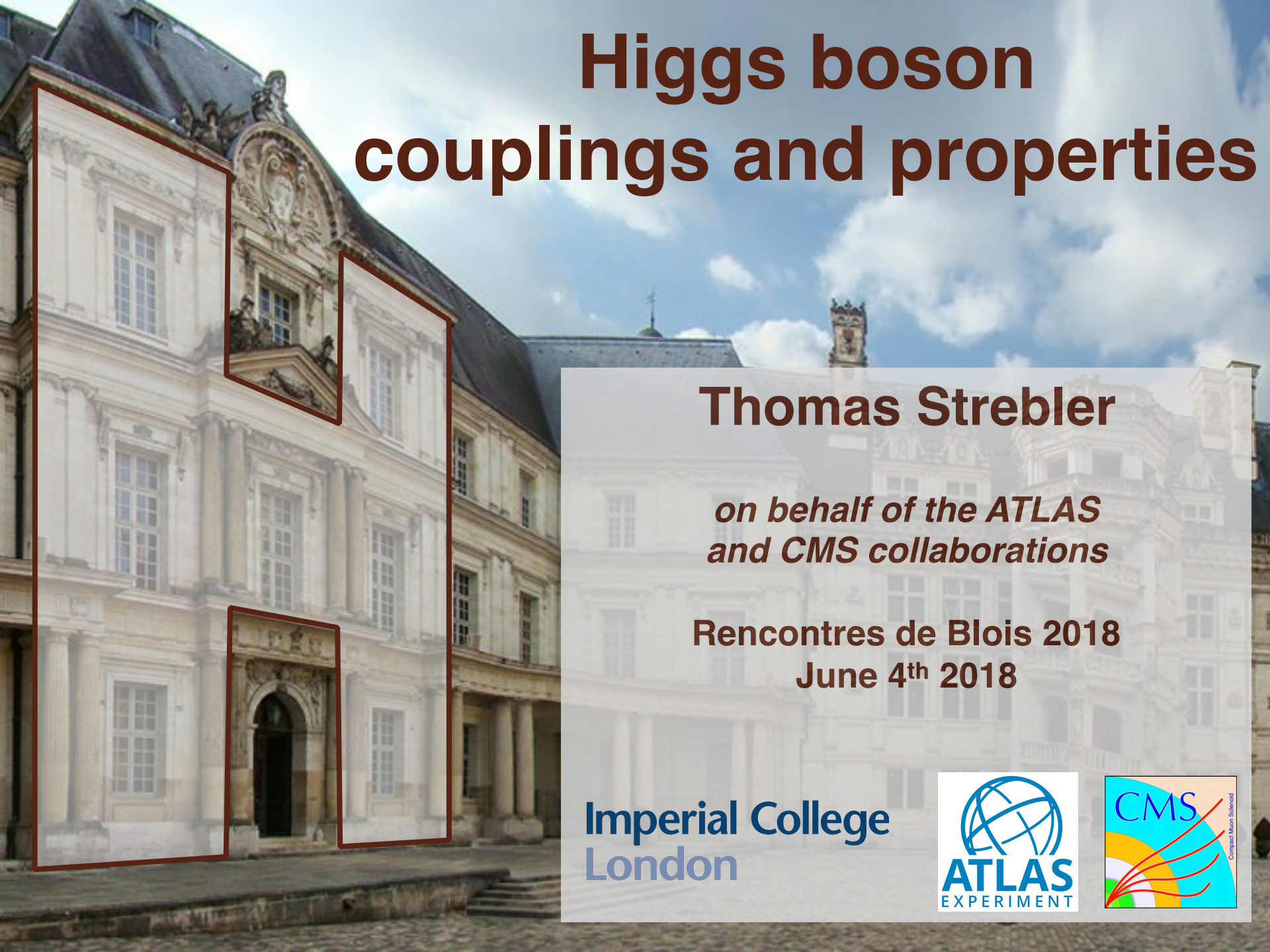


Higgs boson couplings and properties

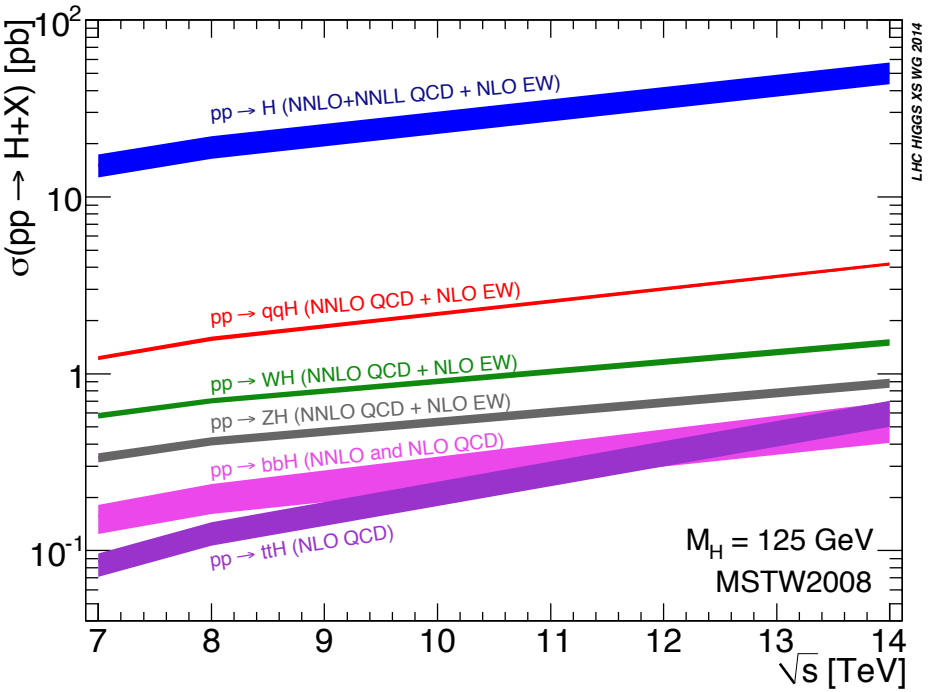
Thomas Strebler

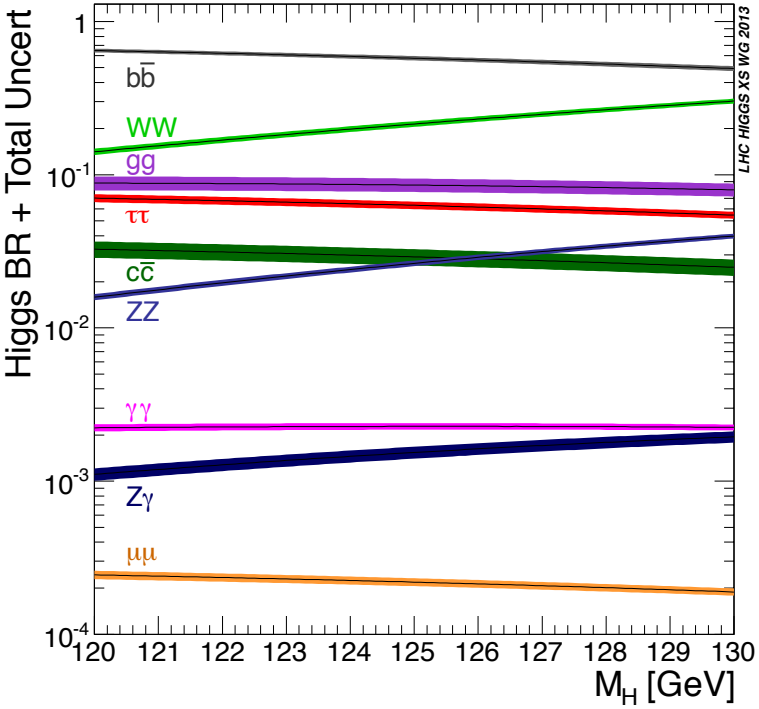
on behalf of the ATLAS and CMS collaborations

Imperial College London

Rencontres de Blois 2018
June 4th 2018

Higgs production at the LHC



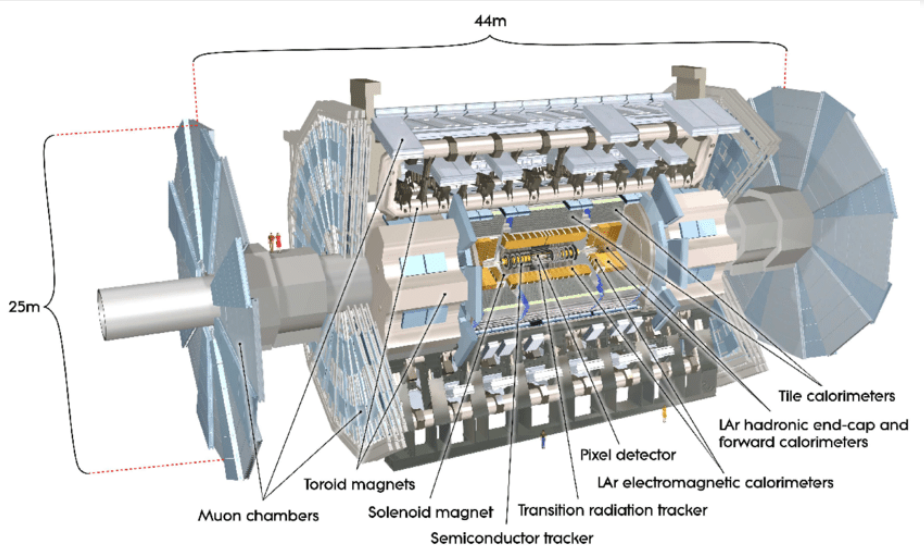


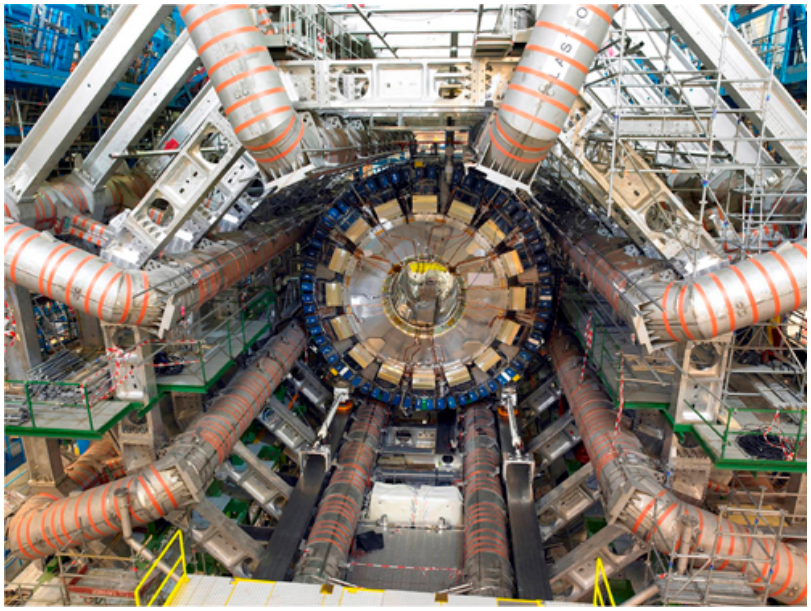
- **New scalar particle observed by ATLAS and CMS in 2012**

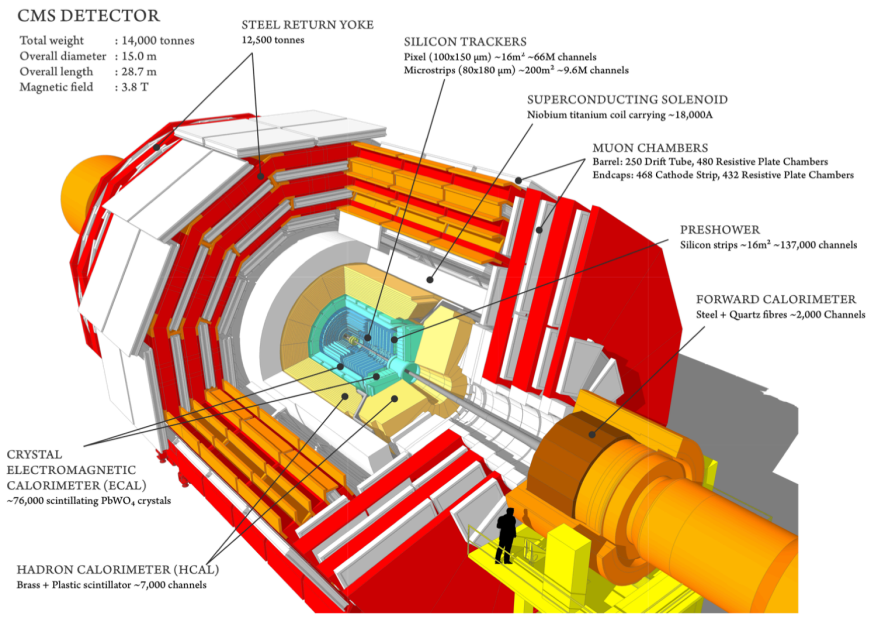
- **Very rich phenomenology associated with the SM Higgs boson at LHC:**
  - 4 main production modes
  - numerous decay channels

- **Very active experimental field:**
  - already a lot of precision measurements at 7-8 TeV
  - will focus here on some of the latest 13 TeV results

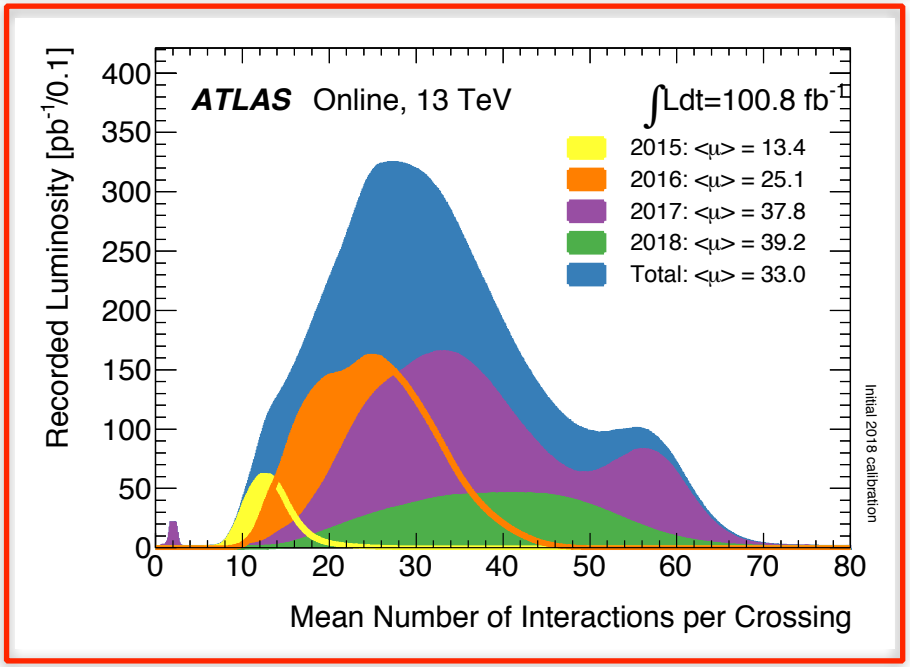
The ATLAS and CMS detectors

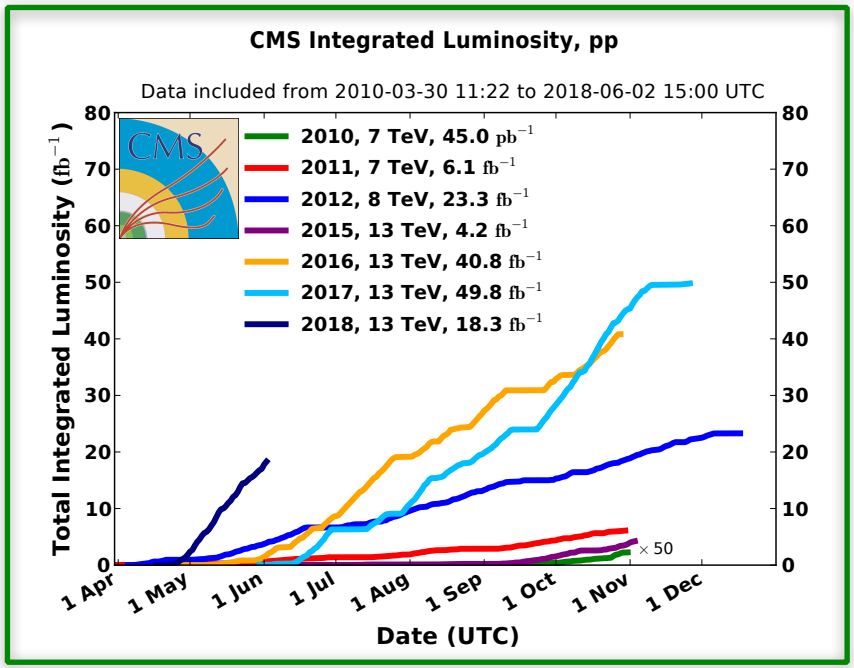






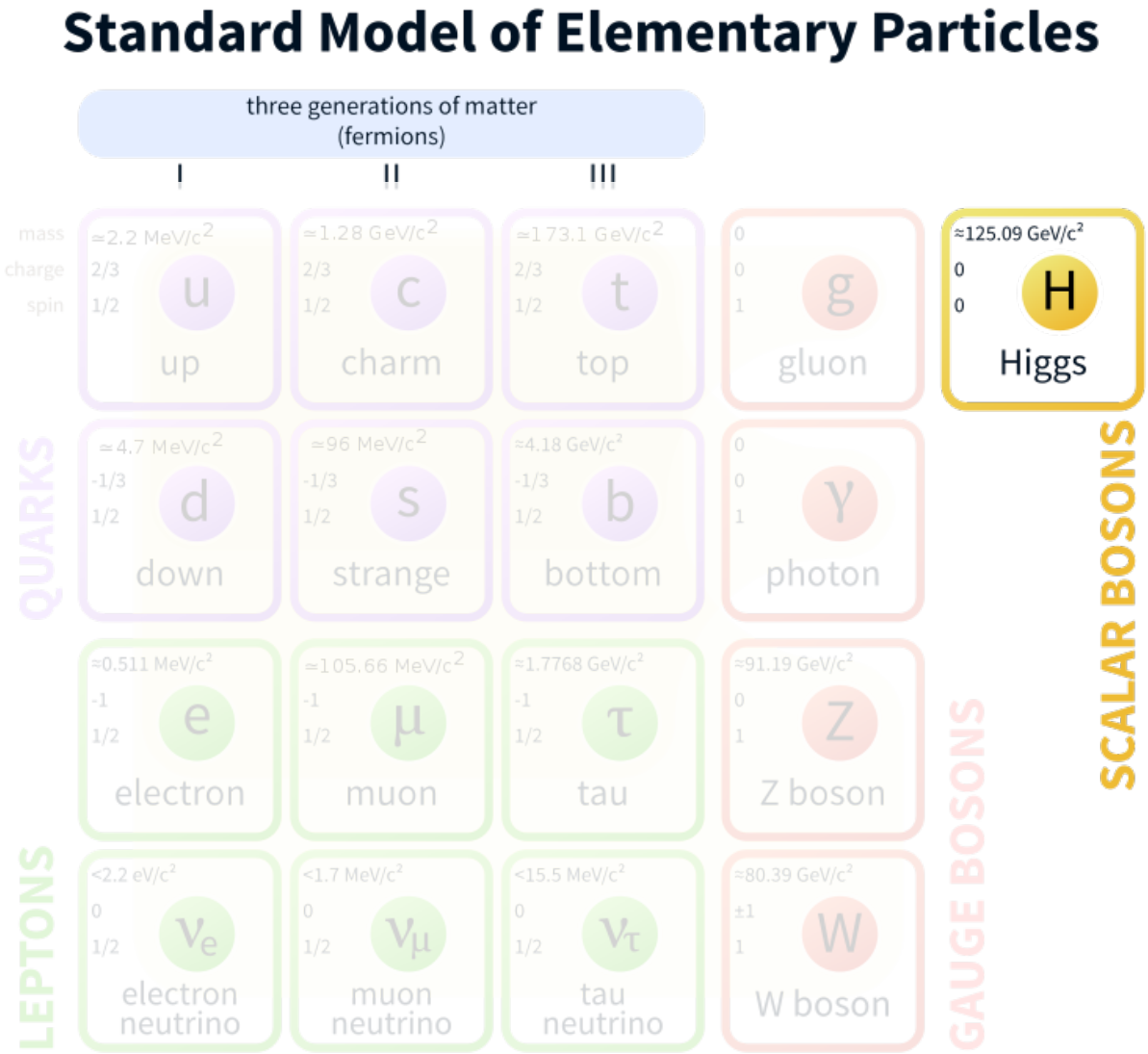
LHC Run 2 so far





- More challenging data-taking conditions due to **higher pile-up**
- But **significant increase in luminosity** with respect to Run 1 + **increase in cross-sections** from 8 to 13 TeV
- **Many new Higgs results benefitting from this:**
  - **Independent observation of the H→ττ decay** *CMS Phys. Let. B 779 (2018) 283, ATLAS-CONF-2018-021*
  - **Evidence for VH, H→bb process** *ATLAS JHEP 12 (2017) 024, CMS Phys. Let. B 780 (2018) 501*
  - **Observation of ttH production** *CMS Phys. Rev. Lett. 120, 231801 (2018), ATLAS arxiv:1806.00425*

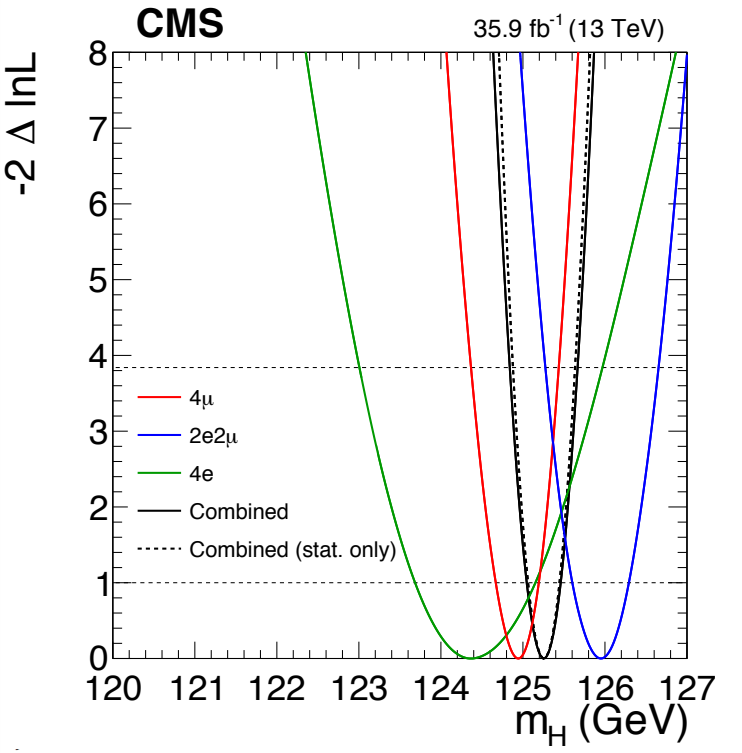
Higgs boson properties



Mass measurements

- **Based on high-resolution decay channels:** H→ZZ→4l and H→$\gamma\gamma$

CMS JHEP 11 (2017) 047



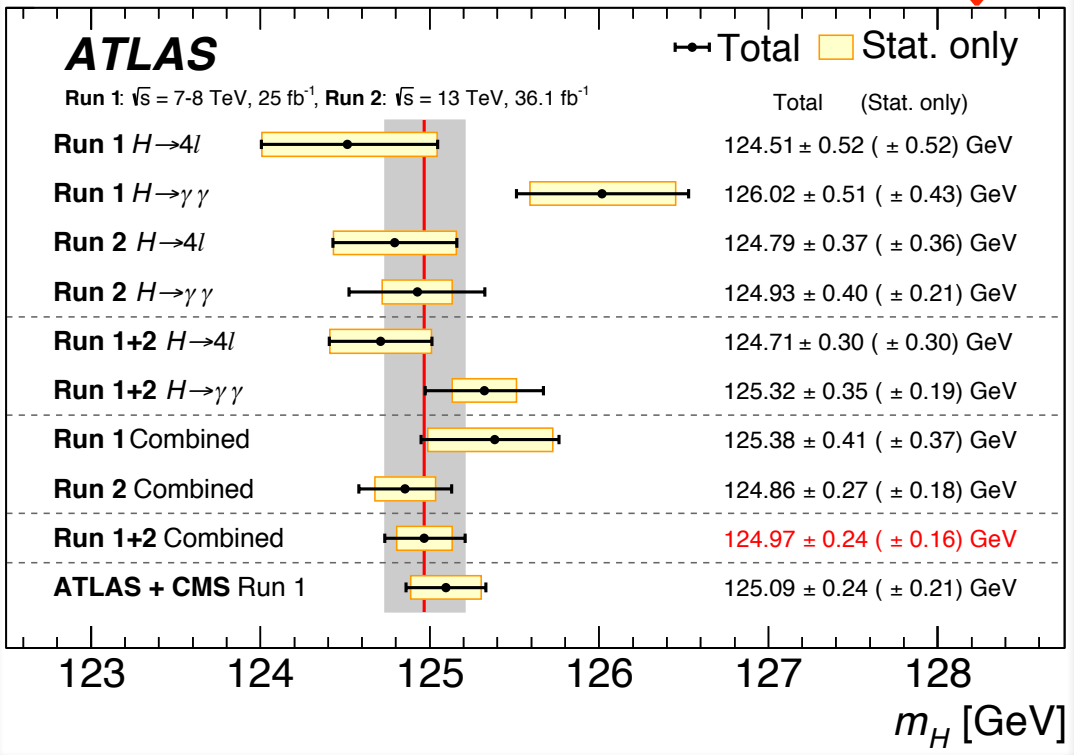
$m_{\mathrm{H}} = 125.26 \pm 0.20\,(\mathrm{stat}) \pm 0.08\,(\mathrm{syst})$ GeV

Width measurement

Parameter	$m_{4\ell}$ range	Observed
ΓH (GeV)	[105, 140]	$0.00^{+0.41}_{-0.00}$ [0.00, 1.10]

ATLAS arxiv:1806.00242

NEW

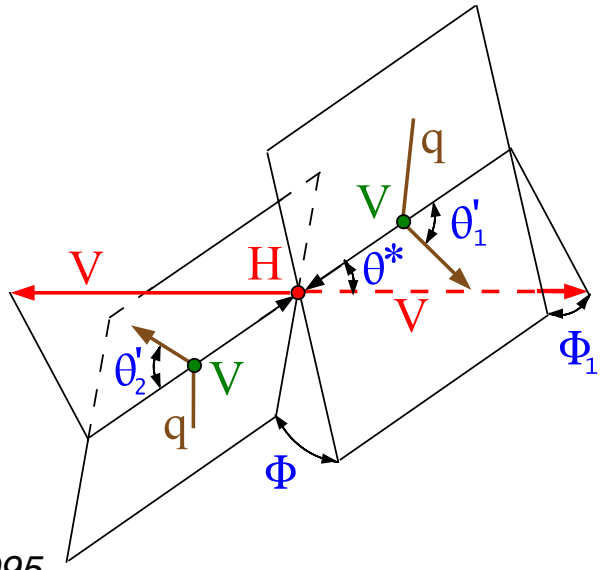


- **Uncertainty:**
  - H→ZZ→4l statistics dominated
  - H→$\gamma\gamma$ systematics dominated

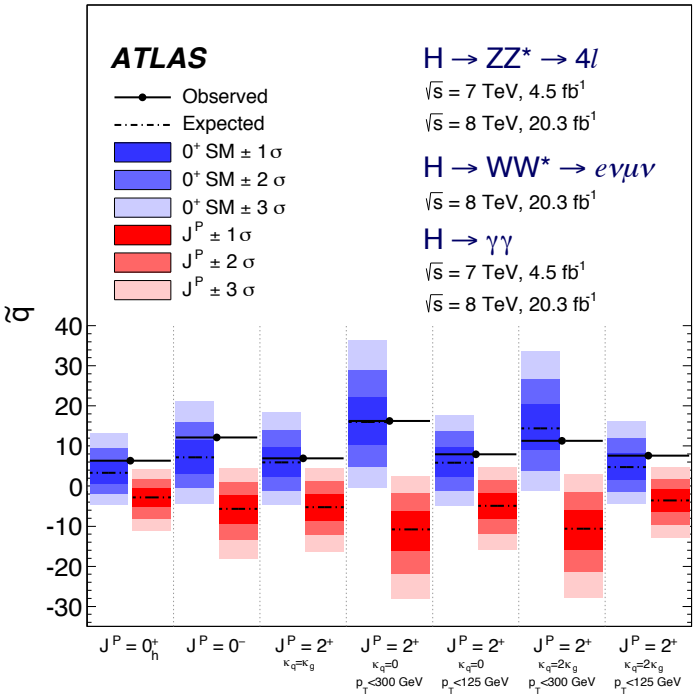
Spin-parity measurements

- **Run 1 analyses based on various decay modes:** H→ZZ→4l, H→WW→lvlv, VBF H→$\tau\tau$…

- Exploiting **angular correlations** between **Higgs decay products** and **objects produced in associated production modes**

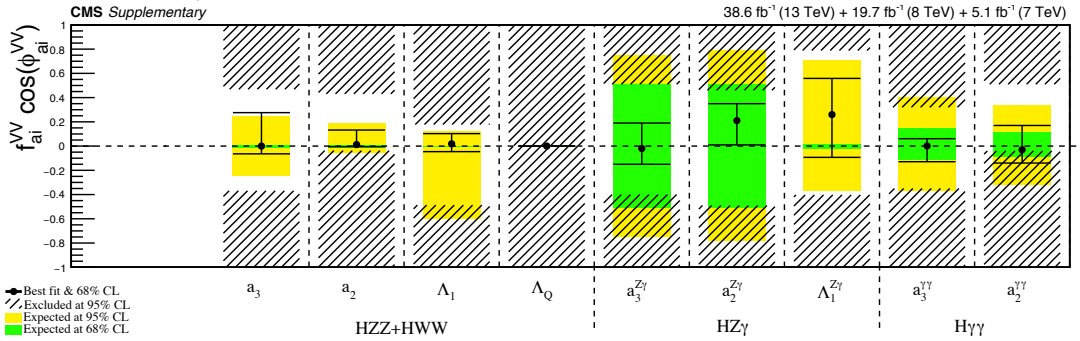


ATLAS Eur. Phys. J. C75 (2015) 476
CMS Phys. Rev. D92 (2015) 012004



- **Run 1 analyses excluded BSM CP numbers**

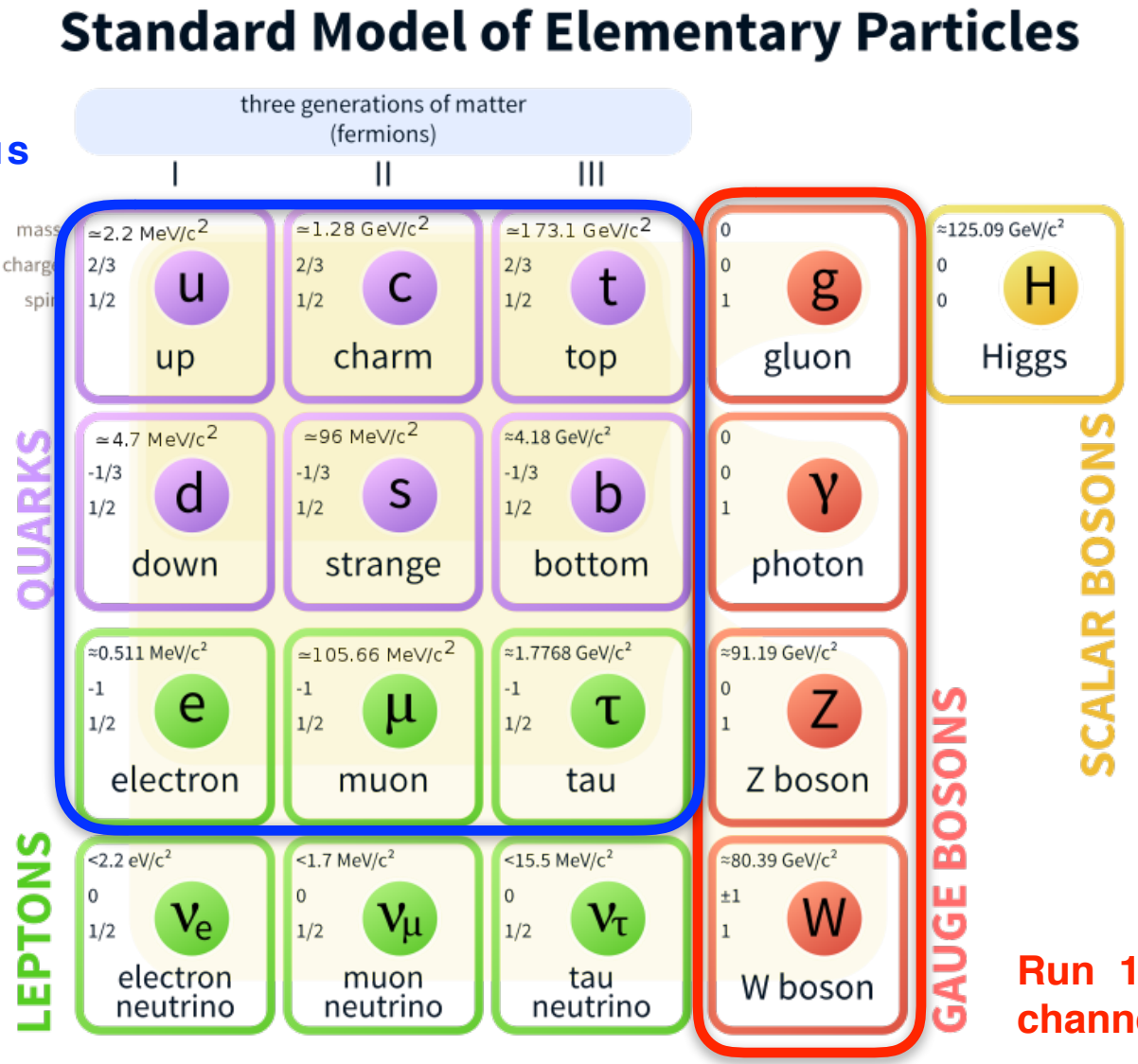
ATLAS JHEP 03 (2018) 095
CMS Phys. Lett. B775 (2017) 1



- Run 2 ATLAS and CMS H→ZZ→4l analyses improved **constraints on tensor structure of Higgs couplings**

