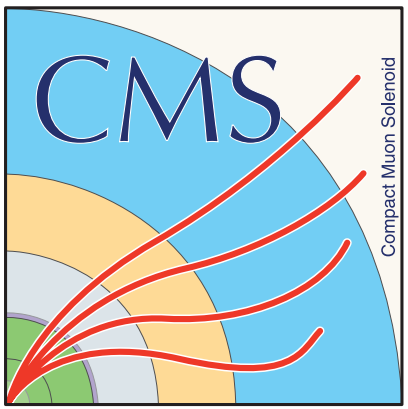
NEW PHYSICS SEARCHES IN SM PROCESSES AT THE LHC.

SM@LHC 2017



James Robinson

on behalf of the ATLAS and CMS collaborations

Amsterdam, 2nd–5th May 2017

HELMHOLTZ ASSOCIATION

DESY

Introduction

What can we get from Standard Model measurements?

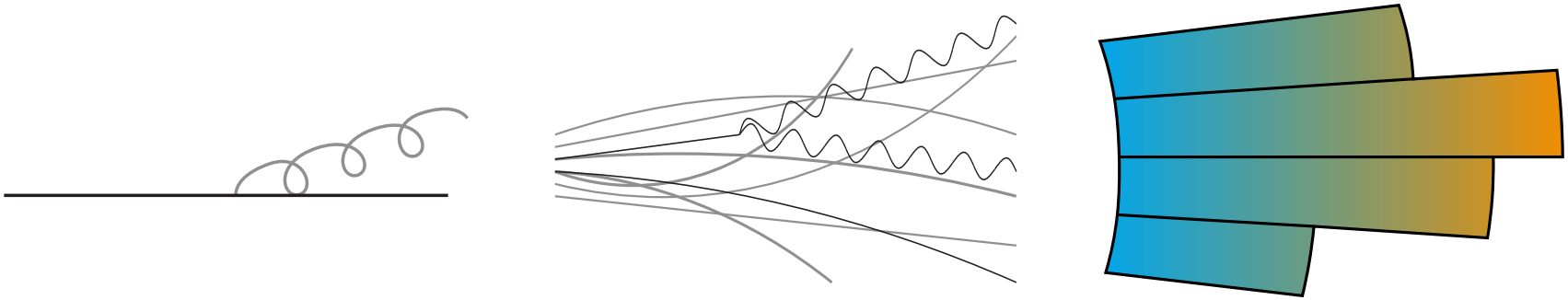
- precision tests of our modelling of SM processes
- direct test for anomalies $\rightarrow$ indirect evidence for BSM physics
- powerful constraints on generic high-scale searches

- Fill in gaps from existing direct BSM searches:
  - low sensitivity, less well-motivated search topologies, kinematic signatures too close to SM
- Provide data ready to constrain new BSM searches:
  - Data able to constrain novel BSM search modes
  - Precursor to new targeted analysis, if needed

Minimise model dependence wherever possible

Fundamental challenge to re-interpretation

Theoretical predictions → Interface to MC or non-perturbative corrections → Exact analysis details: object selection, reconstruction, etc.



parton-level jet | particle-level jet | reconstruction-level jet

Large extrapolation uncertainties. Non-perturbative effects. ← Carefully unfold detector resolution and efficiency effect ← Experimental measurements

Publish particle-level measurements in well-defined fiducial region

Fiducial measurements

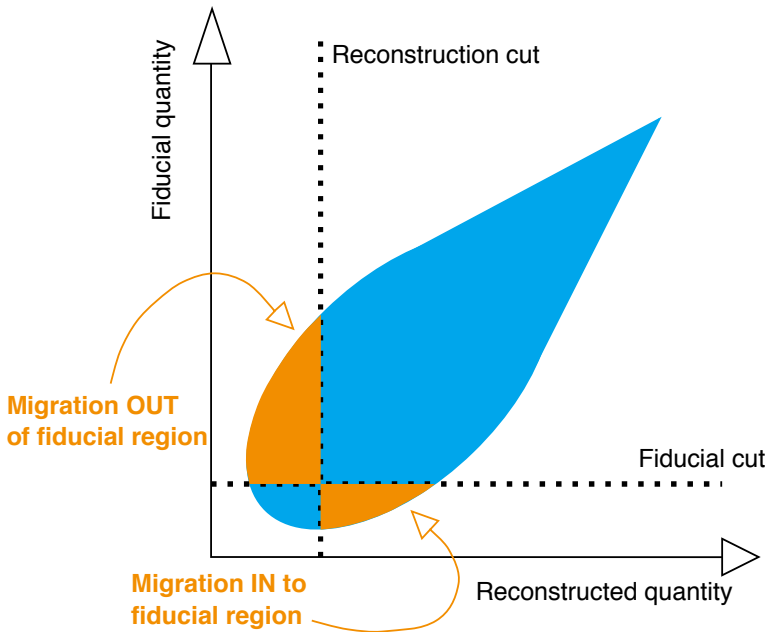
Well-defined fiducial region:

Phase space well-modelled, high efficiency, minimal extrapolation

Unfold measured data to correct for:

- background contamination
- migrations due to efficiency and resolution effects
  $\rightarrow$ these can be in and out or within the fiducial region

$$\sigma_i^{\text{particle-level}} = \sum_j \frac{\left(N_{\text{data}} - N_{\text{bkg}}\right)_j \varepsilon_j^{\text{reco-level}} M_{ij}}{\mathcal{L} \varepsilon_i^{\text{particle-level}}}$$



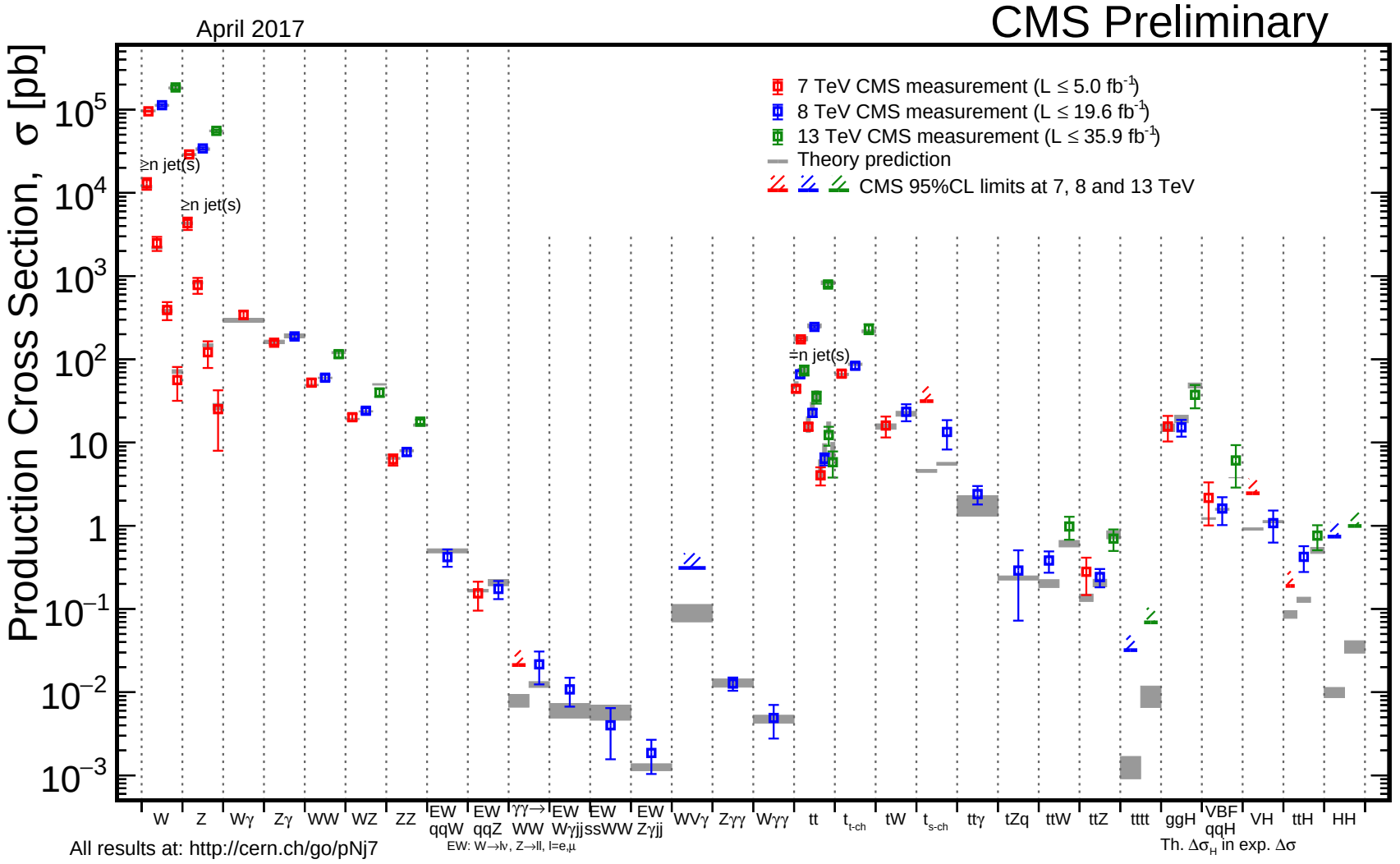
Reduce dependency of resulting measurement on prior assumptions

How do LHC experiments provide data?

- Published on HepData
  - fully-corrected data measurements with uncertainties
  - correlations between bins (and other auxiliary information)
- Published through Rivet
  - analysis routine used by experimental team
    → avoid ambiguity in observable definitions, jet algorithms etc.
  - automatic integration with values published in HepData

ATLAS and CMS aiming to increase proportion of results available

What has been measured at the LHC?



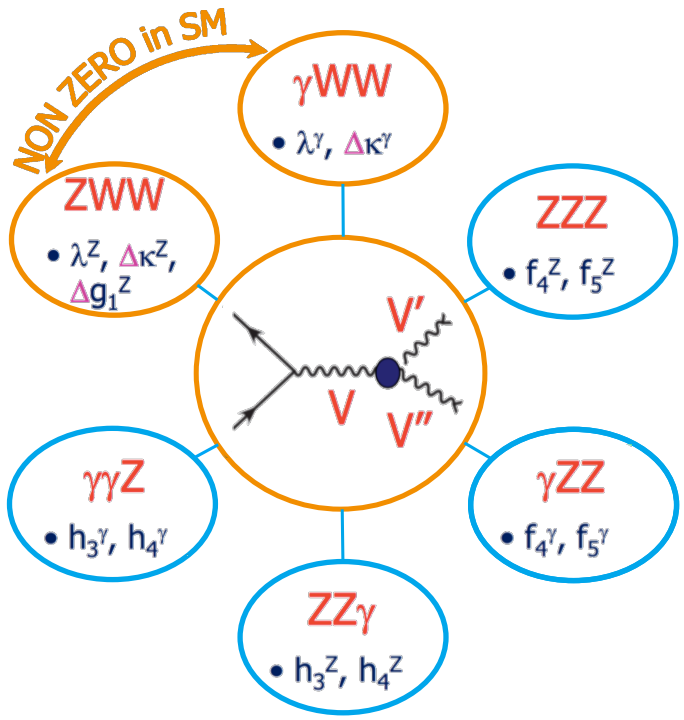
Full information on public webpages for ATLAS and CMS results

Accessing new physics through the Standard Model

- Electroweak measurements
  - constrain anomalous triple and quartic gauge couplings: a(T/Q)GC
  - direct connection to mechanism of EW symmetry breaking
- Top, B-physics and jet measurements
  - sensitivity to SUSY & exotic physics
- Higgs measurements
  - constrain BSM Higgs couplings
  - potential additional scalar particles
  - Higgs portal to dark matter

Anomalous electroweak couplings

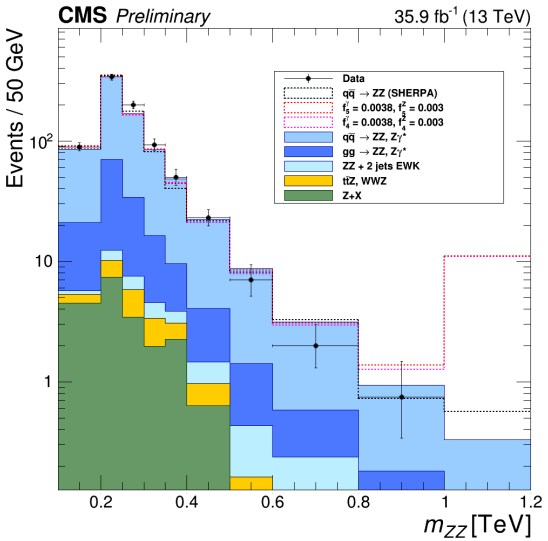
- Anomalous triple/quartic gauge couplings can modify total production rate
- Variety of final states to probe, sensitive to different couplings
- aQGCs parameterised with EFT: dimension-8 coefficients



$$\mathcal{L}_{QGC} = e^2 \left[g_1^{\gamma\gamma} A^\mu A^\nu W_\mu^- W_\nu^+ - g_2^{\gamma\gamma} A^\mu A_\mu W^{-\nu} W_\nu^+ \right]$$
$$+ e^2 \frac{c_w}{s_w} \left[g_1^{\gamma Z} A^\mu Z^\nu \left(W_\mu^- W_\nu^+ + W_\mu^+ W_\nu^- \right) - 2 g_2^{\gamma Z} A^\mu Z_\mu W^{-\nu} W_\nu^+ \right]$$
$$+ e^2 \frac{c_w^2}{s_w^2} \left[g_1^{ZZ} Z^\mu Z^\nu W_\mu^- W_\nu^+ - g_2^{ZZ} Z^\mu Z_\mu W^{-\nu} W_\nu^+ \right]$$
$$+ \frac{e^2}{2 s_w^2} \left[g_1^{WW} W^{-\mu} W^{+\nu} W_\mu^- W_\nu^+ - g_2^{WW} \left(W^{-\mu} W_\mu^+ \right)^2 \right] + \frac{e^2}{4 s_w^2 c_w^4} h^{ZZ} (Z^\mu Z_\mu)^2$$

Anomalous Triple Gauge Couplings

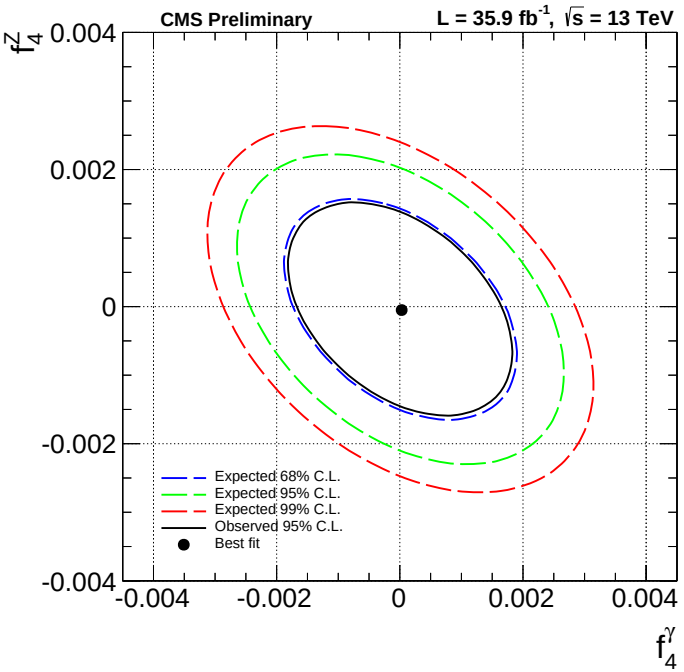
CMS: ZZ $\rightarrow 4\ell$ [13 TeV]

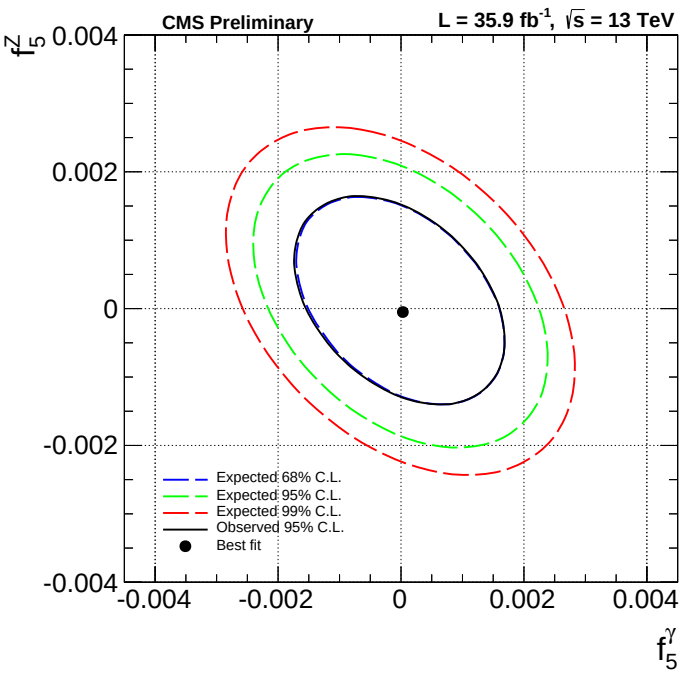


- Probe ZZZ and ZZγ couplings
- CP-violating (f_4^V) and CP-conserving (f_5^V)

$-1.17e{-}3 < f_4^Z < 1.1e{-}3$, $-1.00e{-}3 < f_5^Z < 1.25e{-}3$,

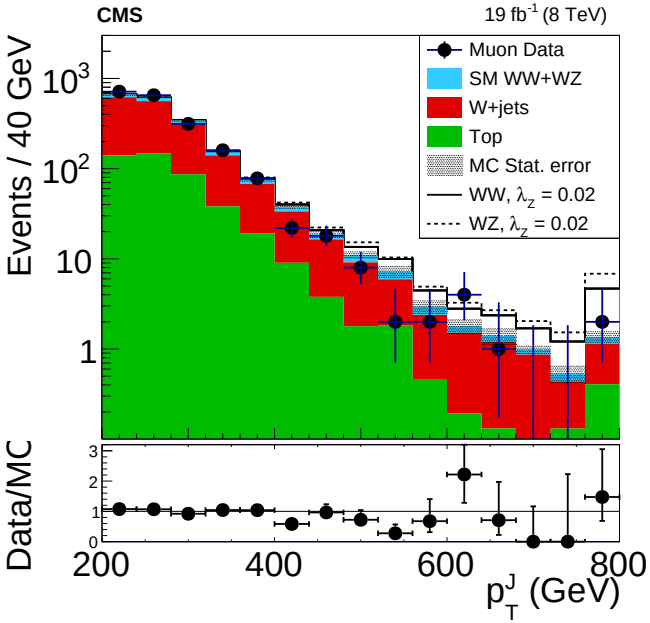
$-1.33e{-}3 < f_4^\gamma < 1.32e{-}3$ and $-1.23e{-}3 < f_5^\gamma < 1.30e{-}3$





