Effective Field Theory in CMS and ATLAS

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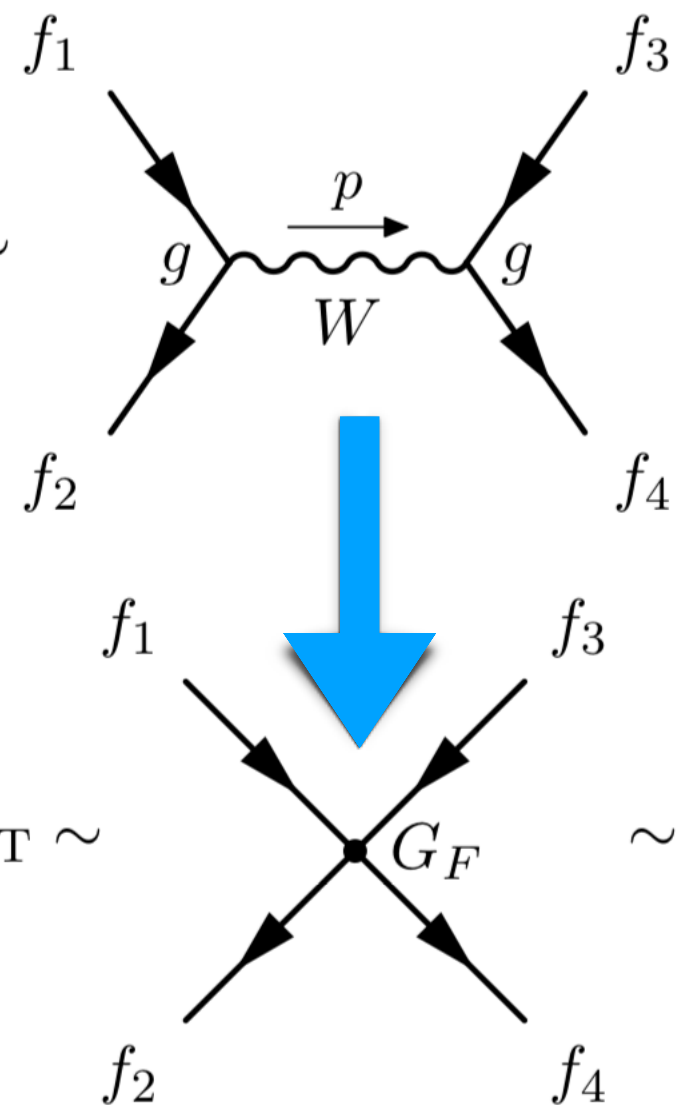
Effective Field Theories

Text book example of EFT: Fermi Theory

$$\mathcal{M}_{\text{full}} \sim \qquad \sim \frac{g^2}{p^2 - m_W^2}$$



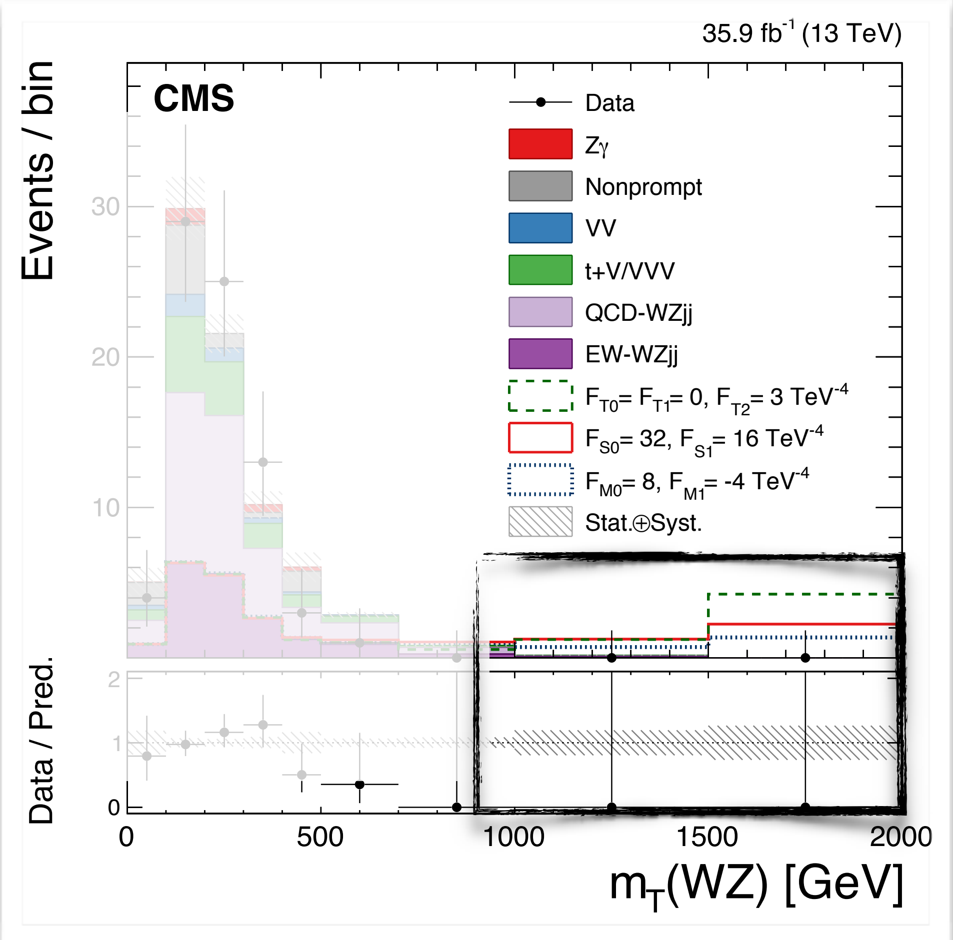
$$\mathcal{M}_{\text{EFT}} \sim \qquad \sim G_F \propto -\frac{g^2}{m_W^2}$$

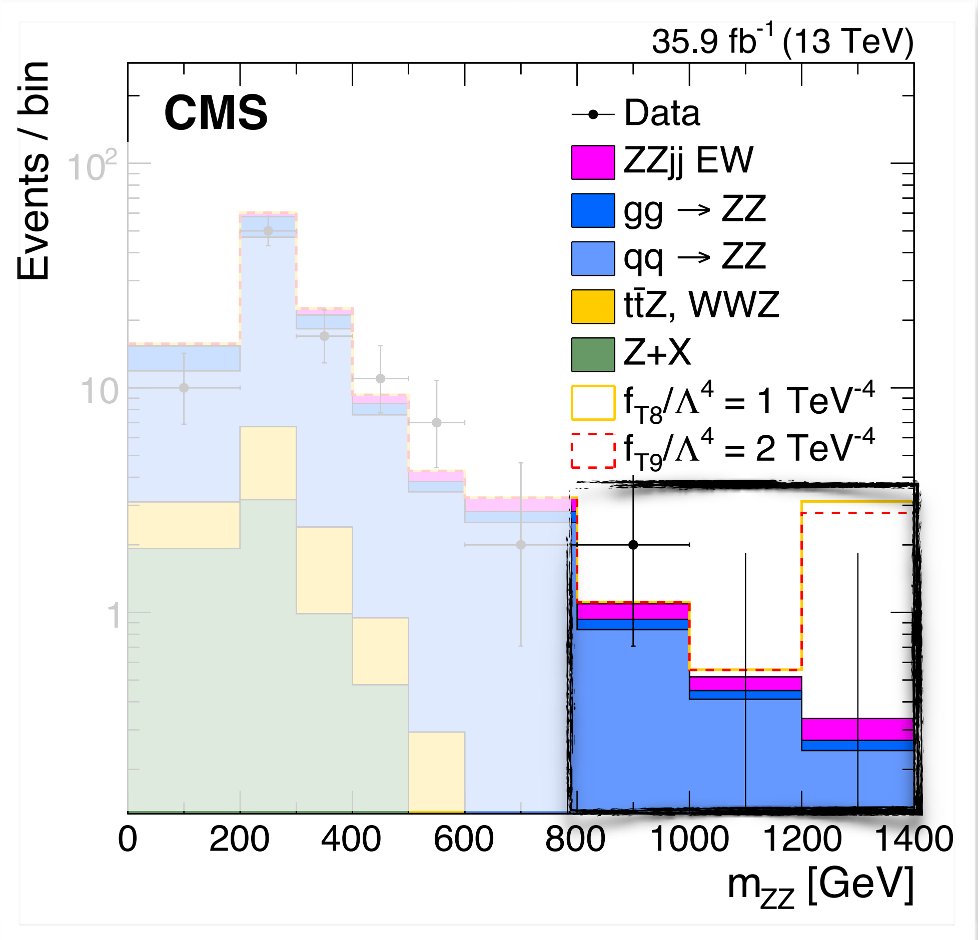
Valid when: $p^2 \ll M_W^2$

Error increases as a function of momentum transfer, √s

Effective Field Theories

Complementary to BSM searches





Instead of bump hunting, looking for new physics in the tails of distributions

Effective Field Theory Framework

https://arxiv.org/pdf/1205.4231.pdf

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\lambda^2}\mathcal{O}_i + \sum_j \frac{f_j}{\lambda^4}\mathcal{O}_j + \cdots$$

- **Requirements:**
  - Any extension of the Standard Model (SM) should satisfy the *S*-matrix axioms of unitarity
  - Symmetries of the SM should be respected
  - The SM should be recoverable in the appropriate limit
  - It should be possible to compute radiative corrections at any order in the extended theory and the SM interactions with this theory

Achieved with effective Quantum Field Theory

EFT Operators

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\lambda^2}\mathcal{O}_i + \sum_j \frac{f_j}{\lambda^4}\mathcal{O}_j + \cdots$$

- **CP conserving trilinear operators are of the form:**

$$\mathcal{O}_{WWW} = \mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W_{\rho}^{\mu}] \qquad \mathcal{O}_B = (\mathcal{D}_\mu\Phi)^\dagger B^{\mu\nu}(\mathcal{D}_\nu\Phi) \qquad \mathcal{O}_W = (\mathcal{D}_\mu\Phi)^\dagger W^{\mu\nu}(\mathcal{D}_\nu\Phi)$$

- **CP conserving quartic operators are of the form:**

$$\mathcal{L}_{\mathrm{S},0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right]$$

Longitudinal operators

$$\mathcal{L}_{\mathrm{M},0} = Tr\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$

Mixed operators

$$\mathcal{L}_{\mathrm{T},0} = Tr\left[W_{\mu\nu}W^{\mu\nu}\right] \times Tr\left[W_{\alpha\beta}W^{\alpha\beta}\right]$$

Transverse operators

EFT Operators

https://arxiv.org/pdf/1205.4231.pdf

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\lambda^2}\mathcal{O}_i + \sum_j \frac{f_j}{\lambda^4}\mathcal{O}_j + \cdots$$

Experimentally limits computed on c_i *and* f_j

- CP conserving trilinear operators are of the form:

$\mathcal{O}_{WW}$ … $^{\mu\nu}(\mathcal{D}_\nu\Phi)$

Explored with diboson final states

- CP conserving quartic operators are of the form:

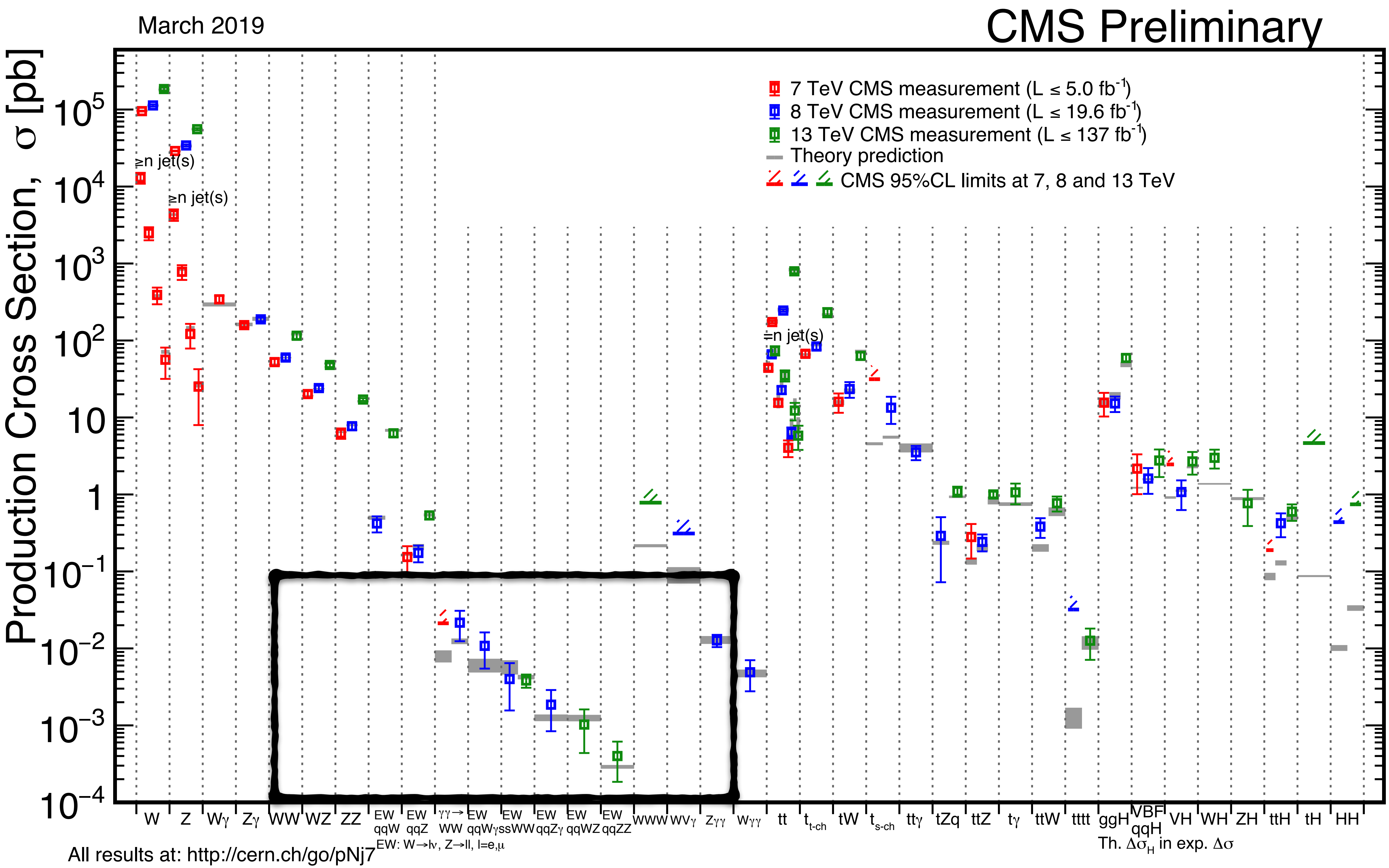
$\mathcal{L}_{S,}$ … $\mathcal{D}^\beta\Phi]$

