Constraints on effective Lagrangians from ATLAS and CMS

Chris Hays, Oxford University
on behalf of the ATLAS and CMS Collaborations

Higgs Couplings 2018
Tokyo Japan
27 November

Overview

The SM effective field theory

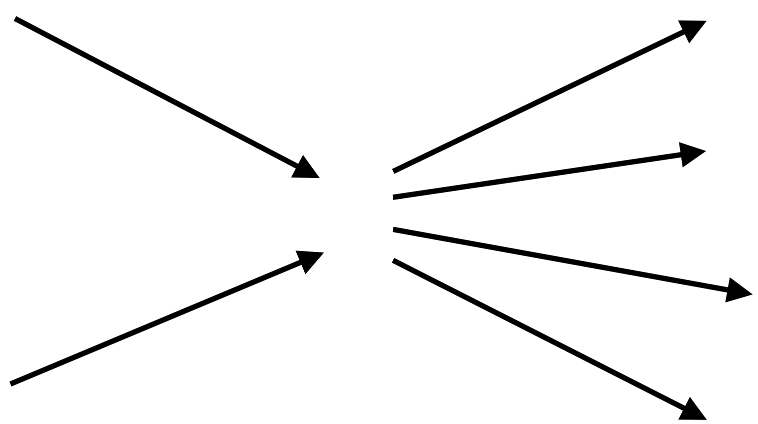
Effective Lagrangians

Constraints on Higgs couplings
- Higgs boson measurements
- Electroweak measurements
- Top quark measurements

Chiral Electroweak Higgs effective field theory
- Combination of Higgs boson measurements

The SM effective field theory

The SMEFT is a general framework for describing non-SM interactions at a high scale
It assumes the low (electroweak) scale is governed by the SM



$$\mathbf{d\sigma(exp) = d\sigma(SM) + d\sigma(\mathit{d} < TeV^{-1})}$$

Expand in orders of the new-physics scale: $\int d\boldsymbol{\sigma}(d < \mathrm{TeV}^{-1}) = A_5 \,/\, \Lambda_{\mathrm{NP}} + A_6 \,/\, \Lambda_{\mathrm{NP}}^2 + \ldots$

The leading lepton-number-conserving term is $A_6 \,/\, \Lambda_{\mathrm{NP}}^2$

Due to interference between SM and short-distance amplitudes: $\mathscr{M}^{\dagger}(\mathrm{SM})\mathscr{M}(d < \mathrm{TeV}^{-1})$

Higher-scale interactions are increasingly sensitive to higher-order terms in $1/\Lambda_{\mathrm{NP}}^n$

Effective Lagrangians

We can calculate the leading new-physics contributions using an operator basis

$\int d\boldsymbol{\sigma}(d < \text{TeV}^{-1}) = A_5 / \boldsymbol{\Lambda}_{\text{NP}} + A_6 / \boldsymbol{\Lambda}_{\text{NP}}^2 + \ldots$

$A_6 = \boldsymbol{\Sigma} c_i$, where c_i are coefficients of effective (dimension-6) Lagrangian operators

The complete basis of operators is large (**59 + h.c.** at this order)

2499 parameters for full flavour generality

Individual measurements constrain Effective Lagrangians

Effective Lagrangians add a few relevant operators to the Lagrangian

Effective Lagrangians typically built from SMEFT operators using the leading c_i terms

A first step towards constraining the complete basis set with combined measurements

$$\mathscr{L} = \mathscr{L}_{SM} + \sum c_i \mathcal{O}_{6i} / \Lambda_{NP}^2$$

Constraints on Higgs couplings

Higgs-boson measurements used to constrain operators with Higgs fields

Example operator set from the strongly-interacting light Higgs (SILH) basis:

Operator	Expression	HEL coefficient	Vertices
$\mathcal{O}_g$	$\lvert H\rvert^2 G^A_{\mu\nu} G^{A\mu\nu}$	$\texttt{cG} = \frac{m_W^2}{g_s^2}\bar{c}_g$	Hgg
$\mathcal{O}_\gamma$	$\lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$	$\texttt{cA} = \frac{m_W^2}{g'^2}\bar{c}_\gamma$	$H\gamma\gamma, HZZ$
$\mathcal{O}_u$	$y_u \lvert H\rvert^2 \bar{u}_l H u_R +$ h.c.	$\texttt{cu} = v^2 \bar{c}_u$	$Ht\bar{t}$
$\mathcal{O}_{HW}$	$i\,(D^\mu H)^\dagger\,\sigma^a\,(D^\nu H)\,W^a_{\mu\nu}$	$\texttt{cHW} = \frac{m_W^2}{g}\bar{c}_{HW}$	HWW, HZZ
$\mathcal{O}_{HB}$	$i\,(D^\mu H)^\dagger\,(D^\nu H)\,B_{\mu\nu}$	$\texttt{cHB} = \frac{m_W^2}{g'}\bar{c}_{HB}$	HZZ
$\mathcal{O}_W$	$i\left(H^\dagger \sigma^a D^\mu H\right) D^\nu W^a_{\mu\nu}$	$\texttt{cWW} = \frac{m_W^2}{g}\bar{c}_W$	HWW, HZZ
$\mathcal{O}_B$	$i\left(H^\dagger D^\mu H\right) \partial^\nu B_{\mu\nu}$	$\texttt{cB} = \frac{m_W^2}{g'}\bar{c}_B$	HZZ

SILH:
Contino, Ghezzi, Grojean, Mühlleitner, & Spira
JHEP 07 (2013) 035

ATLAS,
ATL-PHYS-PUB-2017-018

Here the impact on cross sections is determined using the 'HEL' FeynRules implementation

HEL:
Alloul, Fuks, & Sanz
JHEP 04 (2014) 110

Impact on STXS:
CH, Sanz, & Zemaityte
LHCHXSWG-INT-2017-001

Constraints on Higgs couplings

Three approaches to constraints:

1 Relate model-independent unfolded differential cross sections to operator coefficients
Model-independent measurements minimise assumptions in the relation

2 Relate exclusive cross sections (STXS) to operator coefficients
Acceptance corrections in measurements are derived from the SM

3 Optimize for individual operator coefficients
Results are confined to the specific Effective Lagrangian

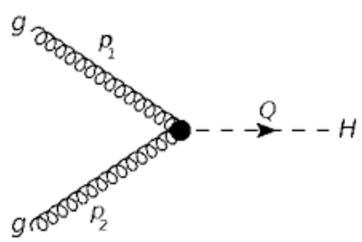
Recent examples:

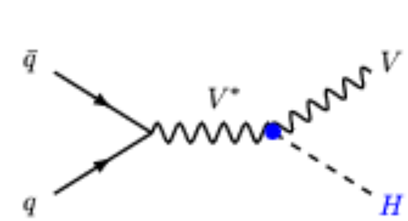
Channel	Approach	
$H\rightarrow\gamma\gamma$	1	*ATLAS, PRD 98 (2018) 052005*
$H\rightarrow\ell\ell\ell\ell$	3	*ATLAS, JHEP 03 (2018) 095*
$H\rightarrow\ell\ell\ell\ell$	3	*CMS, PLB 775 (2017) 1*
$H\rightarrow\gamma\gamma$ + $H\rightarrow\ell\ell\ell\ell$	2	*ATLAS, ATL-PHYS-PUB-2017-018*
H→bb	2	*ATLAS, ATLAS-CONF-2018-053*

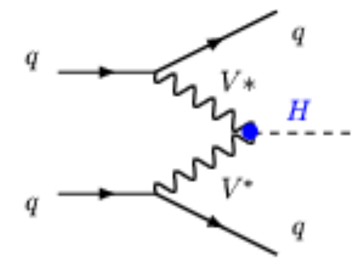
$H \to \gamma\gamma$ unfolded measurements

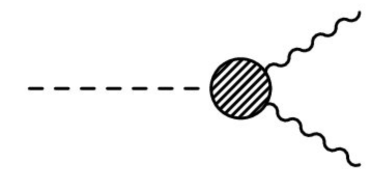
ATLAS measures five unfolded distributions in $H \to \gamma\gamma$ decay channel

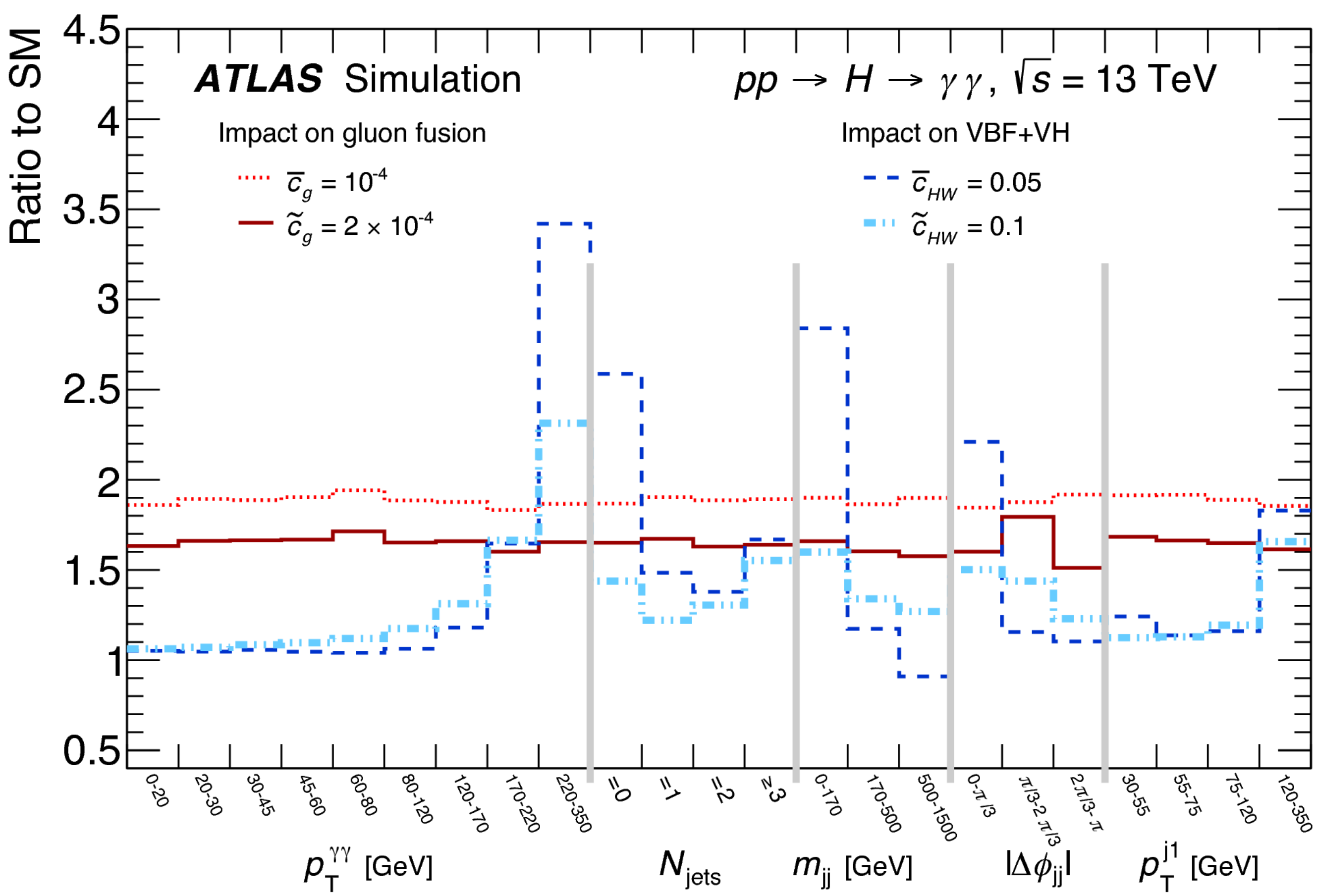
- Dimension-6 ggH coefficient `cG` shows little kinematic dependence ($Q^2 = m_H^2$)
- VVH coefficient `cHW` shows substantial dependence due to associated production

