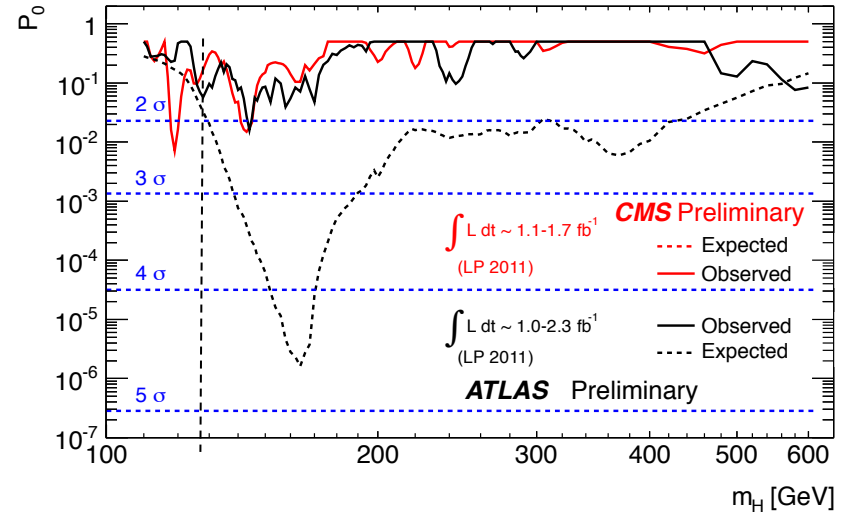
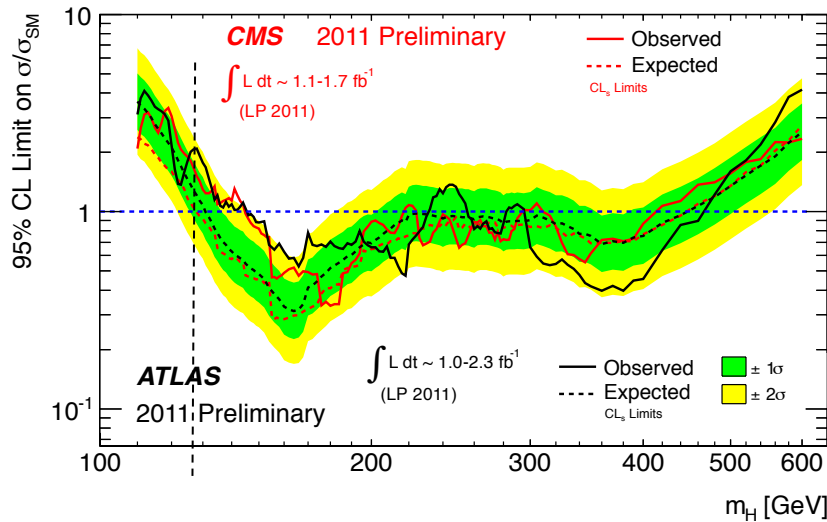
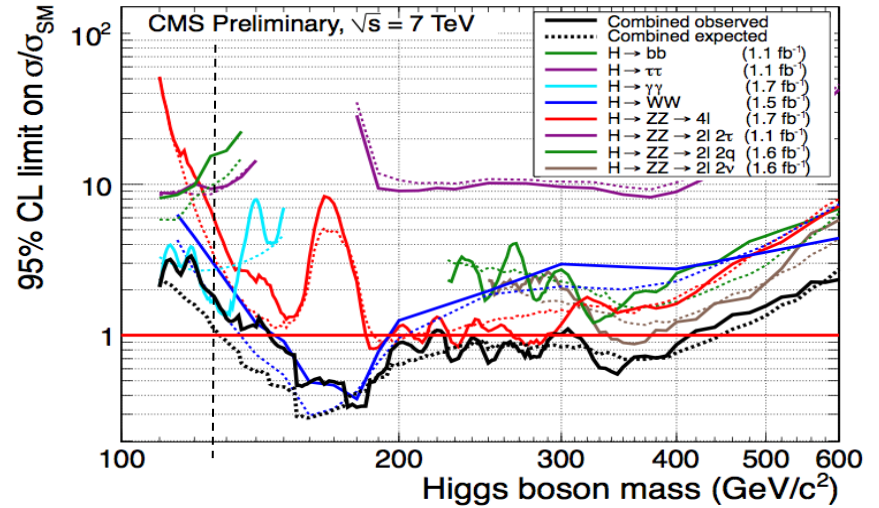
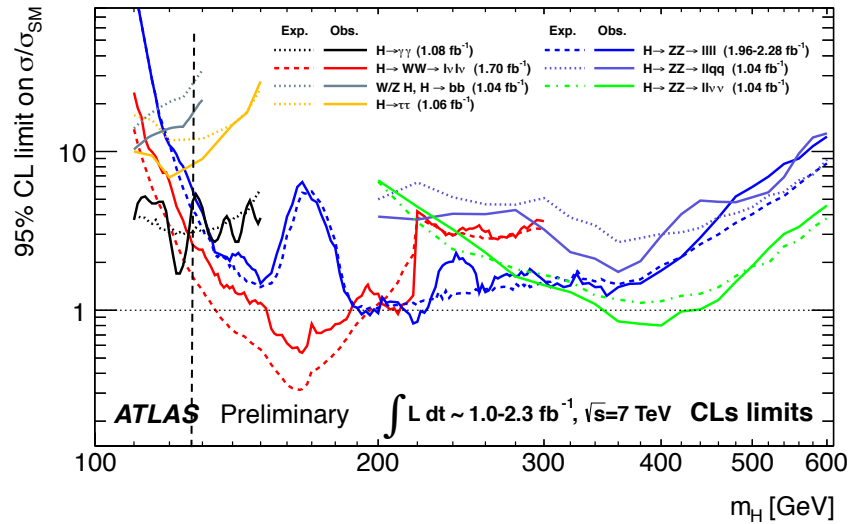
- Transparency (Laser) every 40mn
- Monthly using π^0

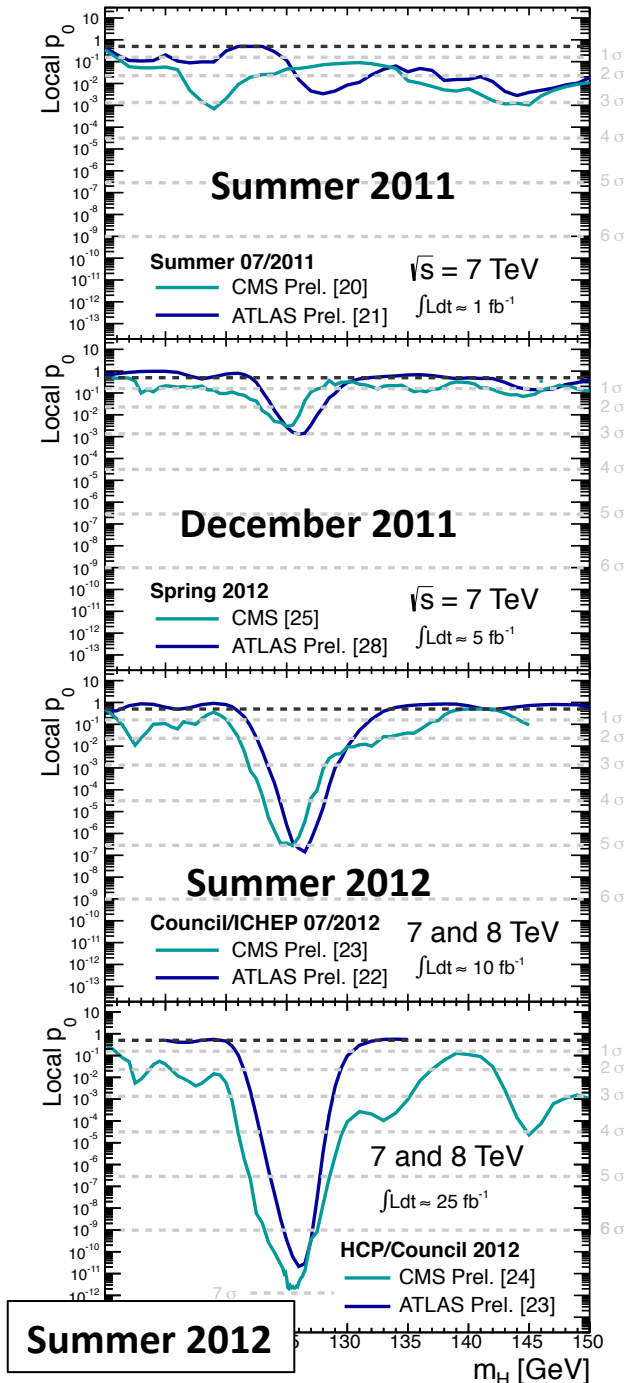
Emphasis on Resolution!

Stability in time within: 0.1%



Summer of 2011: From the Limit to the p0 Era





A Textbook and Timely Discovery

- Summer 2011: EPS and Lepton-Photon
 First (and last) focus on limits (scrutiny of the p_0)
 - December 2011: CERN Council
 First hints
 - Summer 2012: CERN Council and ICHEP
 Discovery!
 - December 2012: CERN Council
 Beginning of a new era
- ✓ Strongly Mostivated
 - ✓ Significance increased with luminosity to reach unambiguous levels
 - ✓ Two experiments
 - ✓ Several channels

Outline

1.- Introduction and Context

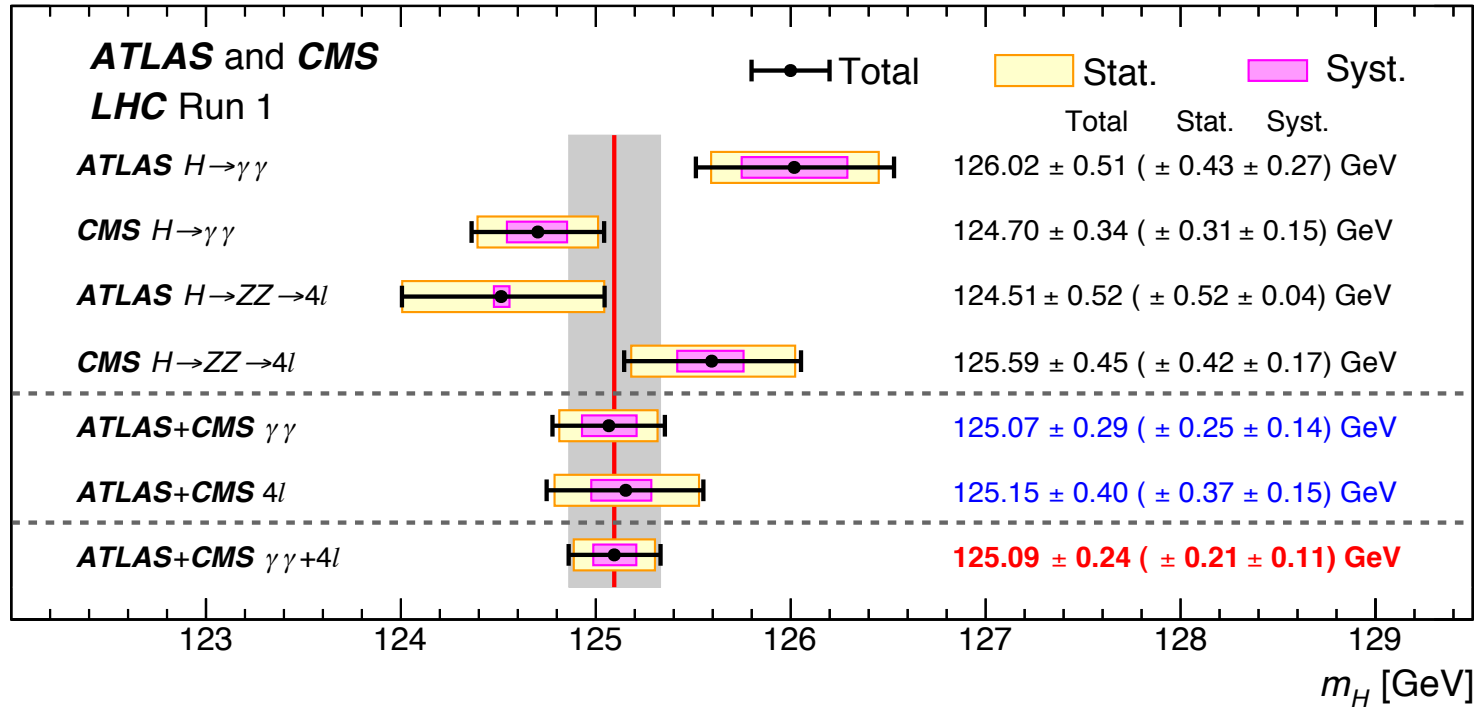
2.- The « Bread and Butter » Discovery Channels, the detectors and the machine.

3.- Discovery channels beyond discovery

4.- Overview of post-discovery Higgs physics

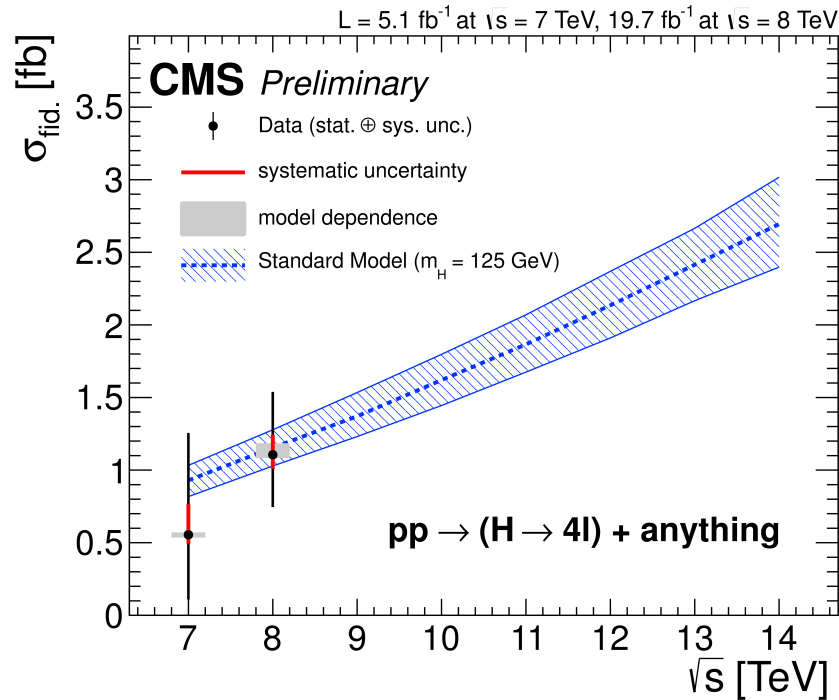
5.- Glimpse at HL-LHC

A Per mille Precision Measurement



- Statistics dominated Measurement
- Systematic uncertainties completely dominated by calibration uncertainties
Required new GEO model and specific calibration
- Compatibility of the four measurements $O(10\%)$
- Slight tension between ATLAS $4l$ and $\gamma\gamma \sim 2\sigma$

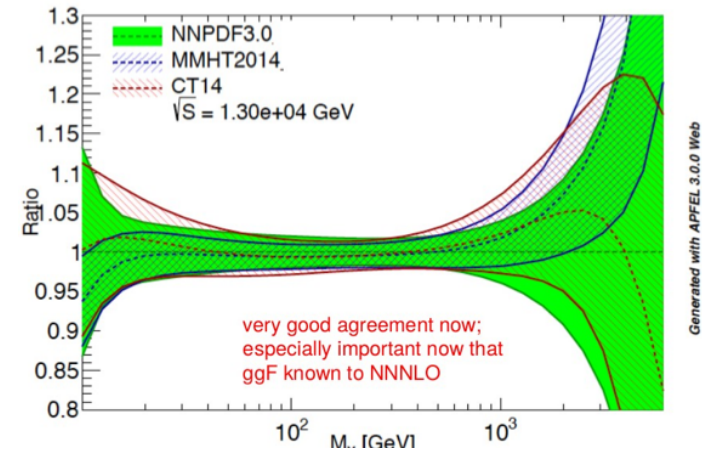
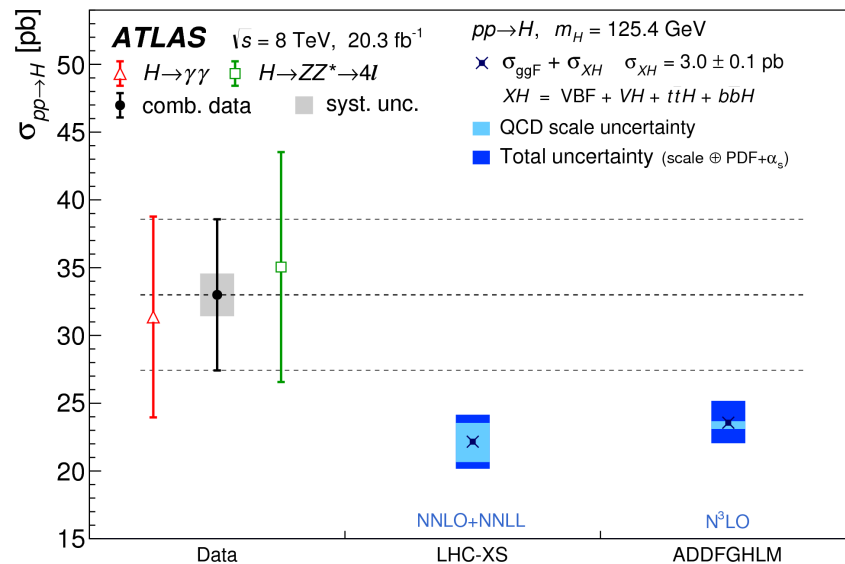
Total and Fiducial Cross Sections



The discovery channels are used to set the best model dependent measurements of the Higgs production cross section: Fiducial, which are extrapolated also to total cross sections.