Explored with vector boson scattering and triboson final states

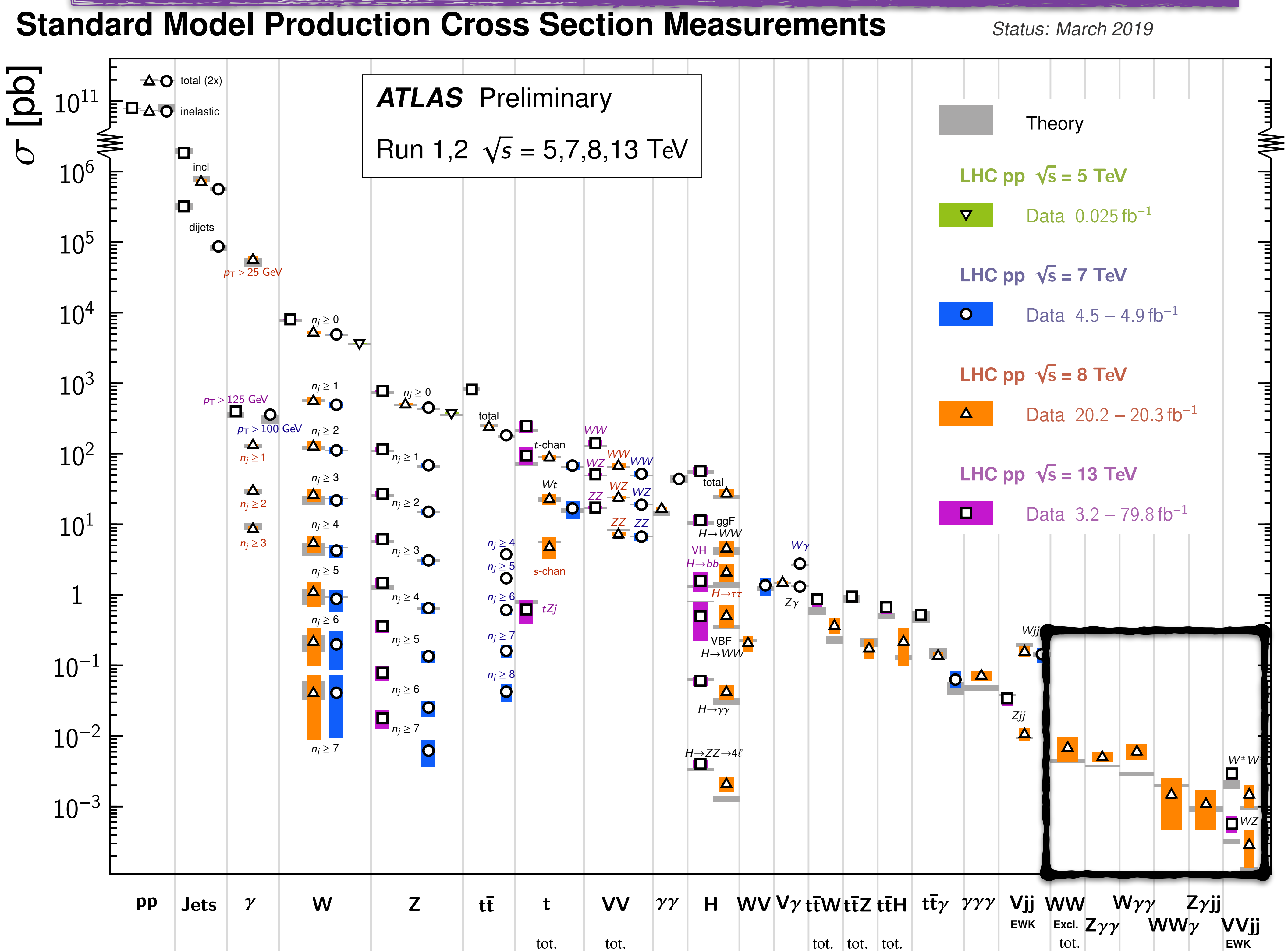
$$\mathcal{L}_{T,0} = Tr\left[W_{\mu\nu}W^{\mu\nu}\right] \times Tr\left[W_{\alpha\beta}W^{\alpha\beta}\right]$$

Transverse operators

SM cross section summary: CMS

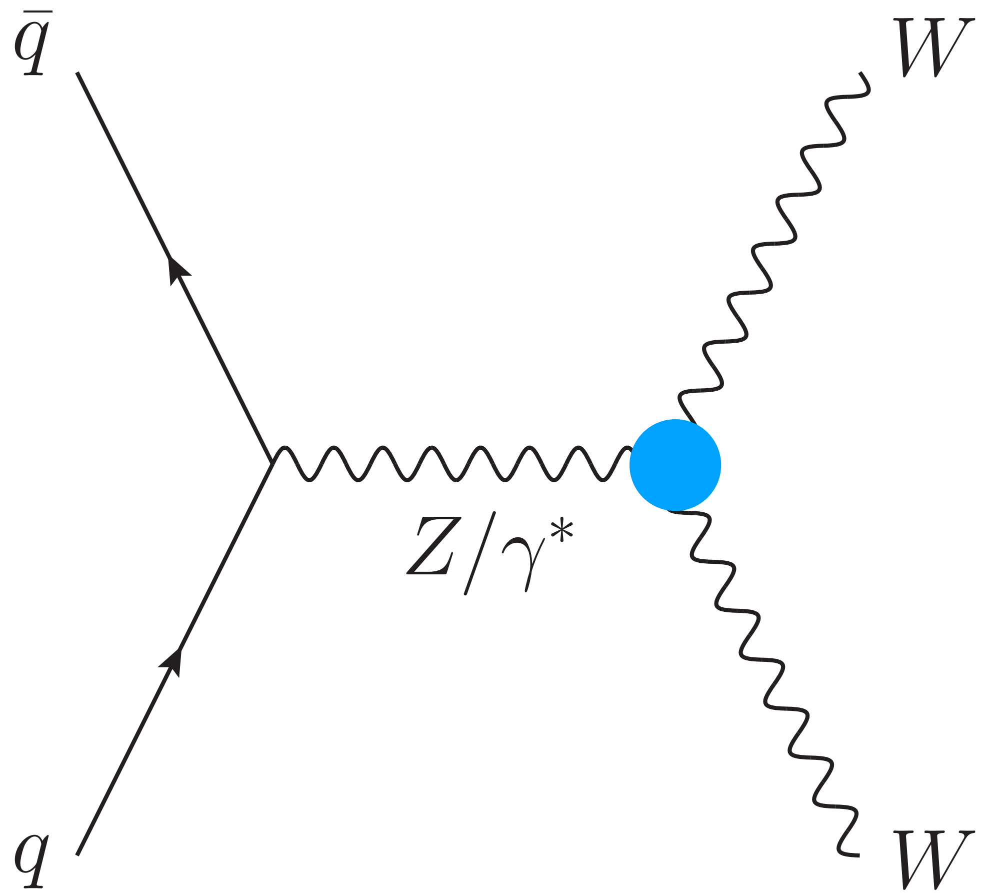


SM cross section summary: ATLAS



Anomalous Trilinear Couplings: W^+W^-

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2017-24/

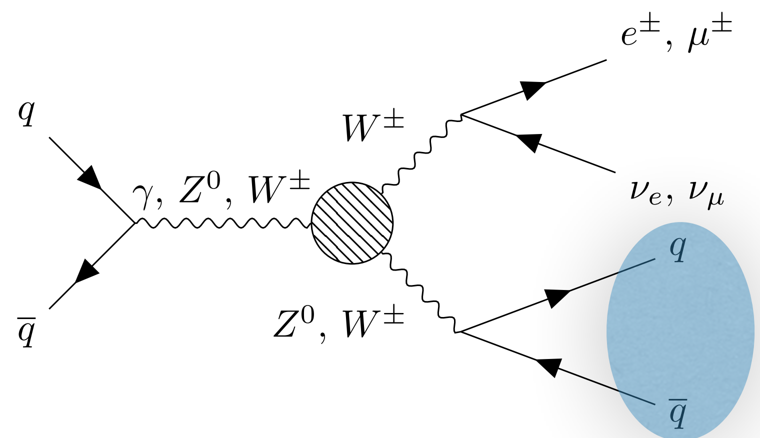


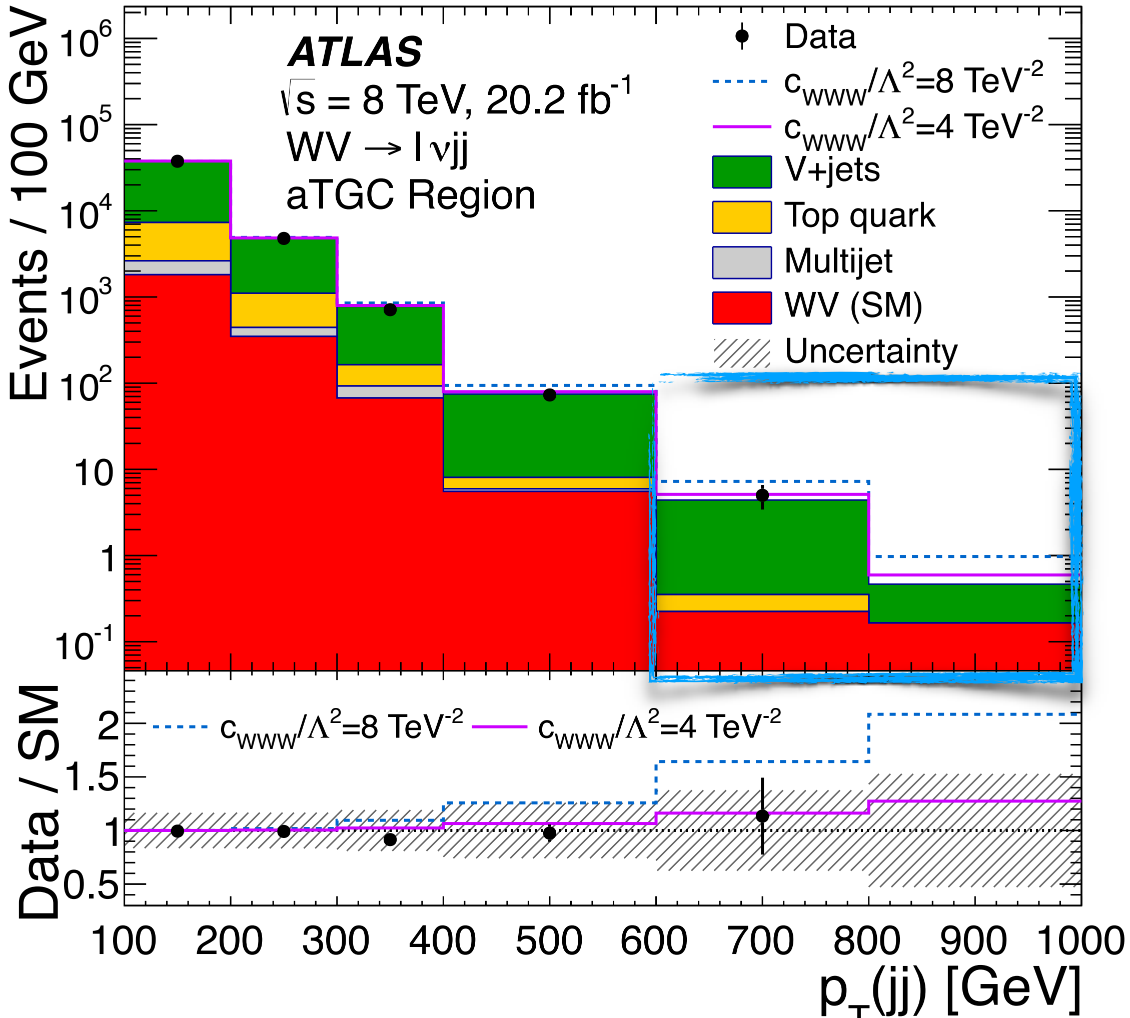
- s-channel diagram can acquire anomalous contributions
- Signal region **defined by presence of $e^{\pm}\mu^{\pm}$**
- **Generic feature in diboson/triboson final states:** b-veto
- Constraints on EFT placed by using unfolded, $\mathbf{P_T}$ of leading lepton, $\mathbf{P_T^{lead}}$

	Parameter	Observed 95% CL [TeV^{-2}]	Expected 95% CL [TeV^{-2}]
CP conserving	c_{WWW}/Λ^2	[−3.4 , 3.3]	[−3.0 , 3.0]
	c_W/Λ^2	[−7.4 , 4.1]	[−6.4 , 5.1]
	c_B/Λ^2	[−21 , 18]	[−18 , 17]
Allowing for CP violation	$c_{\tilde{W}WW}/\Lambda^2$	[−1.6 , 1.6]	[−1.5 , 1.5]
	$c_{\tilde{W}}/\Lambda^2$	[−76 , 76]	[−91 , 91]