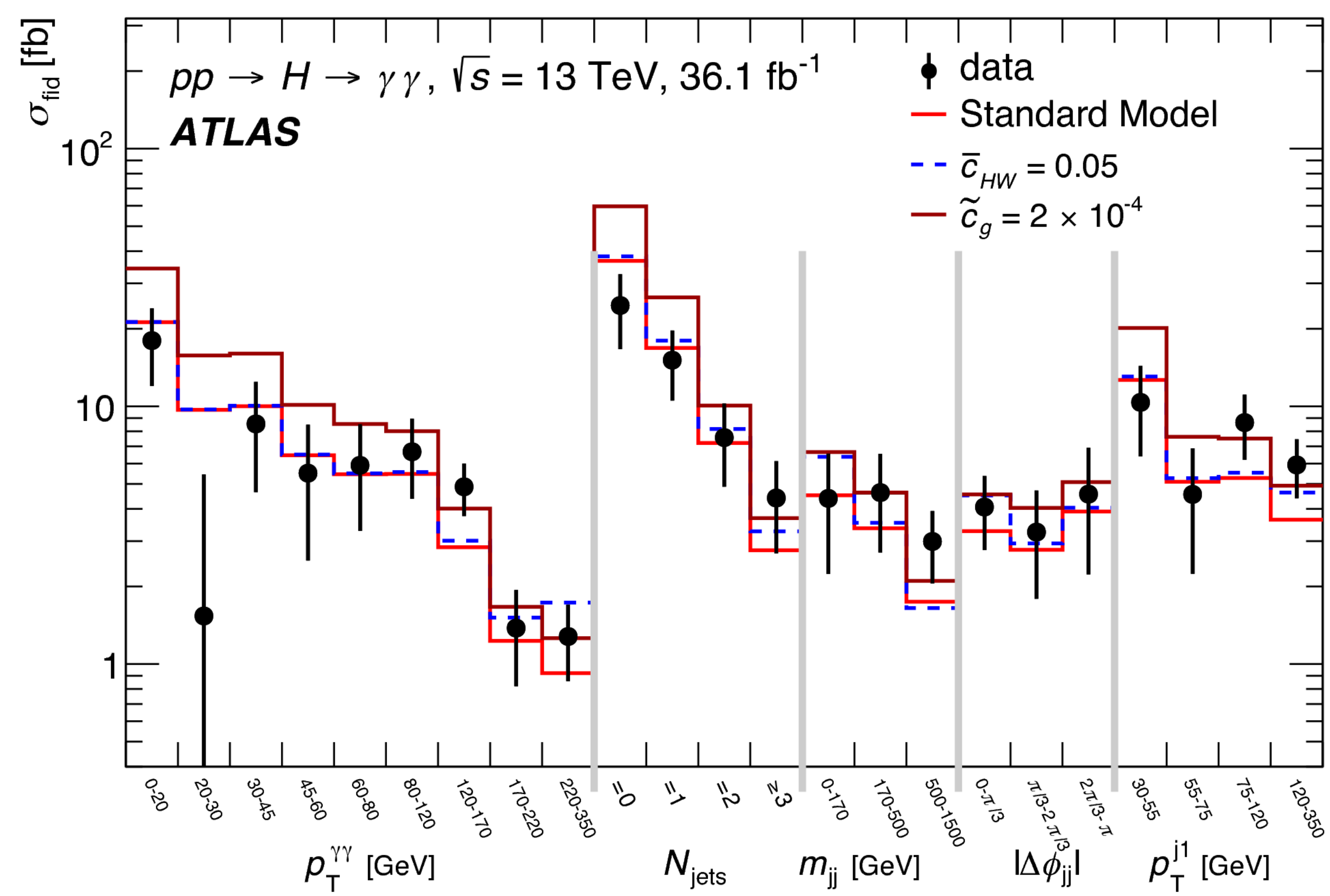












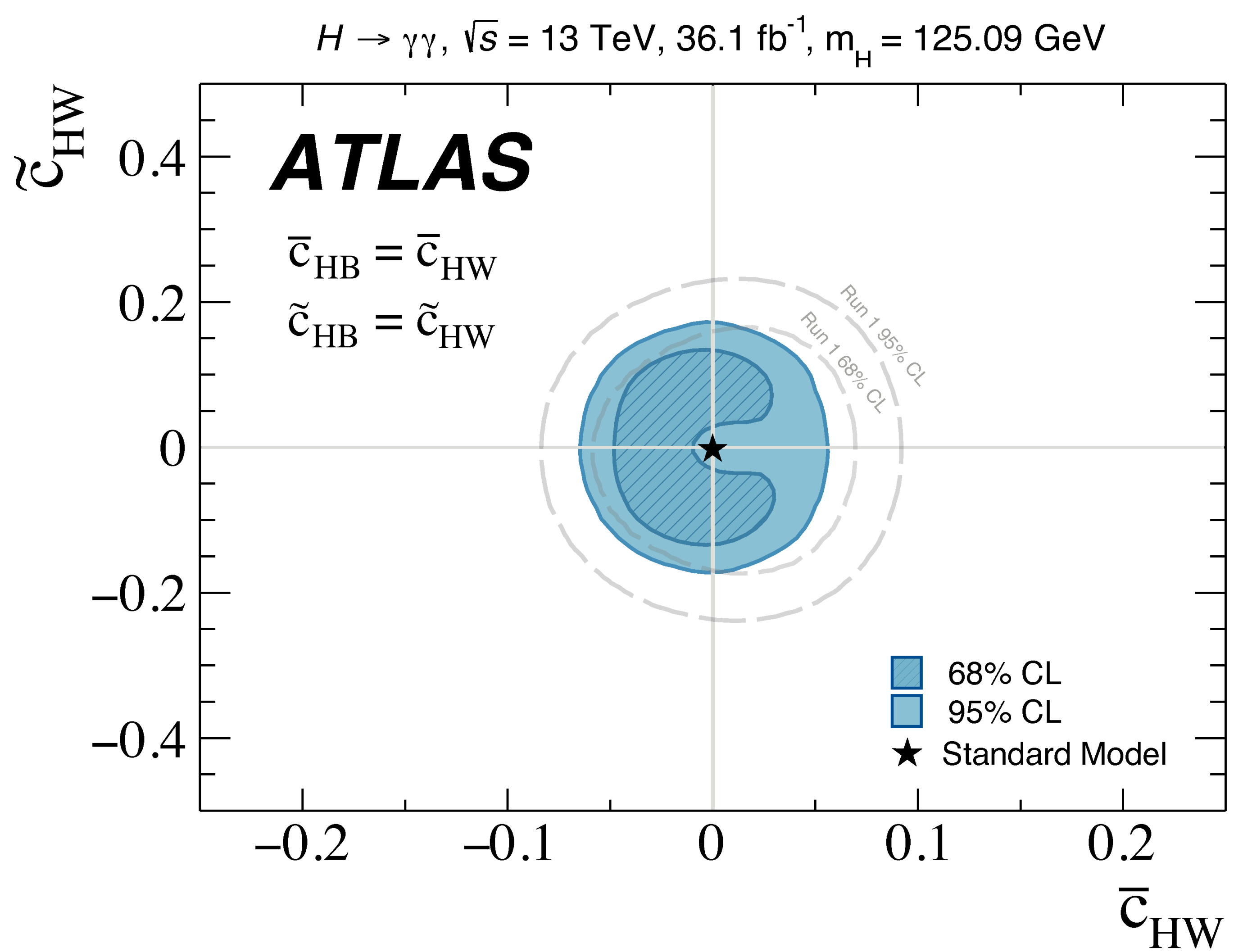
ATLAS, PRD 98 (2018) 052005

$H\to\gamma\gamma$ unfolded measurements

Cross sections calculated with the Effective Lagrangian include $|\mathscr{M}(d < \mathrm{TeV}^{-1})|^2$

These terms provide sensitivity to CP-odd operators from CP-even measurements

The CP-even interference term provides discrimination between CP-even and CP-odd operators in an Effective Lagrangian with these dimension-6 operators

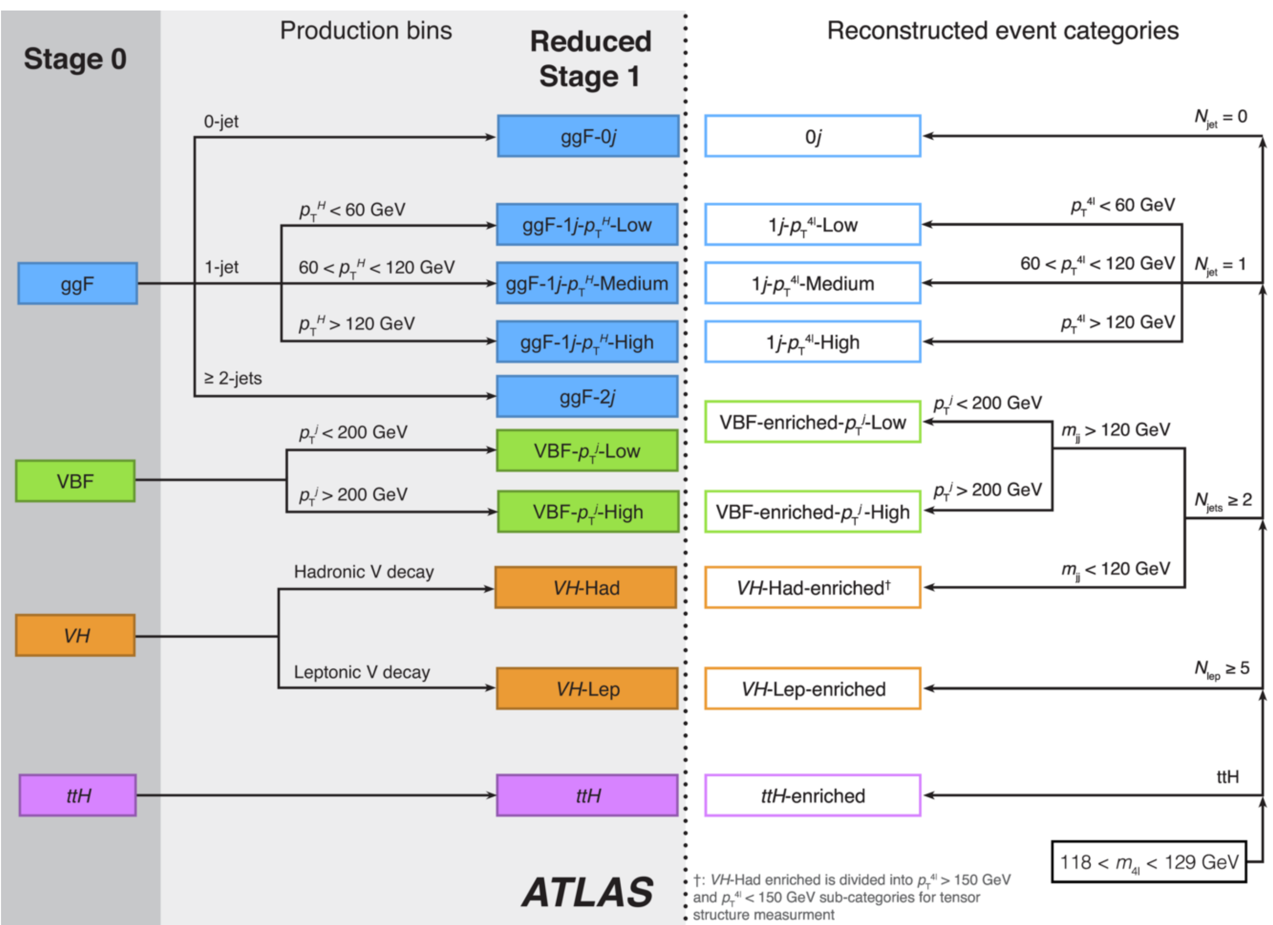


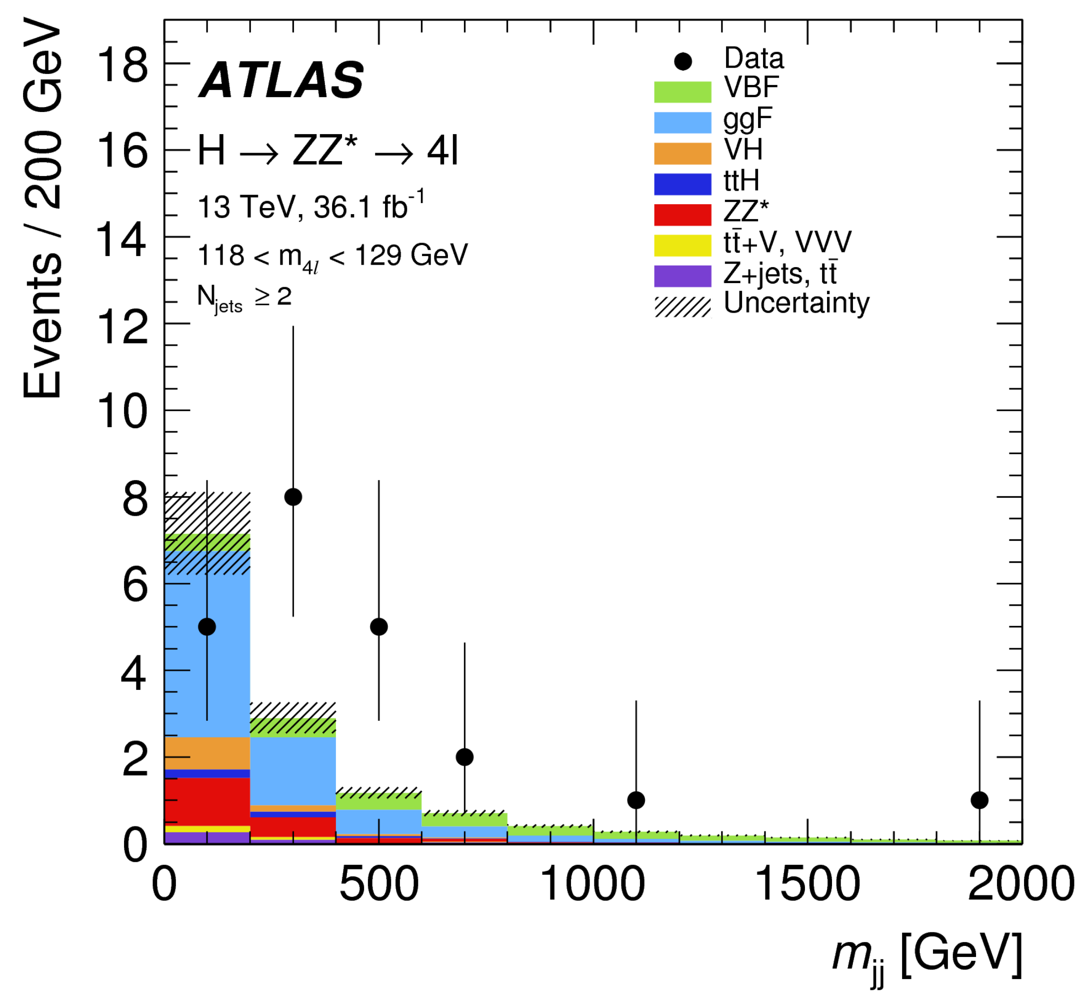
ATLAS, PRD 98 (2018) 052005

H→ℓℓℓℓ measurements

ATLAS measures a set of simplified template cross sections using multiple event categories

A fit to the event categories constrains coefficients of an Effective Lagrangian





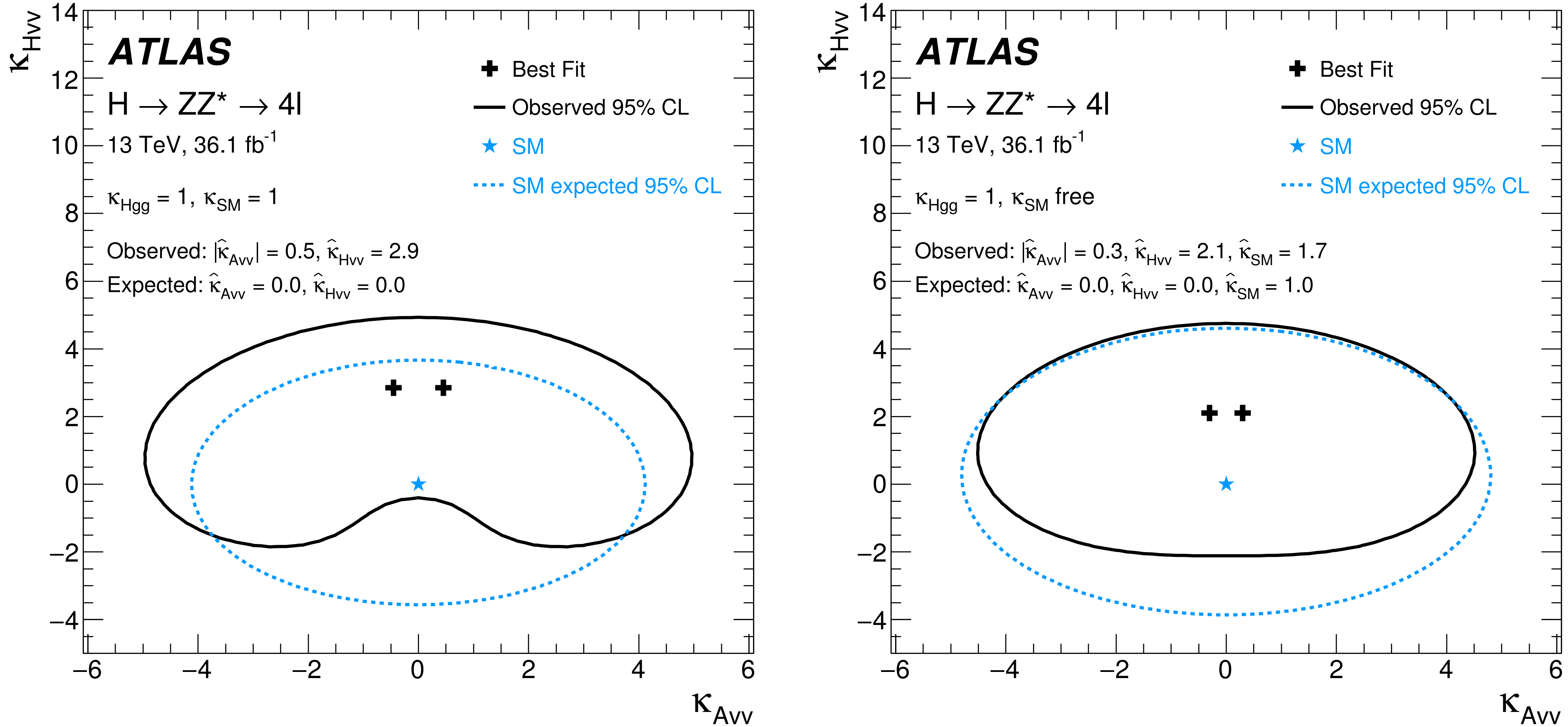
$$
\mathcal{L}_0^V = \Big\{ \kappa_{\rm SM} \left[\frac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W_\mu^+ W^{-\mu} \right]
- \frac{1}{4} \left[\kappa_{Hgg} g_{Hgg} G^a_{\mu\nu} G^{a,\mu\nu} + \tan\alpha \kappa_{Agg} g_{Agg} G^a_{\mu\nu} \tilde{G}^{a,\mu\nu} \right]
- \frac{1}{4} \frac{1}{\Lambda} \left[\kappa_{HZZ}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

The operators of the Higgs Characterization Lagrangian can be expressed in terms of those of a dimension-6 basis (with some redundancy)

ATLAS, JHEP 03 (2018) 095

$H\to\ell\ell\ell\ell$ measurements

ATLAS constrains up to three parameters simultaneously



ATLAS, JHEP 03 (2018) 095

H→$\ell\ell\ell\ell$ measurements

CMS uses multivariate discriminants to constrain parameters of a scattering amplitude

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

$$A(\mathrm{HVV}) \sim \left[a_1^{VV} + \frac{\kappa_1^{VV} q_1^2 + \kappa_2^{VV} q_2^2}{\left(\Lambda_1^{VV}\right)^2} \right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