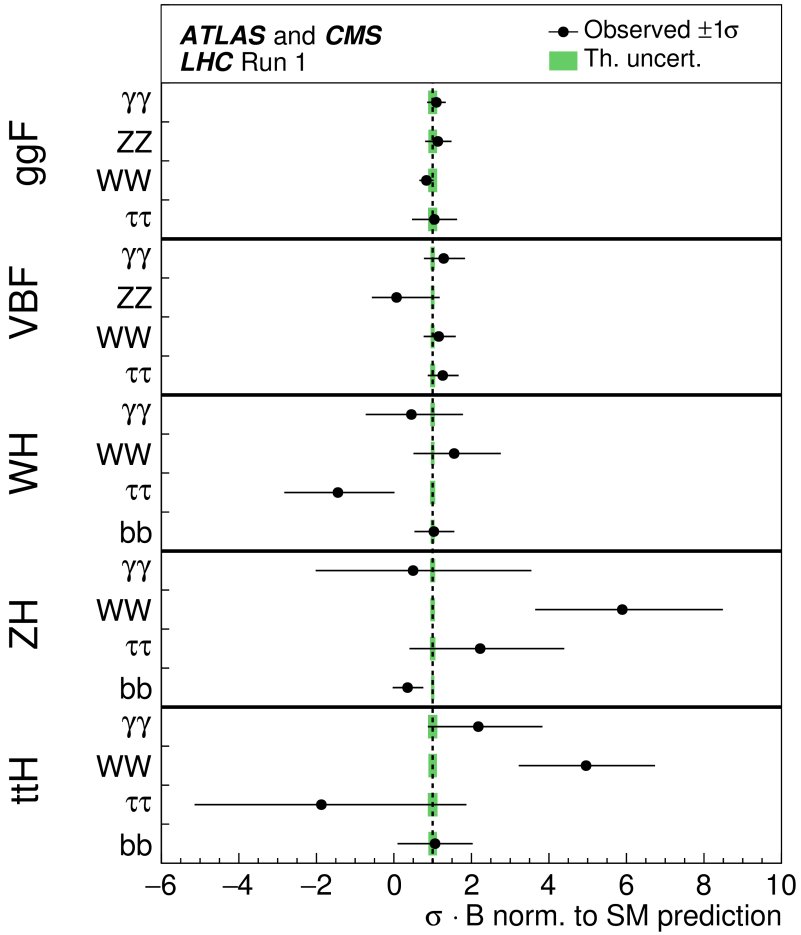
Higgs coupling results

More focus from Run 2



Run 1 discovery channels

Overview of Higgs coupling results

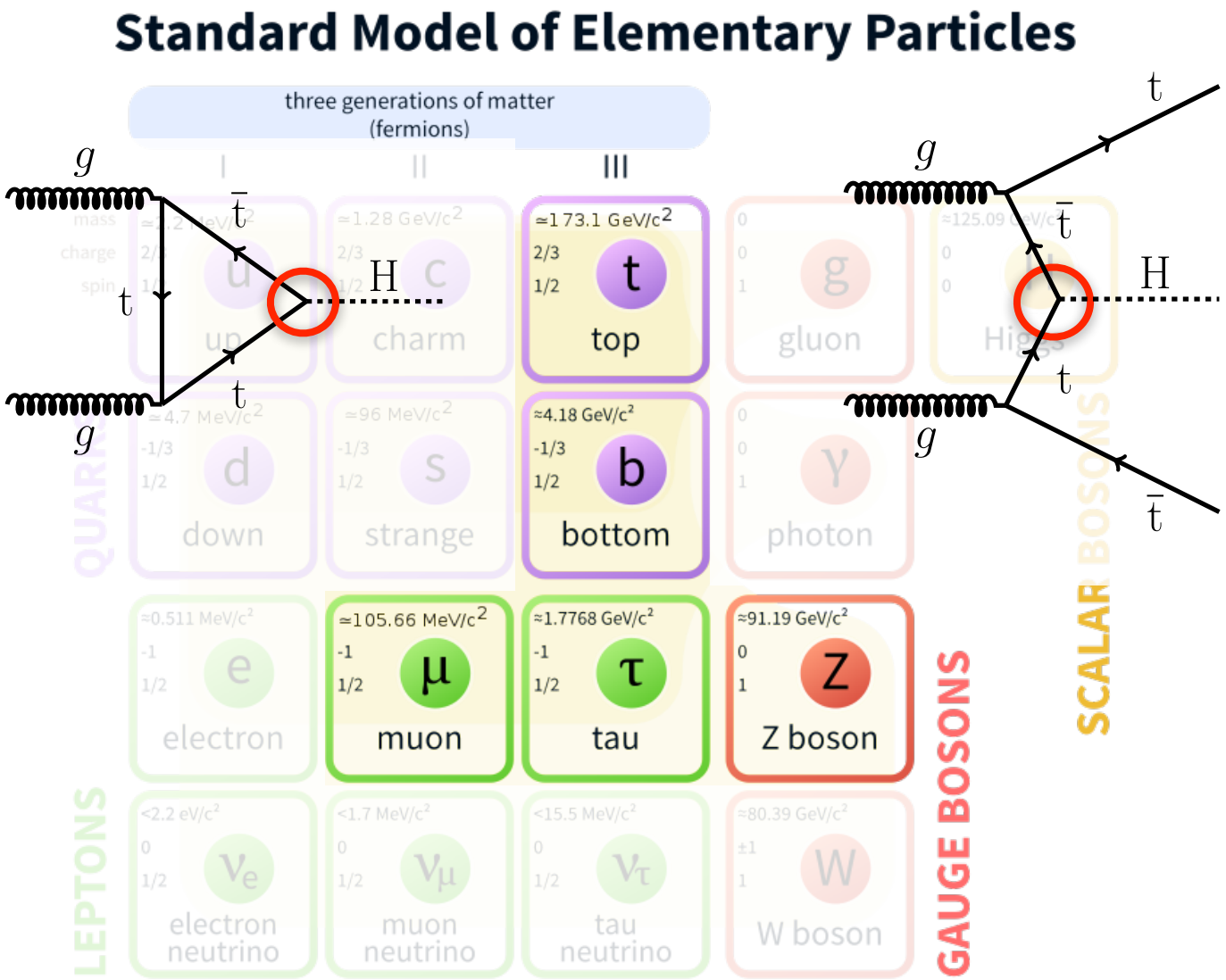


	ggF	VBF	VH	ttH
H→bb	CMS	ATLAS	ATLAS CMS	ATLAS CMS
H→ττ	ATLAS CMS	ATLAS CMS	CMS (not in comb.)	ATLAS CMS
H→WW	ATLAS CMS	ATLAS CMS	ATLAS CMS	ATLAS CMS
H→γγ	ATLAS CMS	ATLAS CMS	ATLAS CMS	ATLAS CMS
H→ZZ→4l	ATLAS CMS	ATLAS CMS	ATLAS CMS	ATLAS CMS
H→μμ	ATLAS CMS	ATLAS CMS		
H→inv.	CMS	CMS	ATLAS CMS	
H→cc			ATLAS	
H→φ/ρ+γ	ATLAS			

- **Run 1 ATLAS+CMS Higgs coupling combination** *JHEP 08 (2016) 045*

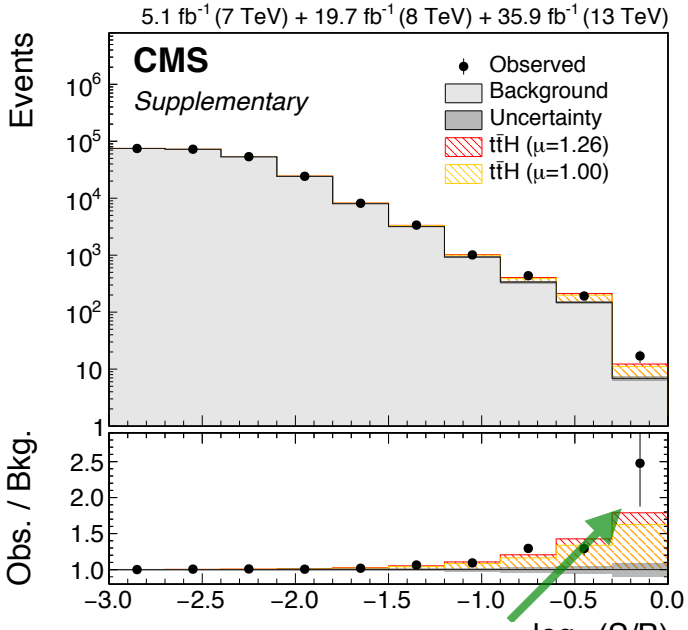
- **Run 2 Higgs results**
  - New wrt Run 1
  - New results for this conference

Focus on a few input analyses



ttH combinations

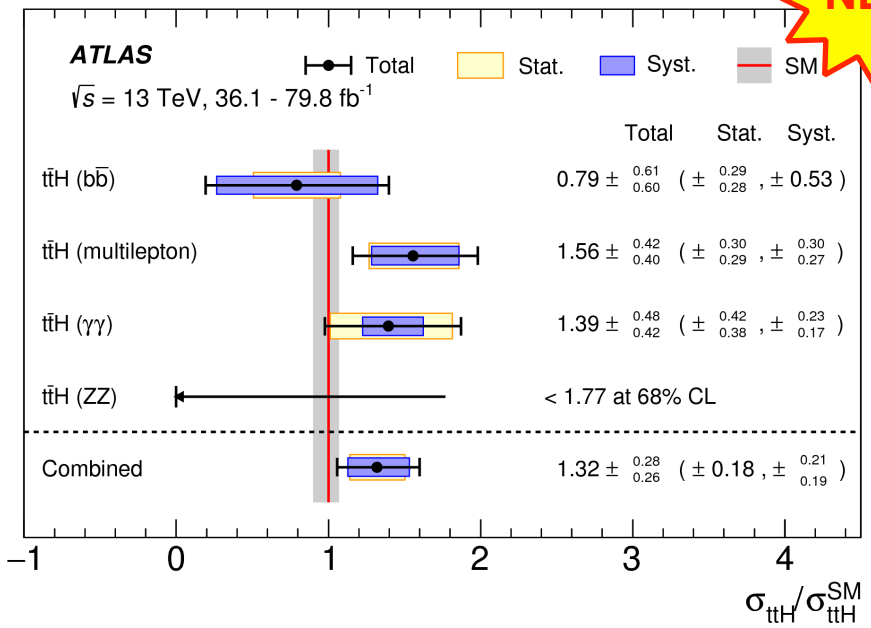
CMS Phys. Rev. Lett. 120, 231801 (2018)
ATLAS arxiv:1806.00425



Visible excess over background

- **ttH combinations results both from ATLAS + CMS (7+8+13 TeV):**
  - dedicated ttH H→bb and ttH multilepton (H→WW/ZZ/$\tau\tau$) analyses
  - dedicated ttH categories in inclusive H→$\gamma\gamma$ and H→ZZ→4l analyses

NEW



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

=> First observations of ttH process!

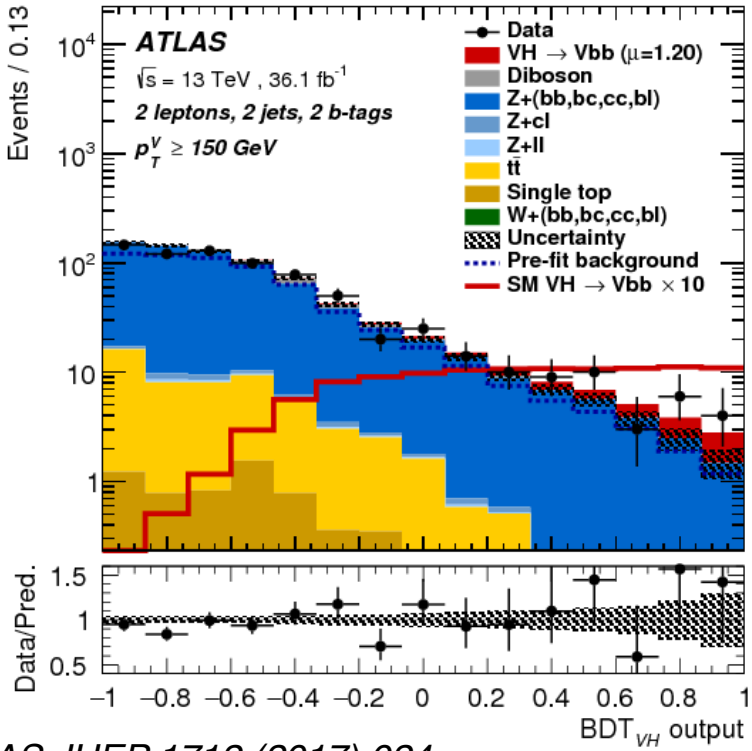
Observation of top-Higgs Yukawa coupling at tree-level

More details in R. Di Nardo's and D. Salerno's talks

H→bb highlights

- **Evidence for VH, H→bb production:**
  Run 1 + Run 2 ATLAS 3.6σ obs. (4.0σ exp.)
  Run 1 + Run 2 CMS 3.8σ obs. (3.8σ exp.)

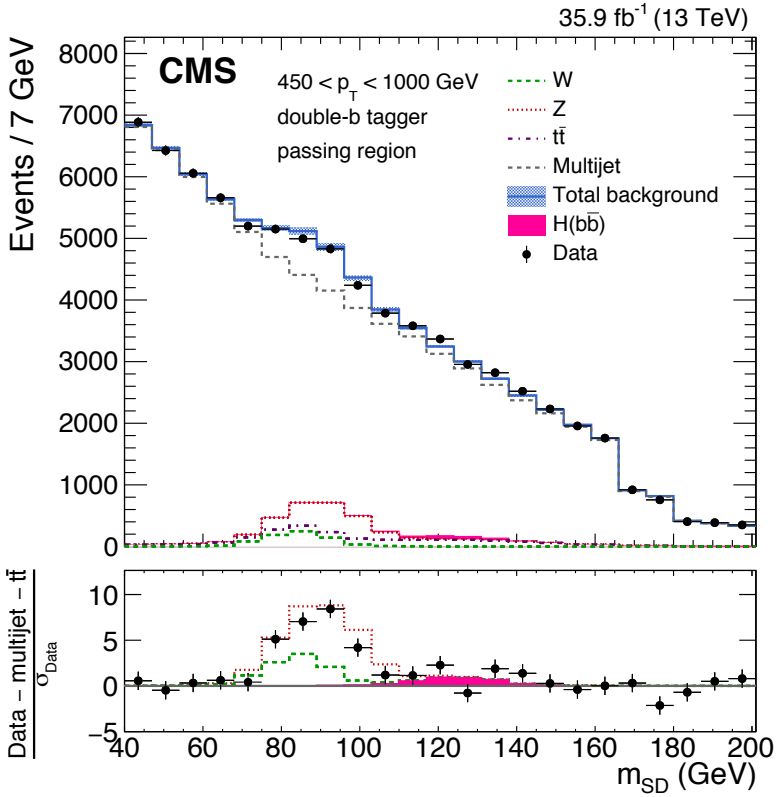
- **Based on MVA analysis,** cross-checked with m(bb) analysis



ATLAS JHEP 1712 (2017) 024
CMS Phys. Lett. B 780 (2018) 501

- **First search targeting boosted ggF, H→bb production:** boosted jet with pT>450 GeV with substructure techniques

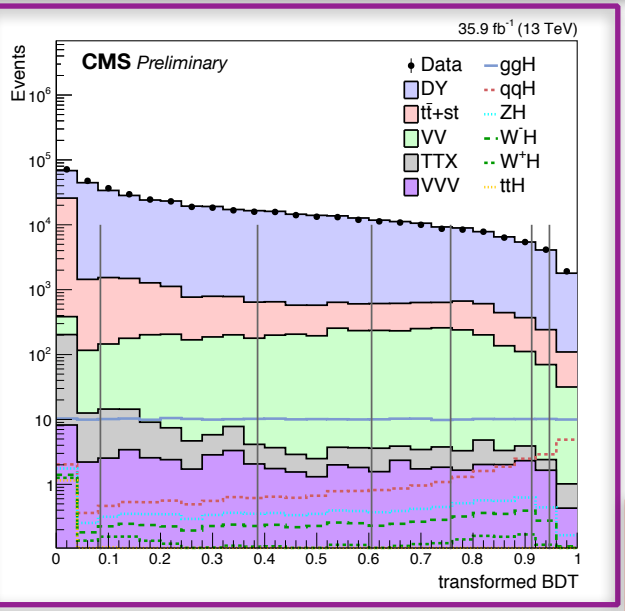
- **Dominant multijet background data-driven**

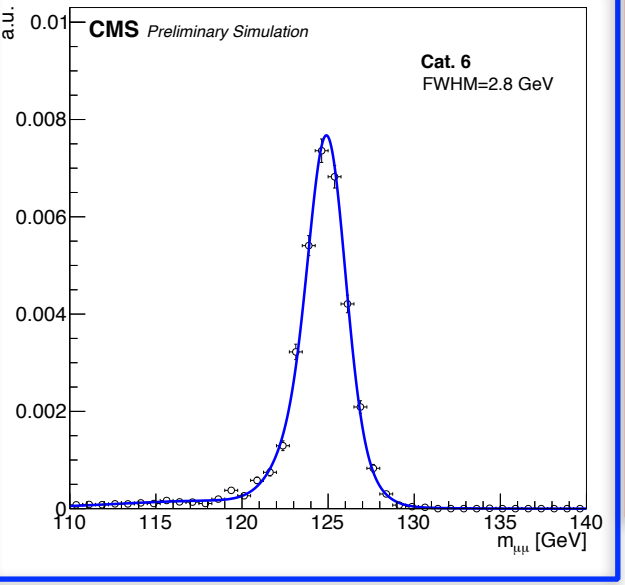


CMS Phys. Rev. Lett. 120 (2018) 071802

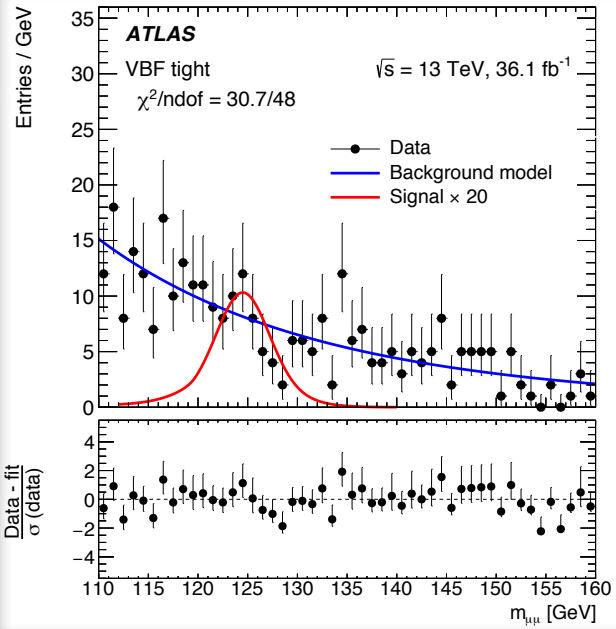
More details in S. Kam-Wah Chan's and M. Missiroli's talks

Higgs decay to muons





- Best process to probe **Higgs Yukawa couplings to 2nd generation fermions**
- **Categorization based on VBF kinematics + expected dimuon mass resolution:** cut-based in ATLAS / BDT-based in CMS
- Look for **excess in dimuon mass spectrum** over falling Drell-Yan background

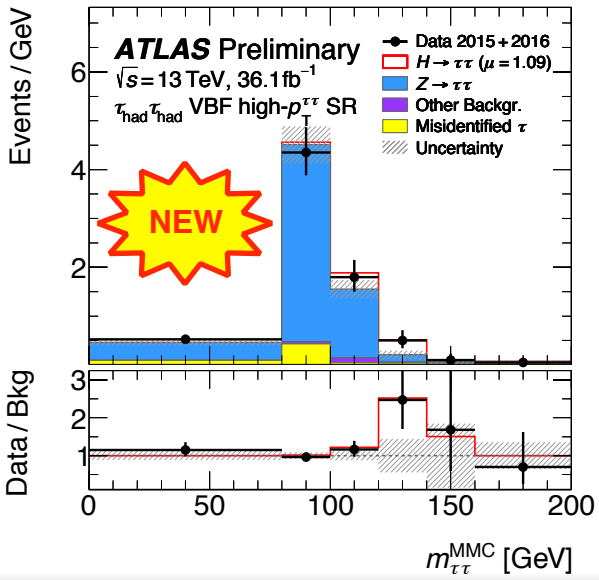


- **No significant excess observed yet in Run 1 + Run 2 combination:**
  - ATLAS μ<2.8 @ 95%CL (μ<2.9 exp.)
  - CMS μ<2.6 @ 95%CL (μ<1.9 exp.)
- **Sensitivity getting close to SM**

ATLAS Phys. Rev. Lett. 119 (2017) 051802
CMS-PAS-HIG-17-019

More details in S. Kam-Wah Chan's and M. Missiroli's talks

H→ττ highlights



- **Independent observation by both CMS and ATLAS of H→ττ decay combining Run 1 + Run 2 data**
  => confirms combined observation in Run 1

- **Analyses focused on ggF and VBF production modes**

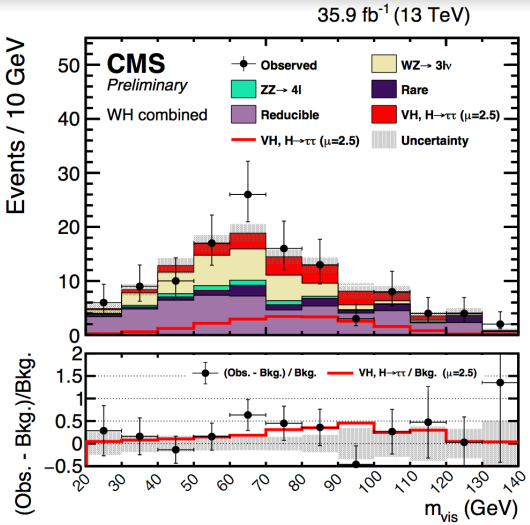
CMS Run 2	**4.9σ obs.** (4.7σ exp.)
ATLAS Run 2	**4.4σ obs.** (4.1σ exp.)
CMS Run 1 + Run 2	**5.9σ obs.** (5.9σ exp.)
ATLAS Run 1 + Run 2	**6.4σ obs.** (5.4σ exp.)

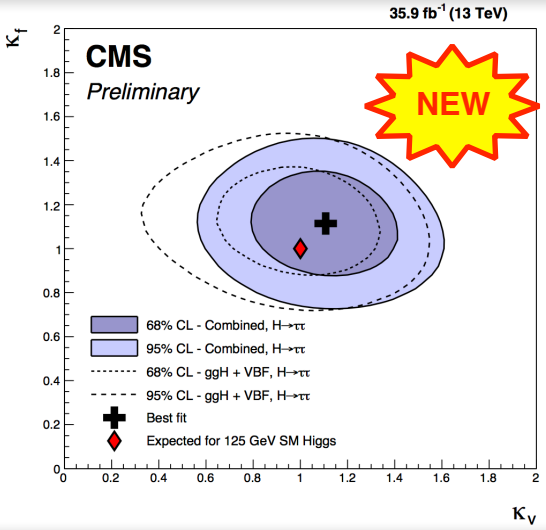
CMS Phys. Let. B 779 (2018) 283, ATLAS-CONF-2018-021

- **New CMS result on VH, H→ττ production:** focusing on Z→ll and W→lν final states

- **Improves precision on Higgs coupling to vector boson in H→ττ final states**

CMS PAS-HIG-18-007



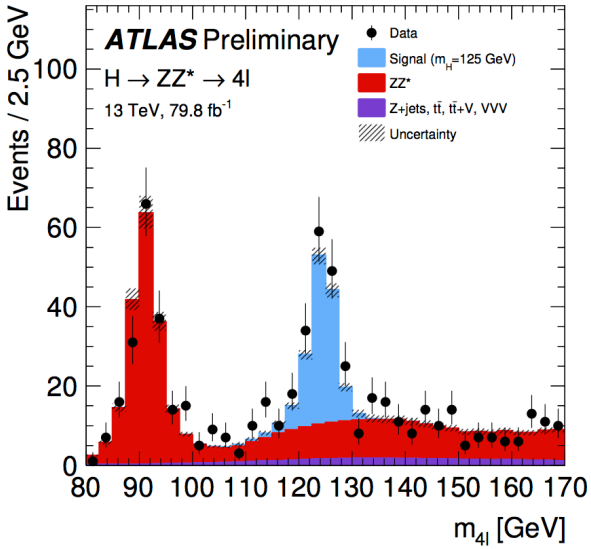


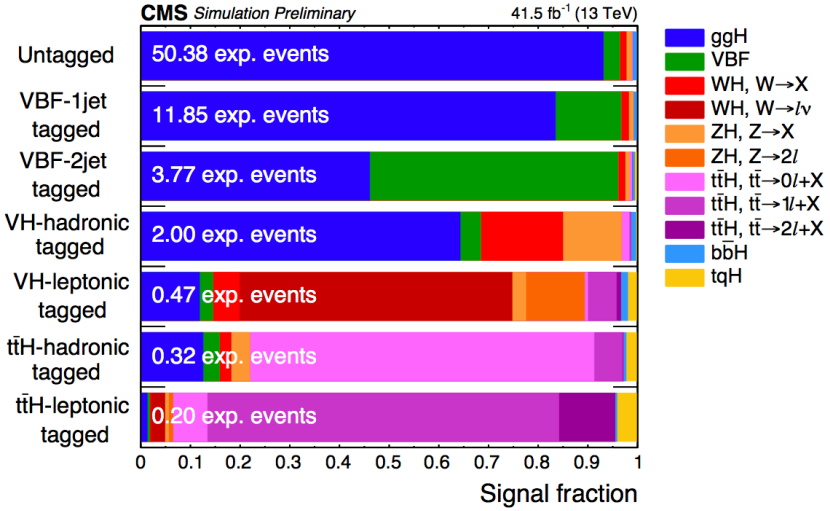
More details in S. Kam-Wah Chan's and M. Missiroli's talks

H→ZZ highlights

NEW

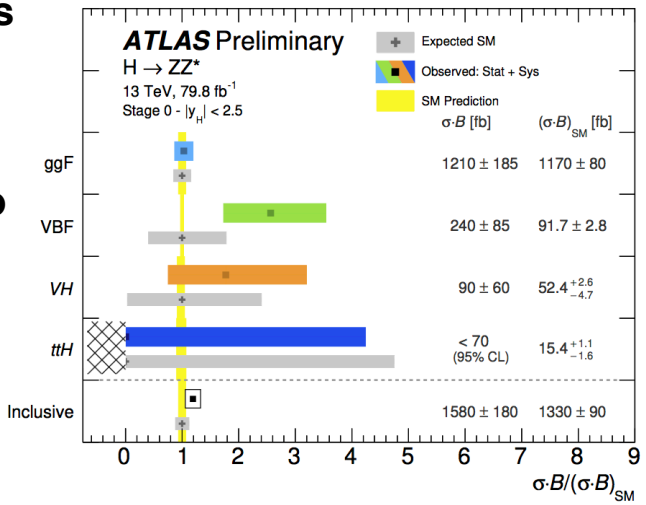
CMS PAS-HIG-18-001
ATLAS-CONF-2018-018

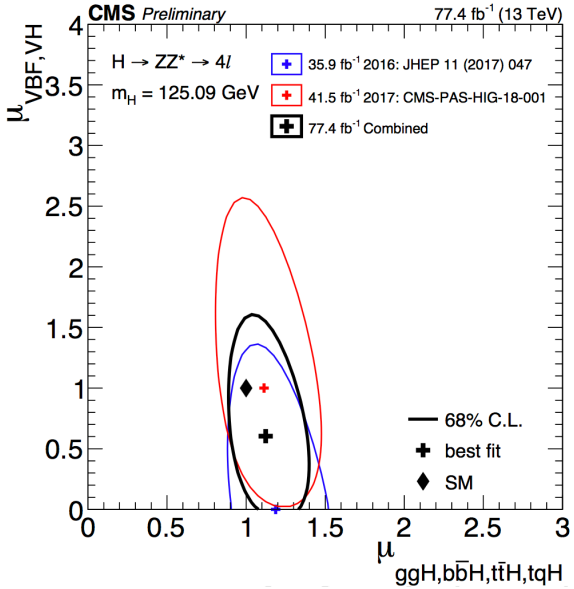




- **New ATLAS + CMS results combining Run 2 dataset**

- Large available statistics
  => categories sensitive to specific production modes + differential measurements (see S. Guindon's talk)





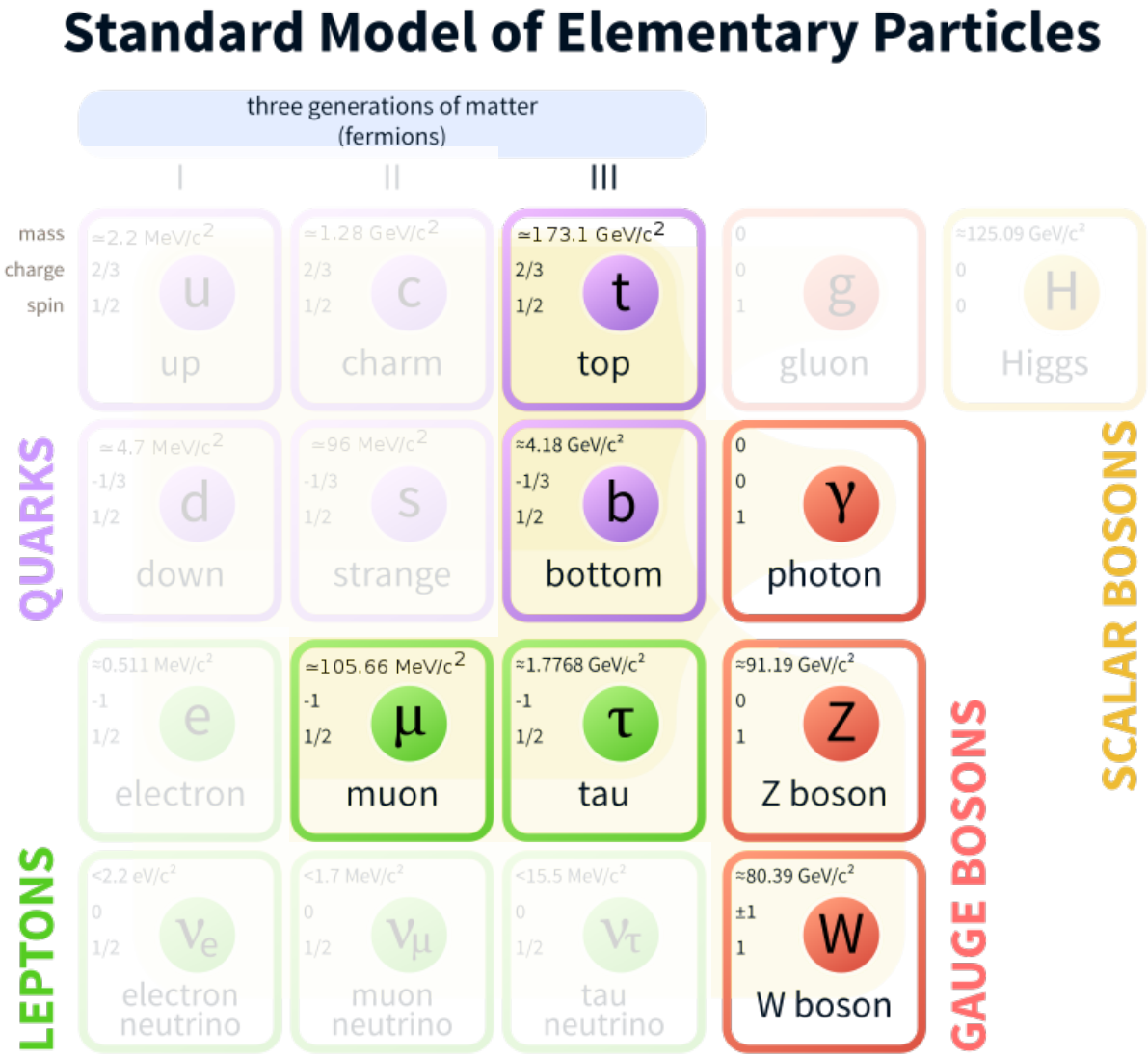
Global signal strength

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

CMS $\mu = 1.06 \pm 0.10(\text{stat})^{+0.08}_{-0.06}(\text{exp. syst})^{+0.07}_{-0.05}(\text{th. syst})$

More details in R. Lafaye's talk

Run 2 coupling measurements



Coupling measurements: the κ framework

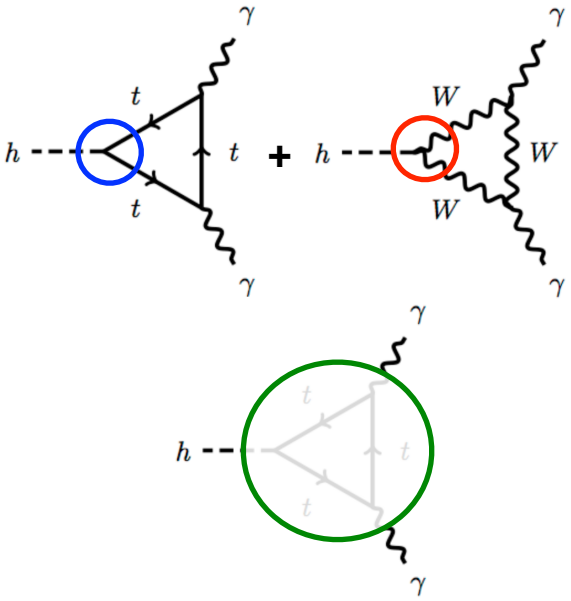
- **Higgs analyses** in ATLAS and CMS usually optimised to **target specific production(s) x decay mode**

$$\mu_i = \frac{\sigma_i}{\sigma_i^{\mathrm{SM}}} \qquad \mu^f = \frac{\mathrm{BR}^f}{\mathrm{BR}^f_{\mathrm{SM}}} \qquad \mu_i^f \equiv \frac{\sigma_i \cdot \mathrm{BR}^f}{(\sigma_i \cdot \mathrm{BR}^f)_{\mathrm{SM}}} = \mu_i \times \mu^f$$

- **Combined analysis** of different final states needed to further disentangle **contributions from different Higgs boson couplings**

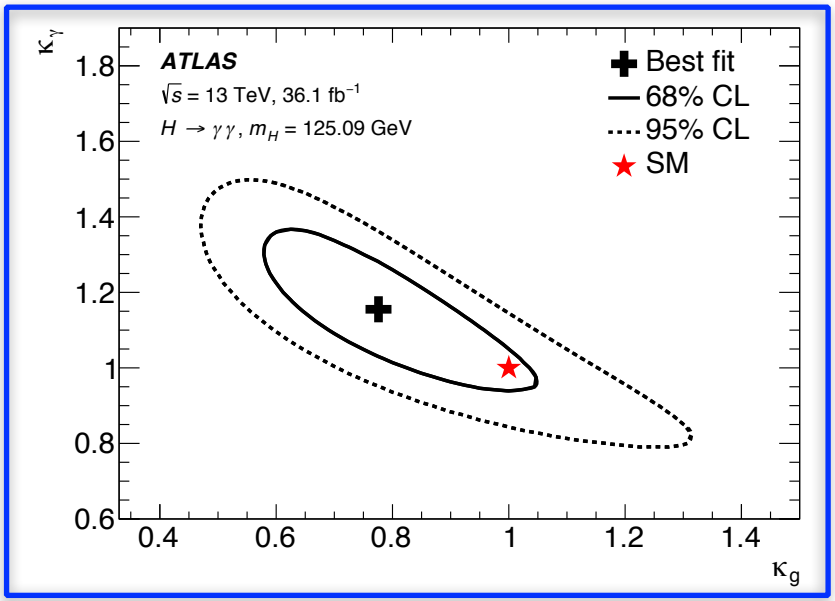
- **κ = coupling modifier**

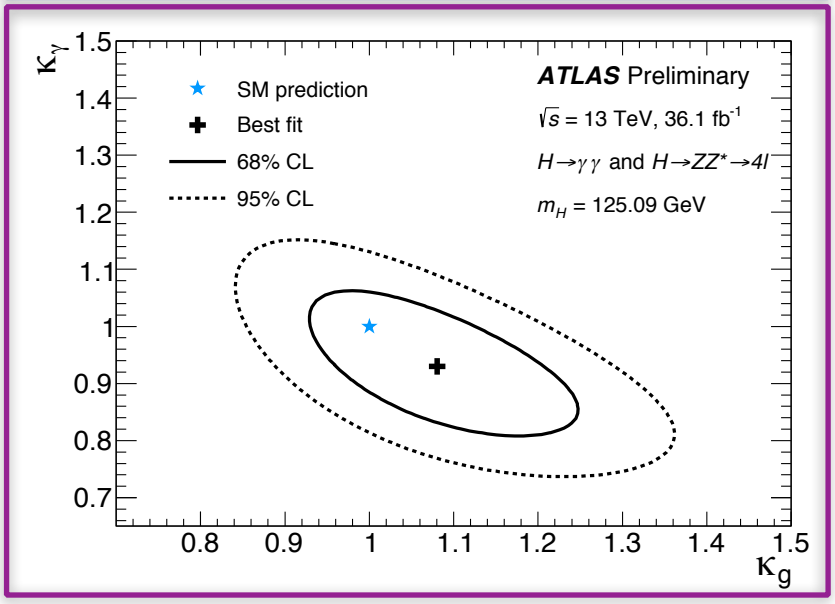
$$\sigma_i \cdot \mathrm{BR}^f = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\Gamma_{\mathrm{H}}}$$



