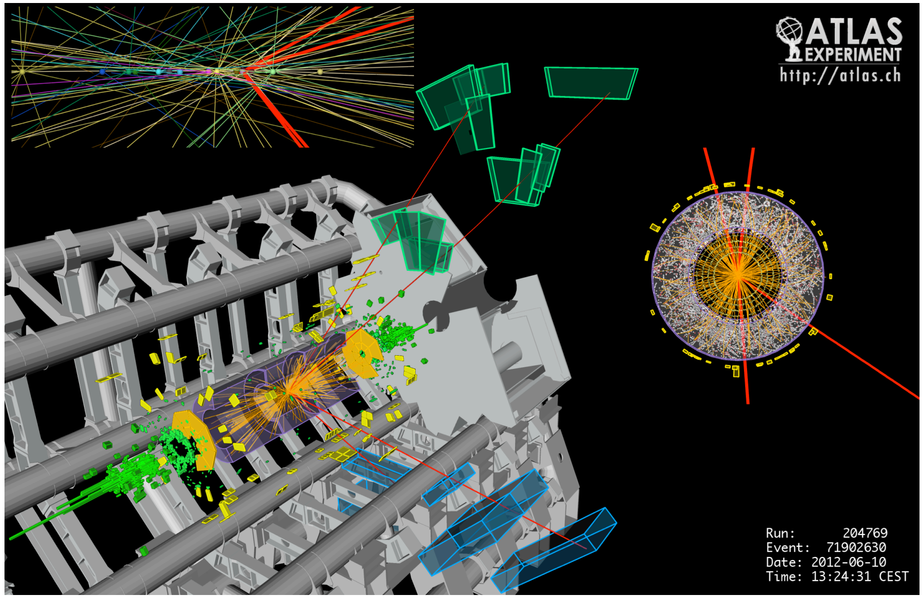
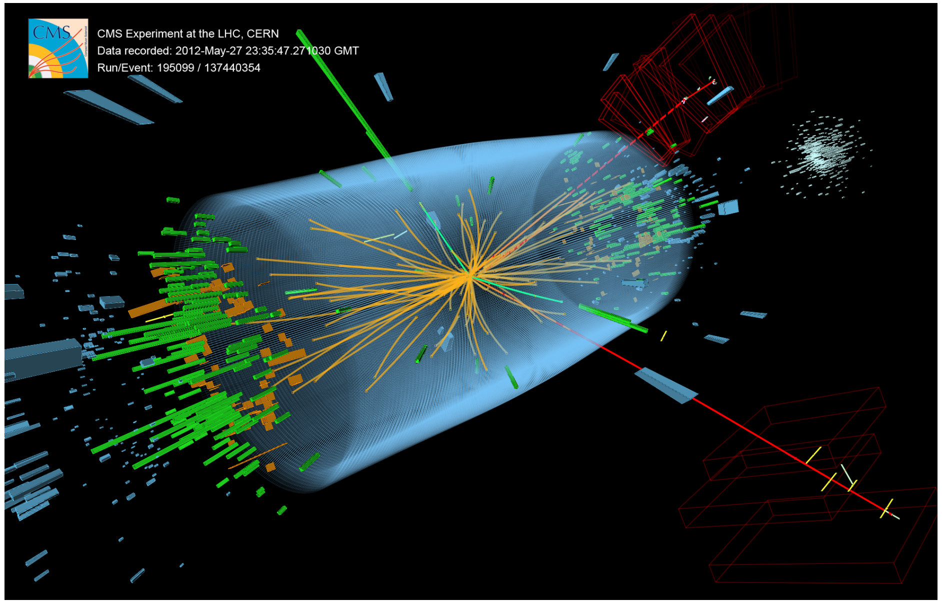
Discovery and experimental studies of the Higgs boson at the LHC





Kirill Prokofiev

INFN Laboratori Nazionali di Frascati

Outline

- Large Hadron Collider at CERN
- Discovery of the new boson
- Status of di-boson decay channels
- Status of fermionic channels
- Properties of the new boson

Large Hadron Collider at CERN

Proton-proton collider

- Circumference 27 km
- 4 main experiments: ALICE (Heavy Ion Collisions), LHC-b (*b*-physics), CMS and ATLAS: general purpose *pp* detectors.

Center-of-Mass Energy:

- Nominal: 14 TeV
- beginning of Run-II: 13 TeV
- Spring-Autumn 2012: 8 TeV
- 2011- beg. 2012: 7 TeV
- 2011: 900 GeV

ATLAS detector overview

EM Calorimeter: ($|\eta|<4.9$) Pb-LAr accordion structure provides e/γ trigger, identification, measurement:

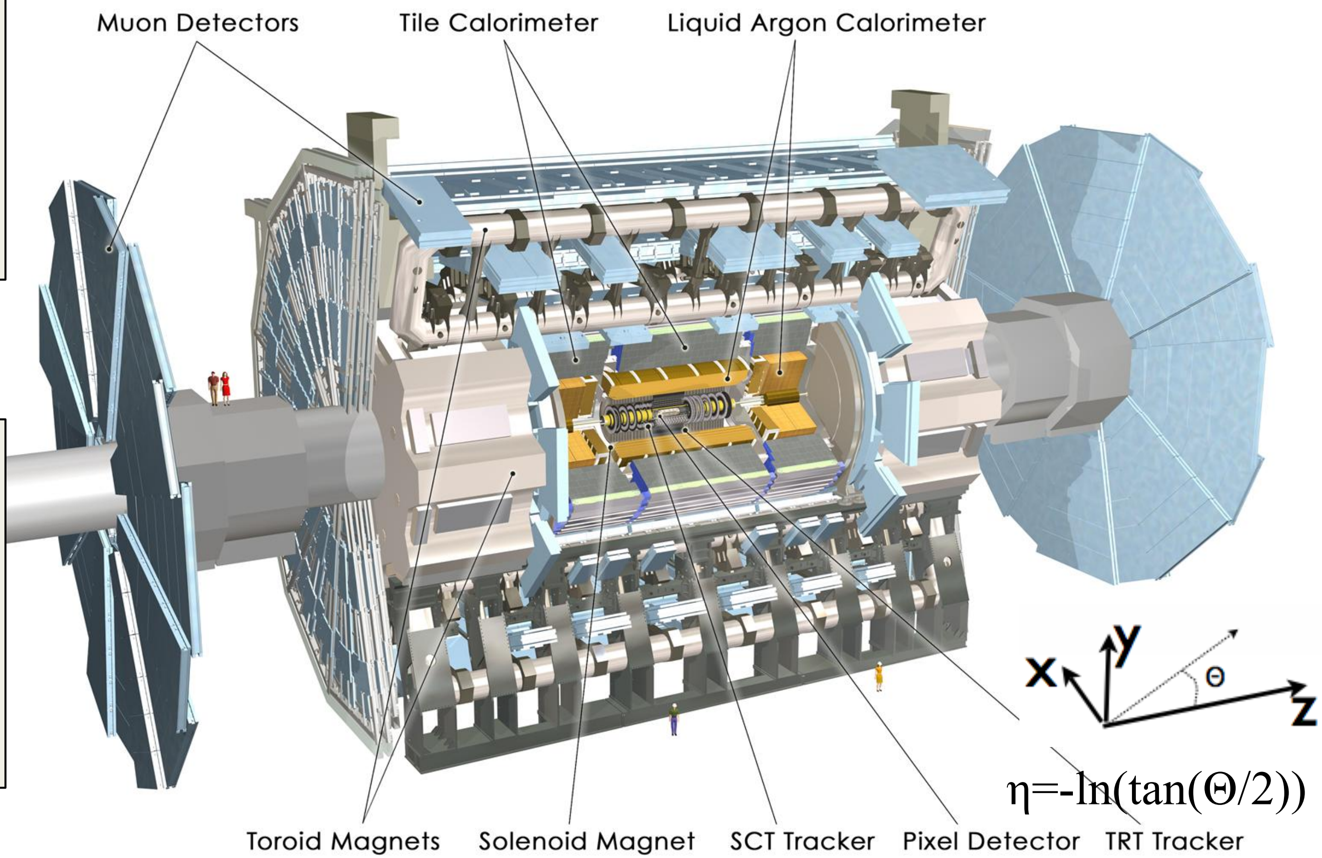
$\sigma/E \sim 10\%\sqrt{E}$

Hadronic (Tile): provides trigger, jet measurement, E_T^{miss}

$\sigma/E \sim 50\%\sqrt{E} \oplus 0.03$. ($|\eta|<1.7$)

The Inner Detector provides around 3 pixel, 8 SCT and 30 TRT measurements per charged track at $\eta = 0$. Coverage: $|\eta| < 2.5$ (2.0 for TRT) Resolution goal:

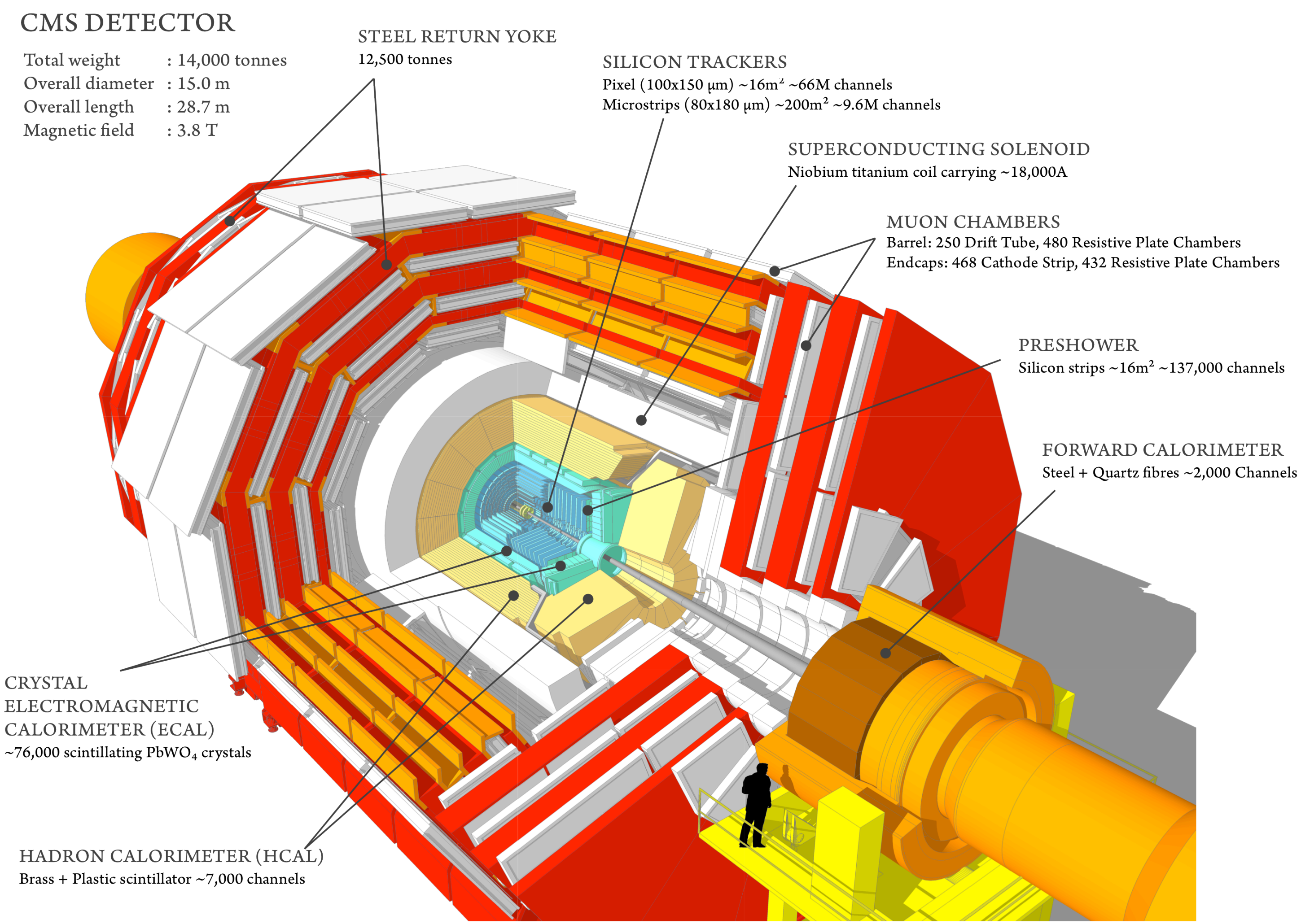
$\sigma_{pT} / p_T = 0.05\%\ p_T \oplus 1\%$



Muon spectrometer: high precision tracking and trigger chambers.
$|\eta|$ coverage up to 2.7.
Magnetic field produced by 3x8 air-core toroids.

CMS detector overview

3.8 T axial superconducting solenoid. Return yoke instrumented with muon chambers: $|\eta| < 2.4$. Silicon strip + pixel tracker $|\eta| < 2.5$. Led-tungsteen crystal Electromagnetic calorimeter, brass + scintillator hadronic calorimeter $|\eta| < 3.0$.



Tracker:

$\sigma_{p_T} / p_T = 1.5\%$ at $p_T = 100$ GeV.

EM Calorimeter:

$\sigma/E \sim 3\%\sqrt{E} + 0.7\%$.

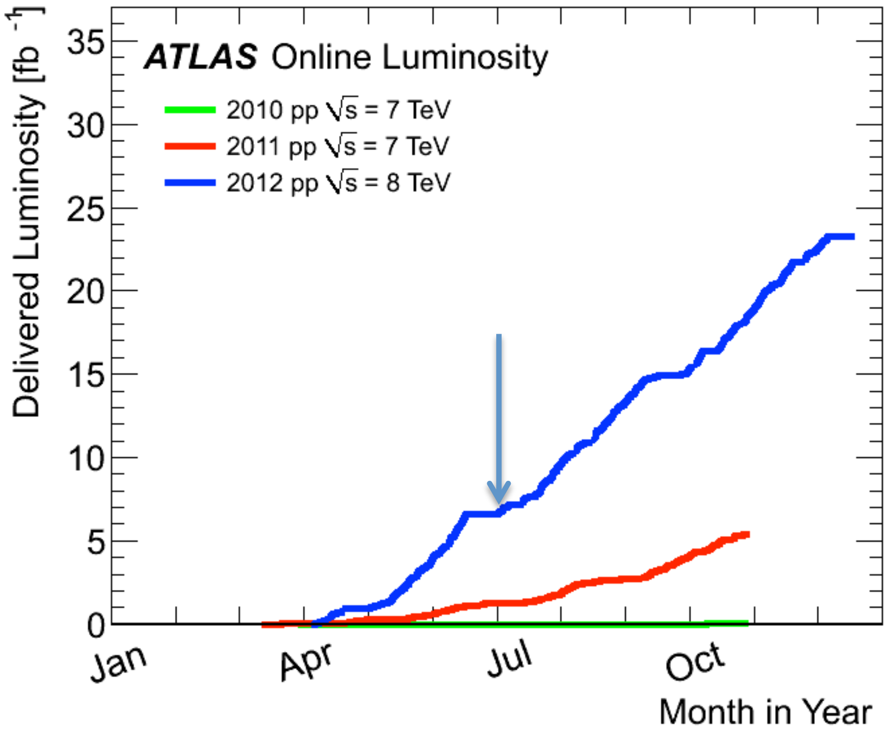
Hadron calorimeter:

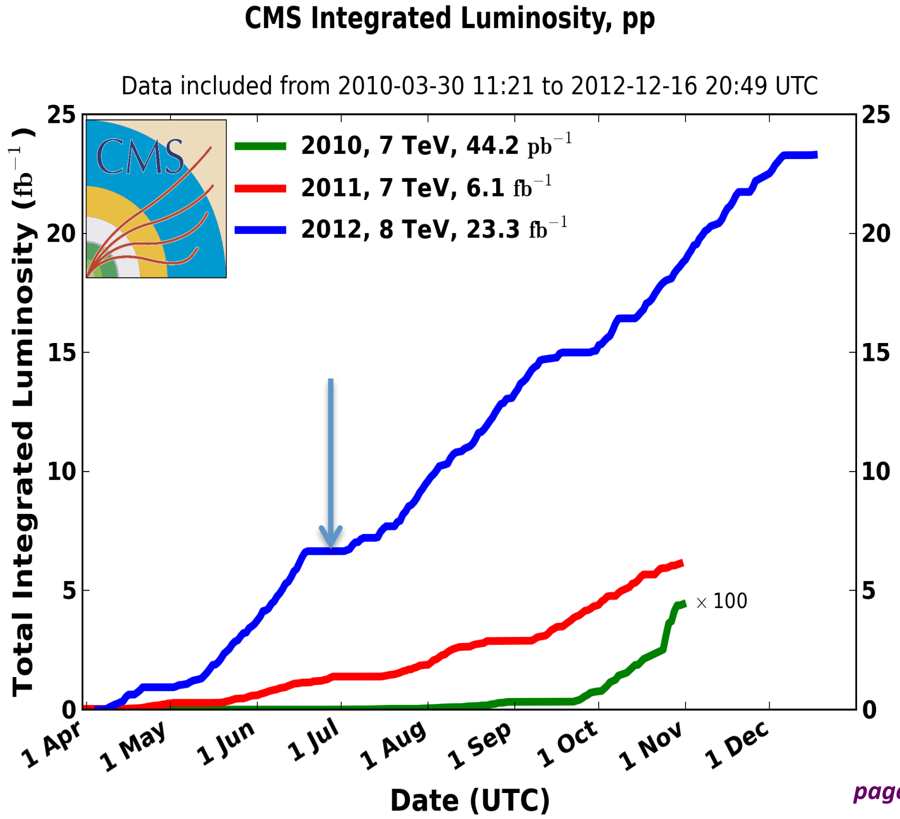
$\sigma/E \sim 85\%\sqrt{E} + 7\%$

ATLAS and CMS during LHC Run-I

	√S	Delivered (fb^{-1})	Recorded (fb^{-1})
pp 2011	7 TeV	**5.61**	**5.25**
pp 2012	8 TeV	**23.3**	**21.7**

	√S	Delivered (fb^{-1})	Recorded (fb^{-1})
pp 2011	7 TeV	**6.1**	**5.55**
pp 2012	8 TeV	**23.3**	**21.79**

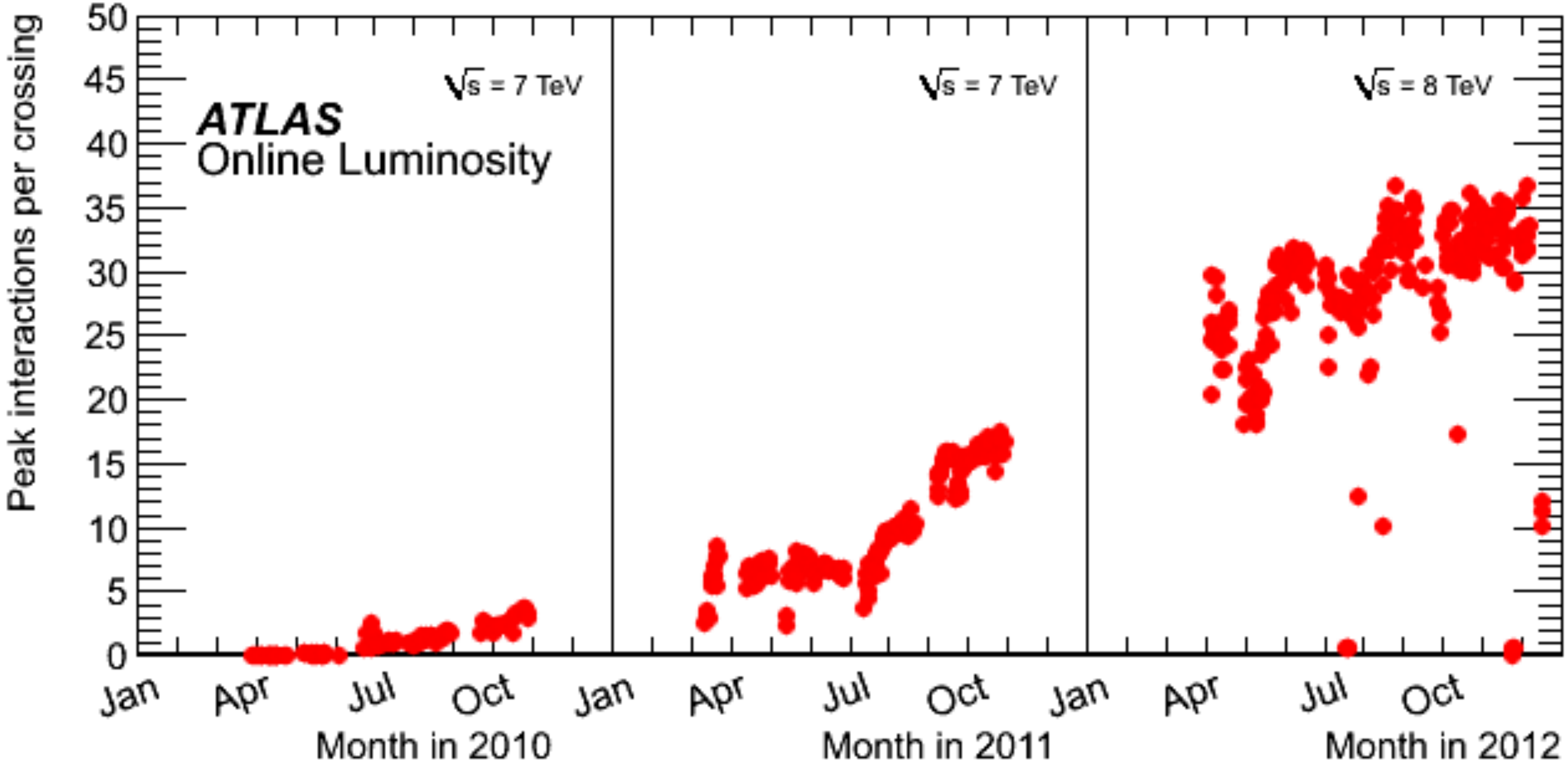




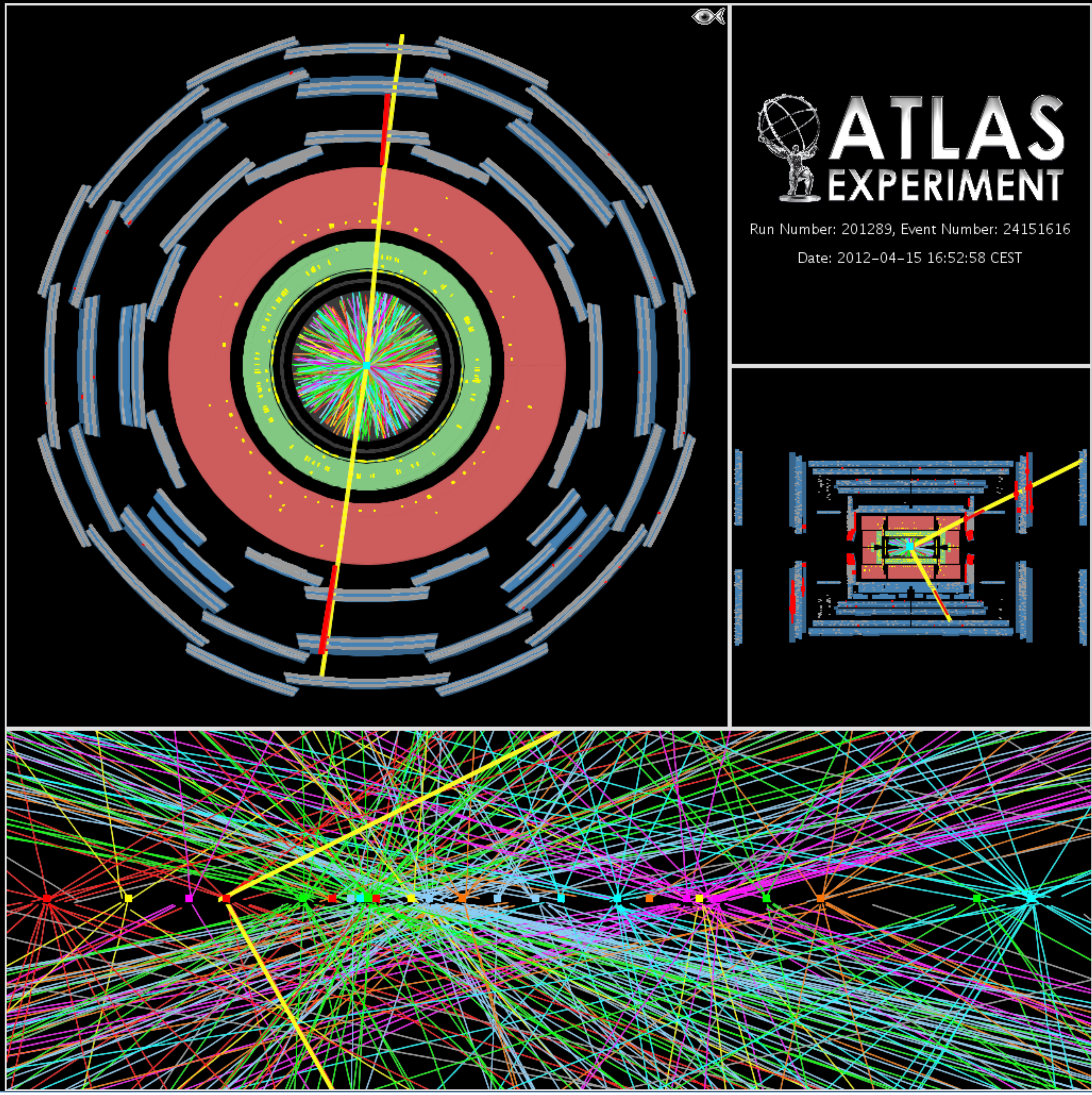
In-time pile-up collisions

Long and very narrow beam spot in ATLAS and CMS.

- Design parameters: in transverse plane $\sigma_{x,y}$ ~ 15µm; In the longitudinal direction σ_Z~5.6cm.
- In-time pile-up: superposition of many *pp* interactions in the same bunch crossing.

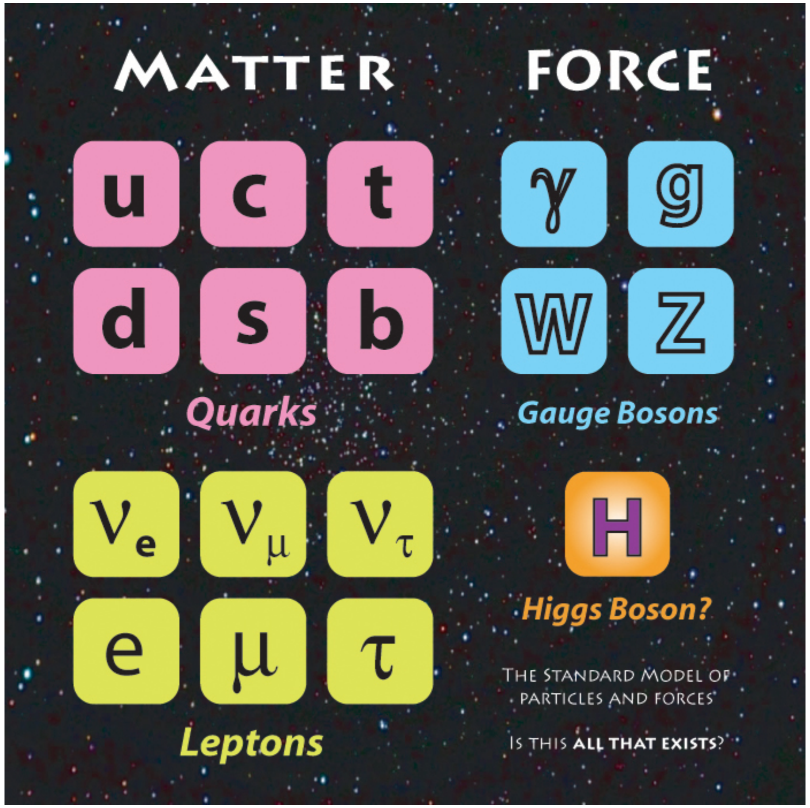


A candidate Z→μμ event with 25 reconstructed pile-up vertices



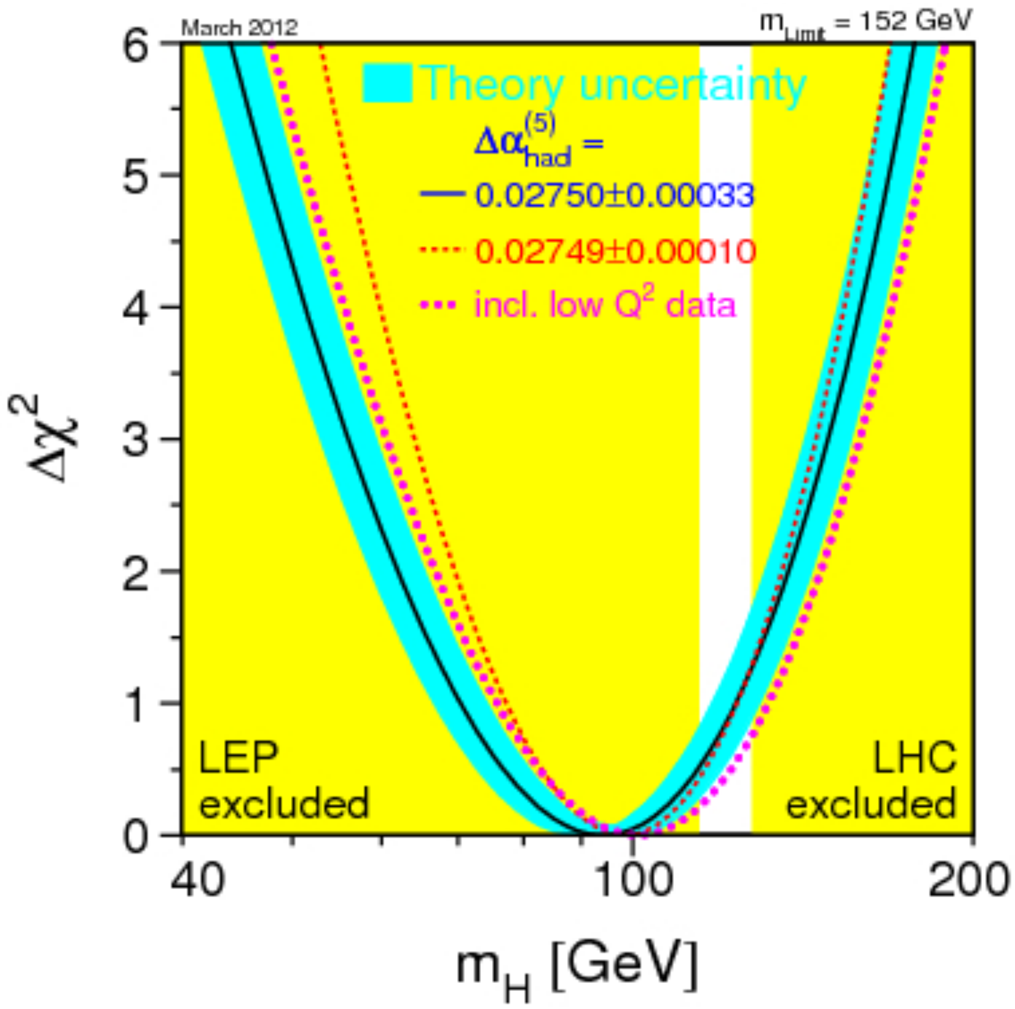
Standard Model Higgs boson

- Higgs mechanism: most probable mechanism for the electroweak symmetry breaking. Used both in the Standard Model and theories beyond.
- In the Standard Model, the vector bosons and the fermions acquire mass via coupling to the Higgs field.
- Physical manifestation of the Higgs field in the Standard Model: single scalar Higgs boson.
- Theories beyond the Standard Model often require presence of several Higgs bosons. So far there is no evidence for multiple Higgs bosons.



arXiv::1203.3774

Standard Model Higgs boson



Mass of the Higgs boson – free parameter of the model.

Situation on March 2012: 4 months before discovery declared.

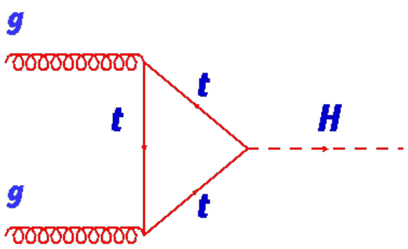
Direct searches ar LEP:
$m_H > 114.4$ GeV.

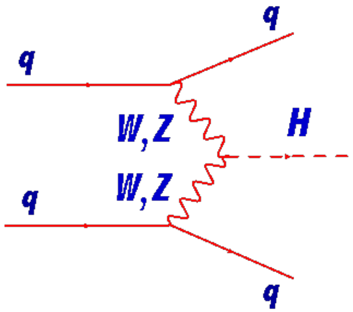
Direct searches at Tevatron:
$m_H < 156$ GeV OR $m_H > 177$ GeV.

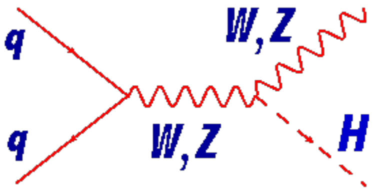
Direct searches at LHC:
$m_H < 127$ GeV OR
600 GeV $< m_H <$ 1 TeV

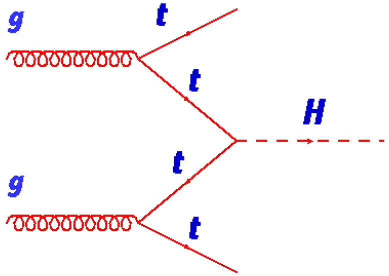
Higgs boson production at LHC

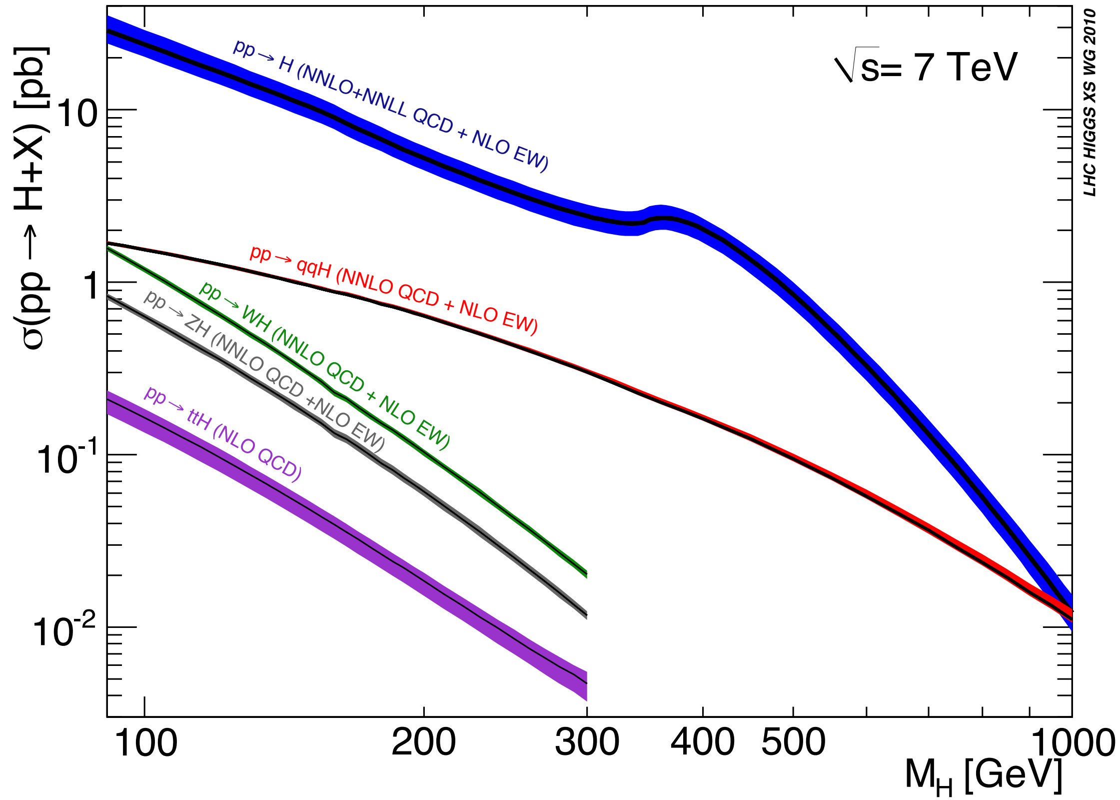
Gluon fusion (ggF)	Vector boson fusion (VBF)	W/Z associated production	tt associated production









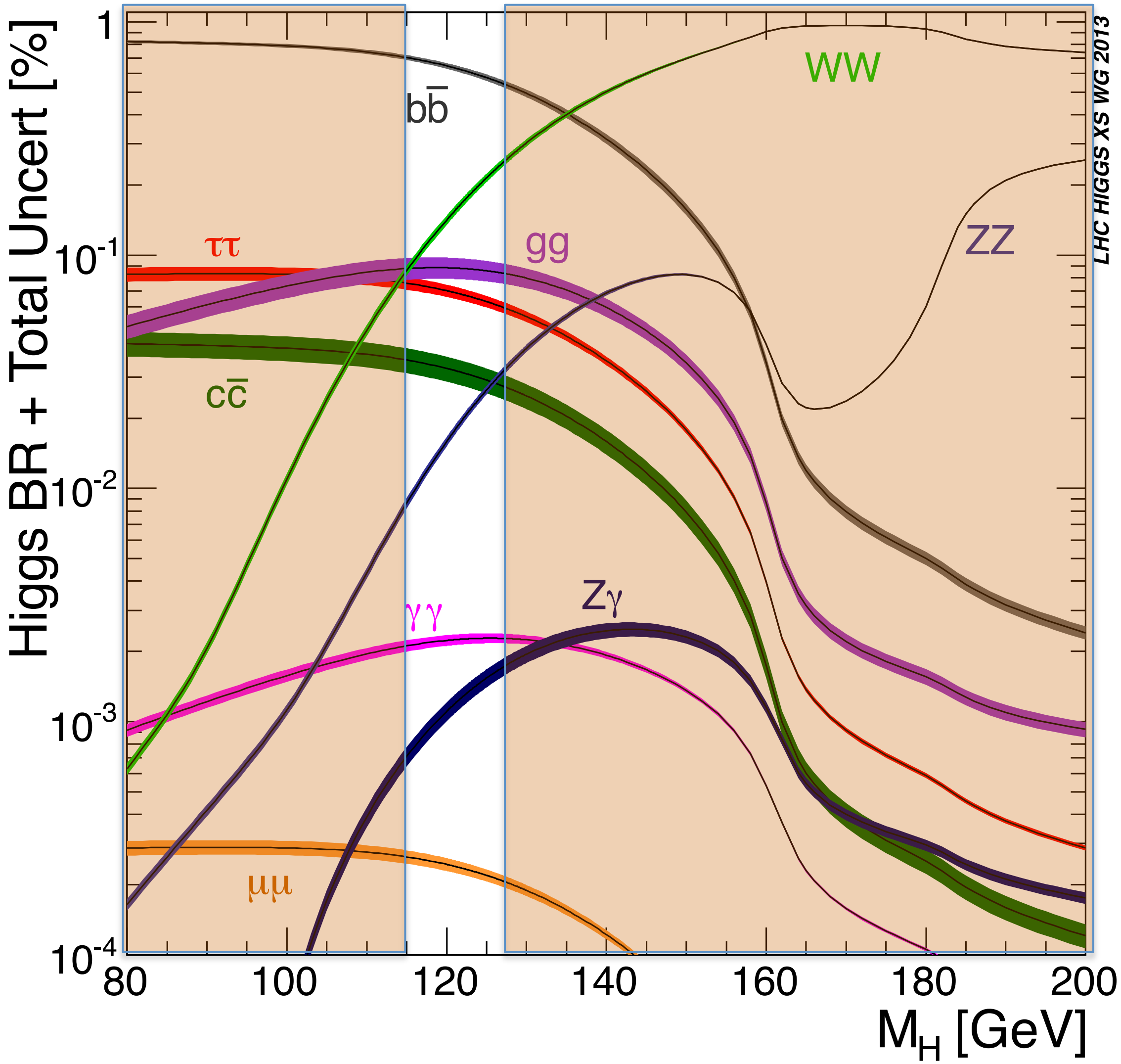


LHC Higgs Cross Section working group: (N)NLO precision calculation for nearly all production processes.