CMS: Boosted WW/WZ [8 TeV]

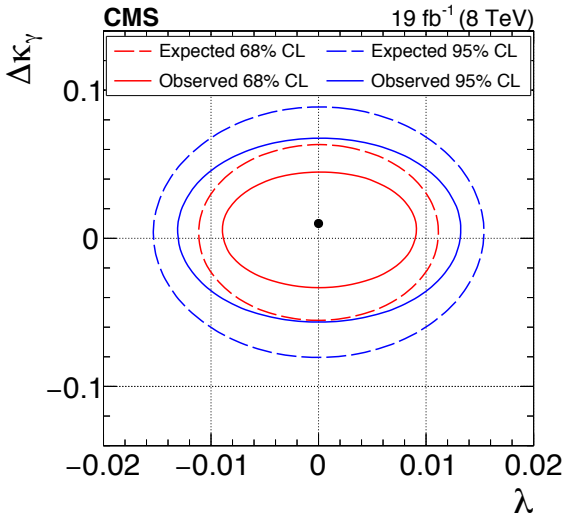
sub. PLB, arXiv:1703.06095

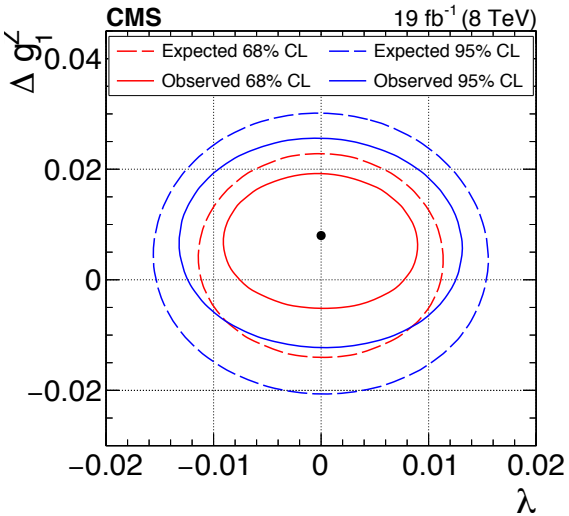


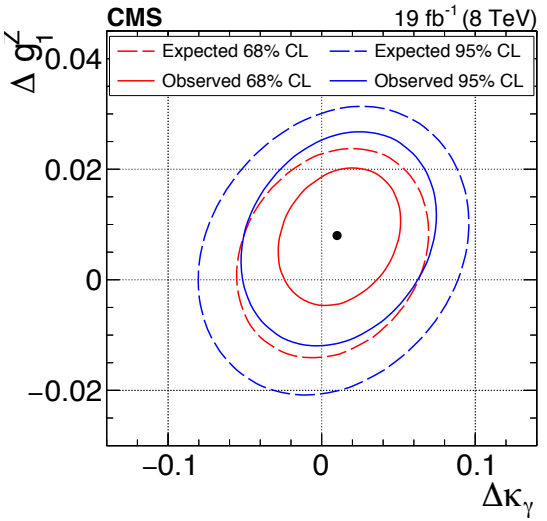
- Leptonic W, boosted hadronic W/Z
- Limits on aTGCs at WWγ (λ, $\Delta\kappa_\gamma$) and WWZ (λ, Δg_1^Z) vertices

$-0.011 < \lambda < 0.011$, $-0.044 < \Delta\kappa_\gamma < 0.063$ and

$-0.0087 < \Delta g_1^Z < 0.024$







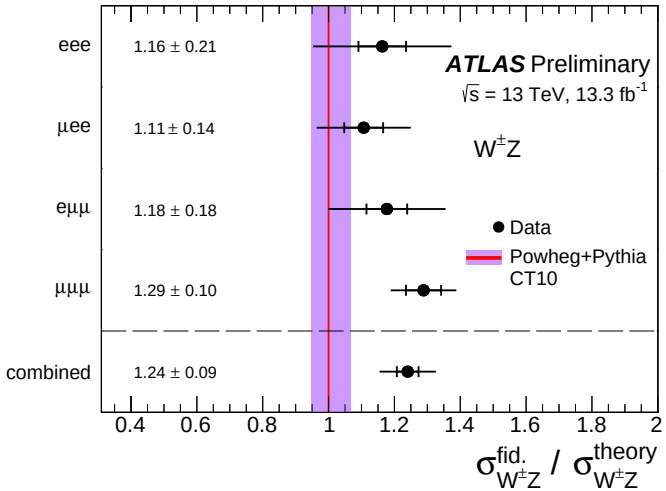
ATLAS: Inclusive WZ [13 TeV]

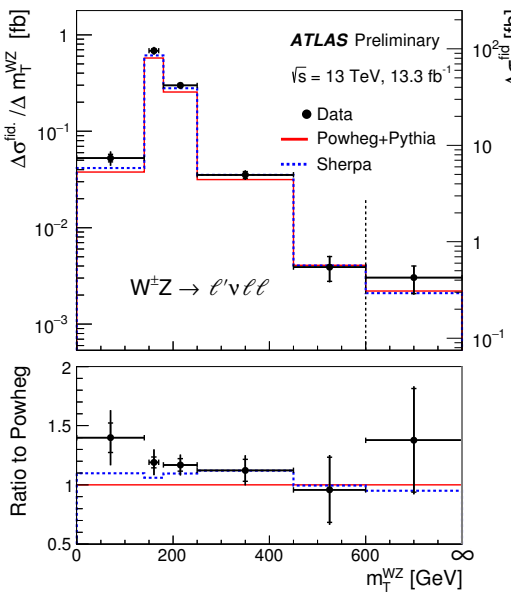
ATLAS-CONF-2016-043

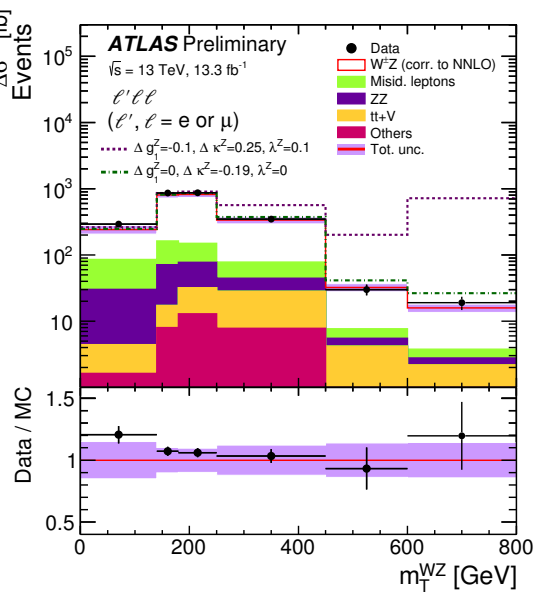
- Fiducial & total cross sections (extrapolated)
- Leptonic channels only
- WWZ (Δg_1^Z, λ^Z, $\Delta\kappa^Z$) limits from m_T^{WZ}

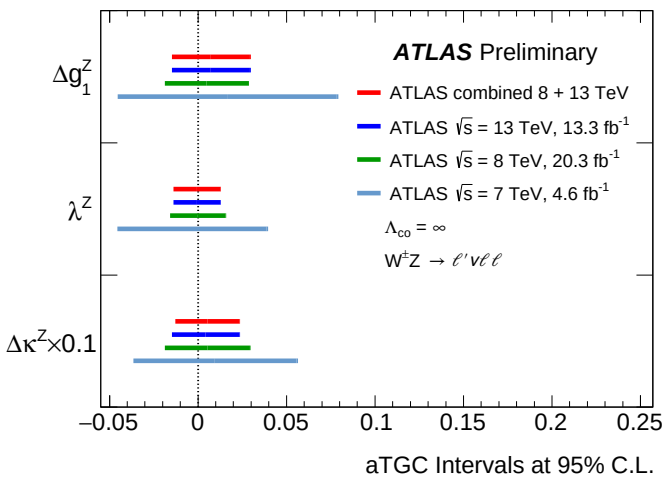
$-0.016 < \lambda < 0.015$, $-0.15 < \Delta\kappa^Z < 0.26$ and

$-0.016 < \Delta g_1^Z < 0.036$

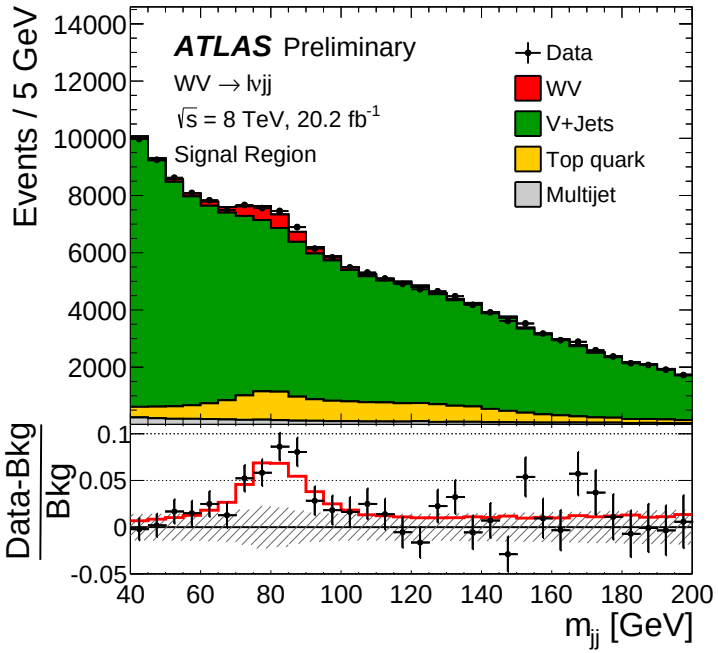


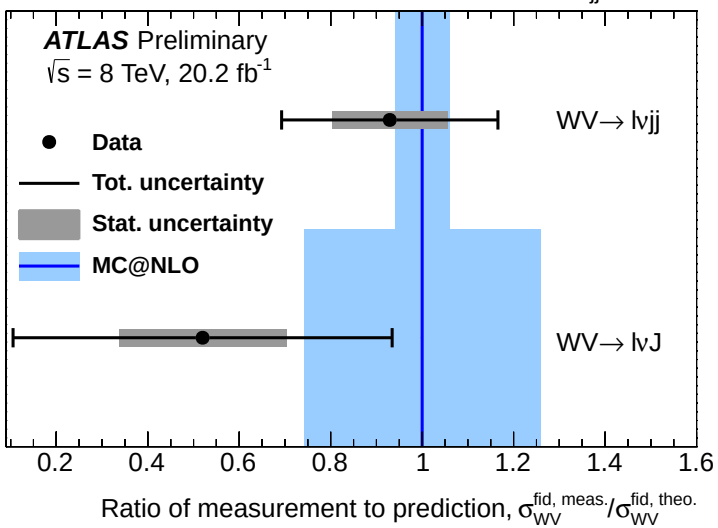






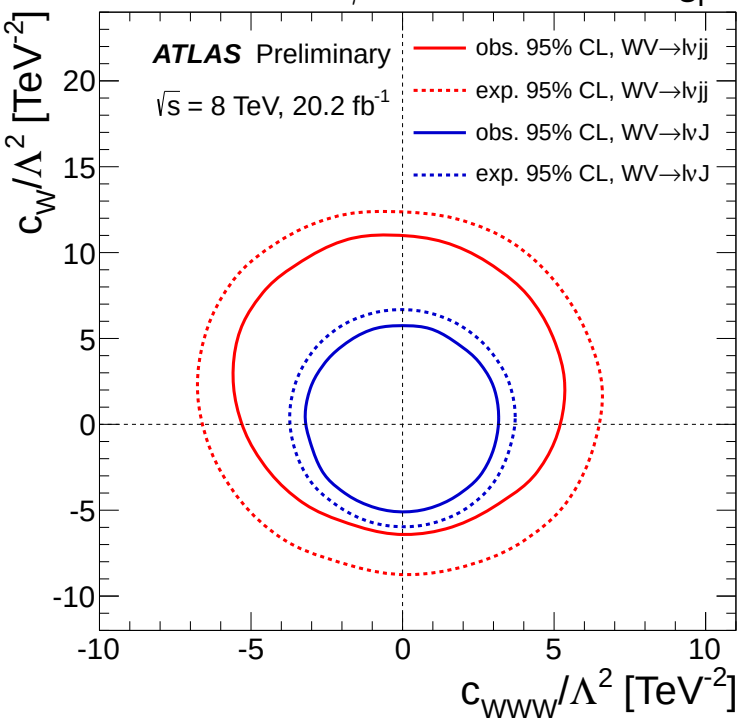
ATLAS: WV [8 TeV]





- Leptonic W, hadronic V boosted/resolved
- Fiducial cross sections: 58 ± 15 fb (boosted), 209 ± 53 fb (resolved)
- EFT: $c_W \propto \Delta g_1^Z$, $c_{WWW} \propto \lambda$

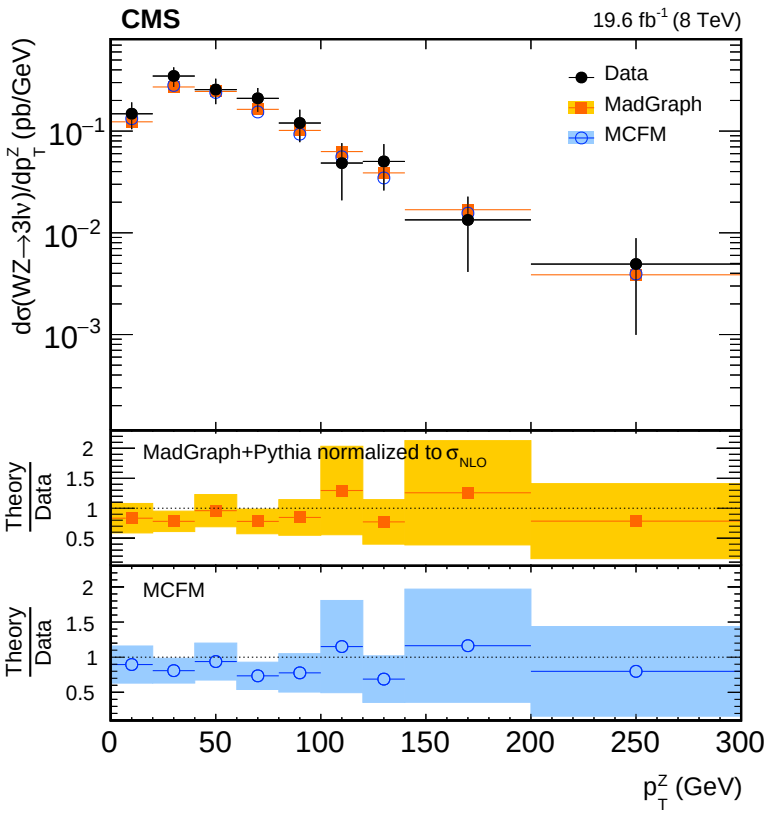
$-0.013 < \lambda < 0.013$, $-0.061 < \Delta\kappa_\gamma < 0.064$ and $-0.021 < \Delta g_1^Z < 0.024$

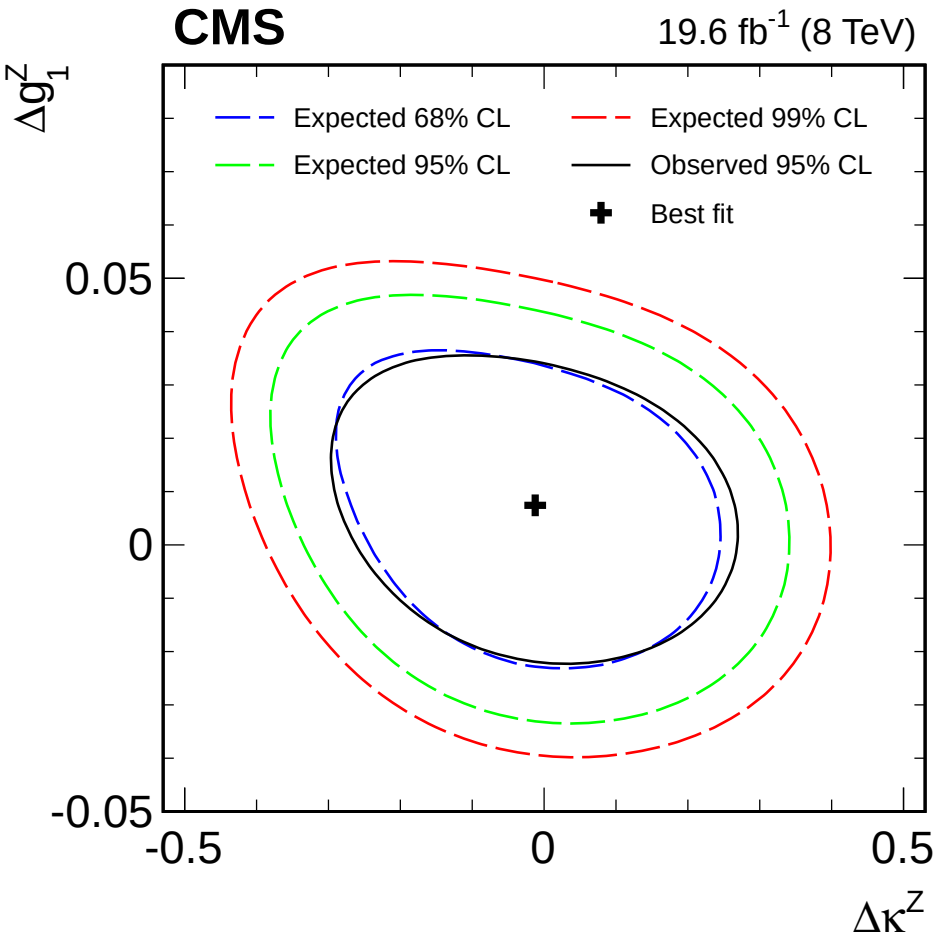


CMS: Inclusive WZ [7, 8 TeV]

acc. EPJC, arXiv:1609.05721

- Fiducial differential cross-sections





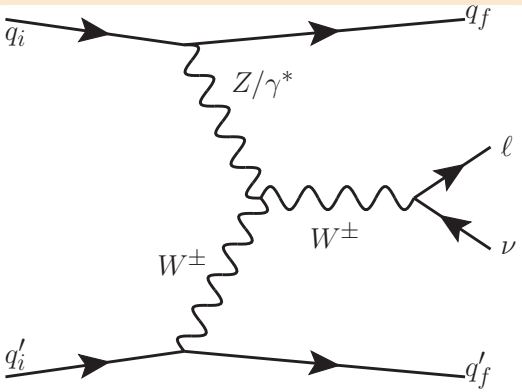
- Anomalous WWZ limits from high p_T^Z behaviour

