Higgs at the LHC: SM properties and BSM searches

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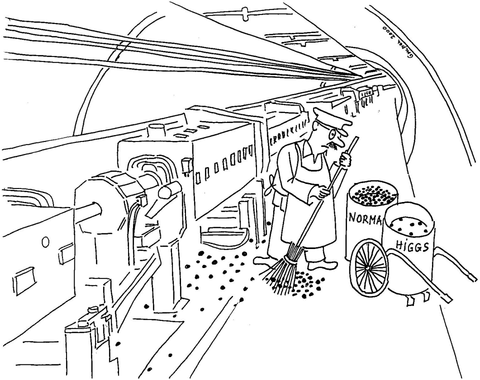
(Imperial College London)
on behalf of the ATLAS
and CMS Collaborations

17/04/2018
Third Alpine LHC Physics Summit

Outline



Higgs Production at the LHC

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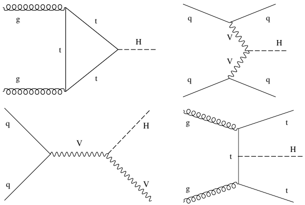
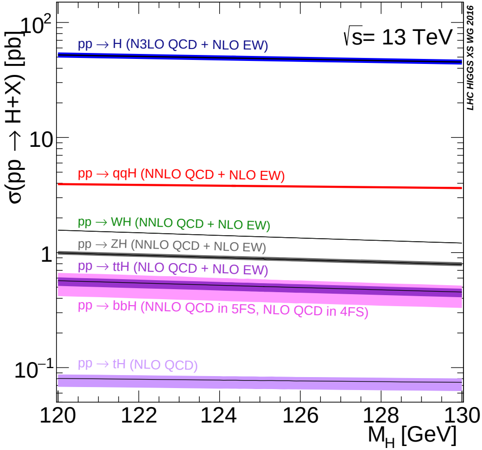
- New scalar particle discovered in 2012.
- Since then, data continue to demonstrate it is very much like **the** SM Higgs boson.
- 4 main production modes.
- Numerous decay channels.





The ATLAS and CMS detectors

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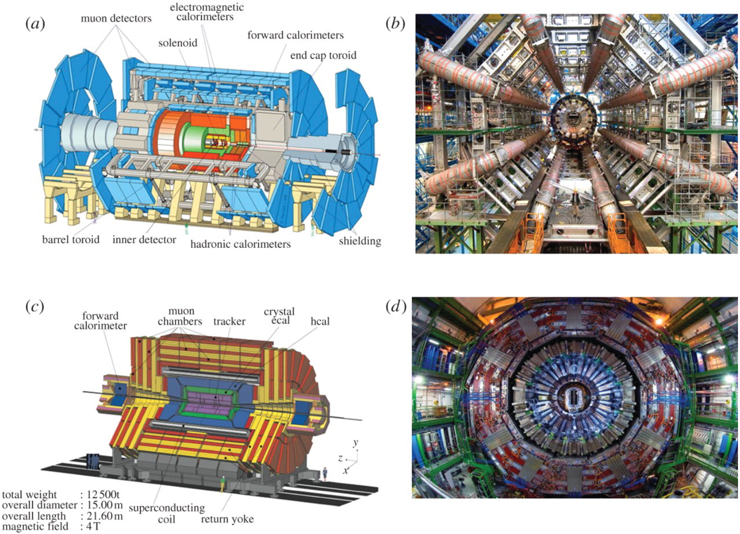

Overview of the data taken so far

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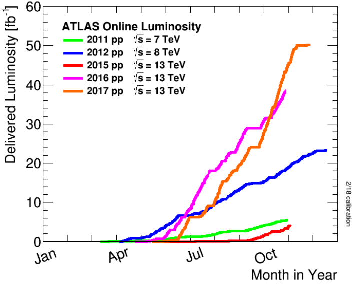

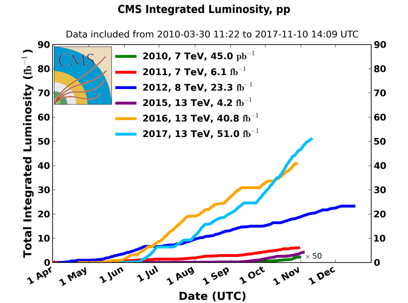

- Discovery with $\gamma\gamma$ and VV final states in July 2012, with 7+8 TeV data, ATLAS , Phys. Lett. B 716 (2012) 1, CMS PLB 716 (2012) 30.
- Discovery of coupling to τ leptons in Run I, JHEP 08 (2016) 045, and by single experiment in July 2017 with 7+8+13 (2016) TeV datasets: CMS Phys. Lett. B 779 (2018) 283.
- Evidence of coupling to b quarks summer 2017 with 7+8+13 (2016) TeV datasets: CMS Phys. Lett. B 780 (2018) 501, ATLAS JHEP 12 (2017) 024.
- Evidence of coupling to top quark by ATLAS in Dec 2017 with 13 (2016) TeV dataset: Phys. Rev. D 97 (2018) 072003.
- Discovery of coupling to top quarks last week by CMS with 7+8+13 (2016) TeV datasets: arXiv:1804.02610.

Outline

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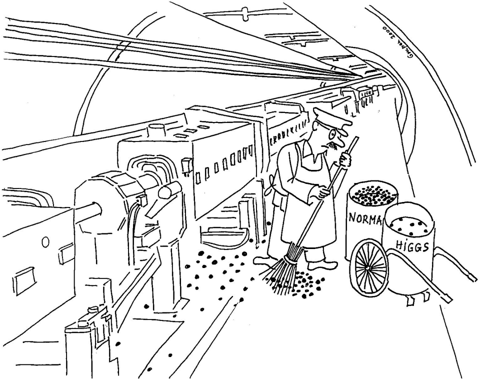
1. Introduction
2. SM Higgs Properties
3. Rare and exotic decays
   - Rare decays
   - Exotic decays
   - Decays to lighter (pseudo)scalar particles
4. BSM Searches
   - Low mass
   - High mass
   - Di-Higgs
   - Charged Higgs
5. Conclusion



Decay channels

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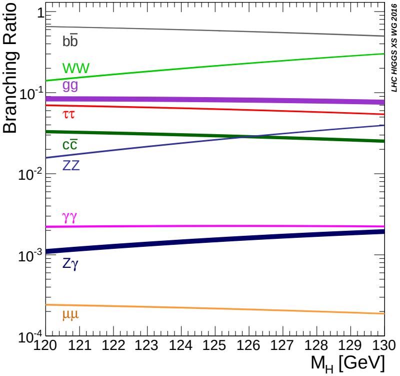
Measurements

- $\gamma\gamma$: mass, coupling, spin, differential measurements.
- ZZ$\rightarrow$4l: mass, spin, parity, coupling, differential measurements.
- $\tau\tau$: coupling.
- bb, WW: coupling.
- Others: rare decays like cc, $\mu\mu$, llγ, (J/Ψ,ϕ,ρ)+γ.

Disclaimer

- Lots of precision measurements with 7+8 TeV datasets.
- Choice to concentrate on a subset of recent results with 2016 13 TeV data.



Mass measurements

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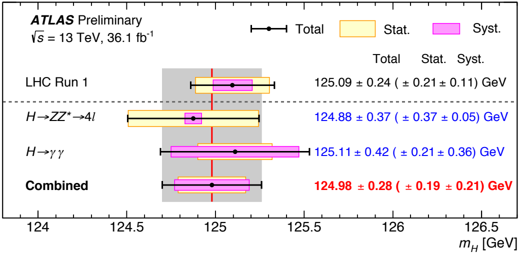
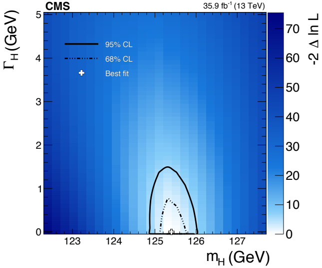
- decay to ZZ to 4l and $\gamma\gamma$: best resolutions and narrow mass distributions.
- RunI legacy: ATLAS+CMS combination Phys. Rev. Lett. 114 (2015) 191803
- RunII updates: ATLAS-CONF-2017-046 and CMS JHEP 11 (2017) 047.





LHC Run I	$125.09 \pm 0.21 \pm 0.11$ GeV
ATLAS 2016	$124.98 \pm 0.19 \pm 0.21$ GeV
CMS 2016	$125.26 \pm 0.20 \pm 0.08$ GeV

Spin and parity measurements

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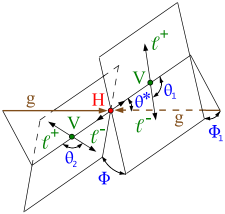
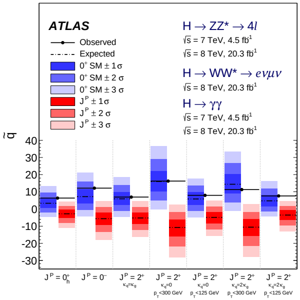
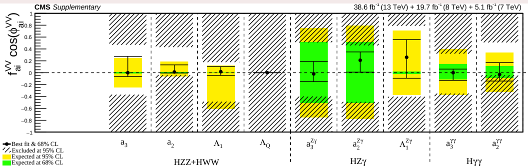
- decay to ZZ to 4l: access to full event kinematics.
- ATLAS Eur. Phys. J. C75 (2015) 476, CMS Phys. Lett. B 775 (2017) 1



SM $J^P = 0^+$ confirmed by data



Constraints on anomalous couplings



Coupling measurements

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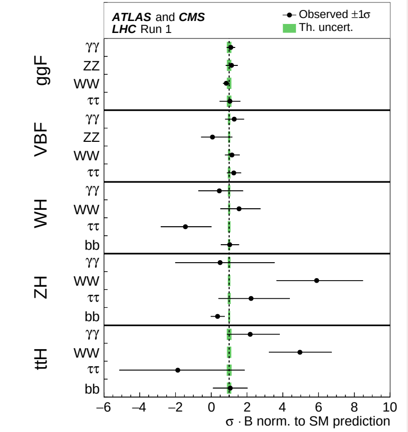
RunI ATLAS+CMS

JHEP 08 (2016) 045



RunII ATLAS

	ggF	VBF	VH	ttH
H→ZZ→4l	●	●	●	●
H→γγ	●	●	●	●
H→WW	●	●		●
H→bb		●	●	●
H→ττ				●
H→μμ	●	●		
H→inv			●	

RunII CMS

	ggF	VBF	VH	ttH
H→ZZ→4l	●	●	●	●
H→γγ	●	●	●	●
H→WW	●	●	●	●
H→bb	●		●	●
H→ττ	●	●		●
H→μμ	●	●		
H→inv	●	●	●	

A few selected Highlights in H→bb

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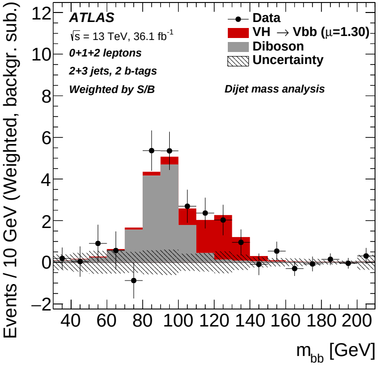
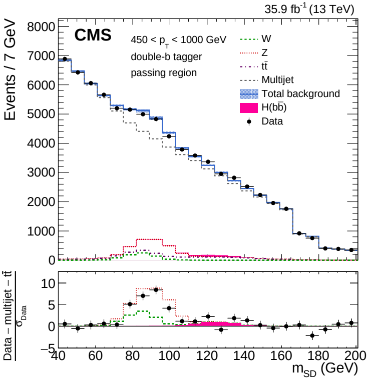
JHEP 12 (2017) 024

- $\mu^{bb}_{7,8,13TeV} = 0.9^{+0.18}_{-0.18}(stat)^{+0.21}_{-0.19}(syst)$
- 3.5σ obs (3.0σ exp.)



Phys. Rev. Lett. 120 (2018) 071802

- Dominant QCD background from data.
- Boosted jet of pT > 450 GeV using substructure techniques.



