The Discovery of the Higgs Boson and Higgs Physics at LHC

Marumi Kado

LAL and CERN

40-4-C08 at CERN
marumi.kado@cern.ch

EDIT School Frascati 2015

Outline

1.- Introduction and Context

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

3.- Discovery channels beyond discovery

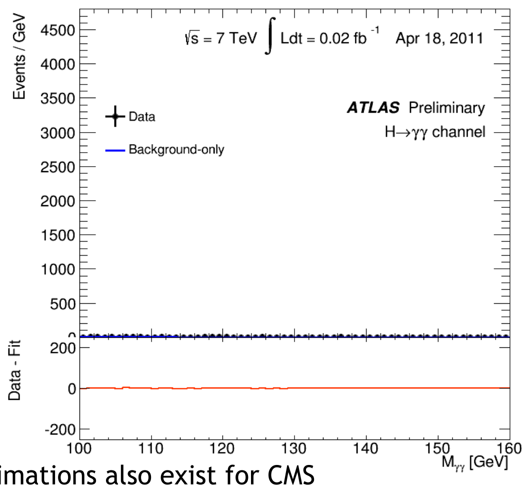
4.- Overview of post-discovery Higgs physics

5.- Glimpse at HL-LHC

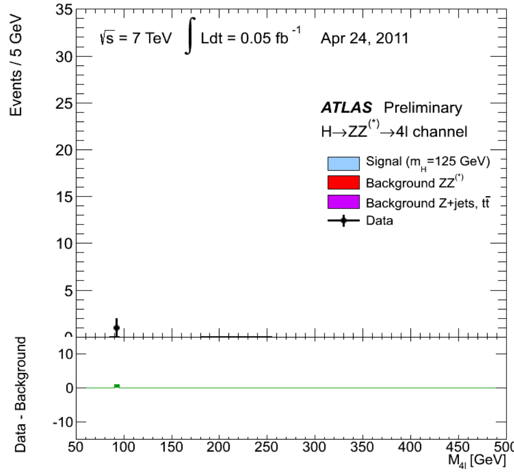
(For other future projects see Michelangelo's Talk)

The Discovery Channels

$pp\ (\rightarrow H)\ \rightarrow \gamma\gamma$

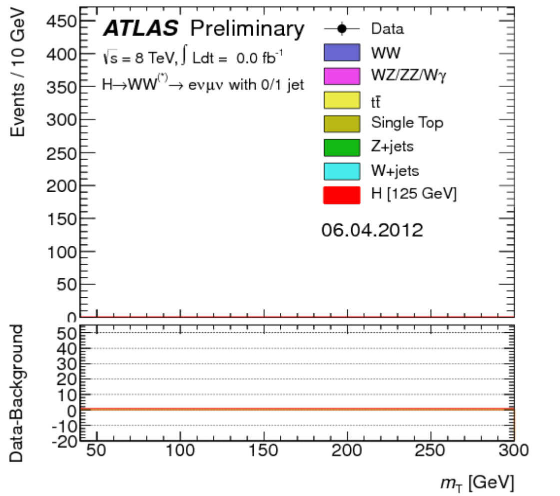


$pp\ (\rightarrow H) \rightarrow ZZ \rightarrow 4l$



Animations also exist for CMS

$pp\ (\rightarrow H) \rightarrow WW \rightarrow l\nu l\nu$



« 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.

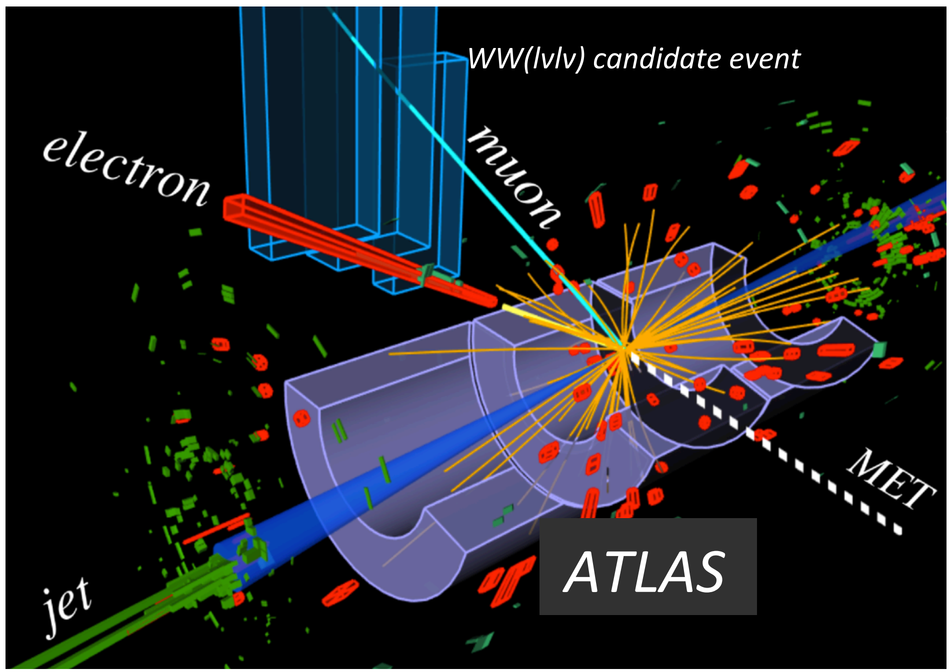
A report is given of studies of:
(a) H -> γγ (work done by C. Seez and T. Virdee)
(b) W H -> γγ (work done by L. DiLella, R. Kleiss, Z. Kunszt and W. J. Stirling)
for Higgs bosons in the intermediate mass range (90< m_H<150 GeV/c^2).
The study of the two photon decay mode is described in detail.

Introduction

A Standard Model neutral Higgs boson having a mass above the highest reach of LEP II (around 90 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->γγ, or, for m_H≥130 GeV/c^2, H^0->ZZ*->$e^+e^-e^+e^-$ [2]. As the decay width of the Higgs is about 5.5 MeV at m_H=100 GeV/c^2, and 8.3 MeV at 150 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 -> Zγ 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) Theory	BEH
Cooper pair condensate	Higgs field
Electrically charged (2e)	Weak charge
Mass of the photon	Mass of the W and Z bosons

The Higgs field is inserted by hand...

Condensate: the vacuum has a weak charge

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

SC (BCS) Th   Particle Th

1954 - Yang-Mills theories for non abelian gauge interactions

1950 – Landau and Ginzburg
JETP 20 (1950) 1064

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

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

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

1960 – Nambu

1961 – Goldstone Theorem

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

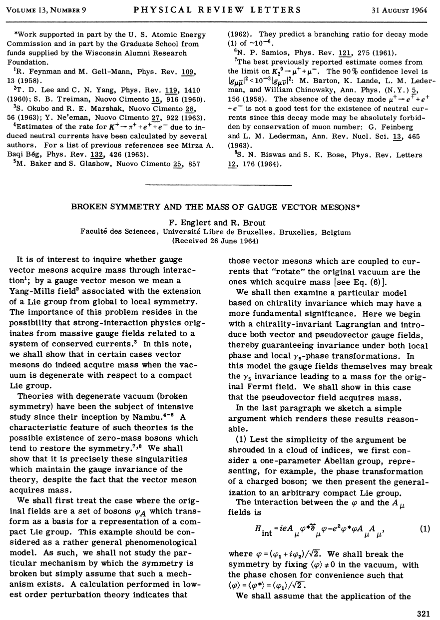
1963 – P. W. Anderson
Gauge field with mass (non relativistic)
Phys. Rev. 130 (1963) 439

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

Thought to be impossible in relativistic theories!

The Seminal Papers

SSB in local (Gauge) symmetries in RQFT

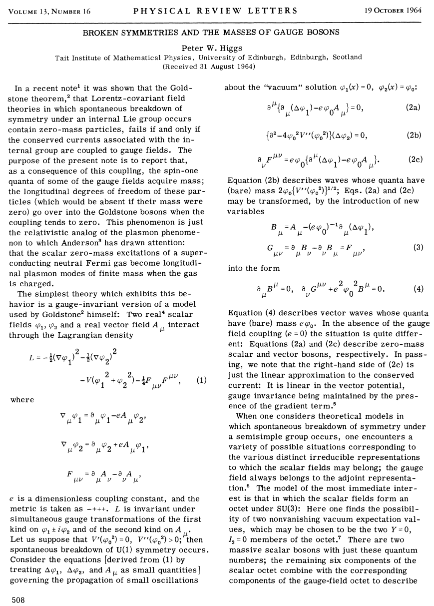

VOLUME 13, NUMBER 9 PHYSICAL REVIEW LETTERS 31 AUGUST 1964

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout

Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium

(Received 26 June 1964)


VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs

Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland

(Received 31 August 1964)

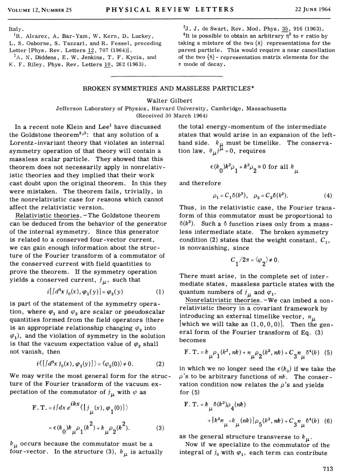

VOLUME 13, NUMBER 20 PHYSICAL REVIEW LETTERS 16 NOVEMBER 1964

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble

Department of Physics, Imperial College, London, England

(Received 12 October 1964)

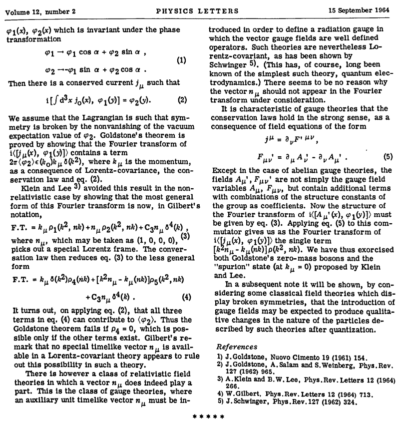

VOLUME 12, NUMBER 25 PHYSICAL REVIEW LETTERS 22 JUNE 1964

BROKEN SYMMETRIES AND MASSLESS PARTICLES*

Walter Gilbert

Jefferson Laboratory of Physics, Harvard University, Cambridge, Massachusetts

(Received 30 March 1964)


Volume 12, number 2 PHYSICS LETTERS 15 September 1964

1964

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

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

A MODEL OF LEPTONS*

Steven Weinberg†
Laboratory for Nuclear Science and Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 17 October 1967)

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

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

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

and on a right-handed singlet

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

The largest group that leaves invariant the kinematic terms $-\bar{L}\gamma^\mu\partial_\mu L - \bar{R}\gamma^\mu\partial_\mu R$ of the Lagrangian consists of the electronic isospin $\vec{T}$ acting on L, plus the 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 $\vec{T}$ and the electronic hyperchange $Y = N_R + \frac{1}{2}N_L$.

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

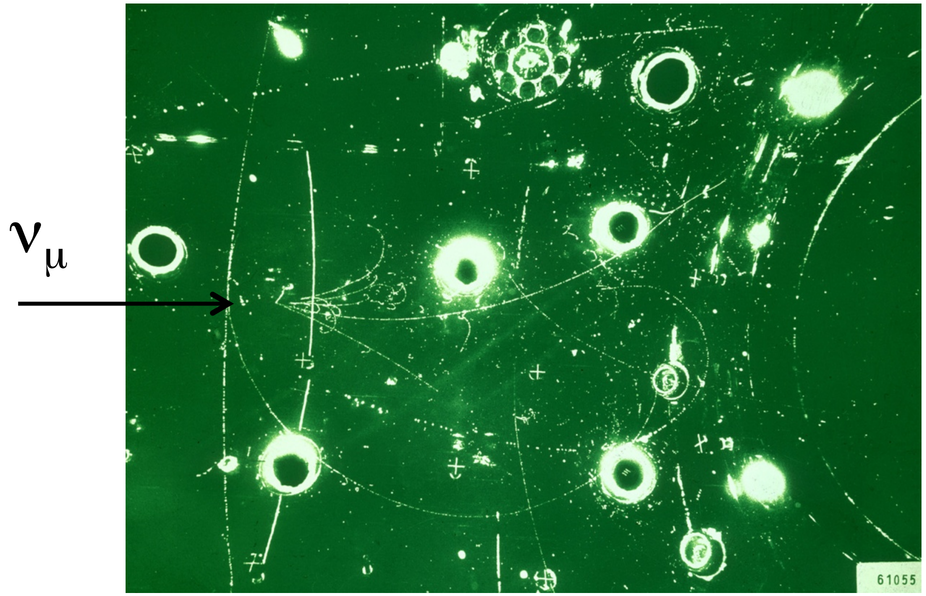
$$\varphi = \begin{pmatrix}\varphi^0 \\ \varphi^-\end{pmatrix} \qquad (3)$$

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

The only unequivocal new predictions made by this model have to do with the couplings of the neutral intermediate meson Z_μ

1973: neutral current discovery
(Gargamelle experiment, CERN)

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



The Standard Model of EW Interactions

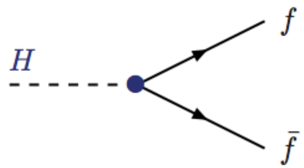
$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\Psi} \not{D} \Psi + h.c.$$

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!

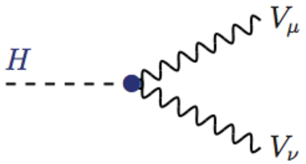


$g_{Hff} = m_f/v$

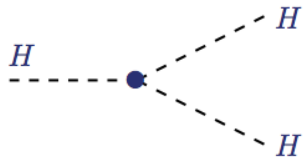
Not explaining the flavor Hierarchy

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



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



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

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

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

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

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

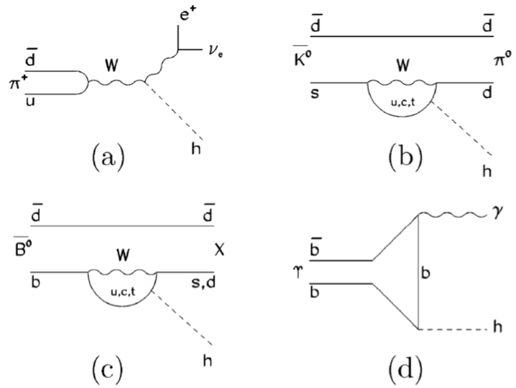
- Nuclear ^{16}O(6.05 MeV) to ground state ($0^+ - 0^+$) transitions (can occur through Higgs emission): $m_H > 18$ MeV
  (Kohler, Watson and Becker, 1974)

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

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.



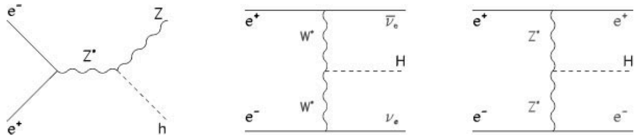
Nano review of Pre-LHC Direct Constraints

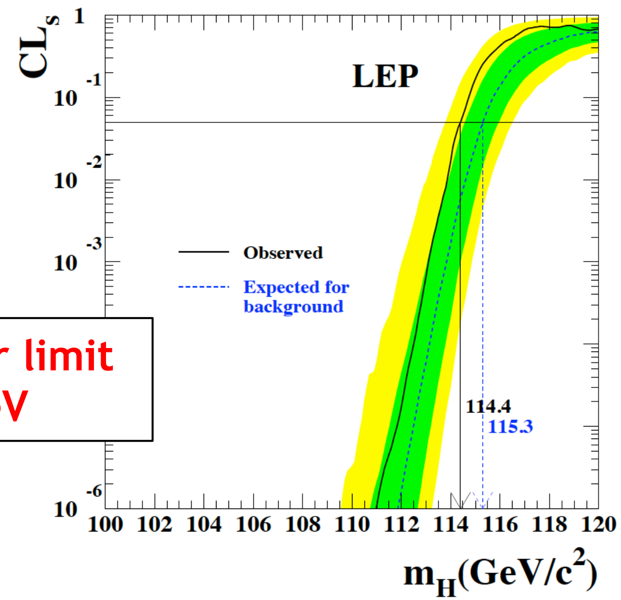
1976 – 2010

- SINDRUM Collaboration measured π to eν H (ee) Yielding a limit on very light Higgs
- CUSB Collaboration Υ .. ..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)

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)



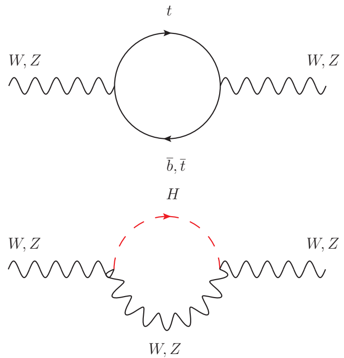


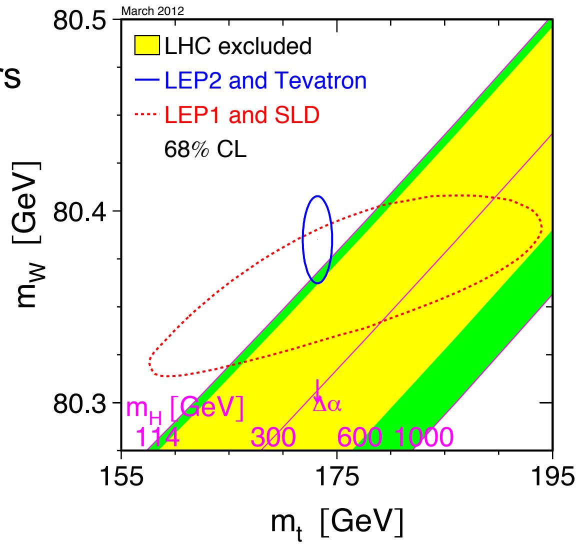
Absoute lower limit at 114 GeV

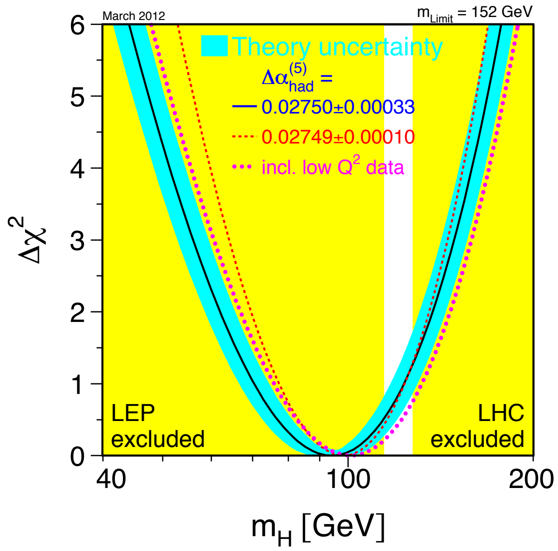
Indirect Direct Constraints from Precision EW

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

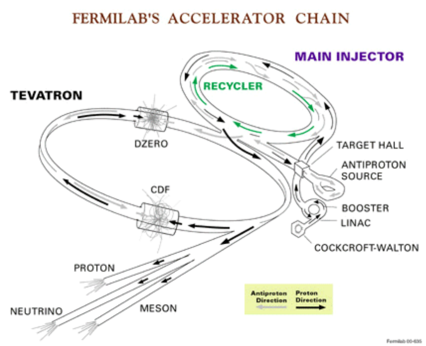
pp ~2TeV

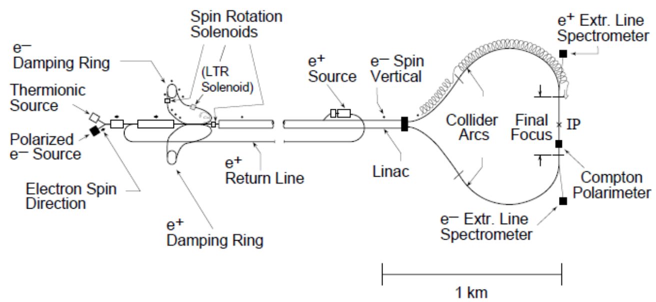
SLC 1988-1998

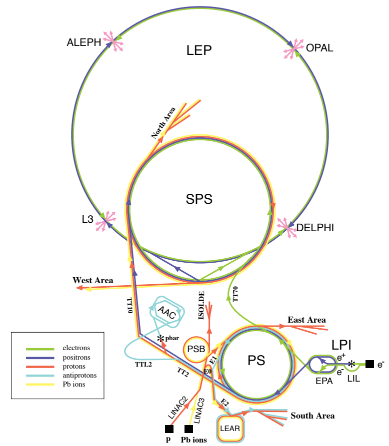
e^+e^- 91GeV

LEP 1989-2000

e^+e^- 91Gev,130-208GeV





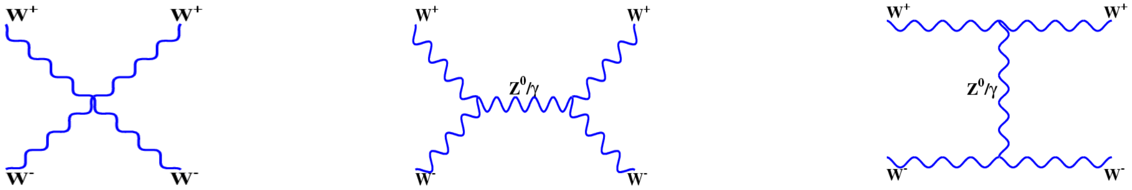


*Approximate

The No Loose Theorem*

The cross section for the thought scattering process :

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



Does not preserve perturbative unitarity.

