EW and Top Measurements at ATLAS and CMS

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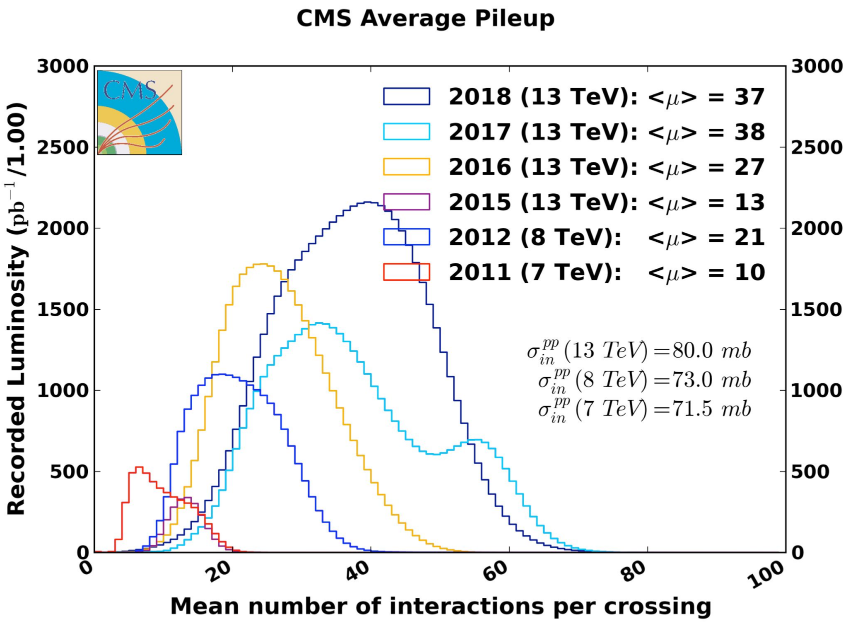
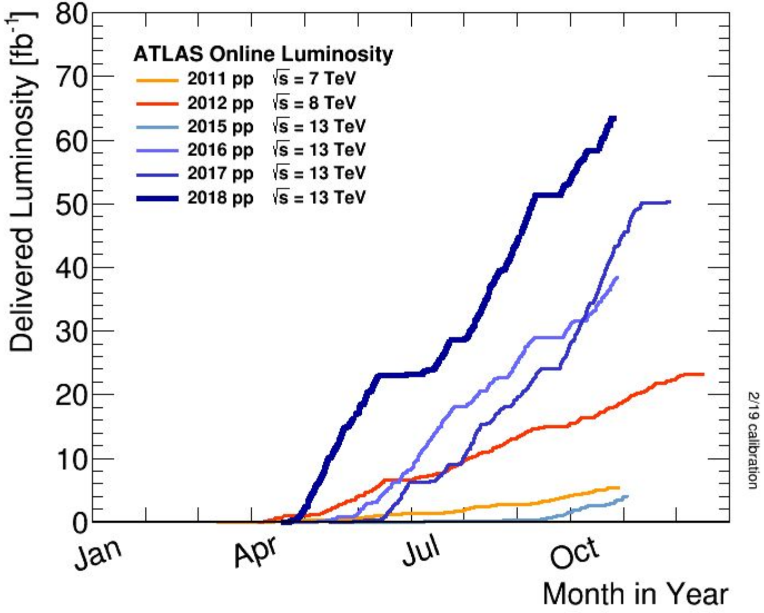
Introduction

- Measurements of vector bosons and top quark at LHC with ATLAS and CMS
- Push the Standard Model to its limits
- Enough data for precision measurements of rare processes!
- Very rich programme, only a few selected results will be presented in this talk
- Exploring the sensitivity to new physics with
    - Precision measurements
    - Unique signatures
    - Indirect searches for loop effects
    - Anomalous couplings
- This was possible thanks to excellent performance of the LHC and as well as ATLAS and CMS detectors

LHC Performance

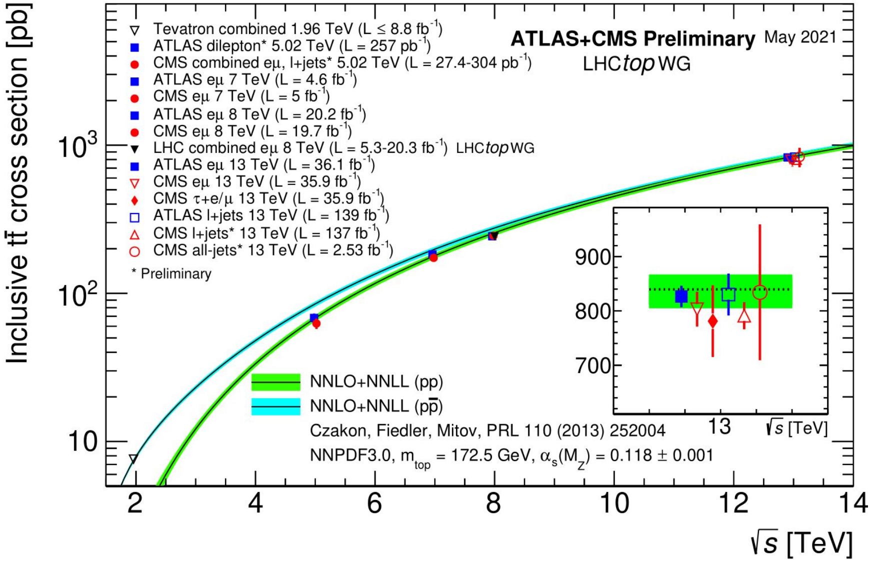
- Run-1 (2011-2012, 25 fb^{-1}) and **Run-2** (2015-2018, 140 fb^{-1}) at the LHC

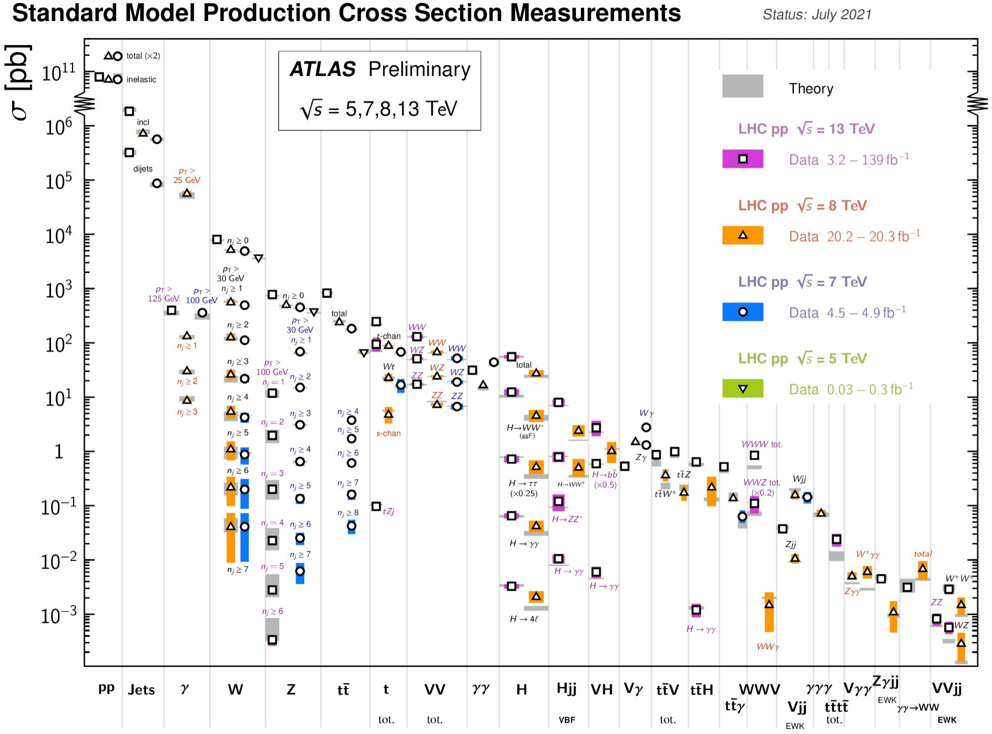




Overview

- Exploring process rates over 15 orders of magnitude at different energies!





For full list of results please visit:
ATLAS Results CMS Results

Results

Precision measurements

- SM parameters
- Mass and properties of *W*, *Z*, *t*
- $\sin^2\theta_W$

- Lepton flavor universality arXiv:2007.14040

Measurements

- Diboson processes
- Differential distributions for probing anomalous couplings
- VBF, ttZ, ttW, ttγ

- ttZ and ttγ arXiv:2103.12603 arXiv:2007.06946
- W branching ratio SMP-18-011
- EW Zγ+2j ATLAS-CONF-2021-038
- $\gamma\gamma$->WW arXiv:2010.04019
- WWW ATLAS-CONF-2021-039

Evidence

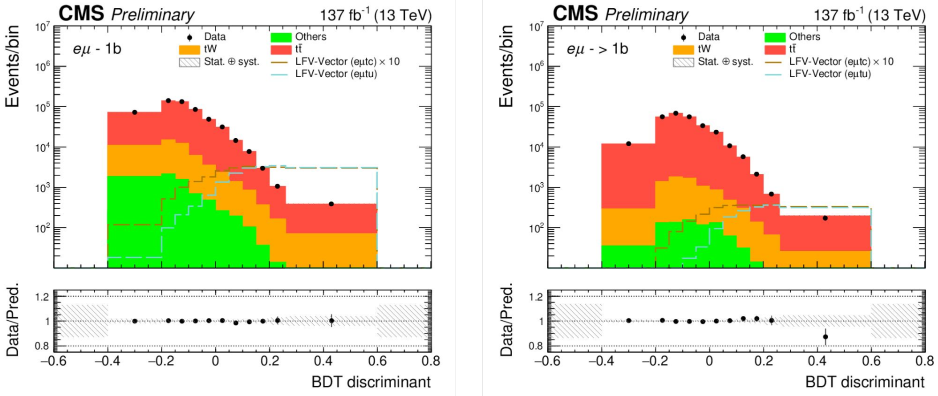
- Triboson and other very rare processes
- 4-t, t-FCNC
- VBS