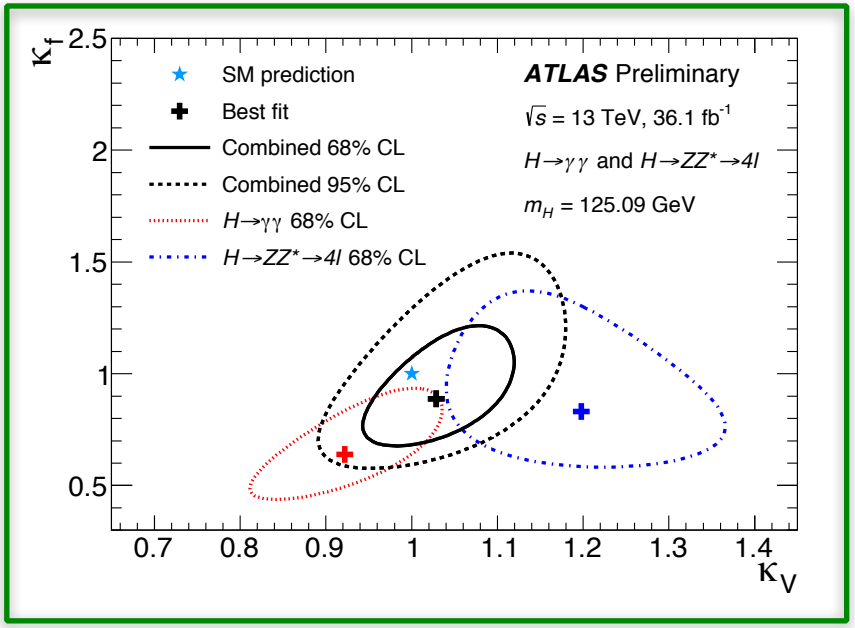
Production	Loops	Interference	Effective scaling factor	Resolved scaling factor
$\sigma(\mathrm{ggH})$	✓	$\mathrm{b}-\mathrm{t}$	κ_{g}^2	$1.04\cdot\kappa_{\mathrm{t}}^2 + 0.002\cdot\kappa_{\mathrm{b}}^2 - 0.038\cdot\kappa_{\mathrm{t}}\kappa_{\mathrm{b}}$
$\sigma(\mathrm{VBF})$	–	–		$0.73\cdot\kappa_{\mathrm{W}}^2 + 0.27\cdot\kappa_{\mathrm{Z}}^2$
$\sigma(\mathrm{WH})$	–	–		κ_{W}^2
$\sigma(\mathrm{qq/qg}\to\mathrm{ZH})$	–	–		κ_{Z}^2
$\sigma(\mathrm{gg}\to\mathrm{ZH})$	✓	$\mathrm{Z}-\mathrm{t}$		$2.46\cdot\kappa_{\mathrm{Z}}^2 + 0.47\cdot\kappa_{\mathrm{t}}^2 - 1.94\cdot\kappa_{\mathrm{Z}}\kappa_{\mathrm{t}}$
$\sigma(\mathrm{ttH})$	–	–		κ_{t}^2
$\sigma(\mathrm{gb}\to\mathrm{WtH})$	–	$\mathrm{W}-\mathrm{t}$		$2.91\cdot\kappa_{\mathrm{t}}^2 + 2.40\cdot\kappa_{\mathrm{W}}^2 - 4.22\cdot\kappa_{\mathrm{t}}\kappa_{\mathrm{W}}$
$\sigma(\mathrm{qb}\to\mathrm{tHq})$	–	$\mathrm{W}-\mathrm{t}$		$2.63\cdot\kappa_{\mathrm{t}}^2 + 3.58\cdot\kappa_{\mathrm{W}}^2 - 5.21\cdot\kappa_{\mathrm{t}}\kappa_{\mathrm{W}}$
$\sigma(\mathrm{bbH})$	–	–		κ_{b}^2
Partial decay width				
Γ^{ZZ}	–	–		κ_{Z}^2
Γ^{WW}	–	–		κ_{W}^2
$\Gamma^{\gamma\gamma}$	✓	$\mathrm{W}-\mathrm{t}$	κ_γ^2	$1.59\cdot\kappa_{\mathrm{W}}^2 + 0.07\cdot\kappa_{\mathrm{t}}^2 - 0.67\cdot\kappa_{\mathrm{W}}\kappa_{\mathrm{t}}$
$\Gamma^{\tau\tau}$	–	–		κ_τ^2
Γ^{bb}	–	–		κ_{b}^2
$\Gamma^{\mu\mu}$	–	–		κ_μ^2
Total width for $\mathrm{BR}_{\mathrm{BSM}} = 0$				
Γ_{H}	✓	–	κ_{H}^2	$0.58\cdot\kappa_{\mathrm{b}}^2 + 0.22\cdot\kappa_{\mathrm{W}}^2 + 0.08\cdot\kappa_{\mathrm{g}}^2 +$ $+ 0.06\cdot\kappa_\tau^2 + 0.026\cdot\kappa_{\mathrm{Z}}^2 + 0.029\cdot\kappa_{\mathrm{c}}^2 +$ $+ 0.0023\cdot\kappa_\gamma^2 + 0.0015\cdot\kappa_{\mathrm{Z}\gamma}^2 +$ $+ 0.00025\cdot\kappa_{\mathrm{s}}^2 + 0.00022\cdot\kappa_\mu^2$

Improving precision with combination





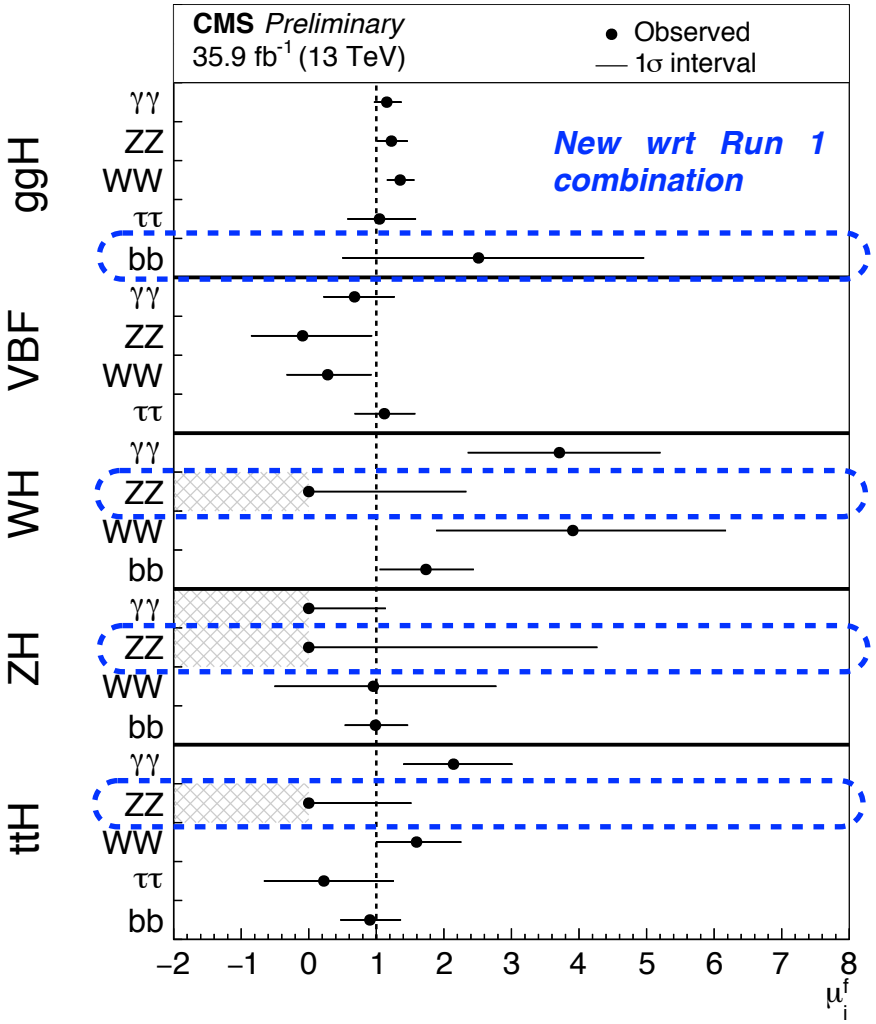
- **H→$\gamma\gamma$** in principle quite powerful to **constrain κ_γ but (anti-)correlated with κ_g** from dominant ggF H→$\gamma\gamma$ production mode
- **Combination with H→ZZ→4l** improves constraint on κ_g and **lifts degeneracy**
- **Better constraints also in κ_f-κ_V measurement**



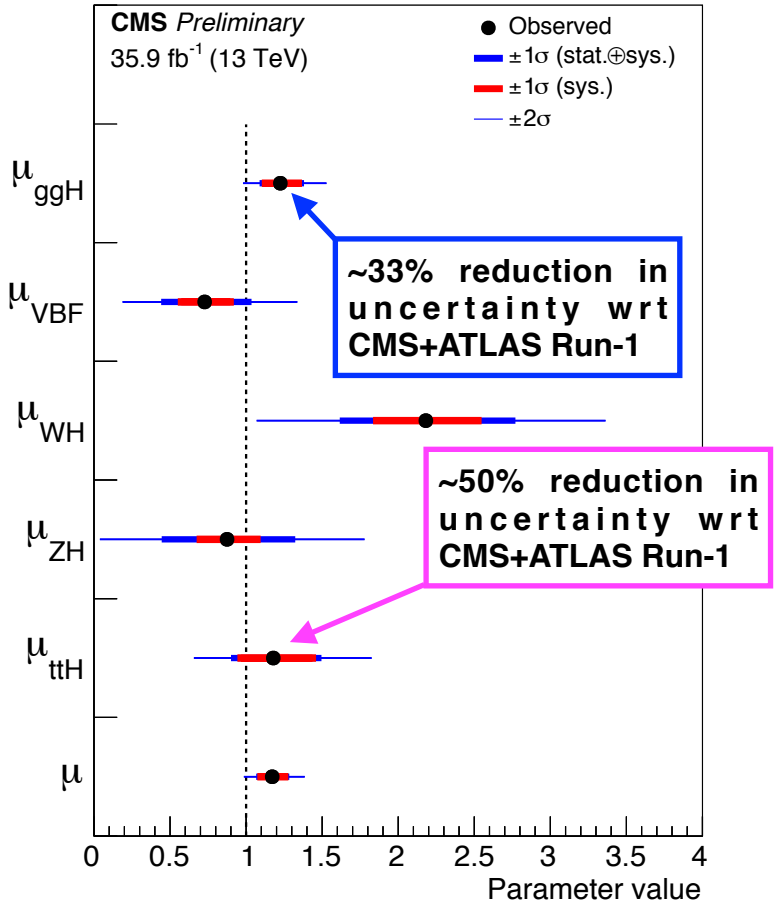
ATLAS arxiv:1802.04146
ATLAS CONF-2017-047

More details in R. Lafaye's talk

CMS grand combination with 2016 data



CMS-PAS-HIG-17-031

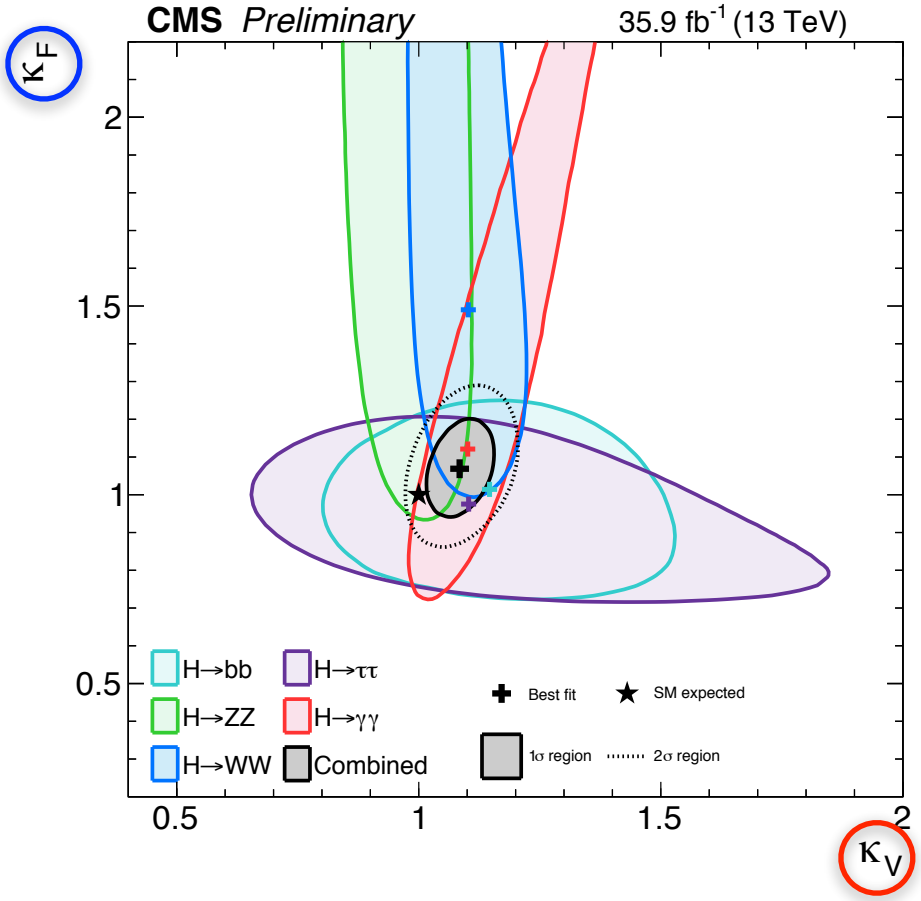


$$\mu = 1.17^{+0.10}_{-0.10} = 1.17^{+0.06}_{-0.06}\,(\text{stat.})\,^{+0.06}_{-0.05}\,(\text{sig. th.})\,^{+0.06}_{-0.06}\,(\text{other sys.})$$

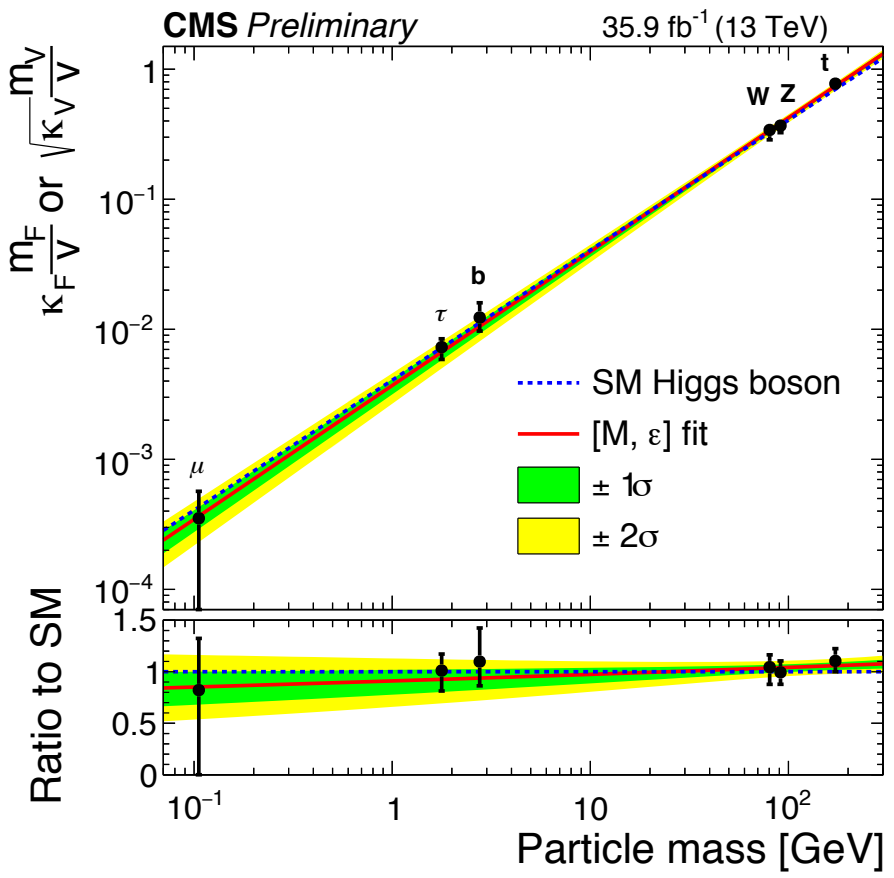
~15% reduction in uncertainty wrt CMS+ATLAS Run-1

Coupling measurements

CMS-PAS-HIG-17-031



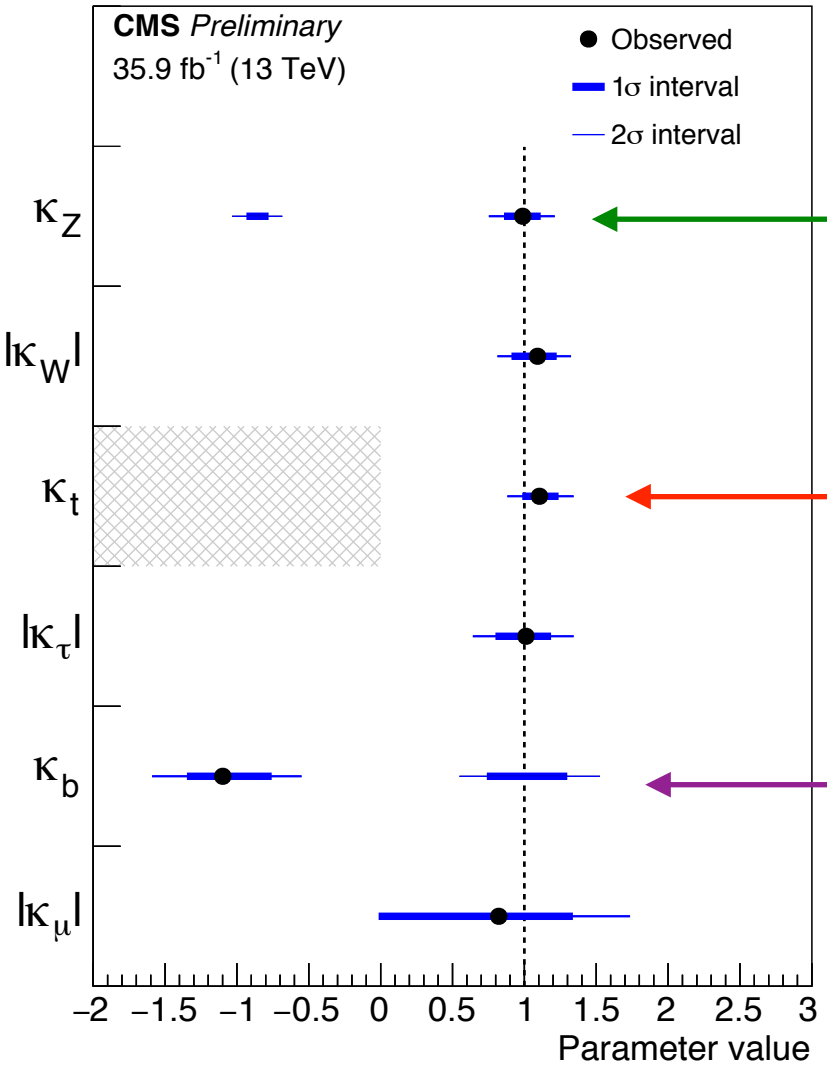
- **Two coupling modifiers, for vector bosons and fermions**



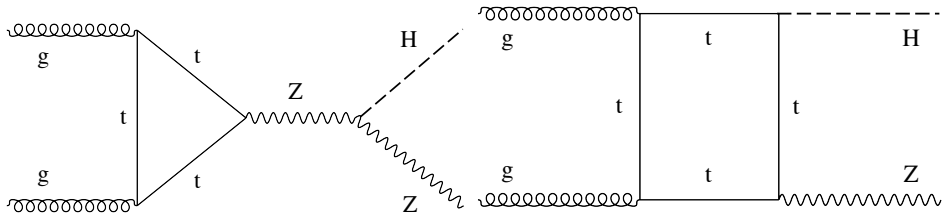
- **One coupling modifier per particle** compared with alternative parametrisation

$$\kappa_F = v\ m_f^{\epsilon}/M^{1+\epsilon} \qquad \kappa_V = v\ m_V^{2\epsilon}/M^{1+2\epsilon}$$

Coupling measurements

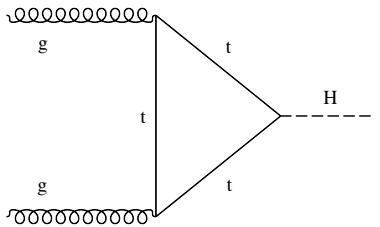


CMS-PAS-HIG-17-031



Sensitivity to sign of κ_Z through gg→ZH

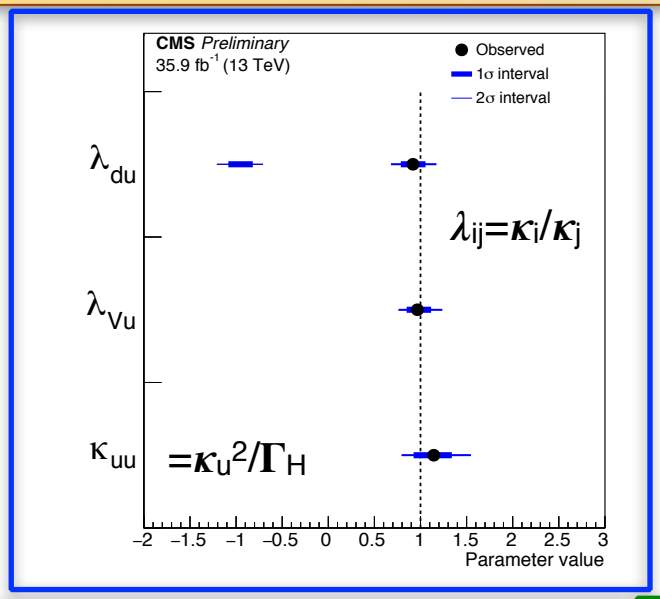
~20% stronger constraint when resolving ggF loop



Mild preference for $\kappa_b<0$ from ggF t/b interference

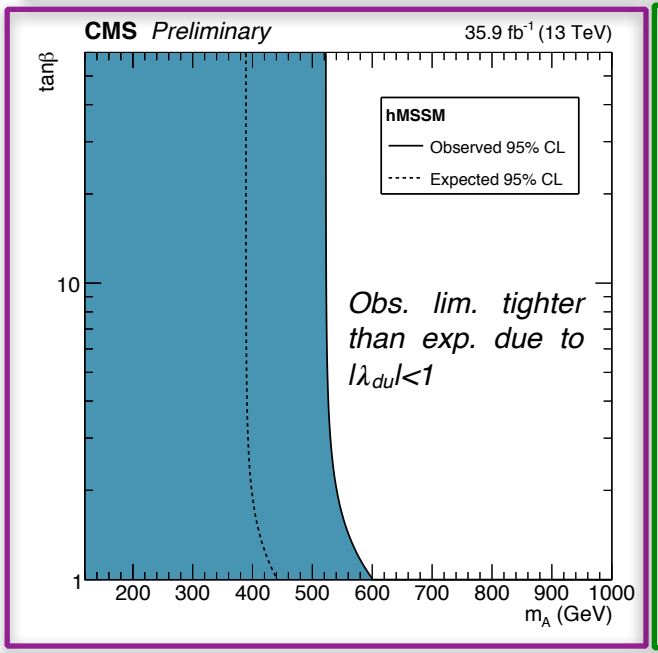
- **All couplings within 1σ of expected SM values**
- **Similar systematic and statistical uncertainties,** expect for κ_μ

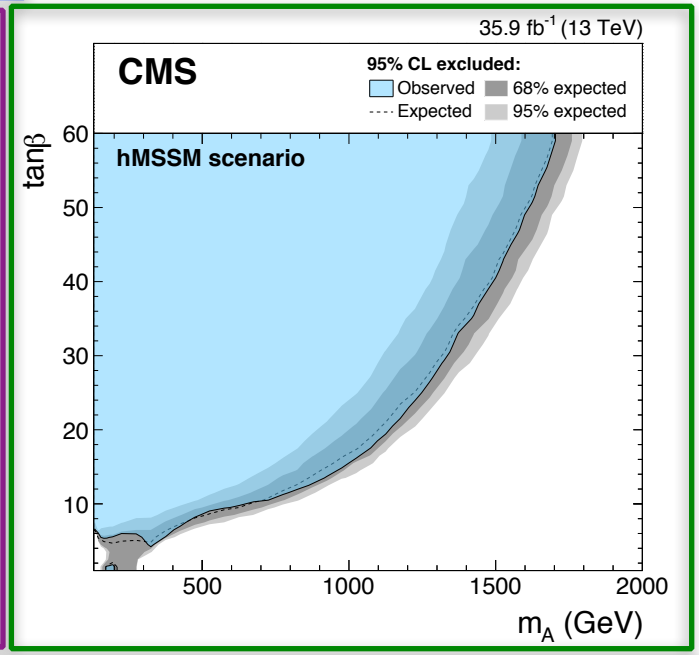
Constraining 2HDMs through 125 GeV Higgs measurements



- **Possible also to measure ratios of coupling modifiers** between up-/down-type fermions or leptons/quarks
- Constraints on ratios can be converted in **2HDM constraints** in tanβ-cos(β-α) or **tanβ-m_A plane**

	2HDM				hMSSM
	type I	type II	Type III	Type IV	
κ_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\frac{s_d+s_u\tan\beta}{\sqrt{1+\tan^2\beta}}$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$s_u\frac{\sqrt{1+\tan^2\beta}}{\tan\beta}$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$s_d\sqrt{1+\tan^2\beta}$
κ_ℓ	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$s_d\sqrt{1+\tan^2\beta}$





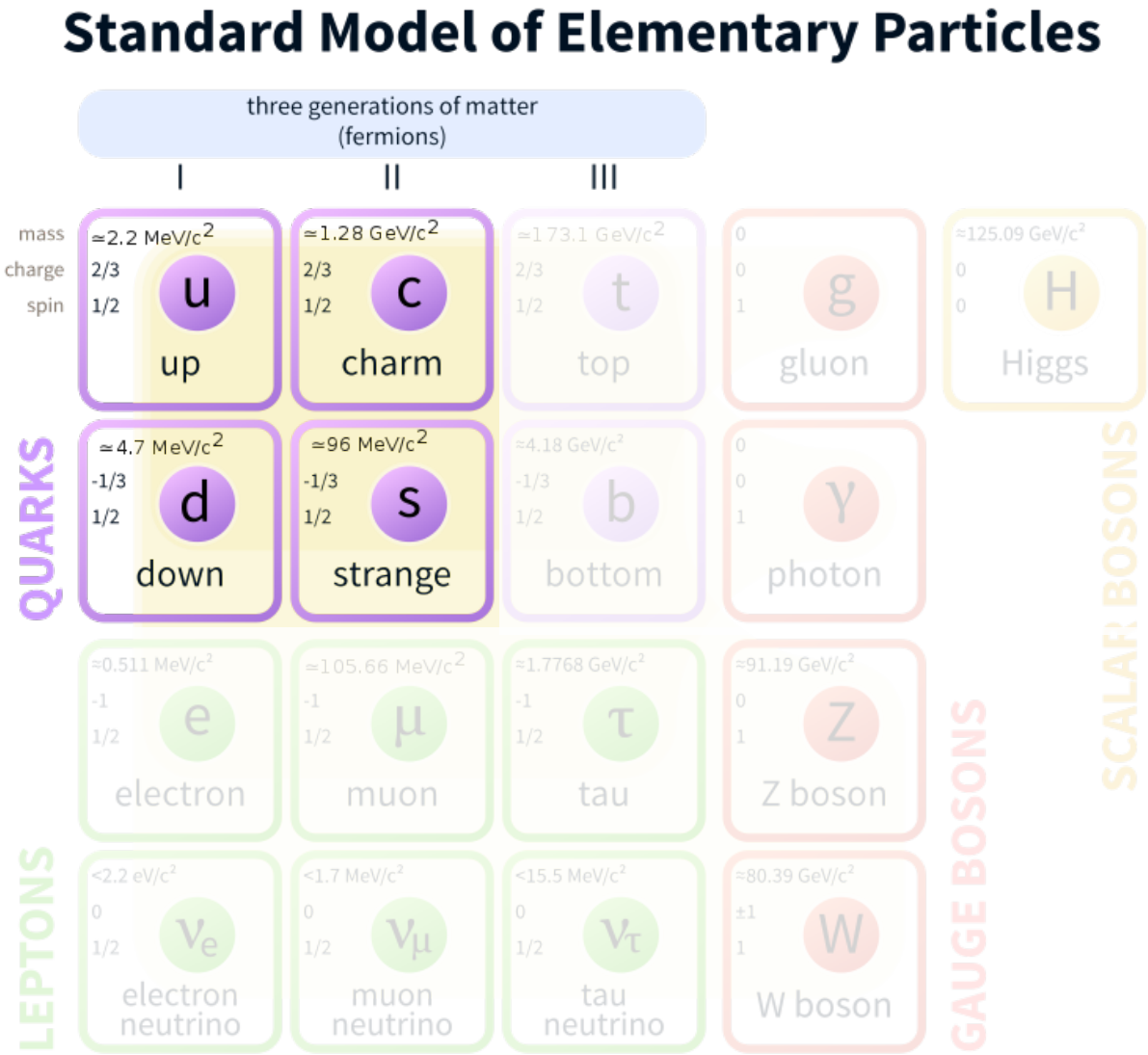
$$s_u = \frac{1}{\sqrt{1+\frac{(m_A^2+m_Z^2)^2\tan^2\beta}{(m_Z^2+m_A^2\tan^2\beta-m_H^2(1+\tan^2\beta))^2}}}$$

$$s_d = s_u \cdot \frac{m_A^2+m_Z^2\tan\beta}{m_Z^2+m_A^2\tan^2\beta-m_H^2(1+\tan^2\beta)}$$

- **Complementary to direct searches, e.g. additional heavy Higgs bosons→$\tau\tau$**

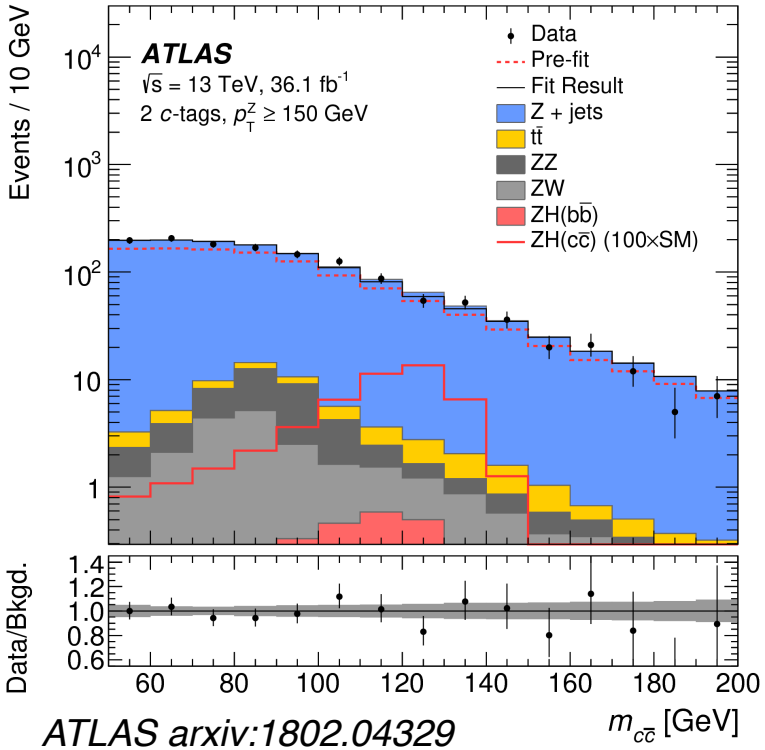
CMS-PAS-HIG-17-031
CMS arxiv:1803.06553

Higgs couplings to 1st/2nd generation quarks



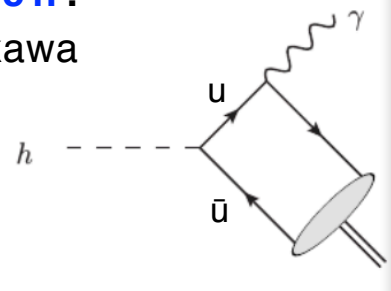
Higgs couplings to 1st/2nd generation quarks

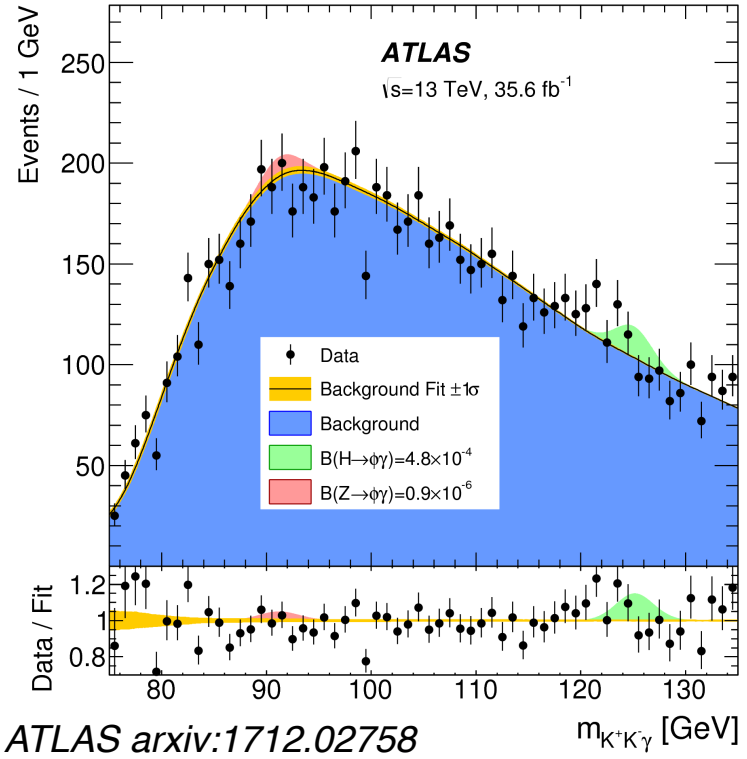
- **ATLAS ZH, H→cc search**: first direct search for H→cc decay
- **Observed limit:** 110x SM production rate
- Complements Run 1 search for H→J/Ψ+γ decay