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

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

This is not only a motivation for the Higgs mechanism but is also a 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

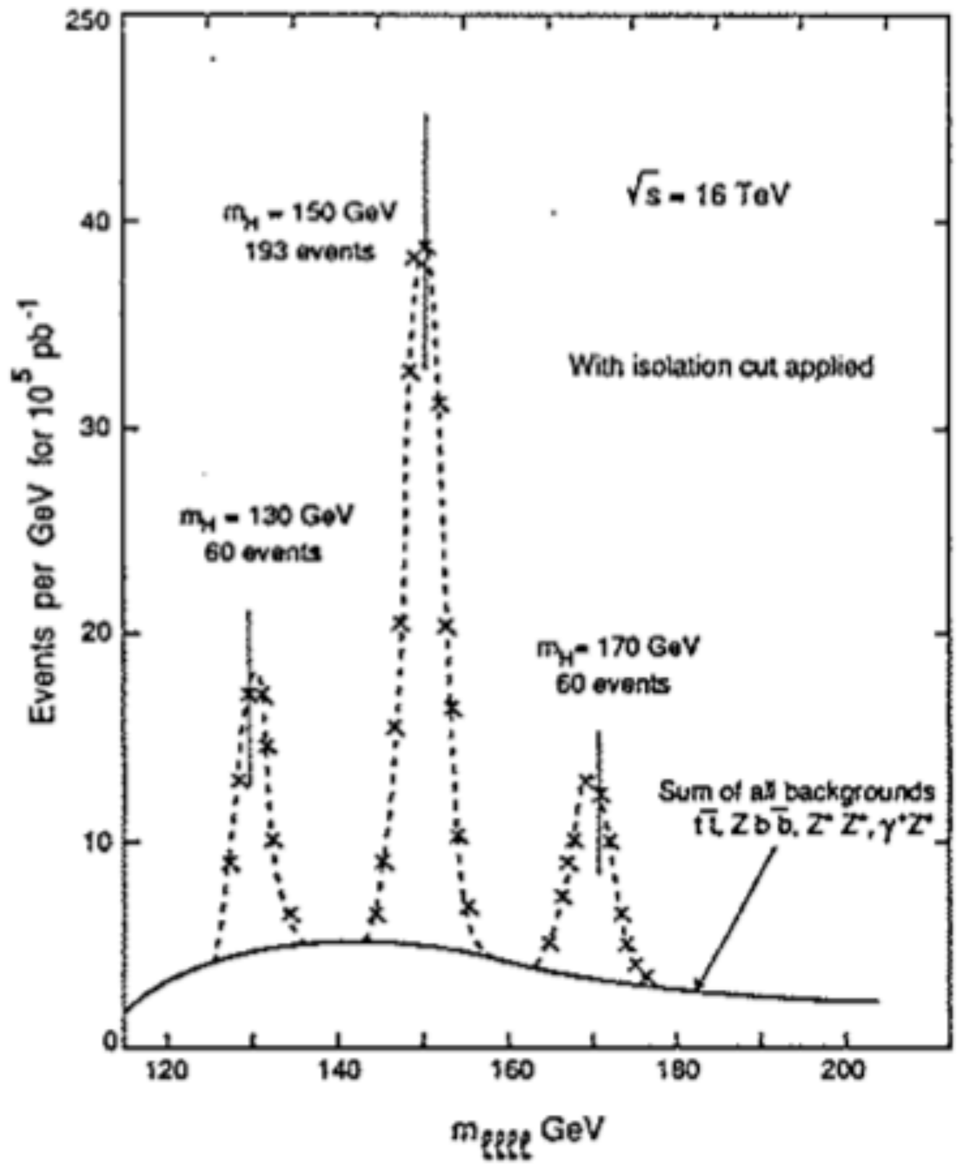
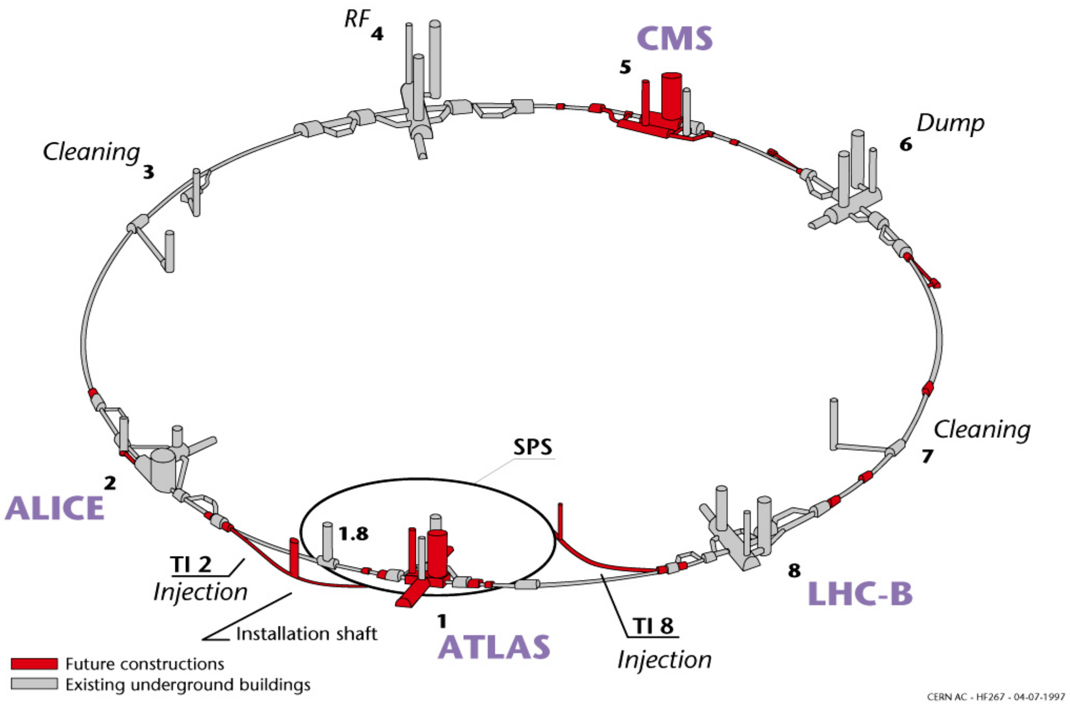


Fig. 10

1990

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

Projected Nominal Specifications of the LHC



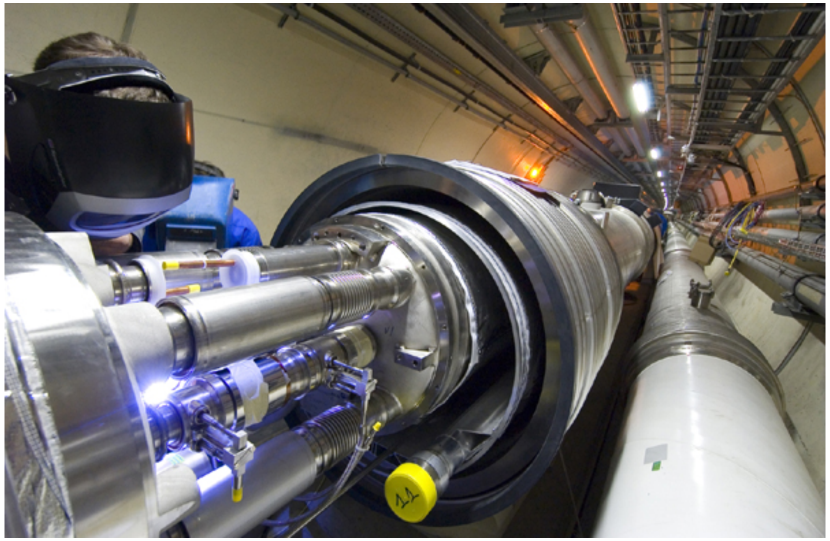
Main Numbers

- 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 10^{11}
Bunch spacing / k	25 ns /2808
ε (mm rad)	3.75
β^* (m)	0.55
L ($cm^{-2}s^{-1}$)	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

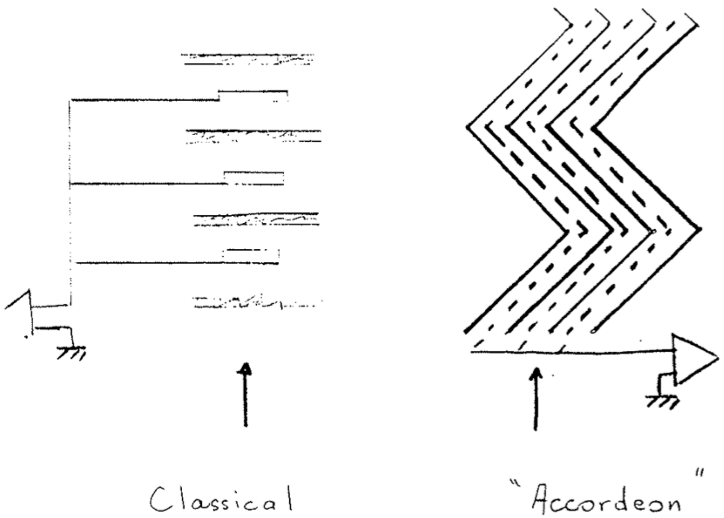
An approach to high granularity,fast Liq Ar calorimetry

using an "accordeon" structure

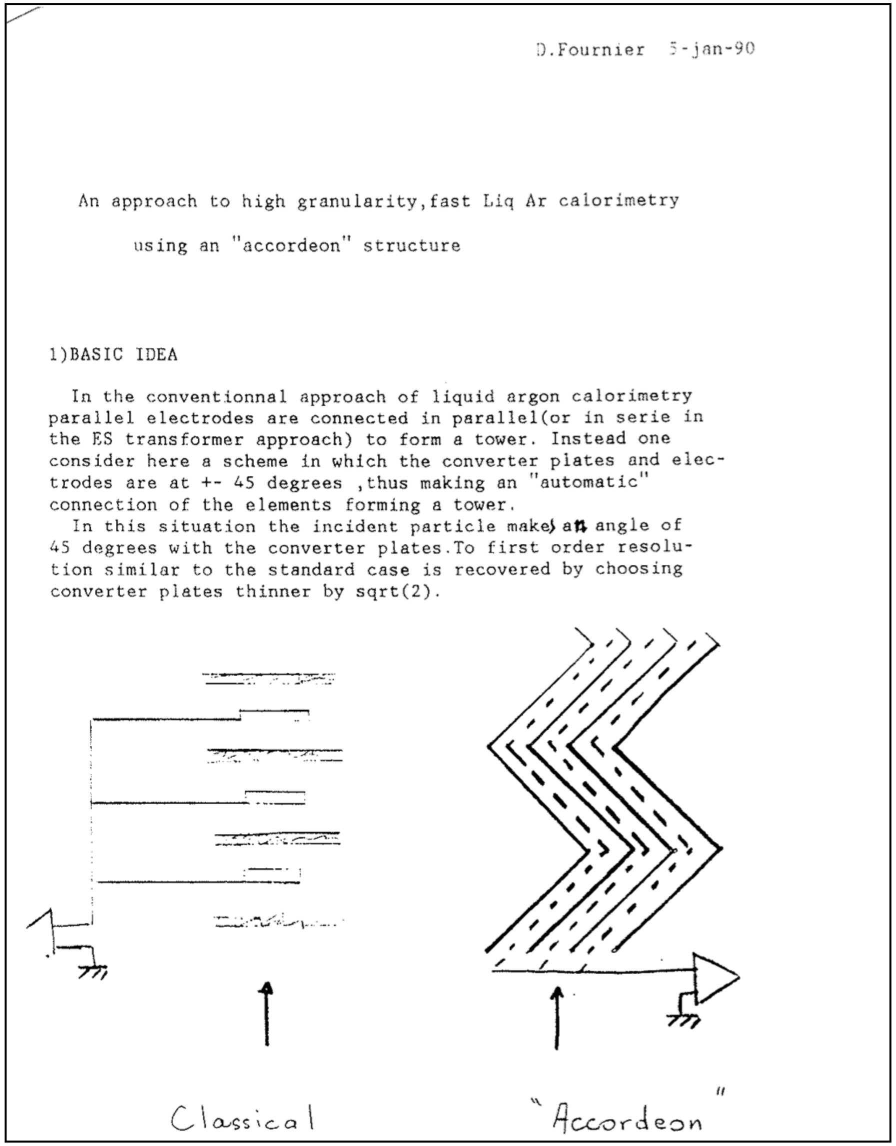
1)BASIC IDEA

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

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



Years of Design, Construction and Commissioning of Experiments



D.Fournier 5-jan-90

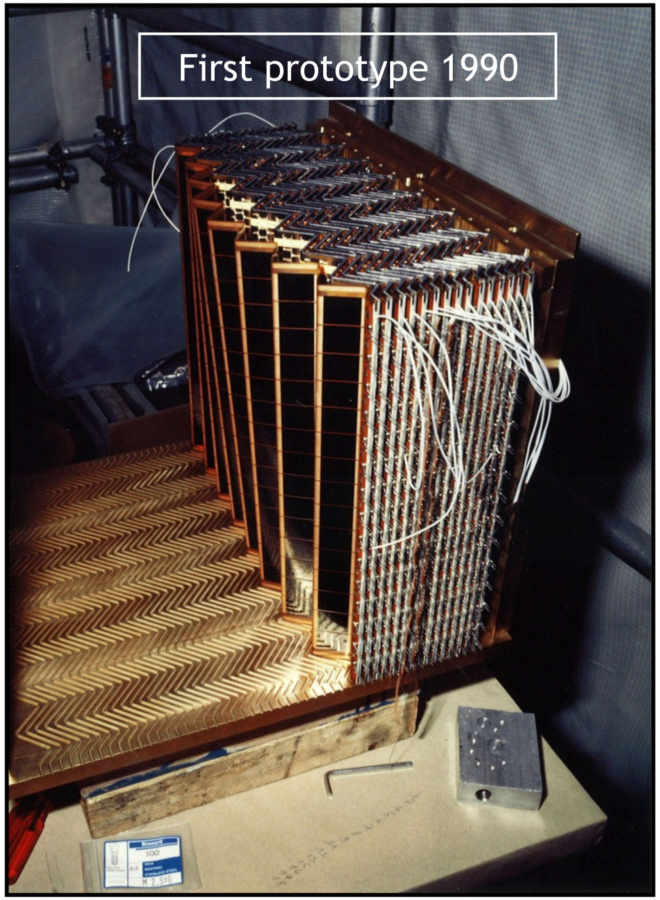
An approach to high granularity,fast Liq Ar calorimetry

using an "accordeon" structure

1)BASIC IDEA

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

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



Years of Design, Construction and Commissioning of Experiments

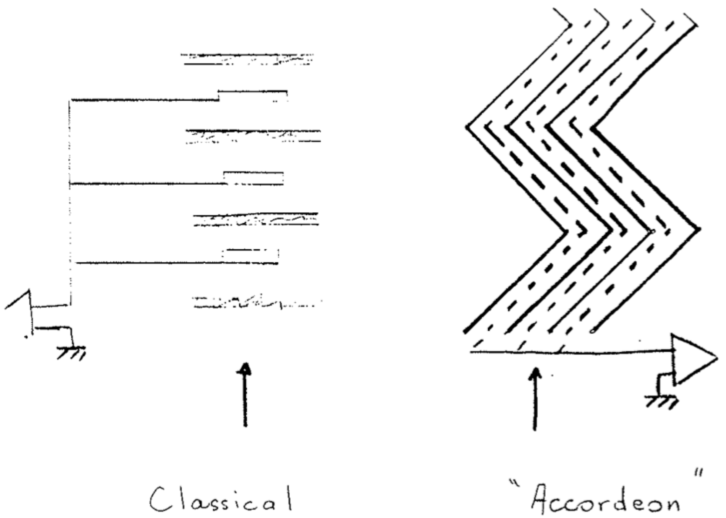
D.Fournier 5-jan-90

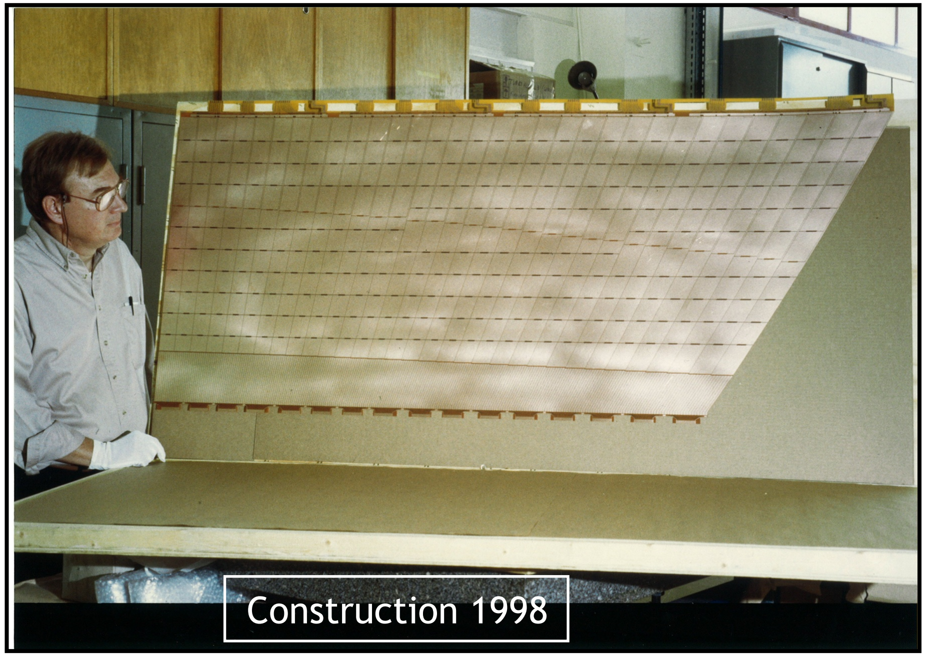
An approach to high granularity,fast Liq Ar calorimetry

using an "accordeon" structure

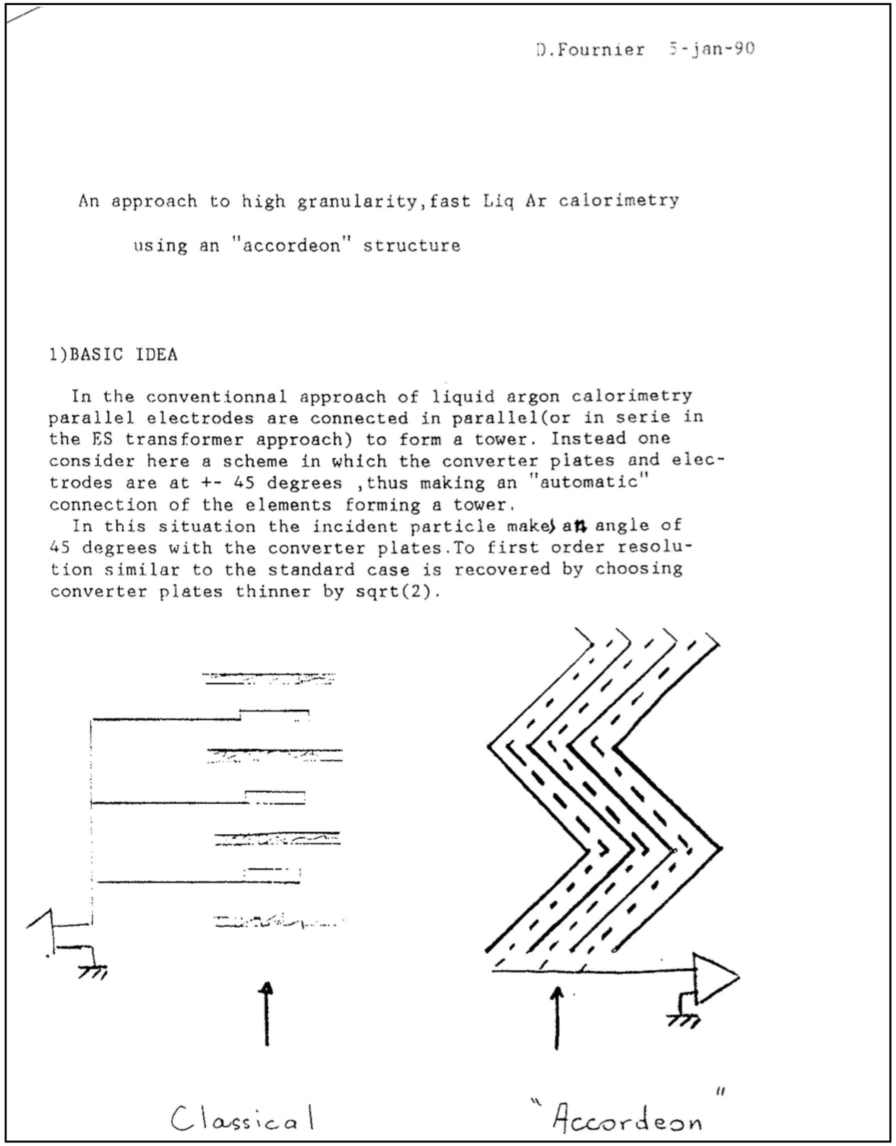
1)BASIC IDEA

In the conventionnal approach of liquid argon calorimetry parallel electrodes are connected in parallel(or in serie in the ES transformer approach) to form a tower. Instead one consider here a scheme in which the converter plates and electrodes are at +- 45 degrees ,thus making an "automatic" connection of the elements forming a tower.
In this situation the incident particle makes an angle of 45 degrees with the converter plates.To first order resolution similar to the standard case is recovered by choosing converter plates thinner by sqrt(2).





Years of Design, Construction and Commissioning of Experiments



D.Fournier 5-jan-90

An approach to high granularity,fast Liq Ar calorimetry

using an "accordeon" structure

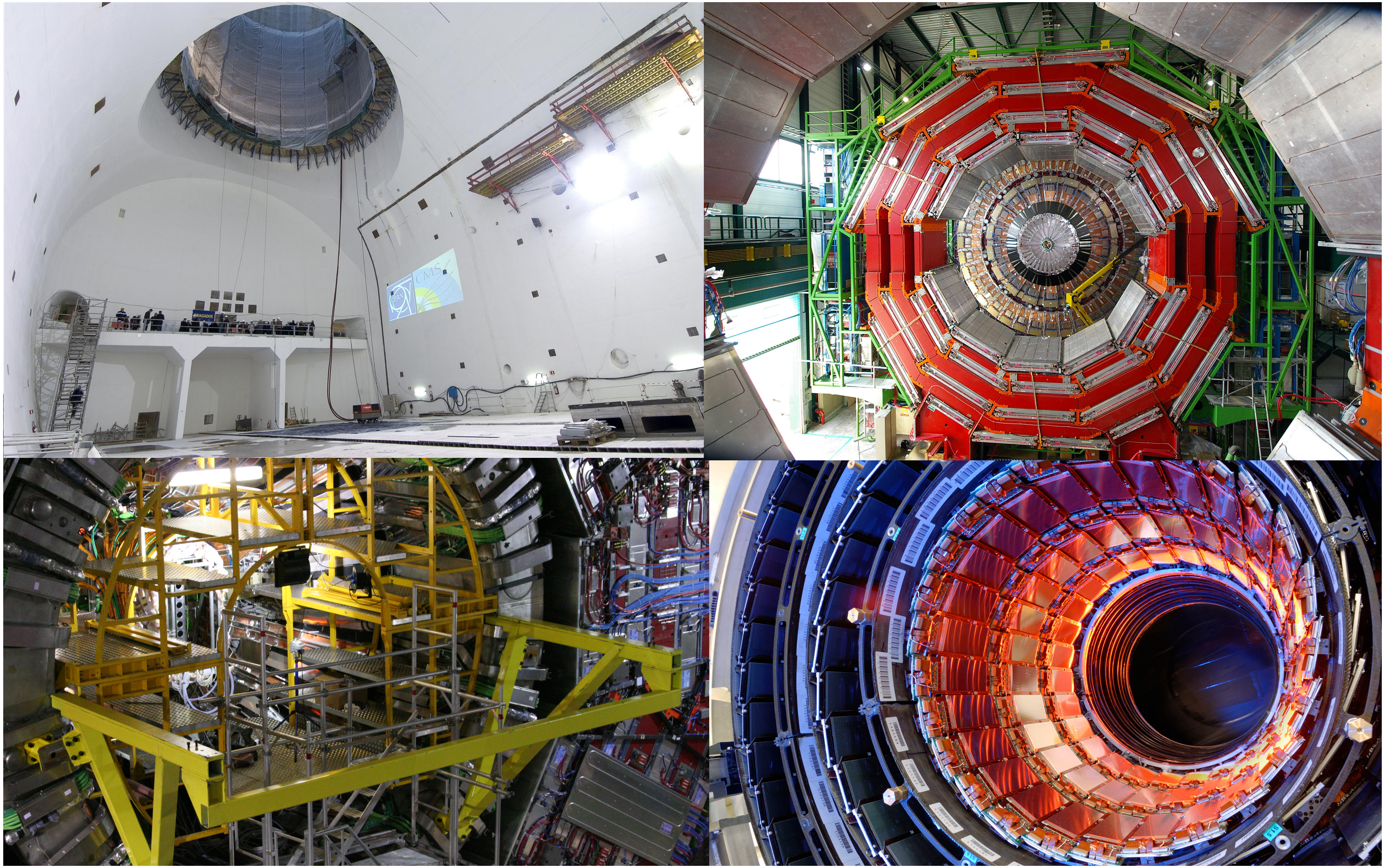
1)BASIC IDEA

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

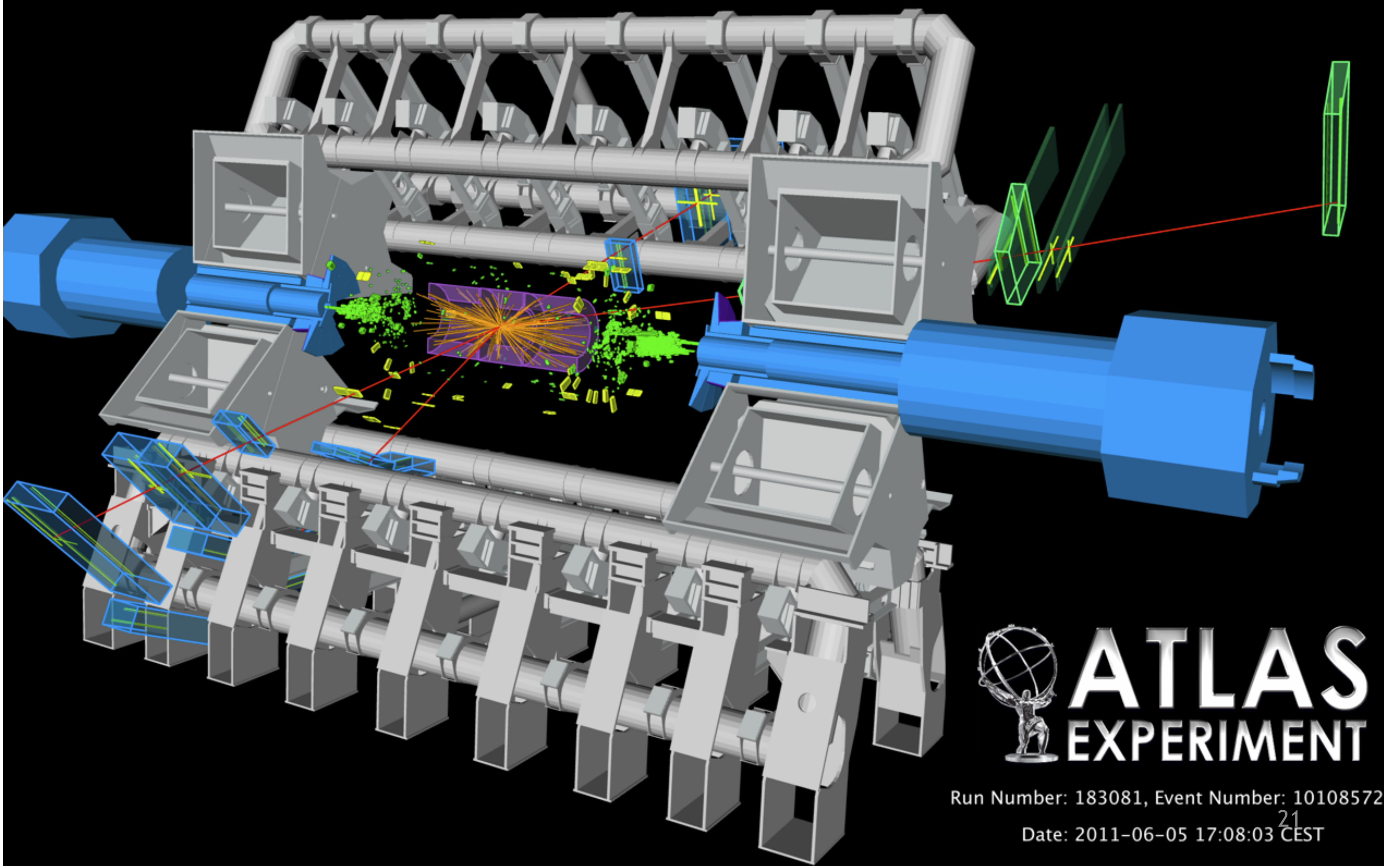
In this situation the incident particle makes an angle of 45 degrees with the converter plates.To first order resolution similar to the standard case is recovered by choosing converter plates thinner by sqrt(2).