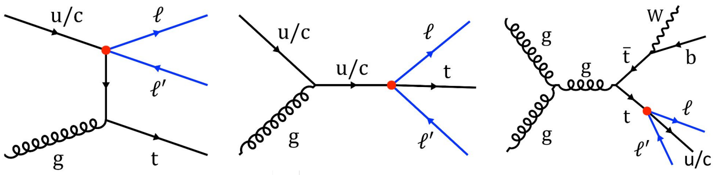
- Charged LFV TOP-19-006
- FCNC t+H TOP-20-007 TOP-19-002
- Boosted ttbar ATLAS-CONF-2021-031
- 4top arXiv:2106.11683

Cross-section order: nb pb fb

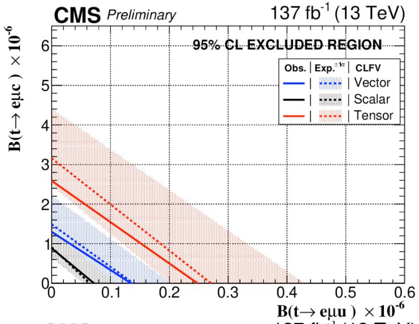
Charged lepton flavor violation

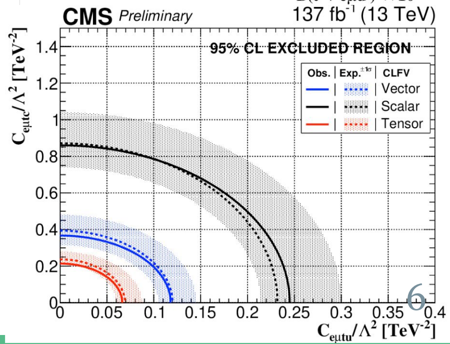
- Opposite charged electron-muon pair + b-jet





Vertex	Int. type	Cross section [fb] Exp.	Obs.
	Vector	7.02	6.78
		[5.33,10.21]	
		(3.39,12.33)	
$e\mu tu$	Scalar	5.63	6.25
		[4.79,9.38]	
		(3.75,12.12)	
	Tensor	10.01	9.18
		[7.51,15.90]	
		(4.59,19.24)	
	Vector	11.21	9.73
		[7.21,16.63]	
		(4.33,21.61)	
$e\mu tc$	Scalar	9.11	8.88
		[6.58,13.10]	
		(3.54,17.41)	
	Tensor	21.02	17.22
		[16.52,29.21]	
		(10.51,42.02)	



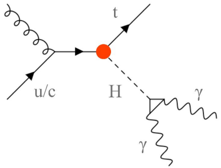


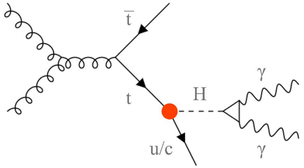
- Limits on the Wilson coefficients converted to limits on the top quark branching fraction
  Bscalar ($t \to e\mu u(c)$) < 0.07 $\times 10^{-6}$ (0.89 $\times 10^{-6}$)
  Bvector ($t \to e\mu u(c)$) < 0.135 $\times 10^{-6}$ (1.3 $\times 10^{-6}$)
  Btensor ($t \to e\mu u(c)$) < 0.25 $\times 10^{-6}$ (2.59 $\times 10^{-6}$)

most restrictive bounds up to now

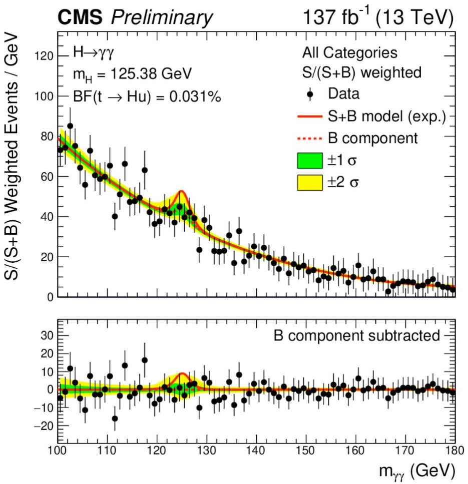
No excess over SM expectation

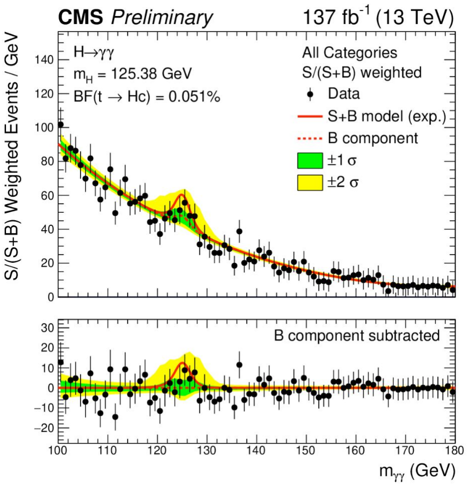
FCNC top+Higgs (diphoton)

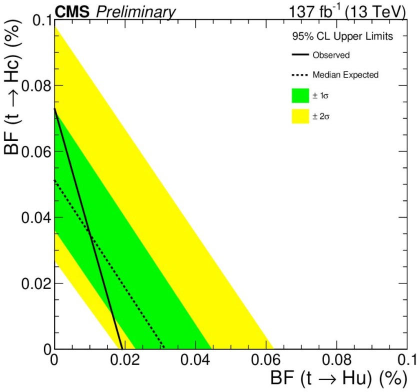


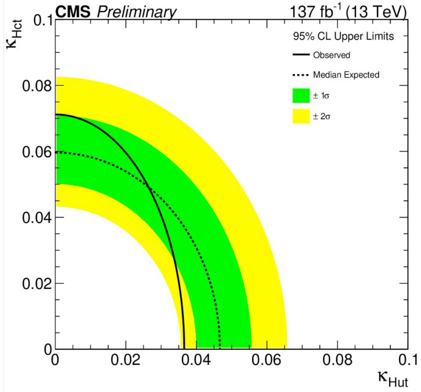


- Flavor changing neutral current interactions of t+Higgs
- Final state: diphoton Higgs + jets and leptons
- Multivariate ML to separate 2 signals from bkg
- $m_{\gamma\gamma}$ fit to extract signals









- Observed (expected) 95% CL
  $B(t \to Hu)$ 1.9×10^{-4} (3.1×10^{-4})
  $B(t \to Hc)$ 7.3×10^{-4} (5.1×10^{-4})

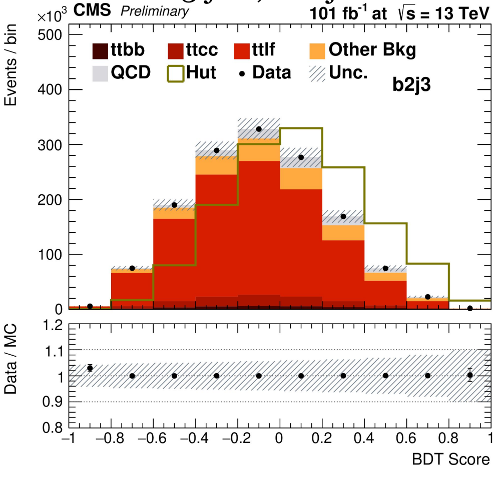
No excess over SM expectation

[CMS-TOP-19-002]

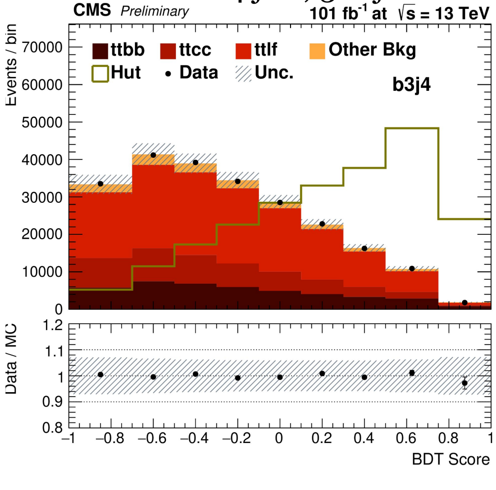
FCNC top+Higgs (bb)

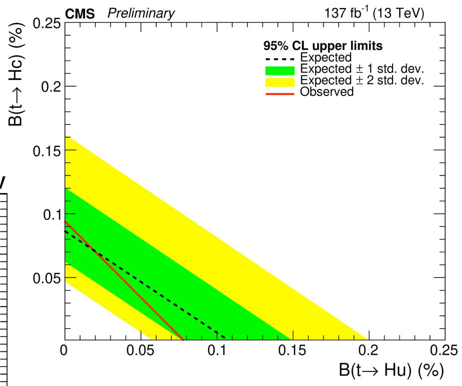
- Flavor changing neutral current interactions of t+bb
- Final state: 1 lepton + at least 3 jets (2 b-jets)
- 5 categories, DNN for event reconstruction
- BDT separate signal from bkg

