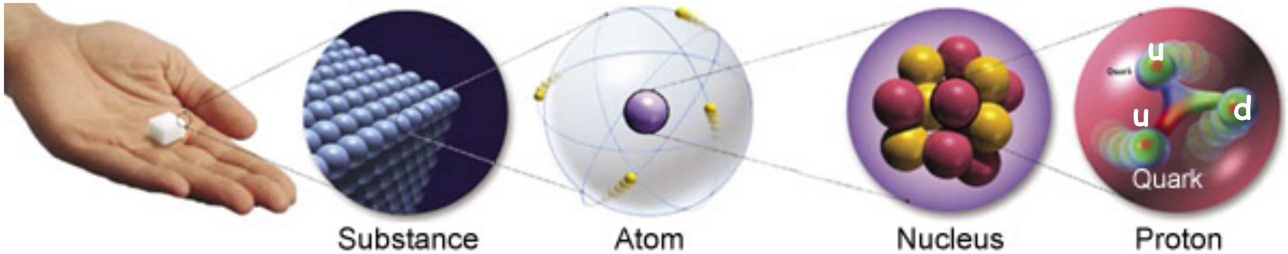
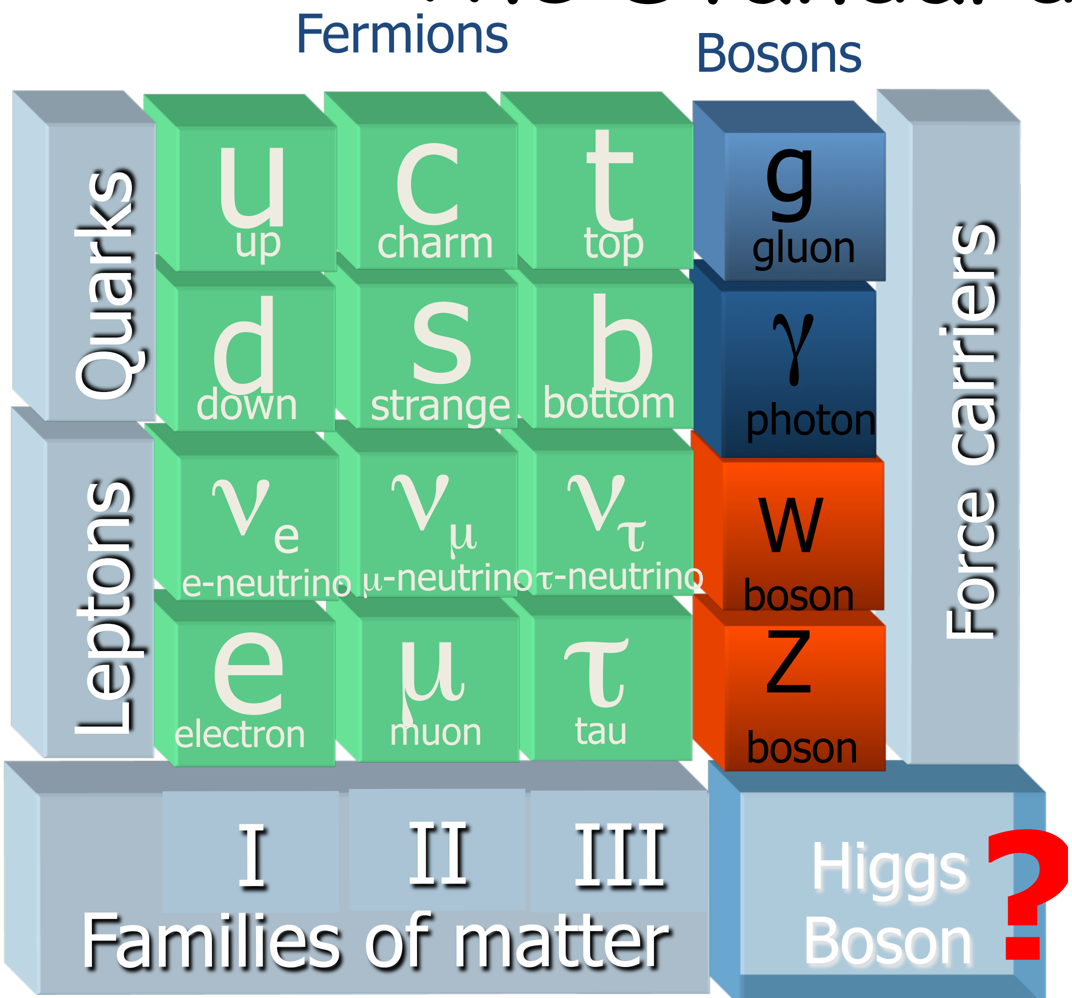
The Higgs search and discovery

N. De Filippis - Politecnico & INFN, Bari

Third International Workshop on recent LHC results and related topics



The Standard Model



Questions:

- why masses of matter particles and forces carriers are so different ?
- Matter particles range from almost 0 to 175 GeV while force carriers range from 0 to 90 GeV.

The simplest solution:

- all particles are massless !!
- a new scalar field pervades the Universe (the Higgs field).
- particles interacting with this field acquire mass: the stronger the interaction the larger the mass...

“The” theory

	Article	Reception date	Publication date
1	F. Englert and R. Brout Phys. Rev. Letters **13-[9]** (1964) 321	26/06/1964	31/08/1964
2	P.W. Higgs Phys. Letters **12** (1964) 132	27/07/1964	15/09/1964
3	P.W. Higgs Phys. Rev. Letters **13-[16]** (1964) 508	31/08/1964	19/10/1964
4	G.S. Guralnik, C.R. Hagen and T.W.B. Kibble Phys. Rev. Letters **13-[20]** (1964) 585	12/10/1964	16/11/1964

The Higgs mechanism

Problem:

Gauge fields Z, W^+, W^- are massive

explicite mass terms in the Lagrangian $\Leftrightarrow$ breaking of gauge invariance

Solution: Higgs mechanism

scalar field postulated, mass terms from coupling to Higgs field

Higgs sector in the Standard Model:

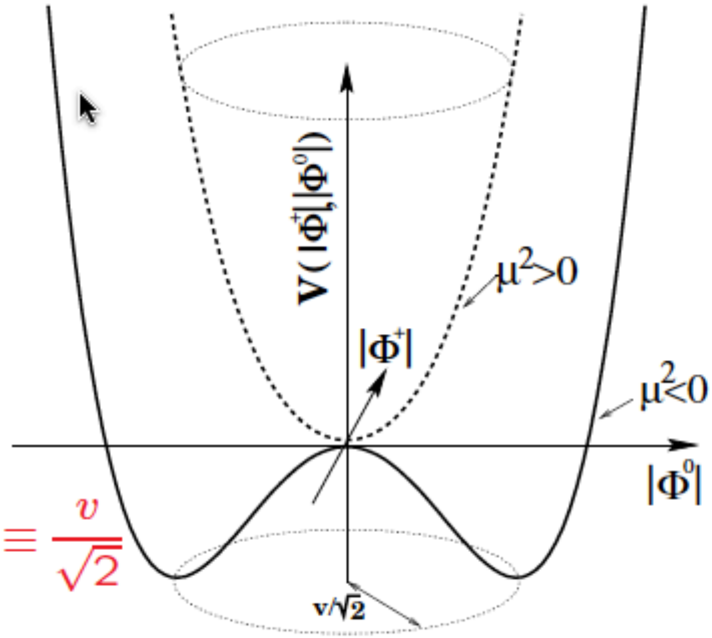
Scalar SU(2) doublet: $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$

Higgs potential:

$$V(\phi) = \mu^2 \left|\Phi^\dagger \Phi\right| + \lambda \left|\Phi^\dagger \Phi\right|^2, \quad \lambda > 0$$

$\mu^2 < 0$: Spontaneous symmetry breaking

minimum of potential at $|\langle\Phi_0\rangle| = \sqrt{\frac{-\mu^2}{2\lambda}} \equiv \frac{v}{\sqrt{2}}$

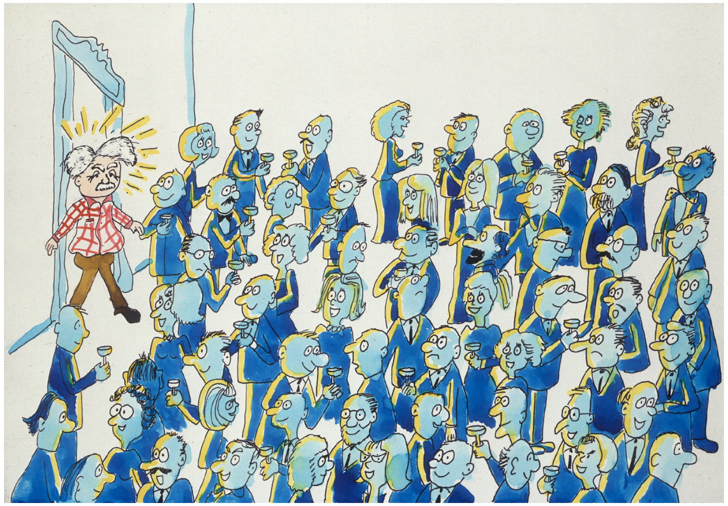


The Higgs mechanism cartoon

Let's imagine a room with many physicists talking each other →

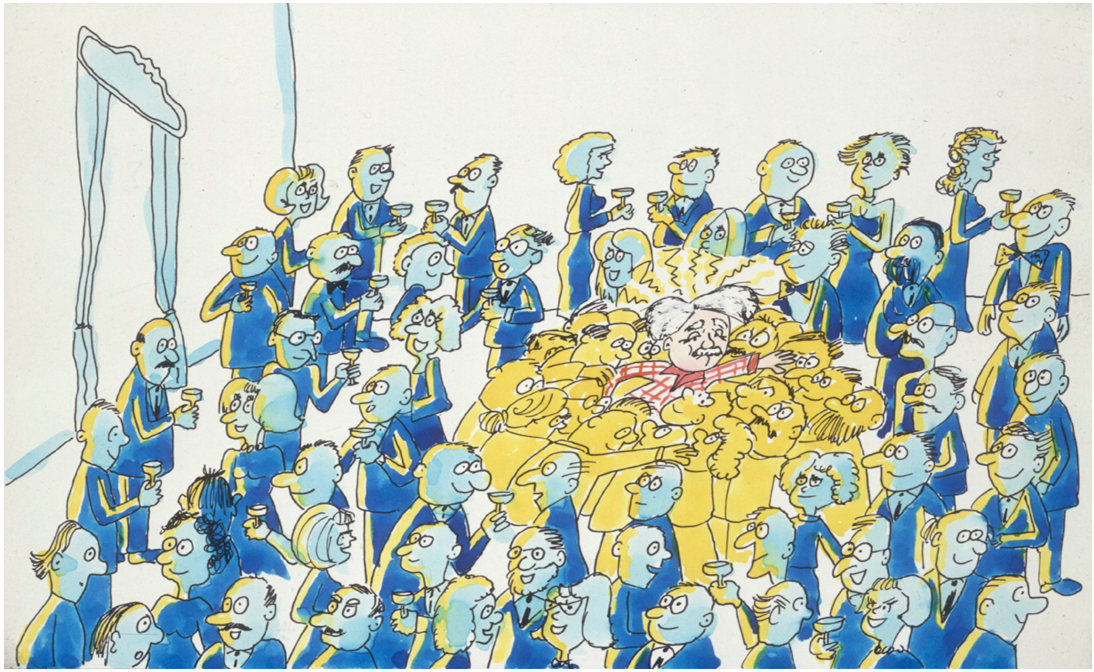
space filled with the Higgs field

A well know scientist starts to move in the room creating disturbance and attracting clusters of admirers at each step.

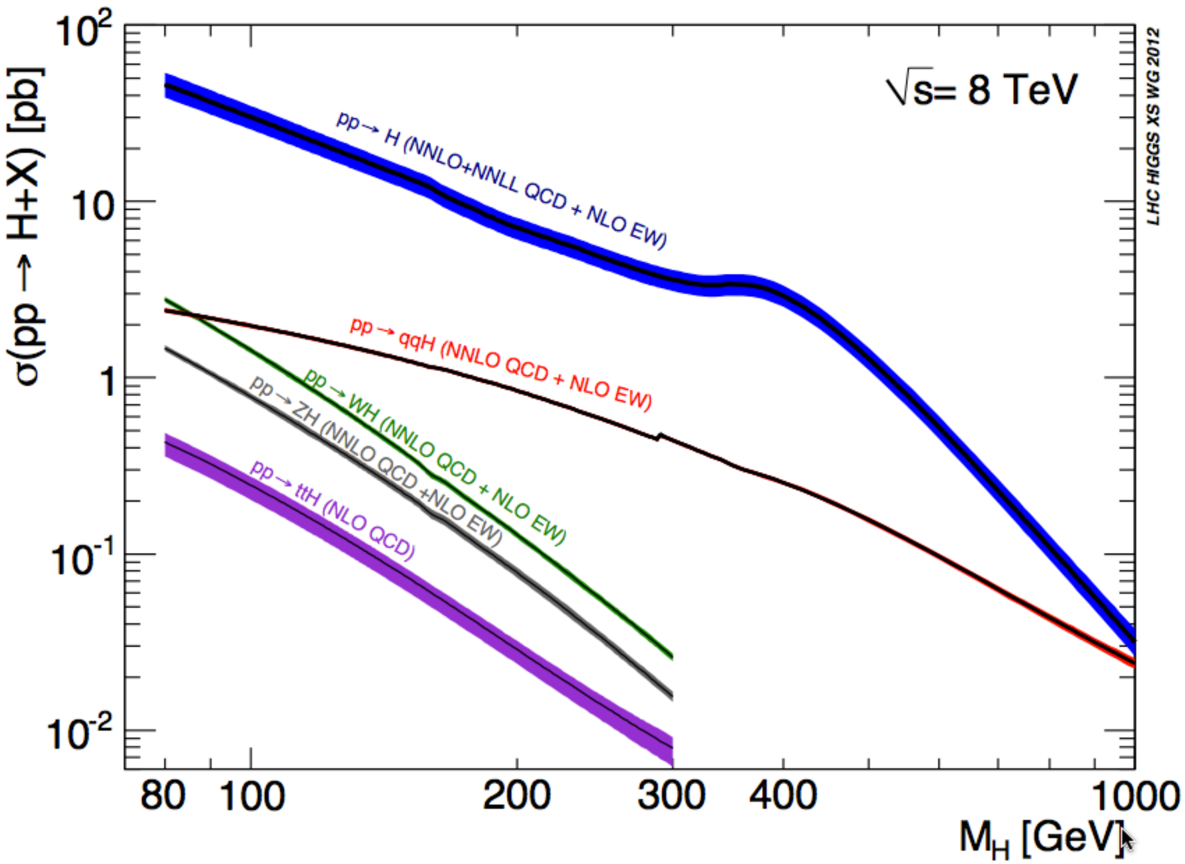


The Higgs mechanism cartoon (2)

That increases the resistance to the motion and so he gets mass like a particle moving in the higgs field



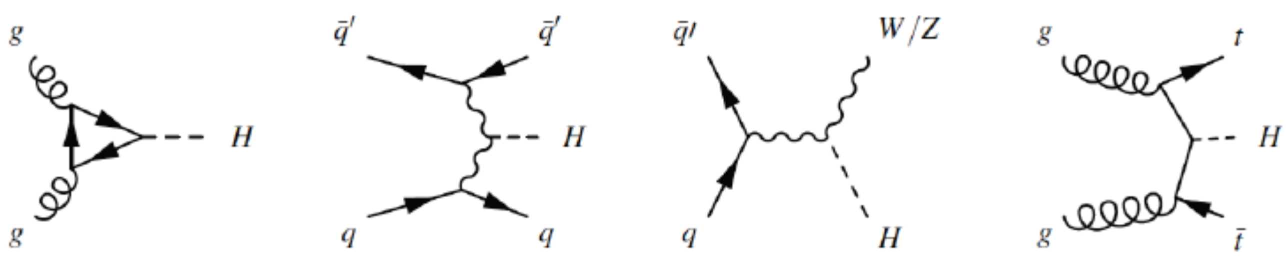
SM Higgs production at the LHC



Gluon-gluon fusion:
→ radiative corrections at:

- NLO QCD
- NNLO QCD
- NNLL QCD
- NLO EW

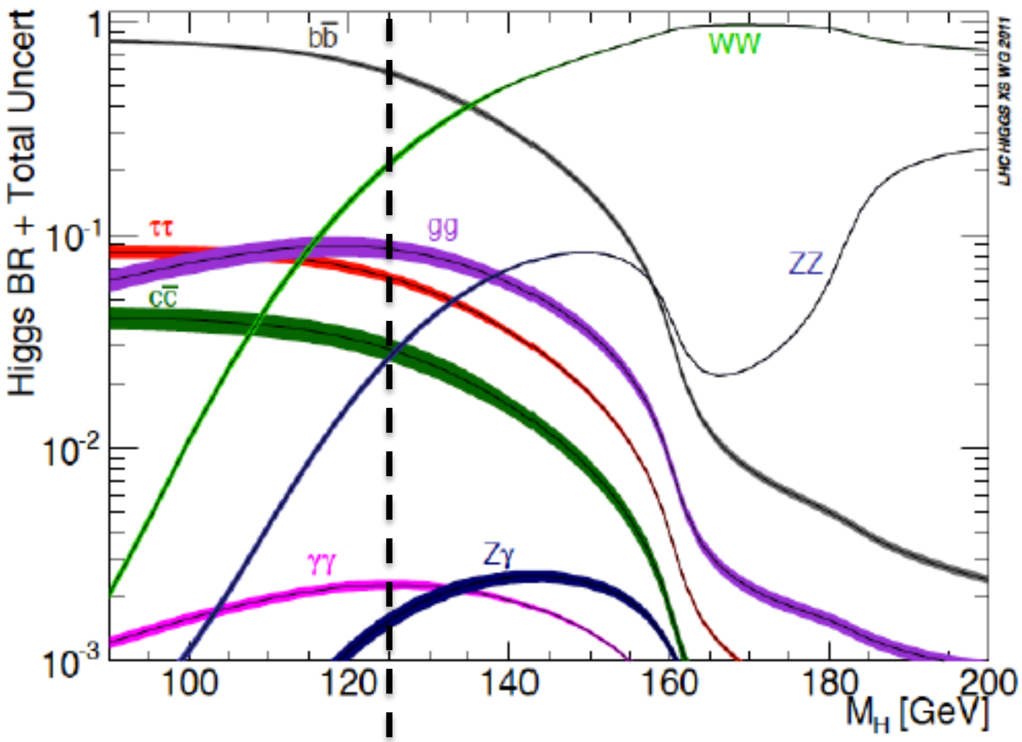
	$K_{NNLO/NLO}$ ($K_{NLO/LO}$)	Scale	PDF+a_s	Total error
ggF	+25% (+100%)	+12% -7%	±8%	+20 -15%
VBF	<1% (+5-10%)	±1%	±4%	±5%
WH/ ZH	+2-6% (+30%)	±1%	±4%	±5%
ttH	- (+5-20%)	+4% -10%	±8%	+12 -18%

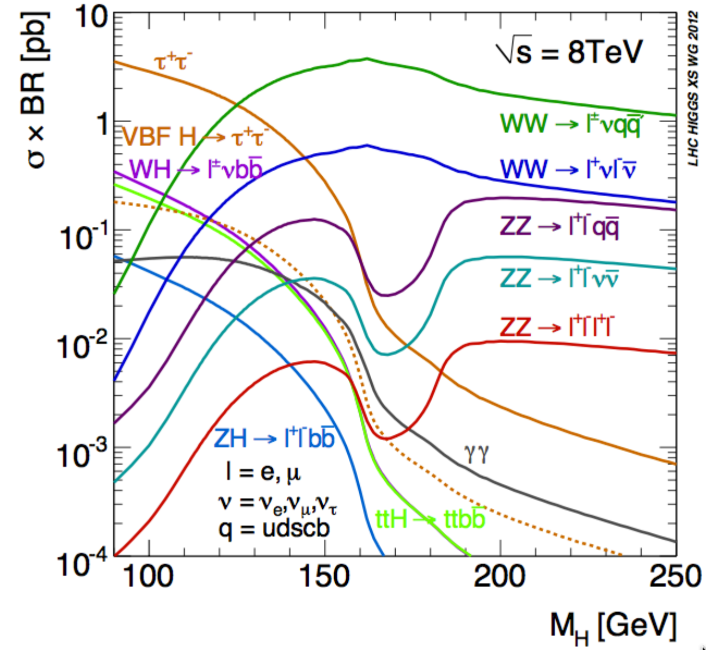


(a) $gg \to H$ (b) VBF (c) VH (d) $t\bar{t}H$

LHC Higgs Xsection WG

Higgs decay channels





At m_H =125 GeV:

- H(bb) = 57.8%
- H(WW) = 21.4%
- H(gg) = 8.19%
- H(ττ) = 6.27%
- H(ZZ) = 2.62%
- H(cc) = 2.89%
- H(γγ) = 0.23%
- H(Zγ) = 0.15 %
- H(μμ) = 0.02%

Channel	m_H resolution
$H \to \gamma\gamma$	1–2%
$H \to \tau\tau \to e\tau_h/\mu\tau_h/e\mu + X$	20%
$H \to \tau\tau \to \mu\mu + X$	20%
$WH \to e\mu\tau_h/\mu\mu\tau_h + \nu's$	20%
$(W/Z)H \to (e\nu/\mu\nu/ee/\mu\mu/\nu\imath$	10%
$H \to WW^* \to 2\ell 2\nu$	20%
$WH \to W(WW^*) \to 3\ell 3\nu$	20%
$H \to ZZ^{(*)} \to 4\ell$	1–2%
$H \to ZZ^{(*)} \to 2\ell 2q$	3% 3%
$H \to ZZ \to 2\ell 2\tau$	10–15%
$H \to ZZ \to 2\ell 2\nu$	7%

Main discovery channels at LHC

H→ZZ→4l - golden channel

- clean experimental signature, four isolated leptons
- benefits from excellent electron and muon resolution
- narrow resonance in four lepton mass spectrum

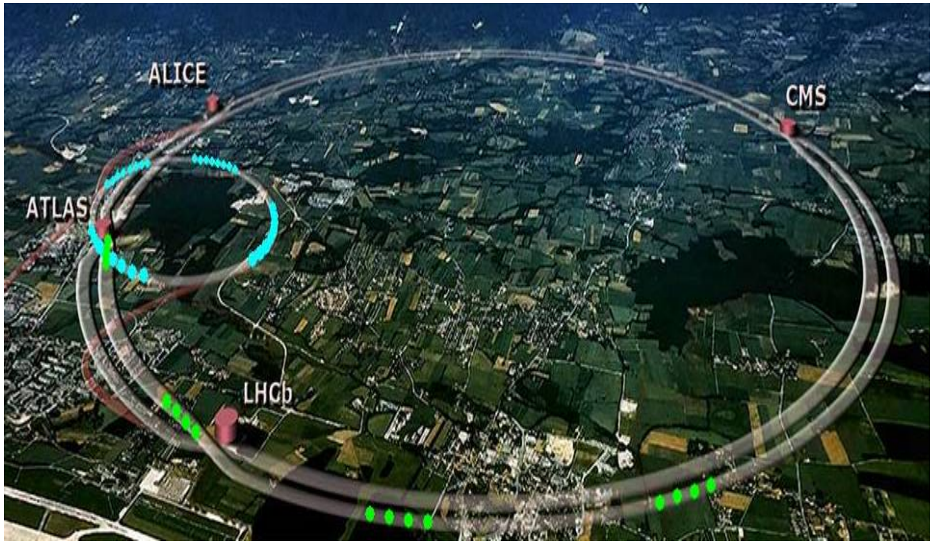
H→γγ

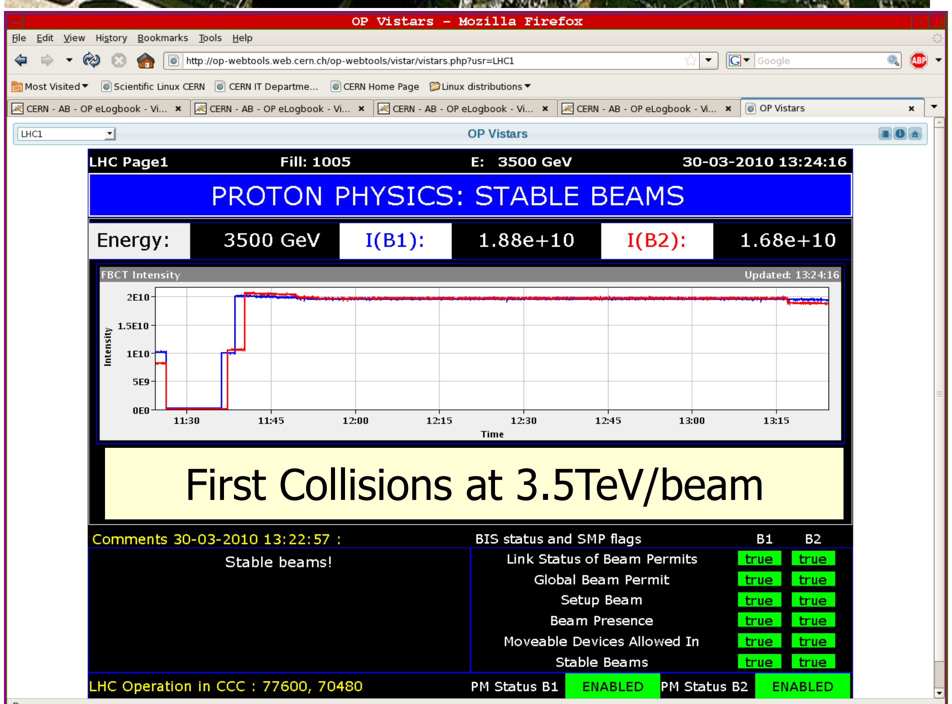
- clean signature of two energetic and isolated photons
- benefits from good photon resolution
- narrow peak in di-photon mass spectrum on the top of continuous background

Both the channels:

- suffer from low signal rate because of small BR
- allow to reconstruct the mass peak

The LHC machine



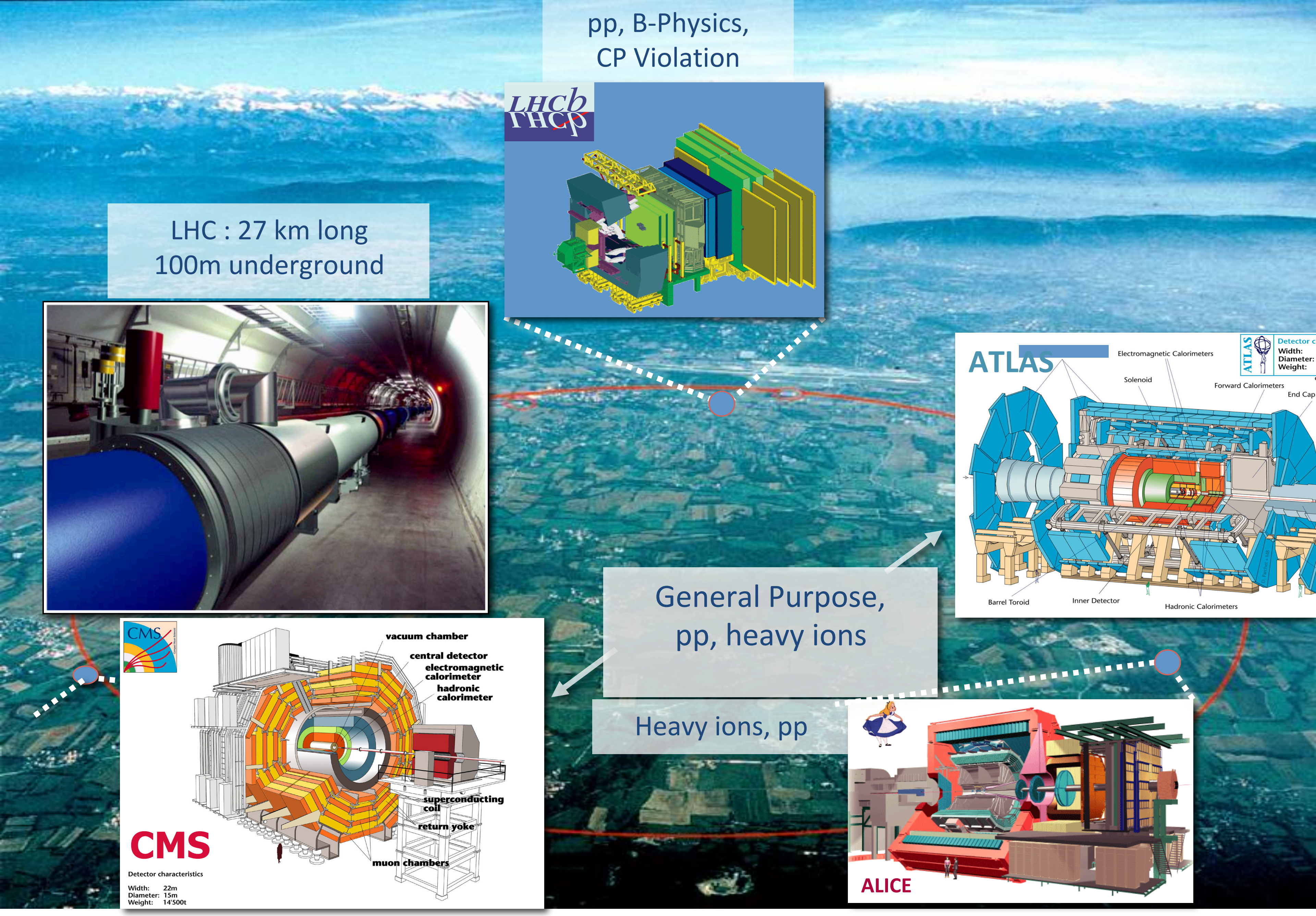


Circumference (km)	26.7
Number of superconducting Dipoles	1232
Length of Dipole (m)	14.3
Dipole Field Strength (Tesla)	8.4
Operating Temperature (K)	1.9
Current in dipole sc coils (A)	13000
Beam Intensity (A)	0.5
Beam Stored Energy (MJoules)	362
Number of particles per bunch	1.15×10^{11}
Number of bunches per beam	2808
Crossing angle (μrad)	285
Bunch length (cm)	7.55
Norm transverse emittance (μm rad)	3.75
Beta function at IP 1,2,5,8 (m)	0.55,10,0.55,10

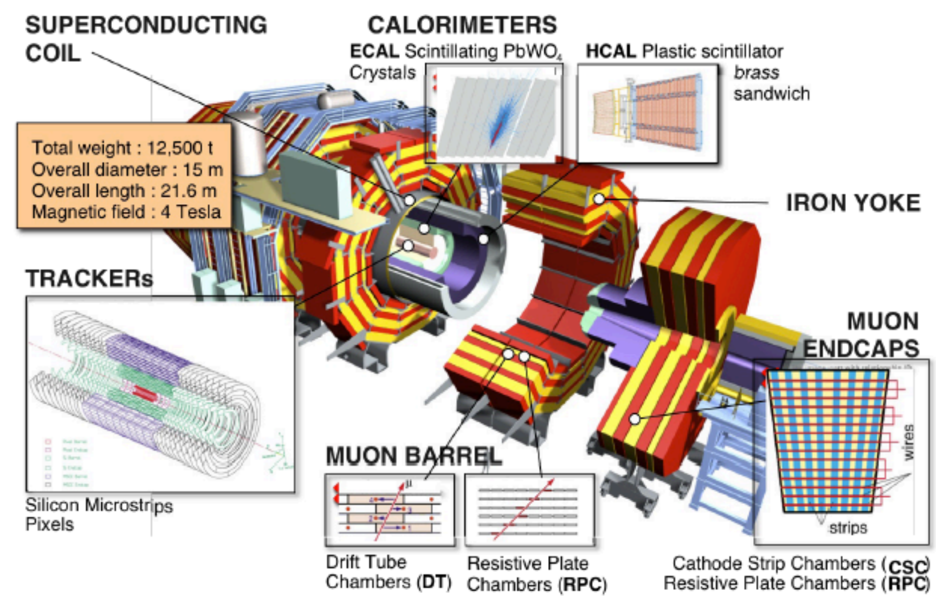
$$L = \frac{N_b^2 n_b f_{rev} \gamma_r}{4\pi \varepsilon_n \beta *} F$$