Unprecedented level of ggF precision: N3LO

Presented at Moriond QCD 2015

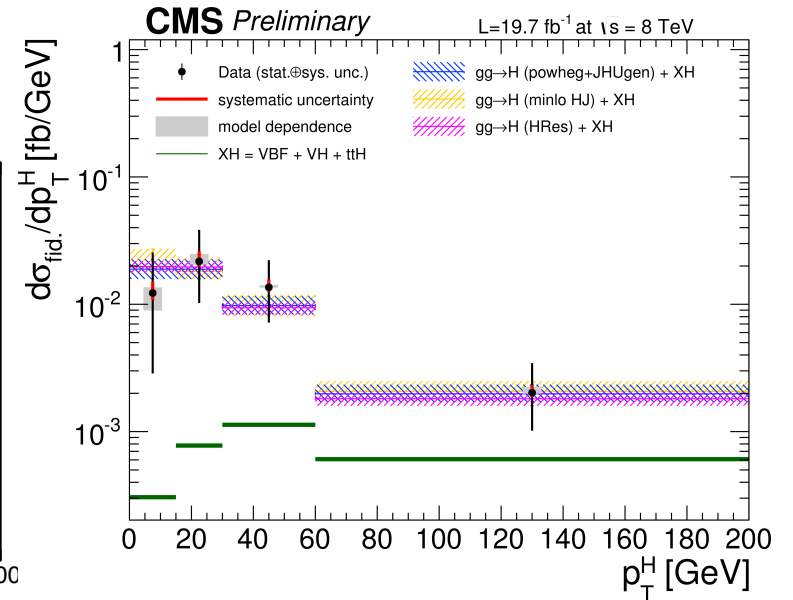
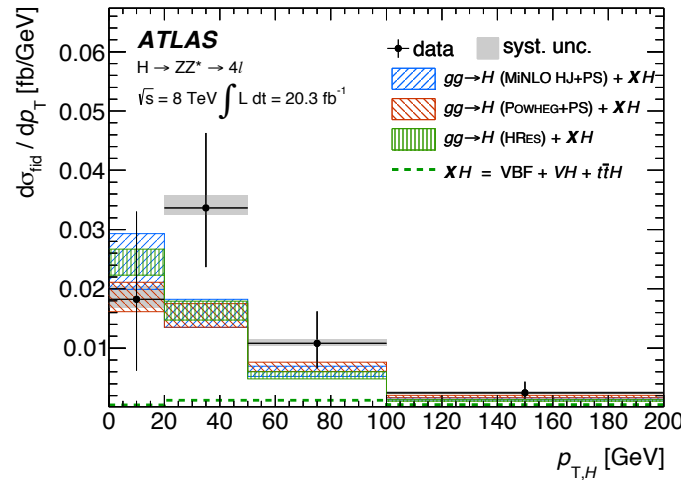


New NNPDF3.0 as well ! α_s ?

Differential Cross Section

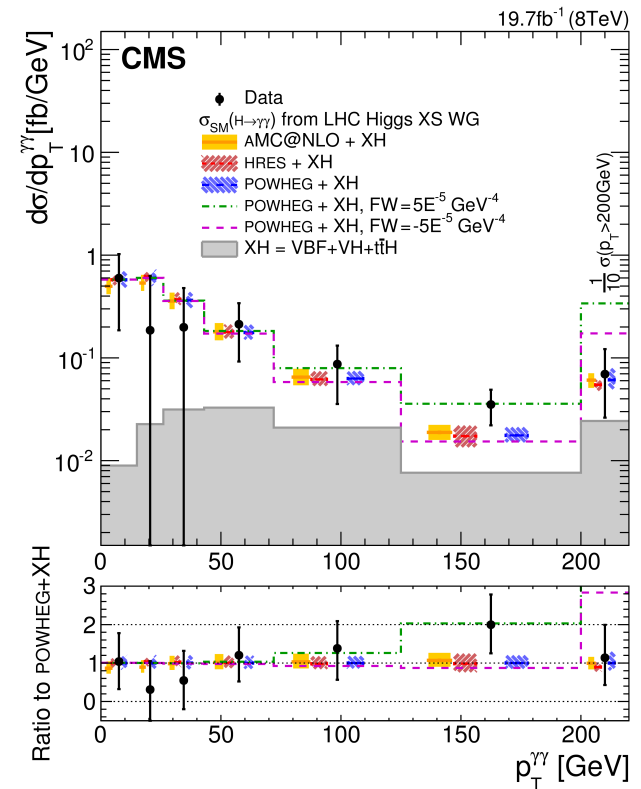
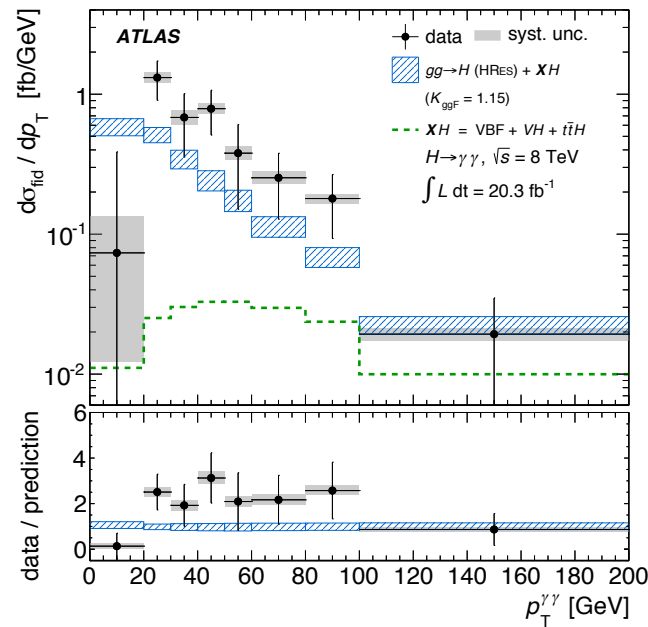
$$H \rightarrow 4l$$

Phys. Lett. B 738 (2014)

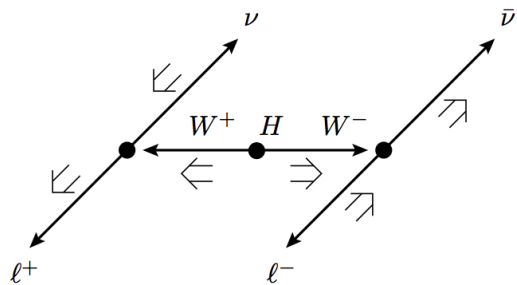
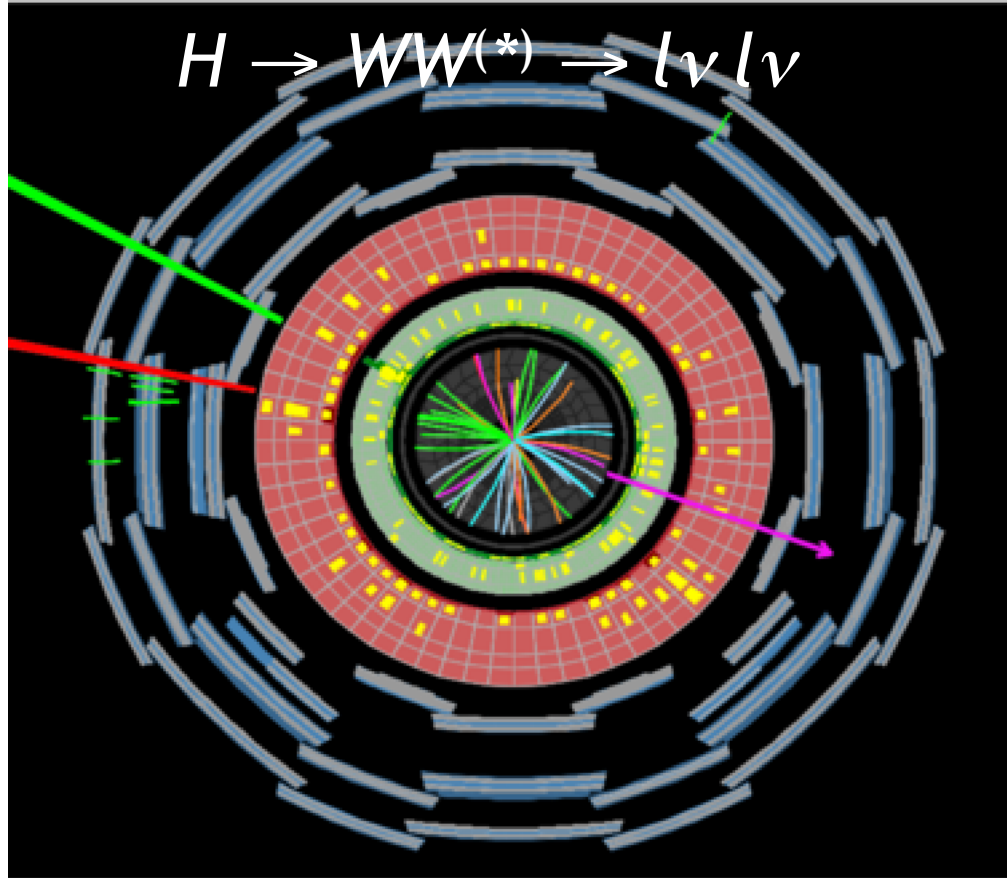


$$H \rightarrow \gamma\gamma$$

JHEP 09 (2014)



A discovery channel of a different kind...



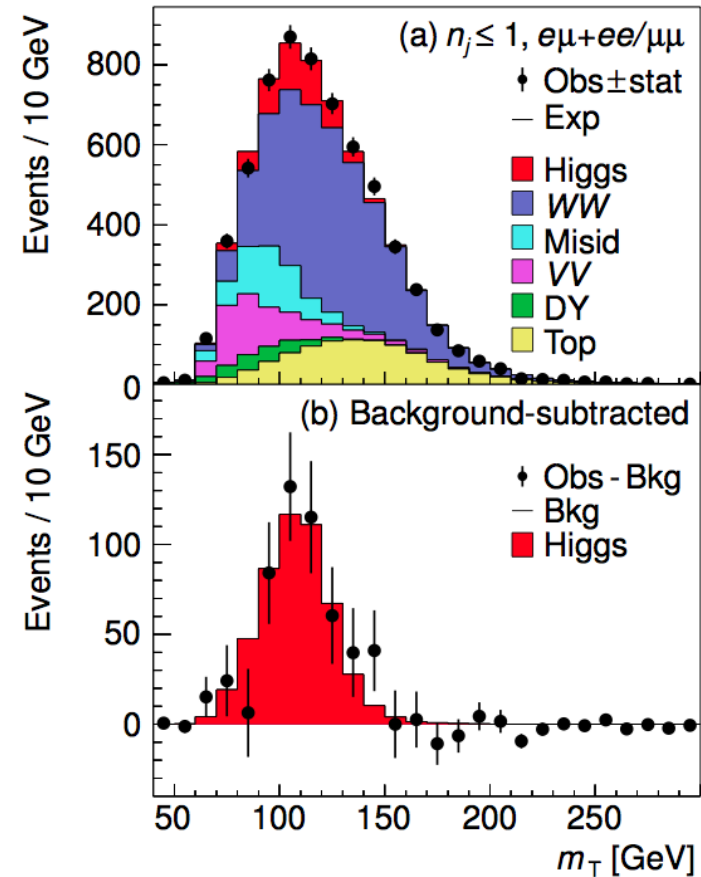
- Intricate analysis
- Moderate s/b ratio starting from approximately 1.5 and reaching more than 10.
- Poor mass resolution

