Higgs to four leptons

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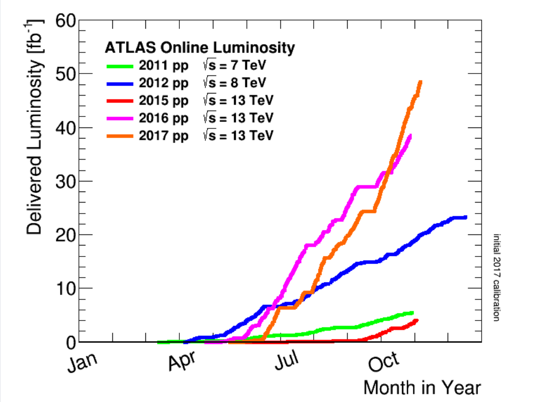
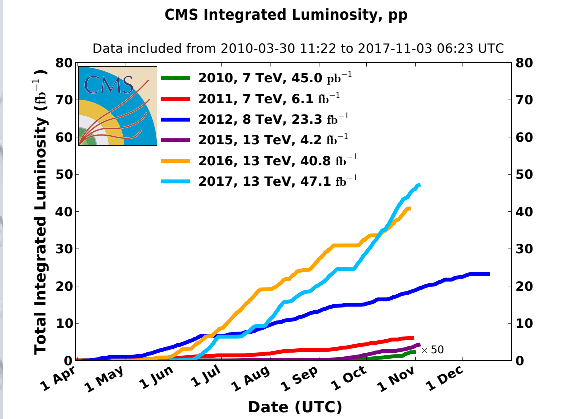
Performance of the LHC





- The LHC has been working remarkably well
- Both experiments are now on course to exceed the data collected in 2016

Outline

Presentation of results mainly with the 2015+16 dataset, including:

- Cross-section measurements
- Mass measurement
- Anomalous couplings
- High mass search

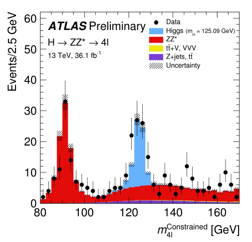
Introduction: $H \to ZZ^* \to 4\ell$: the golden channel

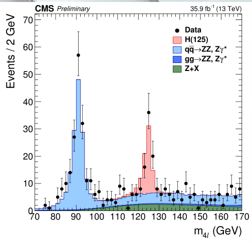
Many useful features:

- Large signal to background ratio ($\sim 2/1$)
- Excellent mass resolution ($\sim 1-2\%$)
- The nearby Z-peak is a good "candle" for the validity of the results
- Main draw-back is the small branching ratio ($\sim 0.02\%$) $\to$ limited statistics

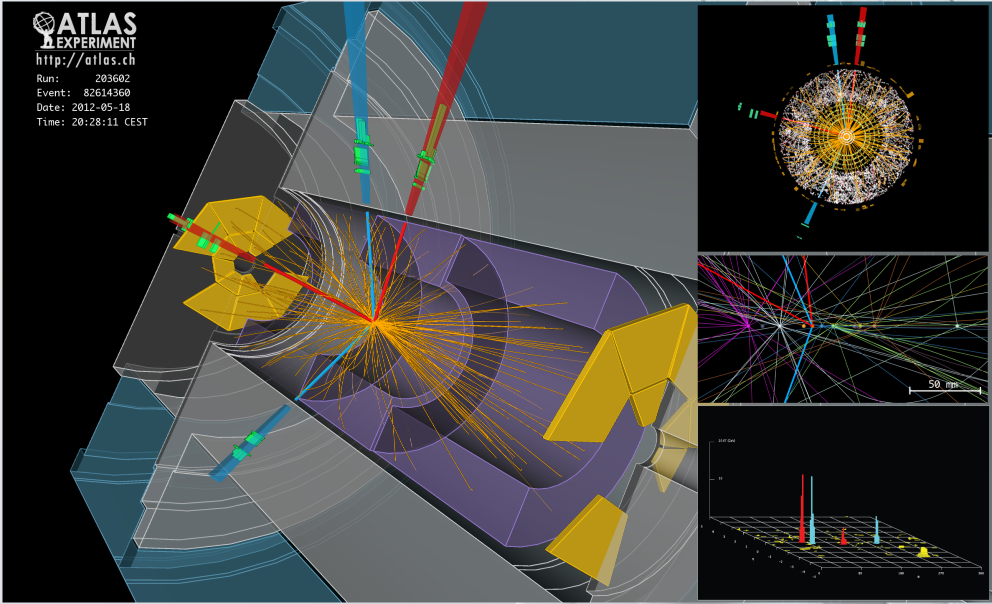
Analysis strategy:

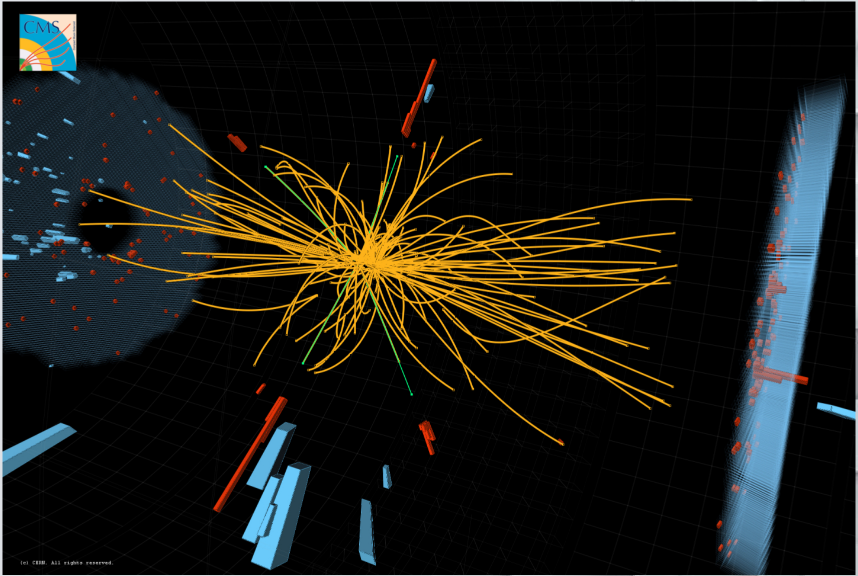
- ATLAS uses invariant mass of the four-lepton system ($m_{4\ell}$) as your observable
- CMS analysis uses a 2D fit ($m_{4\ell}$ vs. kinematic discriminant)





- Non-resonant background coming from ZZ (reduced via MVA)
- Leptons from the Z* are low p_T $\to$ more prone to background contamination
- Fake background estimated in Control regions


ATLAS
EXPERIMENT
http://atlas.ch
Run: 203602
Event: 82614360
Date: 2012-05-18
Time: 20:28:11 CEST
50 mm


CMS
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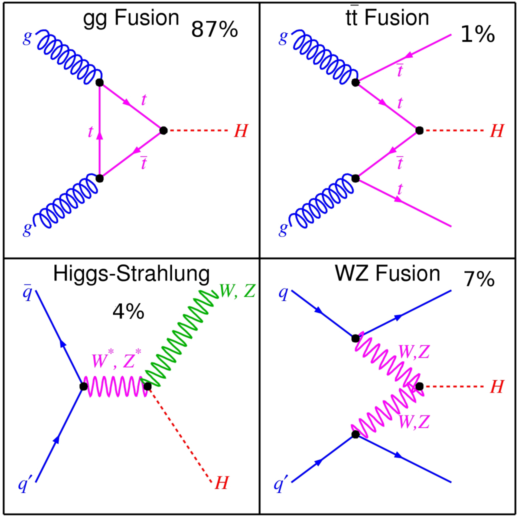
Introduction: Higgs Production Mechanisms (arXiv:1610.07922v2)

	ggF	VBF	WH	ZH	bbH	ttH
8 TeV	21.4	1.60	0.70	0.42	0.20	0.13
13 TeV	48.6	3.78	1.37	0.88	0.49	0.51
ratio	2.3	2.4	2.0	2.1	2.5	3.9