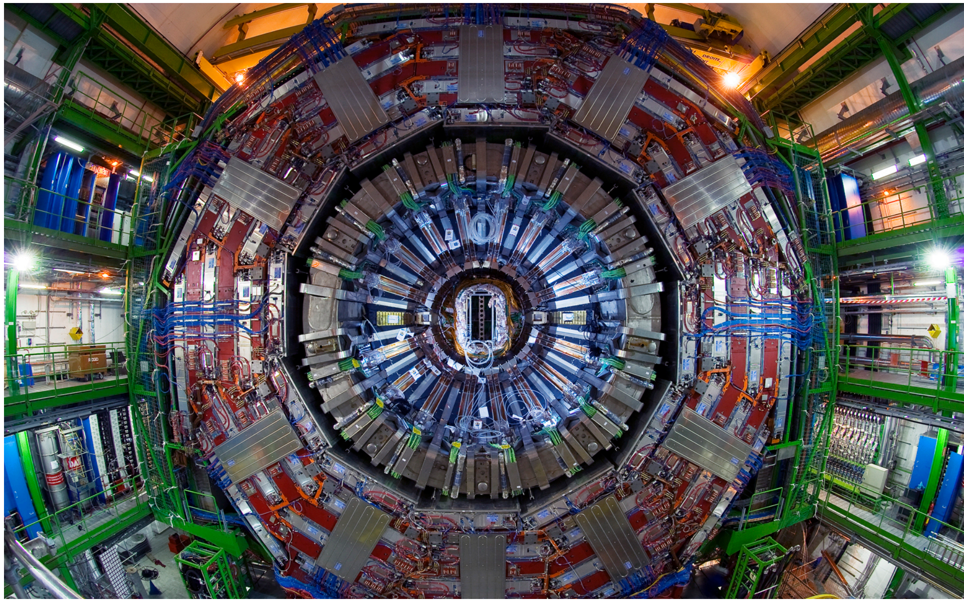
N_b = number of proton per bunch
n_b = number of bunches
f_{rev} = rotation frequency (~ 11Hz)
F = crossing angle factor

Rms transverse beam size $=\sqrt{\varepsilon\ \beta / \gamma}$
ε_n = renorm. transverse emittance
$\beta *$ = optics at beam crossing (m)
γ_r = relativistic factor


pp, B-Physics,
CP Violation
LHCb
LHC : 27 km long
100m underground
ATLAS
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap
Width:
Diameter:
Weight:
Barrel Toroid
Inner Detector
Hadronic Calorimeters
General Purpose,
pp, heavy ions
Heavy ions, pp
CMS
vacuum chamber
central detector
electromagnetic
calorimeter
hadronic
calorimeter
superconducting
coil
return yoke
muon chambers
CMS
Detector characteristics
Width: 22m
Diameter: 15m
Weight: 14'500t
ALICE

CMS in a nutshell





|η|<2.5 : Tracker

$\sigma / p_T \approx 10^{-4} p_T \oplus 0.005$

|η|<4.9 : EM Calorimeter

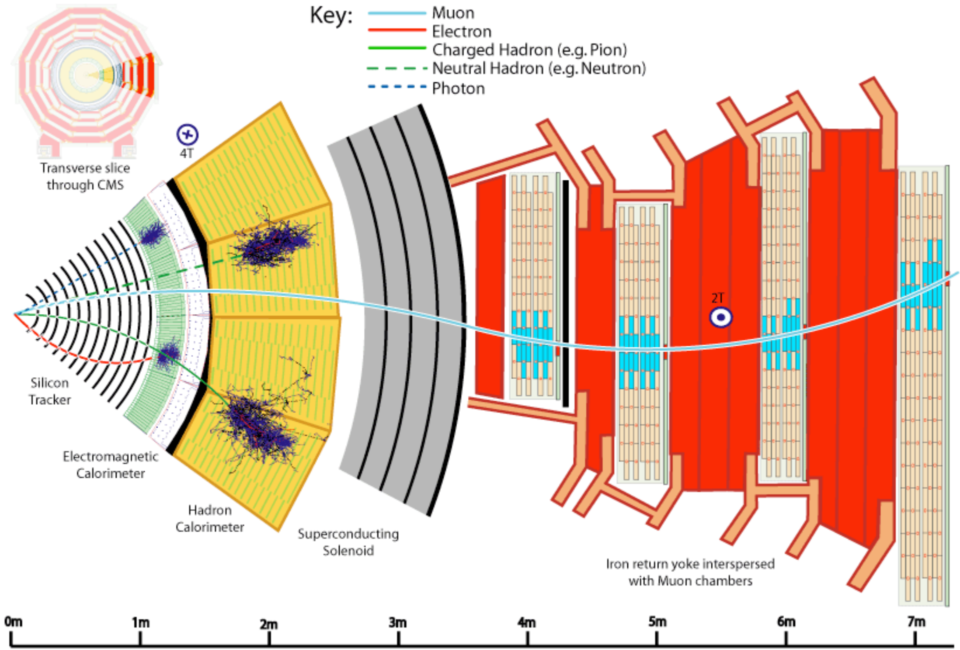
$\sigma / E \approx 0.03 / \sqrt{E} + 0.003$

|η|<4.9 : HAD Calorimeter

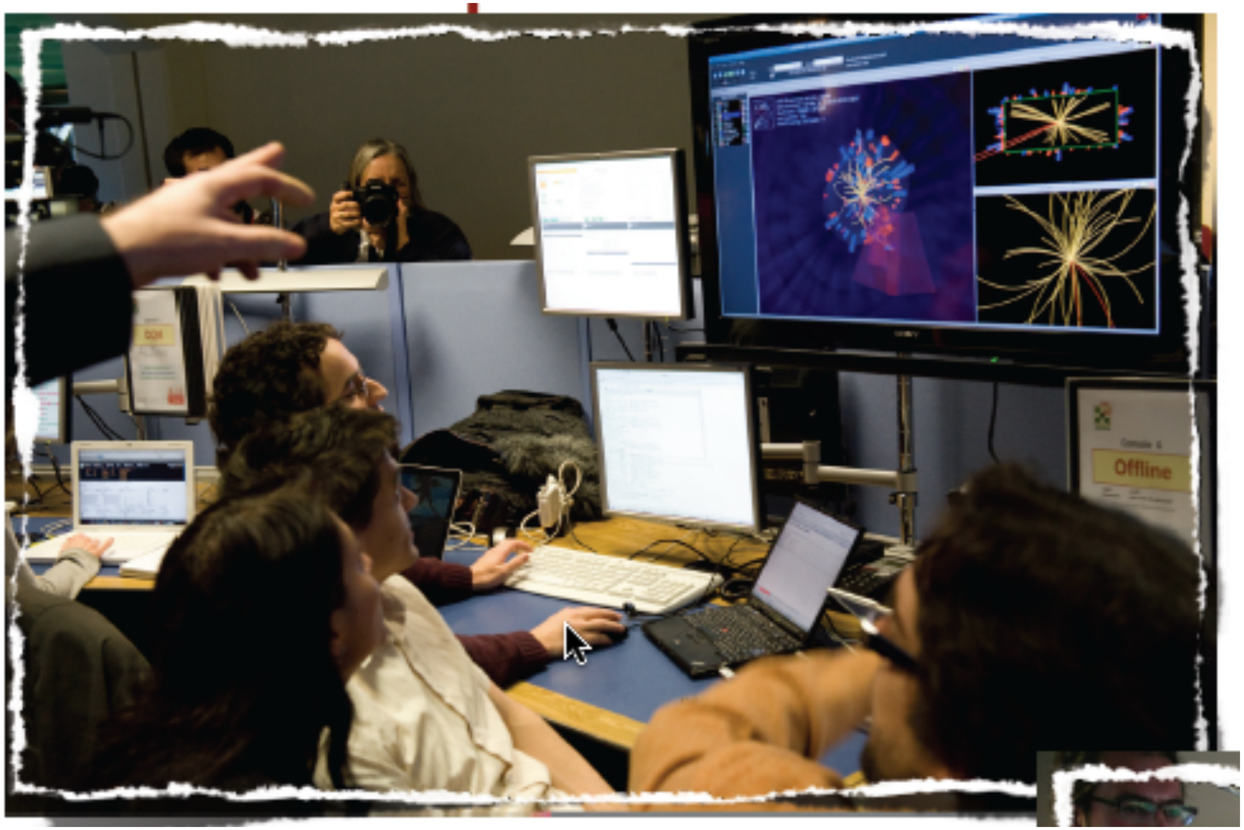
$\sigma / E \approx 1.0 / \sqrt{E} + 0.05$

|η|<2.4 : Muon spectrometer

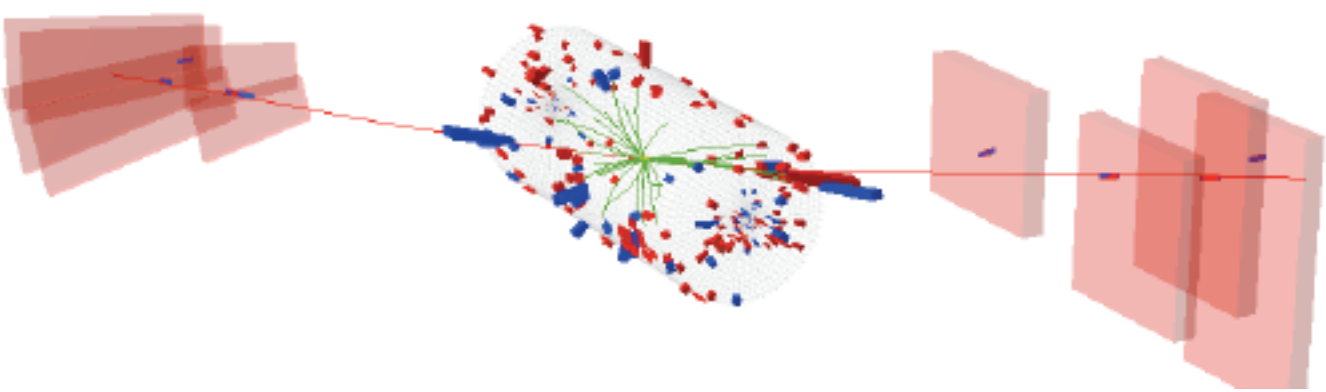
$\sigma / p_T \approx 0.10$ *(1TeV muons)*



First collisions at 7 TeV

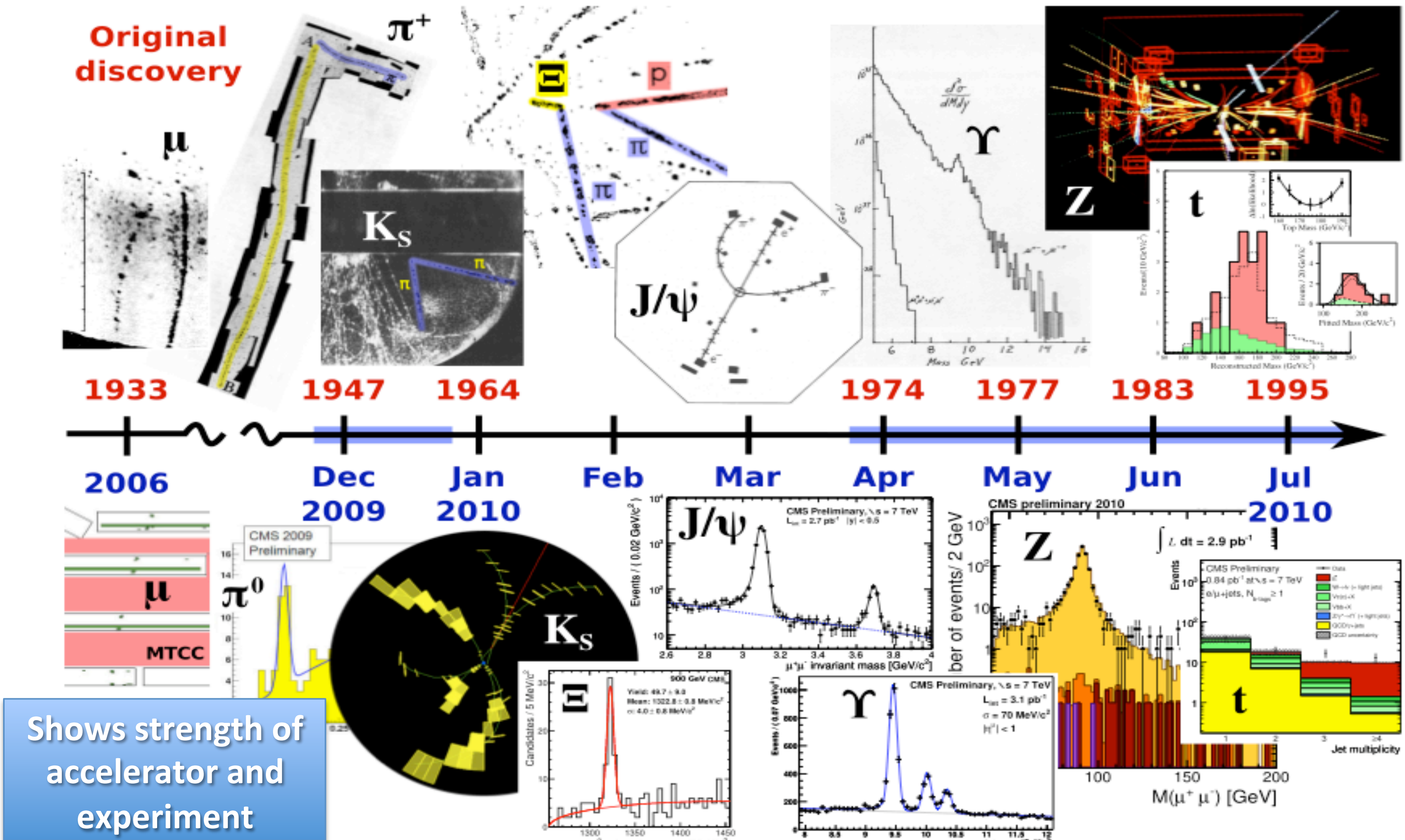


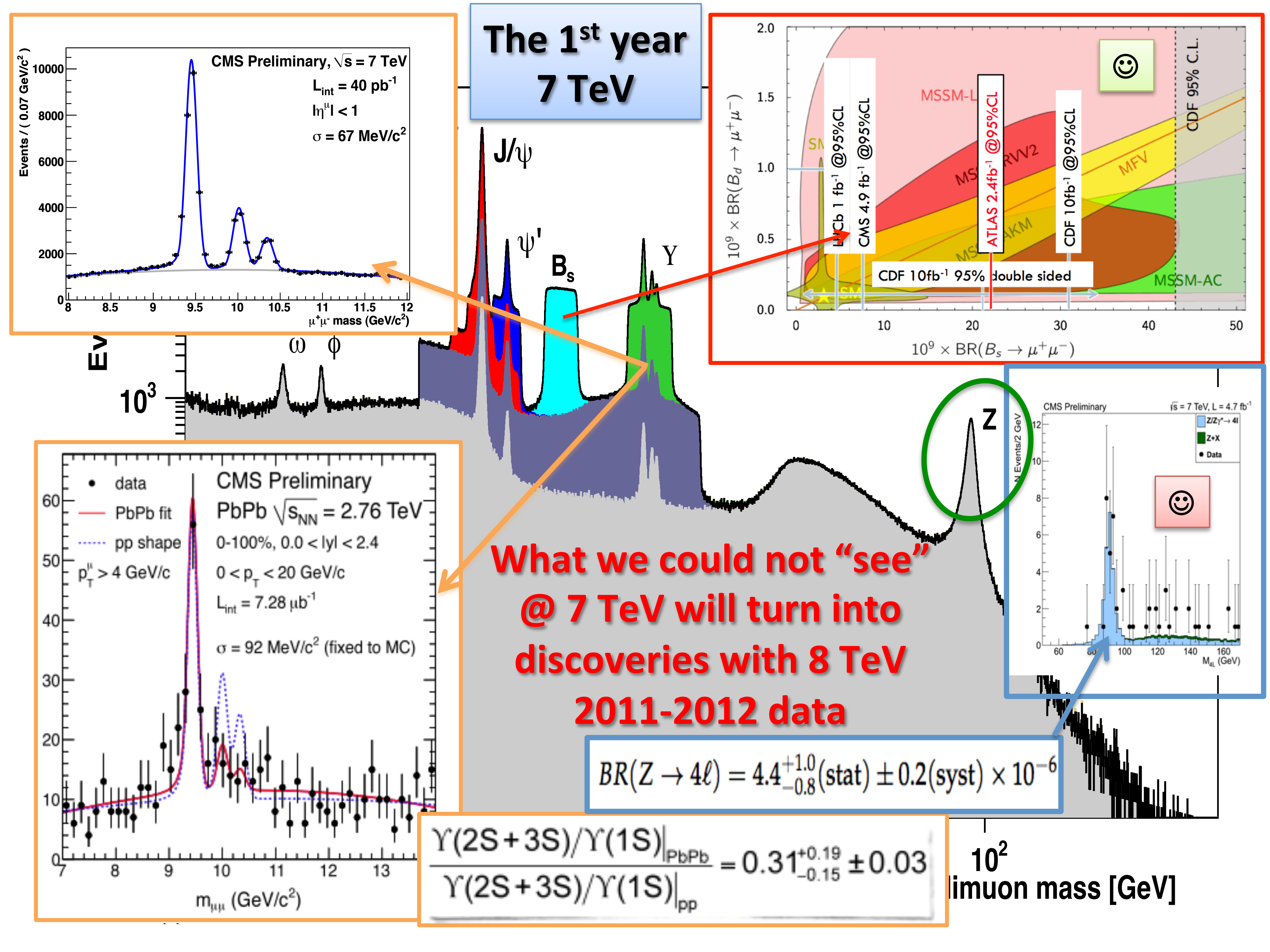
March 2010:
Collisions at 7 TeV.
LHC delivered:
44.22 pb-1
CMS recorded:
40.56 pb-



The first Z→μμ Candidate

2010: CMS "Rediscovers" the Standard Model in Particle Physics



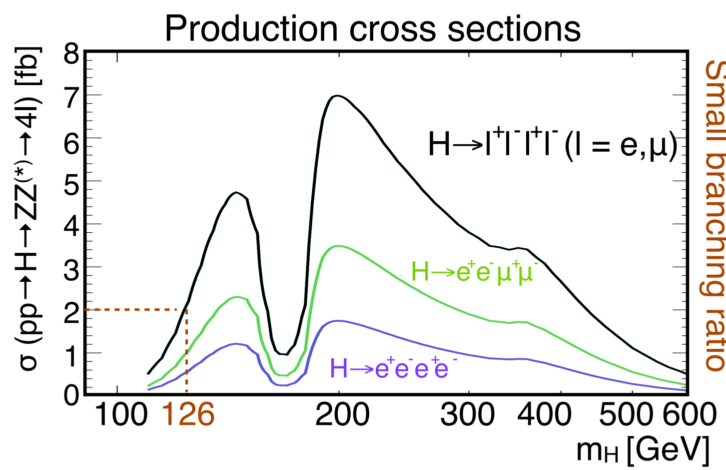


$$BR(Z \to 4\ell) = 4.4^{+1.0}_{-0.8}(\text{stat}) \pm 0.2(\text{syst}) \times 10^{-6}$$

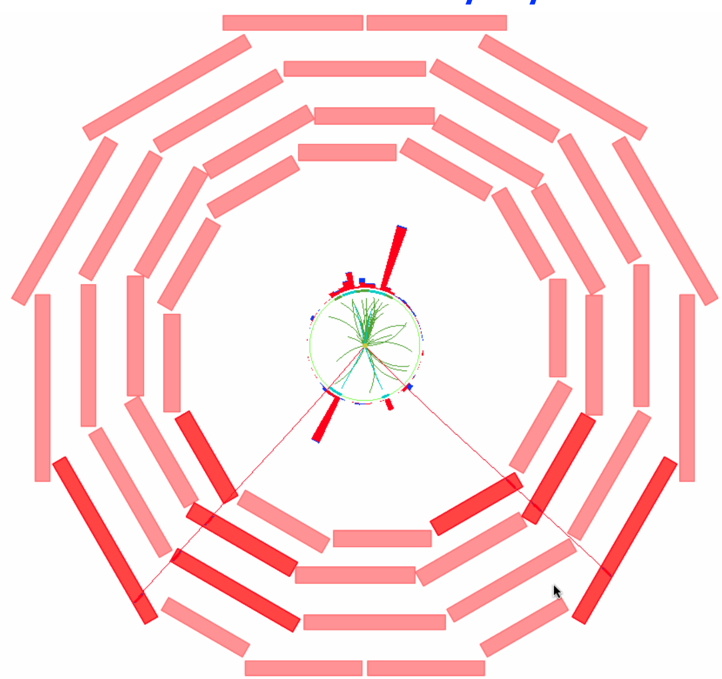
$$\frac{\Upsilon(2S+3S)/\Upsilon(1S)|_{PbPb}}{\Upsilon(2S+3S)/\Upsilon(1S)|_{pp}} = 0.31^{+0.19}_{-0.15} \pm 0.03$$

H→ZZ→4l in a nutshell

- Signatures: **4e, 4mu and 2e2mu** final state
  - clean but extremely demanding channel for requiring the highest possible efficiencies (lepton Reco/ID/Isolation).
  - σ x BR small ≈ few fb

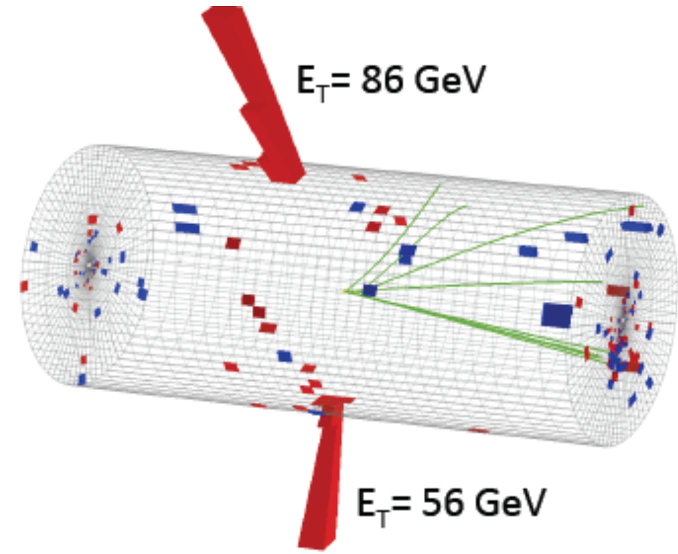


- Backgrounds:
  - Irreducible: ZZ*
  - Reducible: Zbb, tt and tt+jets, Z+jets, WZ+jets



- Sensitivity: 115 < m_H < 600 GeV
- Selection strategy:
  - triggering on double leptons
  - Particle Flow algorithm to build physics objects
  - applying reco, id and isolation of leptons
  - recovery of FSR photons
  - use of impact parameter
  - m_Z and m_{Z*} constraint
  - kinematical discriminant / scalarity of the Higgs

H→γγ in a nutshell



Important channel for Higgs with $110 < m_H < 140$ GeV

- clear signature of two isolated high E_T photons
- small B.R. (0.2%)
- narrow mass peak with very good mass resolution 1-2%
- VBF channels has two additional jets form outgoing quarks

Background:

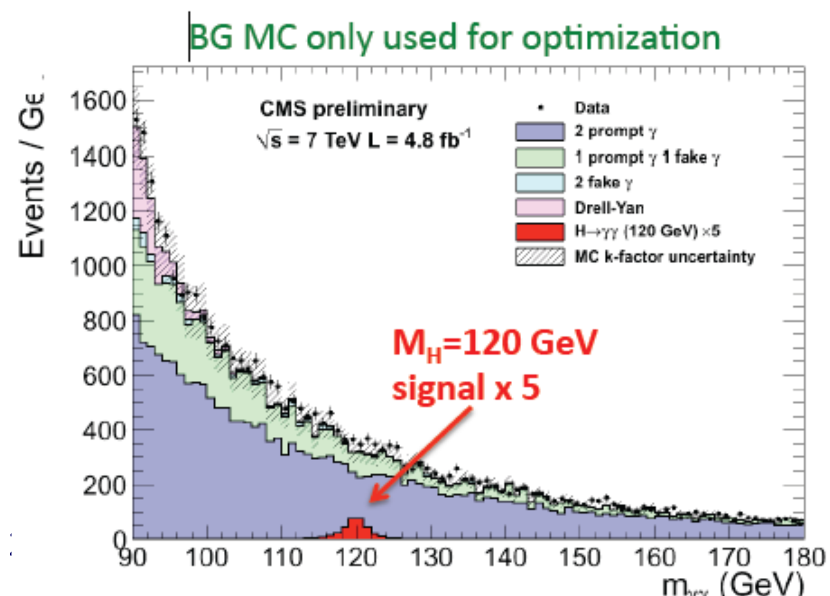
- irreducible : gg→γγ, qqbar, qg→γγ from QCD
- reducible:

  pp → γ+jets (1 prompt γ + 1 fake γ)

  pp → jets (2 fake γ), fake γ from $\pi^0 \to \gamma\gamma$

Analysis strategy based on:

- trigger (double photon HLT)
- vertex ID via BDT MVA
- photon reconstruction, ID and isolation via BDT MVA
- categories of events based on the photon η/shower shape (R_9) to optimize s/b
- look for a peak with cut-based and MVA techniques
- use data to evaluate the background



Test of hypotheses

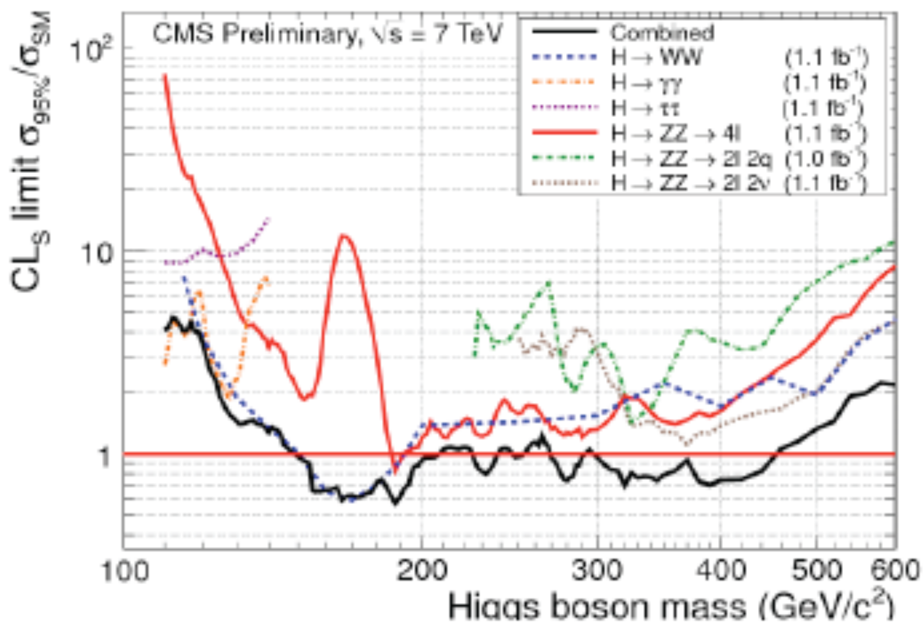
H_0: null hypothesis / no Higgs
H_1: existence of the Higgs

Quantify the level for which the hypotheses are accepted or rejected

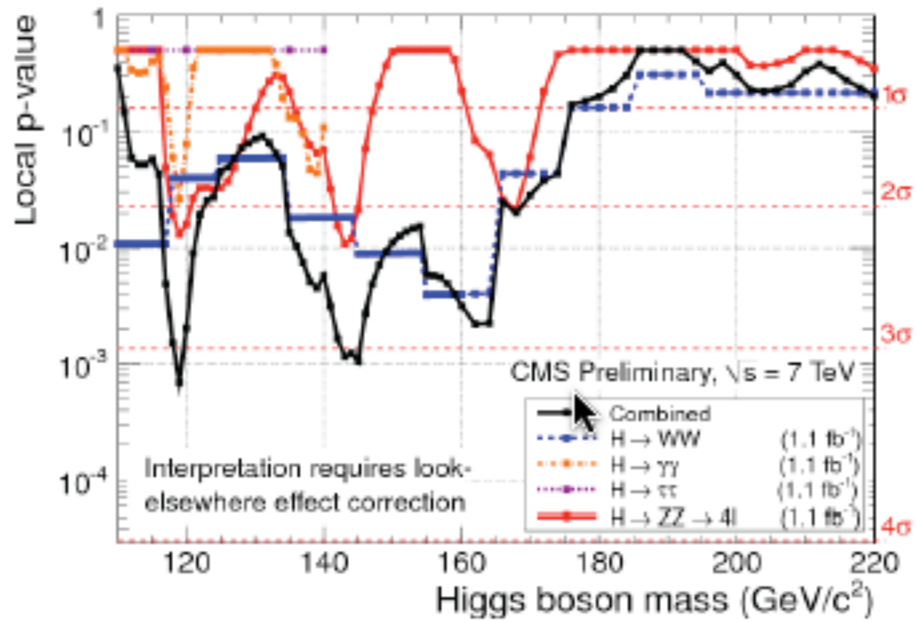
- Identify the experimental observables
- Define a statistical test and the parameters of the model
- Define intervals for the variable to say that H_0 is confirmed or rejected

- Confedence level for the exclusion
- Significance of the discovery

EPS in July 2011 at Grenoble



Observed combined upper limit on $\mu=\sigma/\sigma_{SM}$

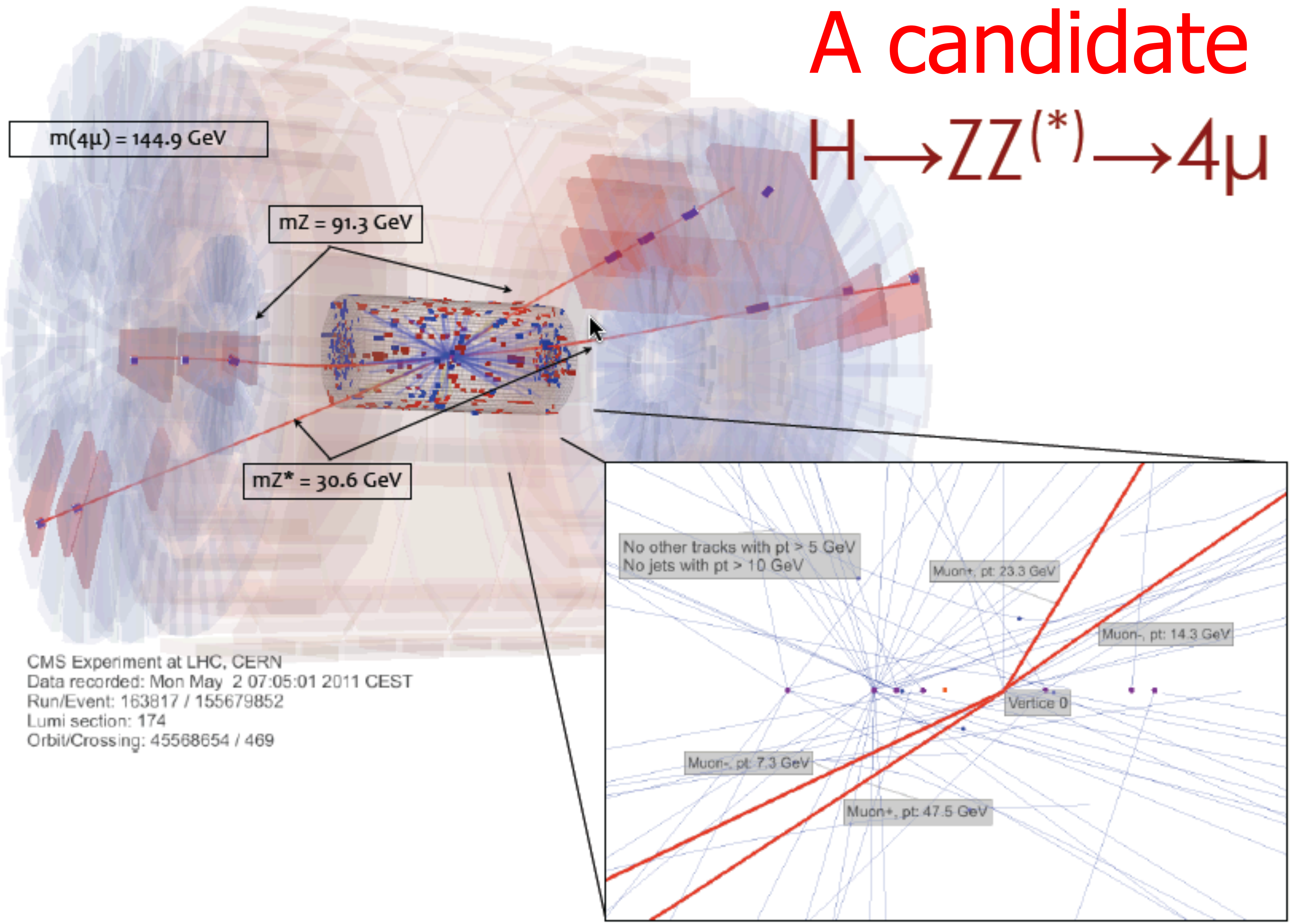


Overall combined local p-values

CMS able to exclude the existence of Higgs in the mass range 149-206 GeV and 300-440 GeV