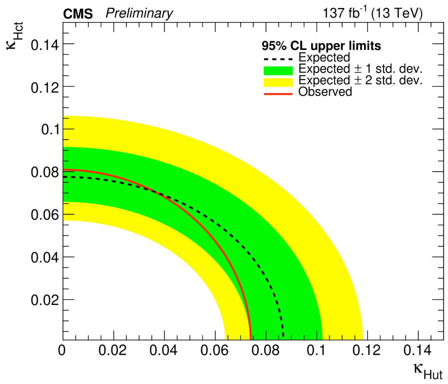
3 jets, 2 b-jets



at least 4 jets, 3 b-jets







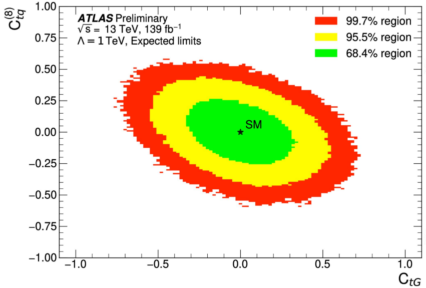
- Observed (expected) 95% CL
  $B(t \rightarrow Hu)$ 7.9×10^{-4} (1.1×10^{-4})
  $B(t \rightarrow Hc)$ 9.4×10^{-4} (8.6×10^{-4})

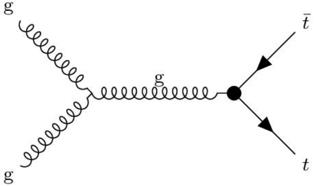
No excess over SM expectation

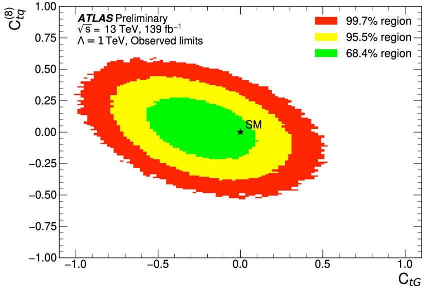
ATLAS-CONF-2021-031

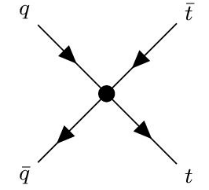
Boosted ttbar

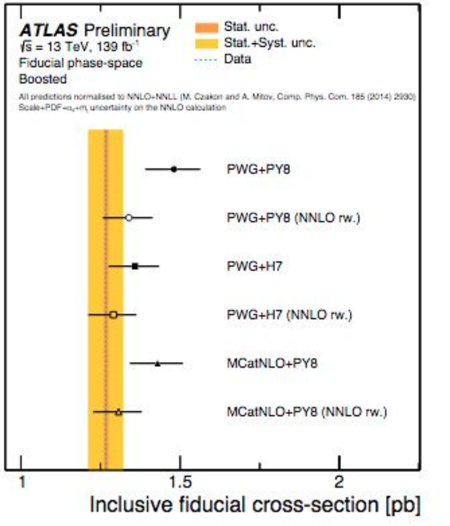
- Selection: 1 lepton, 2 b-jets, 1 top-tagged large jet (R=1, containing 1 b-jet) pT > 355 GeV
- Main bkg: single top and ttV
- Cross-section 1.267 ±0.005 (stat.)±0.053 pb (syst.)

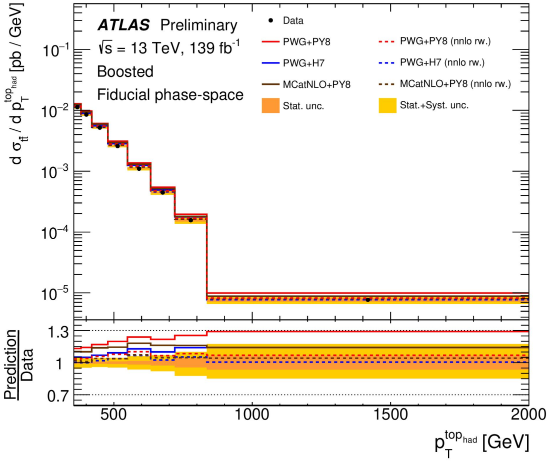












- EFT limits from had top pt distribution
- Wilson coefficients dim-6 operators

$C_{tG} \in [-0.68, 0.21]$

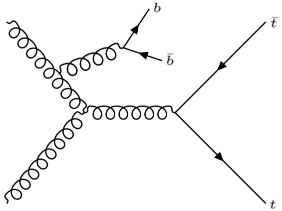
$C^{8}_{tq} \in [-0.30, 0.36]$

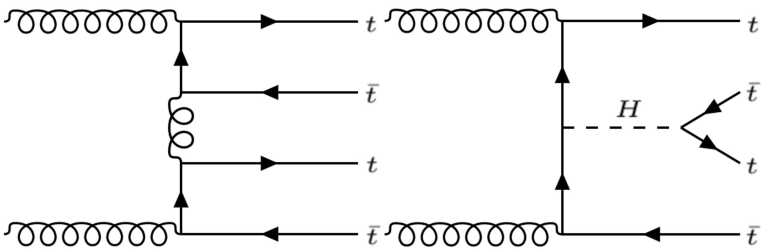
NNLO QCD + NLO EW improves agreement with data

4top

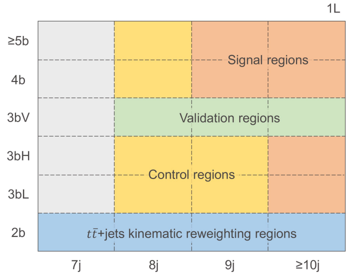
arXiv:2106.11683

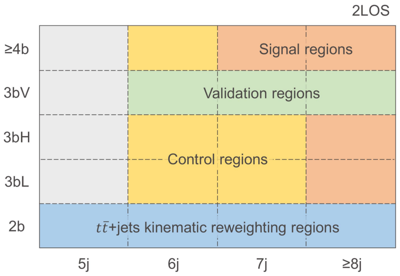
- Final state: e/m or OS lep pair + n jets
- BDT for signal/bkg(ttbb) separation

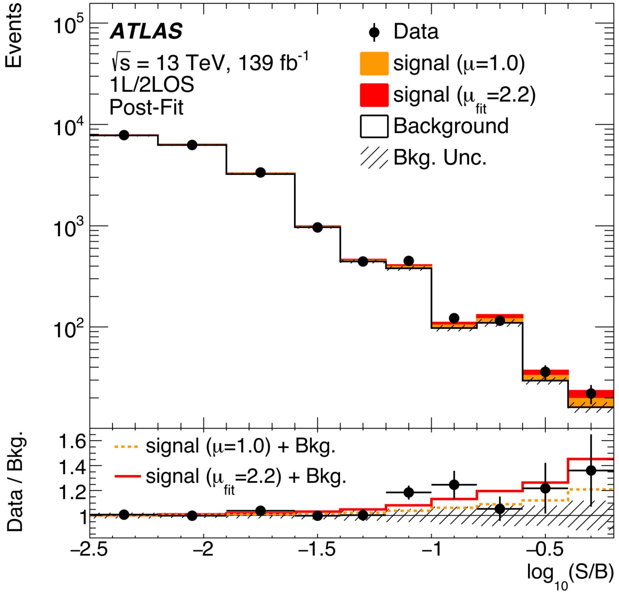


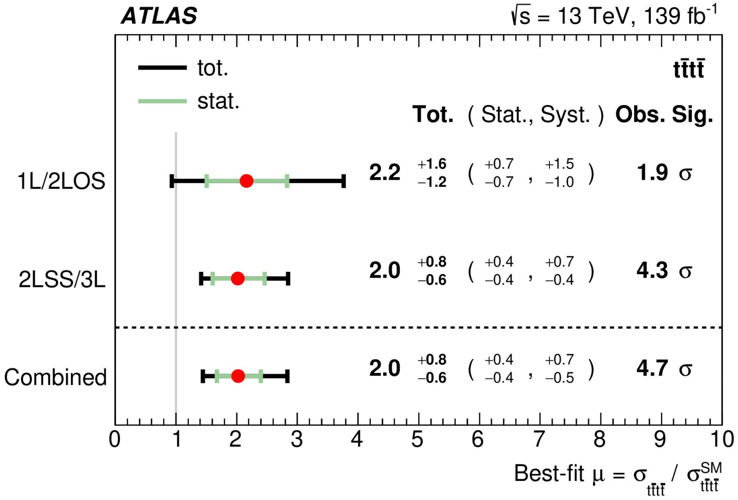


$$\sigma_{t\bar{t}t\bar{t}} = 24 \pm 4\,(\text{stat.})\,^{+5}_{-4}\,(\text{syst.})\,\text{fb} = 24\,^{+7}_{-6}\,\text{fb}.$$

