Higgss boson discovery and measurements

Part 2: Properties measurements

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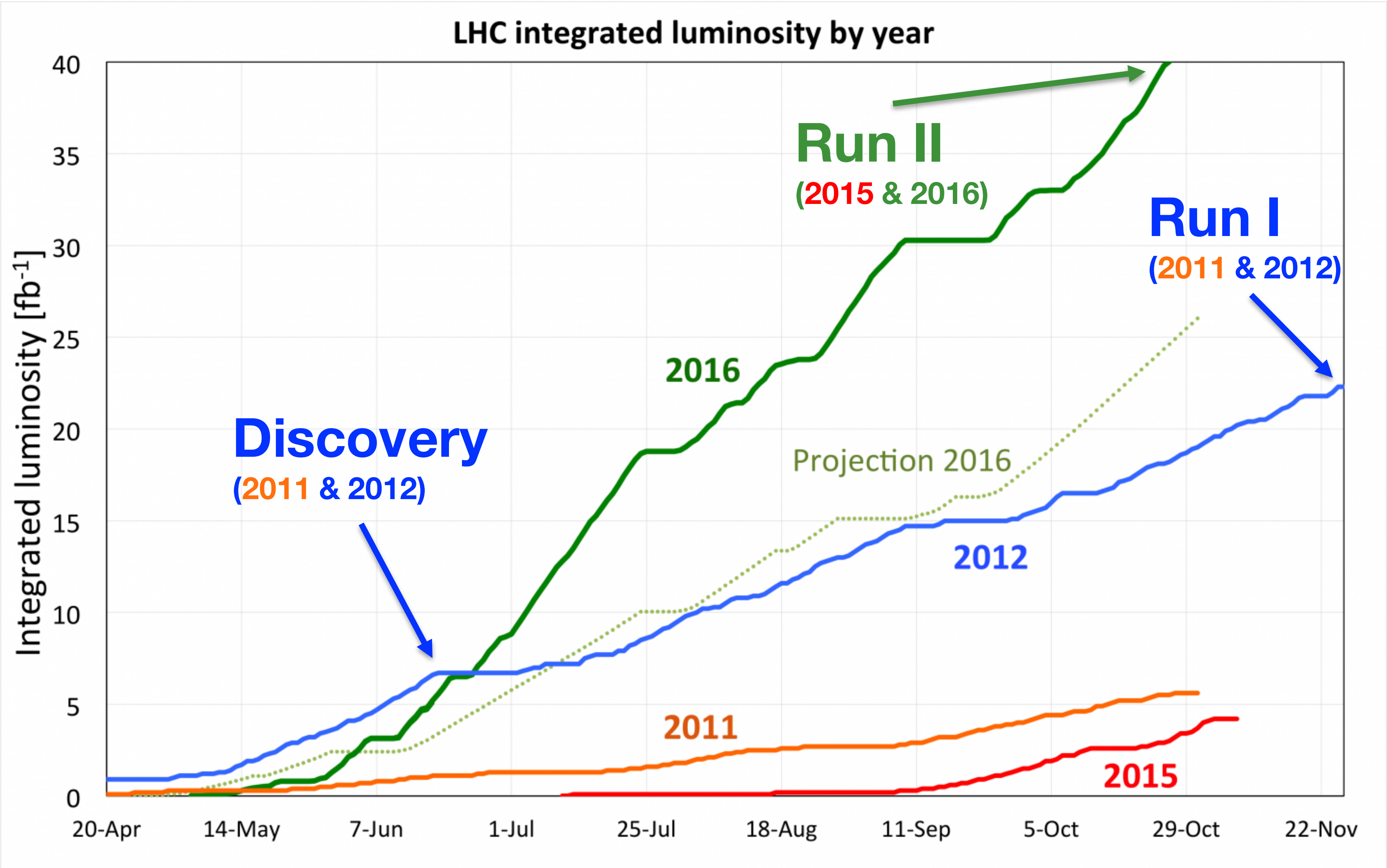
Content

- Evolution of analyses
  - Example: H→ZZ→4l in CMS
  - Run I final significances with H→ZZ→4l and H→$\gamma\gamma$
- Properties measurements
  - With Run I data
    - Mass
    - Width
    - Signal strengths
    - Spin and parity … Jonas Rembser
  - Next lecture
    - Spin, cntd
    - Total and differential cross sections
    - Couplings

Evolution of analyses

- By the time of Higgs boson discovery the analyses for different channels had a form as an outcome
  - … of historical development over the period of about 20 years
  - … of a balance between the best sensitivity for discovery and robustness against false discoveries
- After the discovery, due to
  - … gained confidence in detector and analyses understanding
  - ... increased statistics
  - ... development o new tools and methods
  - ... development of new ideas
- … our analysis have evolved in, for example
  - Adding new events categorisation
  - Improving systematical errors
  - Using more and more complex tools and analyses methods (BDT, NN ...)
  - Adding more channels
  - Exploring some new theoretical ideas
- In what follows we will show few example on how analyses were improved
  - As usual we'll use $H \rightarrow ZZ \rightarrow 4l$ in CMS as an example

LHC luminosity evolution



Analysis steps with some details

… and full of colors ☺

Trigger

Level 1 Trigger: Electron-gamma and muon seed

High Level Trigger : Multilepton paths

Triggered events

Object reconstruction

Electrons
Isolation, ID, SIP_{3D}

Muons
Isolation, ID, SIP_{3D}

FSR photons

+ - …

+ - …

Event selection

Z_1: A pair of opposite sign same flavor leptons closest to Z, with $40 < M_{ll} < 120$ GeV

Z_2: Remaining lepton combination with highest p_T sum and with $12 < M_{ll} < 120$ GeV

Additional: at least one lepton with $p_T > 20$ GeV and one with $p_T > 10$ GeV, all opposite-charge lepton pairs with $m_{ll'} > 4$ GeV

Higgs boson phase space: $m_{4l} > 100$ GeV

Selected events

Analysis

Background estimates

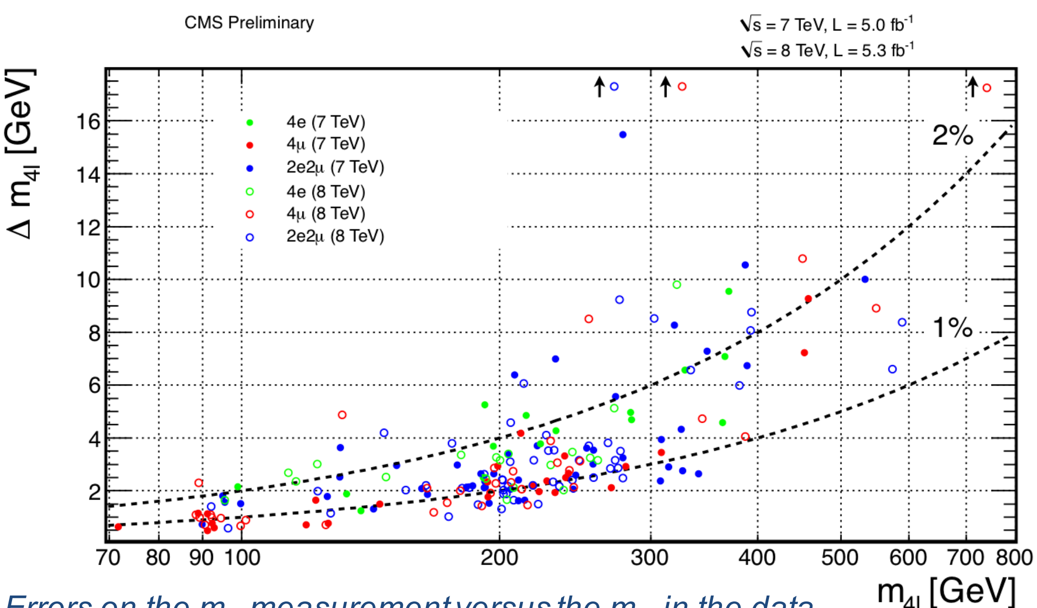
Systematics

Kinematic discriminant

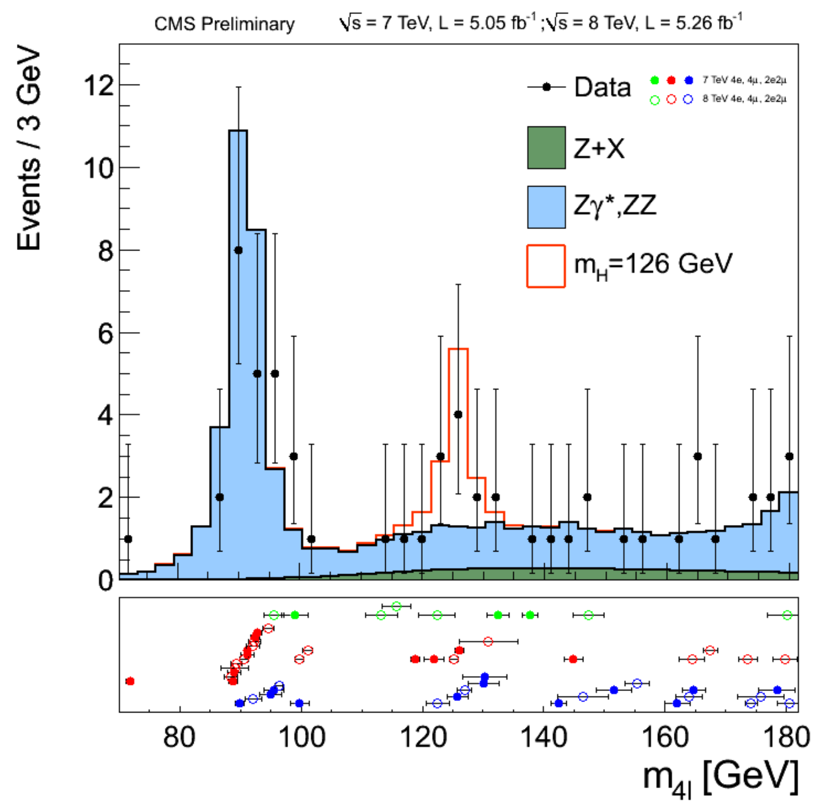
Statistical analysis
- Limits
- P-values
- Signal strength

Per-event mass uncertainties

- Four leptons events were treated in separate final state categories: 4e, 4μ and 2e2μ
- But individual events even in the same category can have different mass resolution
  - Depending on p_T and η of leptons, as well as on lepton reconstruction quality
- We therefore introduced per-event four-lepton mass uncertainty - $\Delta_{m_{4l}}$
  - With basic idea: give more weights to events with smaller four-lepton mass uncertainty
  - This uncertainty was calculated from single lepton resolution (i.e. momentum measurement uncertainty), propagating them to final four-lepton invariant mass formula
  - This was used in mass measurement (already for discovery)



Errors on the m_{4l} measurement versus the m_{4l} in the data for the 4e (green), 4μ (red) and 2e2μ (blue).



Categorisation

- Separate events in categories to
  - Better supress the backgrounds
  - Probe different physical properties (production modes, couplings …)
- Categories for **discovery**
  - By center-of-mass energy: **7** and **8** TeV
  - By final state →
    - ATLAS separated further $2e2\mu$ and $2\mu2e$ according to the flavor of Z_1

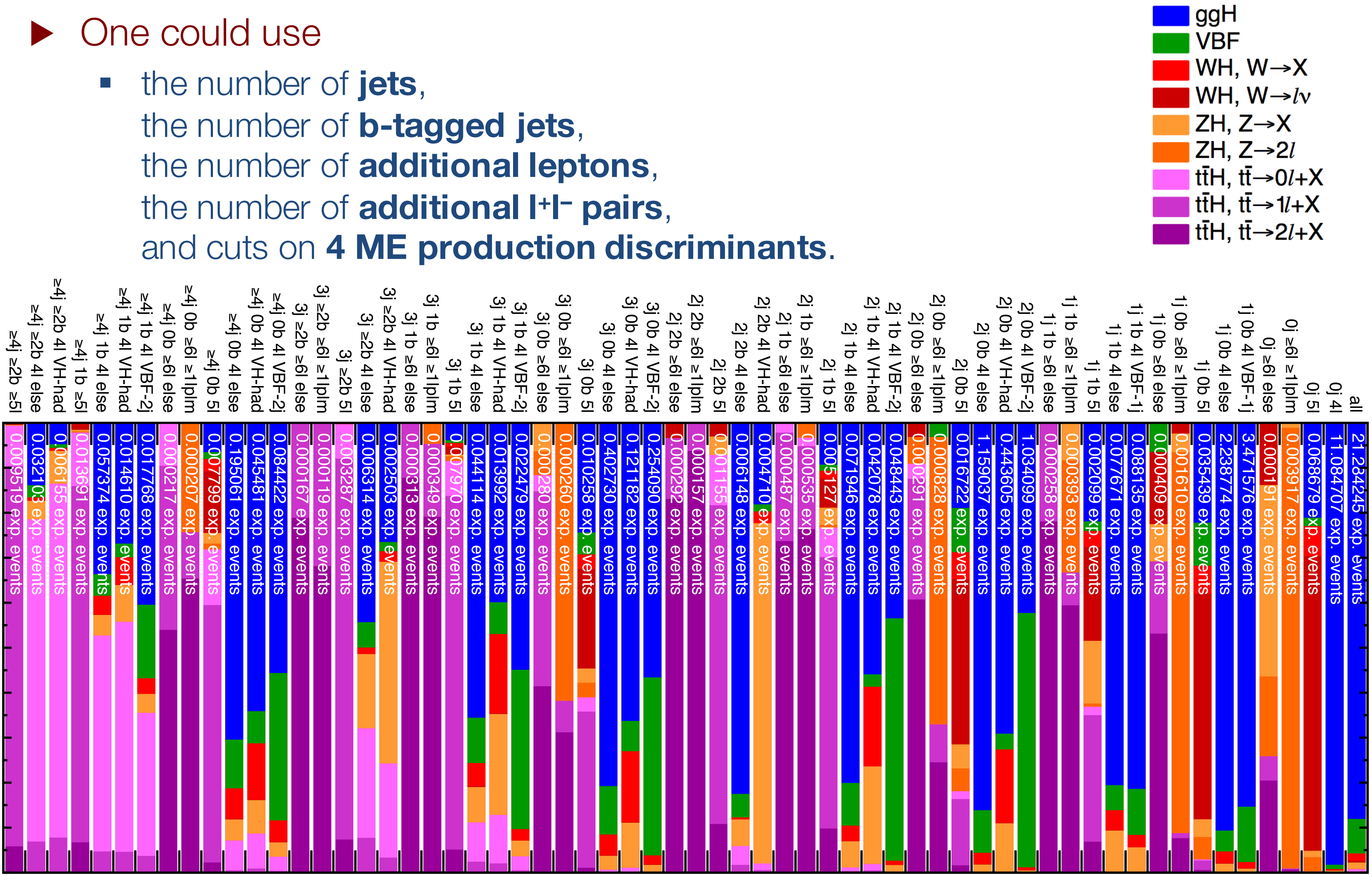
Number of events in $121.5 < m_H < 130.5$ GeV (CMS)			
	4e	4μ	$2e2\mu$
Signal (m_H = 125 GeV)	1.36	2.74	3.44
All backgrounds	0.7	1.3	1.9
Observed	1	3	5

- Additional categories at the end of Run I

	category	cut	ggF+ttH +bbH	VBF	VH	Total H	Total bkgd	Observed
ATLAS	Untagged	All untagged events	12.8	0.57	0.35	13.7	9.8	34
ATLAS	Dijet VBF	At least two jets with $m_{jj} > 130$ GeV	1.18	0.75	0.10	2.03	0.42	3
ATLAS	Dijet VH	$40 < m_{jj} < 130$ GeV & $BDT_{VH} > -0.4$	0.40	0.03	0.21	0.64	0.18	0
ATLAS	Leptonic VH	At least 1 addition. lepton, $p_T > 8$ GeV	0.013	< 0.001	0.069	0.082	0.031	0
CMS	Untagged	All untagged events	15.4	0.70	0.49	16.6	8.5	20
CMS	Dijet	Two or more jets	1.7	0.87	0.37	3.0	0.9	5

Additional categories for Run II (CMS)

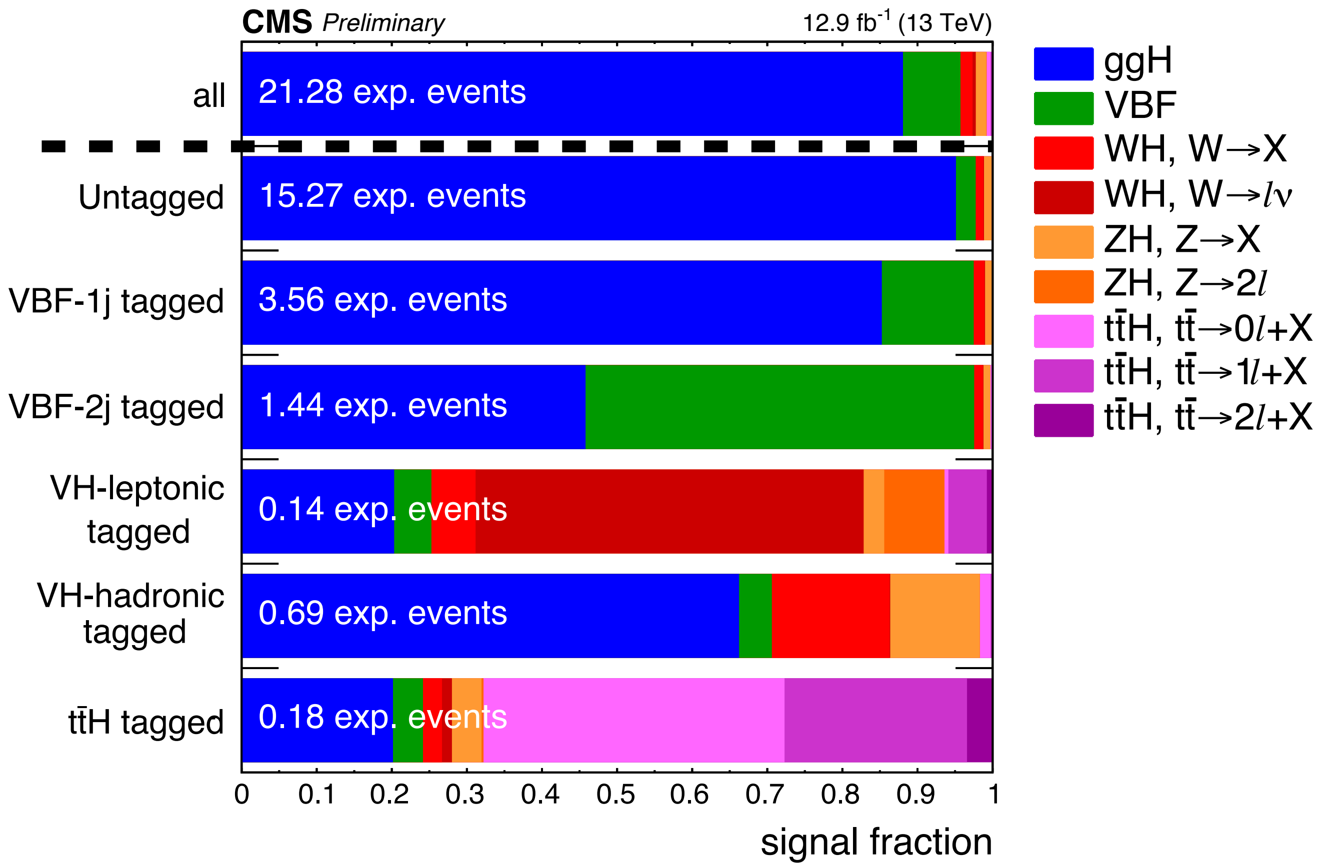
- One could use
  - the number of **jets**,
    the number of **b-tagged jets**,
    the number of **additional leptons**,
    the number of **additional l^+l^- pairs**,
    and cuts on **4 ME production discriminants**.



Additional categories for Run II (CMS)

- At the end we compact all categories to

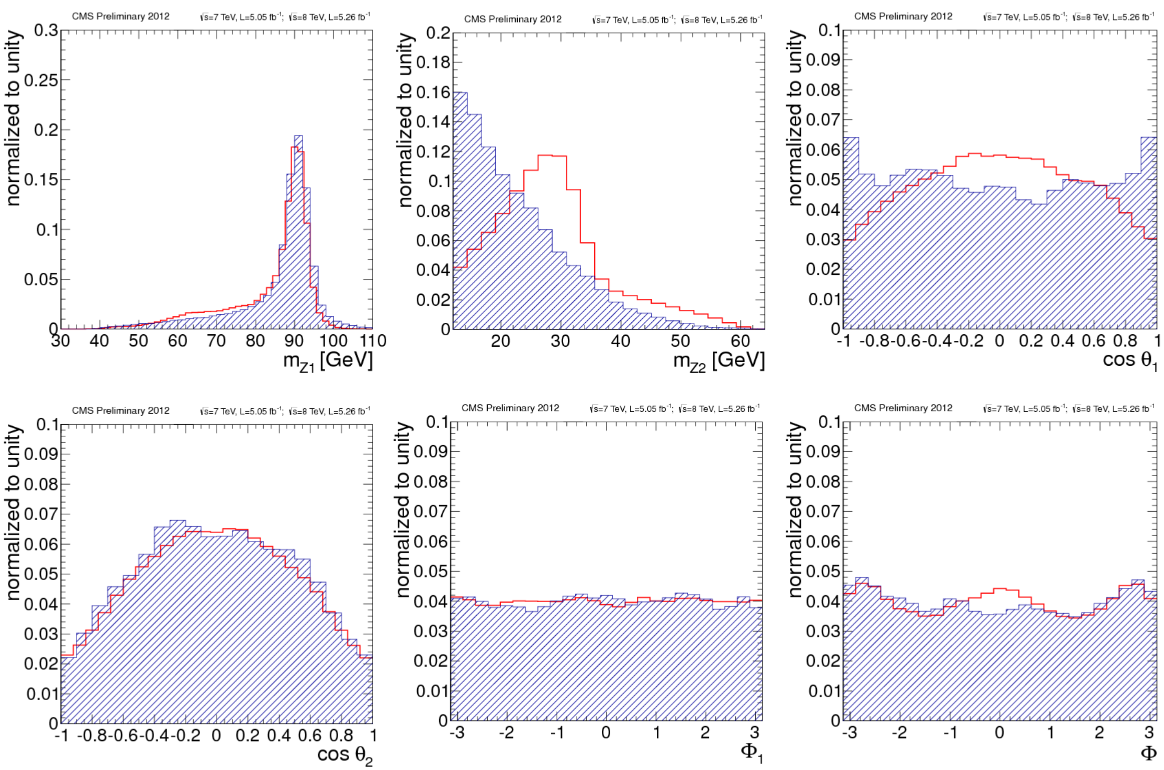
  six mutually exclusive event categories

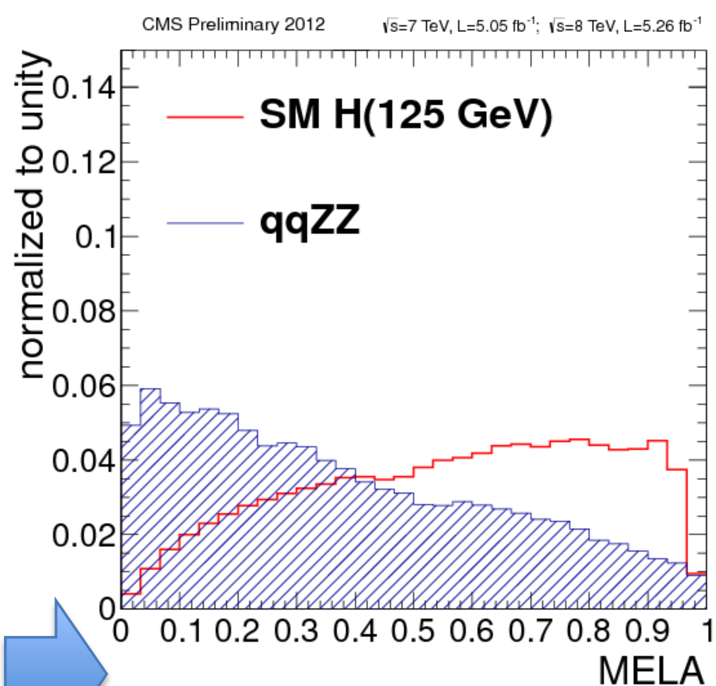


Courtesy of Simon Regnard

Discriminants

- Discriminant: a variable with a significant power to discriminate signal from background
  - Or to discriminate between different hypotheses (see later spin-parity analysis)
  - Can be one variable (for example m_{4l} or p_T^{4l}) or several variables compacted to one (**MELA**, **BDT**, **Neural Networks**, **Fisher Discriminant** …)
- Recall the idea of MELA from Lecture 4/5