ATLAS

$Z = 6.1 (5.8) \sigma$

CMS

$Z = 4.0 (5.0) \sigma$



Systematics (in particular TH systematics) play a very important role

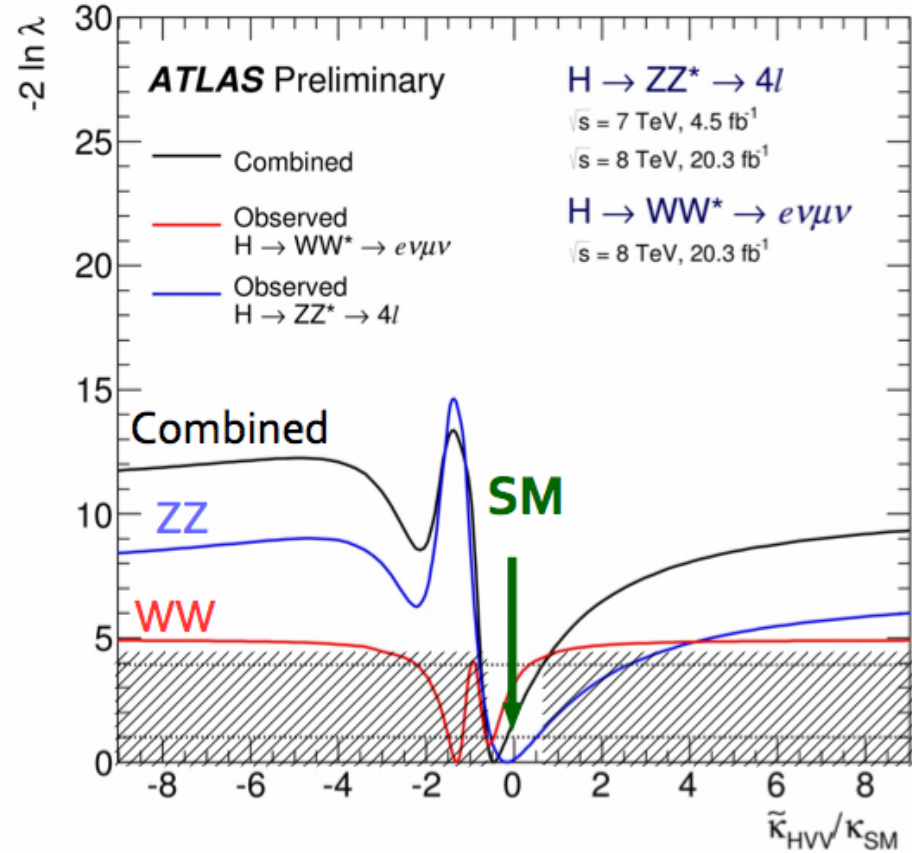
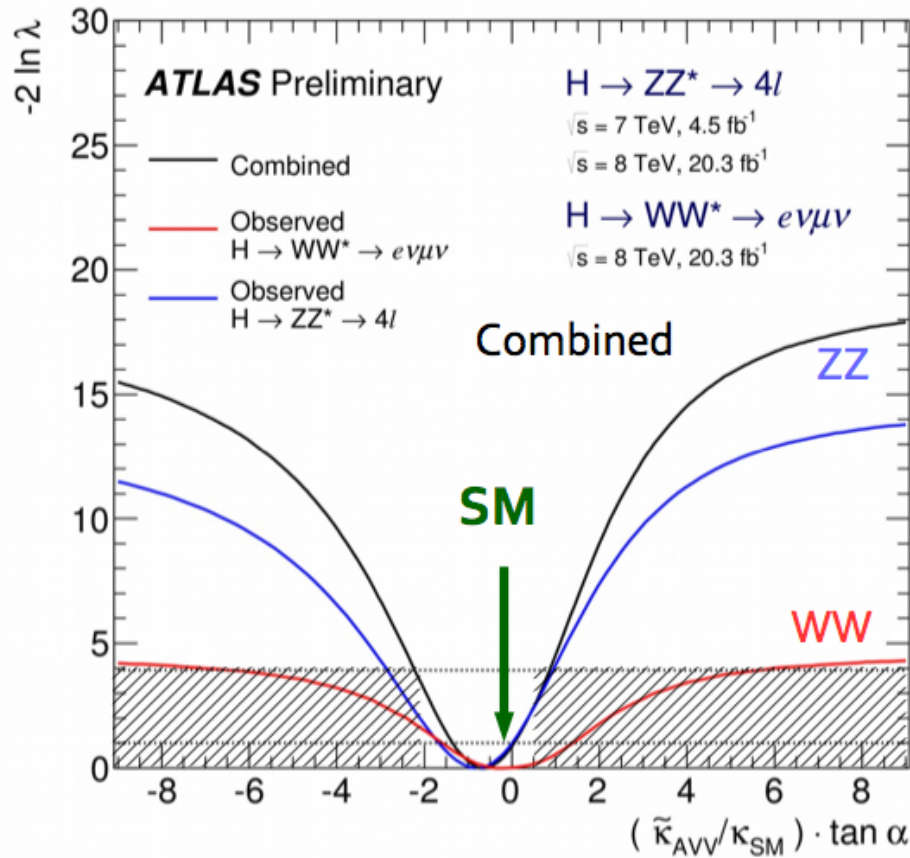
Source	Observed $\mu = 1.08$			Observed $\mu_{\text{ggF}} = 1.01$			Observed $\mu_{\text{VBF}} = 1.27$		
	Error +	-	Plot of error (scaled by 100)	Error +	-	Plot of error (scaled by 100)	Error +	-	Plot of error (scaled by 100)
Data statistics	0.16	0.15		0.19	0.19		0.44	0.40	
Signal regions	0.12	0.12		0.14	0.14		0.38	0.35	
Profiled control regions	0.10	0.10		0.12	0.12		0.21	0.18	
Profiled signal regions	-	-	-	0.03	0.03		0.09	0.08	
MC statistics	0.04	0.04		0.05	0.06		0.05	0.05	
Theoretical systematics	0.13	0.11		0.17	0.14		0.22	0.16	
Signal $H \rightarrow WW^* B$	0.05	0.04		0.05	0.03		0.07	0.04	
Signal ggF normalization	0.06	0.05		0.09	0.06		0.03	0.03	
Signal ggF acceptance	0.05	0.04		0.06	0.05		0.07	0.07	
Signal VBF normalization	0.01	0.01		-	-	-	0.07	0.04	
Signal VBF acceptance	0.02	0.01		-	-	-	0.15	0.08	
Background WW	0.06	0.06		0.08	0.08		0.07	0.07	
Background top quark	0.03	0.03		0.04	0.04		0.06	0.06	
Background misid. factor	0.05	0.05		0.06	0.06		0.02	0.02	
Others	0.02	0.02		0.02	0.02		0.03	0.02	
Experimental systematics	0.07	0.06		0.08	0.07		0.18	0.14	
Background misid. factor	0.03	0.03		0.04	0.04		0.02	0.01	
Bkg. $Z/\gamma^* \rightarrow ee, \mu\mu$	0.02	0.02		0.03	0.03		0.01	0.01	
Muons and electrons	0.04	0.04		0.05	0.04		0.03	0.02	
Missing transv. momentum	0.02	0.02		0.02	0.01		0.05	0.05	
Jets	0.03	0.02		0.04	0.03		0.14	0.11	
Others	0.03	0.02		0.03	0.03		0.06	0.06	
Integrated luminosity	0.03	0.03		0.03	0.02		0.05	0.03	
Total	0.22	0.20		0.27	0.25		0.53	0.45	

In particular background systematic uncertainties play an important role (*which affect the significances* described above*)

Systematic source	Impact on $\hat{\mu}$				Plot of post-fit $\pm \Delta_{\hat{\mu}}$
	Pre-fit $\Delta_{\hat{\mu}}$		Post-fit $\Delta_{\hat{\mu}}$		
	+	-	+	-	
WW , generator modeling	-0.07	+0.07	-0.05	+0.05	
ggF H , QCD scale on total cross section	-0.04	+0.05	-0.04	+0.05	
Top quarks, generator modeling on α_{top}	+0.03	-0.04	+0.03	-0.03	
Misid. of μ , OC uncorrelated corr. factor α_{misid} , 2012	-0.03	+0.04	-0.02	+0.03	
Misid. of e , OC uncorrelated corr. factor α_{misid} , 2012	-0.03	+0.03	-0.02	+0.03	
Integrated luminosity, 2012	-0.02	+0.03	-0.02	+0.03	
ggF H , PDF variations on cross section	+0.02	-0.03	+0.02	-0.03	
ggF H , QCD scale on $n_j \geq 2$ cross section	+0.02	-0.03	+0.01	-0.03	
Muon isolation efficiency	-0.02	+0.02	-0.02	+0.02	
VBF H , UE/PS	-0.02	+0.02	-0.02	+0.02	
ggF H , PDF variations on acceptance	-0.02	+0.02	-0.02	+0.02	
Jet energy scale, η intercalibration	-0.02	+0.02	-0.02	+0.02	
VV , QCD scale on acceptance	-0.01	+0.02	-0.01	+0.02	
ggF H , UE/PS	-	-0.02	-	-0.02	
Light jets, tagging efficiency	+0.01	-0.02	+0.01	-0.02	
Misid. jj , correction on α_{misid}	+0.01	-0.02	+0.01	-0.02	
Electron isolation efficiency	-0.01	+0.02	-0.01	+0.02	
Misid. of μ , closure on α_{misid} , 2011	-0.01	+0.02	-0.01	+0.01	
Electron identification eff. on $p_T^{\ell 2} > 20$ GeV, 2012	-0.01	+0.02	-0.01	+0.02	
ggF H , QCD scale on ϵ_1	-0.01	+0.02	-0.01	+0.02	

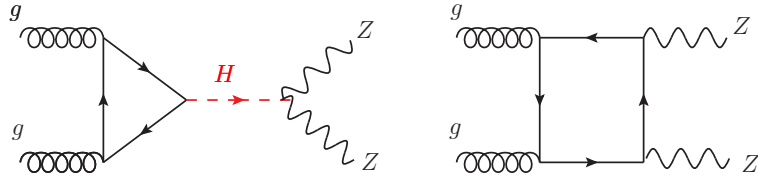
*Discovery with help from Theory

CP Mixing

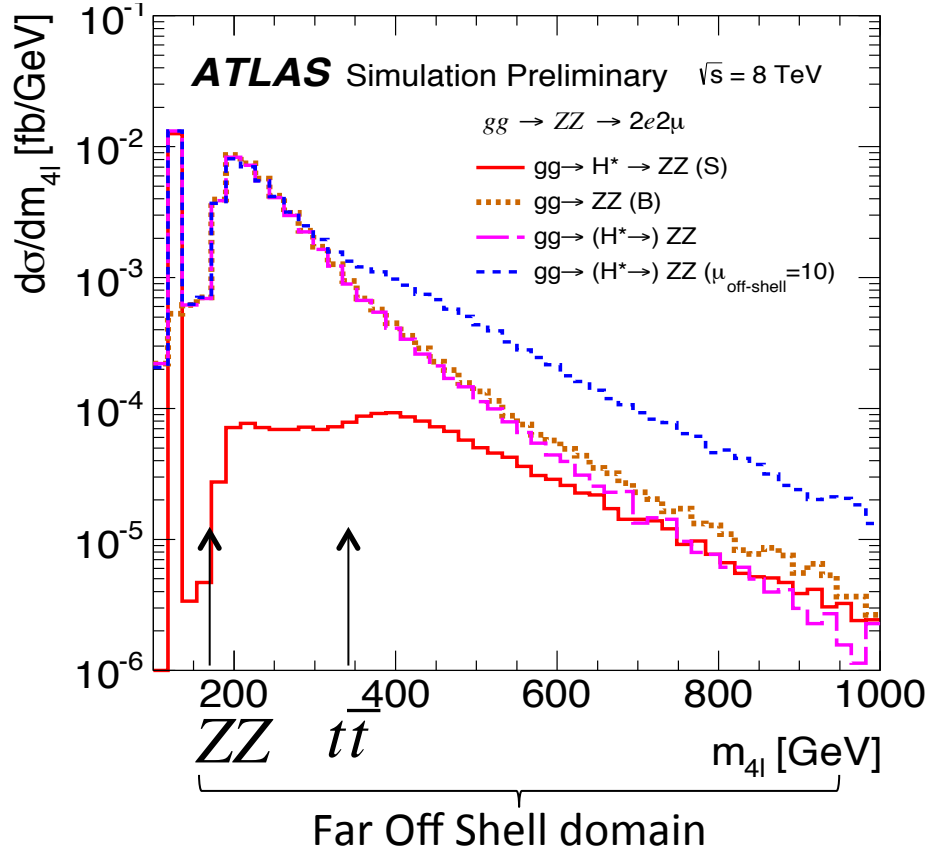


Both ATLAS and CMS find that the observed Higgs boson is compatible with a standard CP-even ()

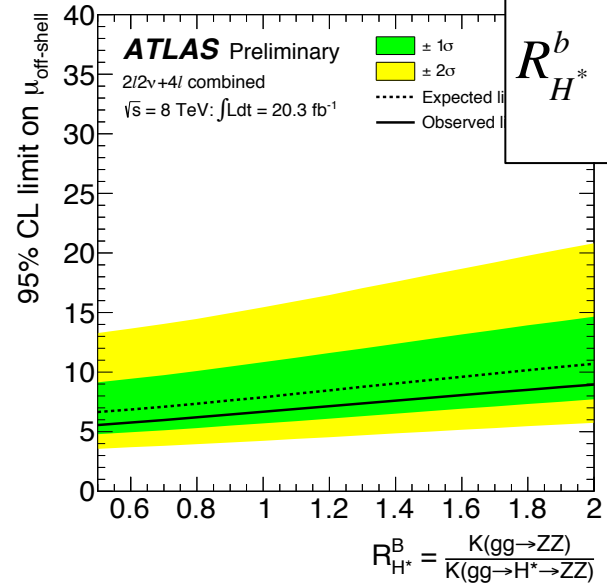
Off Shell Higgs coupling properties Measurement



Higgs boson as a propagator



$$\mu_{OffShell}^* \equiv \frac{\sigma_{gg \rightarrow H^* \rightarrow ZZ}^{OffShell}}{(\sigma_{gg \rightarrow H^* \rightarrow ZZ})_{SM}} = (\kappa_g^2 \kappa_V^2)_{OffShell}$$



$$R_{H^*}^b = \frac{k_{gg \rightarrow ZZ}}{k_{gg \rightarrow H^* \rightarrow ZZ}}$$

$\mu_{OffShell} < 6.2$ @ 95% CL

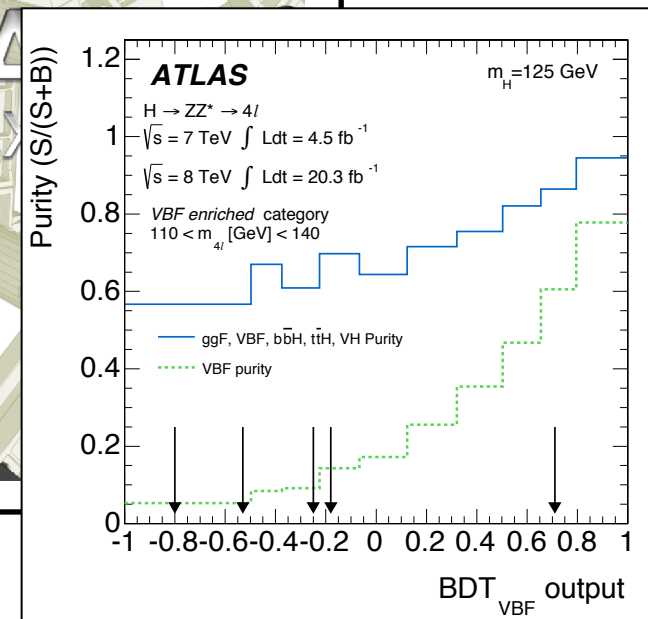
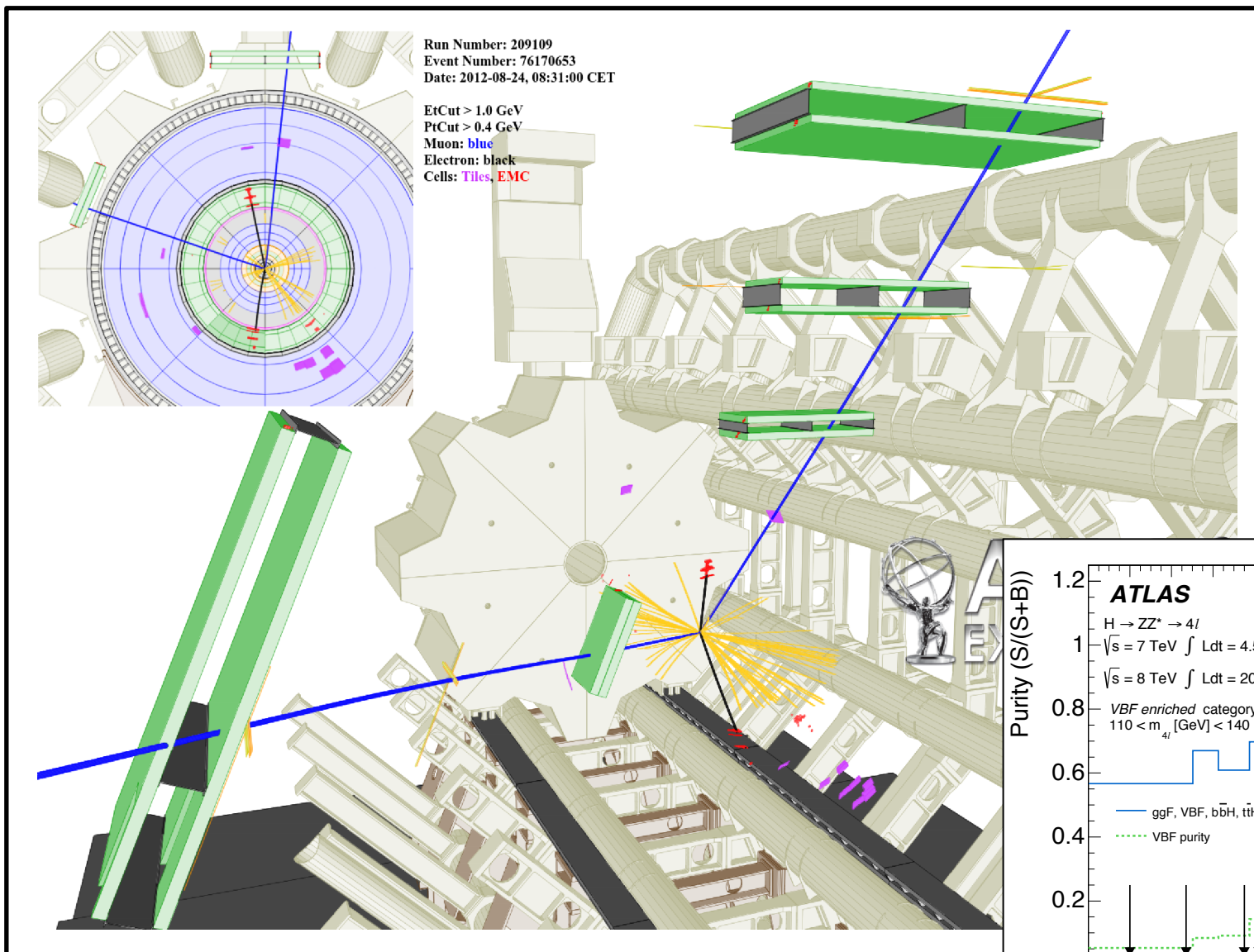
Using:

$$\mu_{OnShell} \equiv \frac{(\kappa_g^2 \kappa_V^2)_{OnShell}}{\Gamma_H / \Gamma_H^{SM}} \quad (\kappa_g^2 \kappa_V^2)_{OnShell} = (\kappa_g^2 \kappa_V^2)_{OffShell}$$

$$\Gamma_H / \Gamma_H^{SM} < 5.5$$

$$\Gamma_H = 4.2_{-2.1}^{+1.5} \text{ MeV}$$

Bright Future for Higgs analyses at Run 2



Outline

1.- Introduction and Context

2.- The « Bread and Butter » Discovery Channels, the detectors and the machine.