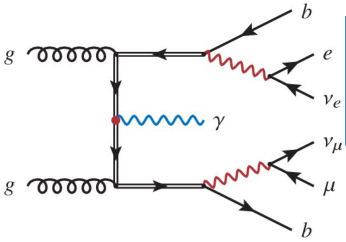






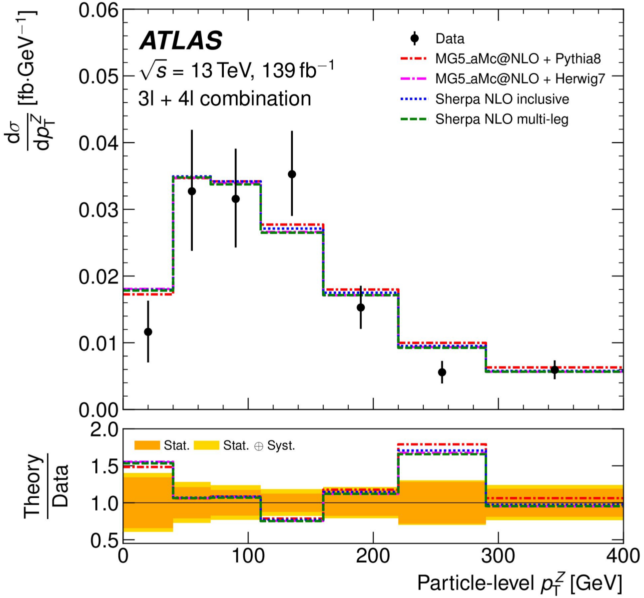


ttbarZ / ttbarγ



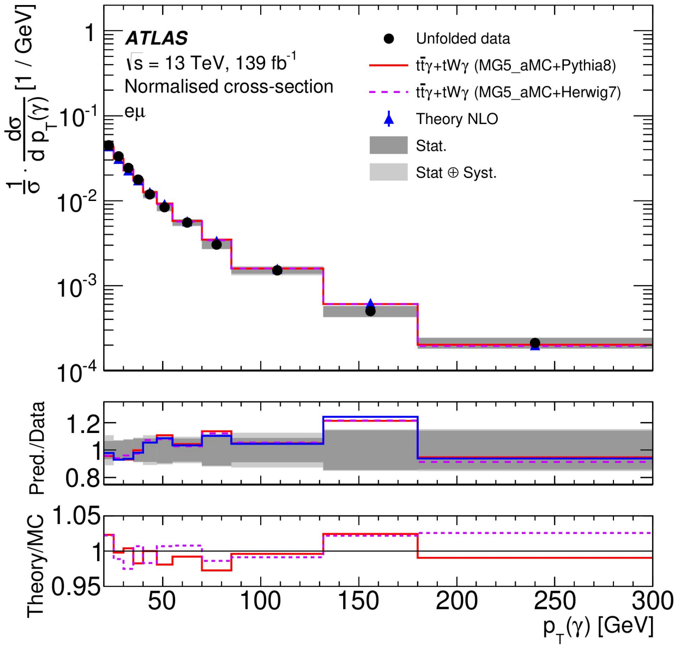
arXiv:2103.12603
arXiv:2007.06946

- Probe neutral t-Z/t-γ coupling with ttbar+Z / ttbar + γ
- Final state: 3 or 4 isolated leptons (ttZ) / γ, OS e+m, 2 jets (1 b-jet) (ttγ)



Inclusive cross section measured with 10% precision

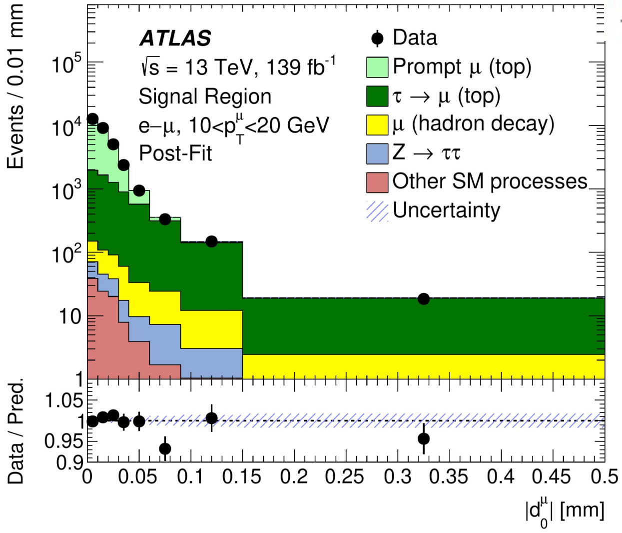
Inclusive cross section measured with 7 % precision



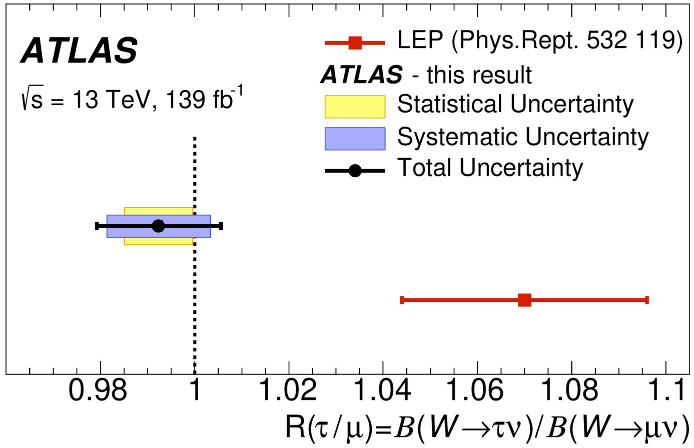
$\sigma_{t\bar{t}Z}$=0.99±0.05(stat.)±0.08(syst.) pb

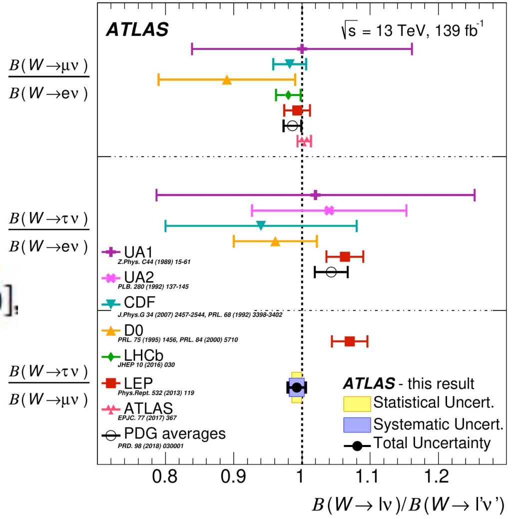
Lepton flavor universality

- From W-decays to tau and muons
- Novel technique using ttbar events
- Fit to d_0 distribution to separate mu from Ws and taus



$$R(\tau/\mu) = 0.992 \pm 0.013\ [\pm 0.007\ (\text{stat}) \pm 0.011\ (\text{syst})],$$

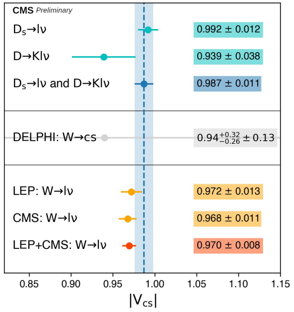


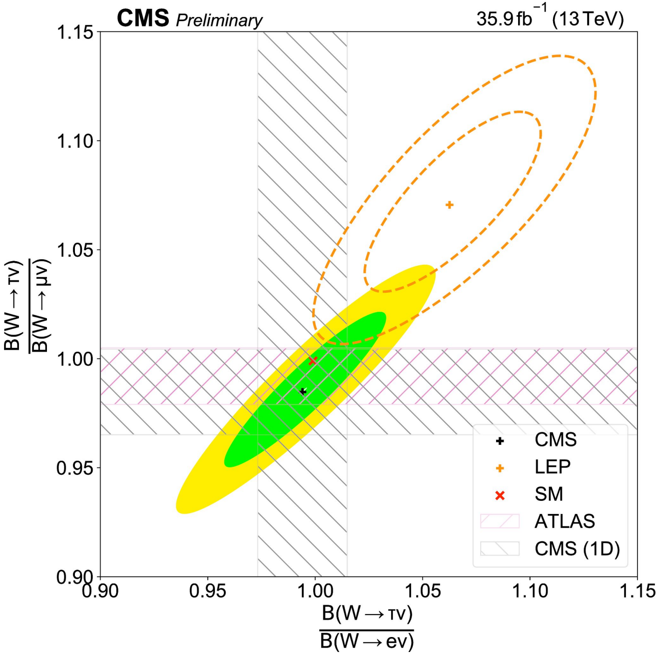


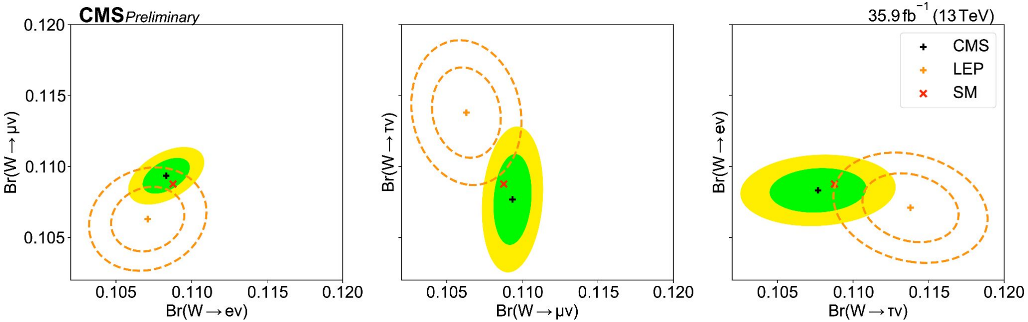
1% precision
better than LEP!