$-0.018 < \lambda < 0.016$, $-0.21 < \Delta\kappa^Z < 0.25$ and $-0.018 < \Delta g_1^Z < 0.035$

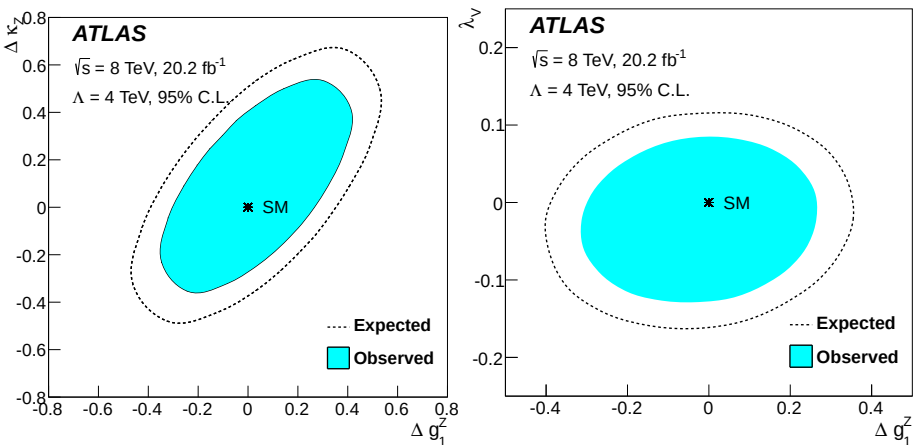
ATLAS: VBF Wjj [7, 8 TeV]

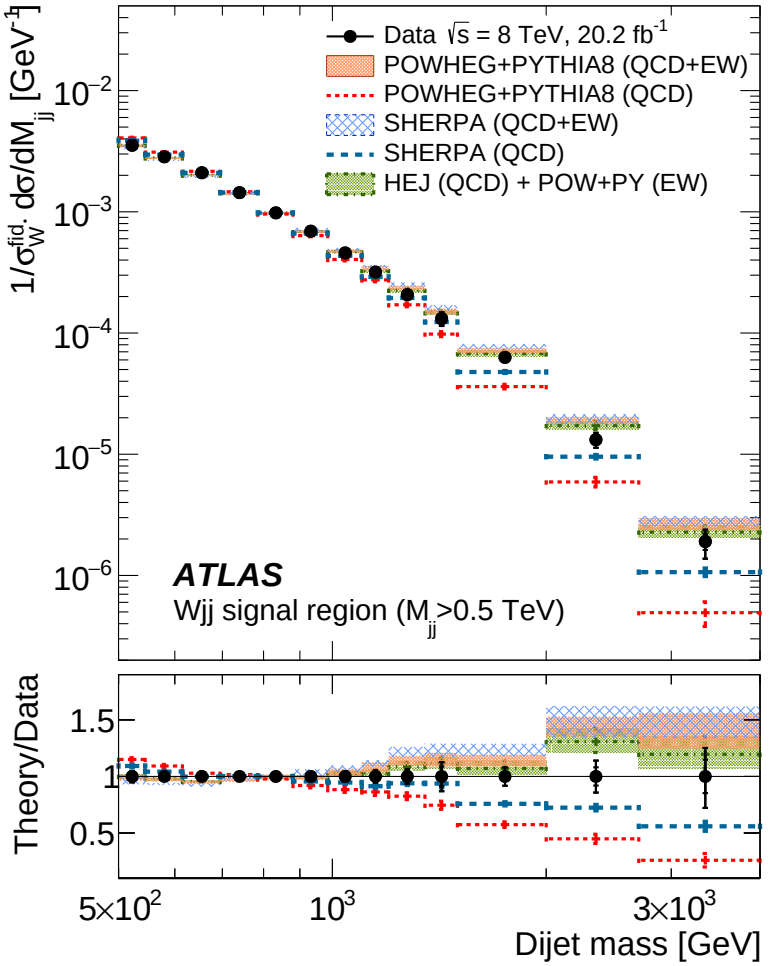
sub. EPJC, arXiv:1703.04362

First observation of EW W production



- Complementary constraints to diboson: WWγ , WWZ



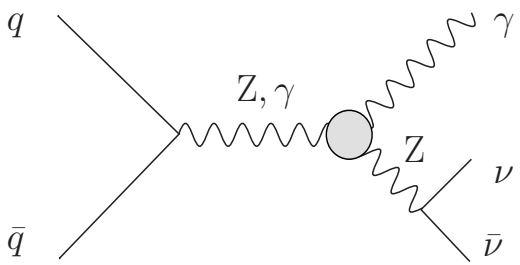


$-0.053 < \lambda < 0.042$, $-0.15 < \Delta\kappa^Z < 0.16$

and $-0.13 < \Delta g_1^Z < 0.12$

CMS: $Z\gamma \rightarrow \nu\nu\gamma$ [8 TeV]

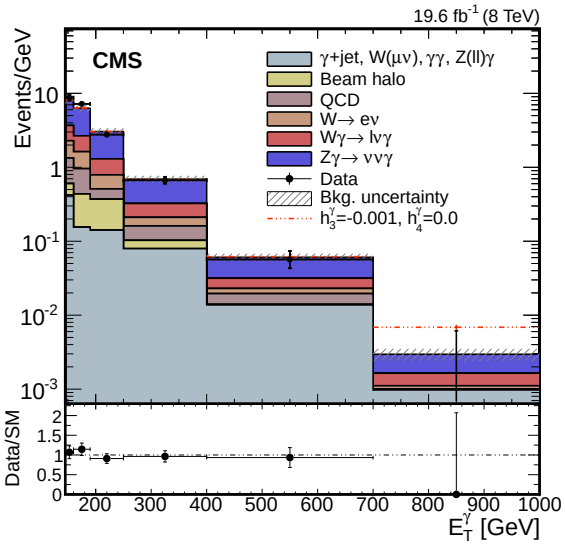
PLB 760 (2016) 448, arXiv:1602.07152

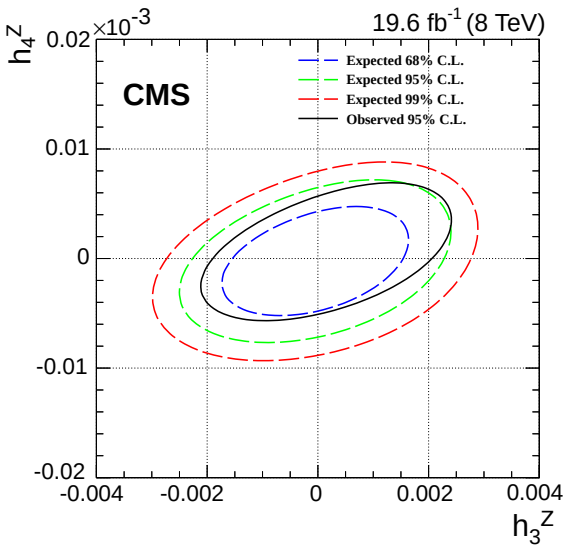


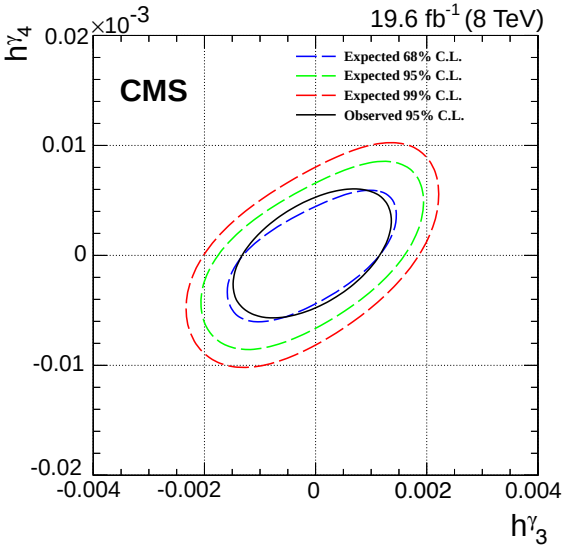
- Total cross section for $Z\gamma$ production
- aTGC limits on $ZZ\gamma$ (h_3^Z, h_4^Z) and $Z\gamma\gamma$ (h_3^γ, h_4^γ) from high E_T^γ

$-1.5e{-}3 < h_3^Z < 1.6e{-}3$, $-3.9e{-}6 < h_4^Z < 4.5e{-}6$,

$-1.1e{-}3 < h_3^\gamma < 0.9e{-}3$ and $-3.8e{-}6 < h_4^\gamma < 4.3e{-}6$



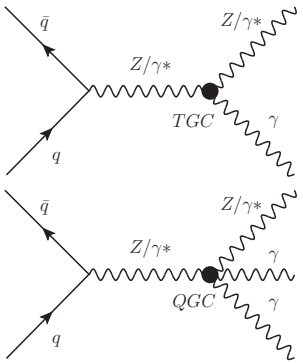




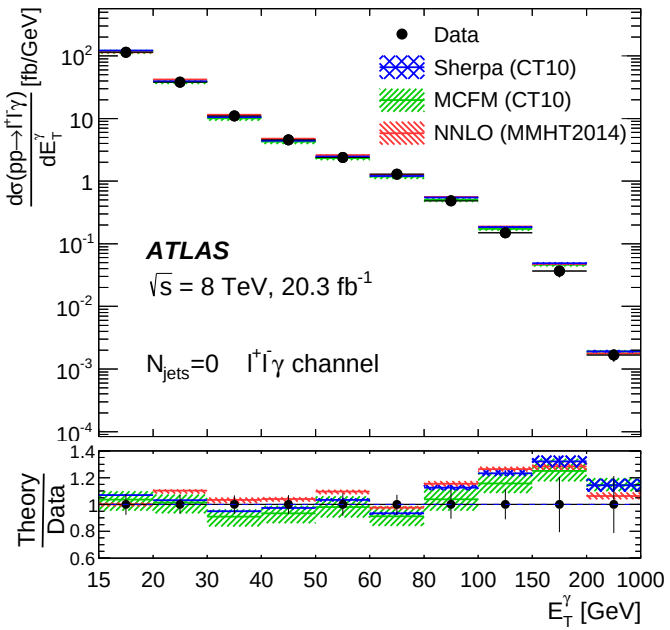
ATLAS: $Z\gamma$ and $Z\gamma\gamma$

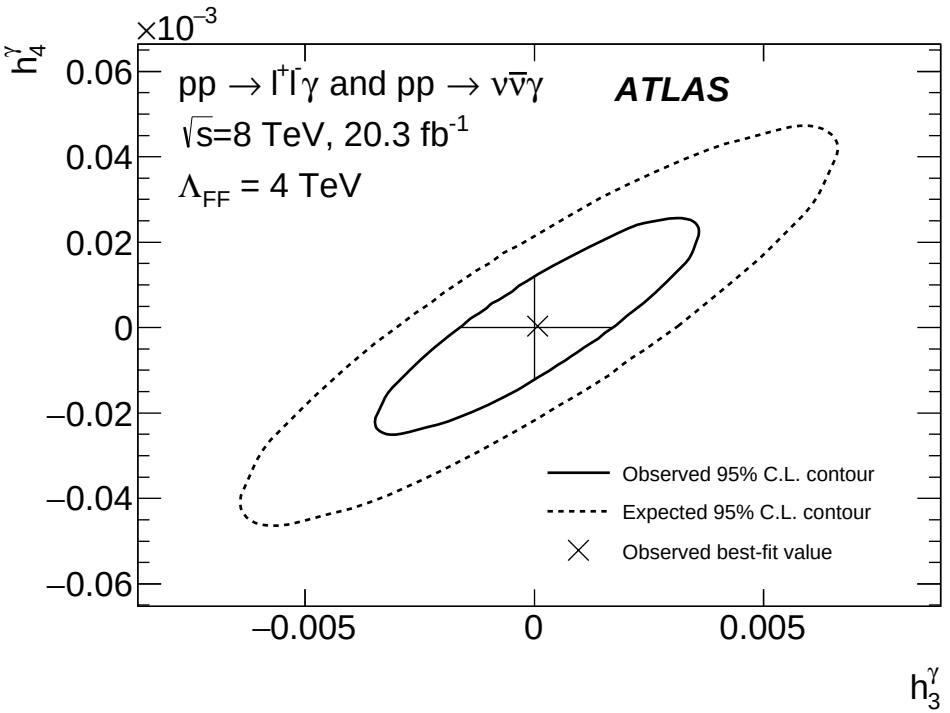
PRD 93, 112002 (2016), arXiv:1604.05232

- Inclusive ($N_{jets} \geq 0$) and exclusive ($N_{jets} = 0$) cross sections
- High E_T^γ (aTGC) and $m_{\gamma\gamma}$ (aQGC)
- $Z\gamma\gamma$ (h_3^γ, h_4^γ) limits shown here



Process	$pp \to \nu\bar{\nu}\gamma$ and $pp \to \ell^+\ell^-\gamma$	
Λ	∞	
	Observed 95% C.L.	Expected 95% C.L.
h_3^γ	$[-9.5, 9.9] \times 10^{-4}$	$[-1.8, 1.8] \times 10^{-3}$
h_3^Z	$[-7.8, 8.6] \times 10^{-4}$	$[-1.5, 1.5] \times 10^{-3}$
h_4^γ	$[-3.2, 3.2] \times 10^{-6}$	$[-6.0, 5.9] \times 10^{-6}$
h_4^Z	$[-3.0, 2.9] \times 10^{-6}$	$[-5.5, 5.4] \times 10^{-6}$
Λ	4 TeV	
	Observed 95% C.L.	Expected 95% C.L.
h_3^γ	$[-1.6, 1.7] \times 10^{-3}$	$[-3.0, 3.1] \times 10^{-3}$
h_3^Z	$[-1.3, 1.4] \times 10^{-3}$	$[-2.5, 2.6] \times 10^{-3}$
h_4^γ	$[-1.2, 1.1] \times 10^{-5}$	$[-2.2, 2.1] \times 10^{-5}$
h_4^Z	$[-1.0, 1.0] \times 10^{-5}$	$[-1.9, 1.9] \times 10^{-5}$

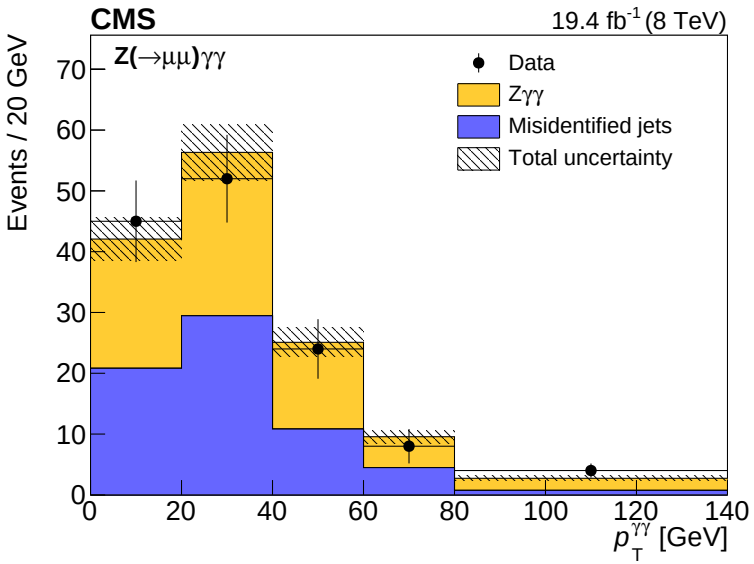


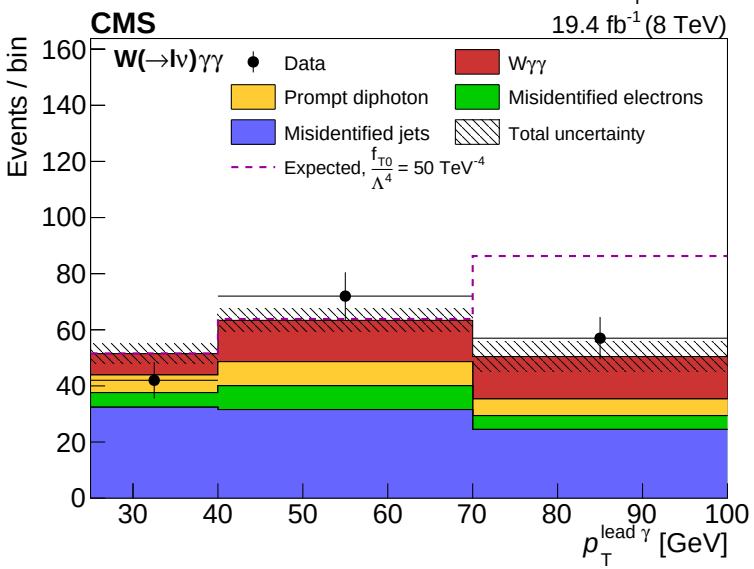


Anomalous Quartic Gauge Couplings

CMS: $W\gamma\gamma$ & $Z\gamma\gamma$ cross sections [8 TeV]

sub. JHEP, arXiv:1704.00366





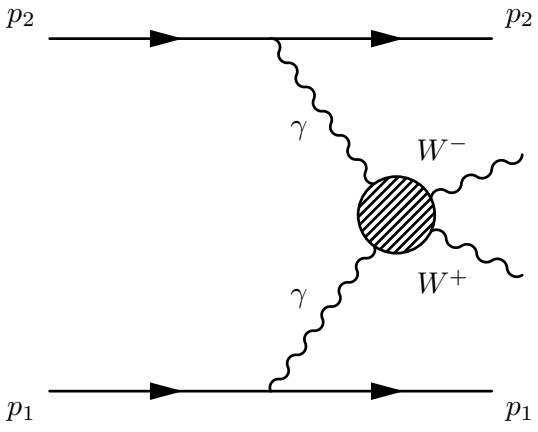
$Z\gamma\gamma$ observation: 5.9σ

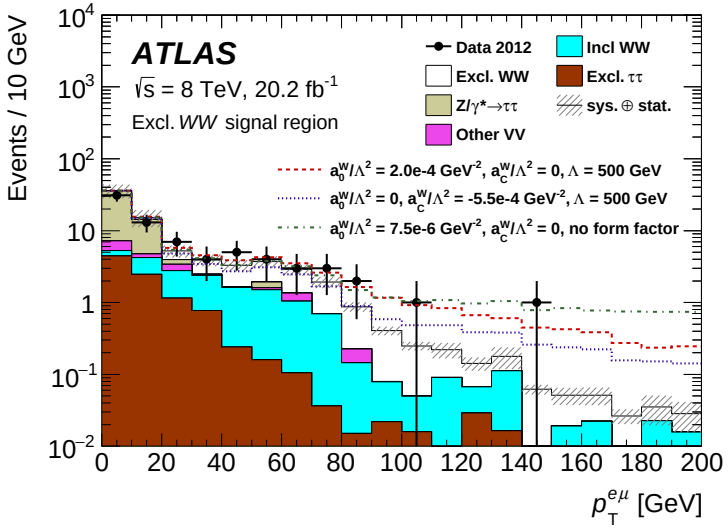
- Fiducial cross sections:
  4.9 ± 2.1 fb ($W\gamma\gamma$), 12.7 ± 2.3 fb ($Z\gamma\gamma$)
- Constrain five of 14 dimension-8 operators affecting $WW\gamma\gamma$