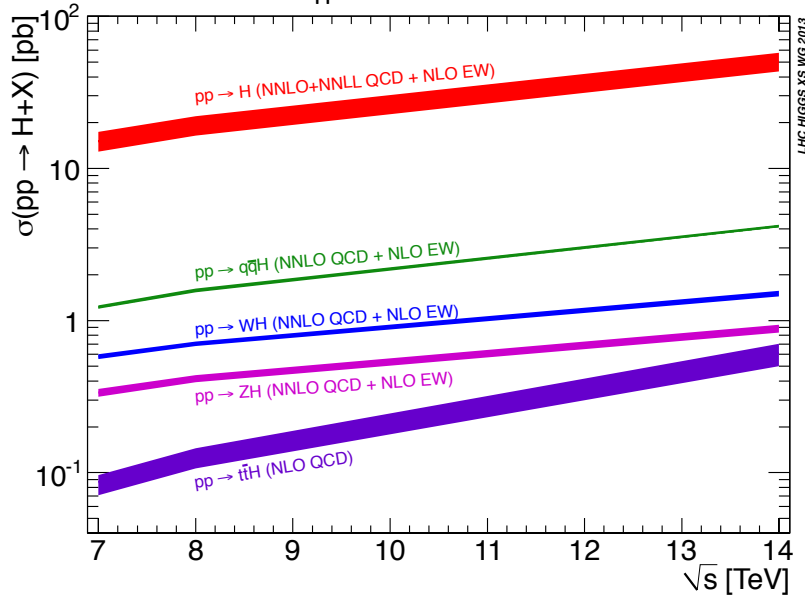
3.- Discovery channels beyond discovery

4.- Overview of post-discovery Higgs physics

5.- Glimpse at HL-LHC

Higgs Production Modes

κ for $m_H = 125.5$ GeV



Gluon fusion process

NNnLO $\sim O(10\%)$

~ 0.5 M events produced

$$\kappa_g \propto 1.06\kappa_t^2 - 0.07 \times \kappa_t \kappa_b + 0.01 \times \kappa_b^2$$

Vector Boson Fusion

NLO TH uncertainty $\sim O(5\%)$

Two forward jets and a large rapidity gap

~ 40 k events produced

$$\propto \kappa_V^2$$

$\propto \kappa_t^2$

Top Assoc. Prod. ~ 3 k evts produced

W and Z Associated Production

NNLO TH uncertainty $\sim O(5\%)$

~ 20 k events produced

$$\propto \kappa_V^2$$

$\propto \kappa_b^2$

B-quark Assoc. Prod. ~ 5 k evts produced

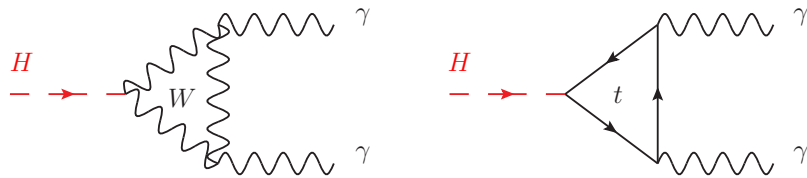
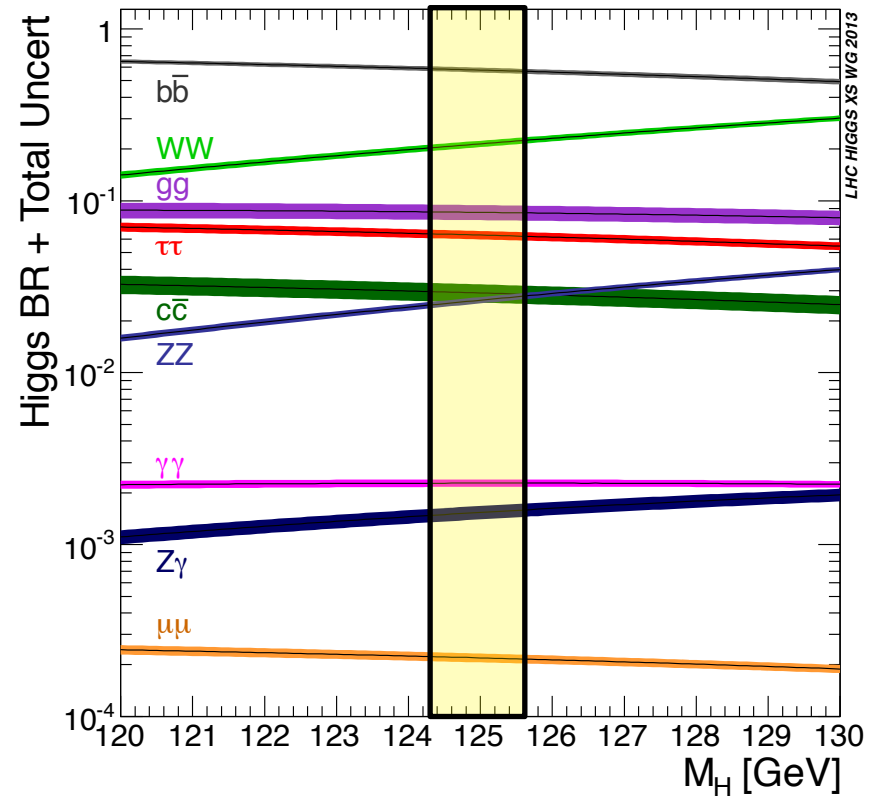
tH

$$\propto 3.3 \times \kappa_W^2 - 5.1 \times \kappa_t \kappa_W + 2.8 \times \kappa_t^2$$

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Higgs Decay Channels

- Dominant: $b\bar{b}$ (57%) $\propto \kappa_b^2 / \kappa_H^2$
- WW channel (22%) $\propto \kappa_W^2 / \kappa_H^2$
- $\tau\tau$ channel (6.3%) $\propto \kappa_\tau^2 / \kappa_H^2$
- ZZ channel (3%) $\propto \kappa_Z^2 / \kappa_H^2$
- $c\bar{c}$ channel (3%) $\propto \kappa_c^2 / \kappa_H^2$
Extremely difficult
- The $\gamma\gamma$ channel (0.2%) $\propto \kappa_\gamma^2 / \kappa_H^2$



$$\kappa_\gamma \propto 1.6 \times \kappa_W^2 - 0.7 \times \kappa_t \kappa_W + 0.1 \times \kappa_t^2$$

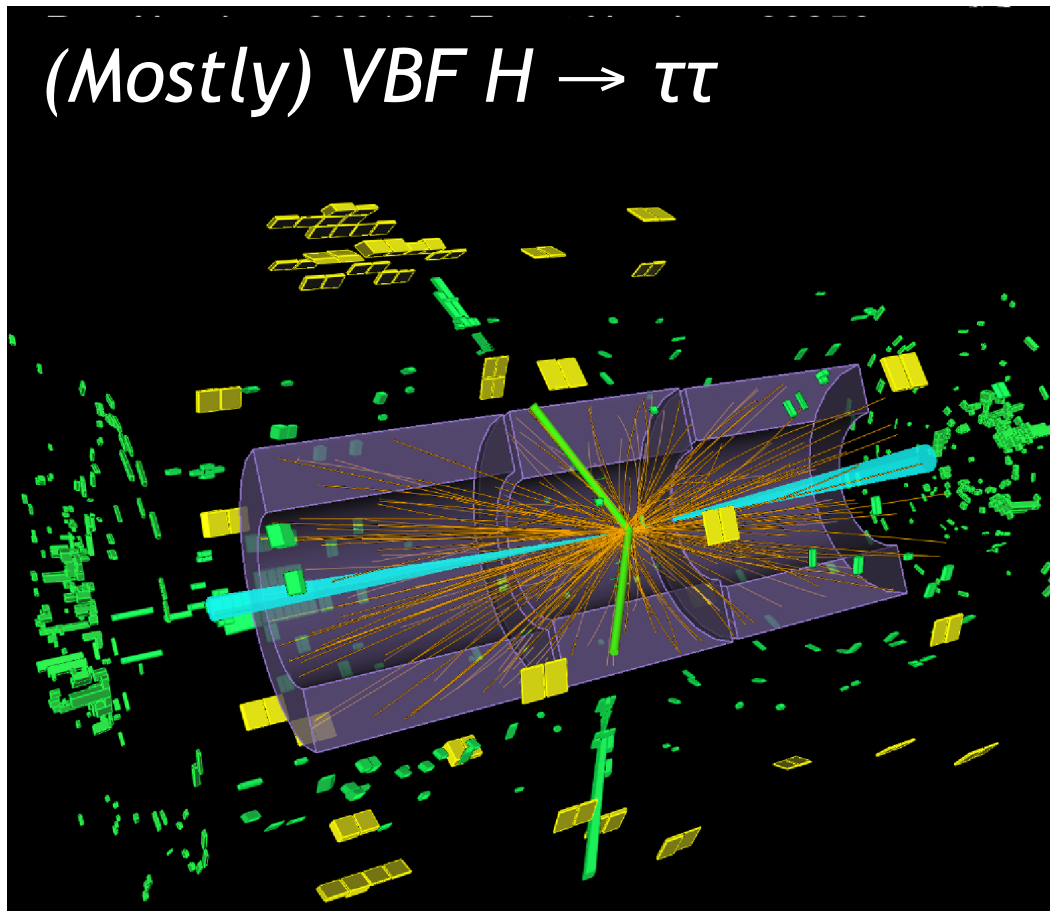
(when assuming no BSM charged in the loop)

- The $Z\gamma$ (0.2%) $\kappa_{Z\gamma} \propto 1.12 \times \kappa_W^2 - 0.15 \times \kappa_t \kappa_W + 0.03 \times \kappa_t^2$
- The $\mu\mu$ channel (0.02%) $\propto \kappa_\mu^2 / \kappa_H^2$

Panorama of Main Higgs Analyses

Channel categories	ggF	VBF	VH	ttH
$\gamma\gamma$	✓	✓	✓	✓
ZZ (llll)	✓	✓	✓	✓
WW (llνlν)	✓	✓	✓	✓
$\tau\tau$	✓	✓	✓	✓
bb	✓	✓	✓	✓
Zγ and $\gamma\gamma^*$	✓	✓		
$\mu\mu$ and ee	✓	✓		
Invisible	✓ (monojet)	✓	✓	

An Important Observation...



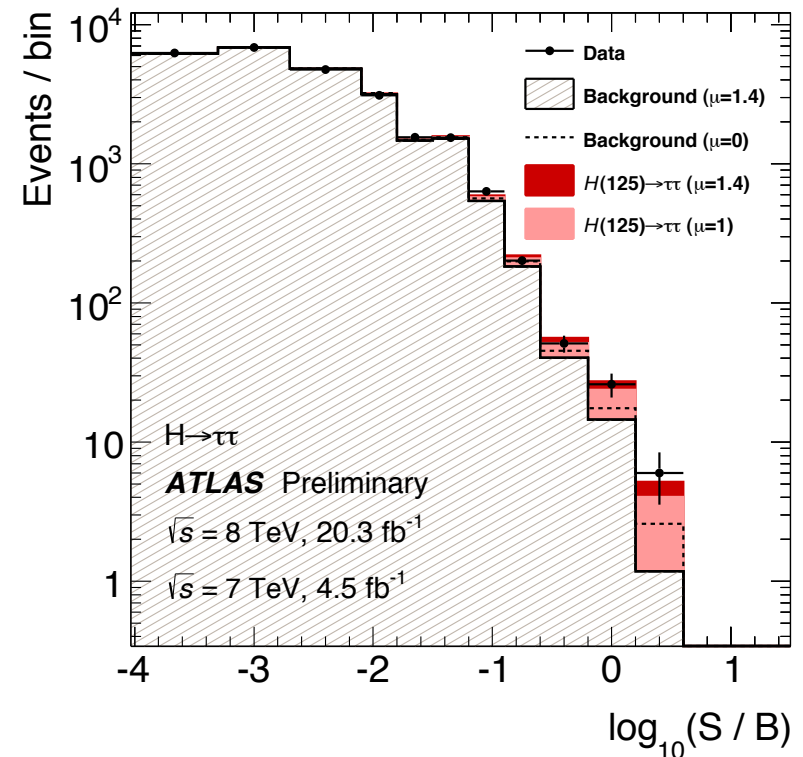
- Control of background through embedding (of taus in dimuon data events)
- Moderate s/b ratio starting from a few percent to approximately 1

ATLAS

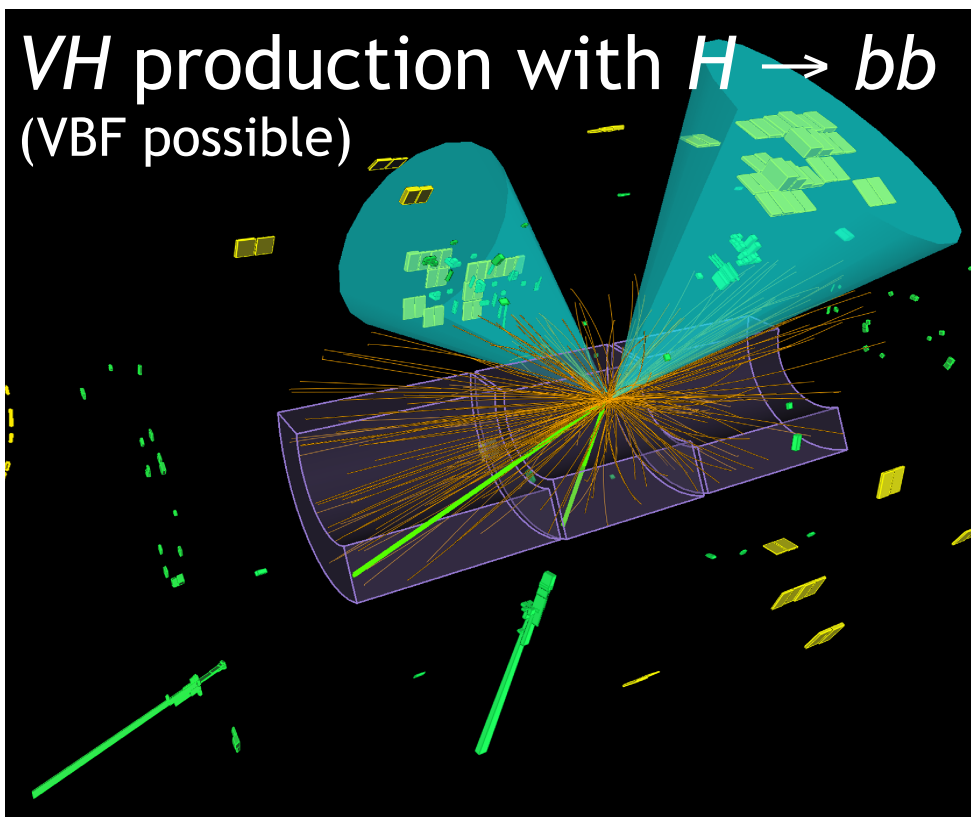
$$Z = 4.5 \text{ (3.5) } \sigma$$

CMS

$$Z = 3.2 \text{ (3.7) } \sigma$$



Cornering the b Yukawa Coupling



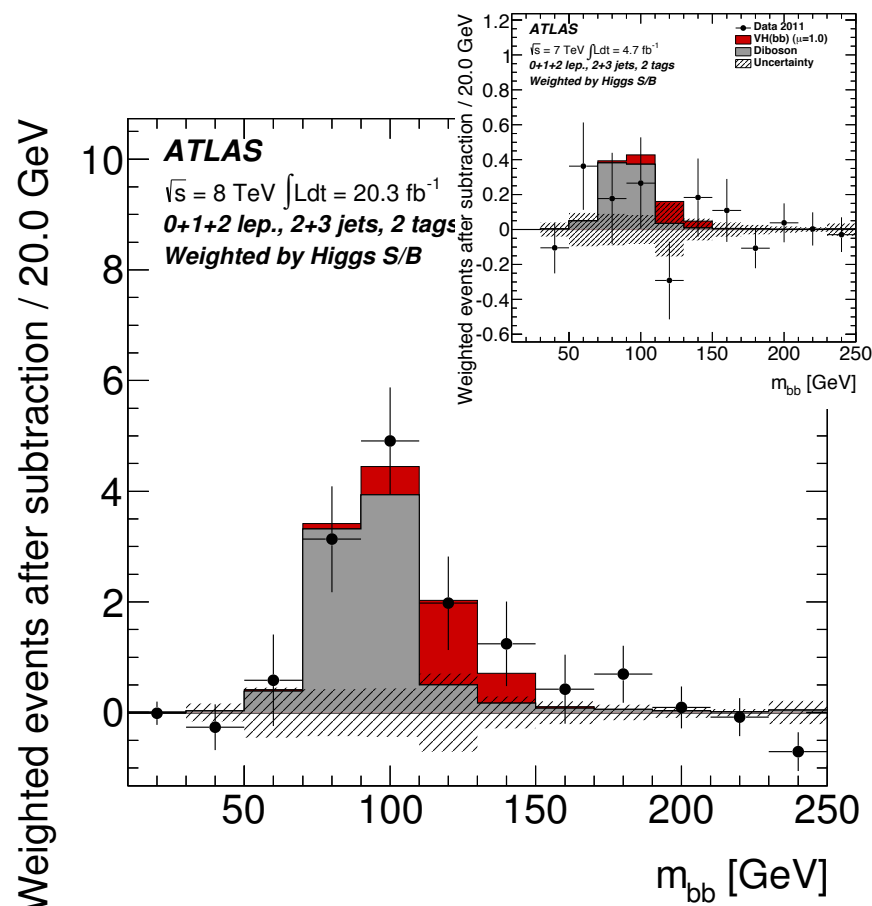
- Analysis using the boost (without substructure)
- Moderate s/b ratio starting from approximately few percent to approximately 30%