W branching ratio

- Leptonic and hadronic branching ratios measured individually using a simultaneous fit of (subleading) lepton pT using tt, tW, and WW events
- Final state: WW or W+jets
- e: (10.83±0.1)%
- m: (10.94±0.08)%
- tau: (10.77±0.21)%

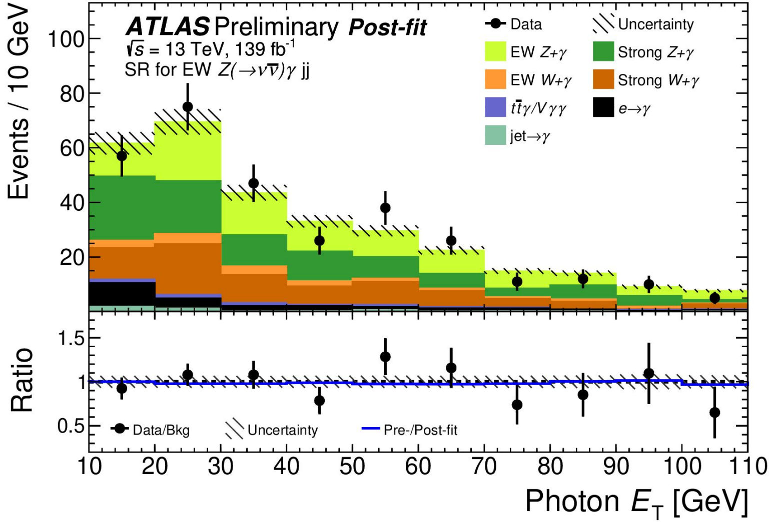


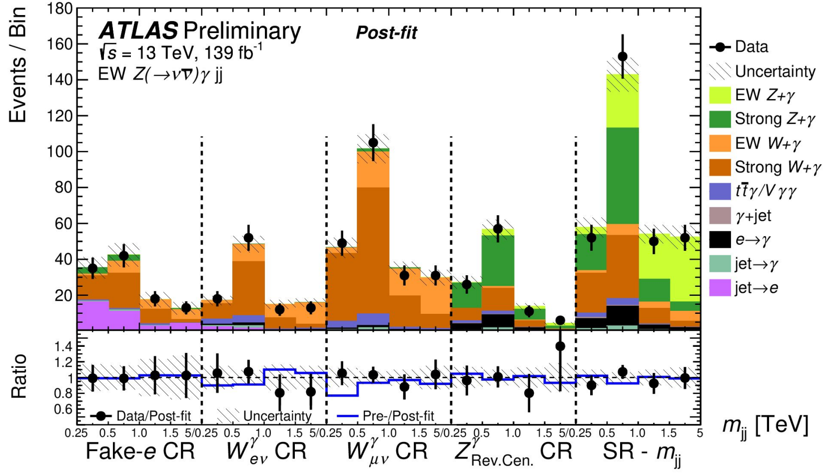




Observation of EW $Z\gamma$+2j

- Z to $\nu\nu$ is interesting for BSM
- Observed with 5.2 σ
- Fiducial cross section:
  1.31 ± 0.20 (stat) ± 0.20 (syst) fb





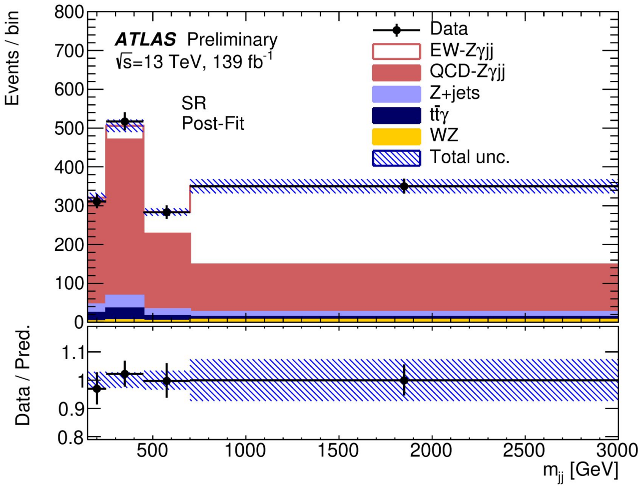
$\mu_{Z\gamma_{\text{EW}}}$	$\beta_{Z\gamma_{\text{QCD}}}$	$\beta_{W\gamma}$
1.03 ± 0.25	1.02 ± 0.41	1.01 ± 0.20

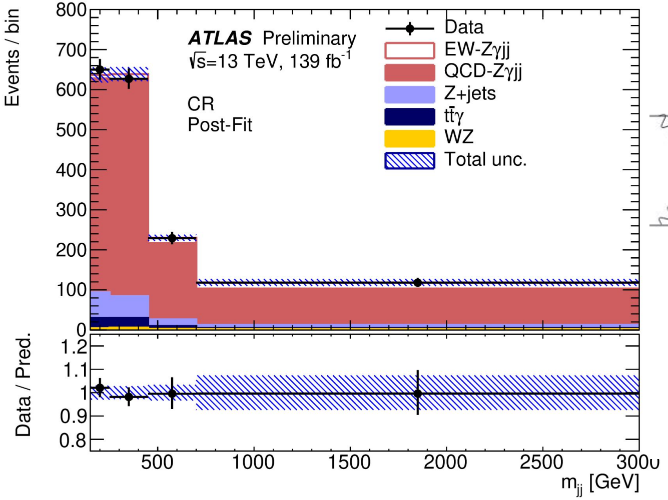
Measurement of EW Zγ+2j

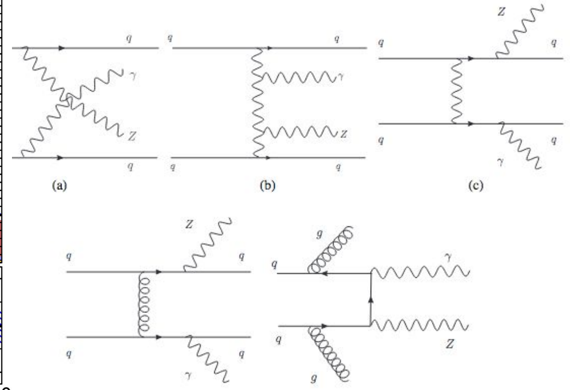
- Z to ll
- Fit to mjj distribution
- Observed with 10 σ

$$\sigma_{EW+QCD} = 20.6 \pm 0.6\,(\text{stat.})^{+1.2}_{-1.0}\,(\text{syst.})\text{ fb},$$

$$\sigma^{pred}_{EW+QCD} = 20.4 \pm 0.1\,(\text{stat.}) \pm 0.2\,(\text{PDF})^{+2.6}_{-2.0}\,(\text{scale})\text{ fb}$$





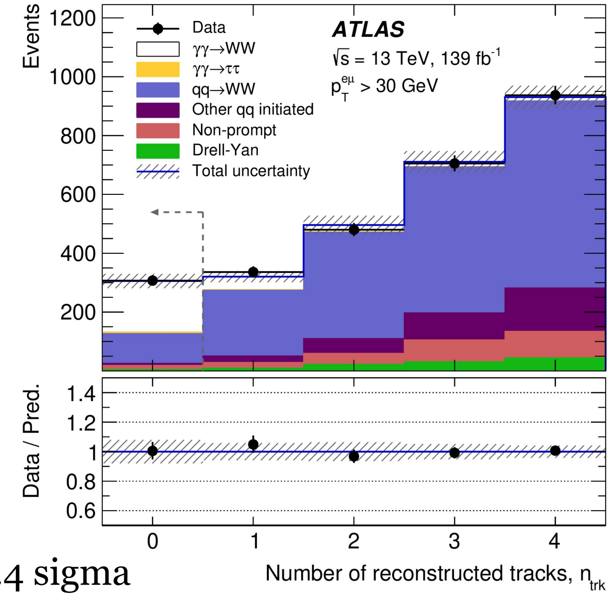


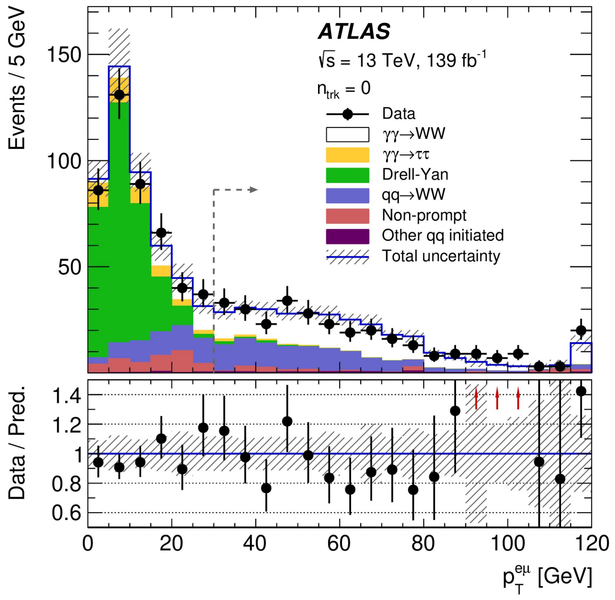
arXiv:2010.04019

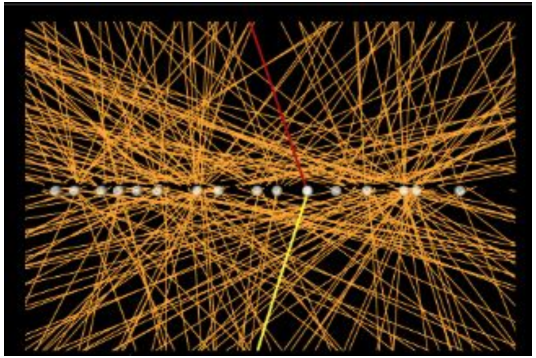
Observation of photon induced WW

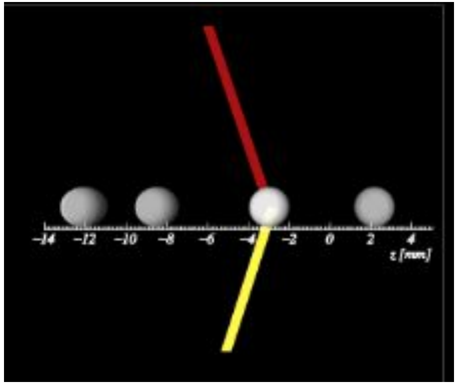
- LHC as photon collider, very rare process
- Final state: e+m OS

$$\sigma_{\text{meas}} = 3.13 \pm 0.31\,(\text{stat.}) \pm 0.28\,(\text{syst.})\ \text{fb}$$