$W\gamma\gamma$	Expected (TeV^{-4})	Observed (TeV^{-4})
$f_{M,2}/\Lambda^4$	$[-549, 531]$	$[-701, 683]$
$f_{M,3}/\Lambda^4$	$[-916, 950]$	$[-1170, 1220]$
$f_{T,0}/\Lambda^4$	$[-26.5, 27.0]$	$[-33.5, 34.0]$
$f_{T,1}/\Lambda^4$	$[-34.5, 34.8]$	$[-44.3, 44.8]$
$f_{T,2}/\Lambda^4$	$[-74.6, 73.7]$	$[-93.8, 93.2]$

ATLAS: exclusive $\gamma\gamma \rightarrow W^+W^-$ [8 TeV]

PRD 94 (2016) 032011, arXiv:1607.03745



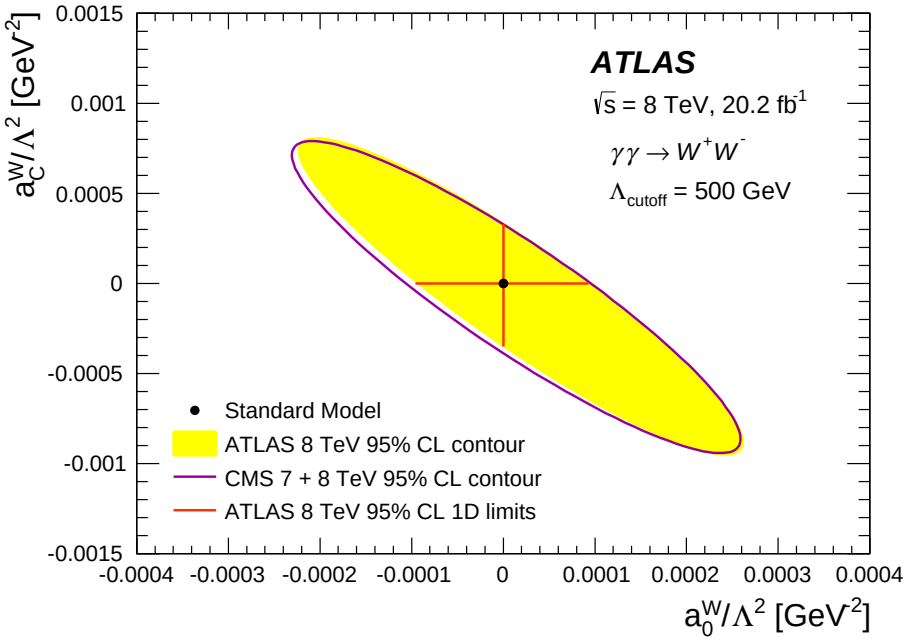


Higgs cross section

$\sigma^{\text{total}}_{\text{exclusive Higgs}} < 1.2$ pb

Evidence for exclusive production: 3.0σ

› Constraints on $WW\gamma\gamma$ aQGCs (dim.-6 operators: a_0^W and a_C^W)

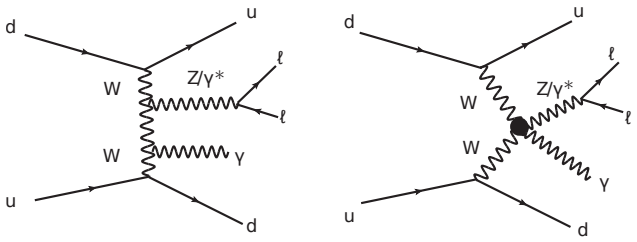


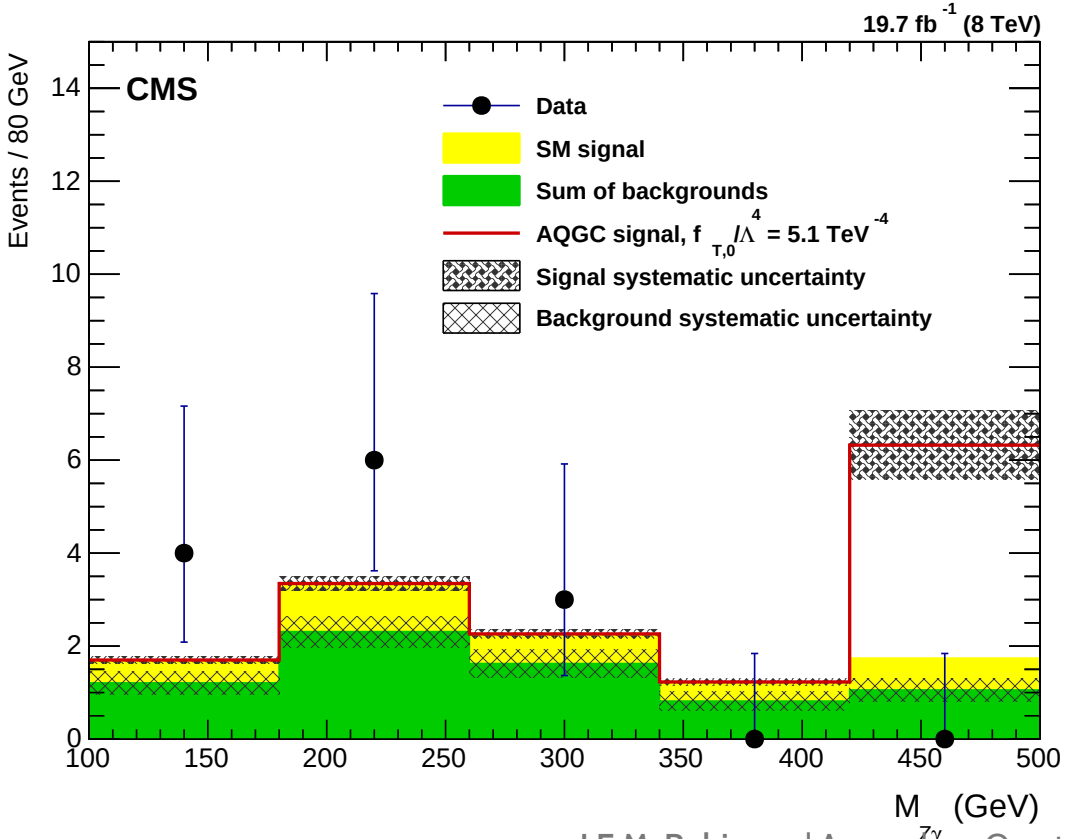
Coupling	Λ_{cutoff}	Observed allowed range $[GeV^{-4}]$	Expected allowed range $[GeV^{-4}]$
$f_{M,0}/\Lambda^4$	500 GeV	$[-3.7 \times 10^{-9},\ 3.6 \times 10^{-9}]$	$[-3.5 \times 10^{-9},\ 3.4 \times 10^{-9}]$
$f_{M,1}/\Lambda^4$	500 GeV	$[-13 \times 10^{-9},\ 14 \times 10^{-9}]$	$[-12 \times 10^{-9},\ 13 \times 10^{-9}]$
$f_{M,0}/\Lambda^4$	∞	$[-6.6 \times 10^{-11},\ 6.6 \times 10^{-11}]$	$[-5.8 \times 10^{-11},\ 6.2 \times 10^{-11}]$
$f_{M,1}/\Lambda^4$	∞	$[-24 \times 10^{-11},\ 25 \times 10^{-11}]$	$[-23 \times 10^{-11},\ 23 \times 10^{-11}]$

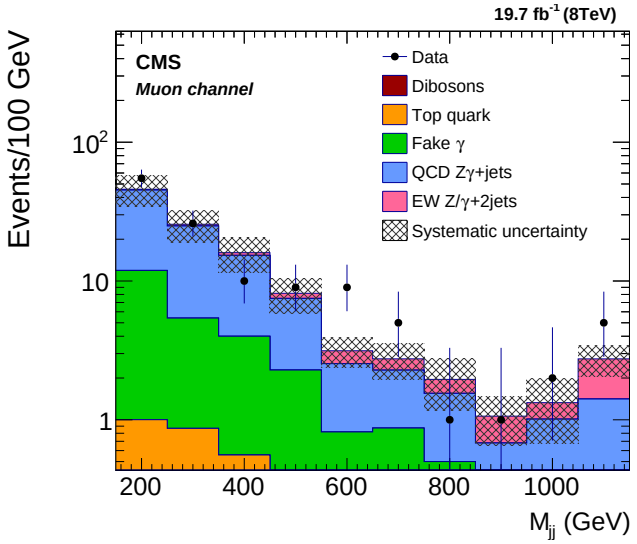
CMS: $Z\gamma jj$ cross sections [8 TeV]

sub. PLB, arXiv:1702.03025

- Leptonic decays (e or μ)
- EW $Z\gamma jj$ cross section: $1.86^{+0.96}_{-0.80}$ fb
- Constrain nine dimension-8 neutral aQGCs (f_{M0-3}, $f_{T1,2,8,9}$)

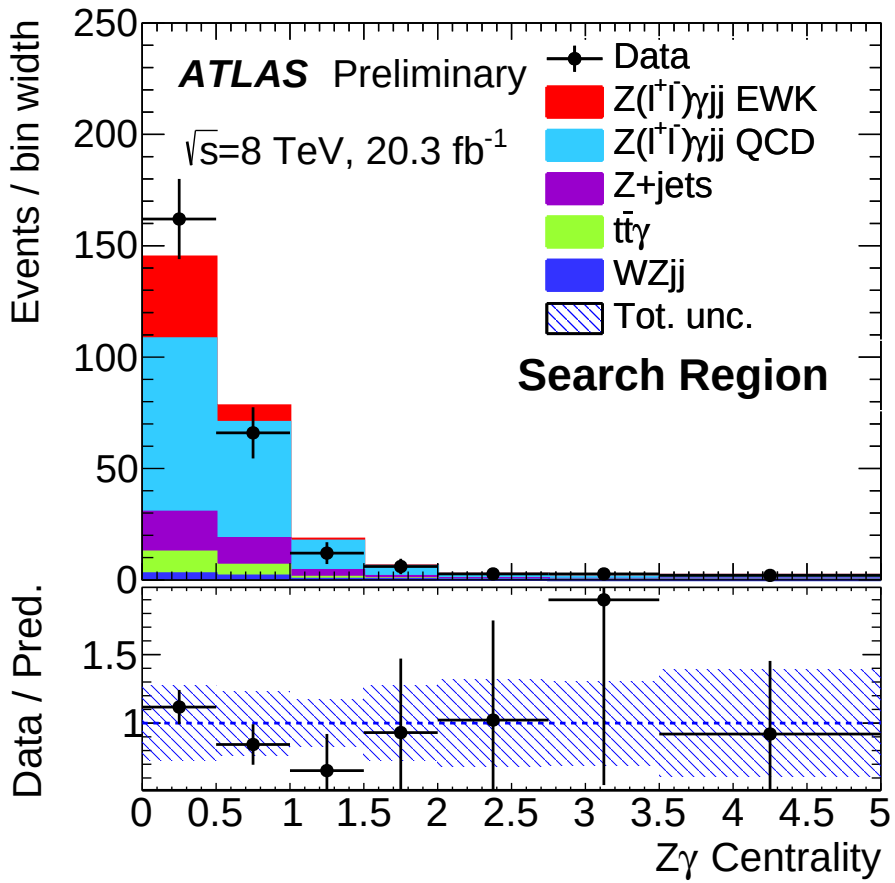


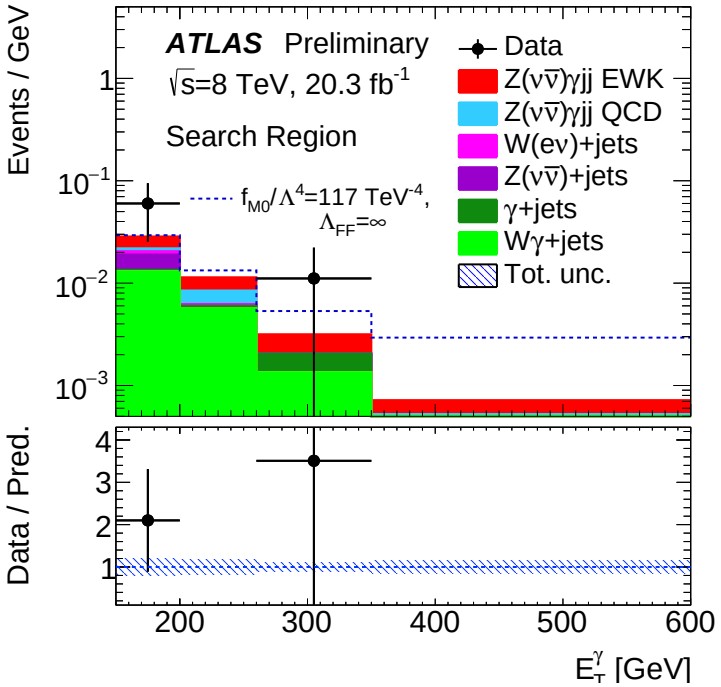


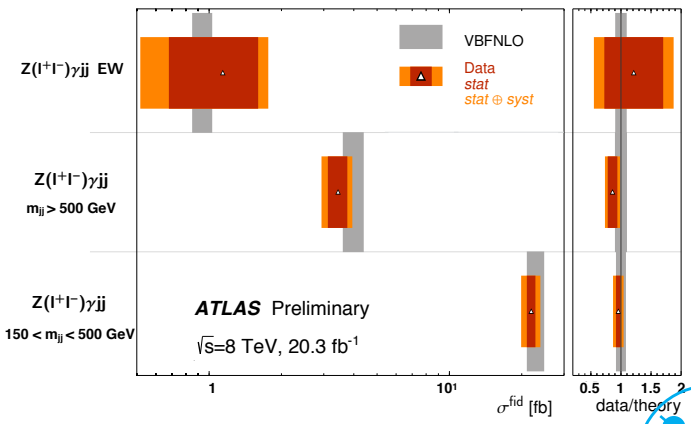


Observed limits (TeV^{-4})	Expected limits (TeV^{-4})
$-71 < f_{M0}/\Lambda^4 < 75$	$-109 < f_{M0}/\Lambda^4 < 111$
$-190 < f_{M1}/\Lambda^4 < 182$	$-281 < f_{M1}/\Lambda^4 < 280$
$-32 < f_{M2}/\Lambda^4 < 31$	$-47 < f_{M2}/\Lambda^4 < 47$
$-58 < f_{M3}/\Lambda^4 < 59$	$-87 < f_{M3}/\Lambda^4 < 87$
$-3.8 < f_{T0}/\Lambda^4 < 3.4$	$-5.1 < f_{T0}/\Lambda^4 < 5.1$
$-4.4 < f_{T1}/\Lambda^4 < 4.4$	$-6.5 < f_{T1}/\Lambda^4 < 6.5$
$-9.9 < f_{T2}/\Lambda^4 < 9.0$	$-14.0 < f_{T2}/\Lambda^4 < 14.5$
$-1.8 < f_{T8}/\Lambda^4 < 1.8$	$-2.7 < f_{T8}/\Lambda^4 < 2.7$
$-4.0 < f_{T9}/\Lambda^4 < 4.0$	$-6.0 < f_{T9}/\Lambda^4 < 6.0$

ATLAS: Zγjj [8 TeV]





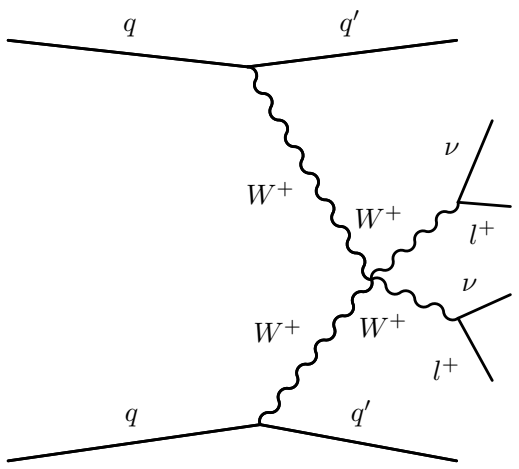


- Fiducial Zγjj cross section: 1.1 ± 0.6 fb
- Constrain VVZγ aQGCs: f_{M0-3}, $f_{T0,8,9}$