ATLAS

$Z = 1.4$ (2.6) σ

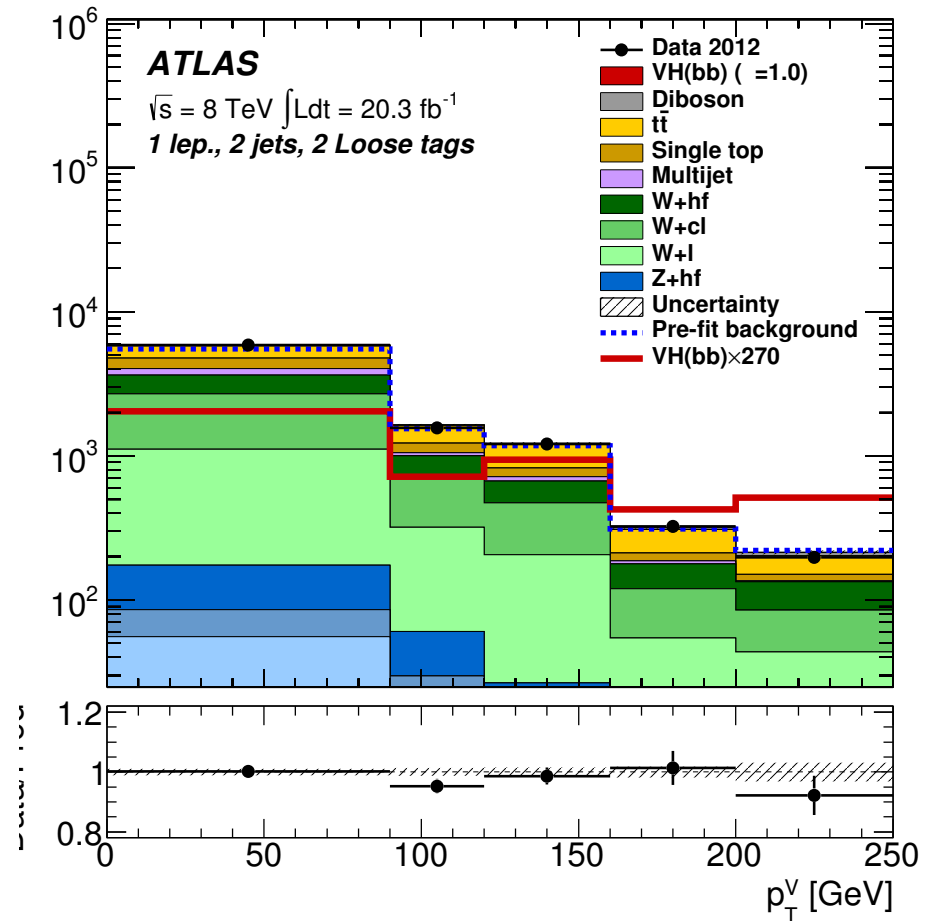
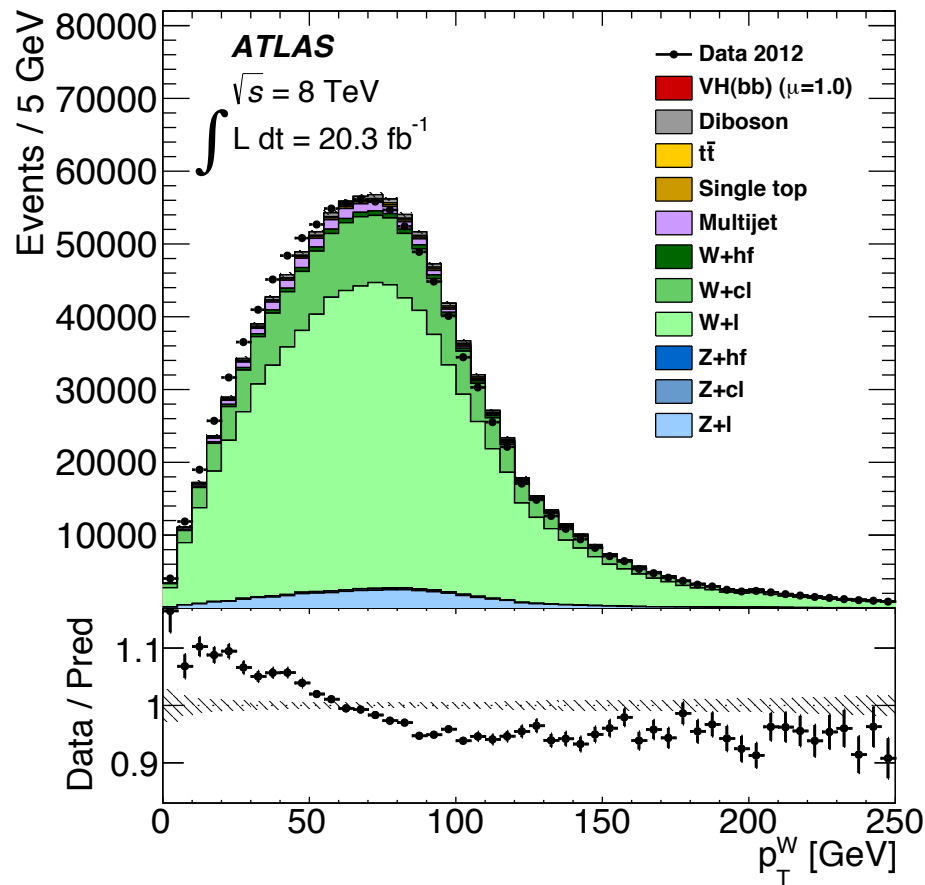
CMS

$Z = 2.1$ (2.1) σ



Boosted Analyses (without substructure)

Simulation of $p_T(V)$ is critical

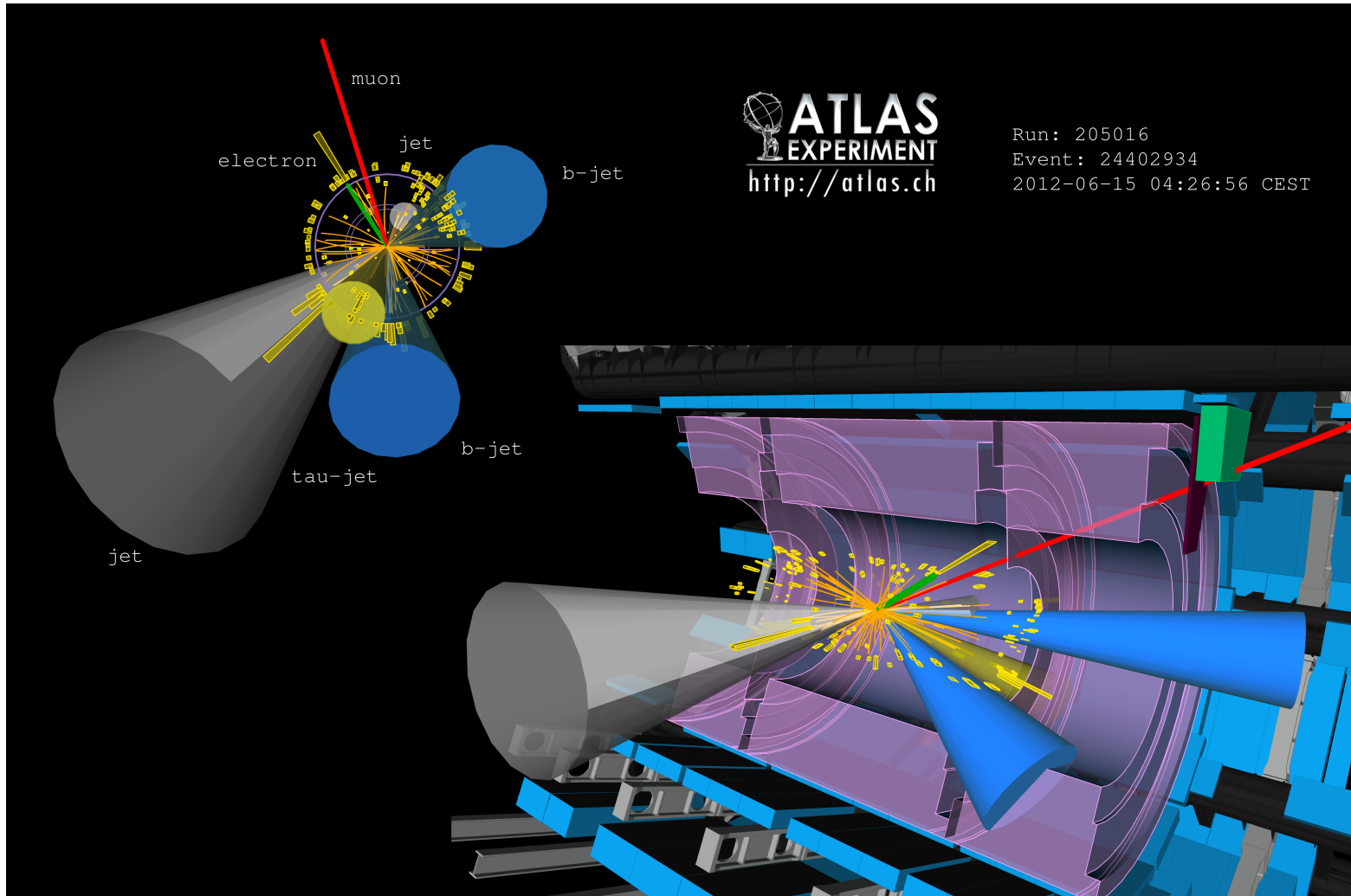


Our precision will depend a lot on the simulation, moving to state-of-the-art MC for Run-2

Cornering (directly) the top Yukawa coupling

Very complex final state that requires a thorough control of the background (as well)

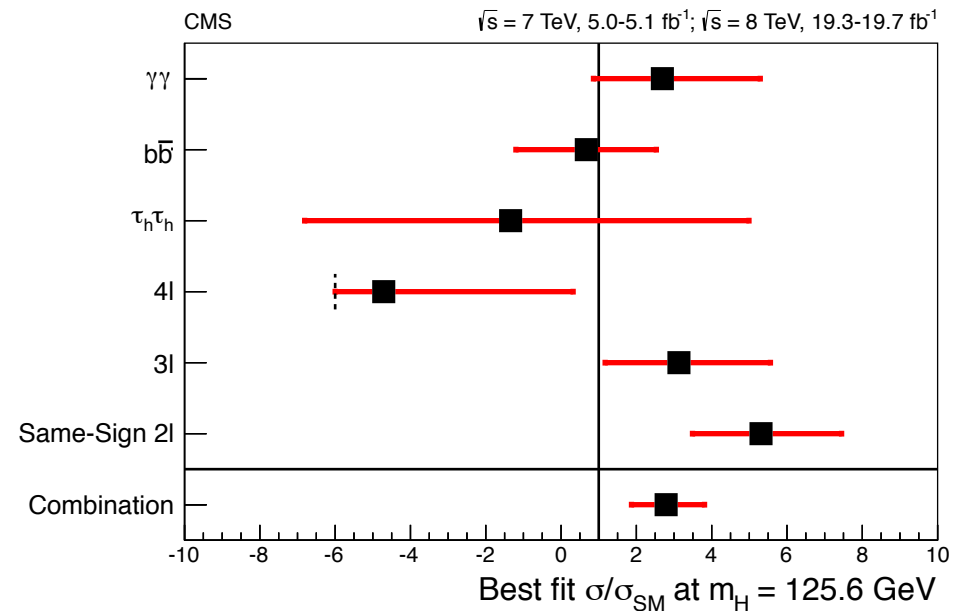
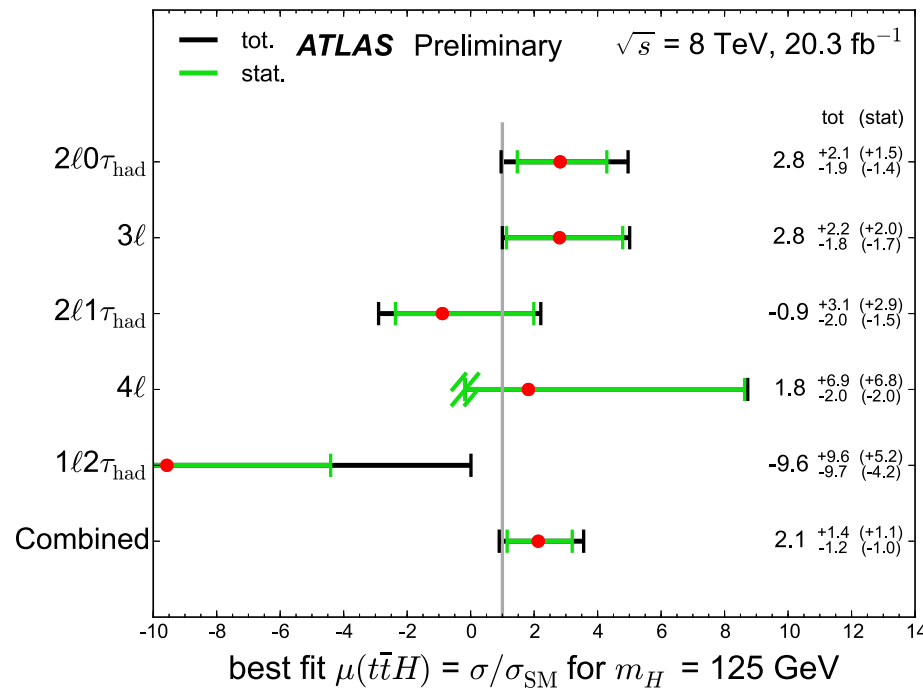
$ttH(ML)$



Cornering (directly) the top Yukawa coupling

Very complex final state that requires a thorough control of the background (as well)

$ttH(ML)$

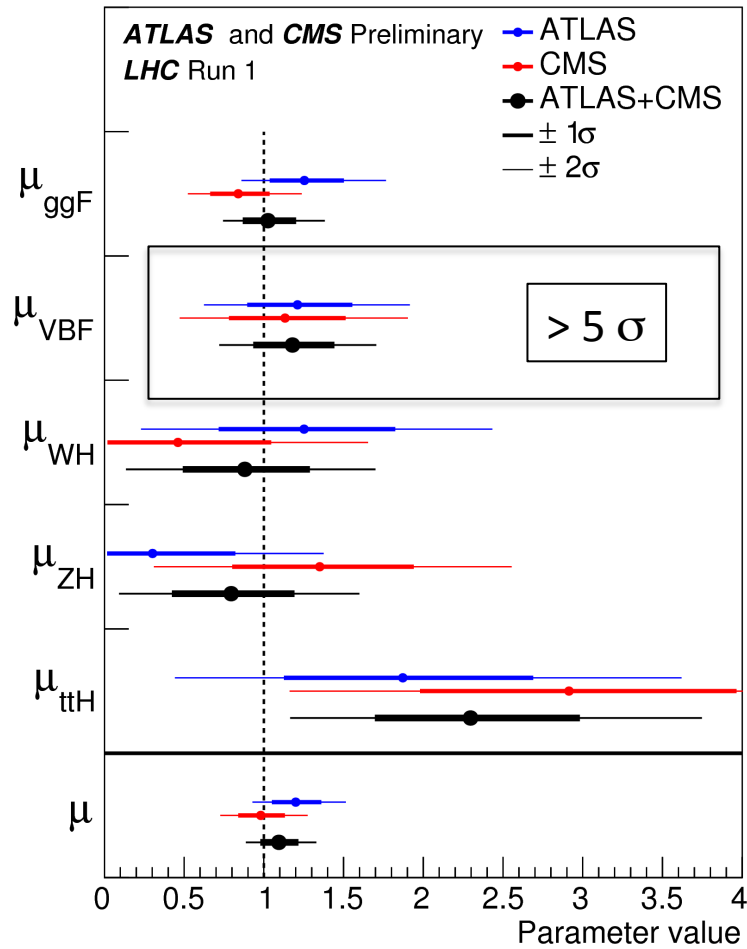


Hints of a signal emerging, a combination of ATLAS and CMS would be of course very interesting... Naive combination yields approximately 2 with an uncertainty of 0.7.