ATLAS arxiv:1802.04329

- **ATLAS H→ϕ/ρ+γ search**: constraints on s, u, d Yukawa couplings
- **Observed limit on BR O(10^{-4}):**
  - 208x SM for H→ϕ+γ
  - 52x SM for H→ρ+γ

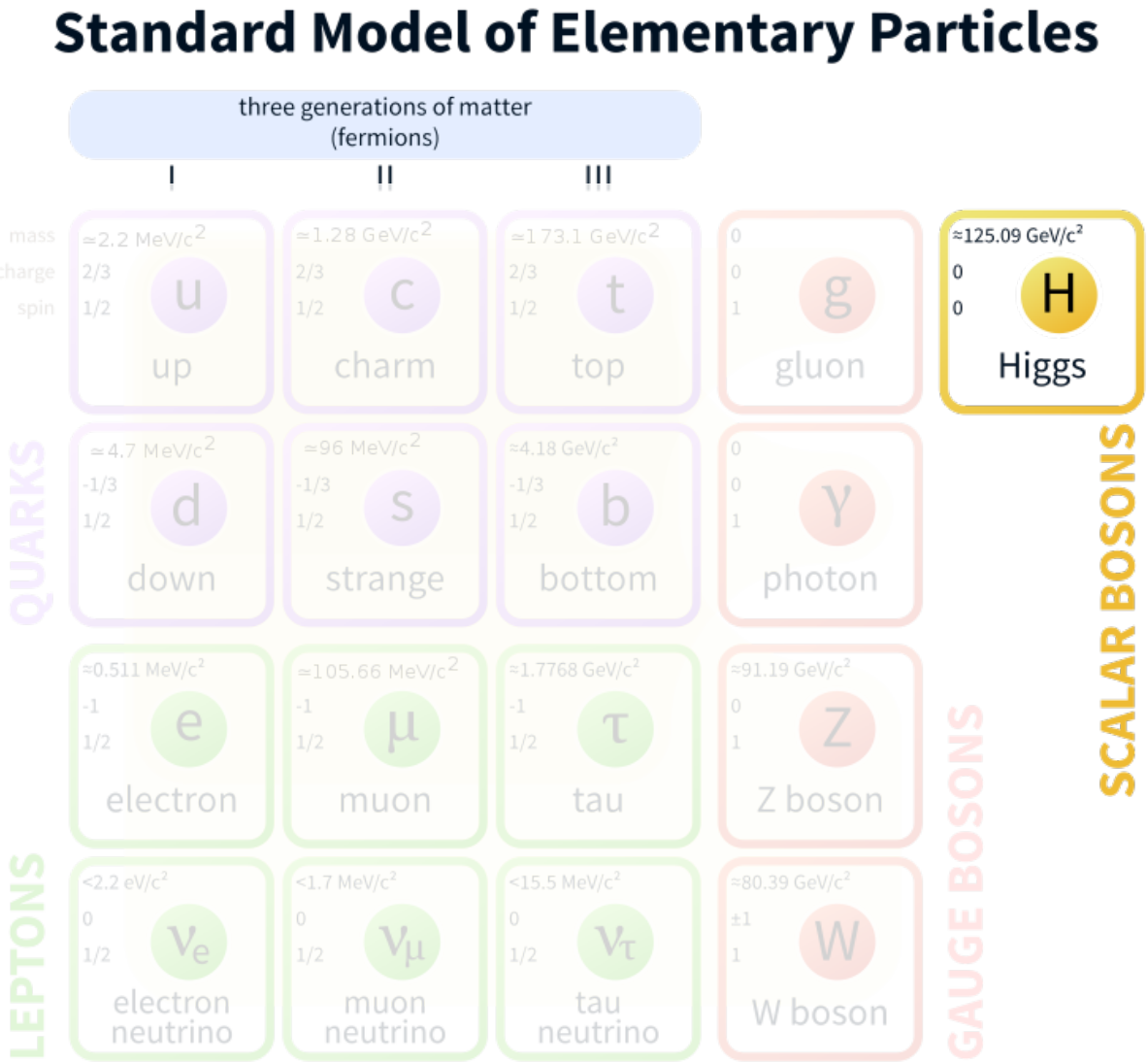




ATLAS arxiv:1712.02758

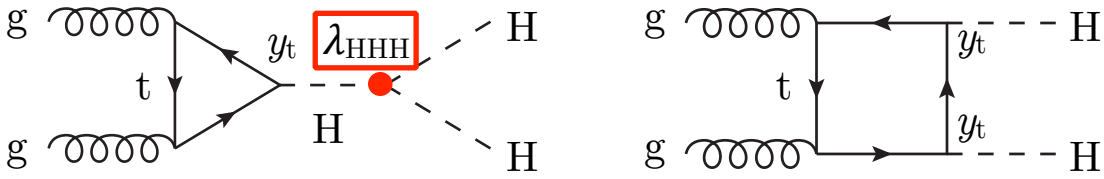
More details in S. Kam-Wah Chan's talk

Higgs self-coupling

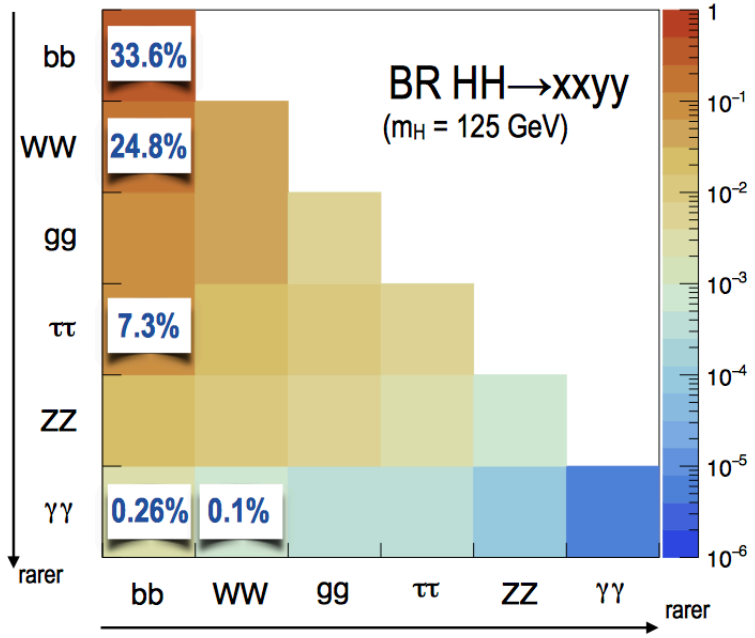


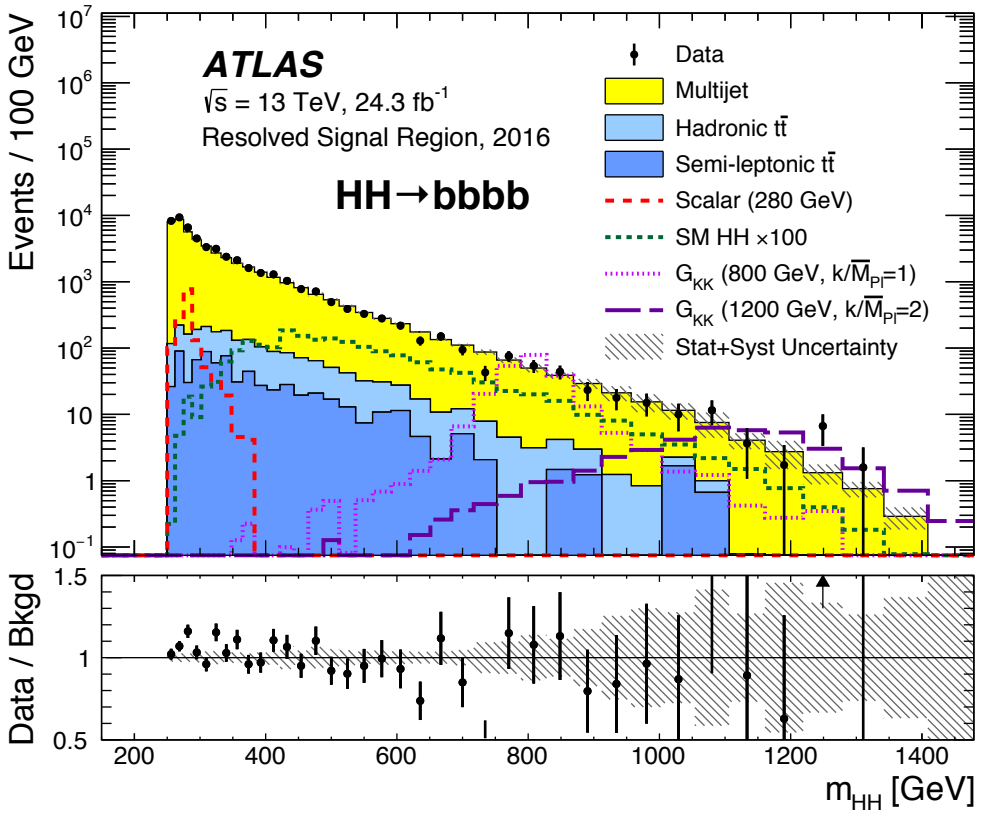
HH analyses and Higgs self-coupling

- **Higgs self-coupling important parameter for EWSB:** can be probed with double Higgs production



- **Large spectrum of possible final states**



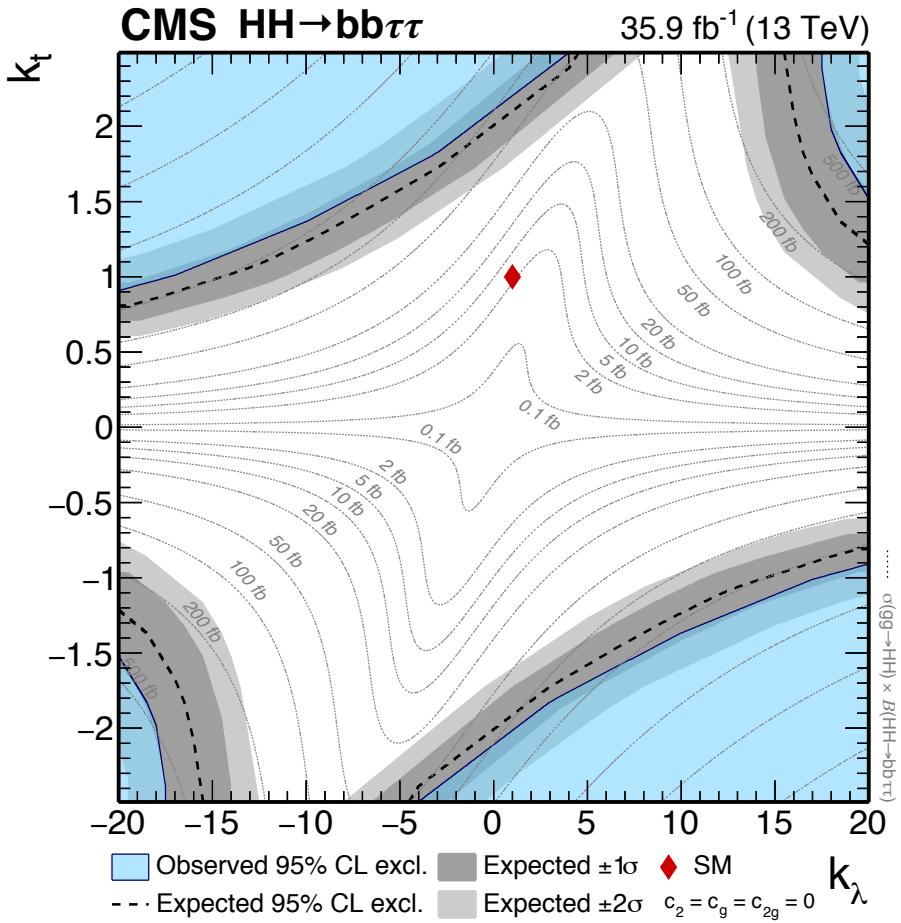


ATLAS arxiv:1804.06174

HH analyses and Higgs self-coupling

- **Constraints on σxBR(HH) can be derived in κt-κλ plane**
- Not expected to be sensitive to SM HH production before HL-LHC but can already **exclude large BSM values of Higgs self-coupling**

13 TeV results	*95% CL upper limit on σxBR(HH)/σxBR(HH)$_{SM}$*
ATLAS HH→bbbb	***13** (21 exp.)*
CMS HH→bbττ	***30** (25 exp.)*
CMS HH→bbWW	***79** (89 exp.)*
CMS HH→bbγγ	***24** (19 exp.)*
ATLAS HH→bbγγ	***22** (28 exp.)*
ATLAS HH→WWγγ	***230** (160 exp.)*

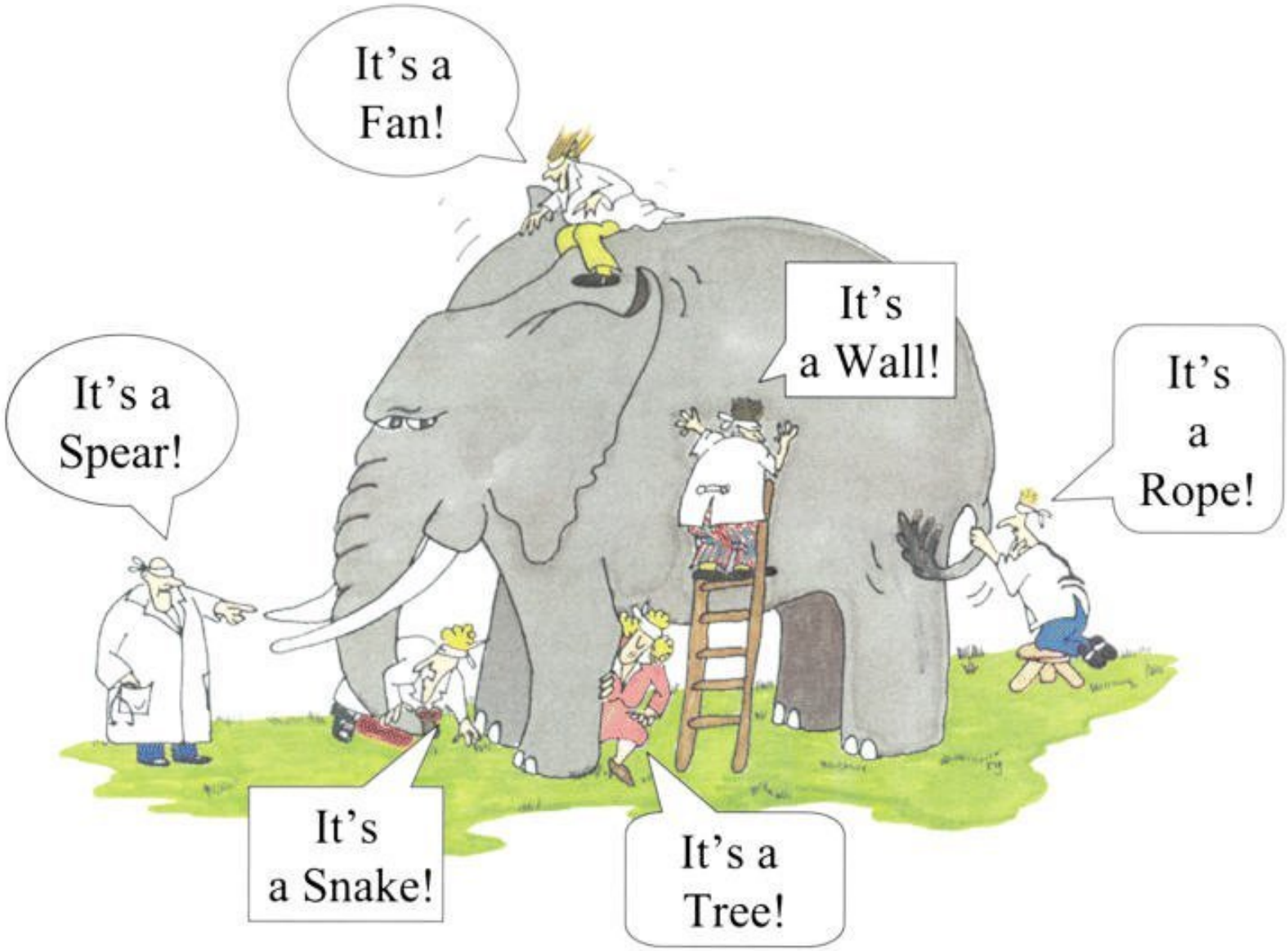


ATLAS arxiv:1804.06174
CMS Phys. Lett. B 778 (2018) 101
CMS JHEP 01 (2018) 054
CMS arxiv:1806.00408

Conclusion

- **Observation of Higgs boson in 2012 opened a new pathway in high energy physics:** a lot of new physics results produced since then to study the properties of the Higgs boson
- **Production and decay modes studied in Run 1 still scrutinised in Run 2:** evidence for VH H→bb, first observation of ttH…
- **Interesting new analyses developed as well:** boosted H→bb, H→cc, H→$\phi/\rho+\gamma$…
- **Ready to look for more and more rare process in Run 3 and beyond:** H→μμ, double Higgs production…
- **Combination of Higgs analyses very useful to measure precisely the couplings of the SM Higgs boson:** Systematic uncertainty start getting dominant **=> hard work needed from theorists and experimentalists**

Thank you for your attention



Back-up

Mass measurements: CMS H→ZZ→4l

CMS JHEP 11 (2017) 047

- **Measurement performed using**
  - m(4l)
  - per-event mass uncertainty D_{mass}
  - ME-based background discriminant against ZZ→4l D^{kin}_{bkg}

- **Kinematic fit using gen-level Z1 mass shape**

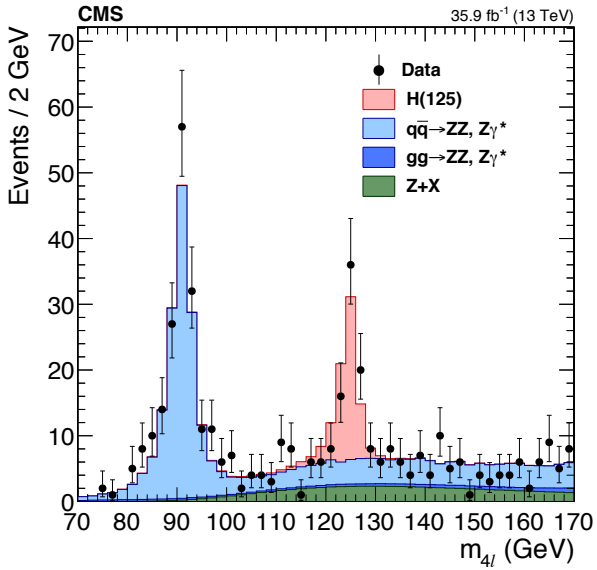
$$\mathcal{L}(\hat{p}^1_{\mathrm{T}}, \hat{p}^2_{\mathrm{T}} | p^1_{\mathrm{T}}, \sigma_{p^1_{\mathrm{T}}}, p^2_{\mathrm{T}}, \sigma_{p^2_{\mathrm{T}}}) = \mathrm{Gauss}(p^1_{\mathrm{T}} | \hat{p}^1_{\mathrm{T}}, \sigma_{p^1_{\mathrm{T}}})$$

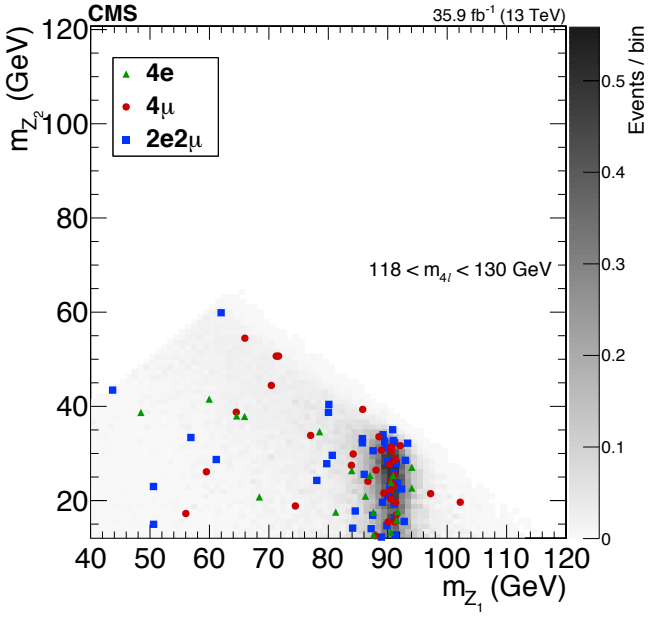
$$\mathrm{Gauss}(p^2_{\mathrm{T}} | \hat{p}^2_{\mathrm{T}}, \sigma_{p^2_{\mathrm{T}}})\, \mathcal{L}(m_{12} | m_{\mathrm{Z}}, m_{\mathrm{H}})$$

- **Signal shape modelled as double-sided Crystal Ball**

No $m(\mathrm{Z}_1)$ constraint	3D: $\mathcal{L}(m_{4\ell}, \mathcal{D}_{\mathrm{mass}}, \mathcal{D}^{\mathrm{kin}}_{\mathrm{bkg}})$	2D: $\mathcal{L}(m_{4\ell}, \mathcal{D}_{\mathrm{mass}})$	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 $m(\mathrm{Z}_1)$ constraint	3D: $\mathcal{L}(m'_{4\ell}, \mathcal{D}'_{\mathrm{mass}}, \mathcal{D}^{\mathrm{kin}}_{\mathrm{bkg}})$	2D: $\mathcal{L}(m'_{4\ell}, \mathcal{D}'_{\mathrm{mass}})$	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

- **Systematics dominated by lepton energy scale << statistical uncertainty**

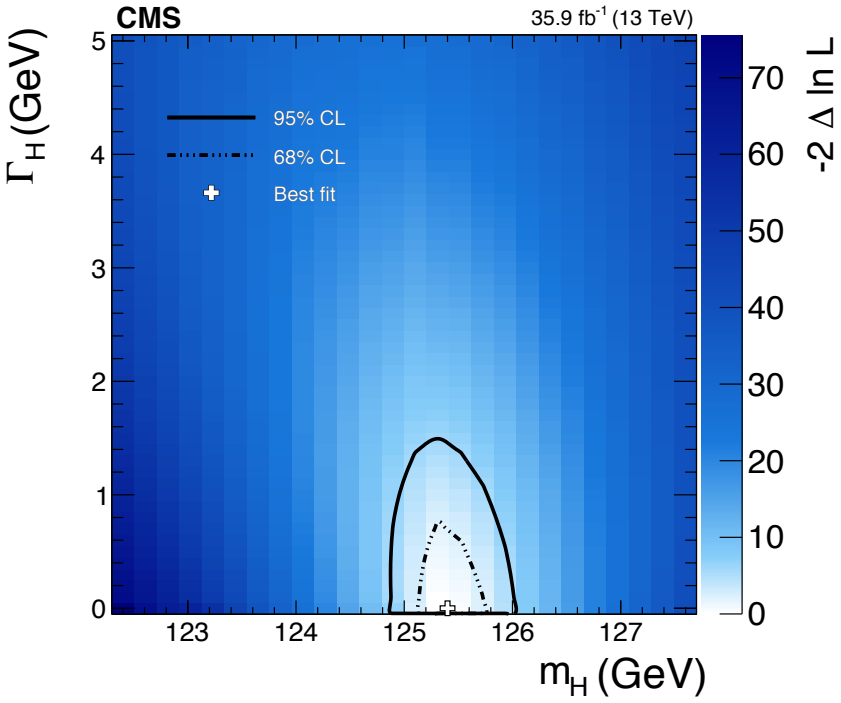


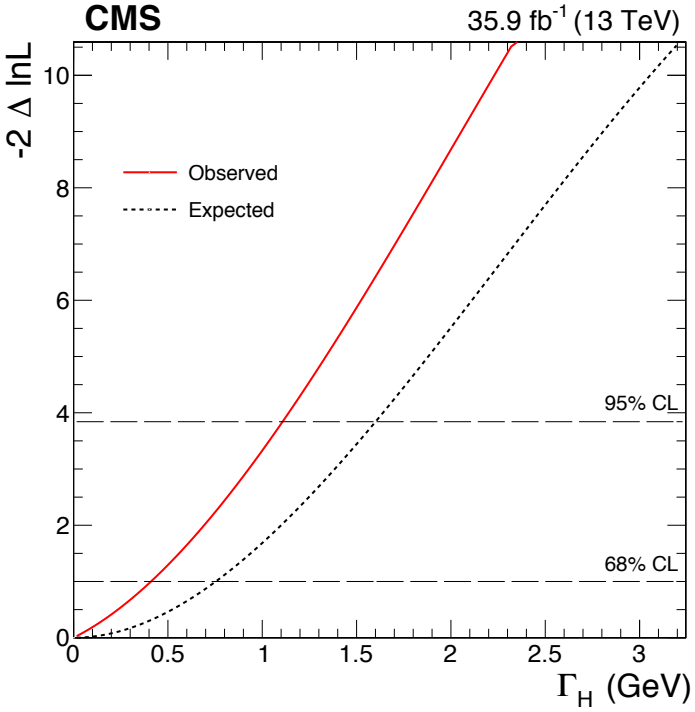


Width measurements: CMS H→ZZ→4l

CMS JHEP 11 (2017) 047

- **On-shell width measurement using m(4l):** limited by m(4l) resolution





Parameter	$m_{4\ell}$ range	Expected	Observed
ΓH (GeV)	$[105, 140]$	$0.00^{+0.75}_{-0.00}$ $[0.00, 1.60]$	$0.00^{+0.41}_{-0.00}$ $[0.00, 1.10]$

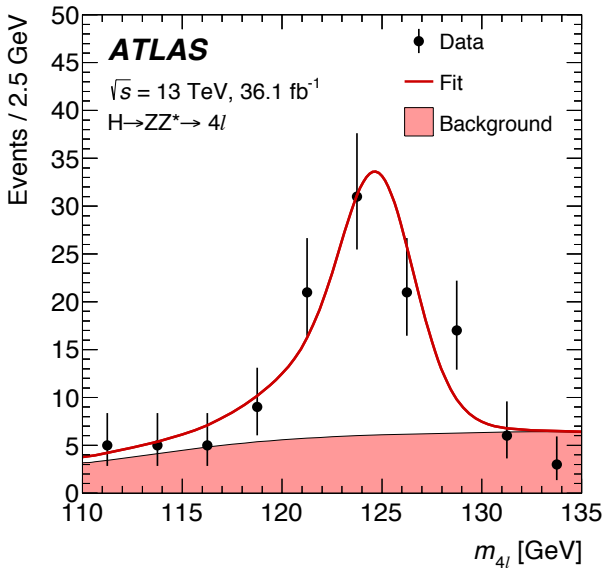
Mass measurements: ATLAS H→ZZ→4l

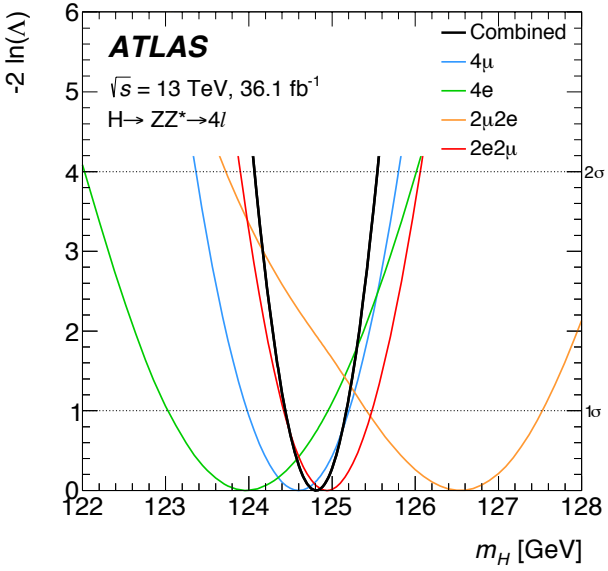
ATLAS arxiv:1806.00242

- **Measurement performed using**
  - m(4l)
  - BDT discriminant against ZZ→4l D^{kin}_{bkg}
- **Kinematic fit using Z1 pole mass**
- **Signal shape modelled as convolution of Breit-Wigner distribution with m(4l) response function**

$$S_{m_H}(m_{4\ell}^{\text{meas}}) = \int_0^\infty F(m_{4\ell}^{\text{meas}} - m_{4\ell}^{\text{true}}) \cdot BW(m_{4\ell}^{\text{true}}, m_H)\, dm_{4\ell}^{\text{true}}$$

- **Systematics dominated by lepton energy scale << statistical uncertainty**



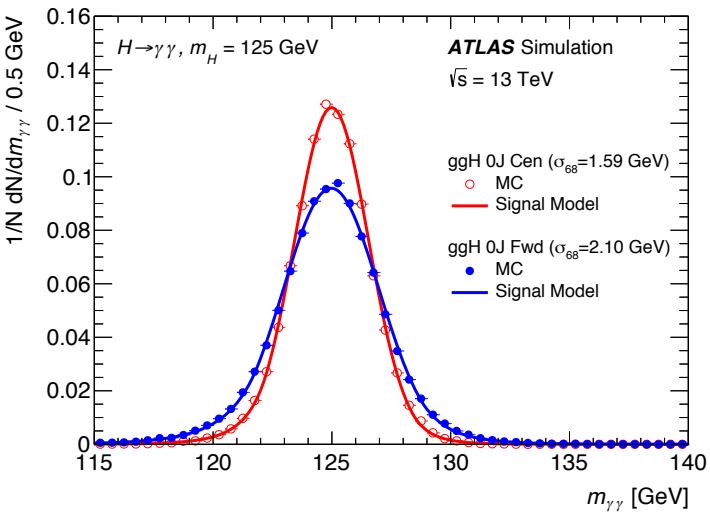


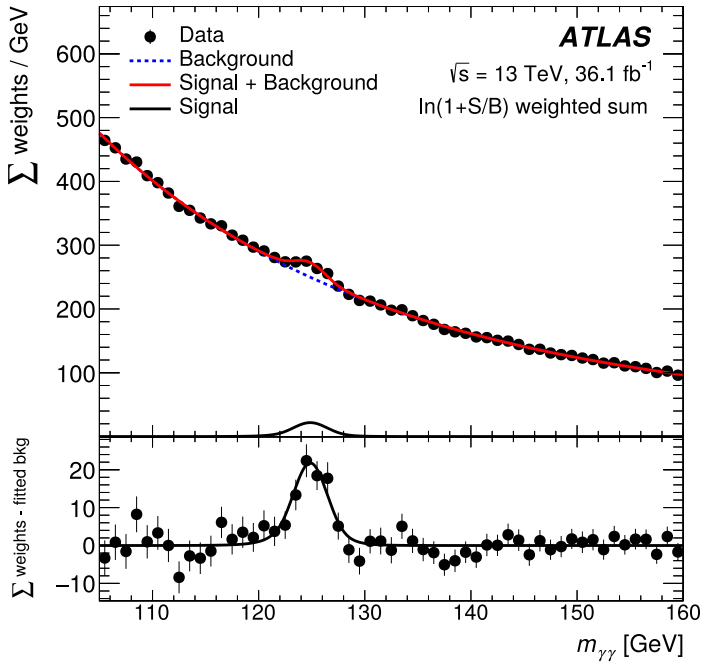
Mass measurements: ATLAS H→$\gamma\gamma$

ATLAS arxiv:1806.00242

- **Measurement performed using m($\gamma\gamma$) in several categories optimised based on expected resolution and production mode identification**
- **Signal shape modelled as double-sided Crystal Ball**
- **Systematics dominated by photon energy scale > statistical uncertainty**

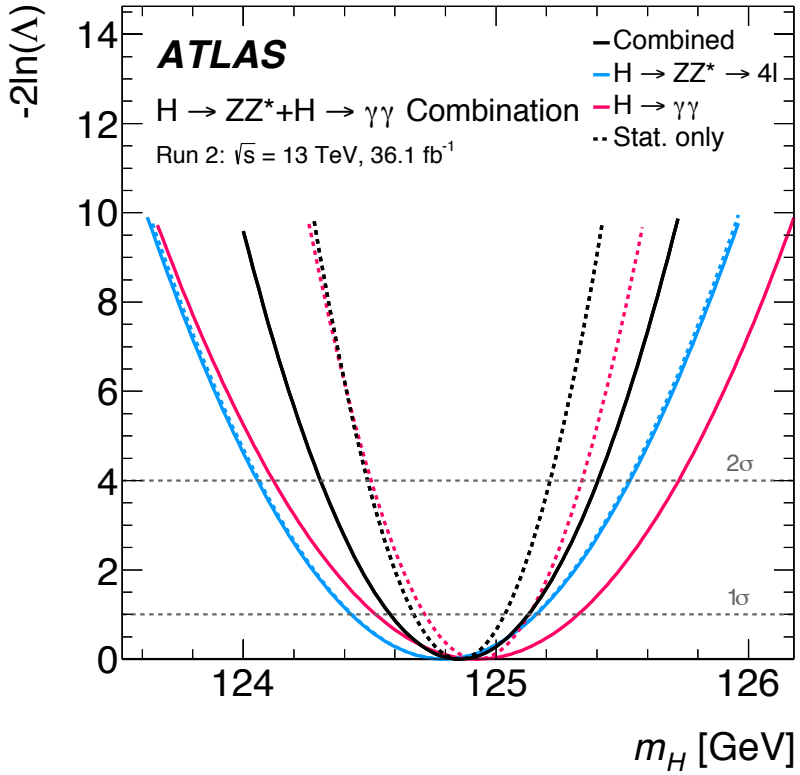
Source	Systematic uncertainty in m_H [MeV]
EM calorimeter response linearity	60
Non-ID material	55
EM calorimeter layer intercalibration	55
$Z \to ee$ calibration	45
ID material	45
Lateral shower shape	40
Muon momentum scale	20
Conversion reconstruction	20
$H \to \gamma\gamma$ background modelling	20
$H \to \gamma\gamma$ vertex reconstruction	15
e/γ energy resolution	15
All other systematic uncertainties	10