ATLAS/CMS: $W^{\pm}W^{\pm}$ [8 TeV]

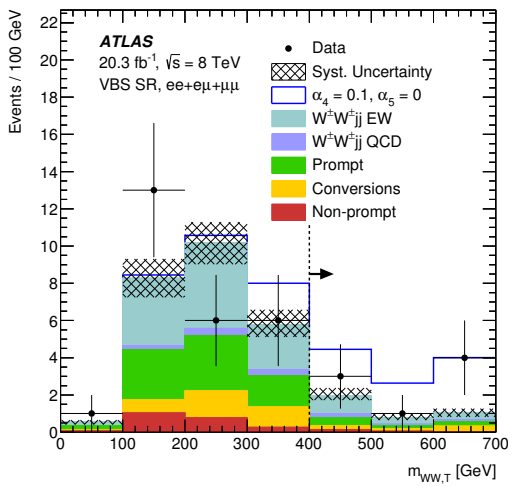
PRL 114, 051801 (2015), arXiv:1410.6315
sub. PRD, arXiv:1611.02428

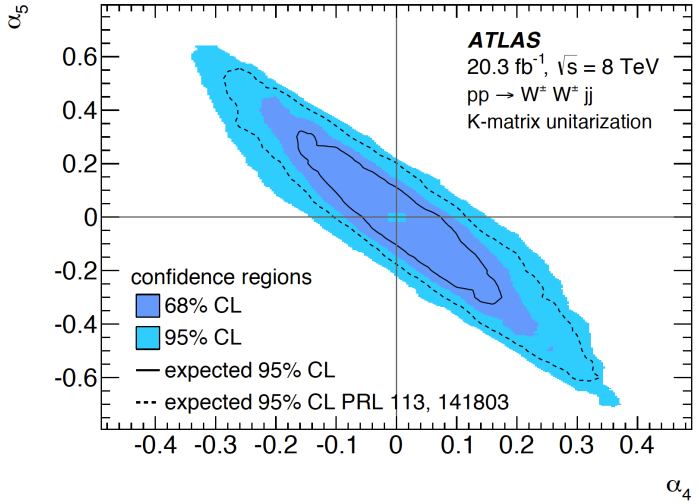
Evidence for EW WWjj production: 3.6σ

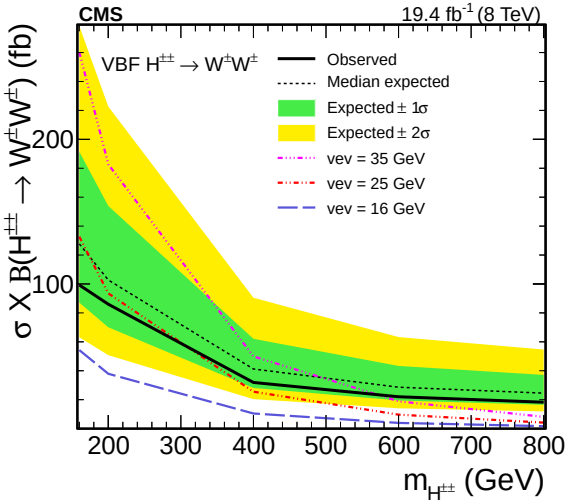


- Same-sign scattering rates
- Bounds on dimension-4 aQGCs (α_4 and α_5)

  $-0.14 < \alpha_4 < 0.15$ and $-0.22 < \alpha_5 < 0.22$
- Interpretation as limits on VBF $H^{\pm\pm}$



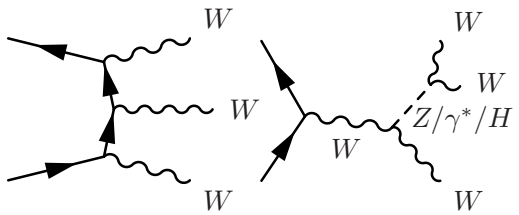


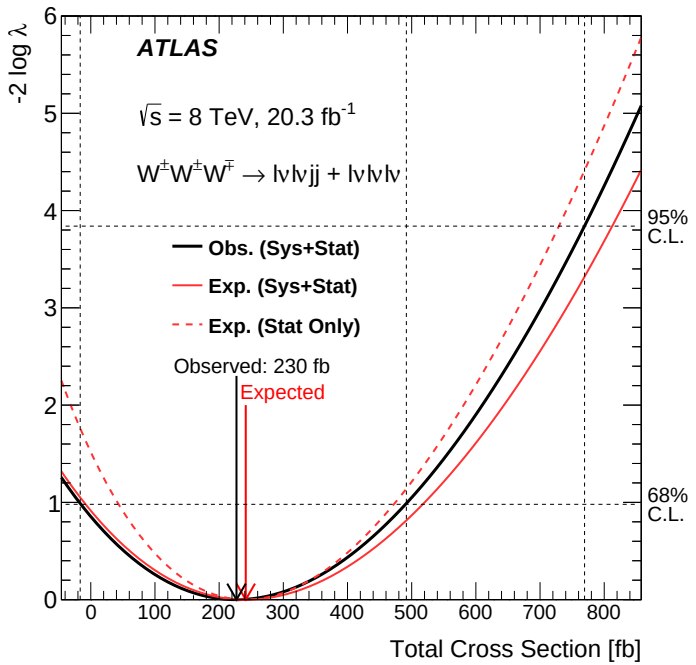


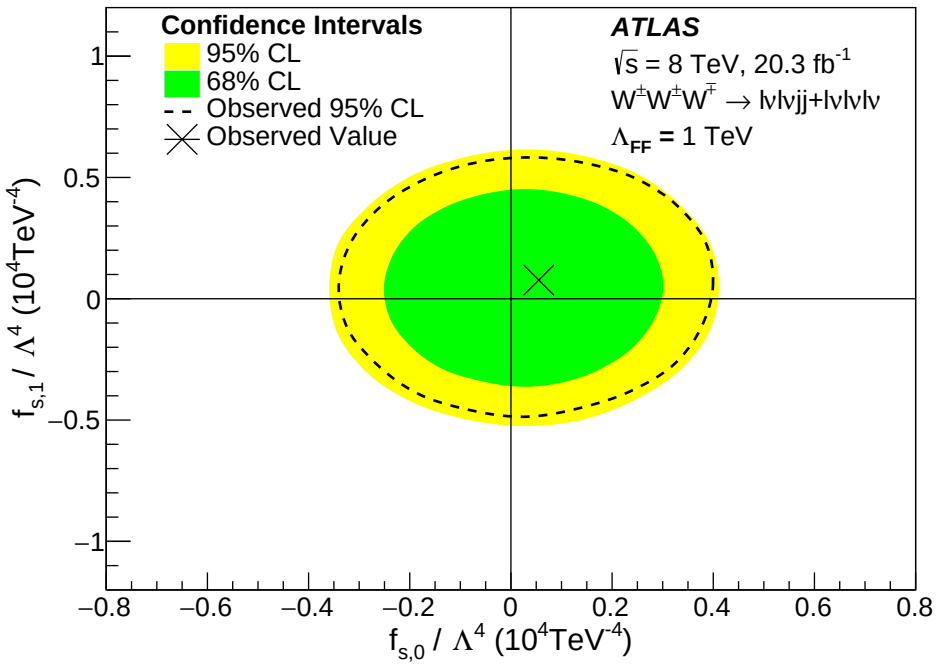
ATLAS: $W^{\pm}W^{\pm}W^{\mp}$ [8 TeV]

EPJC 77 (2017) 141, arXiv:1610.05088

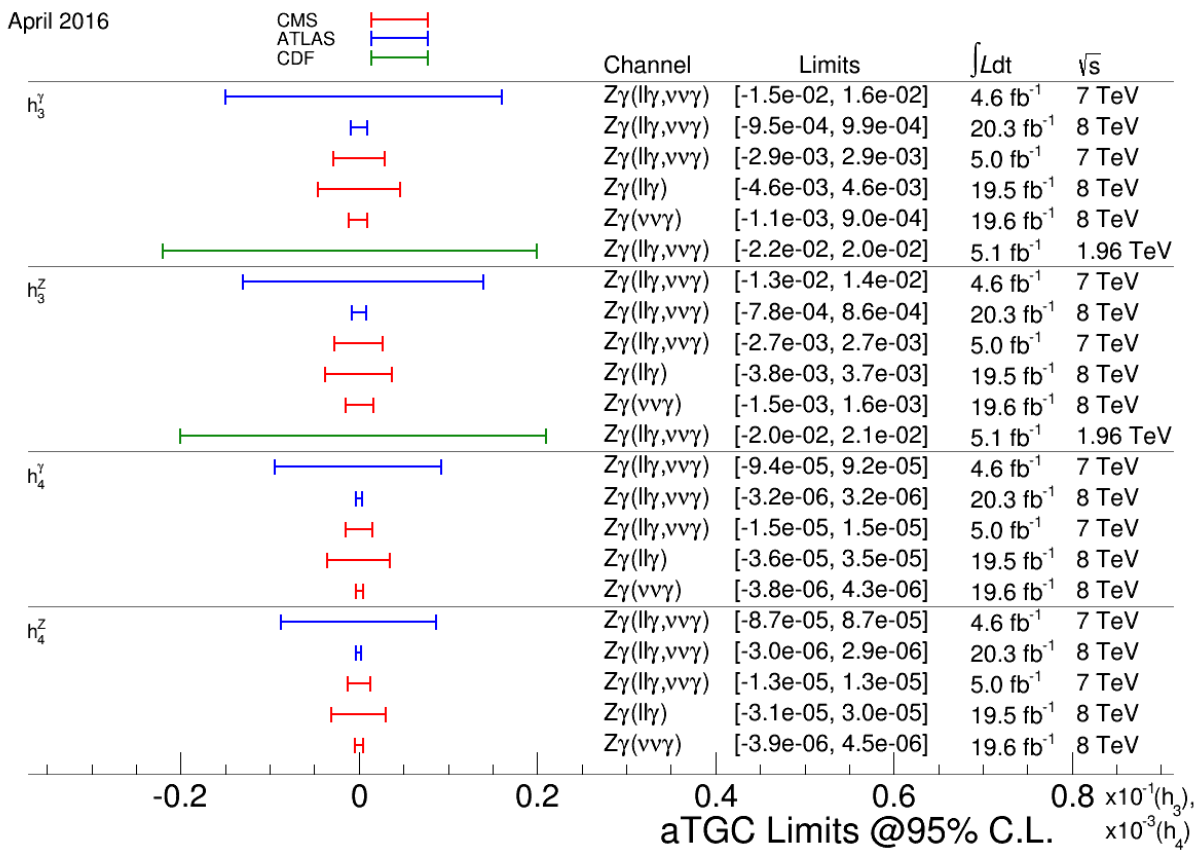
- 95% CL on cross section: 730(560) fb obs. (exp.)
- Limits on anomalous WWWW couplings: dimension-8 $f_{S,0}$ and $f_{S,1}$





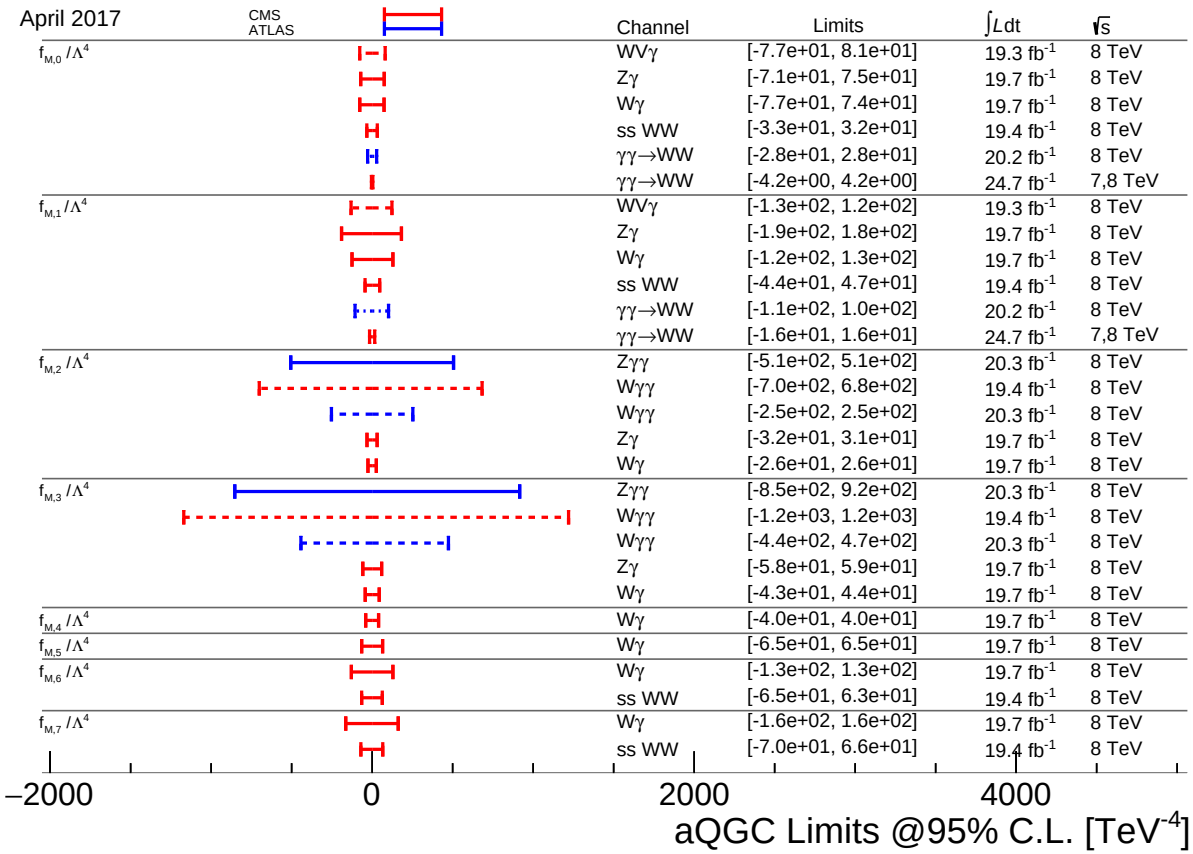


Anomalous electroweak coupling summary



- Many ATLAS and CMS analyses can constrain aTGCs/aQGCs
- First evidence for many of the EW processes considered here
- New limits on many of the aTGCs

Anomalous electroweak coupling summary

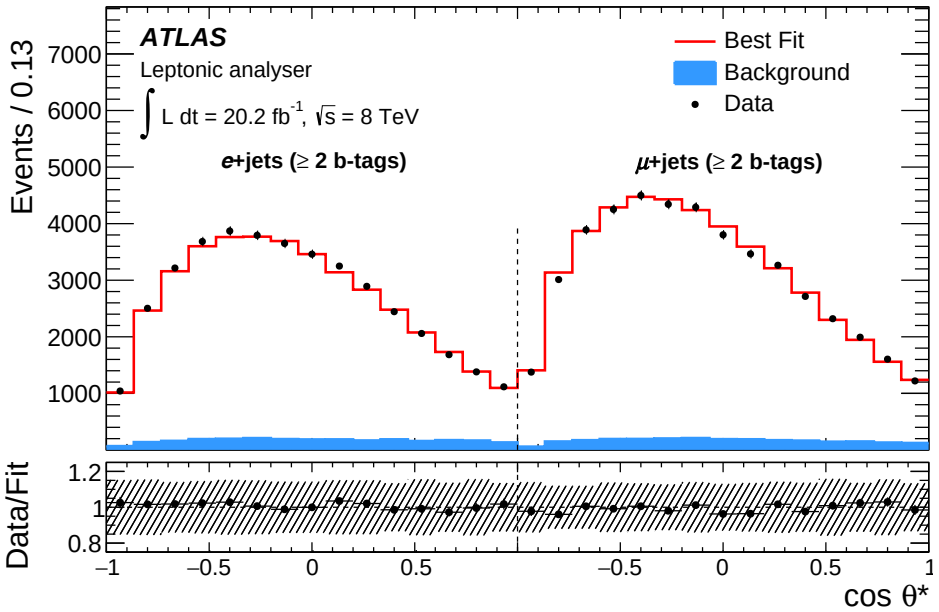


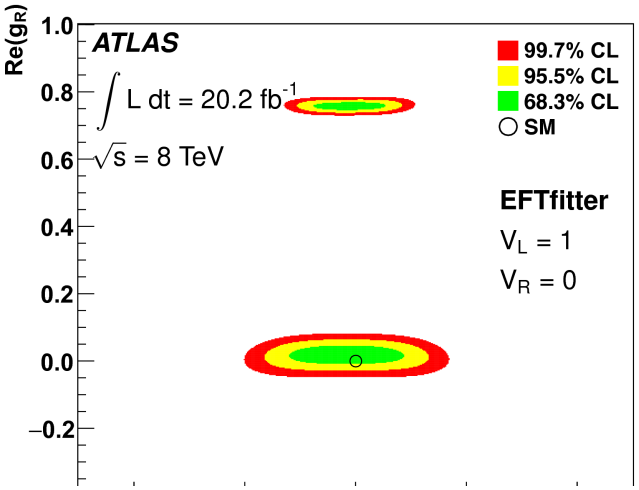
- Many ATLAS and CMS analyses can constrain aTGCs/aQGCs
- First evidence for many of the EW processes considered here
- New limits on many aQGCs through EFT operators