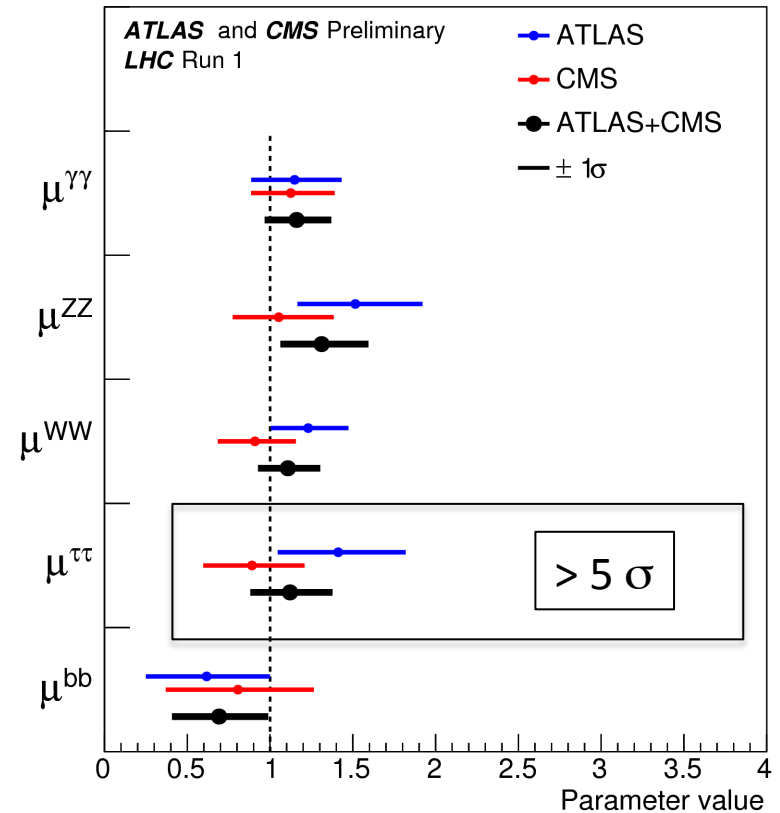
Combining Higgs Channels

- Combining the large number of channels to constrain the coupling properties of the Higgs boson (using different model assumptions).
- These combination have become extremely complex to correctly take into account all the systematic uncertainties and their correlations. More and more important when systematics become dominant.

Couplings Combination (ATLAS-CMS)

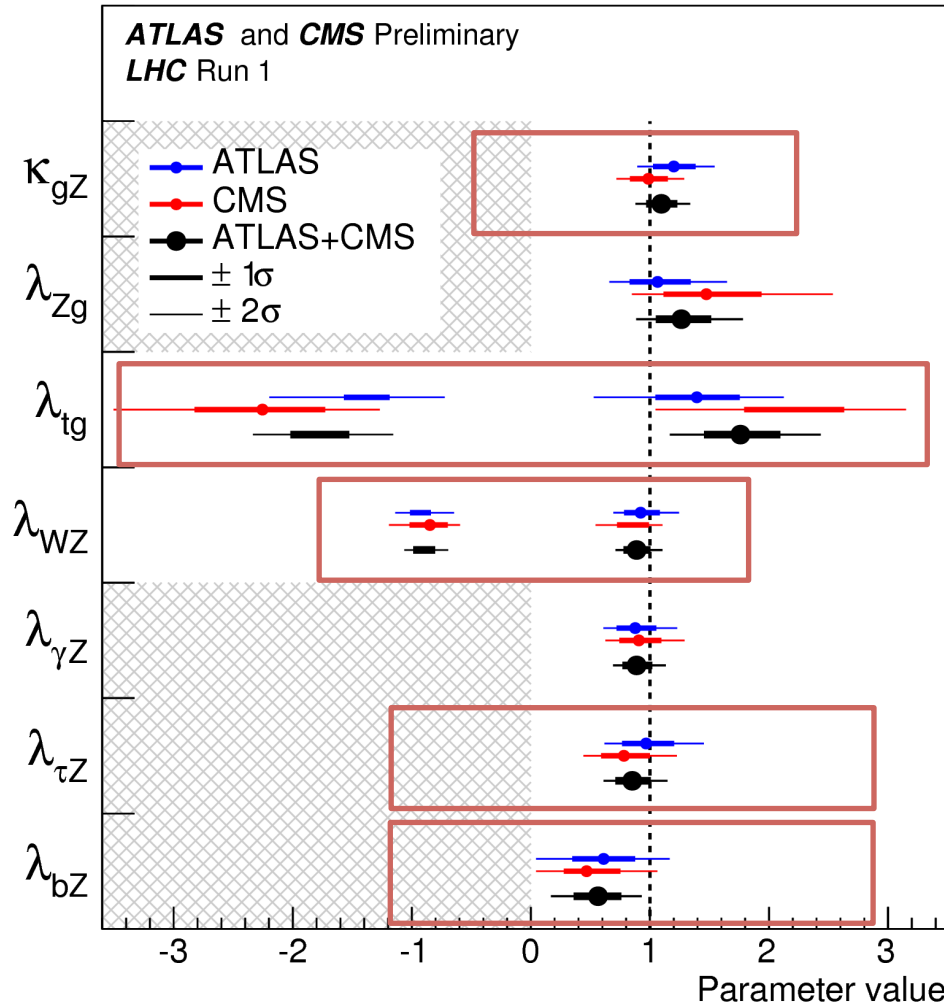


- Hundreds of exclusive analysis categories
- Thousands of nuisance parameters*
- To corner:
 - 5 decay modes
 - 5 Production processes



*Large number of bin stat

A Lot Learned About Coupling Properties



← Direct coupling to the Z

← Direct coupling to the top
(through $t\bar{t}H$ production channels)

← Custodial Symmetry

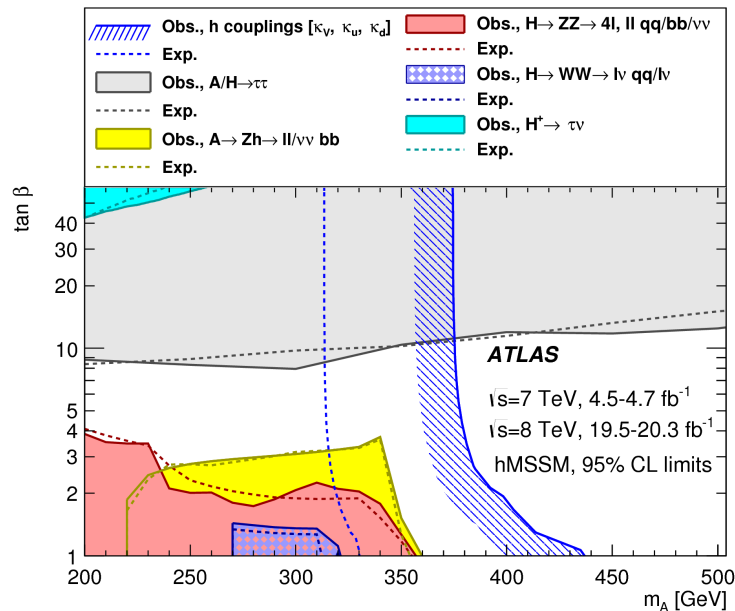
← Direct coupling to τ
(through VBF production)

← Direct coupling to b quarks
(Through mainly VH channels)

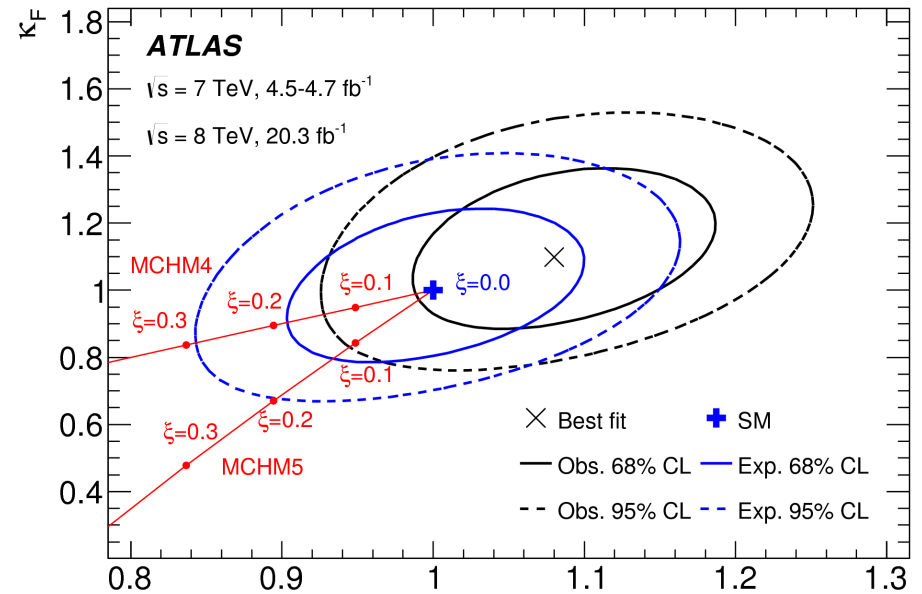
A lot still to be learned!

Extremely important questions for Run 2

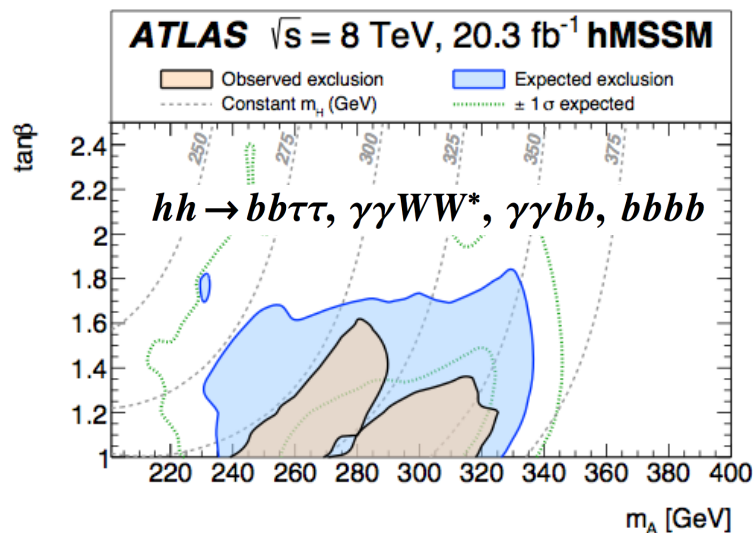
Implications and Direct Searches



hMSSM: Indirect constraints from the up vs down type fermions and vector bosons.



MCHM: Indirect constraints from the up vs down κ_V type fermions and vector bosons.

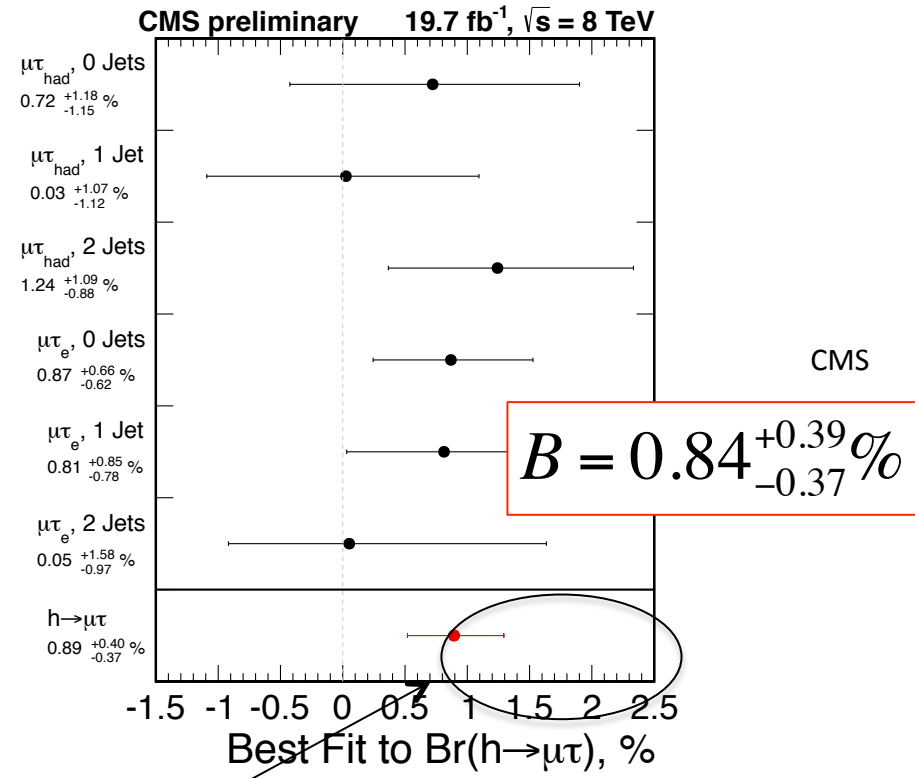
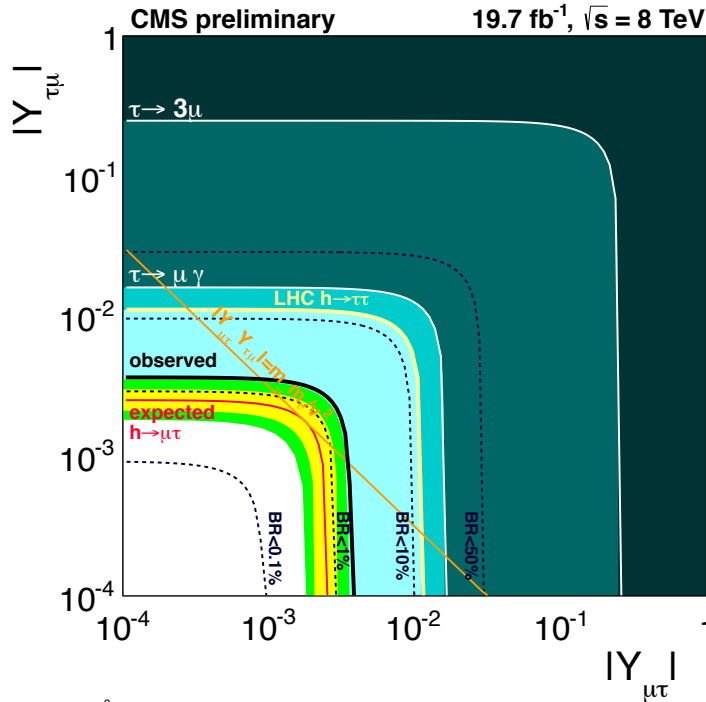


hMSSM: Recent additional constraints

- Combination of HH searches
- To come charged Higgs to tb!