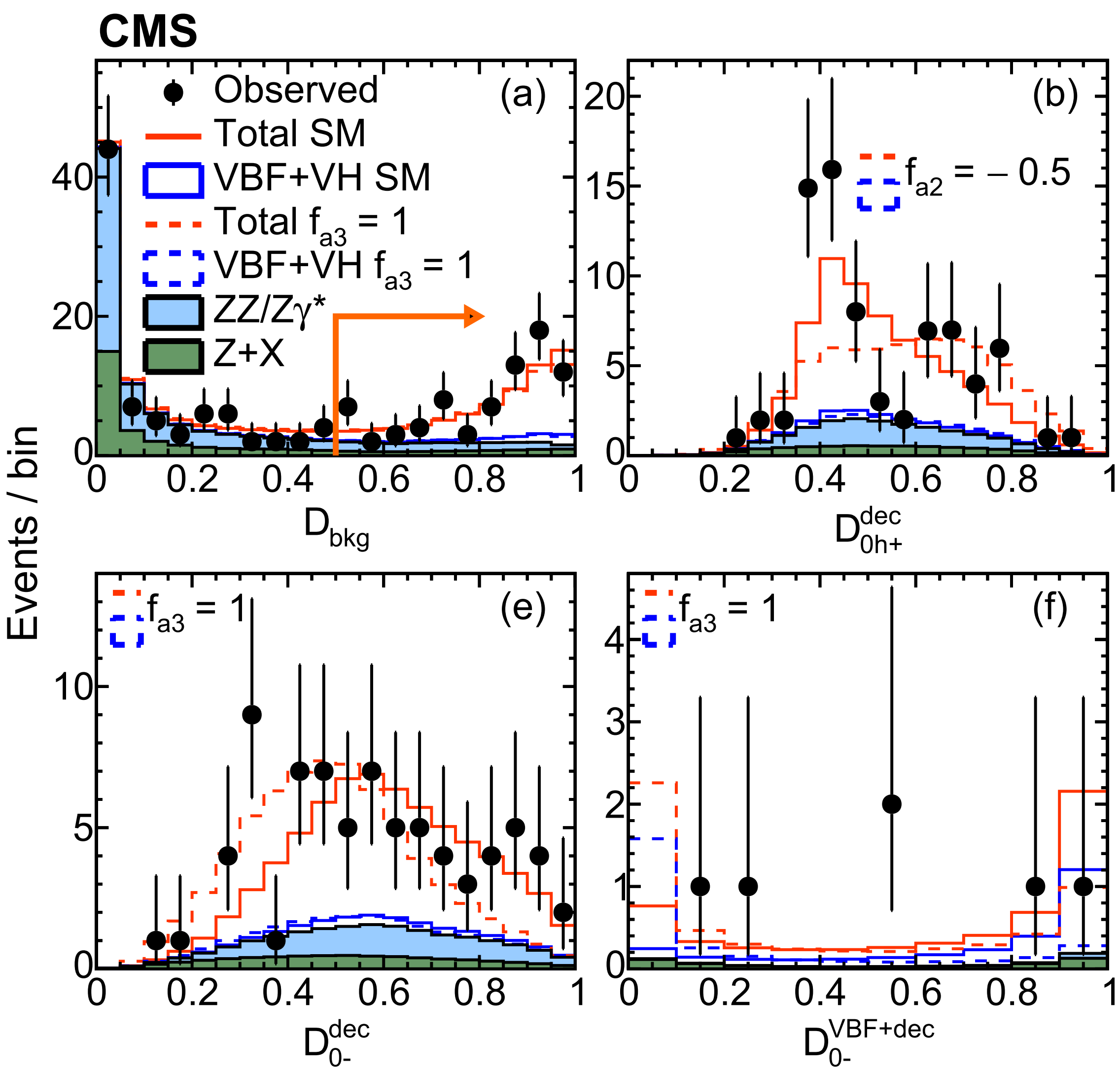
CMS, PLB 775 (2017) 1

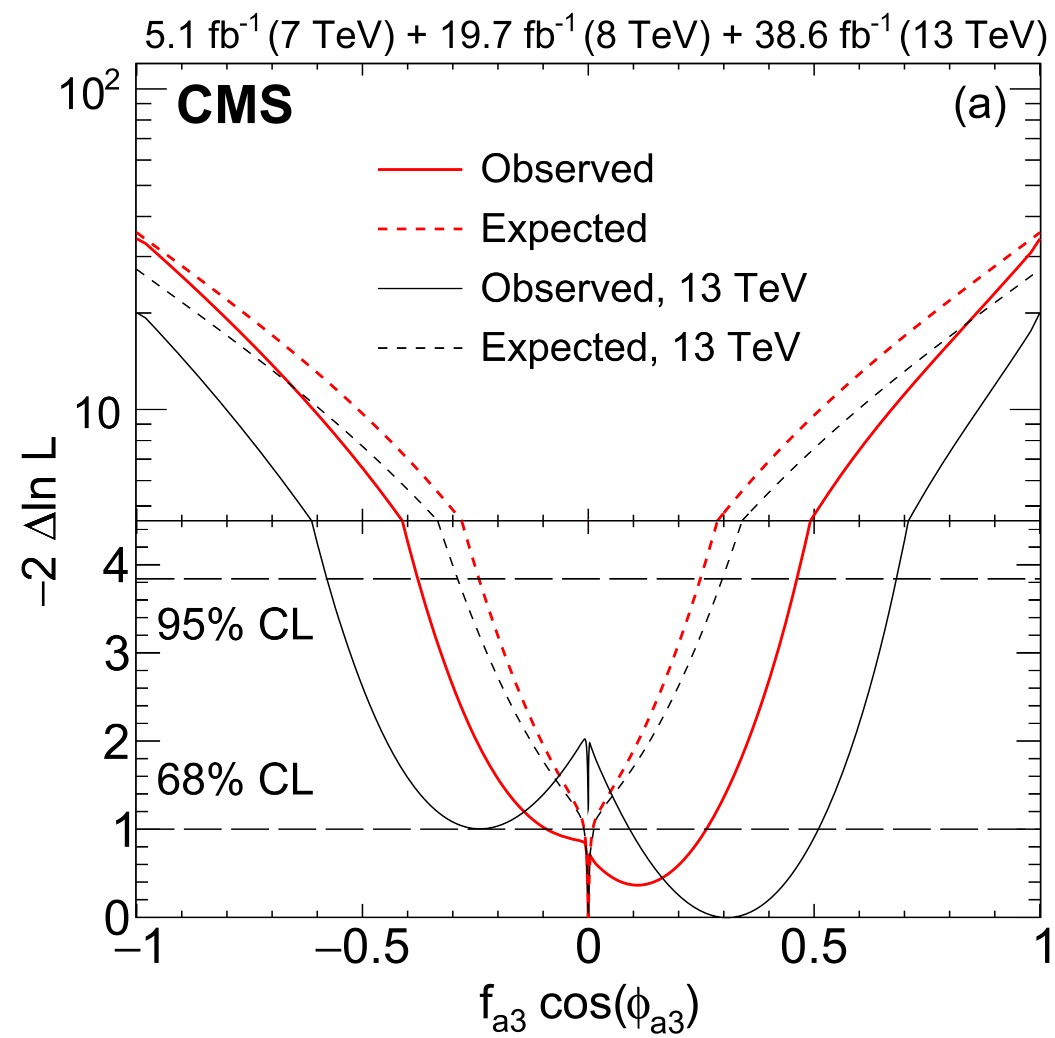
$$\begin{aligned} L(\mathrm{HVV}) \sim\ & a_1 \frac{m_Z^2}{2} \mathrm{H Z}^\mu \mathrm{Z}_\mu - \frac{\kappa_1}{(\Lambda_1)^2} m_Z^2 \mathrm{H Z}_\mu \Box \mathrm{Z}^\mu - \frac{1}{2} a_2 \mathrm{H Z}^{\mu\nu} \mathrm{Z}_{\mu\nu} - \frac{1}{2} a_3 \mathrm{H Z}^{\mu\nu} \tilde{\mathrm{Z}}_{\mu\nu} \\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

Amplitude can be related to parameters of an effective Lagrangian

CMS, PRD 92 (2015) 012004

$H \rightarrow \ell\ell\ell\ell$ measurements





$$f_{ai} = |a_i|^2\sigma_i \Big/ \sum |a_j|^2\sigma_j, \text{ and } \phi_{ai} = \arg(a_i/a_1).$$

CMS, PLB 775 (2017) 1

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

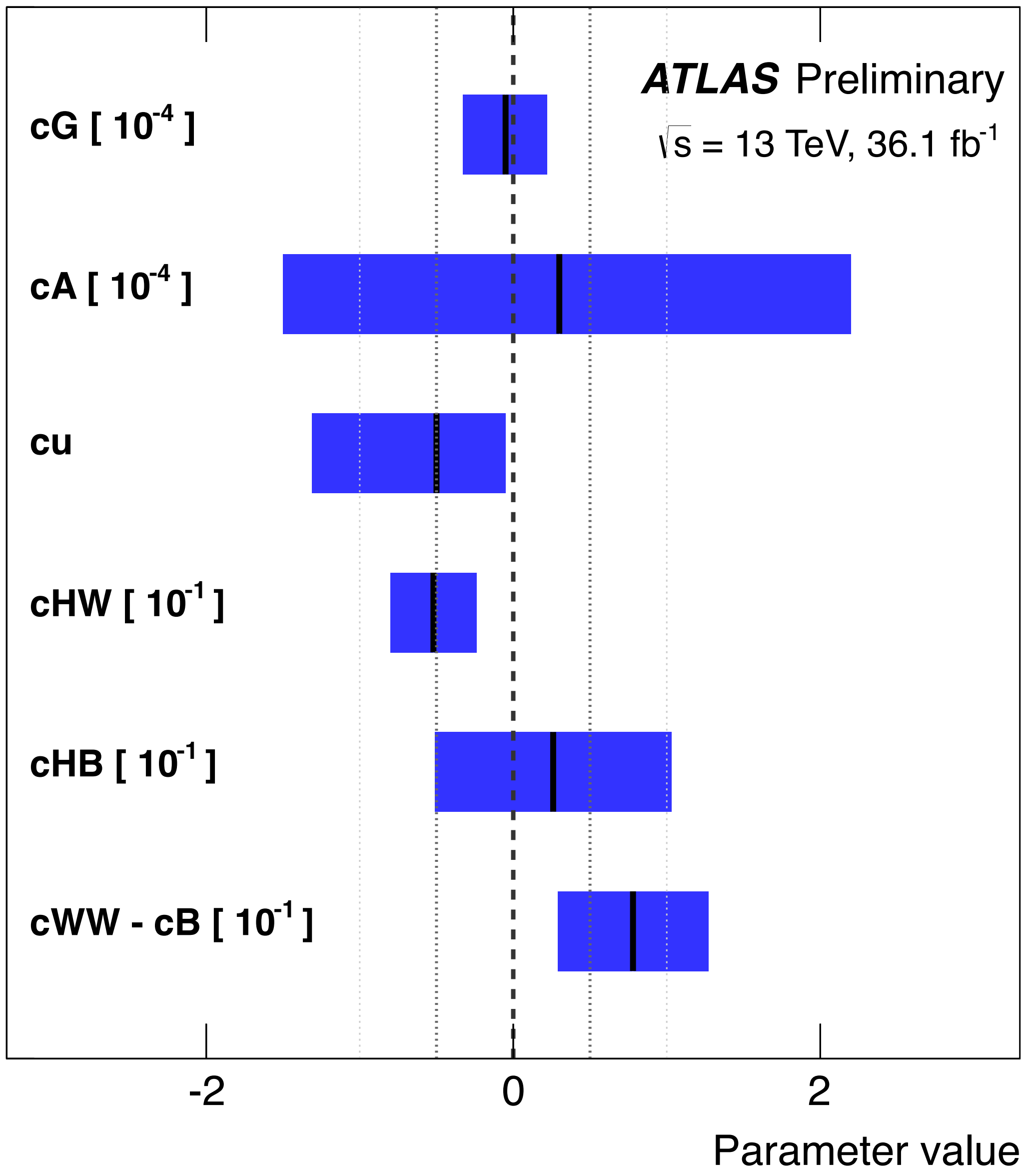
$H\to\gamma\gamma$ and $H\to\ell\ell\ell\ell$ combination

ATLAS combines the measurements from multiple event categories

Categories are combined into STXS to constrain six coefficients of an Effective Lagrangian

$H\to\gamma\gamma$	$H\to ZZ^*\to 4\ell$
$t\bar{t}H$+tH leptonic (two tHX and one $t\bar{t}H$ categories)	$t\bar{t}H$
$t\bar{t}H$+tH hadronic (two tHX and four BDT $t\bar{t}H$ categories)	VH leptonic
VH dilepton	2-jet VH
VH one-lepton, $p_T^{\ell+E_T^{miss}} \geq 150$ GeV	2-jet VBF, $p_T^{j1} \geq 200$ GeV
VH one-lepton, $p_T^{\ell+E_T^{miss}} <150$ GeV	2-jet VBF, $p_T^{j1} <200$ GeV
VH E_T^{miss}, $E_T^{miss} \geq 150$ GeV	1-jet ggF, $p_T^{4\ell} \geq 120$ GeV
VH E_T^{miss}, $E_T^{miss} <150$ GeV	1-jet ggF, 60 GeV$<p_T^{4\ell}<$120 GeV
VH+VBF$p_T^{j1} \geq 200$ GeV	1-jet ggF, $p_T^{4\ell}<$60 GeV
VH hadronic (BDT tight and loose categories)	0-jet ggF
VBF, $p_T^{\gamma\gamma jj} \geq 25$ GeV(BDT tight and loose categories)	
VBF, $p_T^{\gamma\gamma jj} <25$ GeV(BDT tight and loose categories)	
ggF 2-jet, $p_T^{\gamma\gamma} \geq 200$ GeV	
ggF 2-jet, 120 GeV$\leq p_T^{\gamma\gamma}<$200 GeV	
ggF 2-jet, 60 GeV$\leq p_T^{\gamma\gamma}<$120 GeV	
ggF 2-jet, $p_T^{\gamma\gamma} <$ 60 GeV	
ggF 1-jet, $p_T^{\gamma\gamma} \geq 200$ GeV	
ggF 1-jet, 120 GeV$\leq p_T^{\gamma\gamma}<$200 GeV	
ggF 1-jet, 60 GeV$\leq p_T^{\gamma\gamma}<$120 GeV	
ggF 1-jet, $p_T^{\gamma\gamma} <$ 60 GeV	
ggF 0-jet (central and forward categories)	