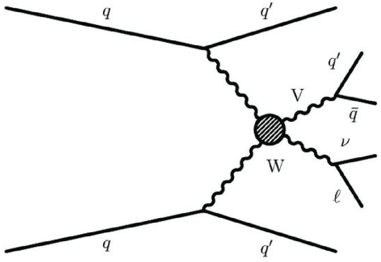


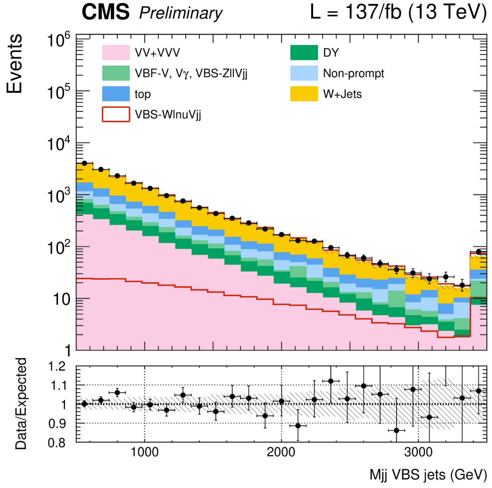


8.4 sigma

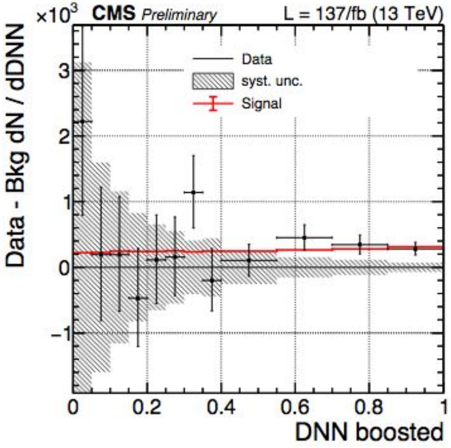
Semileptonic WV VBS

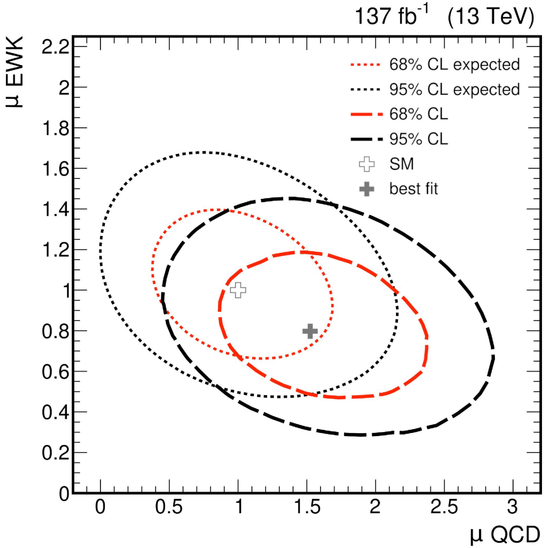
- Selection: 1 lepton, MET, 2 jets (consistent with W/Z decay)
- e/m channels
- Dominant bkg: W+jets and ttbar estimated from CR
- First evidence of VBS in semileptonic channel





$$\mu_{EW} = \sigma^{obs}/\sigma^{SM} = 0.85^{+0.24}_{-0.20} = 0.85^{+0.21}_{-0.17}(\text{syst})\ ^{+0.12}_{-0.12}(\text{stat}),$$

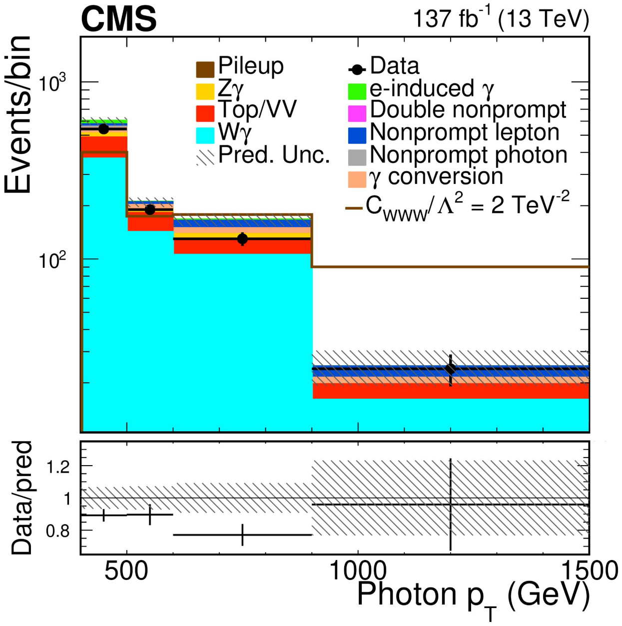


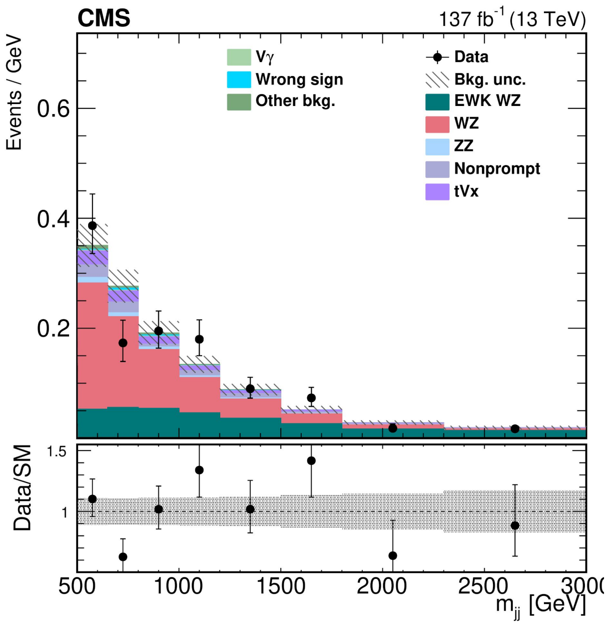


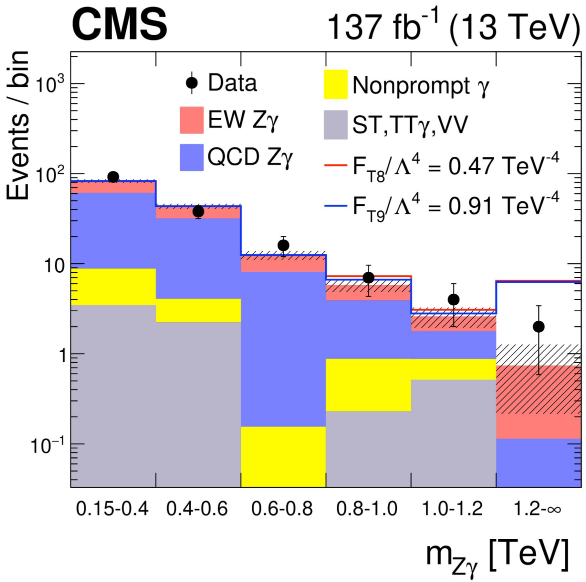
CMS-SMP-19-012
CMS-SMP-19-002
CMS-SMP-20-016

VBS Wγ, WZ, Zγ

- Setting EFT limits, probing aQGC



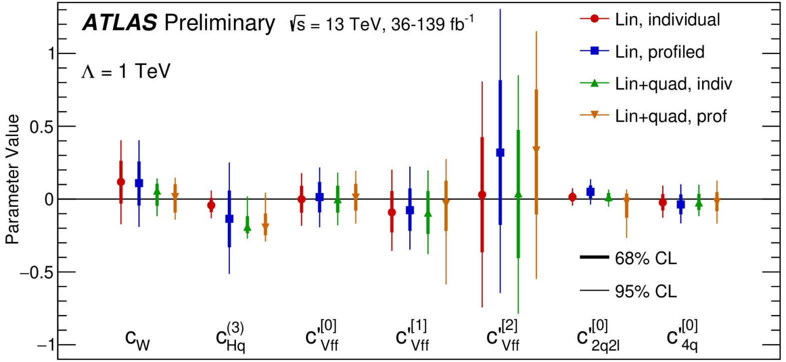




ATL-PHYS-PUB-2021-022

Dim-6 EFT

- Combined interpretation of WW (lep), WZ (lep), 4l, Z->ll (VBF) (6 differential inputs)
  - WW (36 fb^{-1}) : leading lepton pT
  - WZ (36 fb^{-1}) : m_T(WZ)
  - 4ℓ (139 fb^{-1}) : m(Z2) in 3 m(4ℓ) regions
  - VBF Z (139 fb^{-1}) : $\Delta\varphi$(jj)
- 33 operators
- Lin and quad effects constrained separately on 15 Wilson coefficient linear combinations



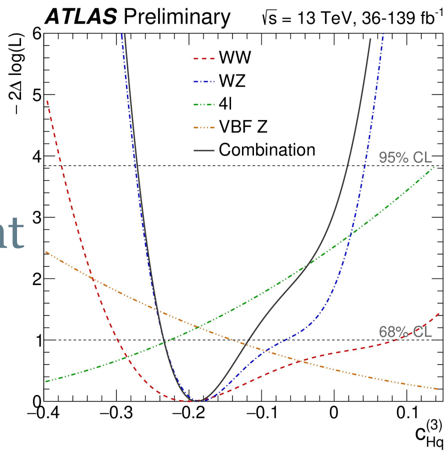
$c'^{[0]}_{Vff} \approx 0.81c_{HWB} + 0.38c_{HD} + 0.13c^{(1)}_{Hl} + 0.37c^{(3)}_{Hl} - 0.14c^{(1)}_{ll} + 0.12c^{(1)}_{Hq}$