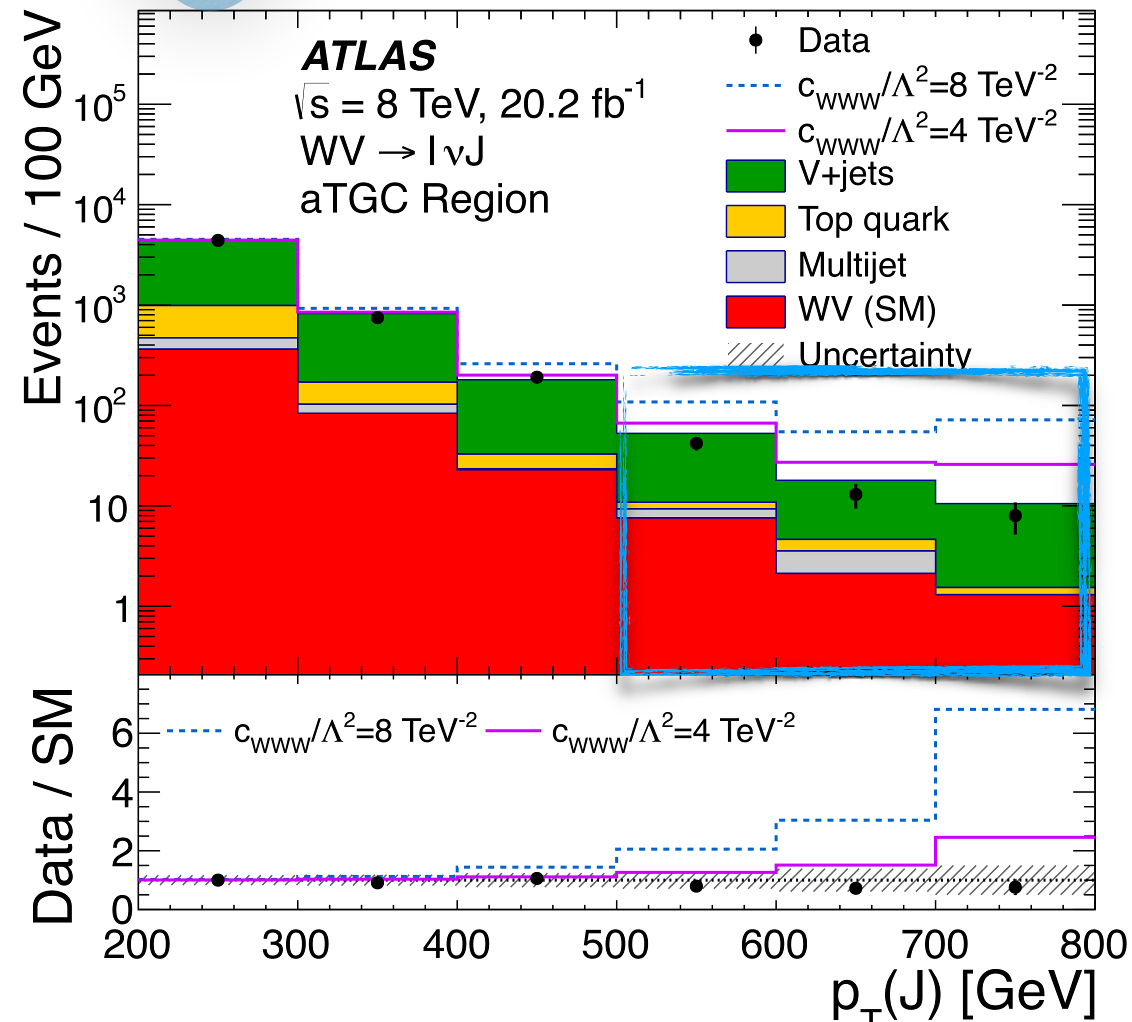
Anomalous Trilinear Couplings: WW/WZ semileptonic

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2015-23/



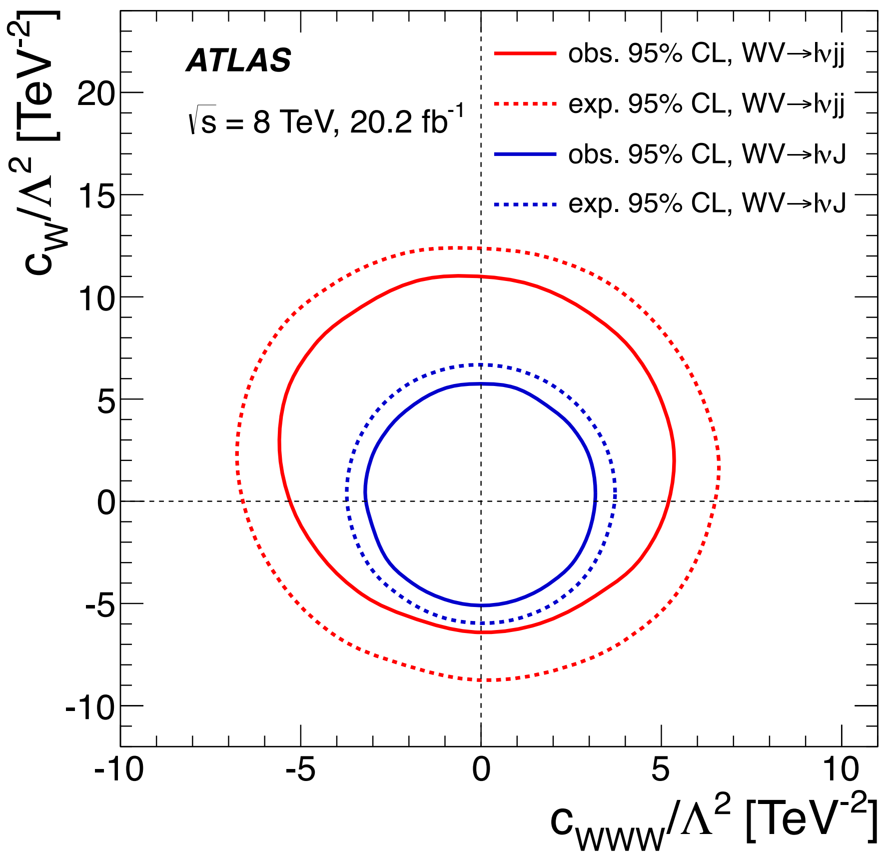


Resolved category



Boosted category

Anomalous Trilinear Couplings: WW/WZ semileptonic



$$\alpha \to \frac{\alpha}{(1 + \hat{s}/\Lambda_{FF}^2)^2}$$

Prevent tree-level unitarity violation by introducing form factor

Use Λ_{FF} = 5 TeV

- **Boosted category more sensitive**
- **Complementary resolved search region**

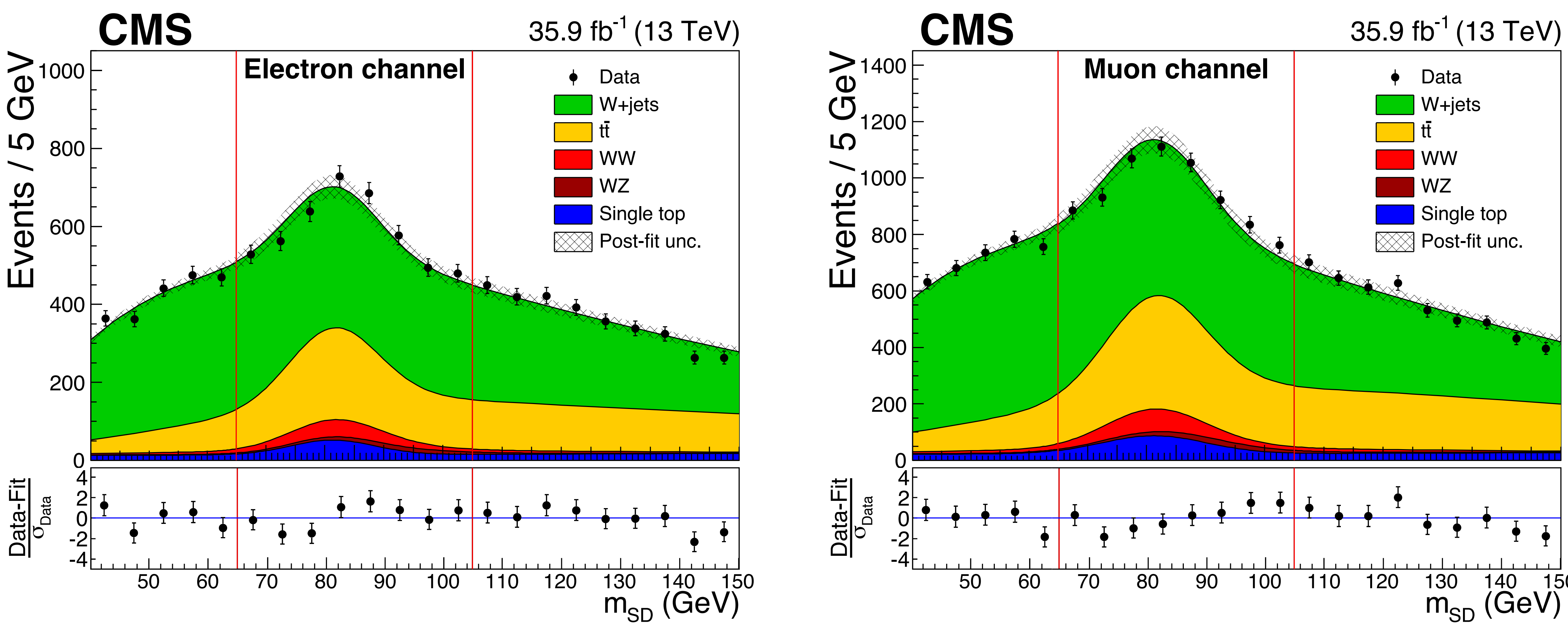
Parameter	Observed [TeV^{-2}] $WV \to \ell\nu jj$	Expected [TeV^{-2}] $WV \to \ell\nu jj$	Observed [TeV^{-2}] $WV \to \ell\nu J$	Expected [TeV^{-2}] $WV \to \ell\nu J$
c_{WWW}/Λ^2	$[-5.3, 5.3]$	$[-6.4, 6.3]$	$[-3.1, 3.1]$	$[-3.6, 3.6]$
c_B/Λ^2	$[-36, 43]$	$[-45, 51]$	$[-19, 20]$	$[-22, 23]$
c_W/Λ^2	$[-6.4, 11]$	$[-8.7, 13]$	$[-5.1, 5.8]$	$[-6.0, 6.7]$

Limit also computed at √s = 13 TeV with 13 fb-1 of data in fully leptonic final state

Anomalous Trilinear Couplings: WW/WZ semileptonic

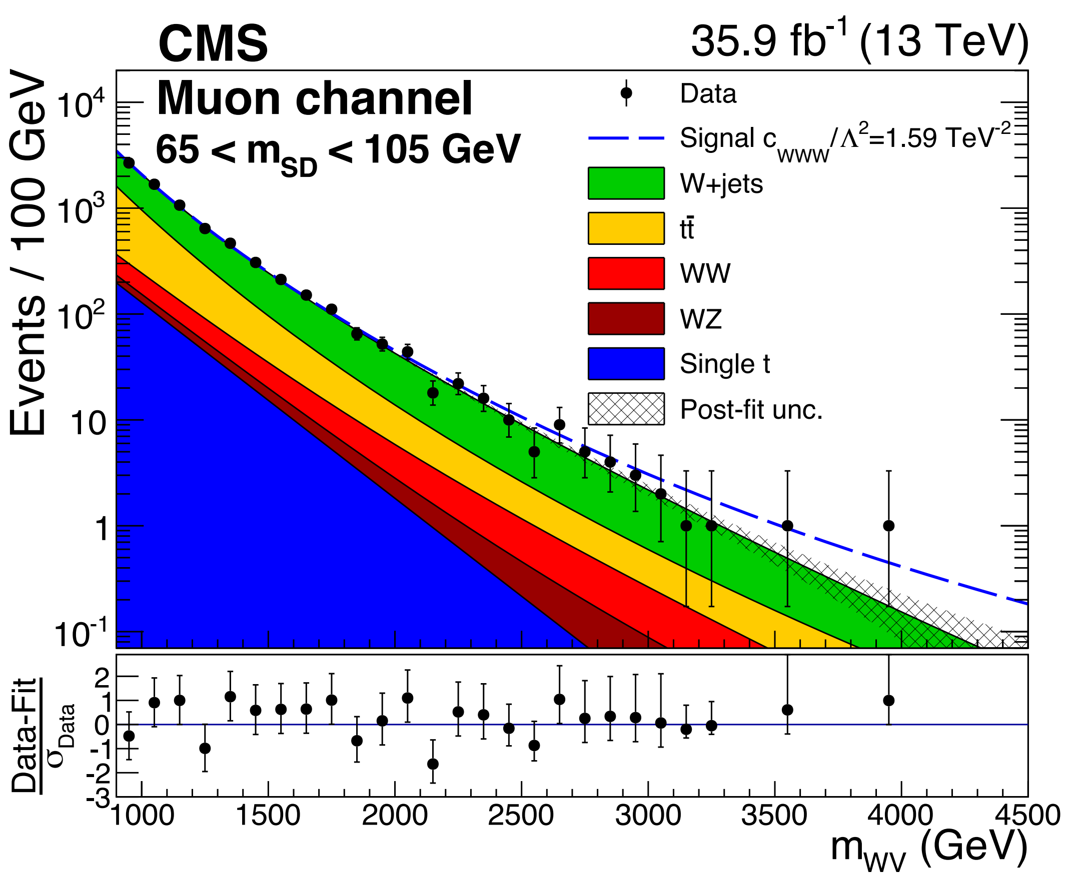
http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP-18-008/

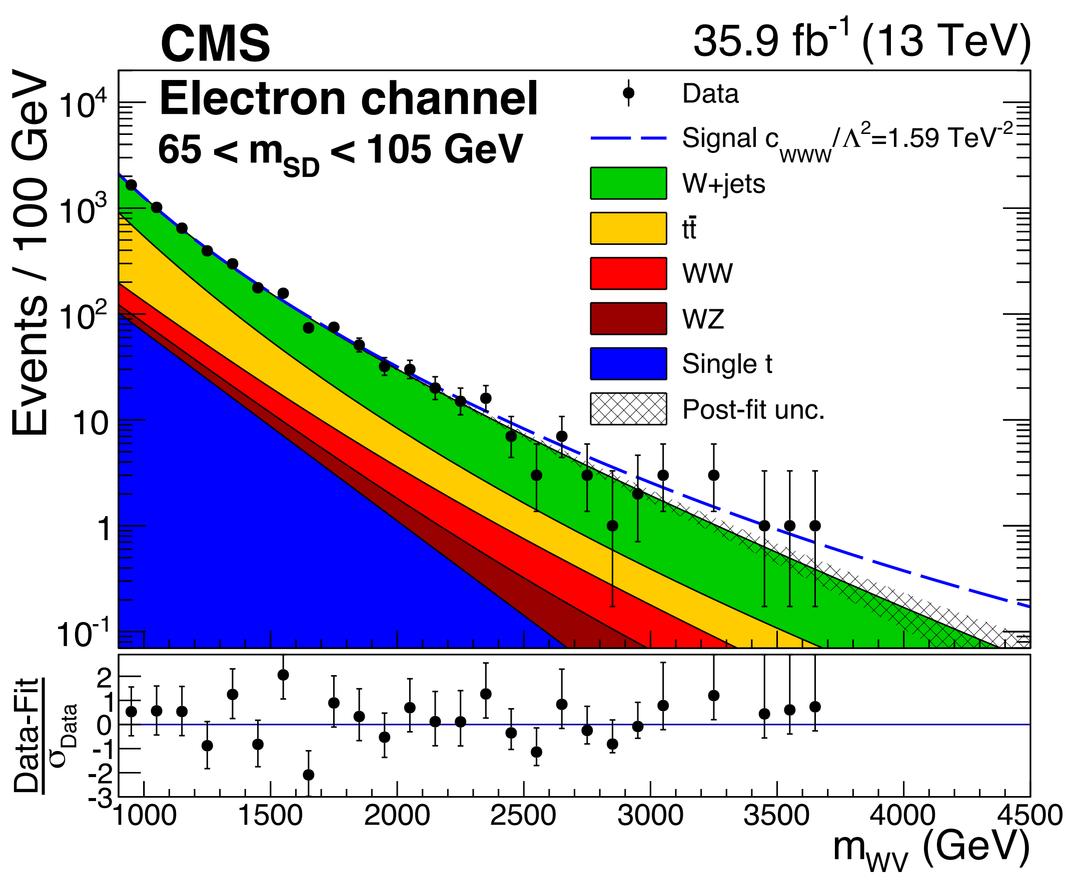
- **Analysis geared toward finding anomalous coupling contribution to the SM**
- Hadronic W/Z candidate: leading AK8 jet with $p_T > 200$ GeV
- **Tail modeled as a sum of exponentials (SM (NNLO) and aTGC)**
- Invariant mass of the diboson system (M_{WZ}) $>$900 GeV
- **Pruned mass: 65-105 GeV and N-subjettiness < 0.6**