Observed HEL constraints with H → ZZ* and H → γγ

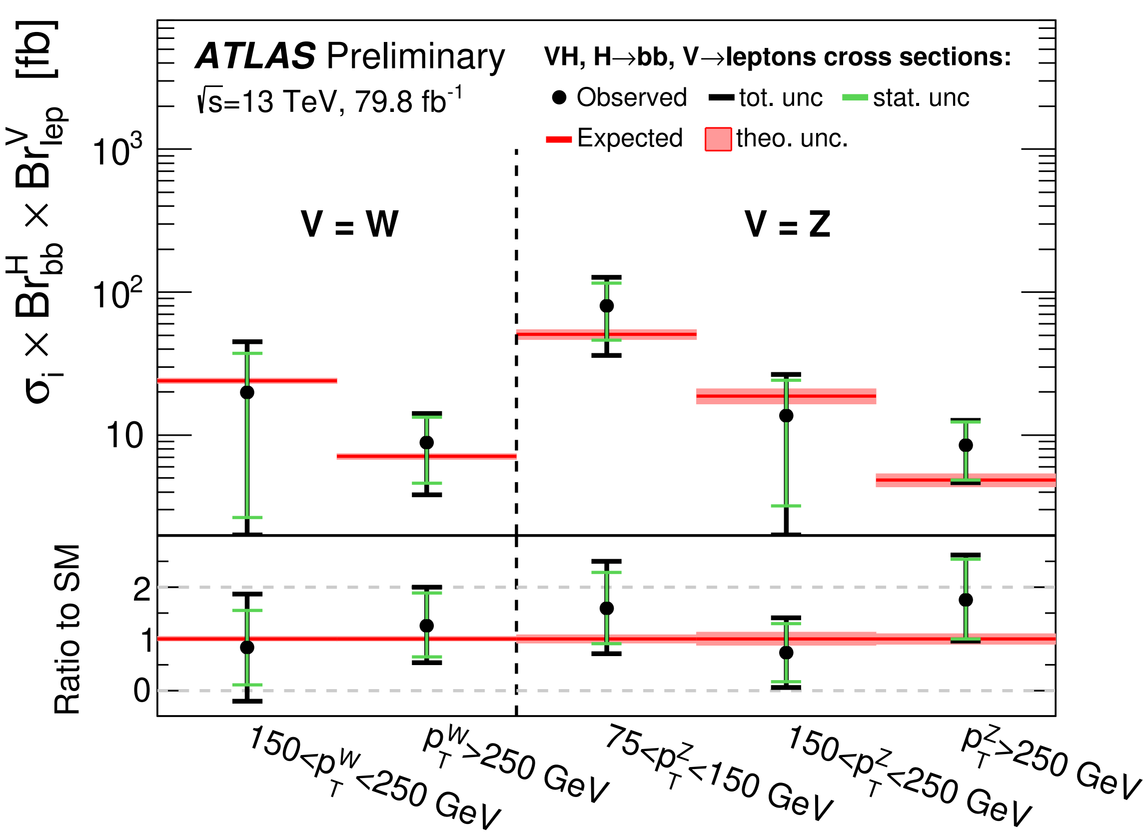


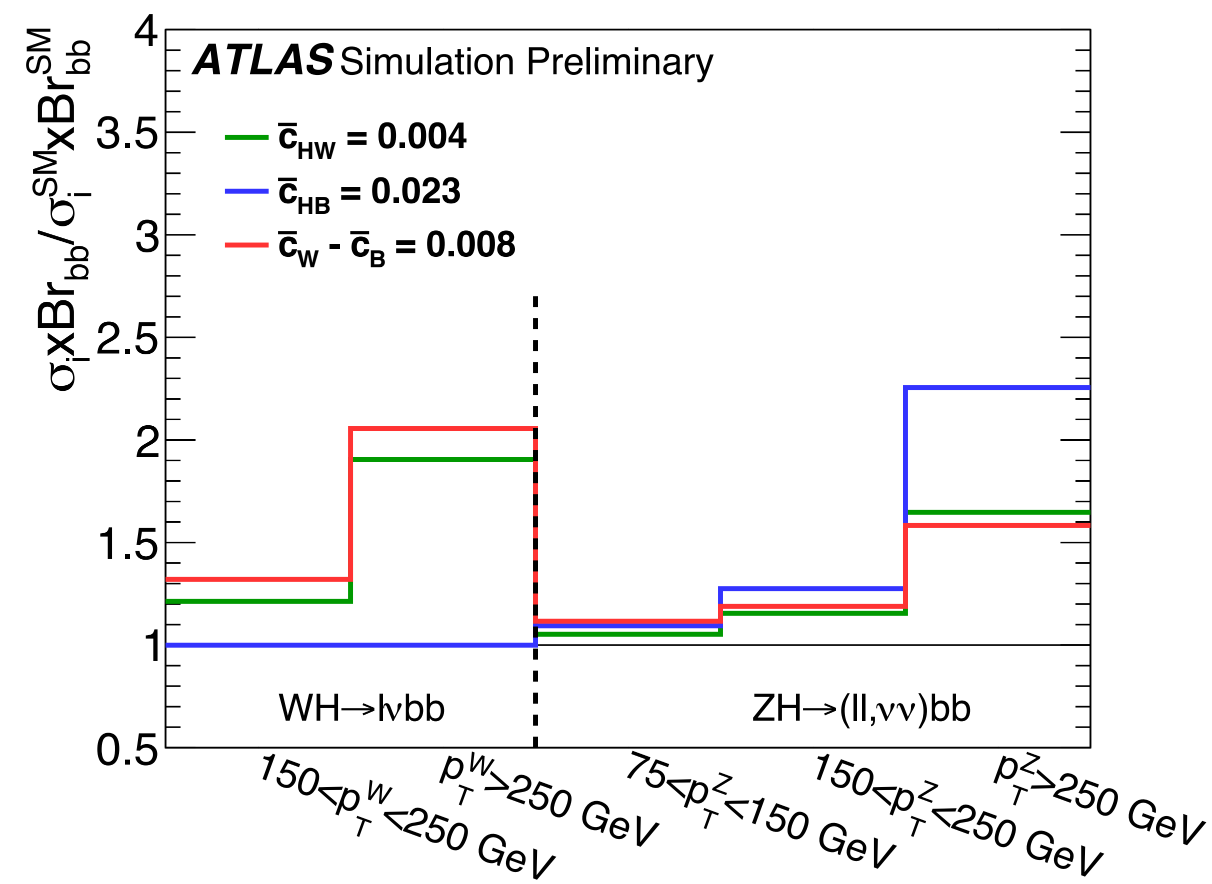
ATLAS, ATL-PHYS-PUB-2017-018

H→bb measurements

ATLAS measures a set of simplified template cross sections using multiple event categories

A fit to the STXS measurements constrains coefficients of an Effective Lagrangian





Coefficients constrained individually

Coefficient	Expected 68% CL intervals	Observed 68% CL intervals
$\bar{c}_{HW}$	[−0.0032, 0.0024]	[−0.0008, 0.0037]
$\bar{c}_{HB}$	[−0.069, −0.036]∪[−0.026, 0.013]	[−0.082, −0.057] ∪ [0.002, 0.017]
$\bar{c}_W - \bar{c}_B$	[−0.0060, 0.0045]	[−0.0020, 0.0065]

See also talk from D. Schaefer

ATLAS, ATLAS-CONF-2018-053

$$\bar{c}_{HW} = \frac{m_W^2}{g}\frac{c_{HW}}{\Lambda^2}, \quad \bar{c}_{HB} = \frac{m_W^2}{g'}\frac{c_{HB}}{\Lambda^2}, \quad \bar{c}_W = \frac{m_W^2}{g}\frac{c_W}{\Lambda^2}, \quad \bar{c}_B = \frac{m_W^2}{g'}\frac{c_B}{\Lambda^2},$$

Electroweak measurements

Measurements of gauge boson production sensitive to operators affecting Higgs physics

Higgs doublet provides longitudinal degrees of freedom to the electroweak bosons

Traditionally constrain triple-gauge couplings with an effective Lagrangian with form factors

Can relate coefficients to those of dimension-6 operators from an SMEFT basis

$$
\begin{aligned}
i\mathcal{L}_{\text{eff}}^{WWV} = g_{WWV} \Big\{ & \Big[g_1^V V^\mu (W^-_{\mu\nu} W^{+\nu} - W^+_{\mu\nu} W^{-\nu}) \\
& + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{m_W^2} V^{\mu\nu} W^{+\rho}_\nu W^-_{\rho\mu} \Big] \\
& - \Big[\frac{\tilde{\kappa}_V}{2} W^-_\mu W^+_\nu \epsilon^{\mu\nu\rho\sigma} V_{\rho\sigma} \\
& + \frac{\tilde{\lambda}_V}{2m_W^2} W^-_{\rho\mu} W^{+\mu}_\nu \epsilon^{\nu\rho\alpha\beta} V_{\alpha\beta} \Big] \Big\},
\end{aligned}
$$

$\longrightarrow$

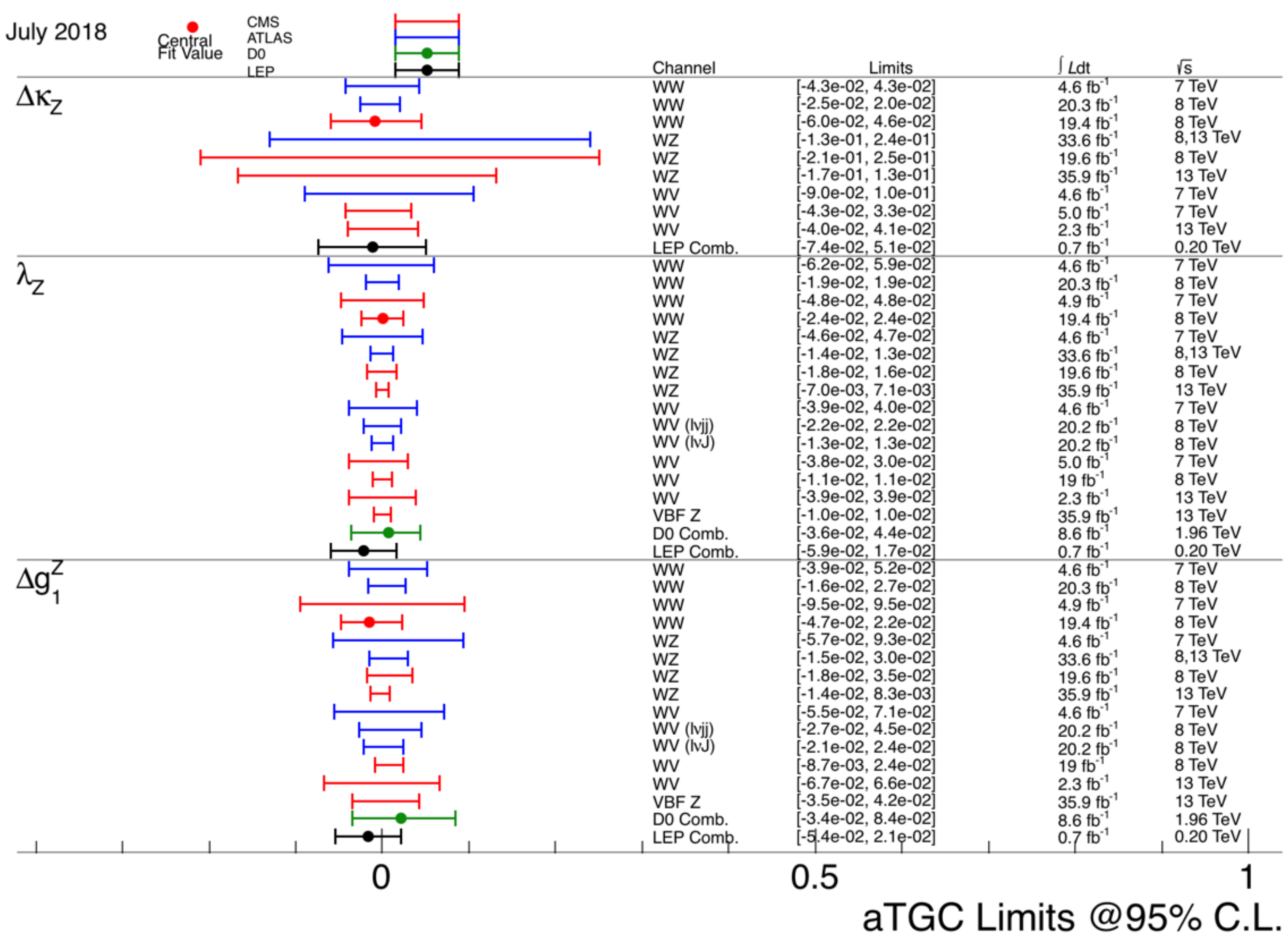
$$
\begin{aligned}
O_B &= (D_\mu H)^\dagger B^{\mu\nu} D_\nu H, \\
O_W &= (D_\mu H)^\dagger W^{\mu\nu} D_\nu H, \\
O_{WWW} &= \mathrm{Tr}[W_{\mu\nu} W^\nu_\rho W^{\rho\mu}], \\
O_{\tilde{W}} &= (D_\mu H)^\dagger \tilde{W}^{\mu\nu} D_\nu H, \\
O_{\tilde{W}WW} &= \mathrm{Tr}[W_{\mu\nu} W^\nu_\rho \tilde{W}^{\rho\mu}],
\end{aligned}
$$

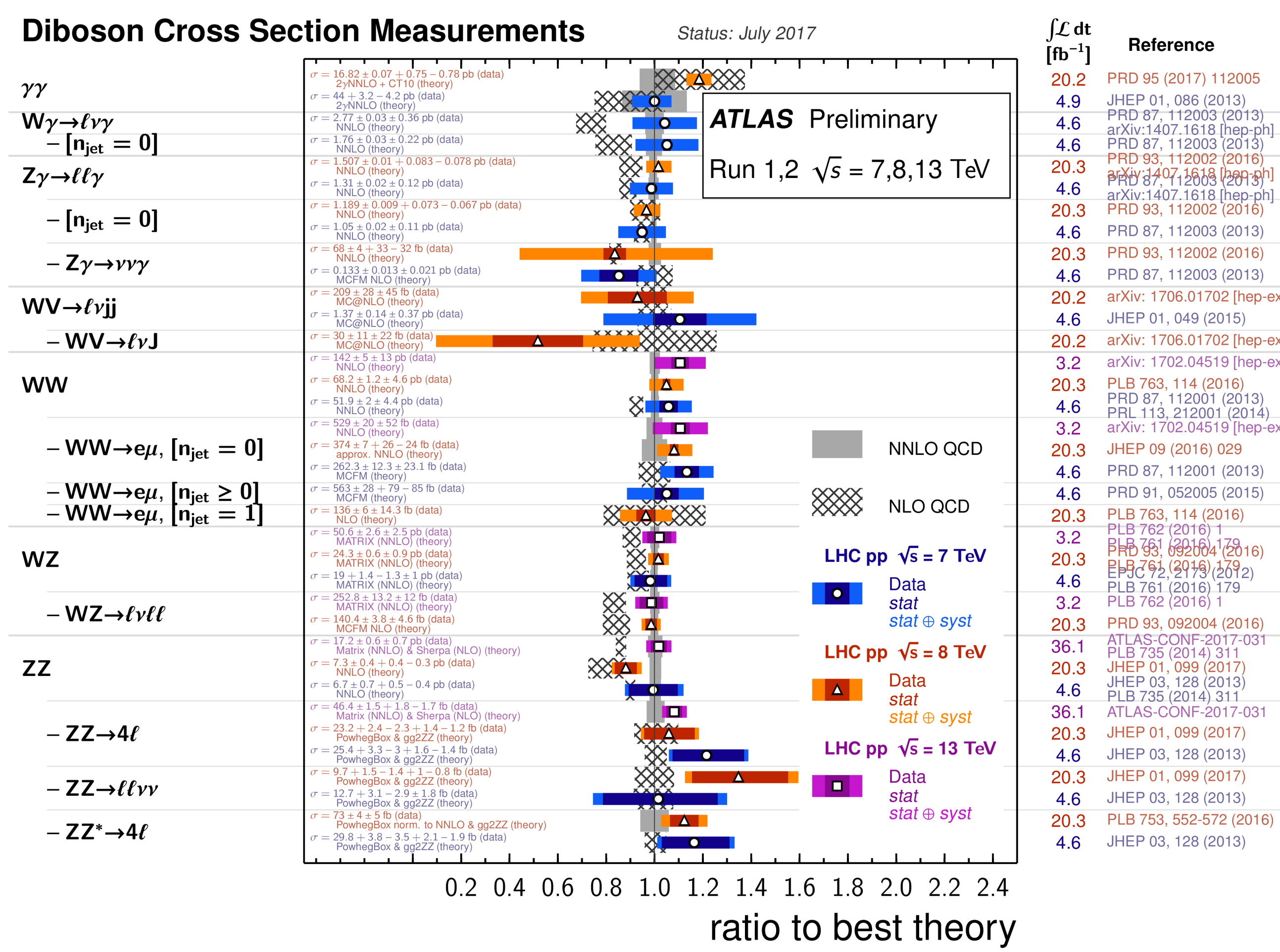
$$
\begin{aligned}
\frac{c_W}{\Lambda^2} &= \frac{2}{m_Z^2}(g_1^Z - 1), \\
\frac{c_B}{\Lambda^2} &= \frac{2}{\tan^2\theta_W m_Z^2}(g_1^Z - 1) - \frac{2}{\sin^2\theta_W m_Z^2}(\kappa_Z - 1), \\
\frac{c_{WWW}}{\Lambda^2} &= \frac{2}{3g^2 m_W^2}\lambda_V, \\
\frac{c_{\tilde{W}}}{\Lambda^2} &= -\frac{2}{\tan^2\theta_W m_W^2}\tilde{\kappa}_Z, \\
\frac{c_{\tilde{W}WW}}{\Lambda^2} &= \frac{2}{3g^2 m_W^2}\tilde{\lambda}_V,
\end{aligned}
$$

Electroweak measurements

Many diboson and vector-boson fusion measurements constrain triple-gauge couplings

- Constraints typically extracted from fits to reconstruction-level distributions
- Fiducial and differential measurements also provided for external fits