Installation 2004

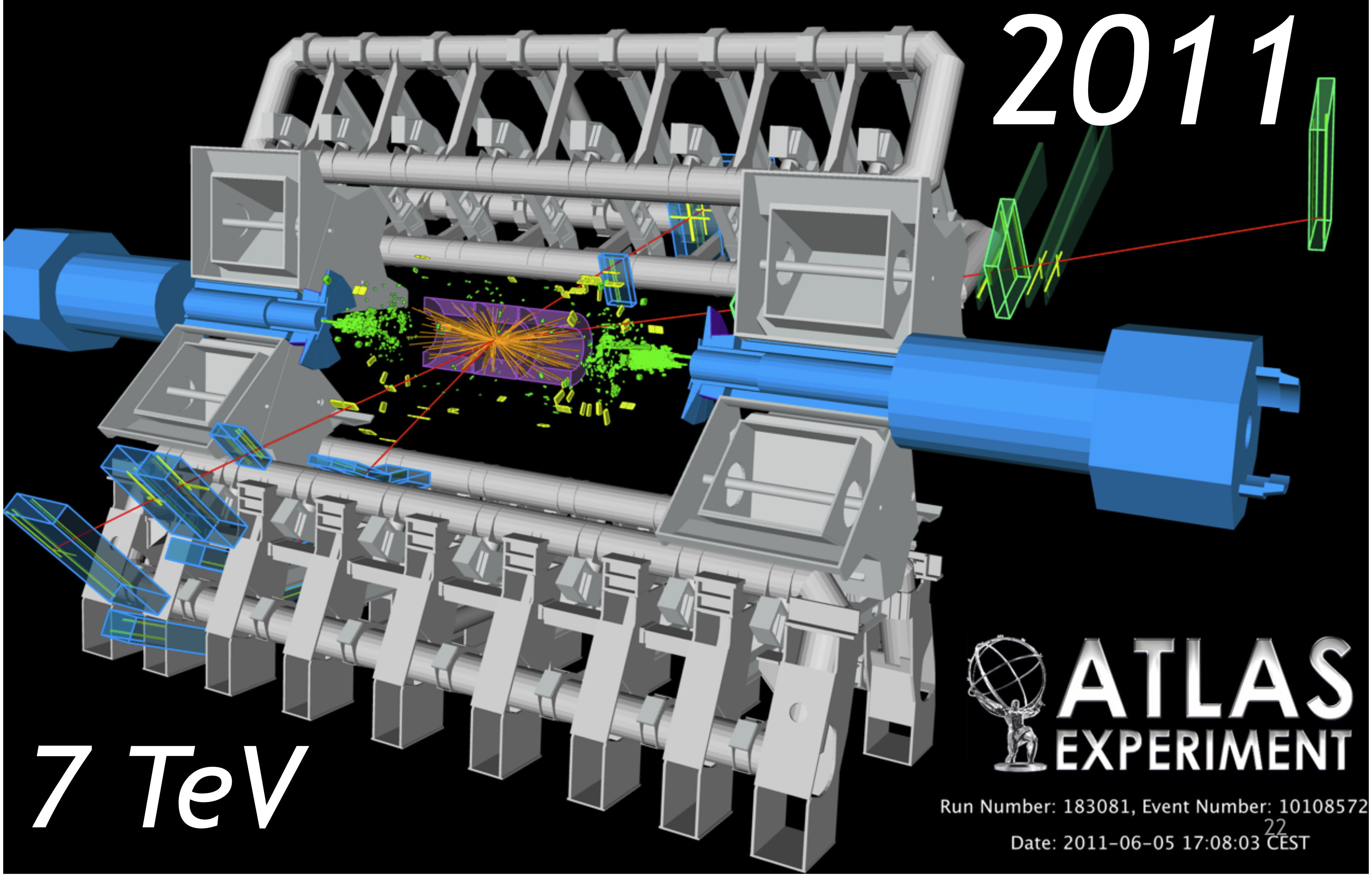
Years of Design, Construction and Commissioning of Experiments



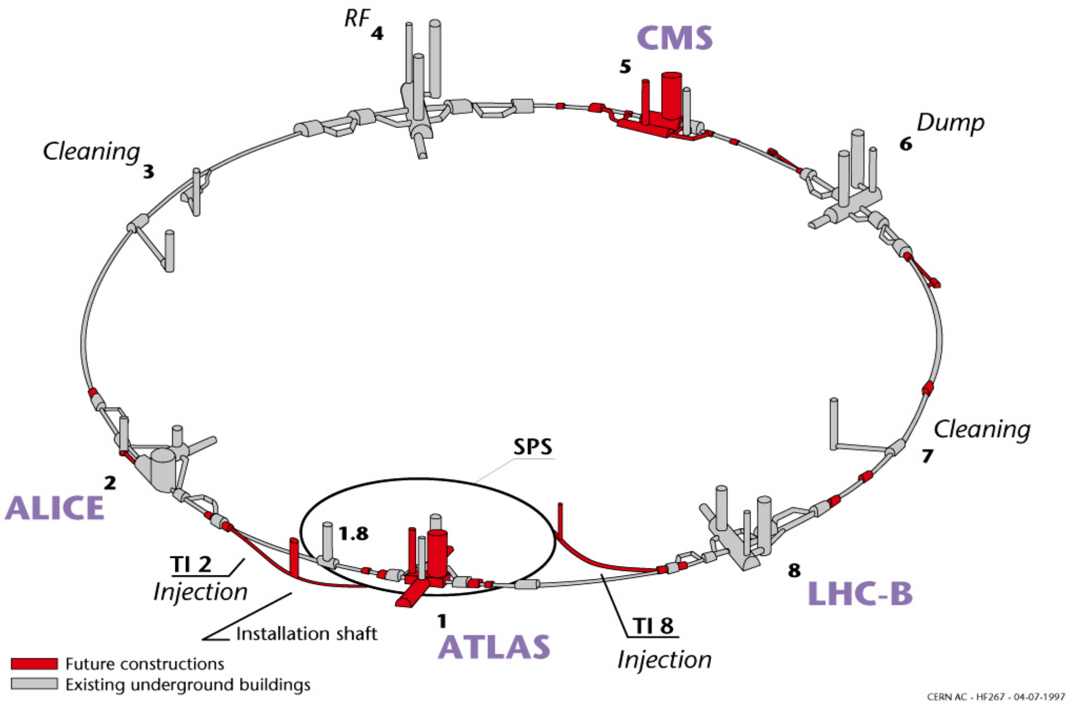
4 μ event … *Standard EW only or Higgs?*



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



Three Years of LHC operations



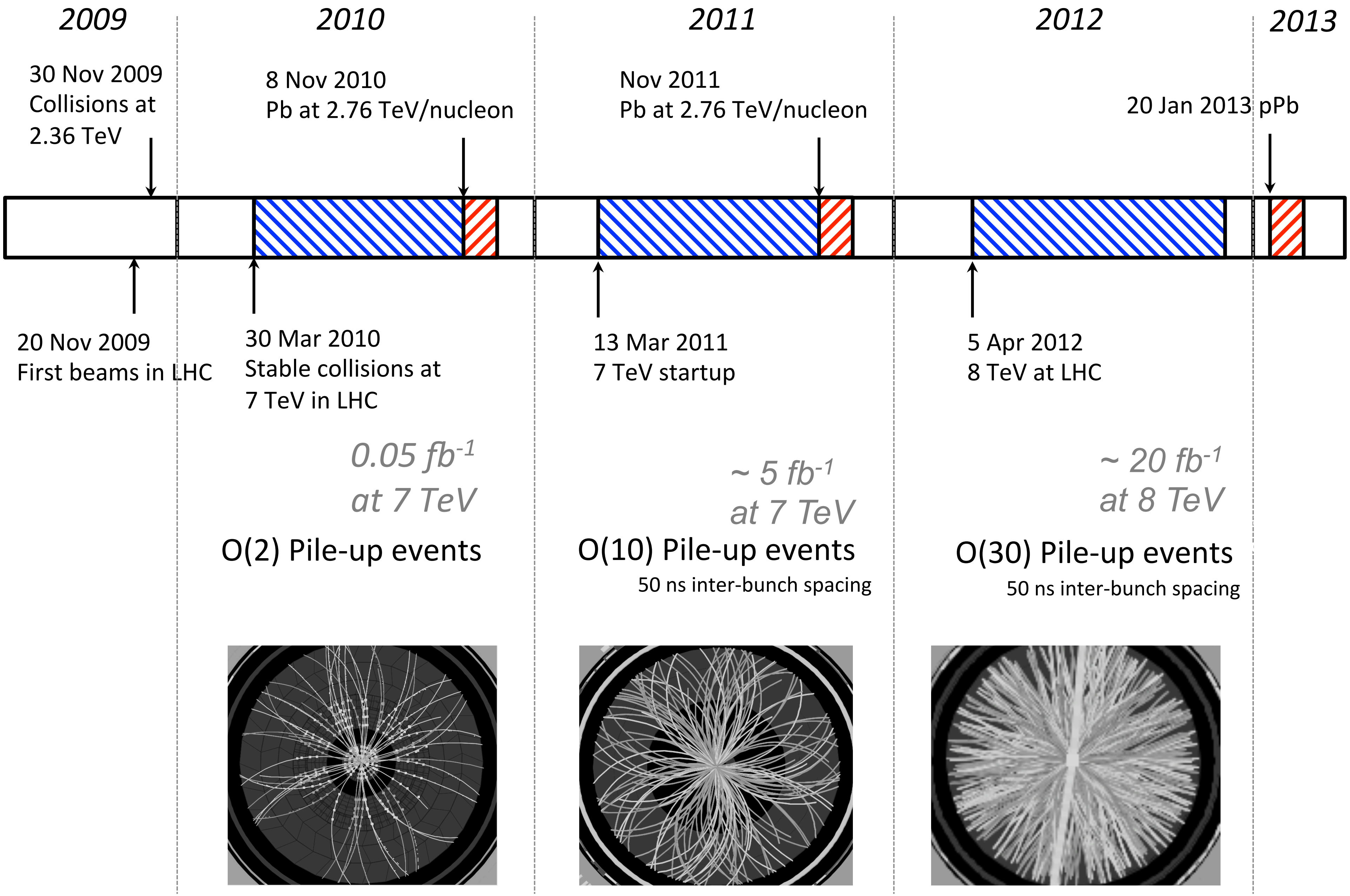
The LHC

- 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)

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

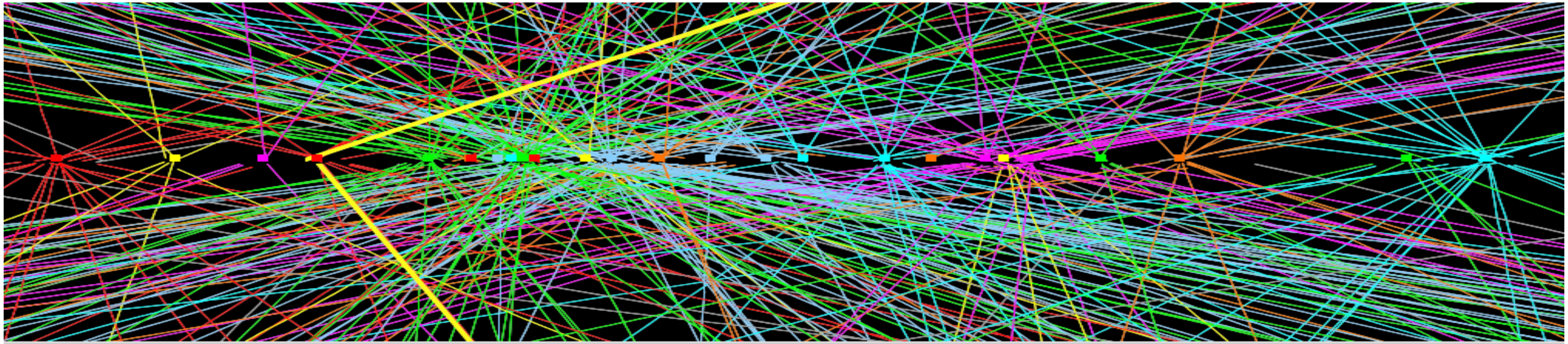
Parameter	2010	2011	2012	Nominal
C.O.M Energy	7 TeV	7 TeV	8 TeV	14 TeV
N_p	$1.1\ 10^{11}$	$1.4\ 10^{11}$	$1.6\ 10^{11}$	$1.15\ 10^{11}$
Bunch spacing / k	150 ns / 368	50 ns / 1380	50 ns /1380	25 ns /2808
ε (mm rad)	2.4-4	1.9-2.3	2.5	3.75
β* (m)	3.5	1.5-1	0.6	0.55
L ($cm^{-2}s^{-1}$)	2×10^{32}	3.3×10^{33}	$\sim 7\times10^{33}$	10^{34}

The LHC Run 1



2009
2010
2011
2012
2013
30 Nov 2009
Collisions at
2.36 TeV
8 Nov 2010
Pb at 2.76 TeV/nucleon
Nov 2011
Pb at 2.76 TeV/nucleon
20 Jan 2013 pPb
20 Nov 2009
First beams in LHC
30 Mar 2010
Stable collisions at
7 TeV in LHC
13 Mar 2011
7 TeV startup
5 Apr 2012
8 TeV at LHC
0.05 fb-1
at 7 TeV
~ 5 fb-1
at 7 TeV
~ 20 fb-1
at 8 TeV
O(2) Pile-up events
O(10) Pile-up events
50 ns inter-bunch spacing
O(30) Pile-up events
50 ns inter-bunch spacing

Detector Challenges

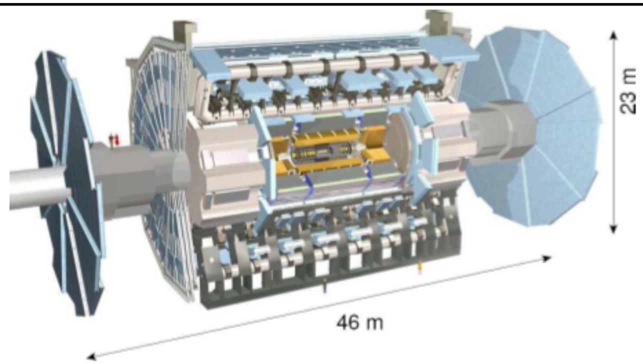
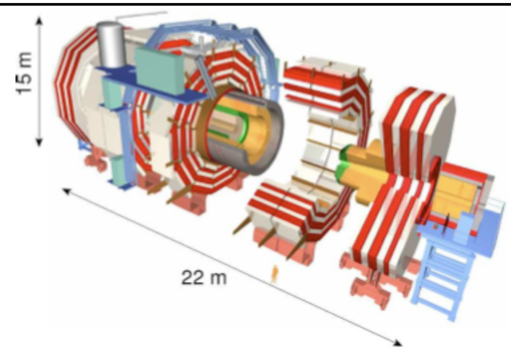


- Trigger Challenge : How to select typically 400-1000 out of 20M events per second while keeping the interesting (including unknown) physics

- 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^{T}_{mis}, b-jets) up to the highest pile-up

The ATLAS and CMS Performance In a Nutshell

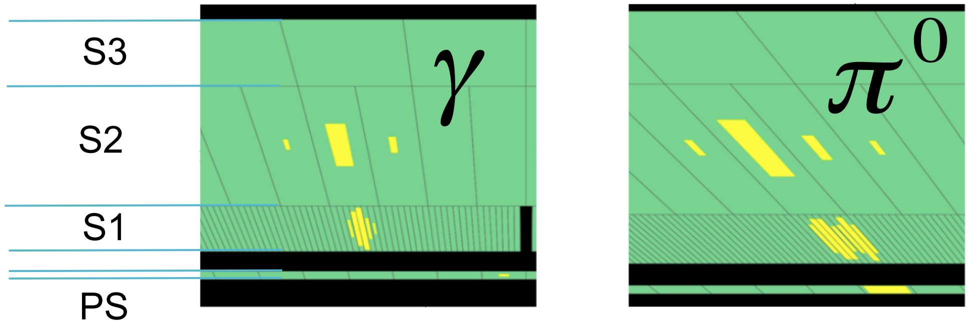
Sub System	ATLAS	CMS
Design		
Magnet(s)	Solenoid (within EM Calo) 2T 3 Air-core Toroids	Solenoid 3.8T Calorimeters Inside
Inner Tracking	Pixels, Si-strips, TRT PID w/ TRT and dE/dx $\sigma_{p_T}/p_T \sim 5\times10^{-4} p_T \oplus 0.01$	Pixels and Si-strips PID w/ dE/dx $\sigma_{p_T}/p_T \sim 1.5\times10^{-4} p_T \oplus 0.005$
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)

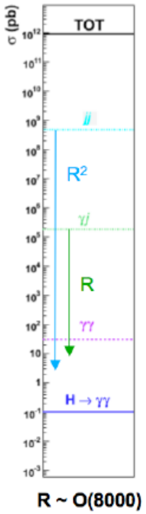
The ATLAS Electromagnetic Calorimeter Granular and Uniform by Construction!

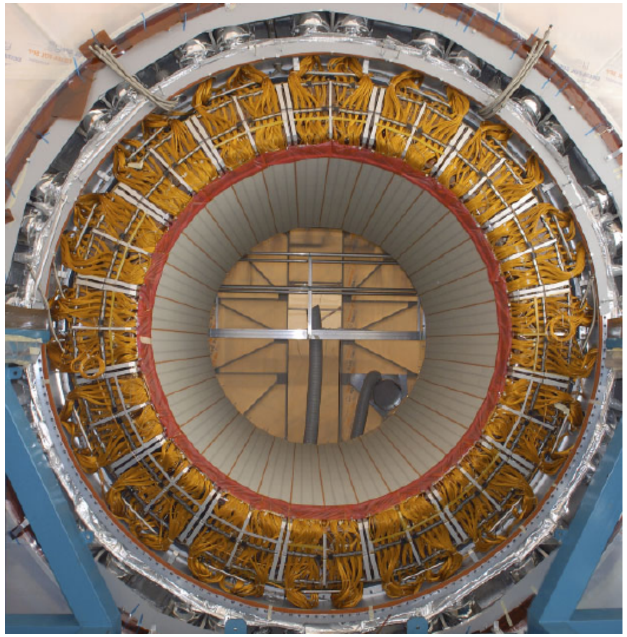
Both longitudinal and transverse granularity:

- Photon – Pion discrimination
- Pointing direction reconstruction

π^0-γ Rejection

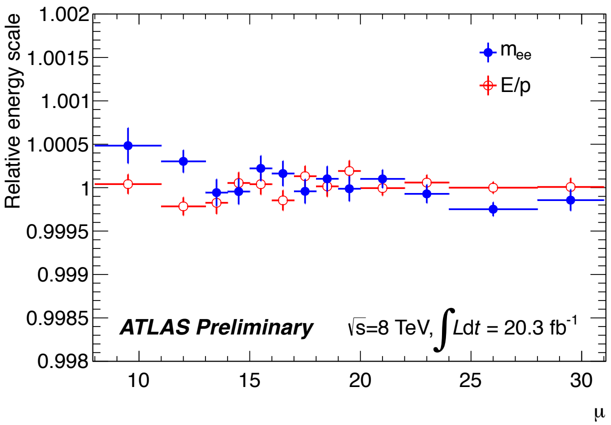






Crack-less Accordion geometry

CERN-PH-EP-2014-153



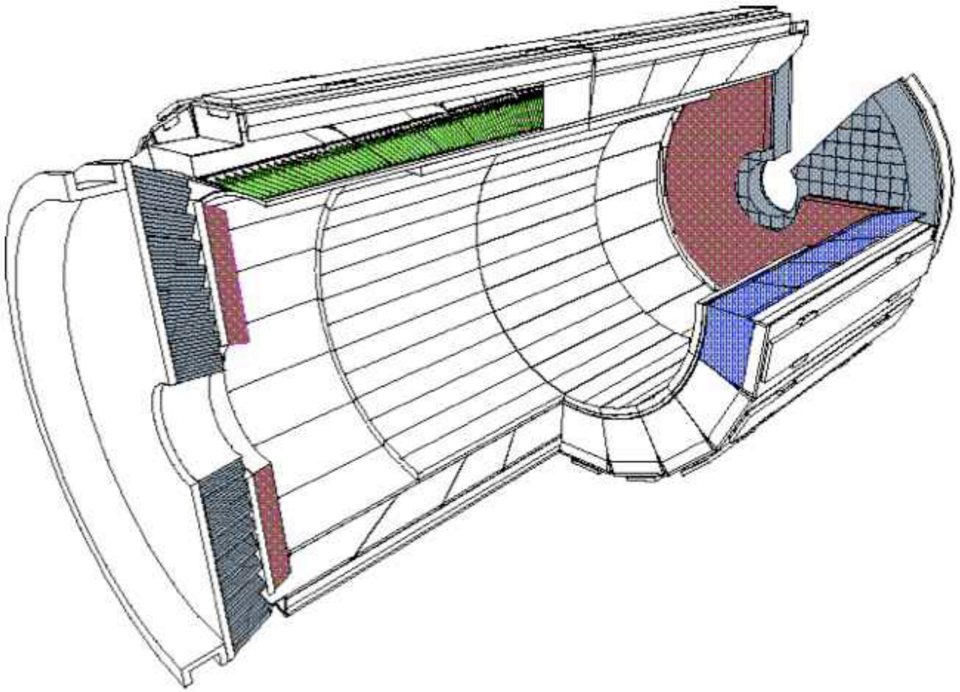
A.- Stability in time within: 0.05%

B.- Stability in PU within: 0.05%

The CMS Crystal Calorimeter

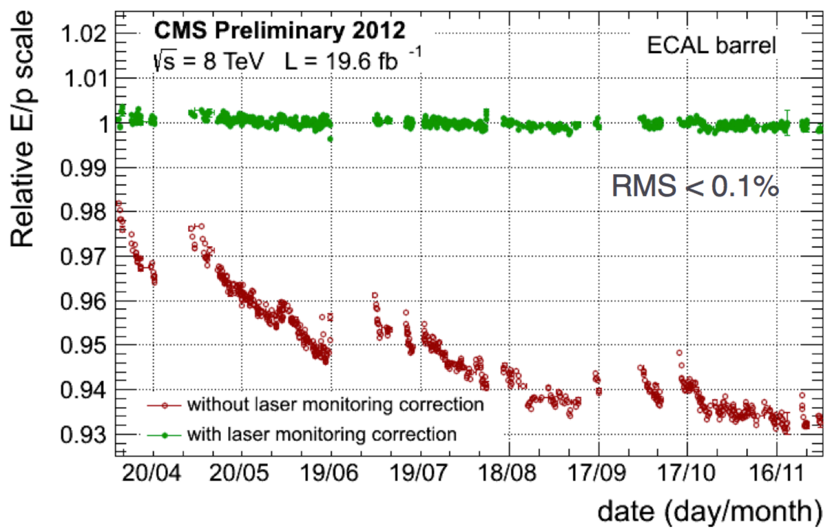
Homogeneous, Compact, Hermetic, Granular $PbWO_4$ Crystal calorimeter

- 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)



Emphasis on Resolution!