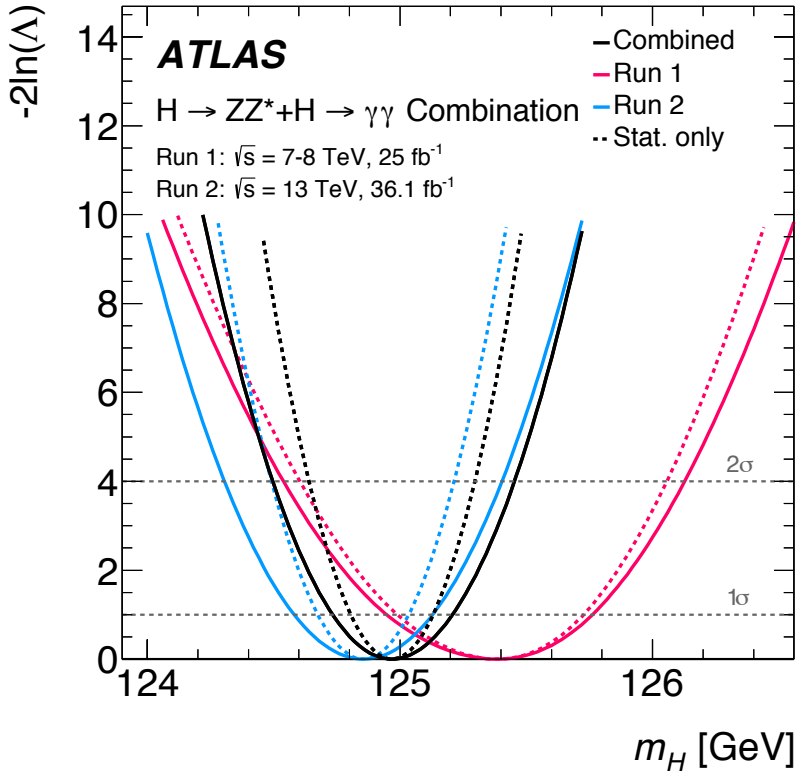




Mass measurements: ATLAS H→ZZ→4l + H→$\gamma\gamma$

ATLAS arxiv:1806.00242





Spin/parity: CMS H→VV Run 1

CMS Phys. Rev. D92 (2015) 012004

- **General HVV amplitude**

$$A(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q^2_{\mathrm{V1}} + \kappa_2^{\mathrm{VV}} q^2_{\mathrm{V2}}}{\left(\Lambda_1^{\mathrm{VV}}\right)^2}\right] m^2_{\mathrm{V1}} \epsilon^*_{\mathrm{V1}} \epsilon^*_{\mathrm{V2}} + a_2^{\mathrm{VV}} f^{*(1)}_{\mu\nu} f^{*(2),\mu\nu} + a_3^{\mathrm{VV}} f^{*(1)}_{\mu\nu} \tilde{f}^{*(2),\mu\nu}$$

SM tree-level **SM loop-induced, small** **CP-odd**

$$\begin{aligned}
L(\mathrm{HVV}) \sim\ & a_1 \frac{m_{\mathrm{Z}}^2}{2} \mathrm{H} \mathrm{Z}^\mu \mathrm{Z}_\mu - \frac{\kappa_1}{\left(\Lambda_1\right)^2} m_{\mathrm{Z}}^2 \mathrm{H} \mathrm{Z}_\mu \Box \mathrm{Z}^\mu - \frac{1}{2} a_2 \mathrm{H} \mathrm{Z}^{\mu\nu} \mathrm{Z}_{\mu\nu} - \frac{1}{2} a_3 \mathrm{H} \mathrm{Z}^{\mu\nu} \tilde{\mathrm{Z}}_{\mu\nu} \\
& + a_1^{\mathrm{WW}} m_{\mathrm{W}}^2 \mathrm{H} \mathrm{W}^{+\mu} \mathrm{W}^-_\mu - \frac{1}{\left(\Lambda_1^{\mathrm{WW}}\right)^2} m_{\mathrm{W}}^2 \mathrm{H} \left(\kappa_1^{\mathrm{WW}} \mathrm{W}^-_\mu \Box \mathrm{W}^{+\mu} + \kappa_2^{\mathrm{WW}} \mathrm{W}^+_\mu \Box \mathrm{W}^{-\mu}\right) \\
& - a_2^{\mathrm{WW}} \mathrm{H} \mathrm{W}^{+\mu\nu} \mathrm{W}^-_{\mu\nu} - a_3^{\mathrm{WW}} \mathrm{H} \mathrm{W}^{+\mu\nu} \tilde{\mathrm{W}}^-_{\mu\nu} \\
& + \frac{\kappa_2^{\mathrm{Z}\gamma}}{\left(\Lambda_1^{\mathrm{Z}\gamma}\right)^2} m_{\mathrm{Z}}^2 \mathrm{H} \mathrm{Z}_\mu \partial_\nu \mathrm{F}^{\mu\nu} - a_2^{\mathrm{Z}\gamma} \mathrm{H} \mathrm{F}^{\mu\nu} \mathrm{Z}_{\mu\nu} - a_3^{\mathrm{Z}\gamma} \mathrm{H} \mathrm{F}^{\mu\nu} \tilde{\mathrm{Z}}_{\mu\nu} - \frac{1}{2} a_2^{\gamma\gamma} \mathrm{H} \mathrm{F}^{\mu\nu} \mathrm{F}_{\mu\nu} - \frac{1}{2} a_3^{\gamma\gamma} \mathrm{H} \mathrm{F}^{\mu\nu} \tilde{F}_{\mu\nu}
\end{aligned}$$

Spin/parity: CMS H→VV Run 1

CMS Phys. Rev. D92 (2015) 012004

Interaction	Anomalous Coupling	Coupling Phase	Effective Fraction	Translation Constant
HZZ	Λ_1	$\phi_{\Lambda 1}$	$f_{\Lambda 1}$	$\sigma_1/\tilde{\sigma}_{\Lambda 1} = 1.45 \times 10^4\,\mathrm{TeV}^{-4}$
	a_2	ϕ_{a2}	f_{a2}	$\sigma_1/\sigma_2 = 2.68$
	a_3	ϕ_{a3}	f_{a3}	$\sigma_1/\sigma_3 = 6.36$
HWW	Λ_1^{WW}	$\phi_{\Lambda 1}^{WW}$	$f_{\Lambda 1}^{WW}$	$\sigma_1^{WW}/\tilde{\sigma}_{\Lambda 1}^{WW} = 1.87 \times 10^4\,\mathrm{TeV}^{-4}$
	a_2^{WW}	ϕ_{a2}^{WW}	f_{a2}^{WW}	$\sigma_1^{WW}/\sigma_2^{WW} = 1.25$
	a_3^{WW}	ϕ_{a3}^{WW}	f_{a3}^{WW}	$\sigma_1^{WW}/\sigma_3^{WW} = 3.01$
HZγ	$\Lambda_1^{Z\gamma}$	$\phi_{\Lambda 1}^{Z\gamma}$	$f_{\Lambda 1}^{Z\gamma}$	$\sigma_1'/\tilde{\sigma}_{\Lambda 1}^{Z\gamma} = 5.76 \times 10^3\,\mathrm{TeV}^{-4}$
	$a_2^{Z\gamma}$	$\phi_{a2}^{Z\gamma}$	$f_{a2}^{Z\gamma}$	$\sigma_1'/\sigma_2^{Z\gamma} = 2.24 \times 10^{-3}$
	$a_3^{Z\gamma}$	$\phi_{a3}^{Z\gamma}$	$f_{a3}^{Z\gamma}$	$\sigma_1'/\sigma_3^{Z\gamma} = 2.72 \times 10^{-3}$
Hγγ	$a_2^{\gamma\gamma}$	$\phi_{a2}^{\gamma\gamma}$	$f_{a2}^{\gamma\gamma}$	$\sigma_1'/\sigma_2^{\gamma\gamma} = 2.82 \times 10^{-3}$
	$a_3^{\gamma\gamma}$	$\phi_{a3}^{\gamma\gamma}$	$f_{a3}^{\gamma\gamma}$	$\sigma_1'/\sigma_3^{\gamma\gamma} = 2.88 \times 10^{-3}$

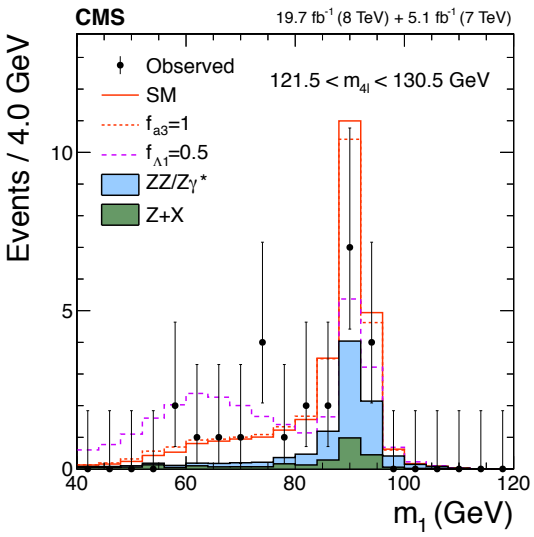
$$f_{\Lambda 1} = \frac{\tilde{\sigma}_{\Lambda 1}/\left(\Lambda_1\right)^4}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1}/\left(\Lambda_1\right)^4 + \ldots}, \qquad \phi_{\Lambda 1},$$

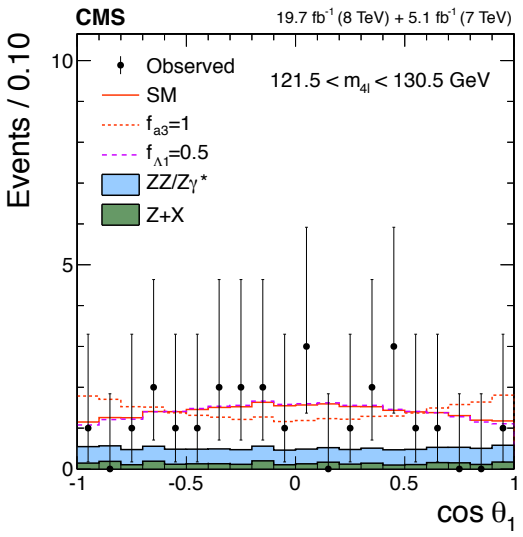
$$f_{a2} = \frac{|a_2|^2\sigma_2}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1}/\left(\Lambda_1\right)^4 + \ldots}, \qquad \phi_{a2} = \arg\left(\frac{a_2}{a_1}\right)$$

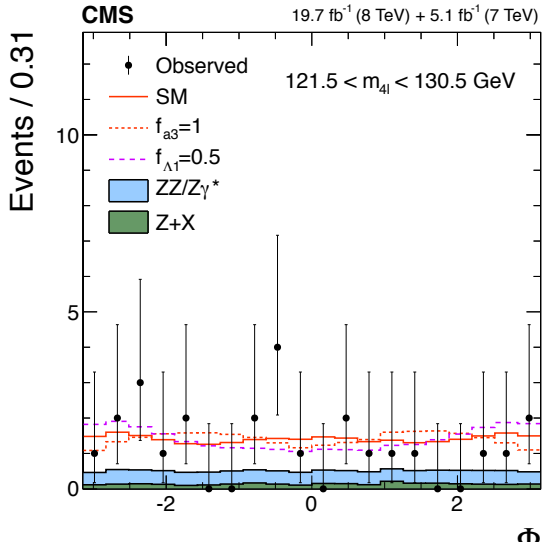
$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1}/\left(\Lambda_1\right)^4 + \ldots}, \qquad \phi_{a3} = \arg\left(\frac{a_3}{a_1}\right)$$

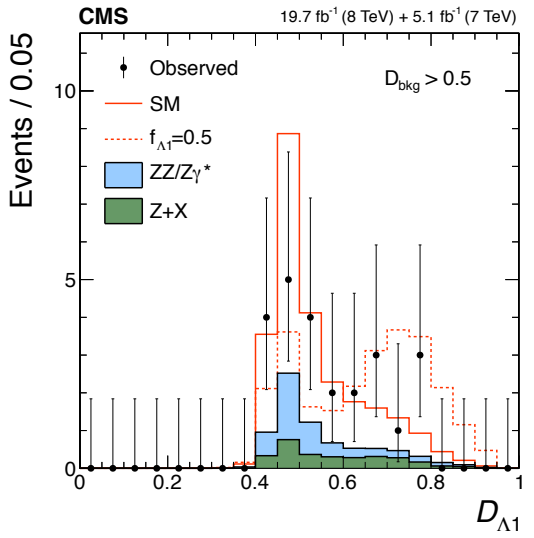
Spin/parity: CMS H→ZZ Run 1

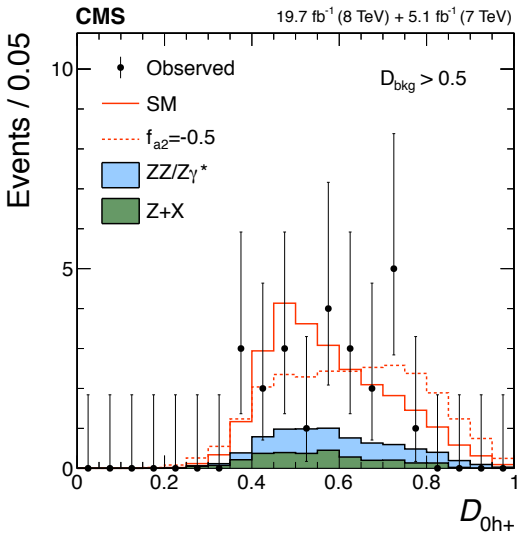
CMS Phys. Rev. D92 (2015) 012004

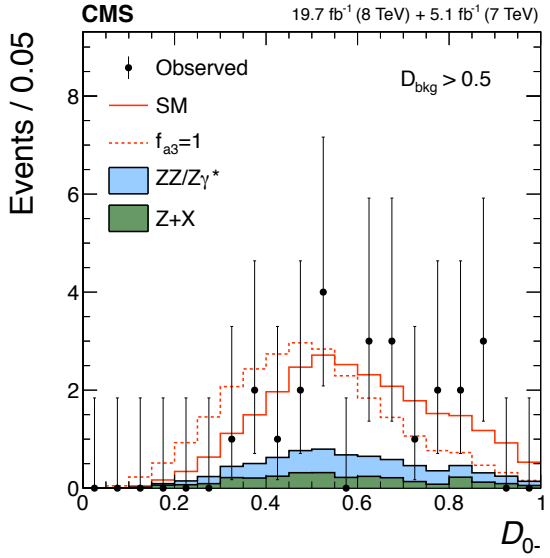






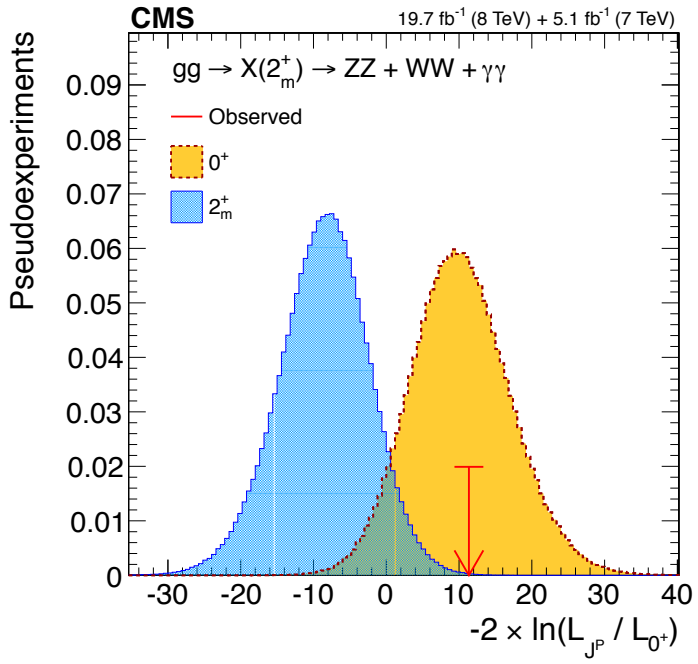




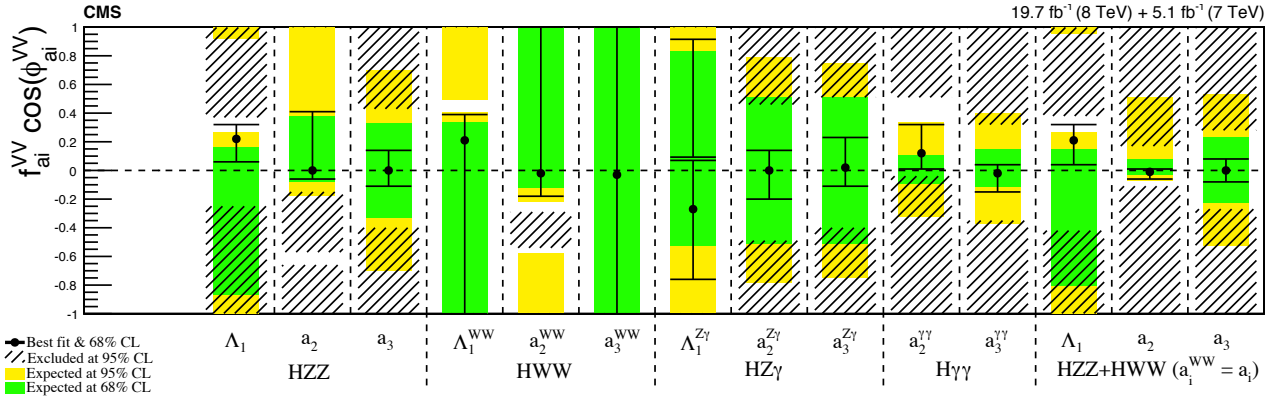


Spin/parity: CMS H→VV Run 1

CMS Phys. Rev. D92 (2015) 012004

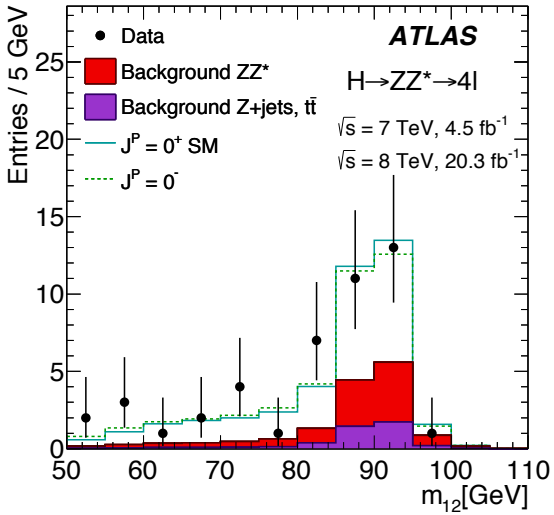


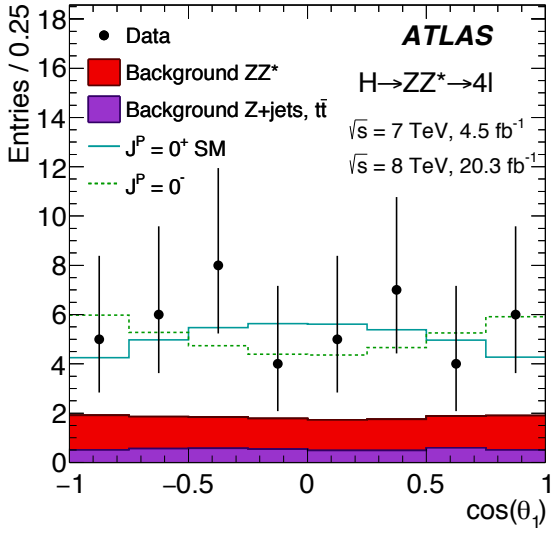
- **Various spin/parity states tested with dedicated ME discriminants**
- **All results consistant with CP-even SM Higgs boson**
- **Constraints derived on coupling parameters in effective Lagrangian**

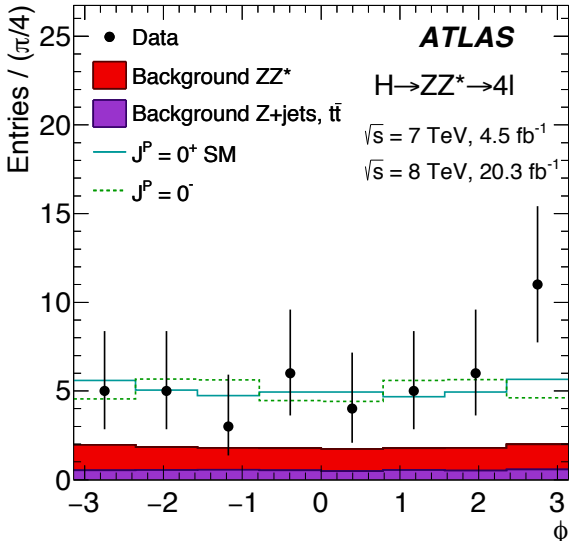


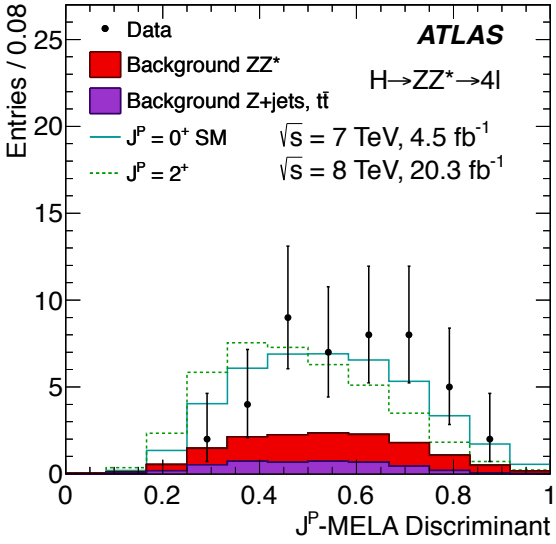
Spin/parity: ATLAS H→VV Run 1

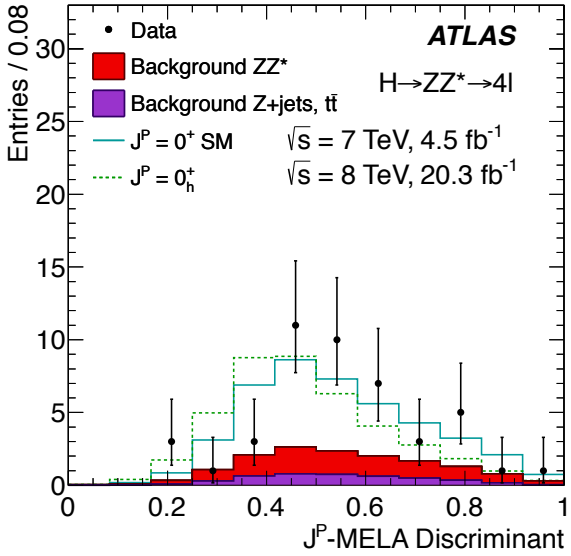
ATLAS Eur. Phys. J. C75 (2015) 476

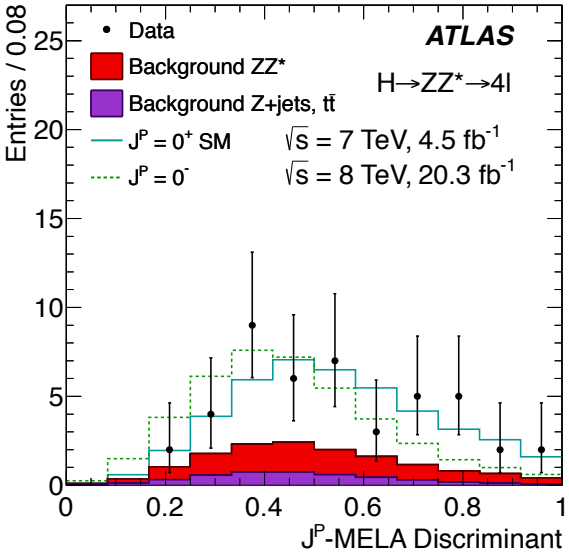








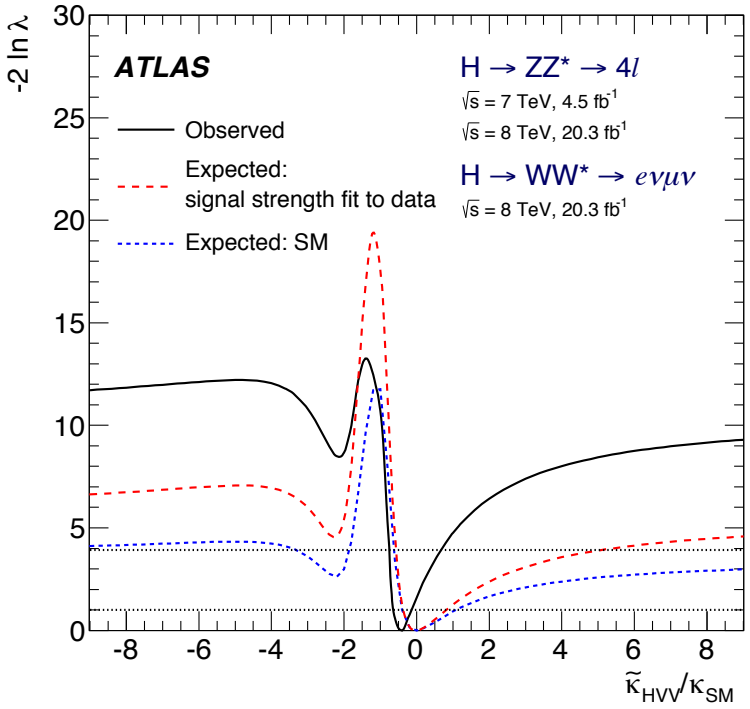


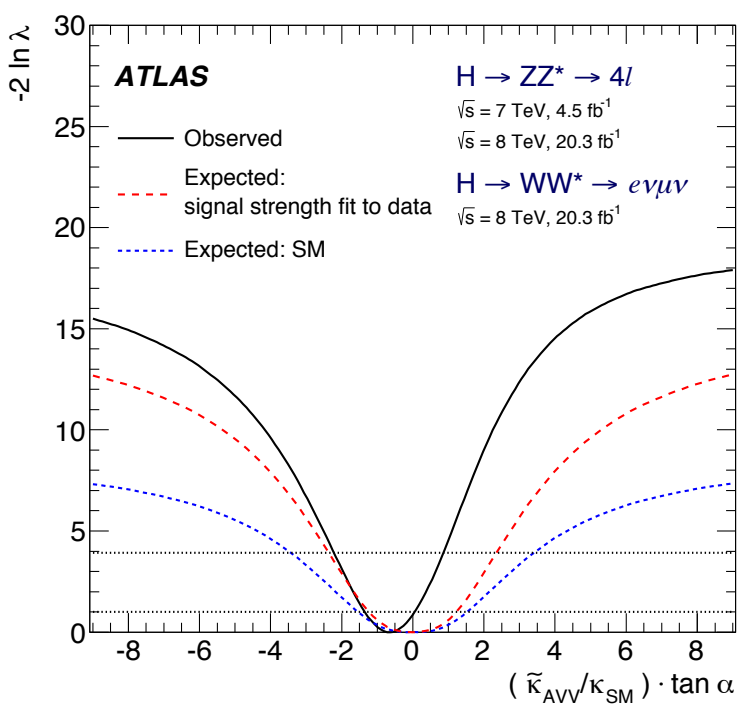


Spin/parity: ATLAS H→VV Run 1

ATLAS Eur. Phys. J. C75 (2015) 476

$$\mathcal{L}_0^V = \Big\{\cos(\alpha)\kappa_{SM}\left[\tfrac{1}{2}g_{HZZ}Z_\mu Z^\mu + g_{HWW}W_\mu^+ W^{-\mu}\right] - \tfrac{1}{4}\tfrac{1}{\Lambda}\left[\cos(\alpha)\kappa_{HZZ}Z_{\mu\nu}Z^{\mu\nu} + \sin(\alpha)\kappa_{AZZ}Z_{\mu\nu}\tilde{Z}^{\mu\nu}\right] - \tfrac{1}{2}\tfrac{1}{\Lambda}\left[\cos(\alpha)\kappa_{HWW}W_{\mu\nu}^+ W^{-\mu\nu} + \sin(\alpha)\kappa_{AWW}W_{\mu\nu}^+ \tilde{W}^{-\mu\nu}\right]\Big\} X_0$$

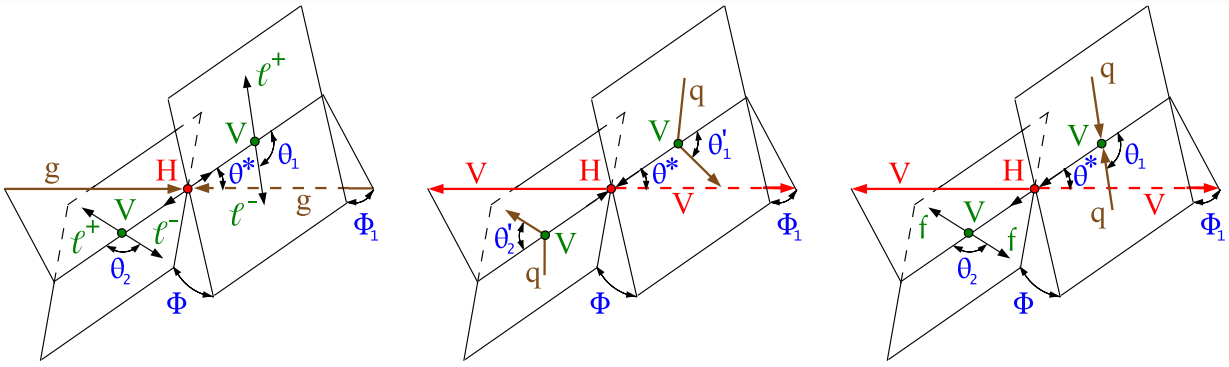




Spin/parity: CMS H→ZZ Run 2

CMS Phys. Lett. B775 (2017) 1

- **Angular information for associated production modes also used**



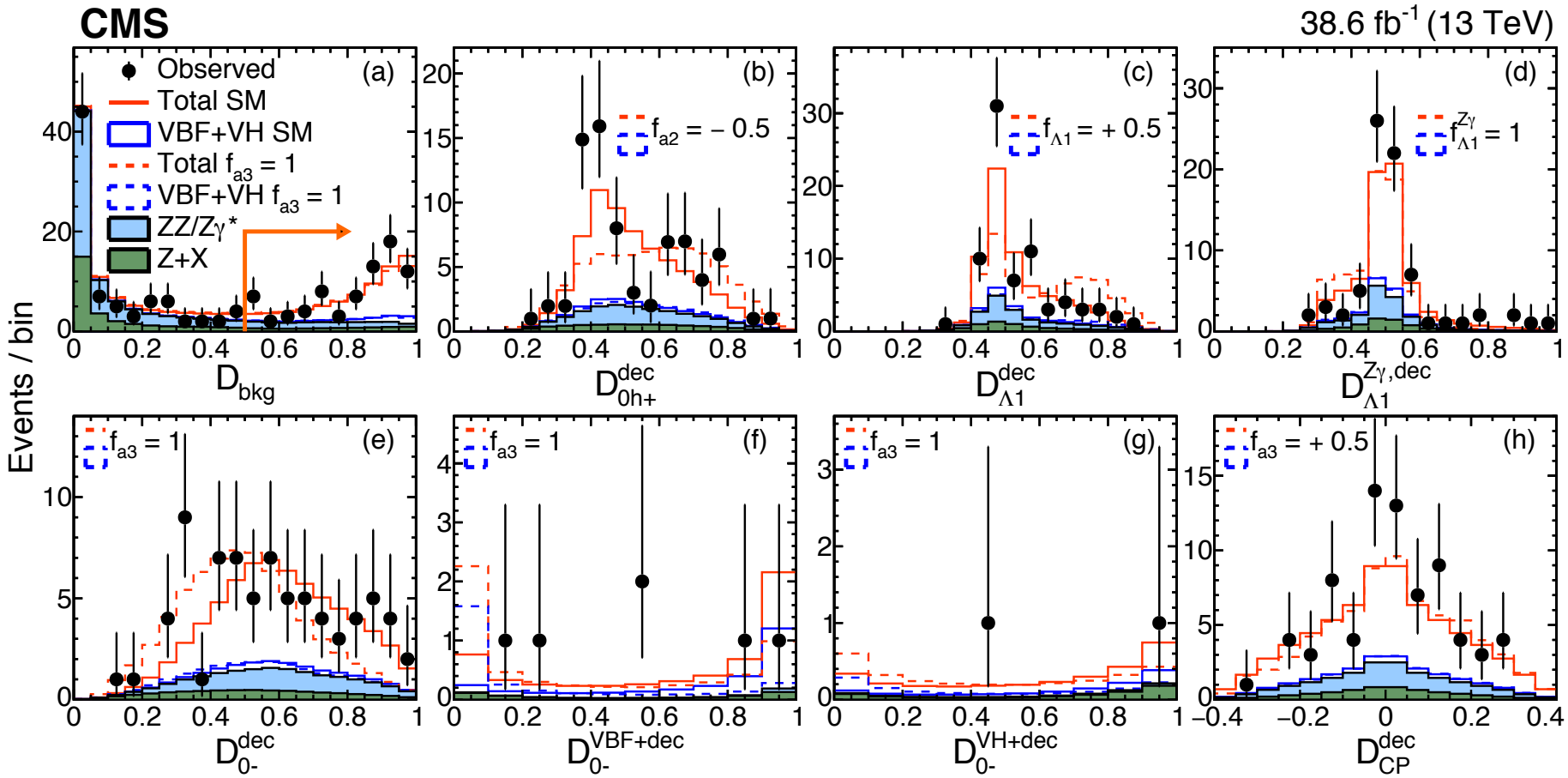
- **Categories defined based on ME discriminant between production modes**

Table 1: Summary of the three production categories in the analysis of 2016 data. The discriminants $\mathcal{D}$ are calculated from Eqs. (4) and (5), as discussed in more detail in the text. For each analysis, the appropriate BSM model is considered in the definition of the categories: $f_{a3} = 1$, $f_{a2} = 1$, $f_{\Lambda 1} = 1$, or $f_{\Lambda 1}^{Z\gamma} = 1$. Three observables (abbreviated as obs.) are listed for each analysis and for each category. They are described in more detail later in the text.