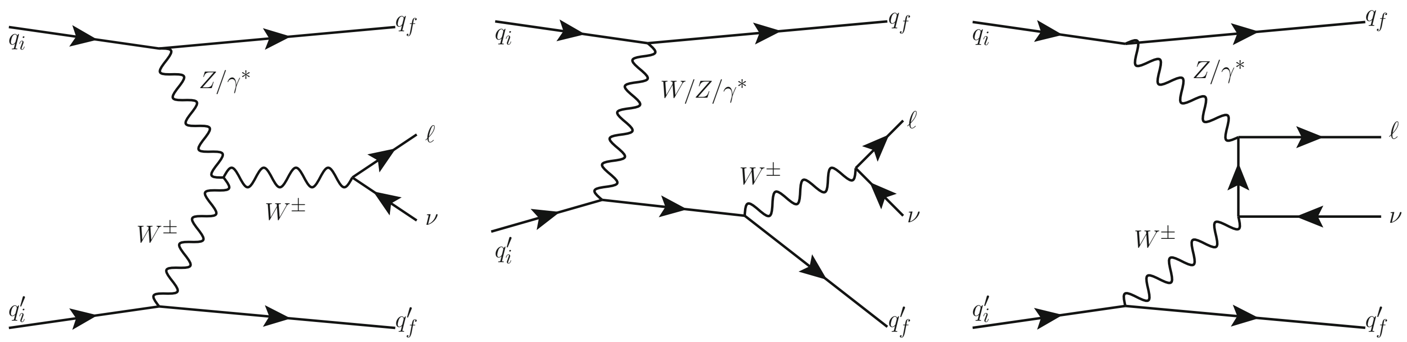




Electroweak measurements

Experiments now quote TGC constraints in terms of SMEFT coefficients

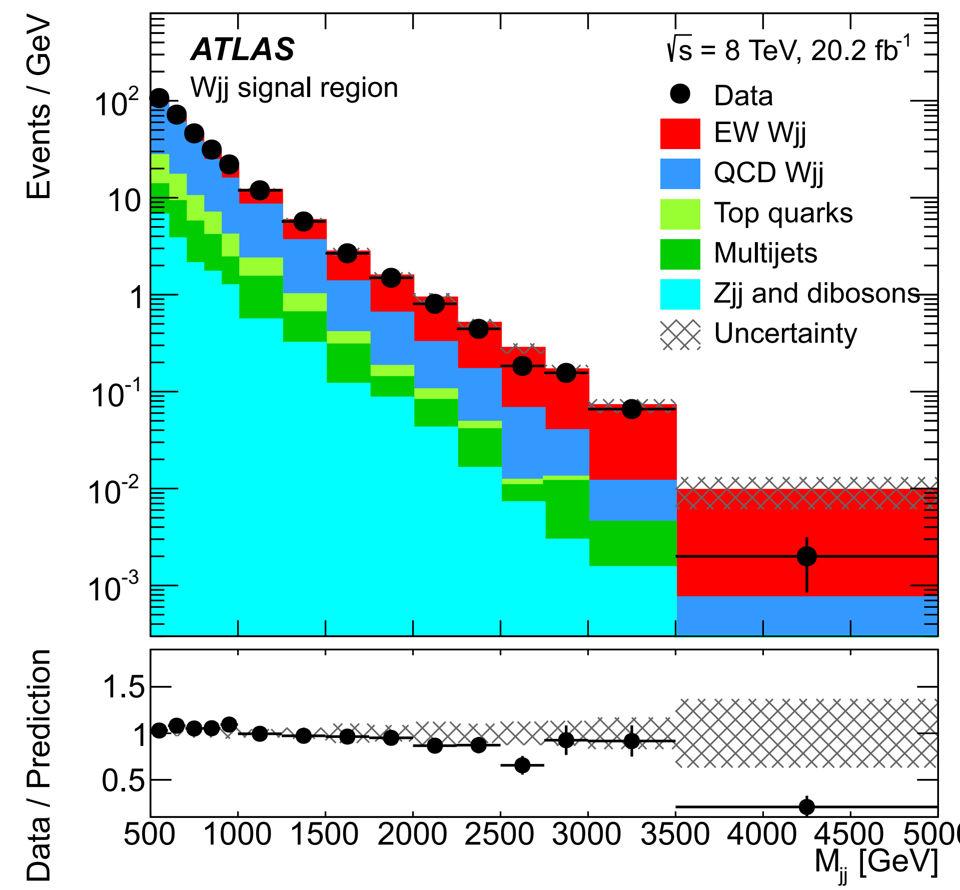
Most recently in measurements of vector-boson fusion W/Z production



(a) Vector boson fusion **(b)** W bremsstrahlung **(c)** Non-resonant

		8 TeV	
		SM prediction	Data
High-q^2 region	$M_{jj} > 1$ TeV, $N^{\text{cen}}_{\text{lepton}} = 1$, $N^{\text{cen}}_{\text{jets}} = 0$, $p_{\text{T}}^{j_1} > 600$ GeV	39	30

Parameter	Expected (TeV^{-2})	Observed (TeV^{-2})
$\frac{c_W}{\Lambda^2}$	[−39, 37]	[−33, 30]
$\frac{c_B}{\Lambda^2}$	[−200, 190]	[−170, 160]
$\frac{c_{WWW}}{\Lambda^2}$	[−16, 13]	[−13, 9]
$\frac{c_{\tilde{W}}}{\Lambda^2}$	[−720, 720]	[−580, 580]
$\frac{c_{\tilde{W}WW}}{\Lambda^2}$	[−14, 14]	[−11, 11]



ATLAS, EPJC 77 (2017) 474

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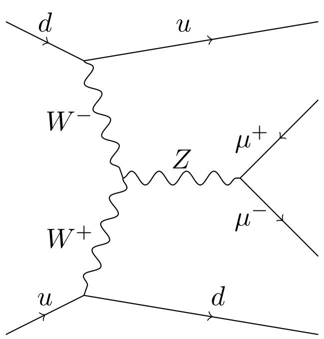
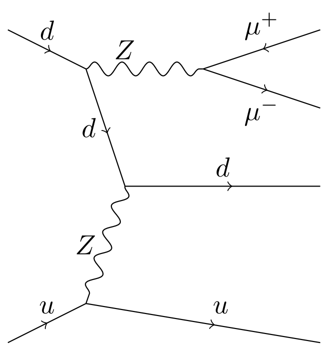
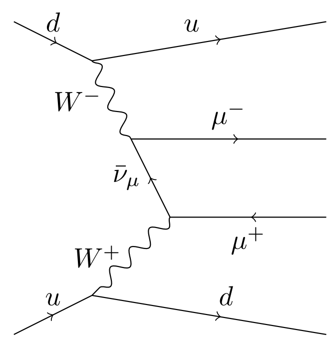
Most recently in measurements of vector-boson fusion W/Z production

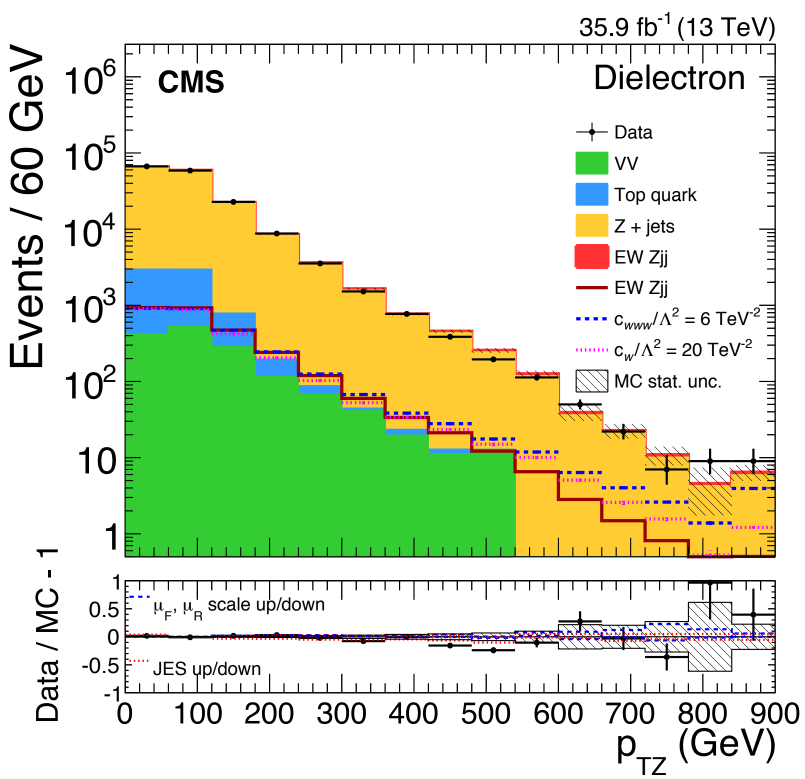


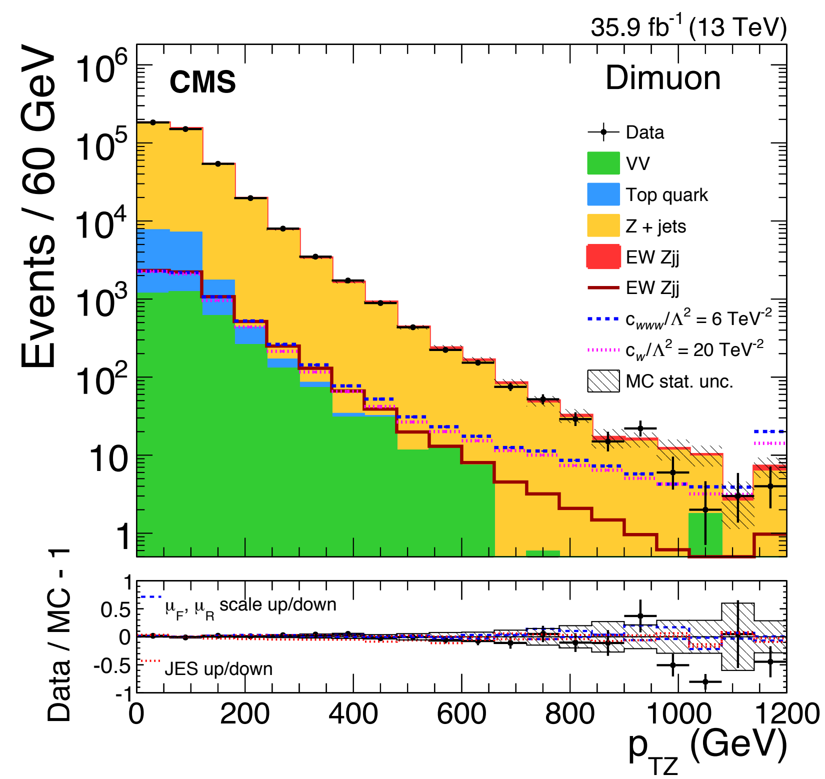


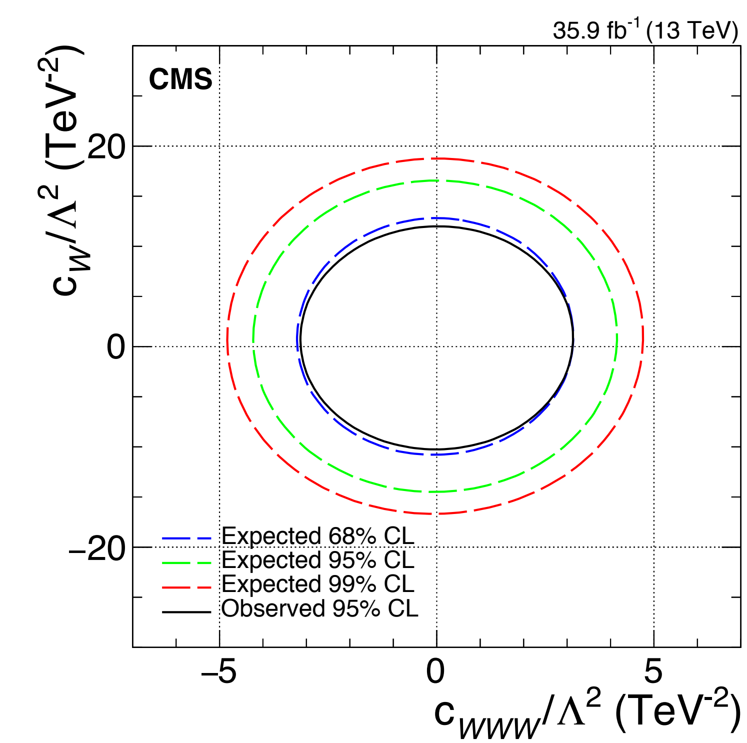


Coupling constant	Expected 95% CL interval (TeV^{-2})	Observed 95% CL interval (TeV^{-2})
c_{WWW}/Λ^2	$[-3.7, 3.6]$	$[-2.6, 2.6]$
c_W/Λ^2	$[-12.6, 14.7]$	$[-8.4, 10.1]$

CMS, 1712.09814 (2017)



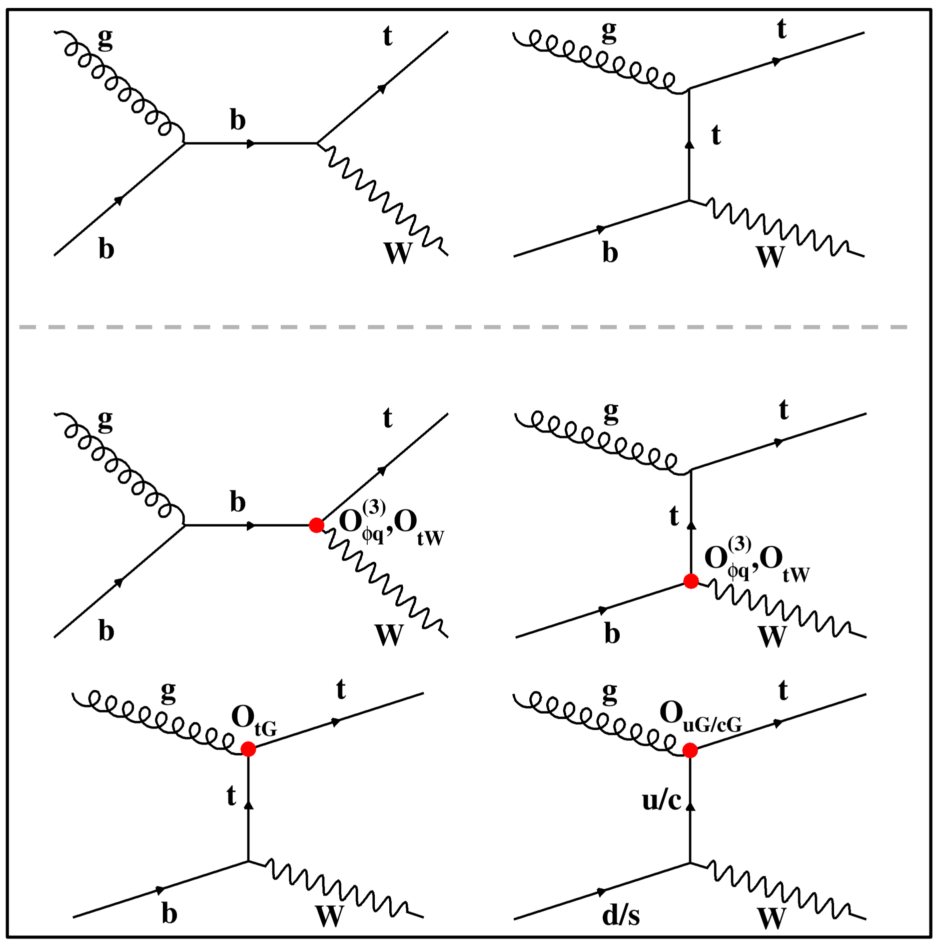


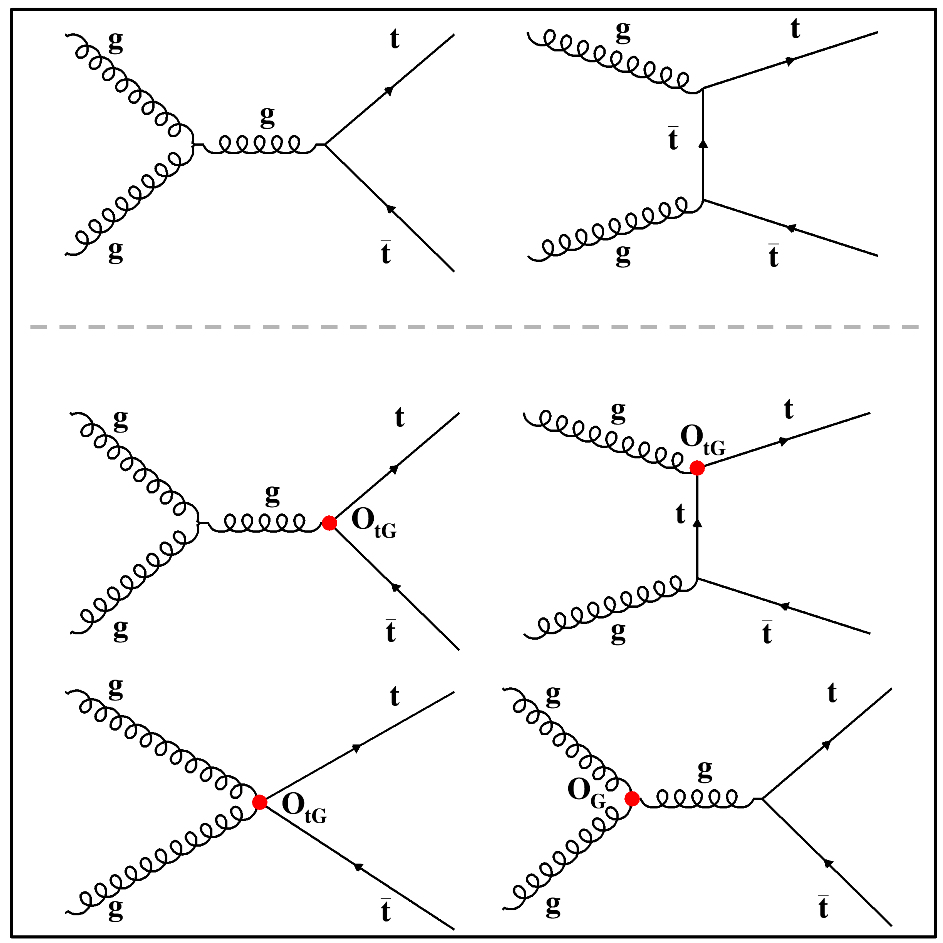


Top quark measurements

Top quark production sensitive to many dimension-6 operators

In a global analysis the production operators need to be constrained to access ttH operator