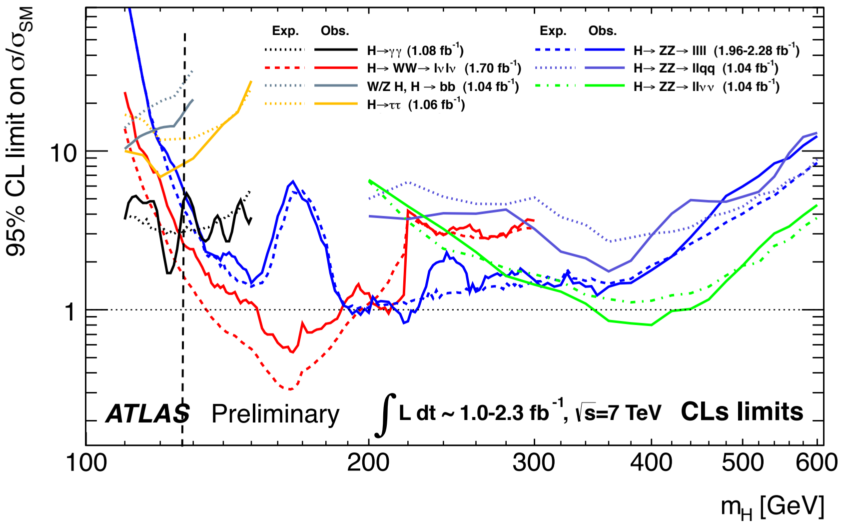
Stability in time within: 0.1%

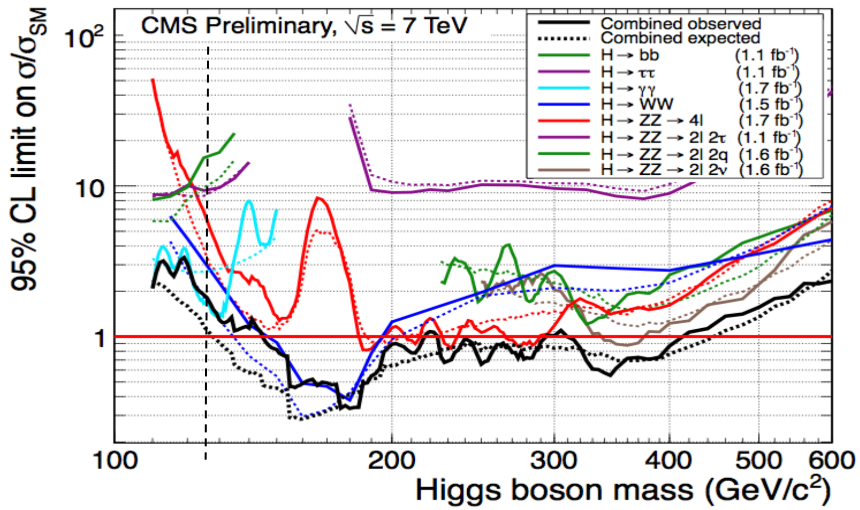


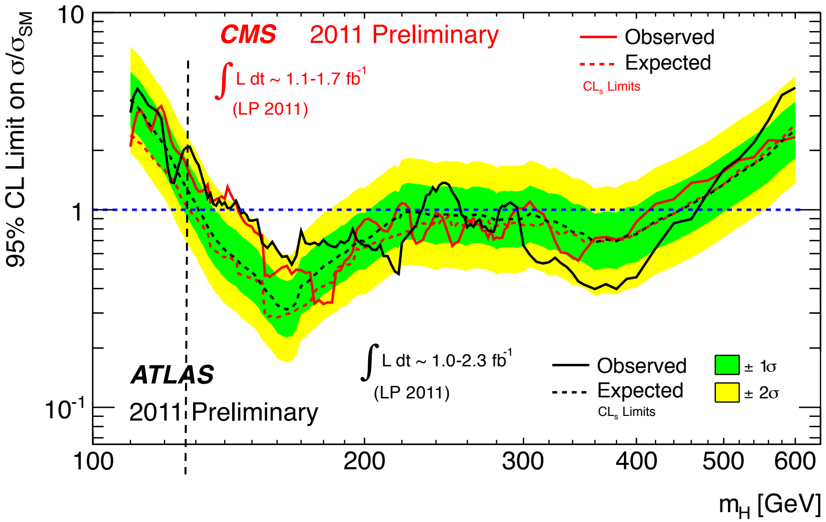
Intercalibration and transparency corrections

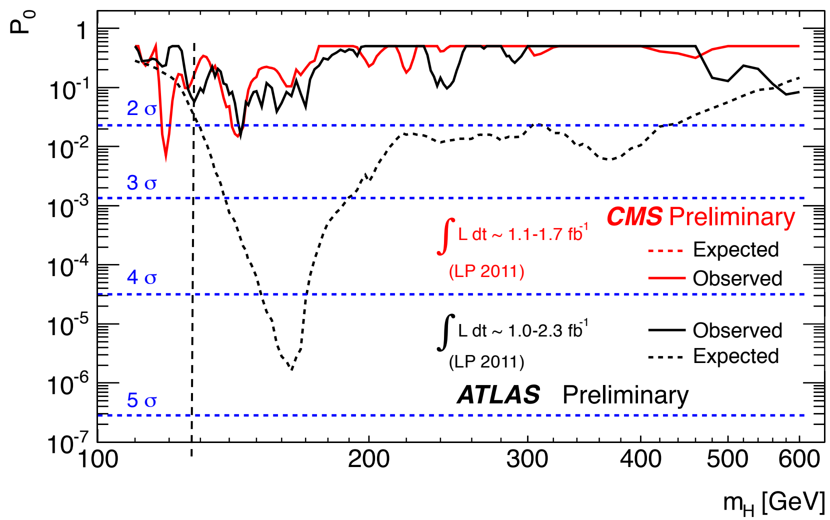
- Transparency (Laser) every 40mn
- Monthly using π^0

Summer of 2011: From the Limit to the p0 Era

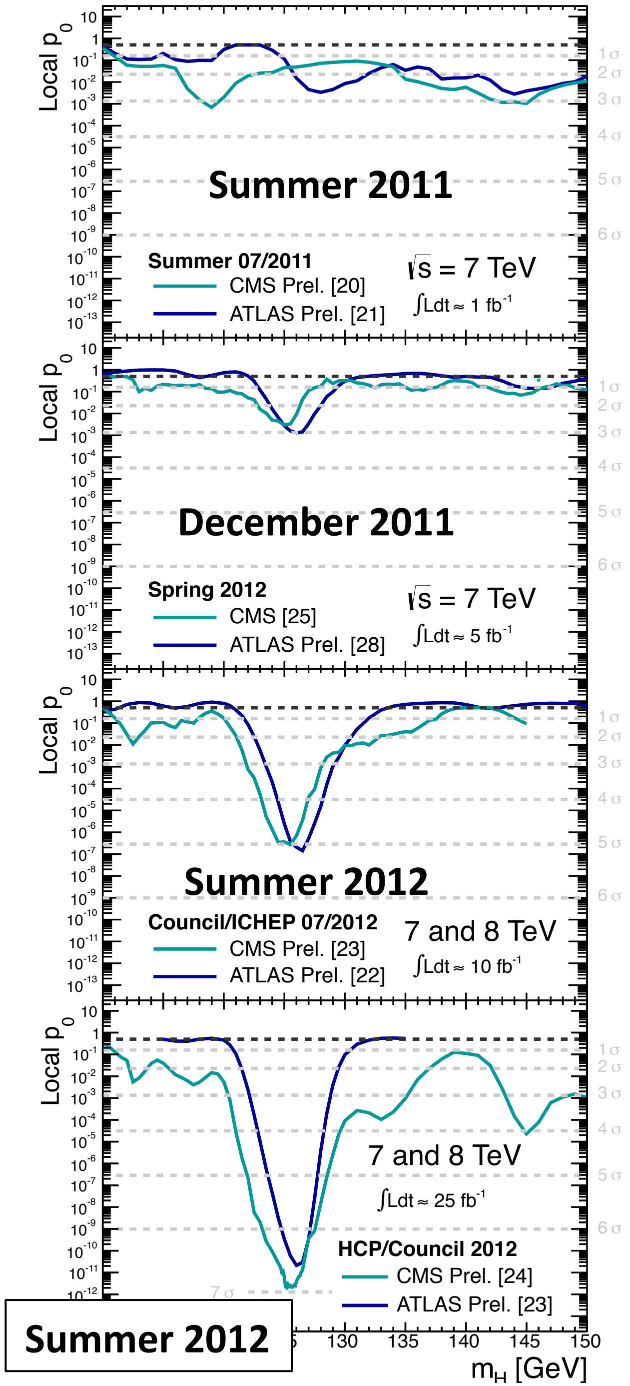








PDG, review of Particle Physics



A Textbook and Timely Discovery

- Summer 2011: EPS and Lepton-Photon

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

- December 2011: CERN Council

  First hints

- Summer 2012: CERN Council and ICHEP

  Discovery!

- December 2012: CERN Council

  Begining of a new era

✓ Strongly Mostivated

✓ Significance increased with luminosity to reach unambiguous levels

✓ Two experiments

✓ Several channels

Outline

1.- Introduction and Context

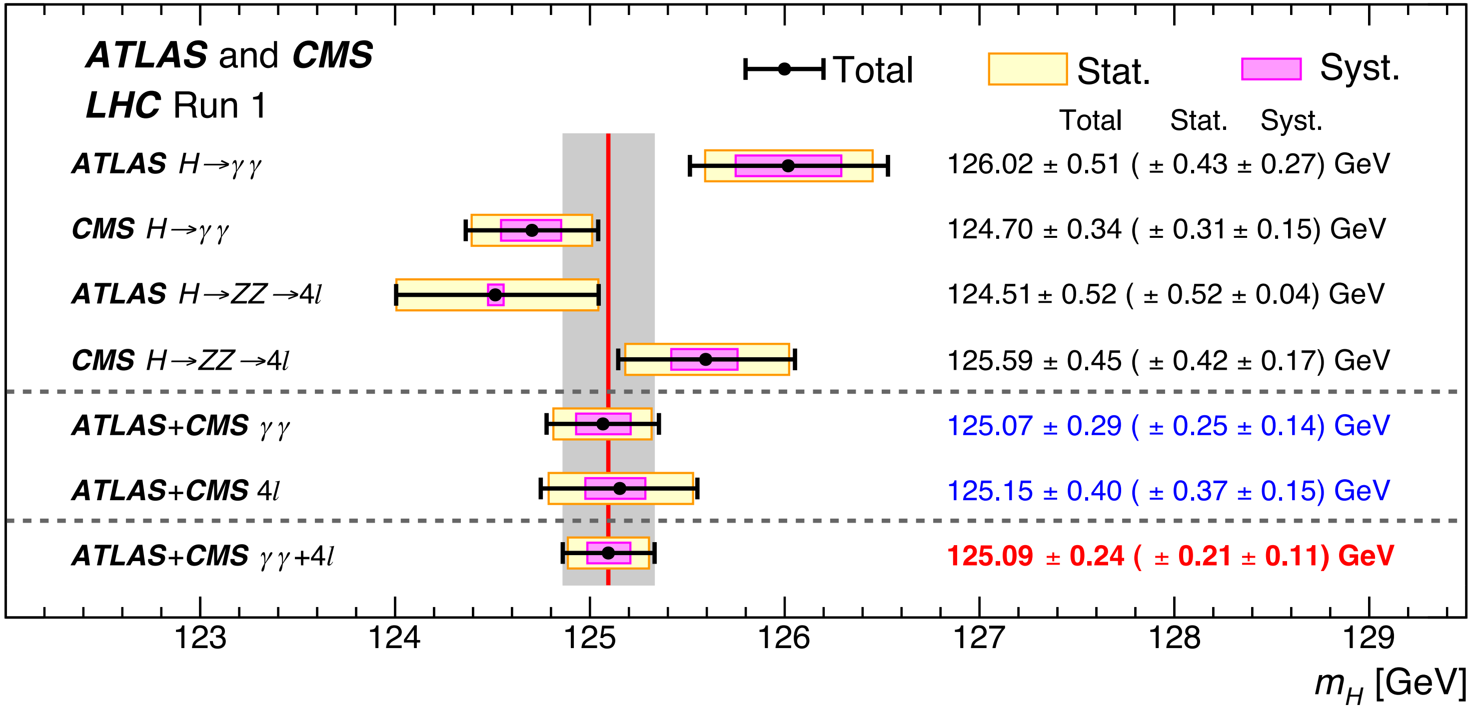
2.- The « Bread and Butter » Discovery Channels, the detectors and the machine.

3.- Discovery channels beyond discovery

4.- Overview of post-discovery Higgs physics

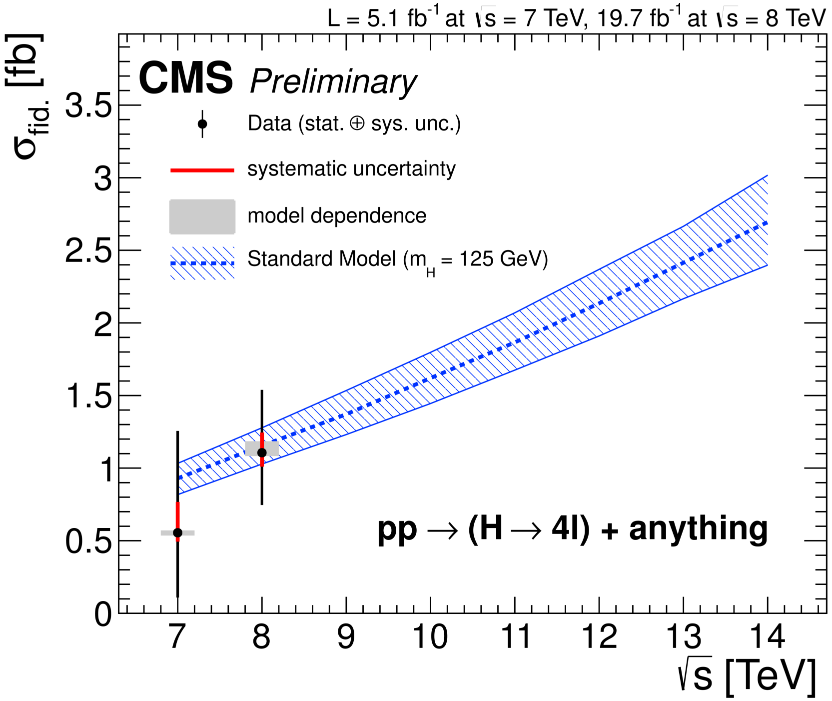
5.- Glimpse at HL-LHC

A Permille Precision Measurement

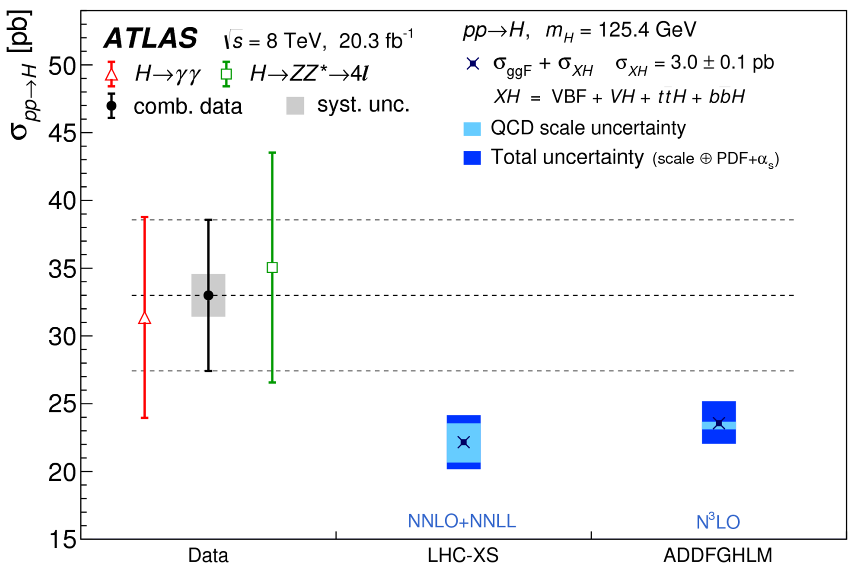


- Statistics dominated Measurement
- Systematic uncertainties completely dominated by calibration uncertainties
  Required new GEO model and specific calibration
- Compatibility of the four measurements O(10%)
- Slight tension between ATLAS 4l and γγ ~2σ

Total and Fiducial Cross Sections

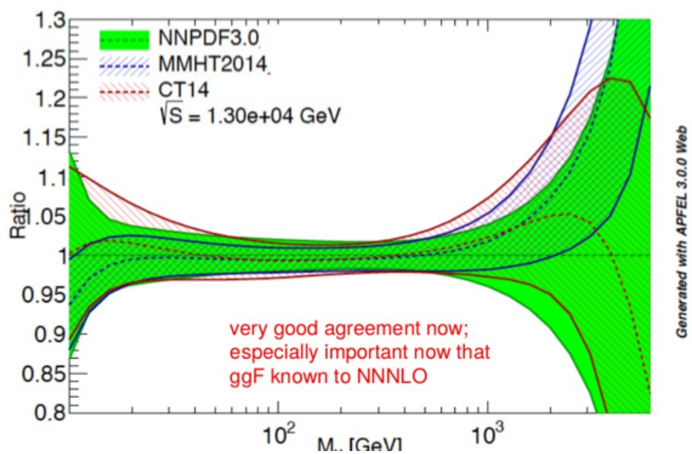


The discovery chanels are used to set the lest model dependent measurements of the Higgs production cross section: Fiducial, which are extrapolated also to total cross sections.



Unprecedented level of ggF precision: N3LO

Presented at Moriond QCD 2015

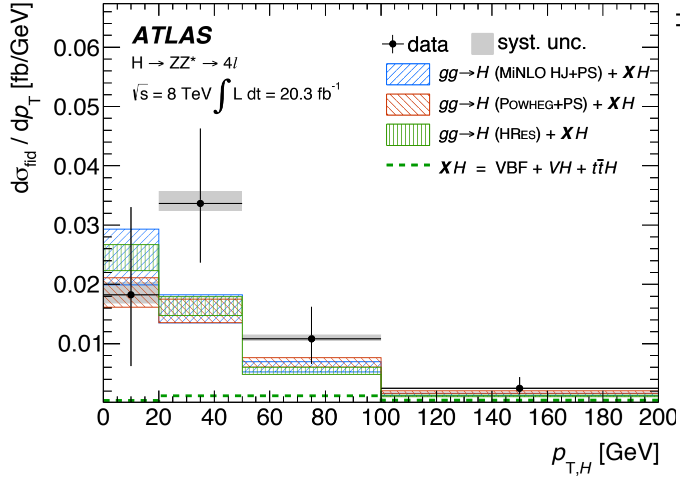


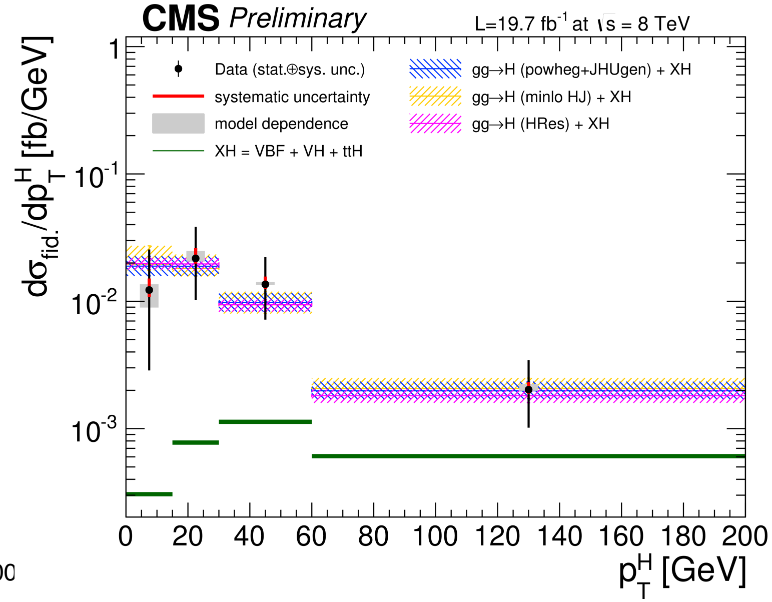
New NNPDF3.0 as well ! α_s ?

Differential Cross Section

$H \rightarrow 4l$

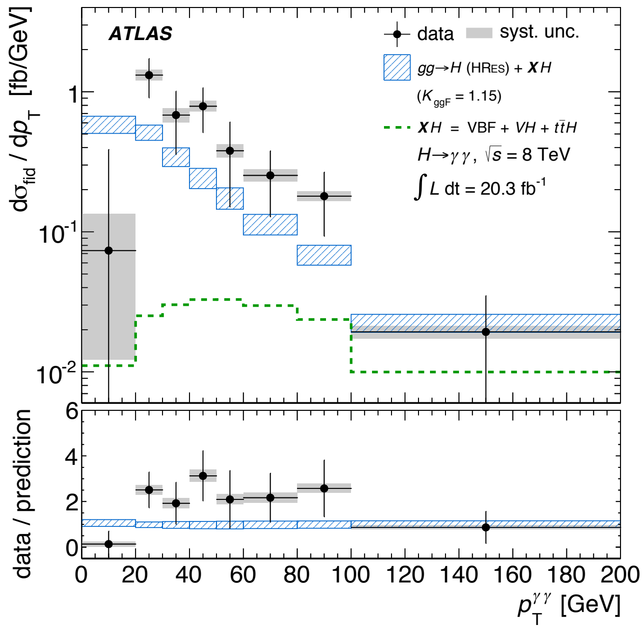
Phys. Lett. B 738 (2014)

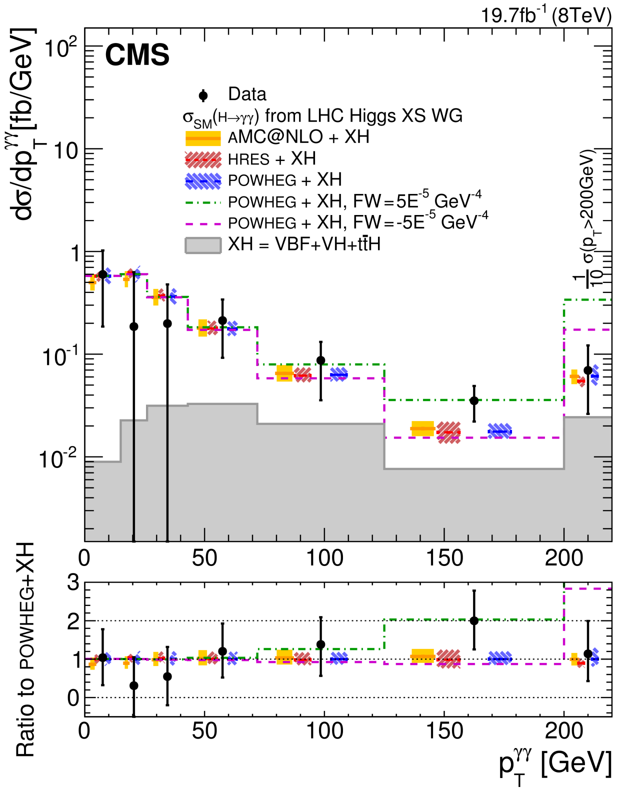




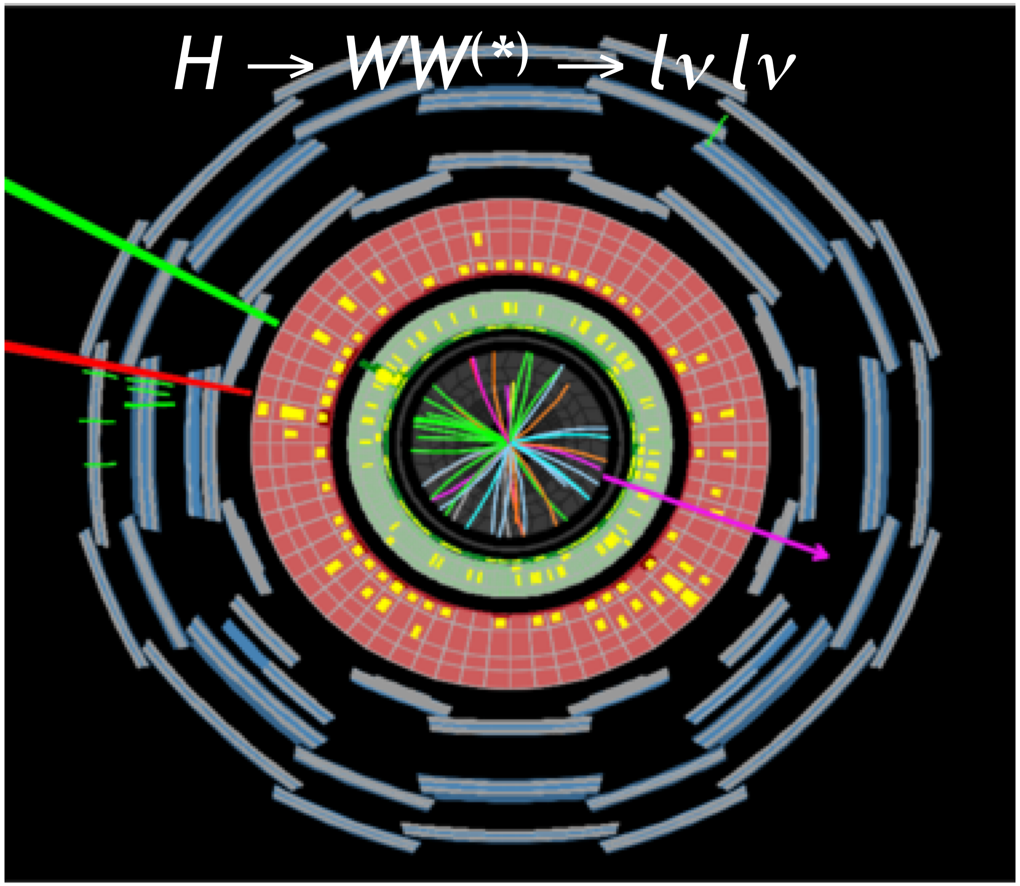
$H \rightarrow \gamma\gamma$

JHEP 09 (2014)