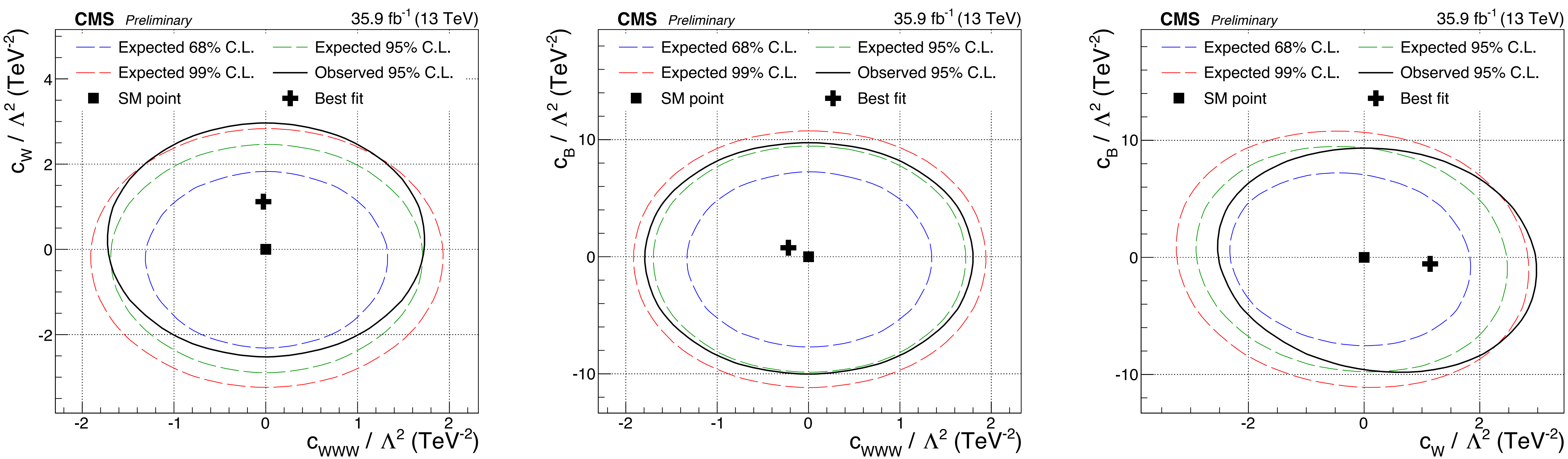
Anomalous Trilinear Couplings: WW/WZ semileptonic

- W+jets and tt are the two main backgrounds
- tt is signal like: hadronic W can be reconstructed as an AK8 jet
- **Shape of the W+jets background estimated in sideband region and tt background estimated from simulations**
- **Contribution from aTGC expected to show up in the tail of the distributions**





Anomalous Trilinear Couplings: WW/WZ semileptonic

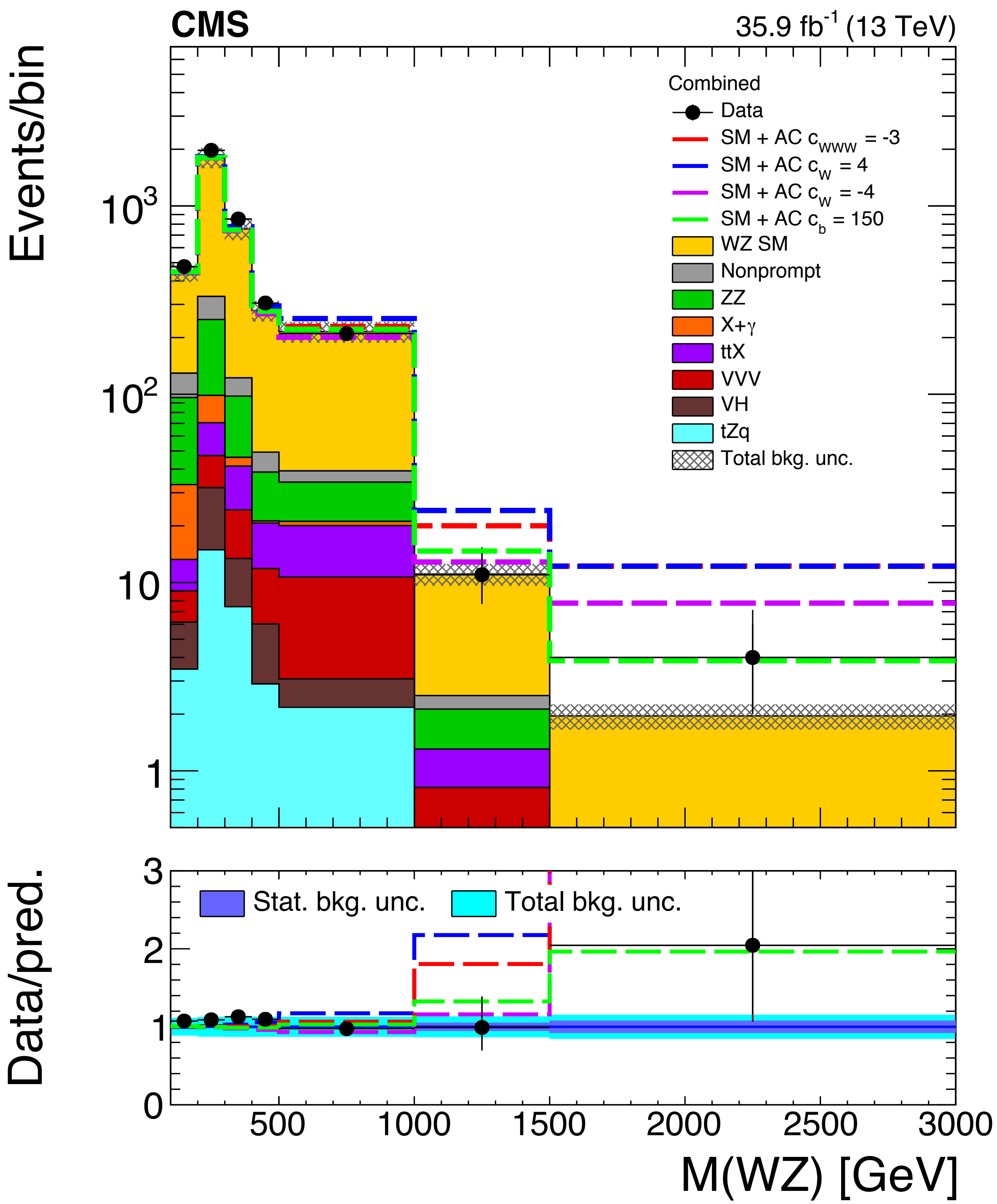


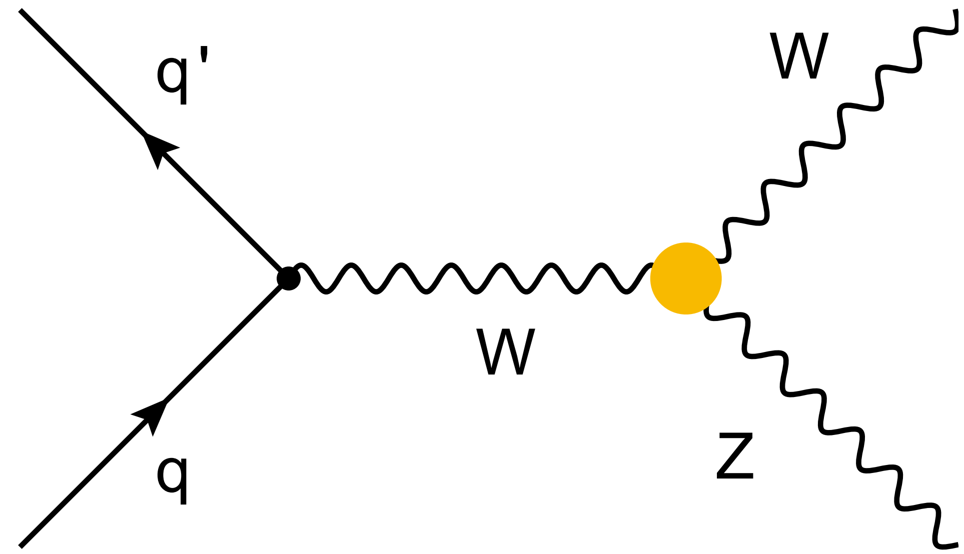
$$\mathcal{O}_{WWW} = \mathrm{Tr}[W_{\mu\nu} W^{\nu\rho} W_{\rho}^{\mu}] \qquad \mathcal{O}_{W} = (\mathcal{D}_\mu \Phi)^\dagger W^{\mu\nu} (\mathcal{D}_\nu \Phi) \qquad \mathcal{O}_{W} = (\mathcal{D}_\mu \Phi)^\dagger W^{\mu\nu} (\mathcal{D}_\nu \Phi)$$

Parametrization	aTGC	Expected limit	Observed limit	Run I limit
EFT	c_{WWW}/Λ^2 (TeV^{-2})	[-1.44, 1.47]	[-1.58, 1.59]	[-2.7, 2.7]
	c_{W}/Λ^2 (TeV^{-2})	[-2.45, 2.08]	[-2.00, 2.65]	[-2.0, 5.7]
	c_{B}/Λ^2 (TeV^{-2})	[-8.38, 8.06]	[-8.78, 8.54]	[-14, 17]

Most stringent limits placed on EFT parameters

Anomalous Trilinear Couplings: WZ leptonic





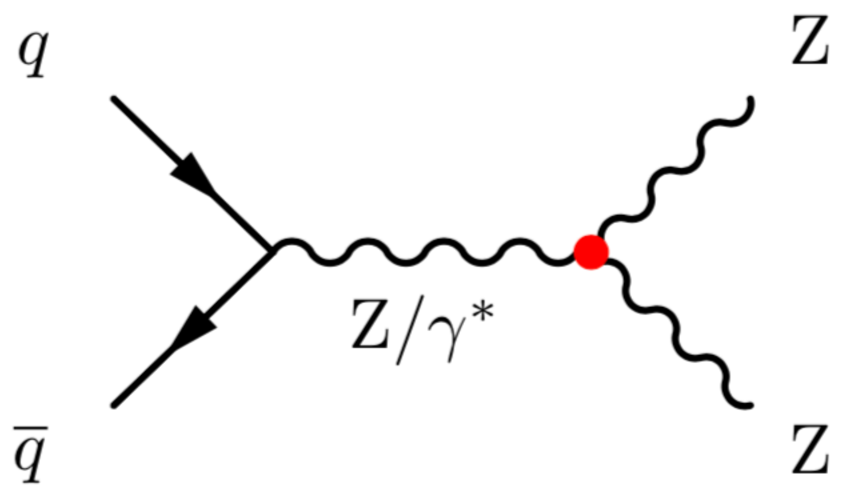
http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP-18-002/

- Reconstructed transverse mass of the WZ system used to search for aTGC
- Presence of aTGC manifests as an excess of events in the tails of the p_T^Z or M_{WZ}

Parameter	95% CI (expected)	95% CI (observed)
c_W/Λ^2	$[-3.3, 2.0]$	$[-4.1, 1.1]$
c_{WWW}/Λ^2	$[-1.8, 1.9]$	$[-2.0, 2.1]$
c_b/Λ^2	$[-130, 170]$	$[-100, 160]$

Anomalous Trilinear Couplings: ZZ leptonic

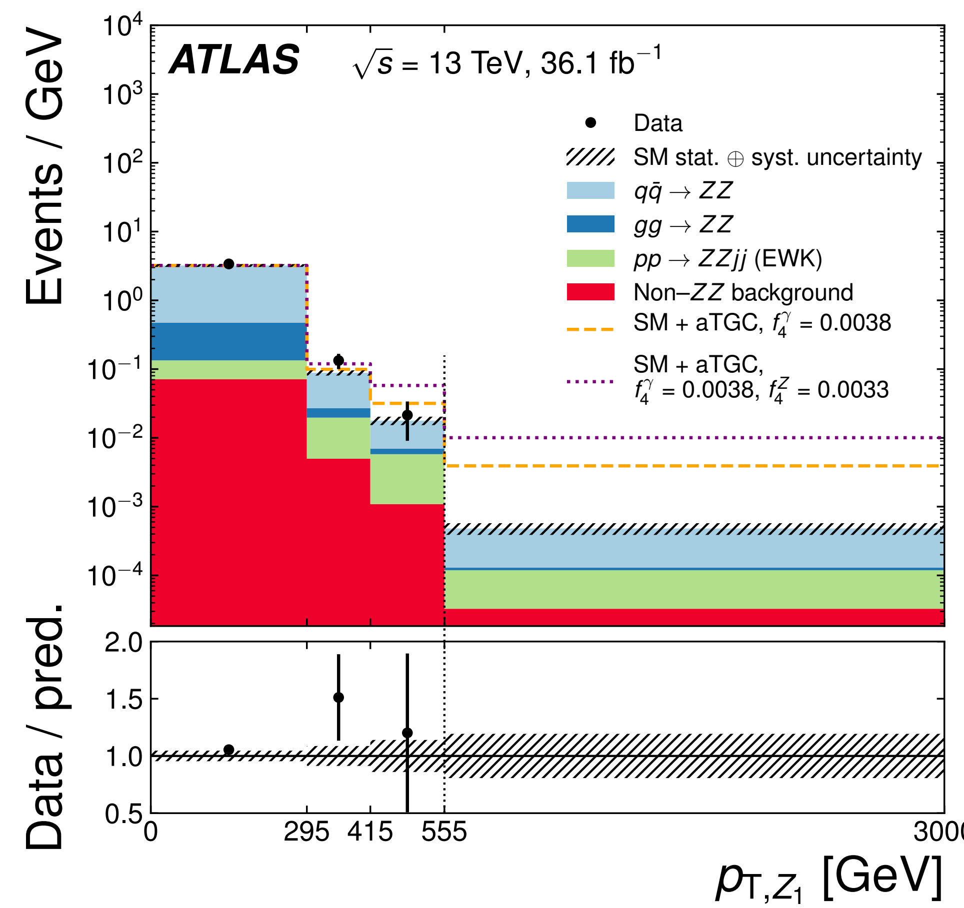
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2016-15/