A candidate

$H \rightarrow ZZ^{(*)} \rightarrow 4\mu$



December 2011

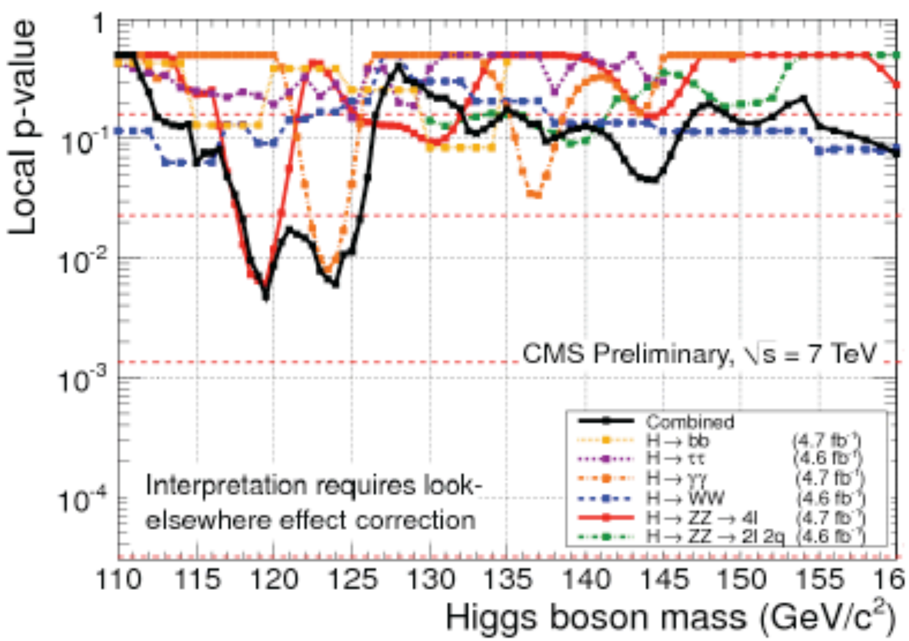
Analysez samples of data: 4.7 fb^{-1} data,

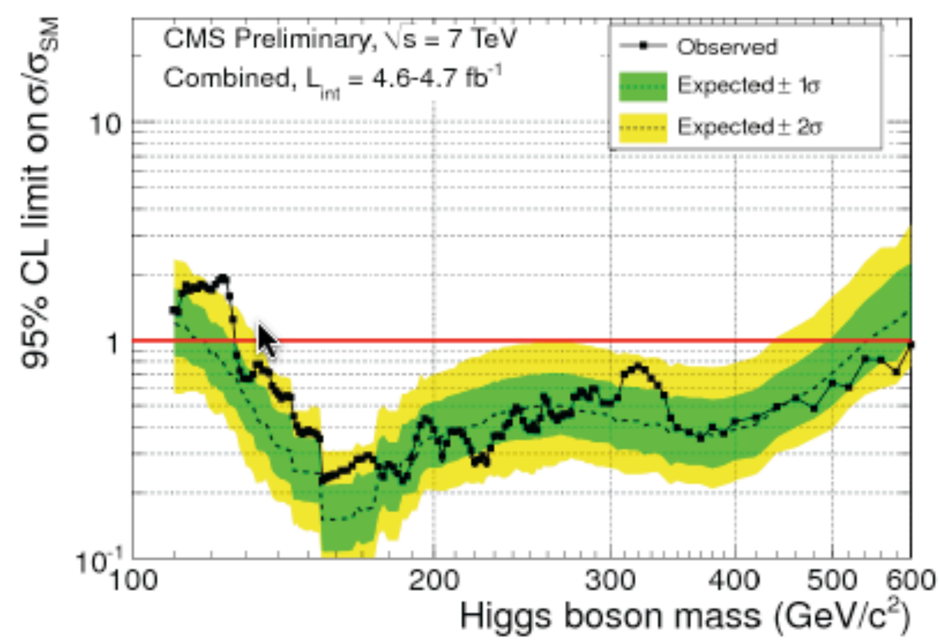
Excluded range of masses with combination of all Higgs analyses:

observed [127-600] GeV

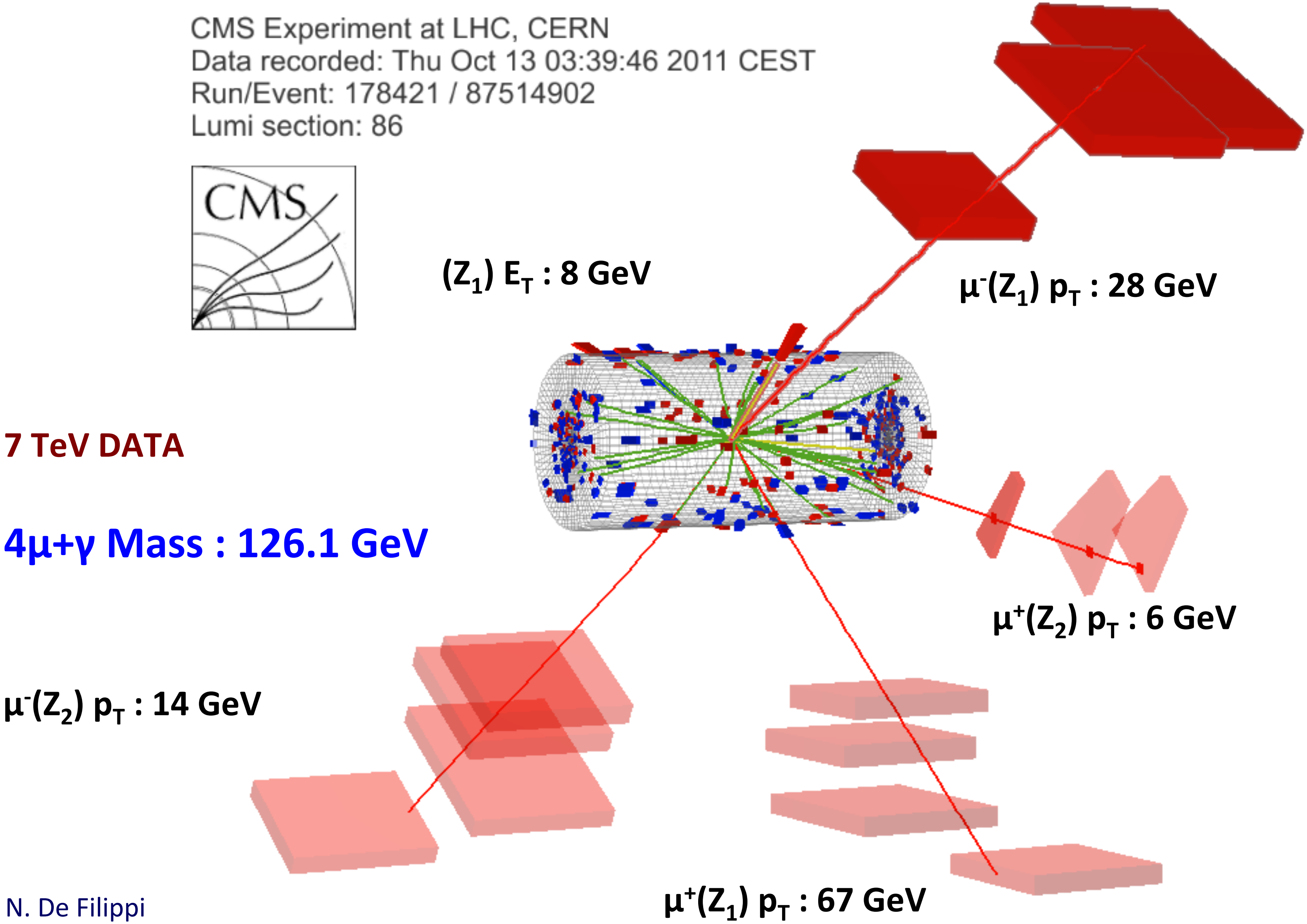
expected [117-543] GeV

With an excess in the range 120-127 GeV



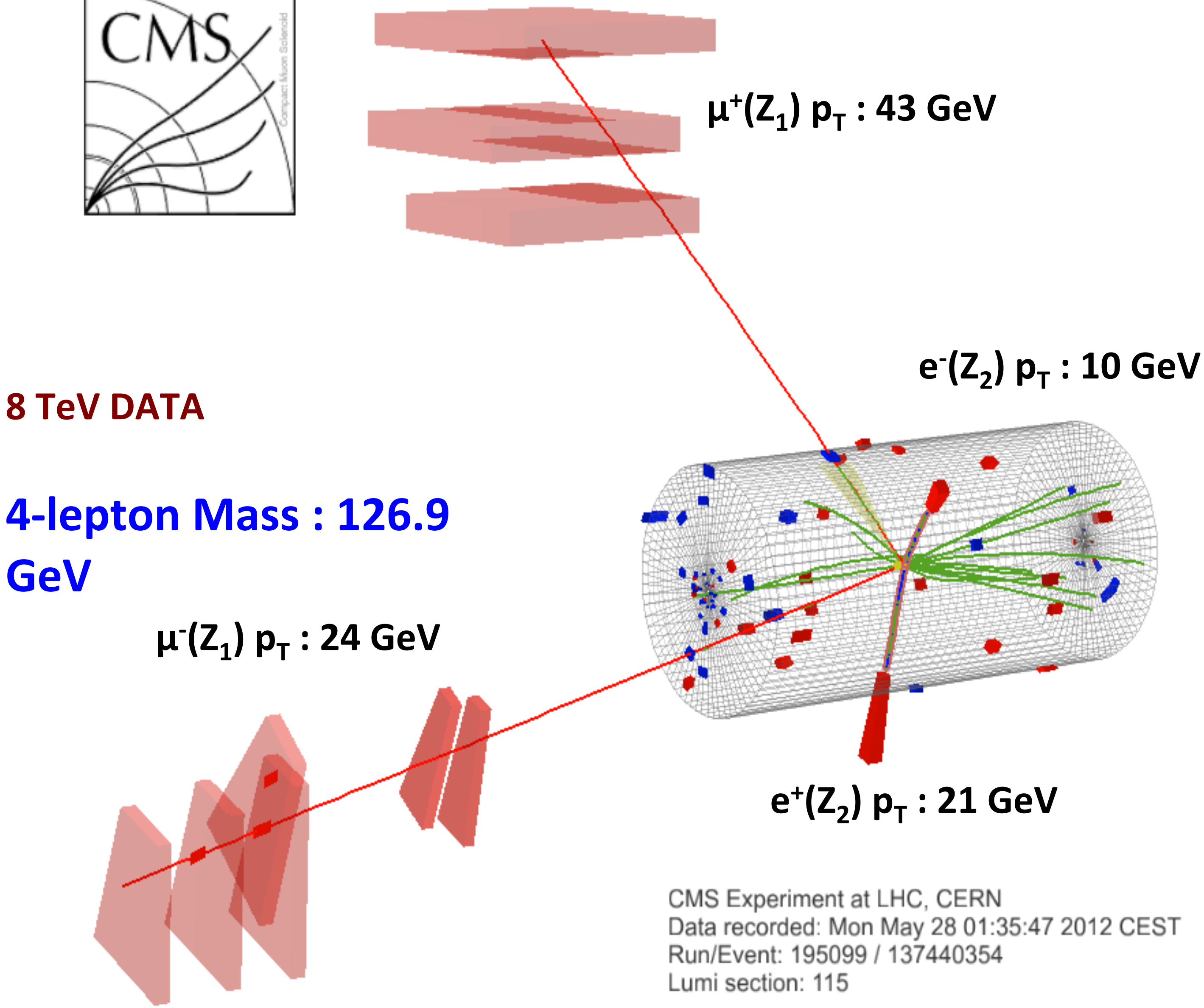


Candidates...



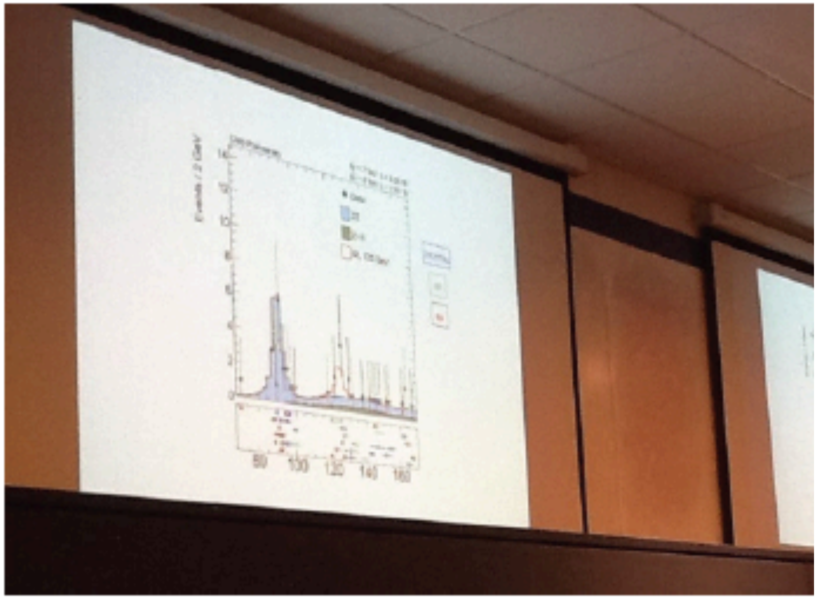
N. De Filippi

Candidates…

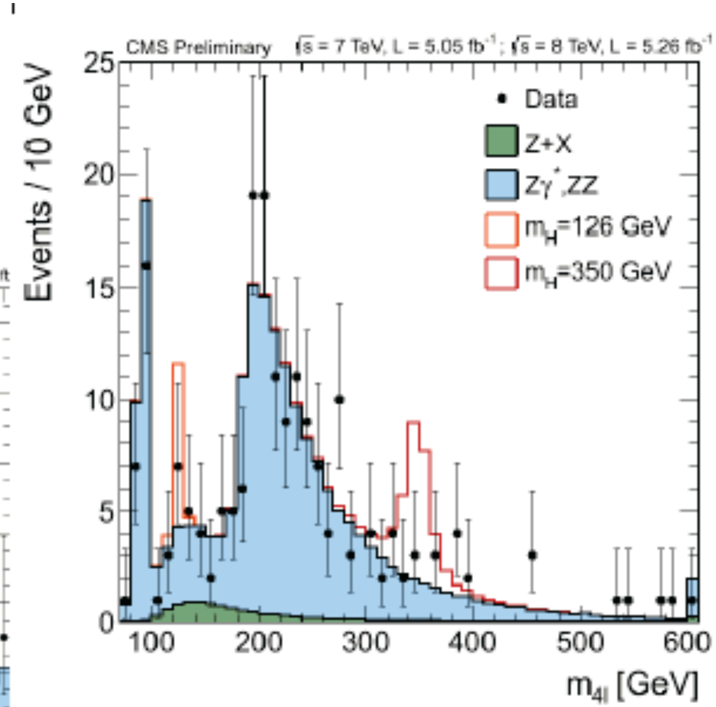


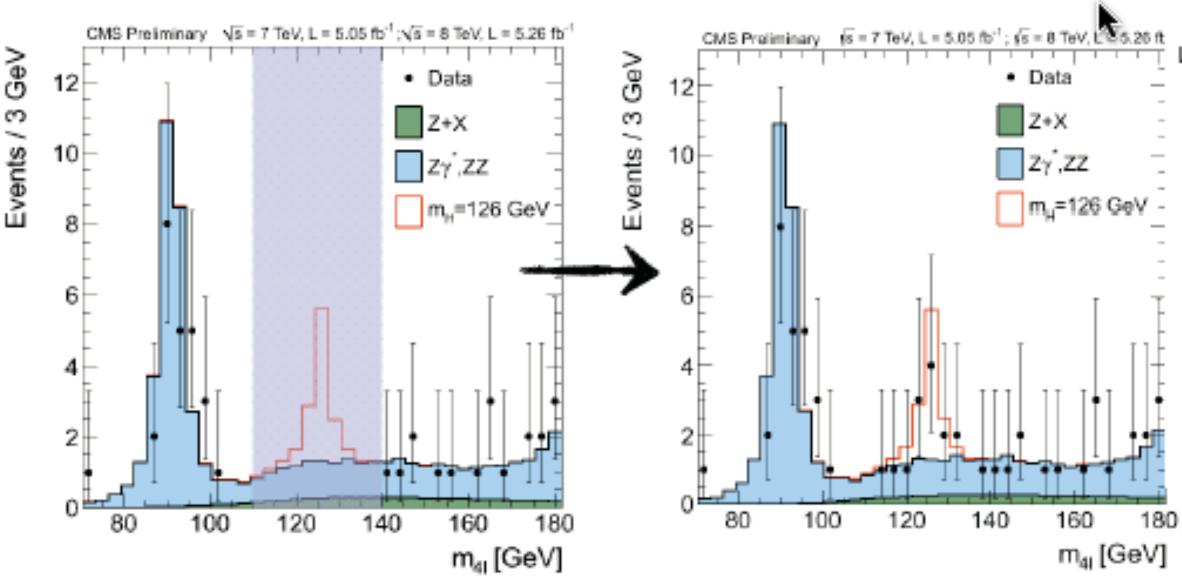
μ+(Z1) pT : 43 GeV
e-(Z2) pT : 10 GeV
8 TeV DATA
4-lepton Mass : 126.9 GeV
μ-(Z1) pT : 24 GeV
e+(Z2) pT : 21 GeV
CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:35:47 2012 CEST
Run/Event: 195099 / 137440354
Lumi section: 115

June 2012:

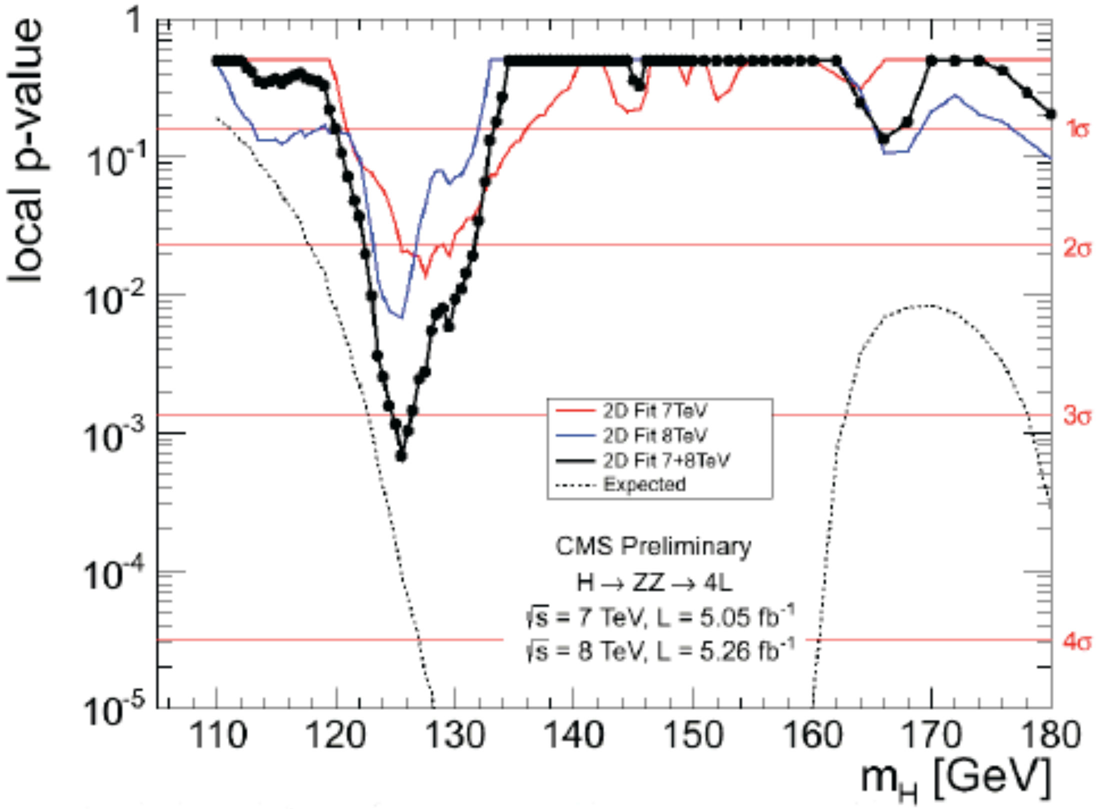


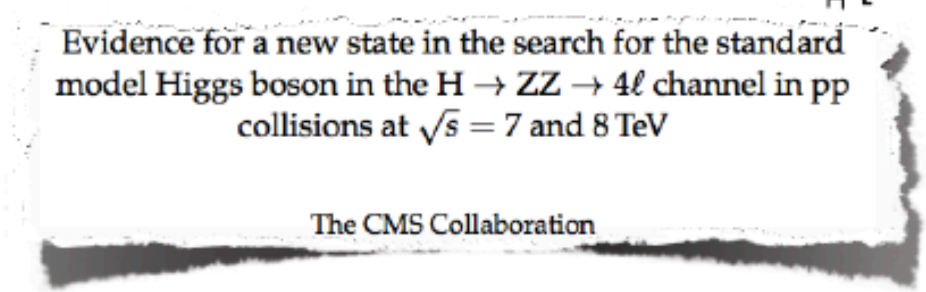
14.6.2012: Approval of **H→ZZ→4l analysis**





Evidence of a new state

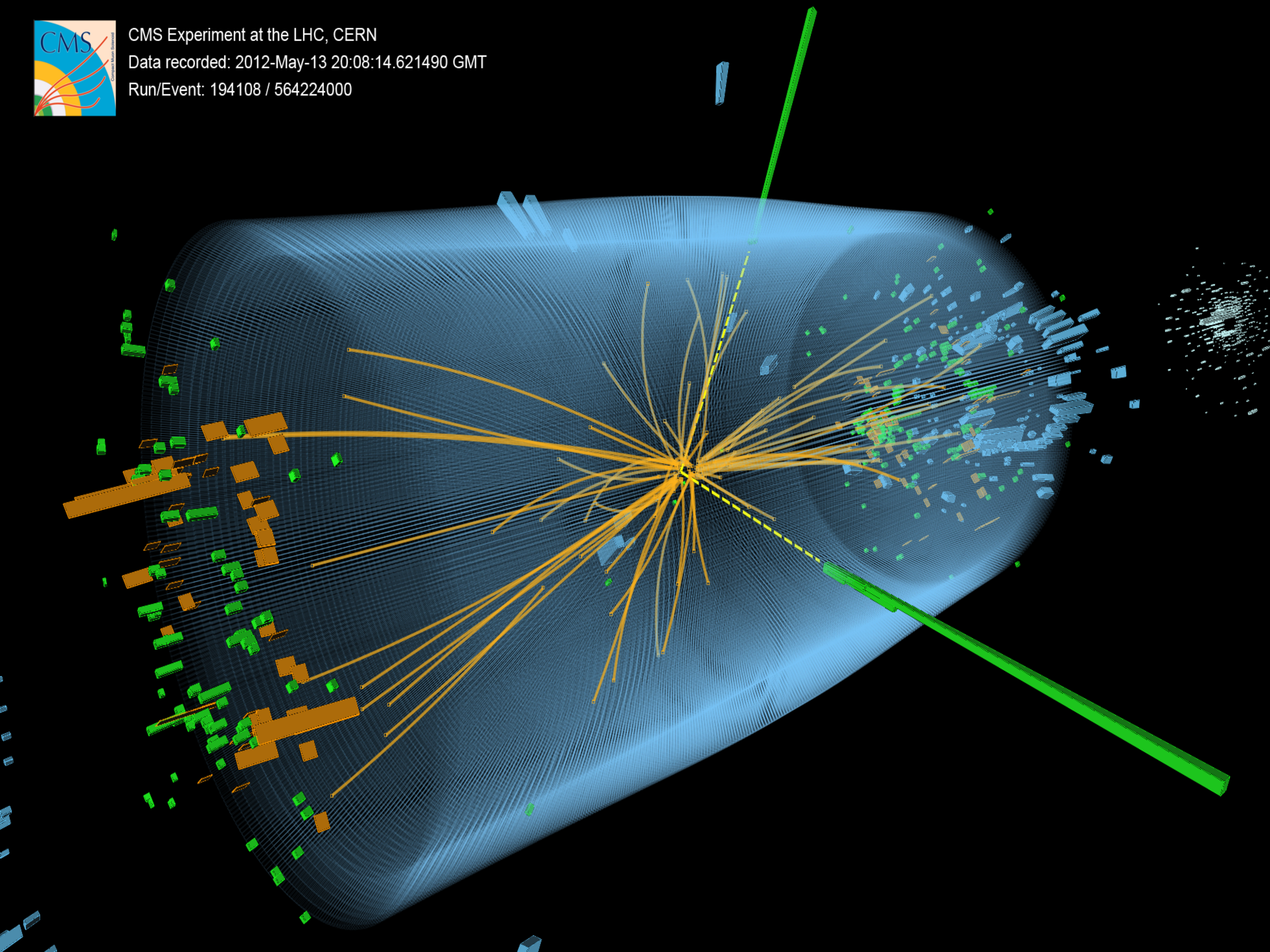




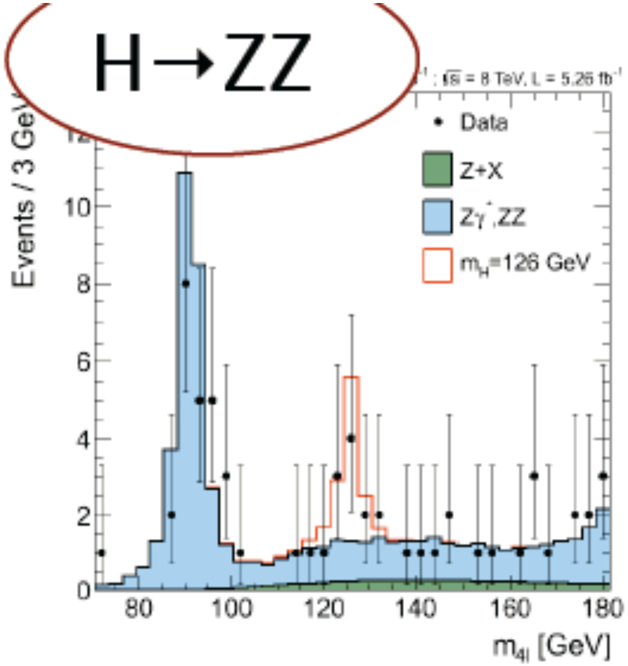
Evidence for a new state in the search for the standard model Higgs boson in the $H \to ZZ \to 4\ell$ channel in pp collisions at $\sqrt{s} = 7$ and 8 TeV

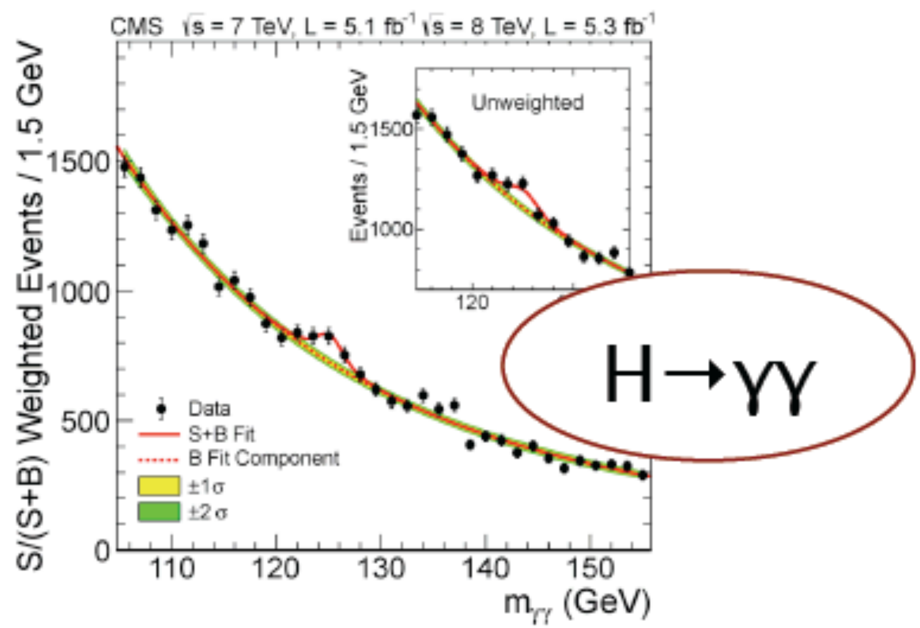
The CMS Collaboration

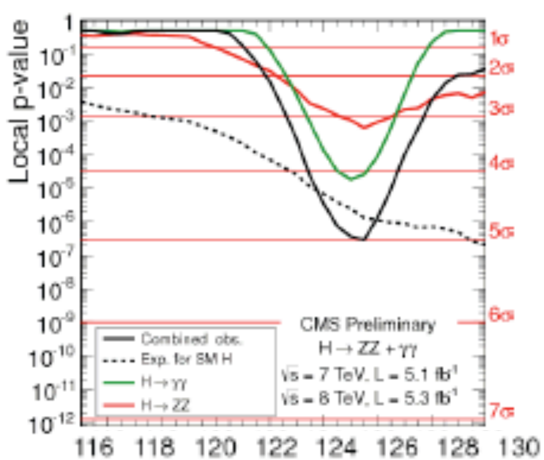
Excess at $m_{4l} \approx 126$ GeV with a p-value of **3.2σ**