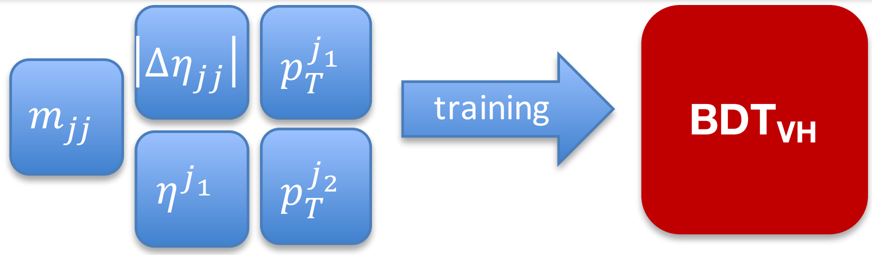




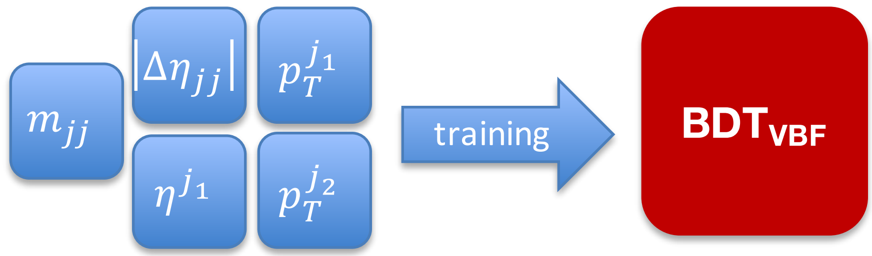
$$MELA \equiv KD$$

Other discriminants

- ATLAS: **BDT$_{VH}$**
  for event categorisation

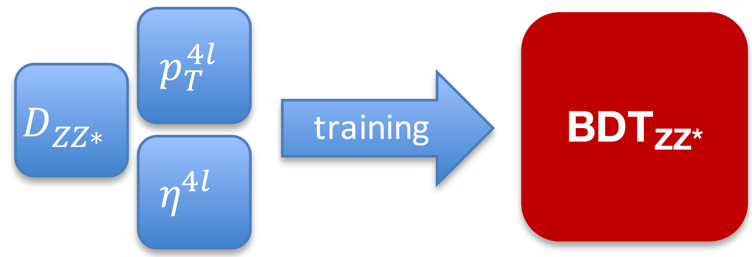


- ATLAS: **BDT$_{VBF}$**
  for VBF vs gluon fusion separation in dijet category



- ATLAS: **BDT$_{ZZ*}$**
  for signal vs background separation

  $D_{ZZ*} = ln\left(\frac{|M_{sig}|^2}{|M_{ZZ}|^2}\right)$: *Matrix-Element discriminant*



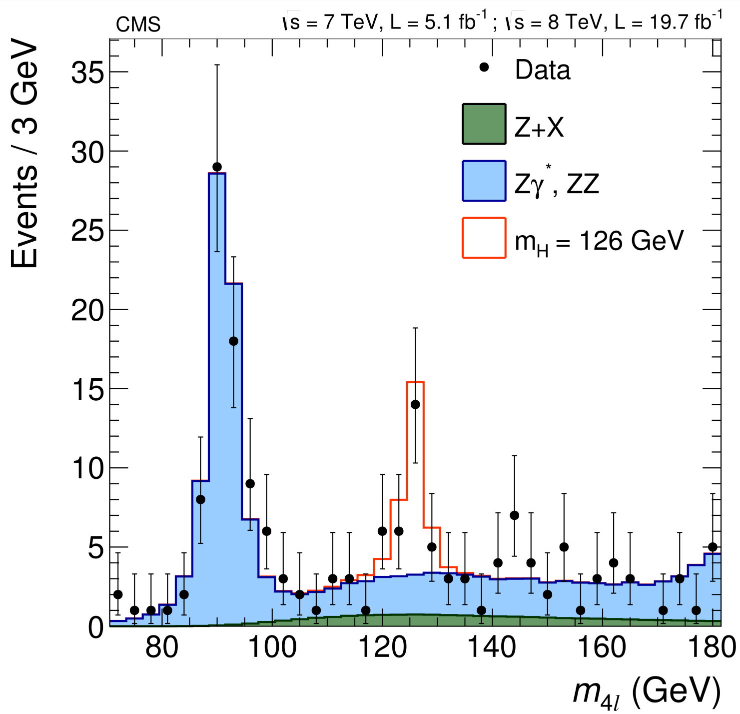
- CMS: **D$_{jet}$**
  for VBF vs gluon fusion separation in dijet category

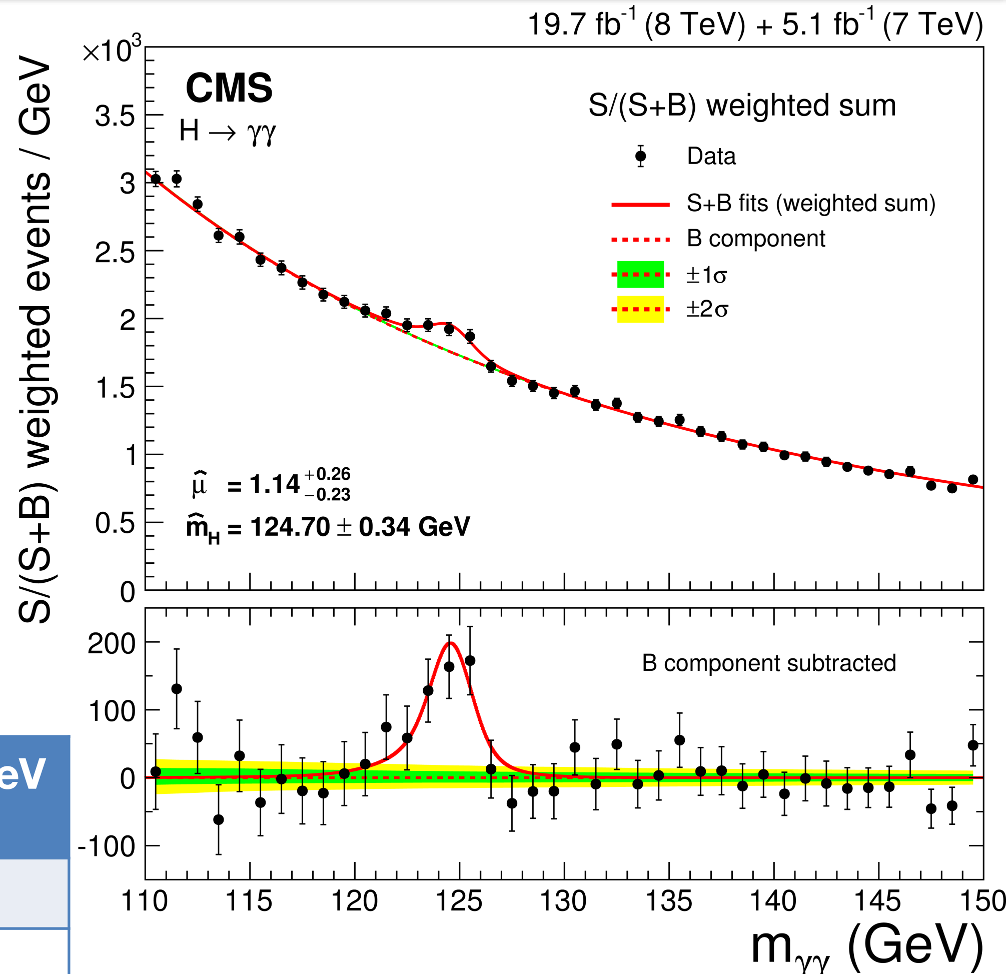
$$D_{jet} = \alpha|\Delta\eta_{jj}| + \beta m_{jj}$$

α and β optimised for max discrimination power

- CMS and ATLAS: using **Matrix-Element discriminant** for spin-parity measurements (see later)

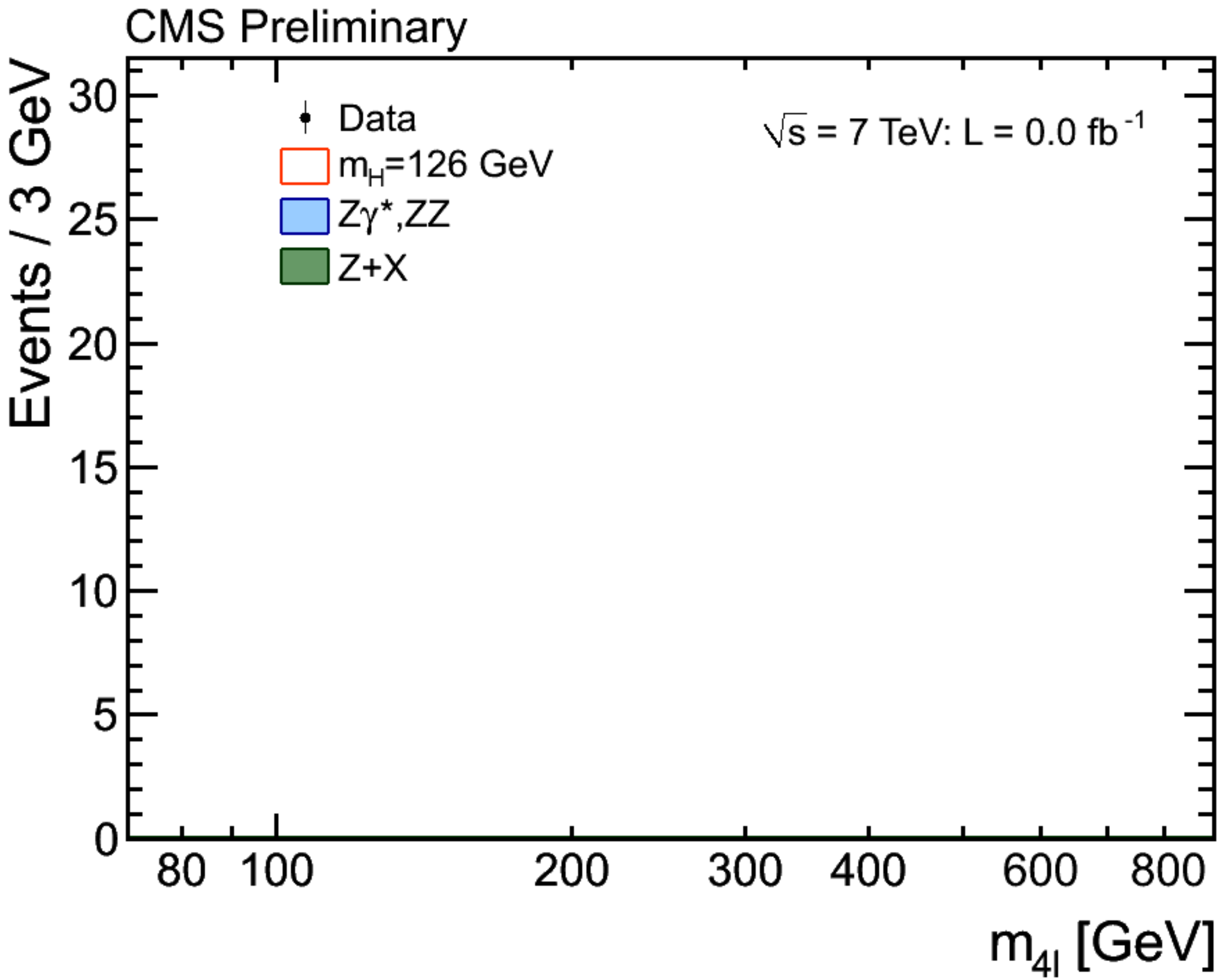
Significance of the observation in Run 1: CMS



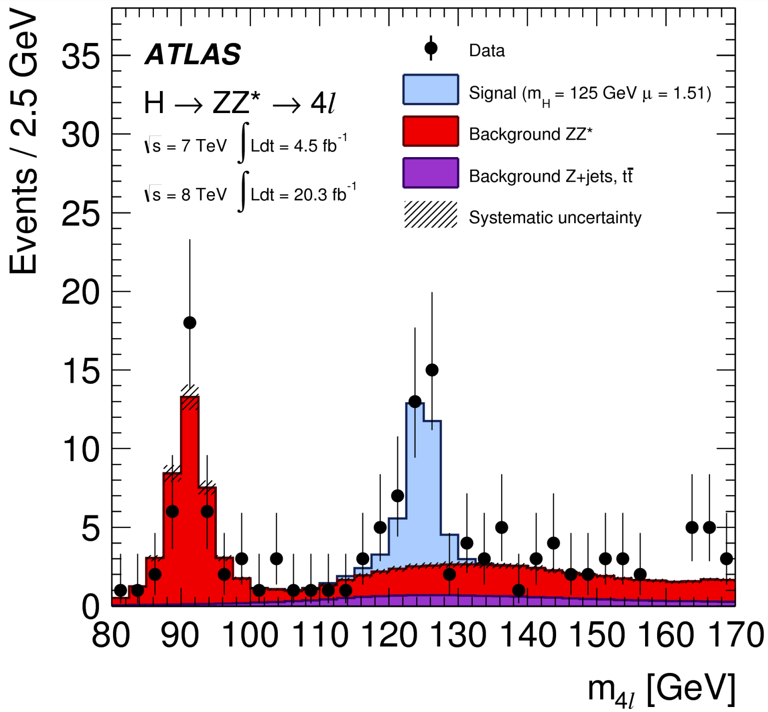


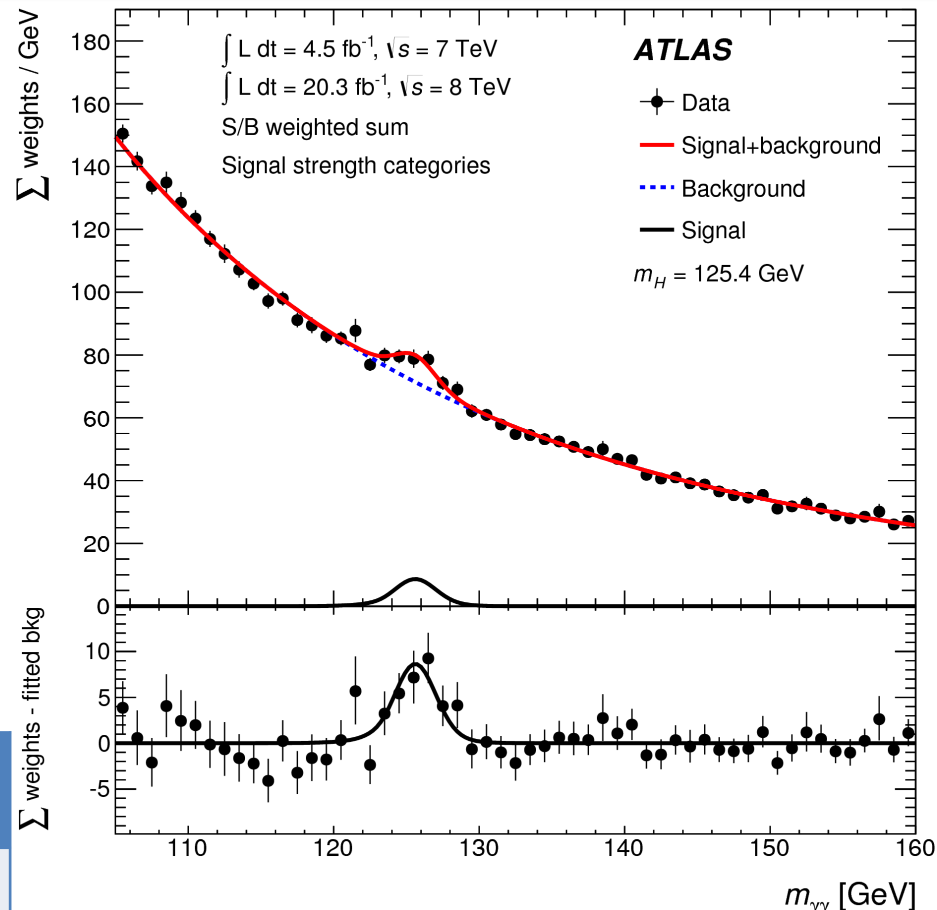
Channel	Significance (σ) @ m_H = 125 GeV Expected	Observed
$H \to ZZ$	6.3	**6.5**
$H \to \gamma\gamma$	5.3	**5.6**
$H \to WW$	5.4	**4.7**
$H \to \tau\tau$	3.9	**3.8**
$H \to bb$	2.6	**2.0**

H→ZZ*→4l in CMS in Run 1



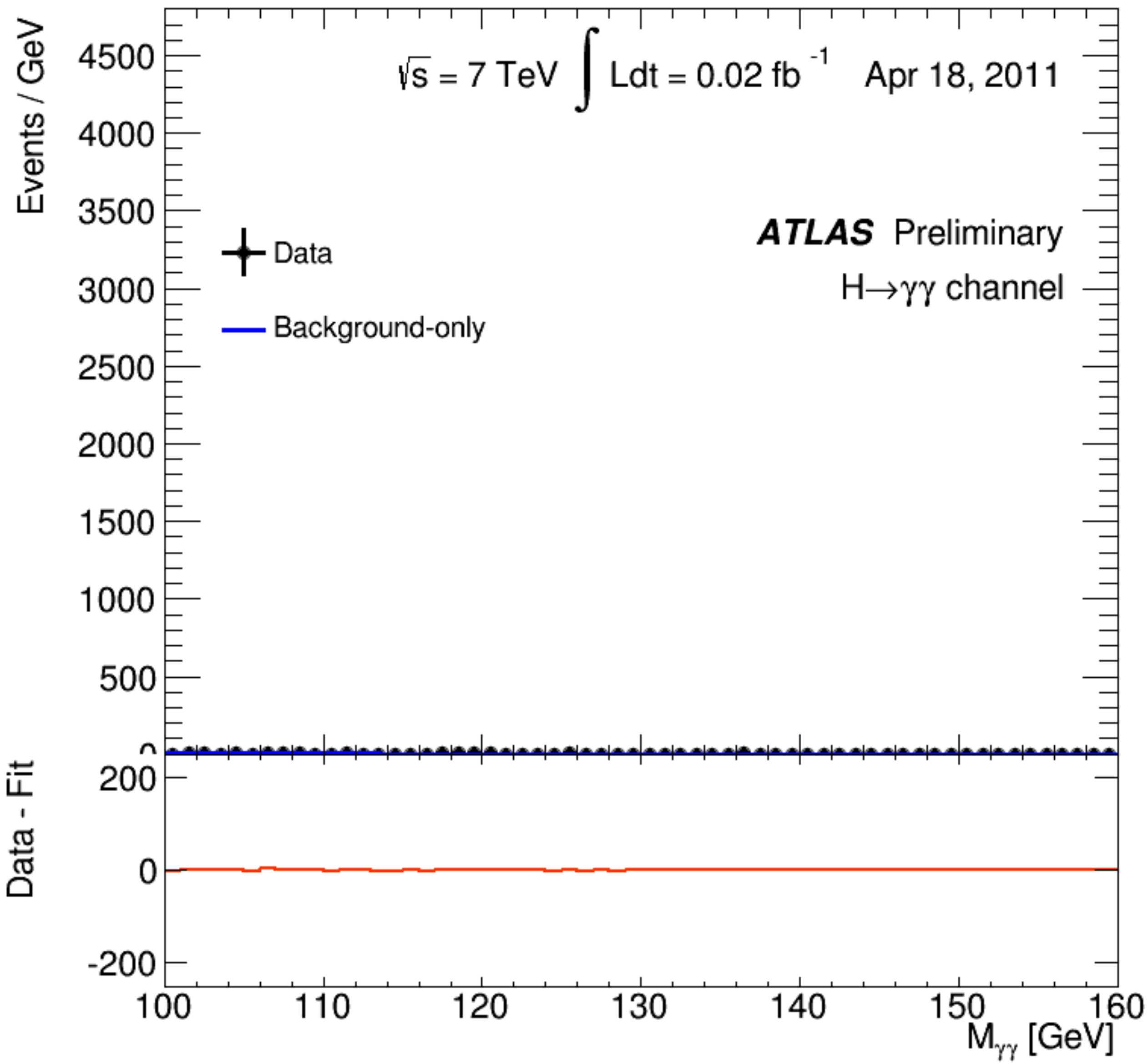
Significance of the observation in Run 1: ATLAS





Channel	Significance (σ) @ m_H = 125.36 GeV Expected	Observed
H → ZZ	6.2	**8.1**
H → γγ	4.6	**5.2**
H → WW	5.9	**6.5**
H → ττ	3.4	**4.5**
H → bb	2.6	**1.4**

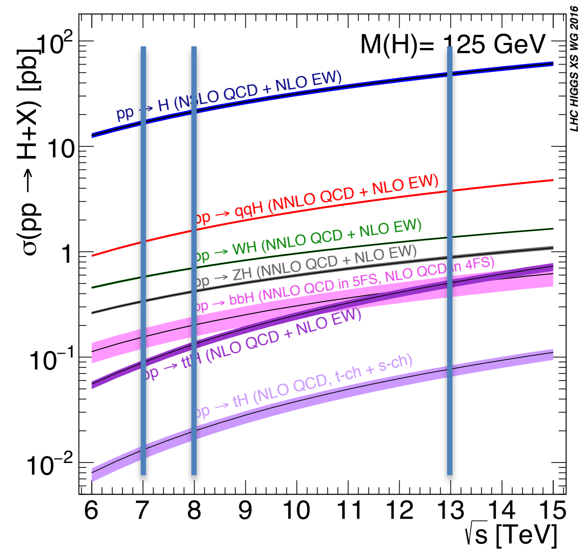
H→γγ in ATLAS in Run 1

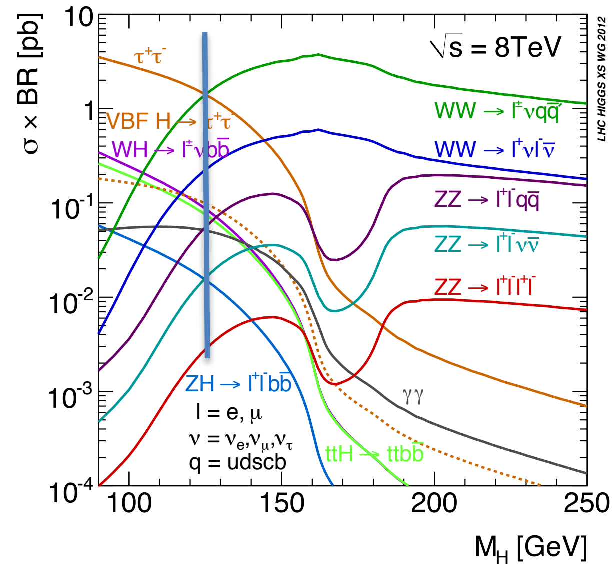


Properties to be measured

- **Mass m_H**
  - Separately in H→4l and H→γγ channels, then combining at the level of ATLAS and CMS, and then combing ATLAS and CMS
- **Total width Γ_H**
  - Directly or indirectly via off-shell production
- **Signal strength μ**
  - Overall, for each decay mode, for each production mode, separately by channels and in combinations
- **Total cross section $\sigma_{fid.}$**
  - In the fiducial volume, but defined in different ways …
- **Differential cross section $d\sigma_{fid}/dx$**
  - In several production-related observables (x), using H→4l and H→γγ channels: Higgs boson's transverse momentum and rapidity, associated jet multiplicity, p_T of leading jet …
- **Spin-parity quantum numbers J^P**
  - Pair-wise tests of SM Higgs vs alternative J^P states, constraints on anomalous decay amplitudes …
- **Couplings λ_i, κ_i**
  - Testing the SM couplings to fermions and bosons, search for deviation from SM couplings, testing custodial symmetry and fermion universality, testing the contribution from hypothetical BSM particles … using all channels