Analysis geared toward exploration of anomalous neutral TGCs in ZZ → 4l

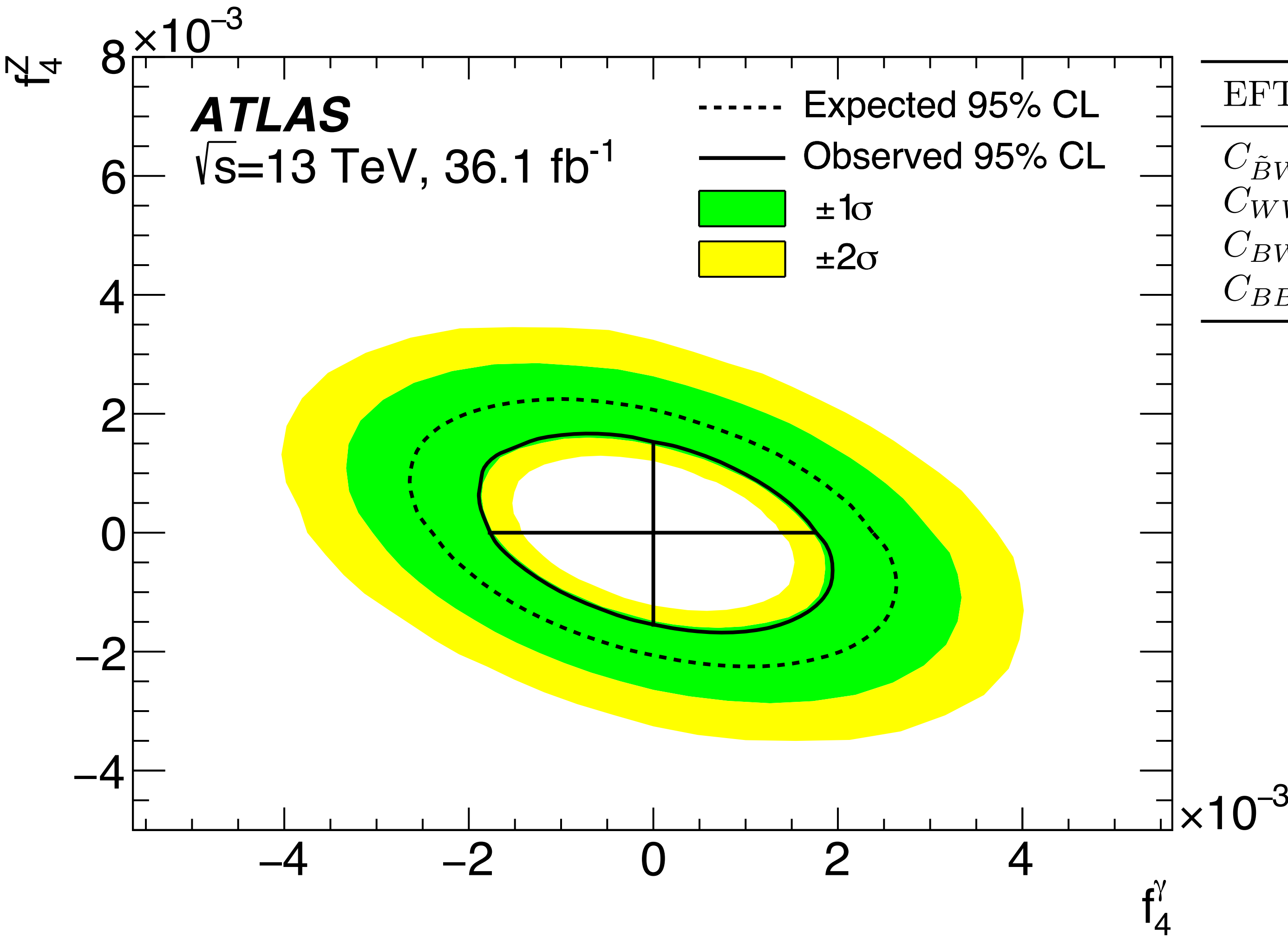
Vertex forbidden in the SM

$$N(f_4^\gamma, f_4^Z, f_5^\gamma, f_5^Z) = N_{\rm SM} + f_4^\gamma N_{01} + f_4^Z N_{02} + f_5^\gamma N_{03} + f_5^Z N_{04} + (f_4^\gamma)^2 N_{11} + f_4^\gamma f_4^Z N_{12} + f_4^\gamma f_5^\gamma N_{13} + f_4^\gamma f_5^Z N_{14} + (f_4^Z)^2 N_{22} + f_4^Z f_5^\gamma N_{23} + f_4^Z f_5^Z N_{24} + (f_5^\gamma)^2 N_{33} + f_5^\gamma f_5^Z N_{34} + (f_5^Z)^2 N_{44}$$



N_{xy} : coefficients associated with yields that depend on final state momenta

Anomalous Trilinear Couplings: ZZ leptonic



EFT parameter	Expected 95% CL $[\text{TeV}^{-4}]$	Observed 95% CL $[\text{TeV}^{-4}]$
$C_{\tilde{B}W}/\Lambda^4$	-8.1, 8.1	-5.9 , 5.9
C_{WW}/Λ^4	-4.0, 4.0	-3.0 , 3.0
C_{BW}/Λ^4	-4.4, 4.4	-3.3 , 3.3
C_{BB}/Λ^4	-3.7, 3.7	-2.7 , 2.8

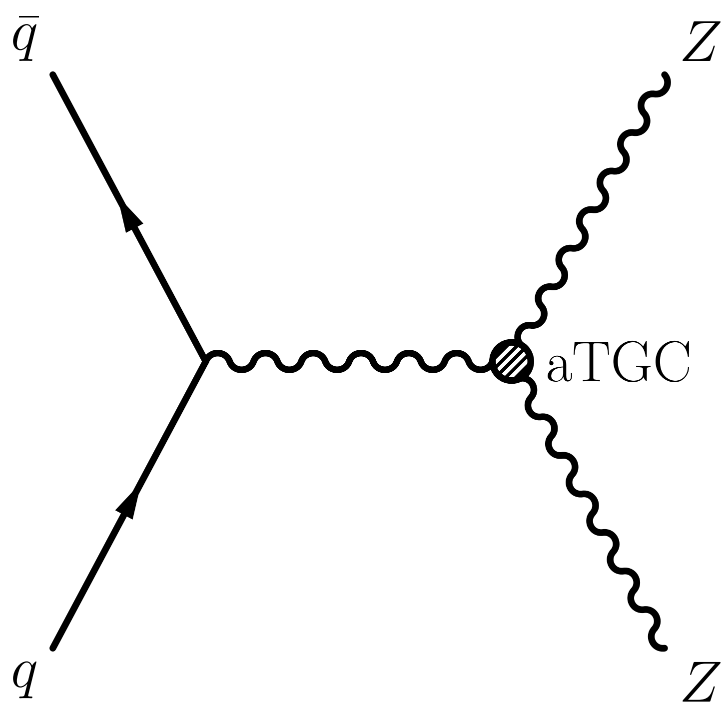
Neutral TGCs arise from dim-8 EFT operators

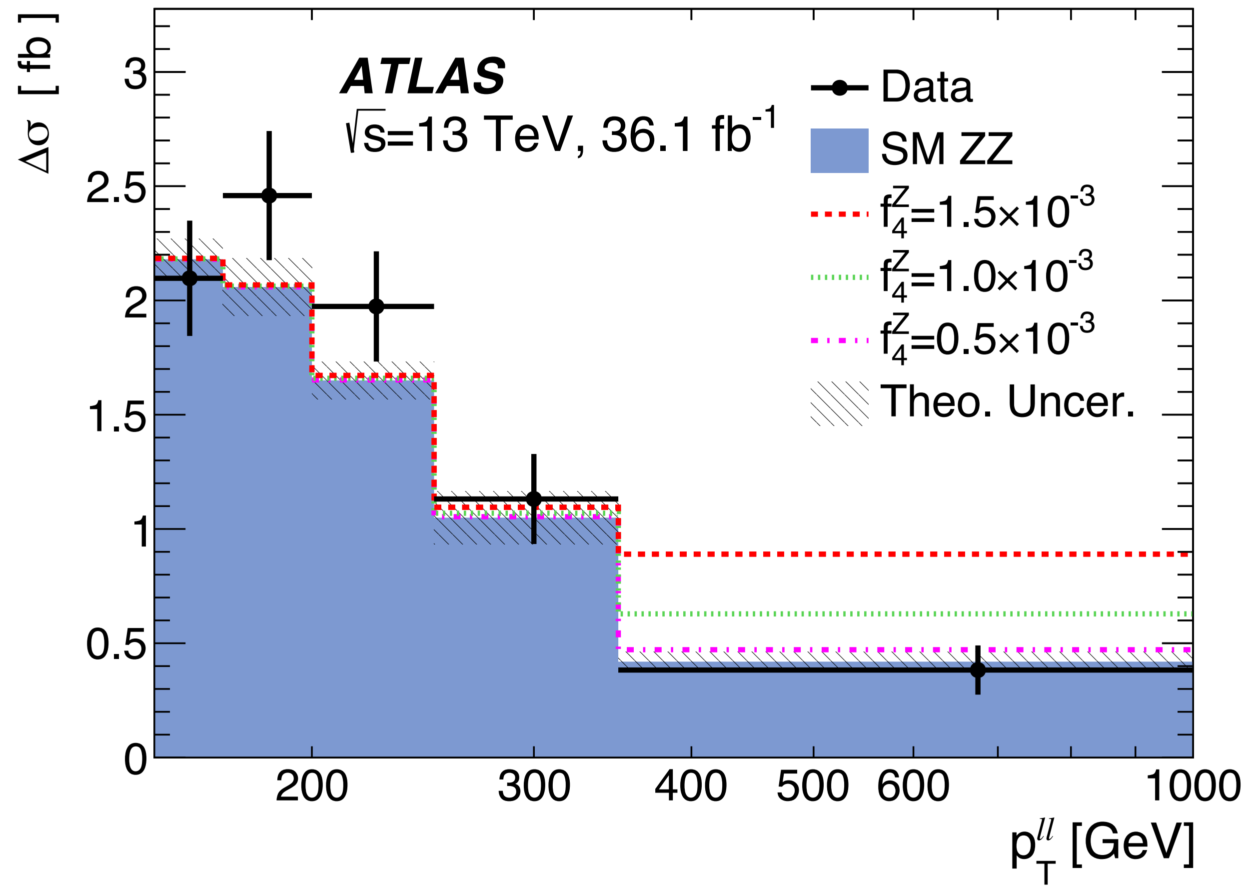
https://arxiv.org/pdf/1308.6323.pdf

Coupling strength	Expected 95% CL $[\times 10^{-3}]$	Observed 95% CL $[\times 10^{-3}]$
f_4^γ	-2.4, 2.4	-1.8, 1.8
f_4^Z	-2.1, 2.1	-1.5, 1.5
f_5^γ	-2.4, 2.4	-1.8, 1.8
f_5^Z	-2.0, 2.0	-1.5, 1.5

Anomalous Trilinear Couplings: ZZ ($Z \to l^+l^-$, $Z \to \nu\bar{\nu}$)

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2017-03/



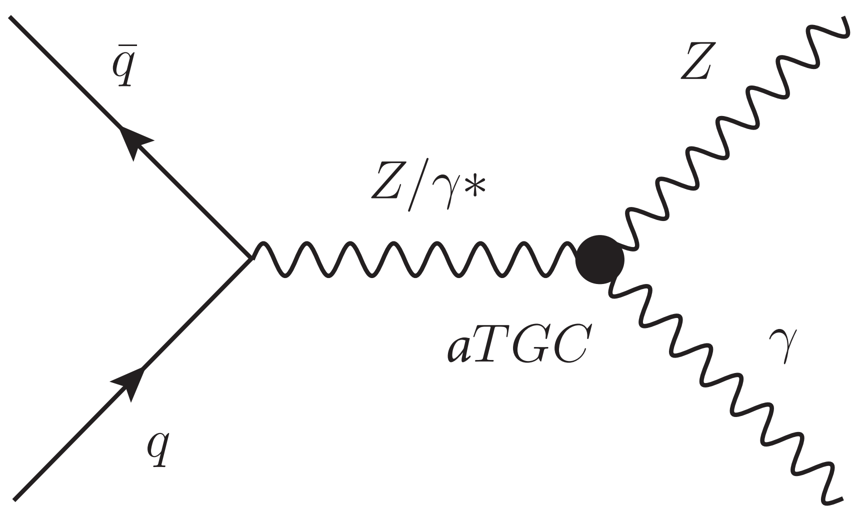


- **Stringent limits set in this channel**
- **Sensitivity enhanced by factor of ~ 2**