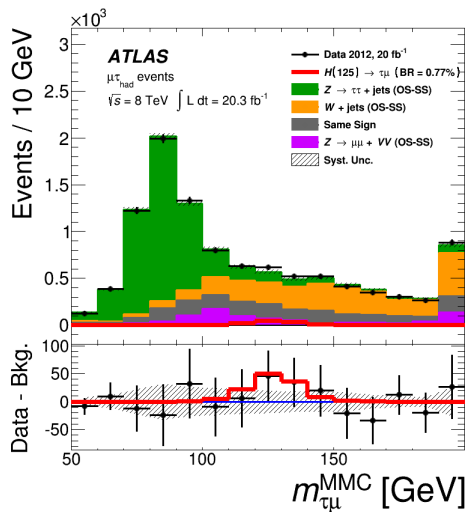
Examples of extremely important searches with sensitivity soon at Run 2

LFV Decays of the Higgs boson



~2.5 σ Deviation...

Excess of similar order in rate (less significant) observed also in ATLAS

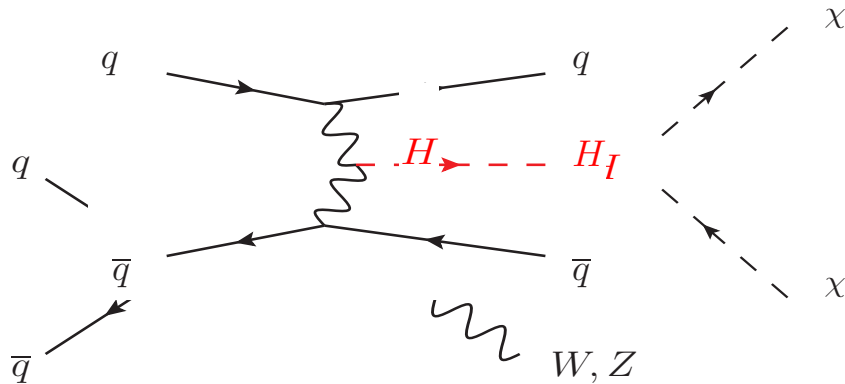


ATLAS

$B = 0.77 \pm 0.62 \%$

Invisible Decays

Very small expected SM signal



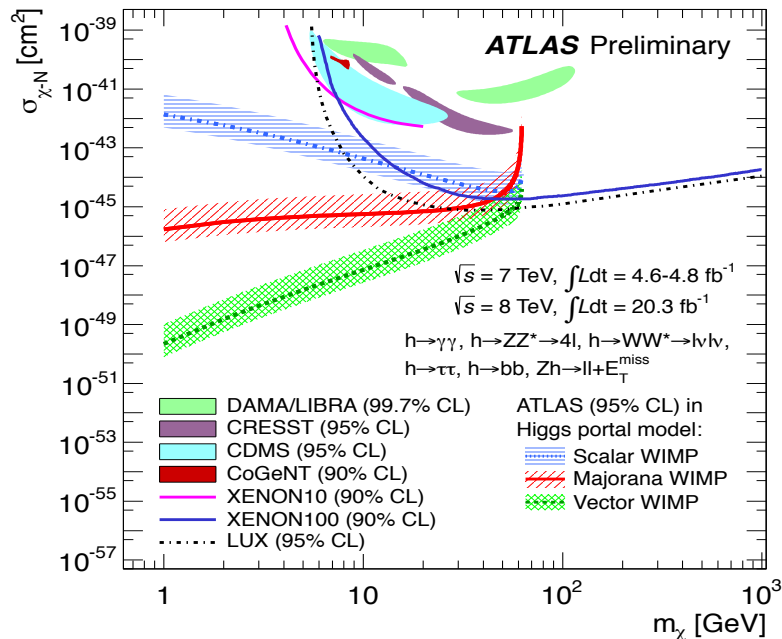
$$Br(H \rightarrow invisible)$$

VH Production

Observed limit 95% CL: approximately **60%**

VBF Production

Observed limit 95% CL: approximately **30%**



Indirect limit from standard combination (assuming Standard couplings to Standard fields)

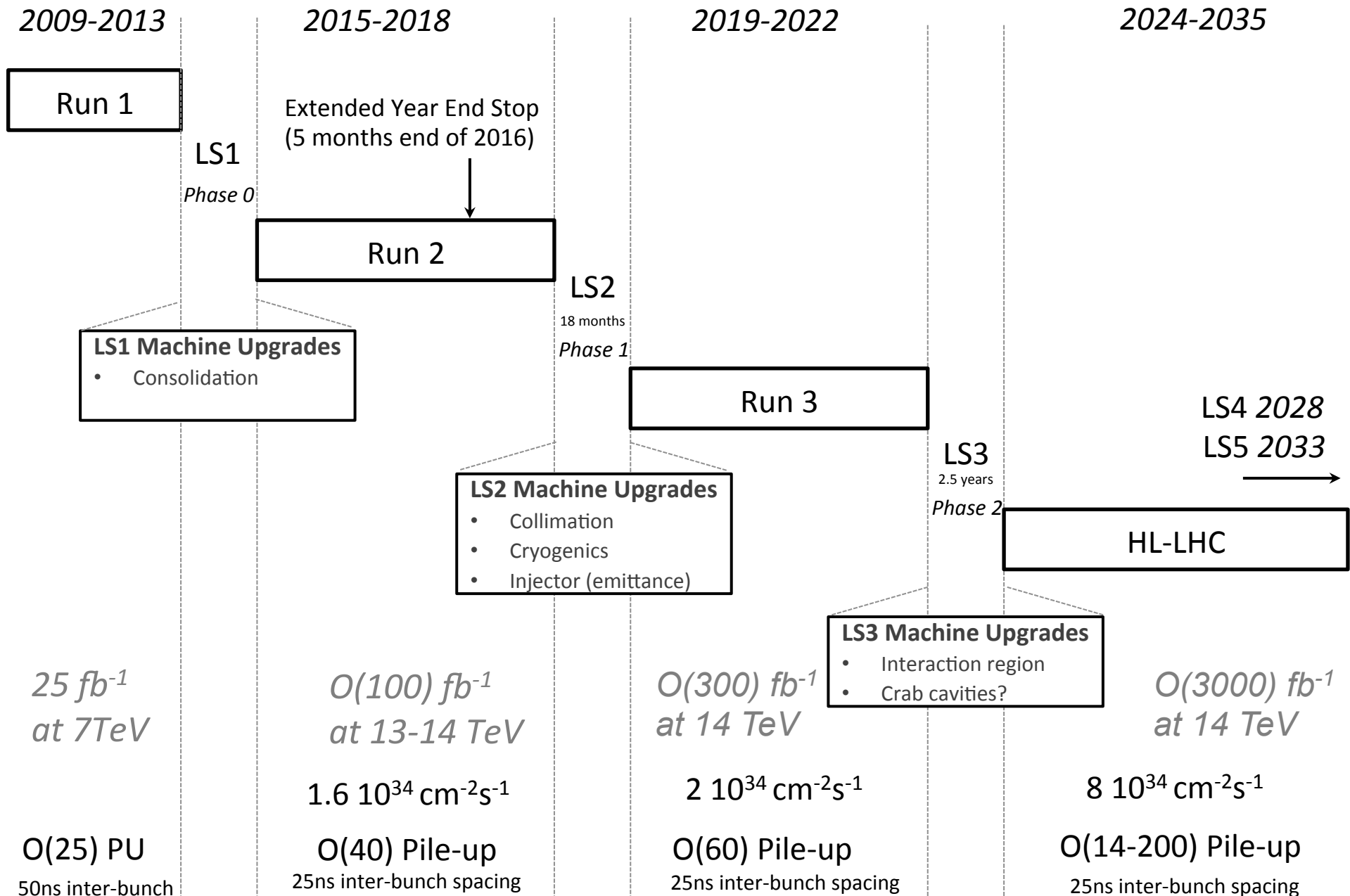
Observed limit 95% CL: approximately **30%**

Searches sensitive to Dark Matter
(if it couples to the Higgs boson
and if it is light enough)

Outline

- 1.- Introduction and Context
- 2.- The « Bread and Butter » Discovery Channels, the detectors and the machine.
- 3.- Discovery channels beyond discovery
- 4.- Overview of post-discovery Higgs physics
- 5.- Glimpse at HL-LHC

The LHC Run 2 and Beyond

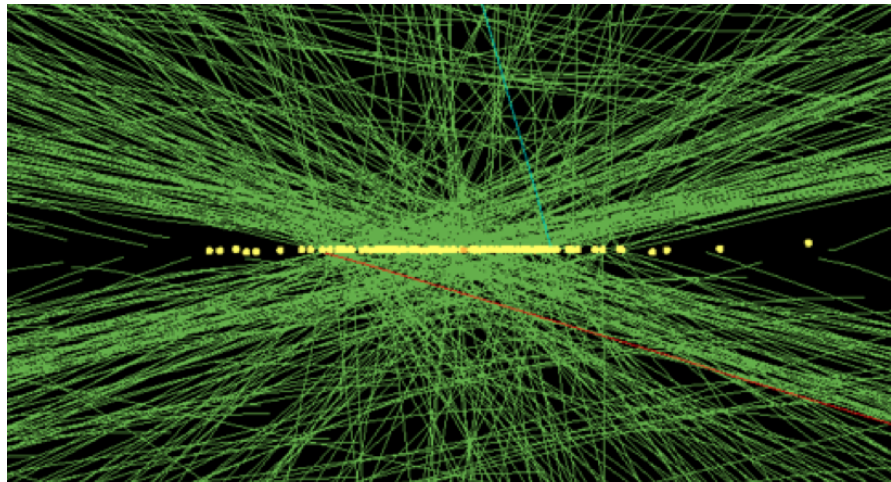


HL-LHC Beam Parameters

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

Two HL-LHC scenarios

Parameter	2012	Nominal	HL-LHC (25 ns)	HL-LHC (50 ns)
C.O.M Energy	8 TeV	13-14 TeV	14 TeV	14 TeV
N_p	$1.2 \cdot 10^{11}$	$1.15 \cdot 10^{11}$	$2.0 \cdot 10^{11}$	$3.3 \cdot 10^{11}$
Bunch spacing / k	50 ns / 1380	25 ns / 2808	25 ns / 2808	50ns / 1404
ϵ (mm rad)	2.5	3.75	2.5	3.0
β^* (m)	0.6	0.55	0.15	0.15
L ($\text{cm}^{-2}\text{s}^{-1}$)	$\sim 7 \cdot 10^{33}$	10^{34}	$7.4 \cdot 10^{34}$	$8.4 \cdot 10^{34}$
Pile up	~25	~20	~140	~260

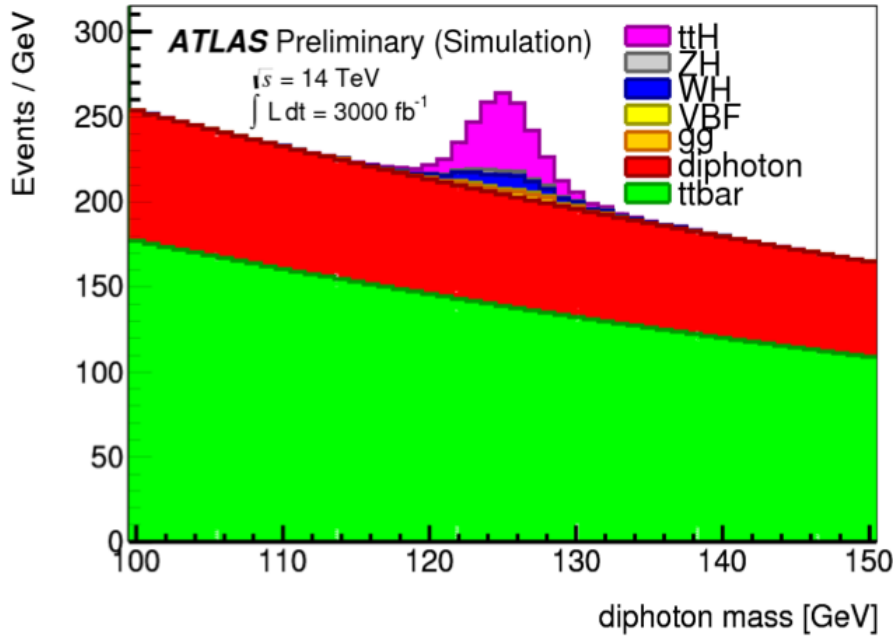


Pile up is critical!

Event with 78 reconstructed vertices

LHC Higgs Physics Program: Rare Modes

Analyses not relying on more intricate decay channels (bb, $\tau\tau$ and WW)

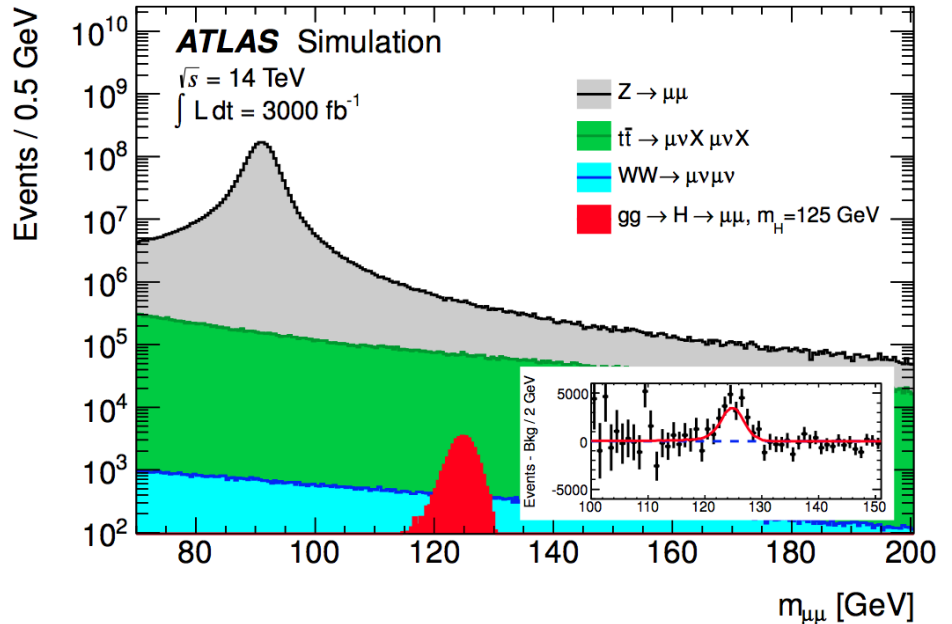


$\mu\mu$ decay mode should reach more than 5 standard deviation

Just two examples but there are many many more!!!