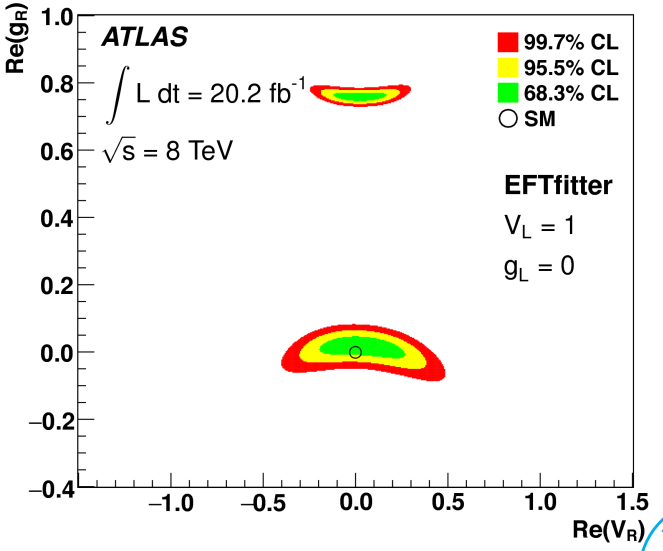
Top coupling

ATLAS: W polarisation [8 TeV]

sub. EPJC, arXiv:1612.02577



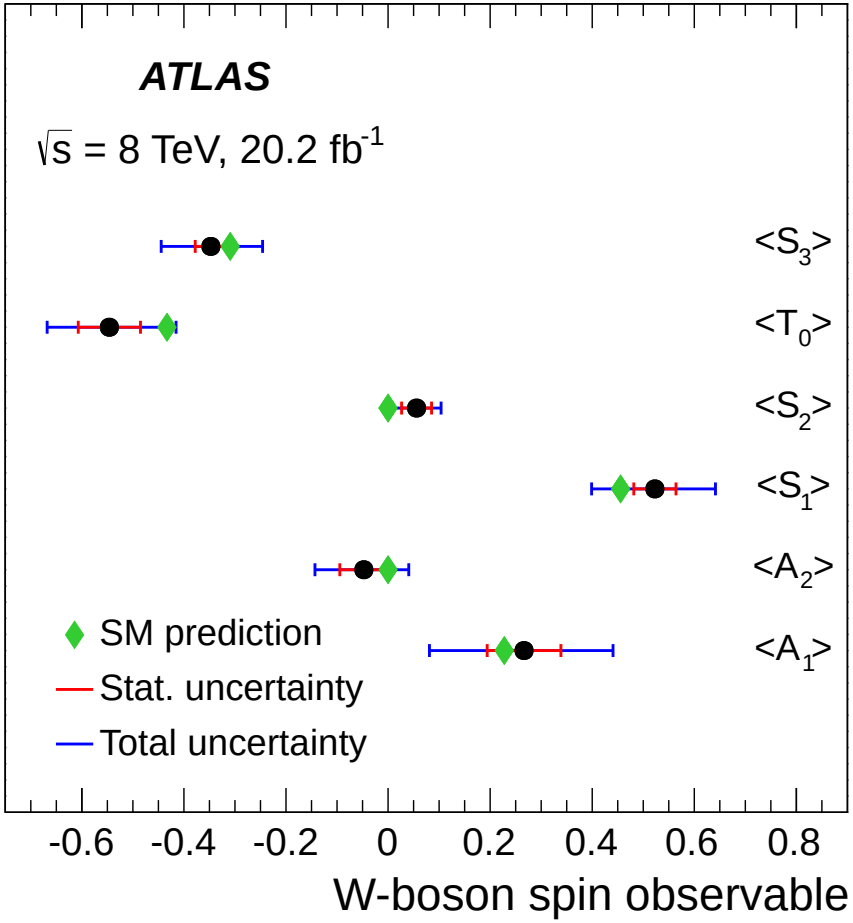




- θ^*: angle between b and t in W rest-frame
- Fit W-boson polarisation
- Limits on Wtb vertex
- LH tensor, RH tensor and vector

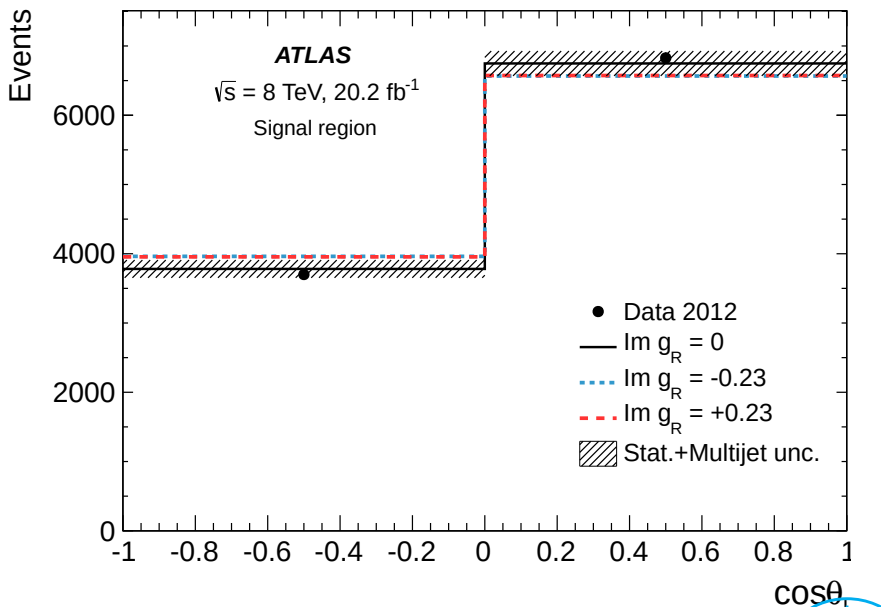
ATLAS: single-top production [8 TeV]

sub. EPJC, arXiv:1702.08309



$$\frac{1}{\Gamma}\frac{d\Gamma}{d(\cos\theta_\ell^*)d\phi_\ell^*} = \frac{3}{8\pi}\left\{\frac{2}{3}+\frac{1}{\sqrt{6}}\langle T_0\rangle\left(3\cos^2\theta_\ell^*-1\right)+\langle S_3\rangle\cos\theta_\ell^* + \langle S_1\rangle\cos\phi_\ell^*\sin\theta_\ell^* + \langle S_2\rangle\sin\phi_\ell^*\sin\theta_\ell^* - \langle A_1\rangle\cos\phi_\ell^*\sin 2\theta_\ell^* - \langle A_2\rangle\sin\phi_\ell^*\sin 2\theta_\ell^*\right\}.$$

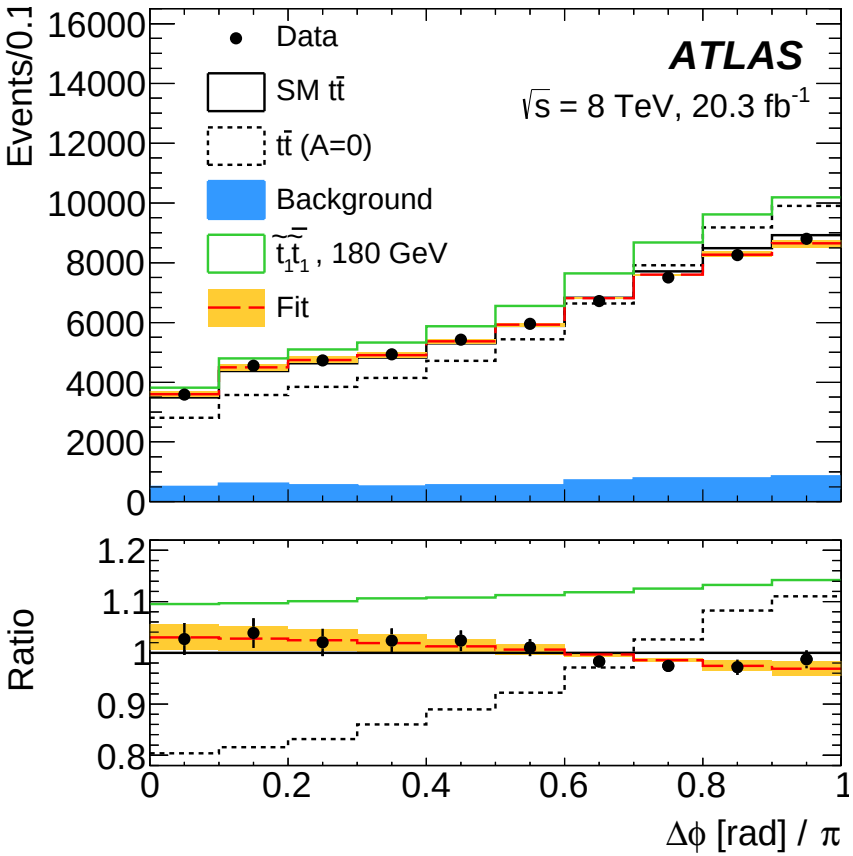
- Decompose W decay width in terms of spin observables
- Measure these from asymmetry distributions
- Limits on imaginary part of RH tensor: $-0.18 < \mathrm{Im}(g_R) < 0.06$



Supersymmetry/Exotics

ATLAS: $t\bar{t}$ spin correlation [8 TeV]

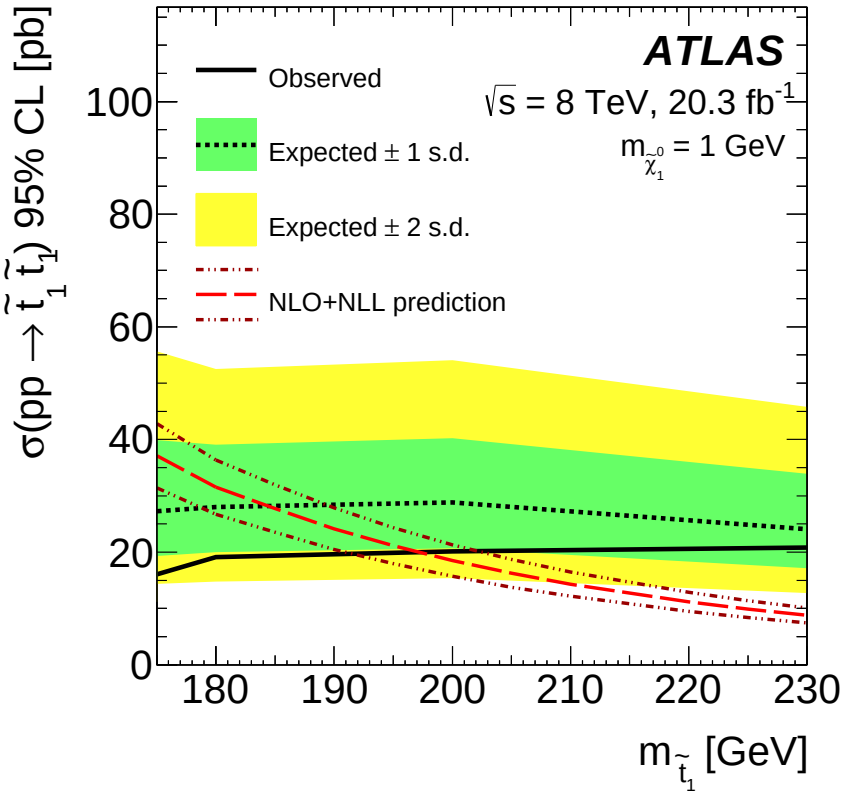
PRL 114 (2015) 142001, arXiv:1412.4742



› Spin correlations from dilepton angular separation

› Interpretation in MSSM

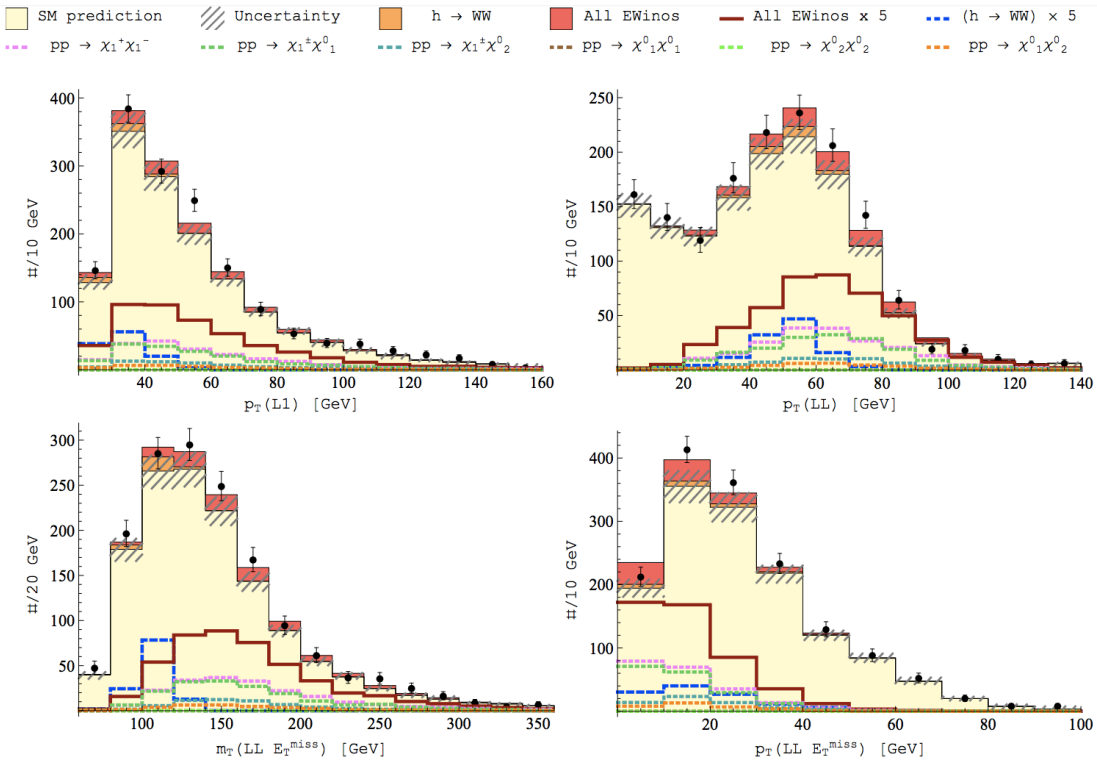
› Exclude $m_t < m_{\tilde{t}} < 191$ GeV



Re-interpretation: SUSY W^+W^- [7, 8 TeV]

- Reinterpretation of ATLAS/CMS Run 1 W^+W^- cross section excess

$$pp \rightarrow \chi^+\chi^- \rightarrow W^+W^-\chi^0\chi^0$$

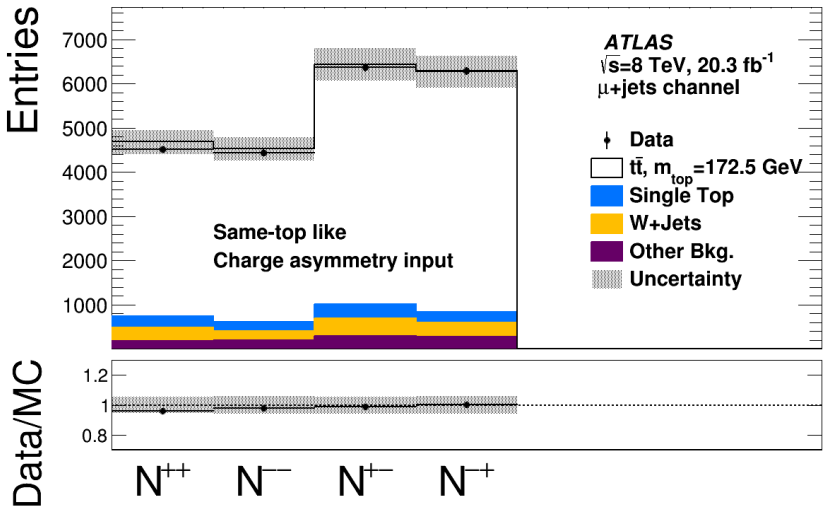


Equally: W^+W^- can constrain SUSY models with small mass splittings

ATLAS: top asymmetries [8 TeV]

JHEP 02 (2017) 071, arXiv:1610.07869

- Charge asymmetry between lepton and muon tagged as coming from b-hadron decay
- Interpret as limits on direct CP asymmetries

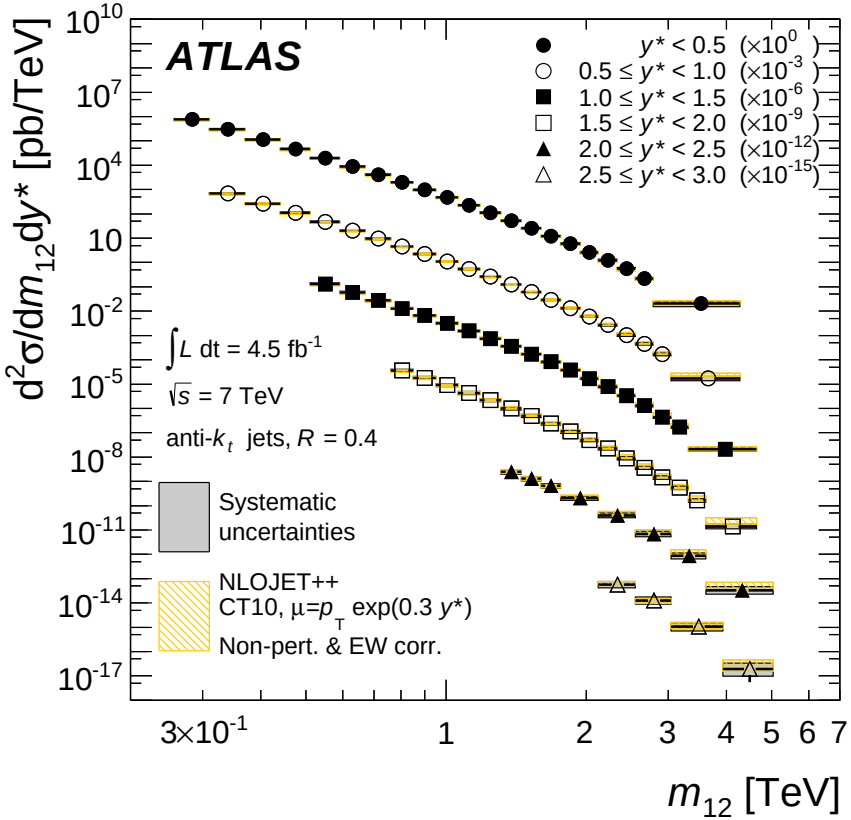


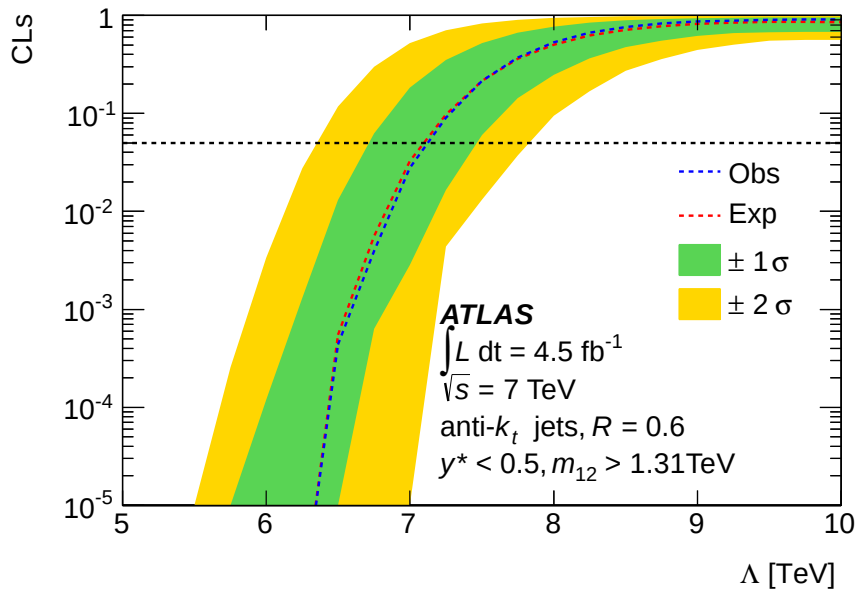
	Data (10^{-2})		MC (10^{-2})		Existing limits (2σ) (10^{-2})		SM prediction (10^{-2})	
A^{ss}	-0.7	$\pm\ 0.8$	0.05	$\pm\ 0.23$	-		$< 10^{-2}$	[19]
A^{os}	0.4	$\pm\ 0.5$	-0.03	$\pm\ 0.13$	-		$< 10^{-2}$	[19]
A^{b}_{mix}	-2.5	$\pm\ 2.8$	0.2	$\pm\ 0.7$	< 0.1	[95]	$< 10^{-3}$	[96] [95]
$A^{b\ell}_{\mathrm{dir}}$	0.5	$\pm\ 0.5$	-0.03	$\pm\ 0.14$	< 1.2	[94]	$< 10^{-5}$	[19] [94]
$A^{c\ell}_{\mathrm{dir}}$	1.0	$\pm\ 1.0$	-0.06	$\pm\ 0.25$	< 6.0	[94]	$< 10^{-9}$	[19] [94]
A^{bc}_{dir}	-1.0	$\pm\ 1.1$	0.07	$\pm\ 0.29$	-		$< 10^{-7}$	[97]