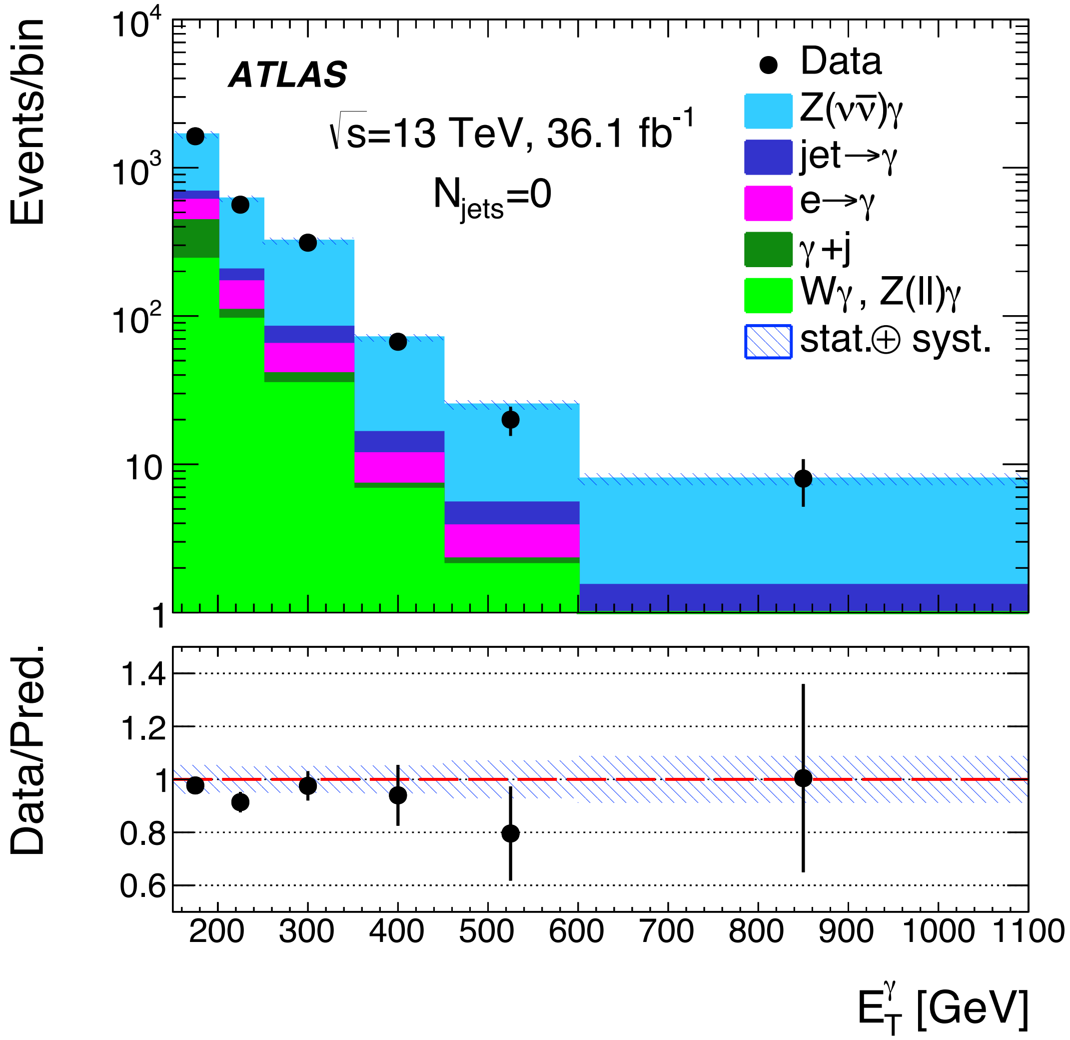
	f_4^γ	f_4^Z	f_5^γ	f_5^Z
Expected $[\times 10^{-3}]$	$[-1.3,\ 1.3]$	$[-1.1,\ 1.1]$	$[-1.3,\ 1.3]$	$[-1.1,\ 1.1]$
Observed $[\times 10^{-3}]$	$[-1.2,\ 1.2]$	$[-1.0,\ 1.0]$	$[-1.2,\ 1.2]$	$[-1.0,\ 1.0]$

Anomalous Trilinear Couplings: $Z\gamma$ ($Z \to \nu\bar{\nu}$)

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2017-18/

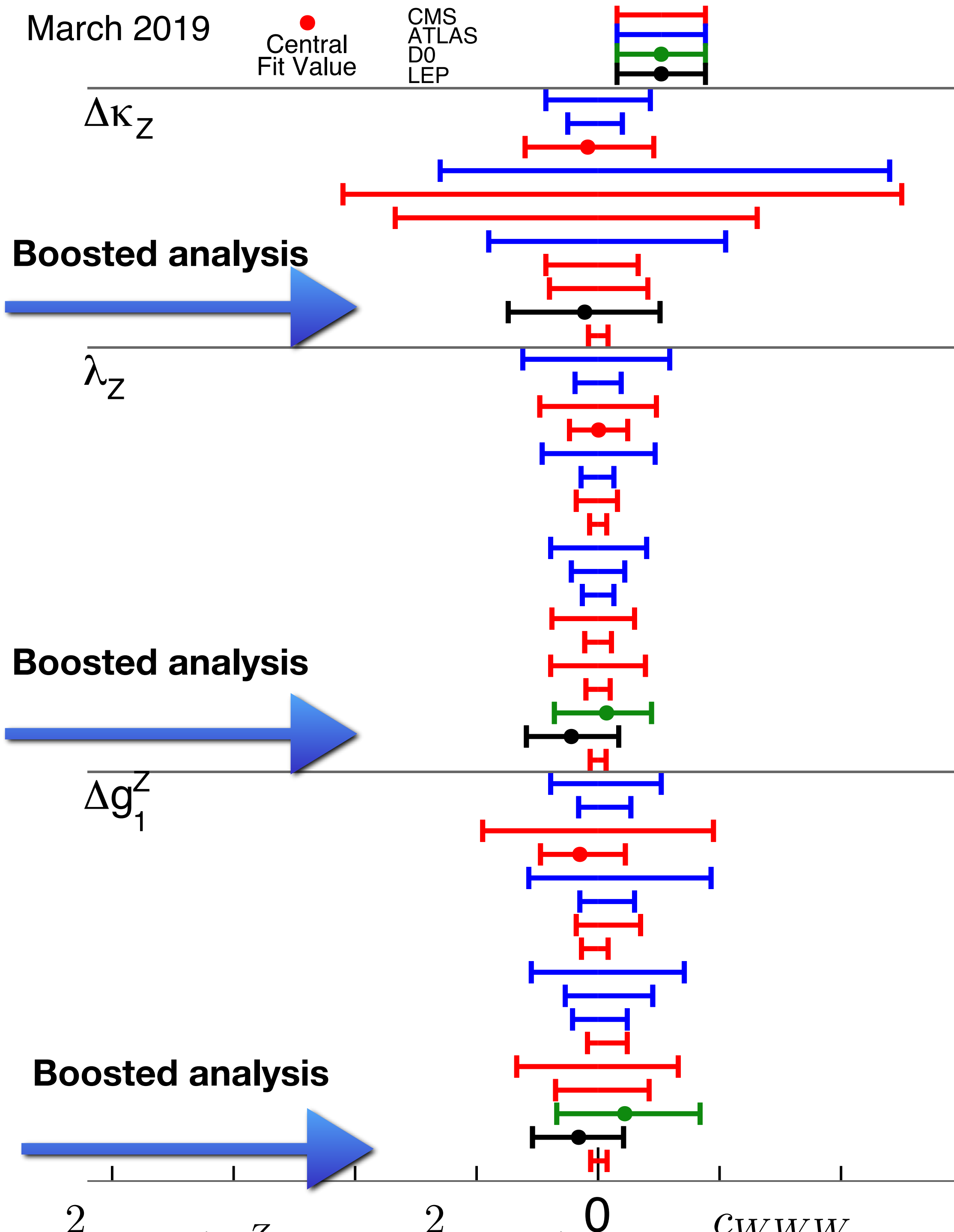


Parameter	Limit 95% CL	
	Measured [TeV^{-4}]	Expected [TeV^{-4}]
$C_{\widetilde{B}W}/\Lambda^4$	$(-1.1, 1.1)$	$(-1.3, 1.3)$
C_{BW}/Λ^4	$(-0.65, 0.64)$	$(-0.74, 0.74)$
C_{WW}/Λ^4	$(-2.3, 2.3)$	$(-2.7, 2.7)$
C_{BB}/Λ^4	$(-0.24, 0.24)$	$(-0.28, 0.27)$



Stringent limits on aTGCs

Summary of limits on anomalous trilinear couplings



Parameter	Channel	Limits	$\int Ldt$	$\sqrt{s}$
$\Delta\kappa_Z$	WW	[-4.3e-02, 4.3e-02]	4.6 fb^{-1}	7 TeV
	WW	[-2.5e-02, 2.0e-02]	20.3 fb^{-1}	8 TeV
	WW	[-6.0e-02, 4.6e-02]	19.4 fb^{-1}	8 TeV
	WZ	[-1.3e-01, 2.4e-01]	33.6 fb^{-1}	8,13 TeV
	WZ	[-2.1e-01, 2.5e-01]	19.6 fb^{-1}	8 TeV
	WZ	[-1.7e-01, 1.3e-01]	35.9 fb^{-1}	13 TeV
	WV	[-9.0e-02, 1.0e-01]	4.6 fb^{-1}	7 TeV
	WV	[-4.3e-02, 3.3e-02]	5.0 fb^{-1}	7 TeV
	WV	[-4.0e-02, 4.1e-02]	2.3 fb^{-1}	13 TeV
	LEP Comb.	[-7.4e-02, 5.1e-02]	0.7 fb^{-1}	0.20 TeV
	WV (lνJ)	[-7.9e-03, 8.2e-03]	35.9 fb^{-1}	13 TeV
λ_Z	WW	[-6.2e-02, 5.9e-02]	4.6 fb^{-1}	7 TeV
	WW	[-1.9e-02, 1.9e-02]	20.3 fb^{-1}	8 TeV
	WW	[-4.8e-02, 4.8e-02]	4.9 fb^{-1}	7 TeV
	WW	[-2.4e-02, 2.4e-02]	19.4 fb^{-1}	8 TeV
	WZ	[-4.6e-02, 4.7e-02]	4.6 fb^{-1}	7 TeV
	WZ	[-1.4e-02, 1.3e-02]	33.6 fb^{-1}	8,13 TeV
	WZ	[-1.8e-02, 1.6e-02]	19.6 fb^{-1}	8 TeV
	WZ	[-7.0e-03, 7.1e-03]	35.9 fb^{-1}	13 TeV
	WV	[-3.9e-02, 4.0e-02]	4.6 fb^{-1}	7 TeV
	WV (lνjj)	[-2.2e-02, 2.2e-02]	20.2 fb^{-1}	8 TeV
	WV (lνJ)	[-1.3e-02, 1.3e-02]	20.2 fb^{-1}	8 TeV
	WV	[-3.8e-02, 3.0e-02]	5.0 fb^{-1}	7 TeV
	WV	[-1.1e-02, 1.1e-02]	19 fb^{-1}	8 TeV
	WV	[-3.9e-02, 3.9e-02]	2.3 fb^{-1}	13 TeV
	VBF Z	[-1.0e-02, 1.0e-02]	35.9 fb^{-1}	13 TeV
	D0 Comb.	[-3.6e-02, 4.4e-02]	8.6 fb^{-1}	1.96 TeV
	LEP Comb.	[-5.9e-02, 1.7e-02]	0.7 fb^{-1}	0.20 TeV
	WV (lνJ)	[-6.5e-03, 6.6e-03]	35.9 fb^{-1}	13 TeV
Δg_1^Z	WW	[-3.9e-02, 5.2e-02]	4.6 fb^{-1}	7 TeV
	WW	[-1.6e-02, 2.7e-02]	20.3 fb^{-1}	8 TeV
	WW	[-9.5e-02, 9.5e-02]	4.9 fb^{-1}	7 TeV
	WW	[-4.7e-02, 2.2e-02]	19.4 fb^{-1}	8 TeV
	WZ	[-5.7e-02, 9.3e-02]	4.6 fb^{-1}	7 TeV
	WZ	[-1.5e-02, 3.0e-02]	33.6 fb^{-1}	8,13 TeV
	WZ	[-1.8e-02, 3.5e-02]	19.6 fb^{-1}	8 TeV
	WZ	[-1.4e-02, 8.3e-03]	35.9 fb^{-1}	13 TeV
	WV	[-5.5e-02, 7.1e-02]	4.6 fb^{-1}	7 TeV
	WV (lνjj)	[-2.7e-02, 4.5e-02]	20.2 fb^{-1}	8 TeV
	WV (lνJ)	[-2.1e-02, 2.4e-02]	20.2 fb^{-1}	8 TeV
	WV	[-8.7e-03, 2.4e-02]	19 fb^{-1}	8 TeV
	WV	[-6.7e-02, 6.6e-02]	2.3 fb^{-1}	13 TeV
	VBF Z	[-3.5e-02, 4.2e-02]	35.9 fb^{-1}	13 TeV
	D0 Comb.	[-3.4e-02, 8.4e-02]	8.6 fb^{-1}	1.96 TeV
	LEP Comb.	[-5.4e-02, 2.1e-02]	0.7 fb^{-1}	0.20 TeV
	WV (lνJ)	[-6.1e-03, 7.4e-03]	35.9 fb^{-1}	13 TeV

$$\frac{C_B}{\Lambda^2} = \frac{2}{\tan^2\theta_W M_Z^2}\Delta g_1^Z - \frac{2}{\sin^2\theta_W M_Z^2}\Delta\kappa_Z \qquad \frac{c_{WWW}}{\Lambda^2} = \frac{2}{3g^2 m_W^2}\lambda_Z$$