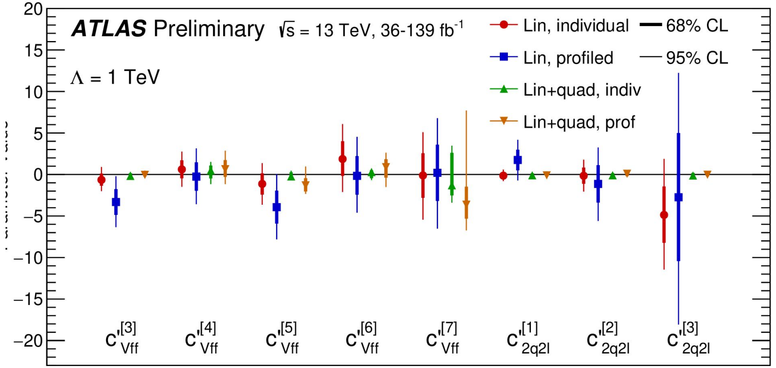
$c'^{[1]}_{Vff} \approx 0.73c^{(1)}_{Hl} - 0.28c^{(3)}_{Hl} - 0.48c_{He} + 0.38c^{(1)}_{ll} + 0.13c^{(1)}_{Hq}$

$c'^{[2]}_{Vff} \approx 0.37c_{HWB} + 0.17c_{HD} - 0.31c^{(1)}_{Hl} - 0.53c^{(3)}_{Hl} + 0.25c_{He} + 0.59c^{(1)}_{ll} - 0.21c^{(1)}_{Hq}$

$c'^{[0]}_{2q2l} \approx -0.37c^{(1)}_{lq} + 0.89c^{(3)}_{lq} - 0.11c_{lu} - 0.21c_{eu} - 0.13c_{qe}$

$c'^{[0]}_{4q} \approx 0.11c^{(11)}_{qq} + 0.22c^{(18)}_{qq} + 0.95c^{(31)}_{qq} - 0.2c^{(38)}_{qq}$





$c'^{[3]}_{Vff} \approx -0.19c^{(1)}_{Hl} - 0.14c^{(3)}_{Hl} + 0.86c^{(1)}_{Hq} + 0.41c_{Hu} - 0.17c_{Hd}$

$c'^{[4]}_{Vff} \approx -0.35c_{HWB} + 0.49c_{HD} + 0.26c^{(1)}_{Hl} + 0.35c^{(3)}_{Hl} + 0.51c_{He} + 0.38c^{(1)}_{ll} + 0.18c^{(1)}_{Hq}$

$c'^{[5]}_{Vff} \approx 0.25c_{HD} + 0.33c^{(1)}_{Hl} - 0.22c^{(3)}_{Hl} + 0.18c_{He} - 0.35c^{(1)}_{ll} - 0.3c^{(1)}_{Hq} + 0.71c_{Hu} - 0.16c_{Hd}$

$c'^{[6]}_{Vff} \approx -0.22c^{(1)}_{Hl} + 0.52c^{(3)}_{Hl} - 0.39c_{He} + 0.44c^{(1)}_{ll} - 0.22c^{(1)}_{Hq} + 0.52c_{Hu}$

$c'^{[7]}_{Vff} \approx -0.28c_{HWB} + 0.71c_{HD} - 0.31c^{(1)}_{Hl} - 0.21c^{(3)}_{Hl} - 0.5c_{He} - 0.14c^{(1)}_{ll}$

$c'^{[1]}_{2q2l} \approx 0.56c^{(1)}_{lq} + 0.44c^{(3)}_{lq} + 0.61c_{eu} - 0.1c_{ed} + 0.34c_{qe}$

$c'^{[2]}_{2q2l} \approx 0.68c^{(1)}_{lq} + 0.15c^{(3)}_{lq} + 0.33c_{lu} - 0.51c_{eu} + 0.13c_{ed} - 0.37c_{qe}$

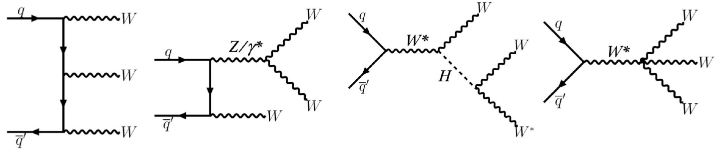
$c'^{[3]}_{2q2l} \approx -0.27c^{(1)}_{lq} + 0.79c_{lu} - 0.39c_{ld} + 0.26c_{eu} - 0.22c_{ed}$ [illegible] c_{qe}

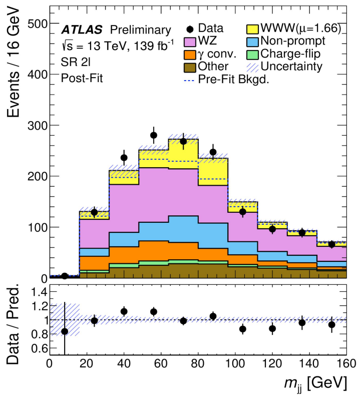
No deviations from SM expectation

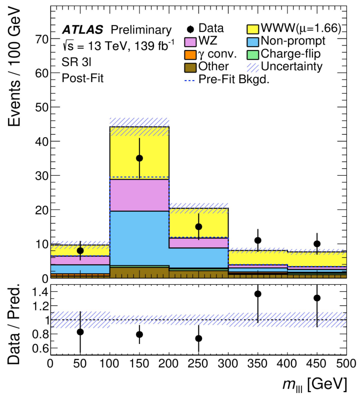
ATLAS-CONF-2021-039

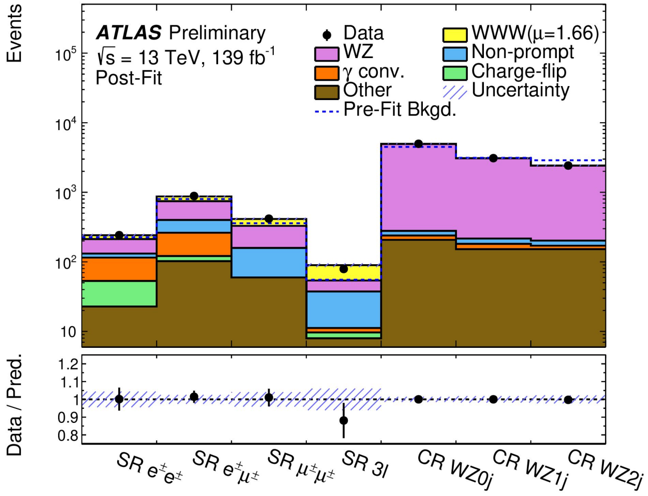
Observation of WWW

- Selection: e/m SS + 2 jets and more or 3 leptons
- Separate BDTs for 2l and 3l channels for signal/bkg separation
- σ_{WWW} = 850 ±100 (stat.) ±80 (syst.) fb



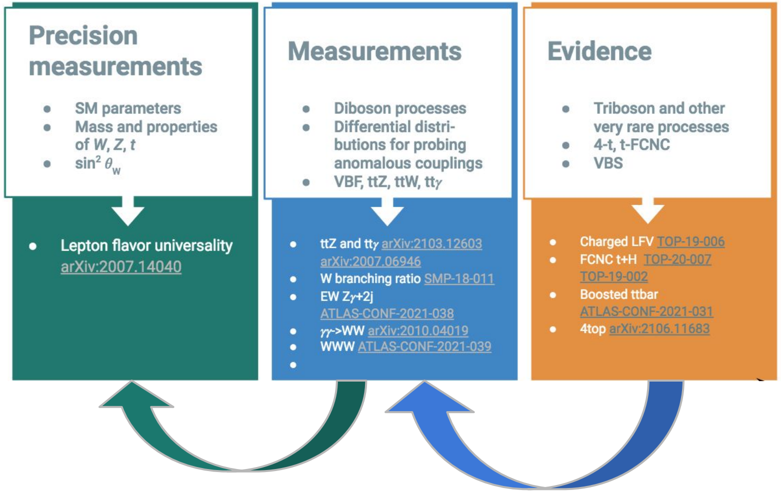






Fit	Observed (expected) significances [σ]	$\mu(WWW)$
$e^\pm e^\pm$	2.3 (1.4)	1.69 ± 0.79
$e^\pm \mu^\pm$	4.6 (3.1)	1.57 ± 0.40
$\mu^\pm \mu^\pm$	5.6 (2.8)	2.13 ± 0.47
2ℓ	6.9 (4.1)	1.80 ± 0.33
3ℓ	4.8 (3.7)	1.33 ± 0.39
Combined	**8.2 (5.4)**	$\mathbf{1.66 \pm 0.28}$

Summary

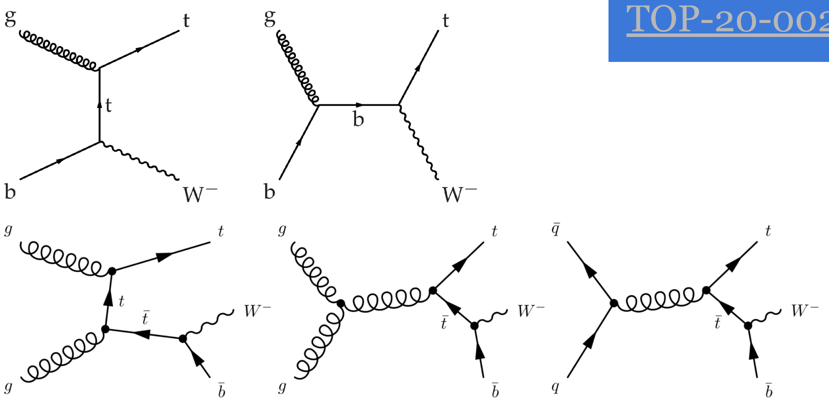


- Very fruitful EW and top programme at ATLAS and CMS experiments
- Almost all results with full Run-2 datasets
- Use of novel analysis techniques
- The gear is switching towards differential distributions and EFT interpretation of the measurements
- Even better precision and evidence for rare processes will be possible with Run-3 data
- Future prospects with even larger dataset at HL-LHC (talk from S. Sekmen)
- Keep an eye on full list of results: ATLAS Results CMS Results