Updated ATLAS measurements

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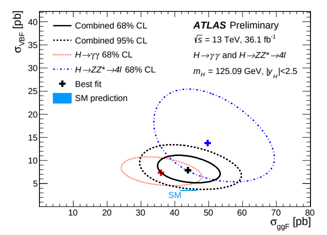
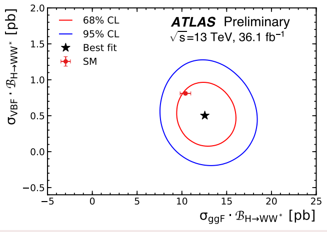
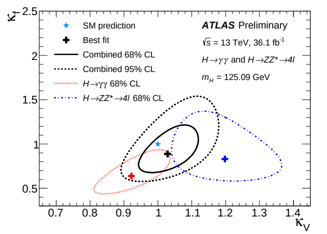
$\gamma\gamma$, ZZ(4l) ATLAS-CONF-2017-047

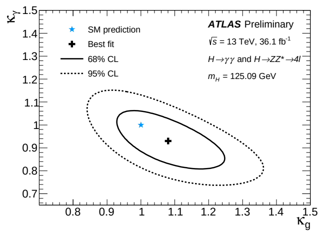


WW ATLAS-CONF-2018-004



$\gamma\gamma$+ZZ(4l), κ framework, no BSM

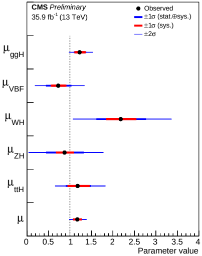


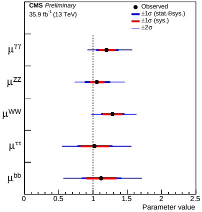


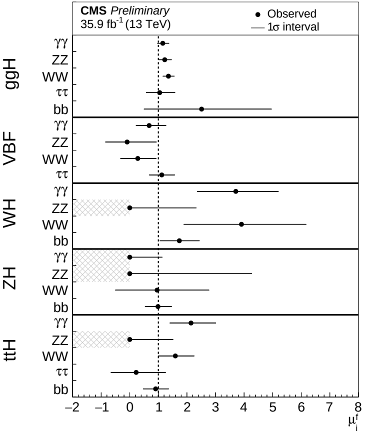
CMS grand combination with 2016 data

- New channels: ZZ, ggH to bb.
- Best accuracy to date for ggH (11%), ttH (26%), combination (9%).

CMS-PAS-HIG-17-031







$$\mu = 1.17^{+0.10}_{-0.10}$$
$$= 1.17^{+0.06}_{-0.06}\ (\text{stat.})\ ^{+0.06}_{-0.05}\ (\text{sig. th.})\ ^{+0.06}_{-0.06}\ (\text{other sys.})$$

RunI signal strength

$$\mu = 1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07}\ (\text{stat})\ ^{+0.04}_{-0.04}\ (\text{expt})\ ^{+0.03}_{-0.03}\ (\text{thbgd})^{+0.07}_{-0.06}\ (\text{thsig})$$

Couplings in the κ framework

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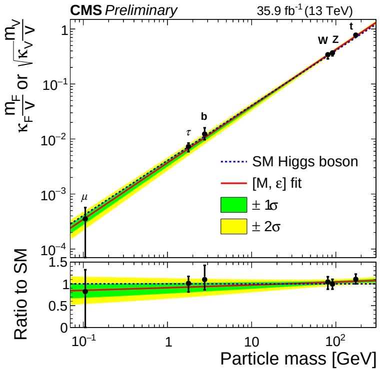
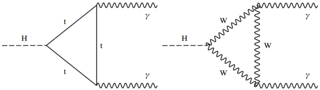
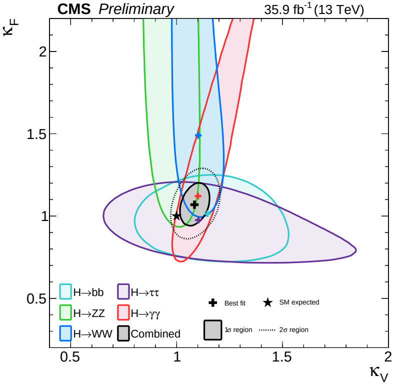
CMS-PAS-HIG-17-031

- Assuming no BSM contributions







Differential xs: H→ $\gamma\gamma$ and H→ 4l

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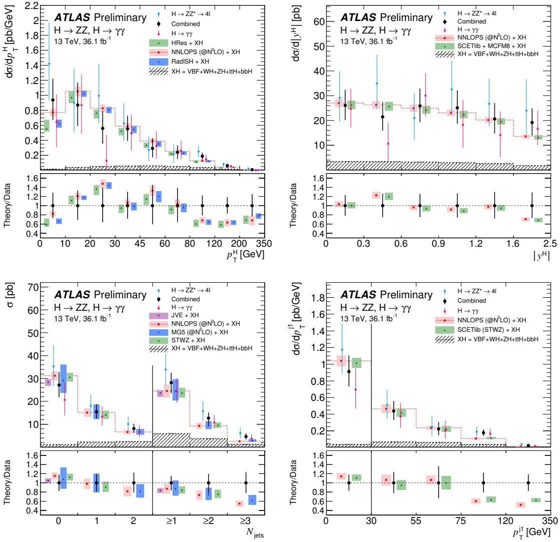
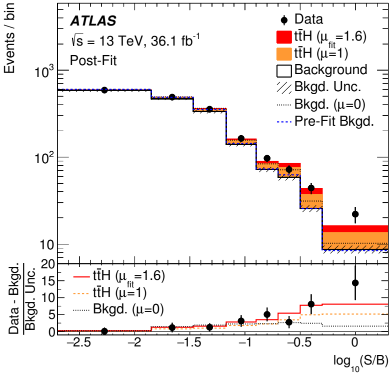
ATLAS-CONF-2018-002

- ggF, VBF, VH with Powheg-box v2, ttH, bbH with Madgraph5_aMC@NLO.
- Normalised to latest calculations (ggF N3LO,...)
- Stat uncertainties dominant: 20-30%.
- Good agreement $\gamma\gamma$ vs 4l, and with predictions.
- CMS h→ $\gamma\gamma$: HIG-16-040, HIG-17-025,
- CMS h to 4l: HIG-16-041

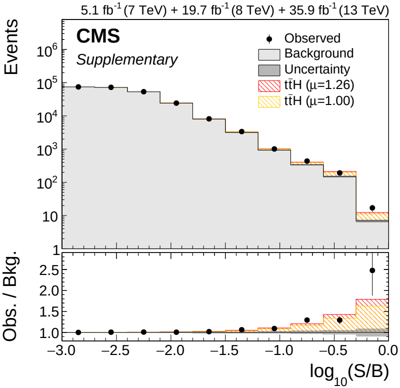


First observation of ttH production !

Phys. Rev. D 97 (2018) 072003



arXiv:1804.02610



- From multileptons analysis, 13 TeV data.
- Targetting WW, ZZ, $\tau\tau$ decays.
- Also available for combination: bb, $\gamma\gamma$ decays.

- From 88 categories combined, 7, 8 and 13 TeV data combined.
- Targetting WW, ZZ, $\tau\tau$, bb, $\gamma\gamma$ decays.

ttH combination results

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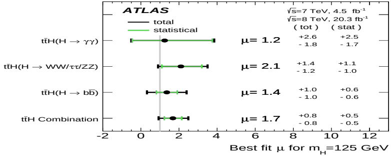
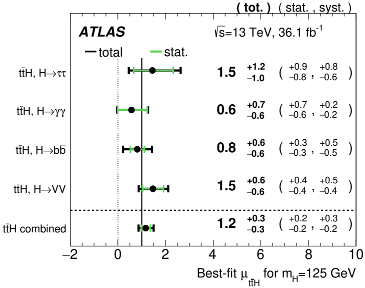
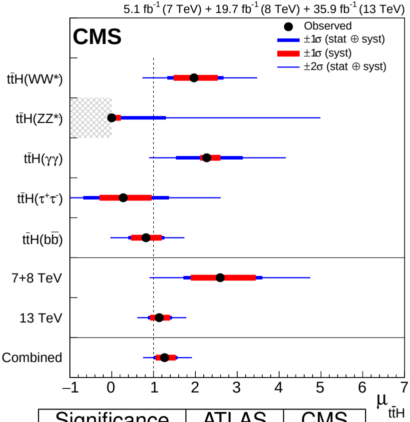
JHEP 05 (2016) 160, Phys. Rev. D 97 (2018) 072003





arXiv:1804.02610



Significance	ATLAS	CMS
Observed	$4.2\ \sigma$	$5.2\ \sigma$
Expected	$3.8\ \sigma$	$4.2\ \sigma$

$$\mu_{t\bar{t}H} = 1.26^{+0.31}_{-0.26} = 1.26^{+0.16}_{-0.16}(\text{stat})^{+0.17}_{-0.15}(\text{expt})^{+0.14}_{-0.13}(\text{bkg th})^{+0.15}_{-0.07}(\text{sig th})$$

More in dedicated talk today at 16.45 by Daniele Madaffari

Constraints from couplings measurements

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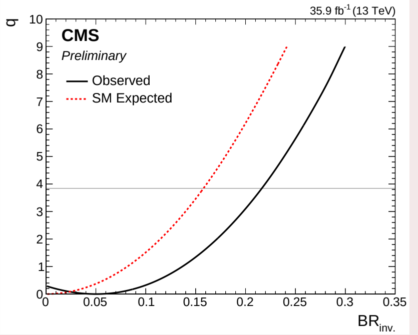
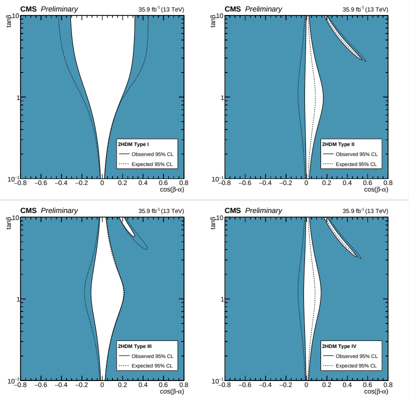
CMS-PAS-HIG-17-031

On BR to invisible: < 0.22@95%CL



On 2HDM



Outline

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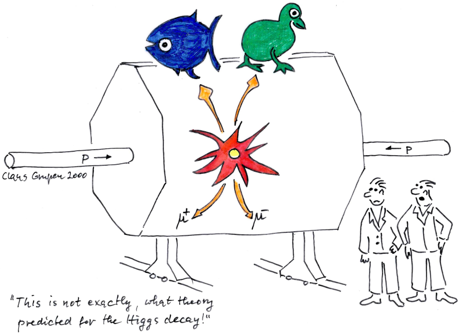
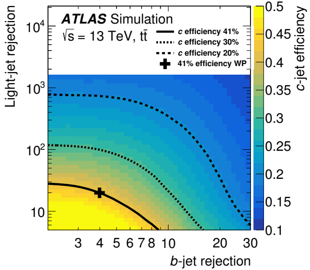
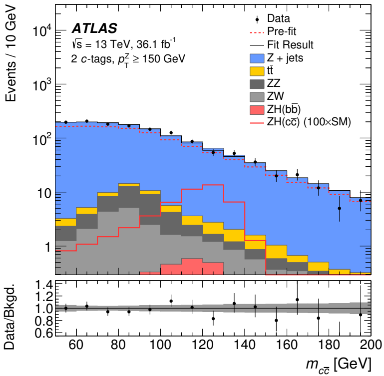


VH, H(125) $\to c\bar{c}$

arXiv:1802.04329



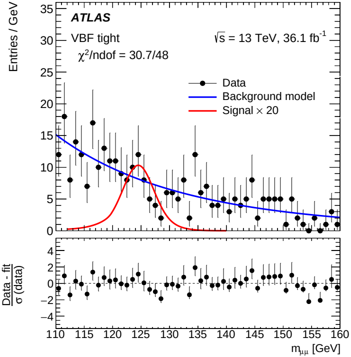


Source	σ/σ_{tot}
Statistical	**49%**
Floating $Z+$jets normalization	31%
Systematic	**87%**
Flavor tagging	73%
Background modeling	47%
Lepton, jet and luminosity	28%
Signal modeling	28%
MC statistical	6%

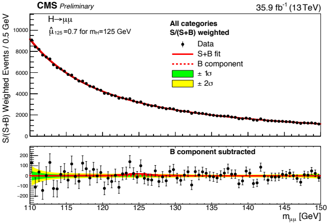
- Observed (exp.) upper limit $\sigma < 2.7(3.9^{+2.1}_{-1.1})$ pb.
- Observed (exp.) signal strength $\mu < 110(150^{+80}_{-40})$.