ATLAS: dijet cross sections [7 TeV]

JHEP 05 (2014) 059, arXiv:1312.3524

- Fully unfolded double differential cross sections
- Scope for reinterpretation…

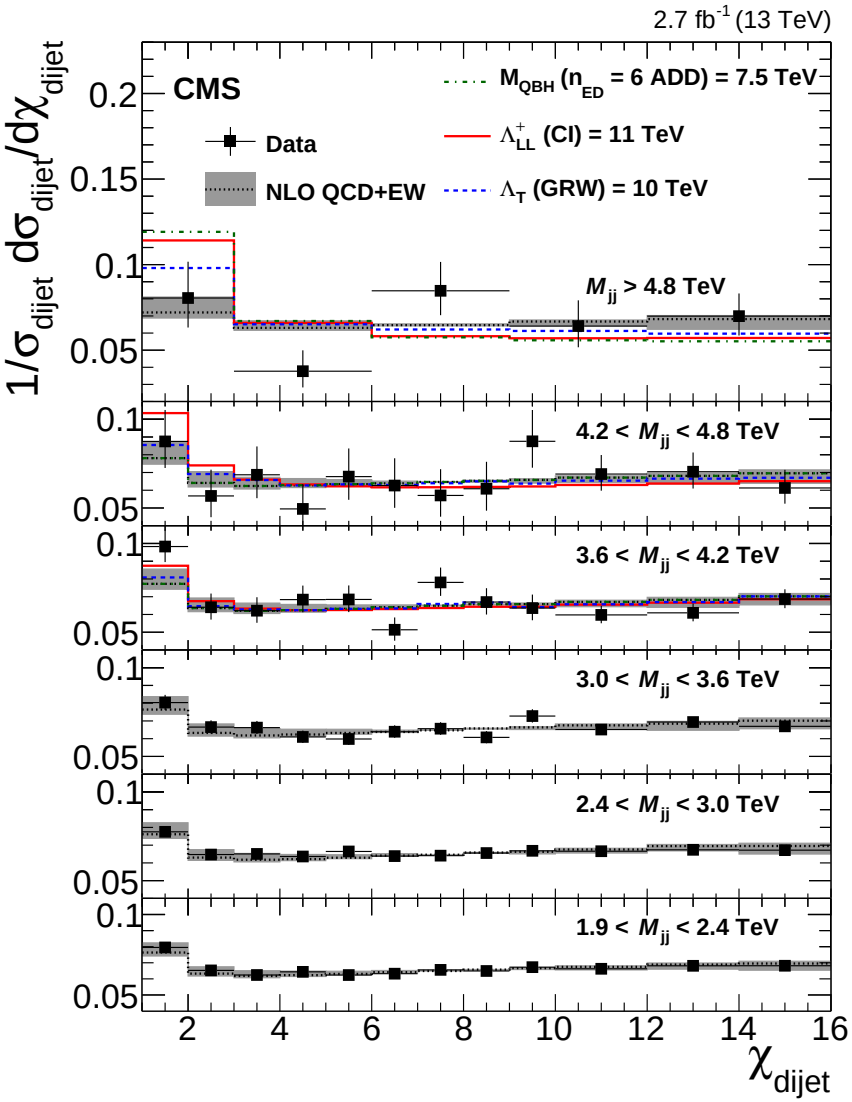




- Set limit on compositeness scale for contact interactions
- Comparable limits ($\Lambda < 7.6$ TeV) to contemporary dedicated search!

CMS: dijet χ [13 TeV]

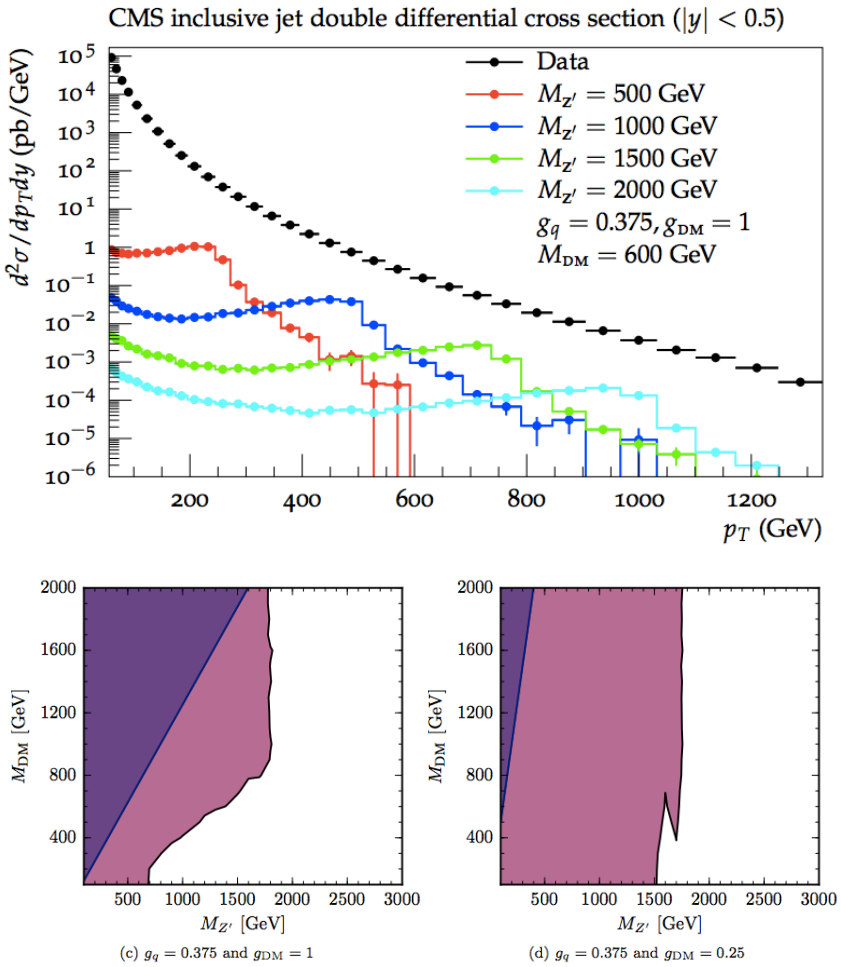
sub. JHEP, arXiv:1703.09986



- Unfolded cross sections as function of $\chi = e^{|y_1 - y_2|}$
- Contact interactions excluded up to 11.5(14.7) TeV
- Dedicated search still providing data in re-interpretable format

Reinterpretation: CONTUR

acc. JHEP, arXiv:1606.05296



Constraints On New Theories Using Rivet

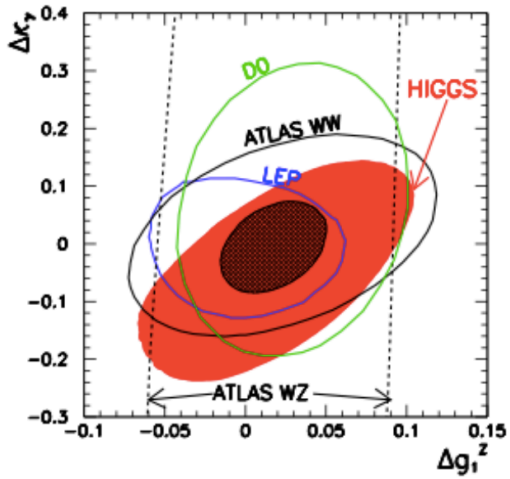
- Simplified DM model: Majorana fermion, ψ interacting through vector Z'
- $Z'\psi\psi$ coupling: g_{DM}, Z'qq coupling: g_q
- Compare to published ATLAS/CMS data from 16 SM papers

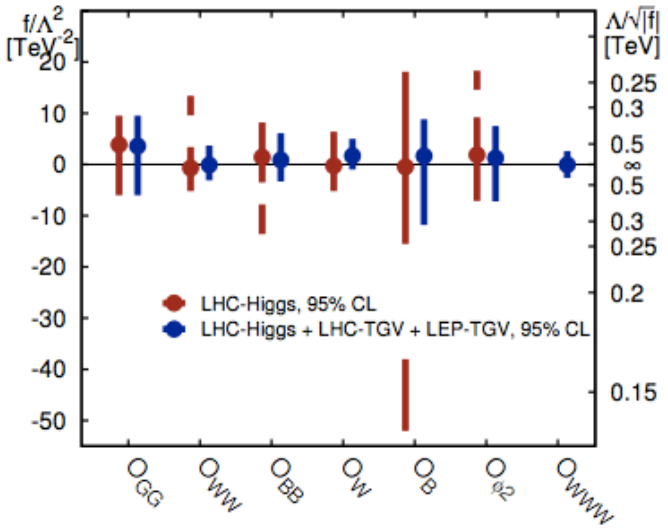
Higgs phenomenology

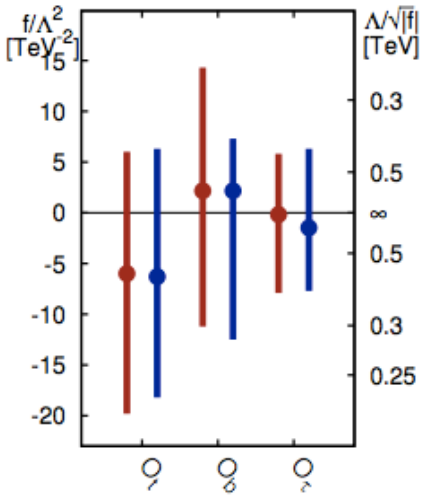
Re-interpretation: Higgs/TGC

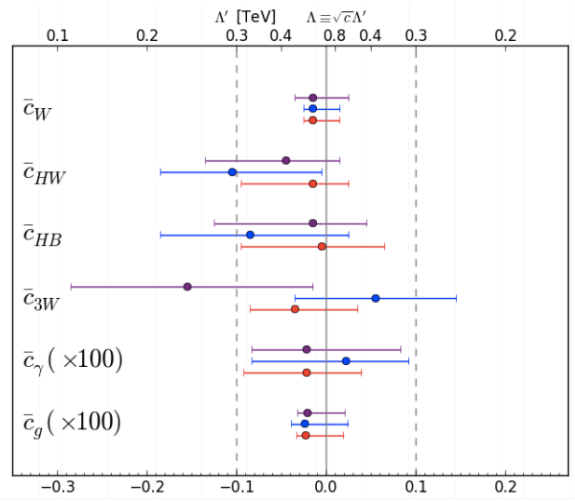
PRL 111 (2013) 011801, arXiv:1304.1151
JHEP 1607 (2016) 152, arXiv:1604.03105
JHEP 1503 (2015) 157, arXiv:1410.7703

- Direct relationship between Higgs couplings/TGCs (in EFTs)
- ATLAS+CMS (W^+W^-, $W^{\pm}Z$, $W\gamma$) data give constraints on Higgs couplings
- Complementary constraints from both datasets benefit from combination





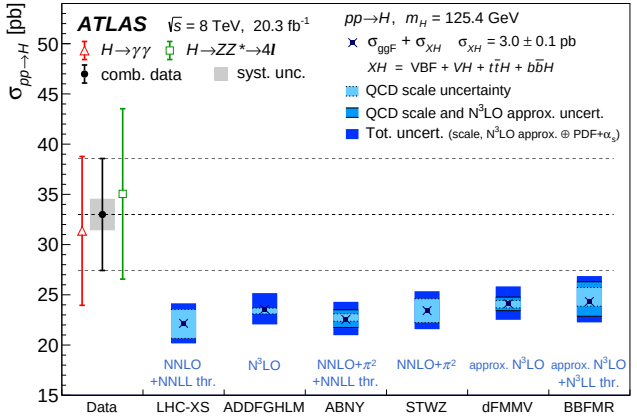


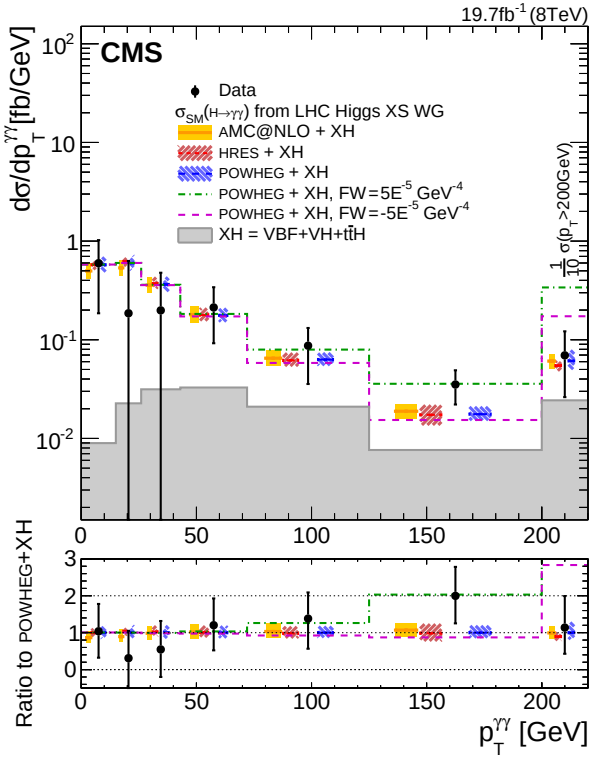


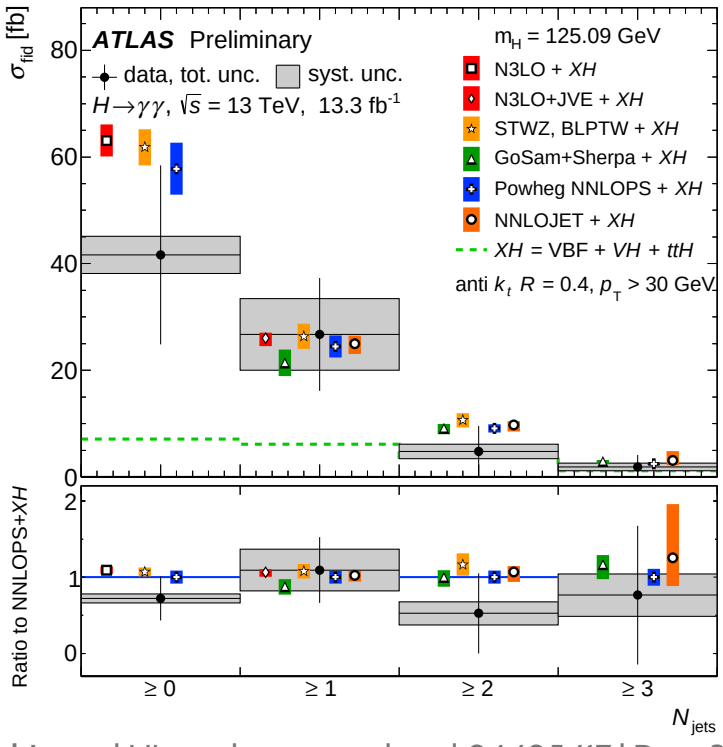
ATLAS/CMS: Higgs cross sections

PRL 115, 091801 (2015), arXiv:1504.05833
EPJC 76 (2016) 13, arXiv:1508.07819
ATLAS-CONF-2016-067

- Higgs fiducial cross sections probe SM
- Unfolded differential cross sections for several kinematic variables