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.	$\mathcal{D}_{bkg}$, $\mathcal{D}_{0h+}^{VBF+dec}$, $\mathcal{D}_{int}^{VBF}$	$\mathcal{D}_{bkg}$, $\mathcal{D}_{0h+}^{VH+dec}$, $\mathcal{D}_{int}^{VH}$	$\mathcal{D}_{bkg}$, $\mathcal{D}_{0h+}^{dec}$, $\mathcal{D}_{int}^{dec}$
$f_{\Lambda 1}$ obs.	$\mathcal{D}_{bkg}$, $\mathcal{D}_{\Lambda 1}^{VBF+dec}$, $\mathcal{D}_{0h+}^{VBF+dec}$	$\mathcal{D}_{bkg}$, $\mathcal{D}_{\Lambda 1}^{VH+dec}$, $\mathcal{D}_{0h+}^{VH+dec}$	$\mathcal{D}_{bkg}$, $\mathcal{D}_{\Lambda 1}^{dec}$, $\mathcal{D}_{0h+}^{dec}$
$f_{\Lambda 1}^{Z\gamma}$ obs.	$\mathcal{D}_{bkg}$, $\mathcal{D}_{\Lambda 1}^{Z\gamma,VBF+dec}$, $\mathcal{D}_{0h+}^{VBF+dec}$	$\mathcal{D}_{bkg}$, $\mathcal{D}_{\Lambda 1}^{Z\gamma,VH+dec}$, $\mathcal{D}_{0h+}^{VH+dec}$	$\mathcal{D}_{bkg}$, $\mathcal{D}_{\Lambda 1}^{Z\gamma,dec}$, $\mathcal{D}_{0h+}^{dec}$

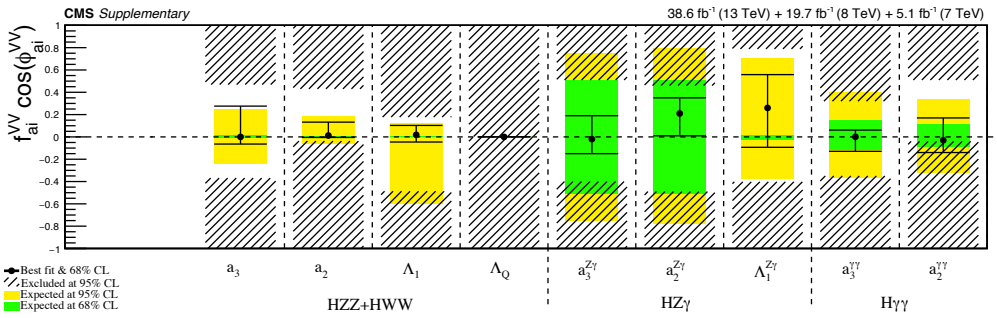
Spin/parity: CMS H→ZZ Run 2

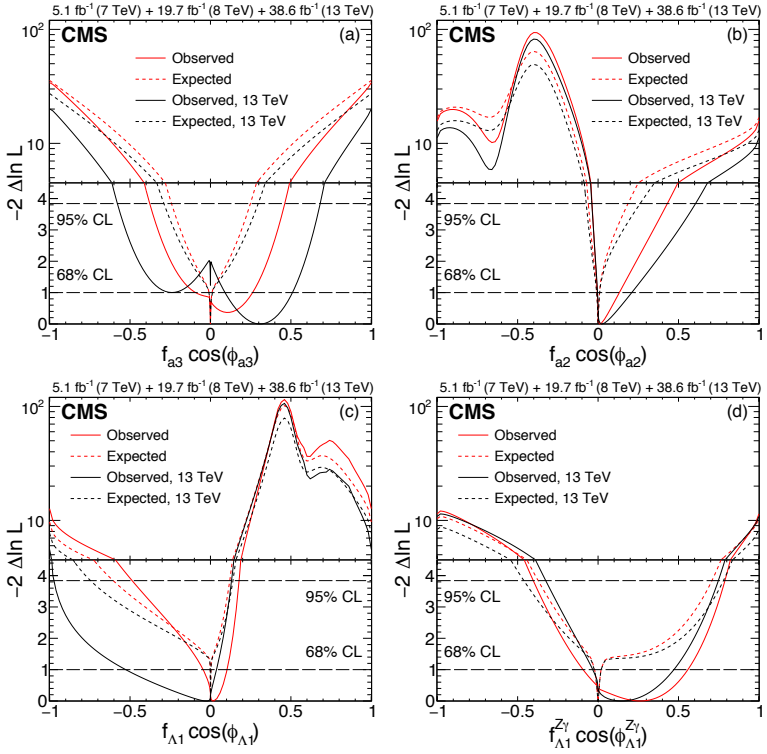
CMS Phys. Lett. B775 (2017) 1



Spin/parity: CMS H→ZZ Run 2

CMS Phys. Lett. B775 (2017) 1





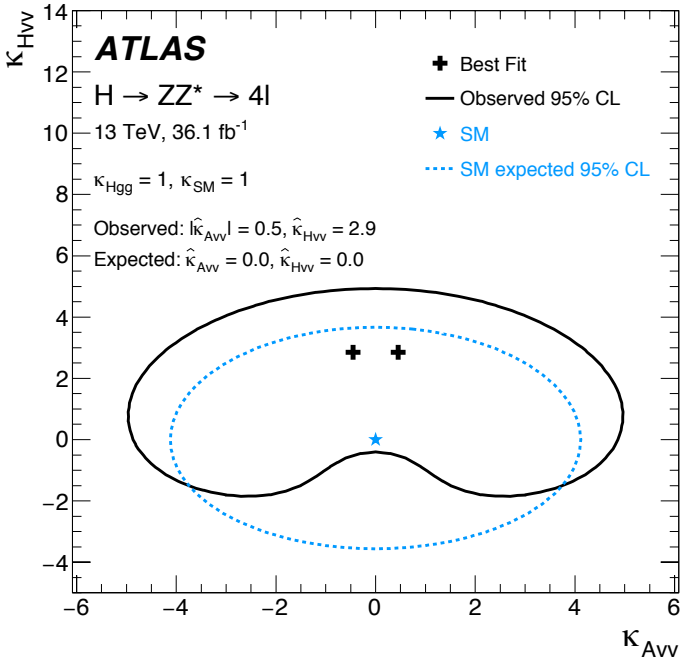
Spin/parity: ATLAS H→ZZ Run 2

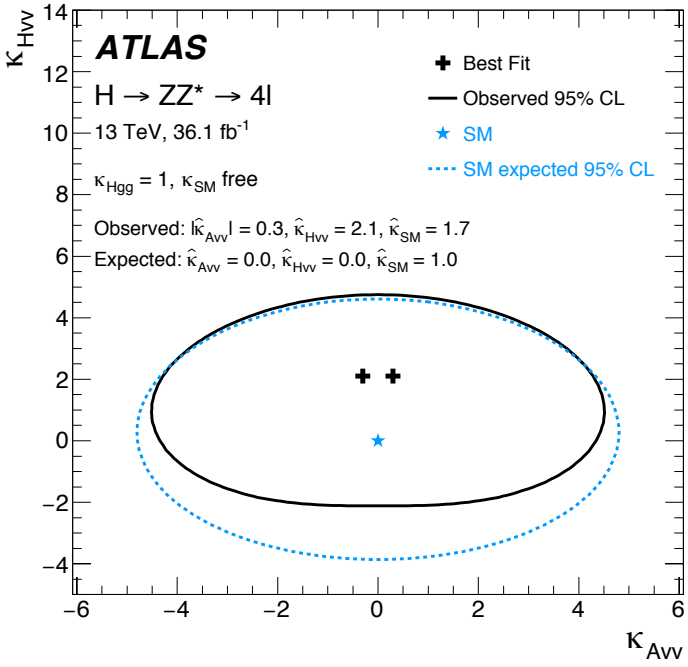
CMS Phys. Lett. B775 (2017) 1

- **Categories defined based on Stage 1 STXS**

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

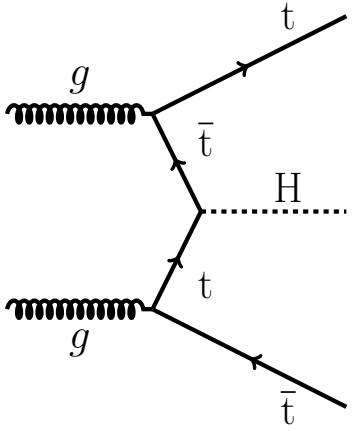
BSM coupling $\kappa_{\rm BSM}$	Fit configuration	Expected conf. inter.	Observed conf. inter.	Best-fit $\hat{\kappa}_{\rm BSM}$	Best-fit $\hat{\kappa}_{\rm SM}$	Deviation from SM
κ_{Agg}	$(\kappa_{Hgg}=1, \kappa_{\rm SM}=1)$	$[-0.47, 0.47]$	$[-0.68, 0.68]$	± 0.43	-	1.8σ
κ_{HVV}	$(\kappa_{Hgg}=1, \kappa_{\rm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

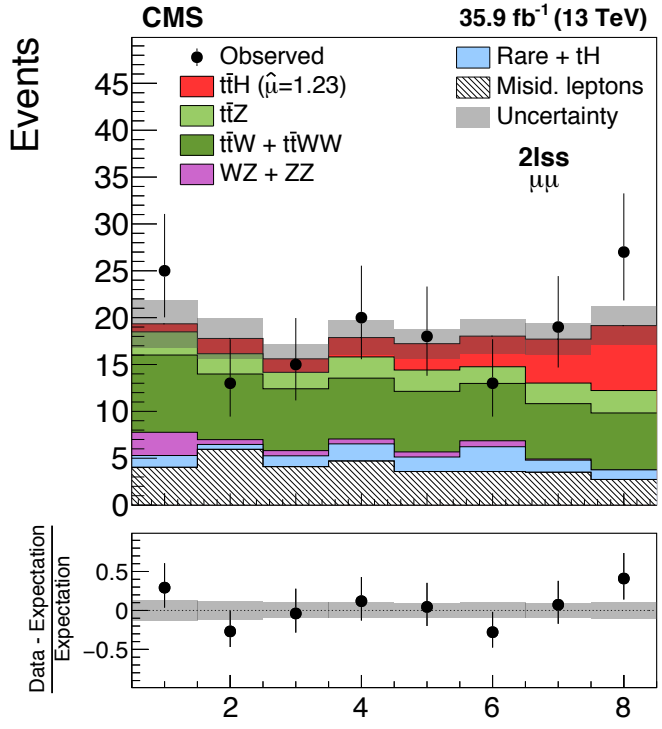




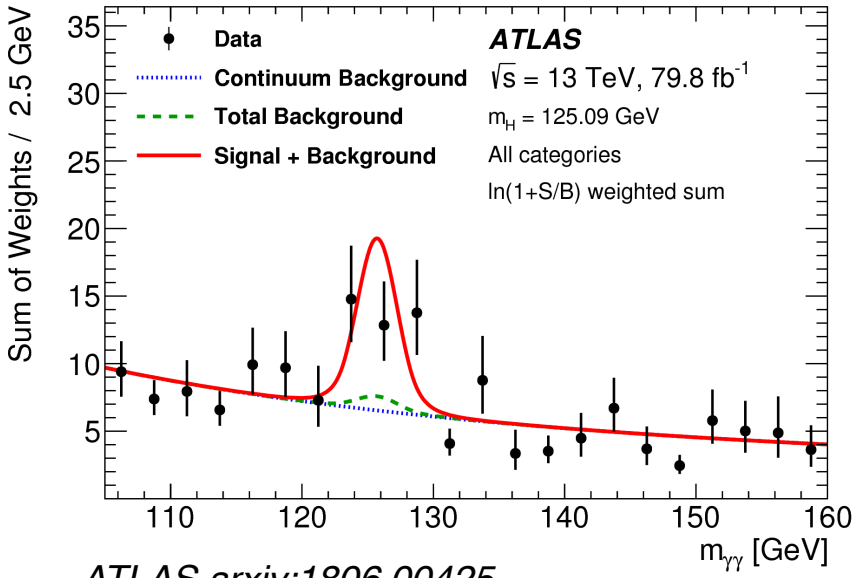
ttH combinations

- **ttH combinations results both from ATLAS (13 TeV) + CMS (7+8+13 TeV):**
  - **dedicated ttH H→bb and ttH multilepton (H→WW/ZZ/$\tau\tau$) analyses:**
    based on dedicated MVA discriminants for signal extraction
  - **dedicated ttH categories in inclusive H→$\gamma\gamma$ and H→ZZ→4l analyses:**
    based on categorisation + mass distribution used for signal extraction





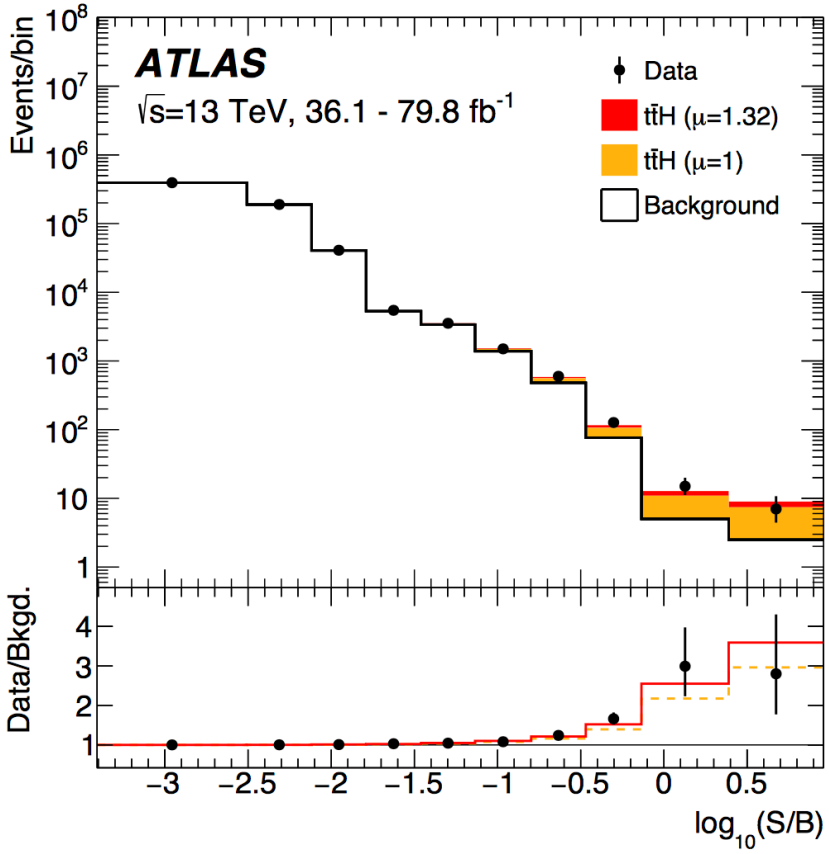
CMS arxiv:1803.05485

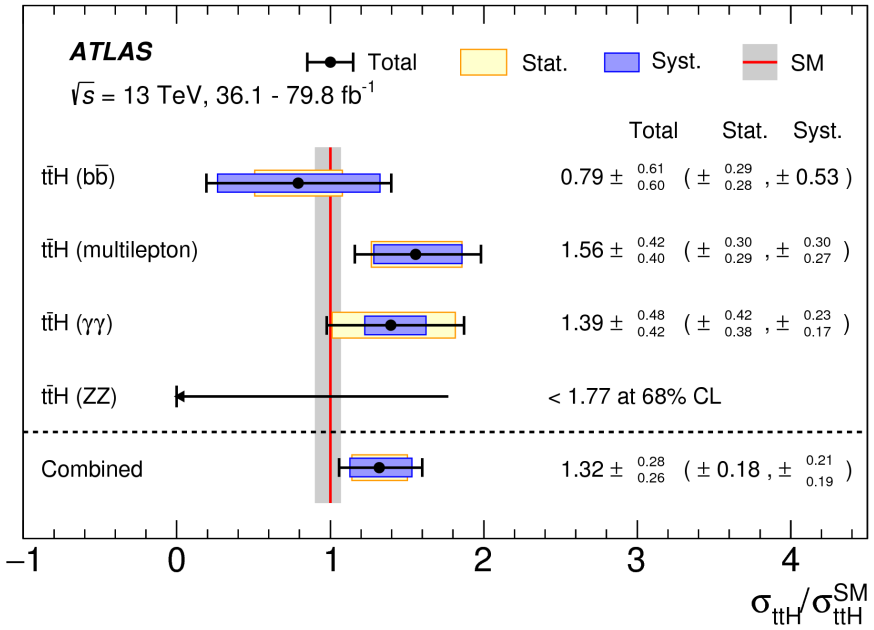


ATLAS arxiv:1806.00425

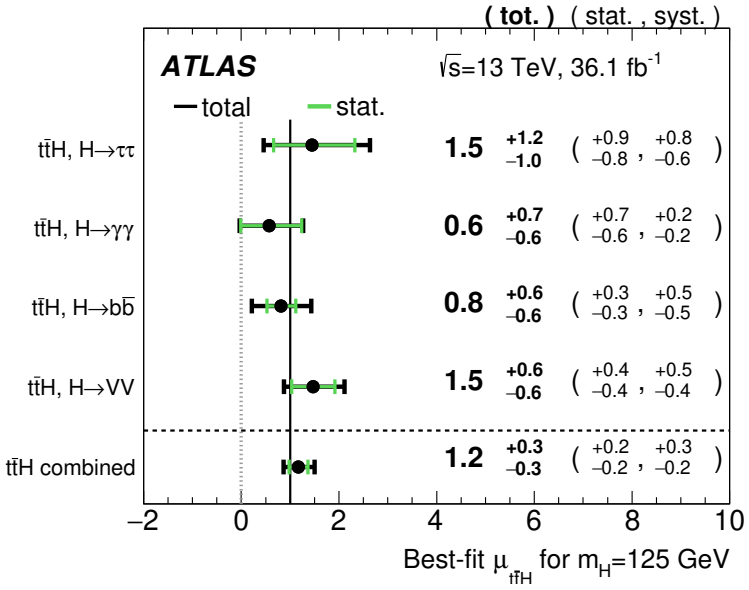
ttH combinations

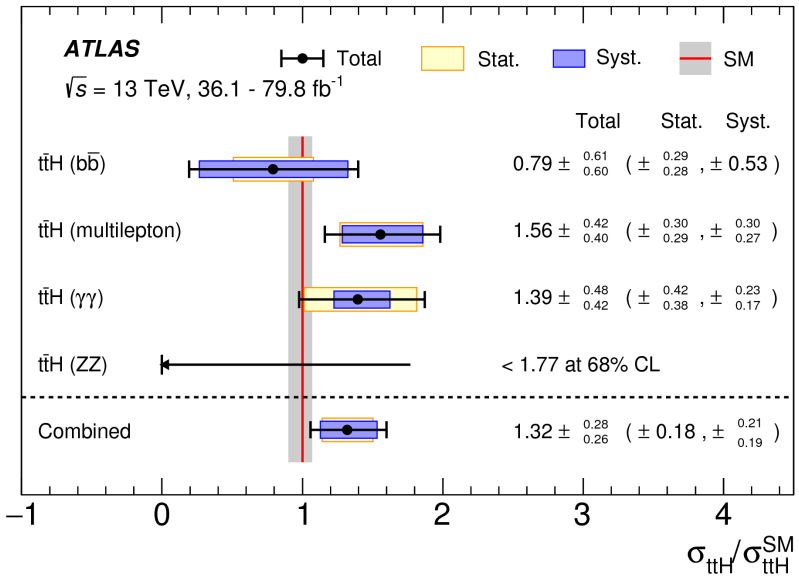
ATLAS arxiv:1806.00425

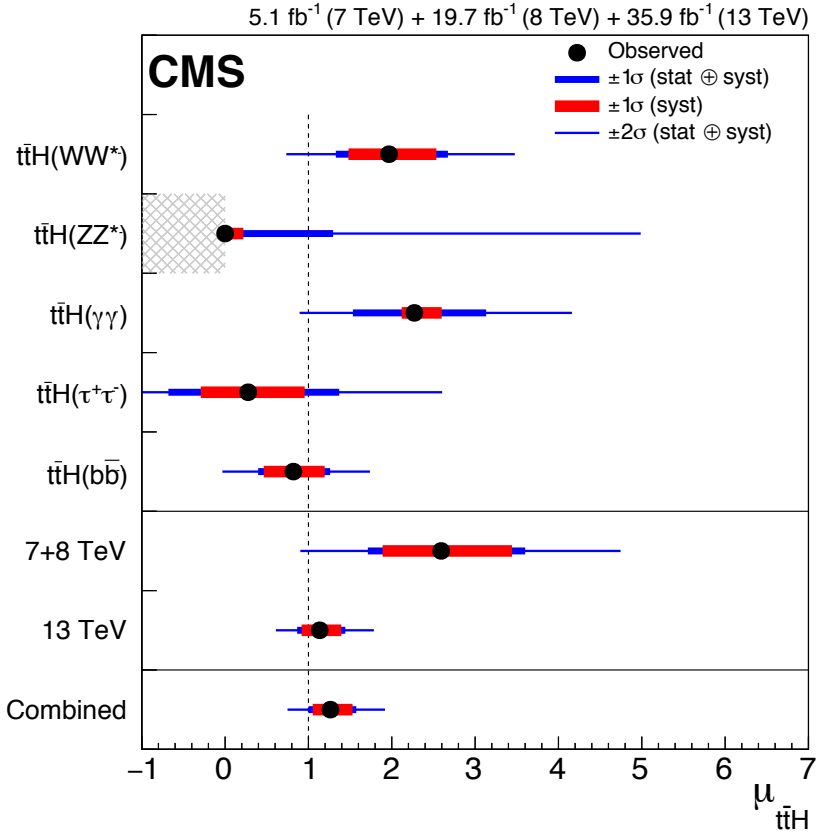




ttH combinations





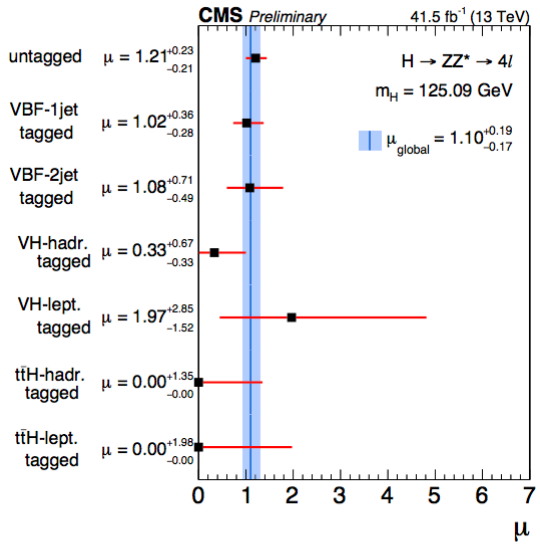


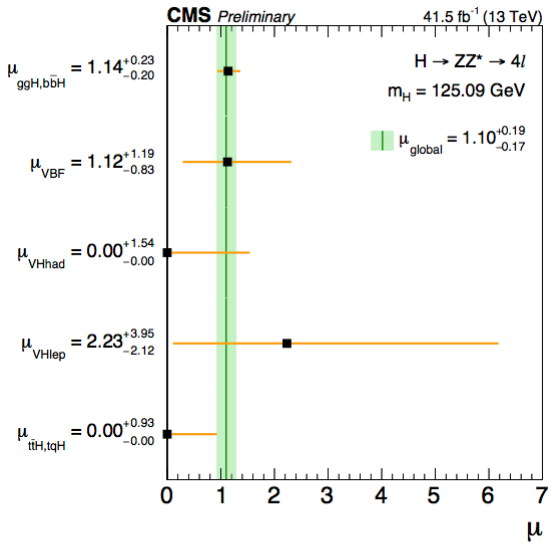
CMS Phys. Rev. Lett. 120, 231801 (2018)
ATLAS Phys. Rev. D97 (2018) 072003
ATLAS arxiv:1806.00425

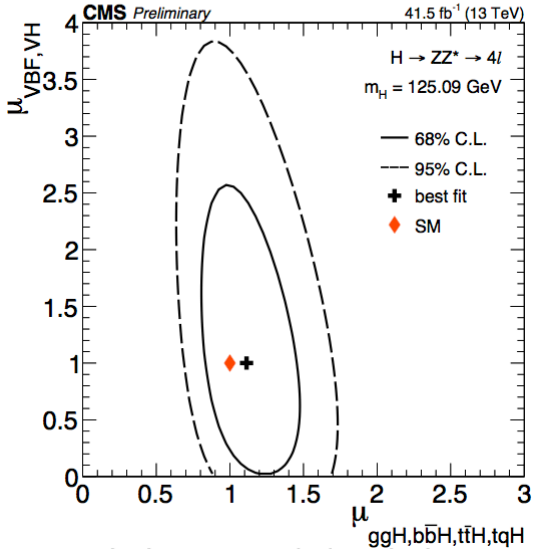
CMS H→ZZ

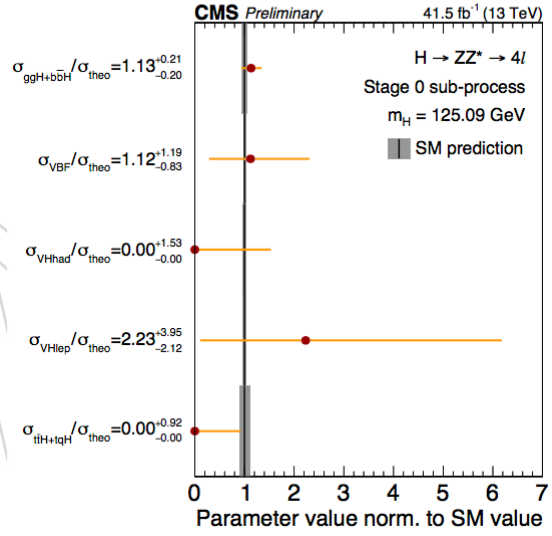
CMS PAS-HIG-18-001

- **2017 dataset**





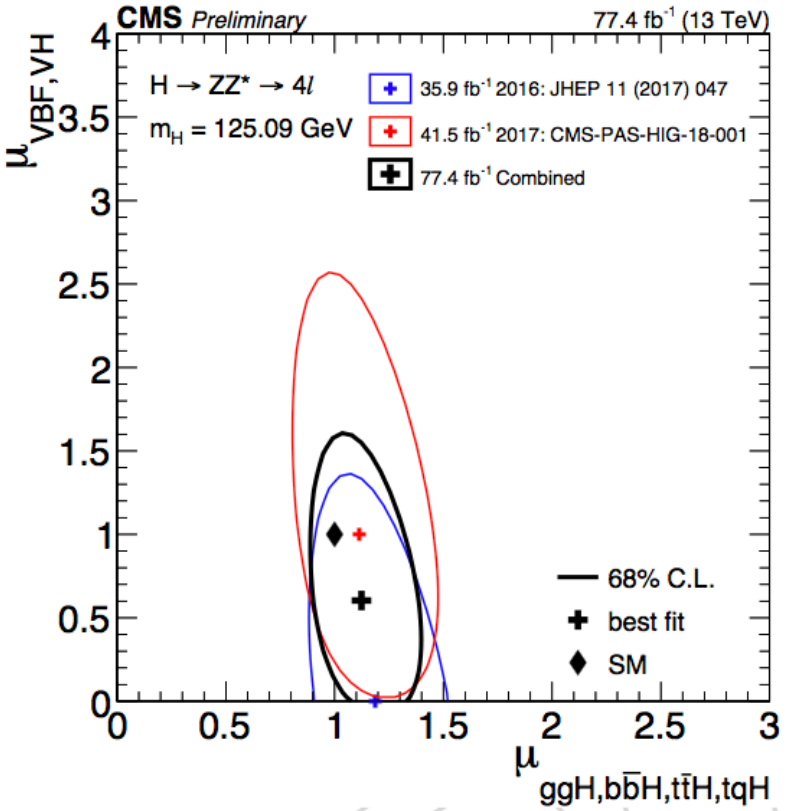


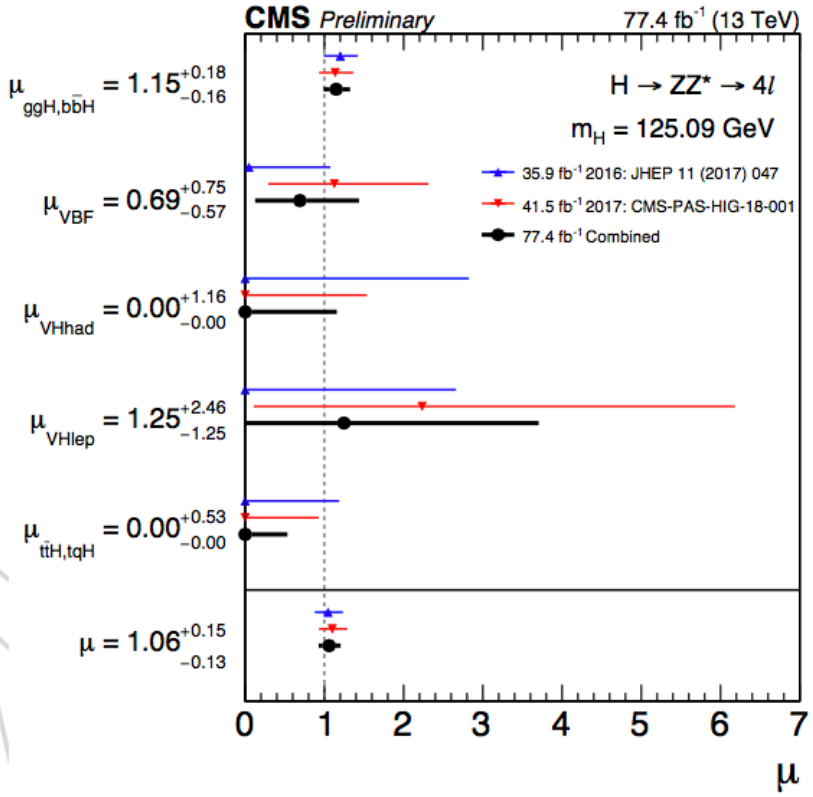


CMS H→ZZ

CMS PAS-HIG-18-001

- **2016+2017 dataset**

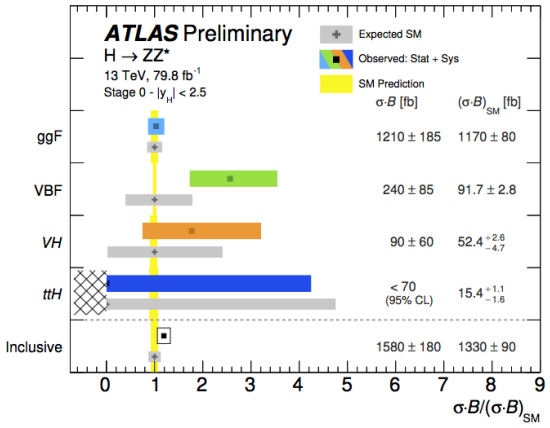




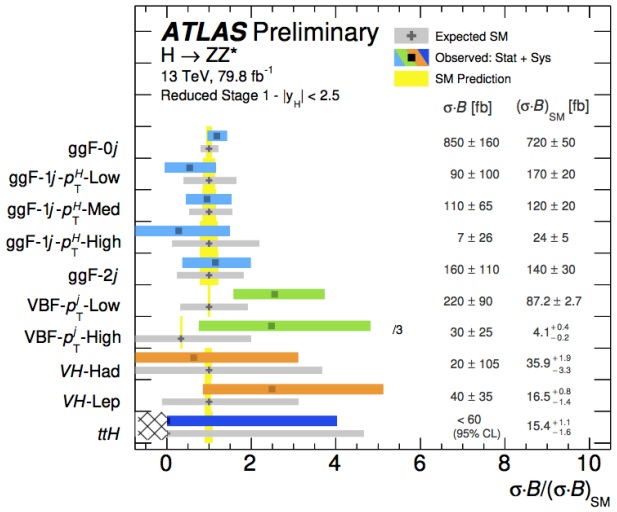
ATLAS H→ZZ

ATLAS-CONF-2018-018

- **2015+2016+2017 dataset**



(a)



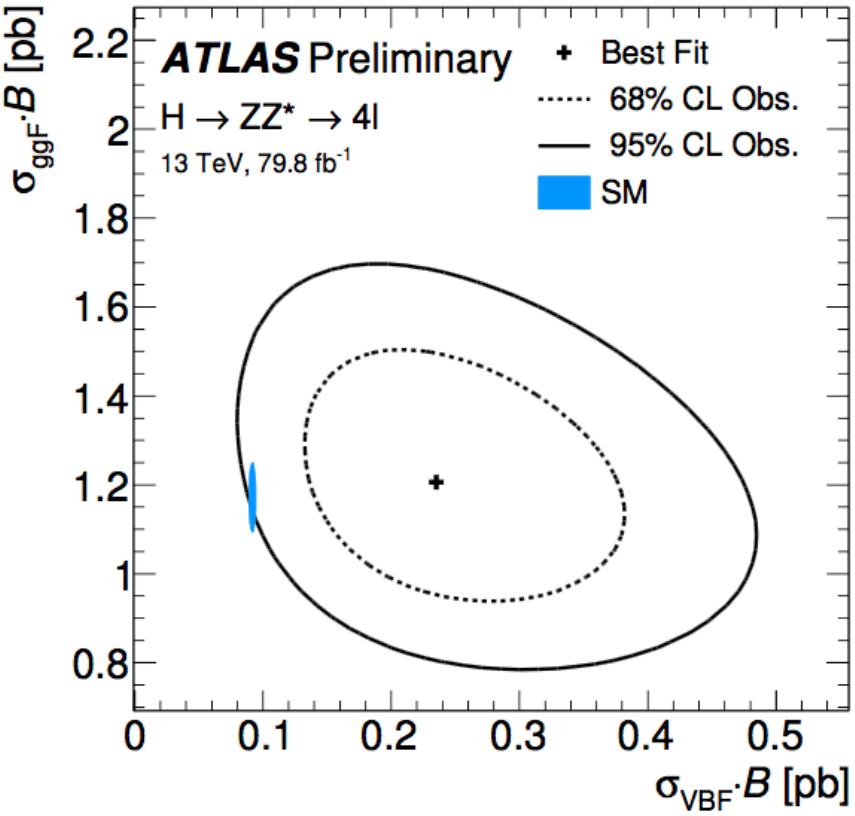
(b)

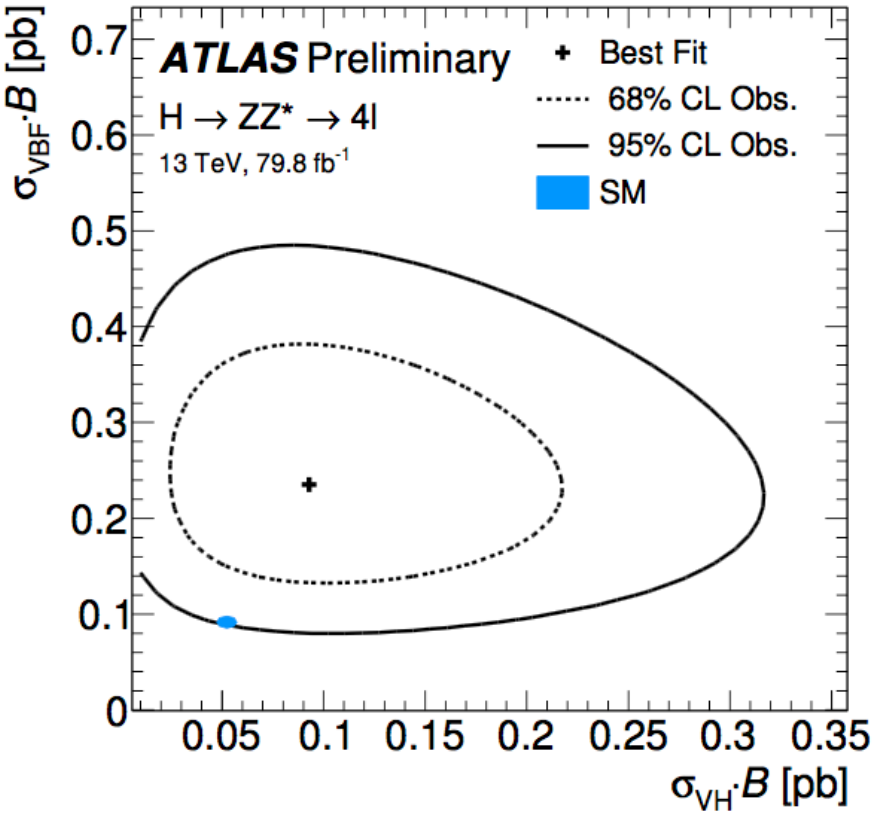
Production bin	Cross section ($\sigma \cdot \mathcal{B}$) [pb]		$(\sigma \cdot \mathcal{B})/(\sigma \cdot \mathcal{B})_{\mathrm{SM}}$
	SM expected	Observed	Observed
Inclusive production, $\lvert y_H \rvert < 2.5$			
	1.33 ± 0.09	$1.58 \pm 0.15 \pm 0.08 \pm 0.04$	$1.19 \pm 0.12 \pm 0.06 \pm 0.02$
Stage-0 production bins, $\lvert y_H \rvert < 2.5$			
ggF	1.17 ± 0.08	$1.21 \pm 0.17 \pm 0.08 \pm 0.04$	$1.03 \pm 0.14 \pm 0.07 \pm 0.03$
VBF	0.0917 ± 0.0028	$0.24 \pm 0.08 \pm 0.02 \pm 0.01$	$2.6 \pm 0.9 \pm 0.2 \pm 0.2$
VH	$0.0524^{+0.0026}_{-0.0047}$	$0.09 \pm 0.06 \pm 0.01 \pm 0.01$	$1.8 \pm 1.2 \pm 0.1 \pm 0.1$
ttH	$0.0154^{+0.0011}_{-0.0016}$	< 0.07	< 4.24
Reduced Stage-1 production bins, $\lvert y_H \rvert < 2.5$			
ggF-0j	0.72 ± 0.05	$0.85 \pm 0.14 \pm 0.08$	$1.19 \pm 0.20 \pm 0.10$
ggF-1j-p_{T}^{H}-Low	0.170 ± 0.020	$0.09 \pm 0.09 \pm 0.04$	$0.5 \pm 0.5 \pm 0.3$
ggF-1j-p_{T}^{H}-Med	0.120 ± 0.020	$0.11 \pm 0.06 \pm 0.02$	$0.95 \pm 0.51 \pm 0.13$
ggF-1j-p_{T}^{H}-High	0.024 ± 0.005	$0.007 \pm 0.026 \pm 0.006$	$0.3 \pm 1.1 \pm 0.3$
ggF-2j	0.140 ± 0.030	$0.16 \pm 0.10 \pm 0.03$	$1.15 \pm 0.76 \pm 0.26$
VBF-p_{T}^{j}-Low	0.0872 ± 0.0027	$0.22 \pm 0.09 \pm 0.02$	$2.6 \pm 1.0 \pm 0.2$
VBF-p_{T}^{j}-High	$0.0041^{+0.0004}_{-0.0002}$	$0.03 \pm 0.02 \pm 0.01$	$7.4 \pm 6.0 \pm 0.7$
VH-Had	$0.0359^{+0.0019}_{-0.0033}$	$0.02 \pm 0.10 \pm 0.01$	$0.6 \pm 2.9 \pm 0.3$
VH-Lep	$0.0165^{+0.0008}_{-0.0014}$	$0.04 \pm 0.03 \pm 0.01$	$2.5 \pm 2.1 \pm 0.1$
ttH	$0.0154^{+0.0011}_{-0.0016}$	< 0.06	< 4.02