At m_H= 125 GeV:

ggF: 19.5 pb; VBF: 1.6 pb
VH: 1.1 pb; ttH: 0.1 pb

Higgs boson decays at the LHC



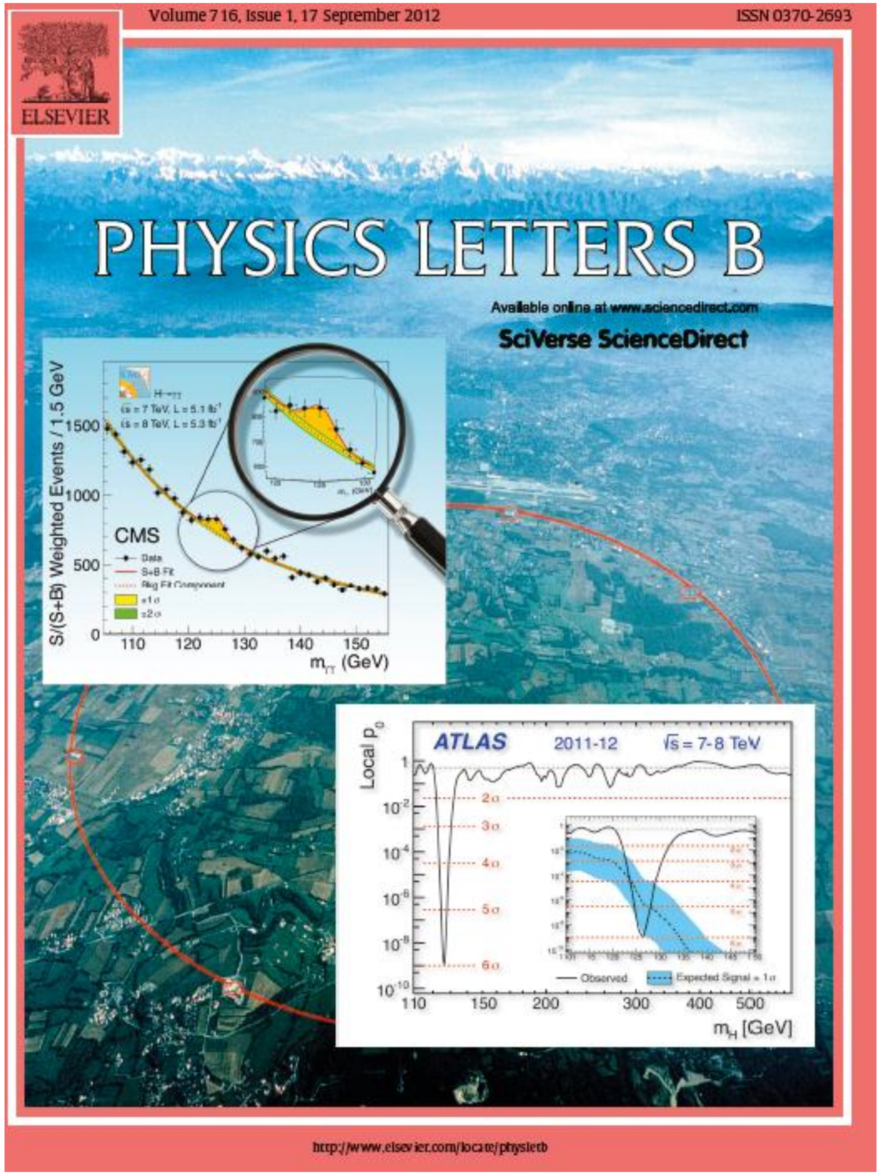
Both fermion and boson couplings.

At m_H= 125 GeV:

bb: 57.7%
WW: 21.5%
ττ: 6.3%
cc: 3%
ZZ: 2.6%
γγ: 0.23%
μμ: 0.02%

Standard Model expected width: Γ = 4 MeV at m_H=125GeV.
Not directly detectable at the LHC.

LHC Higgs Cross-Section Working group



Discovery of a new boson declared by ATLAS and CMS on July 4 2012…

Discovery of the new resonance

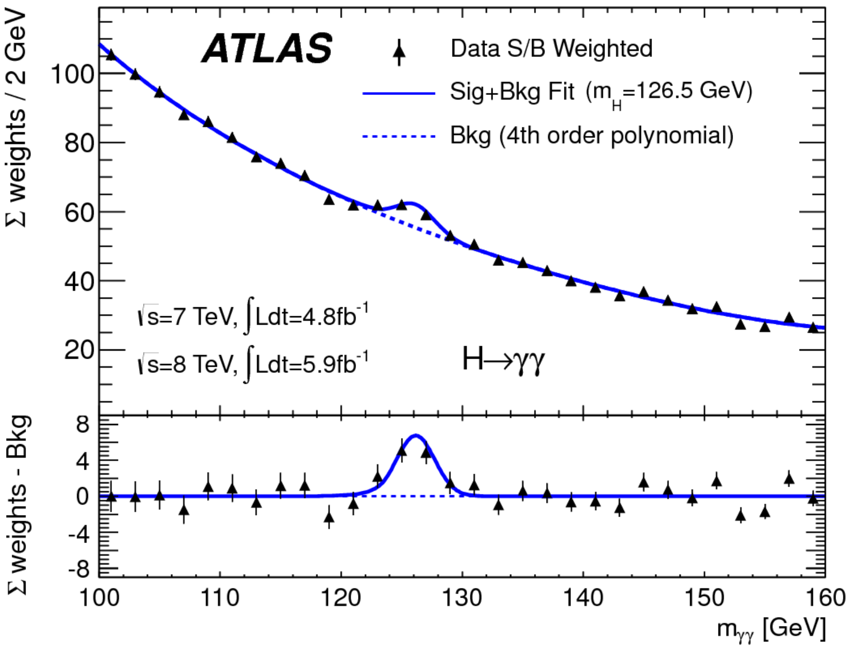
- CMS: 10.4 fb^{-1}. Excess with local significance of 5.0σ (exp. 5.8σ).

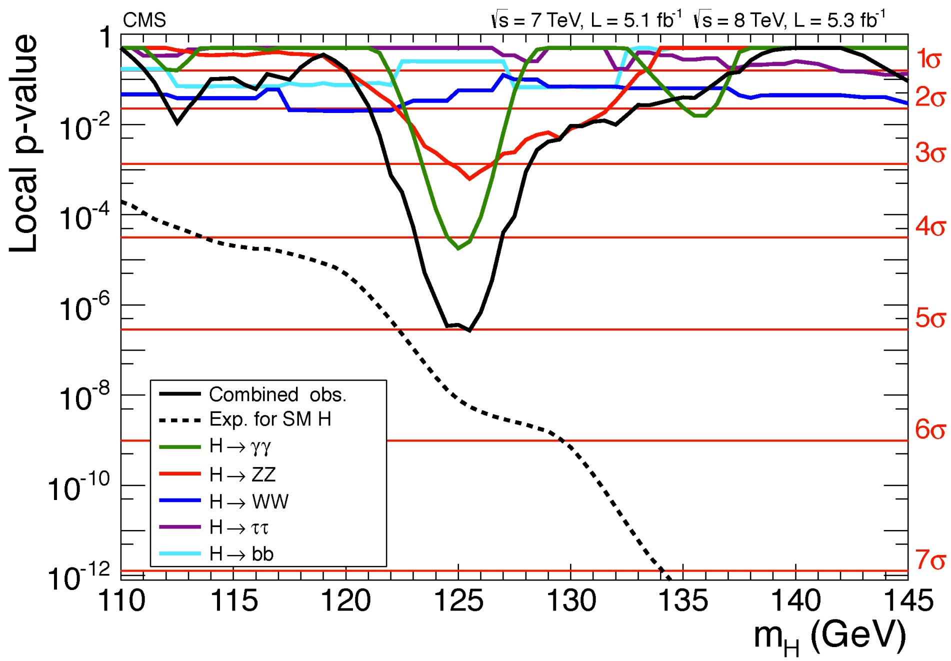
  m_H = 125.3 ± 0.4 (stat) ± 0.5 (sys) GeV.

- ATLAS: 10.6 fb^{-1}. Excess with local significance of 5.9σ (global: 5.1σ).

  m_H = 126.0 ± 0.4 (stat) ± 0.4 (sys) GeV.

In both cases the observed excess is driven by the γγ, ZZ^* and WW^* decay channels.





Phys. Lett. B 716 (2012) 1-29, 30-61

Is it a Higgs boson? More precisely, is it the Standard Model Higgs boson?

http://www.nobelprize.org/nobel_prizes/physics/laureates/2013/press.html

Press Release

8 October 2013

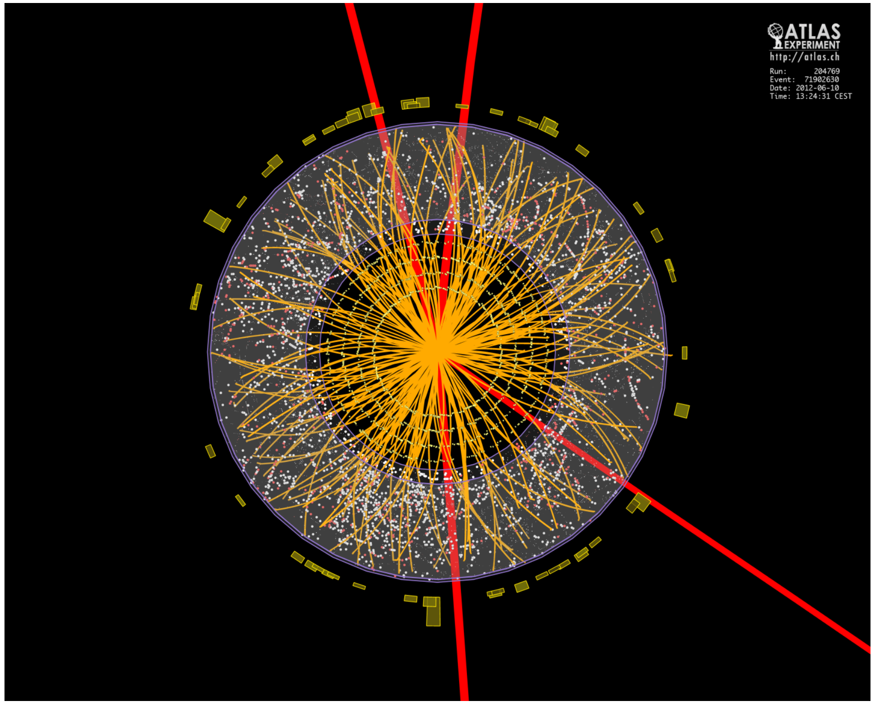
The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2013 to

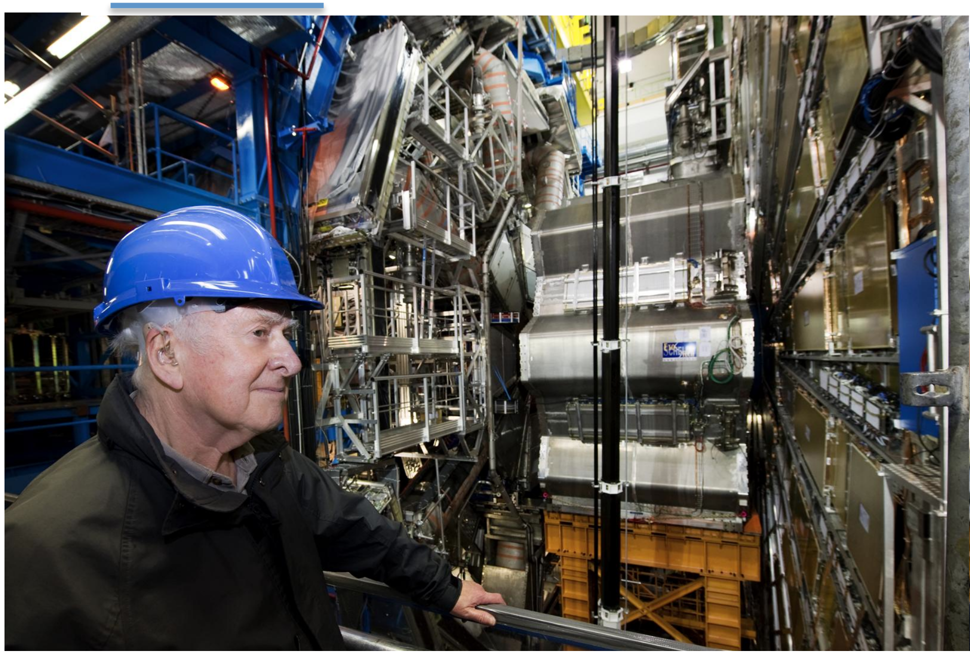
François Englert
Université Libre de Bruxelles, Brussels, Belgium

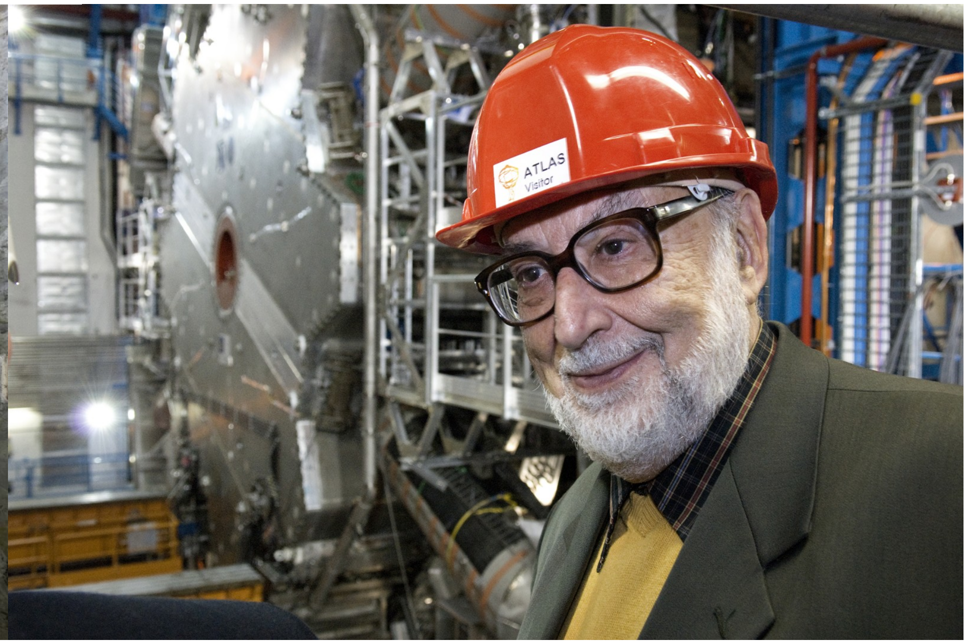
and

Peter W. Higgs
University of Edinburgh, UK

"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"







Main channels investigated

	ATLAS				CMS			
	ggF	VBF	VH	ttH	ggF	VBF	VH	ttH
H→γγ	✔	✔	✔	✔	✔	✔	✔	✔
H→ZZ$^{(*)}$→4l	✔	✔			✔	✔		
H→WW$^{(*)}$→lνlν	✔	✔	✔		✔	✔	✔	
H→ττ	✔	✔	✔		✔	✔	✔	✔
H→bb			✔	✔		✔	✔	✔
H→μμ	(inclusive)							

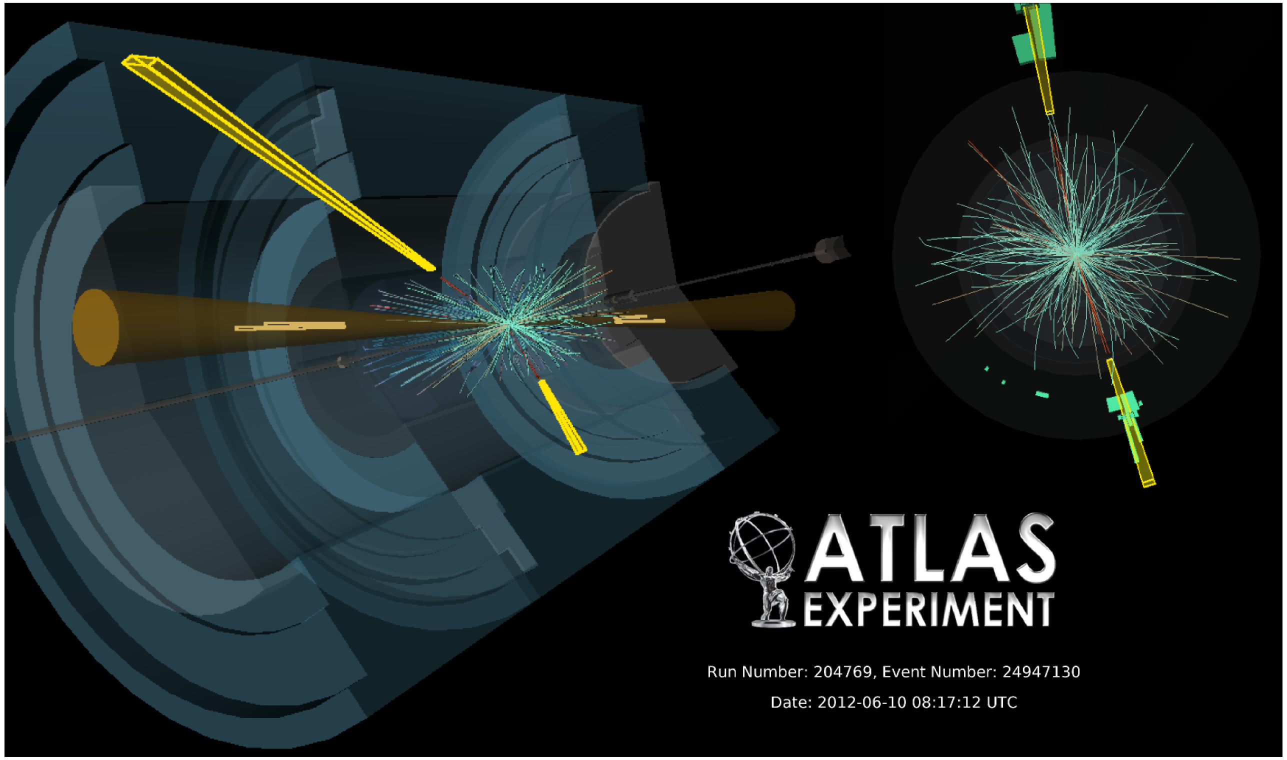
Both Collaborations are currently working on legacy papers for the LHC run-I. More results to come by Spring 2014. Stay tuned…

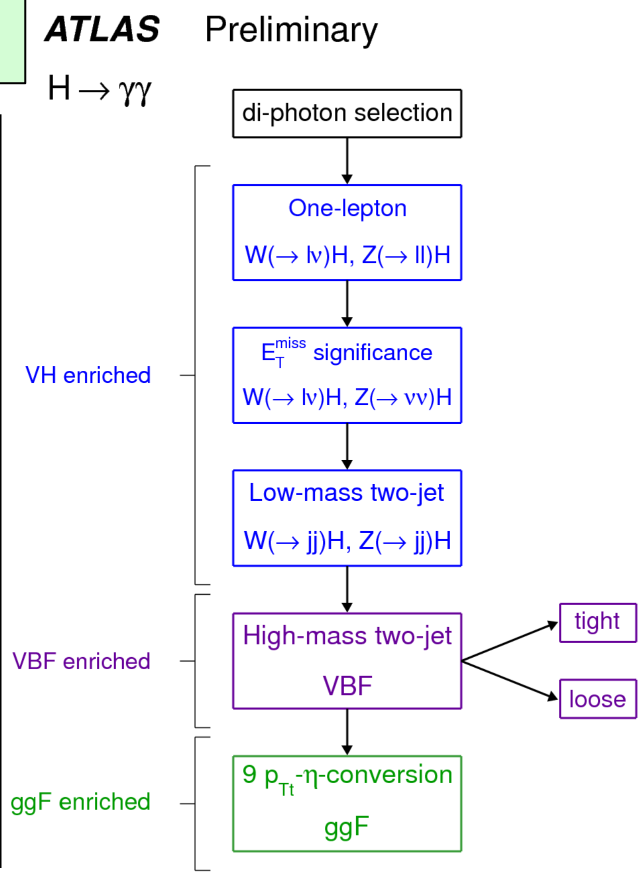
Current status of the Higgs boson:
di-boson decays

Higgs boson searches in H→γγ decay (ATLAS)

- Mass range: 100-160 GeV.
- Two isolated photons with $E_T(\gamma)$>40, 30 GeV.
- 14 exclusive categories according to S/B and resolution. Separate contributions from ggF, VH, VBF.

4.8 fb^{-1} at 7 TeV and 20.7 fb^{-1} at 8 TeV.





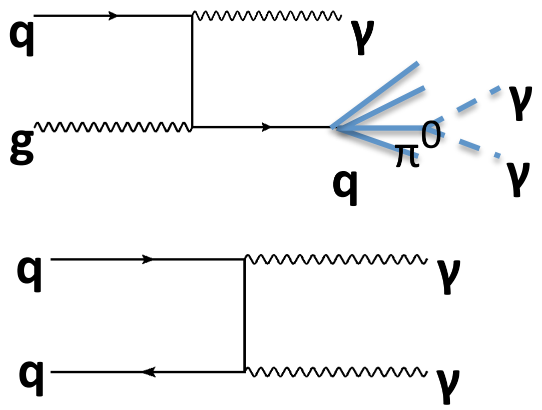
Phys. Lett. B 726 (2013), pp. 120-144 ATLAS-CONF-2013-012

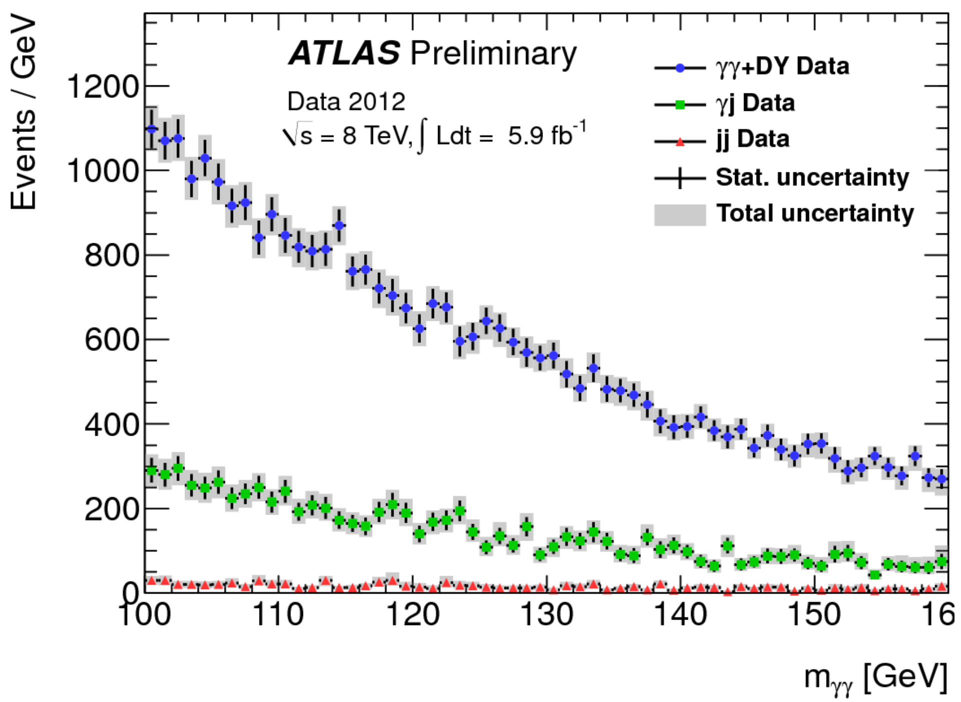
Higgs boson searches in H→γγ decay (ATLAS)

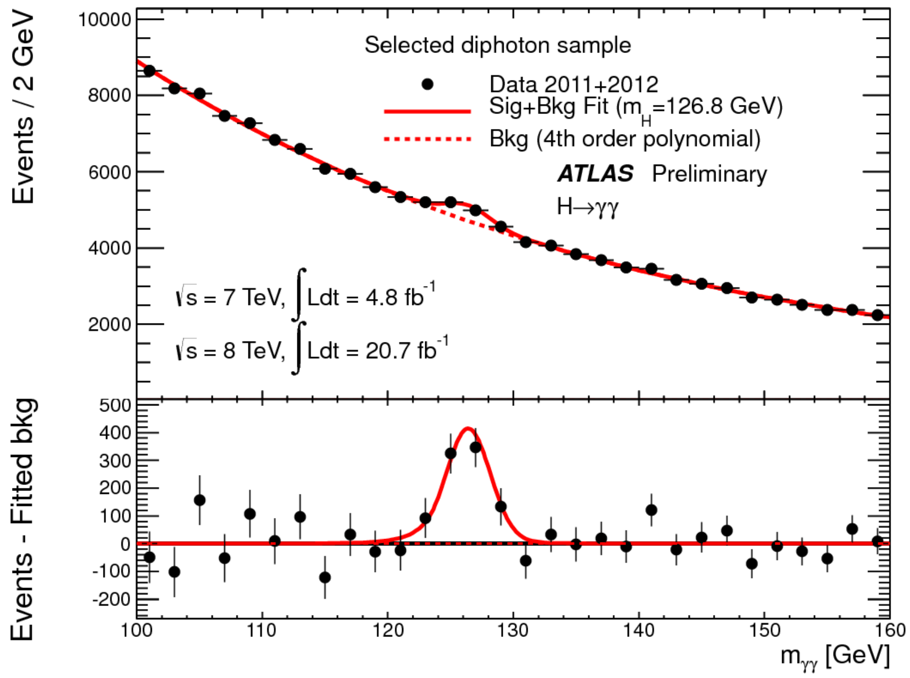
S/B ~3% in mass region around 125 GeV with 90% signal.

Background processes: γγ [~75%], γ-jet and jet-jet [~25%]

Backgrounds extrapolated from side-bands in data.







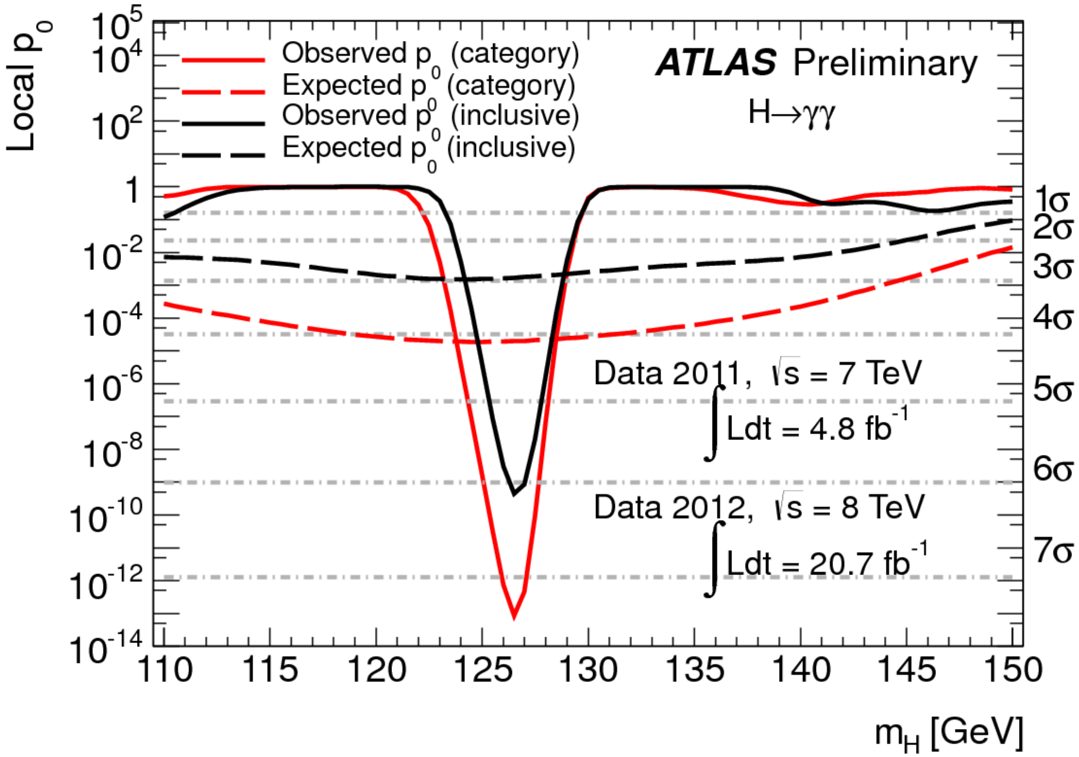
ATLAS-CONF-2013-012

142681 events in 100 <$m_{\gamma\gamma}$<160 GeV

Higgs boson searches in H→γγ decay (ATLAS)

- Categories observed (expected): 7.4σ (4.1σ) at m_H=126.5 GeV.
- Inclusive observed (expected): 6.1σ (2.9σ).

- ATLAS H→γγ can claim a discovery on its own right!



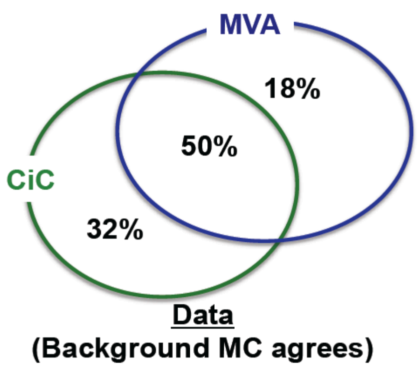
- Best fit mass value:

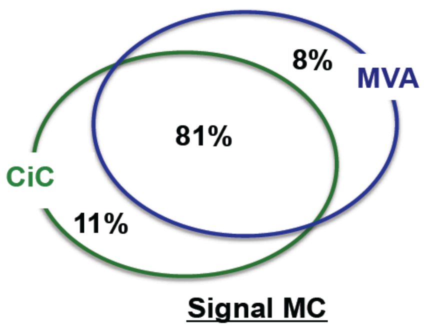
  m_H= 126.8 ± 0.2 (stat.) ± 0.7 (sys) GeV.

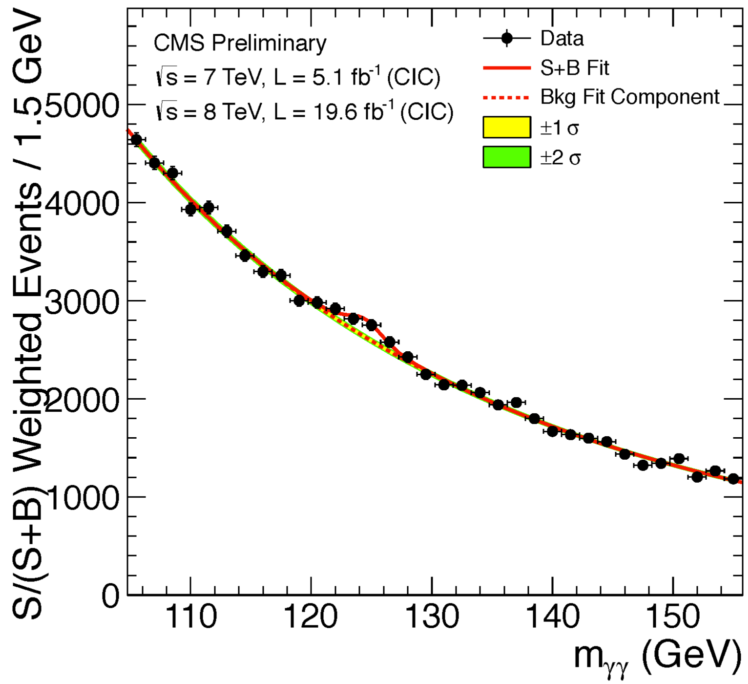
Signal strength: $\mu = \sigma/\sigma^{SM} = 1.65^{+0.24}_{-0.24}$ (stat.) $^{+0.25}_{-0.18}$ (sys.)

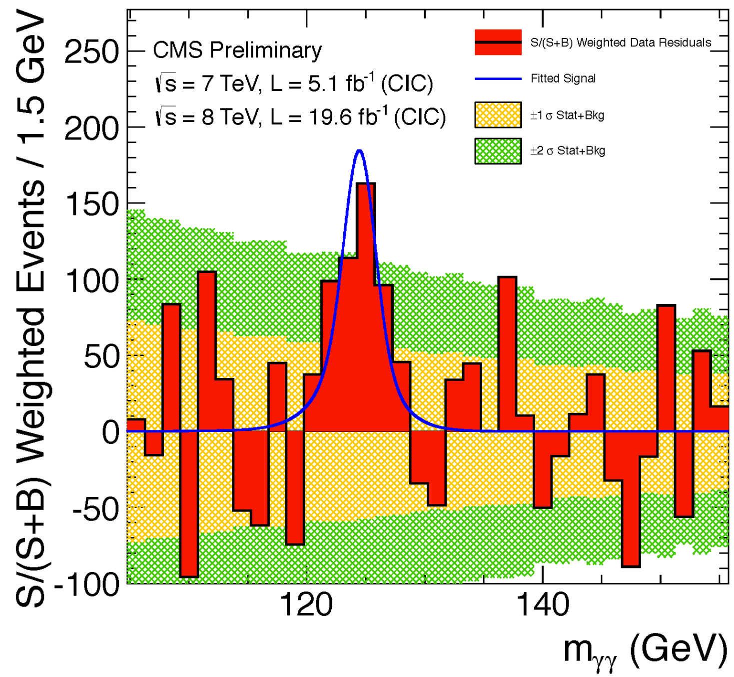
Higgs boson searches in H→γγ decay (CMS)

- Two approaches:
  - Cut-based analysis in categories (similar to ATLAS).
  - MVA classification of events based on di-photon kinematics and mass resolution.
- Weighted di-photon mass spectra for the cut-based analysis.