Representative set of operators affecting tt & tW production (Warsaw basis):

$$O^{(3)}_{\phi q} = (\phi^+ \tau^I D_\mu \phi)(\bar{q}\gamma^\mu \tau^I q),$$

$$O_{tW} = (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi} W^I_{\mu\nu},$$

$$O_{tG} = (\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi} G^A_{\mu\nu},$$

$$O_G = f_{ABC} G^{A\nu}_{\mu} G^{B\rho}_{\nu} G^{C\mu}_{\rho},$$

$$O_{u(c)G} = (\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi} G^A_{\mu\nu},$$

CMS, CMS PAS TOP-17-020 (2017)

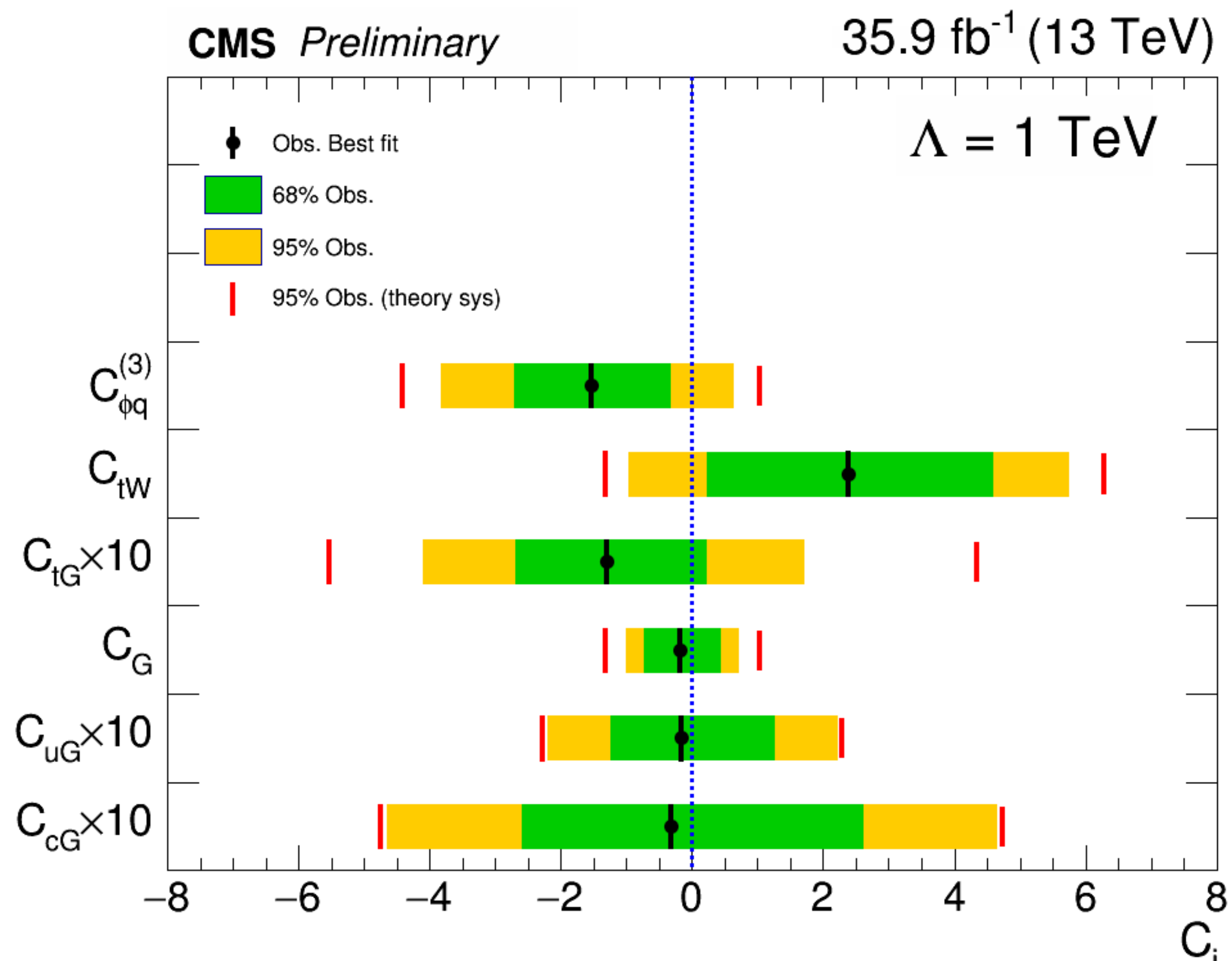
Top quark measurements

CMS constrains six operator coefficients by fitting to signal regions in tt and tW production

Three operators sensitive to flavour

Eff. coupling	Channel	Observed	Expected
C_G	ee	$-0.14^{+0.51}_{-0.82}$ $[-1.14, 0.83]$	$0.00^{+0.59}_{-0.90}$ $[-1.20, 0.88]$
	eμ	$-0.18^{+0.42}_{-0.73}$ $[-1.01, 0.70]$	$0.00^{+0.51}_{-0.82}$ $[-1.08, 0.77]$
	$\mu\mu$	$-0.14^{+0.44}_{-0.75}$ $[-1.06, 0.75]$	$0.00^{+0.57}_{-0.88}$ $[-1.16, 0.85]$
	Combined	$-0.18^{+0.42}_{-0.73}$ $[-1.01, 0.70]$	$0.00^{+0.51}_{-0.82}$ $[-1.07, 0.76]$
$C^{(3)}_{\phi q}$	ee	$1.12^{+2.89}_{-1.18}$ $[-4.03, 4.37]$	$0.00^{+1.74}_{-2.53}$ $[-6.40, 3.27]$
	eμ	$-0.70^{+0.59}_{-2.16}$ $[-3.74, 1.61]$	$0.00^{+1.12}_{-1.34}$ $[-2.57, 2.15]$
	$\mu\mu$	$1.13^{+2.86}_{-0.87}$ $[-3.58, 4.46]$	$0.00^{+1.92}_{-2.20}$ $[-4.68, 3.66]$
	Combined	$-1.52^{-0.33}_{-2.71}$ $[-3.82, 0.63]$	$0.00^{+0.88}_{-1.05}$ $[-2.04, 1.63]$
C_{tW}	ee	$6.18^{+7.81}_{-3.02}$ $[-4.16, 8.95]$	$0.00^{+6.81}_{-2.02}$ $[-3.33, 8.12]$
	eμ	$1.64^{+5.59}_{-0.80}$ $[-1.89, 6.68]$	$0.00^{+6.19}_{-1.40}$ $[-2.39, 7.18]$
	$\mu\mu$	$-1.40^{+7.79}_{-3.00}$ $[-4.23, 9.01]$	$0.00^{+6.97}_{-2.18}$ $[-3.63, 8.42]$
	Combined	$2.38^{+4.57}_{+0.22}$ $[-0.96, 5.74]$	$0.00^{+5.93}_{-1.14}$ $[-1.91, 6.70]$
C_{tG}	ee	$-0.19^{+0.02}_{-0.40}$ $[-0.65, 0.22]$	$0.00^{+0.21}_{-0.22}$ $[-0.44, 0.41]$
	eμ	$-0.03^{+0.11}_{-0.19}$ $[-0.34, 0.27]$	$0.00^{+0.15}_{-0.17}$ $[-0.34, 0.29]$
	$\mu\mu$	$-0.15^{+0.02}_{-0.34}$ $[-0.53, 0.19]$	$0.00^{+0.18}_{-0.19}$ $[-0.40, 0.35]$
	Combined	$-0.13^{+0.02}_{-0.27}$ $[-0.41, 0.17]$	$0.00^{+0.14}_{-0.15}$ $[-0.30, 0.28]$
C_{uG}	ee	$-0.017^{+0.22}_{-0.22}$ $[-0.37, 0.37]$	$0.00^{+0.29}_{-0.29}$ $[-0.42, 0.42]$
	eμ	$-0.017^{+0.17}_{-0.17}$ $[-0.29, 0.29]$	$0.00^{+0.26}_{-0.26}$ $[-0.38, 0.38]$
	$\mu\mu$	$-0.017^{+0.17}_{-0.17}$ $[-0.29, 0.29]$	$0.00^{+0.27}_{-0.27}$ $[-0.38, 0.38]$
	Combined	$-0.017^{+0.13}_{-0.13}$ $[-0.22, 0.22]$	$0.00^{+0.21}_{-0.21}$ $[-0.30, 0.30]$
C_{cG}	ee	$-0.032^{+0.47}_{-0.47}$ $[-0.78, 0.78]$	$0.00^{+0.63}_{-0.63}$ $[-0.92, 0.92]$
	eμ	$-0.032^{+0.34}_{-0.34}$ $[-0.60, 0.60]$	$0.00^{+0.56}_{-0.56}$ $[-0.81, 0.81]$
	$\mu\mu$	$-0.032^{+0.36}_{-0.36}$ $[-0.63, 0.63]$	$0.00^{+0.58}_{-0.58}$ $[-0.84, 0.84]$
	Combined	$-0.032^{+0.26}_{-0.26}$ $[-0.46, 0.46]$	$0.00^{+0.46}_{-0.46}$ $[-0.65, 0.65]$

Eff. coupling	Channel	Categories				
		1-jet,0-tag	1-jet,1-tag	2-jets,1-tag	n-jets,1-tag	≥2-jets,2-tags
C_G	ee	-	Yield	Yield	-	Yield
	eμ	Yield	Yield	Yield	-	Yield
	$\mu\mu$	-	Yield	Yield	-	Yield
$C^{(3)}_{\phi q}$, C_{tW}, C_{tG}	ee	-	NN_{11}	NN_{21}	-	Yield
	eμ	NN_{10}	NN_{11}	NN_{21}	-	Yield
	$\mu\mu$	-	NN_{11}	NN_{21}	-	Yield
C_{uG}, C_{cG}	ee	-	-	-	NN_{FCNC}	-
	eμ	-	-	-	NN_{FCNC}	-
	$\mu\mu$	-	-	-	NN_{FCNC}	-

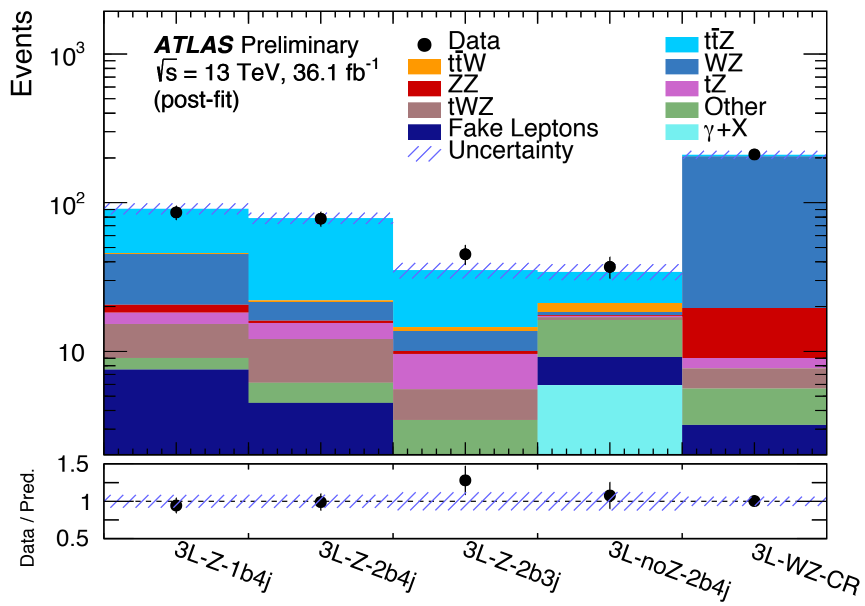


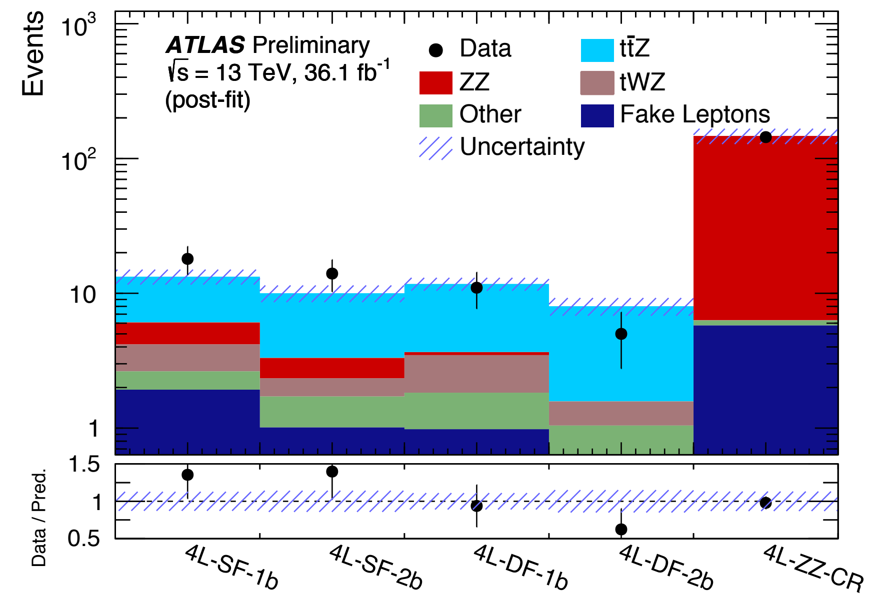
CMS, CMS PAS TOP-17-020 (2017)

Top quark measurements

ATLAS individually constrains four operator coefficients by fitting to signal regions in ttZ production

Process	$t\bar{t}$ decay	Boson decay	Channel
$t\bar{t}W$	$(\ell^{\pm}\nu b)(q\bar{q}b)$	$\ell^{\pm}\nu$	SS dilepton
	$(\ell^{\pm}\nu b)(\ell^{\mp}\nu b)$	$\ell^{\pm}\nu$	Trilepton
$t\bar{t}Z$	$(q\bar{q}b)(q\bar{q}b)$	$\ell^{+}\ell^{-}$	OS dilepton
	$(\ell^{\pm}\nu b)(q\bar{q}b)$	$\ell^{+}\ell^{-}$	Trilepton
	$(\ell^{\pm}\nu b)(\ell^{\mp}\nu b)$	$\ell^{+}\ell^{-}$	Tetralepton





Operator	Expression
$O_{\phi Q}^{(3)}$	$i\frac{1}{2}(\phi^{\dagger}\overleftrightarrow{D}_{\mu}^{I}\phi)(\bar{Q}\gamma^{\mu}\tau^{I}Q)$
$O_{\phi Q}^{(1)}$	$i\frac{1}{2}(\phi^{\dagger}\overleftrightarrow{D}_{\mu}\phi)(\bar{Q}\gamma^{\mu}Q)$
$O_{\phi t}$	$i\frac{1}{2}(\phi^{\dagger}\overleftrightarrow{D}_{\mu}\phi)(\bar{t}\gamma^{\mu}t)$
O_{tW}	$y_t g_w(\bar{Q}\sigma^{\mu\nu}\tau^{I}t)\tilde{\phi}W_{\mu\nu}^{I}$
O_{tB}	$y_t g_Y(\bar{Q}\sigma^{\mu\nu}t)\tilde{\phi}B_{\mu\nu}$