ATLAS H→ZZ

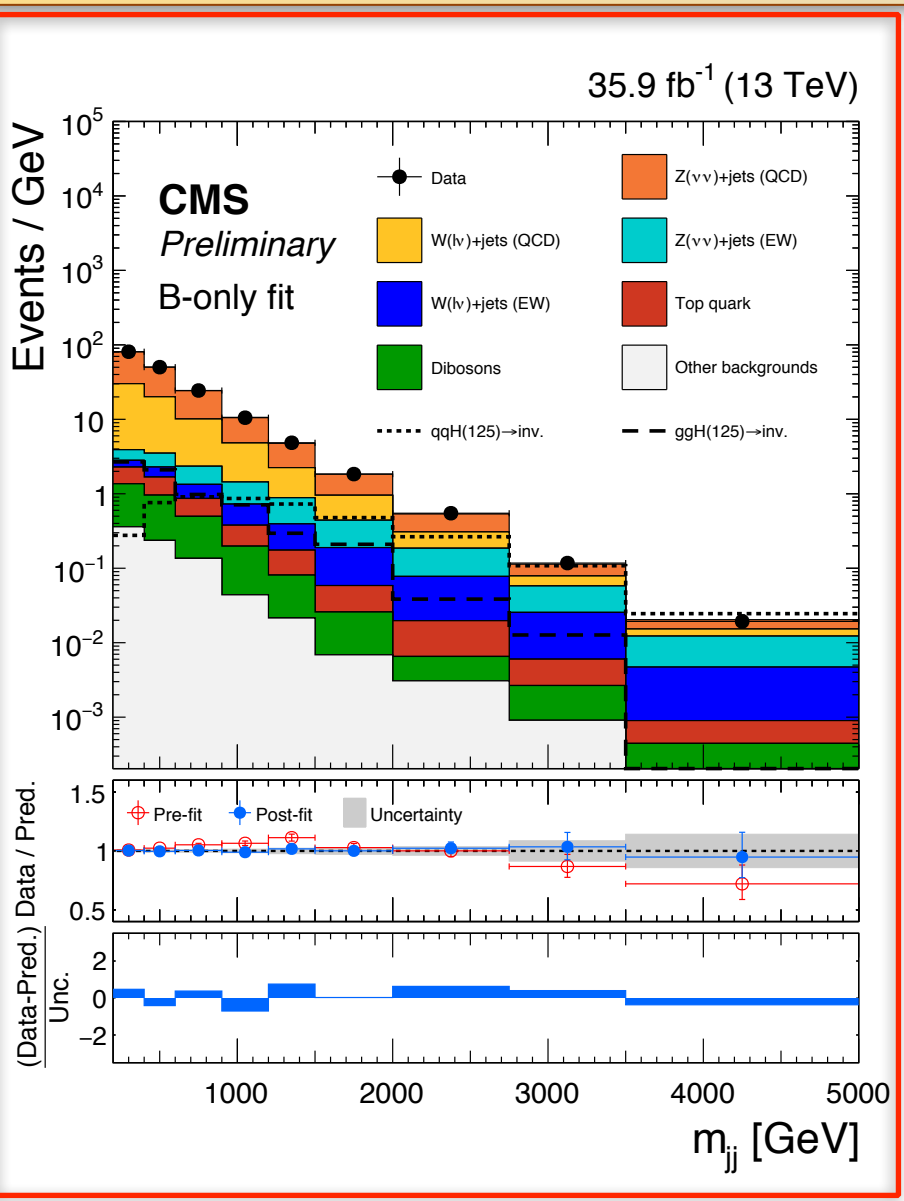
ATLAS-CONF-2018-018

- **2015+2016+2017 dataset**

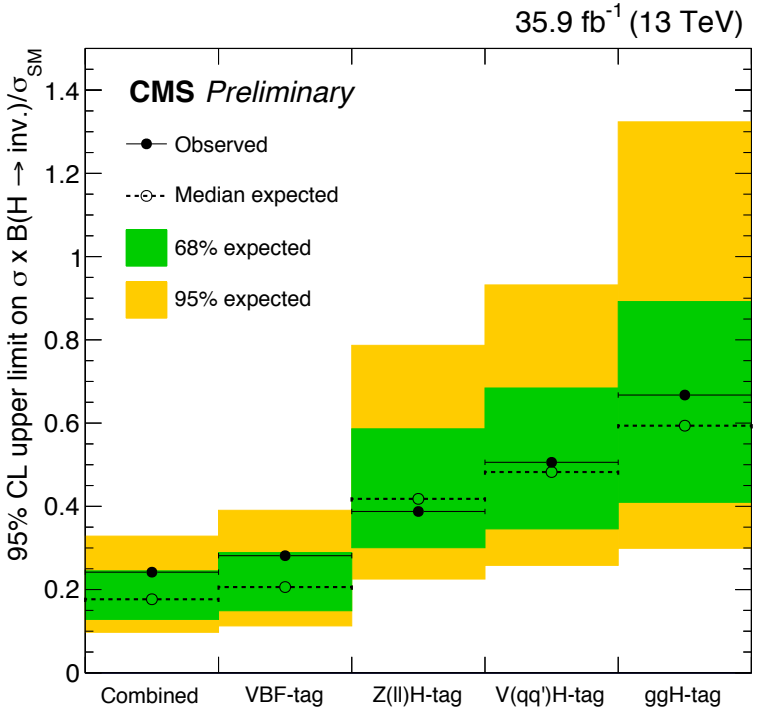




Constraining the invisible Higgs decays



- **Some BSM models predict couplings of DM candidates with SM Higgs boson:** predicts enhanced BR(H→inv.) wrt BR(H→ZZ→4ν)$_{SM}$~0.1%
- **Look for associated production mode (VBF, VH, ggF+ISR) of SM Higgs boson decaying to MET**

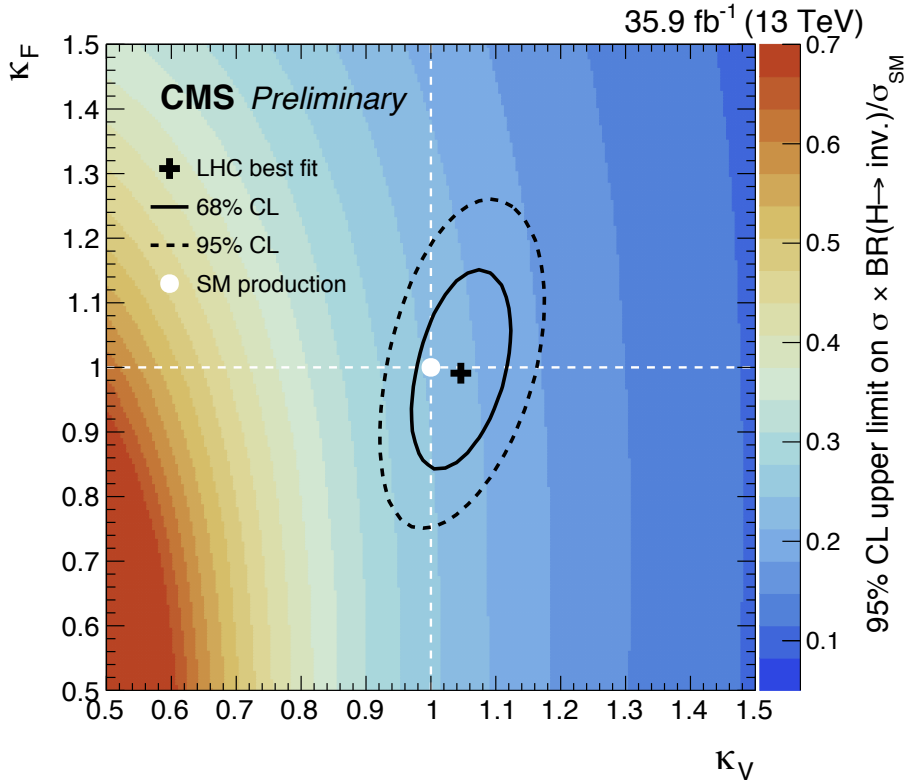


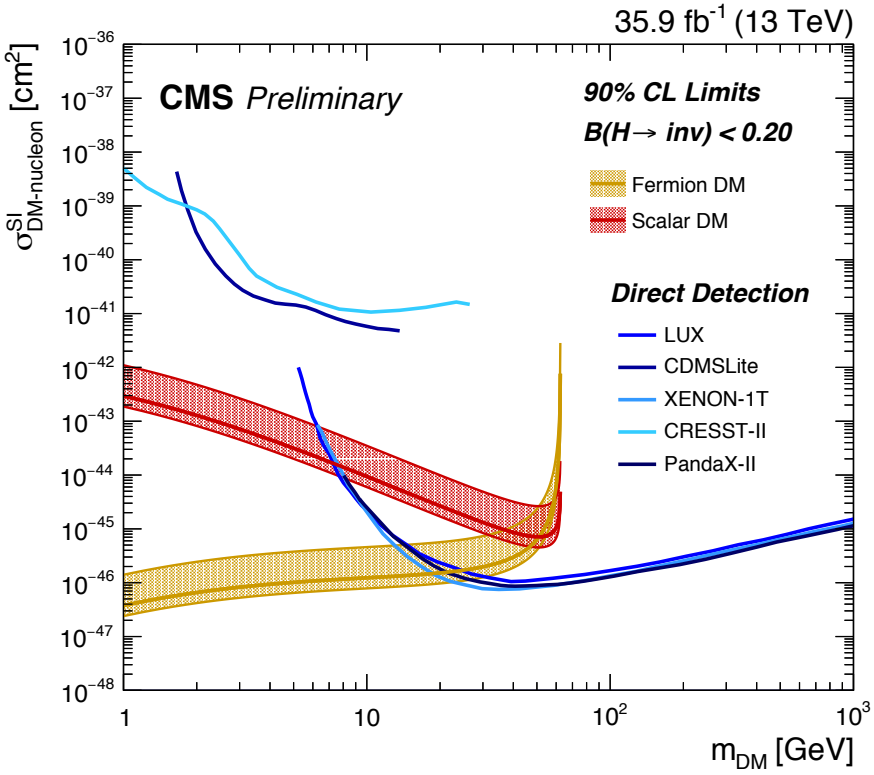
CMS-PAS-HIG-17-023

CMS VBF H→inv.

CMS-PAS-HIG-17-023

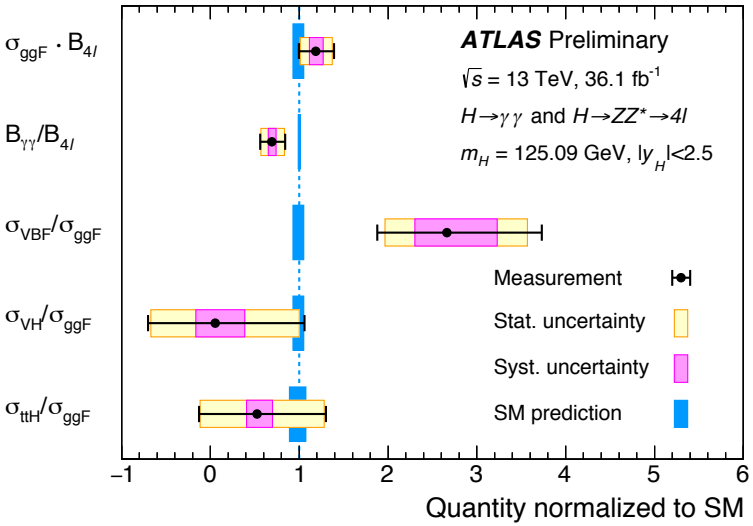
Analysis	Final state	Signal composition	Observed limit	Expected limit
qqH-tagged	VBF-jets + p_T^{miss}	52% qqH, 48% ggH	0.28	0.21
VH-tagged	$Z(\ell\ell) + p_T^{miss}$ [11]	79% qqZH, 21% ggZH	0.40	0.42
	$V(qq') + p_T^{miss}$ [12]	39% ggH, 6% qqH, 33% WH, 22% ZH	0.50	0.48
ggH-tagged	jets + p_T^{miss} [12]	80% ggH, 12% qqH, 5% WH, 3% ZH	0.66	0.59

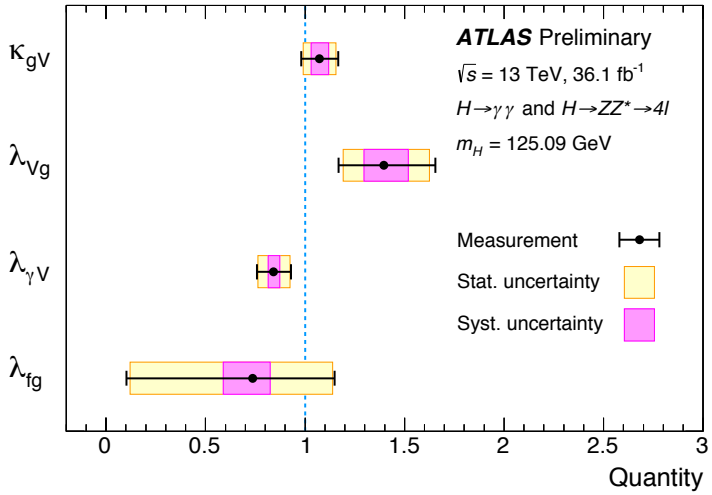


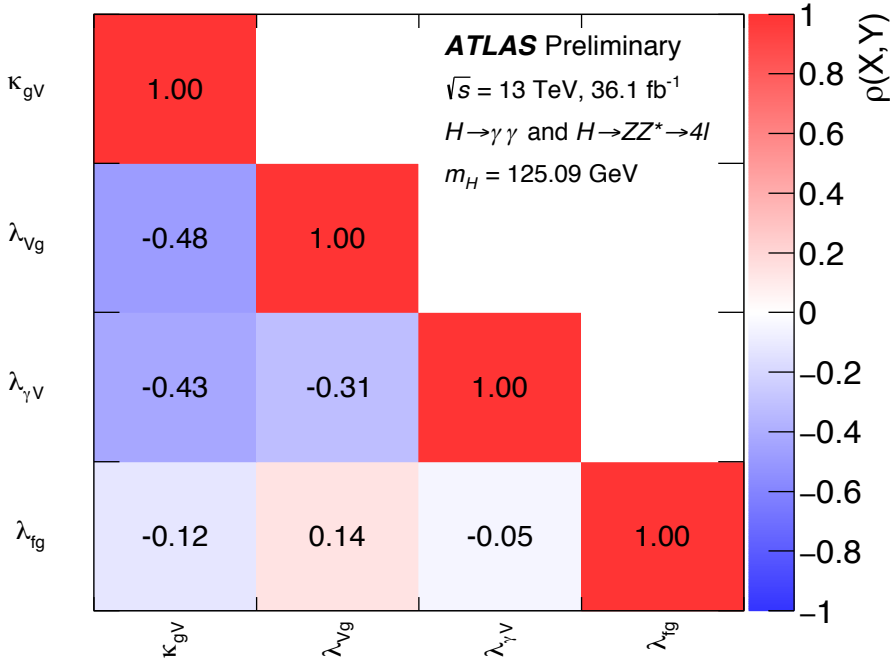


ATLAS H→ZZ + H→γγ combination

ATLAS CONF-2017-047







CMS grand combination with 2016 data

CMS-PAS-HIG-17-031

Production and decay tags		Expected tagged signal fraction	Number of categories	Mass resolution
$H \to \gamma\gamma$, Section 2.1				
$\gamma\gamma$	Untagged	74-91% ggH	4	≈1-2%
	VBF	51-80% VBF	3	
	VH hadronic	25% WH, 15% ZH	1	
	WH leptonic	64-83% WH	2	
	ZH leptonic	98% ZH	1	
	VH p_T^{miss}	59% VH	1	
	ttH	80-89% ttH, ≈8% tH	2	
$H \to ZZ^{(*)} \to 4\ell$, Section 2.2				
4μ, $2e2\mu/2\mu2e$, $4e$	Untagged	≈95% ggH	3	≈1-2%
	VBF 1, 2-jet	≈11-47% VBF	6	
	VH hadronic	≈13% WH, ≈10% ZH	3	
	VH leptonic	≈46% WH	3	
	VH p_T^{miss}	≈56% ZH	3	
	ttH	≈71% ttH	3	
$H \to WW^{(*)} \to \ell\nu\ell\nu$, Section 2.3				
$e\mu/\mu e$	ggH 0, 1, 2-jet	≈55-92% ggH, up to ≈15% $H \to \tau\tau$	17	≈20%
	VBF 2-jet	≈47% VBF, up to ≈25% $H \to \tau\tau$	2	
$ee+\mu\mu$	ggH 0, 1-jet	≈84-94% ggH	6	
$e\mu$+jj	VH 2-jet	22% VH, 21% $H \to \tau\tau$	1	
3ℓ	WH leptonic	≈80% WH, up to 19% $H \to \tau\tau$	2	
4ℓ	ZH leptonic	85-90% ZH, up to 14% $H \to \tau\tau$	2	
$H \to \tau\tau$, Section 2.4				
$e\mu$, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$	0-jet	≈70-98% ggH, 29% $H \to WW$ in $e\mu$	4	≈10-20%
	VBF	≈35-60% VBF, 42% $H \to WW$ in $e\mu$	4	
	Boosted	≈48-83% ggH, 43% $H \to WW$ in $e\mu$	4	
VH production with $H \to bb$, Section 2.5				
$Z(\nu\nu)bb$	ZH leptonic	≈100% VH, 85% ZH	1	≈10%
$W(\ell\nu)bb$	WH leptonic	≈100% VH, ≈97% WH	2	
$Z(\ell\ell)bb$	Low $p_T(V)$ ZH leptonic	≈100% ZH, of which ≈20% ggZH	2	
	High $p_T(V)$ ZH leptonic	≈100% ZH, of which ≈36% ggZH	2	
Boosted H Production with $H \to bb$, Section 2.6				
$H \to bb$	$p_T(H)$ bins	≈72-79% ggH	6	≈10%
ttH production with $H \to$ leptons, Section 2.7				
$H \to WW, \tau\tau, ZZ$	$2\ell ss$	$WW/\tau\tau \approx 4.5$, ≈5% tH	10	
	3ℓ	$WW : \tau\tau : ZZ \approx 15 : 4 : 1$, ≈5% tH	4	
	4ℓ	$WW : \tau\tau : ZZ \approx 6 : 1 : 1$, ≈3% tH	1	
	$1\ell+2\tau_h$	96% ttH with $H \to \tau\tau$, ≈6% tH	1	
	$2\ell ss+1\tau_h$	$\tau\tau : WW \approx 5 : 4$, ≈5% tH	2	
	$3\ell+1\tau_h$	$\tau\tau : WW : ZZ \approx 11 : 7 : 1$, ≈3% tH	1	
ttH production with $H \to bb$, Section 2.8				
$H \to bb$	$t\bar{t} \to$ jets	≈83-97% ttH with $H \to bb$	6	
	$t\bar{t} \to 1\ell$+jets	≈65-95% ttH with $H \to bb$, up to 20% $H \to WW$	18	
	$t\bar{t} \to 2\ell$+jets	≈84-96% ttH with $H \to bb$	3	

CMS grand combination with 2016 data

CMS-PAS-HIG-17-031

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	μ_{ggH}, μ_{VBF}, μ_{WH}, μ_{ZH}, μ_{ttH}
Decay modes	43.4% (4.85)	5	$\mu^{\gamma\gamma}$, μ^{ZZ}, μ^{WW}, $\mu^{\tau\tau}$, μ^{bb}
$\sigma_i \cdot BR^f$ products	50.4% (21.3)	22	$\sigma_{ggH} \cdot BR^{bb}$, $\sigma_{ggH} \cdot BR^{\tau\tau}$, $\sigma_{ggH} \cdot BR^{WW}$, $\sigma_{ggH} \cdot BR^{ZZ}$, $\sigma_{ggH} \cdot BR^{\gamma\gamma}$, $\sigma_{VBF} \cdot BR^{\tau\tau}$, $\sigma_{VBF} \cdot BR^{WW}$, $\sigma_{VBF} \cdot BR^{ZZ}$, $\sigma_{VBF} \cdot BR^{\gamma\gamma}$, $\sigma_{WH} \cdot BR^{bb}$, $\sigma_{WH} \cdot BR^{WW}$, $\sigma_{WH} \cdot BR^{ZZ}$, $\sigma_{WH} \cdot BR^{\gamma\gamma}$, $\sigma_{ZH} \cdot BR^{bb}$, $\sigma_{ZH} \cdot BR^{WW}$, $\sigma_{ZH} \cdot BR^{ZZ}$, $\sigma_{ZH} \cdot BR^{\gamma\gamma}$, $\sigma_{ttH} \cdot BR^{\tau\tau}$, $\sigma_{ttH} \cdot BR^{WW}$, $\sigma_{ttH} \cdot BR^{ZZ}$, $\sigma_{ttH} \cdot BR^{\gamma\gamma}$, $\sigma_{ttH} \cdot BR^{bb}$
Ratios of σ and BR relative to $gg \rightarrow H \rightarrow ZZ$	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	46.9% (5.60)	6	κ_Z, κ_W, κ_t, κ_τ, κ_b, κ_μ
Couplings vs mass	17.1% (3.54)	2	M, ϵ
Couplings, BSM loops	57.7% (5.68)	7	κ_Z, κ_W, κ_t, κ_τ, κ_b, κ_γ, κ_g
Couplings, BSM loops and decays including H $\rightarrow$inv. channels	78.6% (5.53)	9	κ_Z, κ_W, κ_t, κ_τ, κ_b, κ_γ, κ_g, $BR_{inv.}$, $BR_{undet.}$
Ratios of coupling modifiers	56.7% (5.77)	7	κ_{gZ}, λ_{WZ}, $\lambda_{\gamma Z}$, λ_{tg}, λ_{bZ}, $\lambda_{\tau Z}$, λ_{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	κ^{bb}_F, $\kappa^{\tau\tau}_F$, κ^{WW}_F, κ^{ZZ}_F, $\kappa^{\gamma\gamma}_F$, κ^{bb}_V, $\kappa^{\tau\tau}_V$, κ^{WW}_V, κ^{ZZ}_V, $\kappa^{\gamma\gamma}_V$
Up vs down-type couplings	25.5% (4.06)	3	λ_{Vu}, λ_{du}, κ_{uu}
Lepton vs quark couplings	26.5% (3.97)	3	$\lambda_{\ell q}$, λ_{Vq}, κ_{qq}

CMS grand combination with 2016 data

CMS-PAS-HIG-17-031

- **CMS Run 2**

Production process

ggH				VBF				WH				ZH				ttH			
Best fit value	Uncertainty Stat.		Syst.	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	$^{+0.44}_{-0.42}$	$^{+0.39}_{-0.38}$	$^{+0.20}_{-0.18}$	1.18	$^{+0.31}_{-0.27}$	$^{+0.16}_{-0.16}$	$^{+0.26}_{-0.21}$
	$\left(^{+0.11}_{-0.11}\right)$	$\left(^{+0.07}_{-0.07}\right)$	$\left(^{+0.09}_{-0.08}\right)$		$\left(^{+0.29}_{-0.27}\right)$	$\left(^{+0.24}_{-0.23}\right)$	$\left(^{+0.16}_{-0.15}\right)$		$\left(^{+0.53}_{-0.51}\right)$	$\left(^{+0.43}_{-0.42}\right)$	$\left(^{+0.30}_{-0.29}\right)$		$\left(^{+0.42}_{-0.40}\right)$	$\left(^{+0.38}_{-0.37}\right)$	$\left(^{+0.19}_{-0.17}\right)$		$\left(^{+0.28}_{-0.25}\right)$	$\left(^{+0.16}_{-0.16}\right)$	$\left(^{+0.23}_{-0.20}\right)$

Decay mode

$H \to bb$				$H \to \tau\tau$				$H \to WW$				$H \to ZZ$				$H \to \gamma\gamma$			
Best fit value	Uncertainty Stat.		Syst.	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	$^{+0.19}_{-0.17}$	$^{+0.16}_{-0.15}$	$^{+0.10}_{-0.08}$	1.20	$^{+0.17}_{-0.14}$	$^{+0.12}_{-0.11}$	$^{+0.12}_{-0.09}$
	$\left(^{+0.28}_{-0.27}\right)$	$\left(^{+0.19}_{-0.18}\right)$	$\left(^{+0.21}_{-0.20}\right)$		$\left(^{+0.24}_{-0.23}\right)$	$\left(^{+0.15}_{-0.14}\right)$	$\left(^{+0.19}_{-0.17}\right)$		$\left(^{+0.14}_{-0.13}\right)$	$\left(^{+0.09}_{-0.09}\right)$	$\left(^{+0.11}_{-0.10}\right)$		$\left(^{+0.18}_{-0.16}\right)$	$\left(^{+0.15}_{-0.14}\right)$	$\left(^{+0.10}_{-0.08}\right)$		$\left(^{+0.14}_{-0.12}\right)$	$\left(^{+0.10}_{-0.10}\right)$	$\left(^{+0.09}_{-0.07}\right)$

- **ATLAS + CMS Run 1**

Production process	ATLAS+CMS	ATLAS	CMS
μ_{ggF}	$1.03\ ^{+0.16}_{-0.14}\ \left(^{+0.16}_{-0.14}\right)$	$1.26\ ^{+0.23}_{-0.20}\ \left(^{+0.21}_{-0.18}\right)$	$0.84\ ^{+0.18}_{-0.16}\ \left(^{+0.20}_{-0.17}\right)$
μ_{VBF}	$1.18\ ^{+0.25}_{-0.23}\ \left(^{+0.24}_{-0.23}\right)$	$1.21\ ^{+0.33}_{-0.30}\ \left(^{+0.32}_{-0.29}\right)$	$1.14\ ^{+0.37}_{-0.34}\ \left(^{+0.36}_{-0.34}\right)$
μ_{WH}	$0.89\ ^{+0.40}_{-0.38}\ \left(^{+0.41}_{-0.39}\right)$	$1.25\ ^{+0.56}_{-0.52}\ \left(^{+0.56}_{-0.53}\right)$	$0.46\ ^{+0.57}_{-0.53}\ \left(^{+0.60}_{-0.57}\right)$
μ_{ZH}	$0.79\ ^{+0.38}_{-0.36}\ \left(^{+0.39}_{-0.36}\right)$	$0.30\ ^{+0.51}_{-0.45}\ \left(^{+0.55}_{-0.51}\right)$	$1.35\ ^{+0.58}_{-0.54}\ \left(^{+0.55}_{-0.51}\right)$
μ_{ttH}	$2.3\ ^{+0.7}_{-0.6}\ \left(^{+0.5}_{-0.5}\right)$	$1.9\ ^{+0.8}_{-0.7}\ \left(^{+0.7}_{-0.7}\right)$	$2.9\ ^{+1.0}_{-0.9}\ \left(^{+0.9}_{-0.8}\right)$

Decay channel	ATLAS+CMS	ATLAS	CMS
$\mu^{\gamma\gamma}$	$1.14\ ^{+0.19}_{-0.18}\ \left(^{+0.18}_{-0.17}\right)$	$1.14\ ^{+0.27}_{-0.25}\ \left(^{+0.26}_{-0.24}\right)$	$1.11\ ^{+0.25}_{-0.23}\ \left(^{+0.23}_{-0.21}\right)$
μ^{ZZ}	$1.29\ ^{+0.26}_{-0.23}\ \left(^{+0.23}_{-0.20}\right)$	$1.52\ ^{+0.40}_{-0.34}\ \left(^{+0.32}_{-0.27}\right)$	$1.04\ ^{+0.32}_{-0.26}\ \left(^{+0.30}_{-0.25}\right)$
μ^{WW}	$1.09\ ^{+0.18}_{-0.16}\ \left(^{+0.16}_{-0.15}\right)$	$1.22\ ^{+0.23}_{-0.21}\ \left(^{+0.21}_{-0.20}\right)$	$0.90\ ^{+0.23}_{-0.21}\ \left(^{+0.23}_{-0.20}\right)$
$\mu^{\tau\tau}$	$1.11\ ^{+0.24}_{-0.22}\ \left(^{+0.24}_{-0.22}\right)$	$1.41\ ^{+0.40}_{-0.36}\ \left(^{+0.37}_{-0.33}\right)$	$0.88\ ^{+0.30}_{-0.28}\ \left(^{+0.31}_{-0.29}\right)$
μ^{bb}	$0.70\ ^{+0.29}_{-0.27}\ \left(^{+0.29}_{-0.28}\right)$	$0.62\ ^{+0.37}_{-0.37}\ \left(^{+0.39}_{-0.37}\right)$	$0.81\ ^{+0.45}_{-0.43}\ \left(^{+0.45}_{-0.43}\right)$
$\mu^{\mu\mu}$	$0.1\ ^{+2.5}_{-2.5}\ \left(^{+2.4}_{-2.3}\right)$	$-0.6\ ^{+3.6}_{-3.6}\ \left(^{+3.6}_{-3.6}\right)$	$0.9\ ^{+3.6}_{-3.5}\ \left(^{+3.3}_{-3.2}\right)$

CMS grand combination with 2016 data

CMS-PAS-HIG-17-031

- **CMS Run 2**

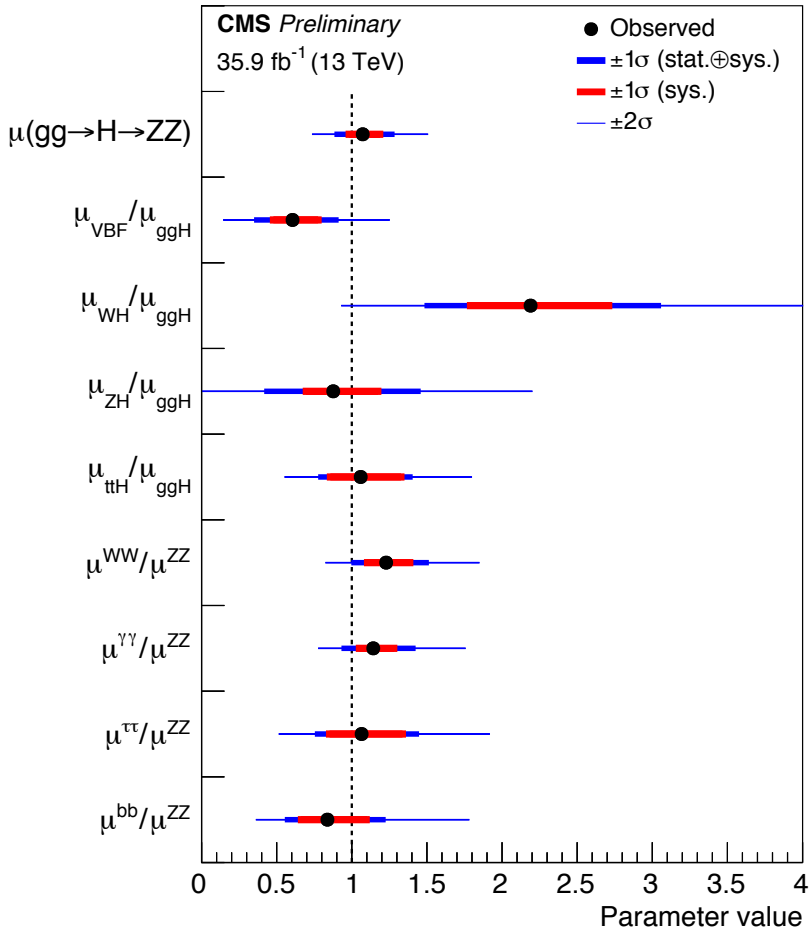
$\mathrm{BR}_{\mathrm{inv.}} = 0$			
		Uncertainty	
Parameter	Best fit	Stat.	Syst.
κ_Z	$0.99\ ^{+0.11}_{-0.11}\ (^{+0.11}_{-0.11})$	$^{+0.09}_{-0.09}\ (^{+0.09}_{-0.09})$	$^{+0.06}_{-0.06}\ (^{+0.06}_{-0.06})$
κ_W	$1.12\ ^{+0.13}_{-0.19}\ (^{+0.12}_{-0.12})$	$^{+0.10}_{-0.18}\ (^{+0.09}_{-0.09})$	$^{+0.08}_{-0.07}\ (^{+0.07}_{-0.07})$
κ_t	$1.09\ ^{+0.14}_{-0.14}\ (^{+0.14}_{-0.15})$	$^{+0.08}_{-0.08}\ (^{+0.08}_{-0.09})$	$^{+0.12}_{-0.12}\ (^{+0.12}_{-0.12})$
κ_τ	$1.01\ ^{+0.17}_{-0.18}\ (^{+0.16}_{-0.15})$	$^{+0.11}_{-0.15}\ (^{+0.11}_{-0.11})$	$^{+0.12}_{-0.09}\ (^{+0.11}_{-0.11})$
κ_b	$1.10\ ^{+0.27}_{-0.33}\ (^{+0.25}_{-0.23})$	$^{+0.19}_{-0.30}\ (^{+0.19}_{-0.17})$	$^{+0.19}_{-0.14}\ (^{+0.17}_{-0.15})$
κ_g	$1.14\ ^{+0.15}_{-0.13}\ (^{+0.14}_{-0.12})$	$^{+0.10}_{-0.09}\ (^{+0.10}_{-0.09})$	$^{+0.11}_{-0.09}\ (^{+0.10}_{-0.09})$
κ_γ	$1.07\ ^{+0.15}_{-0.18}\ (^{+0.12}_{-0.12})$	$^{+0.10}_{-0.17}\ (^{+0.10}_{-0.10})$	$^{+0.11}_{-0.07}\ (^{+0.07}_{-0.07})$