SM expectations



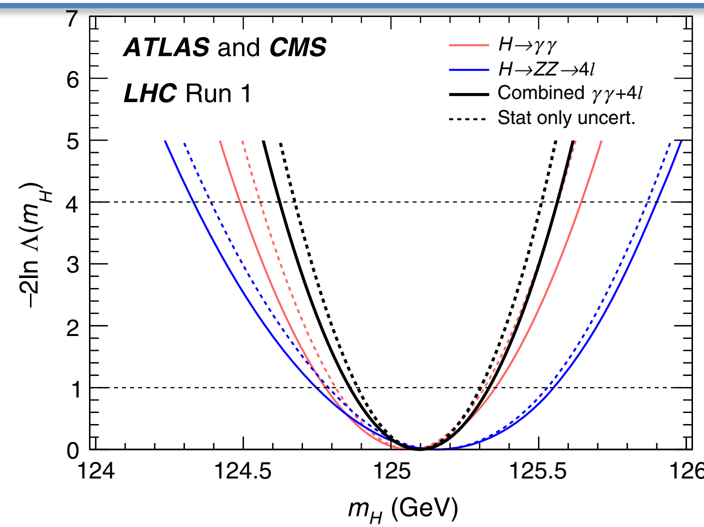


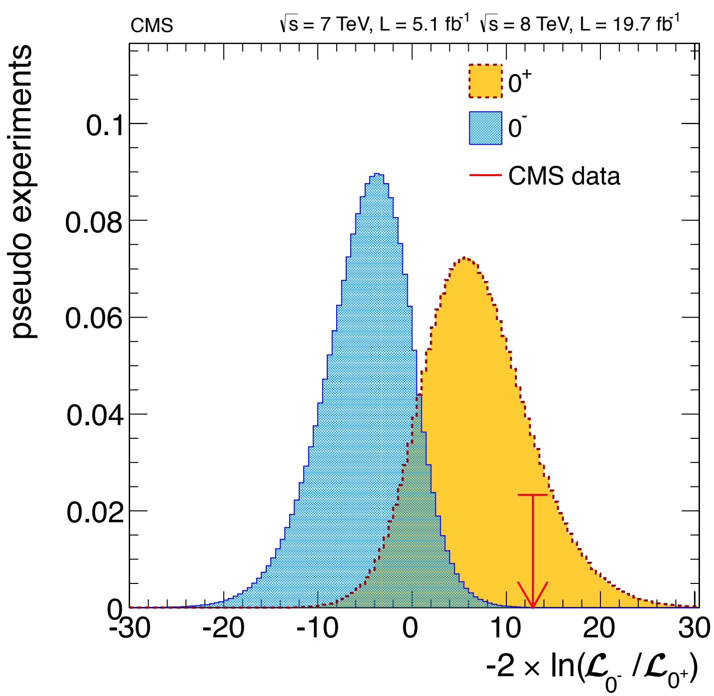
Properties measurements: methods

- Scan of the profile likelihood ratio

$$q(\boldsymbol{a}) = -2\ln\Lambda(\boldsymbol{a}) = -2\ln\frac{\mathcal{L}(data\,|\,s(\boldsymbol{a})+b,\hat{\hat{\boldsymbol{\theta}}}_a)}{\mathcal{L}(data\,|\,s(\hat{\boldsymbol{a}})+b,\hat{\boldsymbol{\theta}})}$$

$\boldsymbol{a}$ - vector of parameters to measure
$\boldsymbol{\theta}$ - vector of nuisance parameters
$\hat{\boldsymbol{a}}, \hat{\boldsymbol{\theta}}$ - values at global maximum of $\mathcal{L}$
$\hat{\hat{\boldsymbol{\theta}}}_a$ - value maximising $\mathcal{L}$ for a given $\boldsymbol{a}$





- Pair-wise test of J^P hypotheses

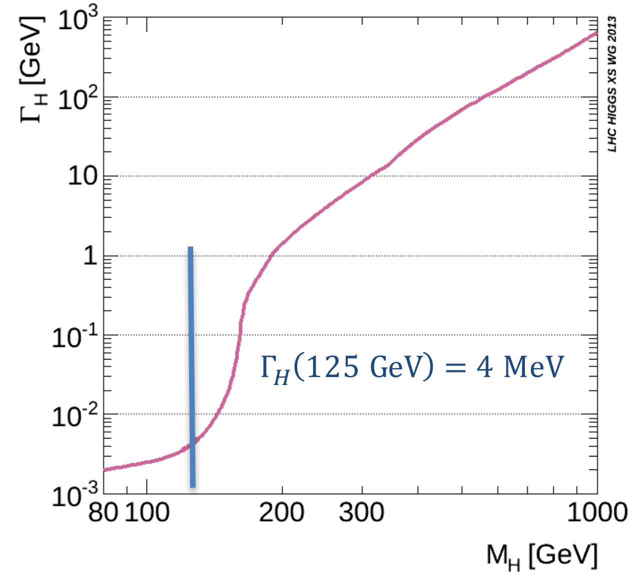
$$q = -2\ln\frac{\mathcal{L}(data\,|\,\hat{\mu}_X\cdot s+b,\hat{\hat{\boldsymbol{\theta}}}_X)}{\mathcal{L}(data\,|\,\hat{\mu}_H\cdot s+b,\hat{\hat{\boldsymbol{\theta}}}_H)}$$

$\boldsymbol{H}$ – SM Higgs boson hypothesis
$\boldsymbol{X}$ - exotic Higgs boson hypothesis

Properties measurements: mass

- Higgs boson mass is estimated from the two most precise channels
  - $H \rightarrow ZZ^* \rightarrow 4l$
  - $H \rightarrow \gamma\gamma$

  where we reconstructed four momenta all
  all final state particles with excellent accuracy
- Theoretical ambiguities are minimized by the assumption the Higgs boson is negligible compared to the experimental resolution
  - This is true for both SM and most alternative models



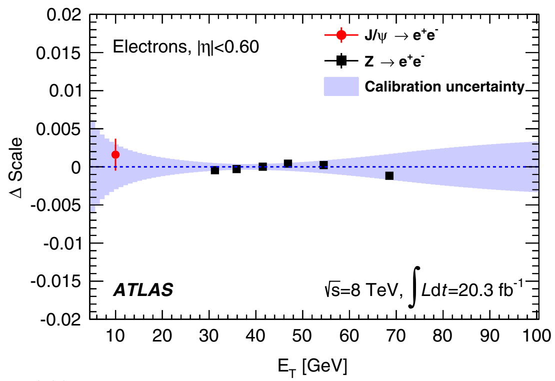
- References:
  - ATLAS measurements
    - ATLAS Collaboration, *Measurement of the Higgs boson mass from the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4l$ channels with the ATLAS detector at the LHC*, Phys. Rev. D **90**, 052004, http://journals.aps.org/prd/abstract/10.1103/PhysRevD.90.052004
  - CMS measurements
    - CMS Collaboration, *Precise determination of the mass of the Higgs boson and tests of compatibility of its couplings with the standard model predictions using proton collisions at 7 and 8 TeV*, Eur. Phys. J. C (2015) 75: 212, http://link.springer.com/article/10.1140%2Fepjc%2Fs10052-015-3351-7
  - ATLAS and CMS combination
    - ATLAS and CMS Collaborations, *Combined Measurement of the Higgs Boson Mass in pp Collisions at $\sqrt{s}$ = 7 and 8 TeV with the ATLAS and CMS Experiments*, Phys. Rev. Lett. **114**, 191803, http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.114.191803

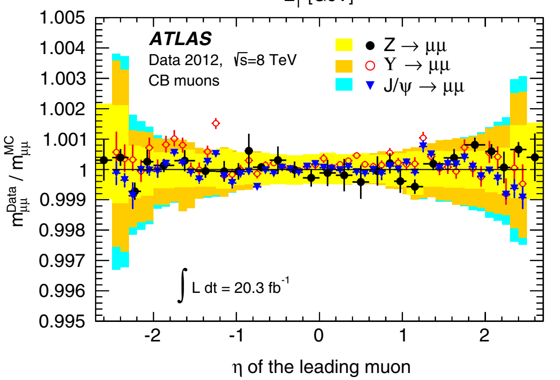
Mass measurements in ATLAS

- Three steps process:
  - 1. Measuring separately by γγ and 4l channels
  - 2. Improving measurements per channel and combining them
  - 3. Further improvements and combination with CMS
- Critical aspects for measurements accuracy and precision:

γ/e±/μ± reconstruction, energy scale calibration and systematic uncertainty

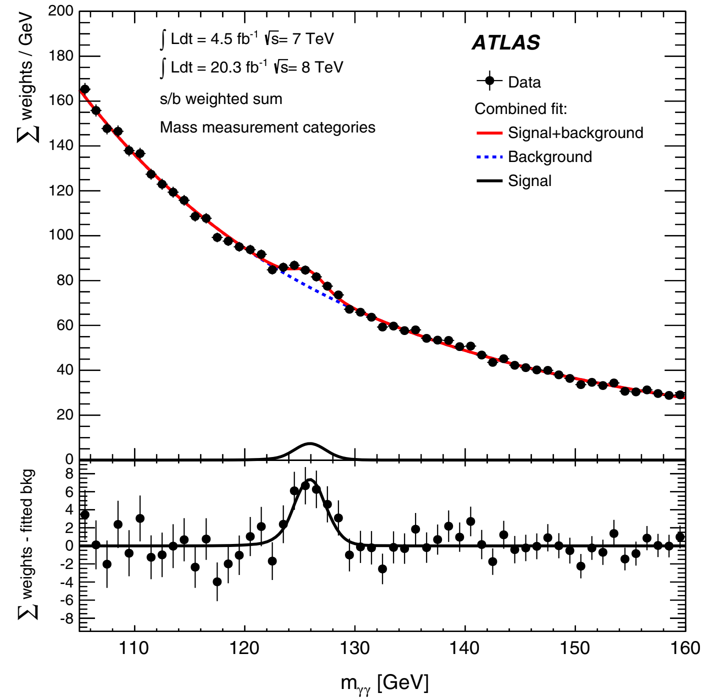
- Example of considered uncertainties in case of E measurements of γ/e±
  - Modeled using 29 independent sources
    - **1** for the uncertainty in the extraction of the calorimeter energy scale from Z→ ee events,
    - **3** for the uncertainty on the nonlinearity of the energy measurement at the cell level,
    - **4** for the uncertainty on the ID material in different eta regions,
    - **6** for the uncertainties affecting the relative calibration of the different calorimeter layers,
    - **10** for the uncertainties on the material after the ID volume and between the presampler and the first calorimeter,
    - **3** for uncertainties in the modeling of the conversion reconstruction performance in the simulation,
    - **2** for the uncertainties in the modeling of the lateral shower shapes, separating converted and unconverted γs.





Mass measurements: H→γγ in ATLAS

- Narrow peak over smooth background
  - Typical mass resolution 1.7 GeV @ m_H = 125 GeV
  - Background: 80% γγ continuum & 20% γ+jets and dijets
- Event selection
  - Diphoton trigger with 99% efficiency
  - Isolated γ passing tight MVA ID, $\epsilon_{ISO} \sim 95\%, \varepsilon_{ID} \in 85-95\%$
  - Primary vertex identification with $\epsilon_{PV} \sim 93\%$
  - Combined signal reconstruction and selection eff. $\sim 40\%$
- Event categorisation
  - 10 mutually exclusive categories with different S/B ratios, different $m_{\gamma\gamma}$ resolution and different systematic uncertainties
  - Optimised for mass measurement, assuming SM yield – improving statistical uncertainty for about 20%
- Signal modeling
  - Sum of Crystal Ball and Gaussian, with parameters extracted from MC simulation
- Background modeling and estimation
  - Directly from a fit to the γγ mass distribution after final selection
  - Exponential function used in 4 categories, exponential + 2nd order polynomial in other 6 categories
- Mass measurement method
  - 10 categories x 2 cms energies are fitted simultaneously
    - assuming s+b hypothesis
    - using an unbinned maximumu likelihood fit



Invariant mass distribution in H→γγ analysis for data (7 TeV and 8 TeV samples combined), showing weighted data points with errors, and the result of the simultaneous fit to all categories. The fitted signal plus background is shown, along with the background-only component of this fit. The different categories are summed together with a weight given by the s=b ratio in each category. The bottom plot shows the difference between the summed weights and the background component of the fit.

Mass measurements: H→γγ in ATLAS

Systematic uncertainties

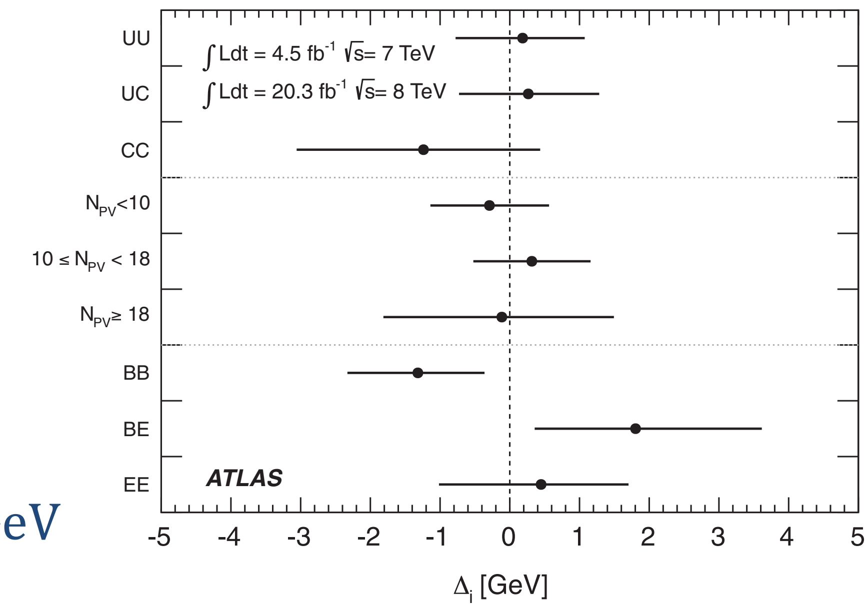
- Example of summary of the relative systematic uncertainties (in %) on the H → γγ mass measurement for the different categories, for unconverted photons. The first seven rows give the impact of the photon energy scale systematic uncertainties.

	Unconverted					
	Central		Rest			
Class	low p_{Tt}	high p_{Tt}	low p_{Tt}	high p_{Tt}	Transition	lo
$Z \to e^+e^-$ calibration	0.02	0.03	0.04	0.04	0.11	
LAr cell nonlinearity	0.12	0.19	0.09	0.16	0.39	
Layer calibration	0.13	0.16	0.11	0.13	0.13	
ID material	0.06	0.06	0.08	0.08	0.10	
Other material	0.07	0.08	0.14	0.15	0.35	
Conversion reconstruction	0.02	0.02	0.03	0.03	0.05	
Lateral shower shape	0.04	0.04	0.07	0.07	0.06	
Background modeling	0.10	0.06	0.05	0.11	0.16	
Vertex measurement						0.03
Total	0.23	0.28	0.24	0.30	0.59	

Results

$$m_H = 125.98 \pm 0.42\,(\text{stat}) \pm 0.28\,(\text{syst})\ \text{GeV}$$
$$= 125.98 \pm 0.50\ \text{GeV}$$

Cross-checks



Differece, Δ_i, between the mass measured in a given γγ subsample and the combined γγ mass, using three different alternative categorizations to define the subsamples.

Mass measurements: H→ZZ*→4l in ATLAS

- Good sensitivity due to its
  - High S/B ratio: about 2 in 120 – 130 GeV mass window
  - Excellent 4l-mass resolution: from about 1.6 GeV in 4μ to about 2.2 GeV in 4e
- Event selection, background estimation, MVA discriminant: see previous slides
- Signal and background model
  - 2D fit to m_{4l} and BDT_{ZZ^*} output $O_{BDT_{ZZ^*}}$ with signal probability density function

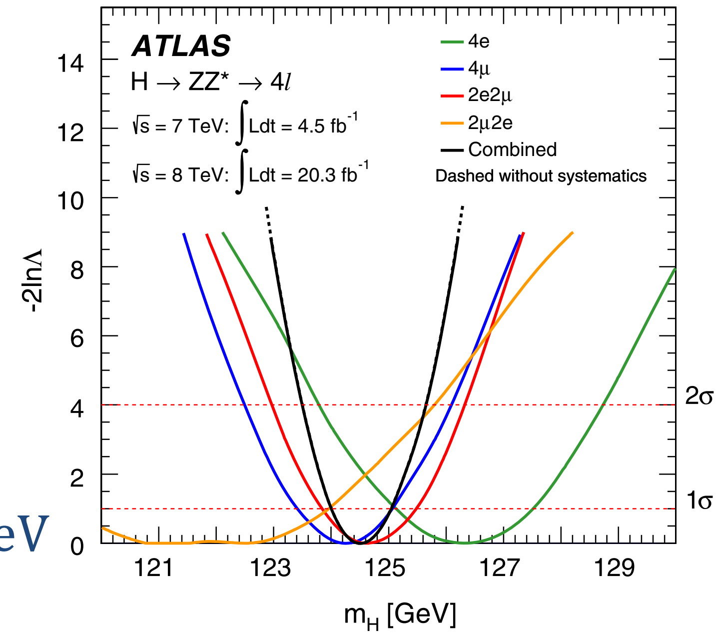
$$P(m_{4l}, O_{BDT_{ZZ^*}} \mid m_H) = P(m_{4l} \mid O_{BDT_{ZZ^*}}, m_H) P(O_{BDT_{ZZ^*}}, \mid m_H)$$
$$\approx \left(\sum_{n=1}^{4} P_n(m_{4l} \mid m_H) \theta_n(O_{BDT_{ZZ^*}}) \right) P(O_{BDT_{ZZ^*}}, \mid m_H)$$

θ_n - four equal-size bins for the values of BDT_{ZZ^*} output

P_n- 1D PDF for m_{4l} for the signal in $O_{BDT_{ZZ^*}}$ bins

- Systematic uncertainties
  - Main source: electron energy scale and muon momentum scale – 0.03% on m_H
  - Theory uncertainties: QCD scale 7%, PDFs 6% and decay BRs 4%
- Results

$$m_H = 124.51 \pm 0.52\ (\text{stat}) \pm 0.06\ (\text{syst})\ \text{GeV}$$
$$= 125.51 \pm 0.52\ \text{GeV}$$



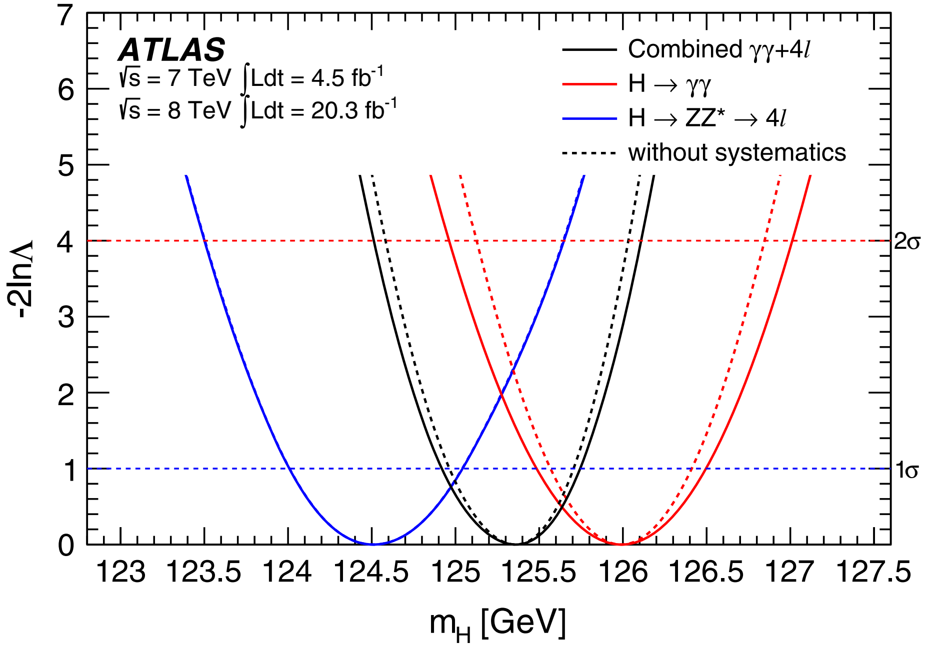
Mass measurements: ATLAS combination

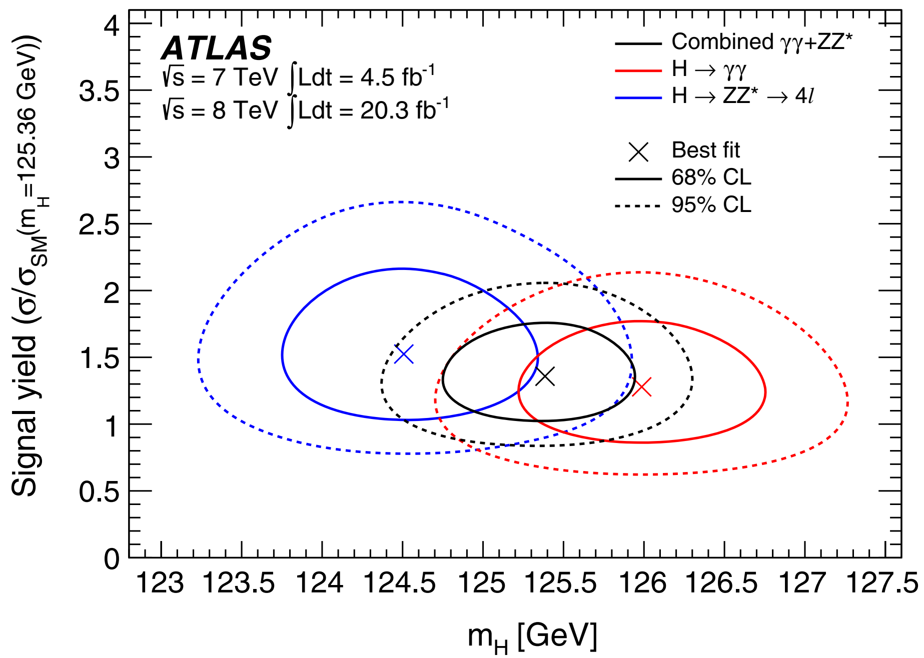
- Using profile likelihood ratio

$$\Lambda(m_H) = \frac{L\left(m_H, \hat{\hat{\mu}}_{\gamma\gamma}(m_H), \hat{\hat{\mu}}_{4l}(m_H), \hat{\hat{\boldsymbol{\theta}}}(m_H)\right)}{L\left(\hat{m}_H, \hat{\mu}_{\gamma\gamma}, \hat{\mu}_{4l}, \hat{\boldsymbol{\theta}}\right)}$$

- Combined mass measurement is

$$m_H = 125.36 \pm 0.37\ (\text{stat}) \pm 0.18\ (\text{syst})\ \text{GeV}$$
$$= 125.36 \pm 0.41\ \text{GeV}$$





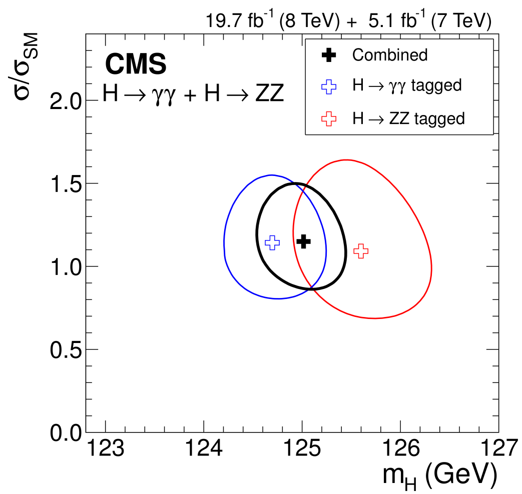
- Compatibility of measurements from two channels is 4.9% → 1.97σ