Coefficient	Expected limits at 68% and 95 % CL	Observed limits at 68% and 95 % CL	Previous constraints at 95 % CL
$(C_{\phi Q}^{(3)} - C_{\phi Q}^{(1)})/\Lambda^2$	[-2.1, 1.9], [-4.6, 3.7]	[-1.0, 2.7], [-3.4, 4.3]	[-3.4, 7.5]
$C_{\phi t}/\Lambda^2$	[-3.8, 2.8], [-23, 5.0]	[-2.0, 3.6], [-27, 5.7]	[-2.0, 5.7]
C_{tB}/Λ^2	[-8.3, 8.6], [-12, 13]	[-11, 10], [-15, 15]	[-16, 43]
C_{tW}/Λ^2	[-2.8, 2.8], [-4.0, 4.1]	[-2.2, 2.5], [-3.6, 3.8]	[-0.15, 1.9]

ATLAS, ATLAS-CONF-2018-047 (2018)

Chiral Electroweak Higgs effective field theory

Alternatively treat Higgs boson as (non-SM) electroweak singlet & expand in chiral dimensions

$$\mathcal{L}_2 = -\frac{1}{2}\langle G_{\mu\nu}G^{\mu\nu}\rangle - \frac{1}{2}\langle W_{\mu\nu}W^{\mu\nu}\rangle - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \sum_{\psi=q_L,l_L,u_R,d_R,e_R} \bar{\psi} i \not{D} \psi$$

$$+\frac{v^2}{4}\,\langle D_\mu U^\dagger D^\mu U\rangle\,(1+F_U(h)) + \frac{1}{2}\partial_\mu h \partial^\mu h - V(h)$$

$$-v\left[\bar{q}_L\left(Y_u + \sum_{n=1}^{\infty} Y_u^{(n)}\left(\frac{h}{v}\right)^n\right) UP_+ q_R + \bar{q}_L\left(Y_d + \sum_{n=1}^{\infty} Y_d^{(n)}\left(\frac{h}{v}\right)^n\right) UP_- q_R\right.$$

$$\left.+\bar{l}_L\left(Y_e + \sum_{n=1}^{\infty} Y_e^{(n)}\left(\frac{h}{v}\right)^n\right) UP_- l_R + \text{h.c.}\right]$$

$$U = \exp(2i\varphi^a T^a / v)$$

At LO Higgs interactions can be expressed as SM-like interactions with different numerical coefficients

e.g. Buchalla, Capozi, Celis, Heinrich, & Scyboz, JHEP 09 (2018) 057

Kappa multipliers to Lagrangian operators

The dominant effects of new physics are in the Higgs sector in the non-linear-EFT scenario
Constrained experimentally using multiplicative κ parameters to the Higgs SM-like interactions

Production modes

$$\frac{\sigma_{\mathrm{ggH}}}{\sigma_{\mathrm{ggH}}^{\mathrm{SM}}} = \begin{cases} \kappa_{\mathrm{g}}^2(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, m_{\mathrm{H}}) \\ \kappa_{\mathrm{g}}^2 \end{cases}$$

$$\frac{\sigma_{\mathrm{VBF}}}{\sigma_{\mathrm{VBF}}^{\mathrm{SM}}} = \kappa_{\mathrm{VBF}}^2(\kappa_{\mathrm{W}}, \kappa_{\mathrm{Z}}, m_{\mathrm{H}})$$

$$\frac{\sigma_{\mathrm{WH}}}{\sigma_{\mathrm{WH}}^{\mathrm{SM}}} = \kappa_{\mathrm{W}}^2$$

$$\frac{\sigma_{\mathrm{ZH}}}{\sigma_{\mathrm{ZH}}^{\mathrm{SM}}} = \kappa_{\mathrm{Z}}^2$$

$$\frac{\sigma_{\mathrm{t\bar{t}H}}}{\sigma_{\mathrm{t\bar{t}H}}^{\mathrm{SM}}} = \kappa_{\mathrm{t}}^2$$

Detectable decay modes

$$\frac{\Gamma_{\mathrm{WW}^{(*)}}}{\Gamma_{\mathrm{WW}^{(*)}}^{\mathrm{SM}}} = \kappa_{\mathrm{W}}^2$$

$$\frac{\Gamma_{\mathrm{ZZ}^{(*)}}}{\Gamma_{\mathrm{ZZ}^{(*)}}^{\mathrm{SM}}} = \kappa_{\mathrm{Z}}^2$$

$$\frac{\Gamma_{\mathrm{b\bar{b}}}}{\Gamma_{\mathrm{b\bar{b}}}^{\mathrm{SM}}} = \kappa_{\mathrm{b}}^2$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma_{\tau^-\tau^+}^{\mathrm{SM}}} = \kappa_{\tau}^2$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{\mathrm{SM}}} = \begin{cases} \kappa_{\gamma}^2(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, \kappa_{\tau}, \kappa_{\mathrm{W}}, m_{\mathrm{H}}) \\ \kappa_{\gamma}^2 \end{cases}$$

See also talk from S. Rosati

Combination of Higgs boson measurements

Combination of many ATLAS production and decay channels constrains κ parameters

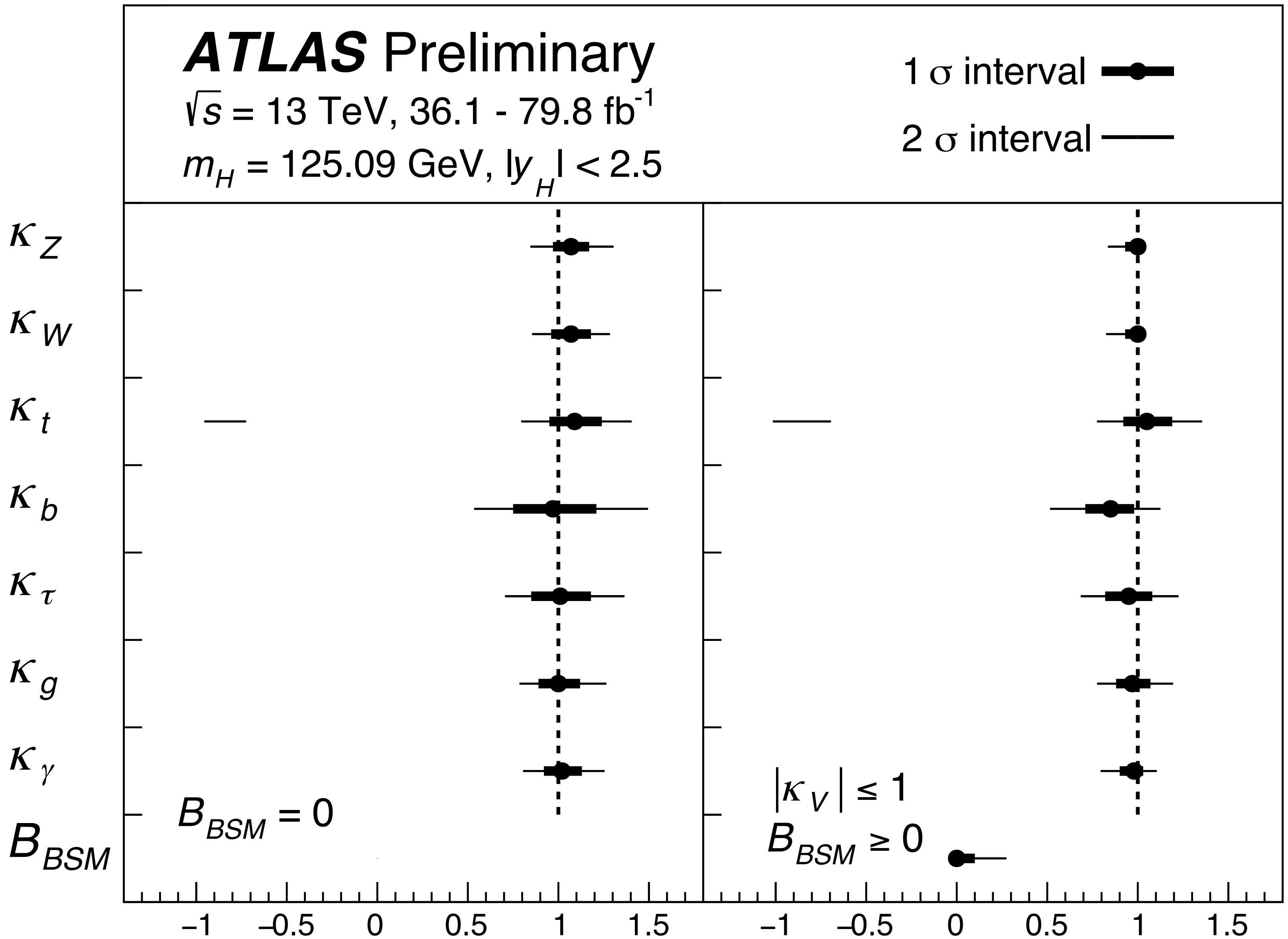
Analysis	Integrated luminosity (fb^{-1})
$H \to \gamma\gamma$ (including $t\bar{t}H$, $H \to \gamma\gamma$)	79.8
$H \to ZZ^* \to 4\ell$ (including $t\bar{t}H$, $H \to ZZ^* \to 4\ell$)	79.8
$H \to WW^* \to e\nu\mu\nu$	36.1
$H \to \tau\tau$	36.1
VH, $H \to b\bar{b}$	36.1
$H \to \mu\mu$	79.8
$t\bar{t}H$, $H \to b\bar{b}$ and $t\bar{t}H$ multilepton	36.1

$H \to \gamma\gamma$	$H \to ZZ^* \to 4\ell$	$H \to WW^*$	$H \to \tau\tau$	$H \to b\bar{b}$
$t\bar{t}H$ leptonic (3 categories) $t\bar{t}H$ hadronic (4 categories)	$t\bar{t}H$ leptonic $t\bar{t}H$ hadronic	$t\bar{t}H$ multilepton 1 ℓ + 2 τ_{had} $t\bar{t}H$ multilepton 2 opposite-sign ℓ $t\bar{t}H$ multilepton 2 same-sign ℓ (categories for 0 or 1 τ_{had}) $t\bar{t}H$ multilepton 3 ℓ (categories for 0 or 1 τ_{had}) $t\bar{t}H$ multilepton 4 ℓ		$t\bar{t}H$ 1 ℓ, boosted $t\bar{t}H$ 1 ℓ, resolved (11 categories) $t\bar{t}H$ 2 ℓ (7 categories)
VH 2 ℓ VH 1 ℓ, $p_{\text{T}}^{\ell+E_{\text{T}}^{\text{miss}}} \geq 150$ GeV VH 1 ℓ, $p_{\text{T}}^{\ell+E_{\text{T}}^{\text{miss}}} <150$ GeV VH $E_{\text{T}}^{\text{miss}}$, $E_{\text{T}}^{\text{miss}} \geq 150$ GeV VH $E_{\text{T}}^{\text{miss}}$, $E_{\text{T}}^{\text{miss}} <150$ GeV VH+VBF $p_{\text{T}}^{j1} \geq 200$ GeV VH hadronic (2 categories)	VH leptonic 0-jet, $p_{\text{T}}^{4\ell} \geq 100$ GeV 2-jet, $m_{jj} < 120$ GeV			2 ℓ, $75 \leq p_{\text{T}}^{V} < 150$ GeV, $N_{\text{jets}} = 2$ 2 ℓ, $75 \leq p_{\text{T}}^{V} < 150$ GeV, $N_{\text{jets}} \geq 3$ 2 ℓ, $p_{\text{T}}^{V} \geq 150$ GeV, $N_{\text{jets}} = 2$ 2 ℓ, $p_{\text{T}}^{V} \geq 150$ GeV, $N_{\text{jets}} \geq 3$ 1 ℓ $p_{\text{T}}^{V} \geq 150$ GeV, $N_{\text{jets}} = 2$ 1 ℓ $p_{\text{T}}^{V} \geq 150$ GeV, $N_{\text{jets}} = 3$ 0 ℓ, $p_{\text{T}}^{V} \geq 150$ GeV, $N_{\text{jets}} = 2$ 0 ℓ, $p_{\text{T}}^{V} \geq 150$ GeV, $N_{\text{jets}} = 3$
VBF, $p_{\text{T}}^{\gamma\gamma jj} \geq 25$ GeV (2 categories) VBF, $p_{\text{T}}^{\gamma\gamma jj} <25$ GeV (2 categories)	2-jet VBF, $p_{\text{T}}^{j1} \geq 200$ GeV 2-jet VBF, $p_{\text{T}}^{j1} <200$ GeV	2-jet VBF	VBF $p_{\text{T}}^{\tau\tau} > 140$ GeV ($\tau_{\text{had}}\tau_{\text{had}}$ only) VBF high-m_{jj} VBF low-m_{jj}	
2-jet, $p_{\text{T}}^{\gamma\gamma} \geq 200$ GeV 2-jet, 120 GeV$\leq p_{\text{T}}^{\gamma\gamma} <200$ GeV 2-jet, 60 GeV$\leq p_{\text{T}}^{\gamma\gamma} <120$ GeV 2-jet, $p_{\text{T}}^{\gamma\gamma} < 60$ GeV 1-jet, $p_{\text{T}}^{\gamma\gamma} \geq 200$ GeV 1-jet, 120 GeV$\leq p_{\text{T}}^{\gamma\gamma} <200$ GeV 1-jet, 60 GeV$\leq p_{\text{T}}^{\gamma\gamma} <120$ GeV 1-jet, $p_{\text{T}}^{\gamma\gamma} < 60$ GeV 0-jet (2 categories)	1-jet, $p_{\text{T}}^{4\ell} \geq 120$ GeV 1-jet, 60 GeV$\leq p_{\text{T}}^{4\ell} <120$ GeV 1-jet, $p_{\text{T}}^{4\ell} < 60$ GeV 0-jet, $p_{\text{T}}^{4\ell} < 100$ GeV	1-jet, $m_{\ell\ell} < 30$ GeV, $p_{\text{T}}^{\ell_2} < 20$ GeV 1-jet, $m_{\ell\ell} < 30$ GeV, $p_{\text{T}}^{\ell_2} \geq 20$ GeV 1-jet, $m_{\ell\ell} \geq 30$ GeV, $p_{\text{T}}^{\ell_2} < 20$ GeV 1-jet, $m_{\ell\ell} \geq 30$ GeV, $p_{\text{T}}^{\ell_2} \geq 20$ GeV 0-jet, $m_{\ell\ell} < 30$ GeV, $p_{\text{T}}^{\ell_2} < 20$ GeV 0-jet, $m_{\ell\ell} < 30$ GeV, $p_{\text{T}}^{\ell_2} \geq 20$ GeV 0-jet, $m_{\ell\ell} \geq 30$ GeV, $p_{\text{T}}^{\ell_2} < 20$ GeV 0-jet, $m_{\ell\ell} \geq 30$ GeV, $p_{\text{T}}^{\ell_2} \geq 20$ GeV	Boosted, $p_{\text{T}}^{\tau\tau} > 140$ GeV Boosted, $p_{\text{T}}^{\tau\tau} \leq 140$ GeV	

ATLAS, ATLAS-CONF-2018-031 (2018)