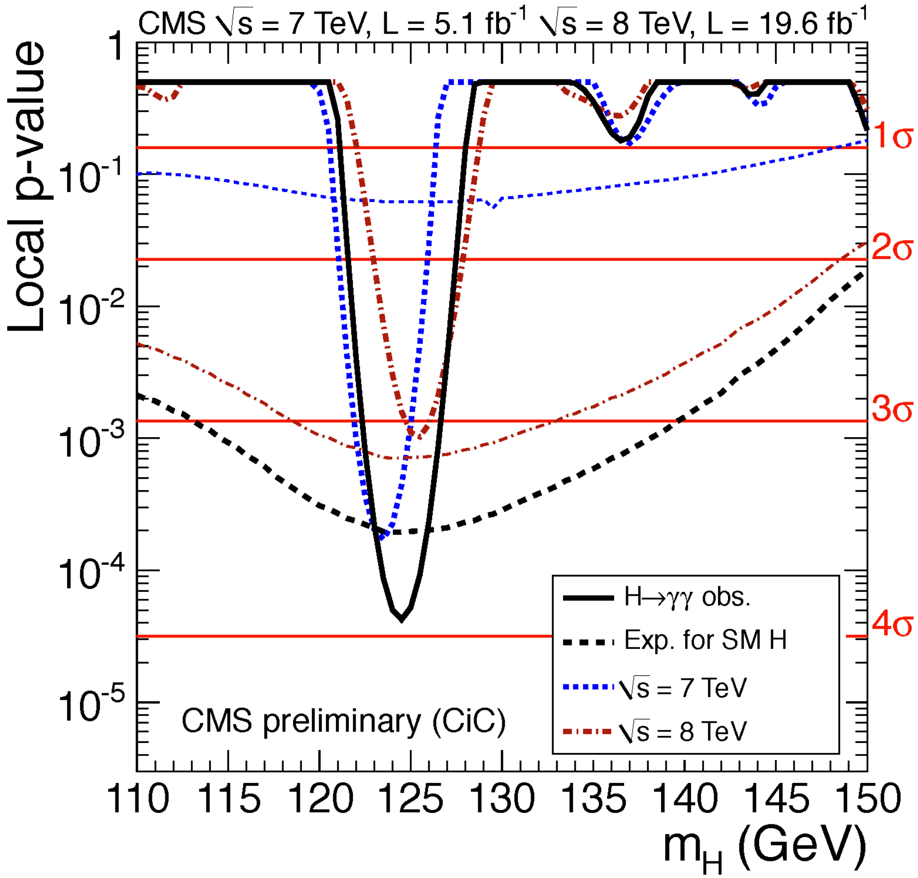






CMS-PAS-HIG-13-001

Higgs boson searches in H→γγ decay (CMS)



Observed excess around m_H=125 GeV.

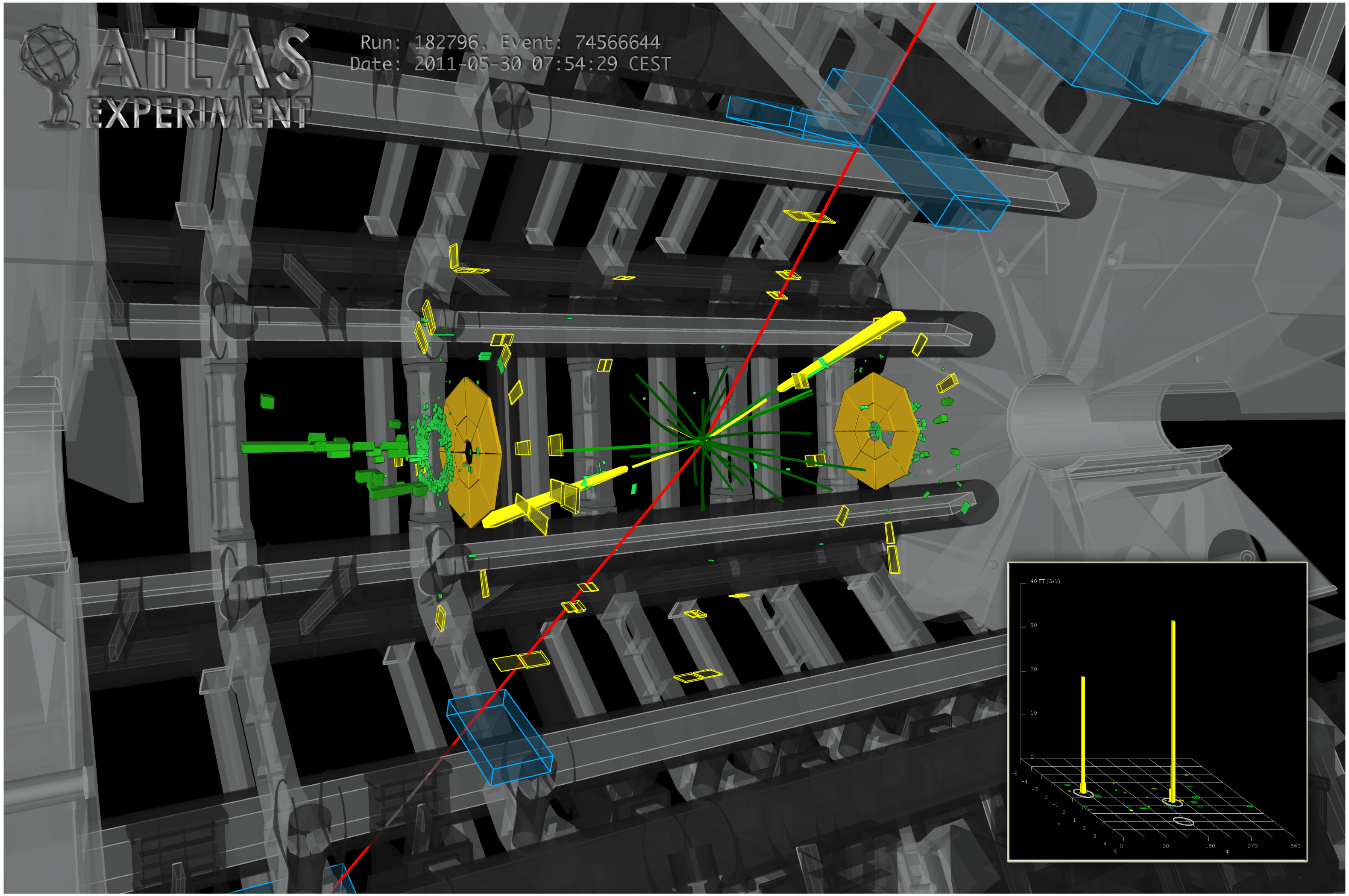
Local significance for the cut-based analysis: 3.9σ (exp. 3.5σ)

… for the MVA analysis: 3.2σ (exp. 4.2σ)

	MVA analysis (at m_H=125 GeV)	cut-based analysis (at m_H=124.5 GeV)
7 TeV	$1.69^{+0.65}_{-0.59}$	$2.27^{+0.80}_{-0.74}$
8 TeV	$0.55^{+0.29}_{-0.27}$	$0.93^{+0.34}_{-0.32}$
7 + 8 TeV	$0.78^{+0.28}_{-0.26}$	$1.11^{+0.32}_{-0.30}$

Best fit
m_H= 125.4 ± 0.8 GeV

Higgs searches in $H \rightarrow ZZ^{(*)} \rightarrow llll$ decay



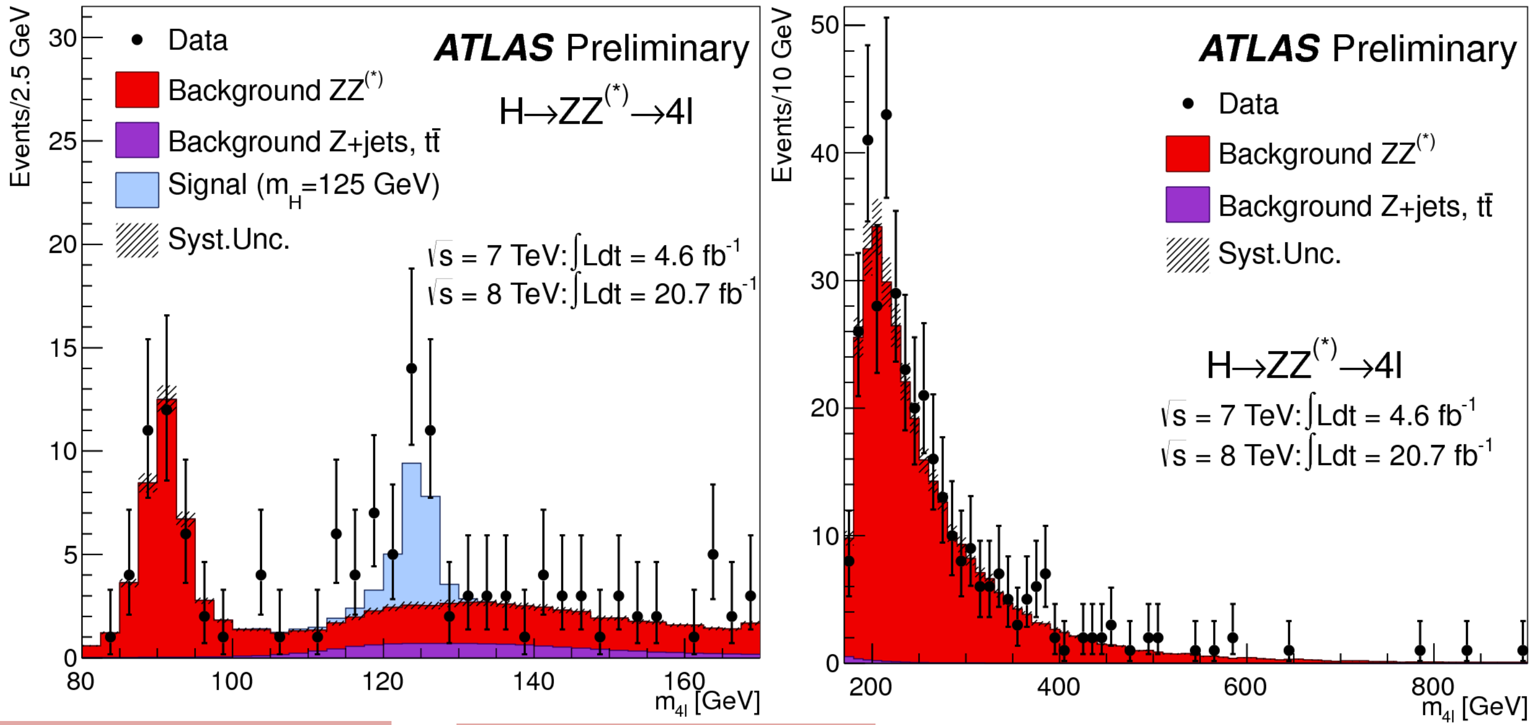
2e2μ event candidate m_{4l} = 124.3 GeV

Higgs searches in H→ZZ$^{(*)}$→llll decay (ATLAS)

- Four isolated leptons: 2 same flavour, opposite charge lepton pairs (one) consistent with Z mass.

- Categories: VBF-like: two high p_T jets; VH-like: not VBF + additional lepton; ggF like: all remaining selected events.

- High S/B ratio, large mass range, channel dominated by statistics.



Phys. Lett. B 726 (2013) pp. 88-119

ATLAS-CONF-2013-013

Higgs searches in H→ZZ$^{(*)}$→llll decay (ATLAS)

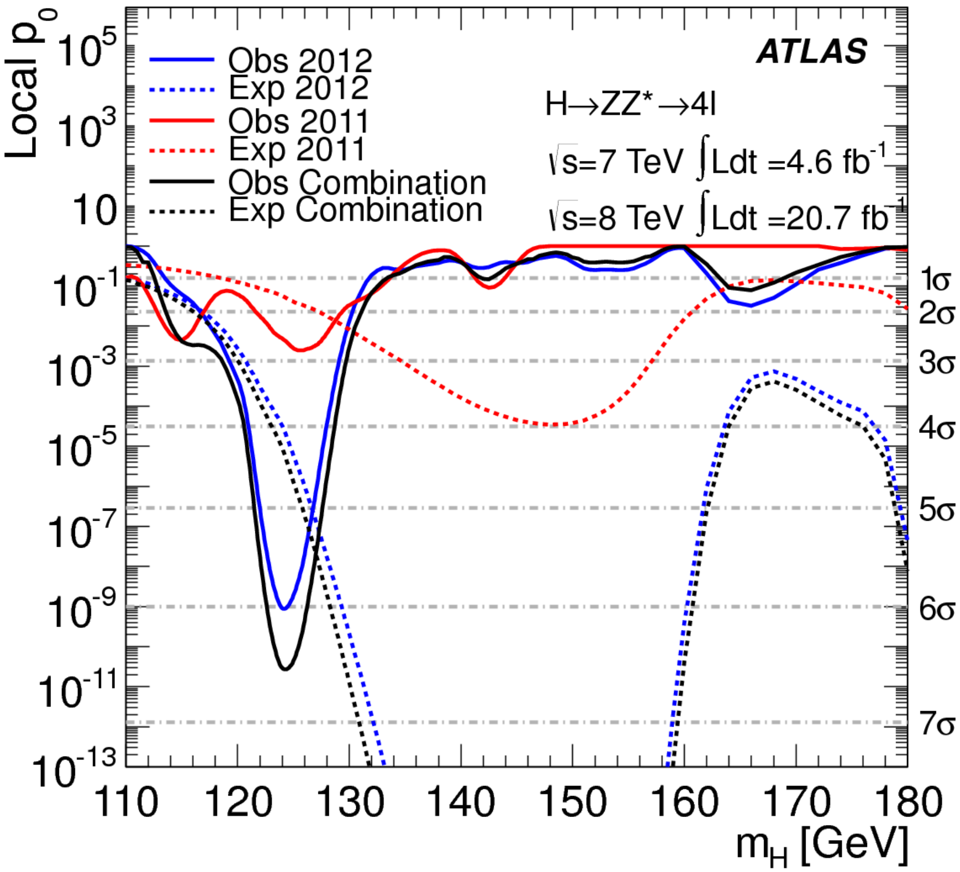
- An excess with a local significance of 6.6σ at 124.3 GeV.
  - The H→ZZ$^{(*)}$→4l can claim discovery on its own right.

Mass measurement:

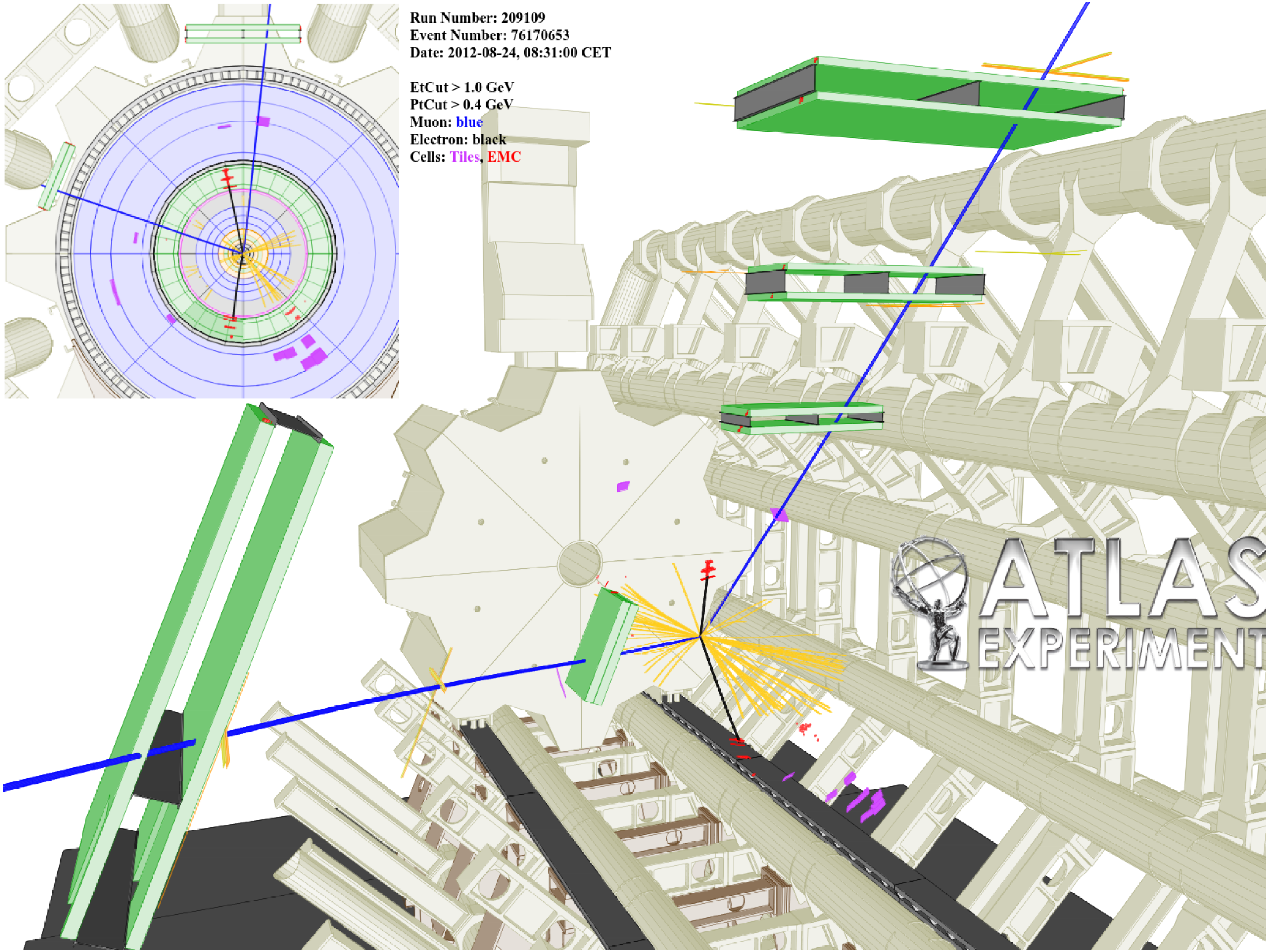
$m_H = 124.3^{+0.6}_{-0.5}$ (stat)$^{+0.5}_{-0.3}$ (syst) GeV.

(note the difference to the H→γγ result)

Measured signal strength:
$\mu = 1.7^{+0.5}_{-0.4}$



H→4l Single Highest Purity VBF Candidate Event (2e2μ)

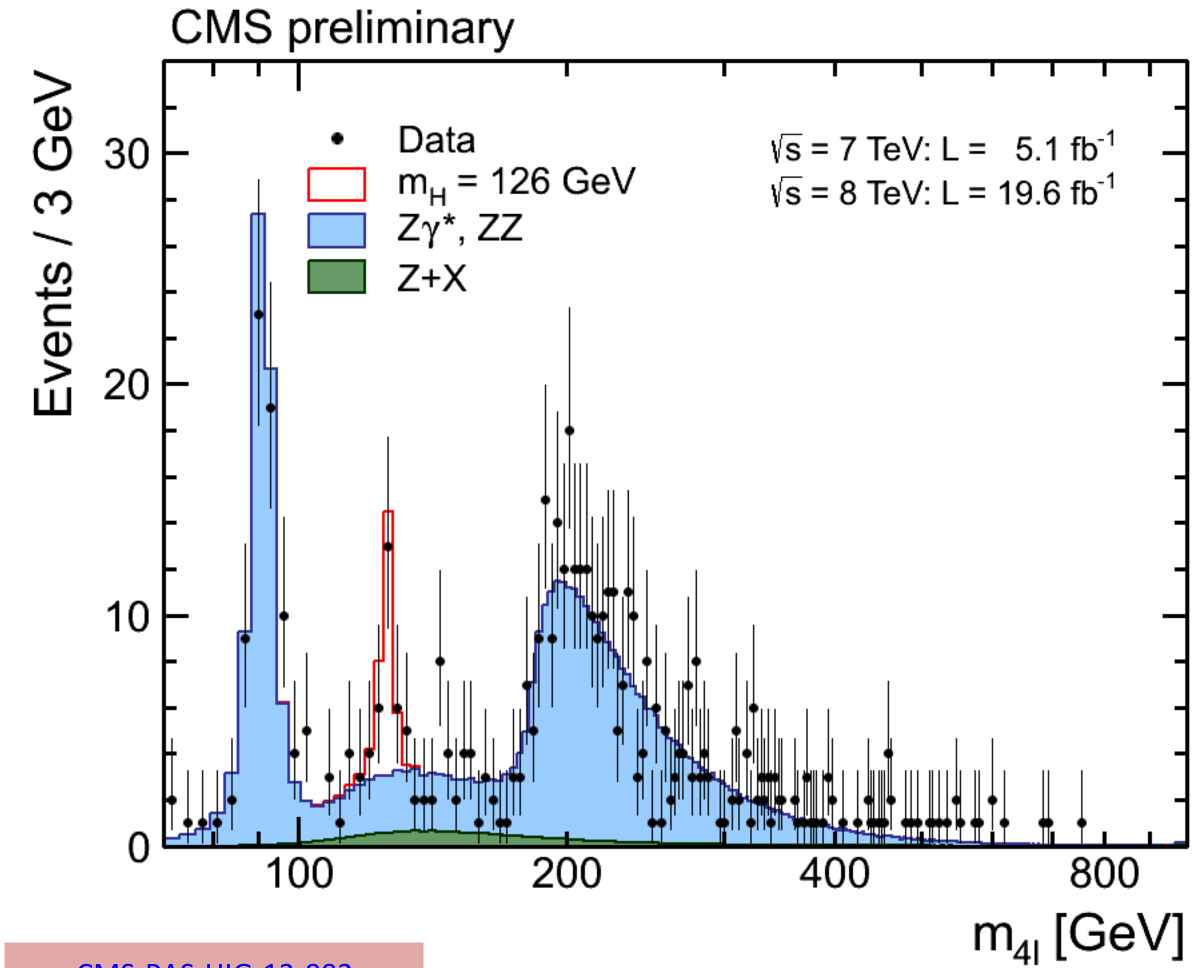


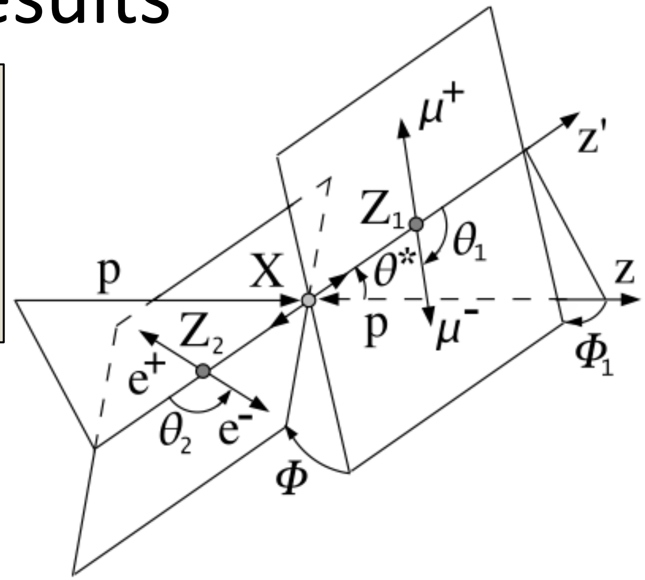
(More on categories and production mechanisms below..)

CMS H→ZZ$^{(*)}$→llll results

Two lepton pairs, one compatible with on-shell Z.

Categories: Events with fewer than two jets (5% VBF)
Events with at least two jets (20% VBF)





Using kinematic variables to suppress the reducible background: m_1, m_2, Θ_1, Θ_2, Φ, Φ_1.

$$\mathrm{MELA} = \left[1 + \frac{\mathcal{P}_{\mathrm{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\mathrm{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$

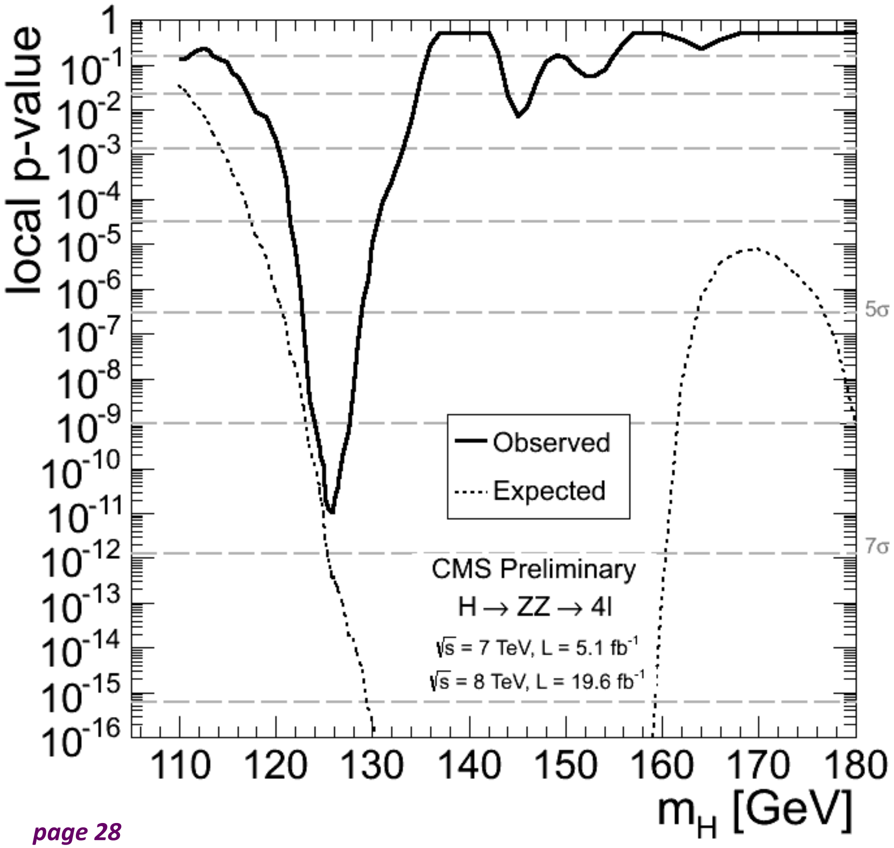
CMS-PAS-HIG-13-002

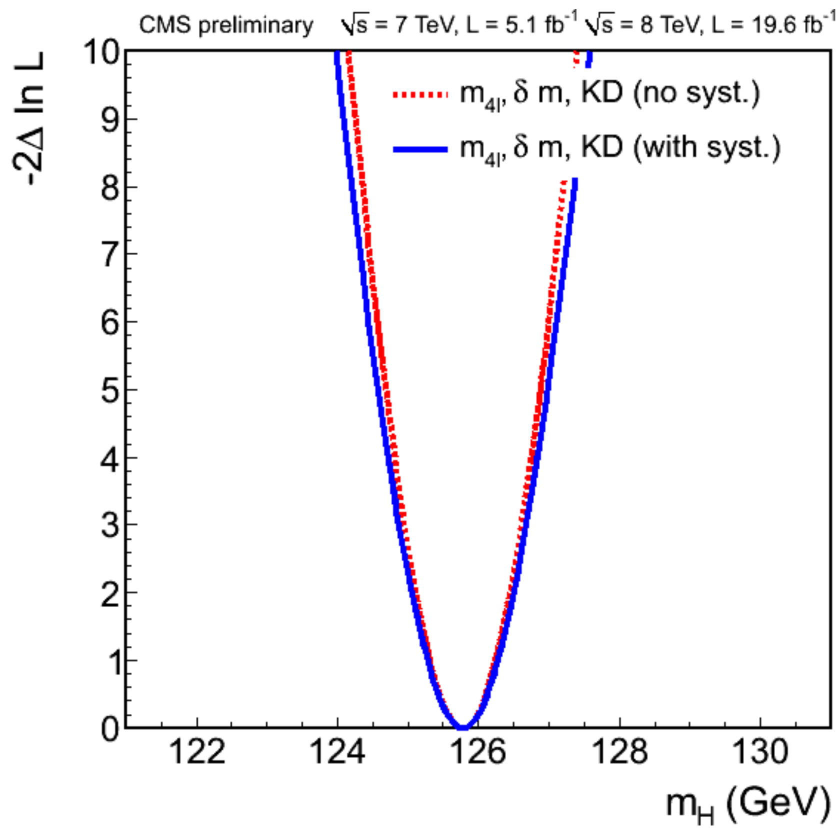
CMS H→ZZ(*)→llll results

Minimum of the local p-value at m_{4l} = 125.8 GeV, corresponds to a local significance of 6.7σ (exp. 7.2σ).

$\mu = 0.91^{+0.30}_{-0.24}$ at 125.8 GeV.

Mass measurement: m_H = 125.8 ± 0.5 (stat.) ± 0.2 (syst.) GeV.





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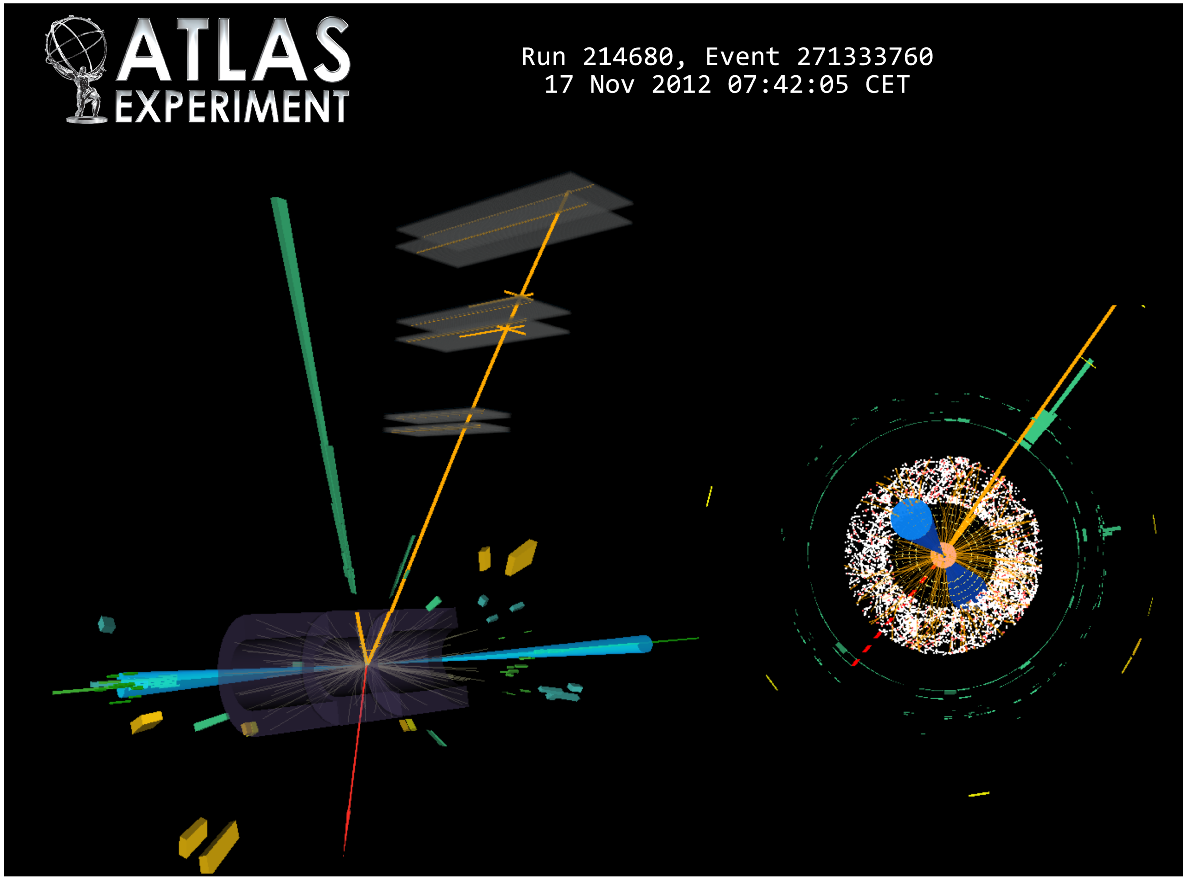
Higgs boson searches in $H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$ (ATLAS)

- Full mass reconstruction is not possible: m_T as discriminating variable.
- Two opposite charge leptons $p_T(l_1,l_2)$>25, 15 GeV + missing E_T.



- Categories: $N_{jet}\leq1$, $N_{jet}\geq2$

- Dominant backgrounds:
  - Dibosons: $WW^{(*)}$ (+ jets).
  - tt, Wt,
  - DY, W+jets etc...
- Mostly estimated from dedicated control regions
- m_{ll}, $\Delta\phi_{ll}$ cuts to suppress WW background.

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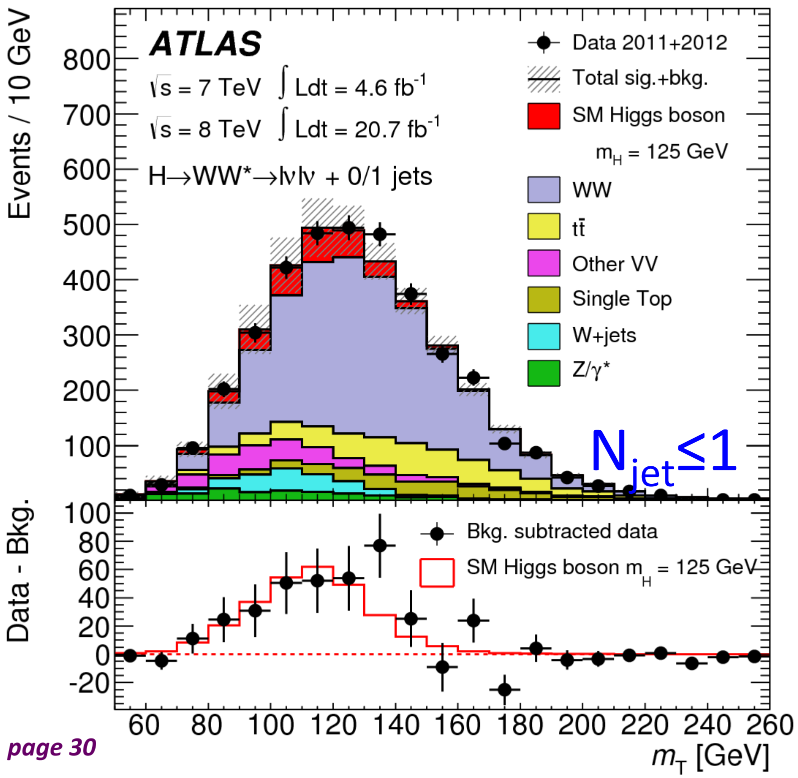
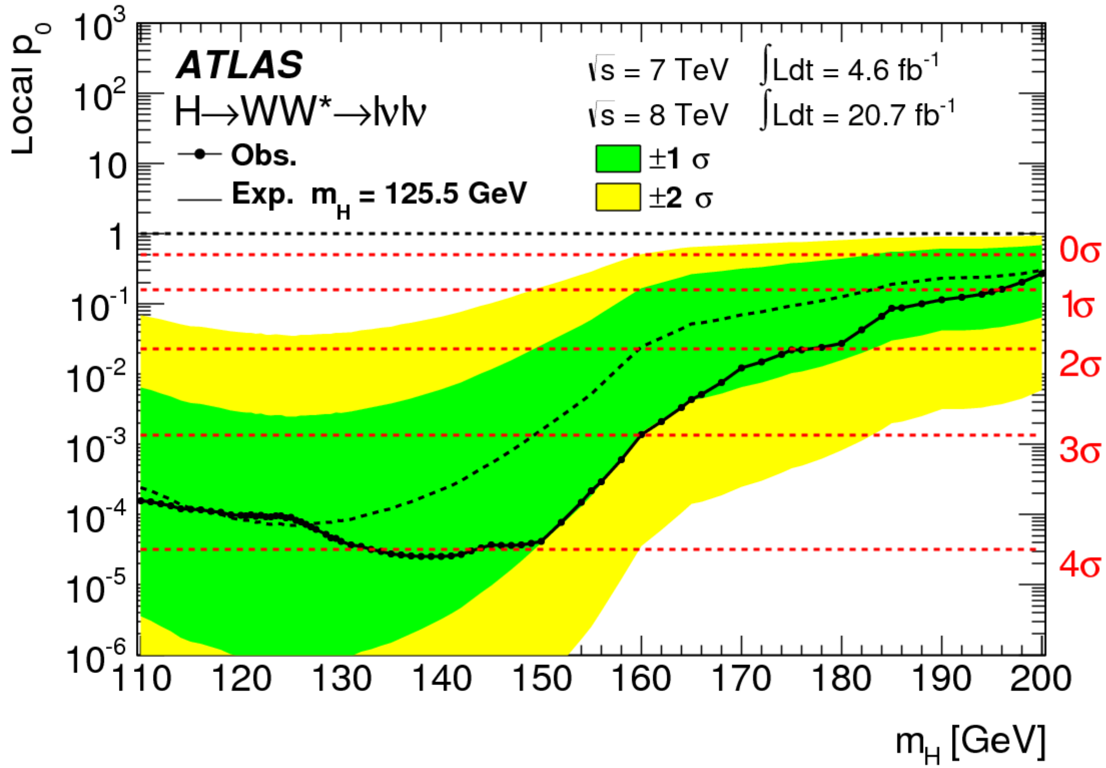
Higgs boson searches in H→WW$^{(*)}$→lνlν (ATLAS)

For m_H around 125 GeV: no signal expected in m_T>150 GeV. Excellent agreement between data and expectations.