A discovery channel of a different kind…

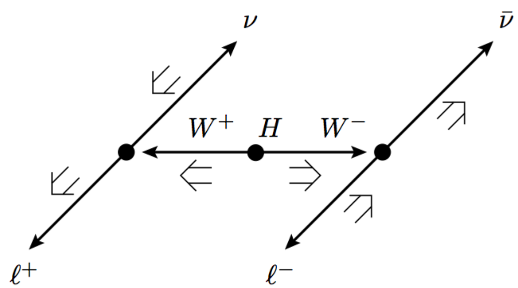


ATLAS

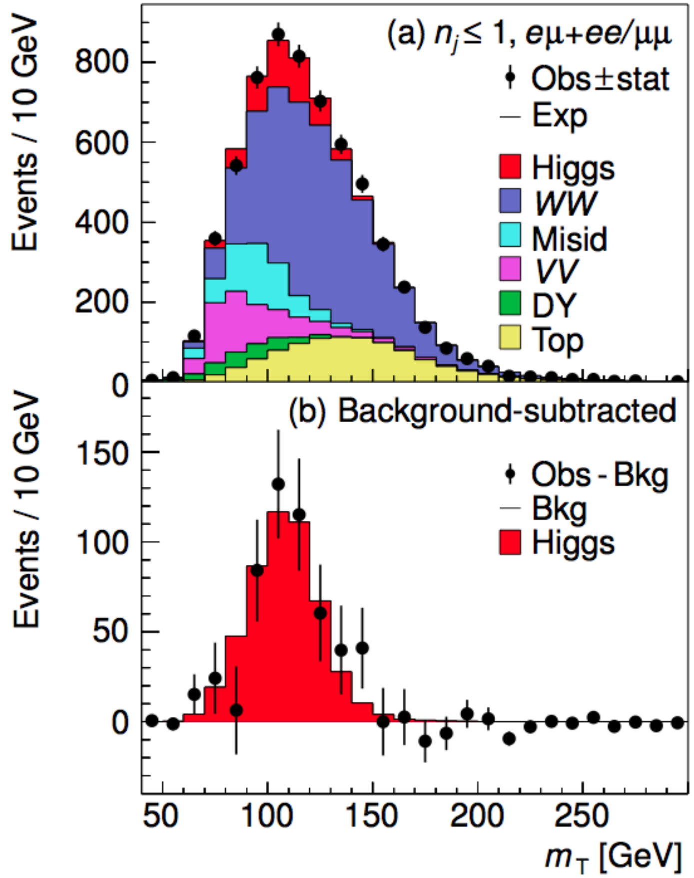
$Z = 6.1\ (5.8)\ \sigma$

CMS

$Z = 4.0\ (5.0)\ \sigma$



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



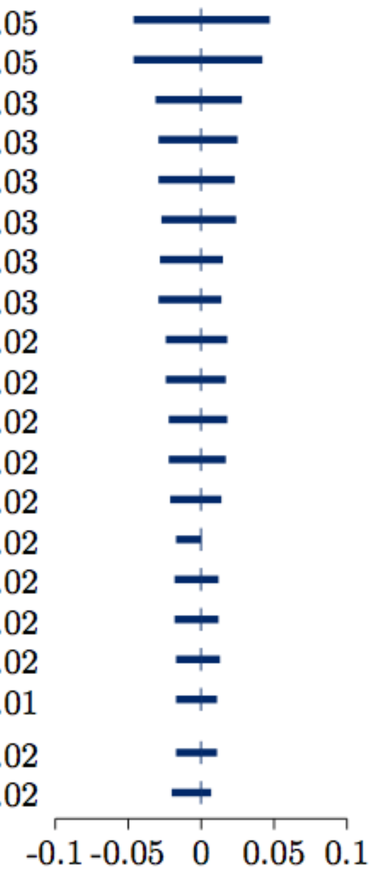
Systematics (in particular TH systematics) play a very important role

Source	Observed $\mu = 1.08$ Error +	Error −	Plot of error (scaled by 100)	Observed $\mu_{ggF} = 1.01$ Error +	Error −	Plot of error (scaled by 100)	Observed $\mu_{VBF} = 1.27$ Error +	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 $H \to WW^* \mathcal{B}$	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. $Z/\gamma^* \to ee, \mu\mu$	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	
			-30 -15 0 15 30			-30 -15 0 15 30			-60 -30 0 30 60

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

Systematic source	Impact on $\hat{\mu}$: Pre-fit $\Delta_{\hat{\mu}}$ +	Pre-fit $\Delta_{\hat{\mu}}$ −	Post-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 $p_{\mathrm{T}}^{\ell 2} > 20\,\mathrm{GeV}$, 2012	-0.01	$+0.02$	-0.01	$+0.02$
ggF H, QCD scale on ϵ_1	-0.01	$+0.02$	-0.01	$+0.02$

Plot of post-fit $\pm\Delta_{\hat{\mu}}$



*Discovery with help from Theory

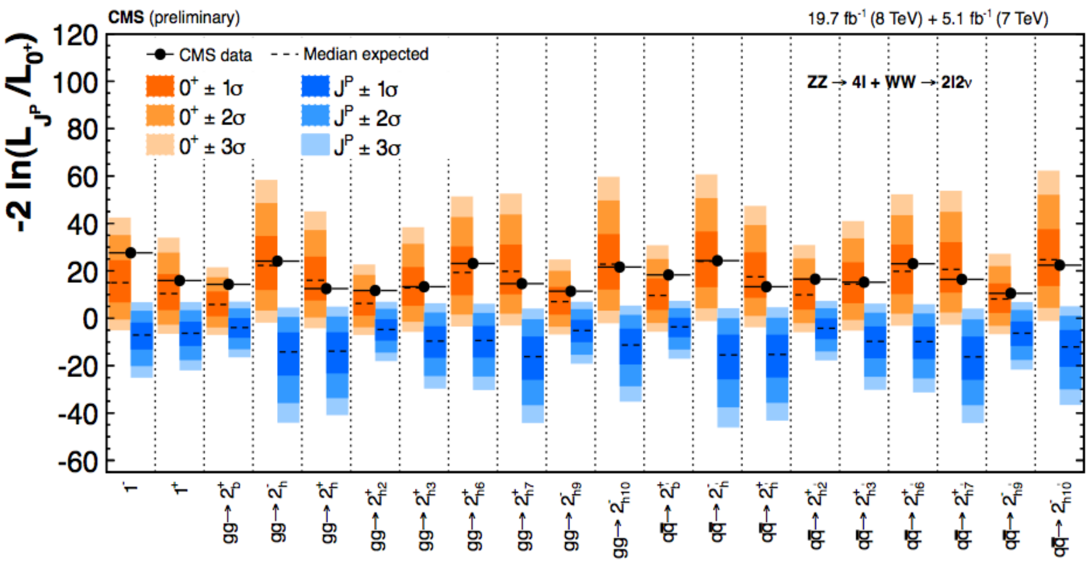
J^{PC}

- The observed rates in the diboson channels already a lot of information:
  - Observation in the diphoton channel J != 1
  - Observation in WW and ZZ channels disfavor the CP-Odd hypothesis (can occur through loops)

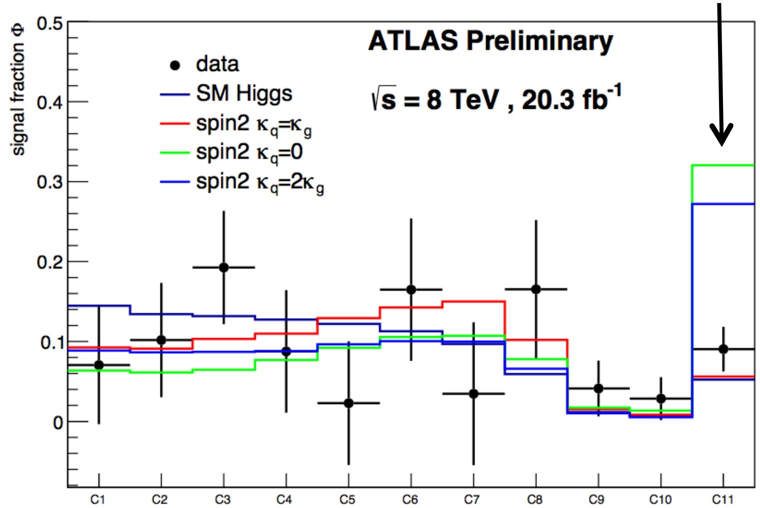
- Spin hypothesis tests (difficult model spin 2) – Combination of ZZ, WW and $\gamma\gamma$

$$\mathcal{L}_2 = \frac{1}{\Lambda}\left[\sum_V \kappa_V X^{\mu\nu}\mathcal{T}^V_{\mu\nu} + \sum_f \kappa_f X^{\mu\nu}\mathcal{T}^f_{\mu\nu}\right]$$

Coupling to energy-momentum tensor

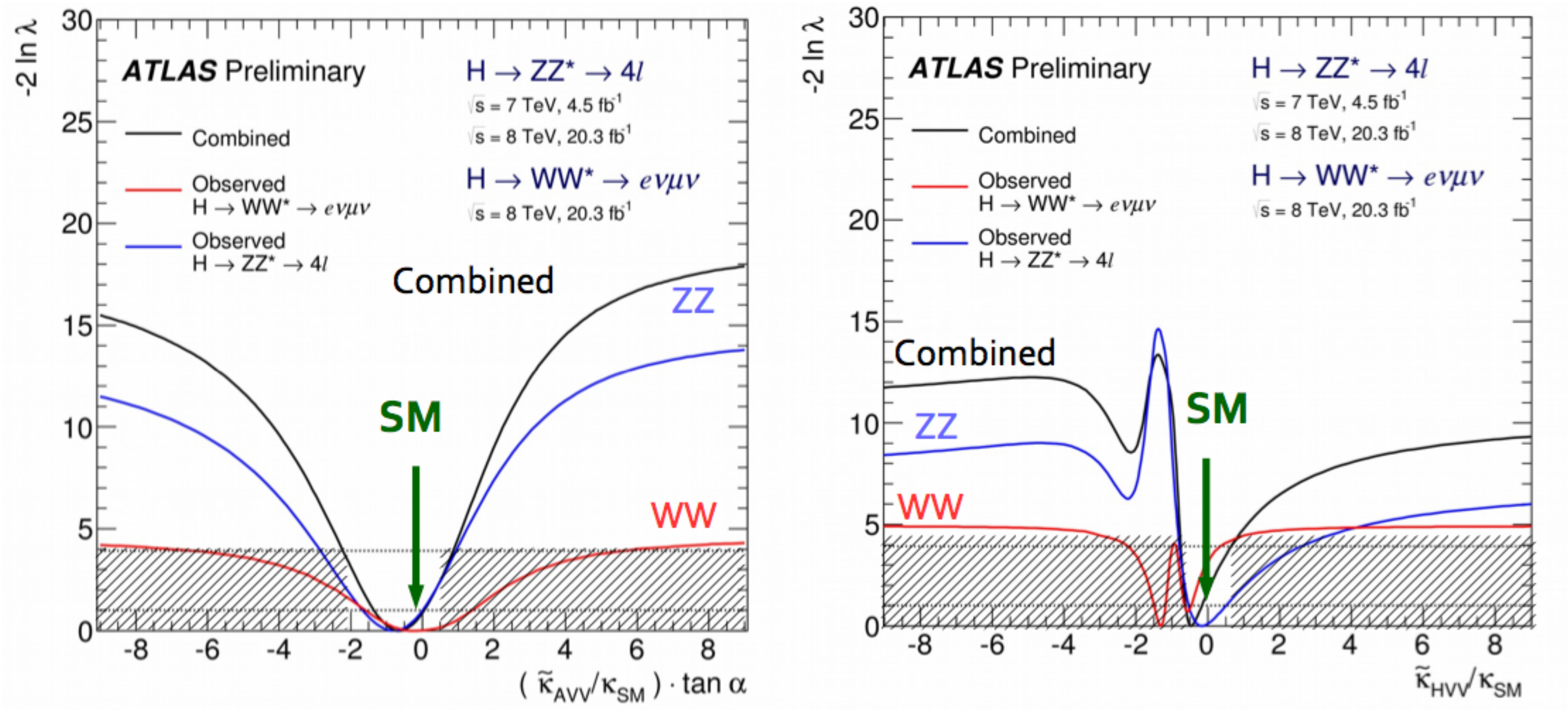


pT [125,300] GeV



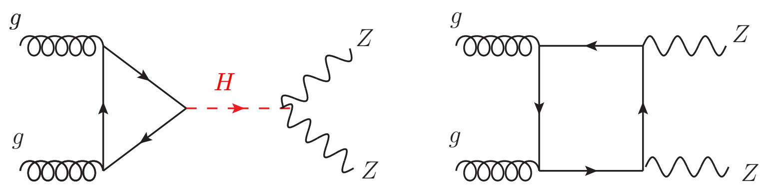
cos θ*

CP Mixing



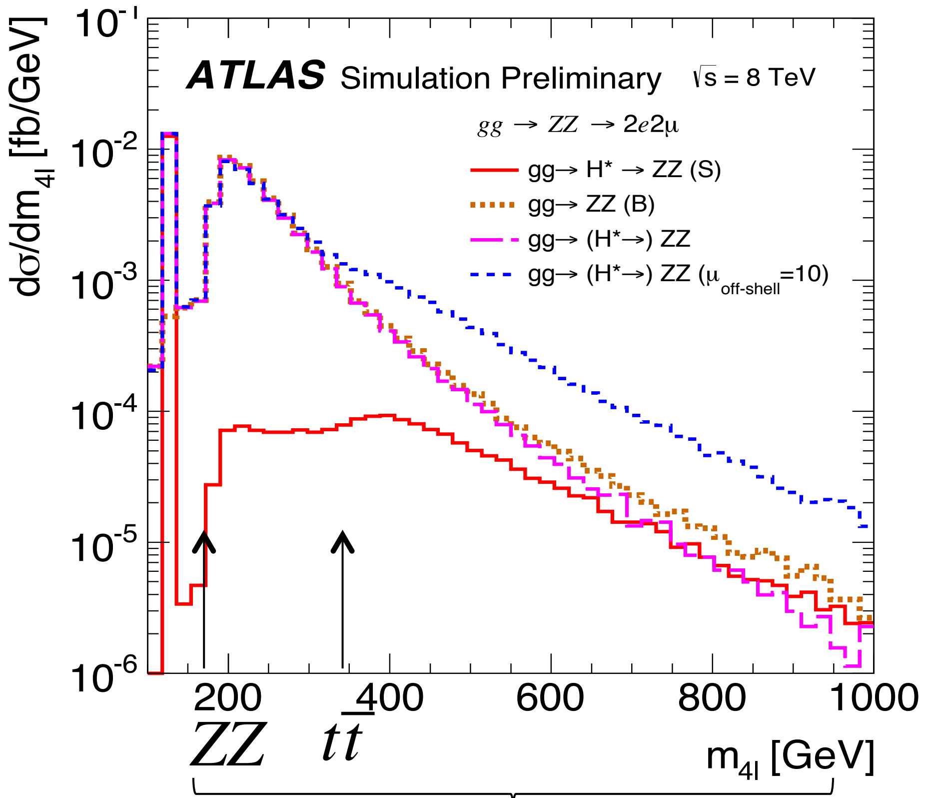
Both ATLAS and CMS find that the observed Higgs boson is compatible with a standard CP-even ()

Off Shell Higgs coupling properties Measurement

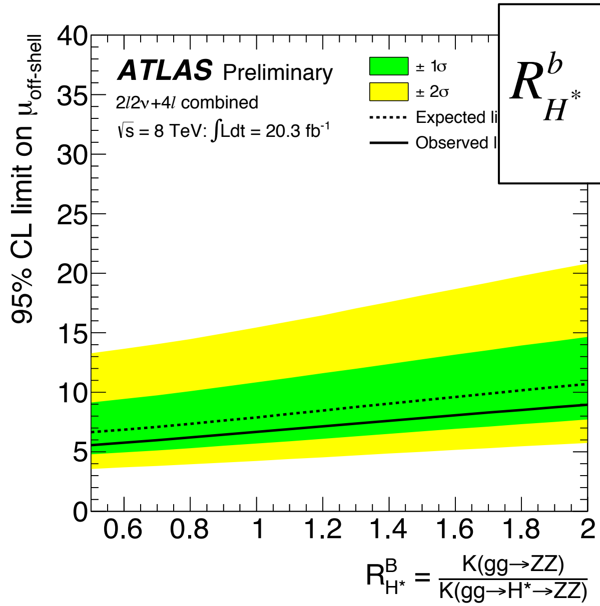


Higgs boson as a propagator

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



Far Off Shell domain



$$R^b_{H^*} = \frac{k_{gg\to ZZ}}{k_{gg\to H^*\to ZZ}}$$

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

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

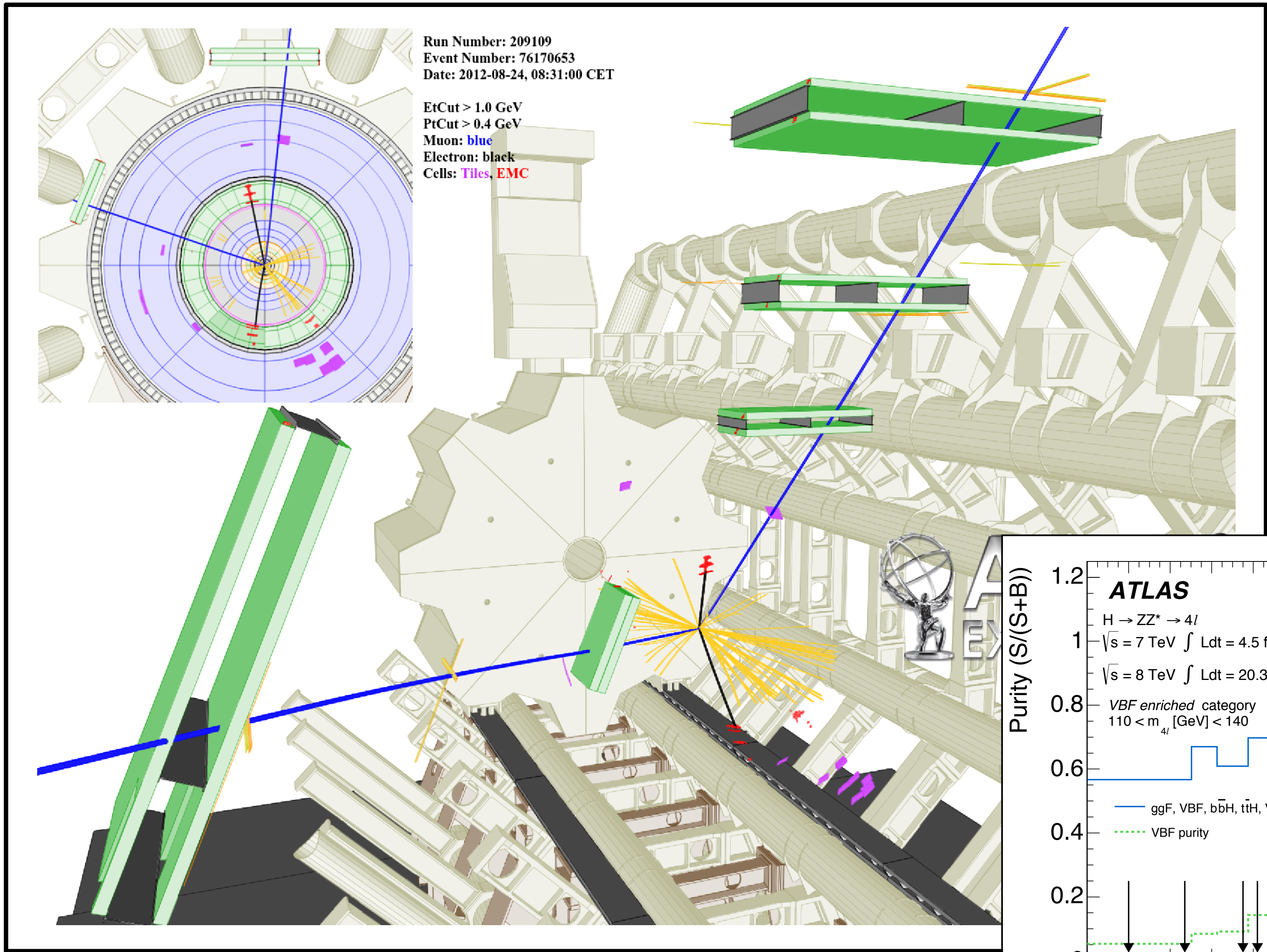
Using:

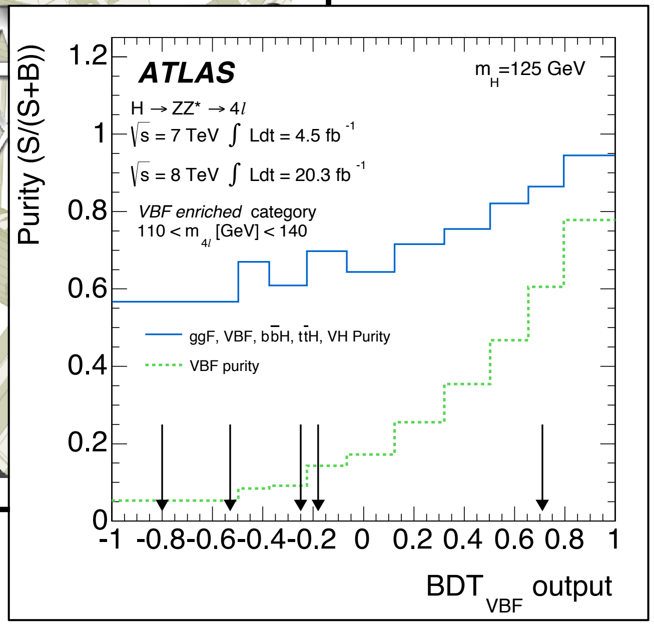
$$(\kappa_g^2 \kappa_V^2)_{OnShell} = (\kappa_g^2 \kappa_V^2)_{OffShell}$$

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

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

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.