Anomalous Quartic Couplings

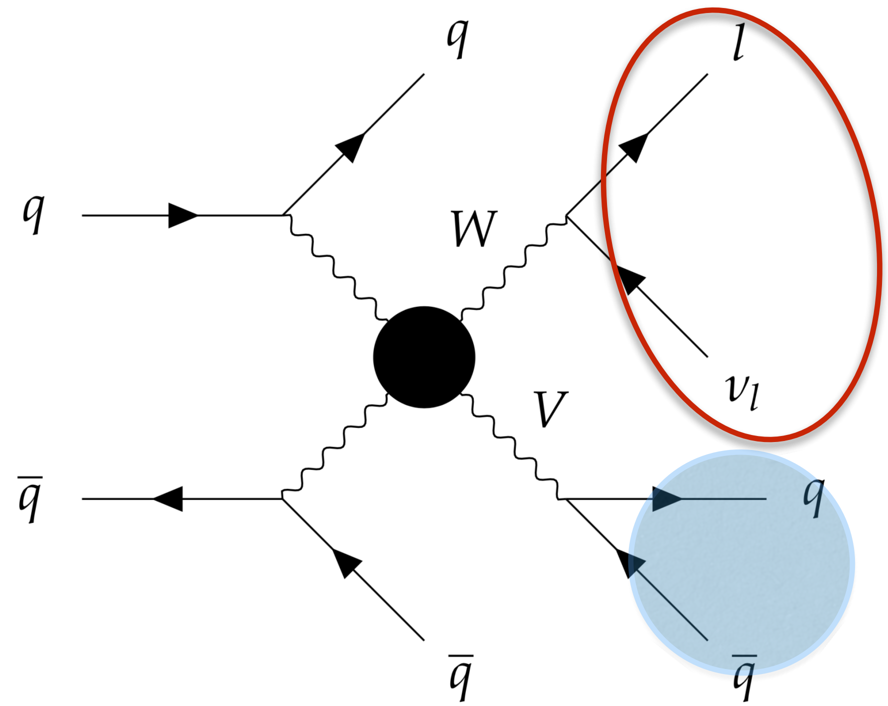
$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\lambda^2}\mathcal{O}_i + \sum_j \frac{f_j}{\lambda^4}\mathcal{O}_j + \cdots$$

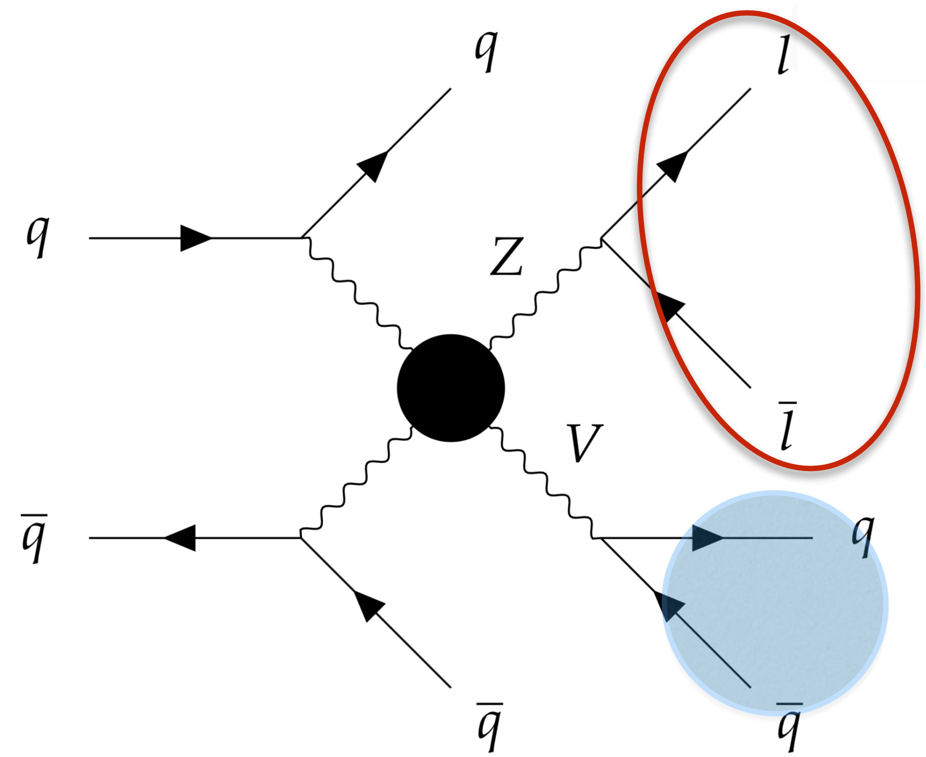
Relevant Operators	WWWW	WWZZ	ZZZZ	ZZZγ
$\mathscr{L}_{S,1}$ $\mathscr{L}_{S,2}$	✅	✅	✅	0
$\mathscr{L}_{M,0}$ $\mathscr{L}_{M,1}$ $\mathscr{L}_{M,6}$ $\mathscr{L}_{M,7}$	✅	✅	✅	✅
$\mathscr{L}_{M,2}$ $\mathscr{L}_{M,3}$ $\mathscr{L}_{M,4}$ $\mathscr{L}_{M,5}$	0	✅	✅	✅
$\mathscr{L}_{T,0}$ $\mathscr{L}_{T,1}$ $\mathscr{L}_{T,2}$	✅	✅	✅	✅
$\mathscr{L}_{T,5}$ $\mathscr{L}_{T,6}$ $\mathscr{L}_{T,7}$	0	✅	✅	✅
$\mathscr{L}_{T,8}$ $\mathscr{L}_{T,9}$	0	0	✅	✅

Search for anomalous quartic couplings

http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP-18-006/

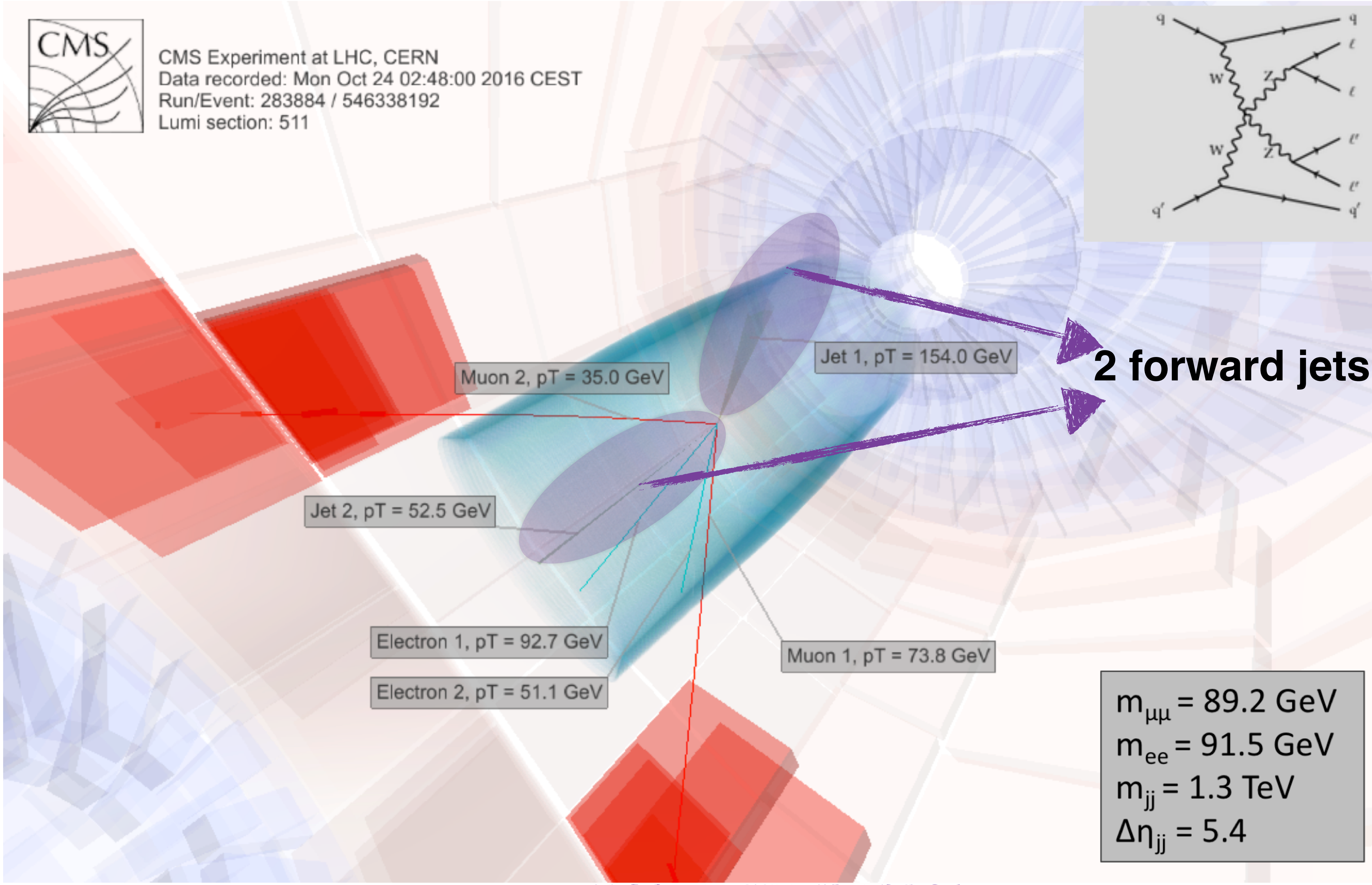
VBS topology to look for anomalous contributions to VV couplings





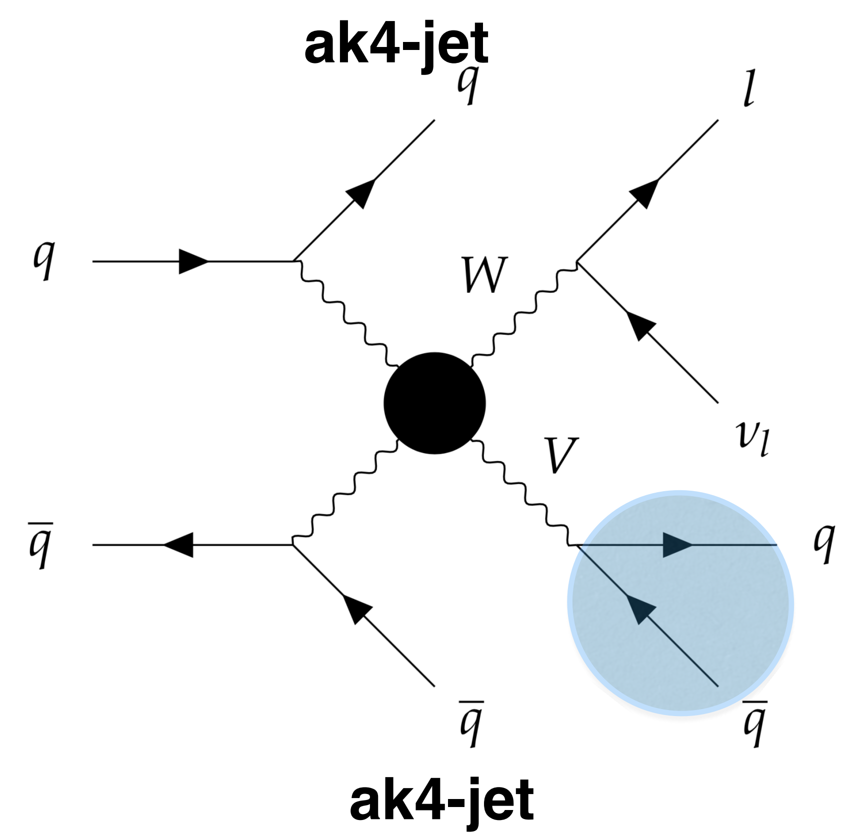
Use semi-leptonic final state to tag boosted regime

Vector Boson Scattering



Analysis Strategy

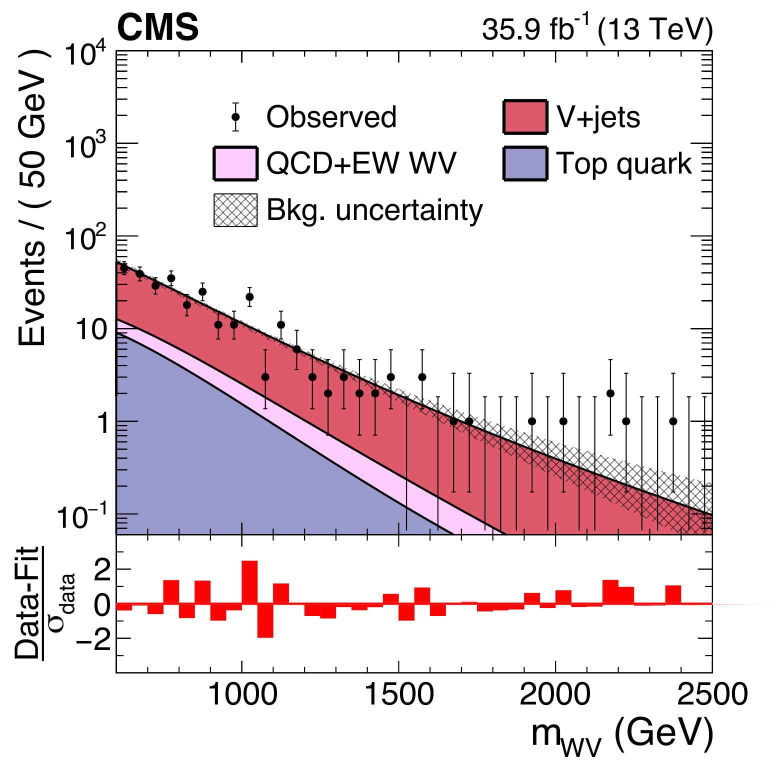
- **Use boosted topology by:**
    - Requiring a Lorentz boosted V-jet (**p_T > 200 GeV**)
    - N-subjettiness **(τ_2/τ_1) < 0.55**
- Mass of V-jet lies between 65-105 GeV
- **Take advantage of VBS topology by:**
    - Requiring 2 ak4 jets with **m_{jj} > 800 GeV**
    - Large η separation (**|Δη| > 4.0**)