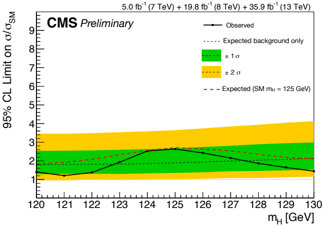
H(125)$\rightarrow \mu\mu$

Phys. Rev. Lett. 119 (2017) 051802



CMS-PAS-HIG-17-019





- ATLAS observed (expected) upper limit is 2.8 (2.9) times the SM prediction
- CMS observed (expected) upper limit is 2.64 (1.89) times the SM prediction

H to llgamma

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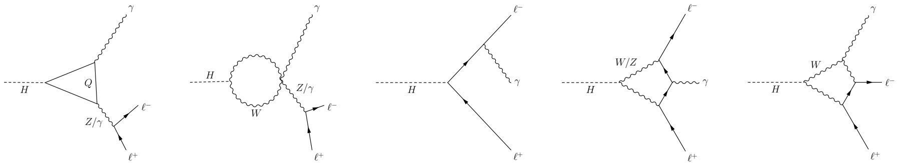
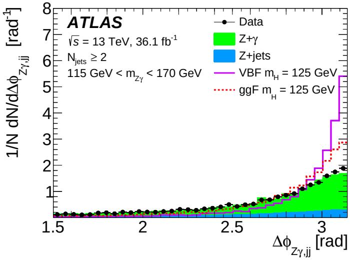
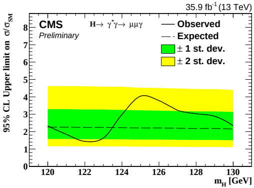
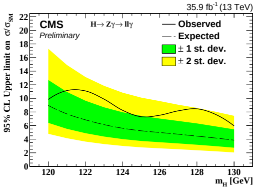


JHEP 10 (2017) 112



CMS-PAS-HIG-17-007



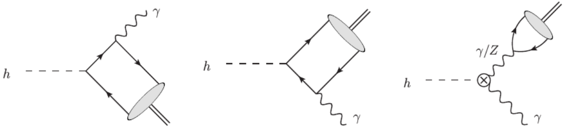


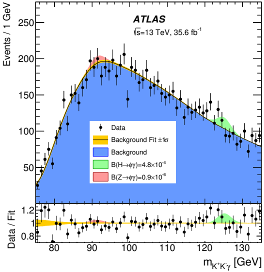
- Interpretation also for high mass spin-0 or spin-2 resonances.
- ATLAS: observed (expected) 95% upper limit 6.6 (5.2) times SM.
- CMS: observed (expected) 95% upper limit 3.9 (2.0) times SM.

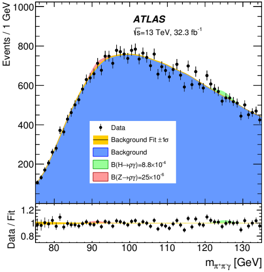
H$\rightarrow \phi\gamma, \rho\gamma$

arXiv:1712.02758

- Test of couplings to light quarks.
- Complementing Run I H$\rightarrow J/\Psi + \gamma$ searches Phys. Rev. Lett. 114 (2015) 121801, PLB 753 (2016) 341.



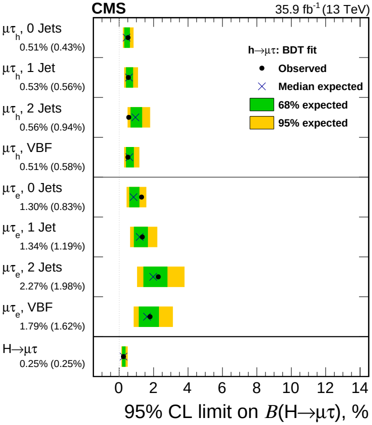




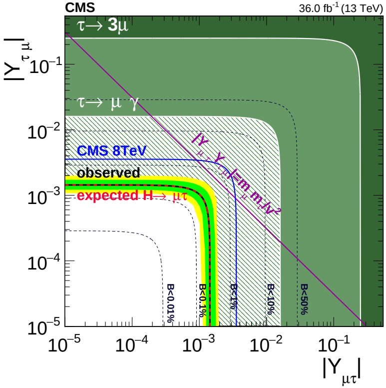
Branching Fraction Limit (95% CL)	Expected	Observed
$\mathcal{B}(H \rightarrow \phi\gamma)\,[10^{-4}]$	$4.2^{+1.8}_{-1.2}$	4.8
$\mathcal{B}(Z \rightarrow \phi\gamma)\,[10^{-6}]$	$1.3^{+0.6}_{-0.4}$	0.9
$\mathcal{B}(H \rightarrow \rho\gamma)\,[10^{-4}]$	$8.4^{+4.1}_{-2.4}$	8.8
$\mathcal{B}(Z \rightarrow \rho\gamma)\,[10^{-6}]$	33^{+13}_{-9}	25

Lepton-flavour violating decays

- Run I: 2.4σ excess (Phys. Lett. B 749 (2015) 337)...
- ... unfortunately ruled out by 2016 data.



arXiv:1712.07173



Higgs to invisible

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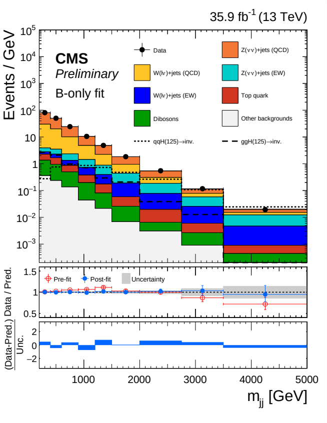
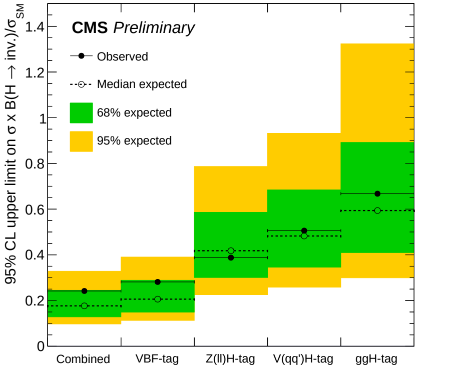
Strategy

- VH, ggH and VBF production modes.
- VBF most sensitive channel, fit to the dijet invariant mass.



CMS-PAS-HIG-17-023

35.9 fb^{-1} (13 TeV)



Analysis	Observed limit	Expected limit	±1 s.d.	±2 s.d.	Signal composition
Shape	0.28	0.21	[0.15–0.29]	[0.11–0.39]	52% qqH, 48% ggH
Cut-and-count	0.53	0.27	[0.20–0.38]	[0.15–0.51]	81% qqH, 19% ggH
ATLAS PLB 776 (2017) 318	0.67	0.39	[0.28--0.56]	[0.21--0.77]	Z(ll)H

DM interpretation: talk by J. Butler Thu 10.10

Higgs to Dark Photons or light pseudoscalars

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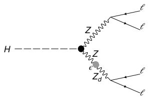
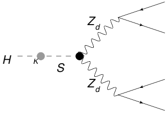
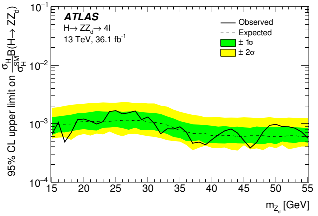
Hypercharge portal



Higgs portal

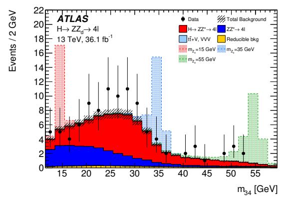


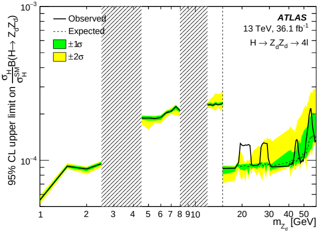
arXiv:1802.03388



Strategy

- Final state 4l, either Z or new vector Z_D / pseudoscalar a.
- Search for peak in m_{ll} distributions.
- Interpretation in several models, also h$\rightarrow aa \rightarrow 4l$



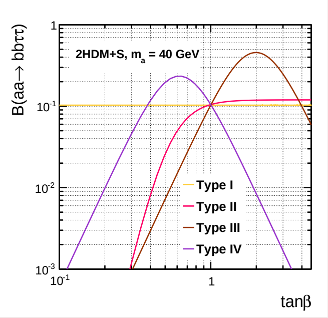


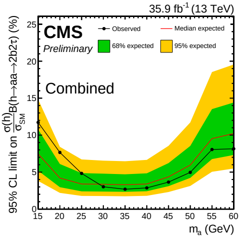
$H_{125} \rightarrow aa \rightarrow bb\tau\tau$

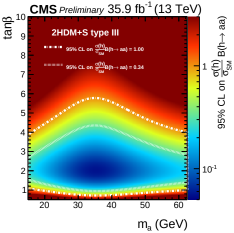
CMS-PAS-HIG-17-024

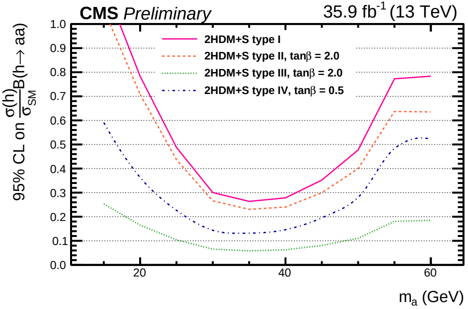
Strategy

- NEW! Large BR in 2HD+S models.
- $e\mu$, $e\tau_{had}$, $\mu\tau_{had}$ channels.
- Fit $m_{\tau\tau}^{vis}$ in bins of $m_{b\tau\tau}^{vis}$.









$H_{125} \to aa \to \mu\mu\tau\tau$

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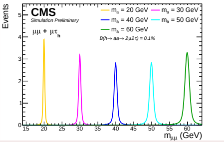
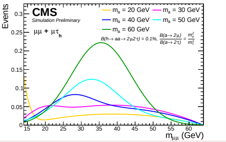
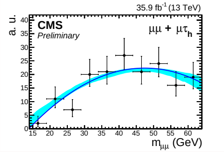
Strategy

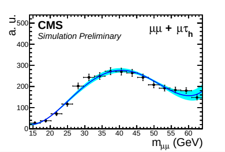
$aa \to \mu\mu\tau\tau$ $aa \to 4\tau \to \mu\mu\tau\tau$





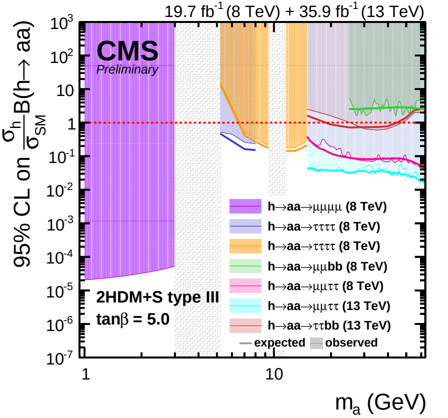
- Parametrise signal and background, look for sharp peak in $m_{\mu\mu}$
- $e\mu$, $e\tau_{had}$, $\mu\tau_{had}$, $\tau_{had}\tau_{had}$ channels.