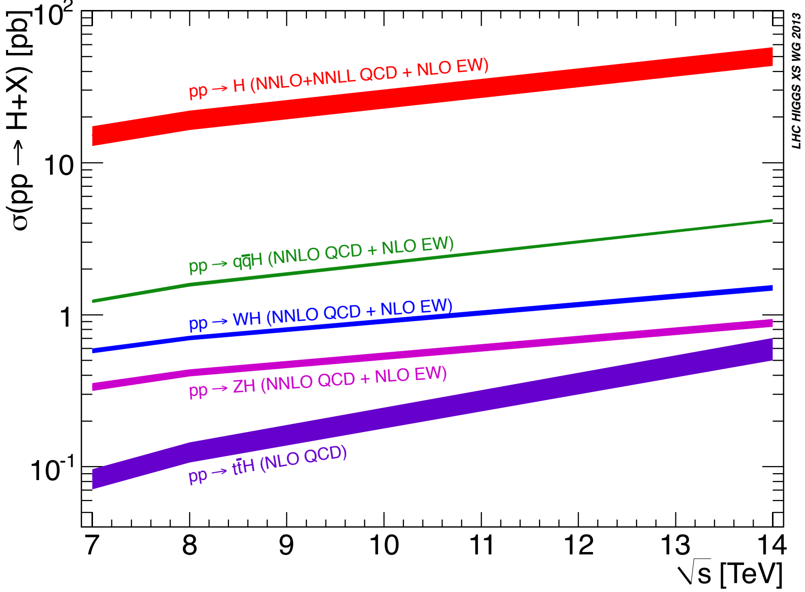
3.- Discovery channels beyond discovery

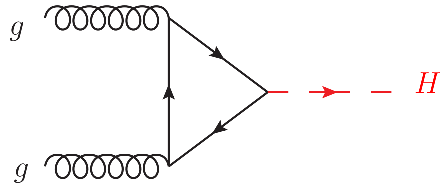
4.- Overview of post-discovery Higgs physics

5.- Glimpse at HL-LHC

Higgs Production Modes

κ for m_H = 125.5 GeV



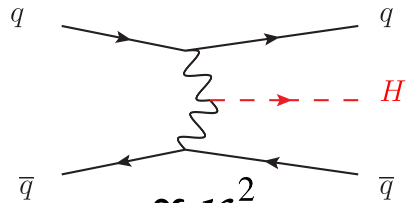


Gluon fusion process

NNnLO ~O(10%)

~0.5 M events produced

$$\kappa_g \propto 1.\times 06\kappa_t^2 - 0.07\times\kappa_t\kappa_b + 0.01\times\kappa_b^2$$



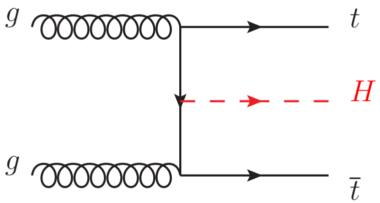
$\propto \kappa_V^2$

Vector Boson Fusion

NLO TH uncertainty ~O(5%)

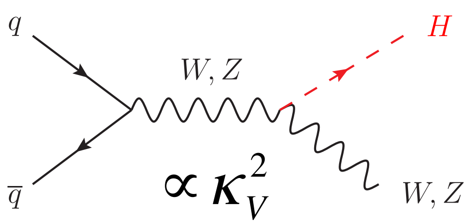
Two forward jets and a large rapidity gap

~40 k events produced



$\propto \kappa_t^2$

Top Assoc. Prod. ~3 k evts produced

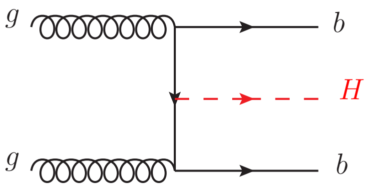


$\propto \kappa_V^2$

W and Z Associated Production

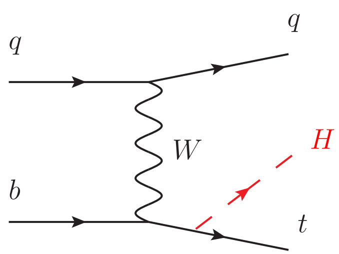
NNLO TH uncertainty ~O(5%)

~20 k events produced

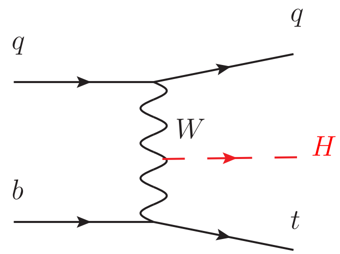


$\propto \kappa_b^2$

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



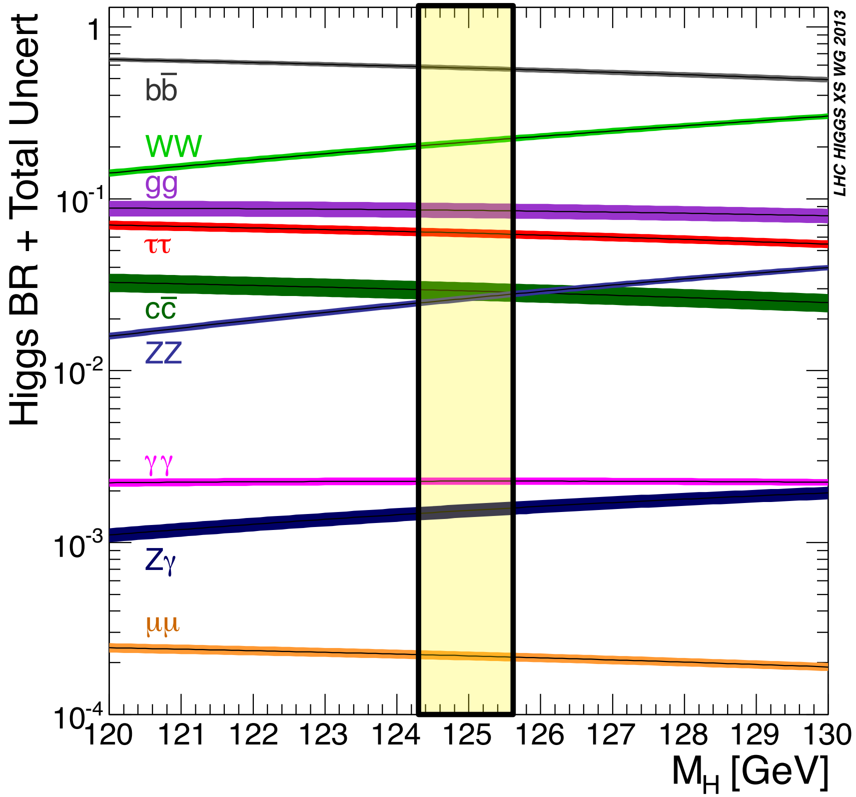
tH

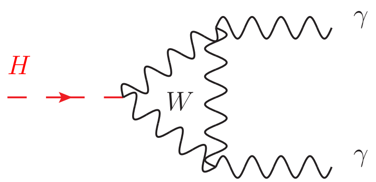


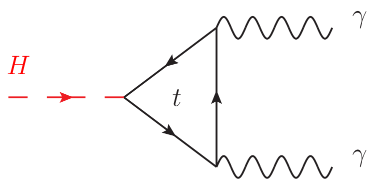
$$\propto 3.3\times\kappa_W^2 - 5.1\times\kappa_t\kappa_W + 2.8\times\kappa_t^2$$

Higgs Decay Channels

- Dominant: bb (57%) $\propto \kappa_b^2 / \kappa_H^2$
- WW channel (22%) $\propto \kappa_W^2 / \kappa_H^2$
- ττ channel (6.3%) $\propto \kappa_\tau^2 / \kappa_H^2$
- ZZ channel (3%) $\propto \kappa_Z^2 / \kappa_H^2$
- cc channel (3%) $\propto \kappa_c^2 / \kappa_H^2$
  Extremely difficult
- The γγ channel (0.2%) $\propto \kappa_\gamma^2 / \kappa_H^2$





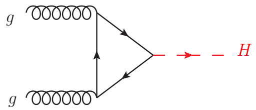
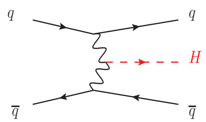
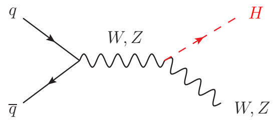
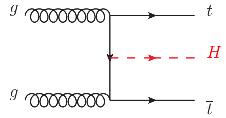


$$\kappa_\gamma \propto 1.6 \times \kappa_W^2 - 0.7 \times \kappa_t \kappa_W + 0.1 \times \kappa_t^2$$

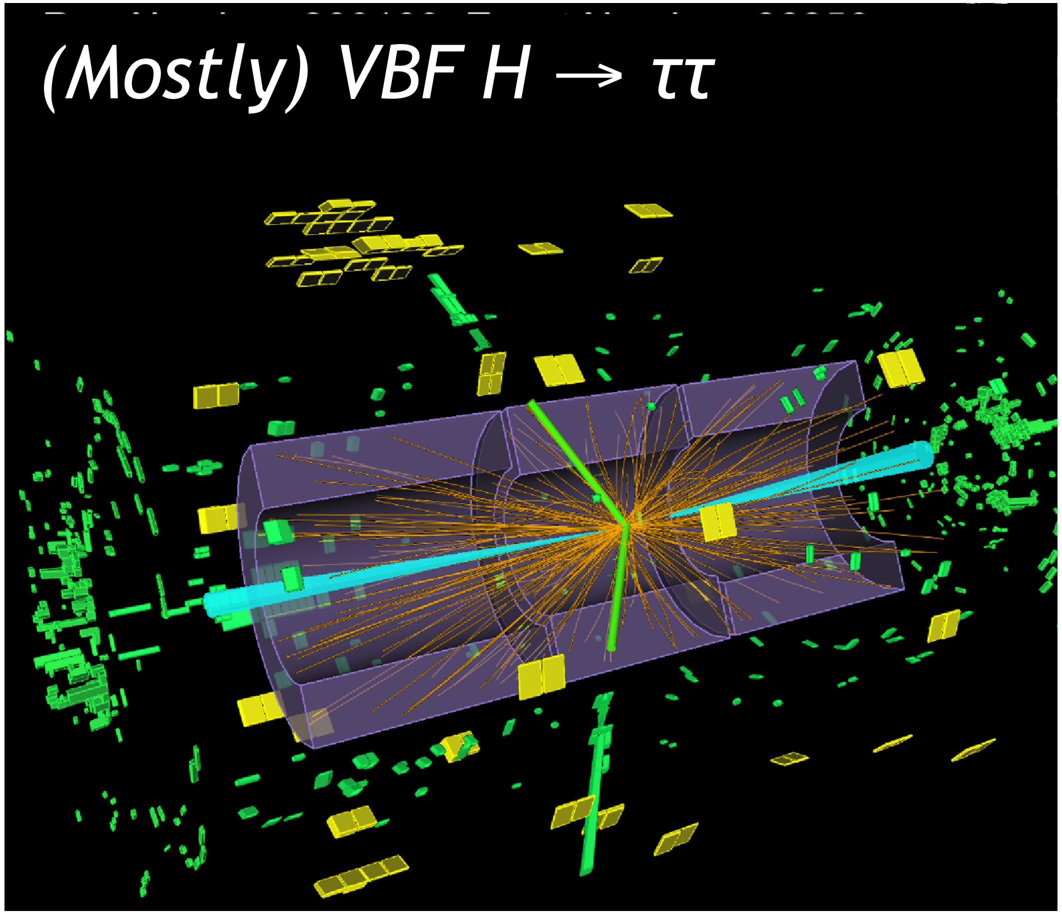
(when assuming no BSM charged in the loop)

- The Zγ (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 μμ channel (0.02%) $\propto \kappa_\mu^2 / \kappa_H^2$

Panorama of Main Higgs Analyses

Channel categories	ggF 	VBF 	VH 	ttH 
γγ	✓	✓	✓	✓
ZZ (llll)	✓	✓	✓	✓
WW (lνlν)	✓	✓	✓	✓
ττ	✓	✓	✓	✓
bb		✓	✓	✓
Zγ and γγ*	✓	✓		
μμ and ee	✓	✓		
Invisible	✓ (monojet)	✓	✓	

An Important Observation…

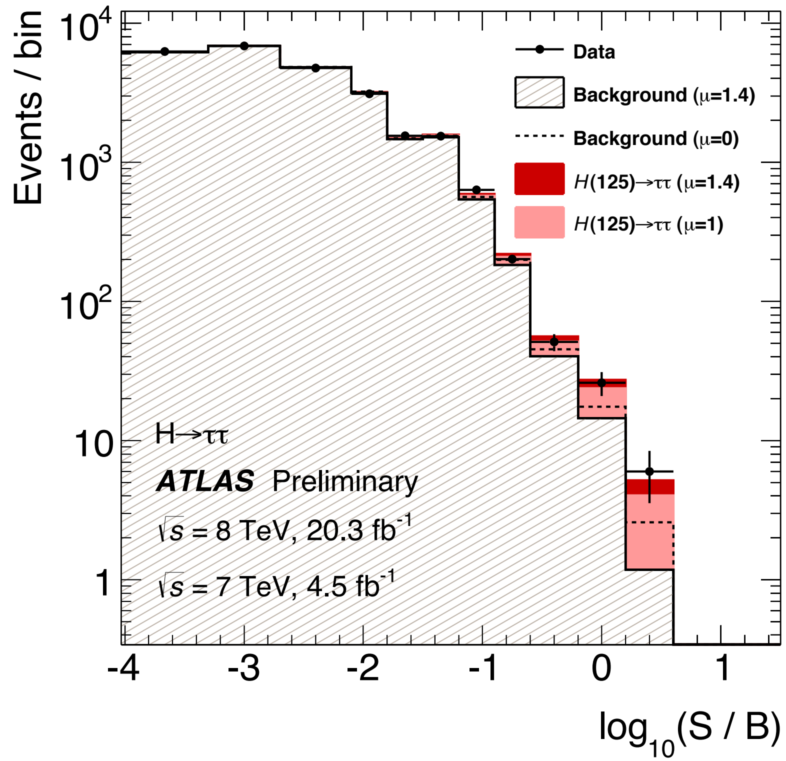


ATLAS

$$Z = 4.5\ (3.5)\ \sigma$$

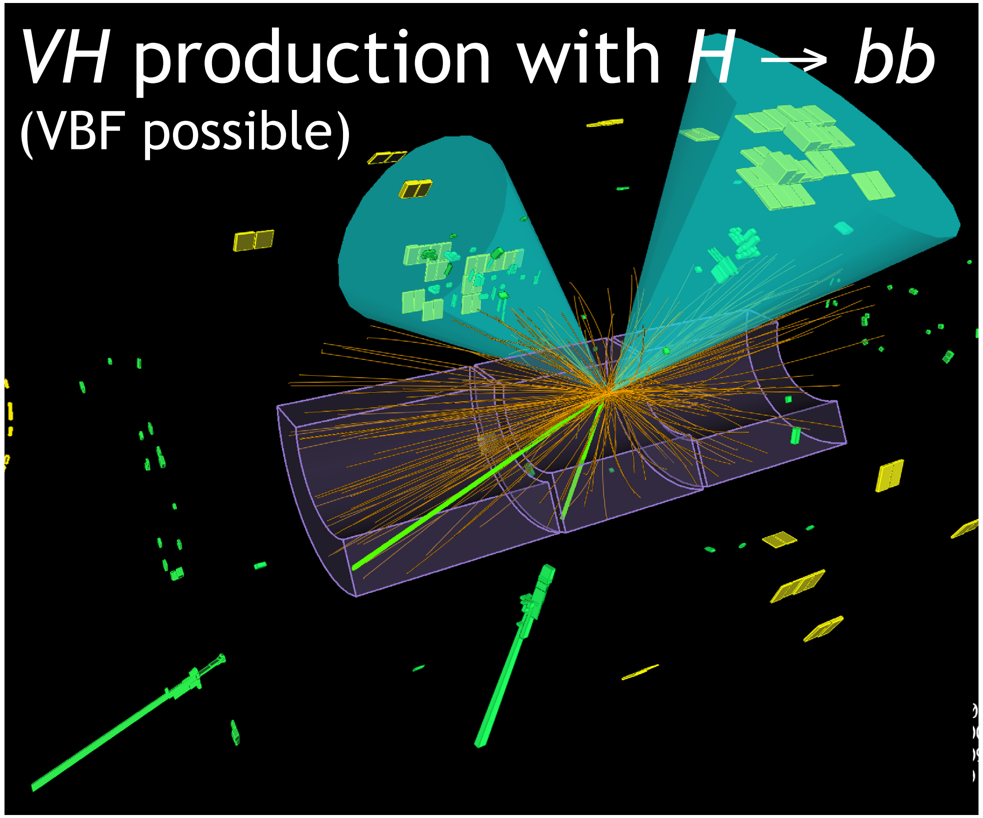
CMS

$$Z = 3.2\ (3.7)\ \sigma$$



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

Cornering the b Yukawa Coupling

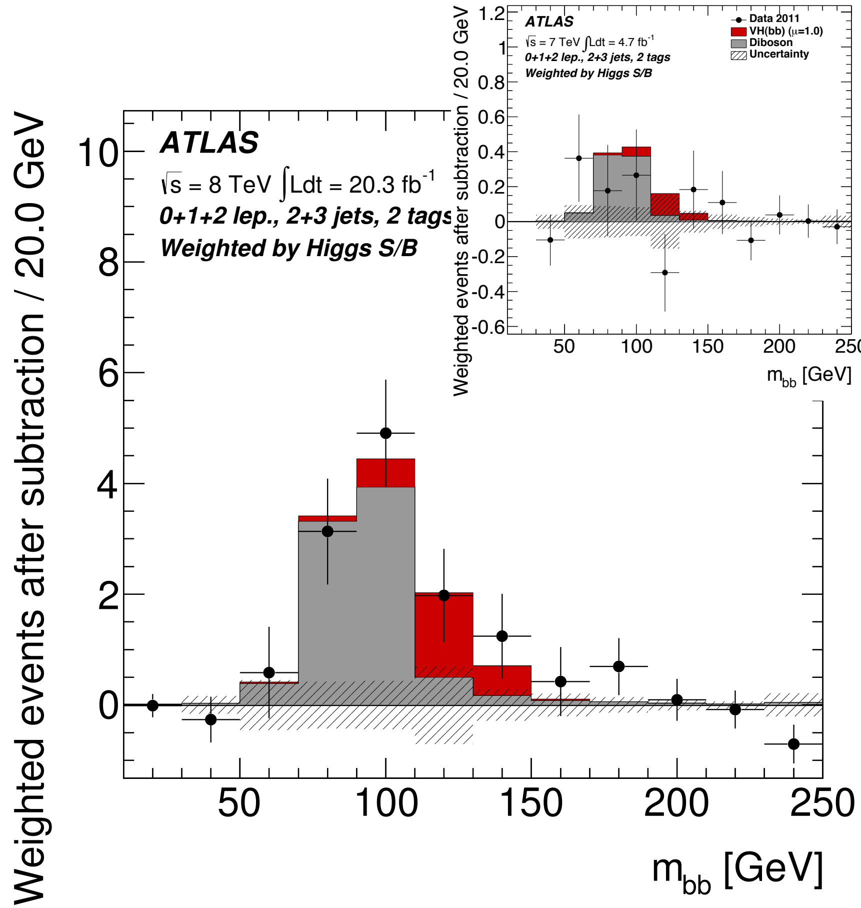


ATLAS

$$Z = 1.4\ (2.6)\ \sigma$$

CMS

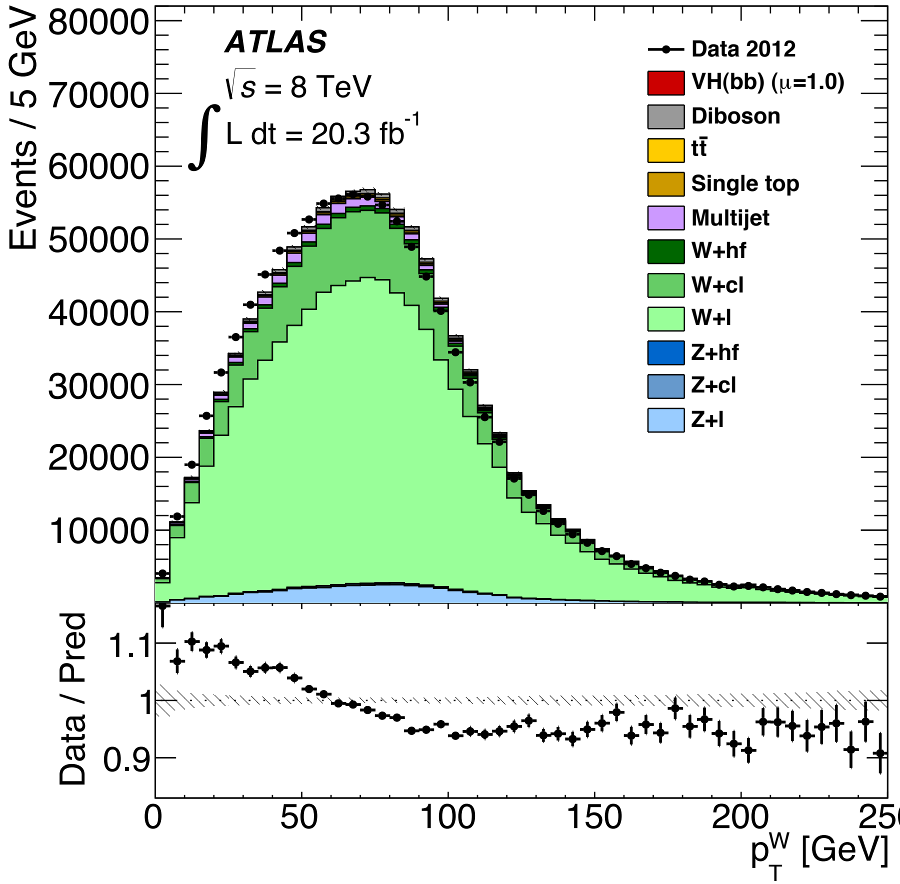
$$Z = 2.1\ (2.1)\ \sigma$$

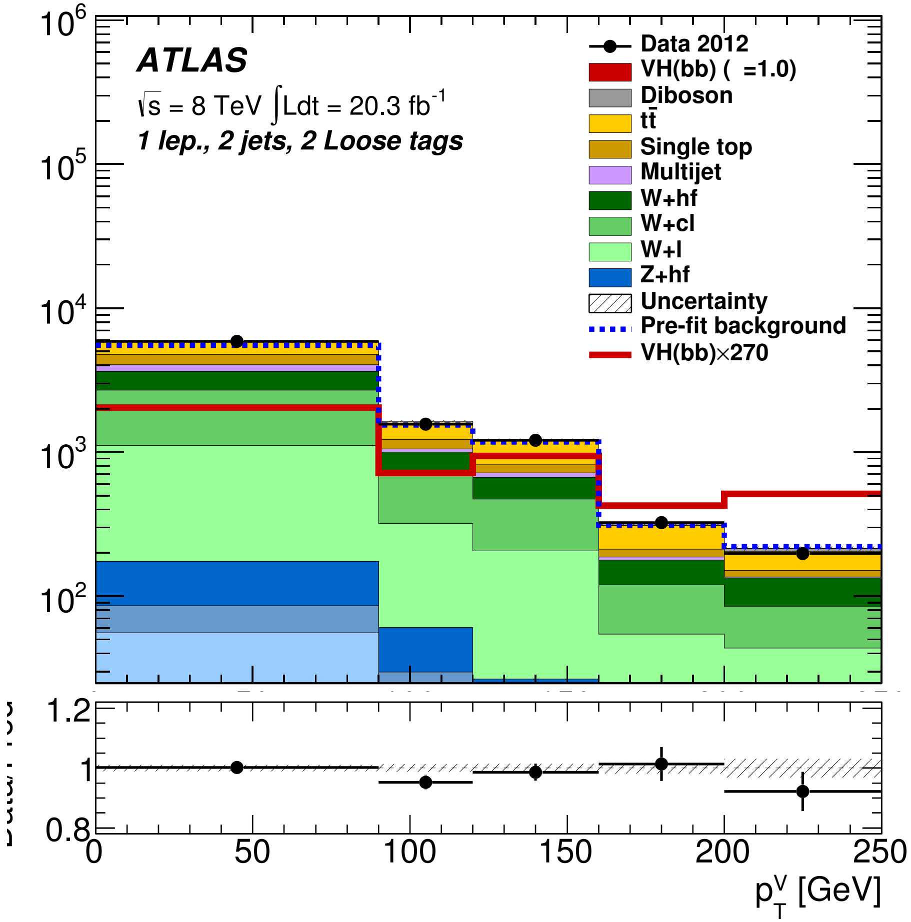


- Analysis using the boost (without substructure)
- Moderate s/b ratio starting from approximately few percent to approximately 30%

Boosted Analyses (without substructure)

Simulation of pT (V) is critical



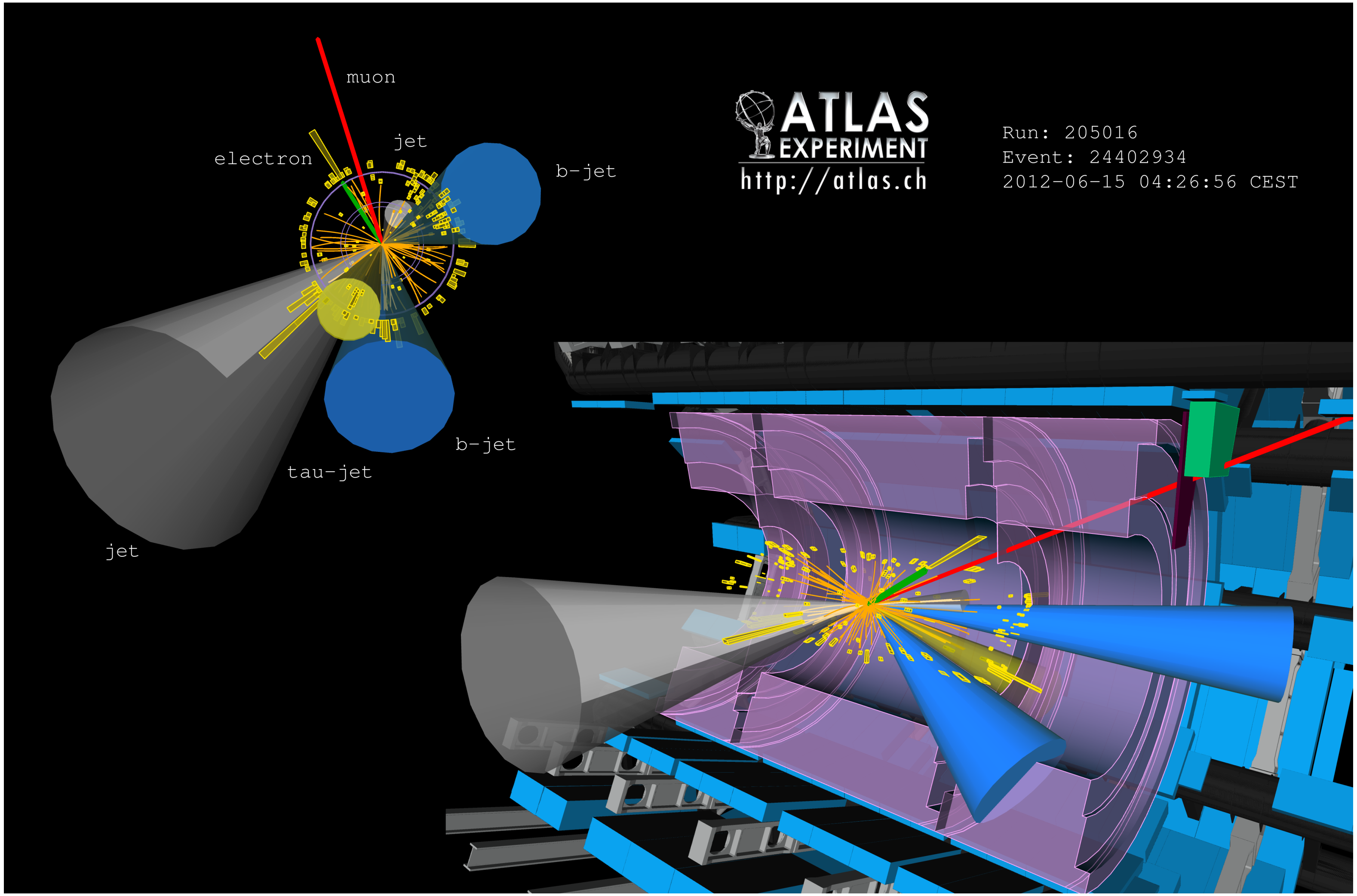


Our precision will depend a lot on the simulation, moving to state-of-the-art MC for Run-2