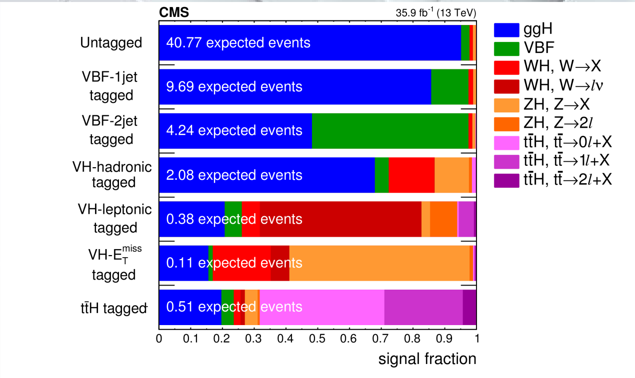
- Largely dominated by gluon-gluon fusion
- Vector boson fusion is distinguished by the presence of widely separated jets in the event, but statistics are very limited
- Rest of production mechanisms have an expectation below one event
- Jet topology is used to discriminate events into different categories



Event Selection

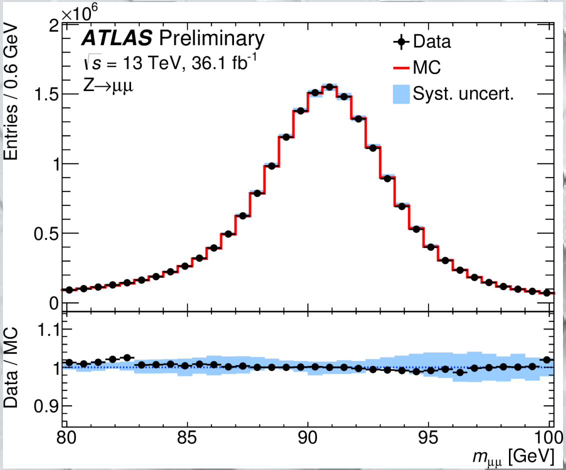
- Events with four well-isolated leptons fulfilling quality cuts, with the leading lepton $p_T > 20$ GeV
- One of the same-flavour pairs has to be within the Z boson mass range
- Z-mass constraint on the leading lepton pair
- Precise measurement of electron and muon momentum leptons is key
- Categorize events depending on the leptonic composition

- Further categorize events to exploit kinematic discriminants (using both decay and production informations) and jet multiplicity:



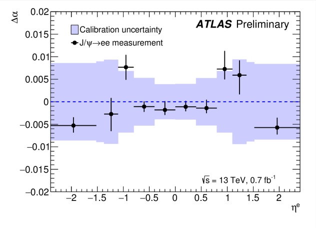
Muon calibrations

- Track reconstructed combining information from Inner Detector (Silicon Tracker for CMS) and muon chamber hits
- Correct Momentum resolution and scale in simulation to account for differences with data:
  - Misalignements in the detector
  - Simulation of the traversed material
  - Magnetic field
- Very precise knowledge of the muon momentum resolution and scale in the Higgs mass range
- Approximately 2% (1%) muon momentum resolution for ATLAS (CMS)

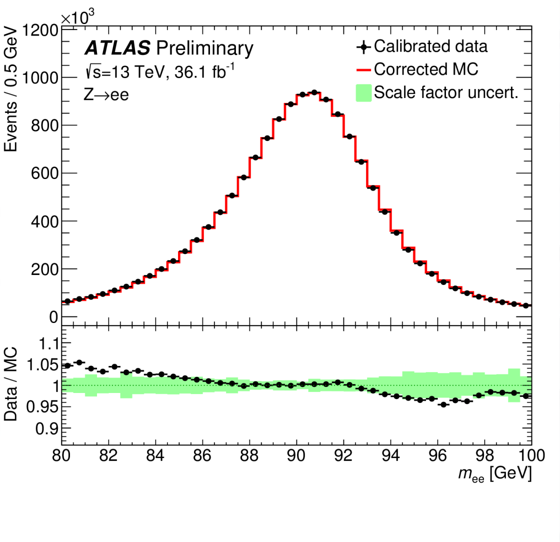


Electron corrections

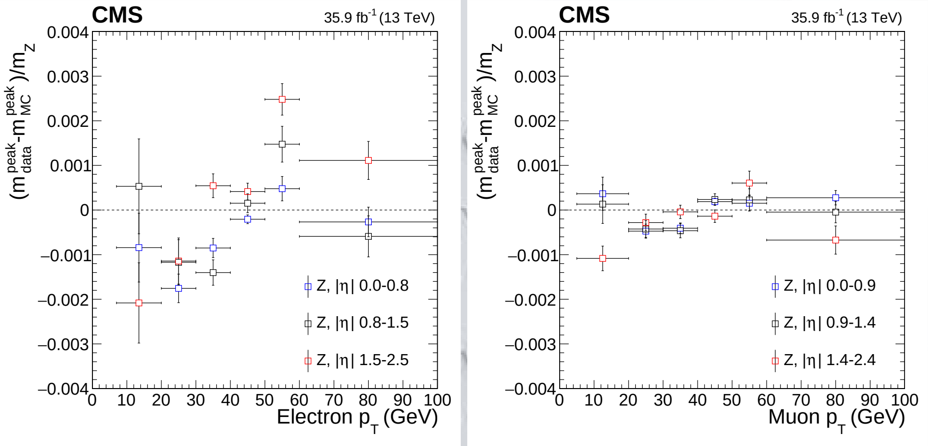
- ATLAS corrects the response at reco cluster in the simulation with an MVA and corrections from $Z/J/\psi$ analysis
- Correct simulation for energy loss in inactive materials



- CMS corrects electrons in bins of lepton η and p_T using tag-and-probe



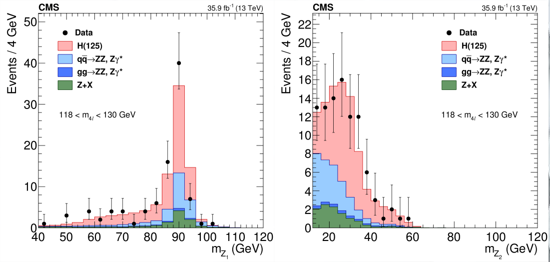
Electron/Muon Lepton Momentum Scale



Electron and muon scales are measured better than 0.2% and 0.05% respectively in CMS

Measurement of the Higgs boson mass[1]

- Combination of the results from the 4ℓ and $\gamma\gamma$ final states (ATLAS)
- The Powheg-Box v2 MC event generator is used for ggF and VBF production signal simulation
- Cross-section times branching ratio are profiled
- The continuum ZZ^* background is simulated using Sherpa 2.2 (ATLAS) and Powheg (CMS)
- Contribution from fake background estimated from data

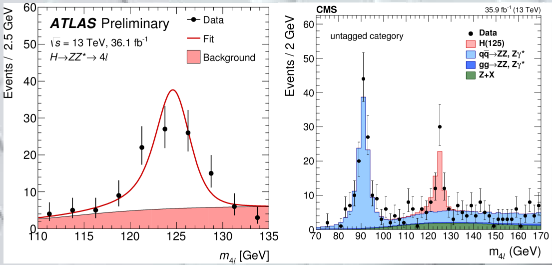


- Expect m_{Z_1} distribution to be centered around the Z-boson mas
- While m_{Z_2} should peak around 35 GeV

[1]ATLAS-CONF-2017-046 & arXiv:1706.09936

Higgs boson mass: Event selection

- Select events with four leptons and categorize them according to the lepton composition (4μ, $4e$, $2\mu 2e$ and $2e2\mu$,)
- Use events only in the range $110 < m_{4\ell} < 135$ GeV (ATLAS) & $118 < m_{4\ell} < 130$ GeV (CMS)
- A kinematic fit is performed to constraint the invariant mass of the leading lepton pair to the Z pole mass
- Find generally good agreement within uncertainties from an SM Higgs with a mass of 125 GeV