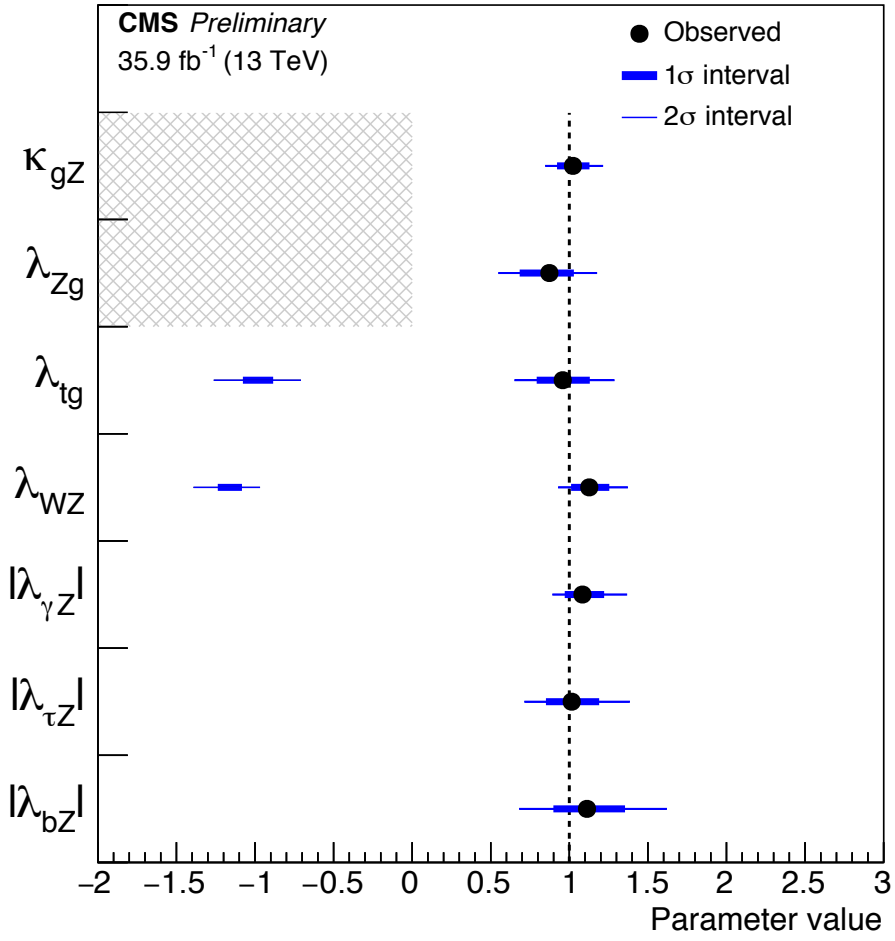
- **ATLAS + CMS Run 1**

Parameter	ATLAS+CMS Measured	ATLAS+CMS Expected uncertainty	ATLAS Measured	CMS Measured
Parameterisation assuming $\mathrm{B}_{\mathrm{BSM}} = 0$				
κ_Z	-0.98 $[-1.08,-0.88]\cup[0.94,1.13]$	$[-1.01,-0.87]\cup[0.89,1.11]$	1.01 $[-1.09,-0.85]\cup[0.87,1.15]$	-0.99 $[-1.14,-0.84]\cup[0.94,1.19]$
κ_W	0.87 $[0.78,1.00]$	$[-1.08,-0.90]\cup[0.88,1.11]$	0.92 $[-0.94,-0.85]\cup[0.78,1.05]$	0.84 $[-0.99,-0.74]\cup[0.71,1.01]$
κ_t	$1.40^{+0.24}_{-0.21}$	$^{+0.26}_{-0.39}$	$1.32^{+0.31}_{-0.33}$	$1.51^{+0.33}_{-0.32}$
$\lvert\kappa_\tau\rvert$	$0.84^{+0.15}_{-0.11}$	$^{+0.16}_{-0.15}$	$0.97^{+0.19}_{-0.19}$	$0.77^{+0.18}_{-0.15}$
$\lvert\kappa_b\rvert$	$0.49^{+0.27}_{-0.15}$	$^{+0.25}_{-0.28}$	$0.61^{+0.26}_{-0.31}$	$0.47^{+0.34}_{-0.19}$
$\lvert\kappa_g\rvert$	$0.78^{+0.13}_{-0.10}$	$^{+0.17}_{-0.14}$	$0.94^{+0.18}_{-0.17}$	$0.67^{+0.14}_{-0.12}$
$\lvert\kappa_\gamma\rvert$	$0.87^{+0.14}_{-0.09}$	$^{+0.12}_{-0.13}$	$0.88^{+0.15}_{-0.15}$	$0.89^{+0.19}_{-0.13}$

CMS grand combination with 2016 data

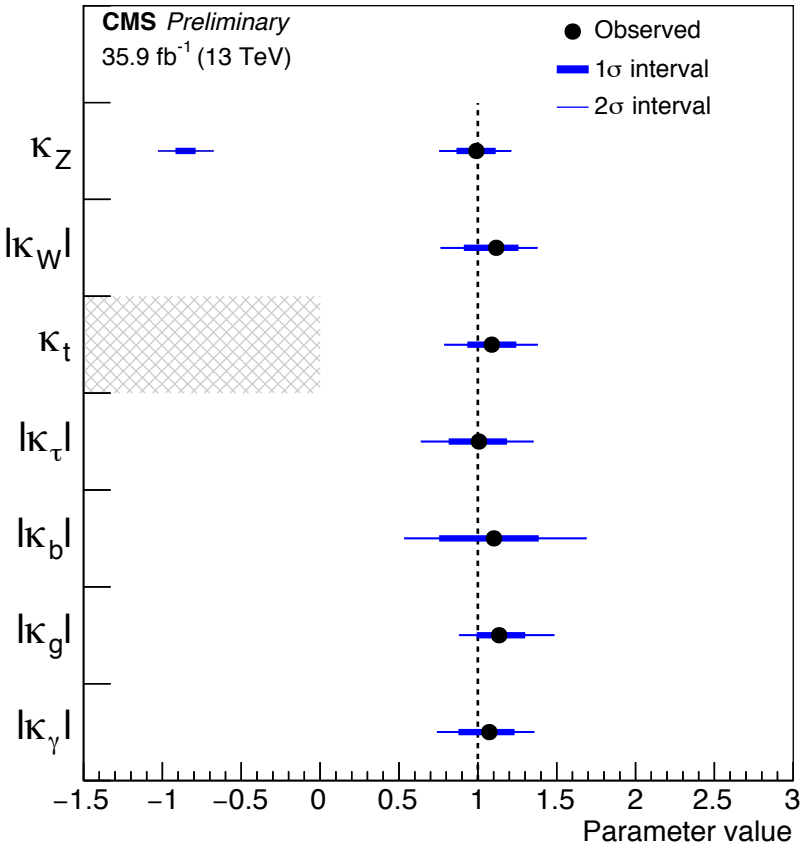
CMS-PAS-HIG-17-031



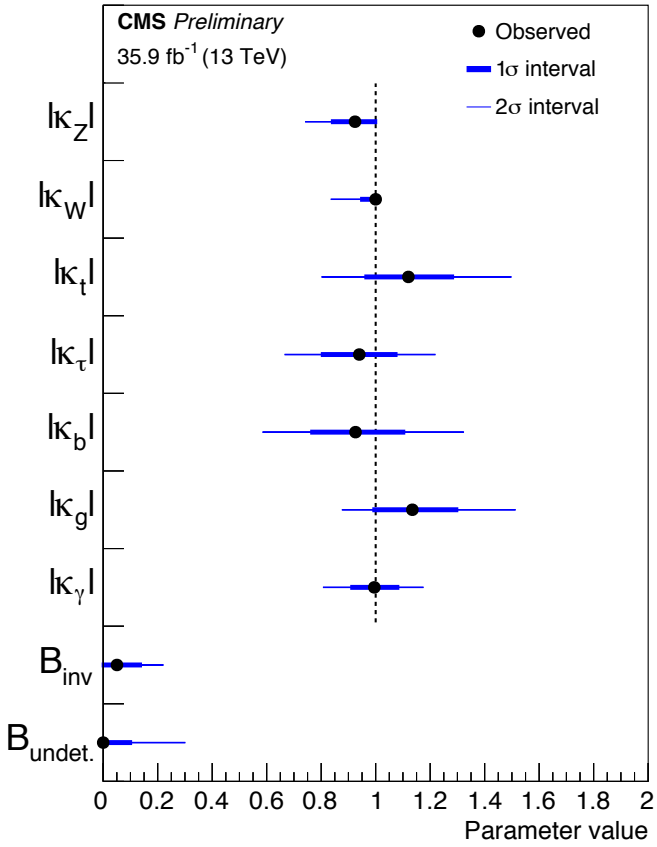


CMS grand combination with 2016 data

CMS-PAS-HIG-17-031



No BSM decay allowed

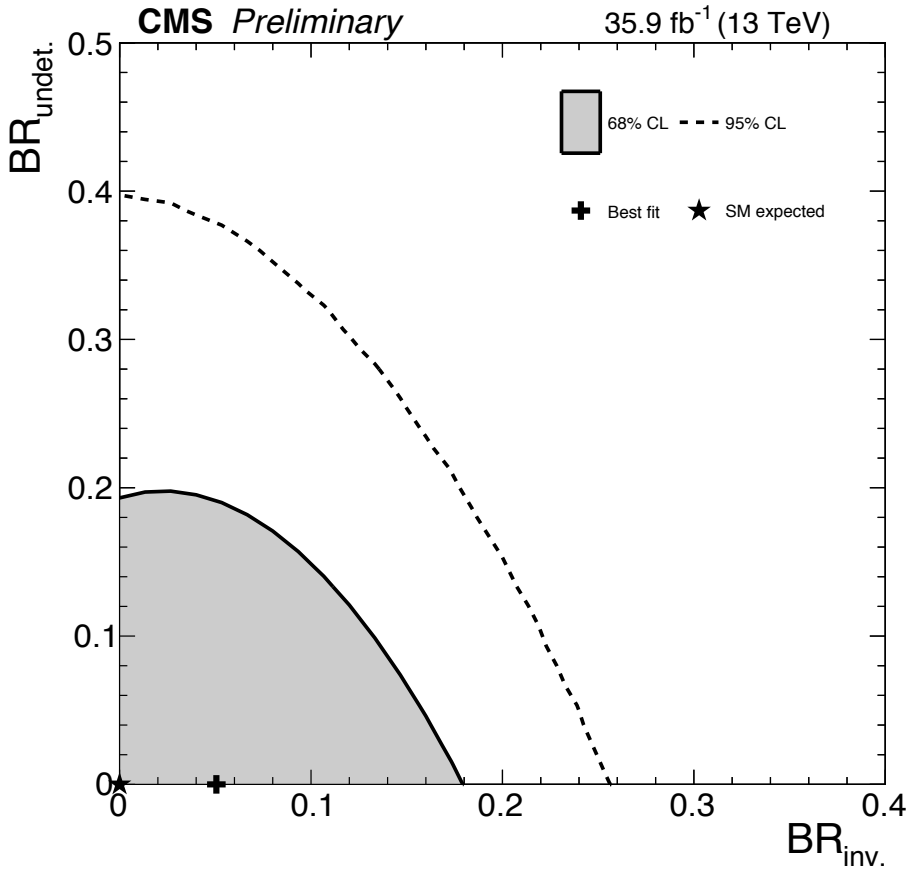


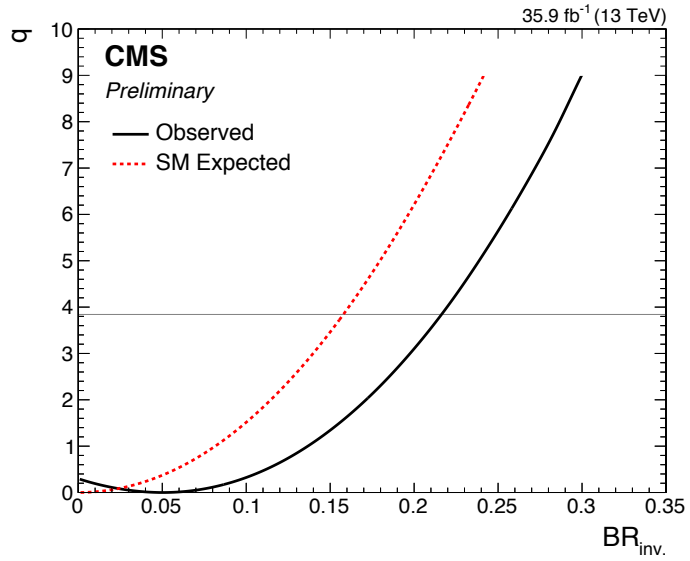
BSM decay allowed
+ $\kappa_V < 1$

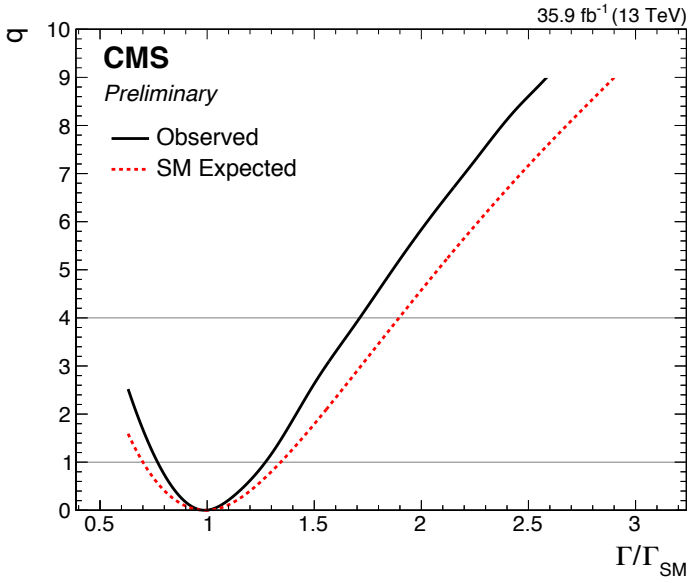
CMS grand combination with 2016 data

CMS-PAS-HIG-17-031

- **Constraints on BSM decays**





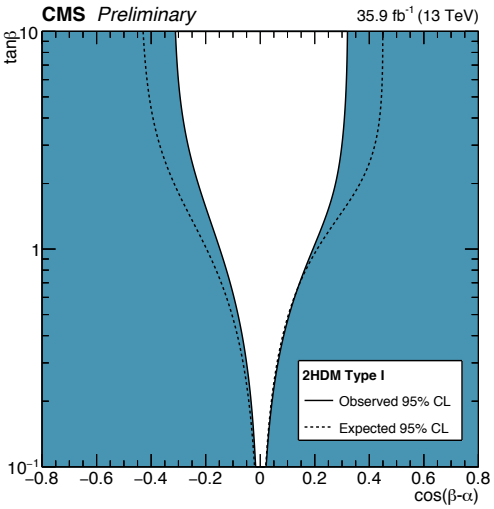


CMS grand combination with 2016 data

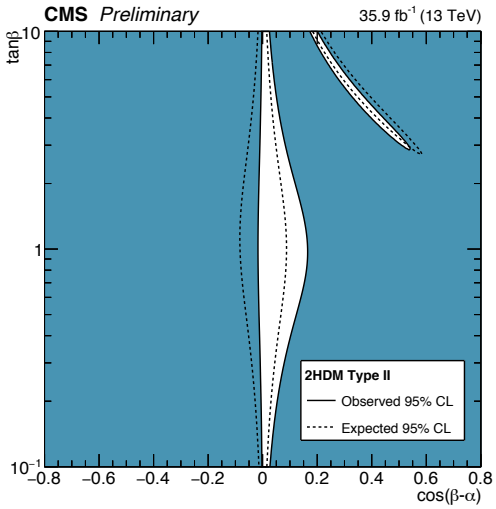
CMS-PAS-HIG-17-031

- **Constraints on 2HDMs**

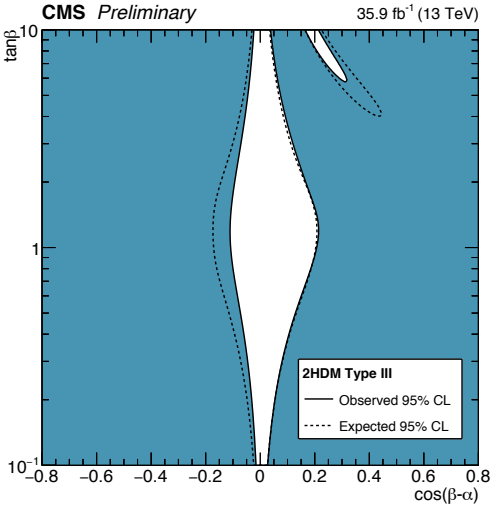
	2HDM			
	type I	type II	Type III	Type IV
κ_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
κ_ℓ	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$



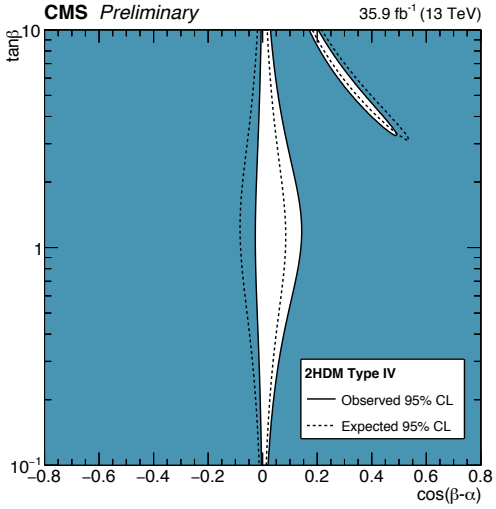
(a)



(b)



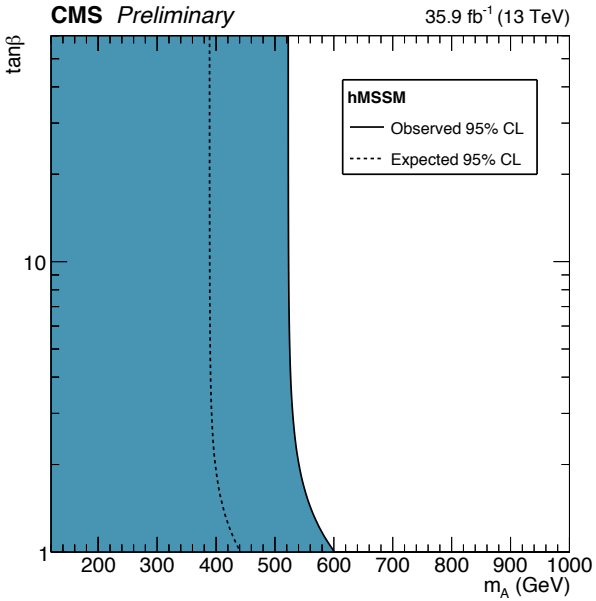
(c)

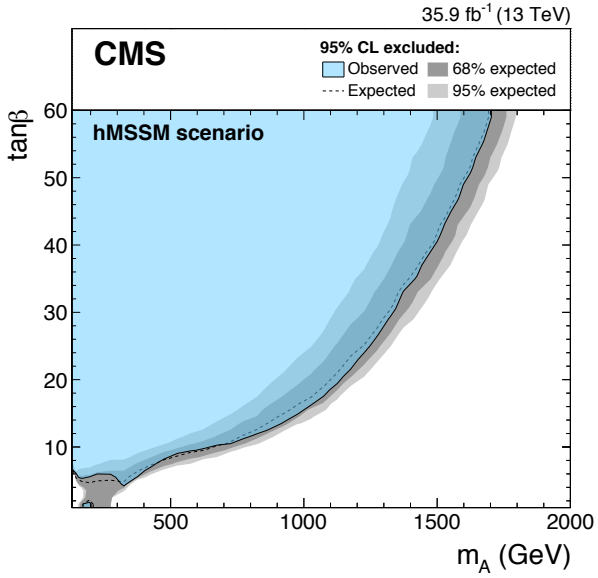


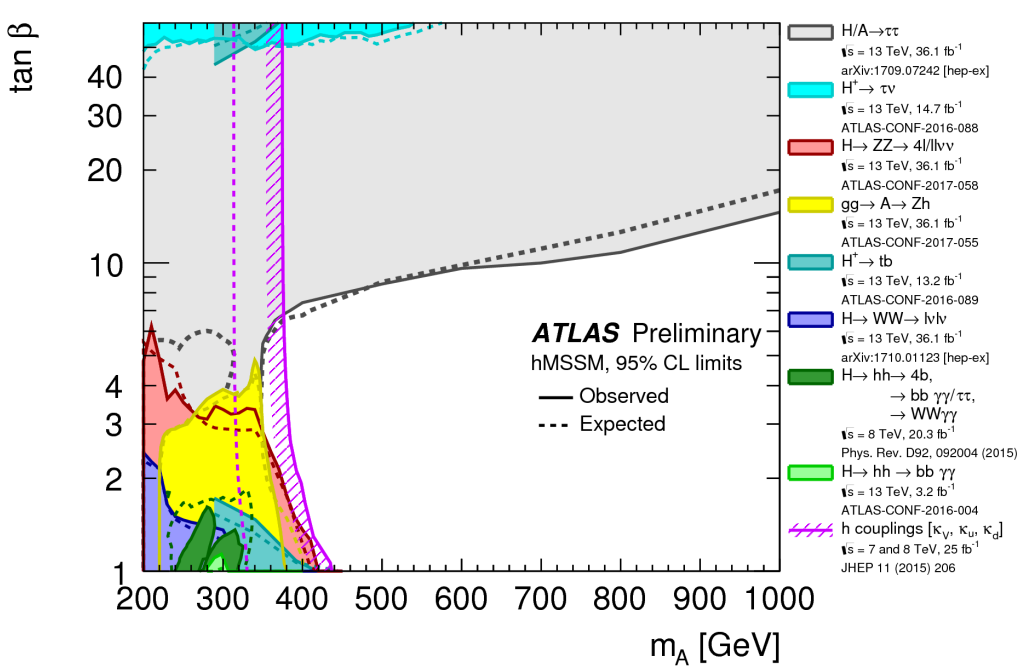
(d)

Lobes due to negative κ_b, κ_τ

Direct constraints on 2HDMs



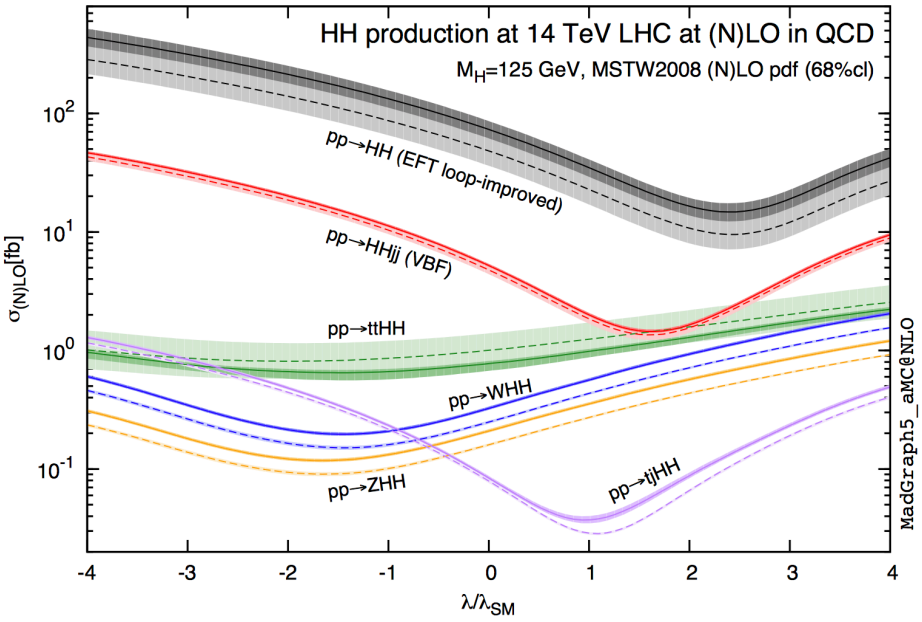




CMS-PAS-HIG-17-031
CMS arxiv:1803.06553

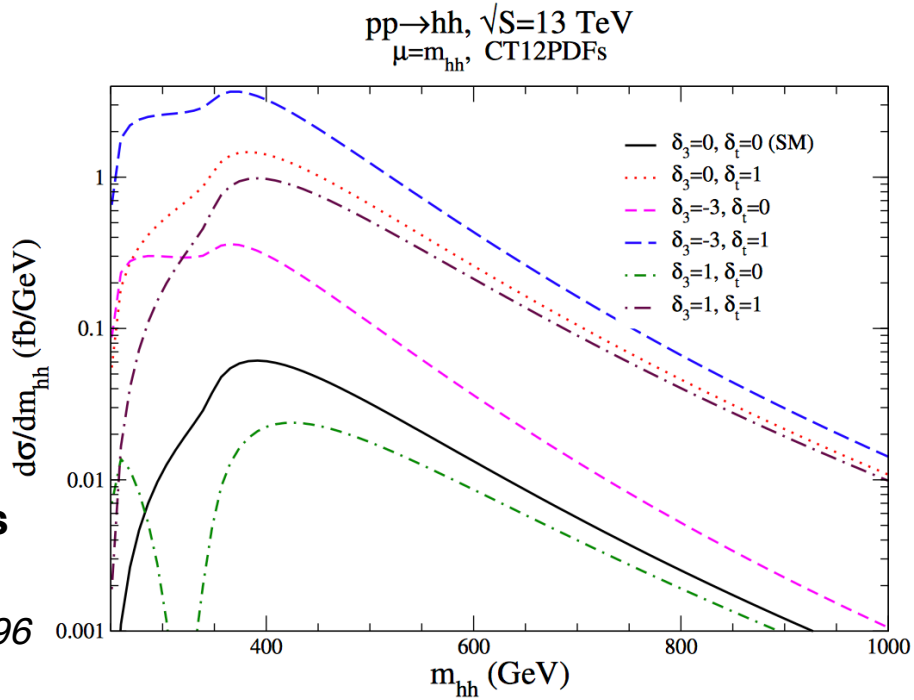
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/HIGGS/ATLAS_HIGGS5101_BSM_hMSSM_tanb_vs_mA_Summary_LargeRange/ATLAS_HIGGS5101_BSM_hMSSM_tanb_vs_mA_Summary_LargeRange.png

HH analyses and Higgs self-coupling



- **Impact of Higgs self-coupling on HH production rate**

Phys. Lett. B 732 (2014) 142-149



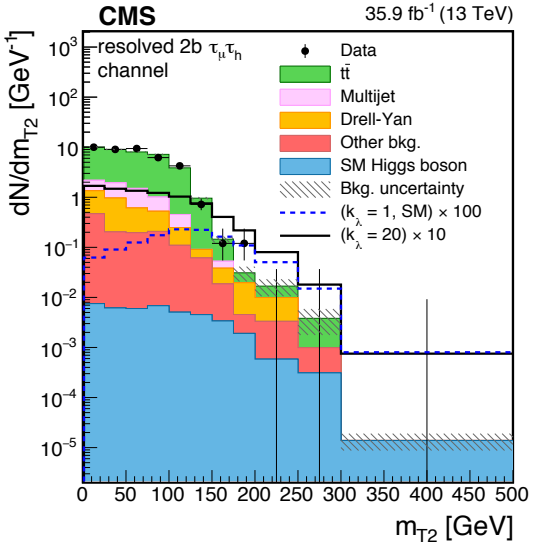
- **Impact of Higgs self-coupling on HH mass spectrum**

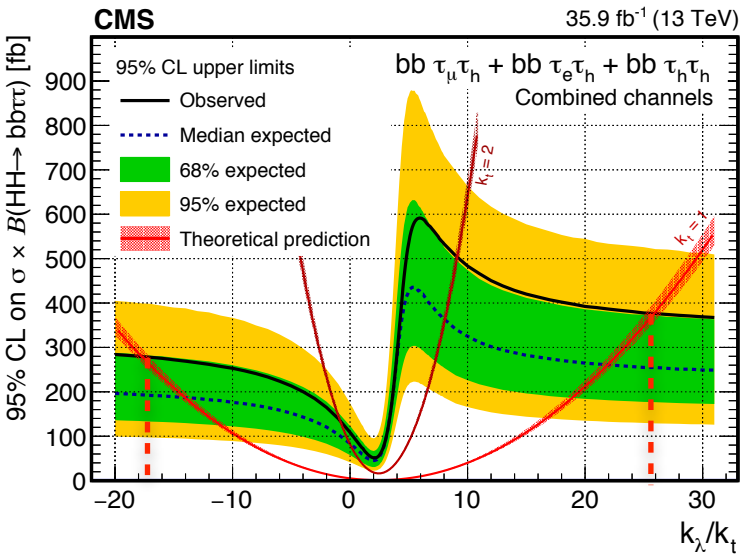
arxiv:1504.05596

HH analyses and Higgs self-coupling

CMS HH→bbττ

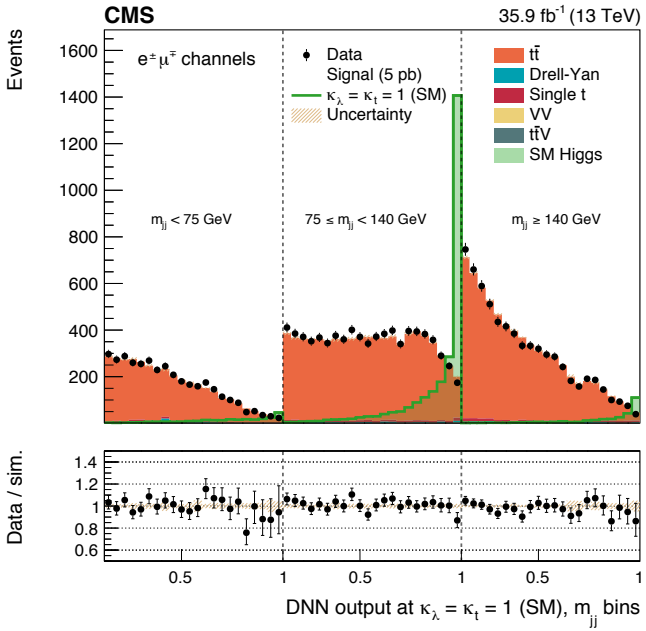
Phys. Lett. B 778 (2018) 101

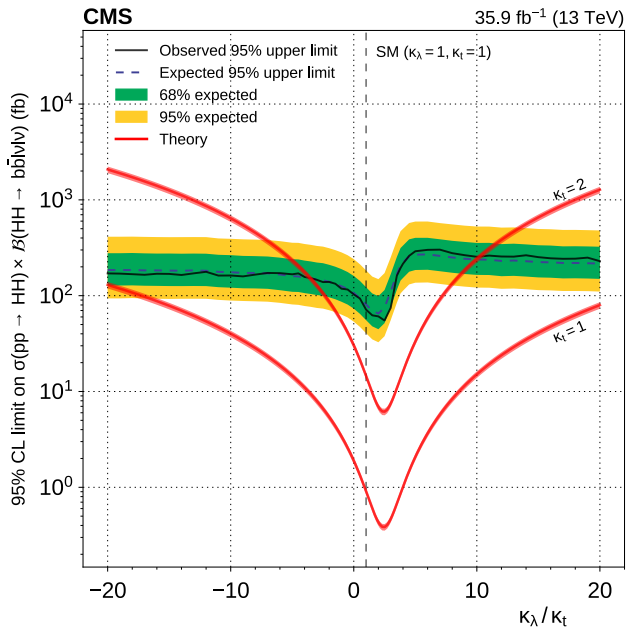




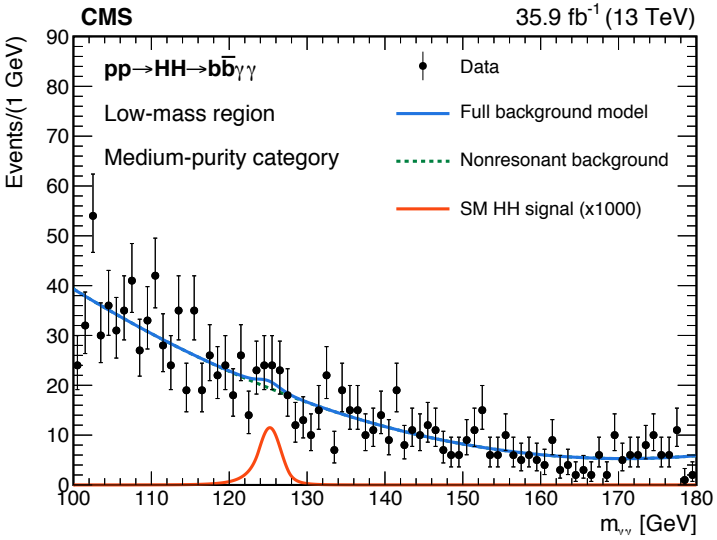
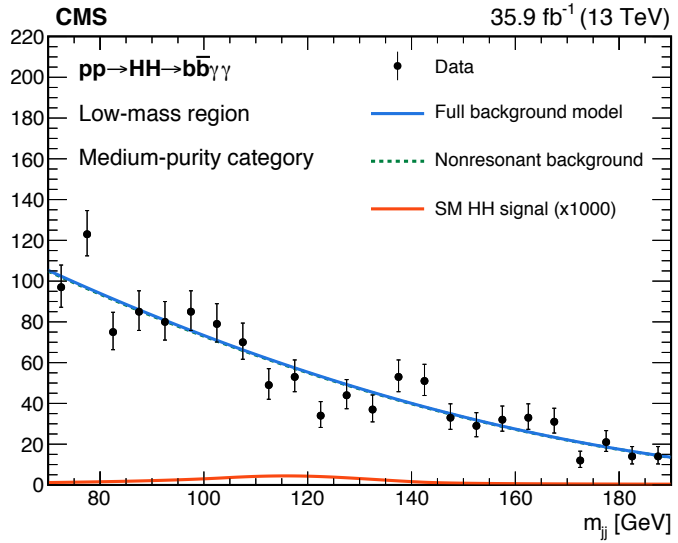
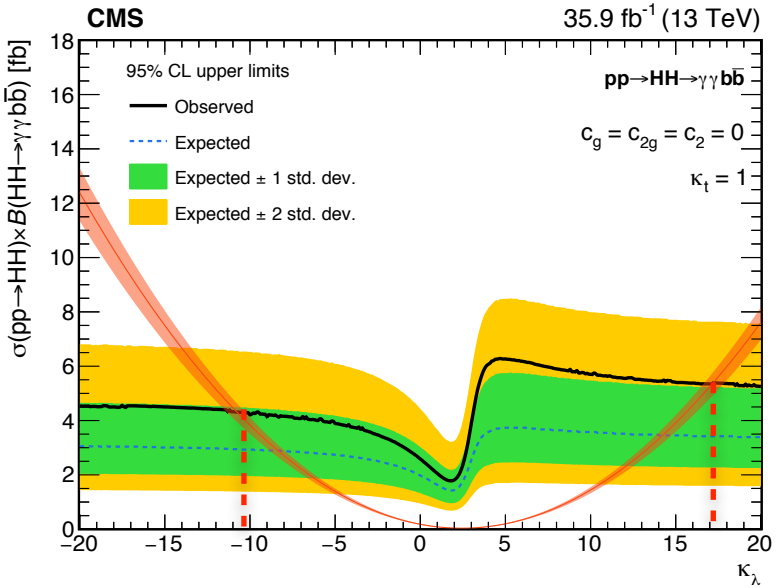
CMS HH→bbWW

JHEP 01 (2018) 054





HH analyses and Higgs self-coupling

CMS HH→bb$\gamma\gamma$

CMS arxiv: 1806.00408