Signal visible in both N_{jet}≤1 and N_{jet}≥2 categories.

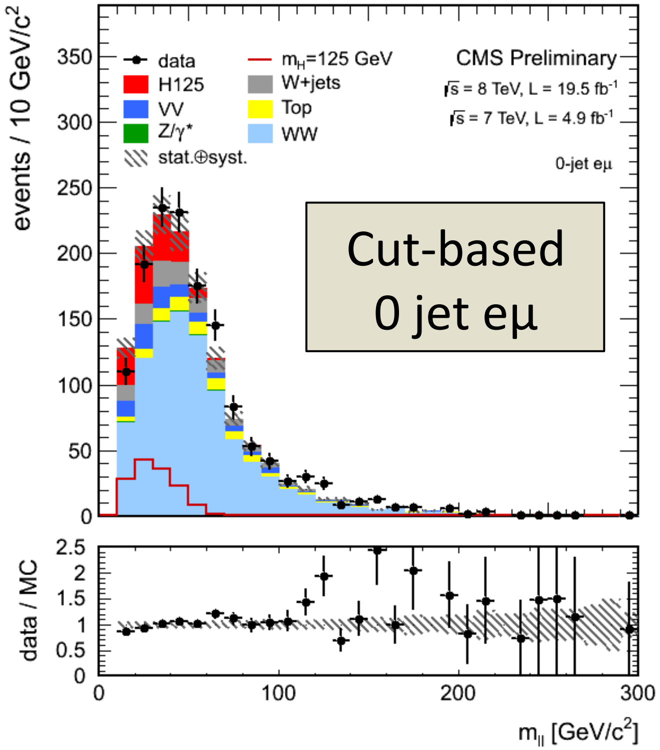
For m_H=125.5 GeV, 3.8σ (exp.3.8σ).

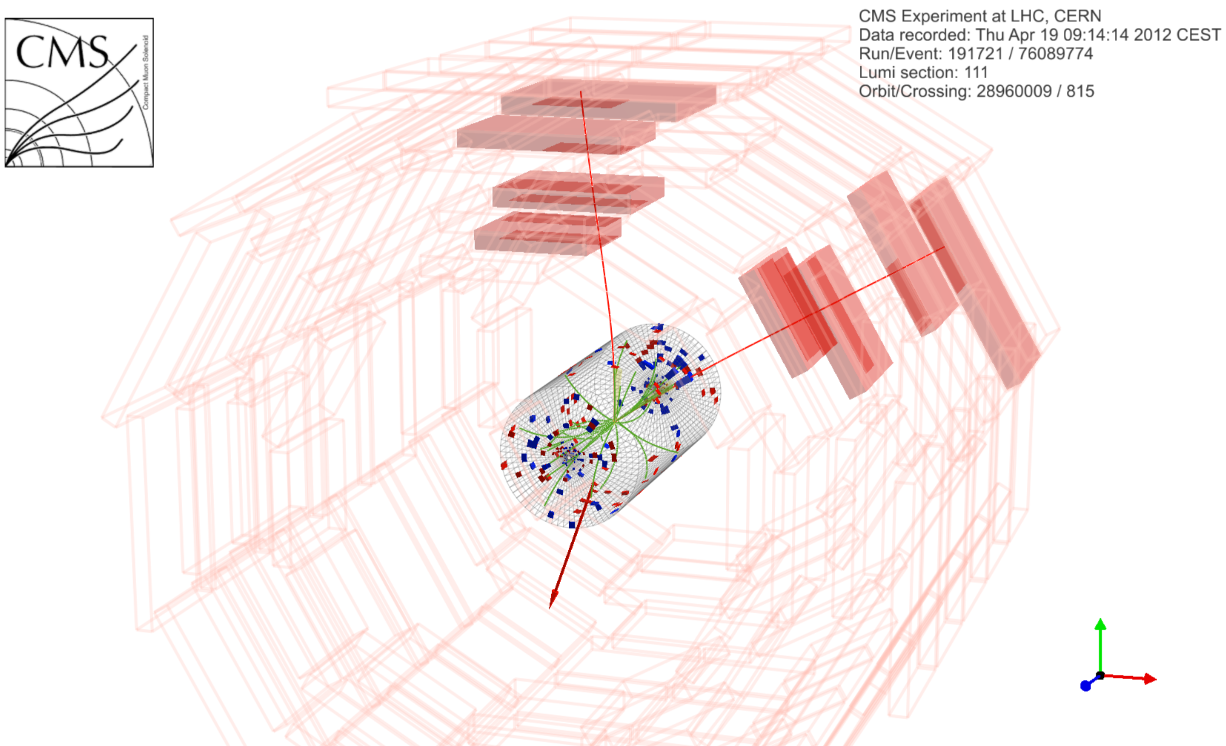




CMS H→WW$^{(*)}$→lνlν results

- Base selection: two oppositely charged leptons with p_T>20GeV; p_T>15(10)GeV. E_T^{miss}>20GeV.
- Cut based analysis: extra requirements on $p^l_T{}^{max}$, $p^l_T{}^{min}$, m_{ll}, $\Delta\phi_{ll}$, m_T.
- 2D shape analysis: m_{ll} vs m_T in 0,1 jets categories to extract the final result.

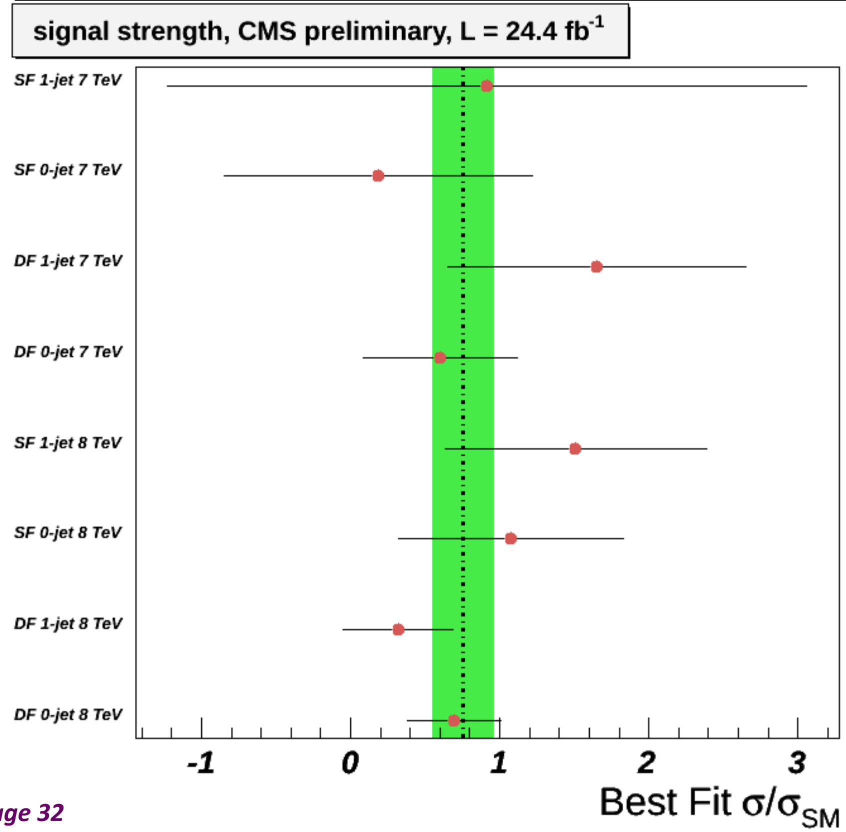


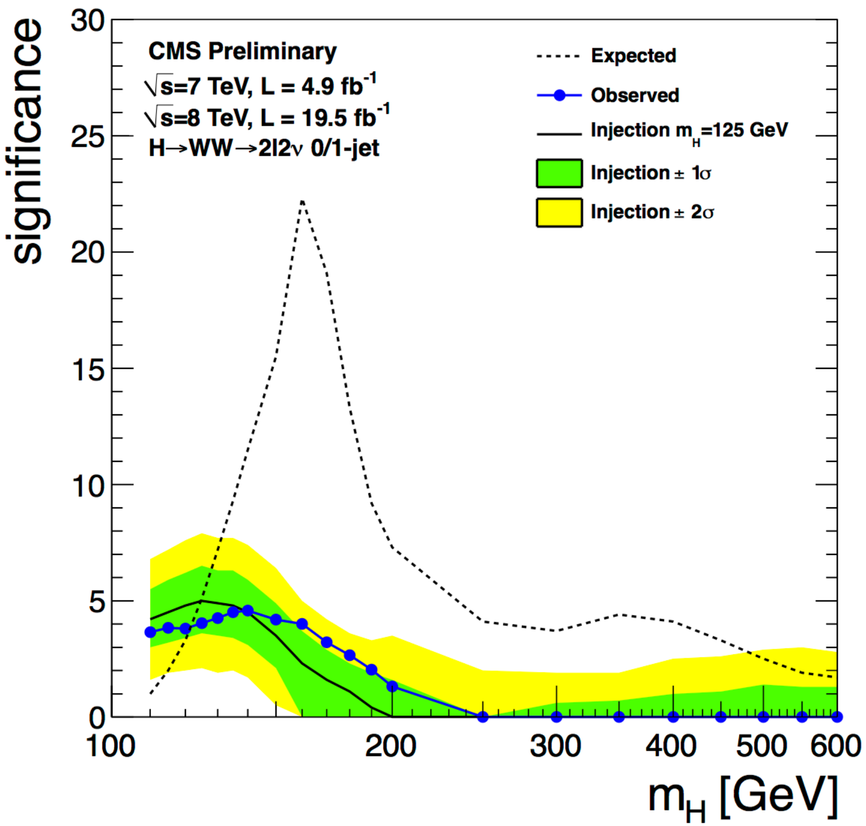


CMS-PAS-HIG-13-003

CMS H→WW(*)→lνlν results

- The combination of 7 TeV and 8 TeV results excludes SM Higgs at 95% CL in 128 GeV - 600 GeV.
- Excess at low masses: 4.0 σ (exp. 5.1 σ)
- Best fit value at 125 GeV: μ=0.76 ± 0.21

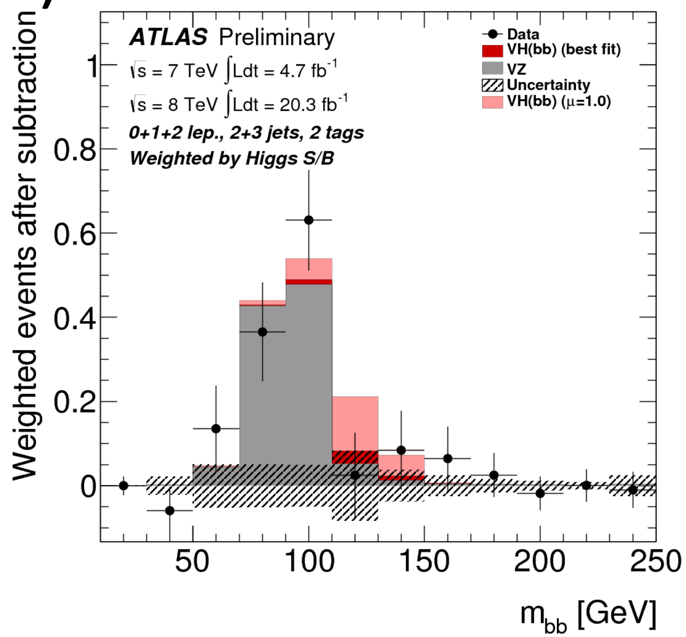




Current status of the new boson:
(some) fermionic channels

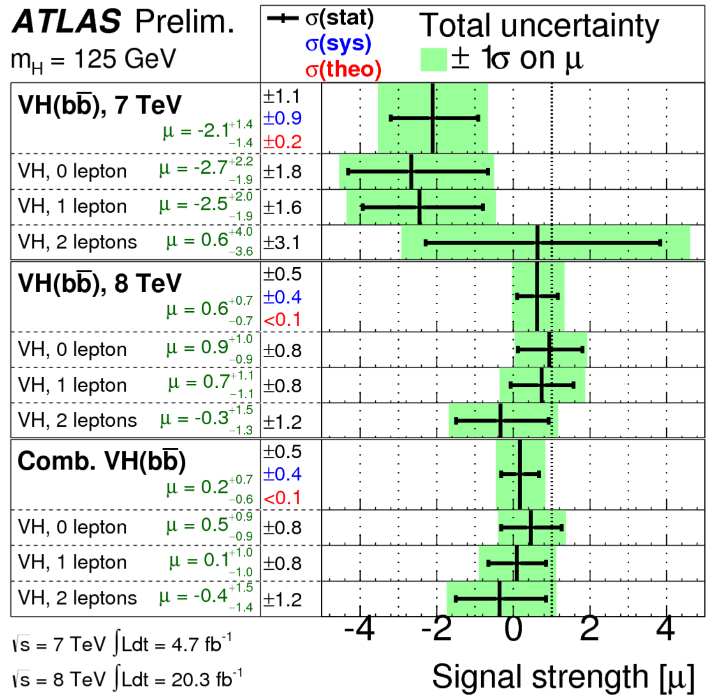
VH(H→bb) (ATLAS)

- 2 b-tagged jets. p_T^V reconstructed from missing E_T and leptons.
- Simultaneous fit to 3 channels in multiple p_T^V bins, lepton, jet and b-tag multiplicities:
  - Helps normalizing backgrounds. Controls effect of systematic uncertainties.
  - Isolates categories with very different S/√B.
- Main backgrounds: ttbar, Z+HF, W+HF.



- 95% CL limit on $\sigma/\sigma_{SM.}$ At m_H=125 GeV Observed (Expected) σ/σ_{SM}: 1.3 (1.4).

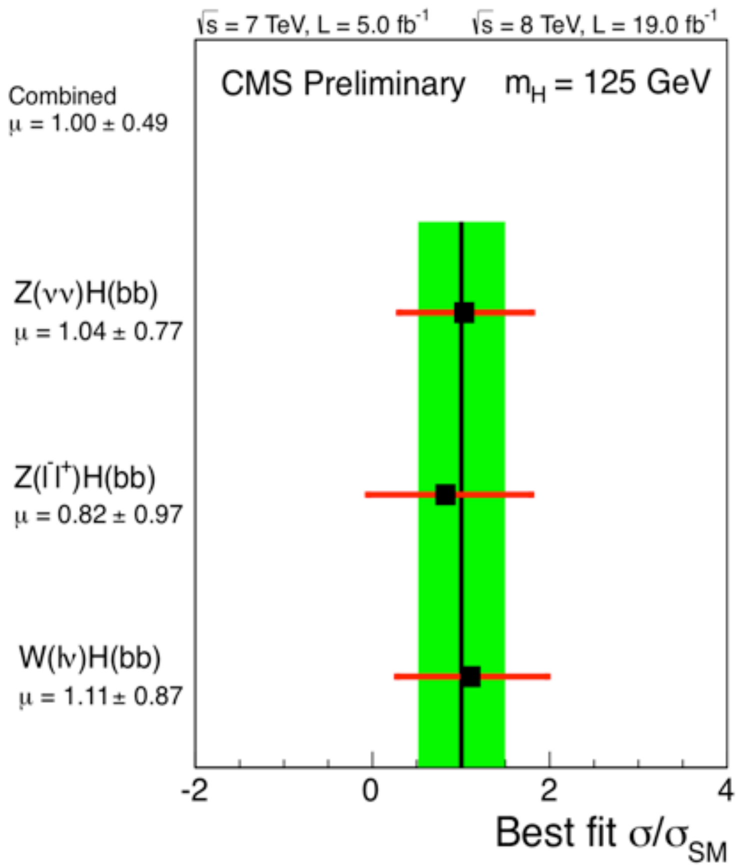
- 0 lept: $\mu = 0.5^{+0.9}_{-0.9}$
  1 lept: $\mu = 0.1^{+1.0}_{-1.0}$
  2 lept: $\mu = -0.4^{+1.5}_{-1.4}$

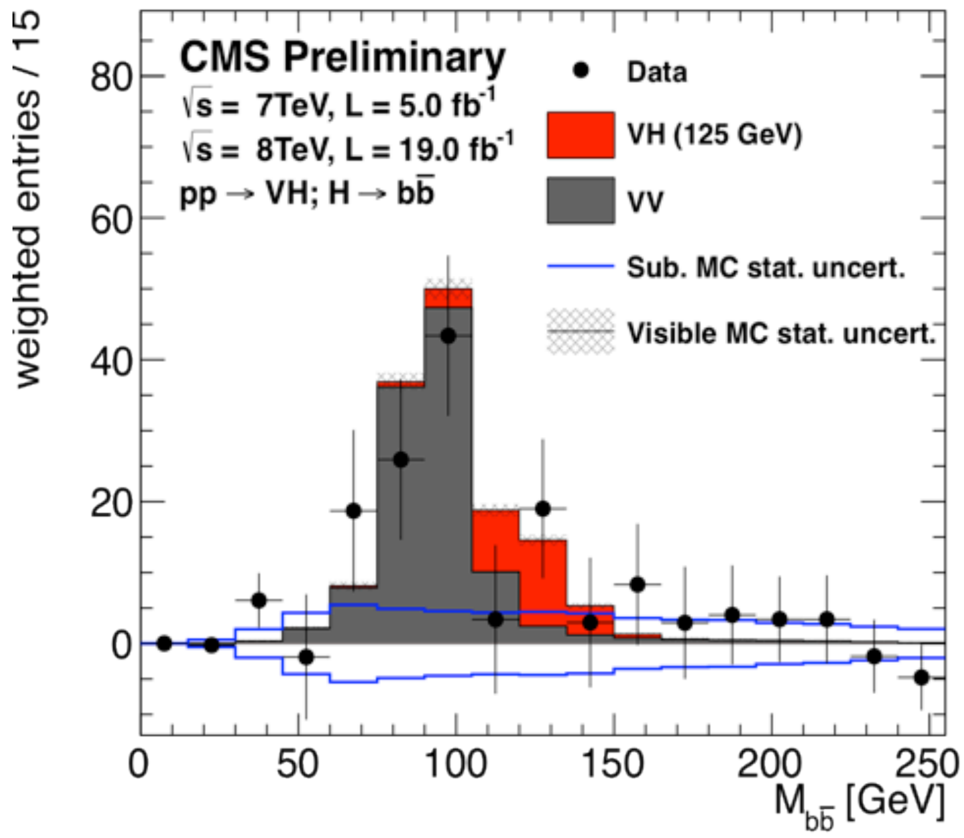


ATLAS-CONF-2013-079

VH(H→bb) (CMS)

- An excess with local significance 2.1 σ.
- At m_H = 125 GeV: Observed 95% CL exclusion: 1.89 σ^{SM} (Expected: 0.95 σ^{SM}).



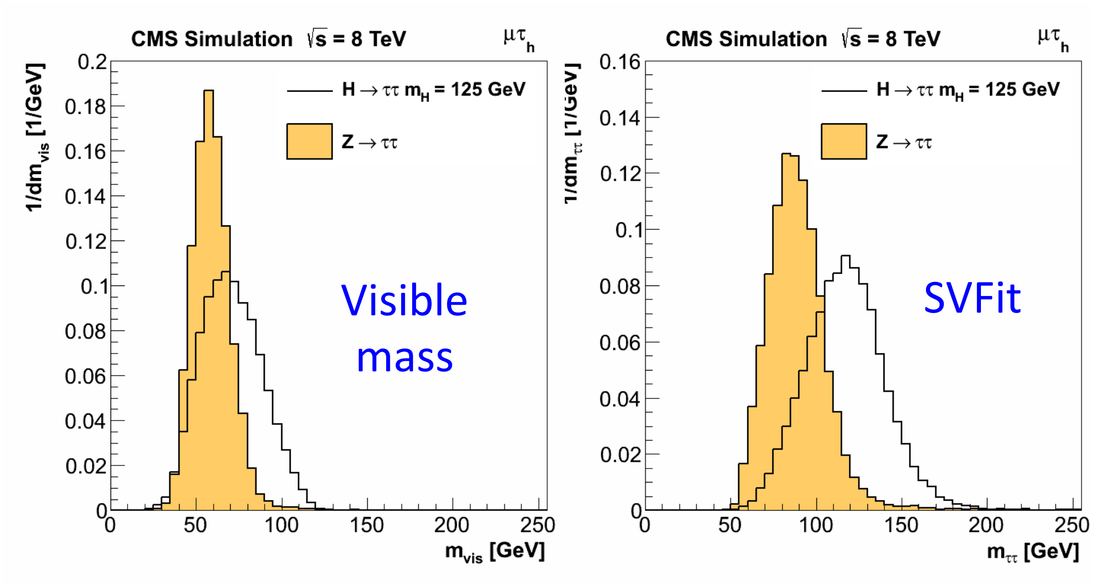


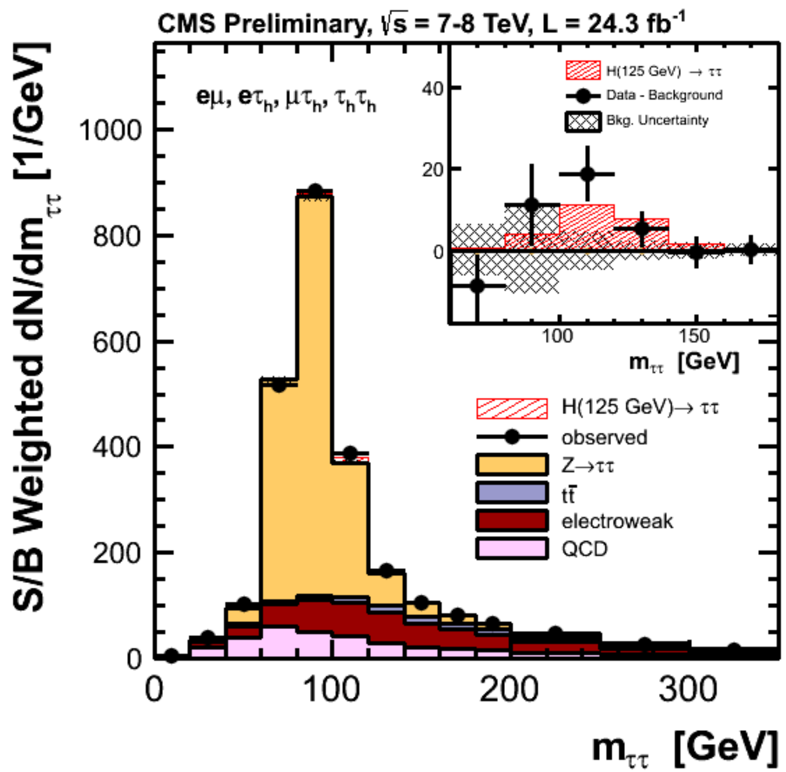
CMS-PAS-HIG-13-012

H→ττ (CMS and ATLAS)

- Hadronic and leptonic τ decays. 2-4 neutrinos in the final state. $H \to \tau^+\tau^- \to ll4\nu$, $l\tau^{had}3\nu$ and $\tau^{had}\tau^{had}\nu\nu$ channels.

- Main background: Z→ττ. Modeled by embedding technique.
- Categories based on jet multiplicity and p_T of visible τ decay products.
- Mass reconstruction: visible mass, collinear approximation, MMC (ATLAS) SVFit (CMS) CMS PAS HIG-13-004. Nucl. Instrum. Methods A654 (2011) 481.

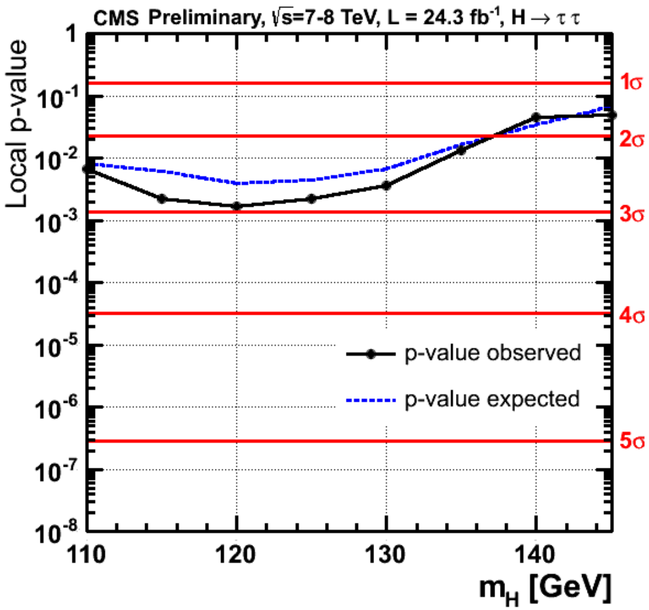




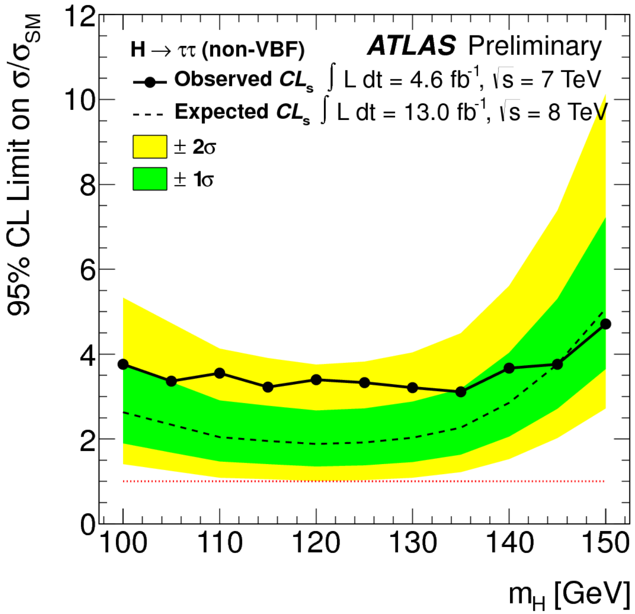
CMS-PAS-HIG-13-004

ATLAS-CONF-2012-160

$H \rightarrow \tau\tau$ (CMS and ATLAS results)



- CMS: combined best fit $\mu = 1.1 \pm 0.4$ at 125 GeV.
- An excess around 125 GeV. (Min. p_0 at 120 GeV)
- At 125.8 GeV: 2.85σ.



- ATLAS: full run-I analysis in progress.
- Observed (expected) 95% CL exclusion for 125 GeV: $1.9\sigma^{SM}(1.2\ \sigma^{SM})$
- Combined $\mu = 0.7 \pm 0.7$

Is it the Standard Model Higgs boson?

- The production of a new resonance with the mass around 125.5 GeV is observed in proton-proton collisions.
  - Main contributors are dibosons: $H \to ZZ^* \to 4l$, $H \to \gamma\gamma$, $H \to WW^* \to l\nu l\nu$
  - Leptonic channels: some sensitivity already.

- The Standard Model Higgs boson:
  - Neutral scalar.
  - CP-even: $J^{CP}=0^{++}$.
    (Charge and Parity transformation)
  - Predicted production and decay modes
  - Predicted couplings to the fermions and bosons.
  - Predicted self-couplings.

Can be tested:

LHC (300 fb^{-1})

LHC and beyond

LHC

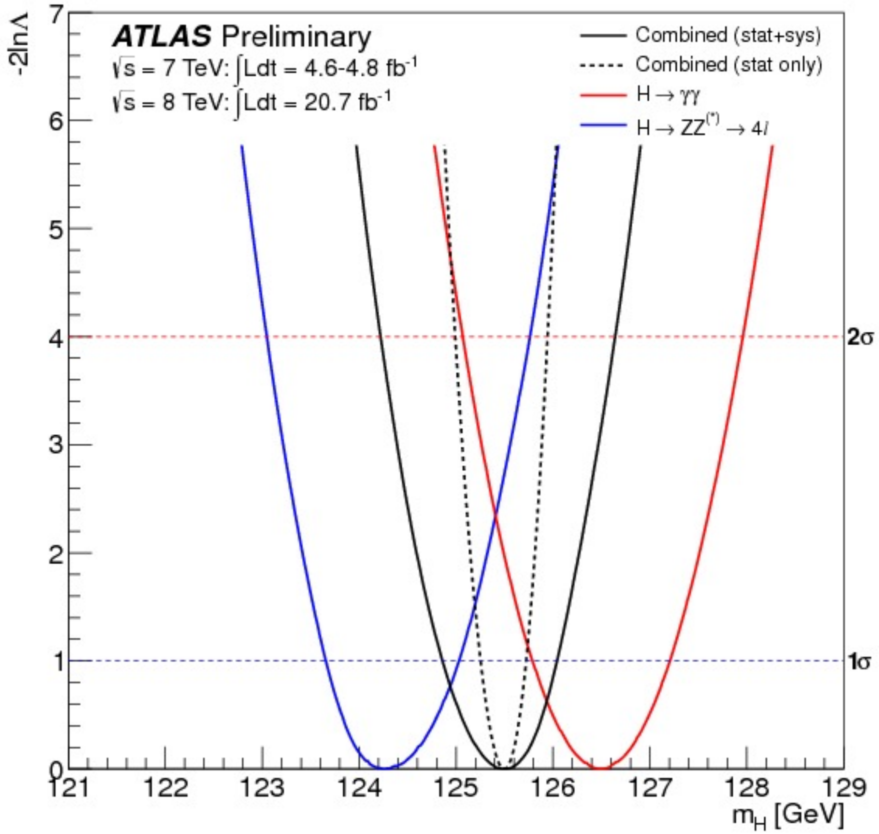
LHC

HL-LHC (3000 fb^{-1}), Higgs factories, TLEP, LEP3, ILC etc.

Mass of the new resonance (ATLAS)

- The analysis of the full 2012 dataset: 4.8 fb^{-1} (7 TeV) and 20.7 fb^{-1} (8 TeV)
  - $m_H(\gamma\gamma)$ = 126.8 ± 0.2 (stat) ± 0.7 (syst) GeV
  - $m_H(ZZ^{(*)})$ = 124.3 $^{+0.6}_{-0.5}$ (stat) $^{+0.5}_{-0.3}$ (syst) GeV

- Combination:
  - $m_H(\gamma\gamma+ZZ)$ = 125.5 ± 0.2 (stat) $^{+0.5}_{-0.6}$ (sys) GeV.



The mass difference between two channels:

$\Delta m_H = 2.3\ ^{+0.6}_{-0.7}$ (stat) ± 0.6 (sys) GeV.

Corresponds to probability of 1.5% (2.4 standard deviations).

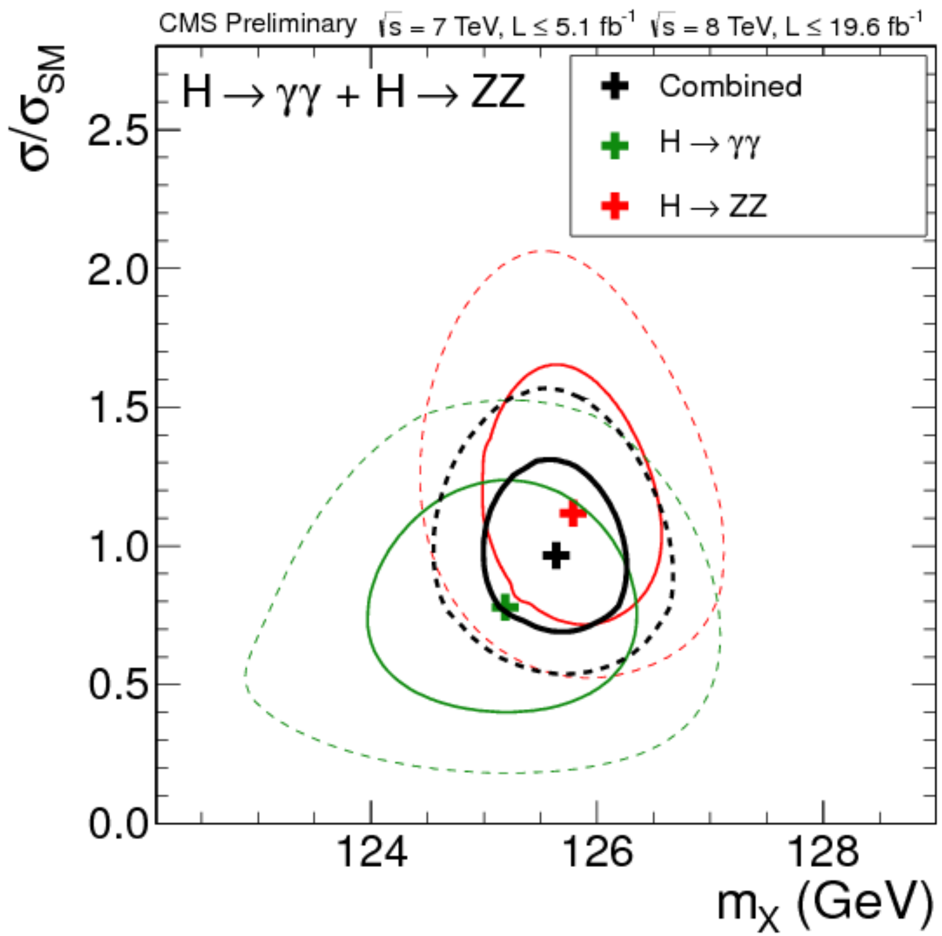
Decays of the same particle?

ATLAS-CONF-2013-012, 013, 014, 030

arXiv:1307.1427

Mass of the new resonance (CMS)

- Analysis of the full 2011+2012 dataset: 5.1 fb^{-1} (7 TeV) and 19.6 fb^{-1} (8 TeV)
  - $m_H(\gamma\gamma)$ = 125.4 ± 0.5(stat.) ± 0.6(syst.) GeV
  - $m_H(ZZ^{(*)})$ = 125.8 ± 0.5(stat.) ± 0.2(syst.)GeV



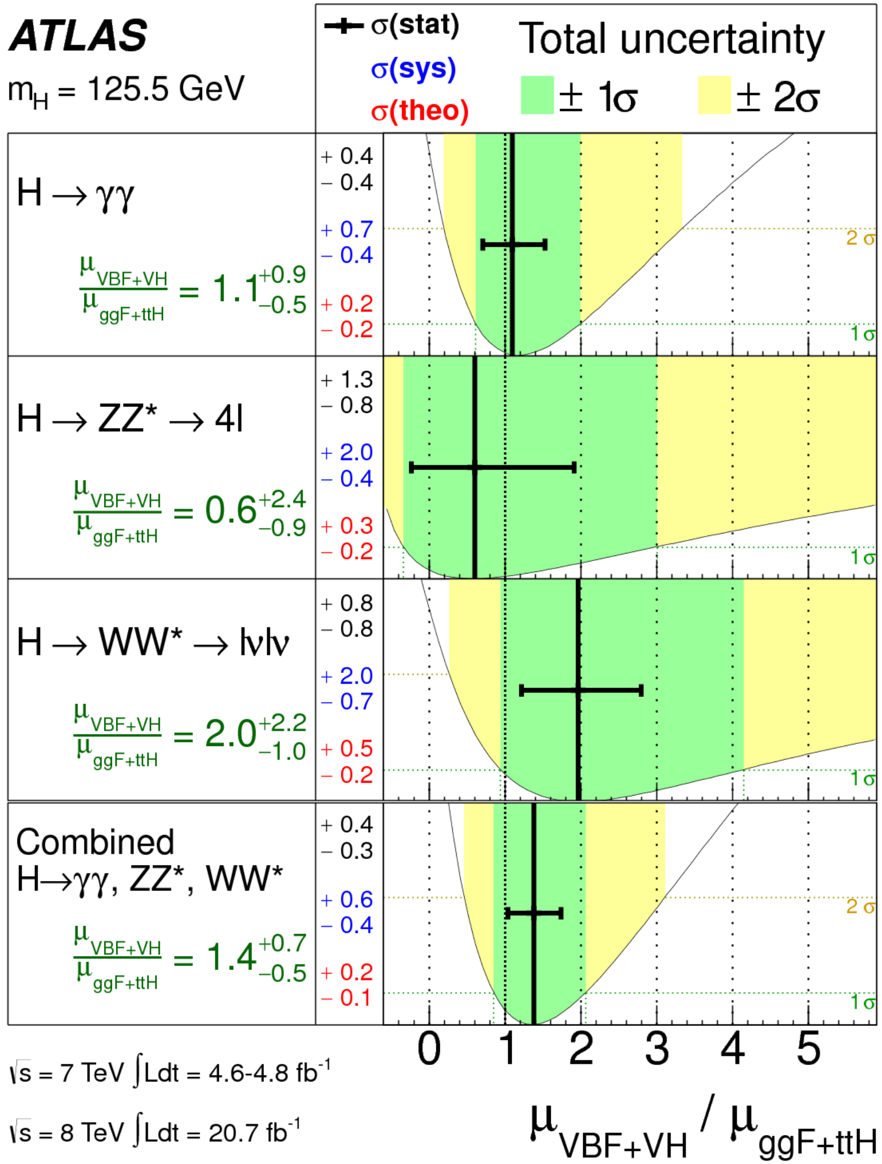
Combined: m_H = 125.7 ± 0.3 (stat.) ± 0.3 (syst.) GeV

CMS-PAS-HIG-13-005 CMS-PAS-HIG-13-001

CMS-PAS-HIG-13-002

Production mechanisms (ATLAS and CMS)

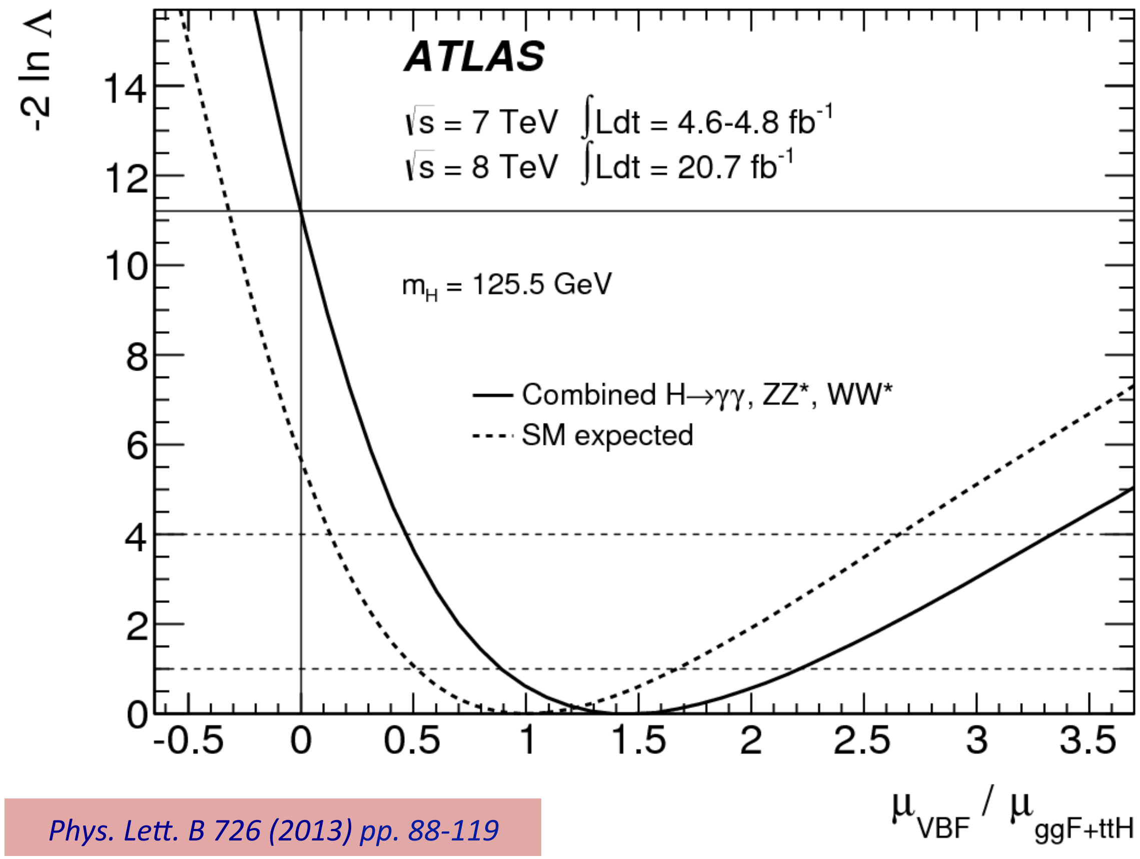
- Defining common scale factors for production modes contributing to the same decay modes:
  - Gluon-mediated (ttH+ggF) and vector-boson mediated (VBF+VH)
  - $\mu_{VBF+VH} = \sigma_{VBF+VH} / \sigma^{SM}_{VBF+VH}$;
  - $\mu_{ttH+ggF} = \sigma_{ttH+ggF} / \sigma^{SM}_{ttH+ggF}$.
- Use the ratio of production modes to eliminate the B/B_{SM} dependence.
- Allows to combine different decay channels.