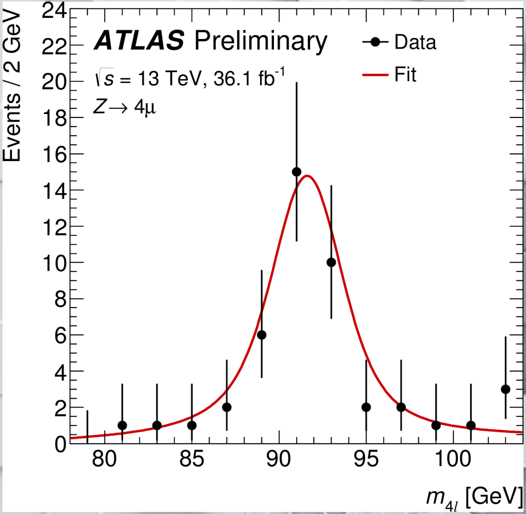
- ATLAS Yields $110 < m_{4\ell} < 135$ GeV:

Final state	Signal (125 GeV)	ZZ^*	$Z+$jets, $t\bar{t}$, WZ, ttV,VVV	Expected	Observed
4μ	20.6 ± 1.7	15.9 ± 1.2	2.0 ± 0.4	38.5 ± 2.1	38
$2e2\mu$	14.6 ± 1.1	11.2 ± 0.8	1.6 ± 0.4	27.5 ± 1.4	34
$2\mu 2e$	11.2 ± 1.0	7.4 ± 0.7	2.2 ± 0.4	20.8 ± 1.3	26
$4e$	11.1 ± 1.1	7.1 ± 0.7	2.1 ± 0.4	20.3 ± 1.3	24
Total	57 ± 5	41.6 ± 3.2	8.0 ± 1.0	107 ± 6	122

Higgs boson mass: per-event method (ATLAS)

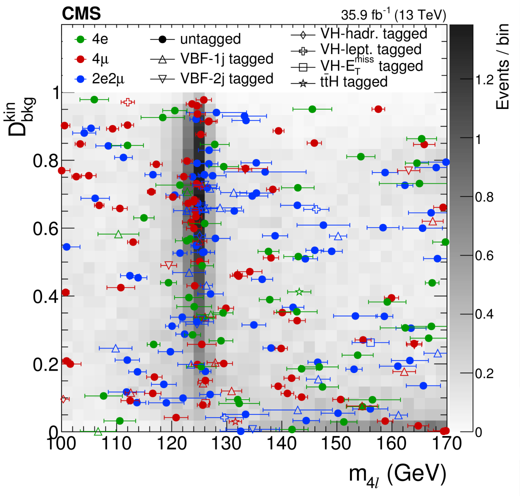
- $m_{4\ell}$ signal distribution modelled as the convolution of the intrinsic Higgs boson lineshape and a four lepton invariant mass response function
- The response function gives the probability of measuring a value $m_{4\ell}^{meas}$ for a truth mass $m_{4\ell}^{true}$
- Validate the method by testing it with the Z boson

Category	m_Z in simulation [GeV]	m_Z in data [GeV]
4μ	$91.19^{+0.41}_{-0.41}$	$91.46^{+0.42}_{-0.41}$
$4e$	$91.19^{+1.02}_{-1.03}$	$91.75^{+1.08}_{-1.06}$
$2\mu 2e$	$91.18^{+1.11}_{-1.11}$	$91.31^{+1.62}_{-1.33}$
$2e2\mu$	$91.19^{+0.90}_{-0.90}$	$92.49^{+0.91}_{-0.94}$
Combined	$91.19^{+0.34}_{-0.34}$	$91.62^{+0.35}_{-0.35}$



Higgs boson mass: per-event method & kinematic discriminant (CMS)

- Uncertainty in the momentum measurement obtained for each lepton
- The full covariance matrix is obtained from the muon track fit (the directional uncertainties neglected)
- Electron momentum uncertainty is estimated from the combination of the ECAL and tracker measurements
- Uncertainty then propagated to the four-lepton candidate mass
- To obtain the result a 3D fit is used ($m_{4\ell}$, Kinematic Discriminant and the per-event mass uncertainty)

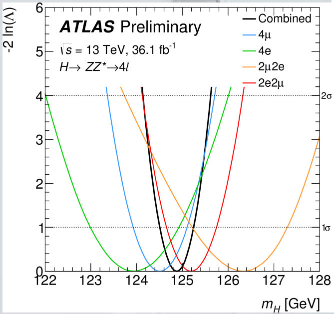


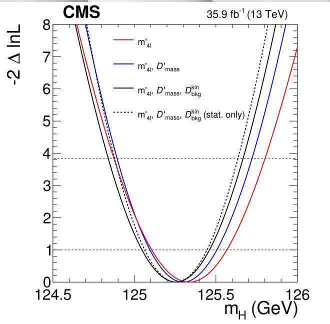
Higgs boson mass: Results

Systematic effect	Uncertainty on $m_H^{ZZ^*}$ [MeV]
Muon momentum scale	40
Electron energy scale	20
Background modelling	10
Simulation statistics	8

- The expected systematic uncertainties are small compared to the statistical uncertainty
- The addition of $D_{\text{bkg}}^{\text{kin}}$ in the CMS measurement improves precision by 11%

No $m(Z_1)$ constraint	3D: $\mathcal{L}(m_{4\ell}, \mathcal{D}_{\text{mass}}, \mathcal{D}_{\text{bkg}}^{\text{kin}})$	2D: $\mathcal{L}(m_{4\ell}, \mathcal{D}_{\text{mass}})$	1D: $\mathcal{L}(m_{4\ell})$
Expected m_H uncertainty change	+8.1%	+11%	+21%
Observed m_H (GeV)	125.28±0.22	125.36±0.24	125.39±0.25
With $m(Z_1)$ constraint	3D: $\mathcal{L}(m'_{4\ell}, \mathcal{D}'_{\text{mass}}, \mathcal{D}_{\text{bkg}}^{\text{kin}})$	2D: $\mathcal{L}(m'_{4\ell}, \mathcal{D}'_{\text{mass}})$	1D: $\mathcal{L}(m'_{4\ell})$
Expected m_H uncertainty change	—	+3.2%	+11%
Observed m_H (GeV)	125.26±0.21	125.30±0.21	125.34±0.23



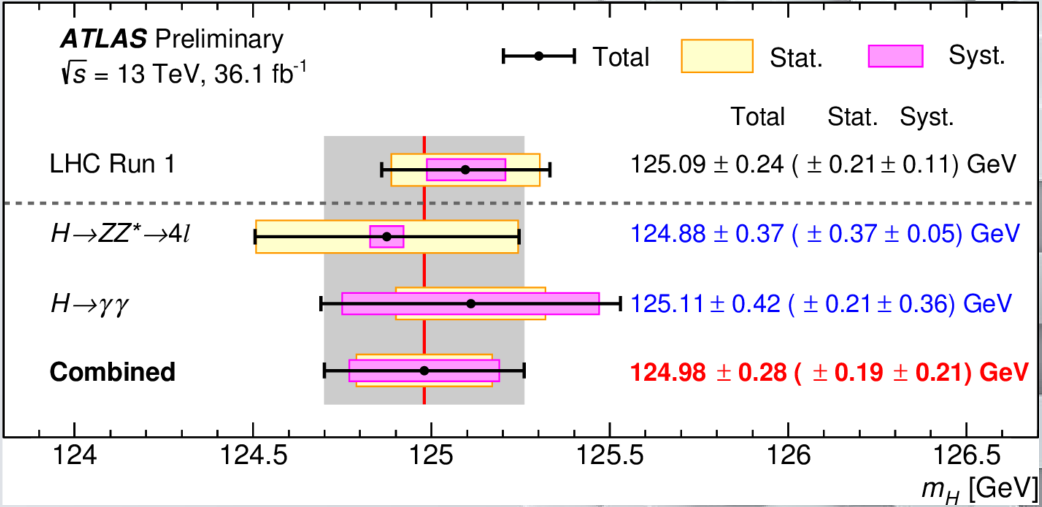


ATLAS: $m_H^{ZZ^*} = 124.88 \pm 0.37 \pm 0.05$ GeV

CMS: $m_H^{ZZ^*} = 125.26 \pm 0.20 \pm 0.08$ GeV

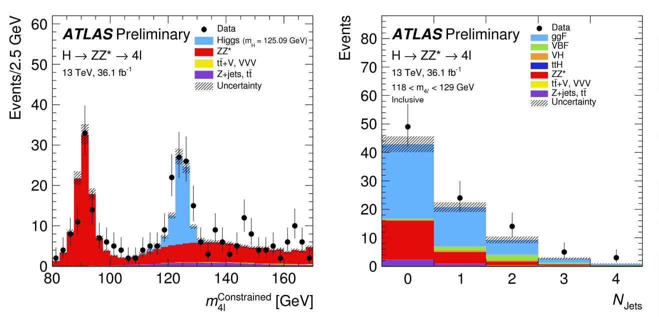
- Good agreement between the results of the two experiments (CMS has better resolution)