CMS
CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000

July 4: seminar at CERN

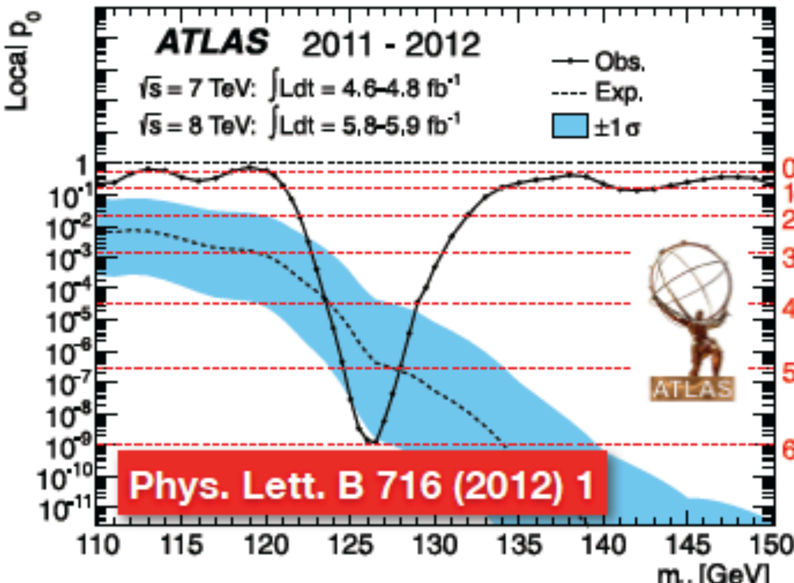


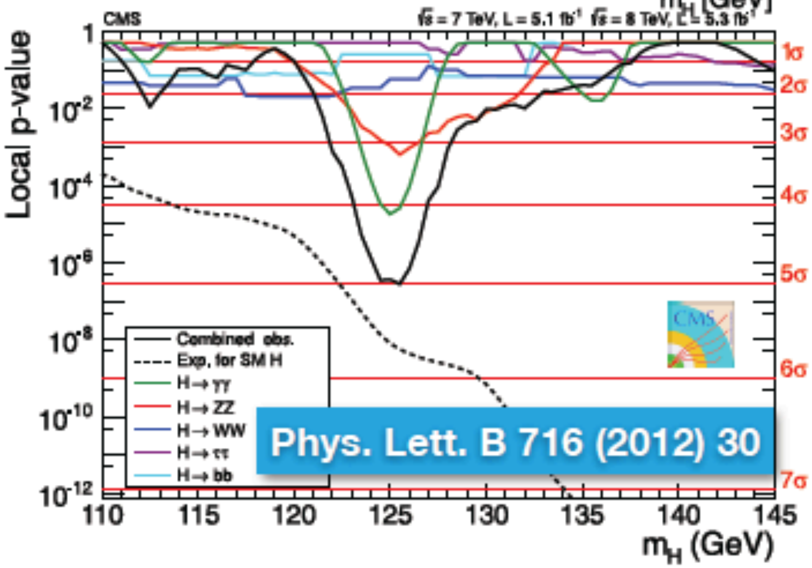


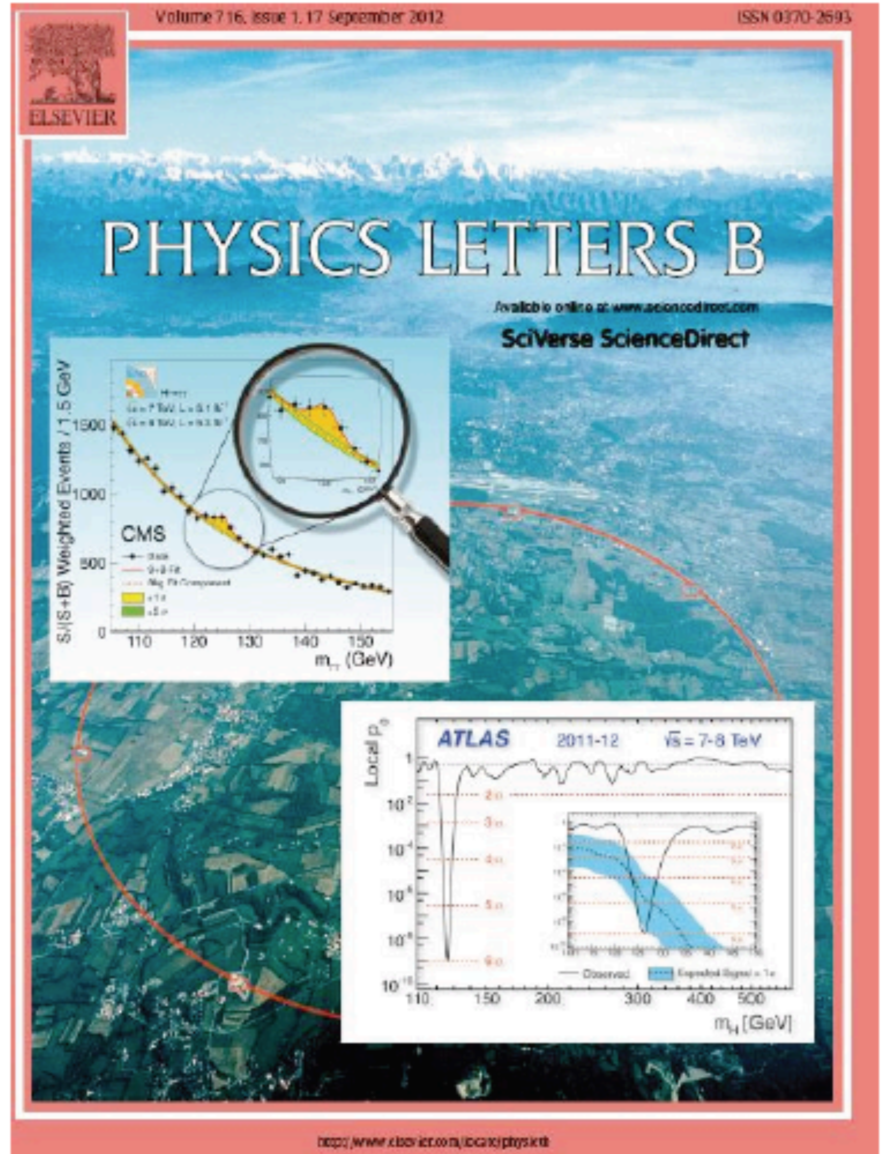


We have observed a new boson with a mass of **125.3 ± 0.6 GeV**

A new boson discovery: 4th of July 2012

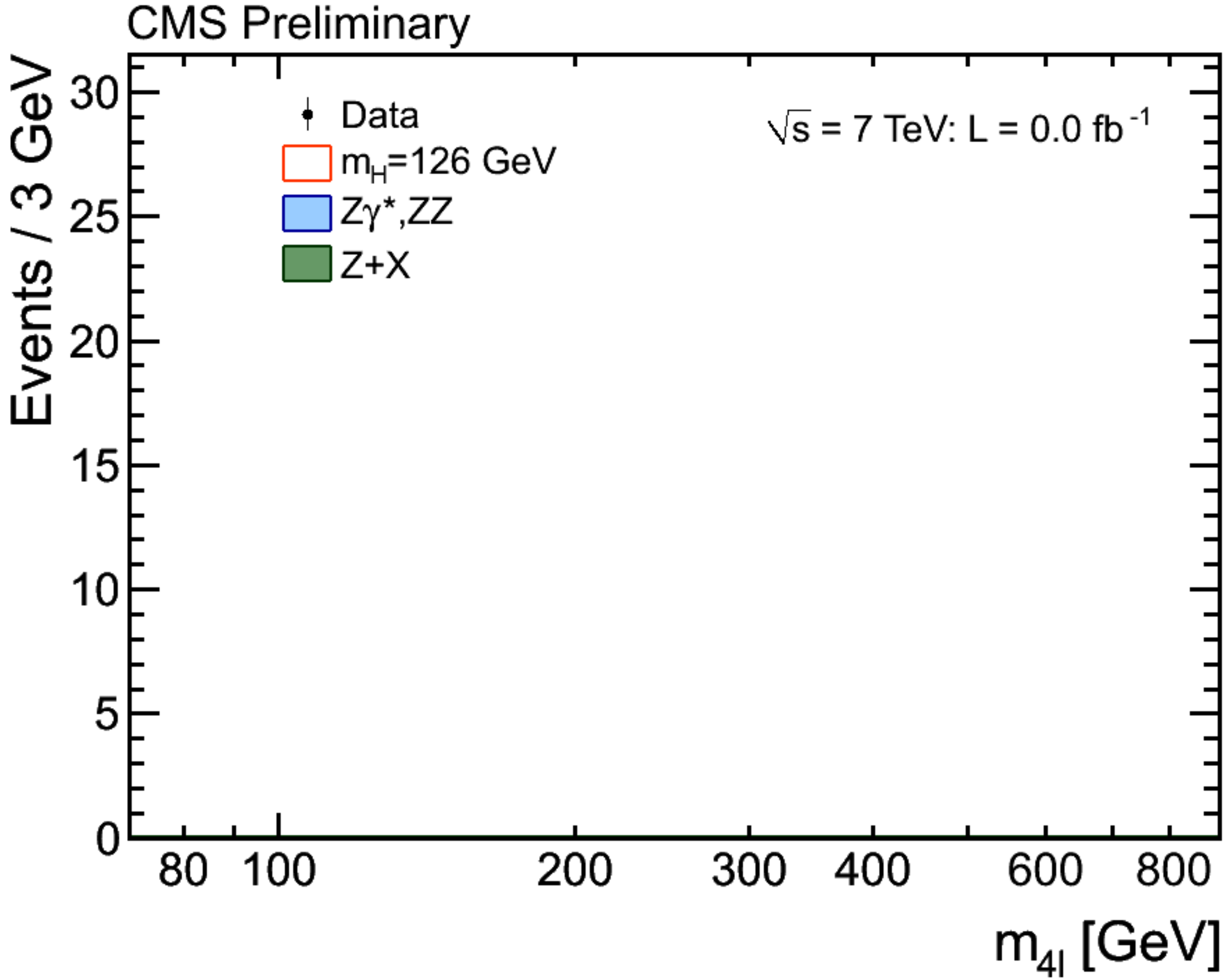




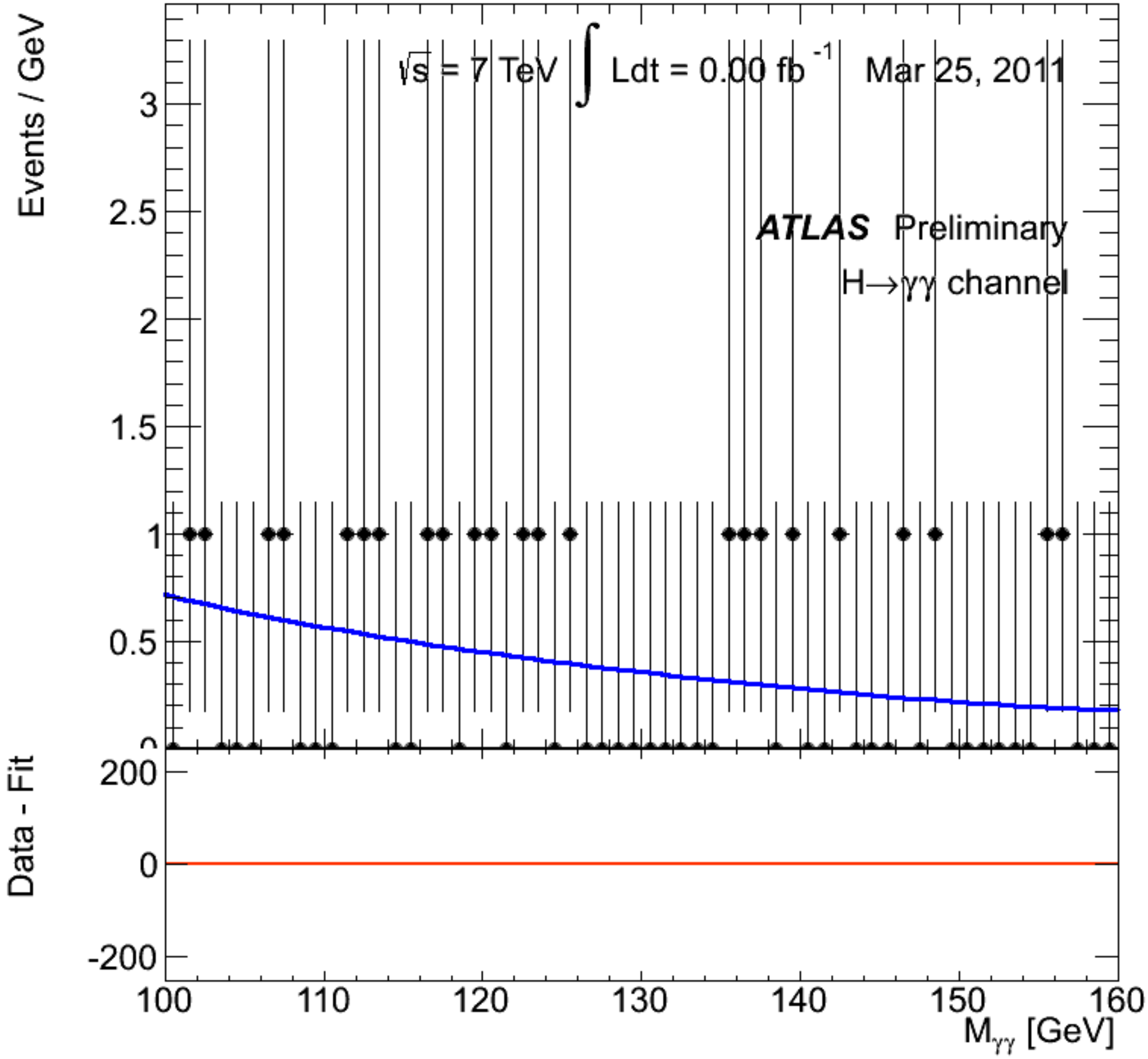


4th of July Fireworks

4-lepton invariant mass: H→ZZ→4l

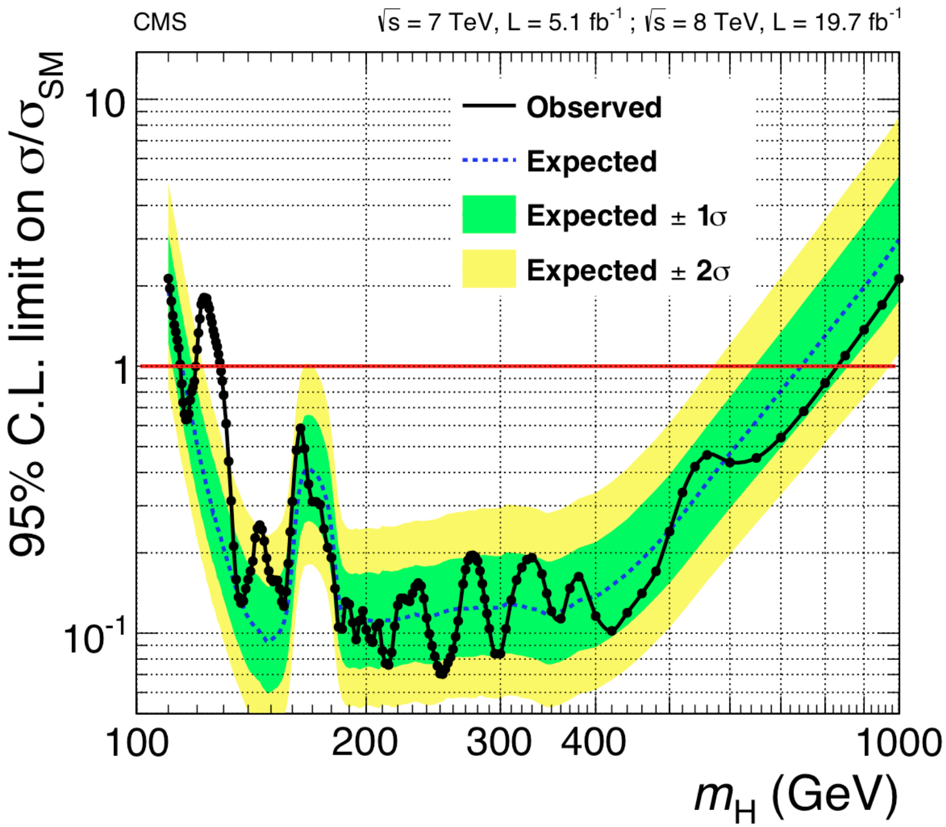


Di-photon invariant mass: H→γγ



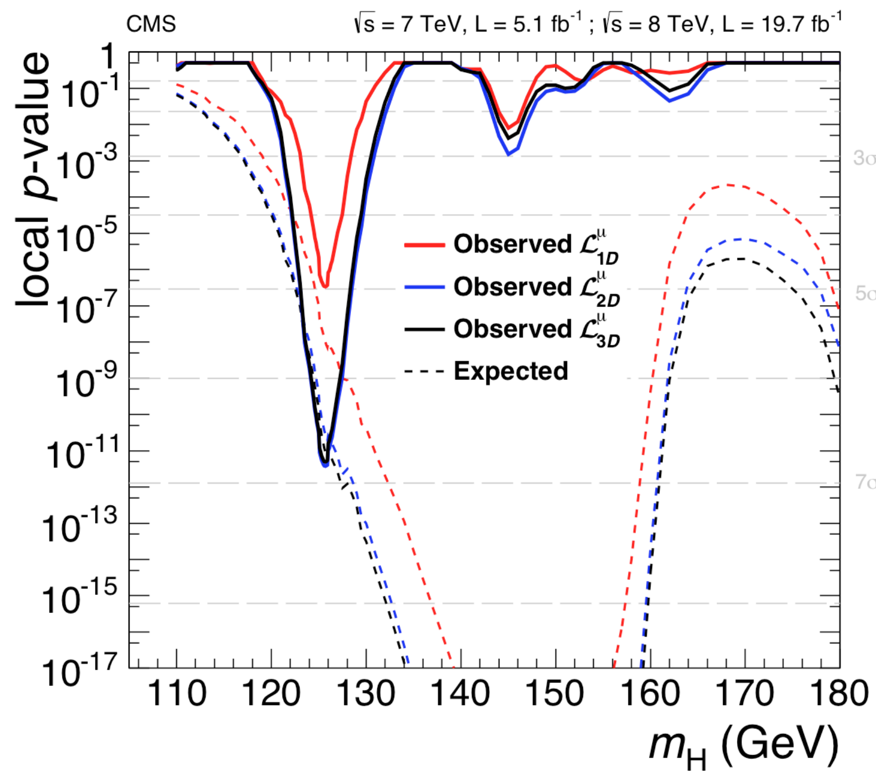
Statistical analysis

CL$_s$ method for exclusion limit



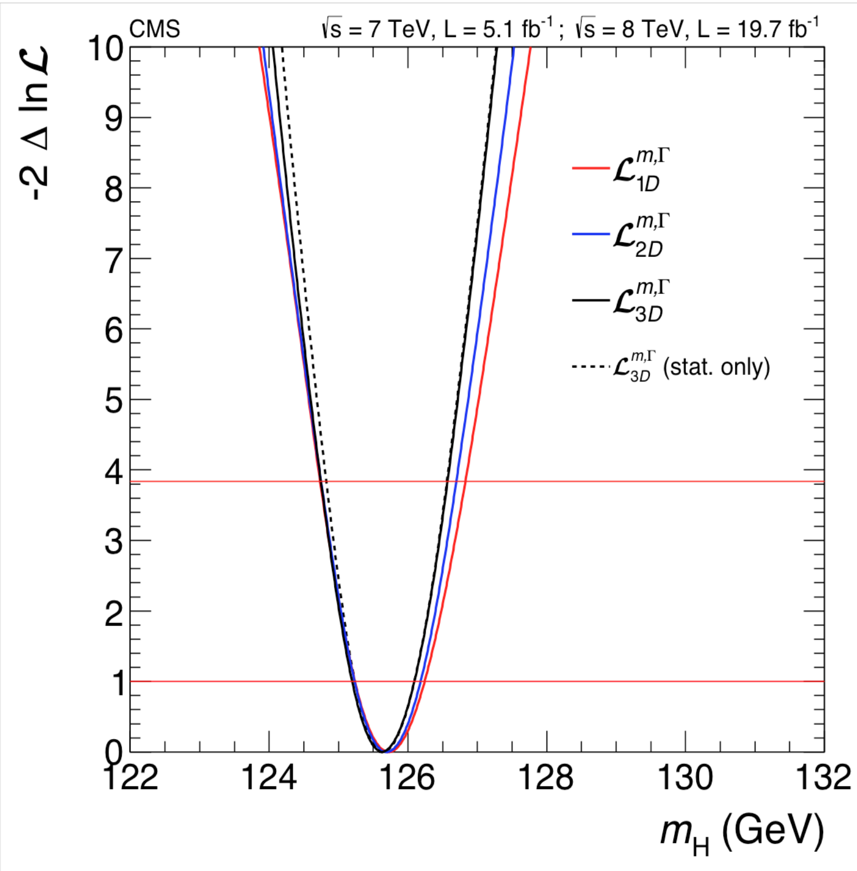
Observed limit: 95% CL exclusion in ranges 114.5-119 and 129–800 GeV

p-value: probability that the background can fluctuate to give an excess of events equal or larger than what observed

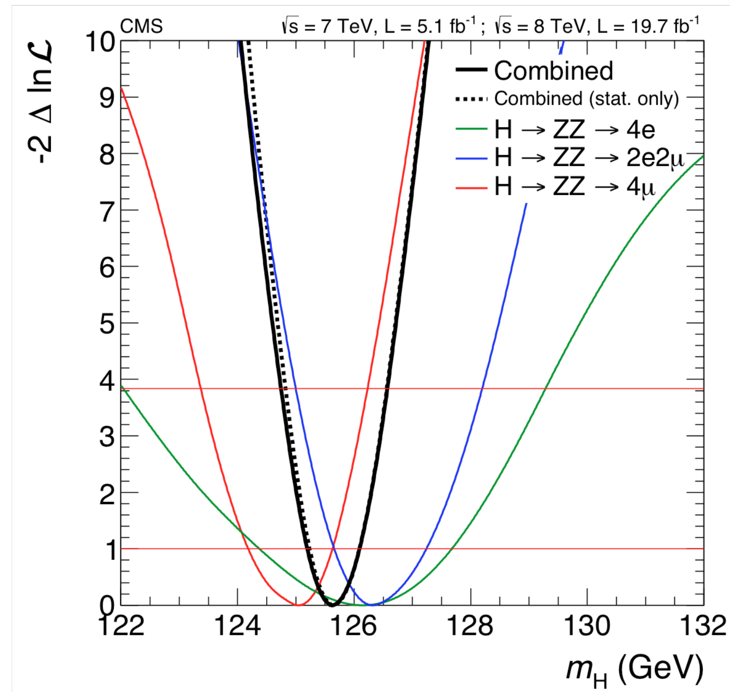


Minimum observed p-value ≈ 6.8σ (6.7σ expected)

Mass measurement



- Event by Event mass error (EBE) included
  - from muon track fit error matrix
  - from electron momentum error
- 3% of better significance
- 10% improvement on error on m_X



The combined best-fit mass is

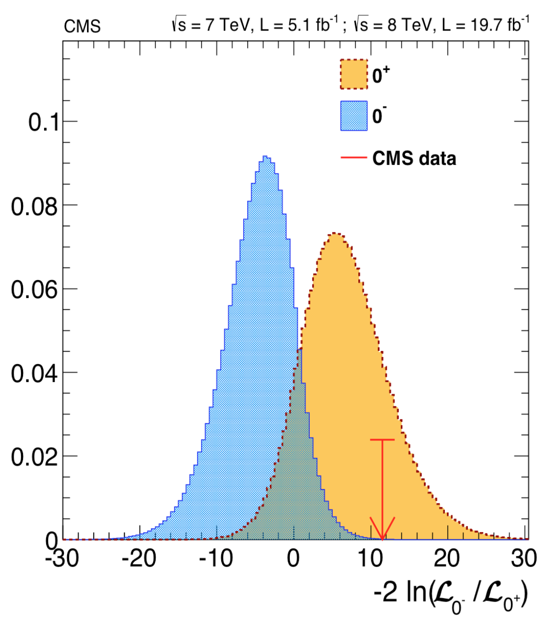
$$m_X = 125.6\ ^{+0.5}_{-0.4}\ \text{(stat)}\ ^{+0.1}_{-0.4}\ \text{(syst) GeV}$$

Statistical analysis: J^{CP}

- Strong exclusion of a spin-1 resonance (could not decay to $H\rightarrow\gamma\gamma$)
- pseudo-scalar excluded at >3σ level
- graviton-like resonances excluded at >~3σ level

J^P model	J^P production	expected (μ=1)	obs. 0^+	obs. J^P	CL_s
0^-	any	2.4σ (2.7σ)	-0.9σ	+3.6σ	0.09%
0_h^+	any	1.7σ (1.9σ)	-0.0σ	+1.8σ	7.1%
1^-	qqbar → X	2.6σ (2.7σ)	-1.4σ	+4.8σ	0.001%
1^-	any	2.6σ (2.6σ)	-1.7σ	+4.9σ	0.001%
1^+	qqbar → X	2.1σ (2.3σ)	-1.5σ	+4.1σ	0.03%
1^+	any	2.0σ (2.1σ)	-1.9σ	+4.5σ	0.01%
2_m^+	gg → X	1.7σ (1.8σ)	-0.8σ	+2.6σ	1.9%
2_m^+	qqbar → X	1.6σ (1.7σ)	-1.6σ	+3.6σ	0.03%
2_m^+	any	1.5σ (1.5σ)	-1.3σ	+3.0σ	1.4%
2_b^+	gg → X	1.6σ (1.8σ)	-1.2σ	+3.1σ	0.9%
2_h^+	gg → X	3.7σ (4.0σ)	+1.8σ	+1.9σ	3.1%
2_h^-	gg → X	4.0σ (4.5σ)	+1.0σ	+3.0σ	1.7%

0^+ vs 0^-



October 8, 2013: Nobel Prize

Nobel Prizes and Laureates

Physics Prizes ‹ 2013 ›

▼ About the Nobel Prize in Physics 2013

- Summary
- Prize Announcement
- Press Release
- Advanced Information
- Popular Information
- Greetings

▶ François Englert

▶ Peter Higgs

All Nobel Prizes in Physics

All Nobel Prizes in 2013

The Nobel Prize in Physics 2013

François Englert, Peter Higgs

The Nobel Prize in Physics 2013

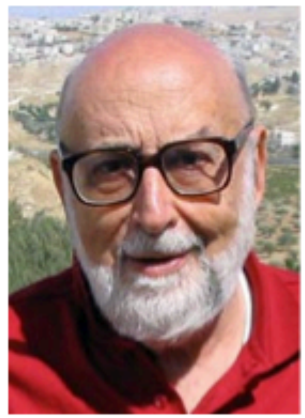


Photo: Pnicolet via Wikimedia Commons

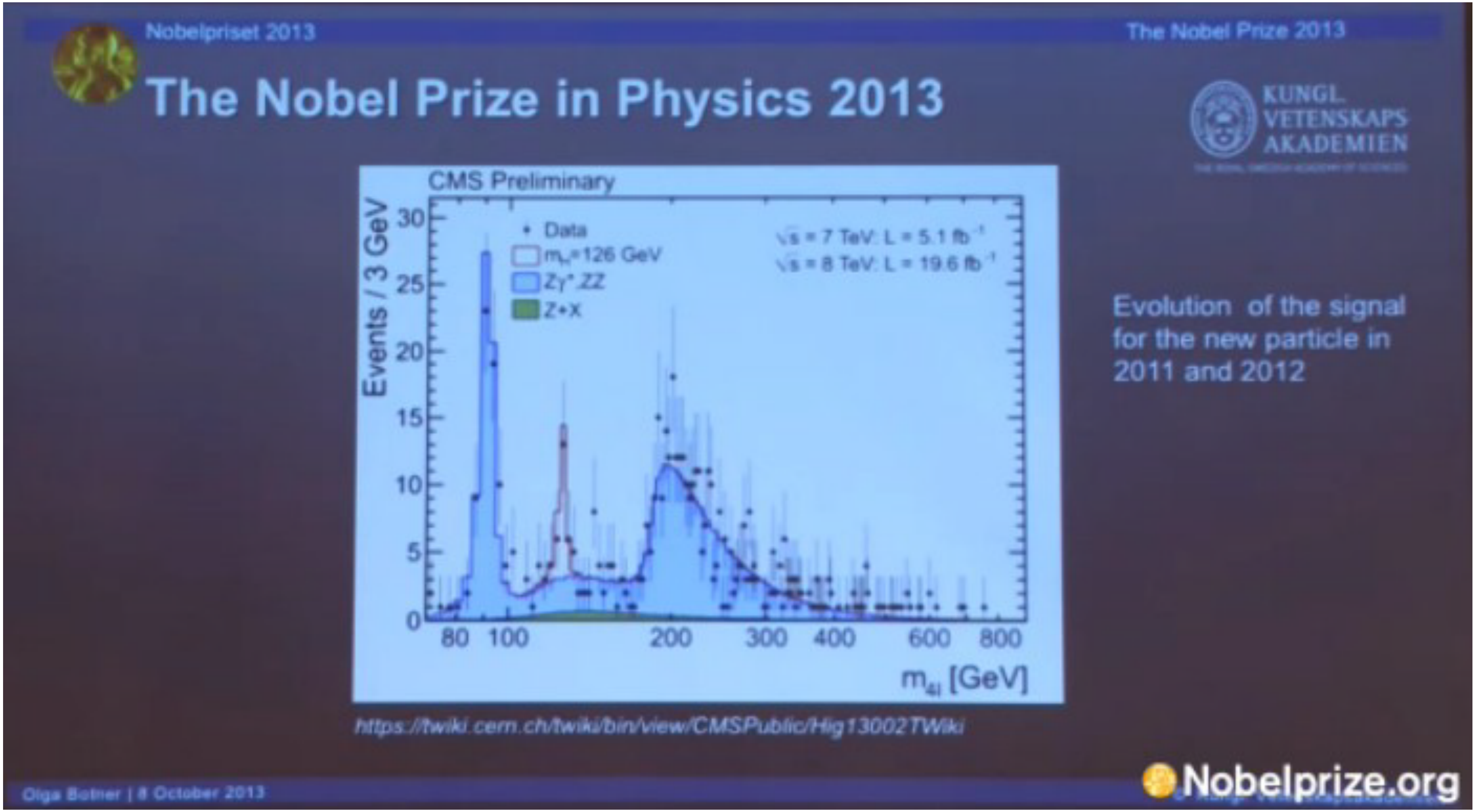
François Englert

Photo: G-M Greuel via Wikimedia Commons

Peter W. Higgs

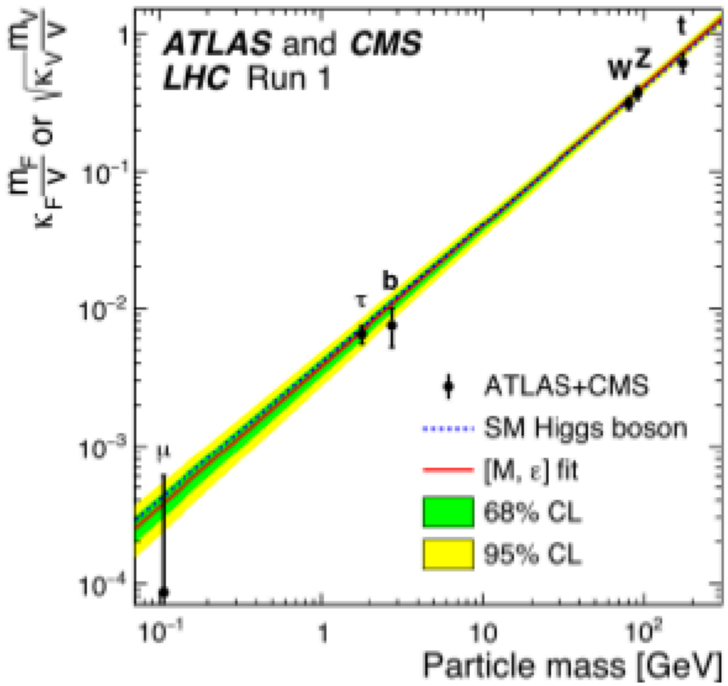
The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

October 8, 2013: Nobel Prize



Higgs properties @ LHC Run 1

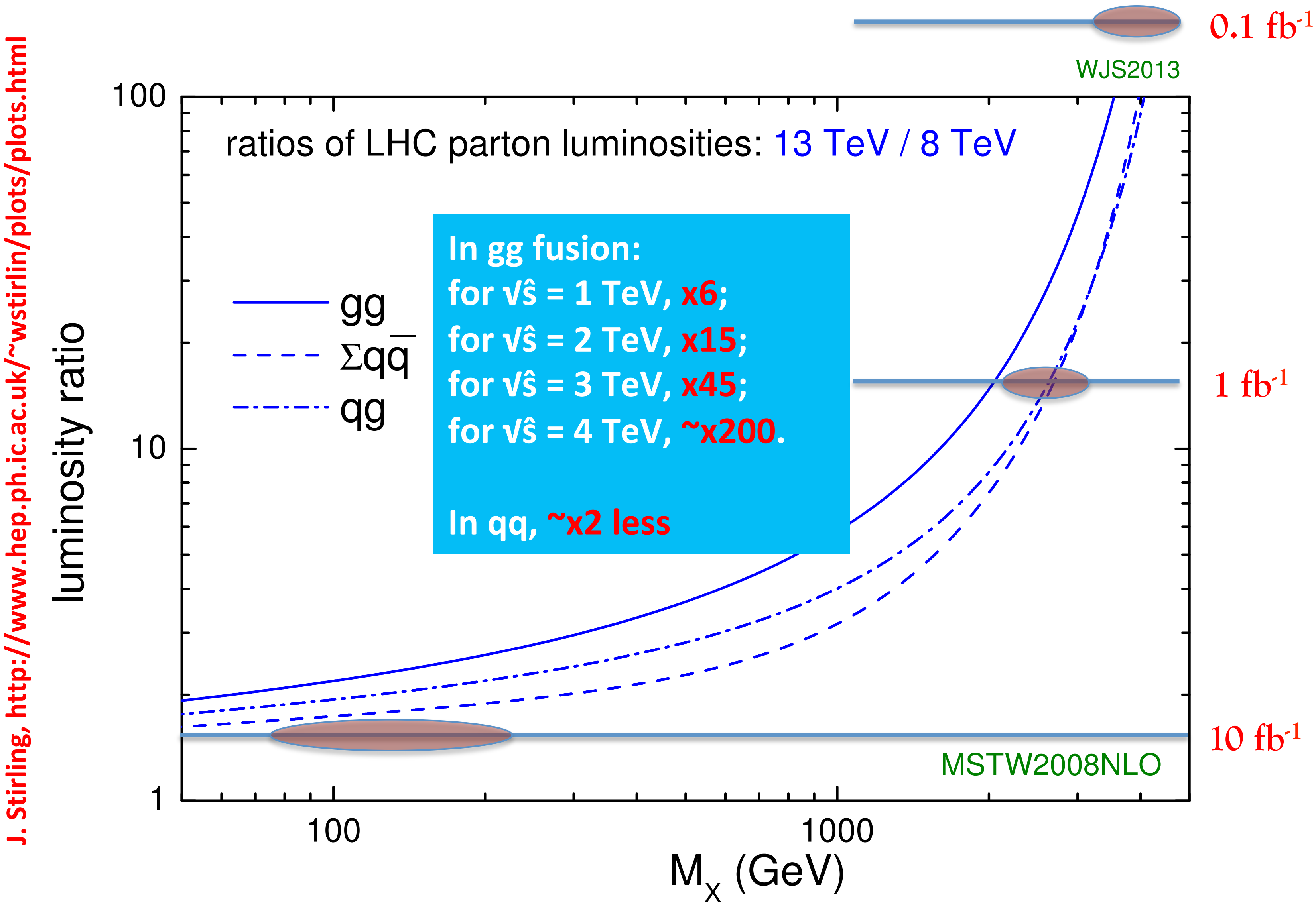
- **Mass:** $125.09 \pm 0.21\,(\mathrm{stat.}) \pm 0.11\,(\mathrm{syst.})\ \mathrm{GeV}$ ATLAS+CMS: PRL 114 (2015) 191803
- **Spin/Parity:** 0^+ ATLAS: EPJC 75 (2015) 476 CMS: PRD 92 (2015) 012004
- **Width:** < 1 GeV (direct)
  CMS: JHEP 11 (2017) 047
  < 0.015 GeV (indirect)
  ATLAS: arXiv:1808.01191 submitted to PLB
- **Observed direct coupling to:**
  - **Vector bosons** ATLAS: PLB 716 (2012) 1-29 CMS: PLB 716 (2012) 30
  - **τ leptons** ATLAS: ATLAS-CONF-2018-021 CMS: PLB 779 (2018) 283
  - **top quarks** ATLAS: PLB 784 (2018) 173 CMS: PRL 120 (2018) 231801



All measurements compatible with SM predictions

LHC Run 2 at 13 TeV

8 TeV → 13 TeV: parton luminosities

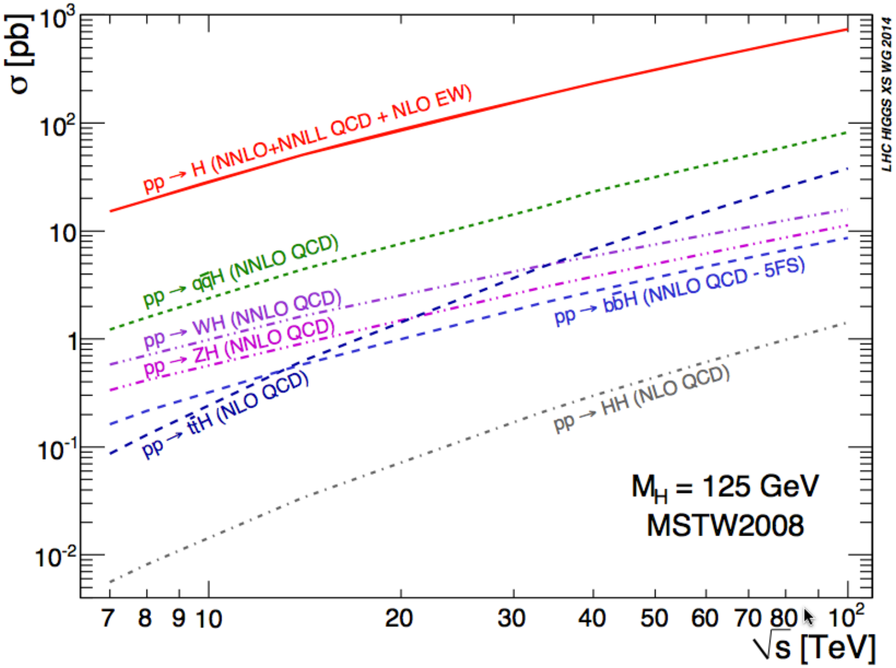


In gg fusion:
for √ŝ = 1 TeV, x6;
for √ŝ = 2 TeV, x15;
for √ŝ = 3 TeV, x45;
for √ŝ = 4 TeV, ~x200.