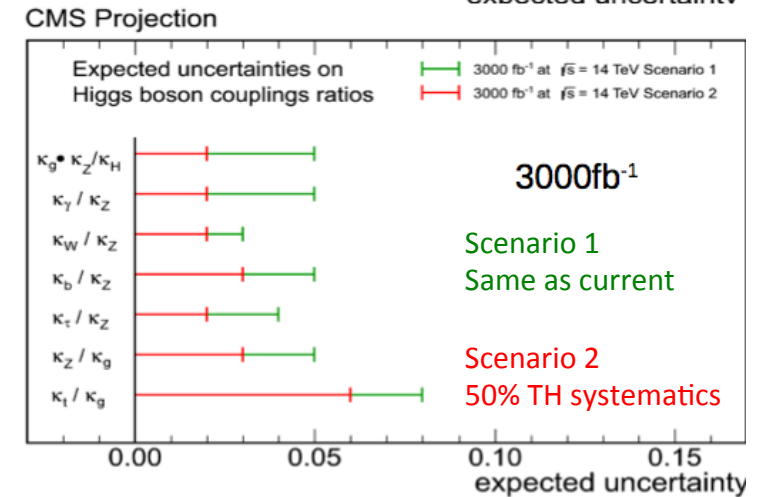
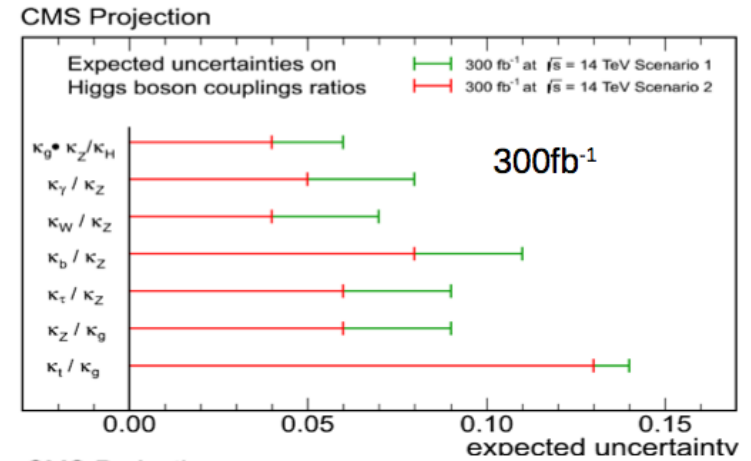
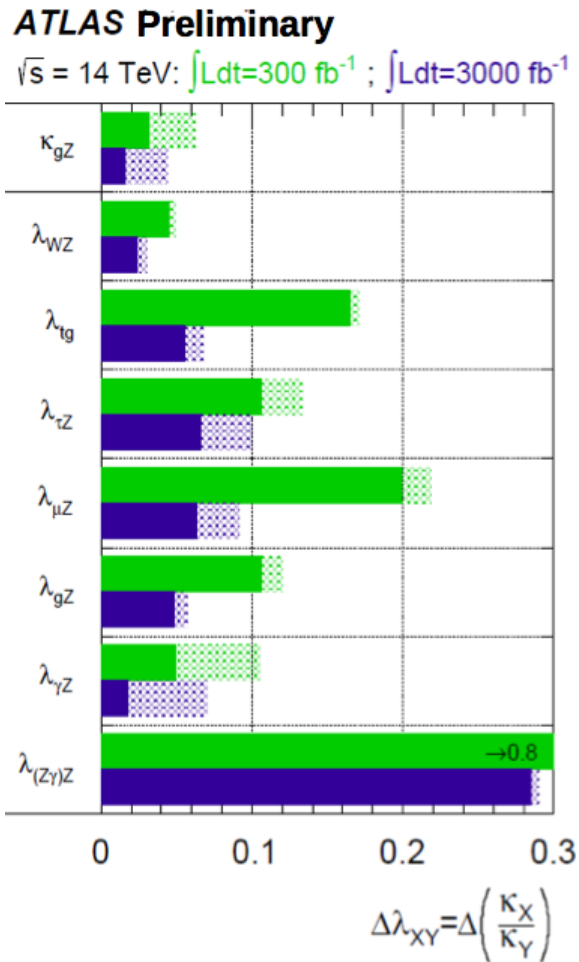
- $\gamma\gamma$ channel: more than 100 Events expected with $s/b \sim 1/5$
- $\mu\mu$ channel: approximately 30 Events expected with $s/b \sim 1$

Analyses (rather) robust to PU



LHC Higgs Physics Program: Main Couplings

Couplings Projections recently reappraised **with a sample of analyses**



Only indirect (however not negligible) constraint on the total width

Necessary to use assumptions or measure ratios: Precision down to $\sim 5\%$ level

Di-Higgs Production Self Couplings

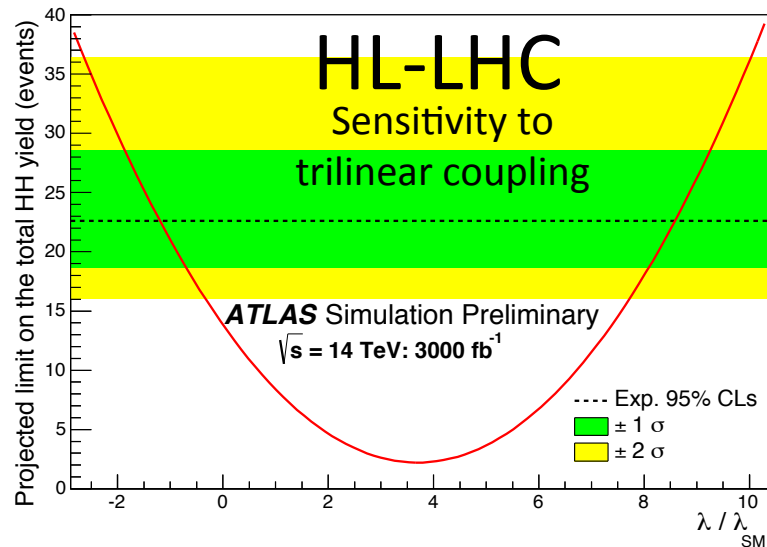
ATL-PHYS-PUB-2014-019

At HL-LHC sensitivity to SM HH

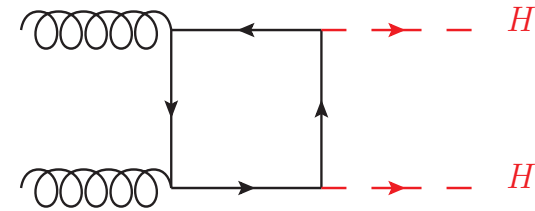
1.3 σ

Extremely challenging!

Similarities with Off-Shell Couplings measurements



Associated production of two Higgs bosons



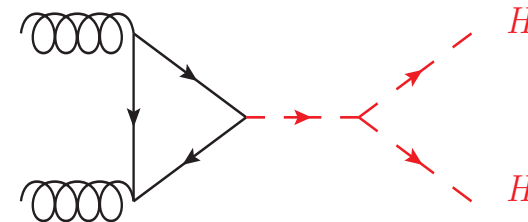
Various channels searched for ($bb\gamma\gamma$)

Limit on non resonant cross section times branching:

$$\sigma_{\text{HH}} \text{ Br}_{bb, \gamma\gamma} < \text{O}(2) \text{ pb}$$

Background to ...

Tri-linear coupling production



λ_3 : Extremely difficult on of the main challenges for the HL-LHC

λ_4 : Incredibly difficult

Conclusions and Outlook

Implications (I) : *The Standard Model is Complete*

There is no need of new physics based on unitarity or vacuum stability

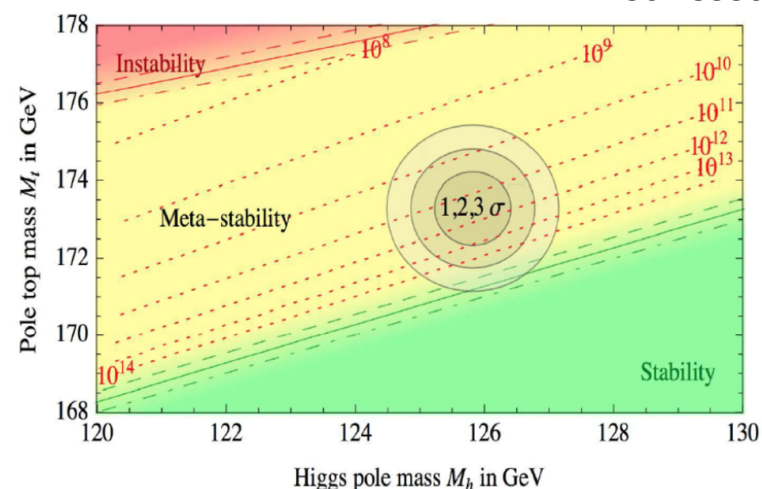
With the discovery of the Higgs,
for the first time in our history,
we have a self-consistent theory
that can be extrapolated to
exponentially higher energies.

Nima Arkani Hamed

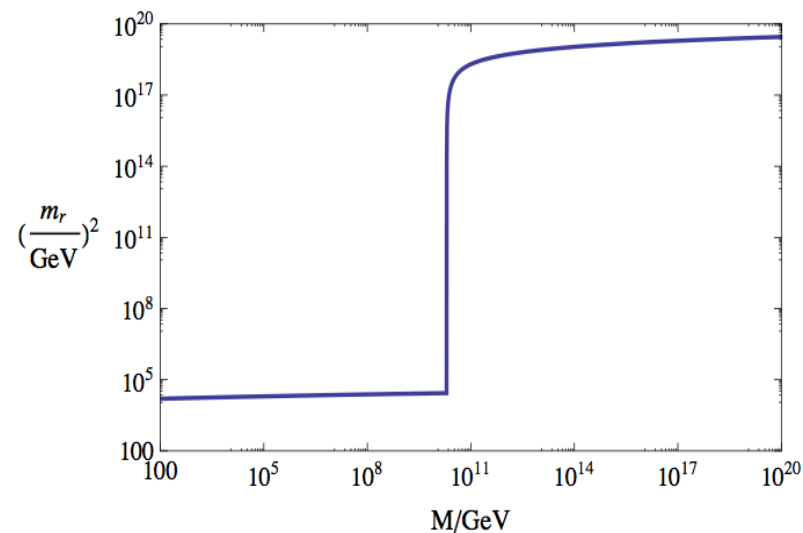
*There is no “No Loose Theorem” anymore,
Naturalness still valid as guiding principle...*

*If there is NP, it would be motivated to be
at relatively low scale to avoid fine tuning.*

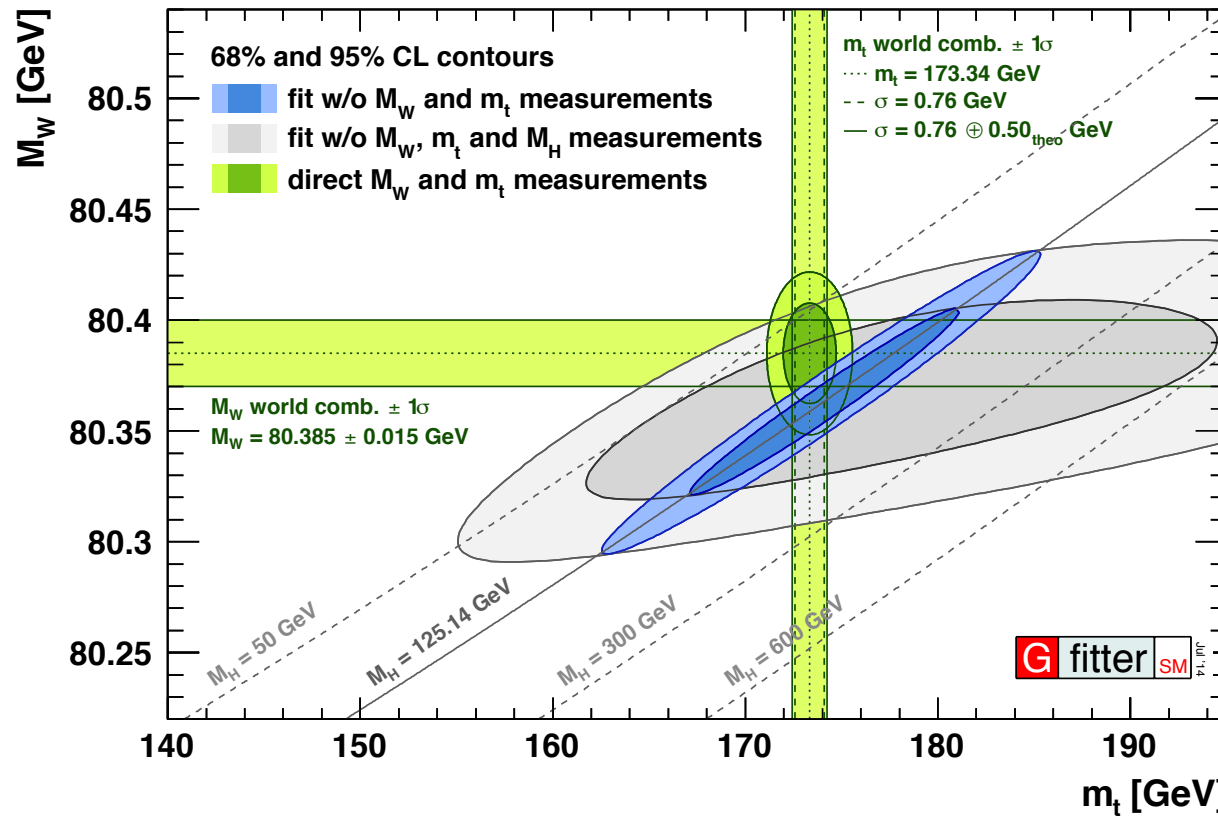
1307.3536



What is this telling us?

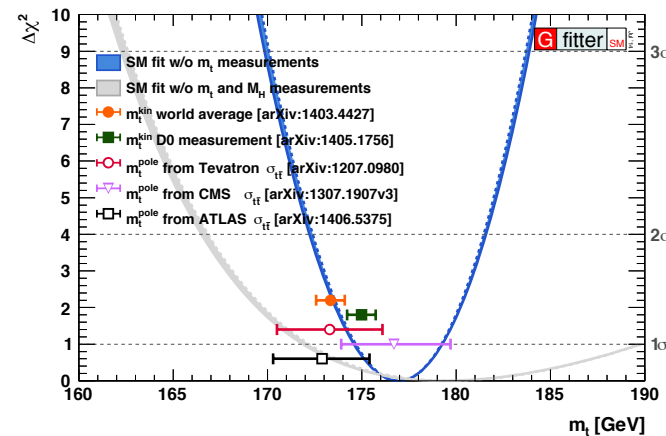
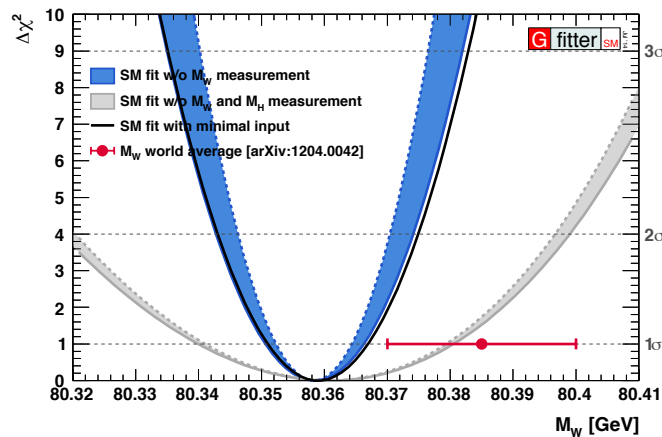


Implications (II) : *EW Precision Fit*



Important to have the Higgs mass, the current uncertainty is irrelevant in the fit

[Eur. Phys. J. C 74, 3046 \(2014\)](https://arxiv.org/abs/1307.1718)



Landscape Redefined

Flurry of new ideas !

Precision

- *Mass and width*
- *Coupling properties*
- *Quantum numbers (Spin, CP)*
- *Differential cross sections*
- *Off Shell couplings and width*
- *Interferometry*

Rare decays

- *$Z\gamma, \gamma\gamma^*$*
- *Muons $\mu\mu$*
- *LFV $\mu\tau, e\tau$*
- *$J/\Psi\gamma, ZY, WD$ etc...*

H⁰

...and More!

- *FCNC top decays*
- *Di-Higgs production*
- *Trilinear couplings prospects*
- *Etc...*

Tool for discovery

- *Portal to DM (invisible Higgs)*
- *Portal to hidden sectors*
- *Portal to BSM physics with H^0 in the final state (ZH^0, WH^0, H^0H^0)*

Is the SM minimal?

- *2 HDM searches*
- *MSSM, NMSSM searches*
- *Doubly charged Higgs bosons*

Already investigated at LHC!

- After 25 years of design, construction and commissioning of the LHC and detectors: with 1% of the foreseen total luminosity of the entire project: it is already a great success!
- The Discovery of the Higgs boson opens a new era in particle physics (experimental and theoretical)
- Within the current precision: The Higgs boson is fully compatible with the SM Higgs
- Increased precision is crucial to further determine the nature of the Higgs and of EWSB in general
- HL-LHC important challenge at the luminosity frontier
- Precision measurements, and in particular of the Higgs, must be pursued at future facilities (beyond HL-LHC)
- We are now exploring the new energy frontier at 13 TeV

Highest Mass Run 1 Di-Jet Event 4.23 TeV