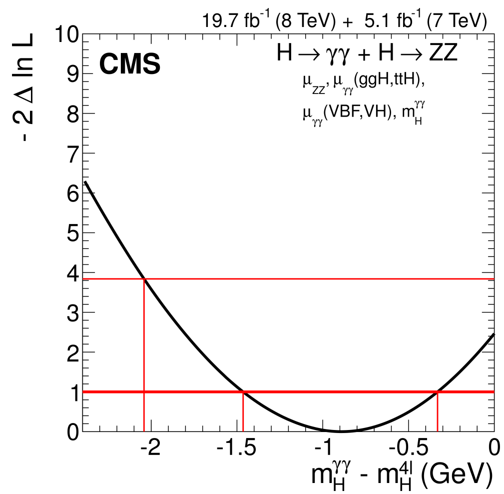
Mass measurements in CMS: results

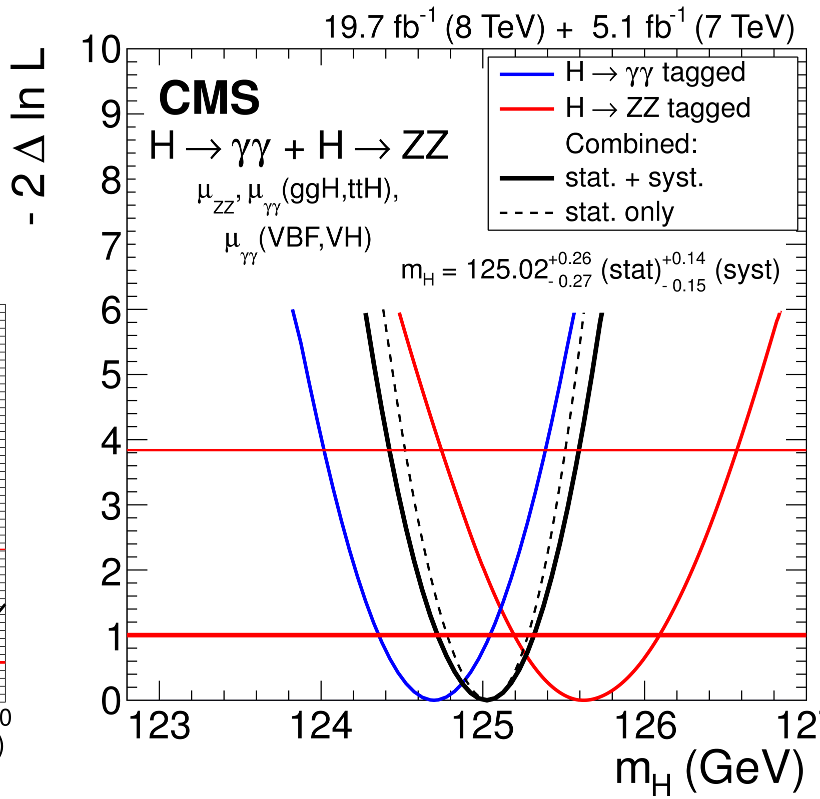
- Similar methods as in ATLAS
  - In H→ZZ*→4l CMS uses 3D PDF with m_{4l}, **MELA** and per-event m_{4l} uncertainty $\sigma_{m_{4l}}$

- Results

$$m_H = 125.36^{+0.26}_{-0.27}\,(\text{stat})^{+0.14}_{-0.15}\,(\text{syst})\text{ GeV}$$

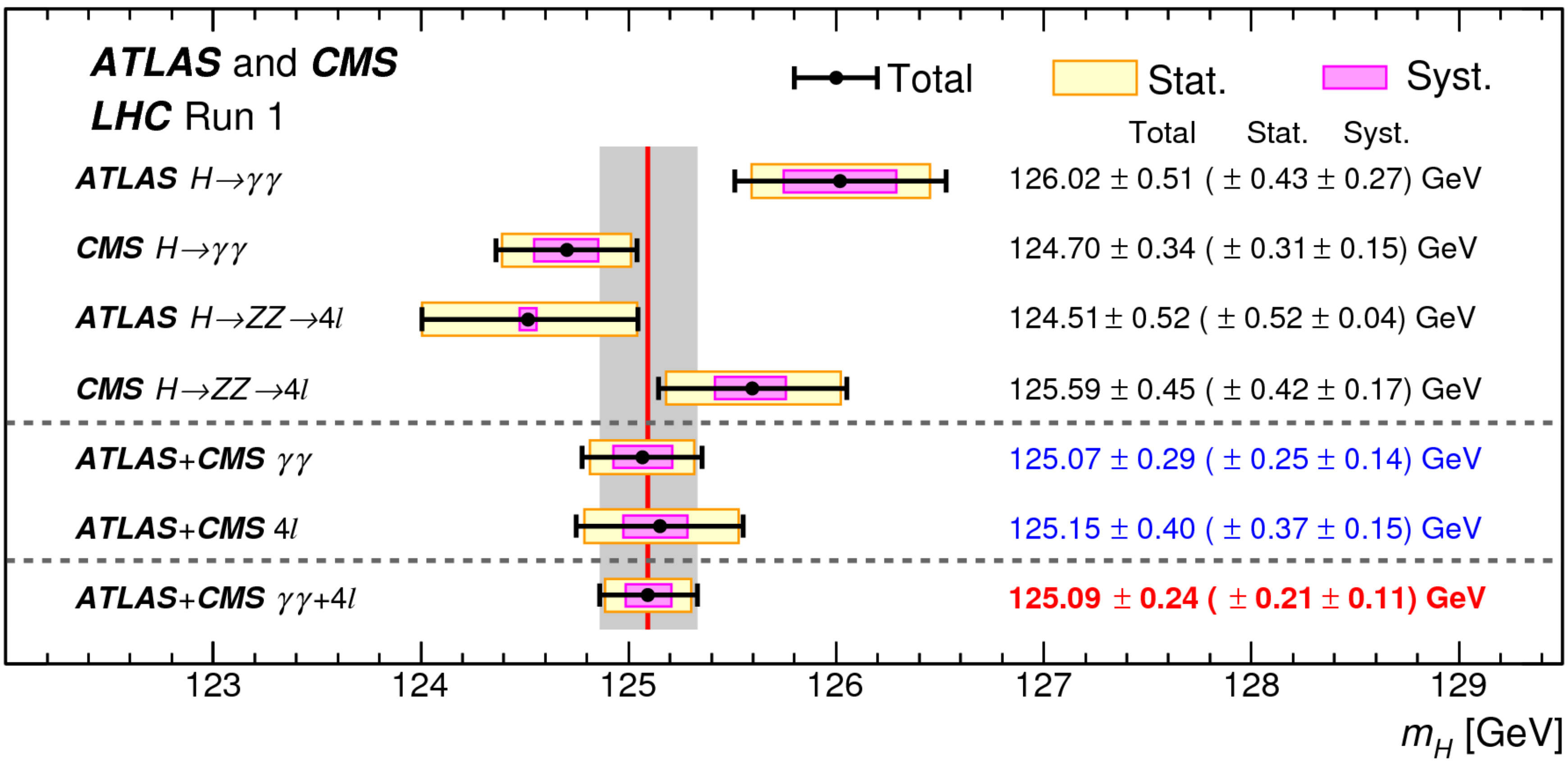






- Compatibility of measurements from two channels is 1.6σ

Mass measurements: ATLAS and CMS

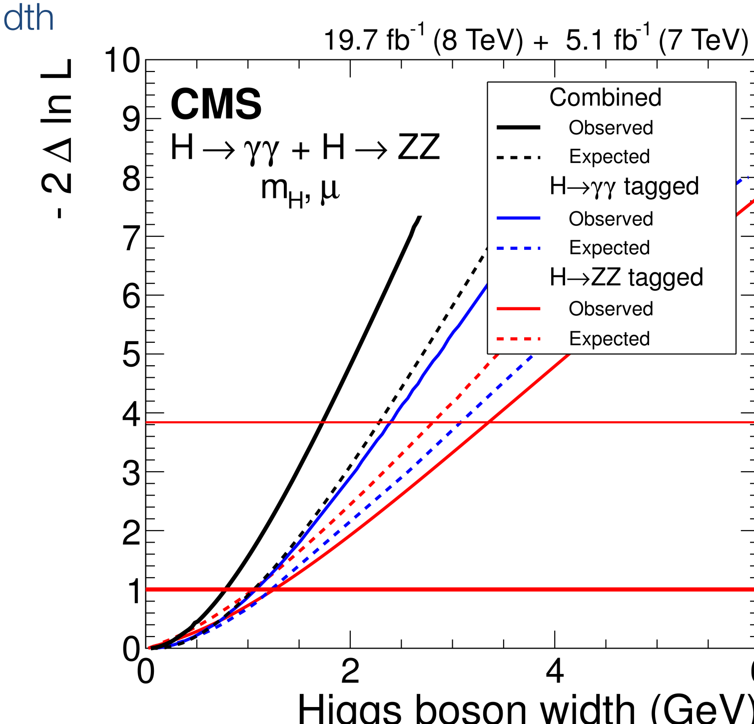


Summary of Higgs boson mass measurements from the individual analyses of ATLAS and CMS and from the combined analysis presented here. The systematic (narrower, magenta-shaded bands), statistical (wider, yellow-shaded bands), and total (black error bars) uncertainties are indicated. The (red) vertical line and corresponding (gray) shaded column indicate the central value and the total uncertainty of the combined measurement, respectively.

Total width measurements: direct

- For $m_H \sim 125$ GeV predicted total width is $\Gamma_{SM} \sim 4$ MeV
- There are two methods to measure the total width
  - Direct: from $\gamma\gamma$ and 4l mass distributions
  - Indirect: from off-shell Higgs boson production
  - Indirect gives much better results, but relies on assumptions on the underlying theory
    - For example is assumes the absence of BSM particles contribution
  - Direct limits have no such assumptions and are only limited by experimental resolution
- Direct measurements method
  - Signal models in $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4l$ use Breit-Wigner distribution for natural width
  - Use likelihood scan as a function of the assumed natural width
    - Mass of the boson and common signal strength are profiled along all other nuisance parameters
- Results

Channel		Upper limit on Γ_H in GeV: Expected	Upper limit on Γ_H in GeV: Observed
CMS	$H \rightarrow ZZ$	3.1	**2.4**
CMS	$H \rightarrow \gamma\gamma$	2.8	**3.4**
CMS	$H \rightarrow ZZ$ and $\gamma\gamma$	2.3	**1.7**
ATLAS	$H \rightarrow ZZ$	6.2	**5.0**
ATLAS	$H \rightarrow \gamma\gamma$	6.2	**2.6**



Total width measurements: indirect

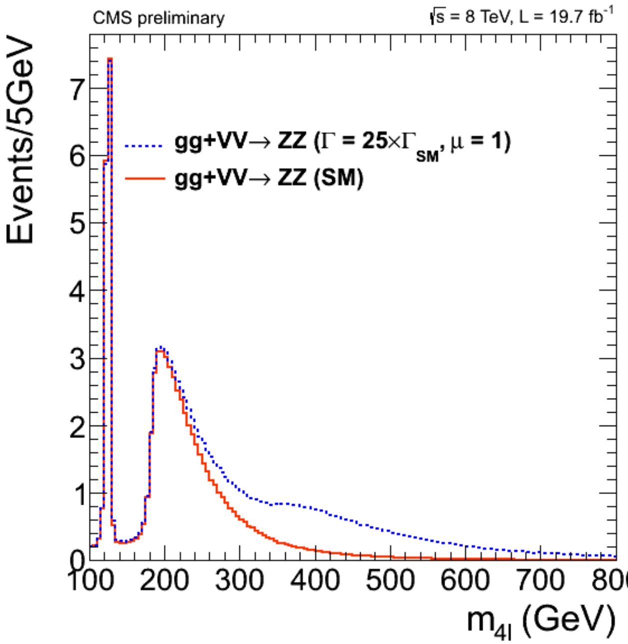
- Basic idea:
  - Gluon fusion production cross section depends on Γ_H through the Higgs boson propagator

$m_{ZZ} < 2m_Z$: $\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H}$

$$\frac{d\sigma_{gg\to H\to ZZ}}{dm^2_{ZZ}} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(m^2_{ZZ} - m^2_H)^2 + m^2_H \Gamma^2_H}$$

$m_{ZZ} > 2m_Z$: $\sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2}$

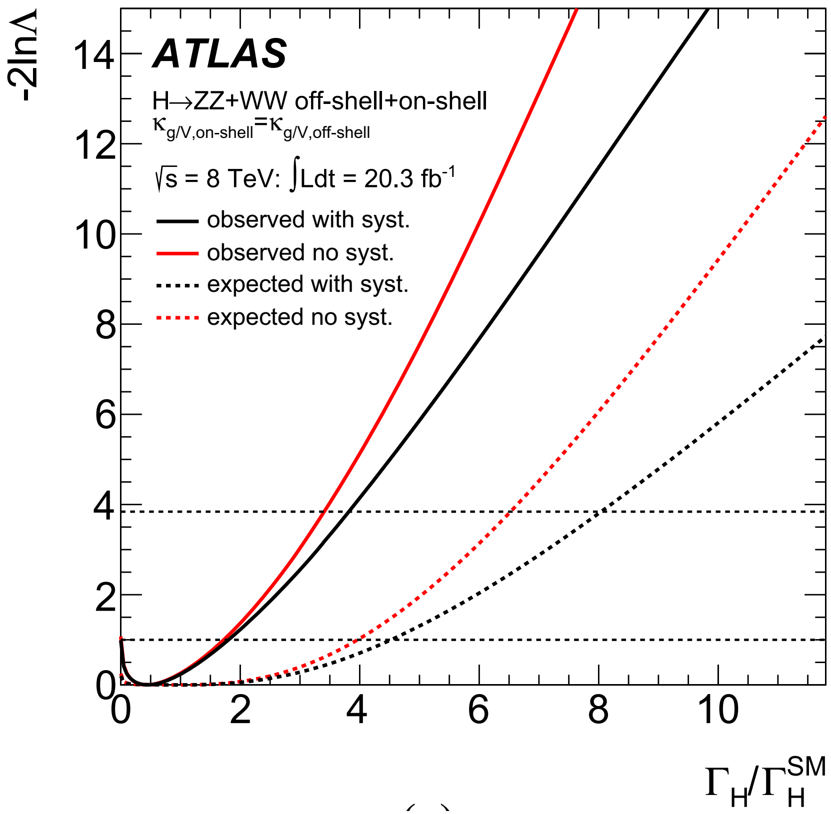
$$\frac{\sigma^{off-shell}_{gg\to H\to ZZ^*}}{\sigma^{on-shell}_{gg\to H\to ZZ^*}} = \frac{m_H \Gamma_H}{(2m_Z)^2}$$

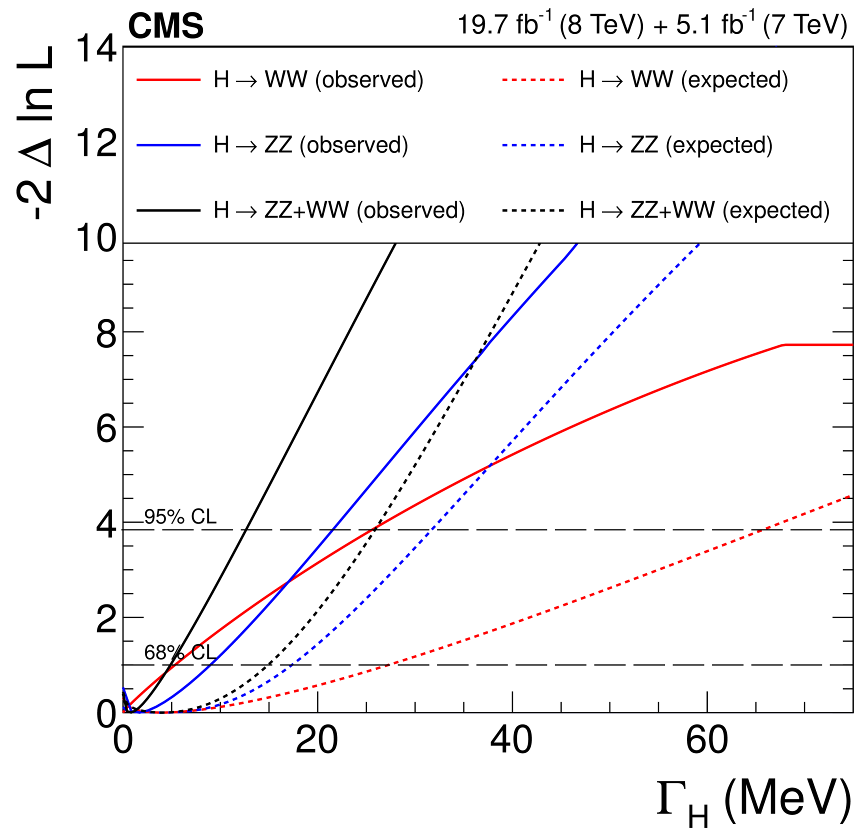


  - Measurement of relative off-shell and on-shell production provides direct information on Γ_H

- More information next week from Giuliano, here final results only
- References:
  - ATLAS Collaboration, *Constraints on the off-shell Higgs boson signal strength in the high-mass ZZ and WW final states with the ATLAS detector*, Eur. Phys. J. C (2015) 75:335, http://link.springer.com/article/10.1140/epjc/s10052-015-3542-2
  - CMS Collaboration, *Constraints on the Higgs boson width from off-shell production and decay to Z-boson pairs, Phys. Lett. B 736 (2014) 64, http://www.sciencedirect.com/science/article/pii/S0370269314004821*
  - CMS Collaboration, *Search for Higgs boson off-shell production in proton-proton collisions at 7 and 8 TeV and derivation of constraints on its total decay width, J. High Energy Phys. 09 (2016) 051, http://link.springer.com/article/10.1007%2FJHEP09%282016%29051*
  - *CMS Collaboration,* Limits on the Higgs boson lifetime and width from its decay to four charged leptons, Phys. Rev. D 92, 072010, http://journals.aps.org/prd/abstract/10.1103/PhysRevD.92.072010

Total width measurements: indirect





Experiment	95% CL upper limit on Γ_H in MeV	
	Expected	Observed
ATLAS	33.0	**22.7**
CMS	26	**13**

Signal strength measurements

- Signal strength $\mu = \frac{\sigma}{\sigma_{SM}}$ is a measure of potential deviations from SM predictions
  - … under the assuption that the Higgs boson production and decay kinematics are not considerably different from SM expectations
  - This assumption is justified by differential σ, spin and CP measurements (see later)
- The tests performed
  1. Overal μ combining all channels
  2. Independent μ in each production mode
  3. Independent μ in each decay mode
  4. Grouping production modes in H-V and H-q couplings
- References:

  - CMS Collaboration, *Precise determination of the mass of the Higgs boson and tests of compatibility of its couplings with the standard model predictions using proton collisions at 7 and 8 TeV*, Eur. Phys. J. C (2015) 75: 212, http://link.springer.com/article/10.1140%2Fepjc%2Fs10052-015-3351-7
  - ATLAS Collaboration, *Measurements of the Higgs boson production and decay rates and coupling strengths using pp collision data at $\sqrt{s}$ = 7 and 8 TeV in the ATLAS experiment*, Eur. Phys. J. C (216) 76:6, http://link.springer.com/article/10.1140/epjc/s10052-015-3769-y
  - ATLAS and CMS Collaborations, *Measurements of the Higgs boson production and decay rates and constraints on its couplings from a combined ATLAS and CMS analysis of the LHC pp collision data at $\sqrt{s}$ = 7 and 8 TeV*, JHEP 08 (2016) 045, http://link.springer.com/article/10.1007/JHEP08(2016)045

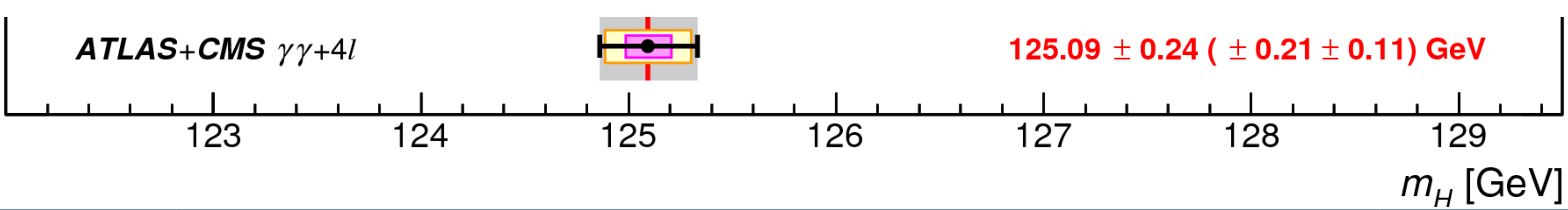
Signal strength measurements: inputs

- Here we describe only final results from ATLAS and CMS combination

Production process	Cross section [pb] $\sqrt{s} = 7$ TeV	Cross section [pb] $\sqrt{s} = 8$ TeV
ggF	15.0 ± 1.6	19.2 ± 2.0
VBF	1.22 ± 0.03	1.58 ± 0.04
WH	0.577 ± 0.016	0.703 ± 0.018
ZH	0.334 ± 0.013	0.414 ± 0.016
$[ggZH]$	0.023 ± 0.007	0.032 ± 0.010
ttH	0.086 ± 0.009	0.129 ± 0.014
tH	0.012 ± 0.001	0.018 ± 0.001
bbH	0.156 ± 0.021	0.203 ± 0.028
Total	17.4 ± 1.6	22.3 ± 2.0

Decay mode	Branching fraction [%]
$H \to bb$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to cc$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

- The Higgs boson mass is assumed to be $m_H = 125.09$ GeV



Signal strengths definitions

- For a specific production process and decay mode $i \to H \to f$
  - The signal strength for production is $\mu_i = \frac{\sigma_i}{(\sigma_i)_{SM}}$
  - The signal strength for decay is $\mu^f = \frac{B^f}{(B^f)_{SM}}$

  where
  - σ_i $(i = ggF, VBF, VH, ZH, ttH)$ are production cross sections for $i \to H$
  - B^f $(f = ZZ, WW, \gamma\gamma, \tau\tau, bb, \mu\mu)$ are branching ratios for $H \to f$
- By definition, for SM: $\mu_i = 1$ and $\mu^f = 1$
- Since μ_i and μ^f cannot be separated without additional assumptions, only the product can be measured experimentally we define signal strengths for the combined production and decay

$$\mu_i^f = \frac{\sigma_i \cdot B^f}{(\sigma_i)_{SM} \cdot (B^f)_{SM}} = \mu_i \cdot \mu^f$$

- Some assumptions used in analysis
    - As some production and decay modes, which are not specifically searched for, contribute to other channels
  - bbH signal strength is the same as ggF
  - tH signal strength is the same as ttH
  - ggZH signal strength is the same as ZH
  - H→gg and H→cc signal strength are the same as H→bb
  - H→Zγ signal strength is the same as H→γγ

Experimental inputs and combination procedure

- Almost all input analyses use categories
  - Based on events kinematics and other properties
  - Categorisation increase sensitivity and allows separation of different processes
- A total of about 600 categories are used
- The signal yield in category k can be expressed as

$$n_{signal}(k) = \mathcal{L}(k) \cdot \sum_i \sum_f \mu_i \mu^f \{\sigma_i^{SM} \cdot A_i^{f,SM}(k) \cdot \varepsilon_i^f(k) \cdot B_{SM}^f\}$$

  - $A_i^{f,SM}(k)$ – the detector acceptance for a given production and decay
  - $\varepsilon_i^f(k)$ – the overall selection efficiency for the signal category k
- Usual statistical procedure is used: profile likelihood method
  - The combination is based on simultaneous fits to the data from both experiments
  - Taking into account the correlations between systematic uncertainties
    - Within each experiment
    - Between two experiments
  - About 4200 nuisance parameters are used in the combination