In qq, ~x2 less

SM Higgs production at the LHC: 8 vs 13 TeV

LHC Higgs Xsection WG



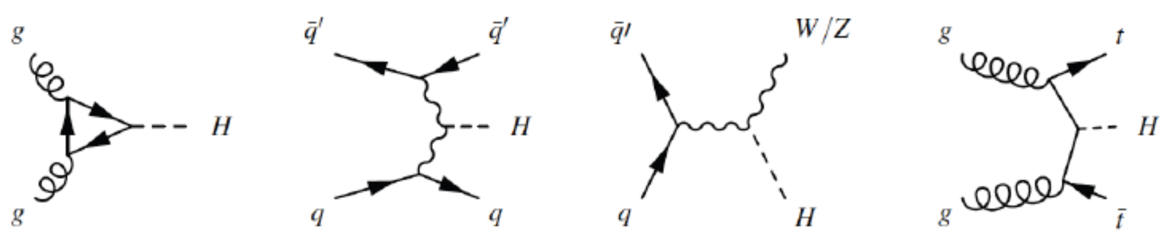
8 TeV

Cross section [pb] at m_H = 125.5 GeV				
ggF	VBF	WH	ZH	ttH
19.1	1.6	0.7	0.4	0.1

13 TeV

Xection [pb]				
ggF	**VBF**	**WH**	**ZH**	**ttH**
43.62	**3.727**	**1.362**	**0.8594**	**0.5027**

	σ(14TeV)/σ(8TeV)
gg→H	2.6 (M_X=M_H)
qq→qqH	2.6 (probes high M_X)
qq→VH	2.1 (M_X=M_V+M_H)
gg→ttH	4.7 (phase space+M_X)



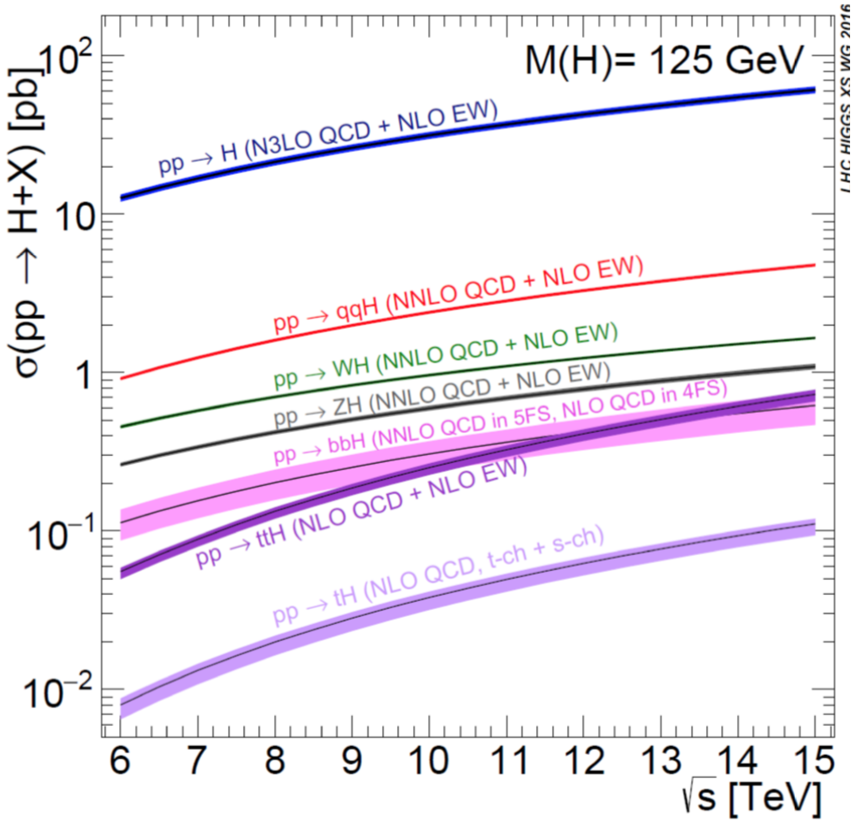
(a) $gg \to H$ (b) VBF (c) VH (d) $t\bar{t}H$

Uncertainty on σ from theory:

@ NNLO/NNLL QCD + NLO EWK
ggF: 8% scale and 7% PDF
VBF: 0.6% scale and 1.7% PDF

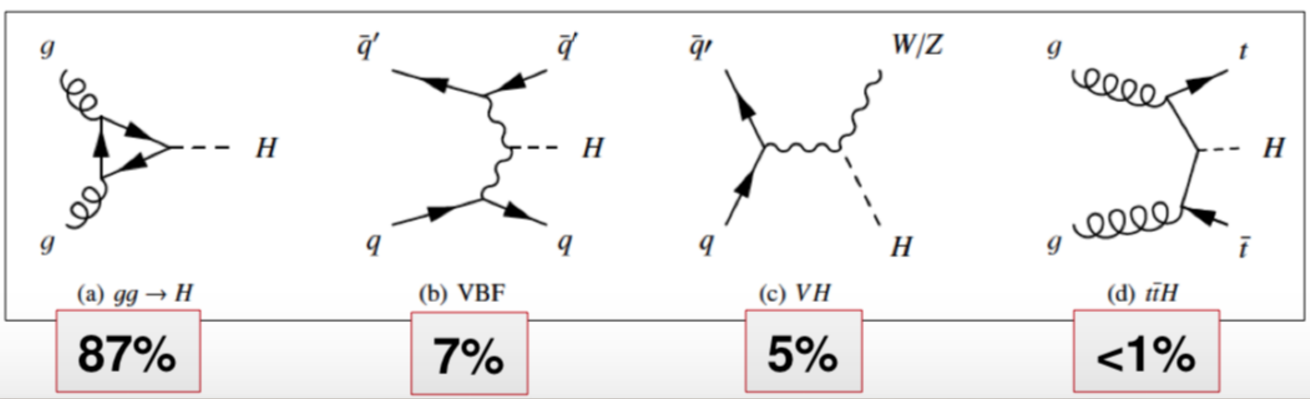
Uncertainty on BRs: 3-5%

SM Higgs production at the LHC



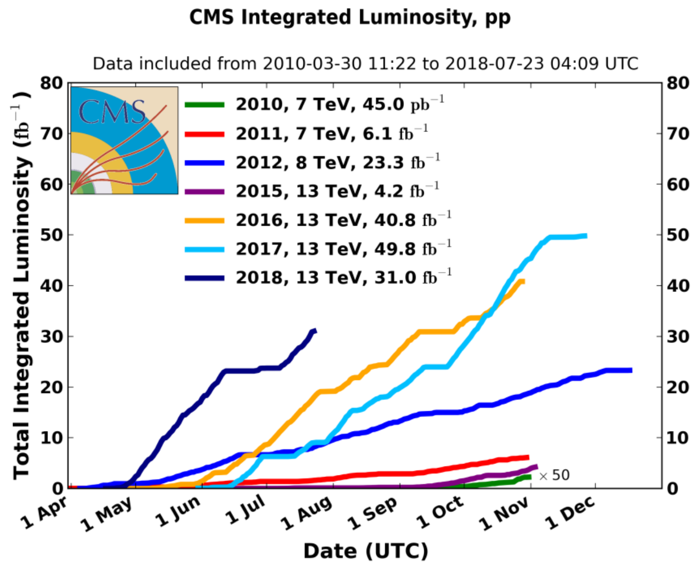
- ggF: dominant, larger initial state radiation from gluons
- VBF: two forward jets with high mass and large rapidity gap
- VH: vector boson (lv, ll', qq')
- ttH: many b-jets, leptons, E_T^{miss}

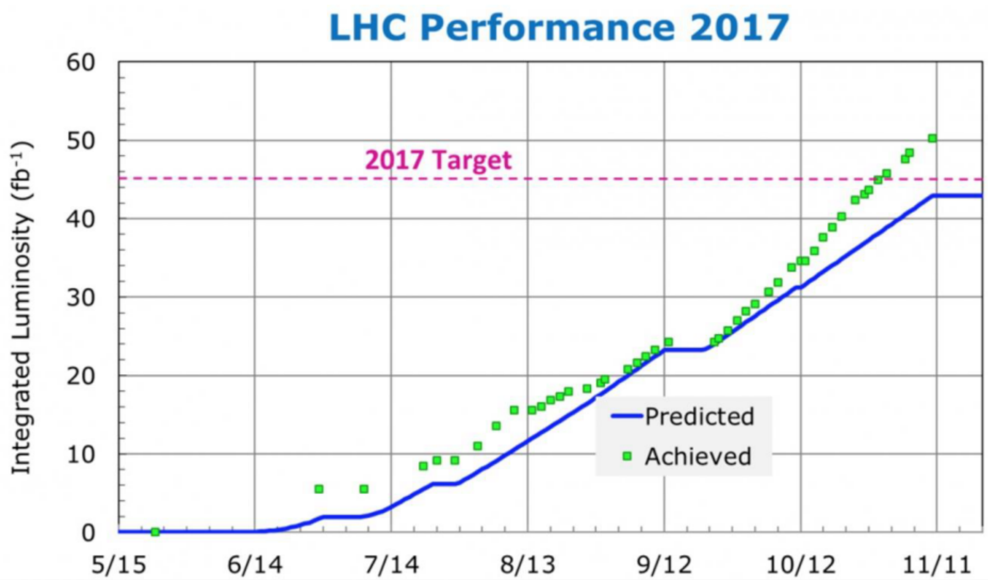
Total cross-section = 56 pb at 13 TeV

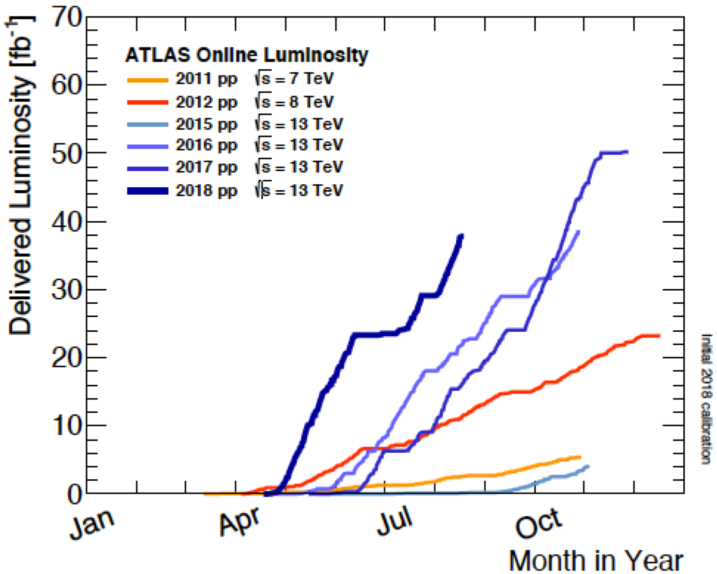


LHC Run 2

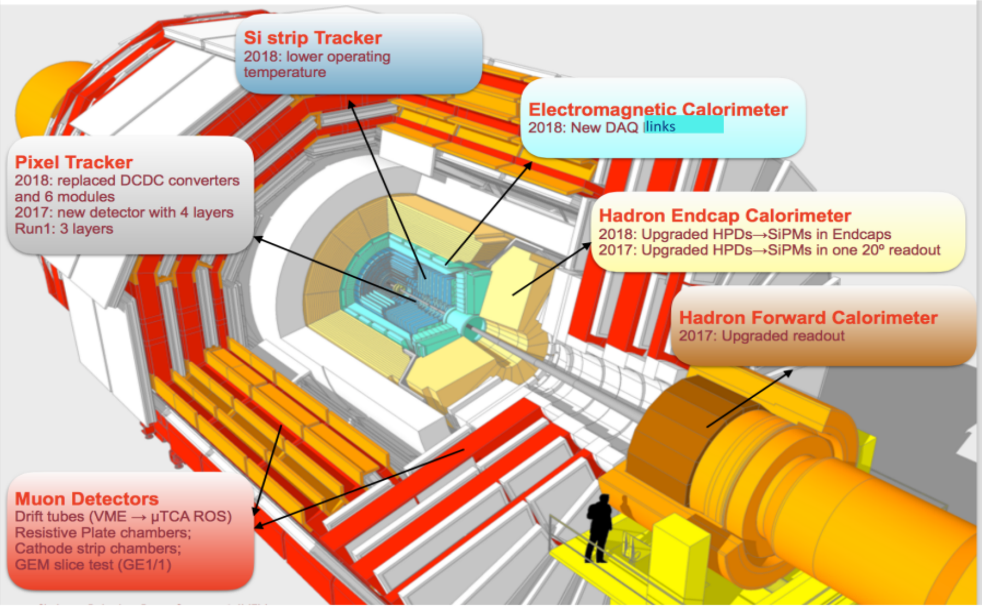
- LHC has produced **> 3 years of 13 TeV** data with fantastic performance
  - expected to result in **>150 fb^{-1}** by the end of the 2018 run
  - Maximum peak luminosity ~$2x10^{34}$ $cm^{-2}s^{-1}$ with mean pileup ~33 in 2017, ~38 in 2018
  - DESIGN peak luminosity exceeded by a factor of 2!

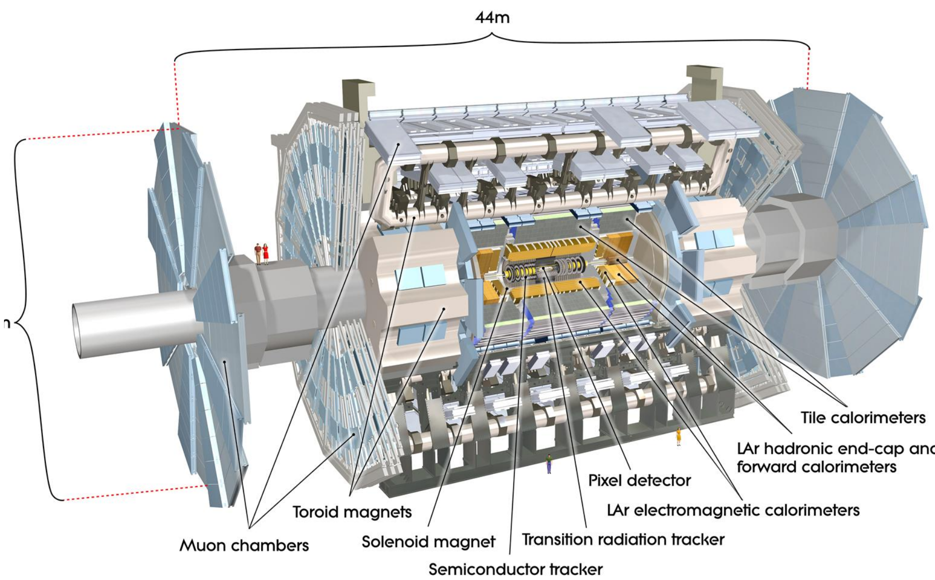


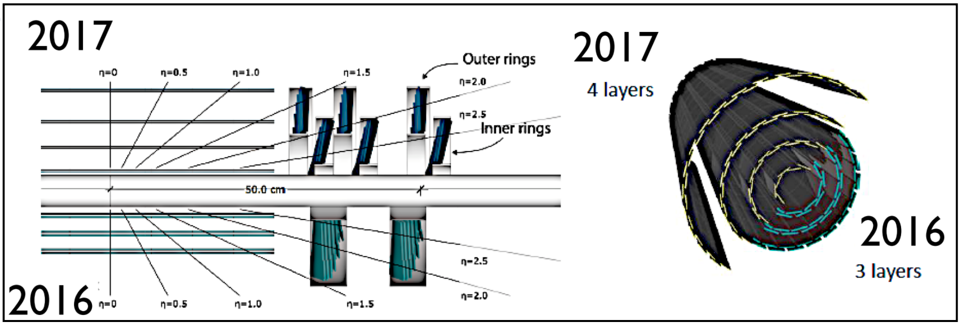




CMS/ATLAS in 2017/2018 (after LS1)

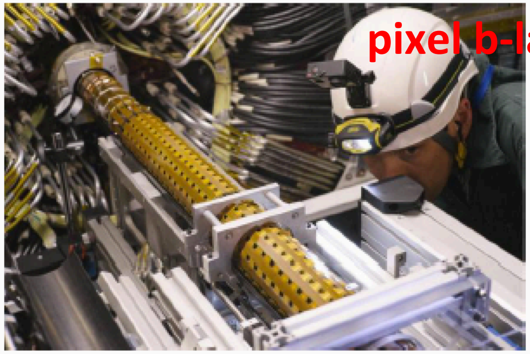






- New IBL detector installed in LS1 (2013-2014)
- Tracking optimized for high-PU and high-p_T environments
- Better ML algorithms

4th insertable pixel b-layer (IBL)



Large impact on b-tagging performance

Highlights for Higgs physics @ Run 2

- It is matter of few weeks (Aug. 28) the announcement of the **observation of $H \rightarrow bb$**

Precise measurements with:

- **$H \rightarrow \gamma\gamma$**
- **$H \rightarrow ZZ$**

Evidence/observation of:

- **$H \rightarrow \tau\tau$**
- **ttH**
- **…**

H→bb

Motivation:

- H→ bb has the largest BR (58%) for m_H=125 GeV
- Unique final state to measure coupling with down-type quarks
- Drives the uncertainty of the total Higgs boson width
- Primary decay mode for searches at LEP and Tevatron
  → a long history or searches

First H→bb searches started at LEP…

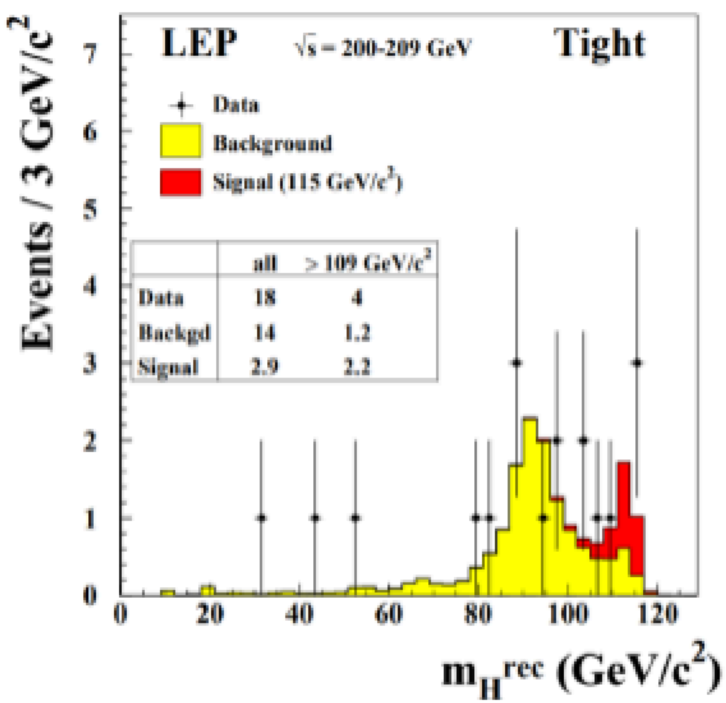
Physics Letters B 565 (2003) 61–75

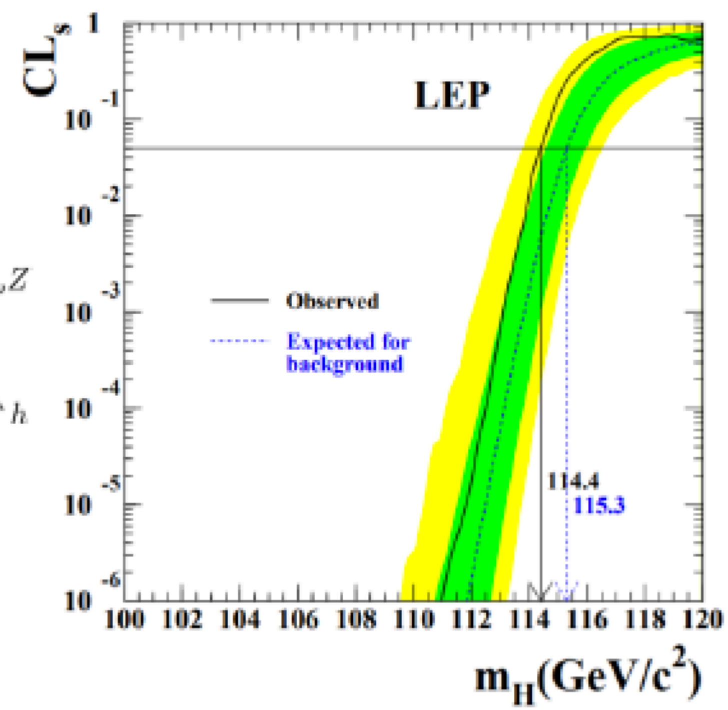
Search for the Standard Model Higgs boson at LEP

ALEPH Collaboration[1] DELPHI Collaboration[2] L3 Collaboration[3] OPAL Collaboration[4]
The LEP Working Group for Higgs Boson Searches[5]

ELSEVIER
PHYSICS LETTERS B

m_H > 114.4 GeV @ 95%CL



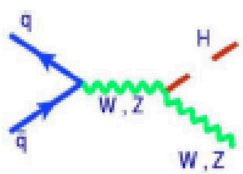


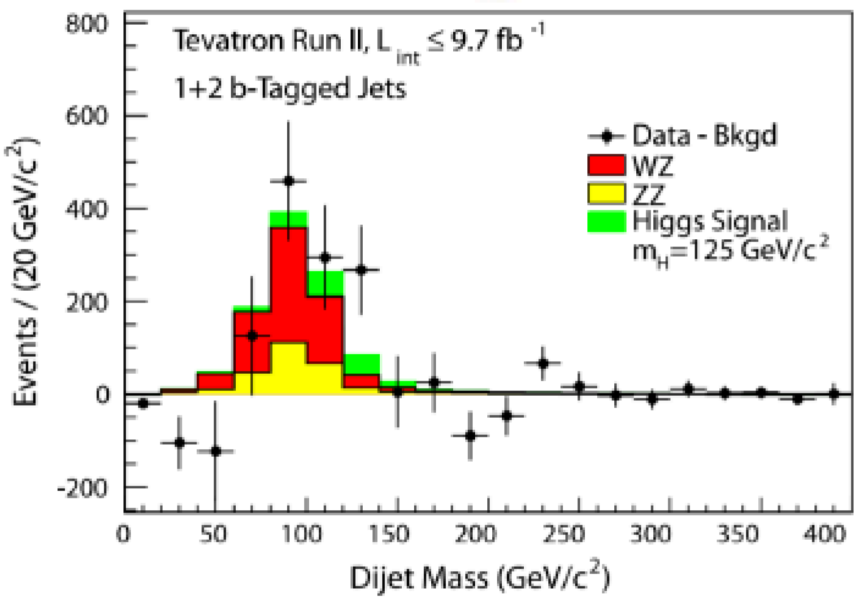
… and continued at Tevatron

PRL 109, 071804 (2012) PHYSICAL REVIEW LETTERS week ending 17 AUGUST 2012

Evidence for a Particle Produced in Association with Weak Bosons and Decaying to a Bottom-Antibottom Quark Pair in Higgs Boson Searches at the Tevatron

(*CDF Collaboration)
(†D0 Collaboration)





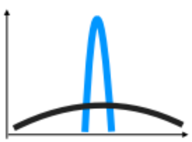
<u>Significance</u>

2.8σ observed @ 125 GeV

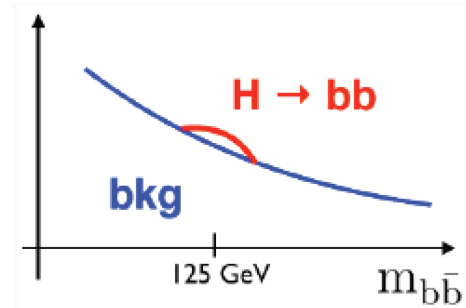
H→bb search challenge:

- **Needs:**
  - Good **b-jets identification** performance:
    70% efficiency with < 1% q/g mis-identification probability
  - Best possible **resolution on m(bb)**
  - Capability to exploit all possible information from the event to **improve S/B**

- **H(bb) compared with discovery channel**



	$H \to 4\ell$	$H \to b\bar{b}$
Branching Ratio	0.03%	58%
mass resolution	1%	10%
S/B	2	0.05



- **Higgs-strahlung - VH (4%) is the most sensitive channel**
  – leptons, E_T^{miss} to trigger and high p_T V to suppress backgrounds

@CMS so far
Evidence established last year
Phys. Lett. B 780 (2018) 501

Data used	Significance expected	Significance observed	Signal strength observed
Run 1	2.5	2.1	$0.89^{+0.44}_{-0.42}$
Run 2	2.8	3.3	$1.19^{+0.40}_{-0.38}$
Combined	3.8	3.8	$1.06^{+0.31}_{-0.29}$

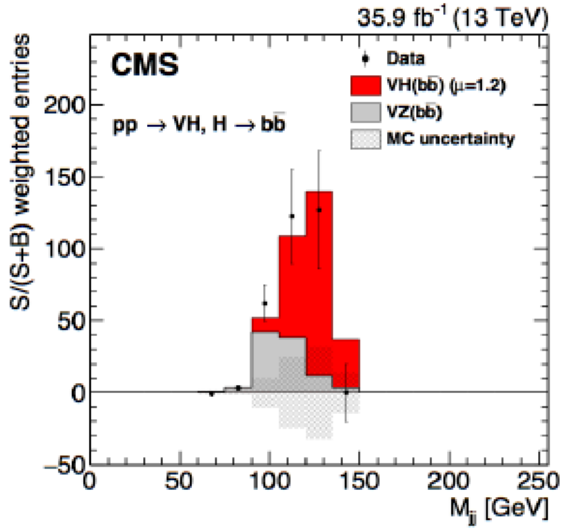
N. De Filippis

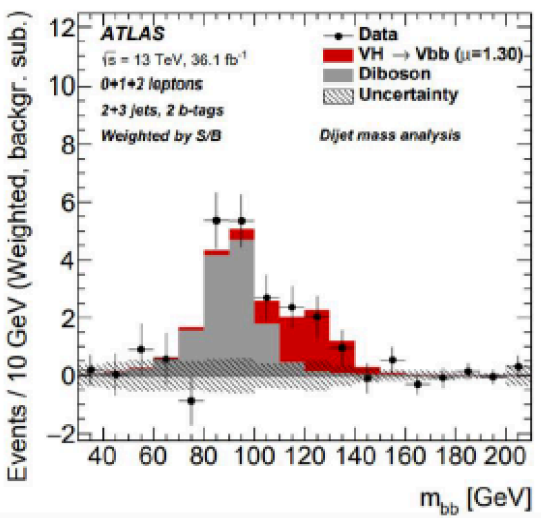
VH, H→bb results at LHC

- **VH(bb) evidence at LHC established with 2016 data by both ATLAS and CMS**
  - Detectors clearly demonstrated ability to deal with very high pile-up for such complex analysis
- **Signal strength uncertainty ~40%**

	signal strength	significance (exp)	significance (obs)
ATLAS Run 1 [1]	$0.52^{+0.40}_{-0.37}$	2.6σ	1.4σ
CMS Run 1 [2]	$0.89^{+0.47}_{-0.44}$	2.5σ	2.1σ
ATLAS+CMS Run 1 [3]	$0.79^{+0.29}_{-0.27}$	3.7σ	2.6σ
ATLAS 2015+2016 [4]	$1.20^{+0.42}_{-0.36}$	3.0σ	**3.5σ**
CMS 2016 [5]	$1.19^{+0.40}_{-0.38}$	2.8σ	**3.3σ**