Higgs boson mass: ATLAS Summary



Measurement of the Higgs boson coupling properties[2]

- Aim to study the Higgs boson couplings to Standard Model Particles
- Cross sections measured for different production modes in several regions of phase space to test SM compatibility
- Probe of admixtures of CP-even and CP-odd interactions in BSM theories

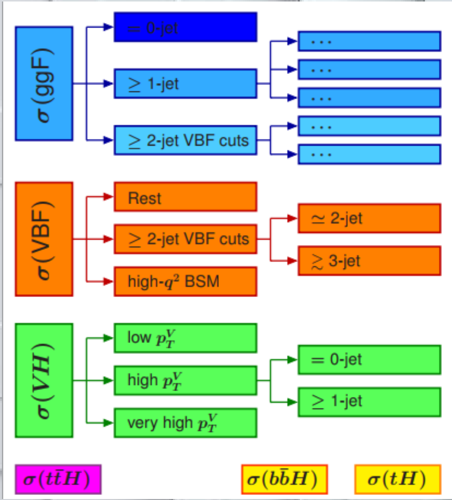


- Look at the $m_{4\ell}$ spectrum in the 118-129 GeV range

[2] ATLAS-CONF-2017-043 & arXiv:1706.09936

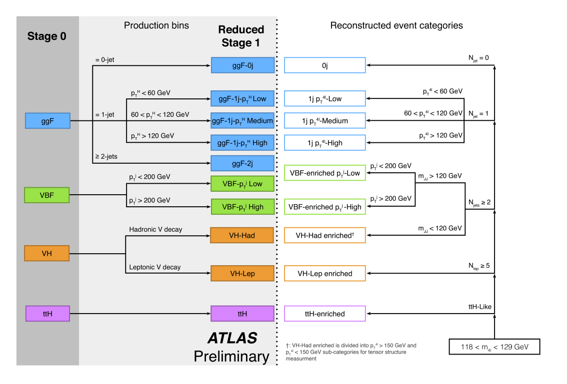
Higgs boson couplings: Simplified template xsec[3]

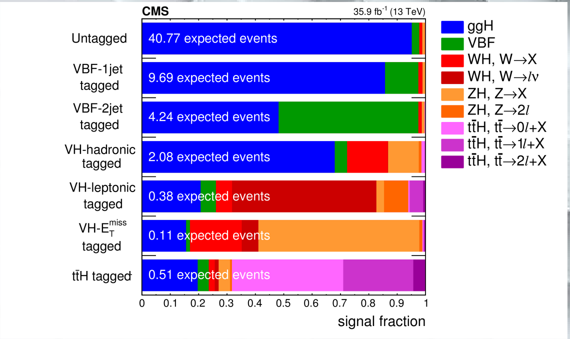
- Aim to maximise the sensitivity of measurements and reduce its dependence on theoretical calculations
- All decay channels are combined
- Cross-sections are measured directly instead of signal strengths
- Results obtained for a given production mode
- No need to normalise to a theory xsec which can change over time



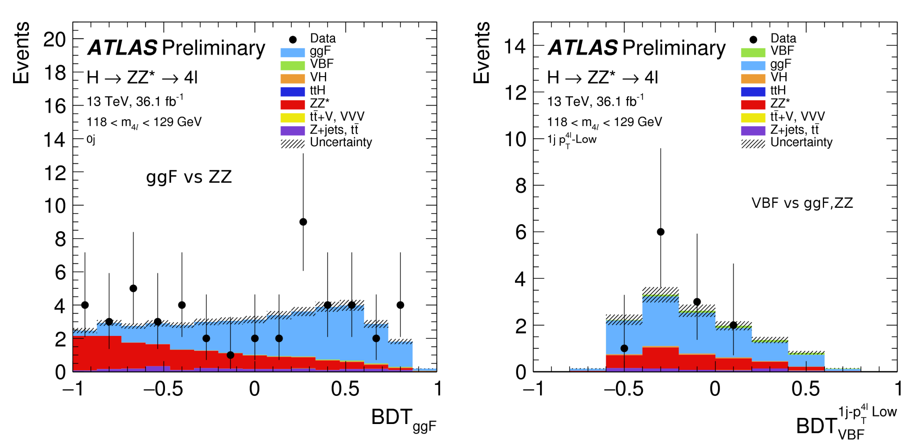
[3] https://arxiv.org/abs/1610.07922

Higgs boson couplings: phase space regions



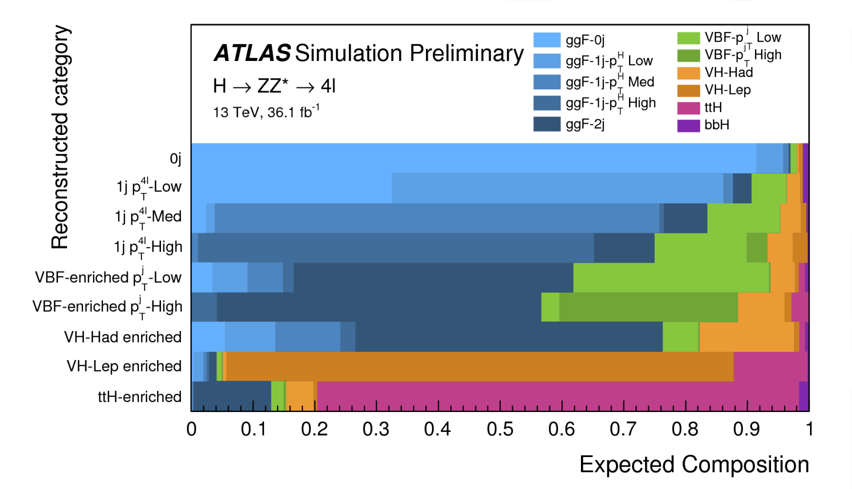


Higgs boson couplings: signal-background discriminants (ATLAS)



- BDT discriminants introduced to discriminate between signal ggF and ZZ^* background and ggF and VBF where statistics allow

Higgs boson couplings: phase space composition (ATLAS)

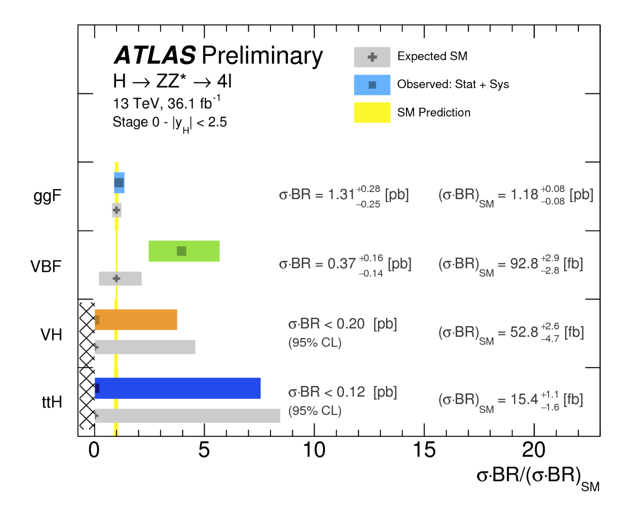


Higgs boson couplings: ATLAS STXS Stage-0 Results

- Uncertainties on Stage-0 production cross-sections:

Production bin	Experimental uncertainties [%]					Theory uncertainties [%]			
	Lumi	e, μ, pileup	Jets, flavour tagging	Higgs mass	Reducible backgr.	ZZ backgr.	Signal theory PDF	Signal theory QCD scale	Signal theory Shower
Inclusive cross section									
	4	3	1	1	1	2	< 1	1	1
Stage-0 production bin cross sections									
ggF	4	3	1	1	1	2	< 1	2	1
VBF	3	3	10	1	< 1	2	2	11	5
VH	3	3	11	2	2	6	2	12	4
ttH	4	3	19	< 1	2	2	3	8	2