CMS-PAS-HIG-13-005 *Phys. Lett. B 726 (2013) pp. 88-119*

Evidence for the VBF production (ATLAS)

- Testing for the presence of production mechanisms other than ggF.
- Standalone fit of the ratio $\mu_{VBF}/\mu_{ggF+ttH}$
- Main systematic uncertainties: theory predictions on ggF contribution to categories and jet multiplicities.



$\mu_{VBF}/\mu_{ggF+ttH}$=

$1.4^{+0.4}_{-0.3}$ (stat) $^{+0.6}_{-0.4}$ (sys)

3.3σ evidence that a fraction of the Higgs production occurs through the VBF.

Phys. Lett. B 726 (2013) pp. 88-119

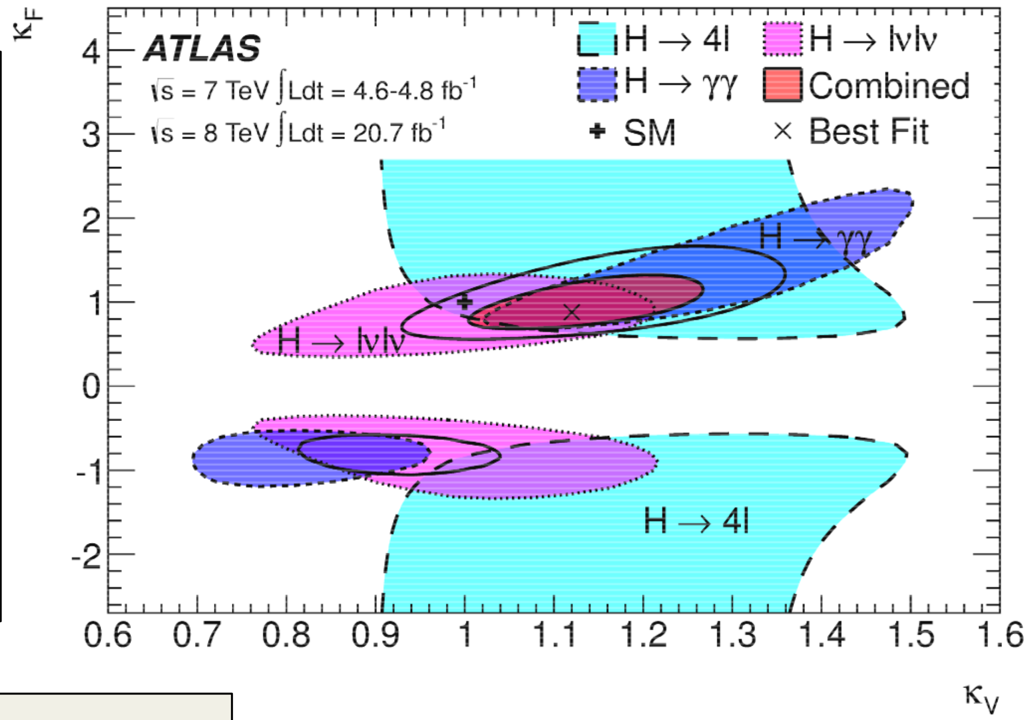
Measurements of couplings

- Assumptions: the resonances observed in different channels belong to the decays of the same particle with the mass around 125.5 GeV.
  – Only Standard Model contributions to the total Higgs width.

- Coupling scale factors k_j, such that the production cross sections and partial decay widths for particle j scale as k_j^2 compared to the SM predictions.

- 2-parameter benchmark model. Group fermion and vector couplings together:
  $\kappa_V = \kappa_W = \kappa_Z$; $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_g$

- Assume only SM particles contribute to κ_g (gg→H) and κ_γ (H→γγ).

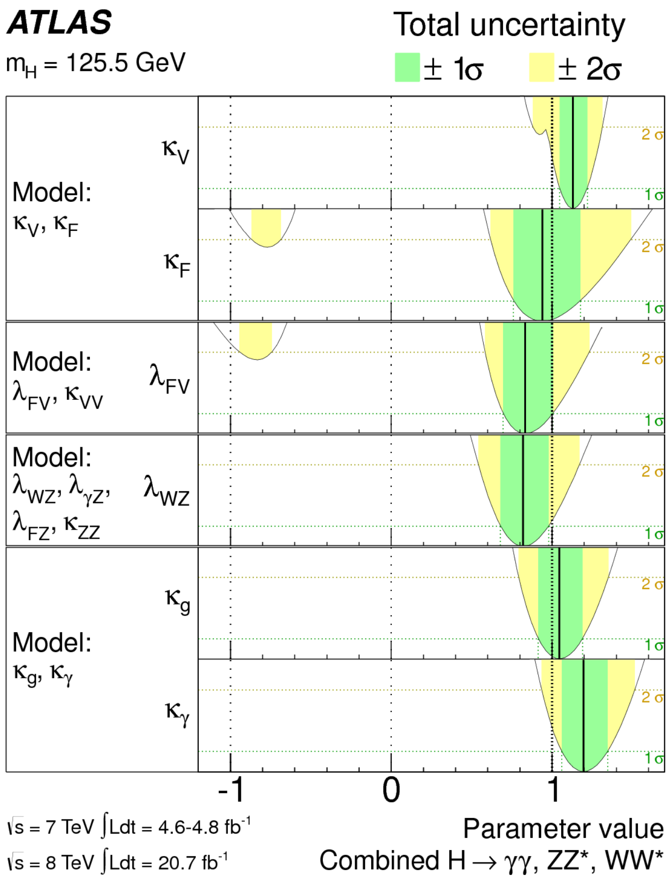


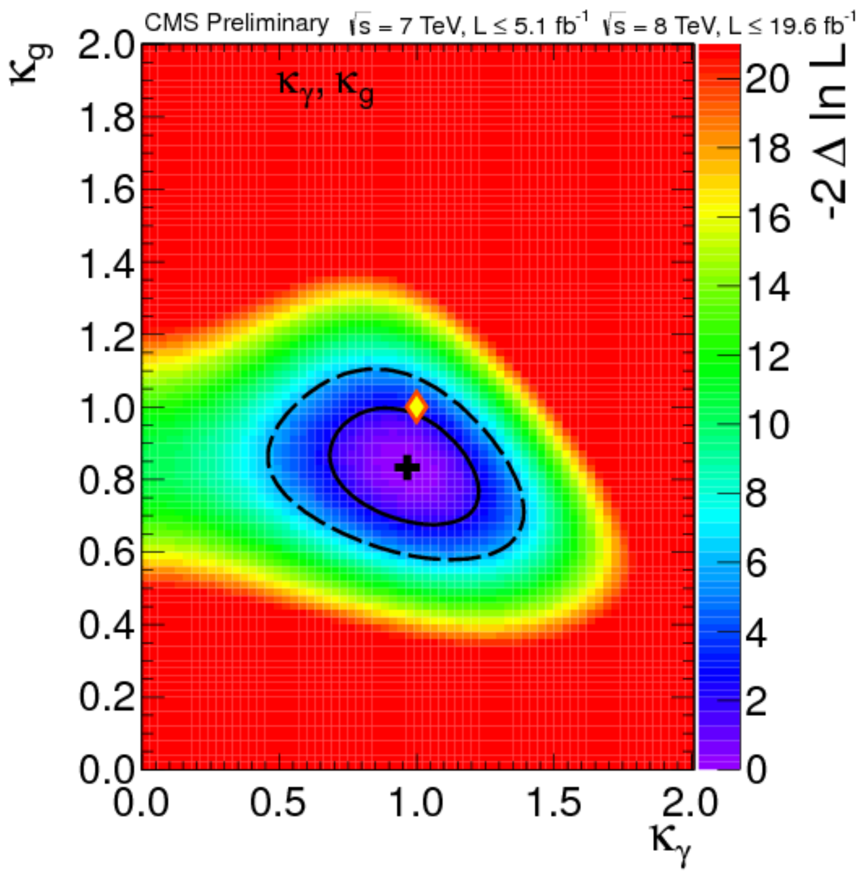
2D compatibility of the best fit value with the Standard Model prediction: 12%.

Phys. Lett. B 726 (2013) pp. 88-119

Measurements of couplings (ATLAS and CMS)

- $\lambda_{FV}=k_F/k_V$. No assumption on contributions from new particles. ATLAS: λ_{FV} [0.7; 1.01].
- Custodial symmetry as predicted by the Standard Model.
- No evidence for BSM contribution in ggH and Hγγ.
  CMS best fit: $(k_\gamma, k_g) = (0.97, 0.83)$.





CMS-PAS-HIG-13-005

Phys. Lett. B 726 (2013) pp. 88-119

Measurements of Higgs boson spin and parity

- The Standard Model Higgs is a neutral scalar: $J^{CP}=0^{++}$.

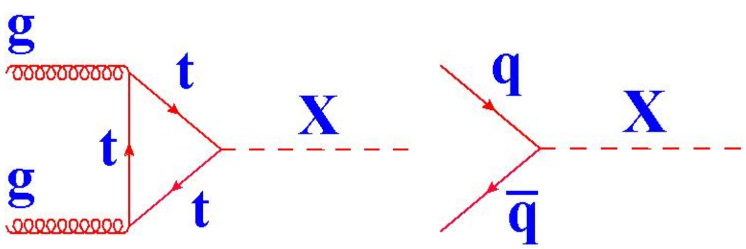
- The new resonance is a neutral boson: it decays to pairs of gauge bosons with total charge 0.

- Spin-1 is strongly disfavored due to the observation of the *γγ* decay
(Landau-Yang theorem: Dokl. Akad. Nauk Ser. Fiz. 60 (1948) 207, Phys. Rev. 77 (1950) 242.)

- To associate this particle to a particular model, one needs to measure the spin and parity in the experiment without theoretical prejudice.
  – Establishing of $J^P=0^+$ in individual channels and combination.
  – Integer spin: currently considering 0, 1 and 2.

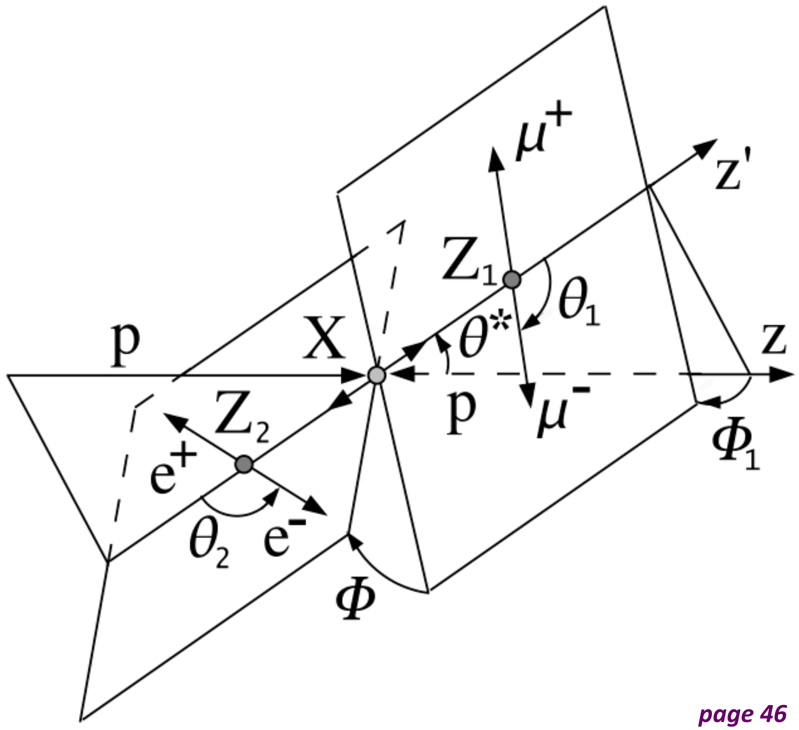
Measurements of Spin and Parity

- Exclusion of alternative hypotheses in favor of the Standard Model $J^P=0^+$:
  - $J^P=0^-$: gluon Fusion production.
  - $J^P=1^+$, 1^-: qqbar production.
  - $J^P=2^+_m$: gluon Fusion and qqbar production.



- Measurement of properties: deduce spin and parity from measured distributions of kinematic observables.

- Observables:
  - Angular distributions of decay products in the rest frame of the resonance.
  - For some channels: invariant masses of the gauge bosons.



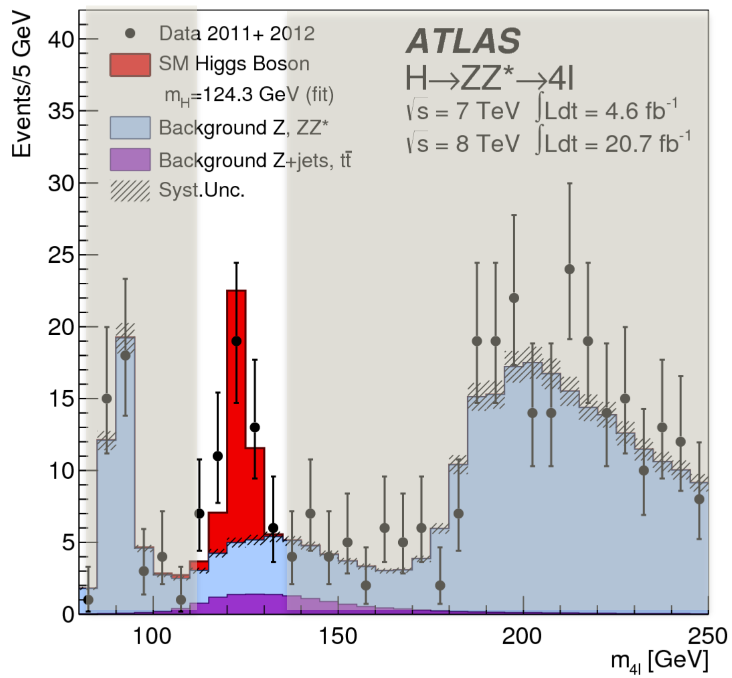
arXiv:1001.3396

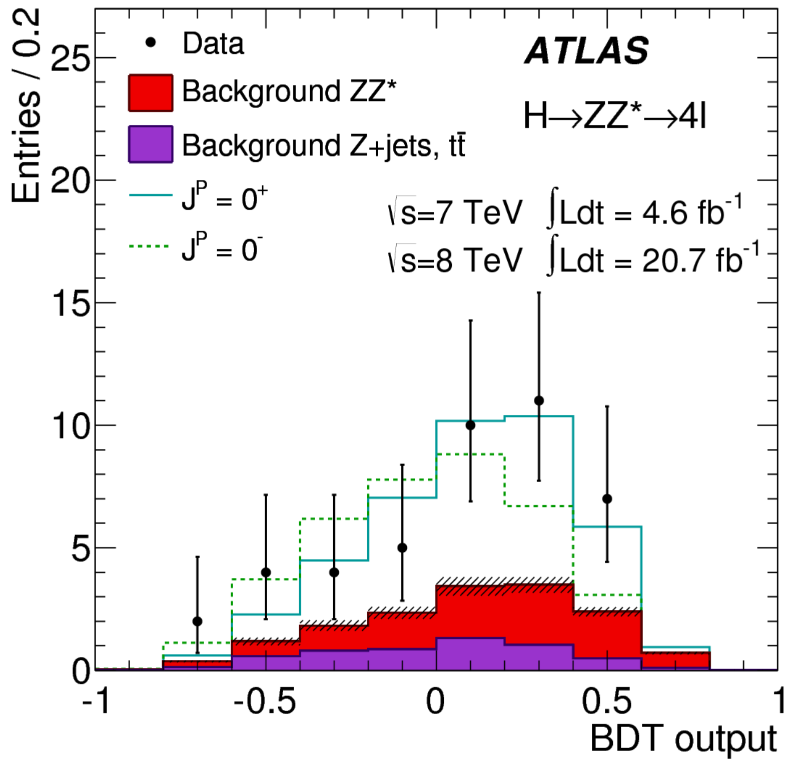
arXiv:1208.4018

Spin measurement in H→ZZ*→4l decay (ATLAS)

Selecting a signal region in data, reconstructing spin and parity-sensitive observables in this region, estimating backgrounds, resolutions etc..

ATLAS: 115 GeV < m_{4l} < 130 GeV.
(43 candidate events)





Multivariate discriminant combining the final state observables. Training on signal Monte Carlo after full reconstruction and selection.

Phys. Lett. B 726 (2013), pp. 120-144

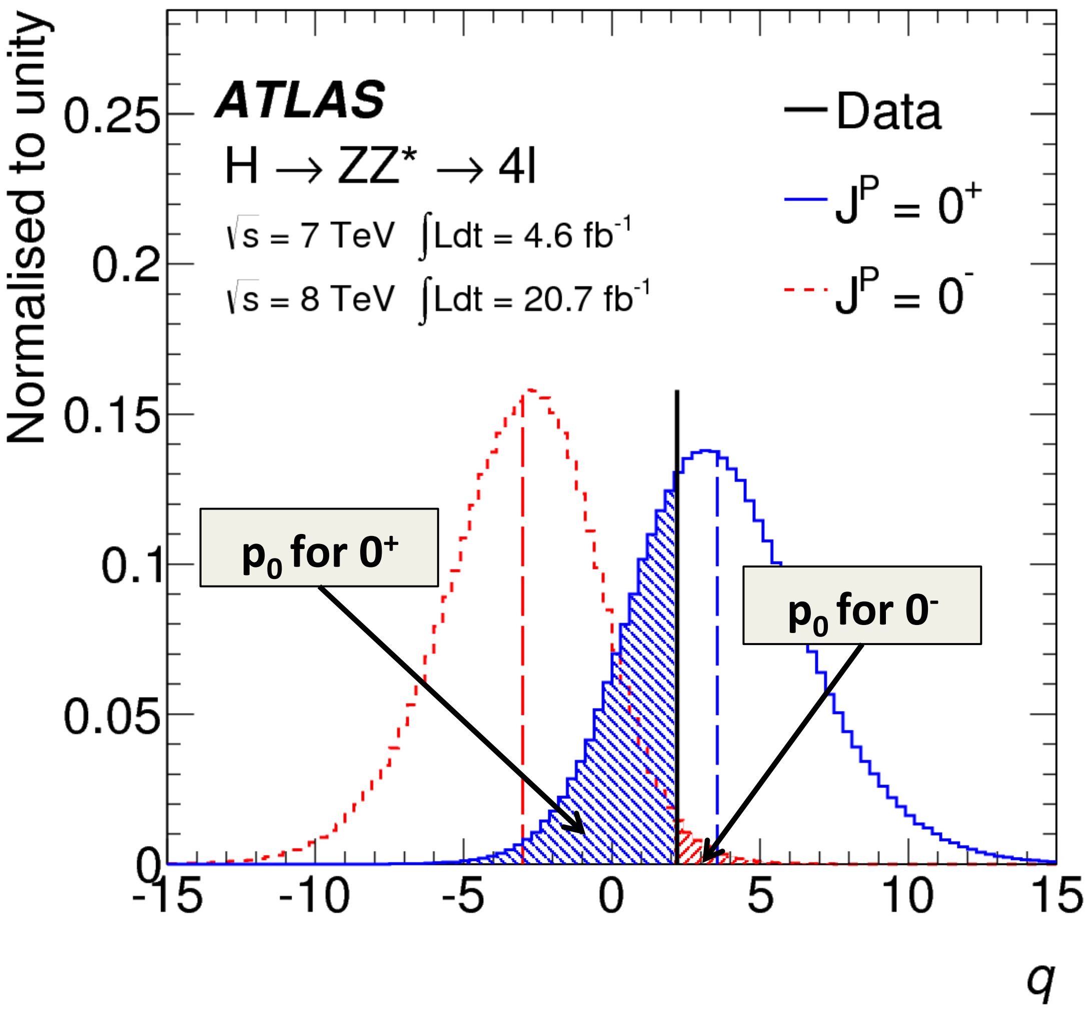
Statistical procedure

Test statistic: Ratio of profiled likelihoods. (Independent signal strength per channel and per spin and parity hypothesis.)

$$q = \log \frac{L(0^+, \hat{\hat{\mu}}_{0^+}, \hat{\hat{\theta}}_{0^+})}{L(J^P_{alt}, \hat{\hat{\mu}}_{J^P_{alt}}, \hat{\hat{\theta}}_{J^P_{alt}})}$$

CL_S: the exclusion of the alternative J^P hypothesis in favour of the Standard Model J^P= 0 hypothesis:

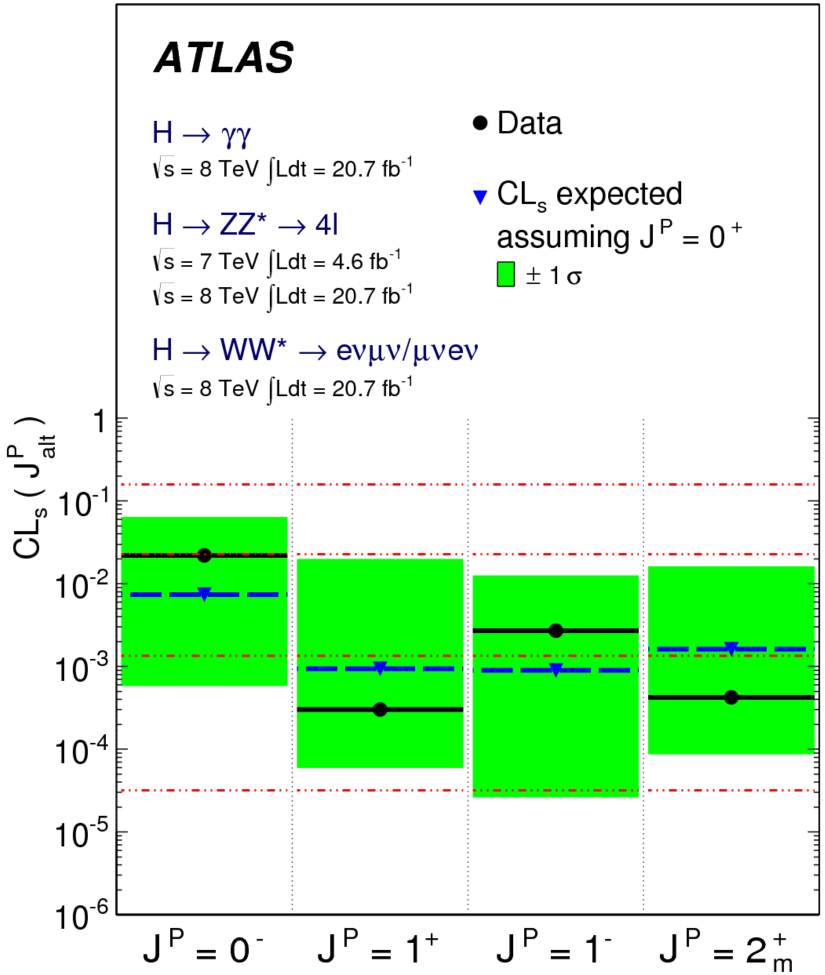
$$CL_S(J^P_{alt}) = \frac{p_0(J^P_{alt})}{1 - p_0(J^P = 0^+)}$$

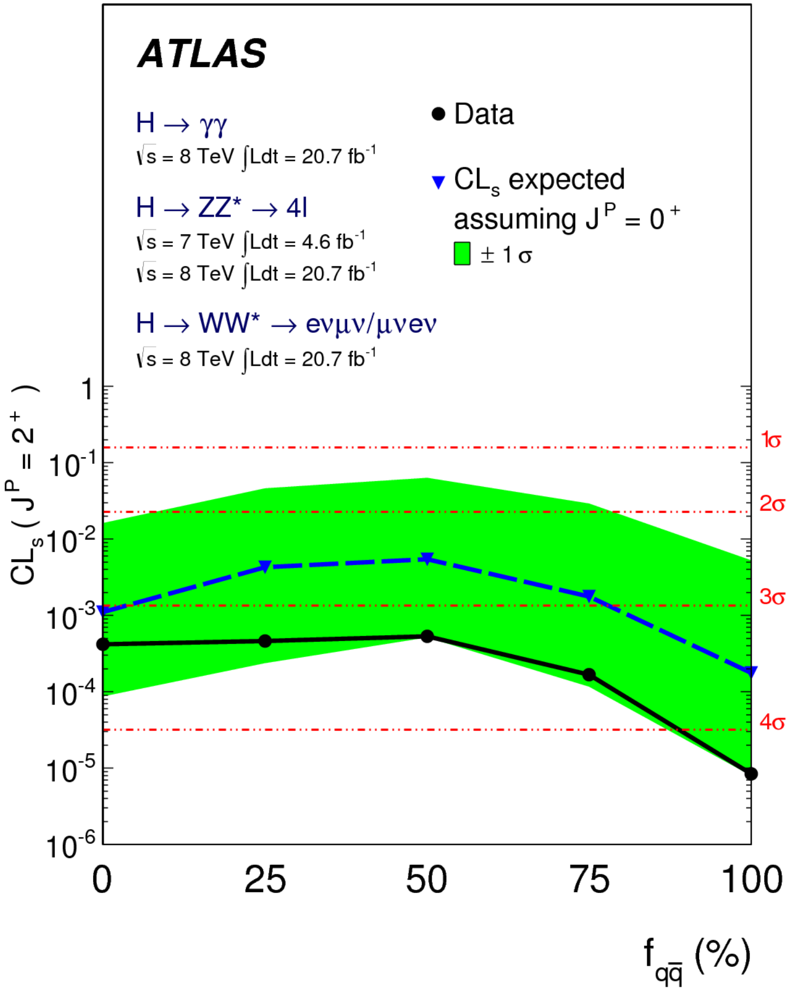


[Phys. Lett. B 726 (2013), pp. 120-144](#)

Spin and parity measurements (ATLAS and CMS)

Exclusion of alternative J^P hypotheses in favor of the SM Higgs model.
ATLAS: $J^P=2^+$ at >99.9% CL independently of f_{qq} ($ZZ^*+WW^*+\gamma\gamma$);
CMS: $J^P=0^-$ at 99.8% CL (ZZ^*); ATLAS: 97.8% CL (ZZ^*).
ATLAS: $J^P=1^-$ at 99.73% CL; $J^P=1^+$: 99.97% CL. (ZZ^*+WW^*). CMS: >99.9% CL (ZZ^*)





Phys. Lett. B 726 (2013), pp. 120-144

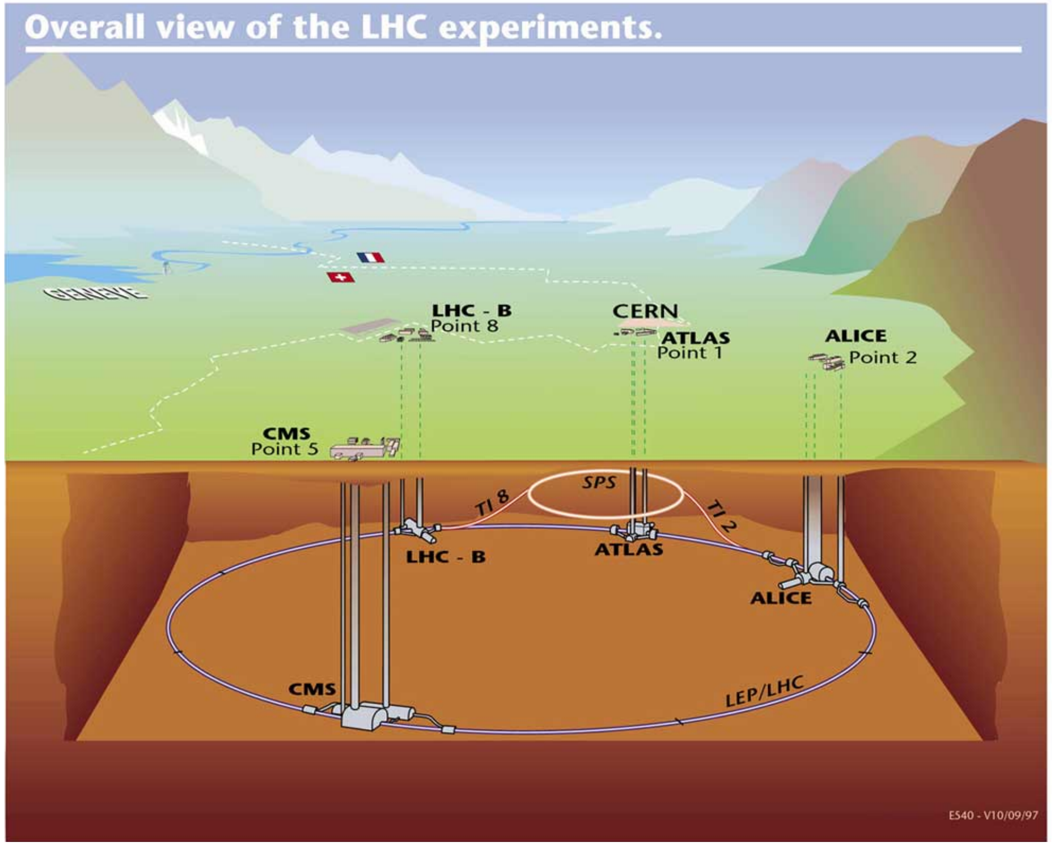
CMS-PAS-HIG-13-002

Summary

- A new neutral boson observed by the ATLAS and CMS collaborations.
- Dominant observed decays: $\gamma\gamma$, ZZ, WW.
- Hints of the fermionic decays: $\tau\tau$, bb.
- Production mechanisms: ggF, evidence for VBF, VH in progress.
- At available statistics, the couplings and signal strengths are compatible with Standard Model expectations.
- Spin and parity measurements: excluded most popular $J^P=0^-,1^+,1^-,2+_m$ models.
- Is this the Standard Model Higgs boson? Some questions remain..
  - Searches for remaining production and decay modes.
  - More precision on couplings and spin.
  - Self-couplings.

Backup

CERN Large Hadron Collider



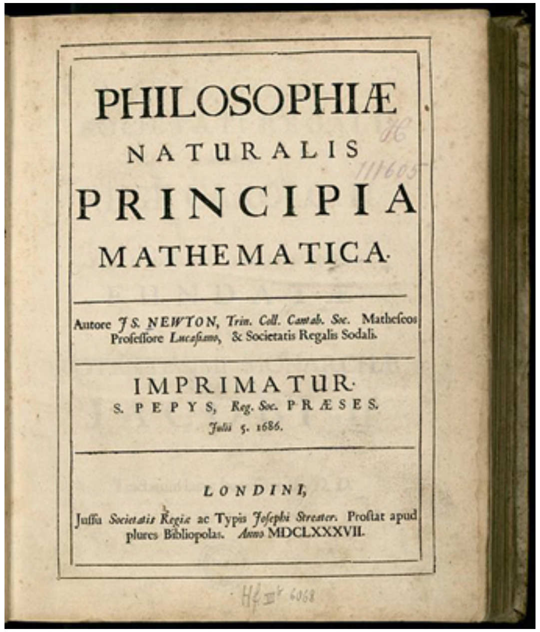
Number of events second generated in LHC collisions

$$N_{events} = L\sigma$$

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

	2010	2011	2012	Nominal
Energy	7 TeV	7 TeV	8 TeV	14 TeV
Bunch spacing	150 ns / 368	50 ns / 1380	50 ns / 1380	25 ns / 2808
L ($cm^{-2}s^{-1}$)	2×10^{32}	3.3×10^{33}	7×10^{33}	10^{34}

Historical context

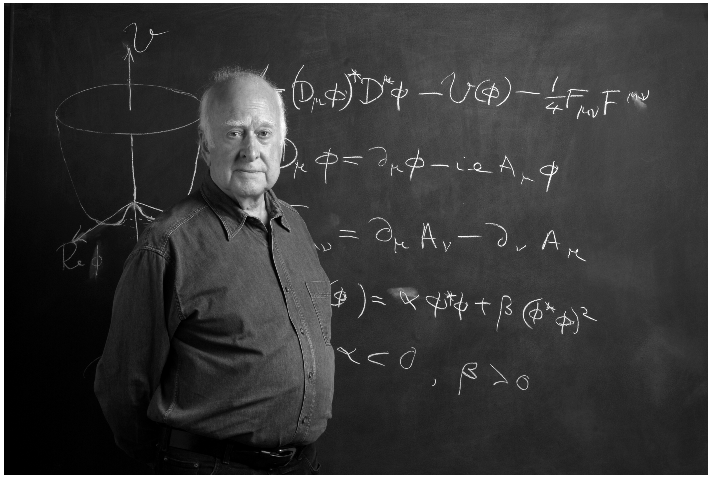


- Gallilean and Newtonian concept of mass.
  - Inertial mass: objects resistance to the change of its velocity
  - Gravitational mass: object's interaction with gravitational force.
  - Intrinsic additive property of the body.

- Einstein: mass is the rest energy of the system.
  - The equivalence principle.

- Higgs mechanism: understanding of mass of fermions and bosons.