Combination of Higgs boson measurements

ATLAS combination constrains seven κ parameters and BSM branching fraction



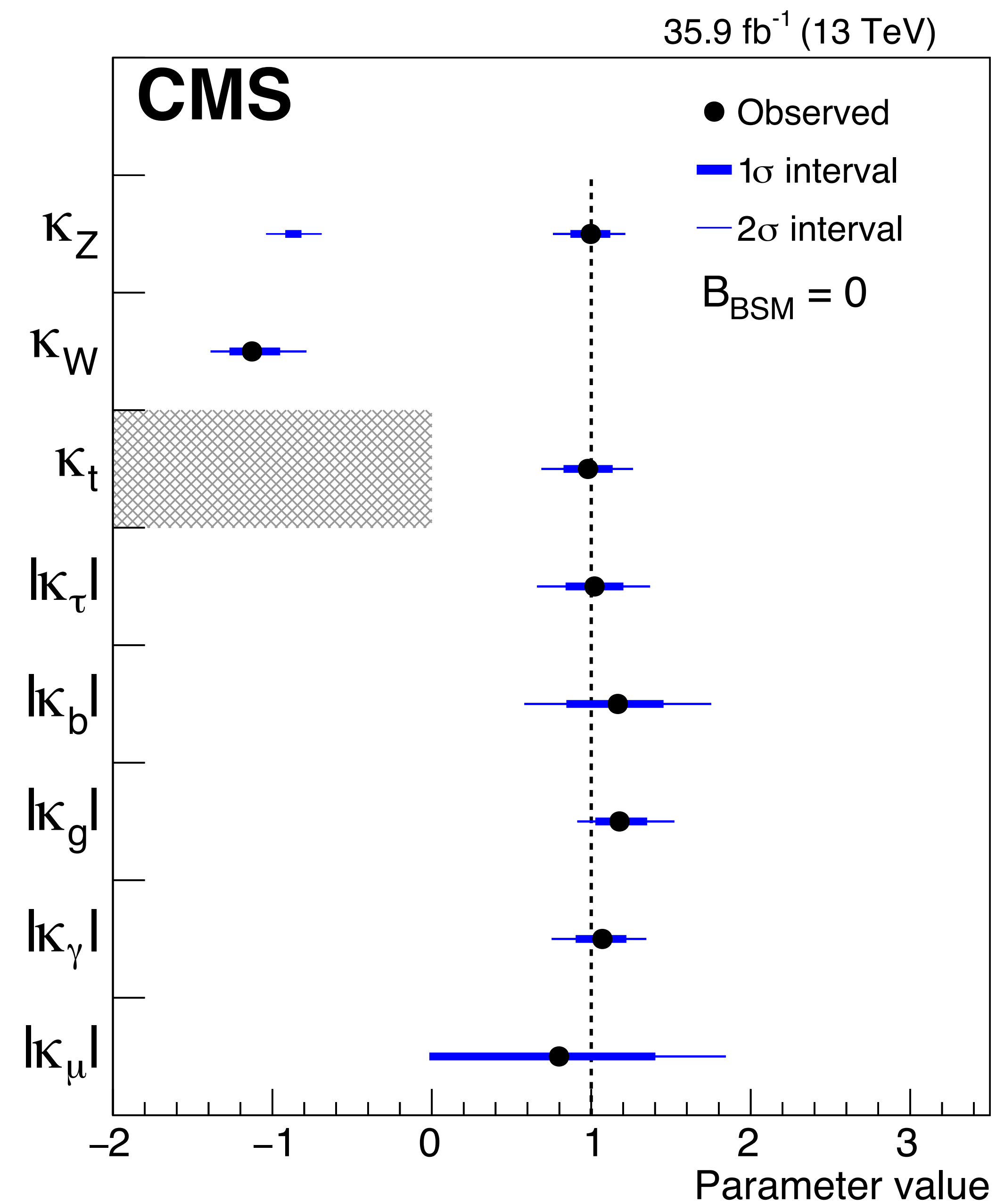
Parameter	(a) no BSM	(b) with BSM
κ_Z	1.07 ± 0.10	restricted to $\kappa_Z \leq 1$
κ_W	1.07 ± 0.11	restricted to $\kappa_W \leq 1$
κ_b	$0.97^{+0.24}_{-0.22}$	$0.85^{+0.13}_{-0.14}$
κ_t	$1.09^{+0.15}_{-0.14}$	$1.05^{+0.14}_{-0.13}$
κ_τ	$1.02^{+0.17}_{-0.16}$	0.95 ± 0.13
κ_γ	$1.02^{+0.09}_{-0.12}$	$0.98^{+0.05}_{-0.08}$
κ_g	$1.00^{+0.12}_{-0.11}$	$0.97^{+0.10}_{-0.09}$
B_{BSM}	-	< 0.26 at 95% CL

ATLAS, ATLAS-CONF-2018-031 (2018)

Combination of Higgs boson measurements

Combination of many CMS production and decay channels constrains eight κ parameters

Production and decay tags		Expected signal composition	Number of categories	Mass resolution
$H \to \gamma\gamma$, Section 3.1				
$\gamma\gamma$	Untagged	74–91% ggH	4	$\approx$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, $\approx$8% tH	2	
$H \to ZZ^{(*)} \to 4\ell$, Section 3.2				
4μ, $2e2\mu/2\mu2e$, 4e	Untagged	$\approx$95% ggH	3	$\approx$1–2%
	VBF 1, 2-jet	$\approx$11–47% VBF	6	
	VH hadronic	$\approx$13% WH, $\approx$10% ZH	3	
	VH leptonic	$\approx$46% WH	3	
	VH p_T^{miss}	$\approx$56% ZH	3	
	ttH	$\approx$71% ttH	3	
$H \to WW^{(*)} \to \ell\nu\ell\nu$, Section 3.3				
$e\mu/\mu e$	ggH 0, 1, 2-jet	$\approx$55–92% ggH, up to $\approx$15% $H \to \tau\tau$	17	$\approx$20%
	VBF 2-jet	$\approx$47% VBF, up to $\approx$25% $H \to \tau\tau$	2	
ee+$\mu\mu$	ggH 0, 1-jet	$\approx$84–94% ggH	6	
$e\mu$+jj	VH 2-jet	22% VH, 21% $H \to \tau\tau$	1	
3ℓ	WH leptonic	$\approx$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 3.4				
$e\mu$, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$	0-jet	$\approx$70–98% ggH, 29% $H \to WW$ in $e\mu$	4	$\approx$10–20%
	VBF	$\approx$35–60% VBF, 42% $H \to WW$ in $e\mu$	4	
	Boosted	$\approx$48–83% ggH, 43% $H \to WW$ in $e\mu$	4	
VH production with $H \to bb$, Section 3.5				
$Z(\nu\nu)bb$	ZH leptonic	$\approx$100% VH, 85% ZH	1	$\approx$10%
$W(\ell\nu)bb$	WH leptonic	$\approx$100% VH, $\approx$97% WH	2	
$Z(\ell\ell)bb$	Low-$p_T(V)$ ZH leptonic	$\approx$100% ZH, of which $\approx$20% ggZH	2	
	High-$p_T(V)$ ZH leptonic	$\approx$100% ZH, of which $\approx$36% ggZH	2	
Boosted H Production with $H \to bb$, Section 3.6				
$H \to bb$	$p_T(H)$ bins	$\approx$72–79% ggH	6	$\approx$10%
ttH production with $H \to$ leptons, Section 3.7.1				
$H \to WW, \tau\tau, ZZ$	2ℓss	$WW/\tau\tau \approx 4.5$, $\approx$5% tH	10	
	3ℓ	$WW : \tau\tau : ZZ \approx 15 : 4 : 1$, $\approx$5% tH	4	
	4ℓ	$WW : \tau\tau : ZZ \approx 6 : 1 : 1$, $\approx$3% tH	1	
	$1\ell+2\tau_h$	96% ttH with $H \to \tau\tau$, $\approx$6% tH	1	
	$2\ell ss+1\tau_h$	$\tau\tau : WW \approx 5 : 4$, $\approx$5% tH	2	
	$3\ell+1\tau_h$	$\tau\tau : WW : ZZ \approx 11 : 7 : 1$, $\approx$3% tH	1	
ttH production with $H \to bb$, Section 3.7.2				
$H \to bb$	$t\bar{t} \to$ jets	$\approx$83–97% ttH with $H \to bb$	6	
	$t\bar{t} \to 1\ell$+jets	$\approx$65–95% ttH with $H \to bb$, up to 20% $H \to WW$	18	
	$t\bar{t} \to 2\ell$+jets	$\approx$84–96% ttH with $H \to bb$	3	
Search for $H \to \mu\mu$, Section 3.8				
$\mu\mu$	S/B bins	56–96% ggH, 1–42% VBF	15	$\approx$1–2%
Search for invisible H decays, Section 3.9				
$H \to$ invisible	VBF	52% VBF, 48% ggH	1	
	ggH + $\geq$ 1 jet	80% ggH, 9% VBF	1	
	VH hadronic	54% VH, 39% ggH	1	
	ZH leptonic	$\approx$100% ZH, of which 21% ggZH	1	



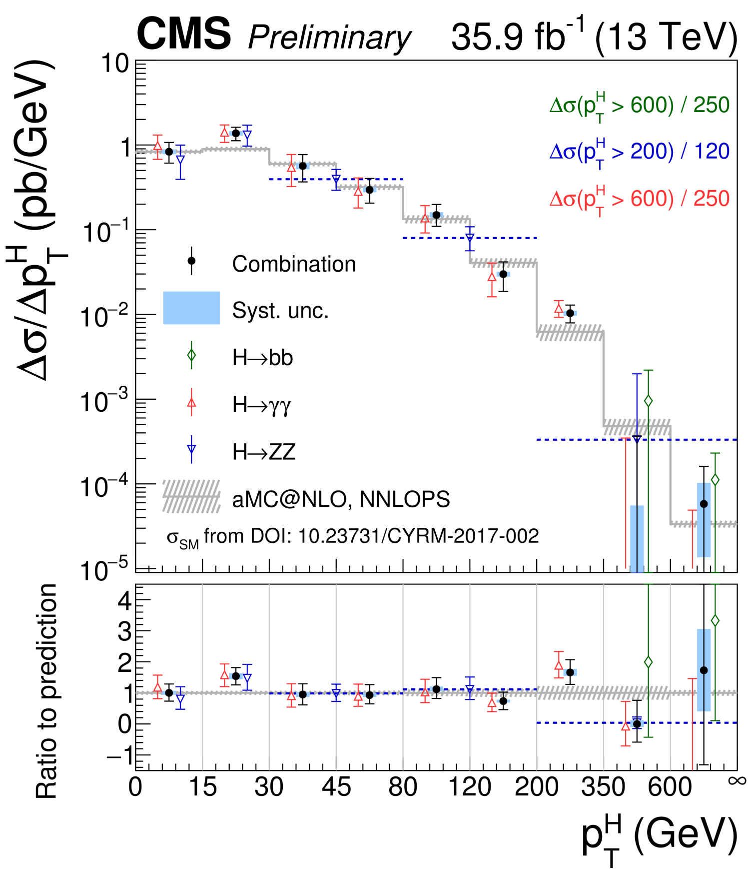
Also constrains BSM branching fraction & invisible decay

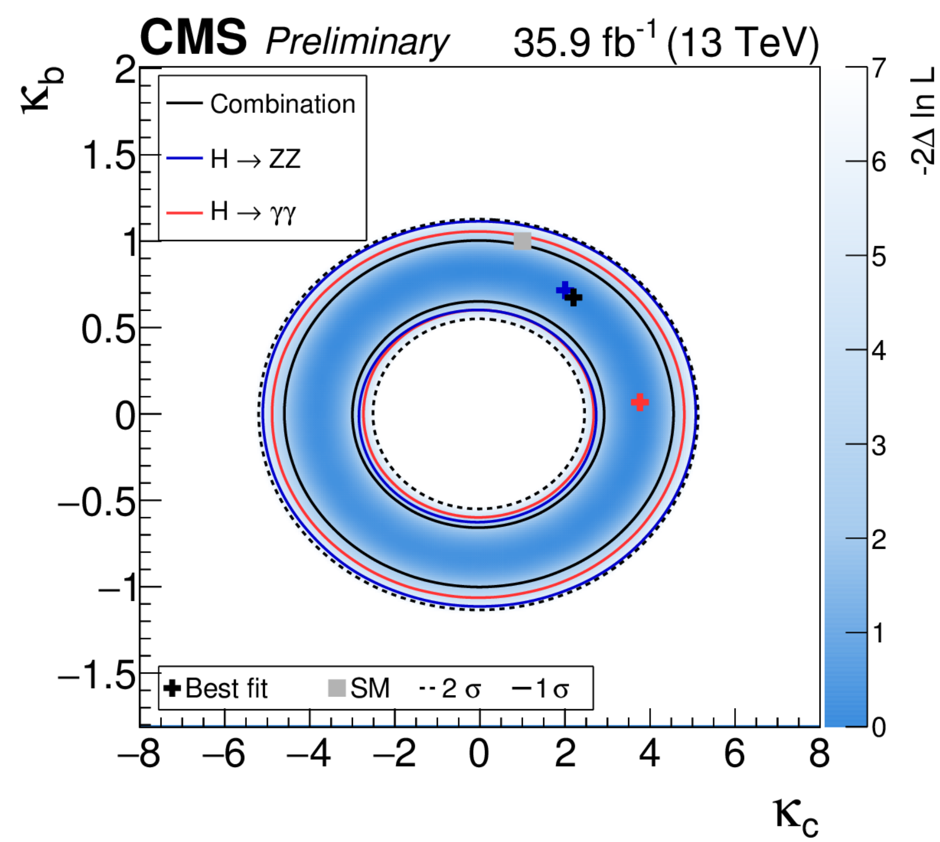
CMS, 1809.10733 (2018)

Combination of Higgs boson measurements

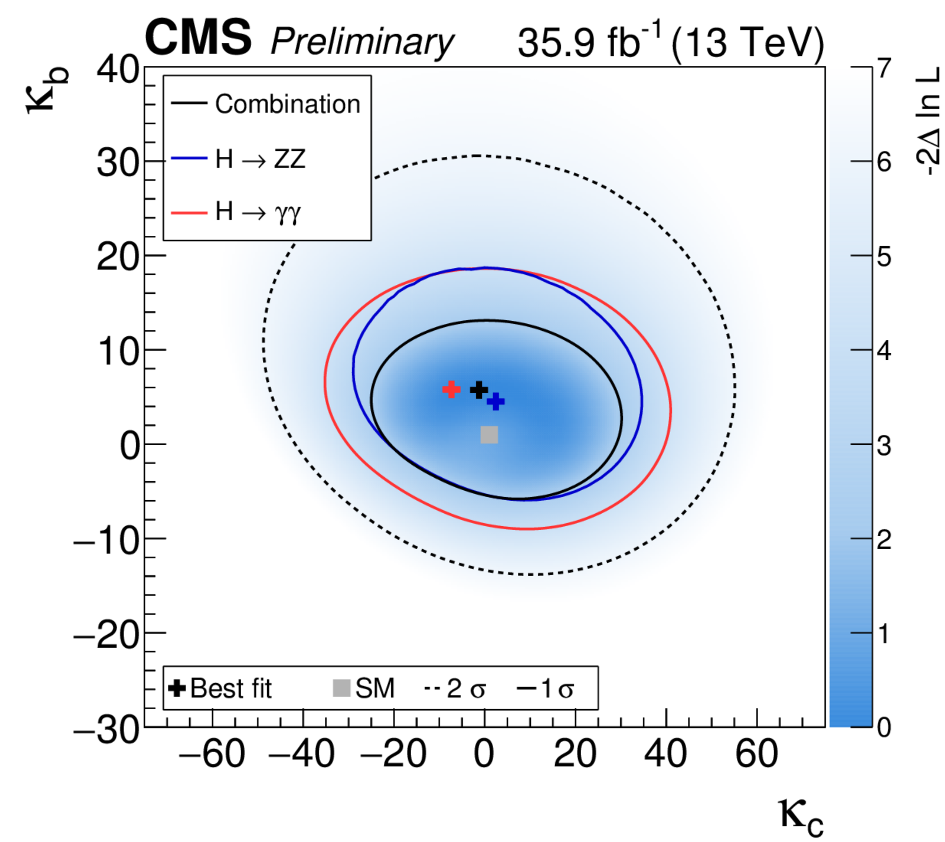
Combination of CMS differential cross sections used to study pairs of κ parameters

- Low p_T^H sensitive to b & c quark loops in gluon fusion
- Constraints on pairs of parameters dominated by rate (through total width)





Rate + shape



Shape only

$-18.0 < \kappa_c < 22.9$

Also study ttH + ggF and ttH + bbH pairs of coupling modifiers

CMS, CMS PAS HIG-17-028 (2018)

See also talk from A. de Wit

Summary

SM effective field theory operators now broadly used to interpret Higgs, Electroweak and top measurements at the LHC

Extensive combination frameworks applied to Higgs measurements to constrain effective couplings

These are the ingredients to a global SM EFT fit

Global fit will require expanded coordination of experimental combination across measurements and theoretical feedback on fit strategies and uncertainties