[1] JHEP 01 (2015) 069
[2] JHEP 08 (2016) 045
[3] JHEP 08 (2016) 045
[4] JHEP 12 (2017) 024
[5] PLB 780 (2018) 501

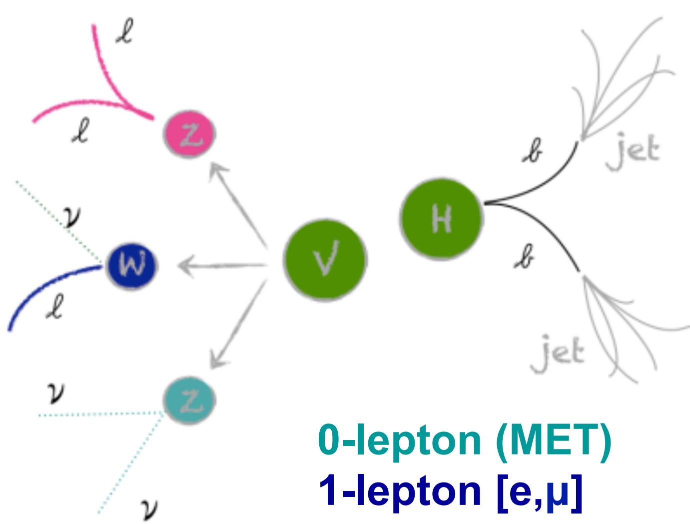




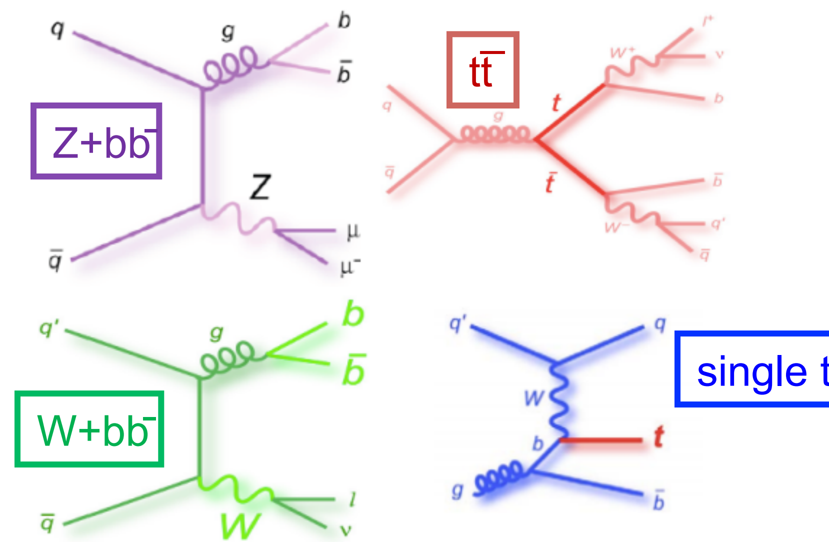
VH(H→bb): analysis strategy

- **Analysis strategy:**
  - **3 channels** with 0, 1, and 2 leptons and 2 b-tagged jets
    - To target Z(vv)H(bb), W(lv)H(bb) and Z(ll)H(bb) processes
  - **Signal region designed to increase S/B**
    - **Large boost** for vector boson
    - **Multivariate analysis** exploiting the most discriminating variables ($m_{b\bar{b}}$, $\Delta R_{b\bar{b}}$, b-tagging)
  - **Control regions**: to validate background samples and control/constrain background normalization and systematics

signal



irreducible backgrounds

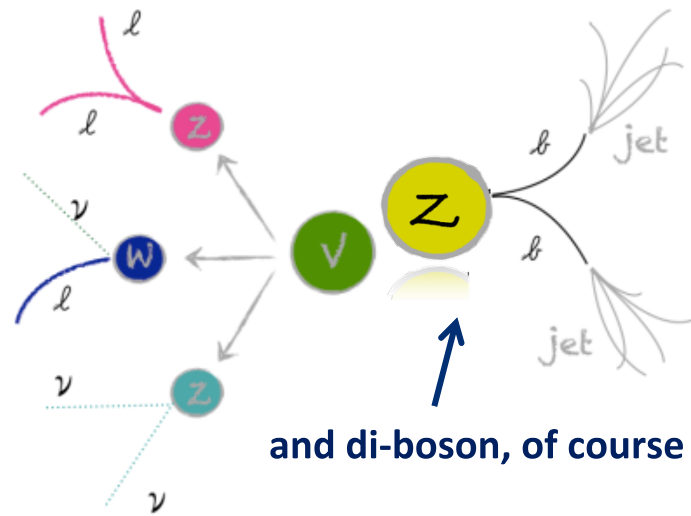


normalization from data, shapes from MC

VH(H→bb): event selection (CMS)

- Jet/lepton p_T **selection** and b-tagging discriminator working points **optimized separately by channel**
  - Boosted Vector Boson
    - 2-lepton: two p_T categories
      - Low: 50 GeV < $p_T(Z)$ < 150 GeV
      - High: $p_T(Z)$ > 150 GeV
    - 1-lepton: $p_T(W)$ > 150 GeV
    - 0-lepton: $p_T(Z)$ > 170 GeV

VZ background



and di-boson, of course

used to validate the analysis strategy

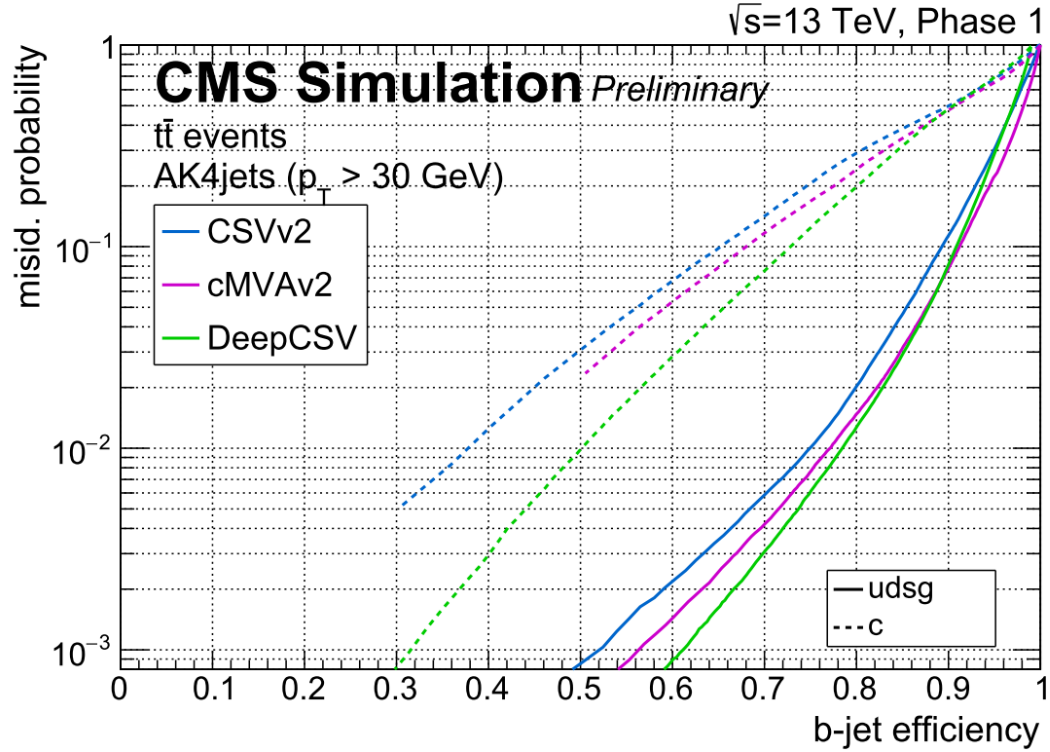
- **Control regions** designed to map closely signal region, with inverted selections to **enhance purity in targeted backgrounds**

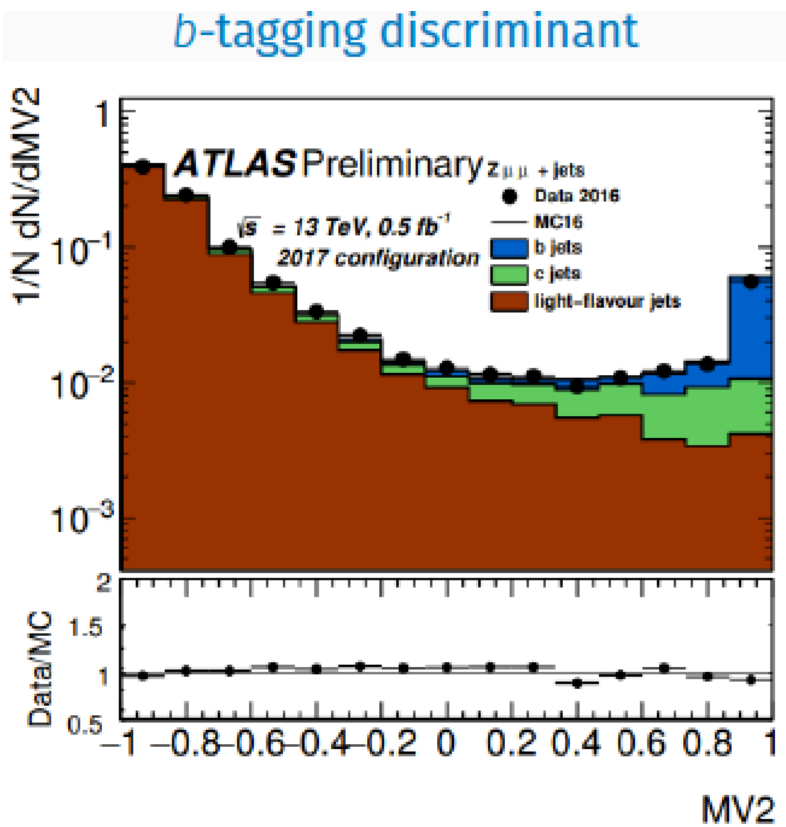
- **Separate** $t\bar{t}$, V+light flavor jets, and V+heavy flavor jets **control regions per channel**

Improvement of b-tagging

CMS: better mis-identification rate and data/MC agreement with Phase 1 pixel detector and DeepCSV algorithm

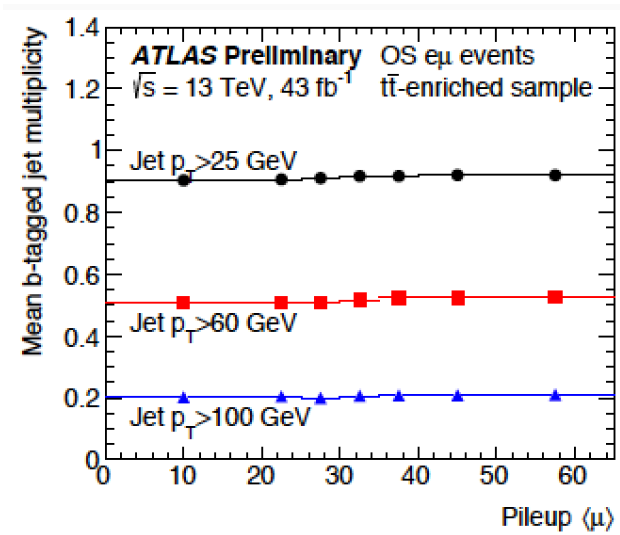
- Efficiency ~70% per fake rate at < 1%



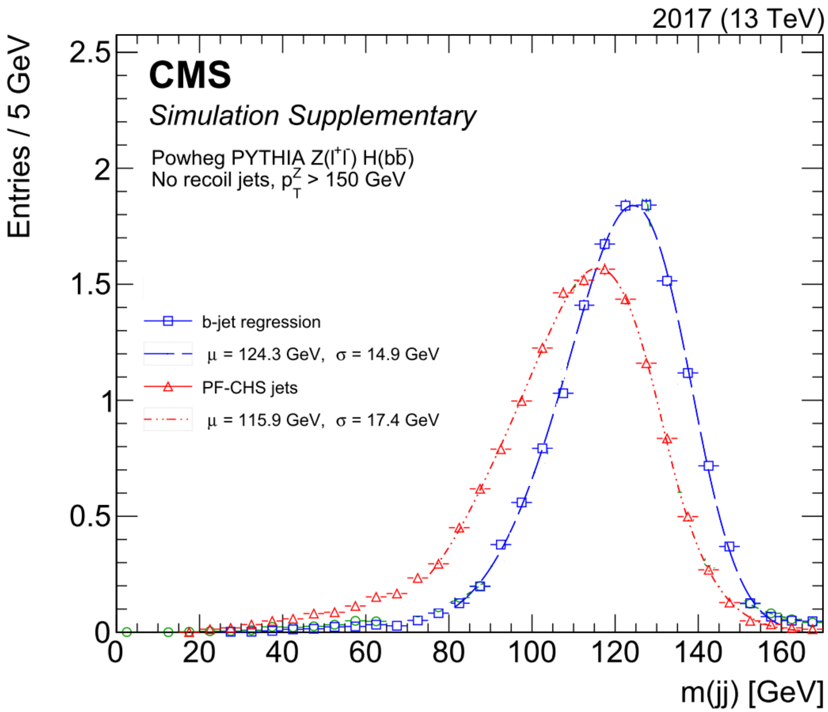


ATLAS:

- rejection of light/c jets 300/8 at 70% b-jet efficiency
- Good performance even at high PU



Improvement of di-jet mass resolution



CMS:

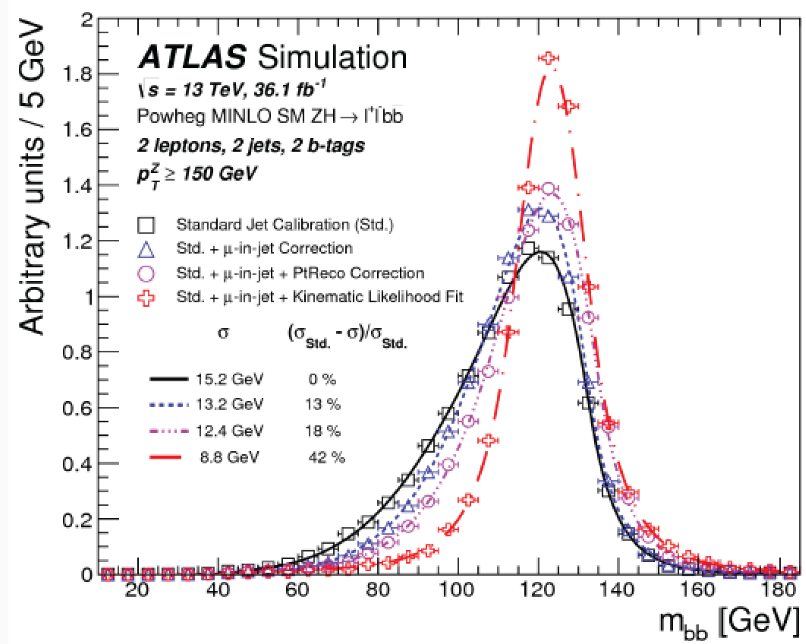
- Regression mainly recovers missing energy in the jet due to neutrino
- Extended set of input variables now including lepton flavour (μ/e), jet mass, p_T wrt to lepton axis, energy fractions in ΔR rings
- Significant m(bb) resolution improvement → σ/peak down to 11.9% in 2017 wrt 13.2% in 2016

ATLAS

Mass resolution improvements

Higgs boson candidate from a pair of b-jets

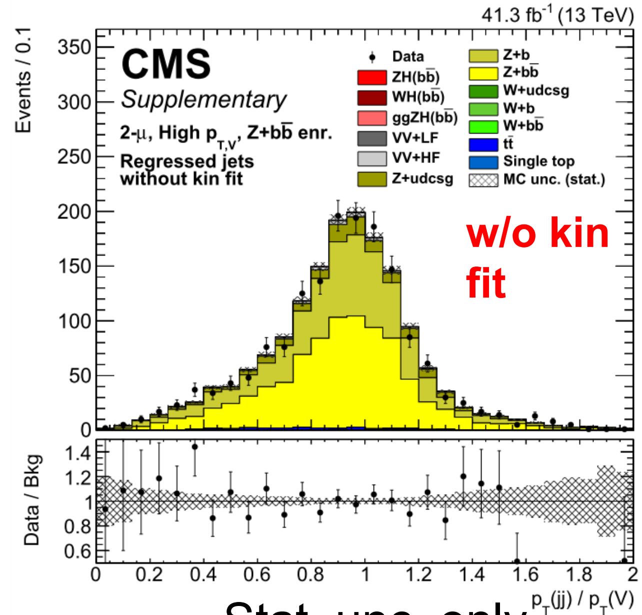
- Add muons in the vicinity (semi-lep. decays)
- Simple average jet p_T correction
  - Accounts for neutrinos, and interplay of resolution and p_T spectrum effects.
- Mass resolution improvement: $\sim$ 18%



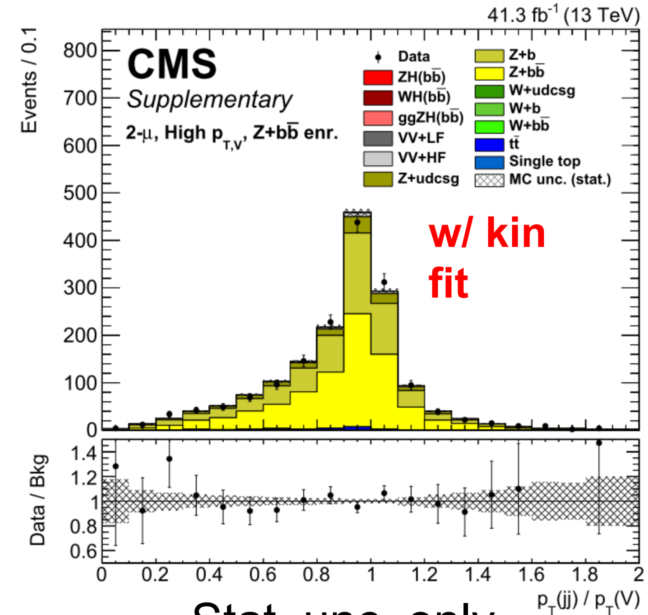
Kinematic fit in 2-lepton channel

CMS:

- No intrinsic missing energy in the Z(ll)H(b$\bar{b}$) process
- Improve jet p_T measurement through kinematic fit procedure
    - Constrain dilepton system to Z mass
    - Balance the ll+bb system in the (p_x, p_y) plane
- Improvement of up to 36% on m(b$\bar{b}$) resolution



Stat. unc. only

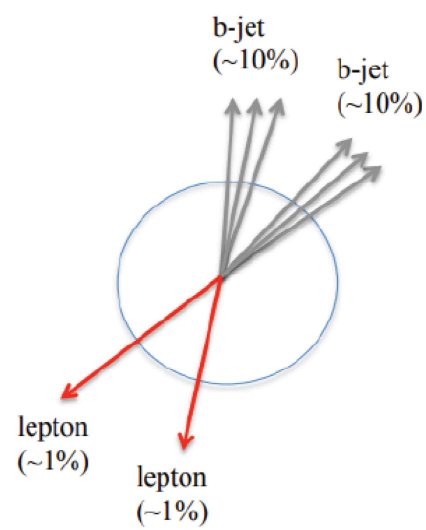


Stat. unc. only

ATLAS:

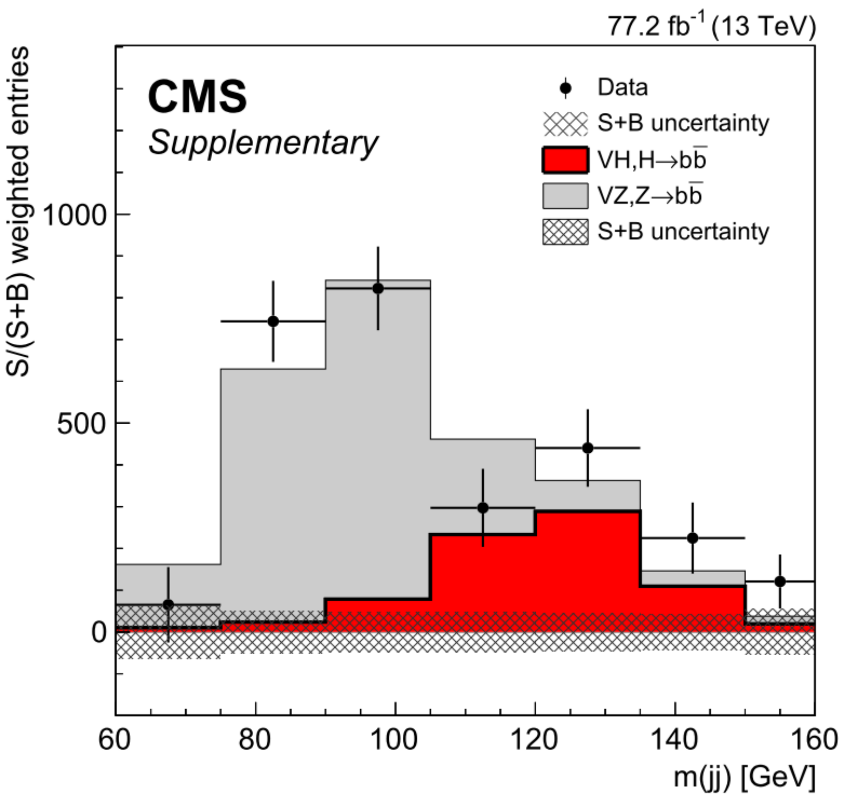
Kinematic Fit in 2-lepton channel

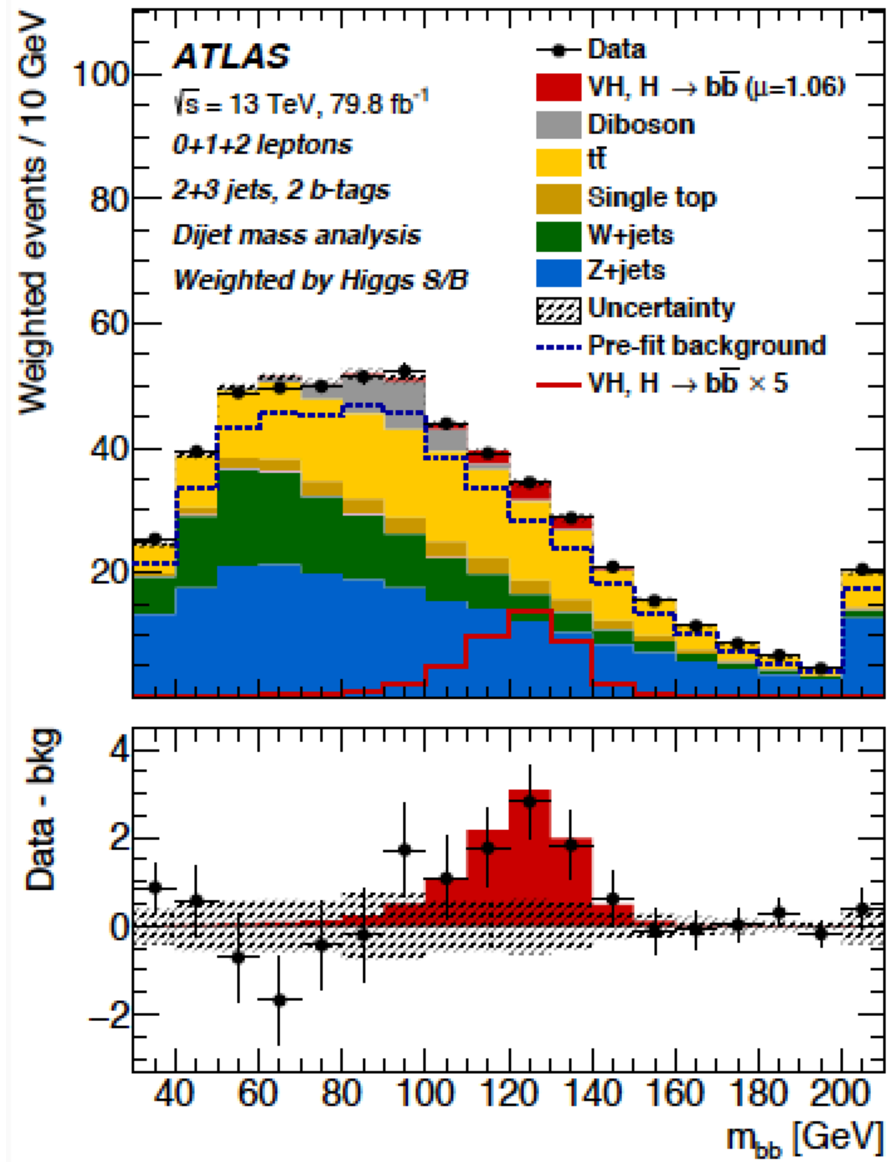
- Final state fully reconstructed
- High resolution on leptons
- Constrain jet kinematics better: $\sum \vec{p_T}(\ell) = -\vec{p_T}(bb)$ modulo soft radiation
- Mass resolution improvement: $\sim 40\%$



VH(H→bb): m(bb)

- **Fit to the m(bb)**: lower sensitivity but direct visualization of the Higgs boson signal.
- The fitted **m(bb) distributions are combined and weighted by S/(S + B)**

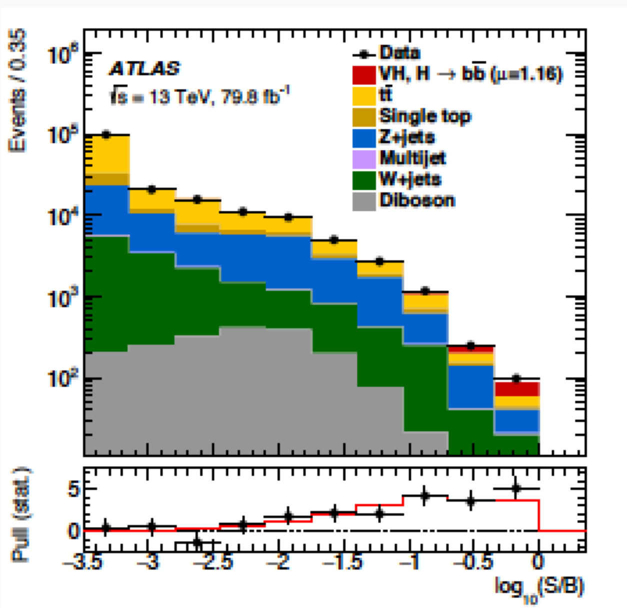


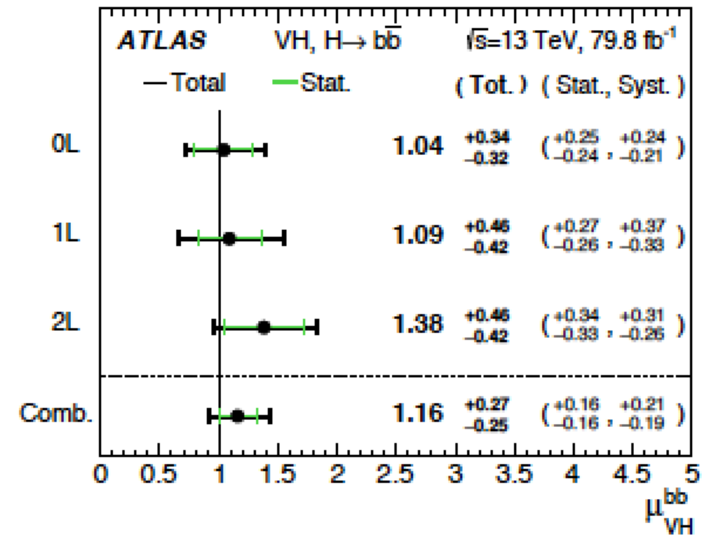


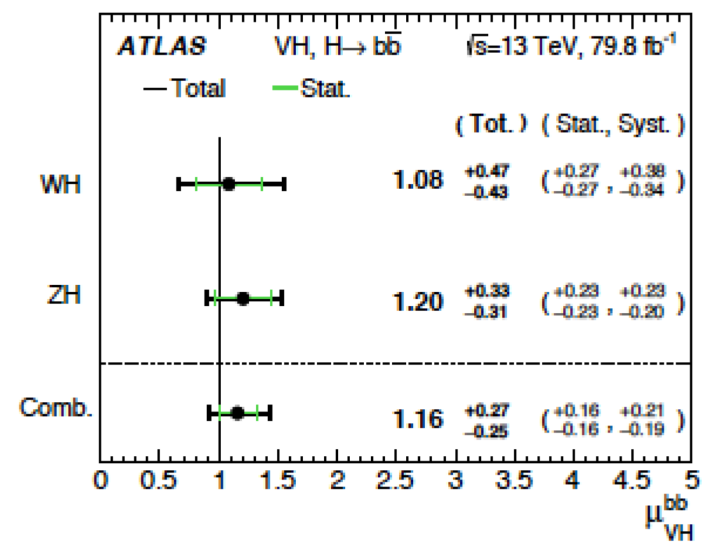
VH(H→bb): significance (ATLAS)

Results

- Significance of *VH*(*bb*) signal at 4.9σ (4.3σ exp.)
  - Signal strength compatible with SM
  - Lepton channels compatible at 80% level
- Individual production modes significances:
  - 2.5σ (2.3σ exp.) for *WH*
  - 4.0σ (3.5σ exp.) for *ZH*

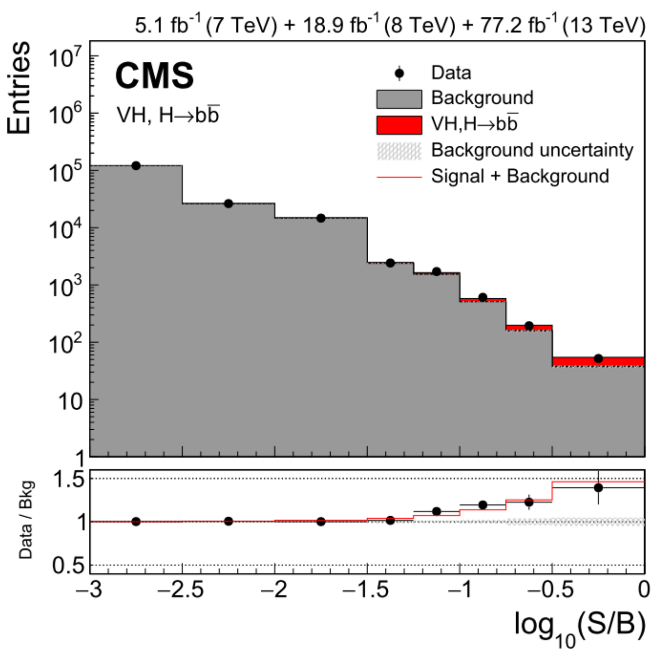


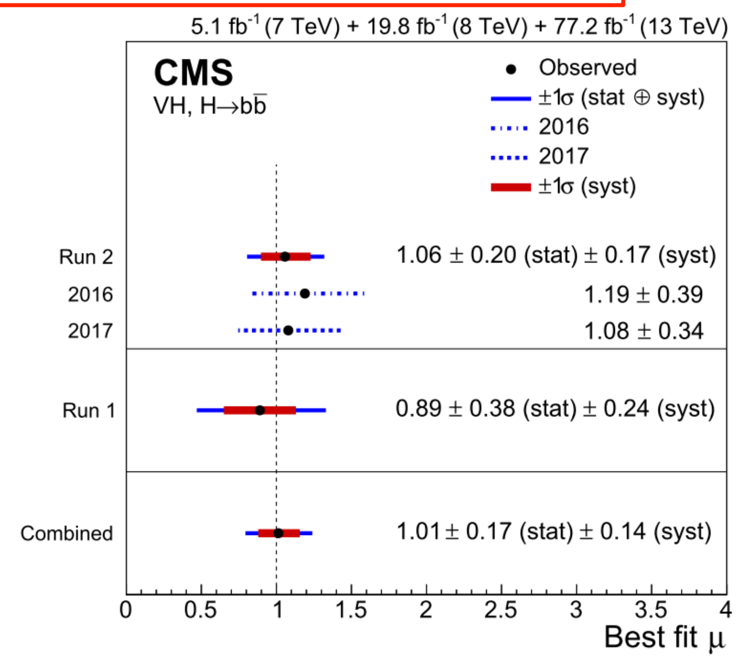




VH(H→bb): Run 1 + Run 2 results (CMS)

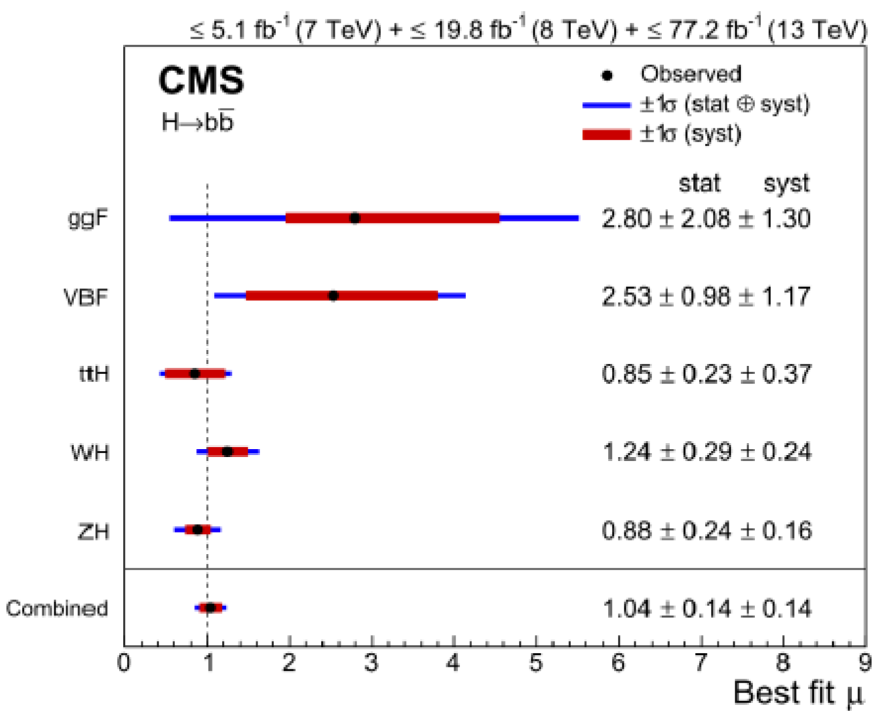
	Significance (σ)		
Data set	Expected	Observed	Signal strength
2017			
0-lepton	1.9	1.3	0.73 ± 0.65
1-lepton	1.8	2.6	1.32 ± 0.55
2-lepton	1.9	1.9	1.05 ± 0.59
Combined	3.1	3.3	1.08 ± 0.34
Run 2	4.2	4.4	1.06 ± 0.26
Run 1 + Run 2	4.9	4.8	1.01 ± 0.23