The Brout-Englert-Higgs mechanism



VOLUME 13, NUMBER 9 PHYSICAL REVIEW LETTERS 31 AUGUST 1964

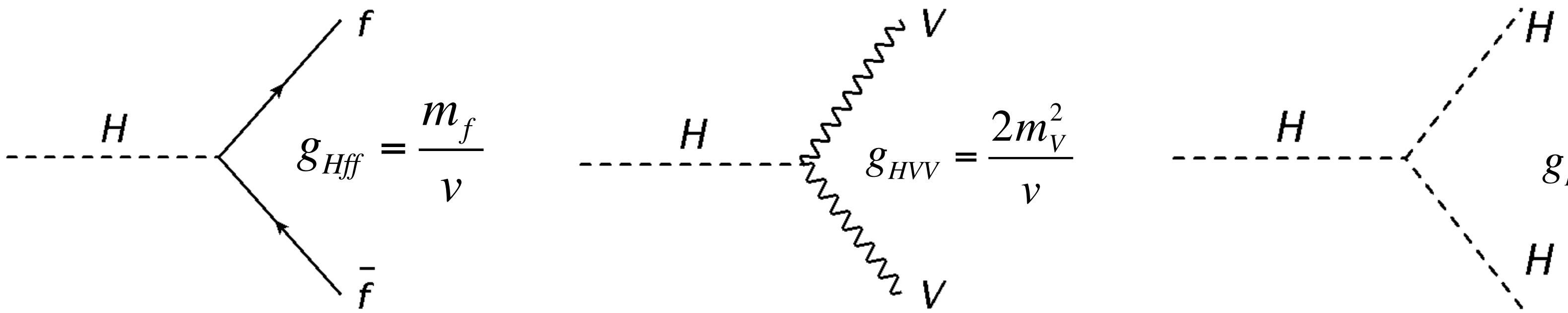
F.Englert, R.Brout. p. 321 (2 pages)
P.W.Higgs, p. 508 (1 page)
G.S.Guralnik, C.R. Hagen and TWB Kibble. P.585 (2 pages)

- 1964: a spontaneous breakdown of the local continuous symmetry deliver longitudinal polarizations to gauge bosons making them massive.

- BEH mechanism: existence of a scalar field (or fields) that reduce the gauge symmetries of the physical vacuum from $SU(3)_C \times SU(2)_L \times U(1)_Y$ down to $SU(3)_C \times U(1)_{EM}$

The Brout-Englert-Higgs mechanism

- Phenomenology



$$g_{Hff} = \frac{m_f}{v} \qquad g_{HVV} = \frac{2m_V^2}{v} \qquad g_{HVV} = \frac{3m_H^2}{v}$$

- Two massive charged vector bosons: $$m_W = \frac{gv}{2}$$
- One massless vector boson: $$m_\gamma = 0$$
- One massive neutral vector boson: $$m_Z = \frac{m_Z}{c_W}$$
- One massive scalar Higgs boson with unknown mass: $$m_H = \sqrt{\lambda / 2} \cdot v$$

Higgs Bosons — H^0 and $H^\pm$

A REVIEW GOES HERE – Check our WWW List of Reviews

CONTENTS:

H^0 (Higgs Boson)

The observed signal is called a Higgs Boson in the following, although its detailed properties and in particular the role that the new particle plays in the context of electroweak symmetry breaking need to be further clarified. The signal was discovered in searches for a Standard Model (SM)-like Higgs. See the following section for mass limits obtained from those searches.

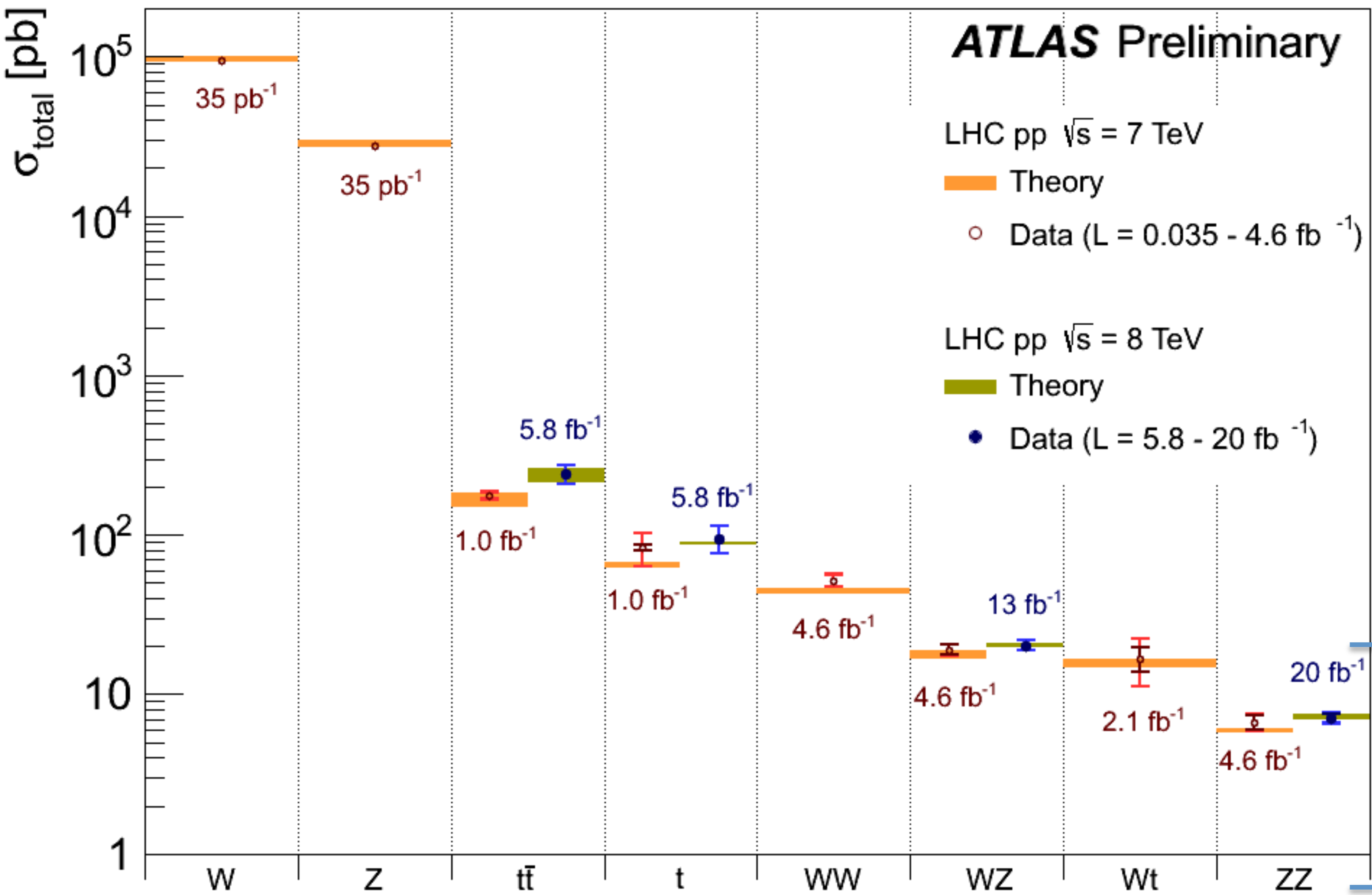
H^0 MASS

VALUE (GeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
125.9±0.4 OUR AVERAGE			
125.8±0.4±0.4	[1] CHATRCHYAN 13J	CMS	pp, 7 and 8 TeV
126.0±0.4±0.4	[2] AAD 12AI	ATLS	pp, 7 and 8 TeV
• • • We do not use the following data for averages, fits, limits, etc. • • •			
126.2±0.6±0.2	[3] CHATRCHYAN 13J	CMS	pp, 7 and 8 TeV
125.3±0.4±0.5	[4] CHATRCHYAN 12N	CMS	pp, 7 and 8 TeV

In 2013 the H^0 particle appears in the PDG particle listing under the “Higgs bosons” section

..previously listed under the “Searches for..” topic.

Standard Model processes at the LHC



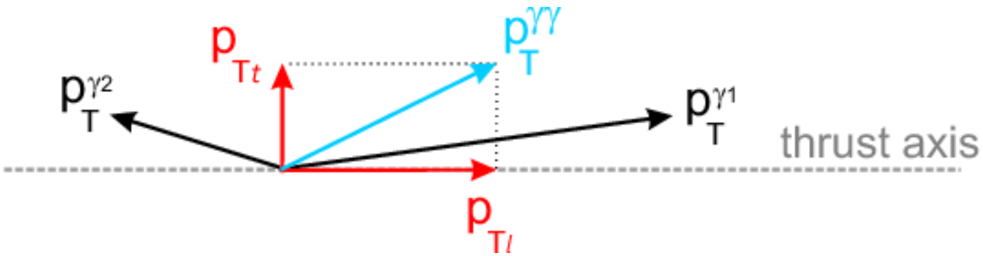
H^0(125GeV)

19.5 pb

$H^0 \rightarrow ZZ$

0.5 pb

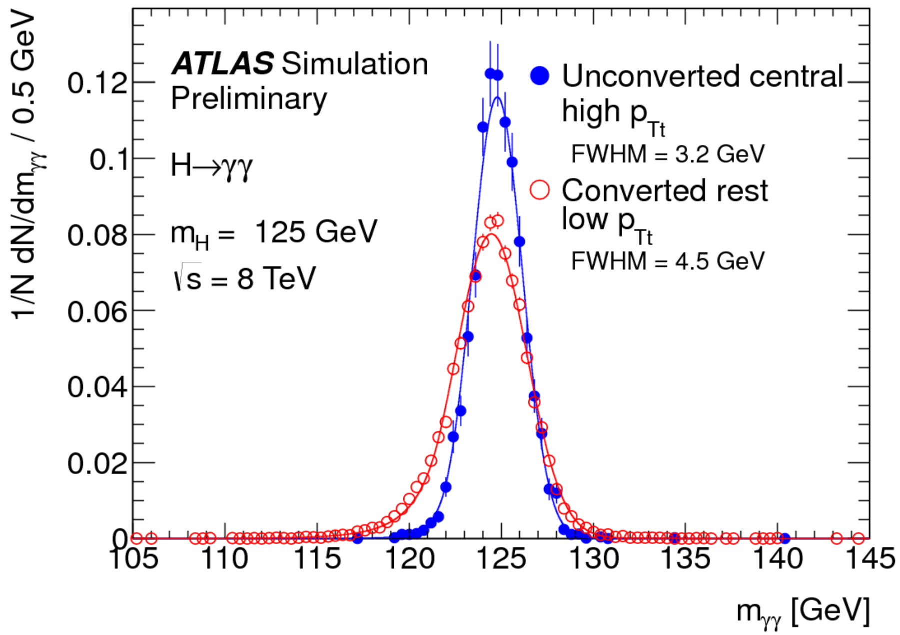
H→γγ analysis: categories

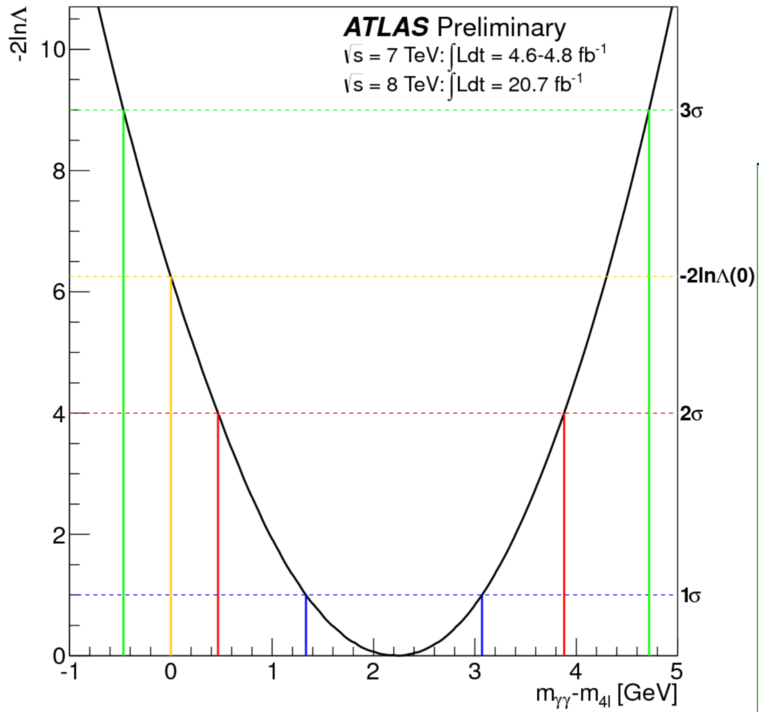


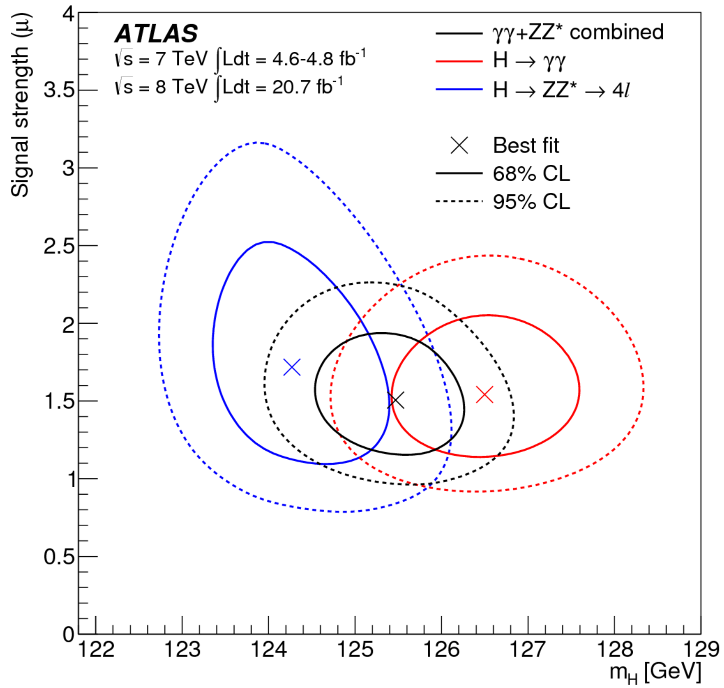
$$\hat{t} = \frac{\vec{p}_T^{\gamma_1} - \vec{p}_T^{\gamma_2}}{\left|\vec{p}_T^{\gamma_1} - \vec{p}_T^{\gamma_2}\right|}$$

- $p_{Tt}(\gamma\gamma)$: slightly better S/B separation than $p_T(\gamma\gamma)$, smoother background.
  - Split sample into high and low $p_{Tt}(\gamma\gamma)$ regions.

- 9 ggF-like categories:
  - Different γ performance in different parts of the detector.
  - Energy resolution, jet rejection.
  - S/B from 5% to 16%
- VH and VBF categories:
  - S/B up to 57%





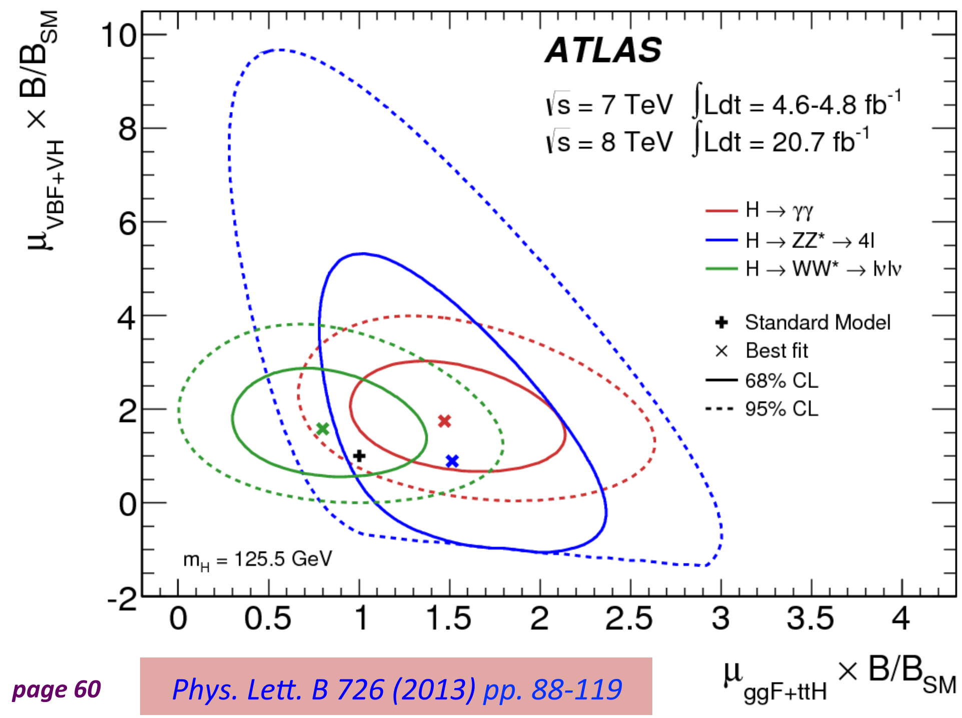


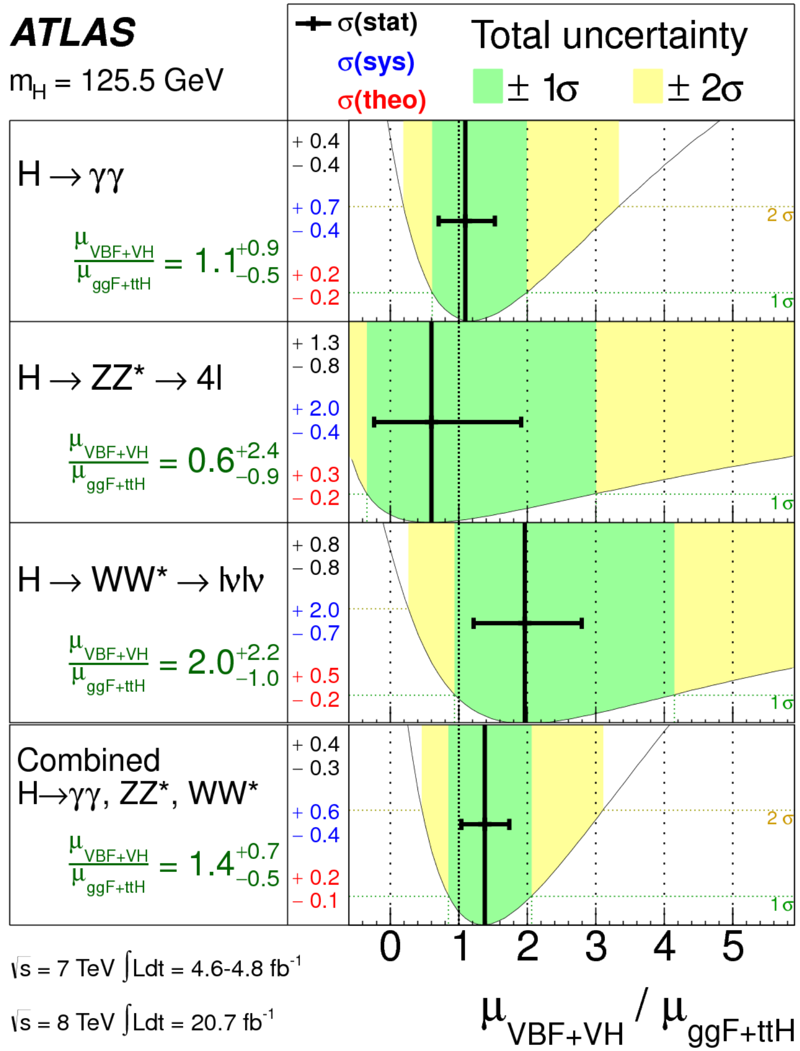
Mass compatibility (ATLAS)

- Combination of mass measurements in $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4l$ channels.
- Profile likelihood ratio, treating signal strengths for both channels as independent nuissance parameters. $m_H = 125.5 \pm 0.2\ (\text{stat})\ ^{+0.5}_{-0.6}\ (\text{sys})$ GeV
- Repeating the stat. analysis for $$\Delta m_H = m_H^{\gamma\gamma} - m_H^{4l}.$$
- $\Delta m_H = 2.3\ ^{+0.6}_{-0.7}\ (\text{stat}) \pm 0.6\ (\text{sys})$ GeV.
  - Corresponds to probability of 1.5% (2.4 standard deviations).

Production mechanisms (ATLAS)

- Defining common scale factors for production modes contributing to the same decay modes:
  - Gluon-mediated (ttH+ggF) and vector-boson mediated (VBF+VH)
  - $\mu_{VBF+VH} = \sigma_{VBF+VH} / \sigma^{SM}_{VBF+VH}$;
  - $\mu_{ttH+ggF} = \sigma_{ttH+ggF} / \sigma^{SM}_{ttH+ggF}$.
- Use the ratio of production modes to eliminate the B/B_{SM} dependence





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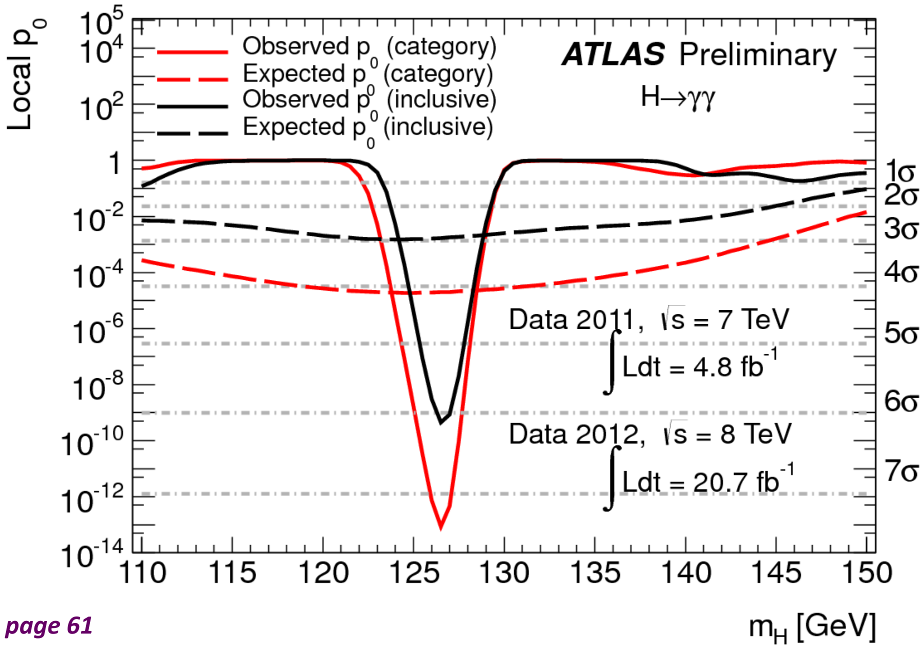
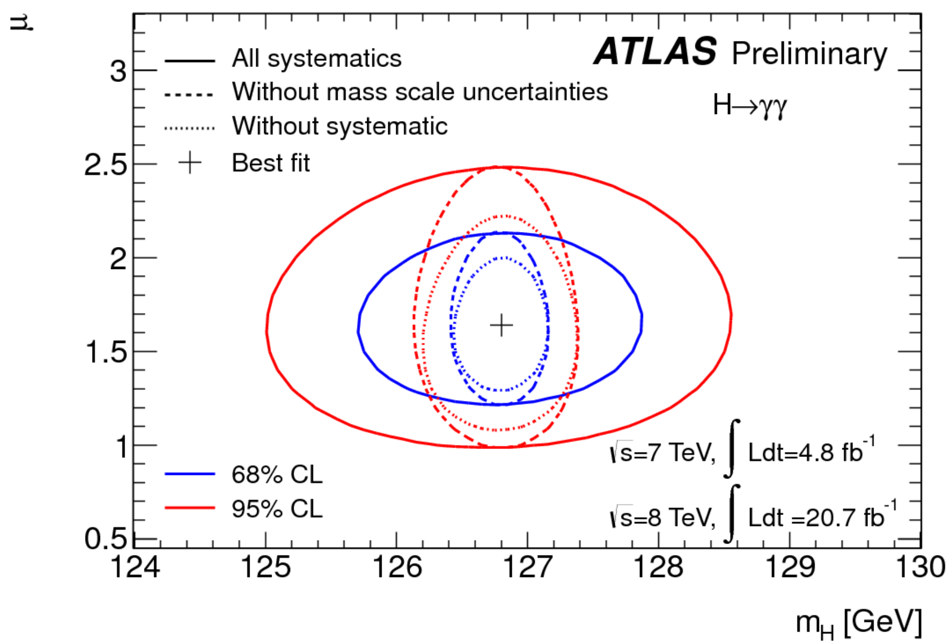
H→γγ (ATLAS) significance, mass, signal strength

- Largest local significance in combination of 7 TeV and 8 TeV data:
- Categories observed (expected): 7.4σ (4.1)σ at m_H=126.5 GeV.
- Inclusive observed (expected): 6.1σ (2.9)σ.

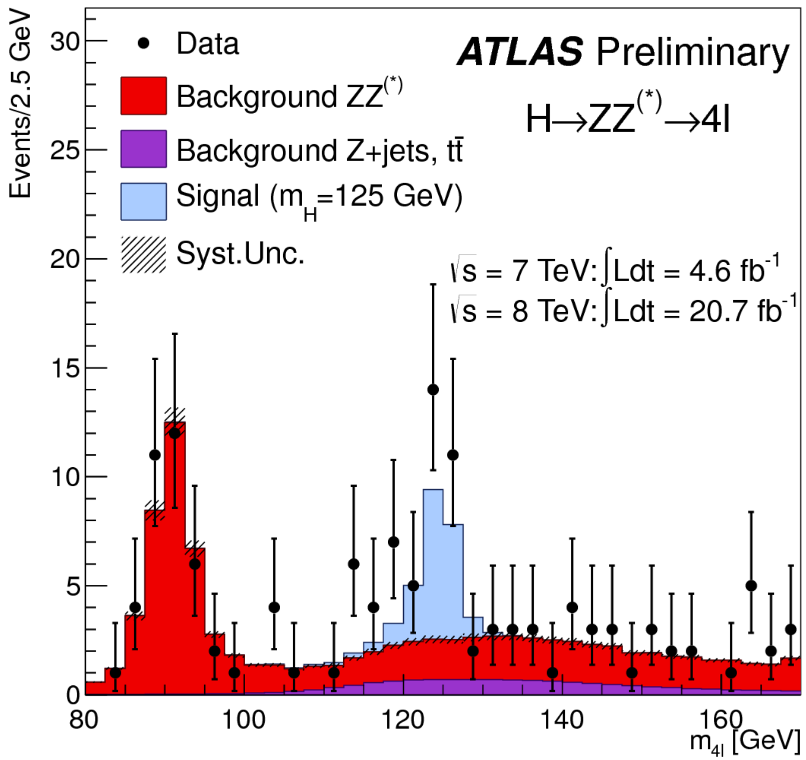
- Best-fit m_H= 126.8±0.2(stat.)±0.7(sys)
- Main systematics: photon energy scale.
- At this m_H: $\mu = 1.65^{+0.24}_{-0.24}$ (stat.) $^{+0.25}_{-0.18}$ (sys.)
- Compatibility with SM μ = 1 at 2.3 σ level

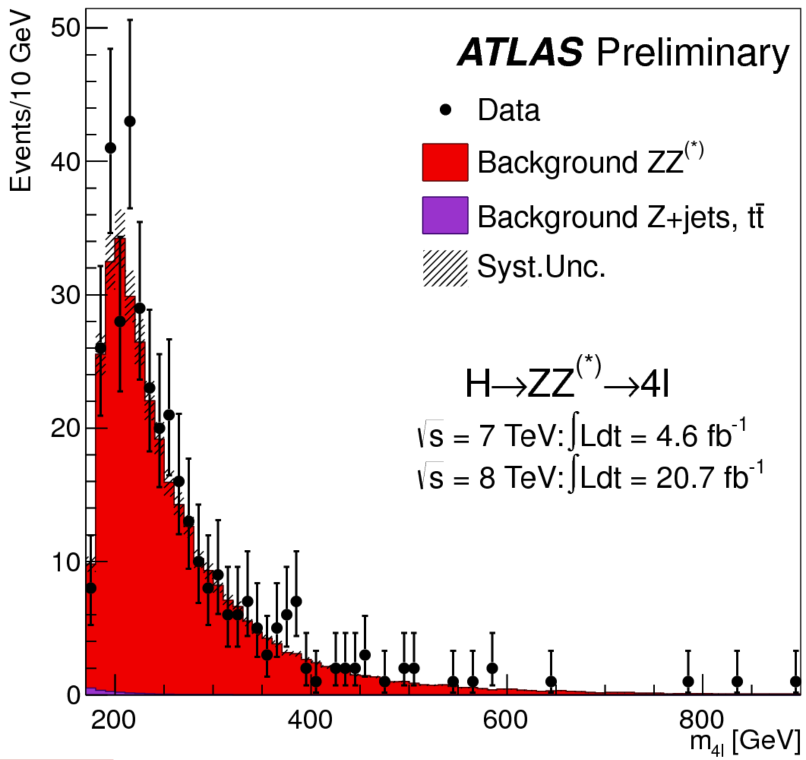




Higgs boson searches in H→ZZ$^{(*)}$→llll channel

- Four isolated leptons: 2 same flavour, opposite charge lepton pairs (one) consistent with Z mass.
  - $p_T^{\mu}>20, 15, 10, 6$ GeV; $|\eta|<2.7$; $p_T^{e}>20, 15, 10, 7$ GeV; $|\eta|<2.47$
- VBF-like: two highest p_T jets; VH-like: not VBF + additional lepton $p_T>8$ GeV; ggF like: all remaining selected events.
- High S/B ratio, large mass range, channel dominated by signal statistics.





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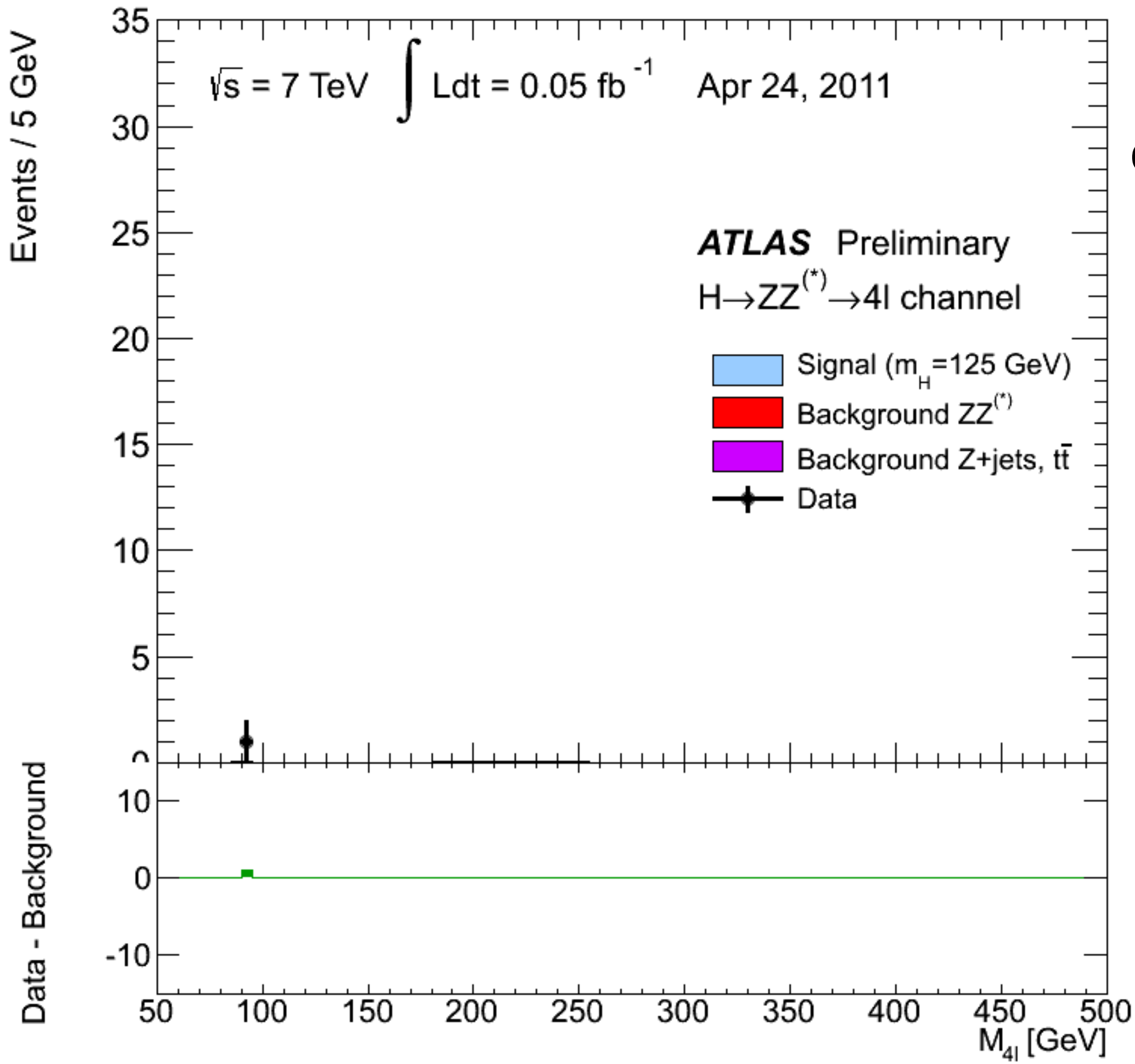
ATLAS-CONF-2013-013



$H \rightarrow ZZ^{(*)} \rightarrow 4l$ channel: mass spectrum evolution

Expected in 125±5 GeV:

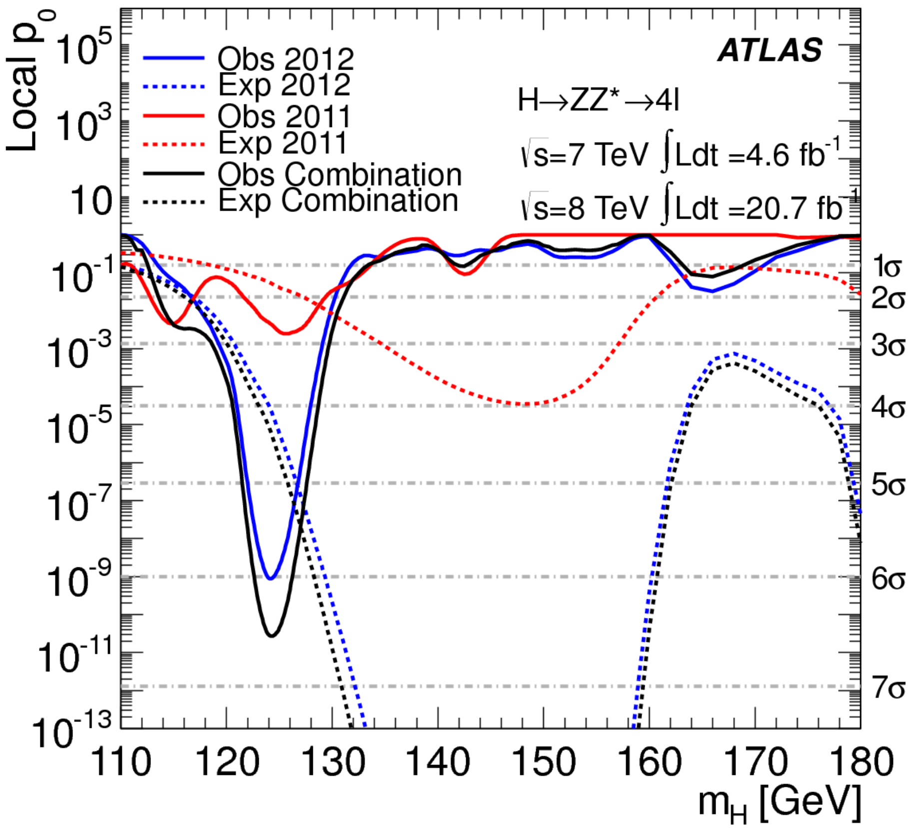
S = 15.9
B = 11.1

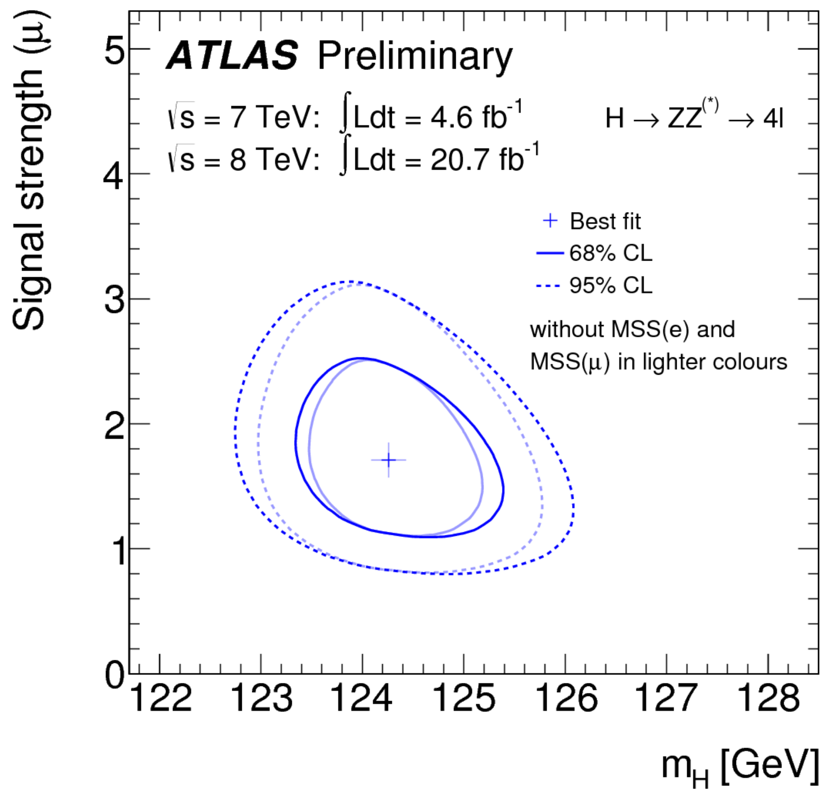
Observed:

32 events.