Reducible bkg Irreducible bkg

CMS-PAS-HIG-17-029



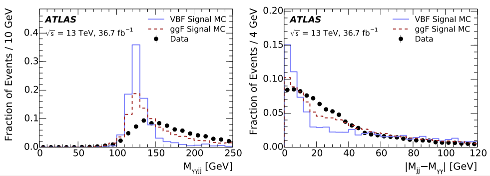
VBF $H_{125} \to aa \to gg\,\gamma\gamma$

CMS — Imperial College London

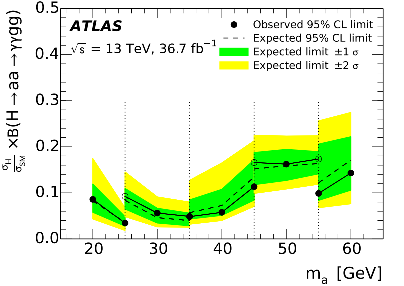
Strategy

- NEW! Target models with fermionic decays suppressed, higher BR than 4γ channel.
- VBF production: 2 jets with $M_{jj} > 500$ GeV.
- Higgs decay: 2 jets + 2 γ, 100 $< m_{\gamma\gamma jj} < 150$ GeV.
- ABCD method for background estimation.

	Photon requirements: TightLoose	Photon requirements: TightTight
$\lvert m_{jj} - m_{\gamma\gamma}\rvert > x_R$	A	C
$\lvert m_{jj} - m_{\gamma\gamma}\rvert \leq x_R$	B	D



arXiv:1803.11145



$m_{\gamma\gamma}$ regime	Definition	Range of m_a values	x_R [GeV]
1	17.5 GeV $< m_{\gamma\gamma} <$ 27.5 GeV	20 GeV $\leq m_a \leq$ 25 GeV	12
2	22.5 GeV $< m_{\gamma\gamma} <$ 37.5 GeV	25 GeV $\leq m_a \leq$ 35 GeV	12
3	32.5 GeV $< m_{\gamma\gamma} <$ 47.5 GeV	35 GeV $\leq m_a \leq$ 45 GeV	16
4	42.5 GeV $< m_{\gamma\gamma} <$ 57.5 GeV	45 GeV $\leq m_a \leq$ 55 GeV	20
5	52.5 GeV $< m_{\gamma\gamma} <$ 65.0 GeV	55 GeV $\leq m_a \leq$ 60 GeV	24

Outline

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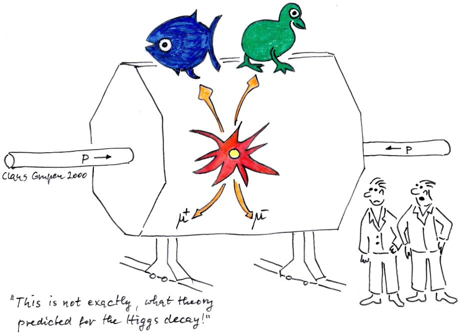
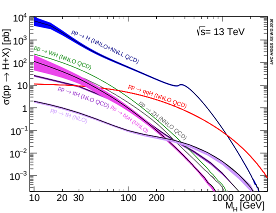
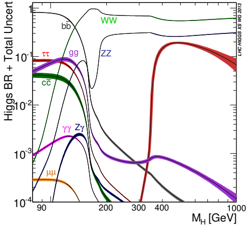
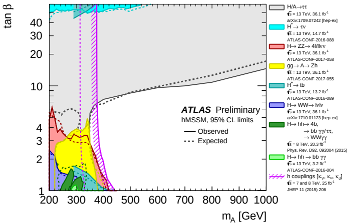


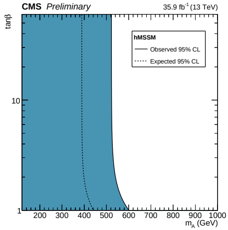
SM-like production and decay, and hMSSM model







CMS-PAS-HIG-17-031



- SM-like: dominant decay to ZZ, WW.
- Opening of ttbar channel above 300 GeV.
- m_A-tanβ plane: enhancement of couplings to τ, b.
- Large parameter space already excluded, remaining region of interest at high mass, low tanβ.
- Indirect limits from visible channels with 13 TeV data already more stringent than 8 TeV direct limits.

Overview of searches for additional neutral Higgs bosons

- Extensions of SM analyses looking for high mass (pseudo)scalars.
- **More on H$\rightarrow \tau\tau$ by Michaela Mlynarikova (ATLAS) and Markus Spanring (CMS) this afternoon**.
- Overall: no significant excess found, limits set in various BSM models.

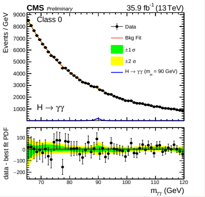
Channel	ATLAS	CMS
H$\rightarrow$ ZZ	arXiv:1712.06386	arXiv:1804.01939
H$\rightarrow$ WW (ll$\nu\nu$)	Eur. Phys. J. C 78 (2018) 24	JHEP 10 (2015) 144 (RunI)
H$\rightarrow$ WW,WZ (lνqq)	JHEP 03 (2018) 042	JHEP 10 (2015) 144 (RunI)
H$\rightarrow \tau\tau$	JHEP 01 (2018) 055	arXiv:1803.06553

- Dedicated 2HDM (+S) searches: detailed in following slides.

Channel	ATLAS	CMS
H$\rightarrow \gamma\gamma$	-	CMS-PAS-HIG-17-013
H/A$\rightarrow$ ZA/H	arXiv:1804.01126	Phys. Lett. B 759 (2016) 369 (RunI)
A$\rightarrow$WH(125), ZH(125)	arXiv:1712.06518	-

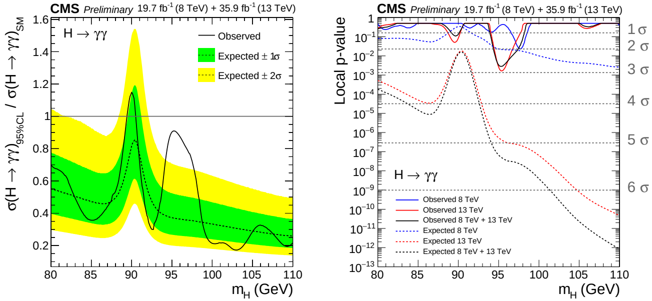
Low mass Higgs to $\gamma\gamma$, $70 < m_H < 110$ GeV

Strategy: bump hunt

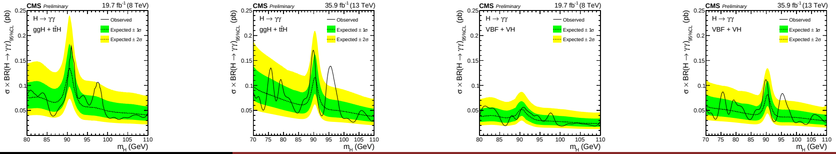


Results

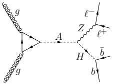
CMS-PAS-HIG-17-013

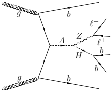


- Local (global) significance @ 95.4 GeV : 2.8 (1.3) σ.
- To be checked with more data!



A to ZH

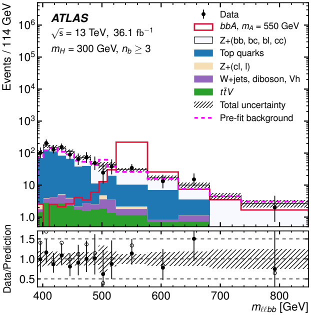


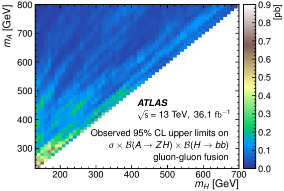


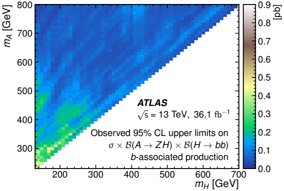
arXiv:1804.01126

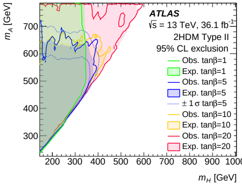
- $m_A > m_H$, Z→ll, H→bb.

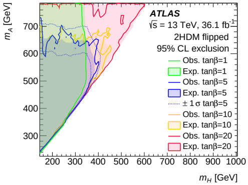
- 2 categories: 2b and >= 3b to target gluon fusion and b-associated productions.
- Fit of m_{llbb} in windows of m_{bb}.





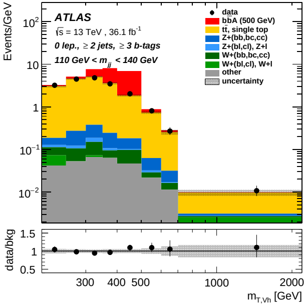


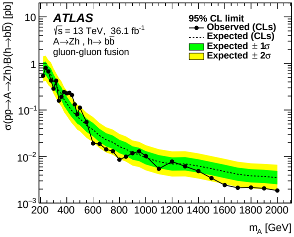


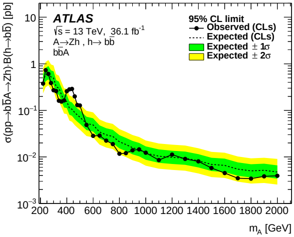


A to WH(125), ZH(125)

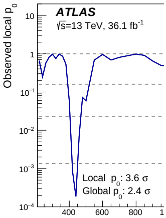
- W→ $l\nu$, Z→ $ll, \nu\nu$, and H(125)→ $b\bar{b}$.
- Resolved and merged topologies.
- Interpretations in heavy-vector-triplet and 2HDM.







arXiv:1712.06518



Overview of di-Higgs searches

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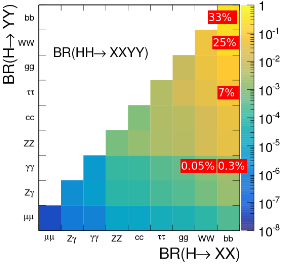
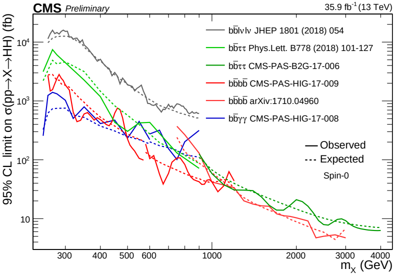
- HH in SM: small cross sections O$\simeq$ 30 fb at 13 TeV.
- HH in BSM: resonant production via new particles, and non-resonant enhancements described in Effective Field Theories (EFT).
- Non-resonant SM Run I limits: ATLAS 70 (48) $\times$ SM (Phys. Rev. D 92, 092004 (2015)), CMS 43 (47) $\times$ SM (Phys. Rev. D 96, 072004 (2017).

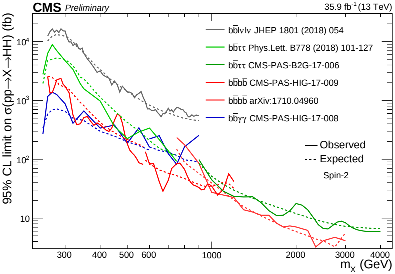


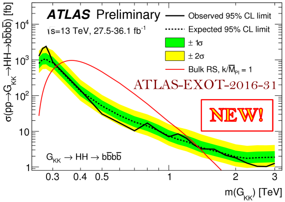
13 TeV results

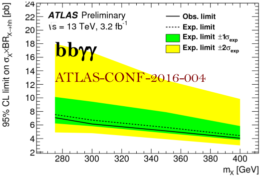
Channel	ATLAS	CMS
4b	ATLAS-EXOT-2016-31	CMS-PAS-HIG-17-009
4b boosted	-	arXiv:1710.04960
2b2W		JHEP 01 (2018) 054
2b2τ		Phys. Lett. B 778 (2018) 101
2b2τ boosted		CMS-PAS-B2G-17-006
2b2γ	ATLAS-CONF-16-004	CMS-PAS-HIG-17-008
2γ2W	ATLAS-CONF-16-071	-

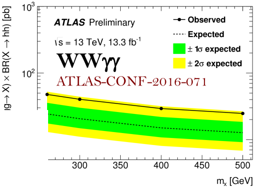
Summary for resonant HH searches



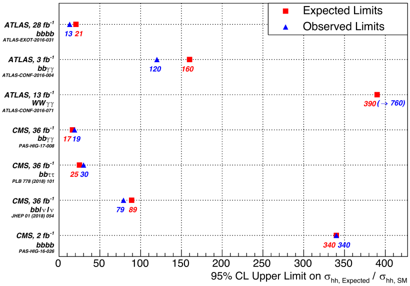








Summary for non-resonant HH searches

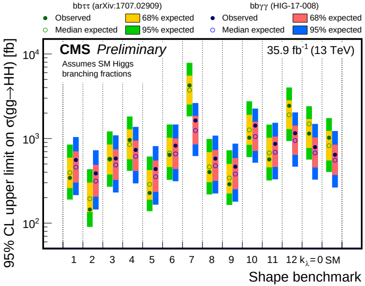


Courtesy of M. Kagan, Moriond EWK

- Reaching O(20 × SM).
- Can expect O(10× SM) by end of Run II.