Sources of uncertainties	
Statistical	From data, including statistical uncert. from background control regions
Theoretical for signal	
Theoretical for backgrounds	
All other	Including experim. uncert. and those related to finite size of MC samples

Overview of channels

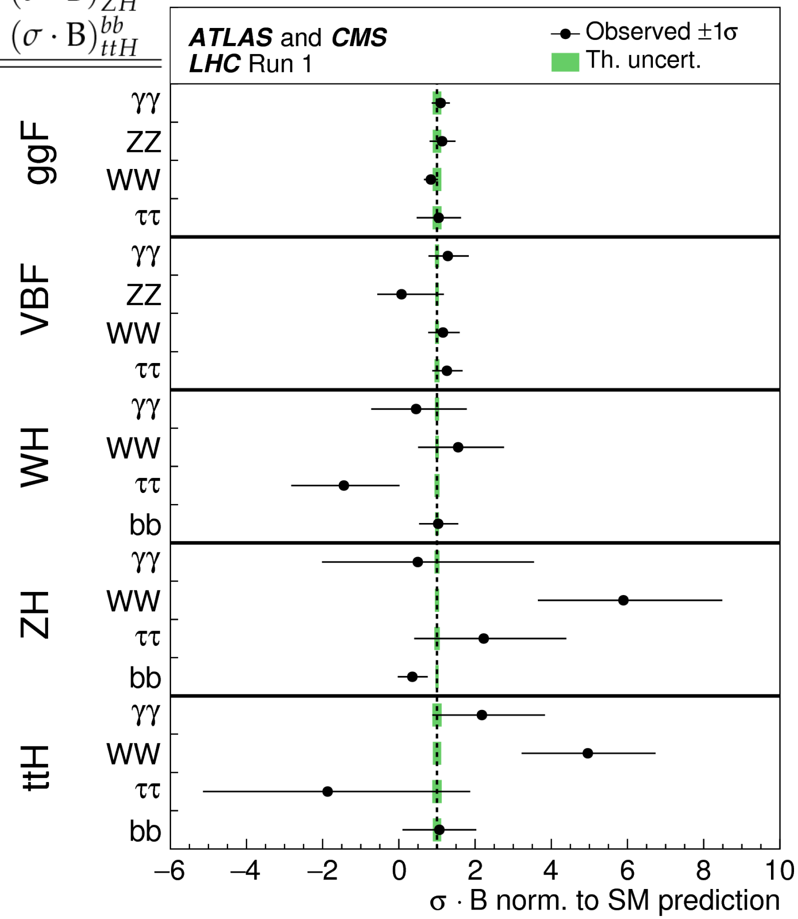
Channel	Signal strength [μ]		Signal significance [σ]	
	from results in this paper (section 5.2)			
	ATLAS	CMS	ATLAS	CMS
$H \to \gamma\gamma$	$1.14^{+0.27}_{-0.25}$	$1.11^{+0.25}_{-0.23}$	5.0	5.6
	$\left({}^{+0.26}_{-0.24}\right)$	$\left({}^{+0.23}_{-0.21}\right)$	(4.6)	(5.1)
$H \to ZZ$	$1.52^{+0.40}_{-0.34}$	$1.04^{+0.32}_{-0.26}$	7.6	7.0
	$\left({}^{+0.32}_{-0.27}\right)$	$\left({}^{+0.30}_{-0.25}\right)$	(5.6)	(6.8)
$H \to WW$	$1.22^{+0.23}_{-0.21}$	$0.90^{+0.23}_{-0.21}$	6.8	4.8
	$\left({}^{+0.21}_{-0.20}\right)$	$\left({}^{+0.23}_{-0.20}\right)$	(5.8)	(5.6)
$H \to \tau\tau$	$1.41^{+0.40}_{-0.36}$	$0.88^{+0.30}_{-0.28}$	4.4	3.4
	$\left({}^{+0.37}_{-0.33}\right)$	$\left({}^{+0.31}_{-0.29}\right)$	(3.3)	(3.7)
$H \to bb$	$0.62^{+0.37}_{-0.37}$	$0.81^{+0.45}_{-0.43}$	1.7	2.0
	$\left({}^{+0.39}_{-0.37}\right)$	$\left({}^{+0.45}_{-0.43}\right)$	(2.7)	(2.5)
$H \to \mu\mu$	$-0.6^{+3.6}_{-3.6}$	$0.9^{+3.6}_{-3.5}$		
	$\left({}^{+3.6}_{-3.6}\right)$	$\left({}^{+3.3}_{-3.2}\right)$		

- To show the relative importance of the various channels, the results from the combined analysis presented in this paper for **m_H = 125.09 GeV** are reported as observed signal strengths μ with their measured uncertainties.
- The expected uncertainties are shown in parentheses.
- Also shown are the observed statistical significances, together with the expected significances in parentheses, except for the H → μμ channel, which has very low sensitivity.

Signal parametrisation using σ and BR products

Production process	Decay channel				
	$H \to \gamma\gamma$	$H \to ZZ$	$H \to WW$	$H \to \tau\tau$	$H \to bb$
ggF	$(\sigma \cdot B)^{\gamma\gamma}_{ggF}$	$(\sigma \cdot B)^{ZZ}_{ggF}$	$(\sigma \cdot B)^{WW}_{ggF}$	$(\sigma \cdot B)^{\tau\tau}_{ggF}$	–
VBF	$(\sigma \cdot B)^{\gamma\gamma}_{VBF}$	$(\sigma \cdot B)^{ZZ}_{VBF}$	$(\sigma \cdot B)^{WW}_{VBF}$	$(\sigma \cdot B)^{\tau\tau}_{VBF}$	–
WH	$(\sigma \cdot B)^{\gamma\gamma}_{WH}$	$(\sigma \cdot B)^{ZZ}_{WH}$	$(\sigma \cdot B)^{WW}_{WH}$	$(\sigma \cdot B)^{\tau\tau}_{WH}$	$(\sigma \cdot B)^{bb}_{WH}$
ZH	$(\sigma \cdot B)^{\gamma\gamma}_{ZH}$	$(\sigma \cdot B)^{ZZ}_{ZH}$	$(\sigma \cdot B)^{WW}_{ZH}$	$(\sigma \cdot B)^{\tau\tau}_{ZH}$	$(\sigma \cdot B)^{bb}_{ZH}$
ttH	$(\sigma \cdot B)^{\gamma\gamma}_{ttH}$	$(\sigma \cdot B)^{ZZ}_{ttH}$	$(\sigma \cdot B)^{WW}_{ttH}$	$(\sigma \cdot B)^{\tau\tau}_{ttH}$	$(\sigma \cdot B)^{bb}_{ttH}$

- Figure: Best fit values of σ_i * B^f for each specific channel i → H→ f
  - as obtained from the generic parameterisation with 23 parameters in the table
- The error bars indicate the 1σ intervals
- Only 20 parameters are shown because some are either
  - not measured with a meaningful precision, in the case of the H → ZZ decay channel for the WH, ZH, and ttH production processes,
  - or not measured at all and therefore fixed to their corresponding SM predictions, in the case of the H → bb decay mode for the ggF and VBF production processes.

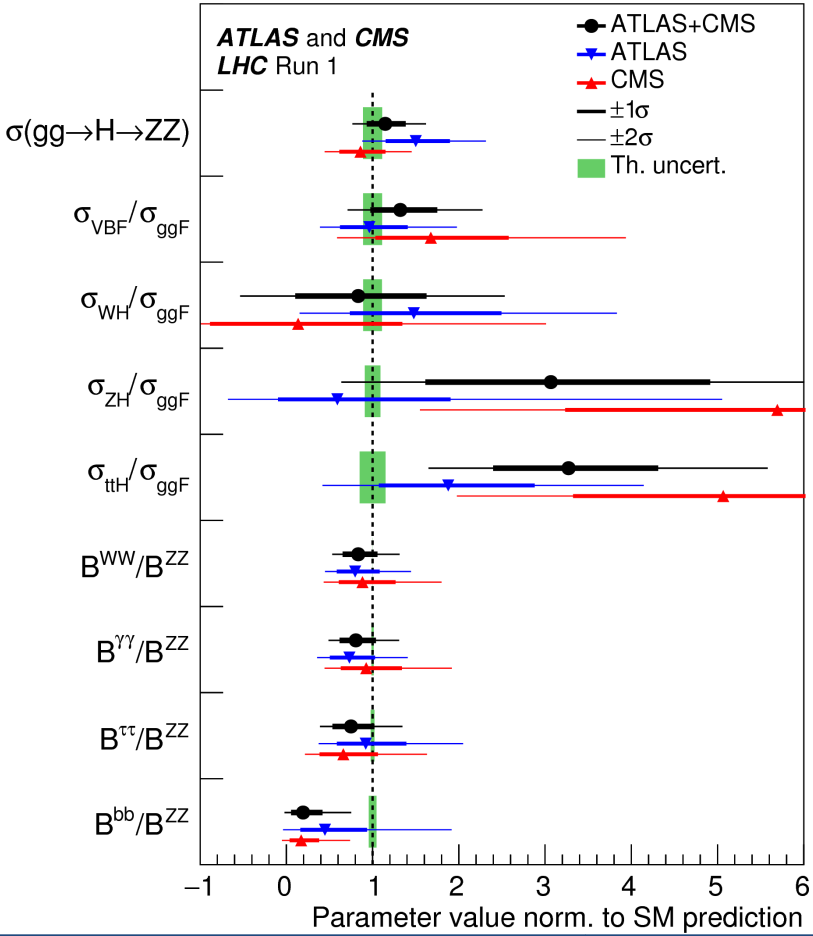


Signal parametrisation using ratios of σs and BRs

- Ratios of σs and BRs can be extracted from a combined fit to the data by normalising the yield to the reference $i \to H \to f$ process
  - gg→ $H \to ZZ$ is chosen as reference as it has
    - small background as well as small overall and systematic uncertainties
- We can then use the ratios in a following way

$$\sigma_i \cdot B^f = \sigma(gg \to H \to ZZ) \cdot \left(\frac{\sigma_i}{\sigma_{ggF}}\right) \cdot \left(\frac{B^f}{B^{ZZ}}\right)$$

- Advantages:
  - Ratios are independent of theoretical predictions for inclusive production cross sections and branching fractions
  - Particularly, ratios are not subject to dominant signal theoretical uncertainties in inclusive cross sections for various production processes
  - These results will be valid even after improved theoretical calculations become available
  - Many experimental uncertainties also cancel in ratios



1 Overal μ combining all channels

- The simplest and most restrictive signal strength parametrisation is to assume the same μ for all production and decay modes
- Results

	Best fit μ	Uncertainty				
		Total	Stat	Expt	Thbgd	Thsig
ATLAS + CMS (measured)	1.09	$^{+0.11}_{-0.10}$	$^{+0.07}_{-0.07}$	$^{+0.04}_{-0.04}$	$^{+0.03}_{-0.03}$	$^{+0.07}_{-0.06}$
ATLAS + CMS (expected)		$^{+0.11}_{-0.10}$	$^{+0.07}_{-0.07}$	$^{+0.04}_{-0.04}$	$^{+0.03}_{-0.03}$	$^{+0.07}_{-0.06}$
ATLAS (measured)	1.20	$^{+0.15}_{-0.14}$	$^{+0.10}_{-0.10}$	$^{+0.06}_{-0.06}$	$^{+0.04}_{-0.04}$	$^{+0.08}_{-0.07}$
ATLAS (expected)		$^{+0.14}_{-0.13}$	$^{+0.10}_{-0.10}$	$^{+0.06}_{-0.05}$	$^{+0.04}_{-0.04}$	$^{+0.07}_{-0.06}$
CMS (measured)	0.97	$^{+0.14}_{-0.13}$	$^{+0.09}_{-0.09}$	$^{+0.05}_{-0.05}$	$^{+0.04}_{-0.03}$	$^{+0.07}_{-0.06}$
CMS (expected)		$^{+0.14}_{-0.13}$	$^{+0.09}_{-0.09}$	$^{+0.05}_{-0.05}$	$^{+0.04}_{-0.03}$	$^{+0.08}_{-0.06}$

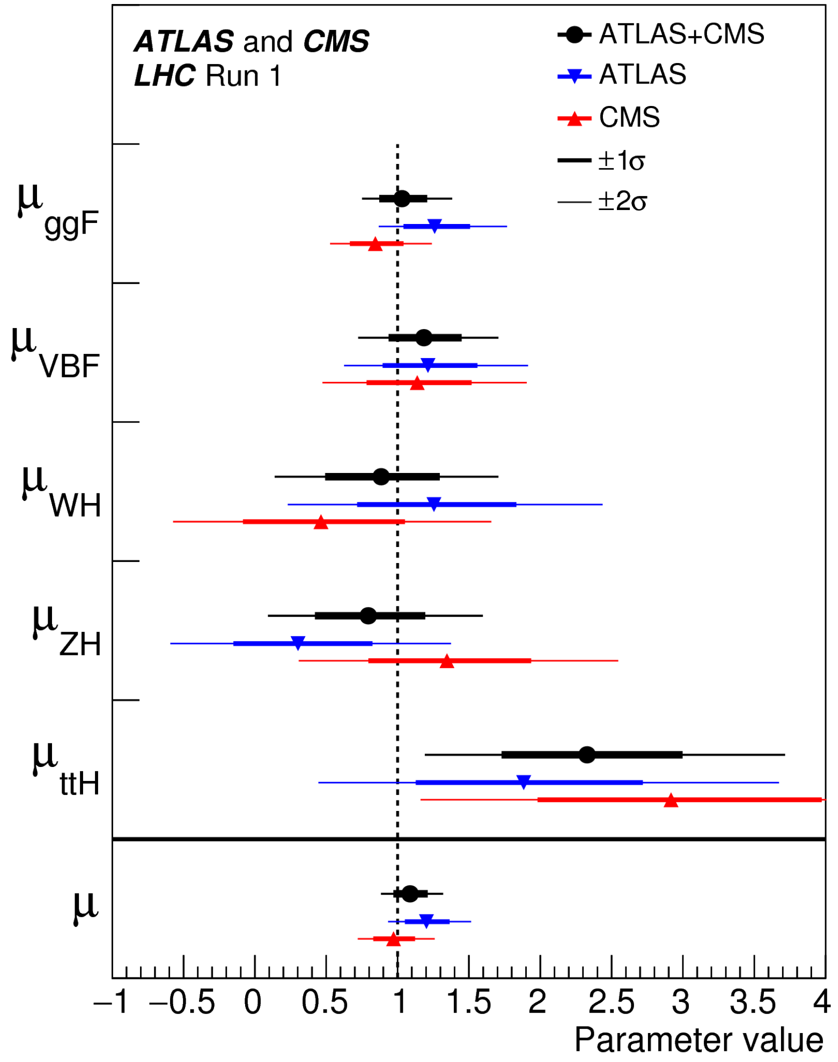
- The overall systematic uncertainties of $^{+0.09}_{-0.08}$ is larger then the statistical uncertainty
  - The largest component is theoretical uncertainty in the *ggF* cross section
- This result is consistent with SMS prediction of $\mu = 1$ within less then 1σ
  - p-value of the compatibility between data and SM predictioni is 40%

2 Independent μ in each production mode

- One global μ is very model dependant
  - Assumption is that all production and decay is as in SM
- Less model-dependent way: relaxing these assumption separately for the production and decay
- Assuming $\mu^f = 1$ we explore production signal strengths:

$$\mu_{ggF}, \mu_{VBF}, \mu_{WH}, \mu_{ZH}, \mu_{ttH}$$

  - Assuming same signal strengths at 7 and 8 TeV
- p-value of data vs SM: 24%



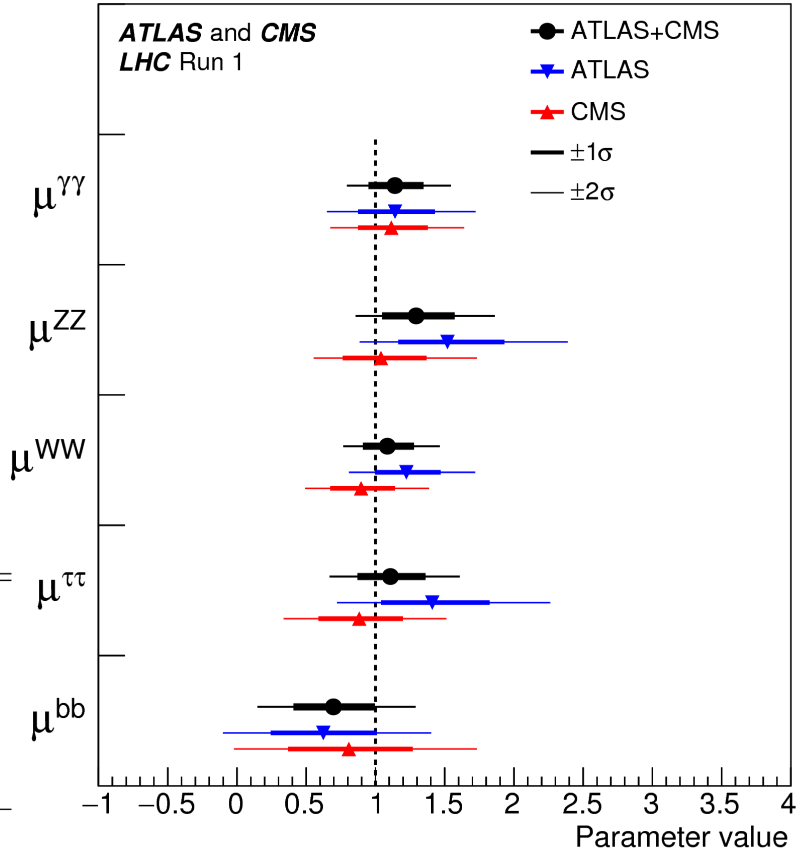
3 Independent μ in each decay mode

- Assuming $\mu_i = 1$ we explore decay signal strengths:

$$\mu^{\gamma\gamma}, \mu^{ZZ}, \mu^{WW}, \mu^{\tau\tau}, \mu^{bb}, \mu^{\mu\mu}$$

  - Assumption of same signal strengths at 7 and 8 TeV is not needed here
- p-value of data vs SM: 75%
- From the combined likelihood scans we can evaluate significances for production and decay modes

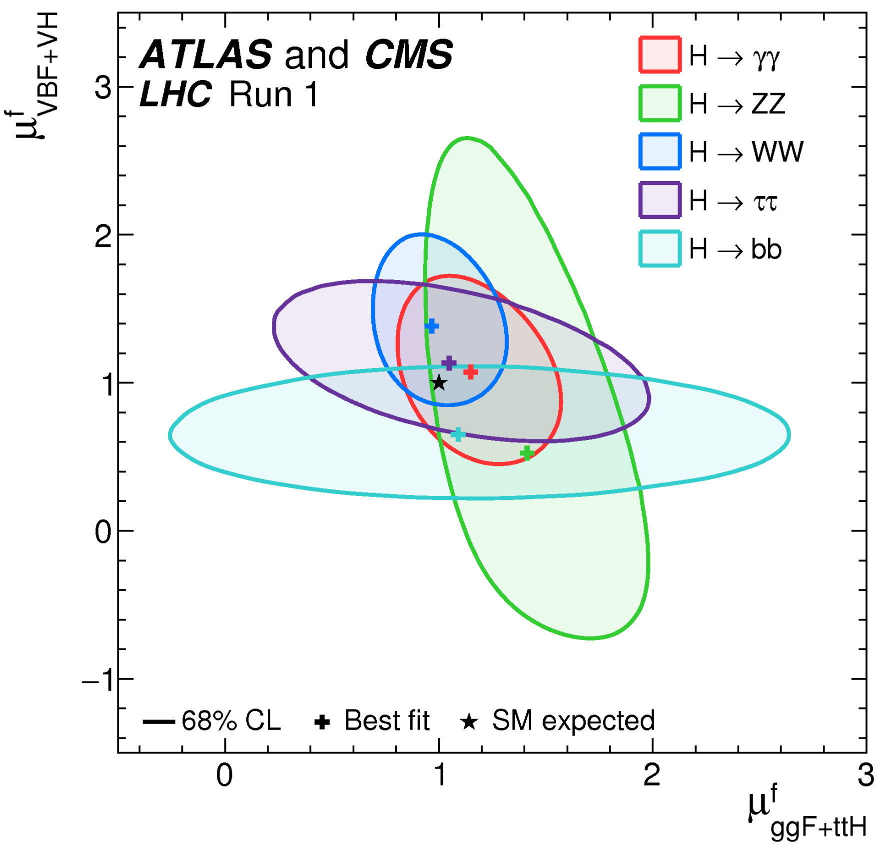
Production process	Measured significance (σ)	Expected significance (σ)
VBF	5.4	4.6
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
$H \to \tau\tau$	5.5	5.0
$H \to bb$	2.6	3.7



- Conclusions
  - VBF and H→ττ above 5σ
  - VH above 3σ
  - ttH 4.4σ measured, while 2.0σ expected

Grouping production modes

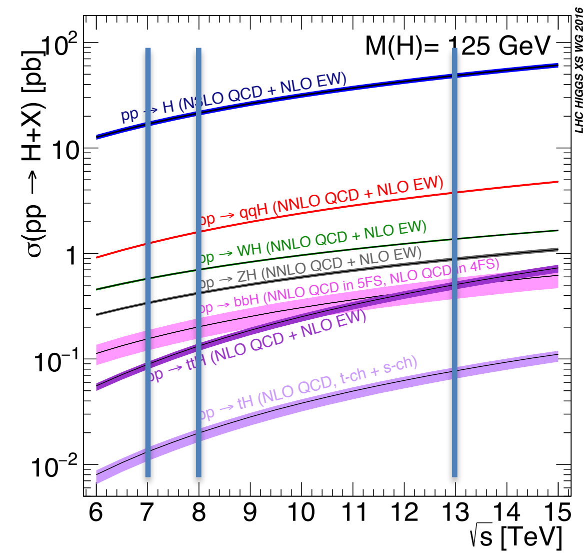
- Higgs boson production processes can be grouped, in each decay channel:
  - Couplings to fermions (ggF and ttH): $\mu_F^f = \mu_{ggF+ttH}^f$
  - Coupling to vector bosons (VBF, WH and ZH): $\mu_V^f = \mu_{VBF+VH}^f$
- Ten-parameter fit of μ_F^f and μ_V^f in each of the five decay channels is performed
- The SM prediction $\mu_F^f = 1$ and $\mu_V^f = 1$ lies within 68% in all measurements
- p-value of data vs SM: 90%
- Six-parameter fit with μ_V/μ_F and μ_F^f for each of the five decay channel has also been performed
  - P-value of data vs SM: 75%
  - $\mu_V/\mu_F = 1.09^{+0.36}_{-0.28}$

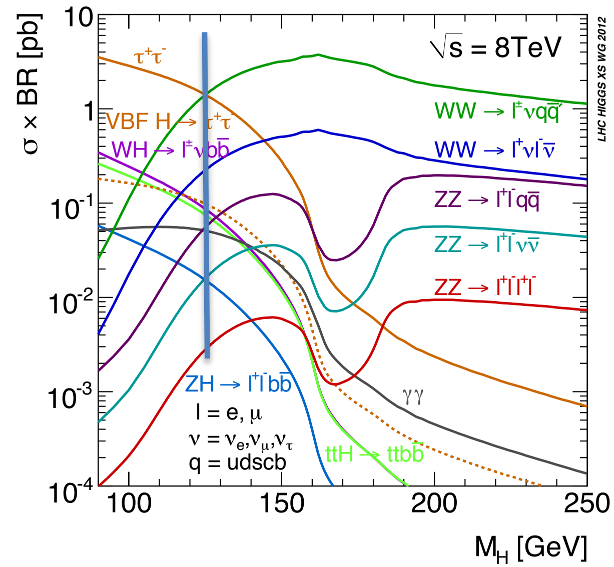


Properties to be measured

- **Mass m_H**
  - Separately in H→4l and H→γγ channels, then combining at the level of ATLAS and CMS, and then combing ATLAS and CMS
- **Total width Γ_H**
  - Directly or indirectly via off-shell production
- **Signal strength μ**
  - Overall, for each decay mode, for each production mode, separately by channels and in combinations
- **Total cross section $\sigma_{fid.}$**
  - In the fiducial volume, but defined in different ways …
- **Differential cross section $d\sigma_{fid}/dx$**
  - In several production-related observables (x), using H→4l and H→γγ channels: Higgs boson's transverse momentum and rapidity, associated jet multiplicity, p_T of leading jet …
- **Spin-parity quantum numbers J^P**
  - Pair-wise tests of SM Higgs vs alternative J^P states, constraints on anomalous decay amplitudes …
- **Couplings λ_i, κ_i**
  - Testing the SM couplings to fermions and bosons, search for deviation from SM couplings, testing custodial symmetry and fermion universality, testing the contribution from hypothetical BSM particles … using all channels