H→ZZ(*)→llll signal significance

- An excess with a local significance of 6.6σ at 124.3 GeV.
  - The H→ZZ(*)→4l can claim discovery on its own right.
- Mass measurement $m_H = 124.3^{+0.6}_{-0.5}$ (stat)$^{+0.5}_{-0.3}$ (syst) GeV.
- Measured signal strength: $\mu = 1.7^{+0.5}_{-0.4}$





Spin-2 models

- Which Spin-2 models makes sense?
  - The interaction of a spin-two particle with electroweak gauge bosons is described by at least 10 independent tensor couplings.
  - Production mechanism can also vary: gg, qq.

- General idea:
  - Given the number of possibilities, we cannot exclude 'generic' spin-2.
  - We should start with the model with minimal couplings and exclude it in favor of the SM hypothesis, which is relatively well defined.
  - If during this study we observe something 'funny' – have a deeper look in spin-2 models.
  - It is possible that both ggF and qq production mechanisms contribute to the spin-2 state. The possible mixtures should thus be studied.

arXiv:1001.3396 arXiv:1208.4018

Common spin and parity models

- Common set of benchmarks for spin studies: ATLAS and CMS.
  - Theoretically sound. Easy to compare and eventually combine.

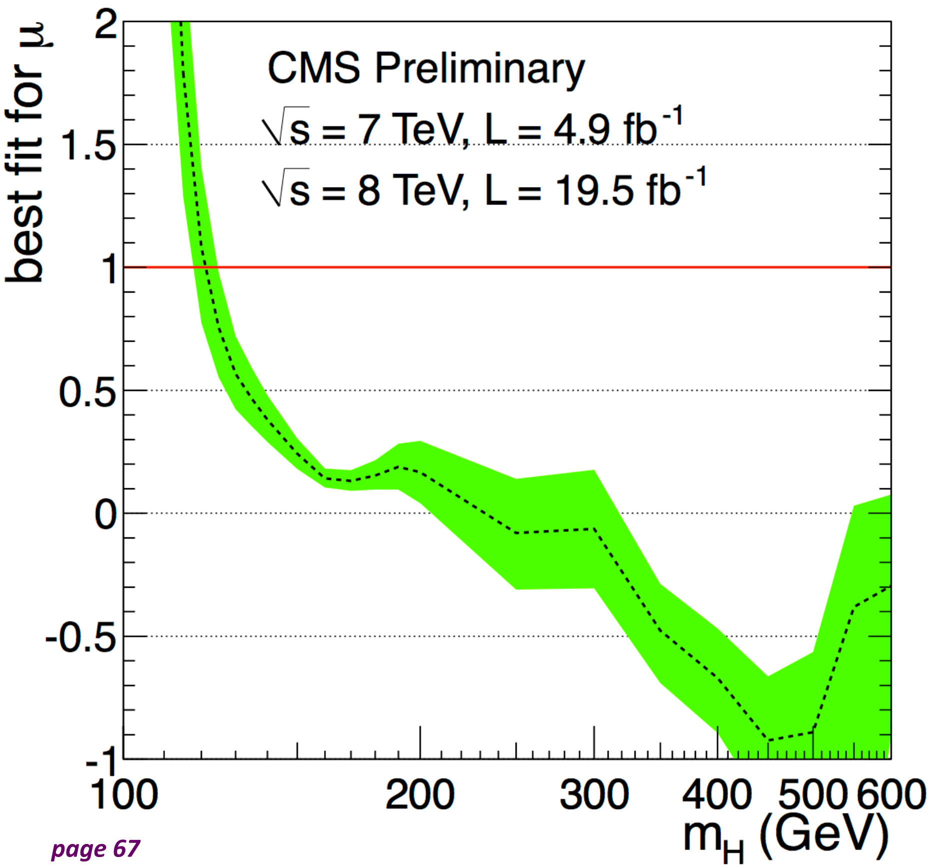
- Spin and parity hypotheses considered in ATLAS : 0^+, 0^-, 1^+, 1^-, graviton-like tensor with minimal couplings 2_m^+.
  - 2_m^+ production. gg->X: g_1=1; qq->X: ρ_{12}=1.
  - 2_m^+ decay g_1=g_5=1.

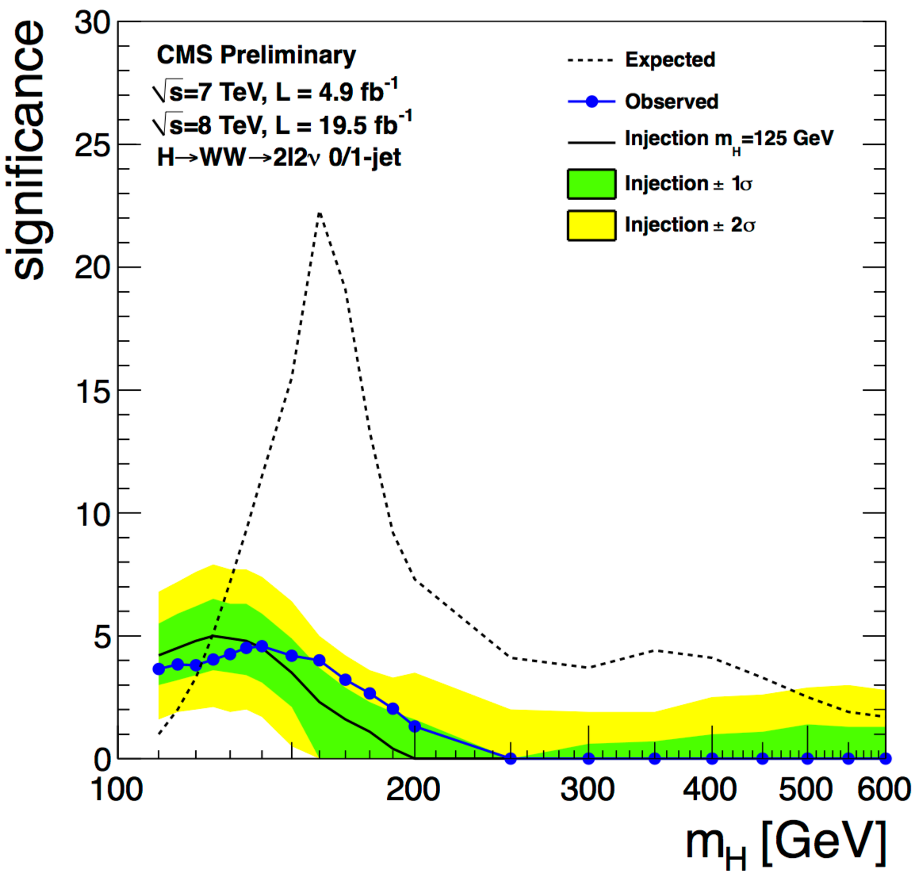
- Several other models including higher dimension operators are considered for future studies: 2^+_h, 2^-_h, 0^+_h etc..

- The choice of coupling constants follows the formalism described in the JHU papers:
  - Y. Gao, *et al., "Spin determination of single-produced resonances at hadron colliders"*, Phys. Rev. D81 (2010) 075022, arXiv:1001.3396 [hep-ph]
  - S. Bolognesi, *et al., "On the spin and parity of a single-produced resonance at the LHC"*, Phys. Rev. D86 (2012) 21.

CMS H→WW$^{(*)}$→lνlν results

- Shape analysis: the combination of 7TeV and 8TeV results excludes SM Higgs at 95% CL in 128 GeV - 600 GeV.
- Excess at low masses: 4.0 σ (exp. 5.1 σ)
- Best fit value at 125 GeV: μ=0.76 ± 0.21

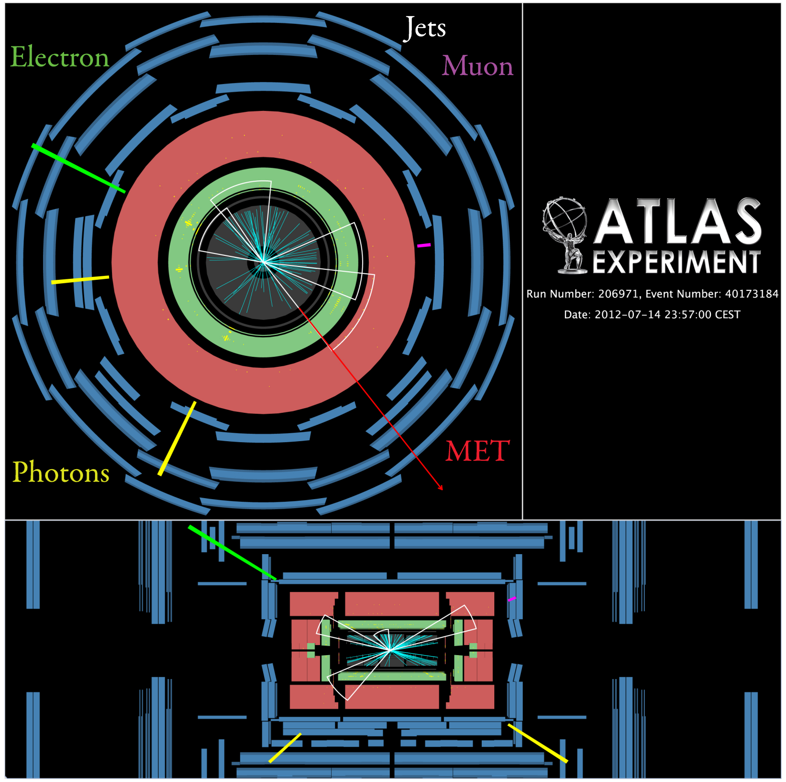


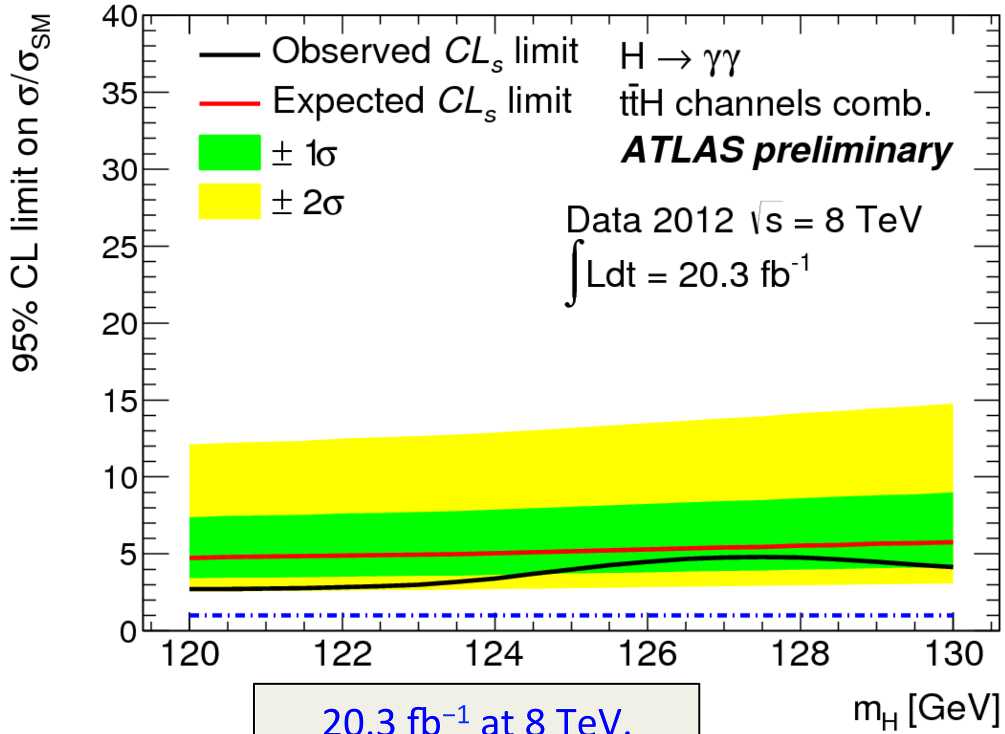


ttH(H→γγ)

- Two high E_T isolated photons as in the main analysis.
- Both leptonic and hadronic ttbar decays.
- Optimized selection to increase ttH
  - Leptonic channel ≥1 lep, MET, ≥1 tag. S/B=0.5
  - Hadronic channel: ≥6jets, ≥2tags. S/B=0.2

- 95% CL limit on σ/σ_{SM}
- At m_H=125GeV:
  - Expected σ/σ_{SM}: 6.4
  - Observed σ/σ_{SM}: 5.3
- Statistically limited.





20.3 fb^{-1} at 8 TeV.

Spin and parity models

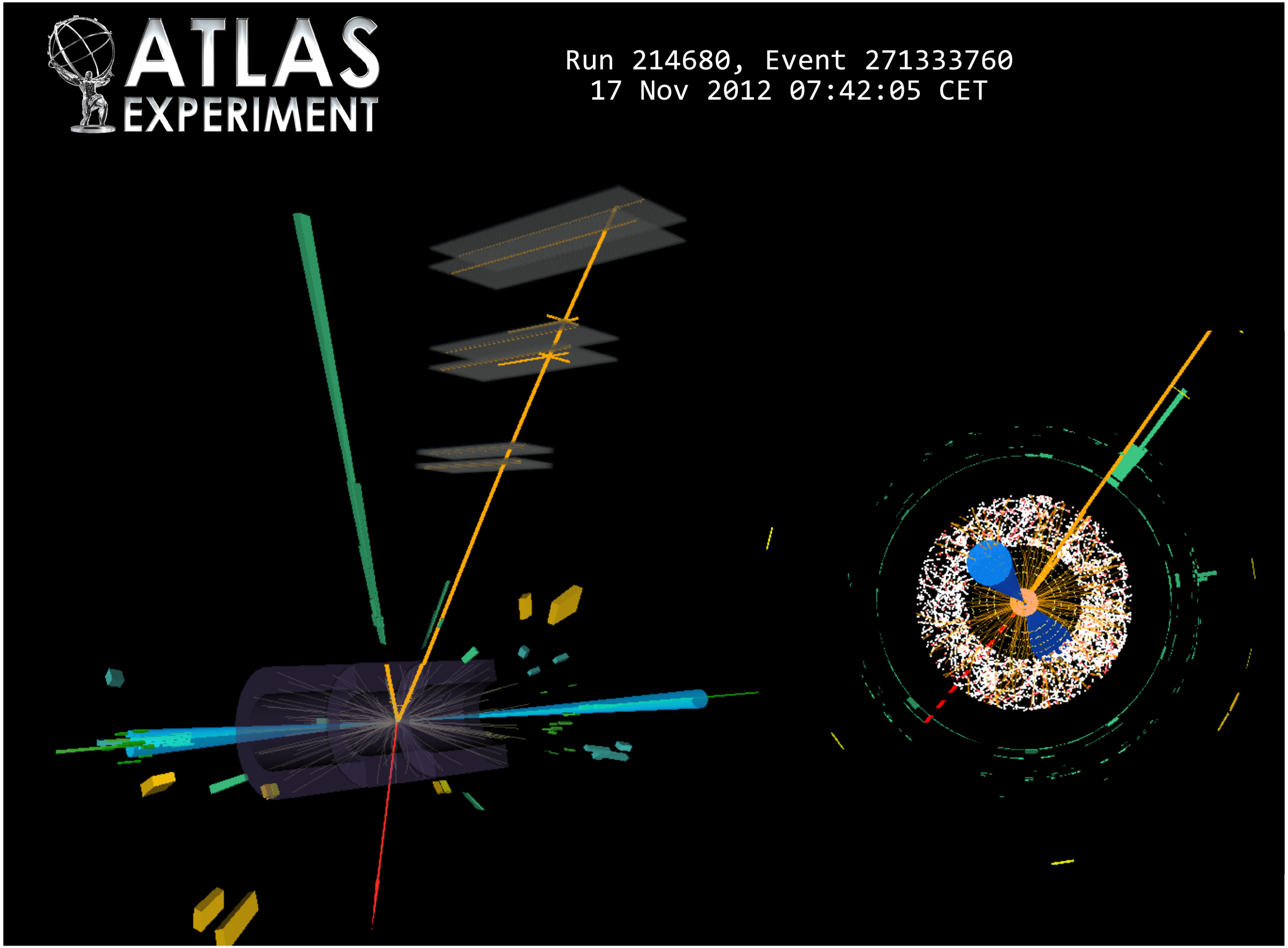
- Non-SM hypotheses which can be excluded at the LHC
  - $J^P=0^-$: ggF $H\rightarrow WW$, $H\rightarrow ZZ$, VBF channels including $H\rightarrow\gamma\gamma$.
  - $J^P=1^+, 1^-$: ggF $H\rightarrow WW$, $H\rightarrow ZZ$.
  - $J^P=2^+, 2^-$: ggF $H\rightarrow WW$, $H\rightarrow ZZ$, $H\rightarrow\gamma\gamma$.

- Which Spin-2 models makes sense?
  - The interaction of a spin-two particle with electroweak gauge bosons is described by at least 10 independent tensor couplings.
  - Production mechanism can also vary: gg, qq.

- General idea:
  - Given the number of possibilities, we cannot exclude 'generic' spin-2.
  - We should start with the model with minimal couplings and exclude it in favor of the SM hypothesis, which is relatively well defined.
  - If disagreement observed – look deeper in spin-2 models.

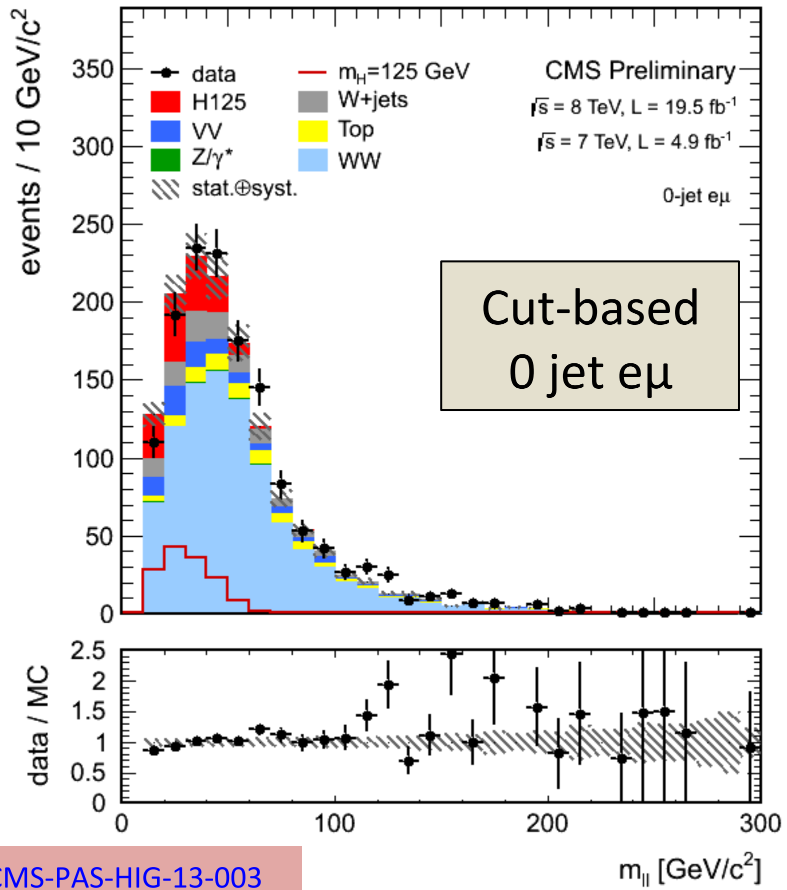
arXiv:1001.3396 arXiv:1208.4018

Higgs boson searches in $H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$ channel

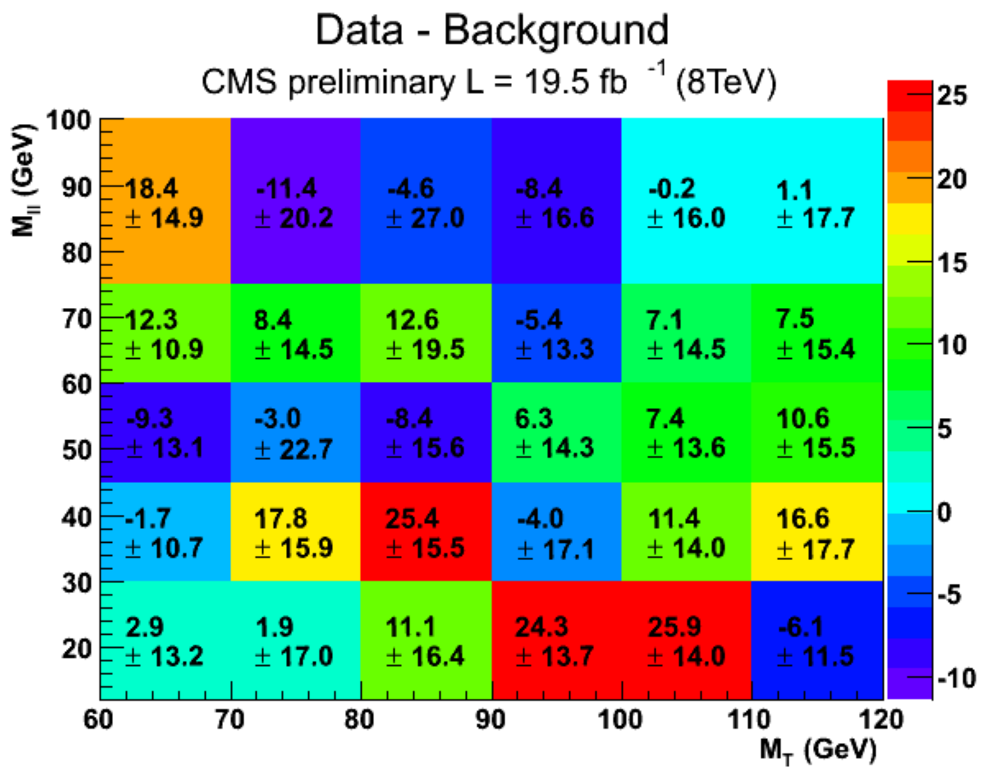


CMS $H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$ results

- Base selection: two oppositely charged leptons with p_T>20GeV; p_T>15(10)GeV. E_T^{miss}>20GeV.
- Cut based analysis: extra requirements on $p^l_T{}^{max}$, $p^l_T{}^{min}$, m_{ll}, $\Delta\phi_{ll}$, m_T.
- 2D shape analysis: m_{ll} vs m_T in 0,1 jets categories to extract the final result.



2D-shape analysis

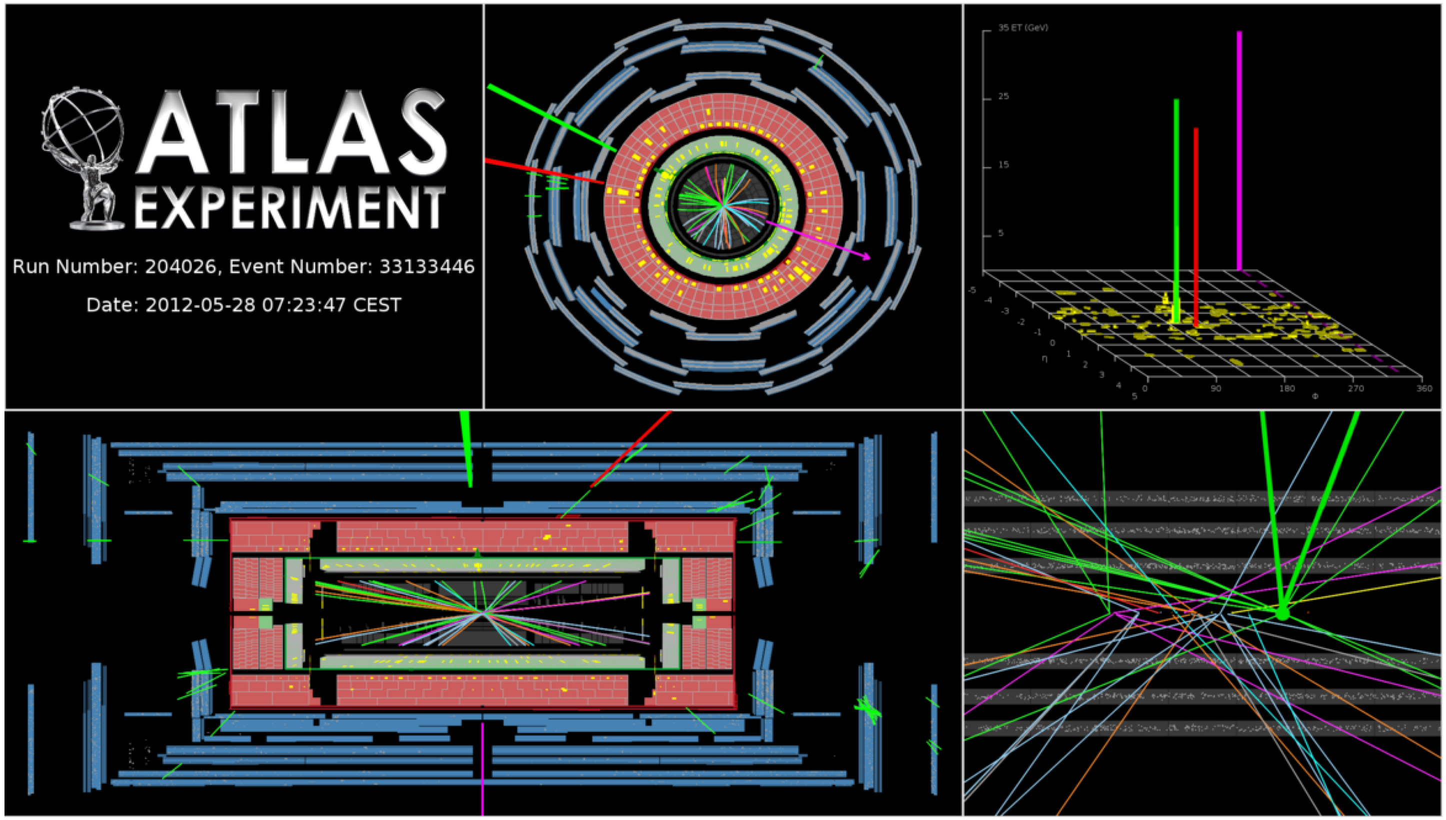


CMS-PAS-HIG-13-003

Higgs boson searches in H→WW$^{(*)}$→lνlν channel

- Signature: H→W(→lν)W$^{(*)}$(→lν).
  - Two opposite charge high p_T leptons.
  - Leptons produced in decay od spin-0 resonance: small angular separation.
  - Two neutrinos: missing E_T signature.

Full mass reconstruction is not possible: m_T as discriminating variable.



Higgs boson searches in $H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$ channel

- Very large BR. Dominant for m_H> 140 GeV.

- Event selection: two isolated leptons $p_T(l_1,l_2)$>25, 15 GeV.
  - ee, eμ, μe and μμ categories. For ee and μμ: $|m_{ll}-m_Z|$>15 GeV, m_{ll}>12 GeV. For eμ, μe: m_{ll}>10 GeV.
  - Missing transverse energy.
  - Jet multiplicity categories: 0,1 and ≥2 jets (VBF): different background compositions and selection cuts.

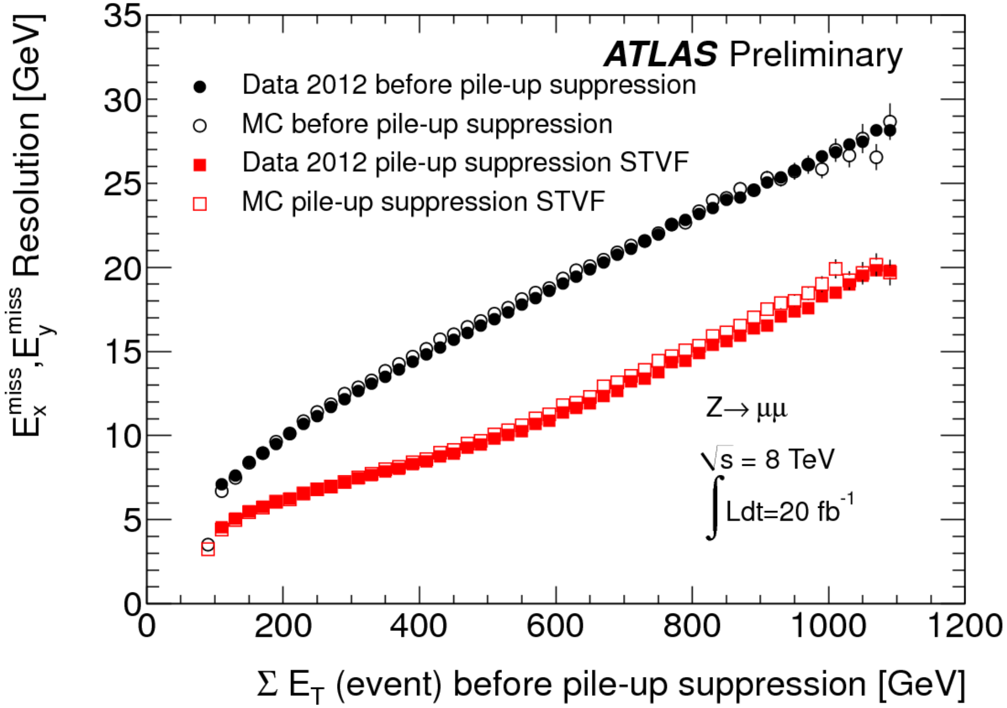
- Dominant backgrounds:
  - Dibosons: $WW^{(*)}$ (+ jets).
  - tt, Wt,
  - DY, W+jets etc...

- Mostly estimated from dedicated control regions

Missing transverse energy

The vector momentum imbalance in the transverse plane obtained from the negative vector sum of the momenta of all particles detected in a *pp* collision. E_t^{miss} is its magnitude.

Calculated by summing all energy deposits in the calorimeter (based on identified objects: e, γ, τ, jets >20 GeV, soft energy depositions incl. tracks, and muons



- Pile-up suppression using the tracking detector.
- Jet Vertex Fraction cuts.

$$\mathrm{JVF} = \sum_{\mathrm{tracks_{jet},PV}} p_T / \sum_{\mathrm{tracks_{jet}}} p_T,$$

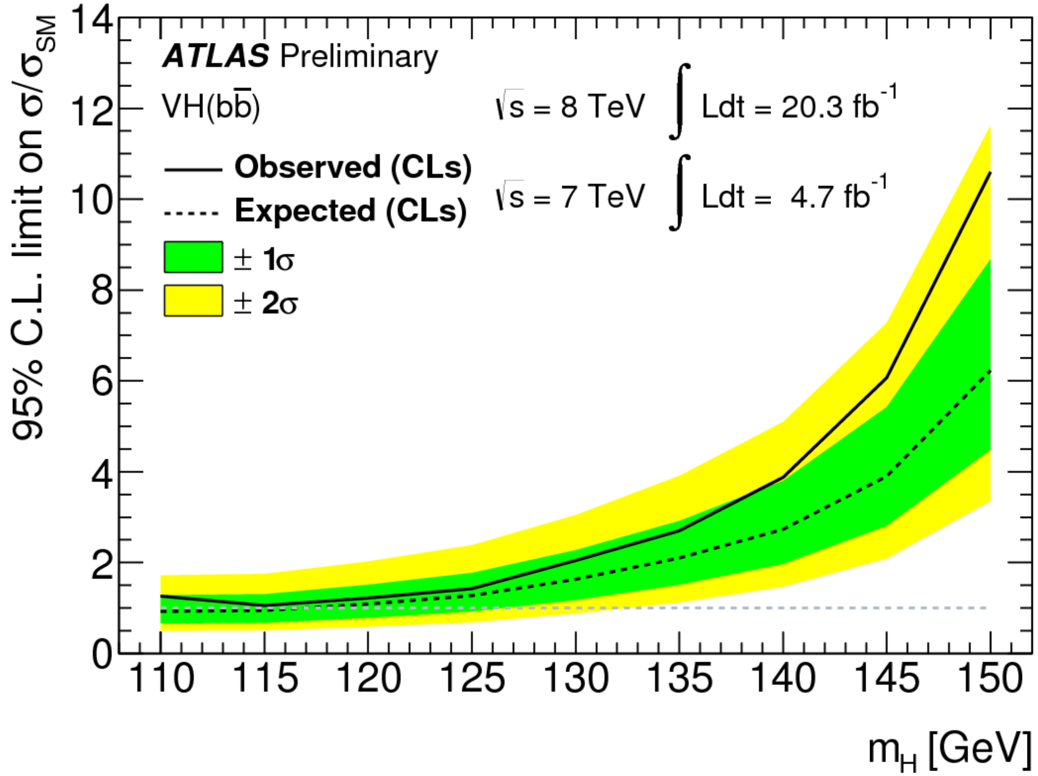
- Scale soft terms with STVF.

$$\mathrm{STVF} = \sum_{\mathrm{tracks_{SoftTerm},PV}} p_T / \sum_{\mathrm{tracks_{SoftTerm}}} p_T$$

VH H→bb (ATLAS)

- 2 b-tagged jets. p_T^V reconstructed from missing E_T and leptons.
- Simultaneous fit to 3 channels in multiple p_T^V bins, jet and b-tag multiplicities:
  - Helps normalizing backgrounds.
  - Controls effect of systematic uncertainties.
  - Isolates categories with very different S/√B.
- Main backgrounds normalizations: ttbar, Z+HF, W+HF.

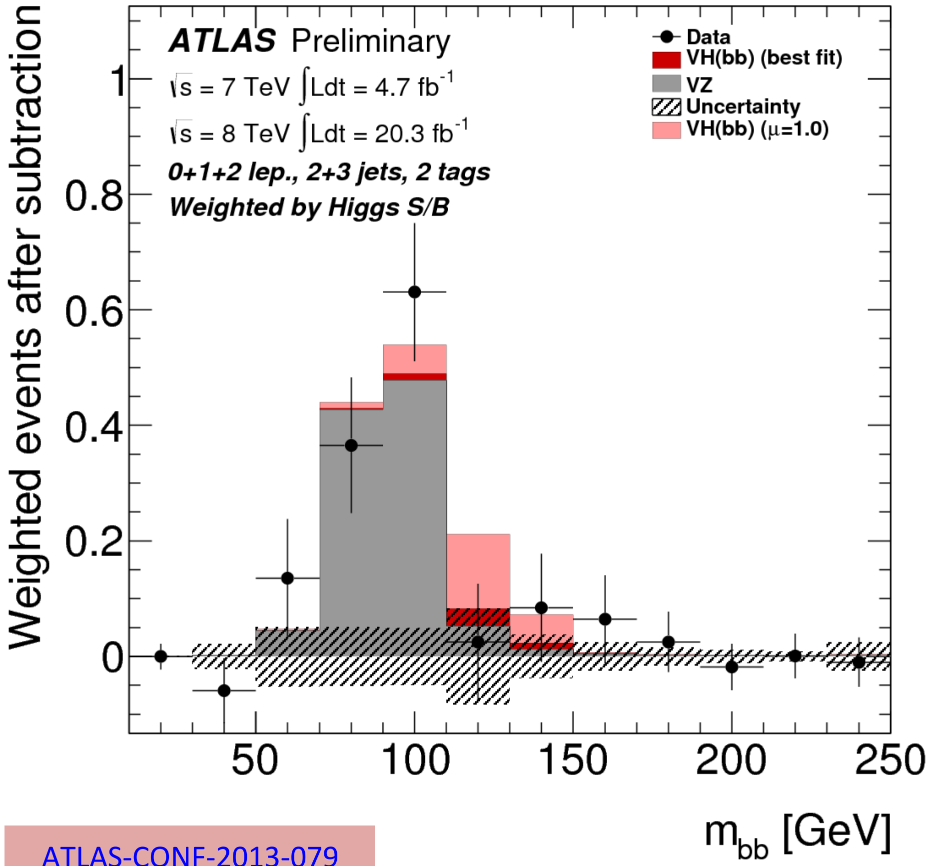
- 95% CL limit on $\sigma/\sigma_{SM.}$ At m_H=125 GeV
  - Observed σ/σ_{SM}: 1.3.
  - Expected σ/σ_{SM}: 1.4.
- Largest systematics: ttbar modelling, *b*-tagging.