EFT param from arXiv:1608.06578

$$\mathcal{L}_H = \frac{1}{2}\partial_\mu H \partial^\mu H - \frac{1}{2} m_H^2 H^2 - \kappa_\lambda \lambda_{SM} \nu H^3 - \frac{m_t}{\nu}(v + \kappa_t H + \frac{c_2}{\nu} HH)(\bar{t}_L t_R + h.c.) + \frac{1}{4}\frac{\alpha_s}{3\pi\nu}(c_g H - \frac{c_{2g}}{2\nu} HH) G^{\mu\nu}G_{\mu\nu}.$$



Overview of searches for charged Higgs bosons

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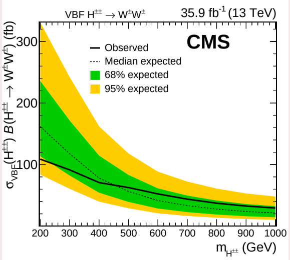
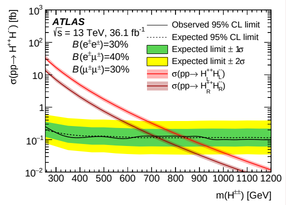
Search	ATLAS	CMS
$H^{\pm} \to c\bar{s}$ 8 TeV	Eur. Phys. J. C, 73 6 (2013) 2465	JHEP 12 (2015) 1
$H^{\pm} \to c\bar{b}$ 8 TeV	-	CMS-PAS-HIG-16-030
$H^{\pm} \to t\bar{b}$ 8 TeV	JHEP 03 (2016) 127	JHEP 11 (2015) 018
$H^{\pm} \to \tau\nu$ 13 TeV	Phys. Lett. B 759 (2016) 555-574	CMS-PAS-HIG-16-031
$H^{\pm} \to t\bar{b}$ 13 TeV	ATLAS-CONF-2016-089	-
$H^{\pm} \to WZ$	Phys. Rev. Lett. 114, 231801 (2015)	PRL 119 (2017) 141802
$H^{\pm\pm} \to$ lll(l) 13 TeV	Eur. Phys. J. C 78 (2018) 199	CMS-PAS-HIG-16-036
$H^{\pm\pm} \to W^{\pm}W^{\pm}$	-	arXiv:1709.05822

Talk by Margherita Ghezzi today 17:45

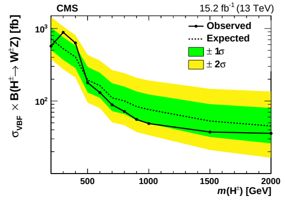
$H^{\pm\pm} \to W^{\pm}W^{\pm}$



$H^{\pm\pm} \to$ leptons



$H^{\pm} \to WZ$



Conclusion

- SM Higgs:
  - Observations of all production modes, including ttH.
  - Observations of "the 5" main decay channels - 3σ evidence for bbbar.
  - Completing coupling measurements in all production modes and "the 5" decay channels.
  - Reaching 2.6$\times$SM in rare decay to $\mu\mu$, 4$\times$SM in rare decay to Zγ
  - Exploring decays to ccbar and meson+γ...
  - ... and many exotic decay modes....
- BSM Higgs:
  - Constraints from visible decay increasingly strong.
  - Many different searches for signs of New Physics.
  - At the moment constraining more and more the parameter space.
  - In the objective "leave no stone unturned", good complementarity between ATLAS and CMS.
- Futur Prospects: see **talk later this morning on "Higgs and SM at the HL-LHC" by Tae Jeong Kim**.

Thank you for your attention

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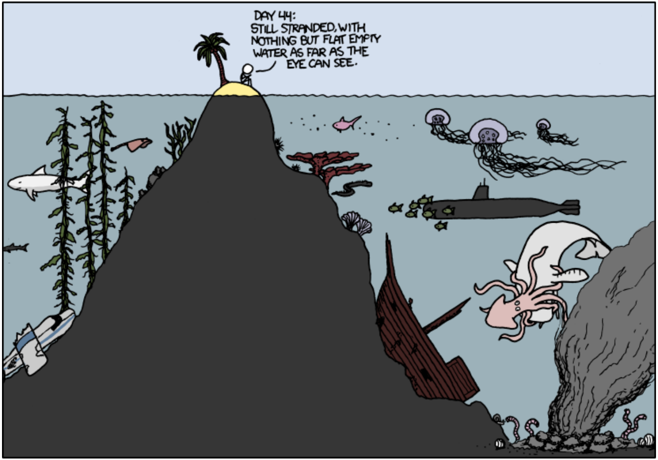

But first 2018 stable beam LHC data expected this morning!!

Backups

BACKUPS

Resolved couplings in the κ framework

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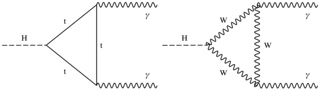
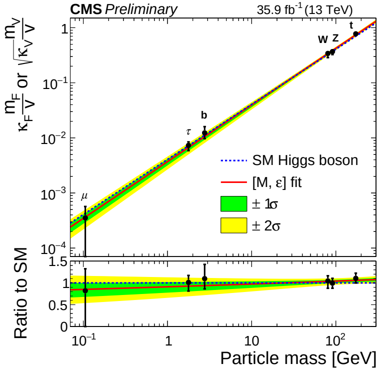
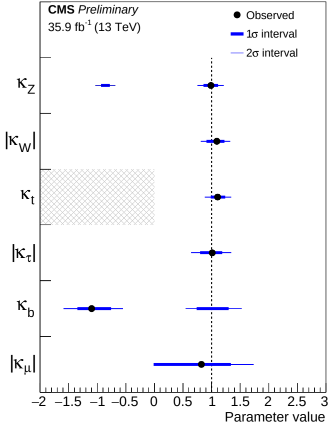
CMS-PAS-HIG-17-031



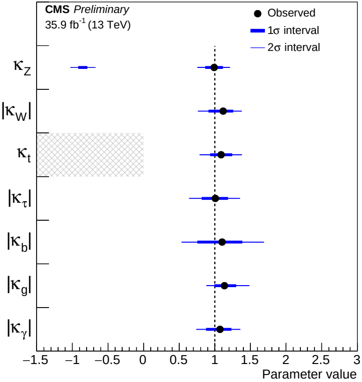
- Assuming no BSM contributions
- κ_Z and κ_b can go negative, not κ_W.



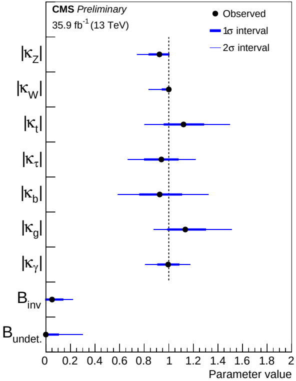


Effective couplings in the κ framework

No BSM decays



$\kappa_V < 1$



CMS Grand combination 2016

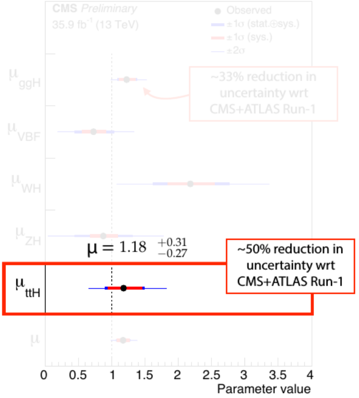
Imperial College London

Analysis	Reference
$H \to ZZ \to 4l$	JHEP 11 (2017) 047
$H \to \gamma\gamma$	arXiv:1804.02716
$H \to WW$	HIG-16-042
$VH \to bb$	PLB 780 (2018) 501
$H \to \tau\tau$	PLB 779 (2018) 283
$H \to \mu\mu$ (*)	HIG-17-019
Boosted $H \to bb$	PRL 120 (2018) 071802
$ttH \to WW/ZZ/\tau\tau$	arXiv:1803.05485
$ttH \to bb$ (leptonic)	HIG-17-026
$ttH \to bb$ (hadronic)	arXiv:1803.06986
$H \to$ invisible (*)	HIG-17-023

Signal strength measurements

$$\mu = 1.17^{+0.10}_{-0.10} \quad = 1.17^{+0.06}_{-0.06}\,(\text{stat.})\,^{+0.06}_{-0.05}\,(\text{sig. th.})\,^{+0.06}_{-0.06}\,(\text{other sys.})$$

- Split by production or decay mode:



Per production mode

- ttH measurement in Run-1:

Production process	ATLAS+CMS	ATLAS	CMS
μ_{ttH}	$2.3^{+0.7}_{-0.6}$ $\left(^{+0.5}_{-0.5}\right)$	$1.9^{+0.8}_{-0.7}$ $\left(^{+0.7}_{-0.7}\right)$	$2.9^{+1.0}_{-0.9}$ $\left(^{+0.9}_{-0.8}\right)$

- Extremely optimistic back-of the-envelope projection of CMS expected Run-1 precision (**84%**) to 13 TeV luminosity and 3.8x σ_{ttH}: **~35%,** compared to actual precision: **28%**

- Achieved by:
  - Targeting additional final states, e.g. all-hadronic ttHbb, leptons + τ_h
  - Improved analysis techniques, e.g. use of matrix-element method / deep neural networks

- **Best overall constraint is obtained by a combined measurement with Run-1 data...**

Production process	Decay mode									
	ggH				VBF				WH	
	Best fit value	Uncertainty	Stat.	Syst.	Best fit value	Uncertainty	Stat.	Syst.	Best fit value	Uncertainty
$H \to bb$	2.51	$^{+2.44}_{-2.01}$	$^{+1.96}_{-1.92}$	$^{+1.46}_{-0.59}$	–				1.73	$^{+0.70}_{-0.68}$
		$\left(^{+2.06}_{-1.86}\right)$	$\left(^{+1.86}_{-1.83}\right)$	$\left(^{+0.89}_{-0.33}\right)$	–					$\left(^{+0.69}_{-0.67}\right)$

Production process	WH		ZH				ttH			
	Stat.	Syst.	Best fit value	Uncertainty	Stat.	Syst.	Best fit value	Uncertainty	Stat.	Syst.
$H \to bb$	$^{+0.53}_{-0.51}$	$^{+0.46}_{-0.44}$	0.99	$^{+0.48}_{-0.45}$	$^{+0.41}_{-0.40}$	$^{+0.23}_{-0.20}$	0.91	$^{+0.45}_{-0.43}$	$^{+0.24}_{-0.24}$	$^{+0.38}_{-0.36}$
	$\left(^{+0.53}_{-0.51}\right)$	$\left(^{+0.45}_{-0.44}\right)$		$\left(^{+0.46}_{-0.44}\right)$	$\left(^{+0.40}_{-0.39}\right)$	$\left(^{+0.23}_{-0.20}\right)$		$\left(^{+0.44}_{-0.42}\right)$	$\left(^{+0.24}_{-0.23}\right)$	$\left(^{+0.37}_{-0.35}\right)$