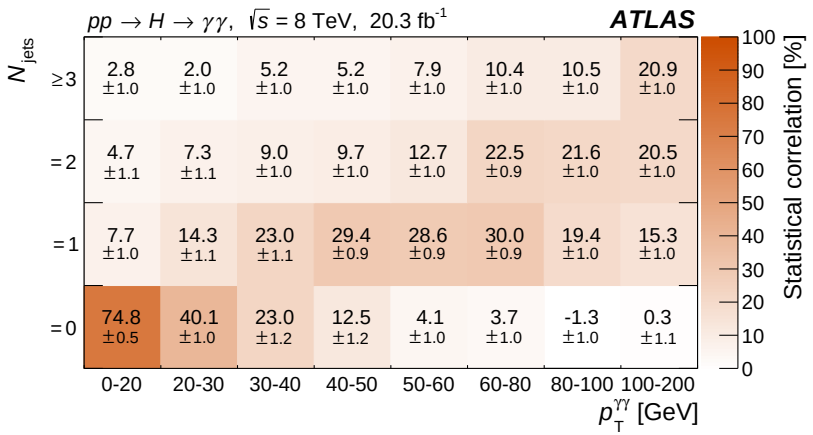


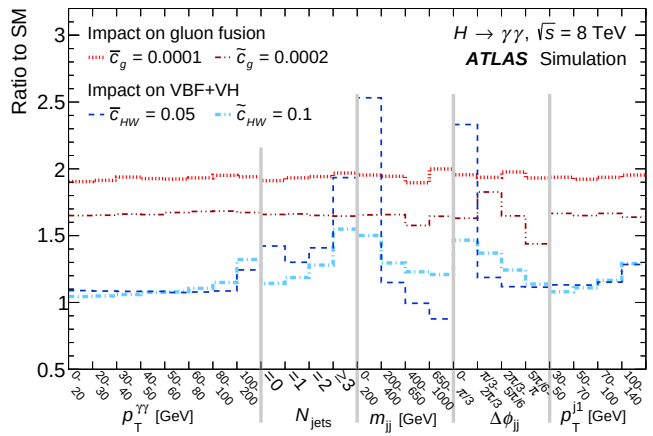


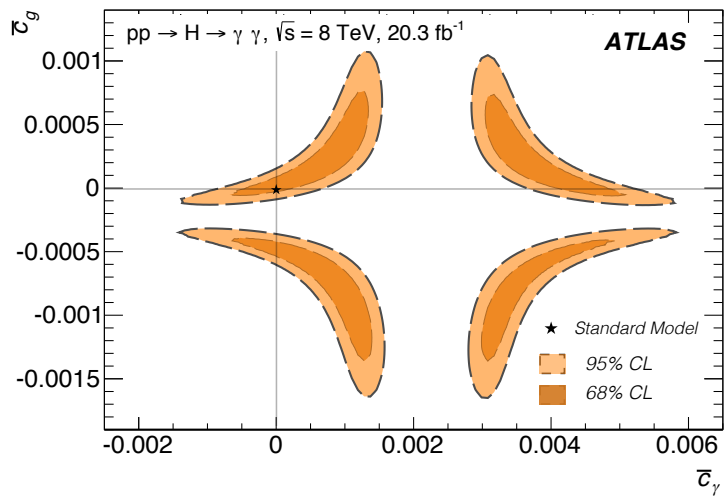
ATLAS: Higgs interpretation

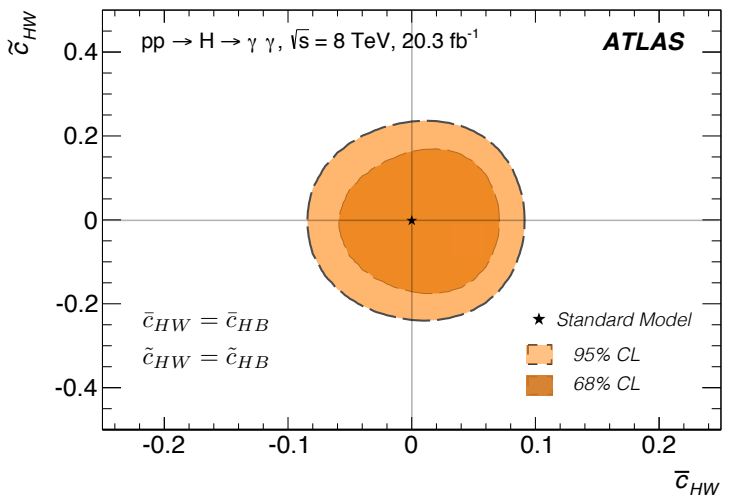
PLB 753 (2016) 69-85, arXiv:1508.02507

- Constraints on EFT Wilson coefficients
- Ratio to theory with varied coefficients → CLs limits





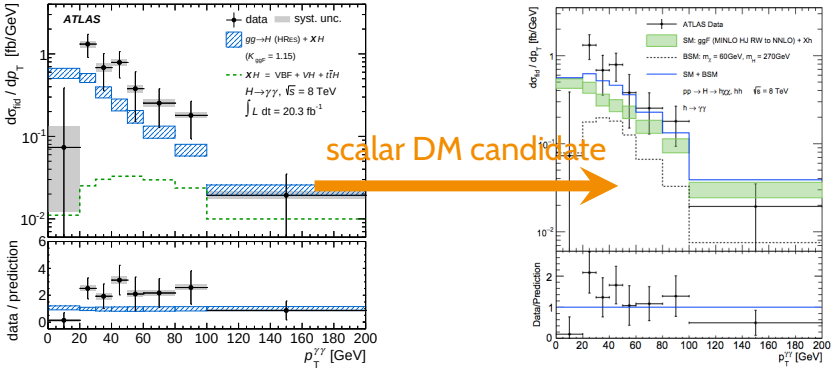


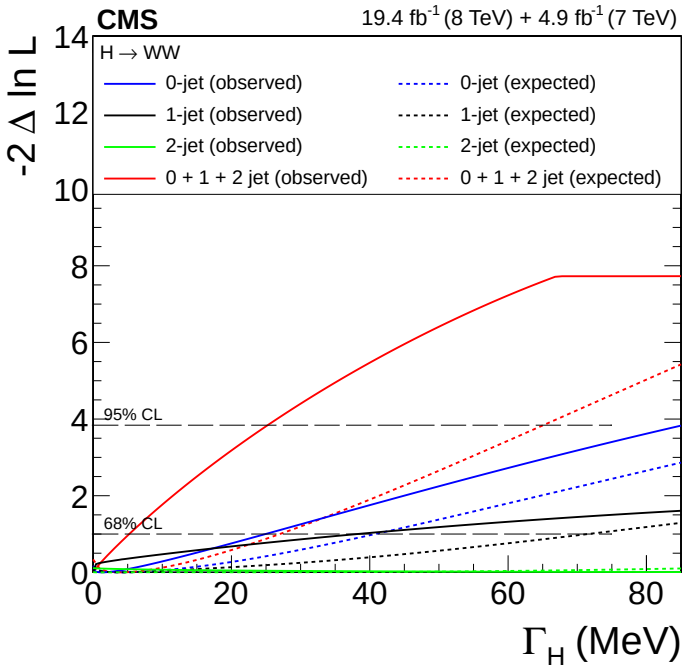


Higgs interpretation

arXiv:1506.00612
JHEP 09 (2016) 051, arXiv:1605.02329

- Reinterpretation in terms of specific models



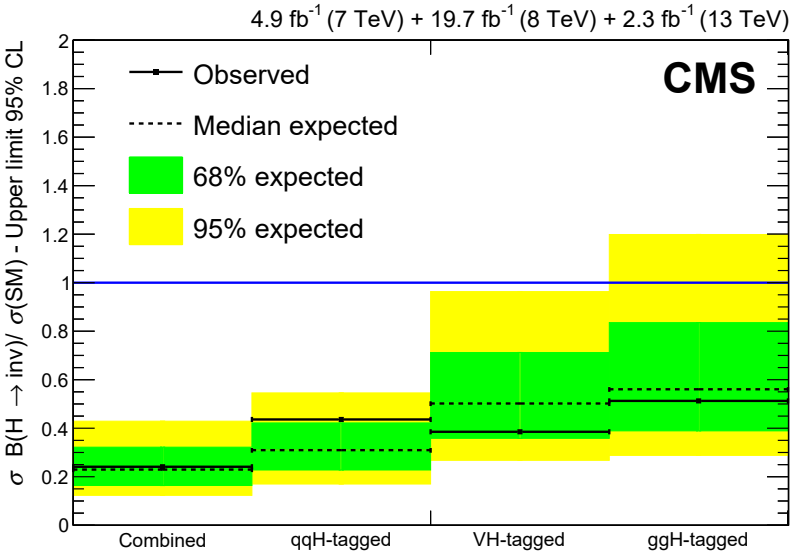


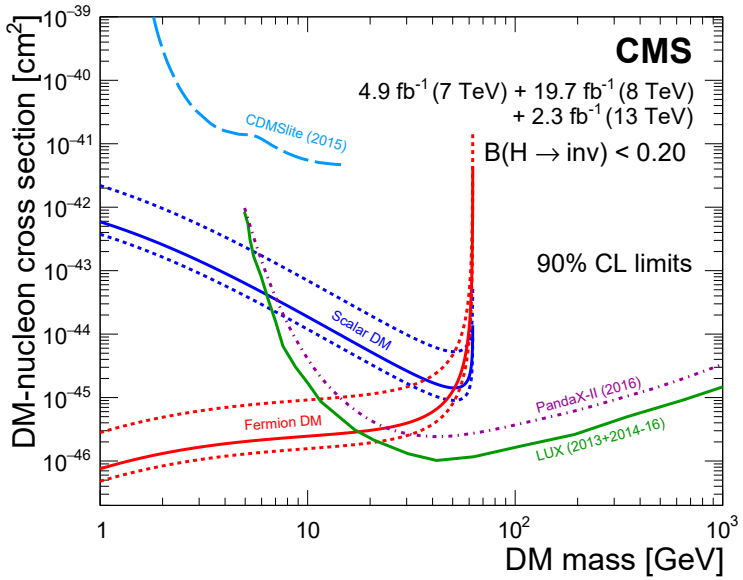
- Measure Higgs width through LL fit to $H \to WW$ rates in bins of $m_{\ell\ell}$
- Combine with $H \to WW/ZZ$ to obtain $\Gamma_H < 13$ MeV

CMS: Invisible Higgs decays [8, 13 TeV]

JHEP 02 (2017) 135, arXiv:1610.09218

- Combination of decay modes: VBF, ZH, ggH + jet
- Limits on Higgs branching ratios to invisible particles
- Dark matter limits through Higgs-portal model

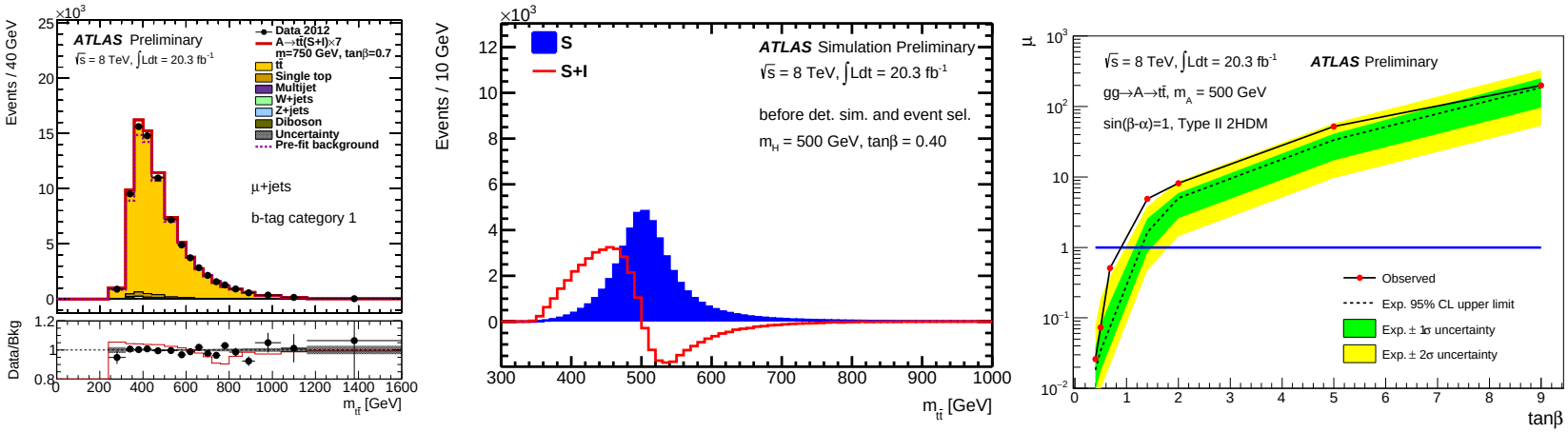




ATLAS: Heavy Higgs in $t\bar{t}$

ATLAS-CONF-2016-073

- Search for (pseudo)scalar resonances decaying to $t\bar{t}$
- Sensitive to BSM signals not previously accessible
- Interference between signal ($gg \rightarrow A/H \rightarrow t\bar{t}$) and SM $t\bar{t}$ bkg
- Signal shape distorted from simple peak to peak-dip structure



Significant sensitivity improvements for $m_{A/H} > 2m_t$ and low tan β

Conclusions

Conclusions

ATLAS and CMS produce a huge variety of SM measurements

- Existing searches complemented by SM reinterpretation
- Limits from unfolded data can complement dedicated searches
  - unfolded results can still have sensitivity
- Unfolded results in HEPDATA ready to be reinterpreted
  - with auxillary information: correlations, Rivet routine
- Enables easy combination with other data in fits
  - potential for even greater discriminating power in future

Only a small subset of reinterpretable data shown today

Backup

aTGC/EFT relations

$$\Delta g_1^Z = c_W \frac{m_Z^2}{2\Lambda^2}$$

$$\Delta \kappa_\gamma = \left(c_W + c_B\right) \frac{m_W^2}{2\Lambda^2}$$

$$\Delta \kappa^Z = \left(c_W - c_B \tan^2 \theta_W\right) \frac{m_W^2}{2\Lambda^2}$$

$$\lambda_Z = \lambda_W = c_{WWW} \frac{3 g^2 m_W^2}{2\Lambda^2}$$

aQGC dimension-6/dimension-8 relations

$$\frac{f_{M,0}}{\Lambda^4} = \frac{a_0^W}{\Lambda^2}\frac{1}{g^2\nu^2}$$

$$\frac{f_{M,1}}{\Lambda^4} = -\frac{a_C^W}{\Lambda^2}\frac{1}{g^2\nu^2}$$

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	95% CL intervals	Measured [TeV^{-4}]	Expected [TeV^{-4}]	Λ_{FF} [TeV]
$n = 0$	f_{T9}/Λ^4	$[-4.1, 4.2] \times 10^3$	$[-2.9, 3.0] \times 10^3$	
	f_{T8}/Λ^4	$[-1.9, 2.1] \times 10^3$	$[-1.2, 1.7] \times 10^3$	
	f_{T0}/Λ^4	$[-1.9, 1.6] \times 10^1$	$[-1.6, 1.3] \times 10^1$	
	f_{M0}/Λ^4	$[-1.6, 1.8] \times 10^2$	$[-1.4, 1.5] \times 10^2$	
	f_{M1}/Λ^4	$[-3.5, 3.4] \times 10^2$	$[-3.0, 2.9] \times 10^2$	
	f_{M2}/Λ^4	$[-8.9, 8.9] \times 10^2$	$[-7.5, 7.5] \times 10^2$	
	f_{M3}/Λ^4	$[-1.7, 1.7] \times 10^3$	$[-1.4, 1.4] \times 10^3$	
$n = 2$	f_{T9}/Λ^4	$[-6.9, 6.9] \times 10^4$	$[-5.4, 5.3] \times 10^4$	0.7
	f_{T8}/Λ^4	$[-3.4, 3.3] \times 10^4$	$[-2.6, 2.5] \times 10^4$	0.7
	f_{T0}/Λ^4	$[-7.2, 6.1] \times 10^1$	$[-6.1, 5.0] \times 10^1$	1.7
	f_{M0}/Λ^4	$[-1.0, 1.0] \times 10^3$	$[-8.8, 8.8] \times 10^2$	1.0
	f_{M1}/Λ^4	$[-1.6, 1.7] \times 10^3$	$[-1.4, 1.4] \times 10^3$	1.2
	f_{M2}/Λ^4	$[-1.1, 1.1] \times 10^4$	$[-9.2, 9.6] \times 10^3$	0.7
	f_{M3}/Λ^4	$[-1.6, 1.6] \times 10^4$	$[-1.4, 1.3] \times 10^4$	0.8

ATLAS/CMS: $W^{\pm}W^{\pm}$ [8 TeV]

PRL 114, 051801 (2015), arXiv:1410.6315
sub. PRD, arXiv:1611.02428

Operator coefficient	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unitarity limit
$F_{S,0}/\Lambda^4$	−42	43	−38	40	0.016
$F_{S,1}/\Lambda^4$	−129	131	−118	120	0.050
$F_{M,0}/\Lambda^4$	−35	35	−33	32	80
$F_{M,1}/\Lambda^4$	−49	51	−44	47	205
$F_{M,6}/\Lambda^4$	−70	69	−65	63	160
$F_{M,7}/\Lambda^4$	−76	73	−70	66	105
$F_{T,0}/\Lambda^4$	−4.6	4.9	−4.2	4.6	0.027
$F_{T,1}/\Lambda^4$	−2.1	2.4	−1.9	2.2	0.022
$F_{T,2}/\Lambda^4$	−5.9	7.0	−5.2	6.4	0.08

ATLAS: $W^{\pm}W^{\pm}W^{\mp}$ [8 TeV]

EPJC 77 (2017) 141, arXiv:1610.05088

Λ_{FF} [TeV]	Expected CI $[\times 10^4\,\mathrm{TeV}^{-4}]$		Observed CI $[\times 10^4\,\mathrm{TeV}^{-4}]$	
	$f_{S,0}/\Lambda^4$	$f_{S,1}/\Lambda^4$	$f_{S,0}/\Lambda^4$	$f_{S,1}/\Lambda^4$
0.5	$[-0.79, 0.89]$	$[-1.06, 1.27]$	$[-0.74, 0.86]$	$[-0.99, 1.20]$
1	$[-0.36, 0.41]$	$[-0.52, 0.60]$	$[-0.34, 0.40]$	$[-0.48, 0.58]$
2	$[-0.22, 0.25]$	$[-0.33, 0.39]$	$[-0.20, 0.24]$	$[-0.29, 0.36]$
3	$[-0.19, 0.22]$	$[-0.29, 0.36]$	$[-0.16, 0.21]$	$[-0.25, 0.33]$
∞	$[-0.16, 0.19]$	$[-0.25, 0.30]$	$[-0.13, 0.18]$	$[-0.21, 0.27]$