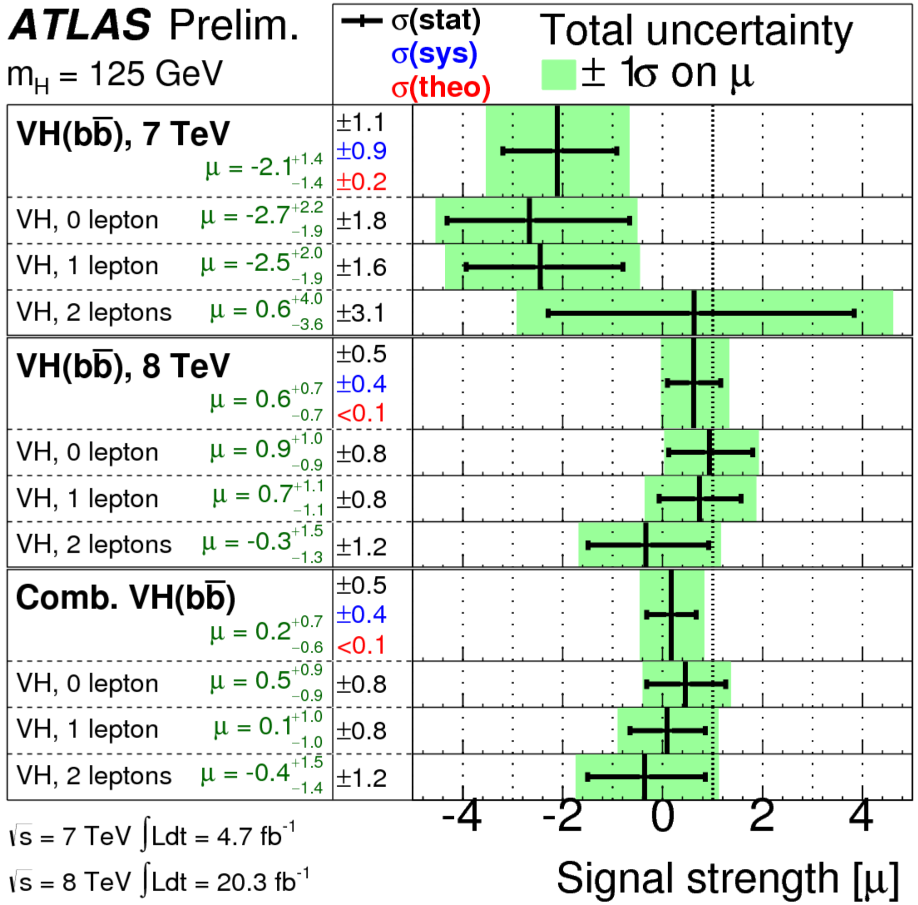


ATLAS-CONF-2013-079

VH H→bb (ATLAS)

- Measured signal strength per category:
  - 0 lept: $\mu = 0.5^{+0.9}_{-0.9}$
    1 lept: $\mu = 0.1^{+1.0}_{-1.0}$
    2 lept: $\mu = -0.4^{+1.5}_{-1.4}$

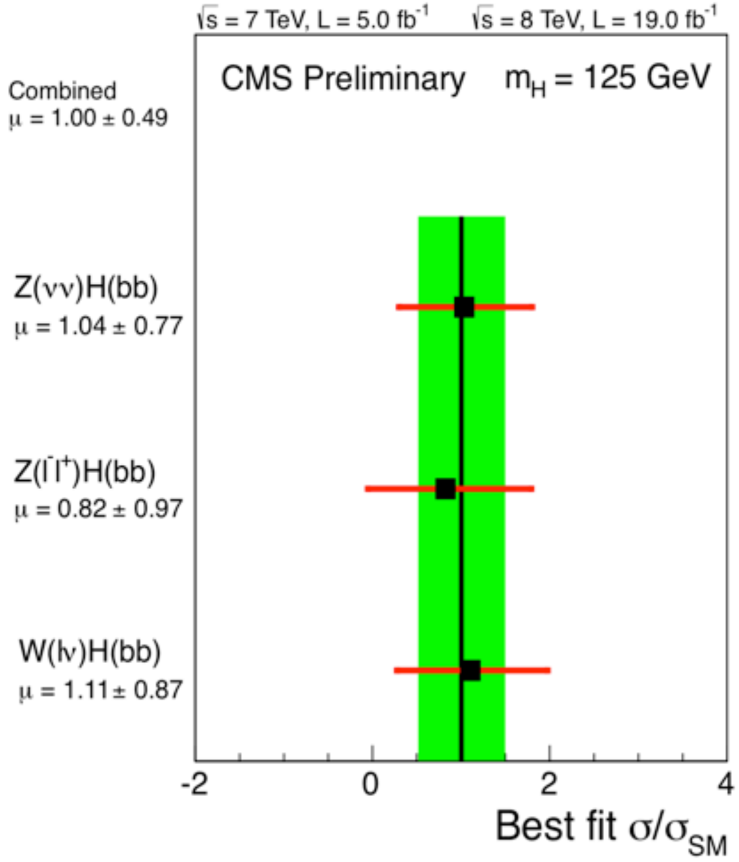


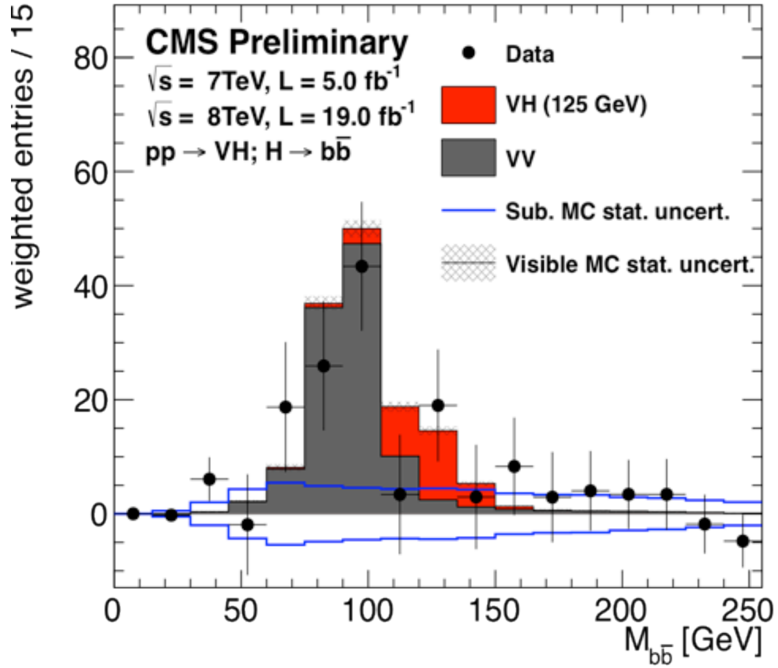


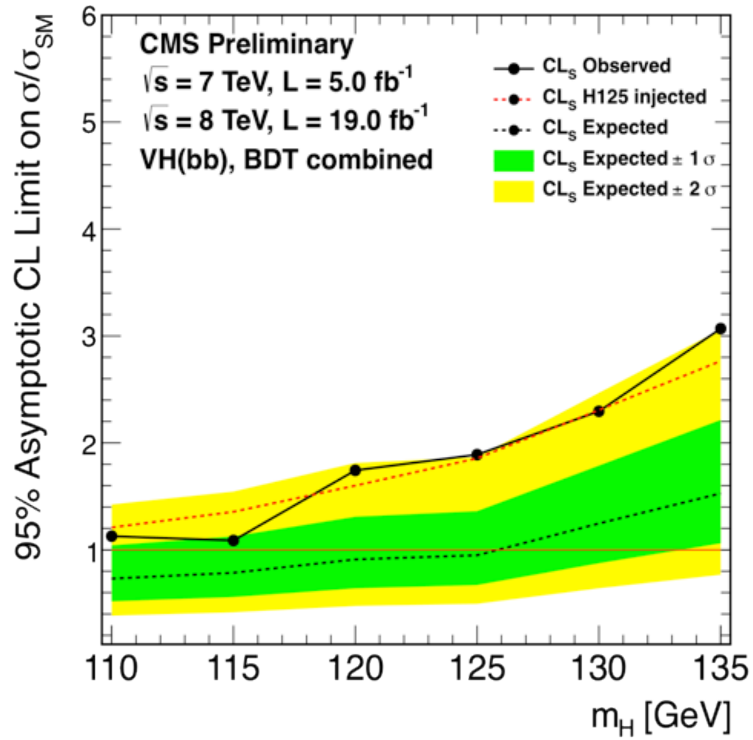
ATLAS-CONF-2013-079

VH H→bb (CMS)

- An excess with local significance 2.1 σ
- At m_H = 125 GeV; Observed 95% CL exclusion: 1.89 σ^{SM} , (Expected: 0.95 σ^{SM})



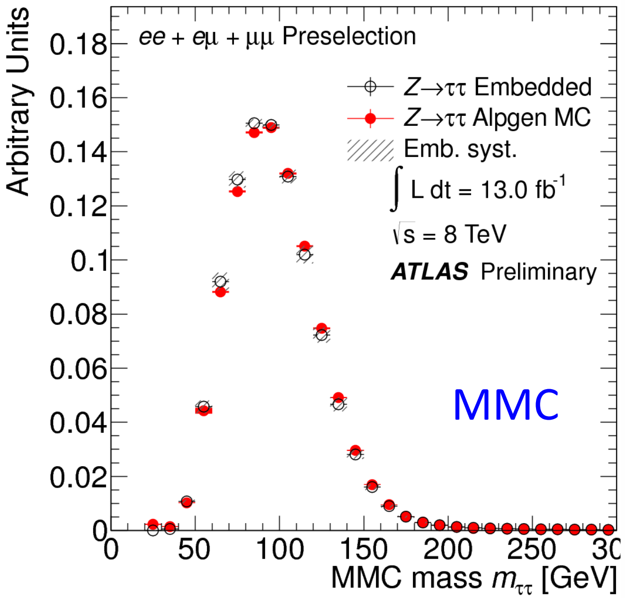


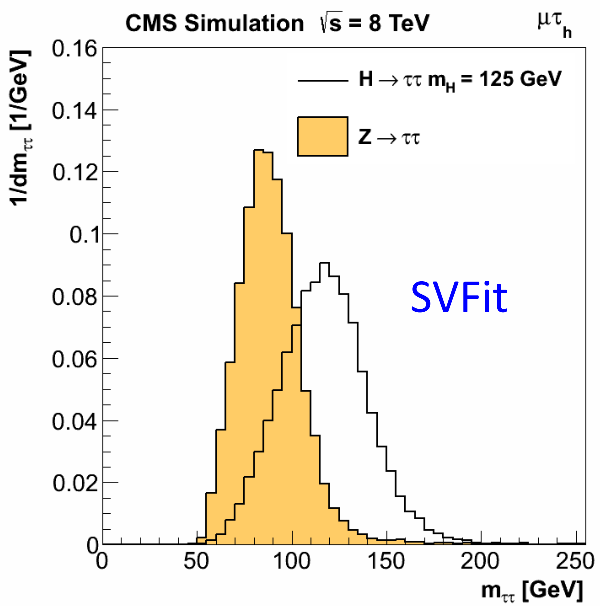


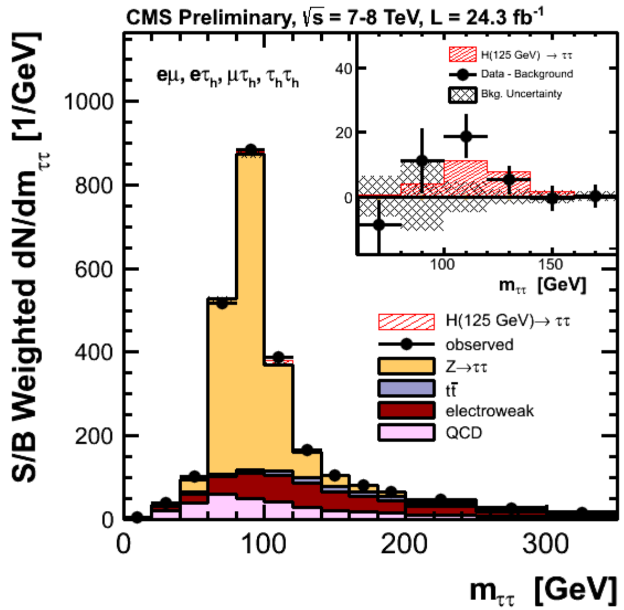
CMS-PAS-HIG-13-012

H→ττ (CMS and ATLAS)

- Hadronic and leptonic τ decays. 2-4 neutrinos in the final state. $H \to \tau^+\tau^- \to ll4\nu$, $l\tau^{had}3\nu$ and $\tau^{had}\tau^{had}\nu\nu$ channels.
- Main background: $Z \to \tau\tau$.
- Categories based on jet multiplicity and p_T of visible τ decay products.
- Mass reconstruction: visible mass, collinear approximation, MMC (ATLAS: Nucl. Instrum. Methods A654 (2011) 481), SVFit (CMS: CMS PAS HIG-13-004).



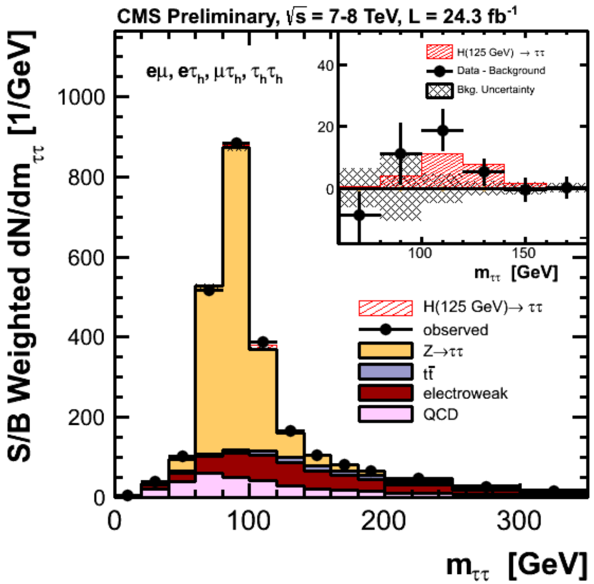


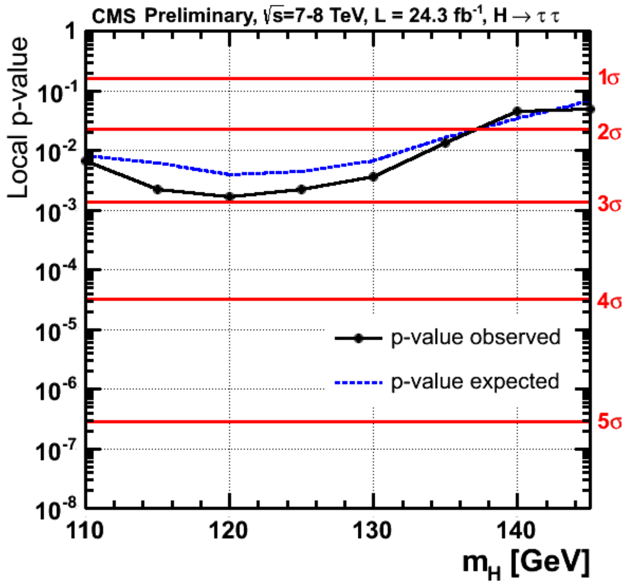


CMS-PAS-HIG-13-004

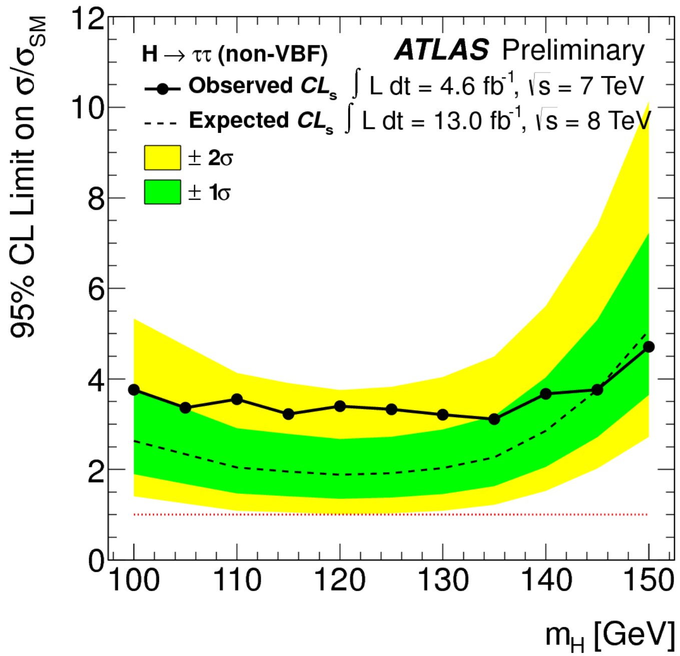
ATLAS-CONF-2012-160

H→ττ (CMS and ATLAS results)





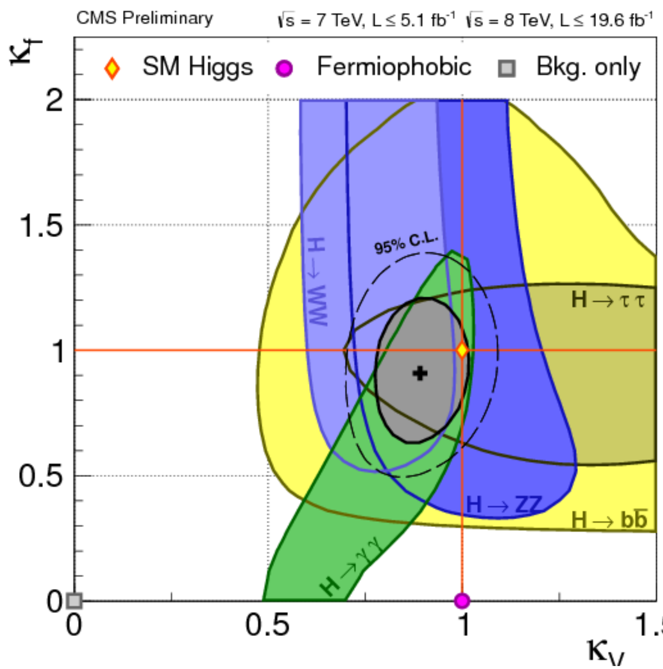
- CMS: combined best fit μ=1.1±0.4 at 125 GeV.
- An excess around 125 GeV. (Min. p_0 at 120GeV)
- At 125.8 GeV: 2.85σ.



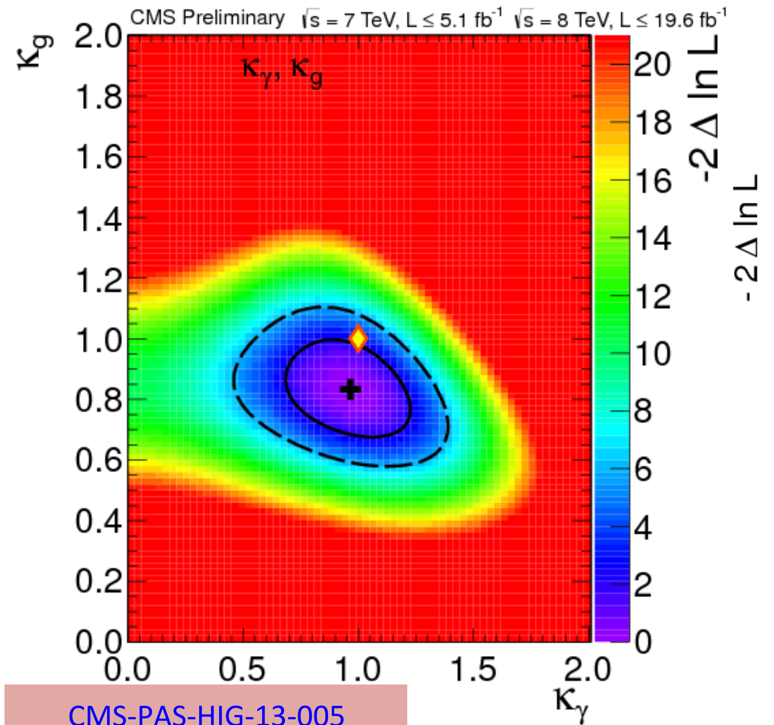
- ATLAS: full run-I analysis in progress.
- Observed (expected) 95% CL exclusion for 125 GeV: $1.9\sigma^{SM}$($1.2\ \sigma^{SM}$)
- Combined μ = 0.7 ± 0.7

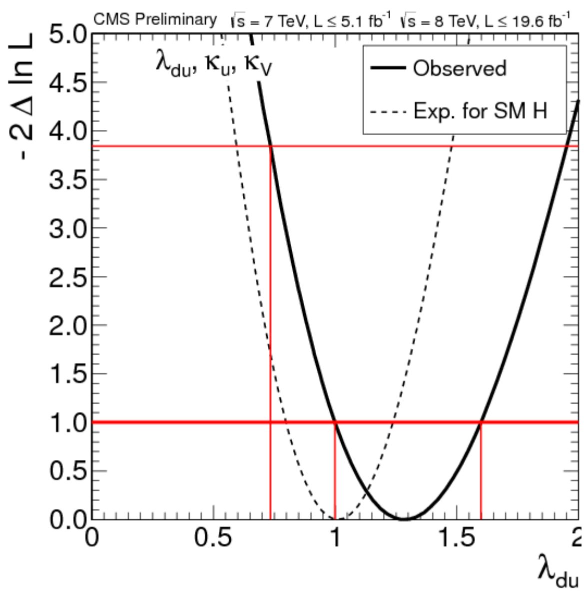
ATLAS-CONF-2012-160

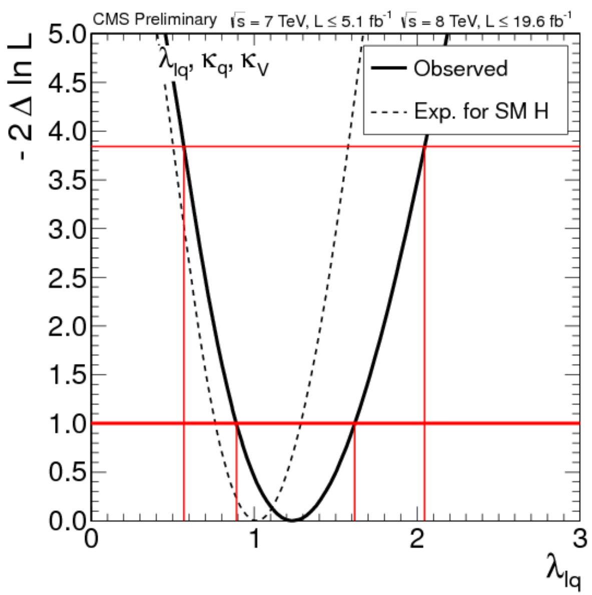
Measurements of couplings (CMS)



- k_V vs k_F fit with no BSM contributions allowed: best fit value consistent with SM within 68% CL.
- Test for BSM contributions in loops: (k_γ, k_g) = (0.97, 0.83)
- Asymmetries in fermion couplings. 95% CL intervals for $\lambda_{du} = k_d/k_u$: [0.74,1.95]; and $\lambda_{lq}=k_l/k_q$:[0.57,2.05].







CMS-PAS-HIG-13-005

Spin and parity measurements (ATLAS)

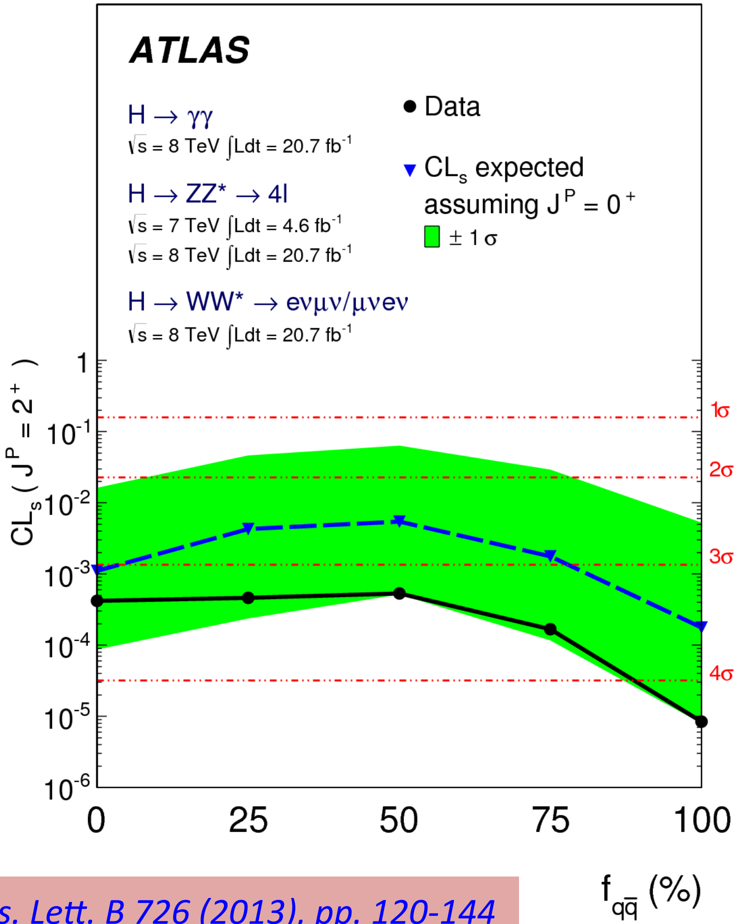
Combination of J^P exclusion on favor of the SM Higgs (ZZ^*, WW^*, $\gamma\gamma$).

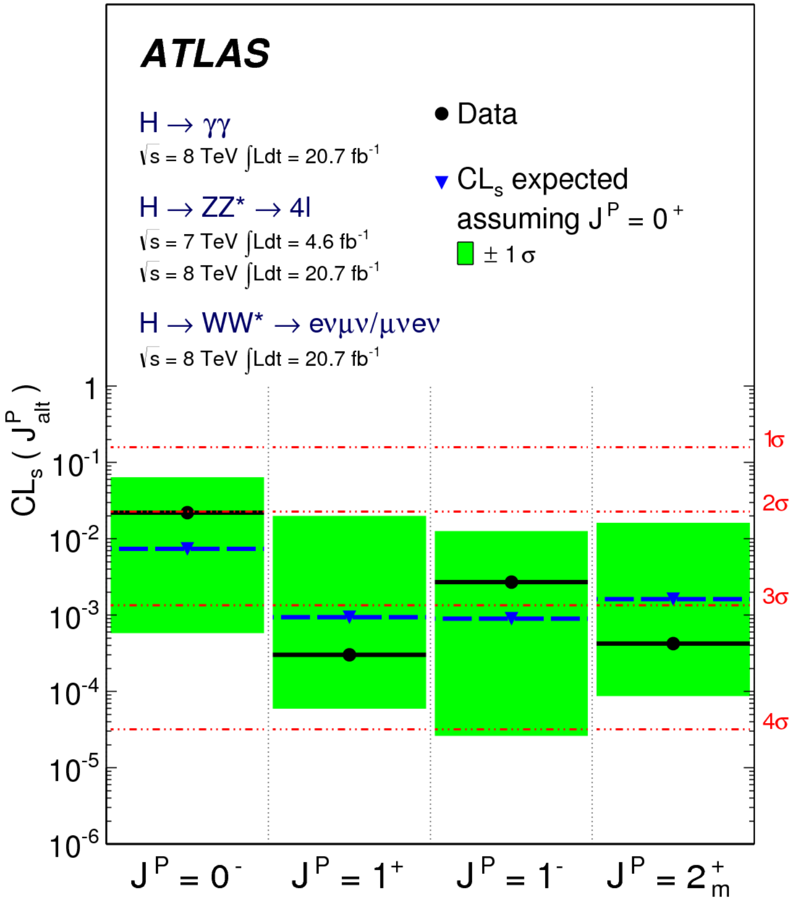
$J^P=2^+$ at >99.9% CL independently of f_{qq} ($ZZ^*+WW^*+\gamma\gamma$);

$J^P=0^-$ at 97.8% CL (ZZ^*);

$J^P=1^-$ at 99.73% CL;

$J^P=1^+$: 99.97% CL. (ZZ^*+WW^*).





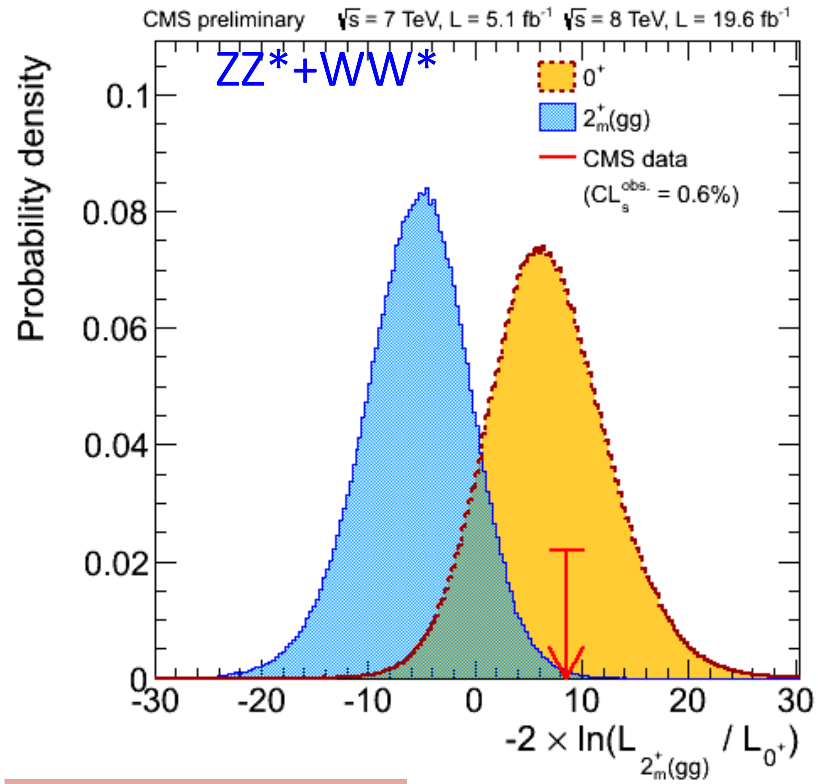
Phys. Lett. B 726 (2013), pp. 120-144

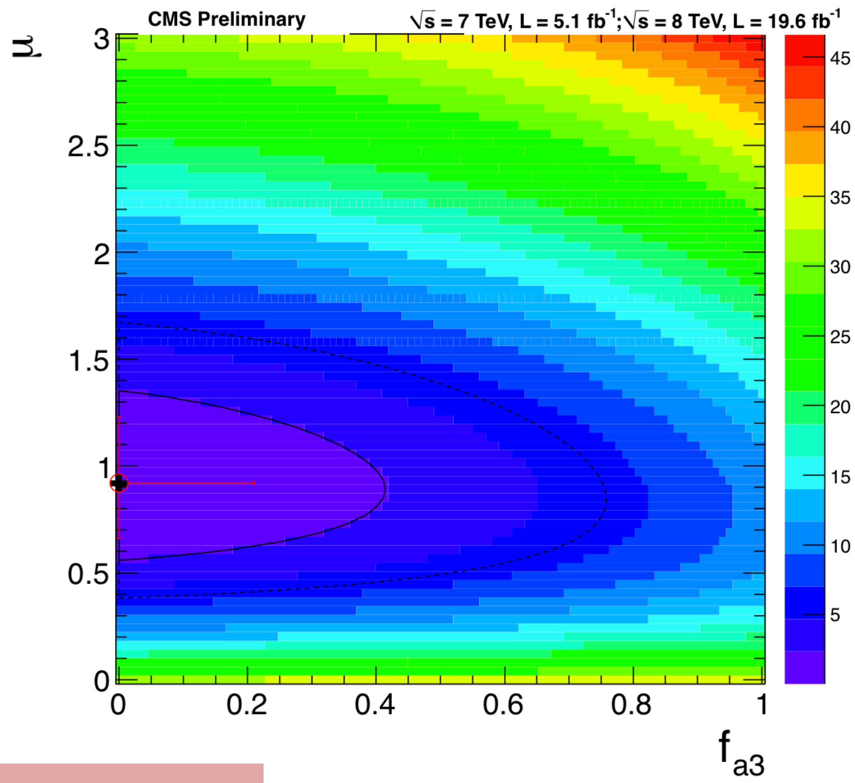
Spin and parity measurements (CMS)

Combination of J^P exclusion on favor of the SM Higgs (ZZ^*, WW^*, $\gamma\gamma$).
$J^P=2^+$ (100%ggF) at >88.8% CL (ZZ^*+WW^*); 2^+ (100% qq) >99.9%CL (ZZ^*)
$J^P=0^-$ at 99.8% CL (ZZ^*);
$J^P=1^-$ and $J^P=1^+$ at >99.9% CL (ZZ^*)

(Several other hypotheses tested)

CP-mixing fraction measurement:
f_{a3}<0.58 at 95%CL.



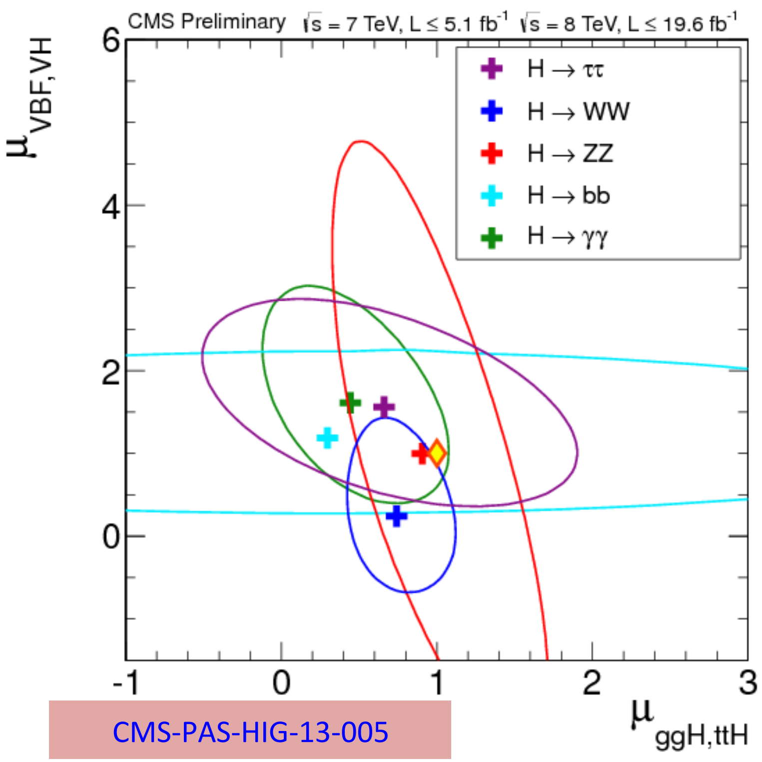


CMS-PAS-HIG-13-005

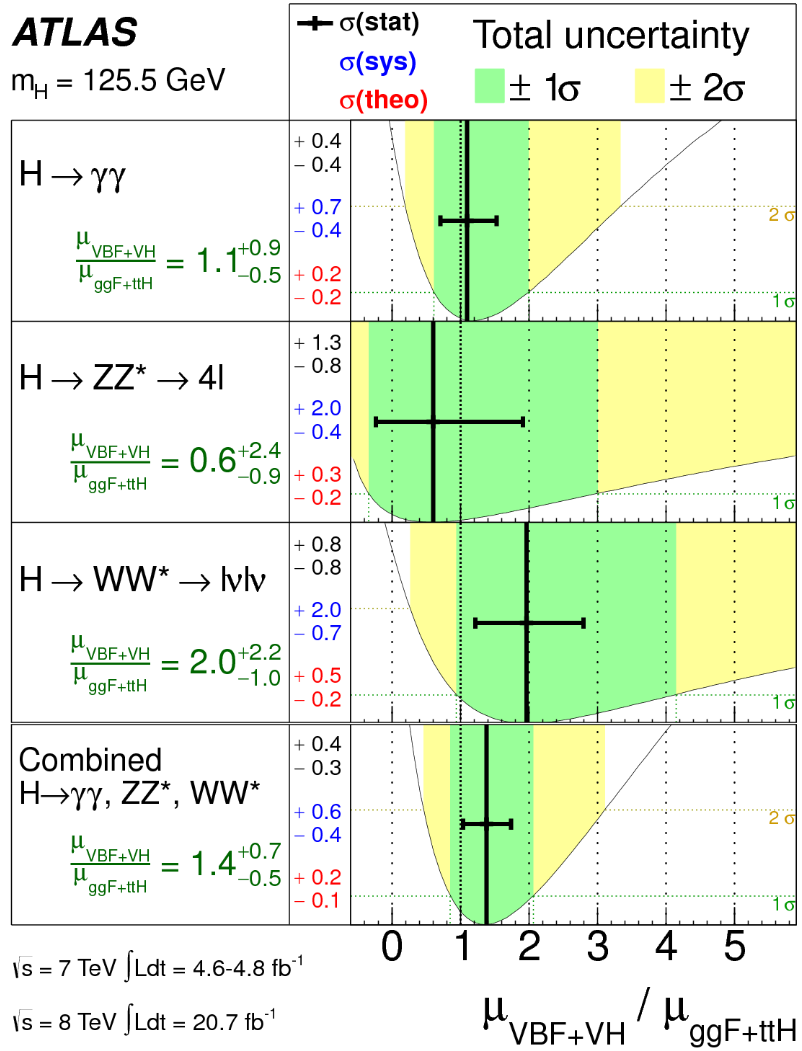
CMS-PAS-HIG-13-002

Production mechanisms (ATLAS and CMS)

- Defining common scale factors for production modes contributing to the same decay modes:
  - Gluon-mediated (ttH+ggF) and vector-boson mediated (VBF+VH)
  - $\mu_{VBF+VH} = \sigma_{VBF+VH} / \sigma^{SM}_{VBF+VH}$;
  - $\mu_{ttH+ggF} = \sigma_{ttH+ggF} / \sigma^{SM}_{ttH+ggF}$.
- Use the ratio of production modes to eliminate the B/B_{SM} dependence



CMS-PAS-HIG-13-005



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