SM expectations





Cross section measurements

- Two classes of measurements
  - Total cross section in fiducial volume, σ_{fid}.
  - Differential cross section in the fiducial volume, $d\sigma_{fid}/dx$
- Fiducial volume
  - Defined by physical detector volume and event selection
    - Therefore different choices possible
- Extrapolation to total cross section takes many assumptions
  - For example: different production process have different detector acceptances
  - Selection efficiencies also depend on signal models
- ATLAS also extrapolated signal strengths measurements to the total cross section estimates
  - But with significant systematics uncertainties still remaining
    - Due to modelling of Higgs boson production and acceptance of event selection
- References

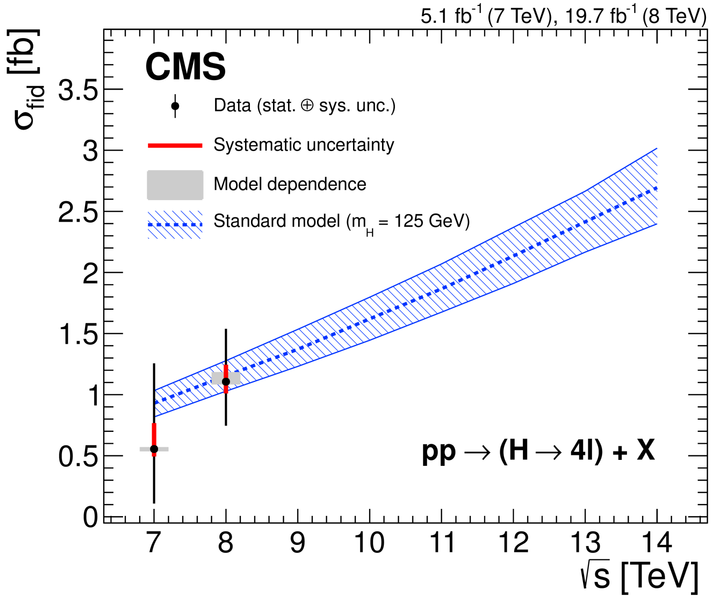
  - CMS Collaboration, *Measurement of differential and integrated fiducial cross sections for Higgs boson production in the four-lepton decay channel in pp collisions at* $\sqrt{s}$ *= 7 and 8 TeV, J. High Enery Phys. 04 (2016) 005,* http://dx.doi.org/10.1007/JHEP04(2016)005
  - CMS Collaboration, *Measurement of differential cross sections for Higgs boson production in the diphoton decay channel in pp collisions at* $\sqrt{s}$ *= 8 TeV, Eur. Phys. J. C 76 (2016) 13,* http://dx.doi.org/10.1140%2Fepjc%2Fs10052-015-3853-3
  - ATLAS Collaboration, *Measurement of fiducial differential cross sections of gluon-fusion production of Higgs bosons decaying to* $WW^* \rightarrow e\nu\mu\nu$ *with the ATLAS detector at* $\sqrt{s} = 8$ *TeV*, JHEP 08 (2016) 104, https://arxiv.org/abs/1604.02997
  - ATLAS Collaboration, *Measurements of the Total and Differential Higgs Boson Production Cross Sections Combining the* $H \rightarrow \gamma\gamma$ *and* $H \rightarrow ZZ^* \rightarrow 4l$ *Decay Channels at at* $\sqrt{s} = 8$ *TeV with the ATLAS Detector*, Phys. Rev. Lett. 115, 091801 (2015), https://arxiv.org/abs/1504.05833
  - ATLAS Collaboration, *Fiducial and differential cross sections of Higgs boson production measured in the four-lepton decay channel in pp collisions at* $\sqrt{s} = 8$ *TeV with the ATLAS detector*, Physics Letters B 738 (2014) 234-253, https://arxiv.org/abs/1408.3226
  - ATLAS Collaboration, *Measurements of fiducial and differential cross sections for Higgs boson production in the diphoton decay channel at* $\sqrt{s} = 8$ *TeV with ATLAS*, JHEP09(2014)112, https://arxiv.org/abs/1407.4222

Total fiducial cross section

- Goal: **determine total cross section in the fiducial volume $\sigma_{fid.}$**
  - Corrected for detector efficiencies, resolution and know systematic biases
    - This is called ***unfolding***
- Procedure is as follows

1. Define the fiducial volume
2. Estimate and correct for detector effects
3. Extract $\sigma_{fid.}$ directly from a maximum likelihood fit

- Same procedure is used for differential cross section
  - only $\sigma_{fid.}$ is replaced by $\sigma^{i}_{fid.}$ in the i^{th} bin of the variable used
- Example of results from CMS →



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Fiducial volume definition

- Goal: minimize model dependence
  - Detector acceptance and event selection efficiency can vary significantly in different production processes or different exotic model of Higgs boson properties
- Therefore: define fiducial volume *(also called **fiducial phase space**)* to match as closely as possible the experimental acc. defined by the reconstruction-level selection
- Examples: fiducial volumes in CMS H→ZZ→4l analysis

Requirements for the $H \to 4\ell$ fiducial phase space	
Lepton kinematics and isolation	
Leading lepton p_T	$p_T > 20\,GeV$
Sub-leading lepton p_T	$p_T > 10\,GeV$
Additional electrons (muons) p_T	$p_T > 7\ (5)\,GeV$
Pseudorapidity of electrons (muons)	$\lvert\eta\rvert < 2.5\ (2.4)$
Sum of scalar p_T of all stable particles within $\Delta R < 0.4$ from lepton	$< 0.4 p_T$
Event topology	
Existence of at least two SFOS lepton pairs, where leptons satisfy criteria above	
Inv. mass of the Z_1 candidate	$40 < m(Z_1) < 120\,GeV$
Inv. mass of the Z_2 candidate	$12 < m(Z_2) < 120\,GeV$
Distance between selected four leptons	$\Delta R(\ell_i \ell_j) > 0.02$
Inv. mass of any opposite-sign lepton pair	$m(\ell_i^+ \ell_j^-) > 4\,GeV$
Inv. mass of the selected four leptons	$105 < m_{4\ell} < 140\,GeV$

  - ATLAS, for example, does not include isolation requirements in fiducial volume definition

2

Unfolding: correcting detector effects

- In order to compare with the theoretical estimations, the measurement needs to be corrected for limited detector efficiency and resolution effects
- Detector effects are estimate from MC simulation
- Example: detector effects in CMS H→ZZ→4l analysis

Signal process	$\mathcal{A}_{\text{fid}}$	ϵ	f_{nonfid}	$(1+f_{\text{nonfid}})\epsilon$
Individual Higgs boson production modes				
$gg \to H$ (POWHEG+JHUGEN)	0.422 ± 0.001	0.647 ± 0.002	0.053 ± 0.001	0.681 ± 0.002
VBF (POWHEG)	0.476 ± 0.003	0.652 ± 0.005	0.040 ± 0.002	0.678 ± 0.005
WH (PYTHIA)	0.342 ± 0.002	0.627 ± 0.003	0.072 ± 0.002	0.672 ± 0.003
ZH (PYTHIA)	0.348 ± 0.003	0.634 ± 0.004	0.072 ± 0.003	0.679 ± 0.005
$t\bar{t}H$ (PYTHIA)	0.250 ± 0.003	0.601 ± 0.008	0.139 ± 0.008	0.685 ± 0.010
Some characteristic models of a Higgs-like boson with exotic decays and properties				
$q\bar{q} \to H(J^{CP} = 1^-)$ (JHUGEN)	0.238 ± 0.001	0.609 ± 0.002	0.054 ± 0.001	0.642 ± 0.002
$q\bar{q} \to H(J^{CP} = 1^+)$ (JHUGEN)	0.283 ± 0.001	0.619 ± 0.002	0.051 ± 0.001	0.651 ± 0.002
$gg \to H \to Z\gamma^*$ (JHUGEN)	0.156 ± 0.001	0.622 ± 0.002	0.073 ± 0.001	0.667 ± 0.002
$gg \to H \to \gamma^*\gamma^*$ (JHUGEN)	0.188 ± 0.001	0.629 ± 0.002	0.066 ± 0.001	0.671 ± 0.002

- A_{fid} - fraction of signal events within the fiducial phase space
- ε - reconstruction efficiency for signal events from within the fiducial phase space
- f_{nonfid} - ratio of reconstructed events which are from outside the fiducial phase space to reconstructed events which are from within the fiducial phase space

3 Extracting $\sigma_{fid.}$ from ML fit

Number of expected events
in each final state *f* and in each bin *i* of a considered observable is expressed as a function of m_{4l}

$$N_{obs}^{f,i}(m_{4l}) =$$

Fiducial signal

$$N_{fid}^{f,i}(m_{4l}) +$$

Nonfiducial signal

$$N_{nonfid}^{f,i}(m_{4l}) +$$

$$\sum_j \epsilon_{i,j}^{f}\left(1 + f_{nonfid}^{f,j}\right)\sigma_{fid}^{f,j}\mathcal{L}P_{res}(m_{4l})$$

Combinatorial contribution from fiducial signal
at least one of the four leptons does not originate from the H→4l decay

$$N_{comb}^{f,i}(m_{4l}) + \rightarrow N_{comb}^{f,i}P_{comb}(m_{4l})$$

Background contribution

$$N_{bkd}^{f,i}(m_{4l}) \rightarrow N_{bkd}^{f,i}P_{bkd}(m_{4l})$$

$\epsilon_{i,j}^{f}$ - detector response matrix maping the number of expected events in a given observable bin *j* at the fiducial level to the number of expected events in the bin *i* at the reconstruction level

$\sigma_{fid}^{f,j}$ - signal cross section for the final state f in bin *j* of the fiducial phase space

$f_{nonfid}^{f,j}$ - ratio of the nonfiducial and fiducial signal contribution in bin *i* at the reconstruction level

$P_{res}(m_{4l})$, $P_{comb}(m_{4l})$, $P_{bkd}(m_{4l})$ - probability density functions for the resonant (fiducial and nonfiducial) signal, combinatorial signal, and background contributions, respectively

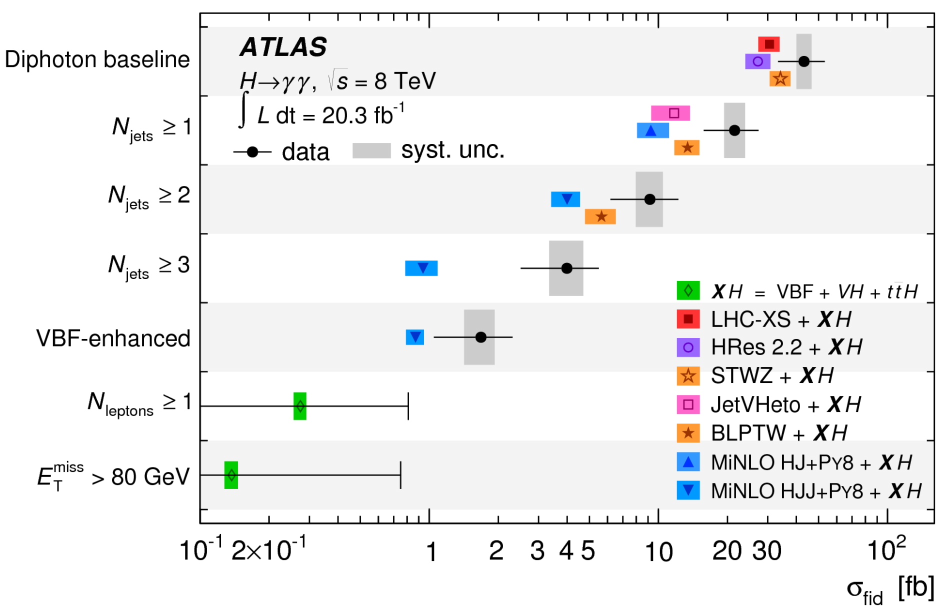
Example of systematical errors

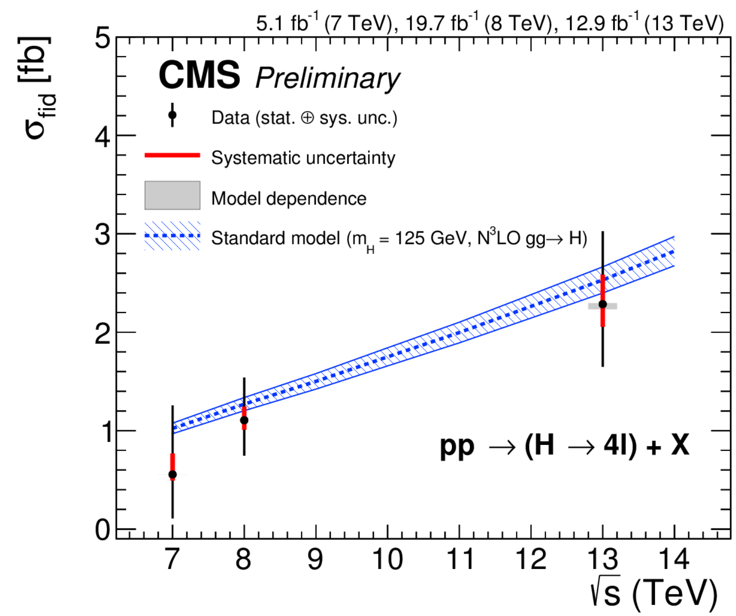
- CMS $H \rightarrow ZZ^* \rightarrow 4l$

Summary of relative systematic uncertainties	
Common experimental uncertainties	
Luminosity	2.2% (7 TeV), 2.6% (8 TeV)
Lepton identification/reconstruction efficiencies	4–10%
Background related uncertainties	
QCD scale ($q\bar{q} \rightarrow ZZ$, $gg \rightarrow ZZ$)	3–24%
PDF set ($q\bar{q} \rightarrow ZZ$, $gg \rightarrow ZZ$)	3–7%
Reducible background ($Z + X$)	20–40%
Jet resolution and energy scale	2–16%
Signal related uncertainties	
Lepton energy scale	0.1–0.3%
Lepton energy resolution	20%
Jet energy scale and resolution	3–12%
Combinatorial signal-induced contribution	
Effect on the final measurement	4–11%
Model dependence	
With exp. constraints on production modes and exotic models	1–5%
No exp. constraints on production modes and exotic models	7–25%

Total fiducial cross section: results

Total fiducial cross section @ 8 TeV		
Channel	Masured	Expected
ATLAS H→ZZ*→4l @ 125.4 GeV	$2.11^{+0.53}_{-0.47}$ (stat) $\pm$ 0.08 (syst) fb	1.30 ± 0.13 fb
ATLAS H→γγ @ 125.4 GeV	43.2 ± 9.4 (stat) $^{+3.2}_{-2.9}$ (syst) $\pm$ 1.2 (lumi) fb	30.5 ± 3.3 fb
CMS H→ZZ*→4l @ 125 GeV	$1.11^{+0.41}_{-0.35}$ (stat) $^{+0.14}_{-0.10}$ (syst) $^{+0.08}_{-0.02}$ (model) fb	$1.15^{+0.12}_{-0.13}$ fb
CMS H→γγ @ 125 GeV	32 ± 10 (stat) $\pm$ 3 (syst) fb	31^{+4}_{-3} fb



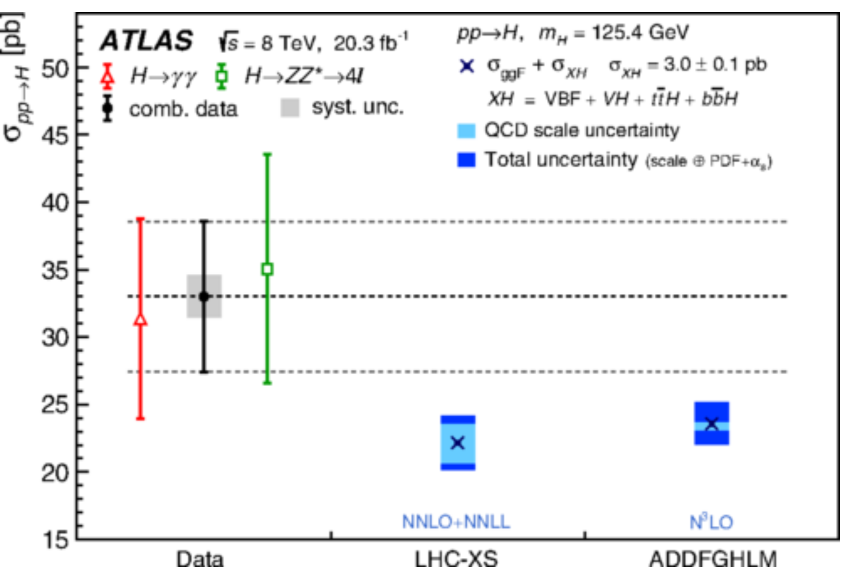


Preliminary results @ 13 TeV

Total cross section measurements: results

- ATLAS attempted to measure the total cross section:
  - 1) Combining H→ZZ*→4l and H→γγ
    - Unfolding fiducial acceptances and branching fractions
  - 2) Using all channels and converting signal strengths to the cross section measurements
- Results for ATLAS Total cross section @ 8 TeV

Channel	Masured	Expected
H→4l and γγ comb. @ 125.4 GeV	$33.0 \pm 5.3\ (\text{stat}) \pm 1.6\ (\text{syst})$ pb	See figure
From signal strengths	$22.7 \pm 3.0\ (\text{stat})^{+2.0}_{-1.7}\ (\text{syst})^{+1.2}_{-0.9}\ (\text{theo})$ pb	22.3 ± 2.0 pb



Measured

Production process	Cross section [pb] at $\sqrt{s} = 8$ TeV	
ggF	23.9 ± 3.6	$\begin{bmatrix} +3.1 & +1.9 & +1.0 \\ -3.1 & -1.6 & -1.0 \end{bmatrix}$
VBF	2.43 ± 0.58	$\begin{bmatrix} +0.50 & +0.27 & +0.19 \\ -0.49 & -0.20 & -0.16 \end{bmatrix}$
VH	1.03 ± 0.53	$\begin{bmatrix} +0.37 & +0.22 & +0.13 \\ -0.36 & -0.20 & -0.06 \end{bmatrix}$
ttH	0.24 ± 0.11	$\begin{bmatrix} +0.07 & +0.08 & +0.01 \\ -0.07 & -0.08 & -0.01 \end{bmatrix}$

Expected

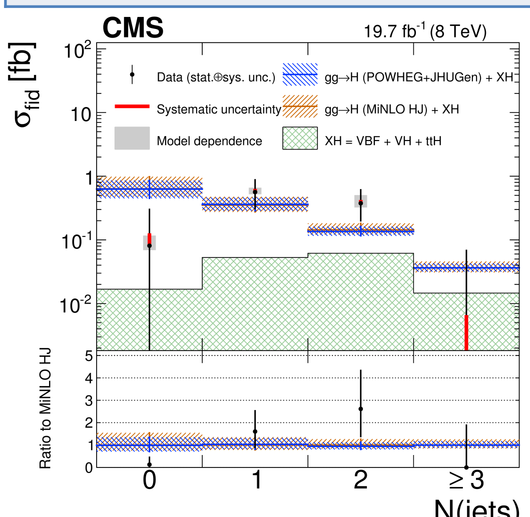
Production process	Cross section [pb] $\sqrt{s} = 7$ TeV	Cross section [pb] $\sqrt{s} = 8$ TeV
ggF	15.0 ± 1.6	19.2 ± 2.0
VBF	1.22 ± 0.03	1.57 ± 0.04
WH	0.573 ± 0.016	0.698 ± 0.018
ZH	0.332 ± 0.013	0.412 ± 0.013
bbH	0.155 ± 0.021	0.202 ± 0.028
ttH	0.086 ± 0.009	0.128 ± 0.014
tH	0.012 ± 0.001	0.018 ± 0.001
Total	17.4 ± 1.6	22.3 ± 2.0

Differential cross section: results

- Measurements are performed for $\frac{d\sigma_{fid}}{dx}$, where x is given in tables

fiducial

H→ZZ*→4l	ATLAS	CMS
p_T^{4l}	✔	✔
$\lvert y^{4l} \rvert$	✔	✔
p_T^{jet1}	✔	✔
$\lvert y_H - y_{jet1} \rvert$	✖	✔
in N_{jets} bins	✔	✔
m_{34}^{2l}	✔	✖
$\lvert cos\theta^* \rvert$	✔	✖

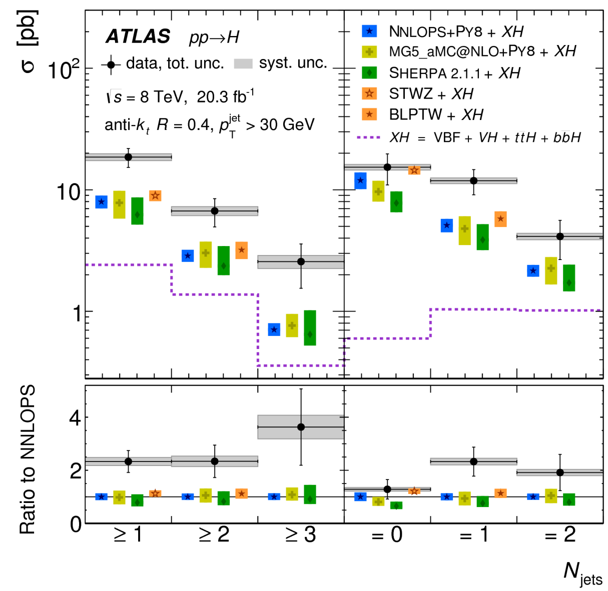


fiducial

H→γγ	ATLAS	CMS
$p_T^{\gamma\gamma}$	✔	✔
$\lvert y^{\gamma\gamma} \rvert$	✔	✔
$\Delta\phi^{\gamma\gamma}$	✖	✔
$\lvert cos\theta^* \rvert$	✔	✔
p_T^{jet1}	✔	✔
p_T^{jet2}	✔	✖
H_T	✔	✖
$\lvert y_H - y_{jet1} \rvert$	✖	✔
in N_{jets} bins	✔	✔
m_{jj}	✖	✔
H+2j: $\Delta\phi^{jj}$	✔	✔
H+2j: $\Delta\eta^{jj}$	✔	✔
H+2j: Zepp. var.	✖	✔
H+2j: $\Delta\phi^{\gamma\gamma,jj}$	✔	✔