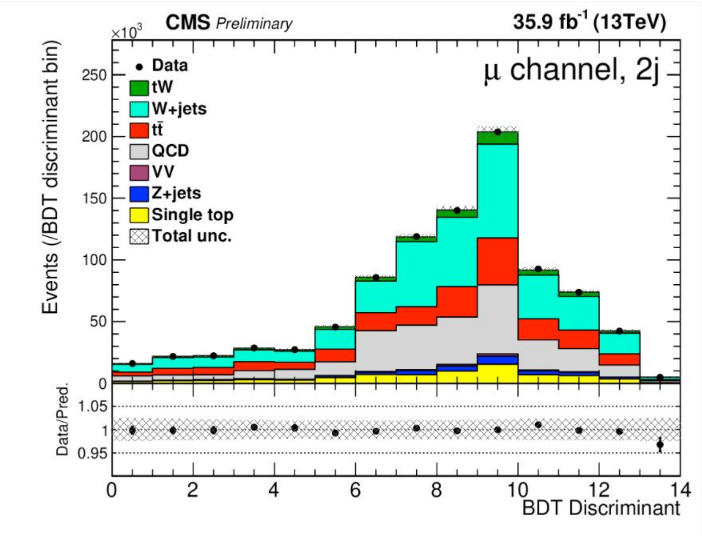
BACKUP

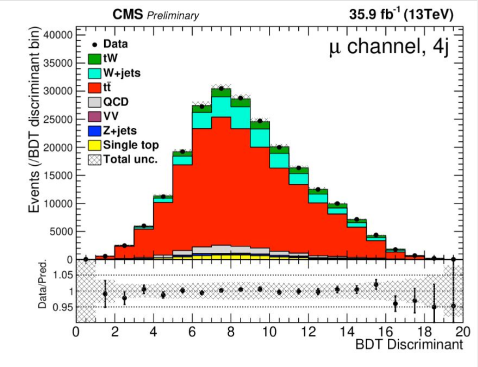
tW production

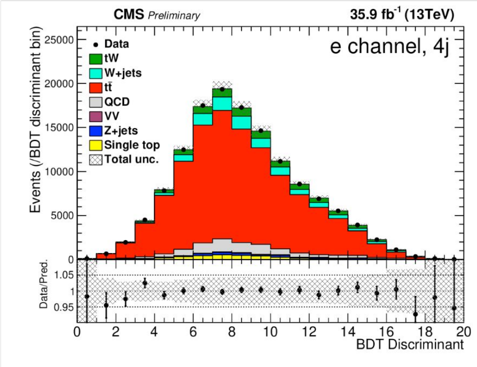
TOP-20-002



- Final state: e/mu + jets
- MVA to separate the signal from dominant ttbar bkg







- Observed significance: > 5 σ
- Measured signal strength is μ = 1.24 ±0.18
- Inclusive cross section 89 ±4 (stat) ±12 (syst) pb

Dim-6 EFT

Parameter	Linear fit					Linear-plus-quadratic fit				
		68% CI Bound.		95% CI Bound.			68% CI Bound.		95% CI Bound.	
	Best fit	Lower	Upper	Lower	Upper	Best fit	Lower	Upper	Lower	Upper
c_W	0.11	-0.04	0.26	-0.19	0.40	0.01	-0.09	0.10	-0.14	0.15
$c_{Hq}^{(3)}$	-0.14	-0.33	0.06	-0.51	0.25	-0.20	-0.25	-0.10	-0.29	0.04
$c'^{[0]}_{Vff}$	0.01	-0.09	0.12	-0.19	0.22	0.01	-0.08	0.10	-0.17	0.19
$c'^{[1]}_{Vff}$	-0.08	-0.22	0.07	-0.35	0.22	-0.03	-0.22	0.13	-0.58	0.27
$c'^{[2]}_{Vff}$	0.32	-0.18	0.82	-0.65	1.30	0.33	-0.10	0.75	-0.55	1.15
$c'^{[3]}_{Vff}$	-3.31	-4.87	-1.76	-6.34	-0.20	-0.05	-0.24	0.22	-0.41	0.47
$c'^{[4]}_{Vff}$	-0.25	-1.96	1.46	-3.58	3.14	0.63	-0.29	1.73	-1.15	2.86
$c'^{[5]}_{Vff}$	-3.93	-5.91	-1.94	-7.81	0.03	-1.30	-2.04	-0.45	-2.33	0.96
$c'^{[6]}_{Vff}$	-0.16	-2.43	2.21	-4.60	4.52	0.89	-0.38	1.84	-1.51	2.62
$c'^{[7]}_{Vff}$	0.20	-3.19	3.59	-6.52	6.78	-3.64	-5.32	-1.47	-6.73	7.71
$c'^{[0]}_{2l2q}$	0.05	0.01	0.09	-0.04	0.14	-0.02	-0.13	0.04	-0.27	0.07
$c'^{[1]}_{2l2q}$	1.75	0.50	2.98	-0.72	4.17	-0.10	-0.22	0.20	-0.30	0.36
$c'^{[2]}_{2l2q}$	-1.13	-3.38	1.12	-5.60	3.25	0.09	-0.19	0.23	-0.30	0.32
$c'^{[3]}_{2l2q}$	-2.75	-10.43	5.00	-18.07	12.24	-0.03	-0.22	0.21	-0.29	0.34
$c'^{[0]}_{4q}$	-0.04	-0.10	0.03	-0.17	0.10	-0.02	-0.08	0.05	-0.17	0.13

Wilson coefficient and operator		Final state affected at leading order			
		$e^\pm\nu\mu^\mp\nu$	$\ell^+\ell^-\ell^\pm\nu$	4ℓ	$\ell^+\ell^-jj$
c_G	$f^{abc}G_\mu^{a\nu}G_\nu^{b\rho}G_\rho^{c\mu}$				✓
c_W	$\epsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	✓	✓		✓
c_{HD}	$\left(H^\dagger D_\mu H\right)^*\left(H^\dagger D_\mu H\right)$		✓	✓	✓
c_{HWB}	$H^\dagger\tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$	✓	✓	✓	✓
$c_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}\gamma^\mu l)$	✓	✓	✓	✓
$c_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{l}\tau^I\gamma^\mu l)$	✓	✓	✓	✓
c_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}\gamma^\mu e)$		✓	✓	✓
$c_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q)$	✓	✓	✓	✓
$c_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{q}\tau^I\gamma^\mu q)$	✓	✓	✓	✓
c_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u)$	✓	✓	✓	✓
c_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)$	✓	✓	✓	✓
$c_{ll}^{(1)}$	$(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$	✓	✓	✓	✓
$c_{lq}^{(1)}$	$(\bar{l}\gamma_\mu l)(\bar{q}\gamma^\mu q)$	✓	✓	✓	(✓)
$c_{lq}^{(3)}$	$(\bar{l}\gamma_\mu\tau^I l)(\bar{q}\gamma^\mu\tau^I q)$	✓	✓	✓	(✓)
c_{eu}	$(\bar{e}\gamma_\mu e)(\bar{u}\gamma^\mu u)$			✓	(✓)
c_{ed}	$(\bar{e}\gamma_\mu e)(\bar{d}\gamma^\mu d)$			✓	(✓)
c_{lu}	$(\bar{l}\gamma_\mu l)(\bar{u}\gamma^\mu u)$	✓		✓	(✓)
c_{ld}	$(\bar{l}\gamma_\mu l)(\bar{d}\gamma^\mu d)$	✓		✓	(✓)
c_{qe}	$(\bar{q}\gamma_\mu q)(\bar{e}\gamma^\mu e)$		✓	✓	(✓)
$c_{qq}^{(1,1)}$	$(\bar{q}\gamma_\mu q)(\bar{q}\gamma^\mu q)$				✓
$c_{qq}^{(1,8)}$	$(\bar{q}T^a\gamma_\mu q)(\bar{q}T^a\gamma^\mu q)$				✓
$c_{qq}^{(3,1)}$	$(\bar{q}\sigma^i\gamma_\mu q)(\bar{q}\sigma^i\gamma^\mu q)$				✓
$c_{qq}^{(3,8)}$	$(\bar{q}\sigma^i T^a\gamma_\mu q)(\bar{q}\sigma^i T^a\gamma^\mu q)$				✓
$c_{uu}^{(1)}$	$(\bar{u}\gamma_\mu u)(\bar{u}\gamma^\mu u)$				✓
$c_{uu}^{(8)}$	$(\bar{u}T^a\gamma_\mu u)(\bar{u}T^a\gamma^\mu u)$				✓
$c_{dd}^{(1)}$	$(\bar{d}\gamma_\mu d)(\bar{d}\gamma^\mu d)$				✓
$c_{dd}^{(8)}$	$(\bar{d}T^a\gamma_\mu d)(\bar{d}T^a\gamma^\mu d)$				✓
$c_{ud}^{(1)}$	$(\bar{u}\gamma_\mu u)(\bar{d}\gamma^\mu d)$				✓
$c_{ud}^{(8)}$	$(\bar{u}T^a\gamma_\mu u)(\bar{d}T^a\gamma^\mu d)$				✓
$c_{qu}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{u}\gamma^\mu u)$				✓
$c_{qu}^{(8)}$	$(\bar{q}T^a\gamma_\mu q)(\bar{u}T^a\gamma^\mu u)$				✓
$c_{qd}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{d}\gamma^\mu d)$				✓
$c_{qd}^{(8)}$	$(\bar{q}T^a\gamma_\mu q)(\bar{d}T^a\gamma^\mu d)$				✓