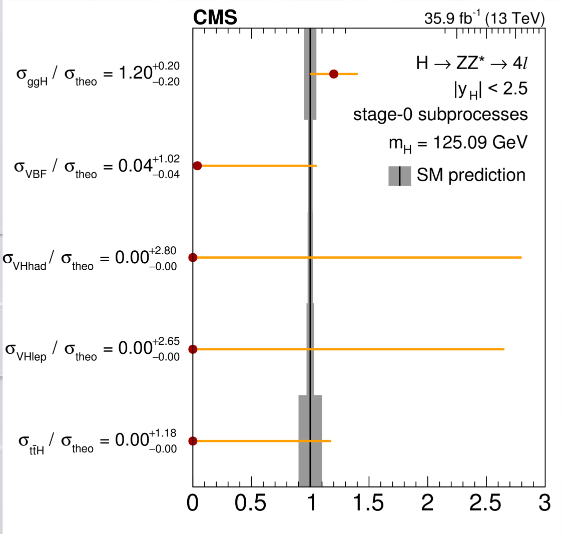
- Signal theory uncertainty includes only acceptance effects and no uncertainty on predicted cross sections



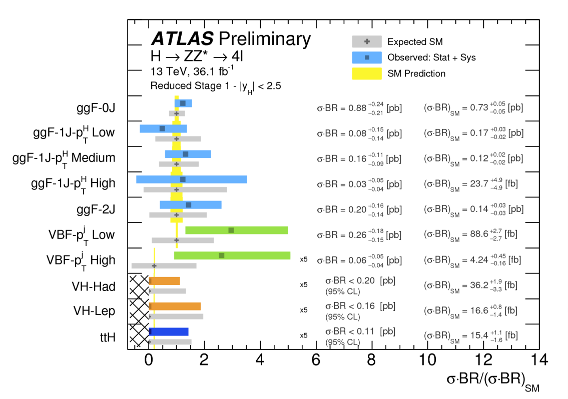
Higgs boson couplings: CMS STXS Stage-0 Results

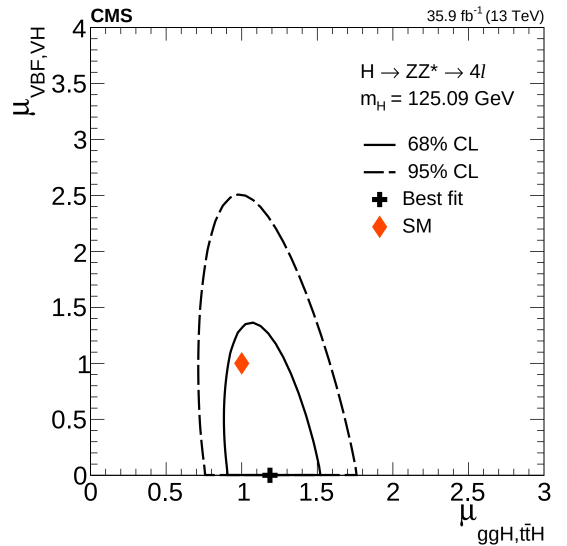
	Event category							
	Untagged	VBF-1j	VBF-2j	VH-hadr.	VH-lept.	VH-E_T^{miss}	$t\bar{t}H$	Inclusive
$q\bar{q} \to ZZ$	19.18	2.00	0.25	0.30	0.27	0.01	0.01	22.01
$gg \to ZZ$	1.67	0.31	0.05	0.02	0.04	0.01	<0.0	2.09
Z+X	10.79	0.88	0.78	0.31	0.17	0.30	0.27	13.52
Sum of backgrounds	31.64	3.18	1.08	0.63	0.49	0.32	0.28	37.62
$gg \to H$	38.78	8.31	2.04	1.41	0.08	0.02	0.10	50.74
VBF	1.08	1.14	2.09	0.09	0.02	<0.01	0.02	4.44
WH	0.43	0.14	0.05	0.30	0.21	0.03	0.02	1.18
ZH	0.41	0.11	0.04	0.24	0.04	0.07	0.02	0.93
$t\bar{t}H$	0.08	<0.01	0.02	0.03	0.02	<0.01	0.35	0.50
Signal	40.77	9.69	4.24	2.08	0.38	0.11	0.51	57.79
Total expected	72.41	12.88	5.32	2.71	0.86	0.43	0.79	95.41
Observed	73	13	4	2	1	1	0	94

- Dominant theoretical uncertainty is the category migration for ggF
- Cross-section is measured in a fiducial volume of $\mathcal{Y}_H < 2.5$
- Analysis has negligible acceptance outside this volume
- Kinematic discriminant used in mass measurement also used for the STXS (slide 15)



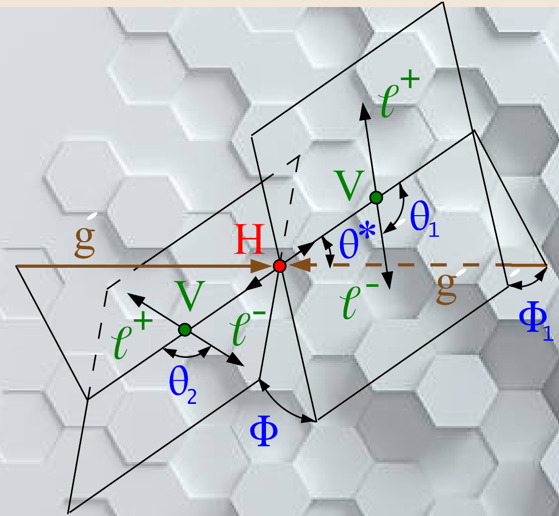
Higgs boson couplings: ATLAS STXS Stage-1 & CMS 2-D Fit





Constraints on anomalous Higgs boson couplings[4]

- Still room for anomalous interactions of the Higgs boson
- Studying the kinematics of leptons from H$\rightarrow ZZ$ allows for such measurements
- Anomalous interactions under spin-1 and 2 hypothesis already ruled out already by Run-1 data
- Constraints were set on anomalous couplings
- Run-2 data allows for more precise test of spin-0 hypothesis



[4] arXiv:1707.00541 & ATLAS-CONF-2017-043

Summary of the three production categories in the analysis:

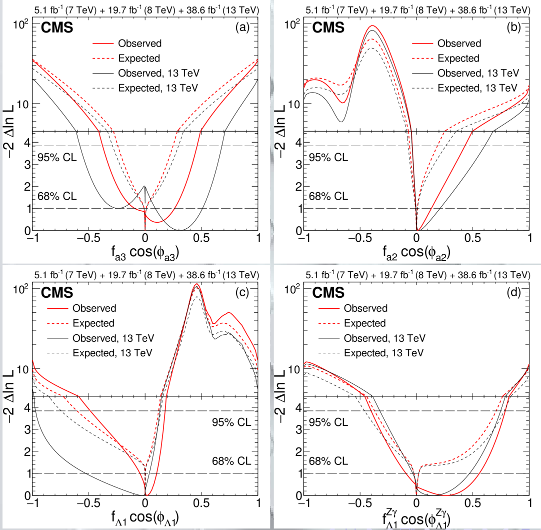
Category	VBF-jet	VH-jet	Untagged
Target	$qq'VV \to qq'H \to (jj)(4\ell)$	$q\bar{q} \to VH \to (jj)(4\ell)$	$H \to 4\ell$
Selection	$\mathcal{D}_{2jet}^{VBF}$ or $\mathcal{D}_{2jet}^{VBF,BSM} > 0.5$	$\mathcal{D}_{2jet}^{ZH}$ or $\mathcal{D}_{2jet}^{ZH,BSM}$ or $\mathcal{D}_{2jet}^{WH}$ or $\mathcal{D}_{2jet}^{WH,BSM} > 0.5$	not VBF-jet not VH-jet
f_{a3} obs.	$\mathcal{D}_{bkg}, \mathcal{D}_{0-}^{VBF+dec}, \mathcal{D}_{CP}^{VBF}$	$\mathcal{D}_{bkg}, \mathcal{D}_{0-}^{VH+dec}, \mathcal{D}_{CP}^{VH}$	$\mathcal{D}_{bkg}, \mathcal{D}_{0-}^{dec}, \mathcal{D}_{CP}^{dec}$
f_{a2} obs.	$\mathcal{D}_{bkg}, \mathcal{D}_{0h+}^{VBF+dec}, \mathcal{D}_{int}^{VBF}$	$\mathcal{D}_{bkg}, \mathcal{D}_{0h+}^{VH+dec}, \mathcal{D}_{int}^{VH}$	$\mathcal{D}_{bkg}, \mathcal{D}_{0h+}^{dec}, \mathcal{D}_{int}^{dec}$
$f_{\Lambda1}$ obs.	$\mathcal{D}_{bkg}, \mathcal{D}_{\Lambda1}^{VBF+dec}, \mathcal{D}_{0h+}^{VBF+dec}$	$\mathcal{D}_{bkg}, \mathcal{D}_{\Lambda1}^{VH+dec}, \mathcal{D}_{0h+}^{VH+dec}$	$\mathcal{D}_{bkg}, \mathcal{D}_{\Lambda1}^{dec}, \mathcal{D}_{0h+}^{dec}$
$f_{\Lambda1}^{Z\gamma}$ obs.	$\mathcal{D}_{bkg}, \mathcal{D}_{\Lambda1}^{Z\gamma,VBF+dec}, \mathcal{D}_{0h+}^{VBF+dec}$	$\mathcal{D}_{bkg}, \mathcal{D}_{\Lambda1}^{Z\gamma,VH+dec}, \mathcal{D}_{0h+}^{VH+dec}$	$\mathcal{D}_{bkg}, \mathcal{D}_{\Lambda1}^{Z\gamma,dec}, \mathcal{D}_{0h+}^{dec}$

- Full kinematic information from each event is extracted using the matrix element calculations in the MELA package
- $\mathcal{D}_{alt}$ is a discriminant containing all information to separate SM hypothesis from alternate hypothesis
- f_{a_2} & f_{a_3} is a CP-violation parameter
- A value $0 < f_{a_3} < 1$ would indicate CP violation, with a possible mixture of scalar and pseudoscalar states

Constraints on anomalous Higgs boson couplings: CMS results

- Improve on the full Run-1 datasets by nearly an order of magnitude
- All parameters consistent with zero within uncertainties

Parameter	Observed	Expected
$f_{a3}\cos(\phi_{a3})$	$0.00^{+0.26}_{-0.09}$ $[-0.38, 0.46]$	$0.000^{+0.010}_{-0.010}$ $[-0.25, 0.25]$
$f_{a2}\cos(\phi_{a2})$	$0.01^{+0.12}_{-0.02}$ $[-0.04, 0.43]$	$0.000^{+0.009}_{-0.008}$ $[-0.06, 0.19]$
$f_{\Lambda1}\cos(\phi_{\Lambda1})$	$0.02^{+0.08}_{-0.06}$ $[-0.49, 0.18]$	$0.000^{+0.003}_{-0.002}$ $[-0.60, 0.12]$
$f^{Z\gamma}_{\Lambda1}\cos(\phi^{Z\gamma}_{\Lambda1})$	$0.26^{+0.30}_{-0.35}$ $[-0.40, 0.79]$	$0.000^{+0.019}_{-0.022}$ $[-0.37, 0.71]$



High mass analysis (ATLAS)[5]: overview

- Select events with four leptons (results combined with $\ell\ell\nu\nu$)
- Invariant mass is used as a discriminant
- Event categorisation:
  - gluon-gluon fusion, further sub-divided in:
    - 4μ
    - $4e$
    - $2\mu 2e$
  - Vector boson fusion, by requiring:
    - two or more jets with $p_T > 30$ GeV
    - $\Delta\eta > 3.3$
    - $m_{jj} > 400$ GeV
  - Very few events expected for VBF
  - Large continuos background $qq \rightarrow ZZ$

[5] ATLAS-CONF-2017-058

High mass analysis: BSM Higgs & Signal Modelling (ATLAS)

Two Higgs Doublet models (2HDM) Models:

- Introduces four Higgs masses, tan β (ratio of vev) and mixing between the two neutral CP states h (SM Higgs) and H
- Four different model types

Type I : one doublet couples to bosons only, the other to fermions

Type II : one doublet couples to up-like quarks, the other to down-like

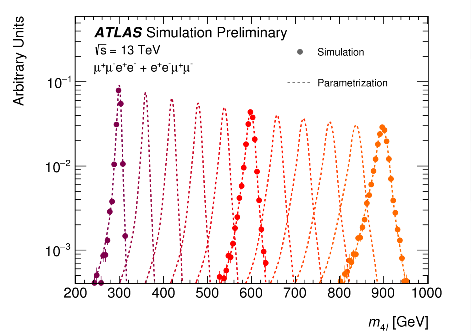
Type III : same couplings to leptons as in type I and to leptons as in type II

Type IV : reverse couplings from type III

- Focus on Type I and II models

Signal distribution is parametrised for any value of m_H:

- Narrow Width Approximation
- Large Width Approximation (1, 5 and 10%)



High mass analysis: Signal acceptance & systematics

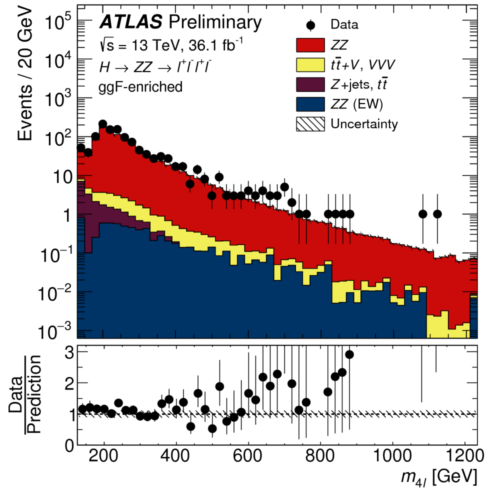
Mass	Production mode	ggF-enriched categories 4μ channel	2e2μ channel	4e channel	VBF-enriched category
300 GeV	ggF	56%	48%	40%	1%
	VBF	36%	30%	24%	21%
600 GeV	ggF	64%	56%	48%	3%
	VBF	36%	34%	32%	26%

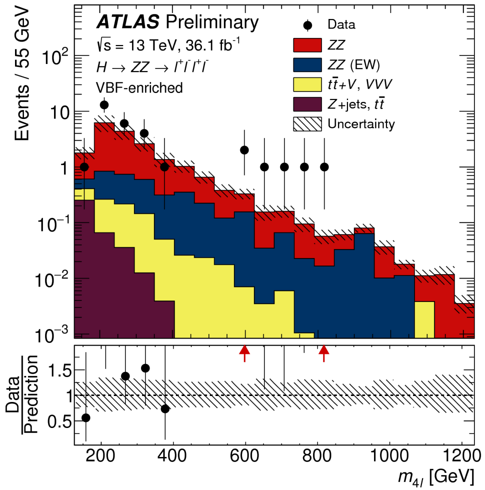
- Low acceptance for VBF process due to the stringent requirements (two jets with $p_T > 30$ GeV, $m_{jj} > 400$ geV & $\delta\eta > 3.3$)
- Any event not classified as VBF enters the ggF category
- The contribution from final states with τ leptons decaying to electrons or muons is found to be negligible

- The uncertainty on the integrated luminosity enters both in the normalisation of the fitted number of signal events as well as in the background expectation from simulation