Combination of H→bb searches by CMS

- **Combination of CMS H→bb measurements : VH, boosted ggH, VBF, ttH**
- **Most sources of systematic uncertainty are treated as uncorrelated**
  - Theory uncertainties are correlated between all processes and data sets
- **Measured signal strength is μ = 1.04 ± 0.20**



<u>Significance</u>

5.5σ expected

5.6σ observed

Observation of the H→bb decay by the CMS Collaboration

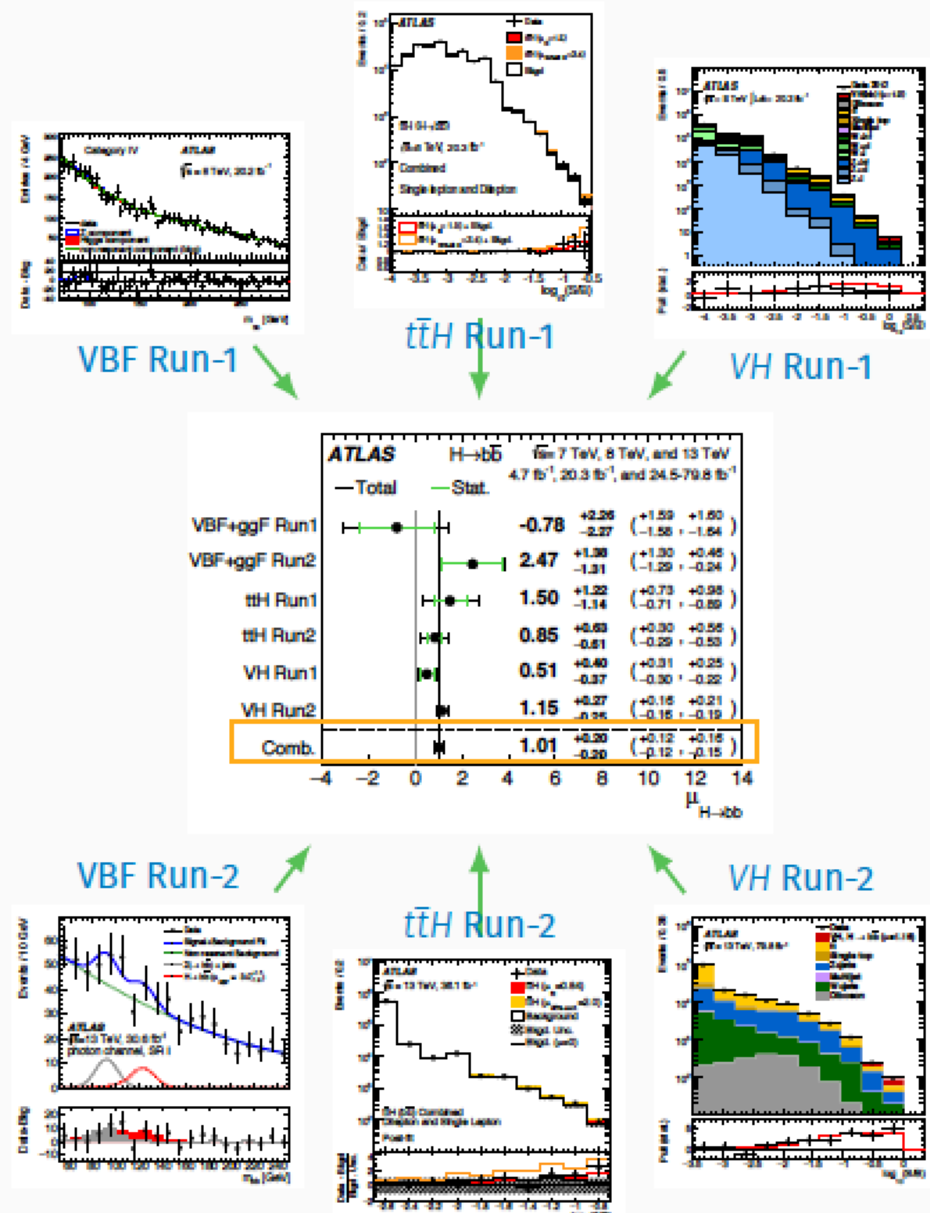
Combination of H→bb searches by ATLAS

$H \to b\bar{b}$ combination

- Combine Run-1 and Run-2 analyses in VH, VBF, $t\bar{t}H$ production modes
  - 2015+2016 Run-2 data for VBF and $t\bar{t}H$
- Uncertainty model from previous Run-1 and Run-2 combinations
- Results assume SM Higgs boson production cross-sections

Results

- Observation of $H \to b\bar{b}$ decays at 5.4σ (5.5σ exp.)
- $\mu_{H\to bb} = 1.01 \pm 0.20$
- Contributions of VBF and $t\bar{t}H$ channels 1.5σ and 1.9σ
- Compatibility of the 6 measurements 54%



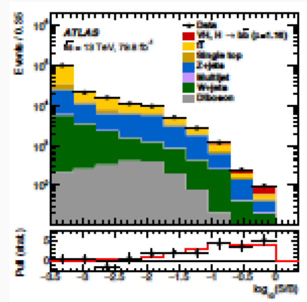
Combination of VH searches by ATLAS

VH combination

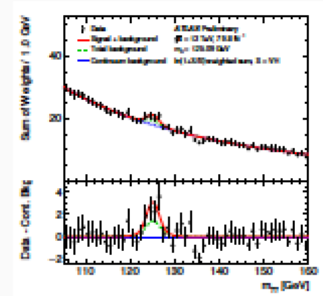
- Combine Run-2 analyses in $b\bar{b}$, $\gamma\gamma$ and 4ℓ decays
  - Updated analyses with 2015-2017 Run-2 data in all channels
- Results assume SM Higgs boson branching fractions

Results

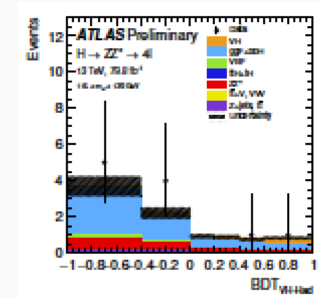
- Observation of *VH* production at 5.3σ (4.8σ exp.)
- $\mu_{VH} = 1.13 \pm 0.24$
- Contributions of 4ℓ and $\gamma\gamma$ channels 1.1σ and 1.9σ
- Compatibility of the 3 measurements 96%



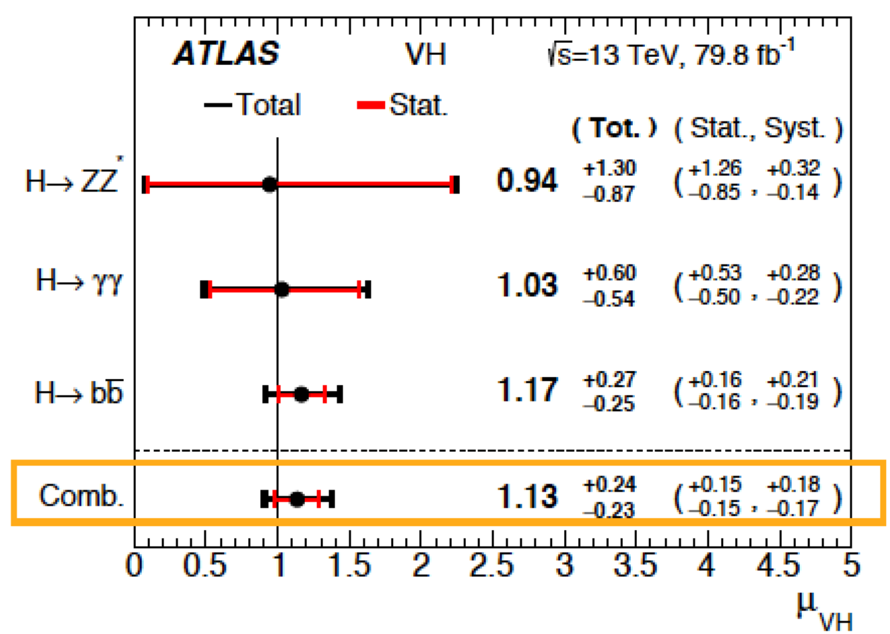
$H \to b\bar{b}$



$H \to \gamma\gamma$



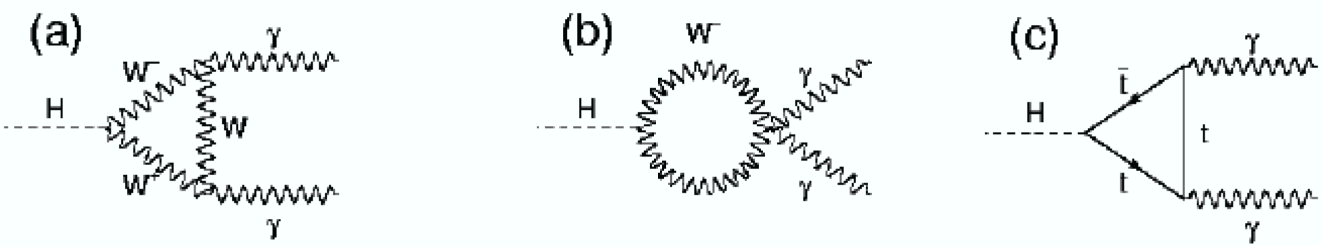
$H \to 4\ell$



$H \rightarrow \gamma\gamma$

H→γγ

CMS-HIG-16-040 (arXiv:1804.02716)
CMS-PAS-HIG-17-015
ATLAS-2016-21 (arXiv:1802.04146)



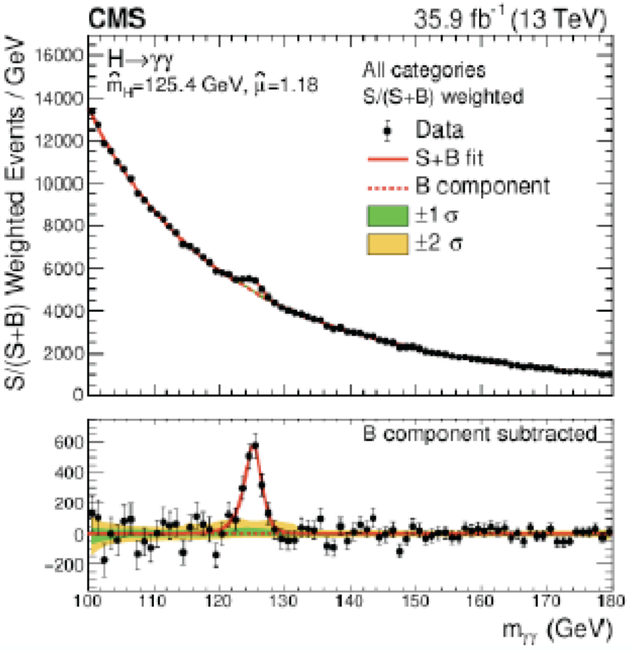
Indirect probe of coupling through production loops
- Sensitive to vector/fermion couplings (k_V, k_F)
- Can test NP in the loops

Search strategy: peak over (abundant) and regular background

Observed width dominated by detector resolution

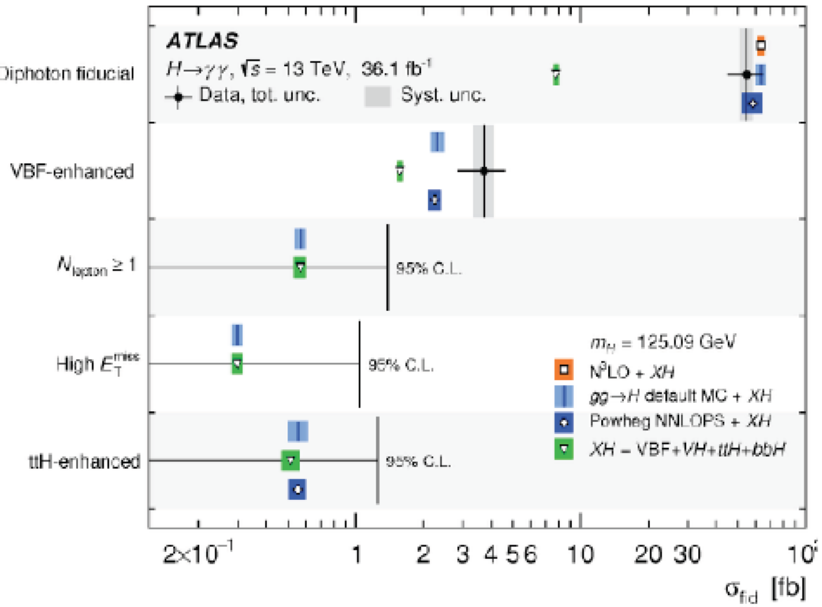
Efficient selection (40%)
- Trigger, photon ID, E_T, isolation,…
- Abundant number of selected events allows for a large number of categories→sensitivity to different production/decay modes

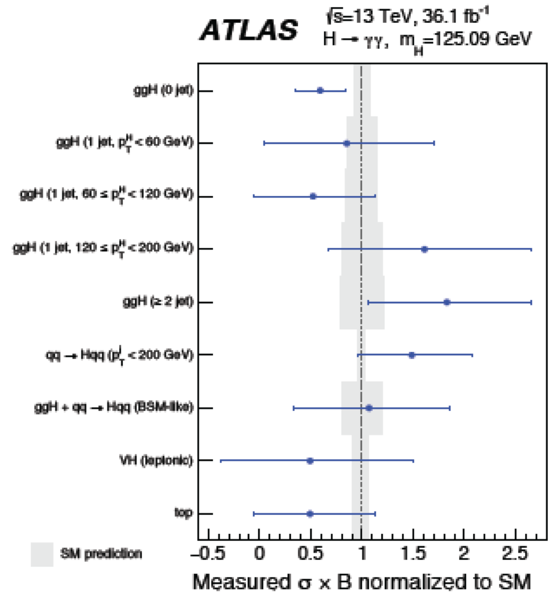
Main uncertainties: photon ID/resolution, luminosity, statistical uncertainty still the largest factor

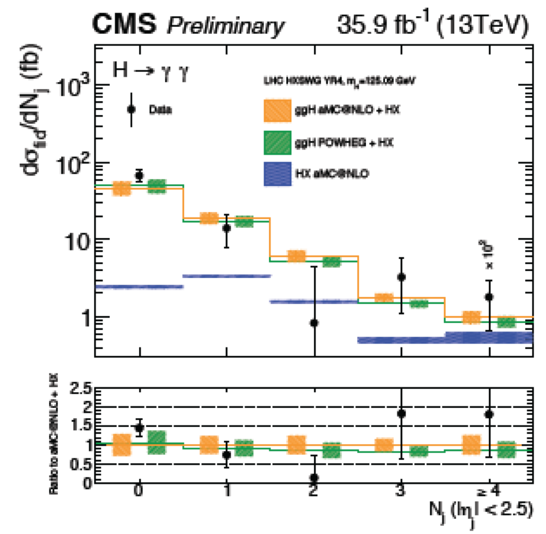


H→γγ: cross section

CMS-PAS-HIG-17-015
ATLAS-2016-21 (arXiv:1802.04146)







Both fiducial (inclusive) cross section, STXS, and differential distributions show good agreement with theoretical predictions

Experimental uncertainties are comparable to theoretical ones in the most populated bins (low p_T, low N_{jets})

Differential cross-section as a function of $p_T(H)$, N_{jet}, y_H, $\cos\vartheta^*$ (see backup)

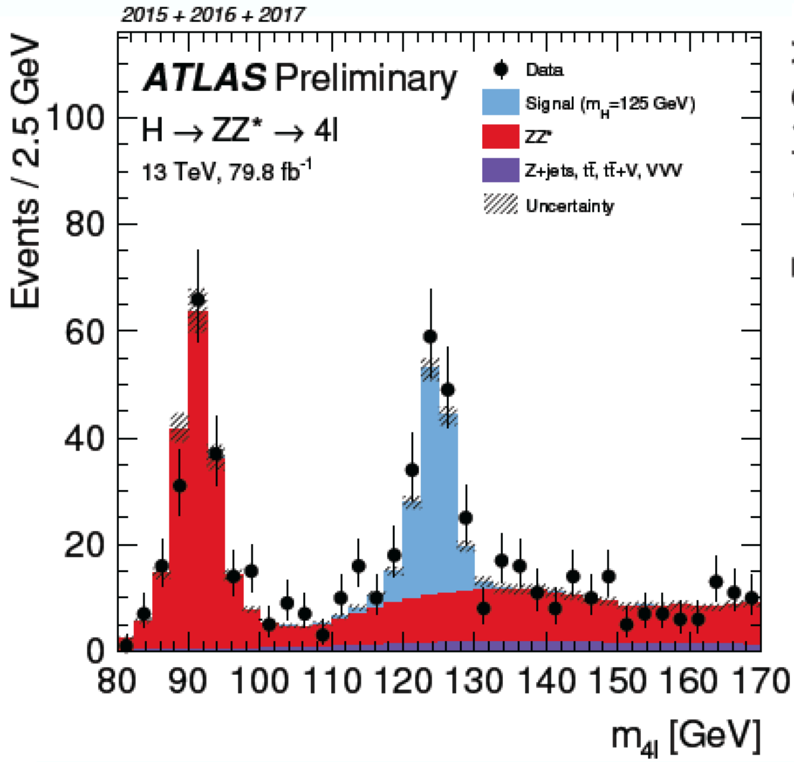
ATLAS: EFT reinterpretation to probe anomalous couplings

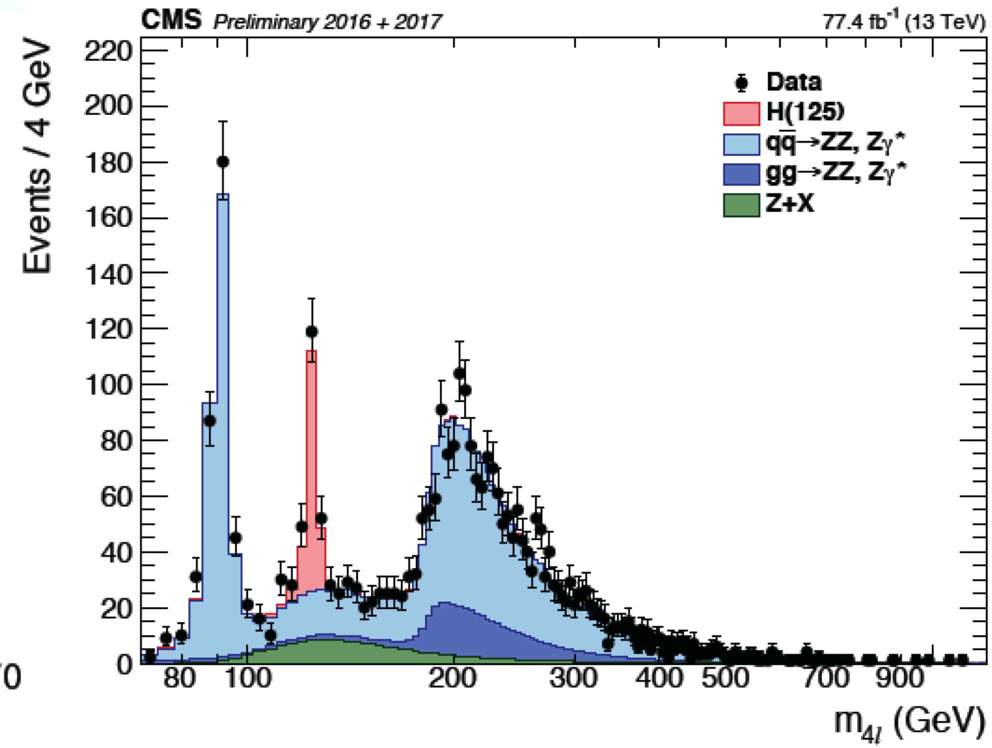
H→ZZ

H→ZZ→4l

CMS-PAS-HIG-18-001 JHEP 03 (2018) 095
Phys. Lett. B 775 (2017) 1 ATLAS-CONF-2018-018

Low signal rate, but very clear signal topology over a small, flat background (mainly qqZZ, Z+jets)
- 4 isolated leptons in final state combined in 2 Z pairs
- Kinematical information (matrix element KD discriminants) or BDT techniques to separate signal and background and categorise events





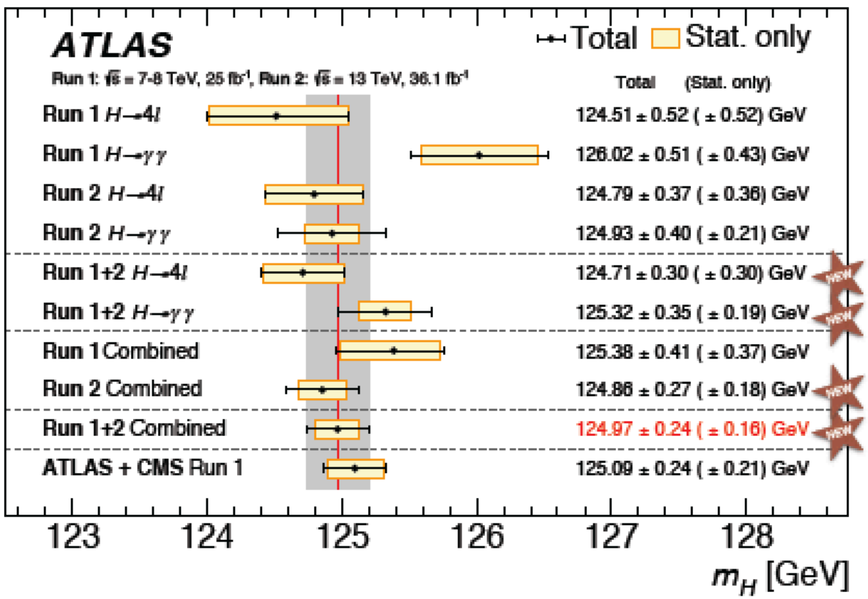
Analysis is still being improved:
- Improved event categorisation to target VH and ttH productions
- CMS: dedicated discriminants to target different production modes (ggH, VBF, VH)

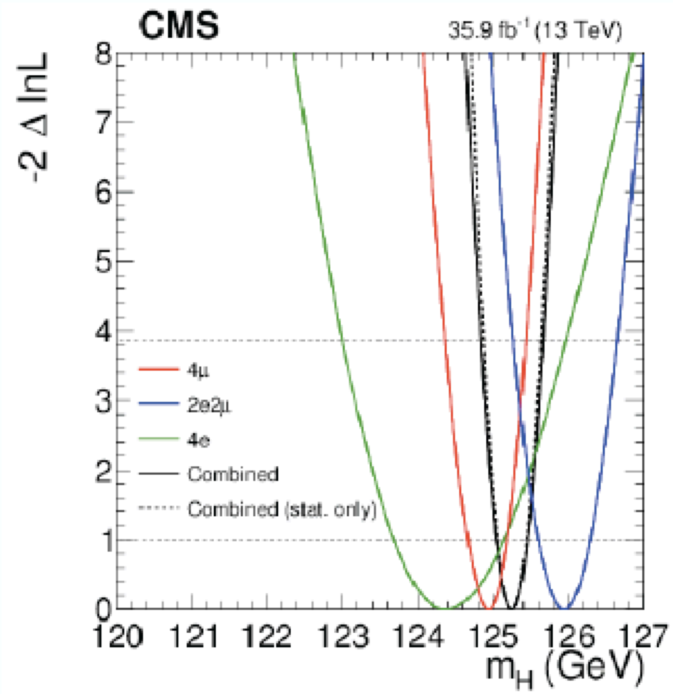
H→ZZ→4l + H→γγ: mass measurement

CMS-PAS-HIG-16-041
arXiv:1806.00242

H→ZZ→4l and H→γγ are the final states with the highest precision for the mass measurement

ATLAS performed the combined measurement of the Run1 and Run2 (2015+2016) H→ZZ→4l and H→γγ mass measurements, m_H = 124.97±0.24 GeV



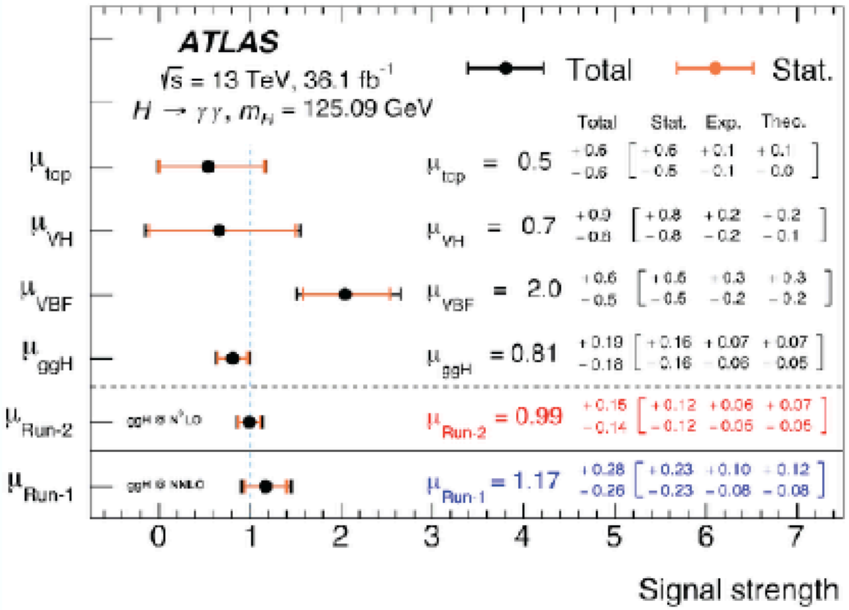


Most precise measurement at the moment comes from CMS H→ZZ→4l mass measurement with 2016 data m_H = 125.26±0.21 GeV

H→ZZ→4l + H→γγ: signal strength

H→γγ

$$\hat{\mu}_{CMS} = 1.18^{+0.17}_{-0.14} = 1.18\ ^{+0.12}_{-0.11}\,(\text{stat})^{+0.09}_{-0.07}\,(\text{syst})^{+0.07}_{-0.06}\,(\text{theo})$$



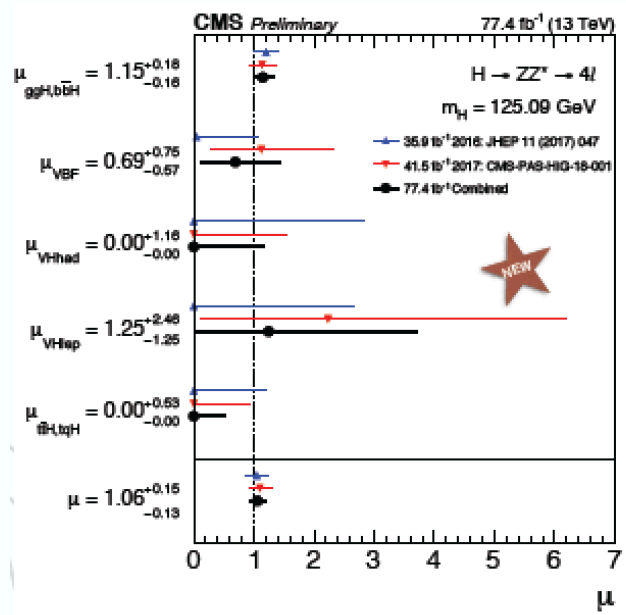
Very good agreement between measurements and with expectations.
Run1: ATLAS excess, CMS deficit

25% improvement on Run1 combination

H→ZZ→4l

ATLAS 2015+2016+2017:

$$\mu = 1.20 \pm 0.12(\text{stat.}) \pm 0.06(\text{exp.})^{+0.08}_{-0.07}(\text{th.})$$
$$= 1.20^{+0.16}_{-0.15}.$$



$H \rightarrow \tau^+\tau^-$

$H \rightarrow \tau^+\tau^-$

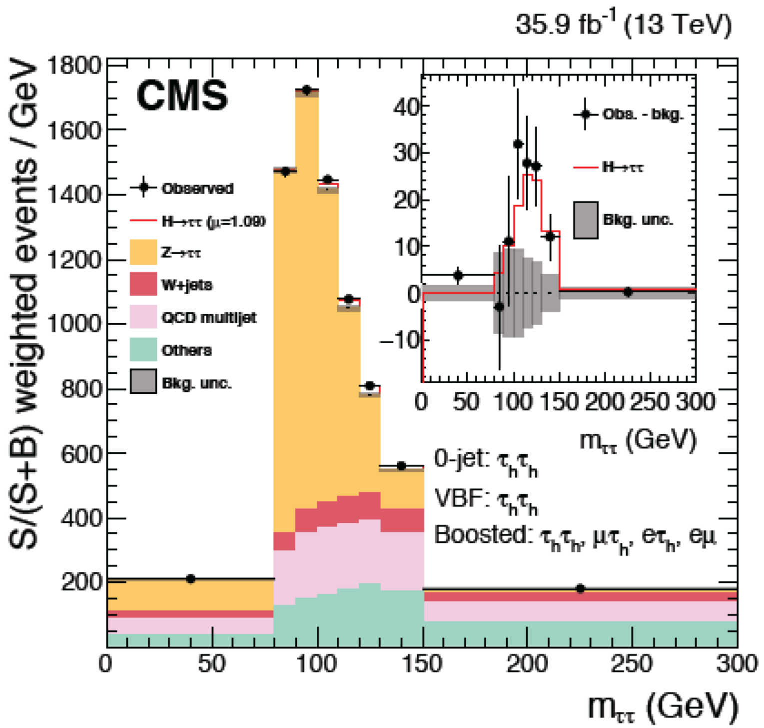
- Higgs boson in ττ decay mode is the most promising channel to explore the Higgs Yukawa coupling to fermions (decay rate to ττ is less than bb, but this channel has much less background)
- Analyzing Run1 data, in 4 production modes led to the first evidence of Higgs coupling to fermions

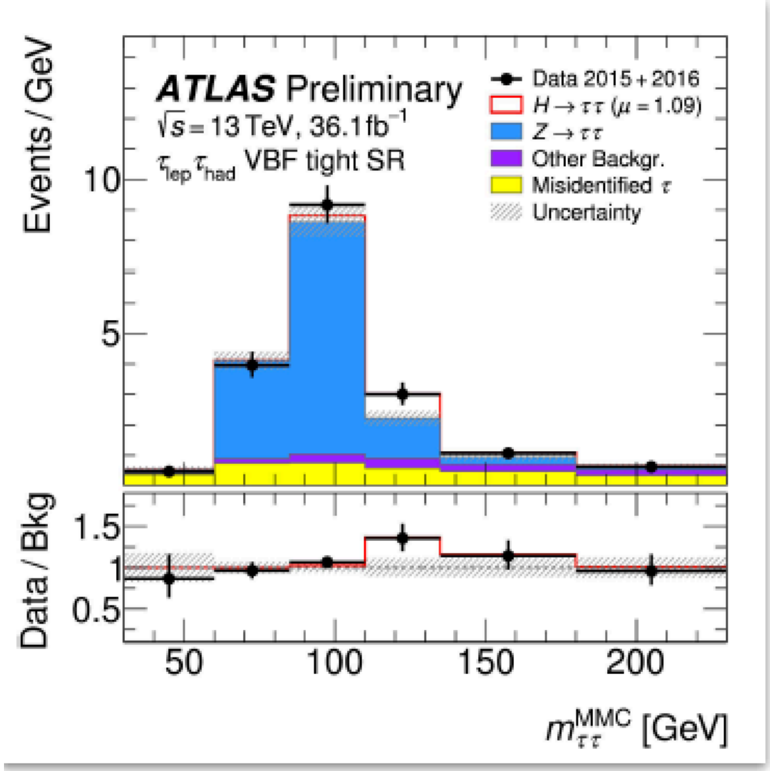
Date	Experiment	Result	Significance Obs. (Exp.) [σ]	Reference
May 2014	CMS	evidence	3.2 (3.7)	JHEP05(2014)104
April 2015	ATLAS	evidence	4.5 (3.4)	JHEP04(2015)117
August 2016	ATLAS+CMS	observation	5.5 (5.0)	JHEP08(2016)045
April 2018	CMS	observation	5.9 (5.9)	Phys.Lett. B779 (2018) 283-316
June 2018	ATLAS	observation	6.4 (5.4)	ATLAS-CONF-2018-021