Production process	ggH best fit	ggH unc.	ggH Stat.	ggH Syst.	VBF best fit	VBF unc.	VBF Stat.	VBF Syst.	WH best fit	WH unc.	WH Stat.	WH Syst.	ZH best fit	ZH unc.	ZH Stat.	ZH Syst.	ttH best fit	ttH unc.	ttH Stat.	ttH Syst.
$H \to \tau\tau$	1.05	$^{+0.53}_{-0.47}$	$^{+0.25}_{-0.25}$	$^{+0.47}_{-0.40}$	1.12	$^{+0.45}_{-0.43}$	$^{+0.37}_{-0.35}$	$^{+0.25}_{-0.25}$	–				–				0.22	$^{+1.03}_{-0.88}$	$^{+0.80}_{-0.71}$	$^{+0.65}_{-0.52}$
		$\left(^{+0.45}_{-0.41}\right)$	$\left(^{+0.23}_{-0.23}\right)$	$\left(^{+0.38}_{-0.34}\right)$		$\left(^{+0.45}_{-0.43}\right)$	$\left(^{+0.37}_{-0.35}\right)$	$\left(^{+0.25}_{-0.24}\right)$	–				–					$\left(^{+0.98}_{-0.87}\right)$	$\left(^{+0.80}_{-0.73}\right)$	$\left(^{+0.56}_{-0.47}\right)$
$H \to WW$	1.35	$^{+0.20}_{-0.19}$	$^{+0.12}_{-0.12}$	$^{+0.17}_{-0.15}$	0.28	$^{+0.64}_{-0.60}$	$^{+0.58}_{-0.53}$	$^{+0.28}_{-0.28}$	3.91	$^{+2.26}_{-2.01}$	$^{+1.89}_{-1.72}$	$^{+1.24}_{-1.05}$	0.96	$^{+1.81}_{-1.46}$	$^{+1.74}_{-1.44}$	$^{+0.51}_{-0.22}$	1.60	$^{+0.66}_{-0.59}$	$^{+0.40}_{-0.39}$	$^{+0.52}_{-0.45}$
		$\left(^{+0.17}_{-0.16}\right)$	$\left(^{+0.10}_{-0.10}\right)$	$\left(^{+0.13}_{-0.12}\right)$		$\left(^{+0.63}_{-0.58}\right)$	$\left(^{+0.57}_{-0.53}\right)$	$\left(^{+0.26}_{-0.25}\right)$		$\left(^{+1.47}_{-1.19}\right)$	$\left(^{+1.32}_{-1.06}\right)$	$\left(^{+0.64}_{-0.54}\right)$		$\left(^{+1.67}_{-1.37}\right)$	$\left(^{+1.61}_{-1.35}\right)$	$\left(^{+0.45}_{-0.20}\right)$		$\left(^{+0.56}_{-0.53}\right)$	$\left(^{+0.38}_{-0.38}\right)$	$\left(^{+0.41}_{-0.38}\right)$
$H \to ZZ$	1.22	$^{+0.24}_{-0.21}$	$^{+0.20}_{-0.19}$	$^{+0.12}_{-0.10}$	−0.09	$^{+1.02}_{-0.76}$	$^{+1.00}_{-0.72}$	$^{+0.21}_{-0.22}$	0.00	$^{+2.32}_{+0.00}$	$^{+2.31}_{-0.00}$	$^{+0.28}_{-0.00}$	0.00	$^{+4.26}_{+0.00}$	$^{+4.19}_{-0.00}$	$^{+0.81}_{-0.00}$	0.00	$^{+1.51}_{+0.00}$	$^{+1.48}_{-0.00}$	$^{+0.31}_{-0.00}$
		$\left(^{+0.22}_{-0.20}\right)$	$\left(^{+0.20}_{-0.19}\right)$	$\left(^{+0.10}_{-0.07}\right)$		$\left(^{+1.27}_{-0.99}\right)$	$\left(^{+1.25}_{-0.97}\right)$	$\left(^{+0.24}_{-0.21}\right)$		$\left(^{+4.45}_{-0.99}\right)$	$\left(^{+4.41}_{-0.99}\right)$	$\left(^{+0.57}_{-0.00}\right)$		$\left(^{+7.58}_{-0.99}\right)$	$\left(^{+7.46}_{-0.99}\right)$	$\left(^{+1.33}_{-0.00}\right)$		$\left(^{+2.95}_{-0.99}\right)$	$\left(^{+2.89}_{-0.99}\right)$	$\left(^{+0.59}_{-0.00}\right)$
$H \to \gamma\gamma$	1.15	$^{+0.21}_{-0.18}$	$^{+0.17}_{-0.15}$	$^{+0.13}_{-0.10}$	0.68	$^{+0.59}_{-0.45}$	$^{+0.49}_{-0.42}$	$^{+0.32}_{-0.18}$	3.71	$^{+1.49}_{-1.35}$	$^{+1.45}_{-1.33}$	$^{+0.35}_{-0.23}$	0.00	$^{+1.13}_{+0.00}$	$^{+1.13}_{-0.00}$	$^{+0.09}_{-0.00}$	2.14	$^{+0.87}_{-0.74}$	$^{+0.81}_{-0.72}$	$^{+0.31}_{-0.14}$
		$\left(^{+0.17}_{-0.16}\right)$	$\left(^{+0.14}_{-0.14}\right)$	$\left(^{+0.11}_{-0.08}\right)$		$\left(^{+0.59}_{-0.48}\right)$	$\left(^{+0.48}_{-0.43}\right)$	$\left(^{+0.34}_{-0.21}\right)$		$\left(^{+1.29}_{-1.16}\right)$	$\left(^{+1.28}_{-1.16}\right)$	$\left(^{+0.13}_{-0.06}\right)$		$\left(^{+2.52}_{-1.04}\right)$	$\left(^{+2.50}_{-1.04}\right)$	$\left(^{+0.24}_{-0.00}\right)$		$\left(^{+0.72}_{-0.62}\right)$	$\left(^{+0.71}_{-0.62}\right)$	$\left(^{+0.15}_{-0.06}\right)$

Production process															
ggH				VBF				WH				ZH			
Best fit value		Uncertainty Stat.	Syst.	Best fit value		Uncertainty Stat.	Syst.	Best fit value		Uncertainty Stat.	Syst.	Best fit value		Uncertainty Stat.	Syst.
1.23	$^{+0.14}_{-0.13}$	$^{+0.08}_{-0.08}$	$^{+0.12}_{-0.10}$	0.73	$^{+0.30}_{-0.27}$	$^{+0.24}_{-0.23}$	$^{+0.17}_{-0.15}$	2.18	$^{+0.58}_{-0.55}$	$^{+0.46}_{-0.45}$	$^{+0.34}_{-0.32}$	0.87	$^{+0.44}_{-0.42}$	$^{+0.39}_{-0.38}$	$^{+0.20}_{-0.18}$
	$\left(^{+0.11}_{-0.11}\right)$	$\left(^{+0.07}_{-0.07}\right)$	$\left(^{+0.09}_{-0.08}\right)$		$\left(^{+0.29}_{-0.27}\right)$	$\left(^{+0.24}_{-0.23}\right)$	$\left(^{+0.16}_{-0.15}\right)$		$\left(^{+0.53}_{-0.51}\right)$	$\left(^{+0.43}_{-0.42}\right)$	$\left(^{+0.30}_{-0.29}\right)$		$\left(^{+0.42}_{-0.40}\right)$	$\left(^{+0.38}_{-0.37}\right)$	$\left(^{+0.19}_{-0.17}\right)$

Production process			
ttH			
Best fit value		Uncertainty Stat.	Syst.
1.18	$^{+0.31}_{-0.27}$	$^{+0.16}_{-0.16}$	$^{+0.26}_{-0.21}$
	$\left(^{+0.28}_{-0.25}\right)$	$\left(^{+0.16}_{-0.16}\right)$	$\left(^{+0.23}_{-0.20}\right)$

Decay mode															
$H \to bb$				$H \to \tau\tau$				$H \to WW$				$H \to ZZ$			
Best fit value		Uncertainty Stat.	Syst.	Best fit value		Uncertainty Stat.	Syst.	Best fit value		Uncertainty Stat.	Syst.	Best fit value		Uncertainty Stat.	Syst.
1.12	$^{+0.29}_{-0.28}$	$^{+0.19}_{-0.19}$	$^{+0.22}_{-0.20}$	1.02	$^{+0.26}_{-0.24}$	$^{+0.15}_{-0.15}$	$^{+0.21}_{-0.19}$	1.28	$^{+0.17}_{-0.16}$	$^{+0.09}_{-0.09}$	$^{+0.14}_{-0.13}$	1.06	$^{+0.19}_{-0.17}$	$^{+0.16}_{-0.15}$	$^{+0.10}_{-0.08}$
	$\left(^{+0.28}_{-0.27}\right)$	$\left(^{+0.19}_{-0.18}\right)$	$\left(^{+0.21}_{-0.20}\right)$		$\left(^{+0.24}_{-0.23}\right)$	$\left(^{+0.15}_{-0.14}\right)$	$\left(^{+0.19}_{-0.17}\right)$		$\left(^{+0.14}_{-0.13}\right)$	$\left(^{+0.09}_{-0.09}\right)$	$\left(^{+0.11}_{-0.10}\right)$		$\left(^{+0.18}_{-0.16}\right)$	$\left(^{+0.15}_{-0.14}\right)$	$\left(^{+0.10}_{-0.08}\right)$

Decay mode			
$H \to \gamma\gamma$			
Best fit value		Uncertainty Stat.	Syst.
1.20	$^{+0.17}_{-0.14}$	$^{+0.12}_{-0.11}$	$^{+0.12}_{-0.09}$
	$\left(^{+0.14}_{-0.12}\right)$	$\left(^{+0.10}_{-0.10}\right)$	$\left(^{+0.09}_{-0.07}\right)$

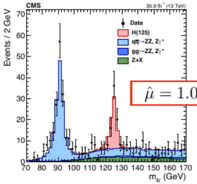
Uncertainty correlations between inputs

- **Signal theory uncertainties,** generally correlated:
  - Systematic uncertainties on cross section due to **renormalisation and factorisation scales** and **PDFs** correlated, as are those on branching ratios due to **partial width** uncertainties
  - **Underlying event** and **parton shower** uncertainties also correlated
- **Background theory uncertainties,** generally correlated:
  - When backgrounds are normalised from MC correlate uncertainties on **cross section**
  - E.g. tt+HF correlated between ttH→bb hadronic and leptonic analyses
- **Correlation of experimental uncertainties,** generally uncorrelated, **except**:
  - **Luminosity**
  - **Pileup modelling** in the MC simulation
  - **Jet energy scale**: correlated between the channels with high sensitivity to this uncertainty (e.g. H→ττ, VH(bb), ttH(bb))
  - **b-tagging**: correlated between ttH channels, but uncorrelated with VH(bb) channel which is sensitive to different kinematic regime

Contributing analyses

	ggF	VBF	VH	ttH
H→ZZ→4l	•	•	•	•
H→γγ	•	•	•	•
H→WW	•	•	•	•
H→bb	•		•	•
H→ττ	•	•		•
H→μμ	•	•		
H→inv	•	•	•	

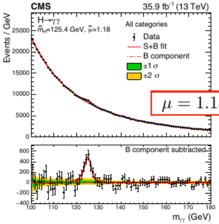
H→ZZ→4l *(June 2017)*



$\hat{\mu} = 1.05^{+0.19}_{-0.17}$

- Main systematics:
  - lepton ID efficiency
  - theoretical uncertainties on ggH prediction

H→γγ *(April 2018)*



$\mu = 1.18^{+0.17}_{-0.14}$

- Paper submitted today, arXiv:1804.02716
- Main systematics:
  - Photon identification and energy scale
  - theoretical uncertainties on ggH prediction

- Differential measurements also performed in both channels (not covered in this talk)