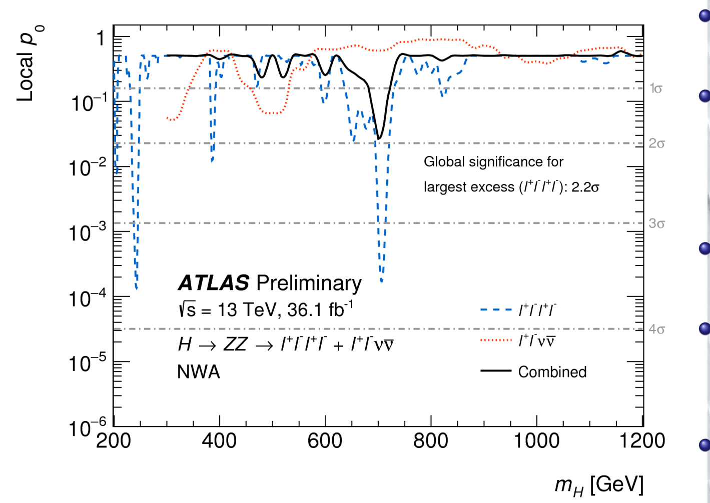
ggF production Systematic source	Impact [%]	VBF production Systematic source	Impact [%]
$m_H = 300$ GeV			
Luminosity	4	Parton showering	9
Z+jets modeling ($\ell^+\ell^-\nu\bar{\nu}$)	3.3	Jet energy scale	4
Parton showering	3.2	Luminosity	4
$e\mu$ statistical uncertainty $\ell^+\ell^-\nu\bar{\nu}$	3.2	$q\bar{q} \to ZZ$ QCD scale (VBF-enriched category)	4
$m_H = 600$ GeV			
Luminosity	6	Parton showering	6
Pileup reweighting	5	Pileup reweighting	6
Z+jets modeling ($\ell^+\ell^-\nu\bar{\nu}$)	4	Jet energy scale	6
QCD scale of $q\bar{q} \to ZZ$	3.1	Luminosity	4
$m_H = 1000$ GeV			
Luminosity	4	Parton showering	6
QCD scale of $gg \to ZZ$	2.3	Jet energy scale	5
Jet vertex tagger	1.9	Z+jets modeling ($\ell^+\ell^-\nu\bar{\nu}$)	4
Z+jets modeling ($\ell^+\ell^-\nu\bar{\nu}$)	1.8	Luminosity	4

High mass analysis: $m_{4\ell}$



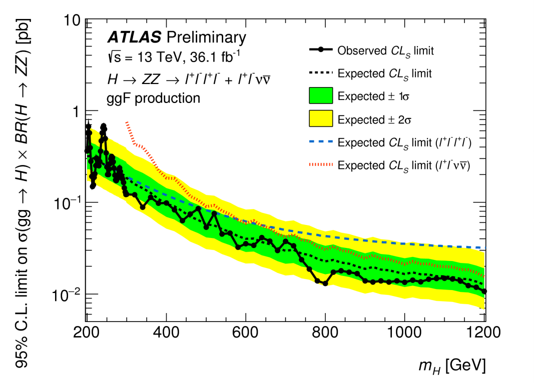


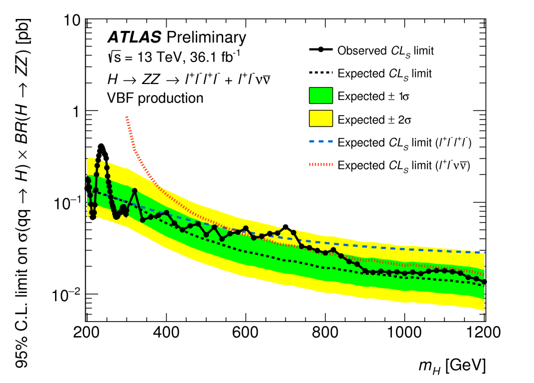
High mass analysis: *p*-value



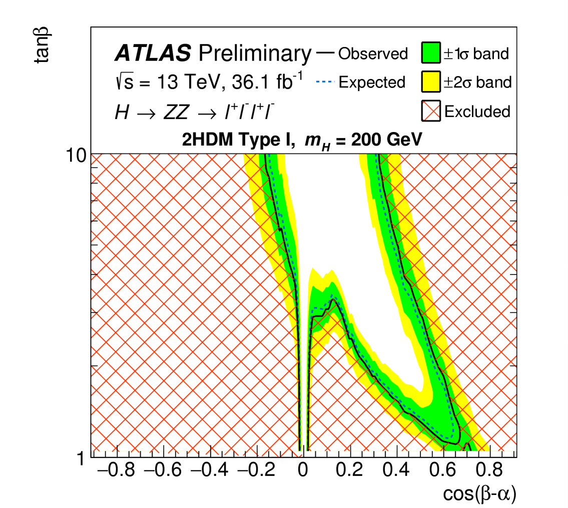
- Two excesses found: 240 and 705 GeV
- The excess at 705 GeV is mainly due to an excess in the 4e category, while the one at 240 GeV is driven by the excess
- Each excess represents a 2.2σ global significance
- Various checks performed but nothing seems fishy, revisit with 2017 dataset
- Excess not found in the $\ell\ell\nu\nu$ channel

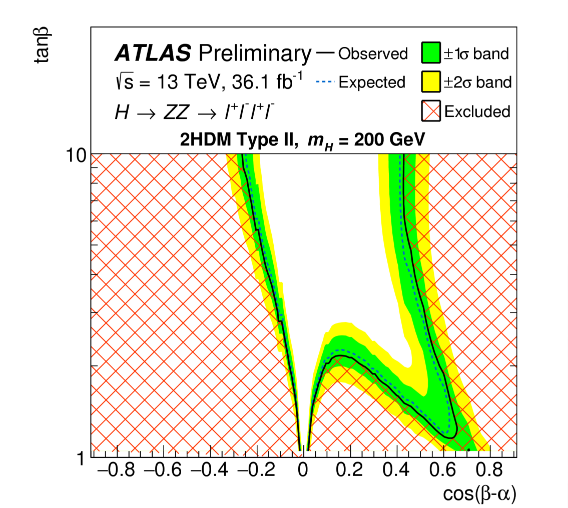
High mass analysis: 95% CL



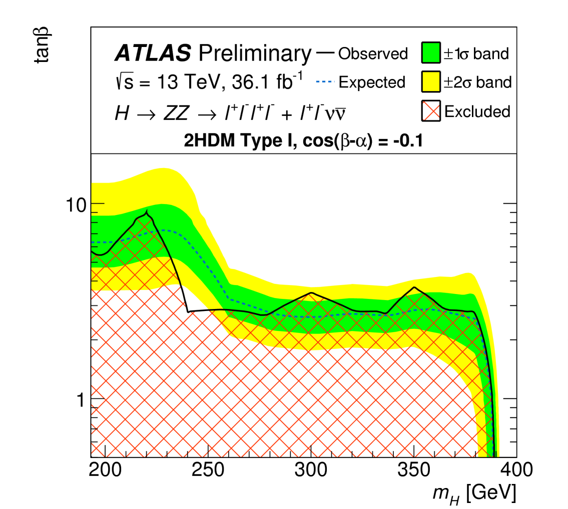


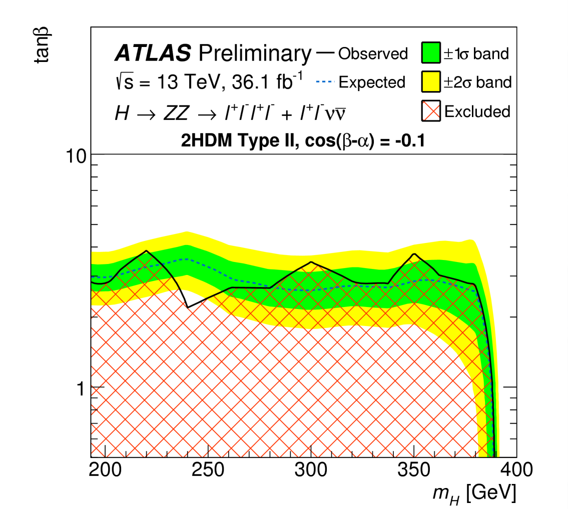
2HDM exclusion contour $tan(\beta)$ vs $cos(\beta-\alpha)$ m_H=200 GeV