Cornering (directly) the top Yukawa coupling

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

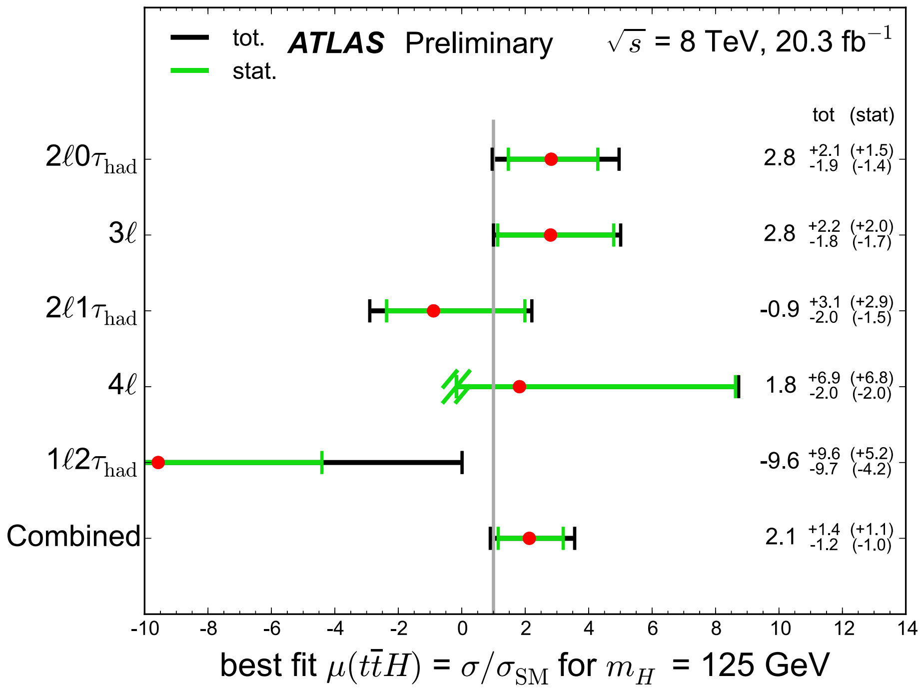
$$ttH\,(ML)$$

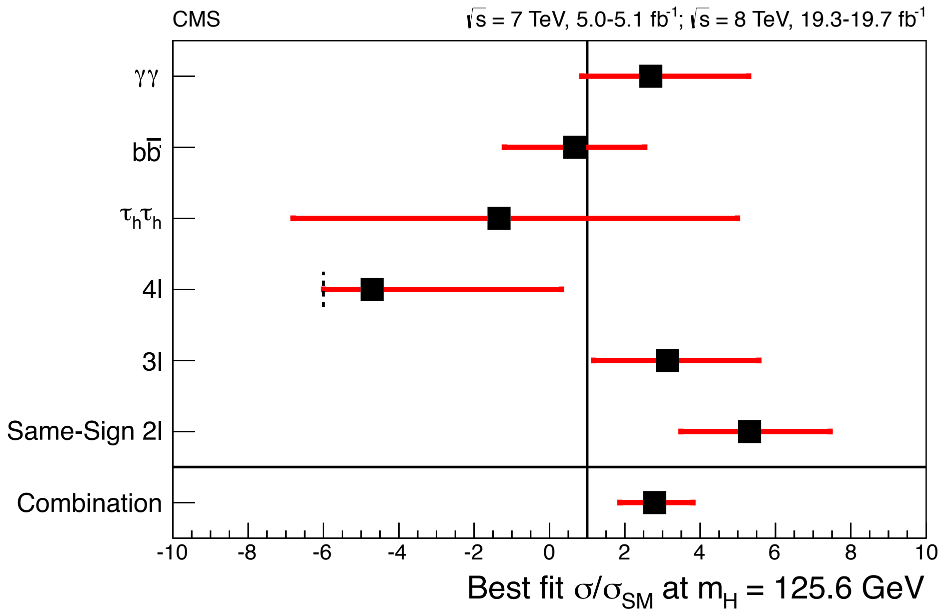


Cornering (directly) the top Yukawa coupling

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

$$ttH(ML)$$





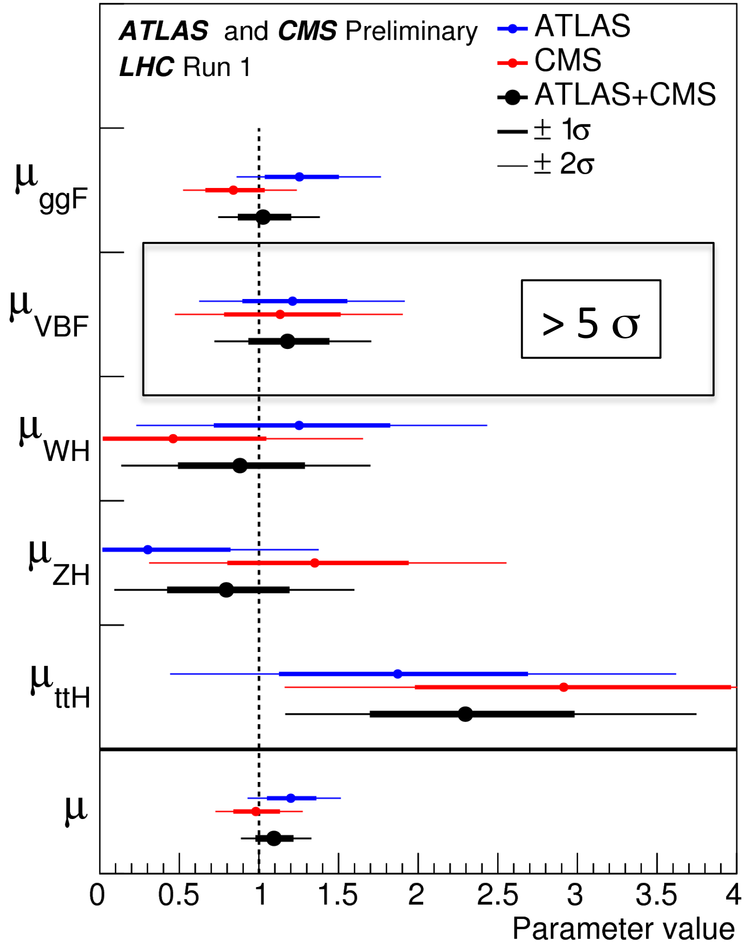
Hints of a signal emerging, a combination of ATLAS and CMS would be of course very interesting… Naive combination yields approximately 2 with an uncertainty of 0.7.

Combining Higgs Channels

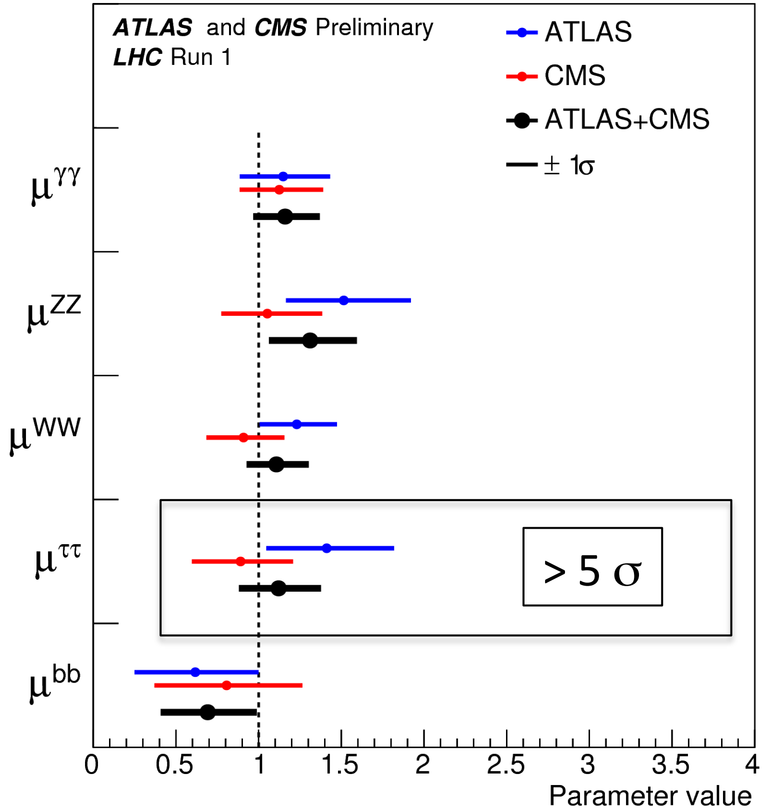
- Combining the large number of channels to constrain the coupling properties of the Higgs boson (using different model assumptions).

- 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)

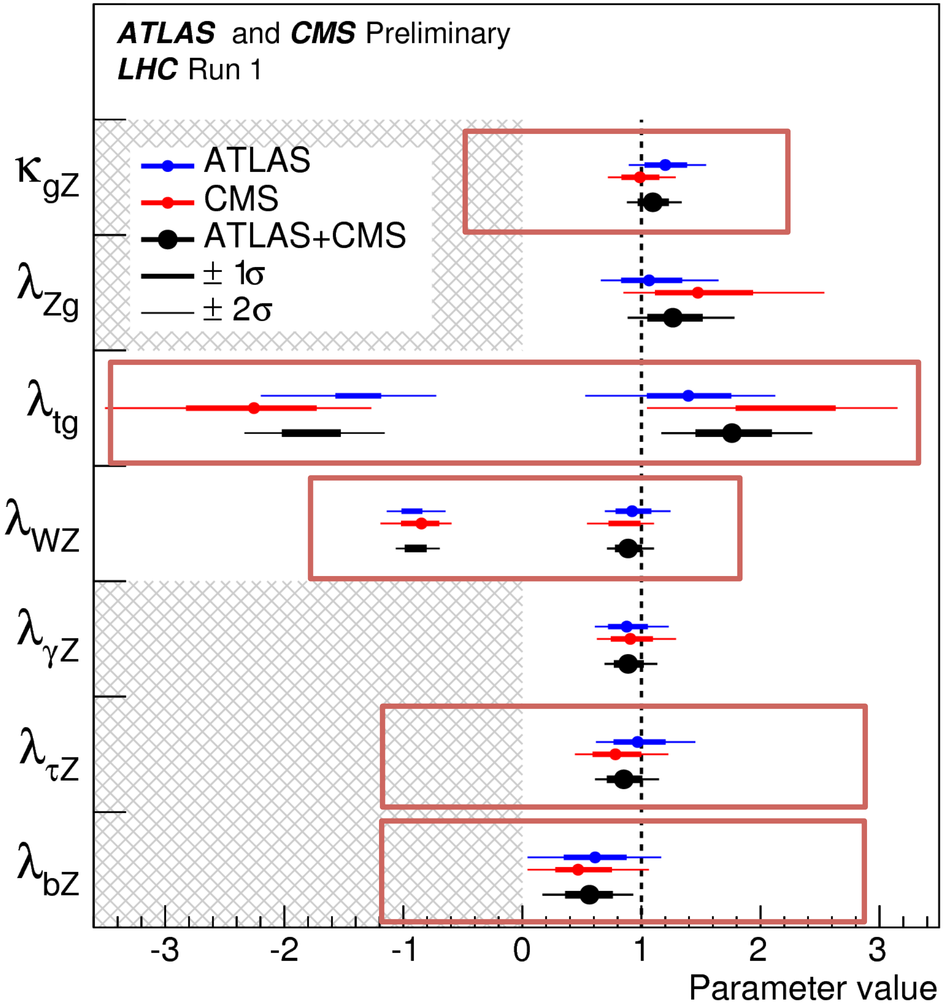


- Hundreds of exclusive analysis categories
- Thousands of nuisance parameters*
- To corner:
  - 5 decay modes
  - 5 Production processes



*Large number of bin stat

A Lot Learned About Coupling Properties



Direct coupling to the Z

Direct coupling to the top
(through ttH production channels)

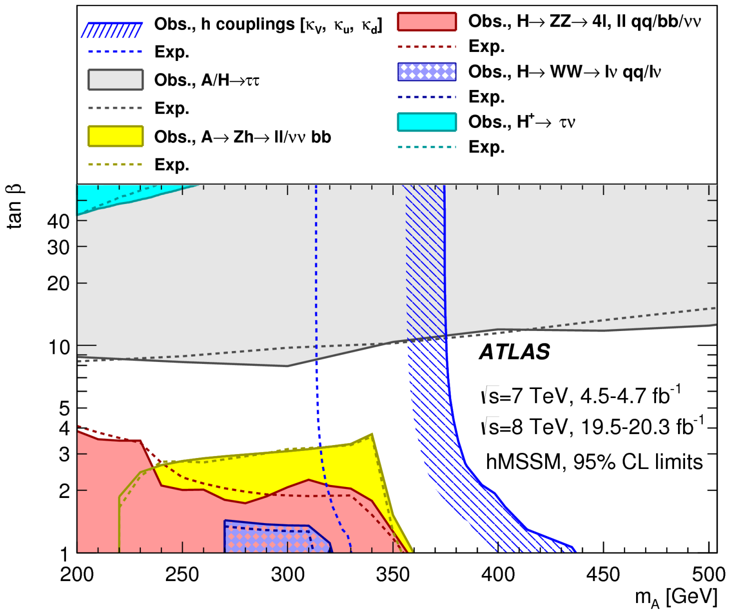
Custodial Symmetry

Direct copling to τ
(through VBF production)

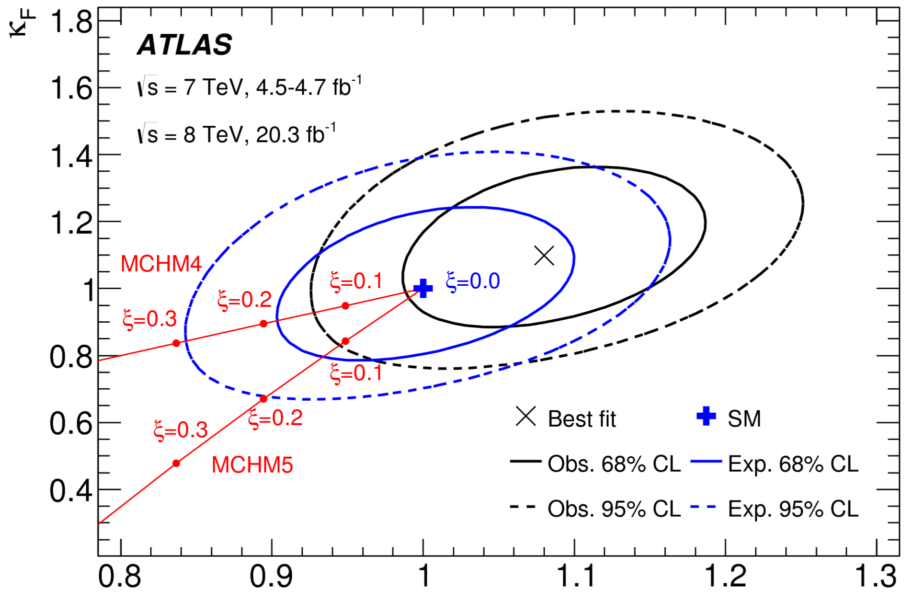
Direct coupling to b quarks
(Through mainly VH channels)

A lot still to be learned! **Extremely important questions for Run 2**

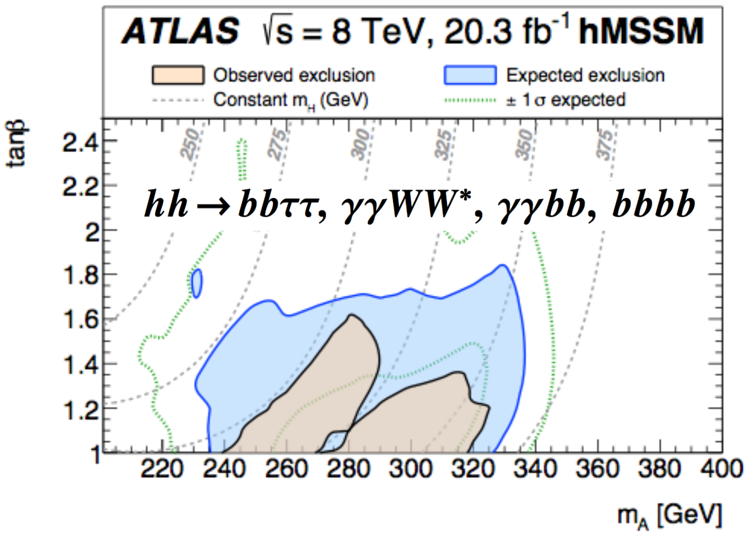
Implications and Direct Searches



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



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

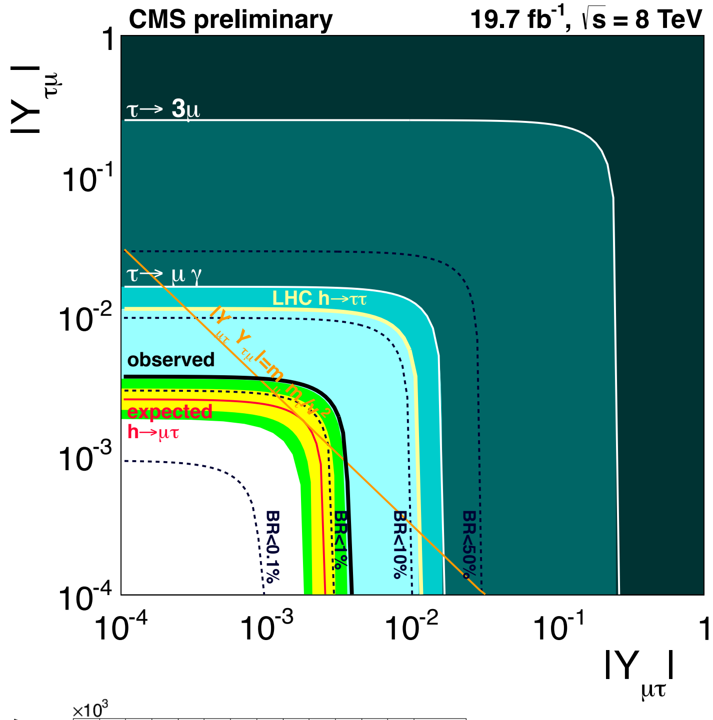


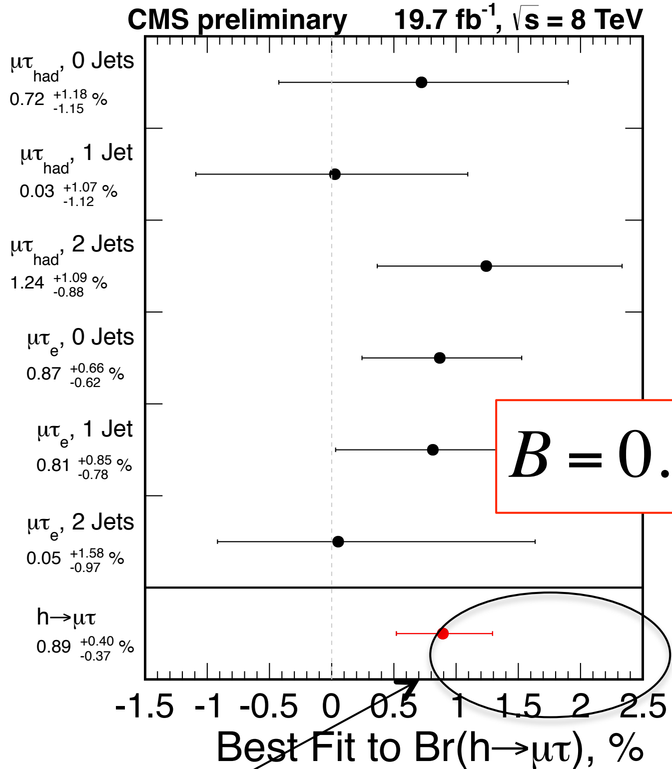
hMSSM: Recent additional constraints

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

Examples of extremely important searches with sensitivity soon at Run 2

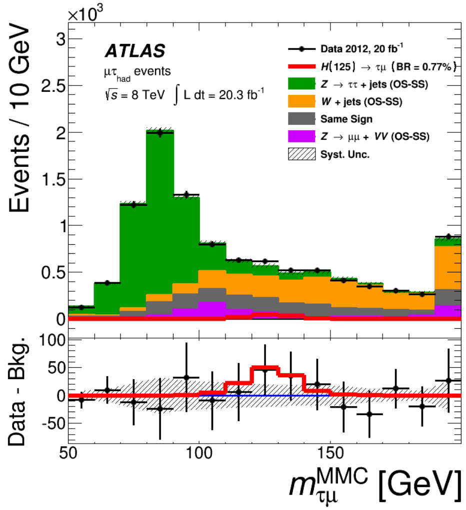
LFV Decays of the Higgs boson





CMS

$$B = 0.84^{+0.39}_{-0.37}\%$$



~2.5σ Deviation…

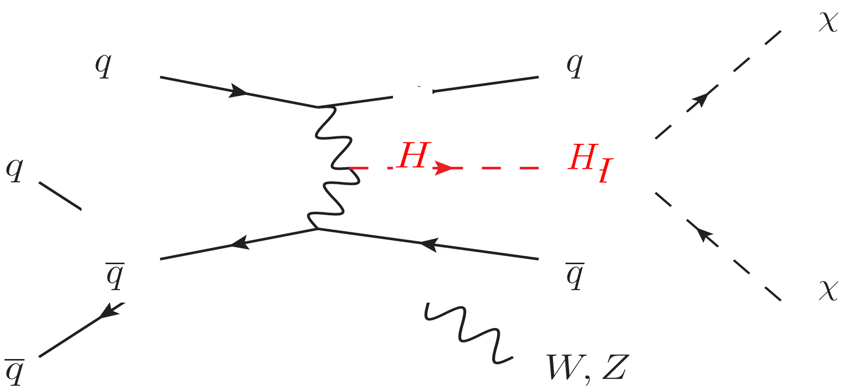
Excess of similar order in rate (less significant) observed also in ATLAS

ATLAS

$$B = 0.77 \pm 0.62\%$$

Invisible Decays

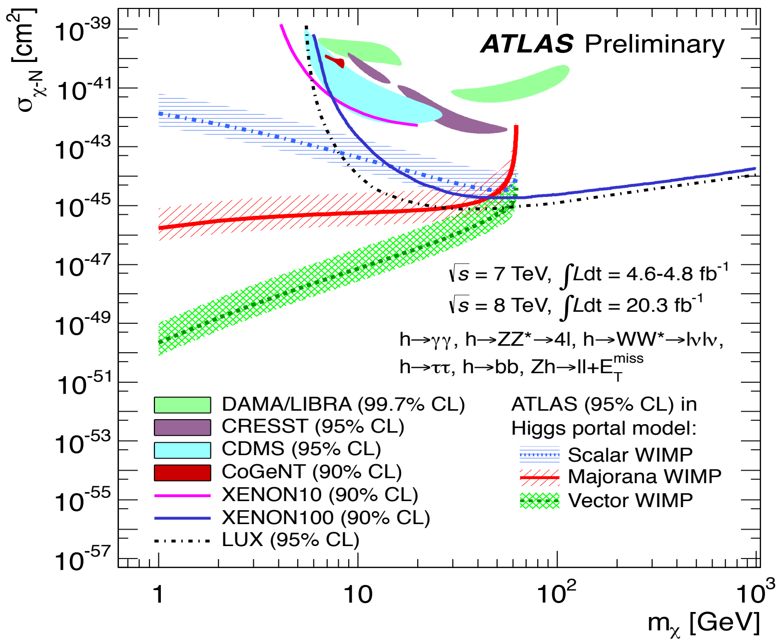
Very small expected SM signal



$$Br(H \rightarrow invisible)$$

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

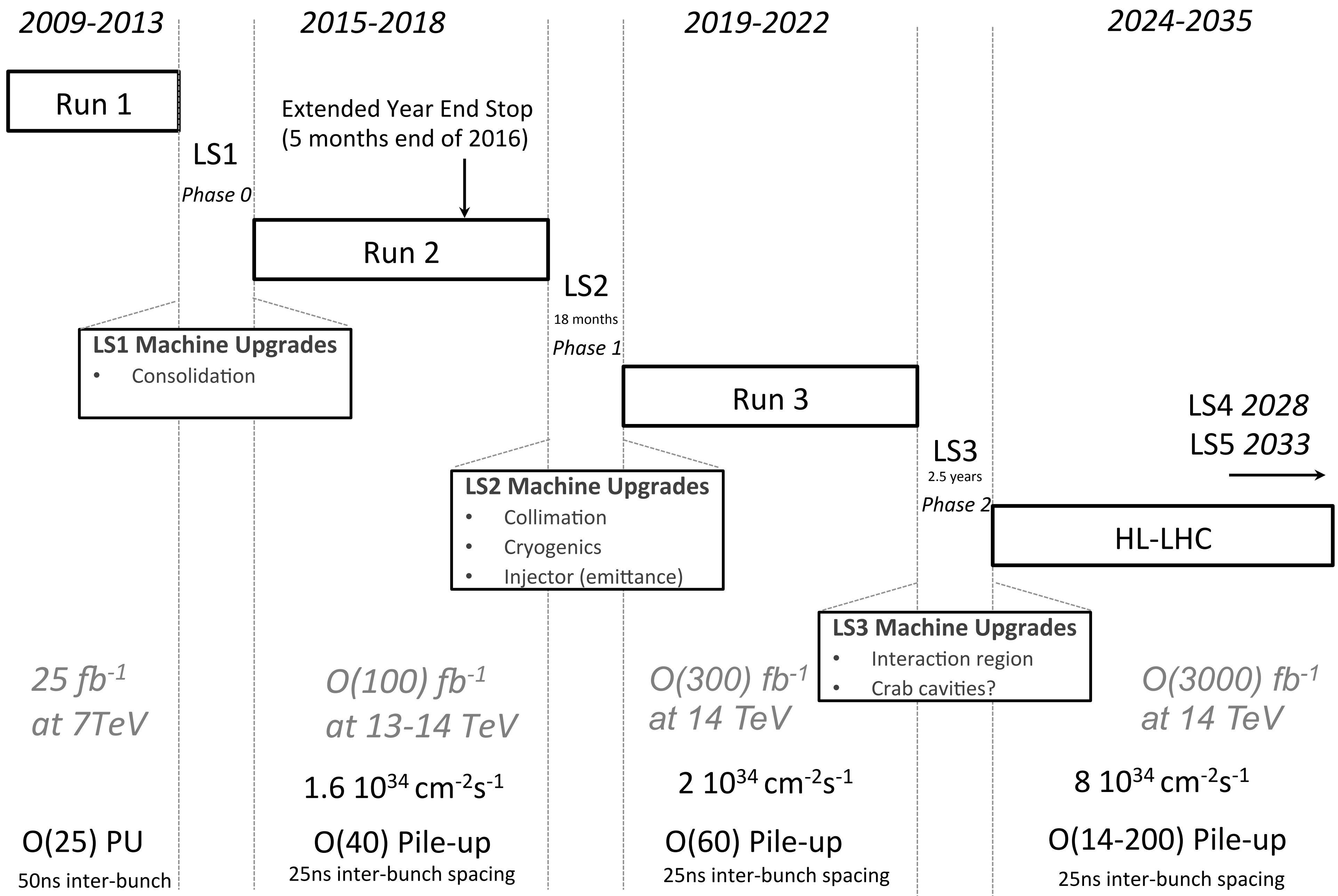
2.- The « Bread and Butter » Discovery Channels, the detectors and the machine.