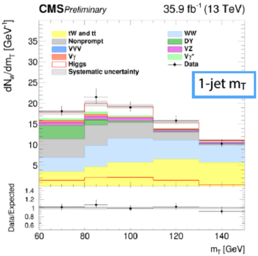
Contributing analyses

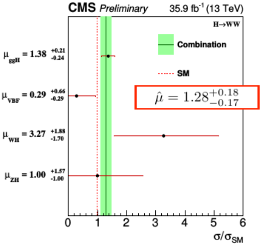
H→WW *(March 2018)*

	ggF	VBF	VH	ttH
H→ZZ→4l	•	•	•	•
H→γγ	•	•	•	•
H→WW	•	•	•	•
H→bb	•		•	•
H→ττ	•	•		•
H→μμ	•	•		
H→inv	•	•	•	

- Dedicated event categories targeting ggH (0/1 jet), VBF and VH production, control regions to determine WW, top and DY backgrounds
- Categories for same-flavour (ee/μμ) lepton final state as well as different-flavour (eμ)

- Main systematics:
  - background determination
  - luminosity
  - theoretical uncertainties on signal normalisation and acceptance





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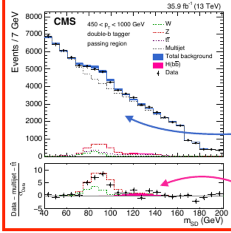
Contributing analyses

	ggF	VBF	VH	ttH
H→ZZ→4l	•	•	•	•
H→γγ	•	•	•	•
H→WW	•	•	•	•
H→bb	•		•	•
H→ττ	•	•		•
H→μμ	•	•		
H→inv	•	•	•	

ggH→bb *(Sept 2017)*

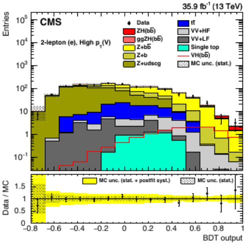


	H
Observed signal strength	$2.3^{+1.8}_{-1.6}$
Expected UL signal strength	< 3.3
Observed UL signal strength	< 5.8
Expected significance	0.7σ
Observed significance	1.5σ

Dominant QCD background from data

Reconstruct H→bb decay within a single boosted jet of $p_T > 450$ GeV, using substructure techniques

VH→bb *(Sept 2017)*



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

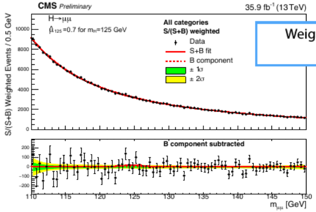
BDT-based discriminant in 0, 1 and 2 lepton categories with high p_T(V)
Main backgrounds from V + HF/LF jet production and $t\bar{t}$

- Main systematic uncertainties from background normalisation and modelling, MC statistics, b-tagging efficiency

Contributing analyses

	ggF	VBF	VH	ttH
H→ZZ→4l	•	•	•	•
H→γγ	•	•	•	•
H→WW	•	•	•	•
H→bb	•		•	•
H→ττ	•	•		•
H→μμ	•	•		
H→inv	•	•	•	

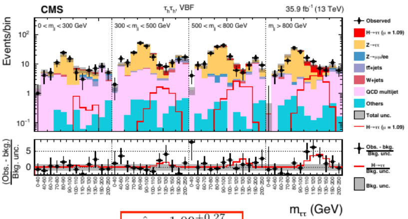
H→μμ *(Nov 2017)*



Weighted sum of all 15 event categories

$\hat{\mu} = 0.7 \pm 1.0$

H→ττ *(August 2017)*



$\hat{\mu} = 1.09^{+0.27}_{-0.26}$

- Main experimental uncertainties from τ_h and p_T^{miss} scales, background normalisation and MC statistics
- Main theory uncertainties on signal cross section and gluon-fusion category migration

Parameterisation	p-value (q_{SM})	DOF	Parameters of interest
Global signal strength	6.12% (3.51)	1	μ
Production processes	9.21% (9.46)	5	$\mu_{ggH}, \mu_{VBF}, \mu_{WH}, \mu_{ZH}, \mu_{ttH}$
Decay modes	43.4% (4.85)	5	$\mu^{\gamma\gamma}, \mu^{ZZ}, \mu^{WW}, \mu^{\tau\tau}, \mu^{bb}$
$\sigma_i \cdot BR^f$ products	50.4% (21.3)	22	$\sigma_{ggH}\cdot BR^{bb}$, $\sigma_{ggH}\cdot BR^{\tau\tau}$, $\sigma_{ggH}\cdot BR^{WW}$, $\sigma_{ggH}\cdot BR^{ZZ}$, $\sigma_{ggH}\cdot BR^{\gamma\gamma}$, $\sigma_{VBF}\cdot BR^{\tau\tau}$, $\sigma_{VBF}\cdot BR^{WW}$, $\sigma_{VBF}\cdot BR^{ZZ}$, $\sigma_{VBF}\cdot BR^{\gamma\gamma}$, $\sigma_{WH}\cdot BR^{bb}$, $\sigma_{WH}\cdot BR^{WW}$, $\sigma_{WH}\cdot BR^{ZZ}$, $\sigma_{WH}\cdot BR^{\gamma\gamma}$, $\sigma_{ZH}\cdot BR^{bb}$, $\sigma_{ZH}\cdot BR^{WW}$, $\sigma_{ZH}\cdot BR^{ZZ}$, $\sigma_{ZH}\cdot BR^{\gamma\gamma}$, $\sigma_{ttH}\cdot BR^{\tau\tau}$, $\sigma_{ttH}\cdot BR^{WW}$, $\sigma_{ttH}\cdot BR^{ZZ}$, $\sigma_{ttH}\cdot BR^{\gamma\gamma}$
Ratios of σ and BR relative to $gg \to H \to ZZ$	24.5% (11.5)	9	μ^{ZZ}_{ggH}, μ_{VBF}/μ_{ggH}, μ_{WH}/μ_{ggH}, μ_{ZH}/μ_{ggH}, μ_{ttH}/μ_{ggH}, μ^{WW}/μ^{ZZ}, $\mu^{\gamma\gamma}/\mu^{ZZ}$, $\mu^{\tau\tau}/\mu^{ZZ}$, μ^{bb}/μ^{ZZ}
Simplified template cross sections with branching fractions relative to BR^{ZZ}	17.2% (14.0)	10	$\sigma_{ggH}\cdot BR^{ZZ}$, $\sigma_{VBF}\cdot BR^{ZZ}$, $\sigma_{H+V(qq)}\cdot BR^{ZZ}$, $\sigma_{H+W(\ell\nu)}\cdot BR^{ZZ}$, $\sigma_{H+Z(\ell\ell/\nu\nu)}\cdot BR^{ZZ}$, $\sigma_{ttH}\cdot BR^{ZZ}$, BR^{bb}/BR^{ZZ}, $BR^{\tau\tau}/BR^{ZZ}$, BR^{WW}/BR^{ZZ}, $BR^{\gamma\gamma}/BR^{ZZ}$
Couplings, SM loops	35.4% (5.54)	5	$\kappa_Z, \kappa_W, \kappa_t, \kappa_\tau, \kappa_b$
Couplings vs mass	17.1% (3.54)	2	M, ϵ
Couplings, BSM loops	57.7% (5.68)	7	$\kappa_Z, \kappa_W, \kappa_t, \kappa_\tau, \kappa_b, \kappa_\gamma, \kappa_g$
Couplings, BSM loops and decays including H →inv. channels	78.6% (5.53)	9	$\kappa_Z, \kappa_W, \kappa_t, \kappa_\tau, \kappa_b, \kappa_\gamma, \kappa_g, BR_{inv.}, BR_{undet.}$
Ratios of coupling modifiers	56.7% (5.77)	7	$\kappa_{gZ}, \lambda_{WZ}, \lambda_{\gamma Z}, \lambda_{tg}, \lambda_{bZ}, \lambda_{\tau Z}, \lambda_{Zg}$
Fermion and vector couplings	16.9% (3.55)	2	κ_F, κ_V
Fermion and vector couplings, per decay mode	63.9% (7.89)	10	$\kappa_F^{bb}, \kappa_F^{\tau\tau}, \kappa_F^{WW}, \kappa_F^{ZZ}, \kappa_F^{\gamma\gamma}, \kappa_V^{bb}, \kappa_V^{\tau\tau}, \kappa_V^{WW}, \kappa_V^{ZZ}, \kappa_V^{\gamma\gamma}$
Up vs down-type couplings	25.5% (4.06)	3	$\lambda_{Vu}, \lambda_{du}, \kappa_{uu}$
Lepton vs quark couplings	26.5% (3.97)	3	$\lambda_{\ell q}, \lambda_{Vq}, \kappa_{qq}$

Coupling modifier model

- Use the LO coupling modifier or "kappa" framework to probe for deviations from the SM
- Parameters scale cross sections and partial widths relative to SM

$$\kappa_j^2 = \sigma_j / \sigma_j^{\rm SM} \qquad \kappa_j^2 = \Gamma_j / \Gamma_j^{\rm SM}$$

$$\Rightarrow \quad \sigma_i \cdot {\rm BR}^f = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\Gamma_{\rm H}}$$ where total width $\Gamma_{\rm H}$ given by $$\frac{\Gamma_{\rm H}}{\Gamma_{\rm H}^{\rm SM}} = \frac{\kappa_{\rm H}^2}{1 - ({\rm BR}_{\rm undet.} + {\rm BR}_{\rm inv.})}$$

where $\kappa_H^2 = \sum_j {\rm BR}_{\rm SM}^j \kappa_j^2$

- Option to consider decay to BSM particles via BR_{undet} and BR_{inv} terms which also scale total width
  - BR_{inv}: Scales signal normalisation in direct H→invisible searches
  - BR_{undet}: Represents branching ratio to any final state not directly detected by analyses

Coupling modifier model

- Summary of how all production and decay processes scale as a function of the κ parameters:

Production	Loops	Interference	Effective scaling factor	Resolved scaling factor
$\sigma(\text{ggH})$	✓	b − t	κ_g^2	$1.04 \cdot \kappa_t^2 + 0.002 \cdot \kappa_b^2 - 0.038 \cdot \kappa_t\kappa_b$
$\sigma(\text{VBF})$	–	–		$0.73 \cdot \kappa_W^2 + 0.27 \cdot \kappa_Z^2$
$\sigma(\text{WH})$	–	–		κ_W^2
$\sigma(\text{qq/qg} \to \text{ZH})$	–	–		κ_Z^2
$\sigma(\text{gg} \to \text{ZH})$	✓	Z − t		$2.46 \cdot \kappa_Z^2 + 0.47 \cdot \kappa_t^2 - 1.94 \cdot \kappa_Z\kappa_t$
$\sigma(\text{ttH})$	–	–		κ_t^2
$\sigma(\text{gb} \to \text{WtH})$	–	W − t		$2.91 \cdot \kappa_t^2 + 2.40 \cdot \kappa_W^2 - 4.22 \cdot \kappa_t\kappa_W$
$\sigma(\text{qb} \to \text{tHq})$	–	W − t		$2.63 \cdot \kappa_t^2 + 3.58 \cdot \kappa_W^2 - 5.21 \cdot \kappa_t\kappa_W$
$\sigma(\text{bbH})$	–	–		κ_b^2
Partial decay width				
Γ^{ZZ}	–	–		κ_Z^2
Γ^{WW}	–	–		κ_W^2
$\Gamma^{\gamma\gamma}$	✓	W − t	κ_γ^2	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.67 \cdot \kappa_W\kappa_t$
$\Gamma^{\tau\tau}$	–	–		κ_τ^2
Γ^{bb}	–	–		κ_b^2
$\Gamma^{\mu\mu}$	–	–		κ_μ^2
Total width for $\text{BR}_{\text{BSM}} = 0$				
Γ_H	✓	–	κ_H^2	$0.58 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.08 \cdot \kappa_g^2 + 0.06 \cdot \kappa_\tau^2 + 0.026 \cdot \kappa_Z^2 + 0.029 \cdot \kappa_c^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.0015 \cdot \kappa_{Z\gamma}^2 + 0.00025 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$

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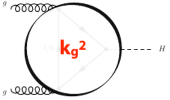
Coupling modifier model

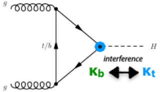
- Contrary to signal strength model have interference effects in some production and decay processes:

Production	Loops	Interference	Effective scaling factor	Resolved scaling factor
$\sigma(\mathrm{ggH})$	✓	b − t	κ_g^2	$1.04 \cdot \kappa_t^2 + 0.002 \cdot \kappa_b^2 - 0.038 \cdot \kappa_t \kappa_b$
Partial decay width				
Γ^{ZZ}	–	–		κ_Z^2
Γ^{WW}	–	–		κ_W^2
$\Gamma^{\gamma\gamma}$	✓	W − t	κ_γ^2	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.67 \cdot \kappa_W \kappa_t$

Gluon fusion production can be scaled by an independent effective coupling parameter: allows for contribution of BSM particles in the loop

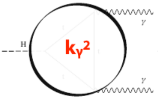


Effective coupling

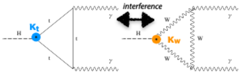


Resolved in terms of t and b couplings

Similar for H→γγ. When resolved into scaling by κ_t and κ_W we are sensitive to the relative sign: $\Gamma_{\gamma\gamma}/\Gamma_{\gamma\gamma}^{SM} = 2.3$ when $\kappa_W \cdot \kappa_t = -1$



Effective coupling



Resolved in terms of t and W couplings

ttH combination

$$\mu_{t\bar{t}H} = 1.26^{+0.31}_{-0.26} = 1.26^{+0.16}_{-0.16}(\text{stat})^{+0.17}_{-0.15}(\text{expt})^{+0.14}_{-0.13}(\text{bkg th})^{+0.15}_{-0.07}(\text{sig th})$$

- Each of the four uncertainty components of comparable magnitude
- More detailed breakdown into sources reveals the specific uncertainties that dominate
- **Signal theory** mainly from inclusive ttH prediction
- **Background theory** mainly from tt+heavy flavour prediction in ttH(bb)
- **Experimental** more varied, but lepton efficiencies, lepton mis-id, b-tagging and MC stats all important

Uncertainty source	$\Delta\mu$	
Signal theory	+0.15	−0.07
Inclusive ttH normalisation (cross section and BR)	+0.15	−0.07
ttH acceptance (scale, pdf, PS and UE)	+0.004	−0.004
Other Higgs boson production modes	+0.002	−0.003
Background theory	+0.14	−0.13
tt + bb/cc prediction	+0.13	−0.11
tt + V(V) prediction	+0.06	−0.06
Other background uncertainties	+0.03	−0.03
Experimental	+0.17	−0.15
Lepton (inc. τ_h) trigger, ID and iso. efficiency	+0.08	−0.06
Misidentified lepton prediction	+0.06	−0.06
b-Tagging efficiency	+0.05	−0.04
Jet and τ_h energy scale and resolution	+0.04	−0.04
Luminosity	+0.04	−0.03
Photon ID, scale and resolution	+0.01	−0.01
Other experimental uncertainties	+0.01	−0.01
Finite number of simulated events	+0.08	−0.07
Statistical	+0.16	−0.16
Total	+0.31	−0.26

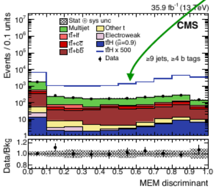
Due to correlations in the combined fit between parameters in different sources the sum in quadrature of sources ≠total component

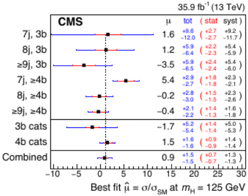
Contributing analyses

ttH→bb (hadronic) *(March 2018)*

	ggF	VBF	VH	ttH
H→ZZ→4l	•	•	•	•
H→γγ	•	•	•	•
H→WW	•	•	•	•
H→bb	•		•	•
H→ττ	•	•		•
H→μμ	•	•		
H→inv	•	•	•	

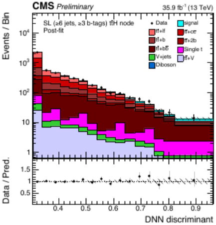
Large QCD multijet background, mitigated with quark-gluon discrimination

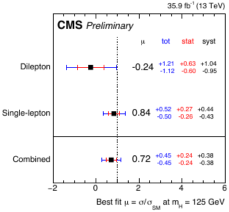




ttH→bb (leptonic) *(March 2018)*

- Utilises multivariate methods to separate signal from background:
  - 2D BDT + MEM approach in dilepton
  - Deep neural network classification in single-lepton
- Main systematics include b-tagging efficiency, MC stats., and tt̄+heavy flavour normalisation and modelling



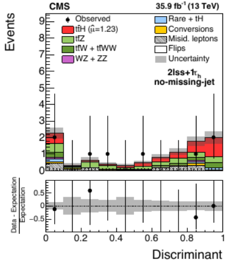


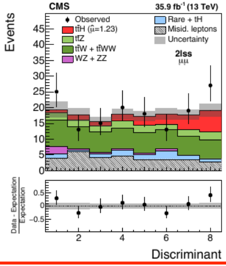
Contributing analyses

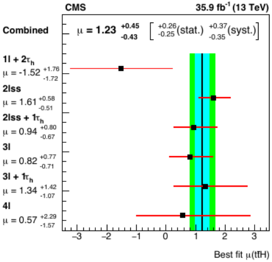
ttH→multileptons *(March 2018)*

	ggF	VBF	VH	ttH
H→ZZ→4l	•	•	•	•
H→γγ	•	•	•	•
H→WW	•	•	•	•
H→bb	•		•	•
H→ττ	•	•		•
H→μμ	•	•		
H→inv	•	•	•	

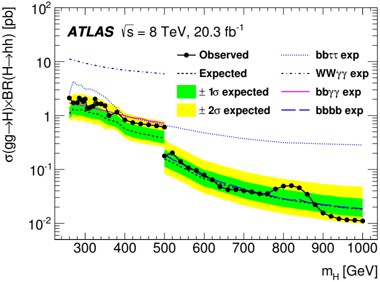
- Six search categories based on number of light (e/μ) leptons and hadronic taus
- Discrimination from main backgrounds (ttW, ttZ, lepton fakes) via a mixture of BDT and matrix element method techniques
- Main systematic uncertainties: lepton efficiencies, lepton mis-id., normalisation of irreducible backgrounds

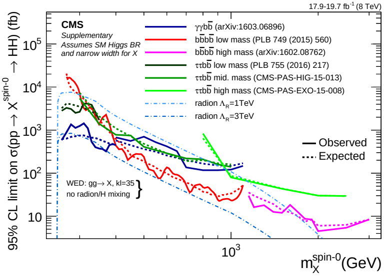






Run-I diHiggs results

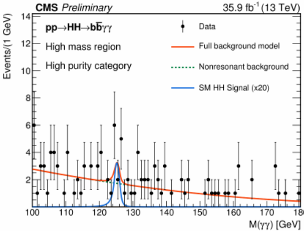


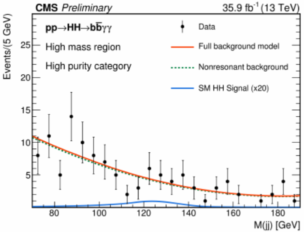


hh → bbγγ CMS

PAS-HIG-17-008 11

- Event Selection
  - Two γ's and two jets
  - $m_{\gamma\gamma}$ and m_{jj} in Higgs mass window
  - BDT classifier, including b-tagging information, used to define high/low signal-purity events
  - Classify "mass region" with corrected total mass: $\tilde{M}_X = m_{jj\gamma\gamma} - m_{jj} - m_{\gamma\gamma} + 250$
- Main background from QCD
- Signal estimates
  - Likelihood fits simultaneous to m_{bb} and $m_{\gamma\gamma}$ with parametric functions

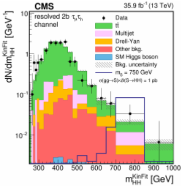


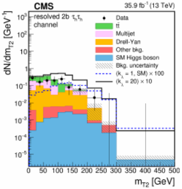


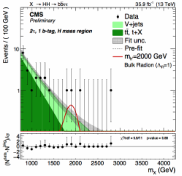
hh → bbττ CMS

Phys. Lett. B 778 (2018) 101
PAS-B2G-17-006

- Final states: $(e/\mu/\tau_h + \tau_h)$+2 jets or 1 large-R jet
  - Low / high mass resolved, and a boosted selection
  - For m_{HH}>1 TeV: dedicated boosted di-τ reconstruction
  - Categorize by 2/1 b-tags
  - Main backgrounds: Top, $Z \to \tau\tau$, Multijet
- Selection:
  - Likelihood fit to estimate $m_{\tau\tau}$, including p_T^{miss}
  - m_{bb} and $m_{\tau\tau}$ in Higgs mass window
  - BDT used to reduce top events in $(e/\mu + \tau_h)$ channels
- Signal estimates in likelihood fit to discriminant:
  - Resonant: m_{HH}^{KinFit}
  - Non-resonant: m_{T2}



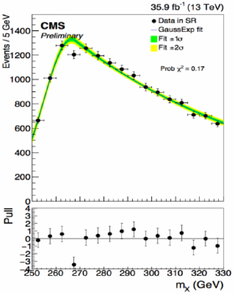


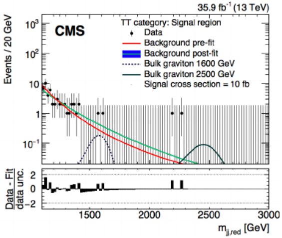


CMS hh → bbbb

arXiv:1710.04960
PAS-HIG-17-009

- Resolved
  - 4 b-jets, combination of Higgs candidates with smallest χ^2 when compared with expected Higgs mass
  - Parametric fit to m_{4b} distribution constrained from mass and b-tag sidebands
- Boosted
  - Two large-R jets, passing N-subjettiness substructure requirements
  - Dedicated MVA "double-b-tagger" used to identify Higgs candidates
  - Parametric fit to m_{hh} distribution



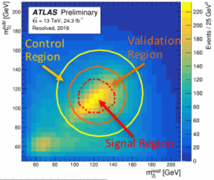


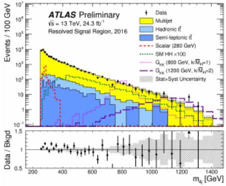
hh → bbbb ATLAS

NEW!

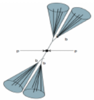
ATLAS-EXOT-2016-31

- Selection:
  - *Resolved*: 4 b-tagged jets
  - *Boosted*: 2 larger-R jets, with 2/3/4 small-R b-tagged jets
- Signal region:
  - Both Higgs candidate masses consistent with expected m_h within resolution
- Background 90% QCD
  - Estimated from data with fewer b-tags
- Signal Estimation
  - Binned fit to m_{hh} distribution

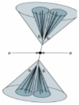


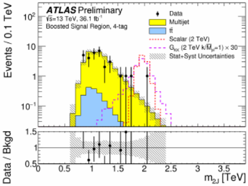


Resolved



Boosted



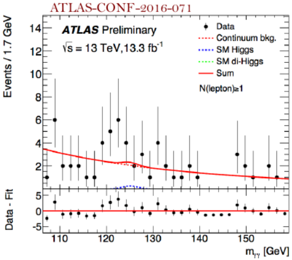


Systematics

- ATLAS 4b [ATLAS-EXOT-2016-31]
  - B-tagging: 12-14%
  - Jet energy scale: 6-7%
  - Background model: 2-6%
- CMS $bb\tau\tau$ [Phys. Lett. B 778 (2018) 101]
  - Tau energy scale, Jet energy scale, b-tagging: 2-10%
- CMS $bb\gamma\gamma$ [PAS-HIG-17-008]
  - Jet energy resolution, b-tagging: 3-5%

hh→WWγγ and hh→bbVV(→lνlν)

- ATLAS WWγγ
  - Require 2 γ's and 0/1 lepton (e/μ)
  - Parameterized fit to $m_{\gamma\gamma}$ to for signal search



- CMS bblνlν
  - Require 2 leptons (e/μ) and 2 b-jets
  - Parameterized Deep Neural Network output distribution fit for signal