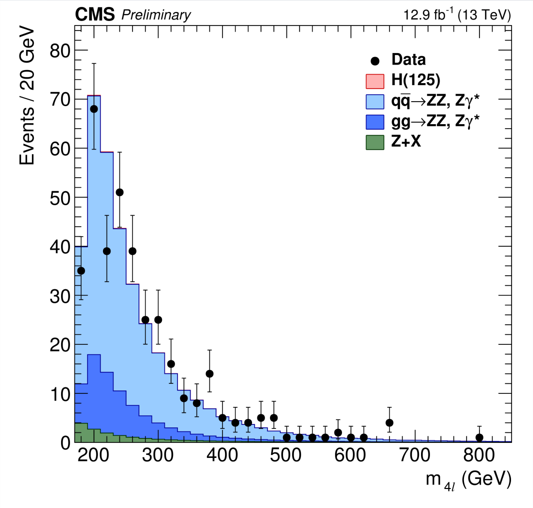


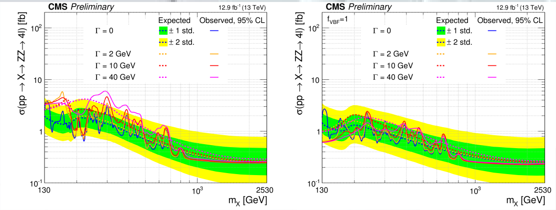
2HDM Type I Exclusion Contour $tan(\beta)$ vs m_H $cos(\beta-\alpha)$=-0.1





High mass analysis (CMS): Results





- Limits extracted assuming various width values
- No significant excess found in CMS[a]
- Still awaiting for an update on this search

[a] CMS-PAS-HIG-16-033

Conclusions

- Various measurements of the Higgs boson in the 4ℓ channel presented
- Still fairly limited by statistics...
- But we are having week after week of glorious data collection
- So far all compatible with SM expectation but some interesting areas should receive updates soon
- As usual, stay tuned!

Summary of publications

CMS Collaboration:

- HIG-16-041 accepted for publication in J. High Energy Phys. (arXiv:1706.09936)
- HIG-17-011 accepted for publication in Phys. Lett. B (arXiv:1707.00541)
- HIG-PAS-16-033

ATLAS Collaboration:

- ATLAS-CONF-2017-043
- ATLAS-CONF-2017-046
- ATLAS-CONF-2017-058

BACKUP SLIDES

Constraints on anomalous Higgs boson couplings: ATLAS

Interactions of the Higgs boson with SM particles are described in terms of the effective Lagrangian:

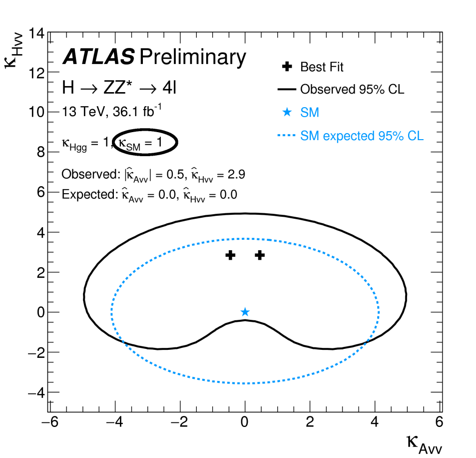
$$\mathcal{L}_0^V = \Big\{\kappa_{SM}\left[\tfrac{1}{2}g_{HZZ}Z_\mu Z^\mu + g_{HWW}W^+_\mu W^{-\mu}\right] - \tfrac{1}{4}\left[\kappa_{Hgg}g_{Hgg}G^a_{\mu\nu}G^{a,\mu\nu} + \tan\alpha\,\kappa_{Agg}g_{Agg}G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}\right] - \tfrac{1}{4}\tfrac{1}{\Lambda}\left[\kappa_{HZZ}Z_{\mu\nu}Z^{\mu\nu} + \tan\alpha\,\kappa_{AZZ}Z_{\mu\nu}\tilde{Z}^{\mu\nu}\right] - \tfrac{1}{2}\tfrac{1}{\Lambda}\left[\kappa_{HWW}W^+_{\mu\nu}W^{-\mu\nu} + \tan\alpha\,\kappa_{AWW}W^+_{\mu\nu}\tilde{W}^{-\mu\nu}\right]\Big\}X_0.$$

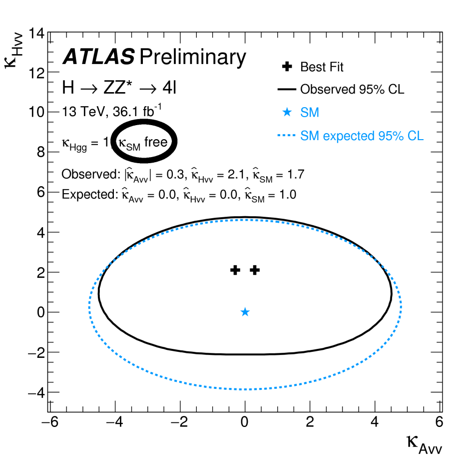
- Assume no BSM particles below 1 TeV
- κ_{HVV} & κ_{AVV} describe the CP-even (scalar) and CP-odd (pseudo-scalar) BSM interaction with vector boson

BSM coupling κ_{BSM}	Fit configuration	Expected limit	Observed limit	Best-fit $\hat{\kappa}_{BSM}$	Best-fit $\hat{\kappa}_{SM}$	Deviation from SM
κ_{Agg}	($\kappa_{Hgg}=1$, $\kappa_{SM}=1$)	[-0.47, 0.47]	[-0.68, 0.68]	$\pm$0.43	-	1.8σ
κ_{HVV}	($\kappa_{Hgg}=1$, $\kappa_{SM}=1$)	[-2.9, 3.2]	[0.8, 4.5]	2.9	-	2.3σ
κ_{HVV}	($\kappa_{Hgg}=1$, κ_{SM} free)	[-3.1, 4.0]	[-0.6, 4.2]	2.2	1.2	1.7σ
κ_{AVV}	($\kappa_{Hgg}=1$, $\kappa_{SM}=1$)	[-3.5, 3.5]	[-5.2, 5.2]	$\pm$2.9	-	1.4σ
κ_{AVV}	($\kappa_{Hgg}=1$, κ_{SM} free)	[-4.0, 4.0]	[-4.4, 4.4]	$\pm$1.5	1.2	0.5σ

- The BSM couplings are assumed to be the same for W and Z bosons
- Value of α set to 45 degrees such that the CP-odd couplings can be written as $\kappa_{AVV}\tan(\alpha) \rightarrow \kappa_{AVV}$
- Measured only in production, not decay

Constraints on anomalous Higgs boson couplings: ATLAS results

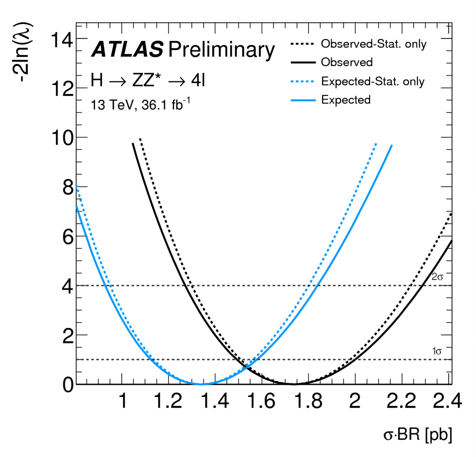




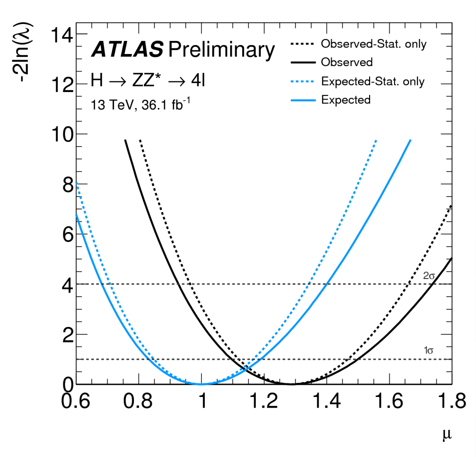
Best fit values compatible with SM within 2σ

Higgs boson couplings: Likelihood scan (ATLAS)

As a function of $\sigma \cdot BR(H \to ZZ^*)$



As a function of the inclusive signal strength



Higgs boson couplings: CMS signal strength Results