3.- Discovery channels beyond discovery

4.- Overview of post-discovery Higgs physics

5.- Glimpse at HL-LHC

The LHC Run 2 and Beyond

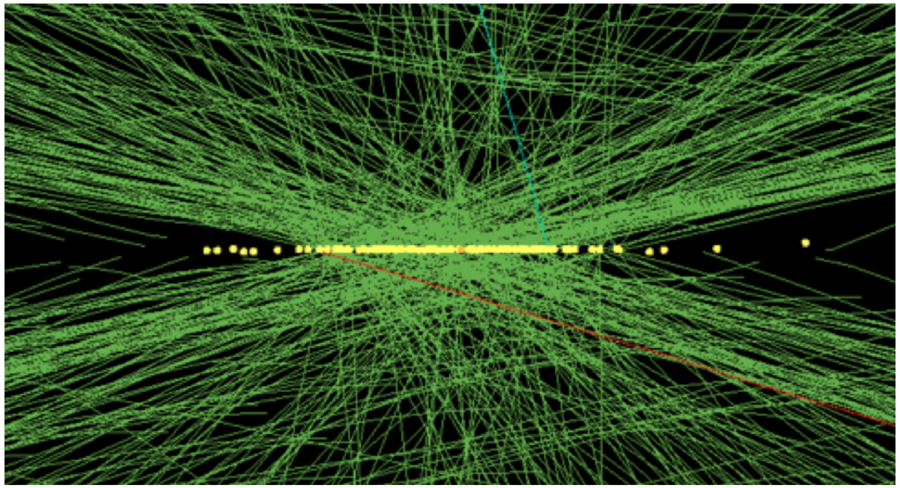


HL-LHC Beam Parameters

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

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	$1.2\ 10^{11}$	$1.15\ 10^{11}$	$2.0\ 10^{11}$	$3.3\ 10^{11}$
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 ($cm^{-2}s^{-1}$)	$\sim 7\times 10^{33}$	10^{34}	$7.4\ 10^{34}$	$8.4\ 10^{34}$
Pile up	~25	~20	~140	~260

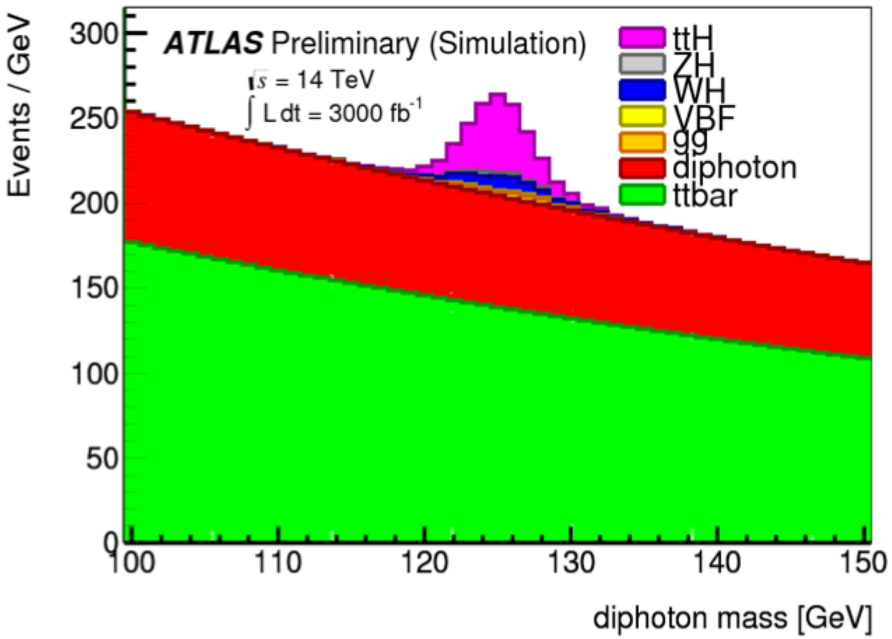


Pile up is critical!

Event with 78 reconstructed vertices

LHC Higgs Physics Program: Rare Modes

Analyses not relying on more intricate decay channels (bb, ττ and WW)



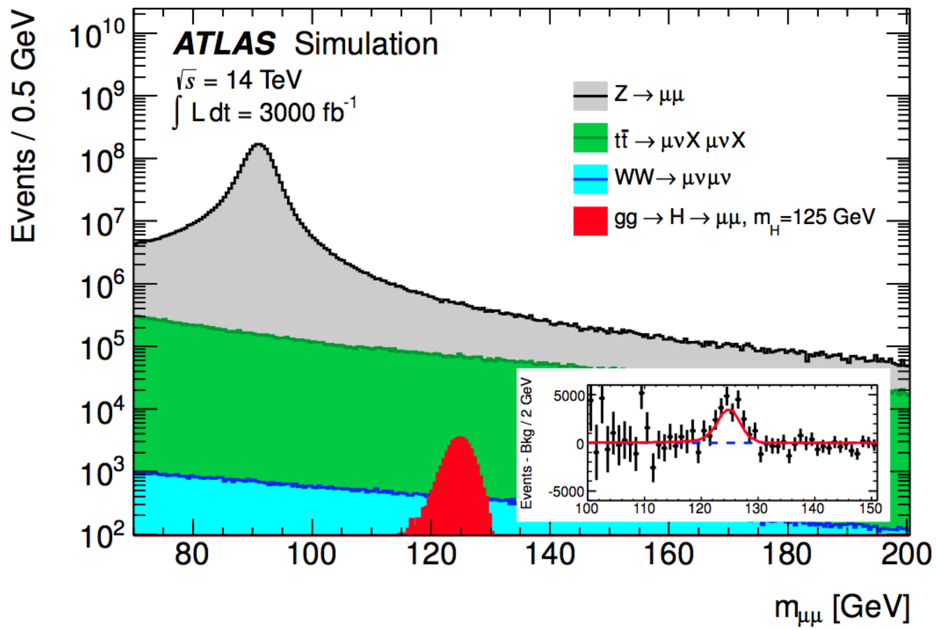
– γγ channel: more than 100 Events expected with s/b~1/5

– μμ channel: approximately 30 Events expected with s/b~1

Analyses (rather) robust to PU

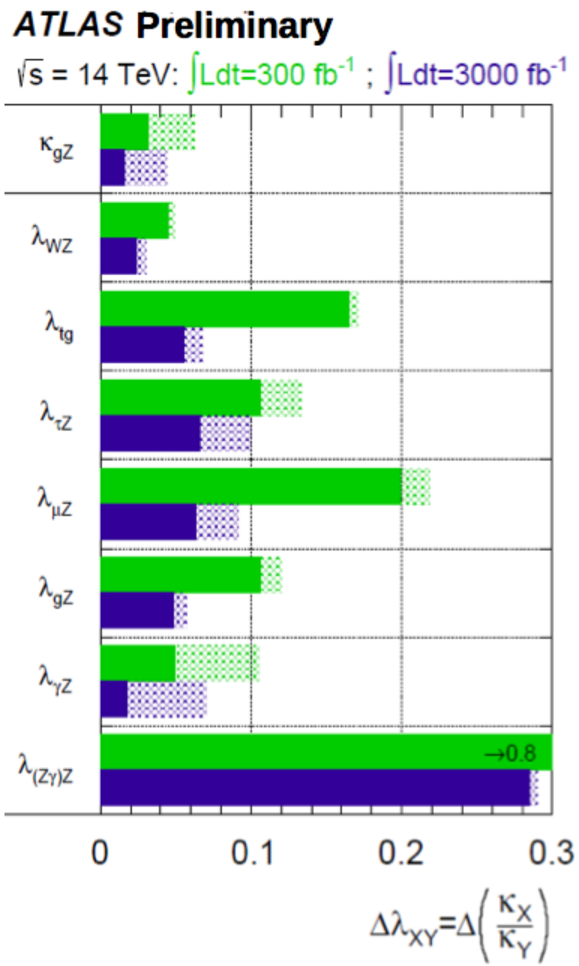
μμ decay mode should reach more than 5 standard deviation

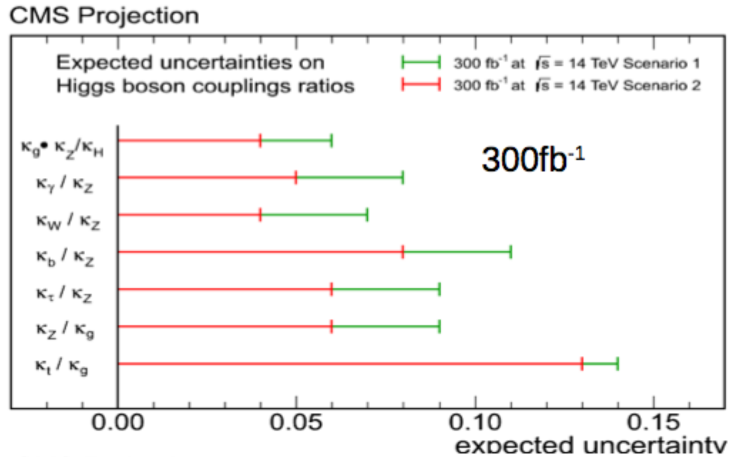
Just two examples but there are many many more!!!

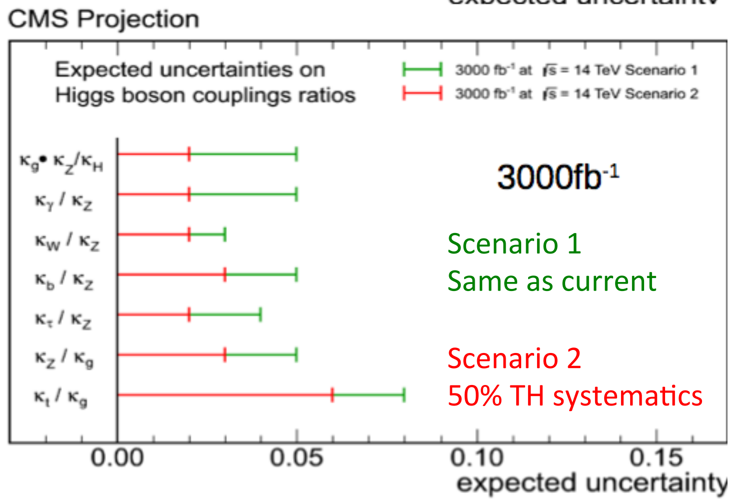


LHC Higgs Physics Program: Main Couplings

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 ~5% level

Di-Higgs Production
Self Couplings

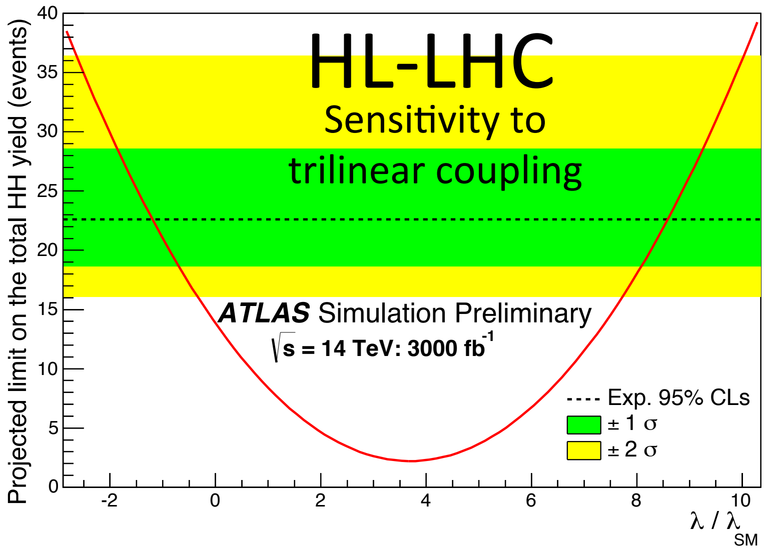
ATL-PHYS-PUB-2014-019

At HL-LHC sensitivity to SM HH

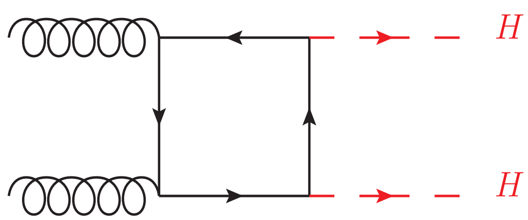
$1.3\ \sigma$

Extremely challenging!

Similarities with Off-Shell Couplings measurements



Associated production of two Higgs bosons



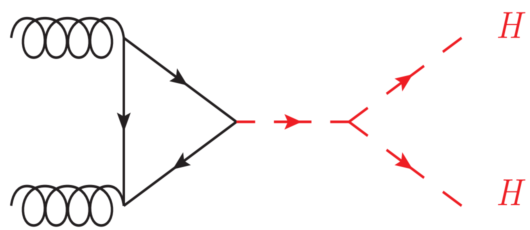
Various channels searched for (bbγγ)

Limit on non resonant cross section times branching:

$\sigma_{HH}\,Br_{bb,\,\gamma\gamma} < O(2)$ 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

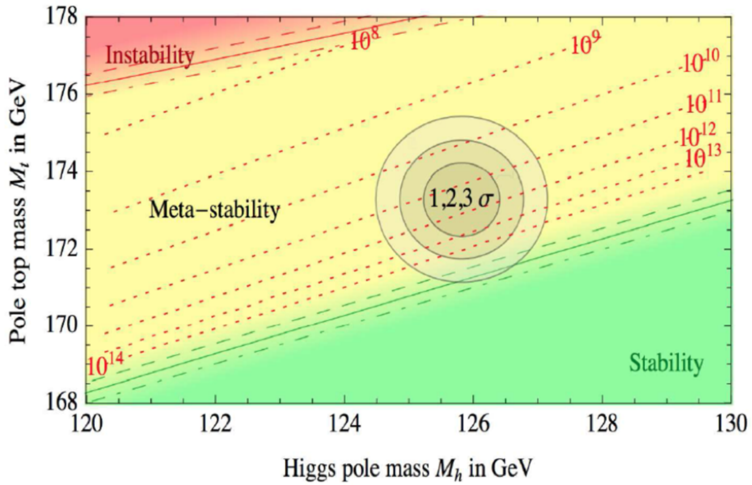
Implications (I) : *The Standard Model is Complete*

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

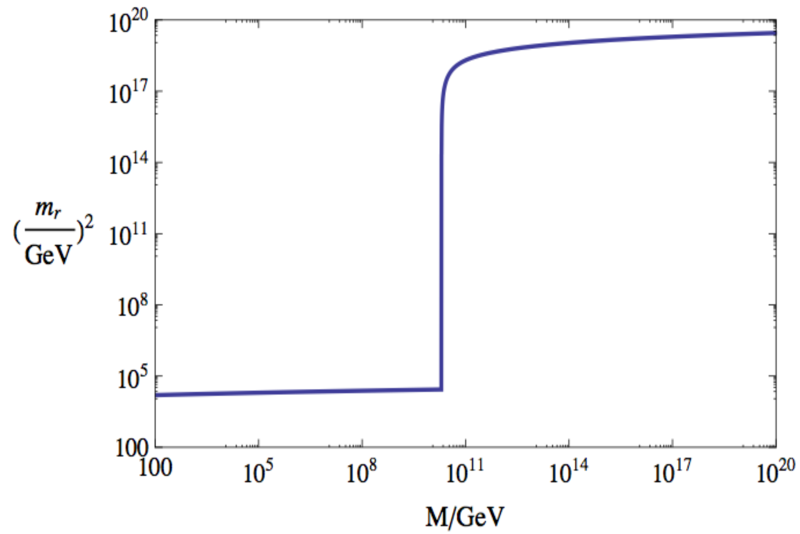
1307.3536

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



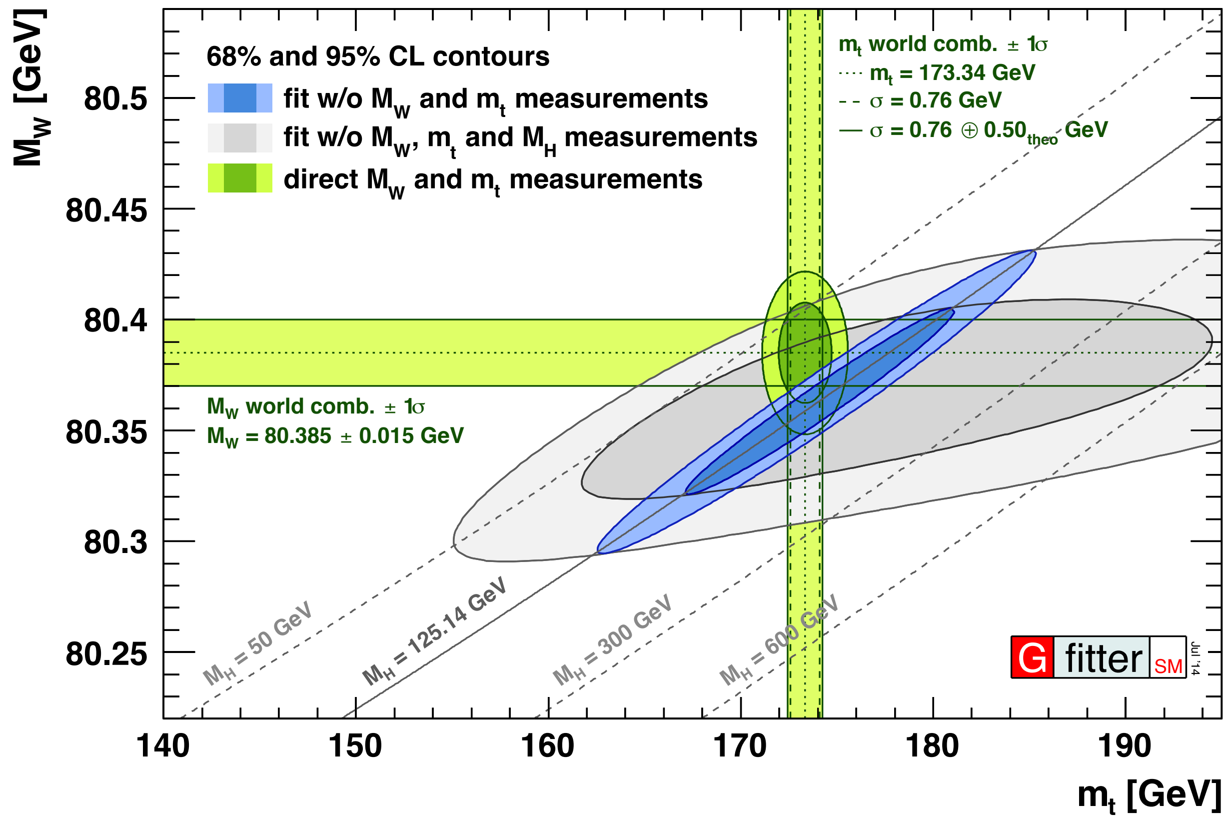
What is this telling us?



There is no "No Loose Theorem" anymore,
Naturalness still valid as guiding principle…

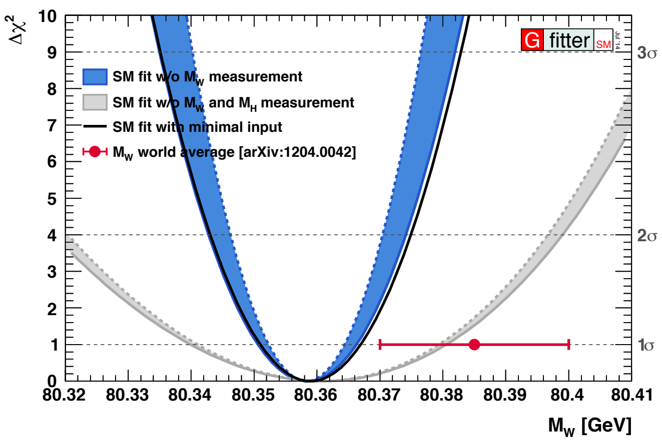
If there is NP, it would be motivated to be at relatively low scale to avoid fine tuning.

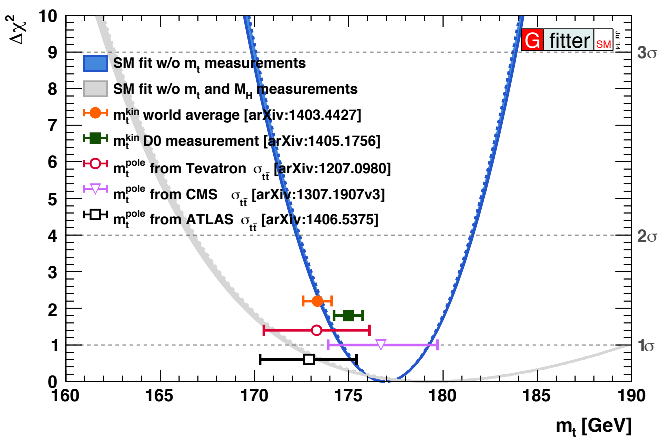
Implications (II) : *EW Precision Fit*



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

[Eur. Phys. J. C **74**, 3046 (2014)]





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* $\mu\tau$, $e\tau$
- $J/\Psi\gamma$, $Z\Upsilon$, *WD etc…*

$$H^0$$

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)

…and More!

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

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 lumiosity 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 facitlities (beyond HL-LHC)
- We are now exploring the new energy forntier at 13 TeV

Highest Mass Run 1 Di-Jet Event 4.23 TeV