$H \rightarrow \tau^+\tau^-$

CMS: Event categorization changed in Run2

- 4 different final states (based on tau decays)
- 3 main categories (mainly) based on the n. jet
- events split depending on tau decay modes/muon p_T (in 0jet), p_T of the Higgs boson(in boosted) and mass of the two forward jets(in VBF mode)





$\tau_{lep}\tau_{had}$ VBF

√s (TeV)	7, 8	13	Combined
Observed (σ)	4.5	4.4	6.4
Expected (σ)	3.4	4.1	5.4

Combining 2016 data with Run1 → 5.9 σ

PLB 779 (2018) 283

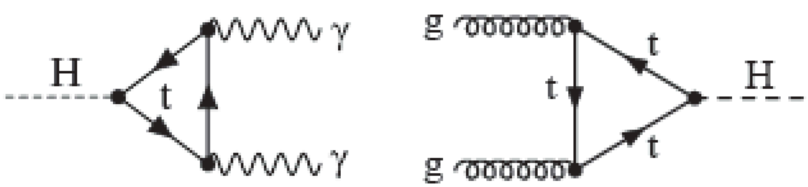
The first observation of the Higgs coupling to tau leptons in a single experiment

ttH

ttH

Motivation

- Provides a **direct probe** of the important top–Higgs coupling
  - Yukawa coupling $y_t \sim 1$
  - Indirect loop measurements can be influenced by BSM physics



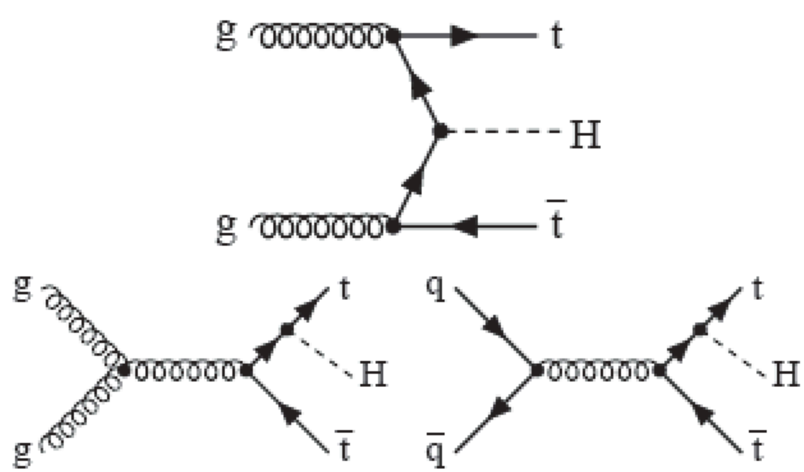
- First measurement of Higgs coupling to up-type fermion
- Non-SM ttH rate could indicate presence of new physics

Properties

CERN-2017-002-M

LHC Higgs Cross Section WG Report 4

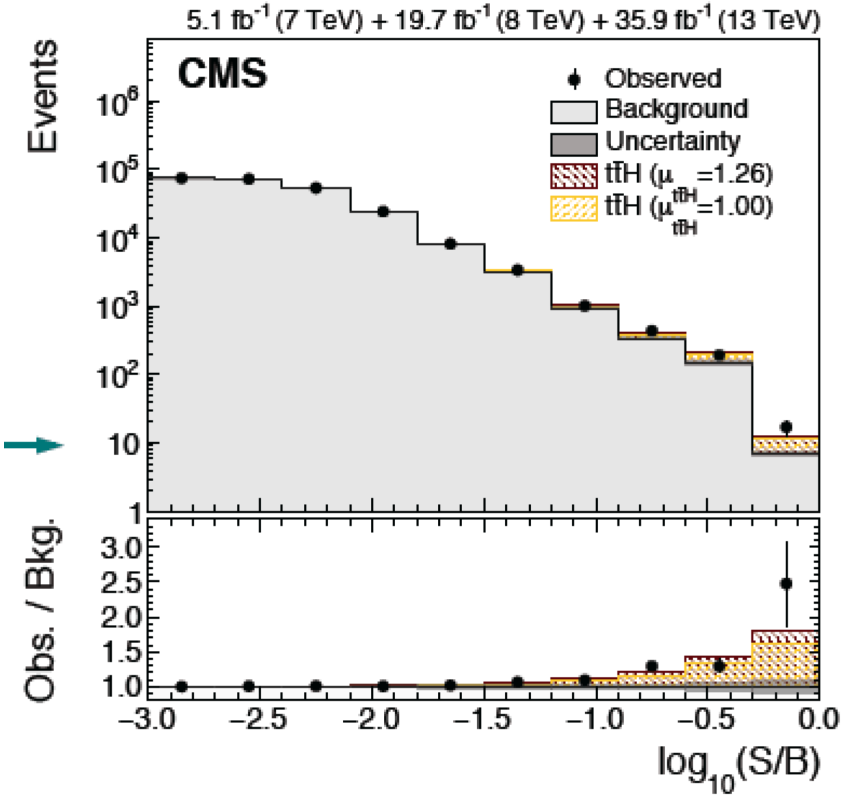
- Xsec: 0.5071 pb +6.8/−9.9%
  - NLO QCD and NLO EW accuracy
- **Expect ~18,000 SM ttH events** in 2016 data at CMS
  - ~ 36 fb^{-1}
- LO Feynman diagrams:

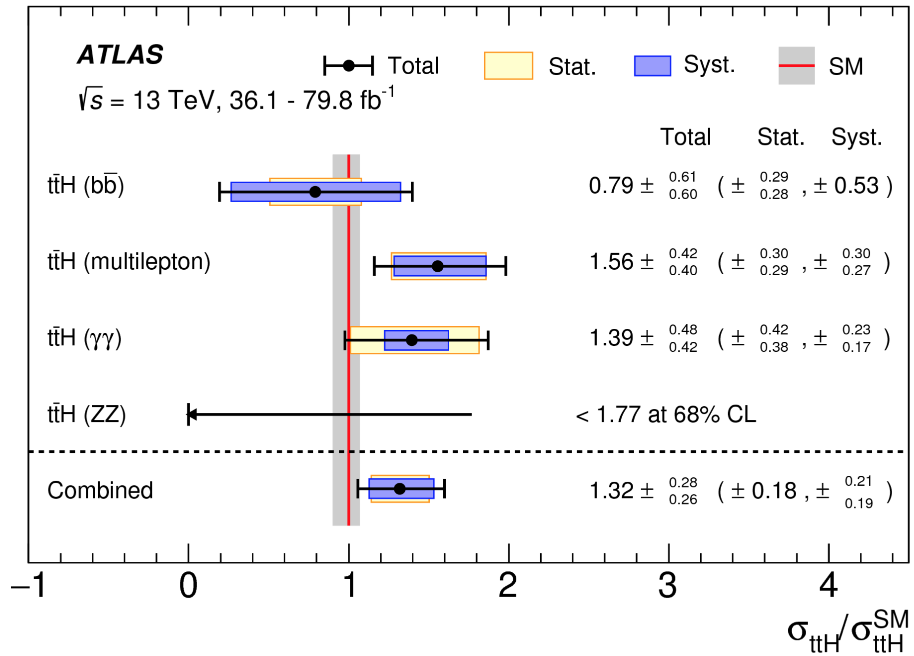


ttH

CMS Phys. Rev. Lett. 120, 231801 (2018)
ATLAS arxiv:1806.00425

Decay channels analysed:
Fermions: H→bb H→ττ
Bosons: H→WW H→ZZ H→γγ



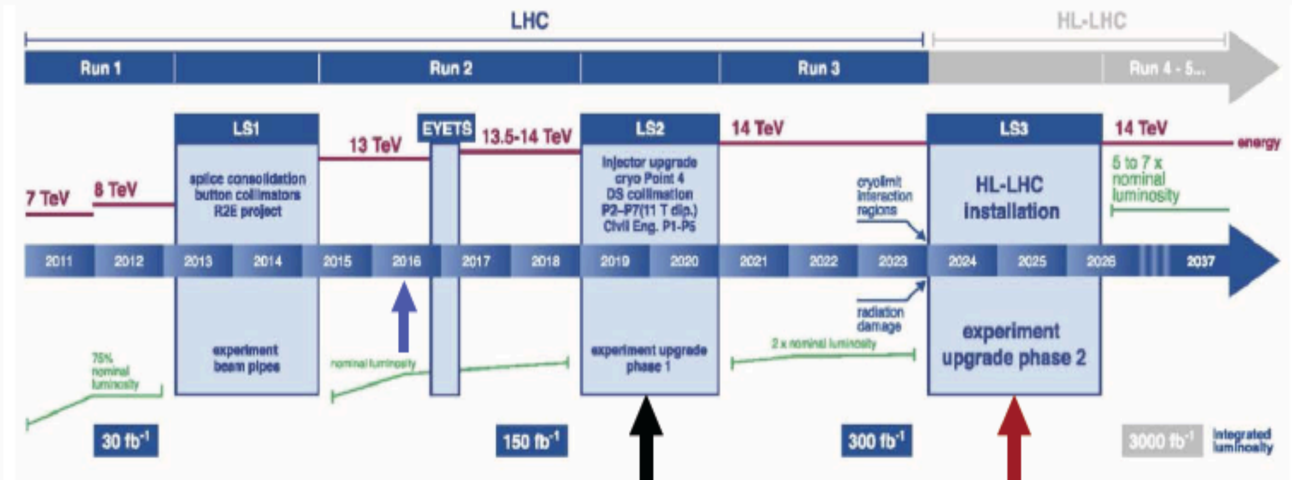


CMS Run 2 (2016)	**4.5σ obs.** (4.1σ exp.)
ATLAS Run 2 (2015-2016)	**4.2σ obs.** (3.8σ exp.)
ATLAS Run 2 (2015-2017)	**5.8σ obs.** (4.9σ exp.)
CMS Run 1 + Run 2 (2016)	**5.2σ obs.** (4.2σ exp.)
ATLAS Run 1 + Run 2 (2015-2017)	**6.3σ obs.** (5.1σ exp.)

- First observation of tree-level Higgs–top coupling
- Consistent with standard model Higgs within 1 sigma

LHC and HL-LHC

- LHC
  - 300 fb^{-1} by 2023
    - 30 fb^{-1} Run 1
    - >100 fb^{-1} so far
    - ...
- HL-LHC
  - ~3000 fb^{-1} by ~2035



LS2 (2019-2020):
- ❑ LHC Injectors Upgrade (LIU)
- ❑ Civil engineering for HL-LHC equipment @ P1,P5
- ❑ First 11 T dipoles P7; cryogenics in P4
- ❑ Phase-1 upgrade of LHC experiments

LS3 (2024-2026):
- ❑ **HL-LHC installation**
- ❑ Phase-2 upgrade of ATLAS and CMS

ATLAS, CMS Upgrade plan

8x10^{33} Hz/cm^{2}
30 fb^{-1}
PU ~40

LS1

2x10^{34} Hz/cm^{2}
300 fb^{-1}
PU ~50

Phase 1 Upgrade

5x10^{34} Hz/cm^{2}
3000 fb^{-1}
PU ~140

LS3

Phase 2 Upgrade

Phase II upgrades and Higgs @ HL-LHC

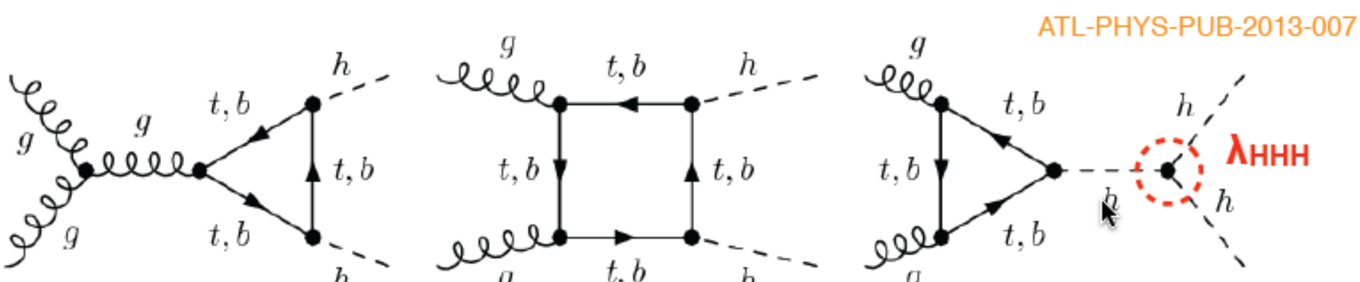
Phase II Detector Upgrades:

Significant upgrades of ATLAS and CMS for HL-LHC conditions

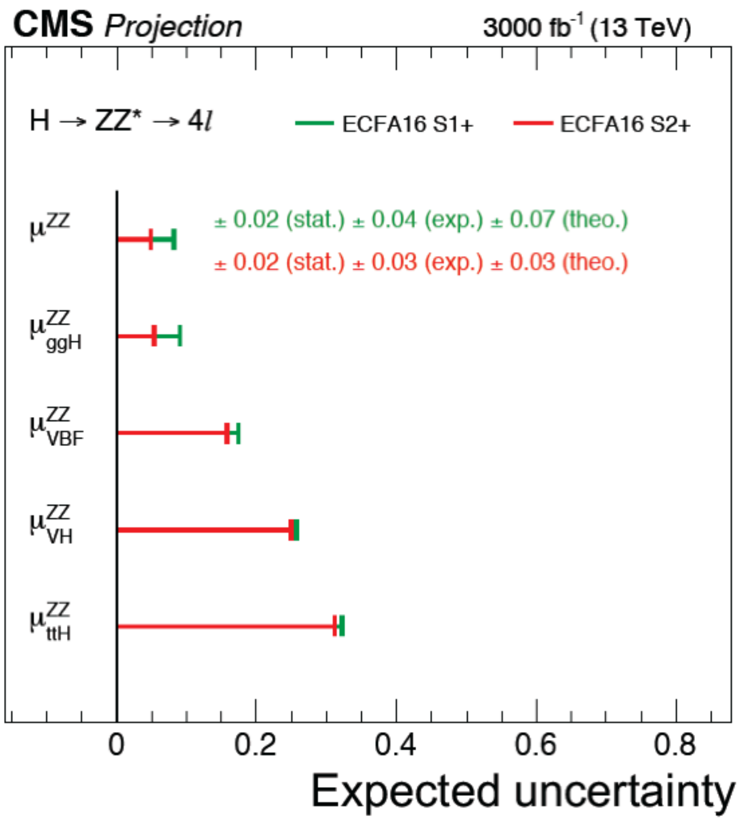
- Radiation hardness
- Mitigate physics impact of high pileup

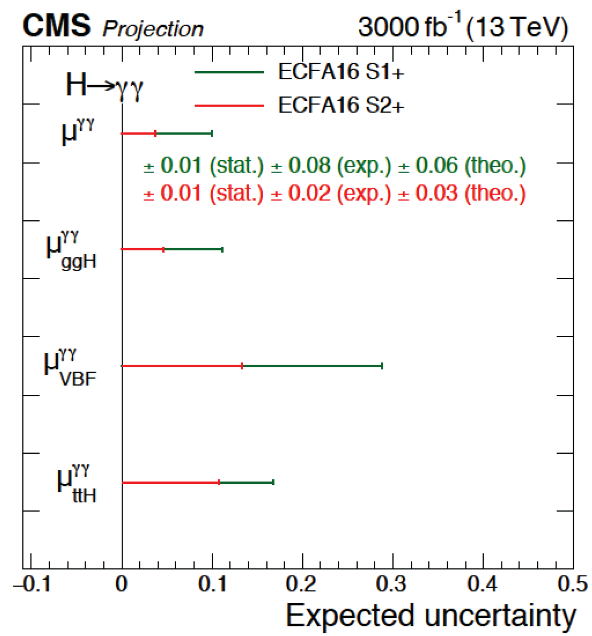
Higgs@HL-LHC:

- Precision Measurements (Couplings, Cross Sections, Width, Differential Distributions,…)
- Rare decays and couplings
- BSM Higgs searches: extra scalars, BSM Higgs resonances, exotic decays, anomalous couplings
- VV scattering
- Di-Higgs production ➜ self coupling

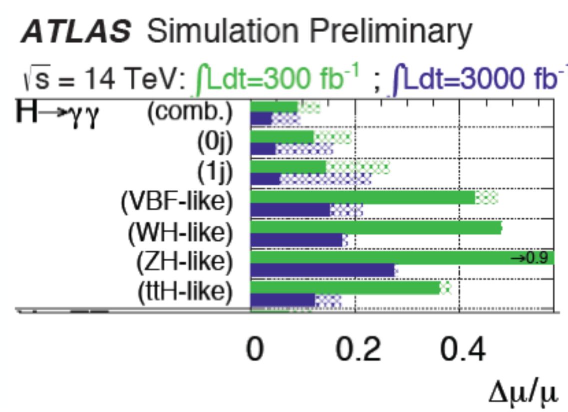


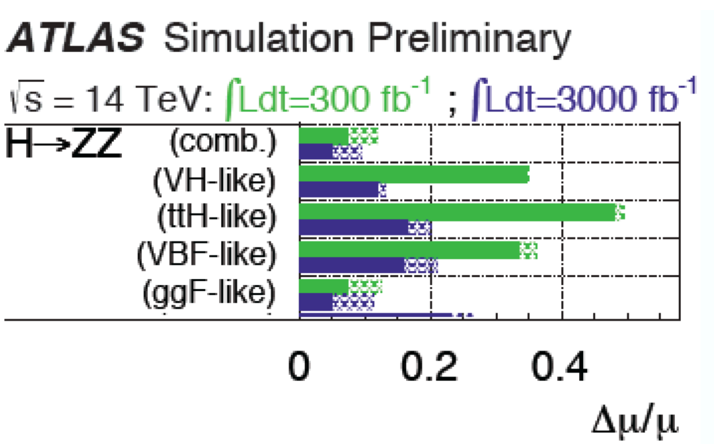
Higgs signal strength: $\mu=\sigma/\sigma_{SM}$ – 3000 fb^{-1}





ECFA 16





- Similar expected sensitivities between the two experiments
- Precision larger than 5-10%

Conclusions

- Highlights of the run 2:
  - CMS/ATLAS reached **> 5σ** observation of the **H→bb** decays
  - New mass measurement combining H→ZZ→4l and H→**γγ** in both Run1 and Run2 →towards the measurement of **differential distributions** and crosssections
  - First observation of tree-level Higgs–top coupling with **ttH** events (Run1 + Run2 data)
  - The first observation of the Higgs coupling to **tau** leptons in a single experiment using 2016 and Run1 data
  - Promising physics at the HL-HC also approaching

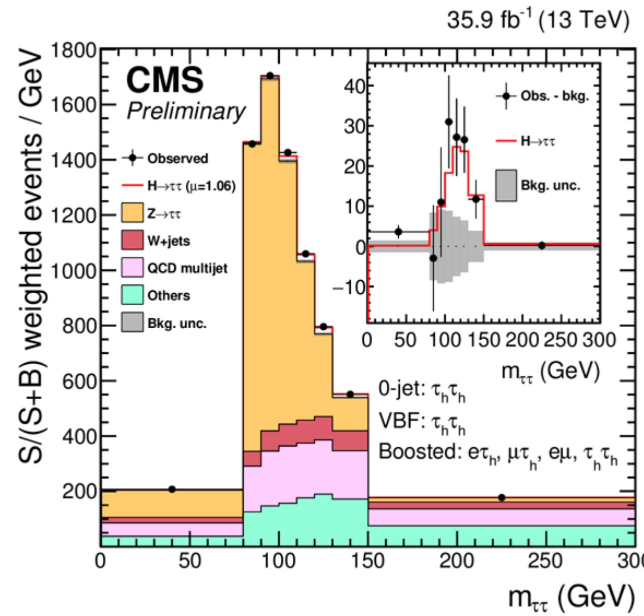
Exiting Higgs Physics so far and in the future

Backup

The LHC/Higgs era at Run 2

H→ ττ :

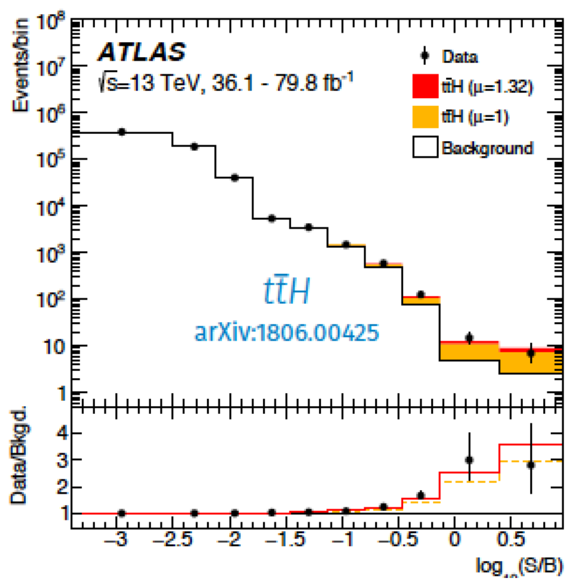
Observation of the SM scalar boson decaying to a pair of τ leptons with the CMS experiment at the LHC (**4.9σ** *vs* 4.7σ expected) → HIG-16-043

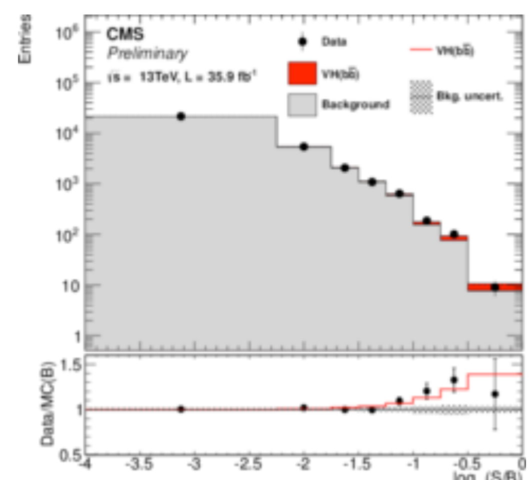


H→bb :

CMS has **3.8σ** evidence (3.8σ expected) for Higgs boson decays to b-quarks and for its production in association with a vector boson → HIG-16-044, arXiv:1709.07497

ttH→ZZ,WW,ττ → multi-leptons: evidence observed (expected) significance of **3.3σ** (2.5σ), by the combination of the 2016 results with 2015 → HIG-17-004





* Similar results from ATLAS

$H \rightarrow bb$

VH(H→bb): improvement wrt 2016

CMS

- Extensive use of **deep neural network (DNN)**
  - To **identify b-jet** candidates
  - To **regress the energy** of reconstructed b-jet
  - To **discriminate among the background components** in some Vector boson + heavy flavor jets control regions
  - To **discriminate signal from background**
- **Kinematic fit** in 2-lepton channel
- **FSR jet recovery**
- New **Pythia8 Underlying Event Tune**

- **Improved mass resolution (~10%) leads to 10% increase of the analysis sensitivity**

Systematic uncertainties

Source of uncertainty		σ_μ
Total		0.259
Statistical		0.161
Systematic		0.203
Experimental uncertainties		
Jets		0.035
E_T^{miss}		0.014
Leptons		0.009
b-tagging	*b*-jets	0.061
	c-jets	0.042
	light-flavour jets	0.009
	extrapolation	0.008
Pile-up		0.007
Luminosity		0.023
Theoretical and modelling uncertainties		
Signal		0.094
Floating normalisations		0.035
Z + jets		0.055
W + jets		0.060
$t\bar{t}$		0.050
Single top quark		0.028
Diboson		0.054
Multi-jet		0.005
MC statistical		0.070

Analysis dominated by systematic uncertainties

Measured by impact on signal strength (μ)

Many important sources !

b-tagging both *b* and *c* jet tagging calibration

- Resp. ~3% and ~10% per jet

Background modelling Z+hf, W+hf, $t\bar{t}$

- Mainly shape and extrapolation uncertainties

Signal modelling little impact on significance

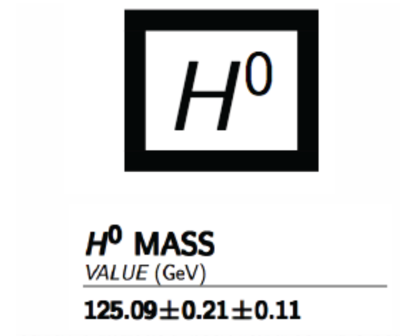
- Dominated by systematic uncertainties on the acceptance

MC stats never-ending race between data stat and MC stat

- Use of dedicated MC filters
- Not easy in all cases, e.g $t\bar{t}$ phase space in 0/1-lepton

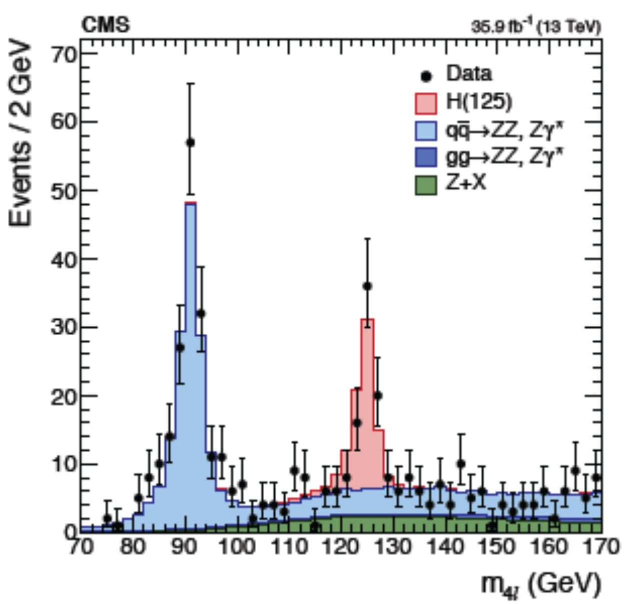
The LHC/Higgs era at Run 2

- Re-discovery of the Higgs
- measur. Higgs properties
  - cross section (also differential)
  - mass & width
  - couplings:
    - to gauge bosons, to fermions
    - tensor structure and effective couplings in the lagrangian
    - ttH couplings
  - Searches for BSM Higgs

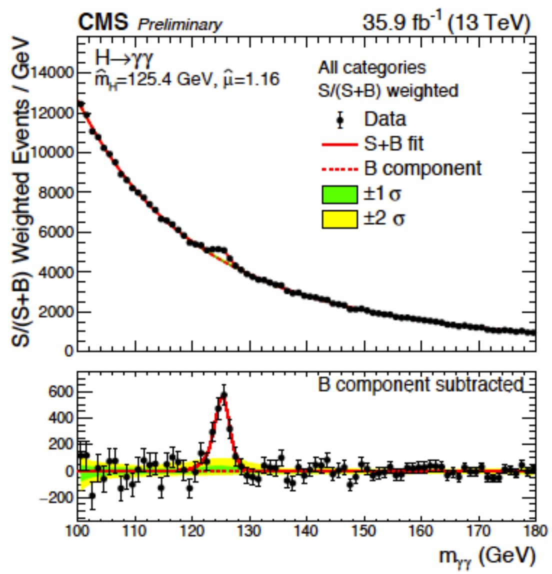


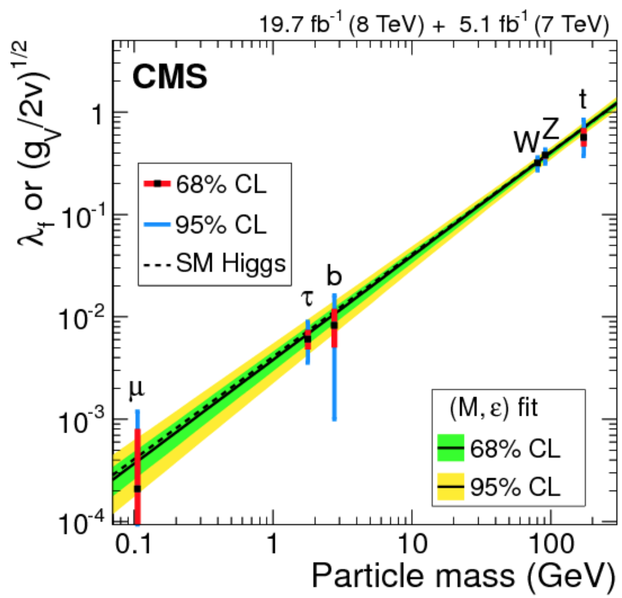
- Mass measured to 0.2%
- Main couplings to ~10%

HIG-16-041

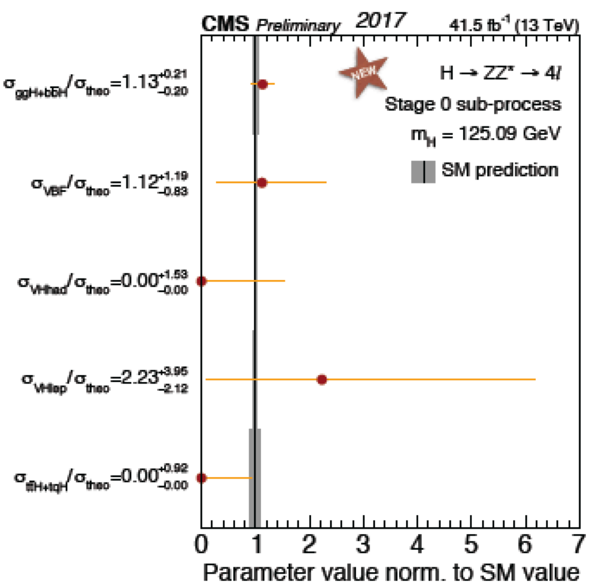


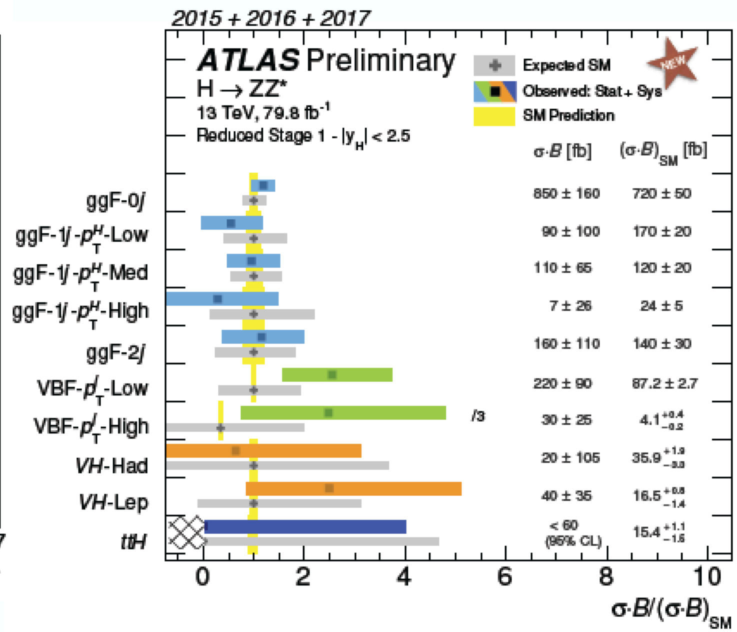
HIG-16-040

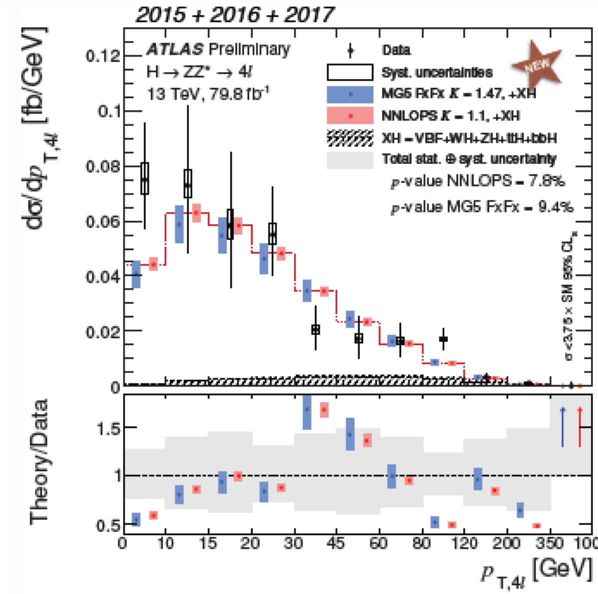




H→ZZ→4l: cross section







ATLAS already attempting at (simplified) stage-1 STXS subprocesses.

CMS show a small excess (mostly driven by excess in 2e2μ)

no ttH event observed yet in either of the experiments