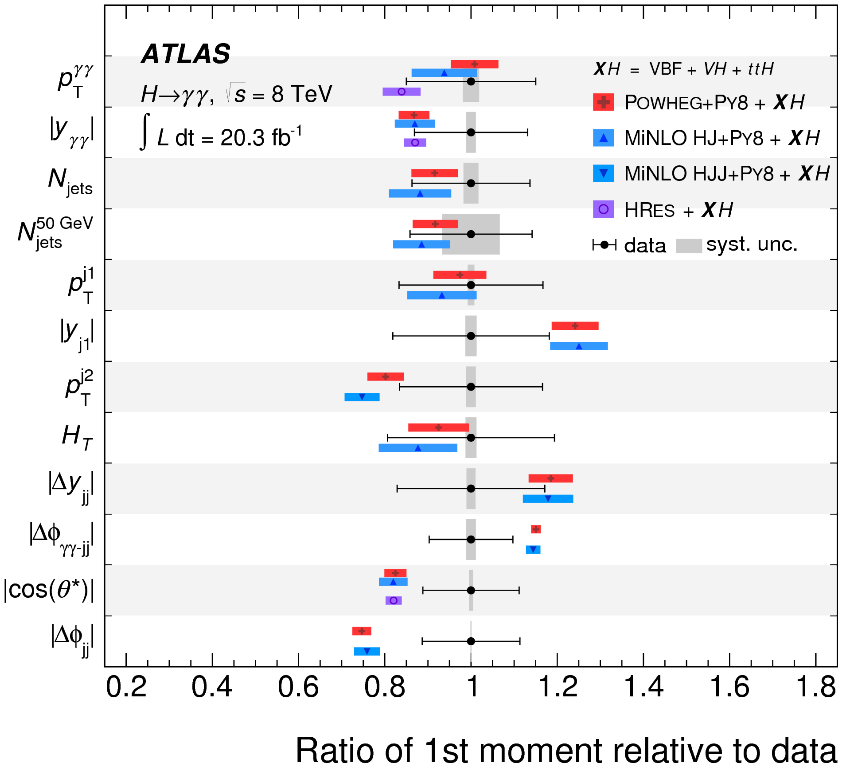
total

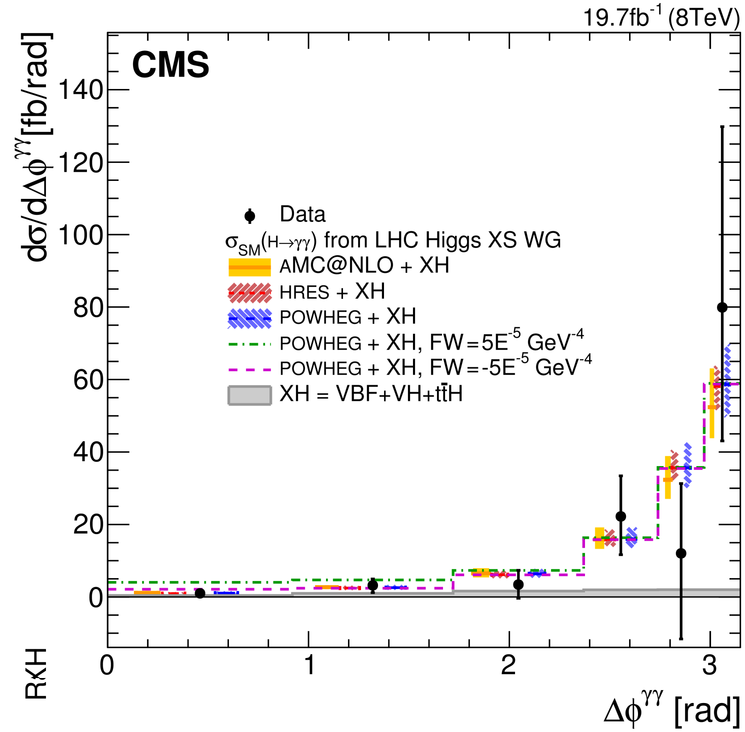
H→4l & γγ	ATLAS	CMS
p_T^{H}	✔	✖
$\lvert y^{H} \rvert$	✔	✖
p_T^{jet1}	✔	✖
in N_{jets} bins	✔	✖

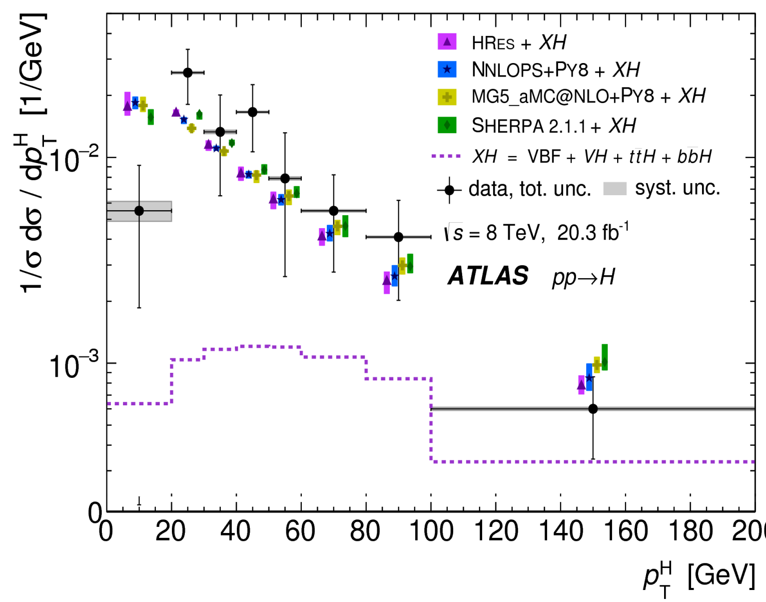


Diff. σ: some plots

- General conclusions:
  - Results consistent with predictions
  - Statistical uncertainties still to large to distinguish between different theoretical calculations







Spin-parity quantum numbers measurements

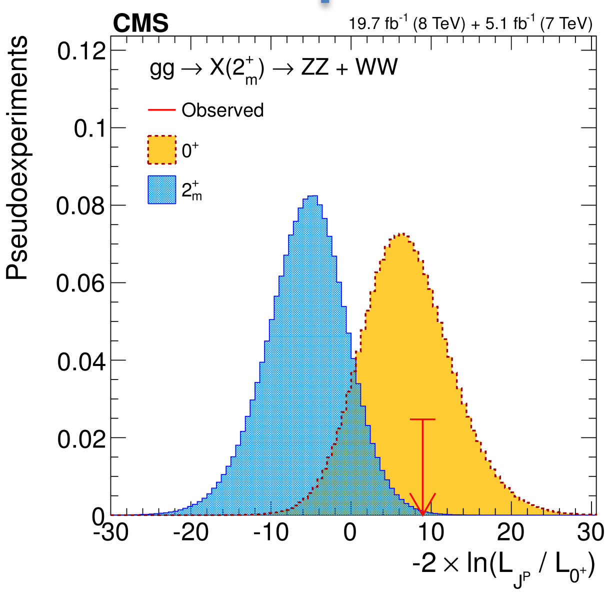
- SM Higgs boson has spin zero and positive parity $J^P = 0^+$
- Observation of $H \rightarrow \gamma\gamma$ decay
  - Sets charge conjugation parity to one, C = +1
  - Excludes spin 1 (J = 1) by Landau-Yang theorem
- We will determine spin-parity quantum numbers using
  - $H \rightarrow ZZ^* \rightarrow 4l$ and $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ to study spin 0, 1 and 2 states, and also probe anomalous HVV couplings for spin 0 state
  - $H \rightarrow \gamma\gamma$ to test various spin two hypotheses

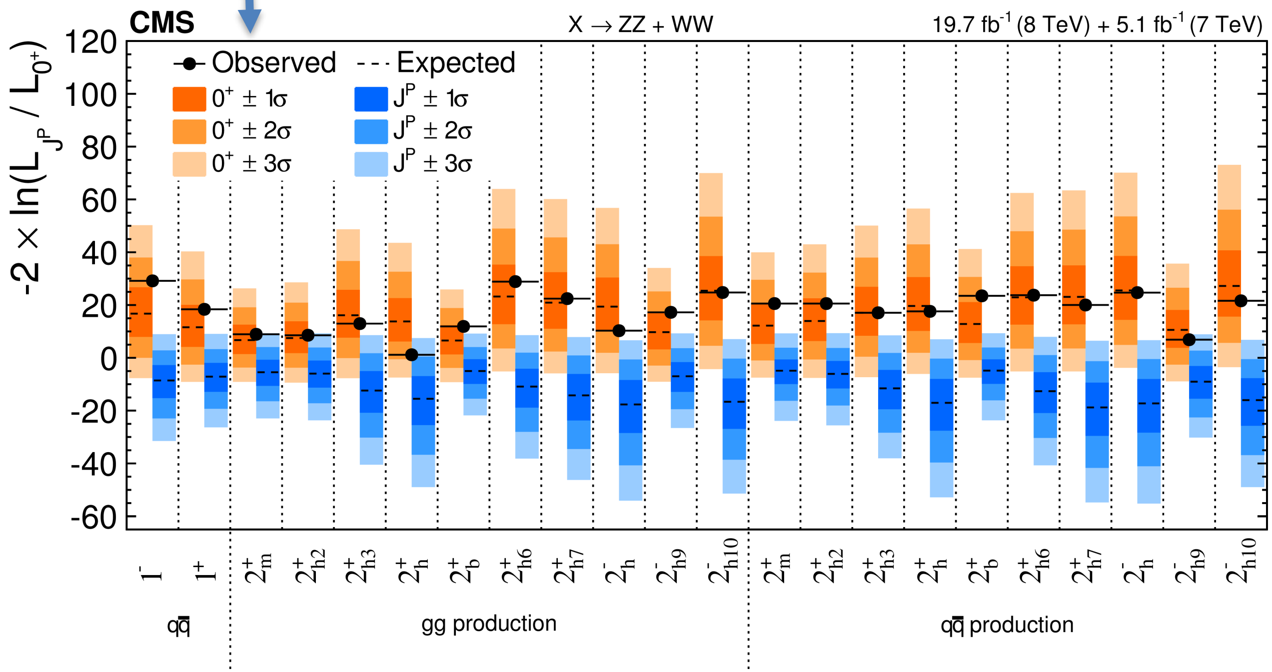
- References:

  - ATLAS Collaboration, *Study of the spin and parity of the Higgs boson in diboson decays with the ATLAS detector*, Eur. Phys. J. C (2015) 75: 476, http://link.springer.com/article/10.1140/epjc/s10052-015-3685-1
  - ATLAS Collaboration, *Determination of spin and parity of the Higgs boson in the $WW^* \rightarrow e\nu\mu\nu$ decay channel with the ATLAS detector*, Eur. Phys. J. C (2015) 75: 231, http://link.springer.com/article/10.1140/epjc/s10052-015-3436-3
  - ATLAS Collaboration, *Evidence for the spin-0 nature of the Higgs boson using ATLAS data*, Phys. Lett. B 726 (2013), pp. 120-144, http://www.sciencedirect.com/science/article/pii/S0370269313006527
  - CMS Collaboration, *Constraints on the spin-parity and anomalous HVV couplings of the Higgs boson in proton collisions at 7 and 8 TeV*, Phys. Rev. D **92**, 012004, http://journals.aps.org/prd/abstract/10.1103/PhysRevD.92.012004
  - CMS Collaboration, *Observation of the diphoton decay of the Higgs boson and measurement of its properties*, Eur. Phys. J. C (2014) 74: 3076, http://link.springer.com/article/10.1140%2Fepjc%2Fs10052-014-3076-z
  - CMS Collaboration, *Measurement of the properties of a Higgs boson in the four-lepton final state*, Phys. Rev. D **89**, 092007, http://journals.aps.org/prd/abstract/10.1103/PhysRevD.89.092007
  - CMS Collaboration, *Measurement of Higgs boson production and properties in the WW decay channel with leptonic final states*, High Energ. Phys. (2014) 2014: 96, http://link.springer.com/article/10.1007%2FJHEP01%282014%29096
  - CMS Collaboration, *Study of the Mass and Spin-Parity of the Higgs Boson Candidate via Its Decays to Z Boson Pairs*, Phys. Rev. Lett. **110**, 081803, http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.110.081803

SM Higgs vs alternative J^P states

- For the method see Jonas' talk
- ATLAS and CMS explored many alternative J^P states for 0, 1 and 2 spin options
- Example of results:





- Conclusion: **all tested alternatives are excluded at 99% CL or higher**
  - While data agree well with SM Higgs boson in each test

Spin 0: testing anomalous effects

- General Lagrangian describing on-shell spin-0 Higgs boson decay H→VV (V = W±, Z) is *[A. Djuadi and M. Grazzini in WS "Discovery of the Higgs boson"]*

$$\mathcal{L}_{HVV} \sim \kappa_V \frac{m_V^2}{v} HV^\mu V_\mu + \frac{\alpha_V}{v} HV^\mu \Delta V_\mu + \frac{\beta_V}{v} HV^{\mu\nu} V_{\mu\nu} + \frac{\gamma_V}{v} HV^{\mu\nu} V_{\mu\nu}$$

- SM Higgs boson 0^+
- Dim-3 operator
- $\kappa_Z = 1, \kappa_W = 2$

- Dim-5 operators
- α_V and β_V are even-parity scalars
- γ_V is pseudoscalar

- Since absolute cross sections were not used in analysis only relevant variables were ratios of couplings
  - Assuming identical valued for HZZ and HWW interactions

		α/κ	β/κ	γ/κ
CMS	observed	-	[-0.63,0.73]	[-0.83,2.18]
	expected	-	[-4.80,0.55]	[-2.30,2.33]
ATLAS	observed	[-1.66,1.57]	[-0.76,0.58]	[-1.57,1.54]
	expected	[-∞,1.57] ∪ [9.0,+∞]	[-1.67,0.45]	[-2.65,2.65]
Exp. SM loop contr.		< O(10^{-2})	< O(10^{-2})	< O(10^{-11})

[M. Duehrssen and G. Petrucciani in WS "Discovery of the Higgs boson"]

- Conclusions
  - **all anomalous effects are consistent with 0**
    - Which is SM prediction too
  - **CMS excluded pure pseudoscalar state at 99.98% CL**

Coupling strength measurements

- These measurements are done under the same assumptions as for the signal strength measurements *(see Lecture 7)*
- The production and decay through the process $i \rightarrow H \rightarrow f$ can factorised

$$\sigma_i \cdot B^f = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\Gamma_H}$$

$\vec{\kappa}$ - a set of modifers for Higgs boson couplings to SM boson and fermions

Introduced to parametrise possible deviation from the SM prediction to couplings

For a given production or decay mode, denoted "j":

$$\kappa_j^2 = \sigma_j / \sigma_j^{SM} \text{ or } \kappa_j^2 = \Gamma^j / \Gamma_{SM}^j$$

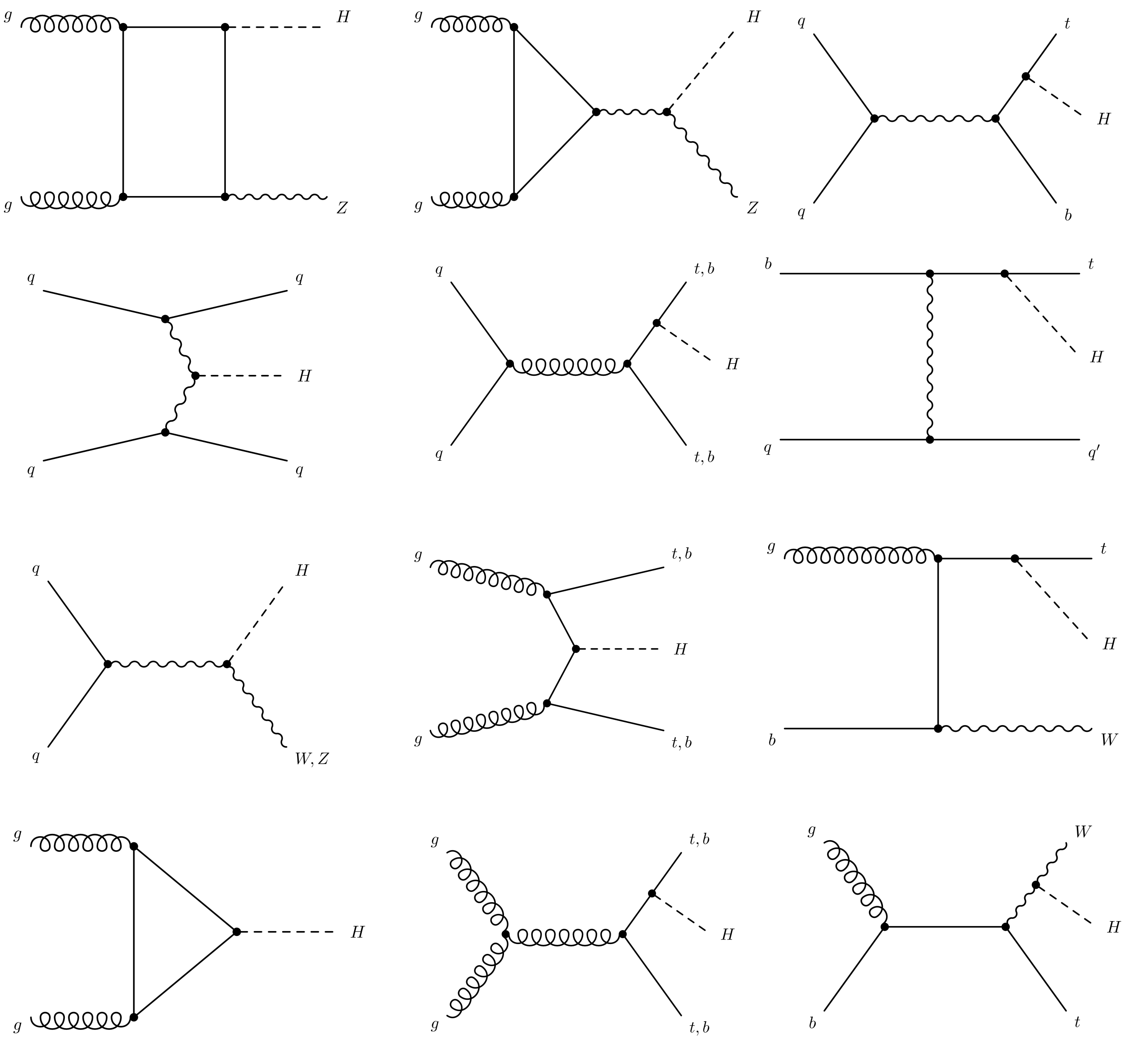
In SM all $\kappa_j = 1$

- References:

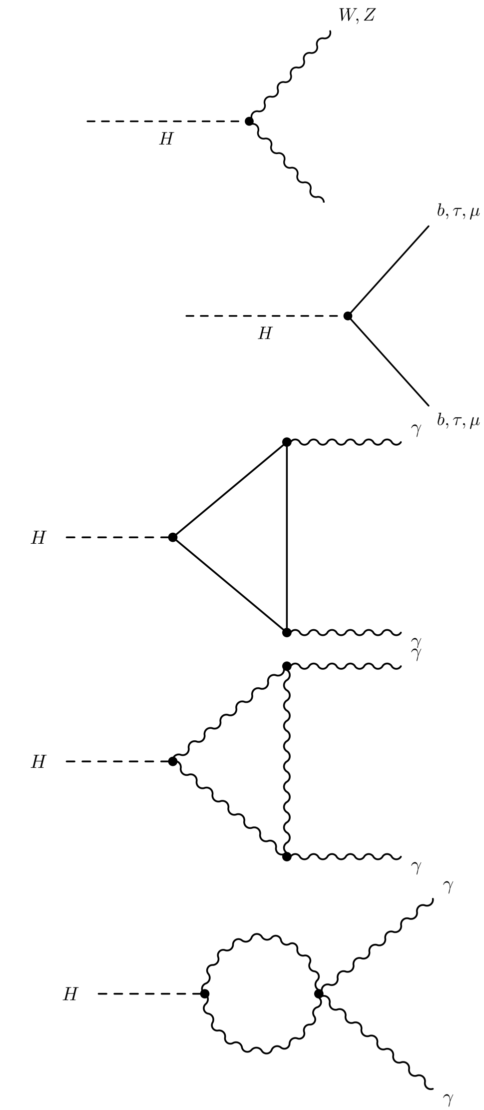
  - CMS Collaboration, *Precise determination of the mass of the Higgs boson and tests of compatibility of its couplings with the standard model predictions using proton collisions at 7 and 8 TeV*, Eur. Phys. J. C (2015) 75: 212, http://link.springer.com/article/10.1140%2Fepjc%2Fs10052-015-3351-7
  - ATLAS Collaboration, *Measurements of the Higgs boson production and decay rates and coupling strengths using pp collision data at $\sqrt{s}$ = 7 and 8 TeV in the ATLAS experiment*, Eur. Phys. J. C (216) 76:6, http://link.springer.com/article/10.1140/epjc/s10052-015-3769-y
  - ATLAS and CMS Collaborations, *Measurements of the Higgs boson production and decay rates and constraints on its couplings from a combined ATLAS and CMS analysis of the LHC pp collision data at $\sqrt{s}$ = 7 and 8 TeV*, JHEP 08 (2016) 045, http://link.springer.com/article/10.1007/JHEP08(2016)045
  - A. Djouadi and M. Grazzini, *The Higgs boson in the Standard Model*, in 'Discovery of the Higgs Boson', World Scientific 2016
  - M. Duehrssen and G. Petrucciani, *Higgs combination and properties of the Higgs boson*, in 'Discovery of the Higgs Boson', World Scientific 2016

Feynman diagrams

Production



Decay



Summary of coupling modifiers

Production	Loops	Interference	Effective scaling factor	Resolved scaling factor
$\sigma(ggF)$	✓	t–b	κ_g^2	$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t\kappa_b$
$\sigma(\mathrm{VBF})$	–	–		$0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	–	–		κ_W^2
$\sigma(qq/qg \to ZH)$	–	–		κ_Z^2
$\sigma(gg \to ZH)$	✓	t–Z		$2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z\kappa_t$
$\sigma(ttH)$	–	–		κ_t^2
$\sigma(gb \to tHW)$	–	t–W		$1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t\kappa_W$
$\sigma(qq/qb \to tHq)$	–	t–W		$3.40 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t\kappa_W$
$\sigma(bbH)$	–	–		κ_b^2
Partial decay width				
Γ^{ZZ}	–	–		κ_Z^2
Γ^{WW}	–	–		κ_W^2
$\Gamma^{\gamma\gamma}$	✓	t–W	κ_γ^2	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W\kappa_t$
$\Gamma^{\tau\tau}$	–	–		κ_τ^2
Γ^{bb}	–	–		κ_b^2
$\Gamma^{\mu\mu}$	–	–		κ_μ^2
Total width ($B_{\mathrm{BSM}} = 0$)				
Γ_H	✓	–	κ_H^2	$0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 +$ $0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 +$ $0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{(Z\gamma)}^2 +$ $0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$

- Since Γ_H is not experimentally constrained with sufficient precision only the **ratios of couplings** can be measured in the most generic parametrisation

- Individual modifiers are tree-level, except two loop-level
  - κ_g for ggF production
  - κ_γ for H→γγ production
- Interference effects provide some sensitivity to relative signs of modifiers
- Coefficients in "Resolved scaling factors" are derived from the best th. predictions
  - Up to NNLO QCD and NLO EW
- Changes in the values of couplings will results in a variation of the Γ_H
  - New modifier is defined

$$\kappa_H^2 = \sum_j B_{SM}^j \kappa_j^2$$

- In case deviation Γ_H becomes

$$\Gamma_H = \frac{\kappa_H^2 \cdot \Gamma_H^{SM}}{1 - B_{BSM}}$$

- B_{BSM} is total branching fraction into BSM decays, of three types
  - BSM decays invisible to the detectors
  - BSM decays producing topologies that are not searched for
  - Modification of SM decay branching fractions that are not directly measured, like H→cc

Coupling strengths: results

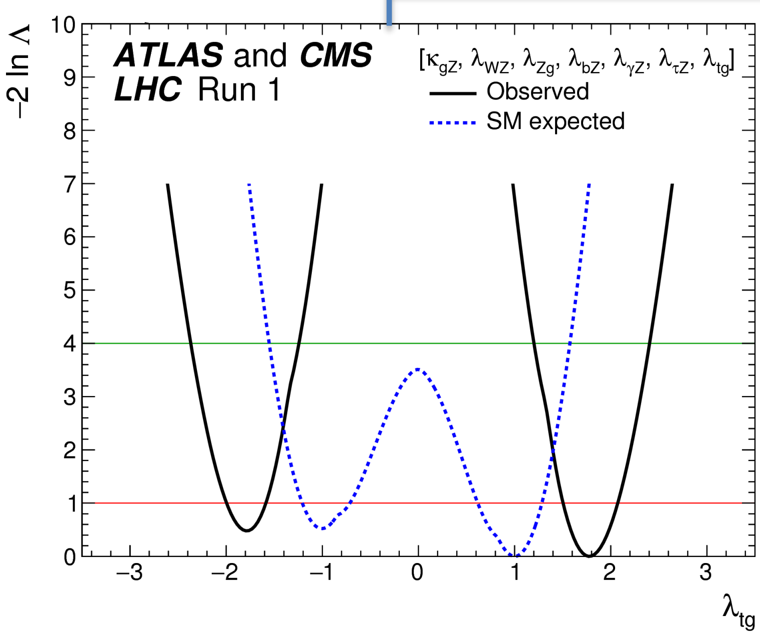
- Results of ATLAS and CMS combination are grouped according to the parametrisation used:

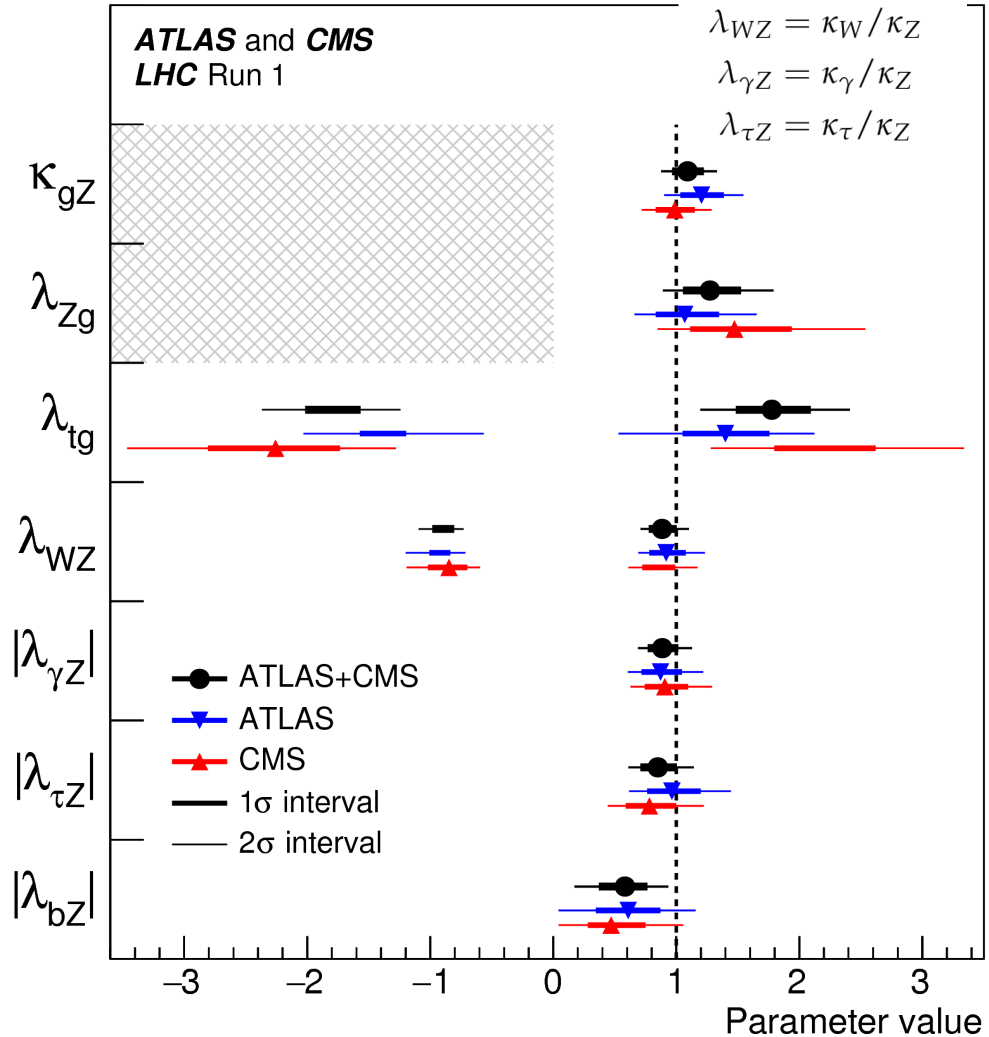
1. Coupling modifier ratios
2. Allowing contribution from BSM particle in loops and decays
3. Assuming SM structure of the loops and no BSM decays
4. Related to the fermion sector only
   - Probing up- and down-type fermion symmetry
   - Probing lepton and quark symmetry
5. Related to fermion and vector boson couplings

Parametrisation using coupling modifier ratios

- p-value of data and SM compatibility is 13%
- All results are consistent with the SM prediction within less than 2σ, except λ_{tg} and λ_{bZ}

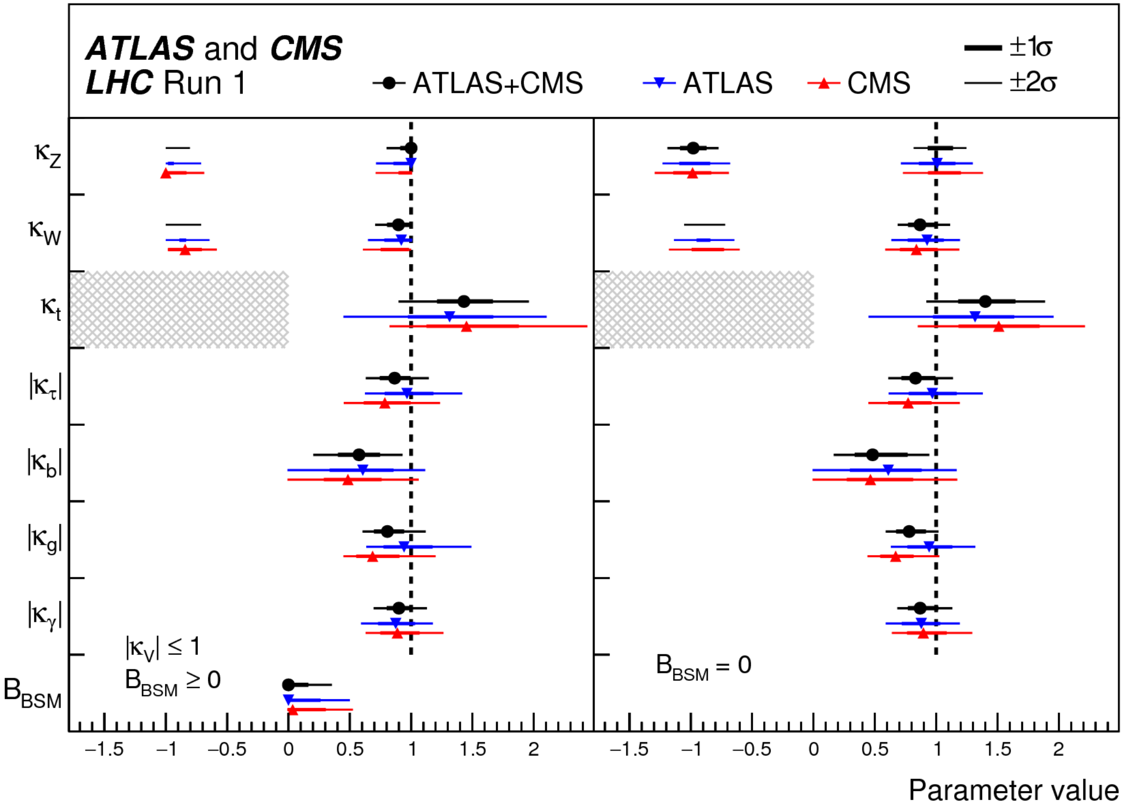
$$\kappa_{gZ} = \kappa_g \cdot \kappa_Z / \kappa_H$$
$$\lambda_{Zg} = \kappa_Z / \kappa_g$$
$$\lambda_{tg} = \kappa_t / \kappa_g$$
$$\lambda_{WZ} = \kappa_W / \kappa_Z$$
$$\lambda_{\gamma Z} = \kappa_\gamma / \kappa_Z$$
$$\lambda_{\tau Z} = \kappa_\tau / \kappa_Z$$





Parametrisation allowing BSM particles

- As already said (see first slide of this section): $\sigma_i \cdot B^f \sim 1/\Gamma_H$
  - Γ_H is sensitive to potential invisible or undetected decays predicted by BSM models
- Therefore, to directly measure individual κ_i we need an assumption about Γ_H
  - Two scenarios considered here:
    - 1) Leaving B_{BSM} free, with $B_{BSM} \geq 0, |\kappa_W| \leq 1, |\kappa_Z| \leq 1$
    - 2) Assuming $B_{BSM} = 0$



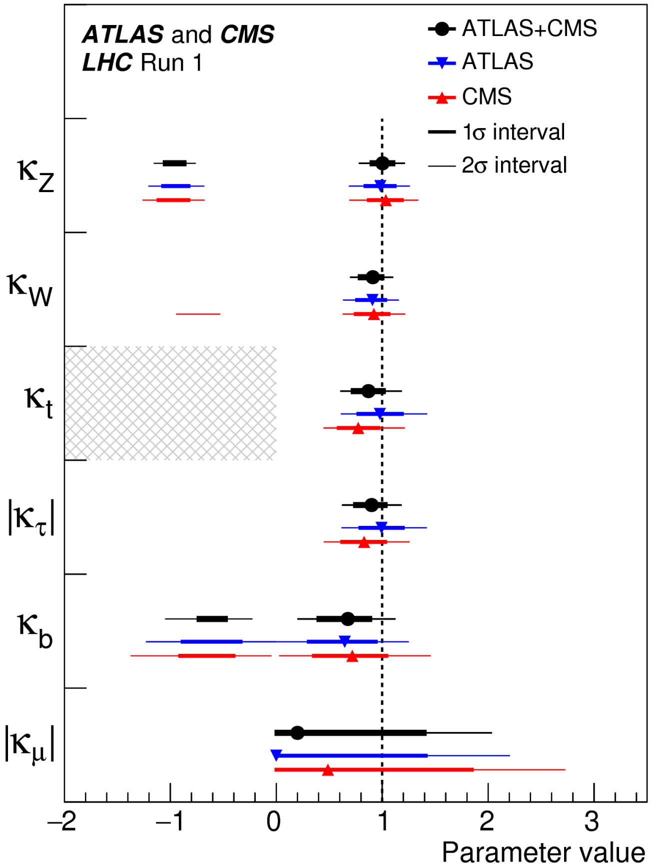
- Conclusions
  - Upper limit on $B_{BSM} = 0.34$ **@ 95% CL**
    - Expected 0.39
  - p-value of data vs SM in $B_{BSM} = 0$ scenario is 11%

Parametrisation without BSM particles

3

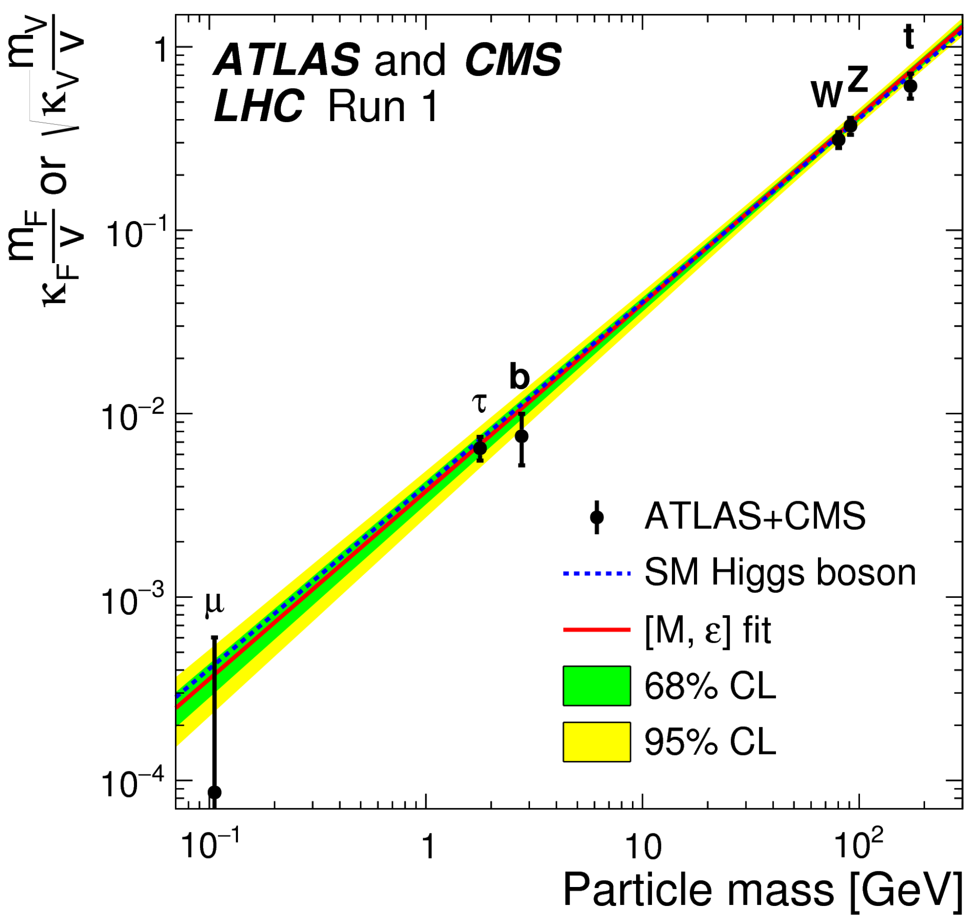
- Assumption: no new particles in the ggF or H→γγ loops
  - This is supported by measurements of κ_g and κ_γ, which are consistent with SM
- Results with the parametrisation given in the table on slide 19:

p-value of data vs SM: 74%



- Results with the parametrisation:

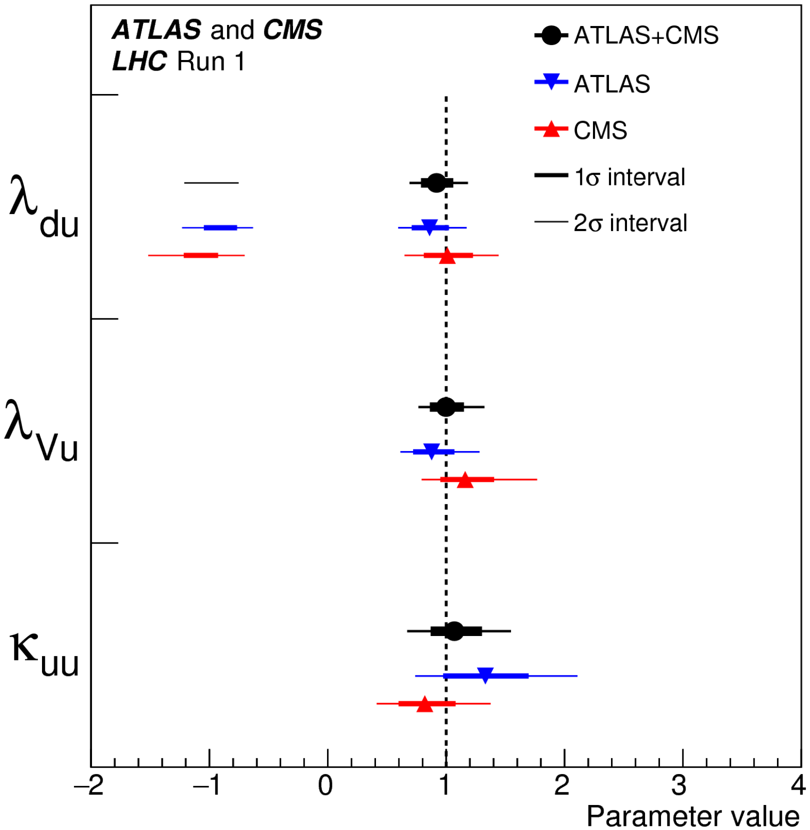
$$\kappa_{F,i} \cdot y_{F,i}/\sqrt{2} = \kappa_{F,i} \cdot m_{F,i}/v \qquad \sqrt{\kappa_{V,i} \cdot g_{V,i}/2v} = \sqrt{\kappa_{V,i}} \cdot m_{V,i}/v$$



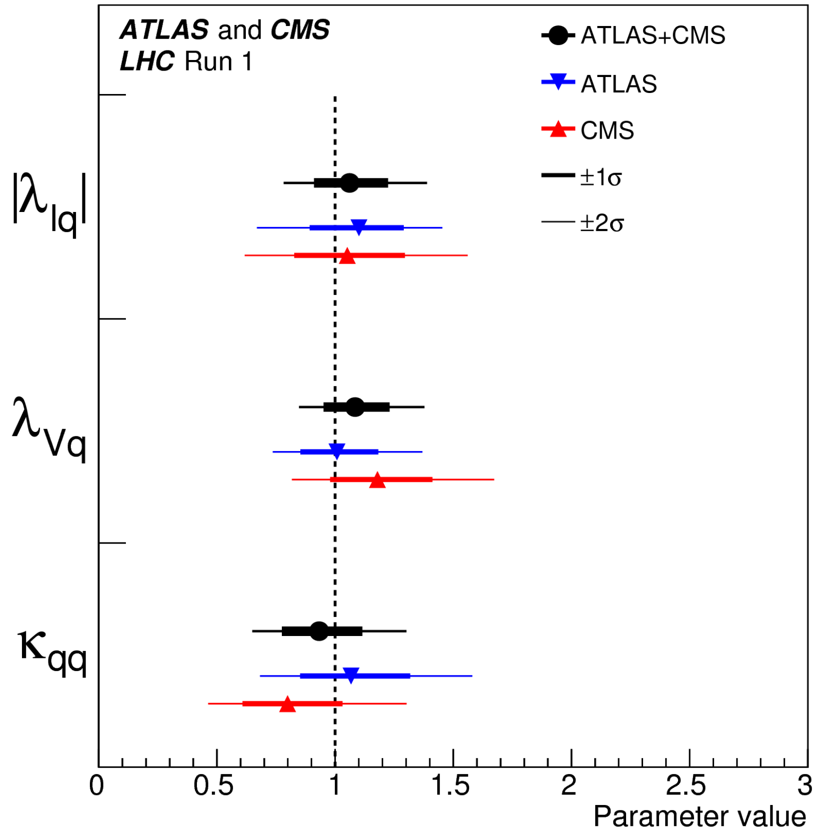
4 Probing fermion sector

- Common coupling modifiers for up-type fermions vs down-type fermions or for leptons vs quarks are predicted by many extensions of SM
  - For example the 2 Higgs Doublet Model (2HDM)

- Probing up- and down-type fermion symmetry
  p-value of data vs SM: 72%

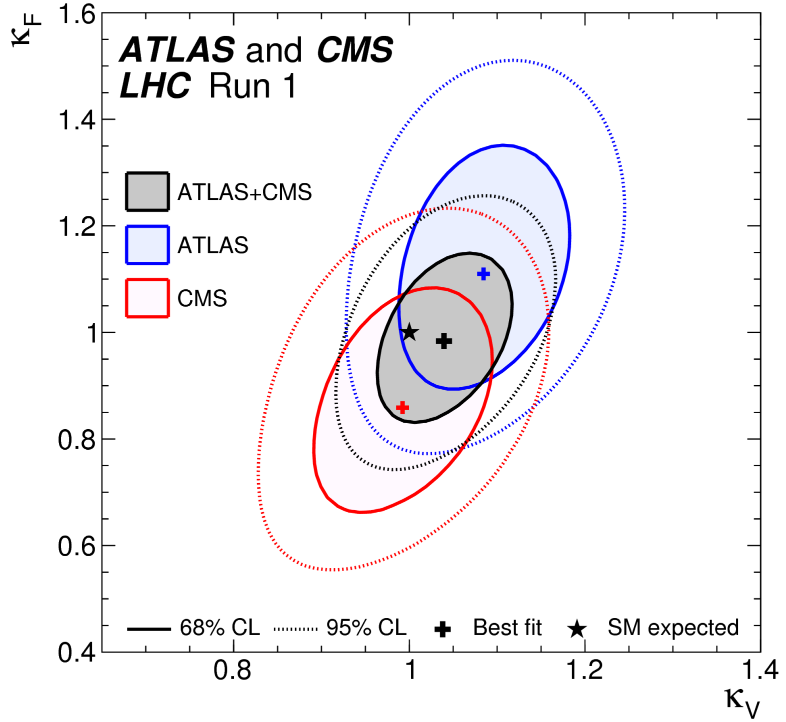


- Probing lepton and quark symmetry
  p-value of data vs SM: 79%

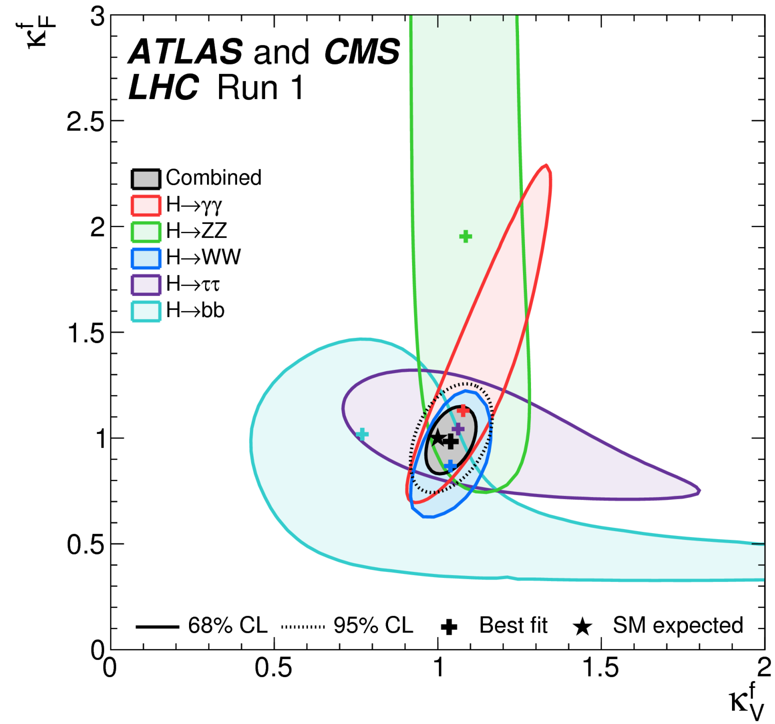


Fermion and vector boson couplings

- The most constrained parametrisation, motivated by
  - Couplings to weak vector bosons originate from EWSB
  - Couplings to fermions are due to Yukawa couplings



Negative log-likelihood contours at 68% and 95% CL in the (κ_F, κ_V) plane on an enlarged scale for the combination of ATLAS and CMS and for the global fit of all channels.

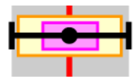


Negative log-likelihood contours at 68% CL in the (κ_F^f, κ_V^f) plane for the combination of ATLAS and CMS and for the individual decay channels as well as for their global combination (κ_F versus κ_V), assuming that all coupling modifiers are positive.

- Conclusion: all results in agreement with SM prediction $\kappa_F^f = 1, \kappa_V^f = 1$
  - p-value of data vs SM is 59%

Properties: summary

- **Mass m_H**

  ATLAS+CMS $\gamma\gamma+4l$  **125.09 ± 0.24 (± 0.21 ± 0.11) GeV**

- **Total width Γ_H - consistent with SM expectation**
  - Direct 95% CL upper limits: 1.7 GeV (CMS, H→4l and γγ), 2.6 (ATLAS, H→γγ)
  - Indirect 95% CL upper limits: 13 MeV (CMS), 22.7 MeV ATLAS
- **Signal strength μ - consistent with SM expectations**
  - With the precision of about 20%
  - Some excess in ttH production – follow in Run 2
- **Total fiducial cross section $\sigma_{fid.}$ - consistent with SM expectations**
  - Total cross section also estimated, but with limited precision
- **Differential cross sections $d\sigma_{fid}/dx$ - consistent with SM expectations**
  - Although with limited precision – improve in Run 2
- **Spin-parity quantum numbers J^P - consistent with SM expectations of 0^+**
  - Exclude all tested spin 1 and 2 hypotheses, as well as pure CP-odd Higgs boson
  - Limits provided on non-SM CP-even and CP-add admixtures in H→VV decays
- **Couplings λ_i, κ_i - consistent with SM expectations**
  - Best measurements reach precision of about 15%
  - Some excess in quantities related to the top-quark couplings – follow in Run 2