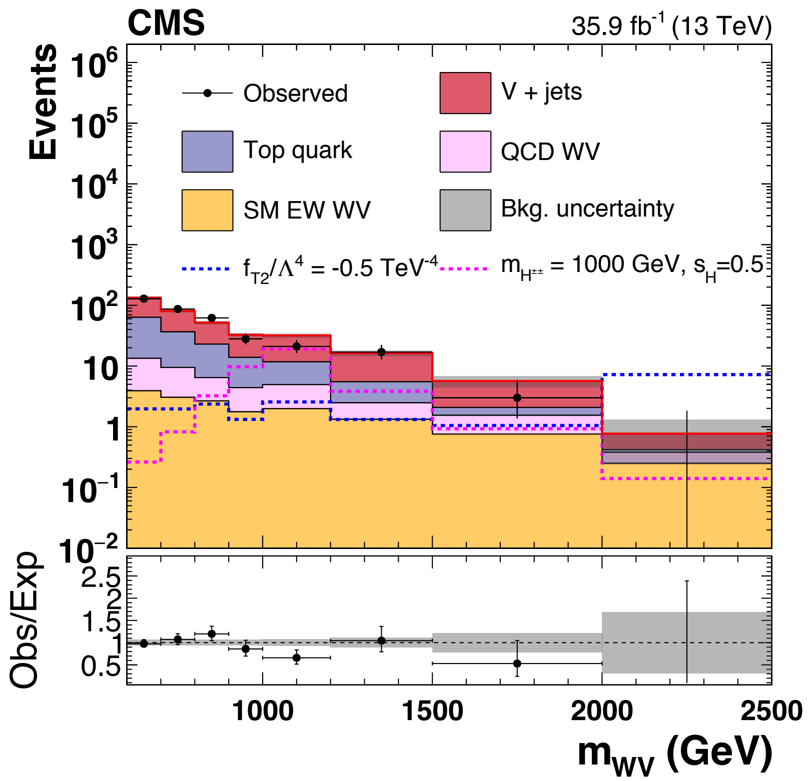
- Use VBS topology to take advantage of **η separation** between ***W/V*** and ***forward jets***
- Require V-boson centrality

Background estimation

- **Major backgrounds: W+jets** and **Z+jets**
- **Estimate background from signal side-bands**
  - **$M_V \in$ [40, 65]** ∪ **[105, 150]** GeV
  - perform maximum-likelihood fit to $M_{W/ZV}$ in data
  - Model background with parametric form: f = **$\exp(-m/(c_0 + c_1 . m))$**
- **Analysis sets most sensitive bounds on anomalous couplings**



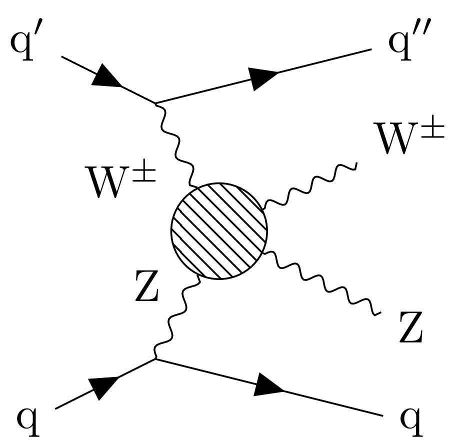
Background modeling

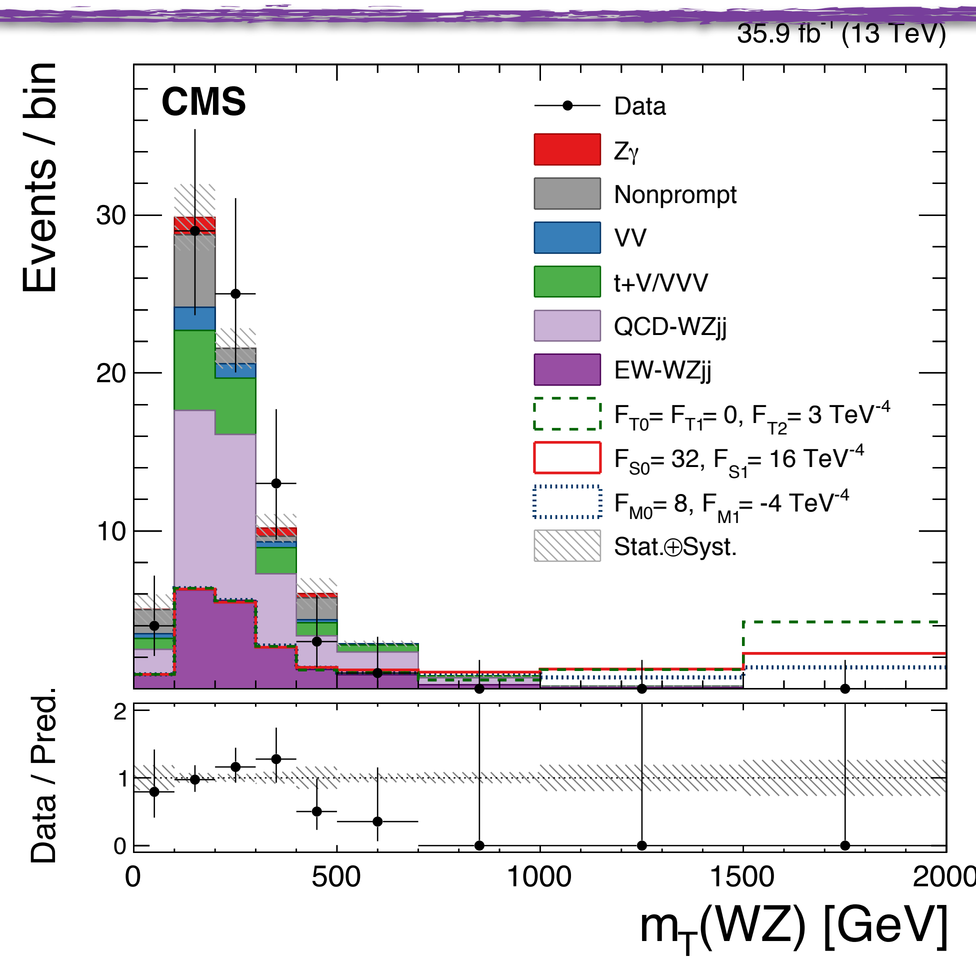


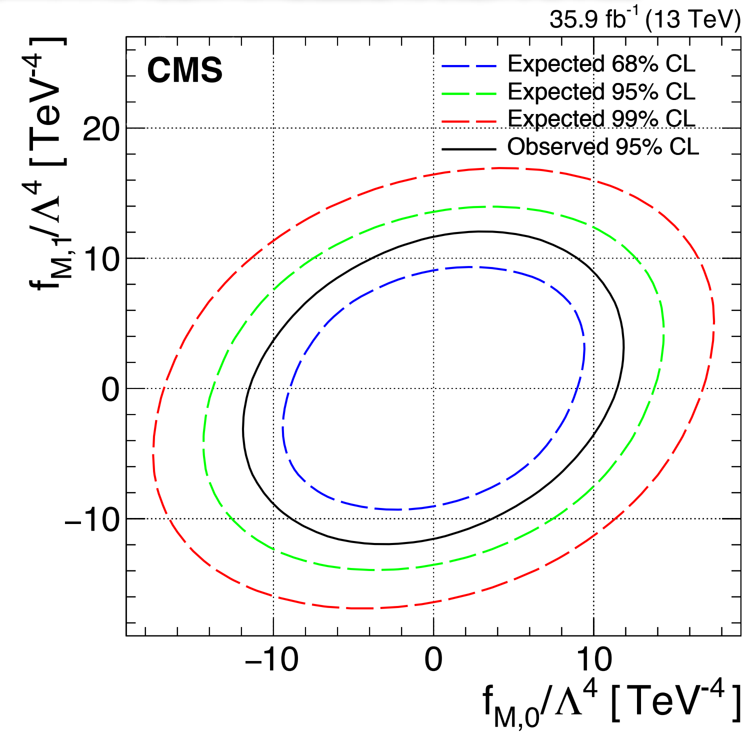
Signal region

Anomalous Quartic Couplings
WZ (fully leptonic)

http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP-18-001/



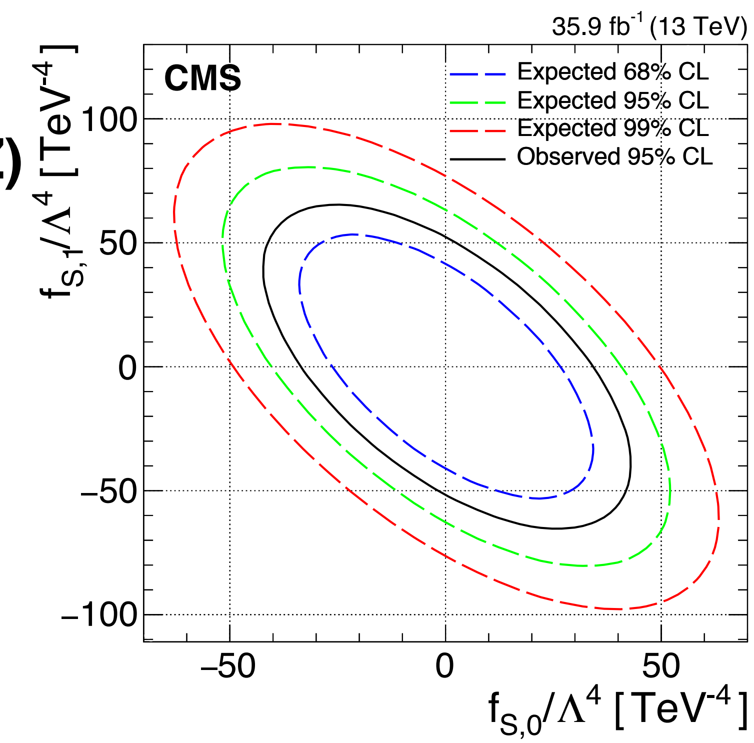




$$\mathcal{L}_{M,0} = Tr\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$

Contribution of aQGC expected to appear in the tail of $m_T(WZ)$

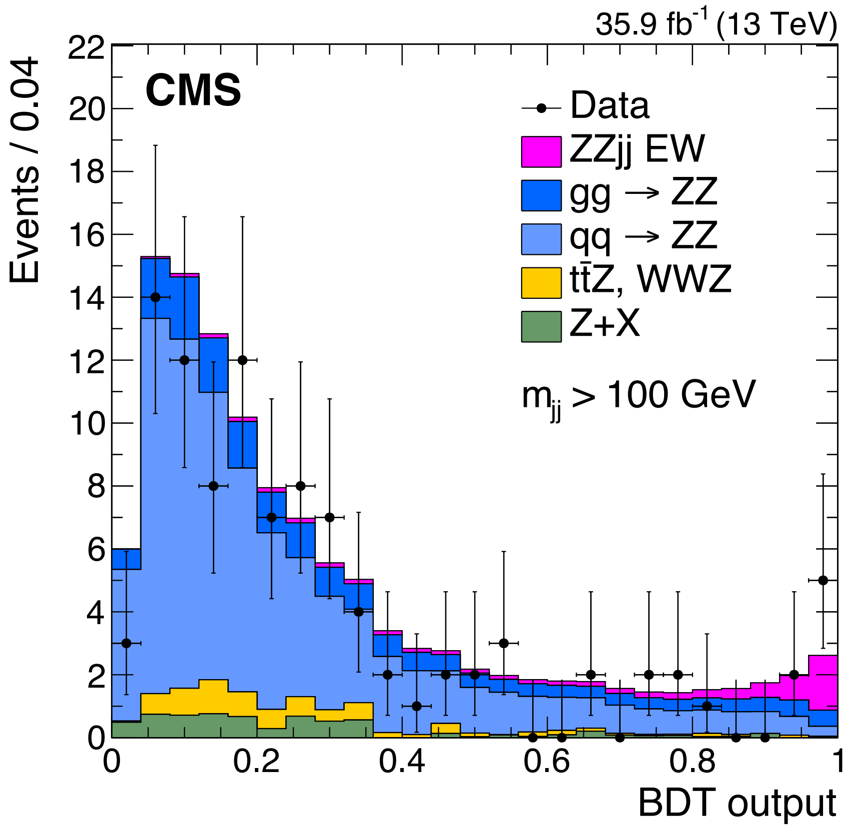
Parameters	Exp. limit	Obs. limit
f_{M0}/Λ^4	$[-11.2, 11.6]$	$[-9.15, 9.15]$
f_{M1}/Λ^4	$[-10.9, 11.6]$	$[-9.15, 9.45]$
f_{S0}/Λ^4	$[-32.5, 34.5]$	$[-26.5, 27.5]$
f_{S1}/Λ^4	$[-50.2, 53.2]$	$[-41.2, 42.8]$
f_{T0}/Λ^4	$[-0.87, 0.89]$	$[-0.75, 0.81]$
f_{T1}/Λ^4	$[-0.56, 0.60]$	$[-0.49, 0.55]$
f_{T2}/Λ^4	$[-1.78, 2.00]$	$[-1.49, 1.85]$

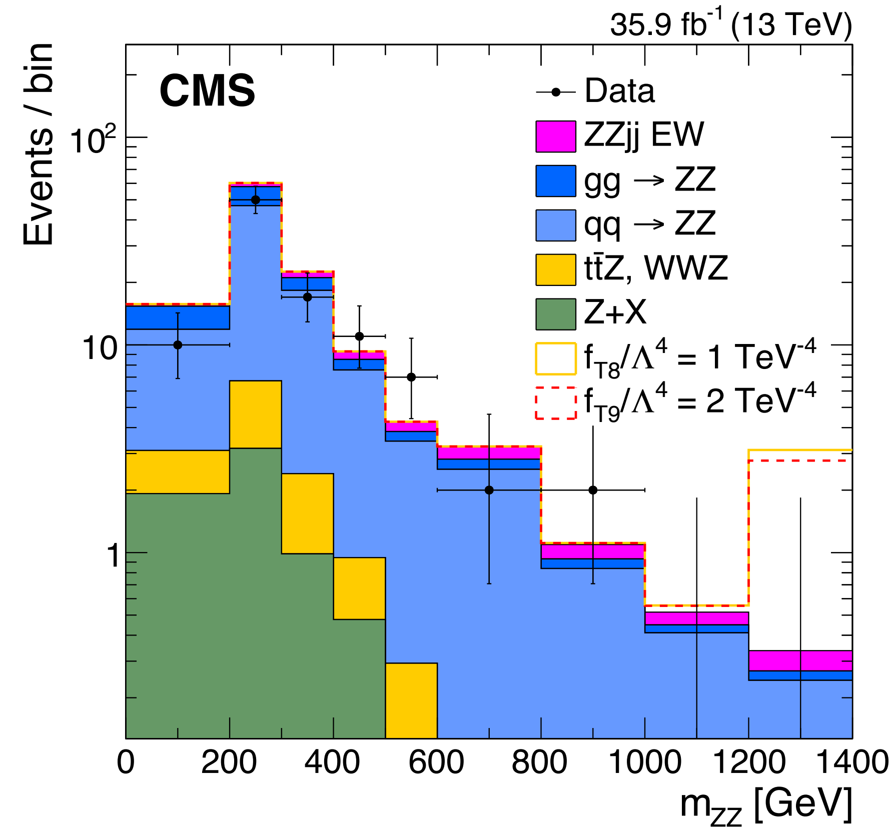


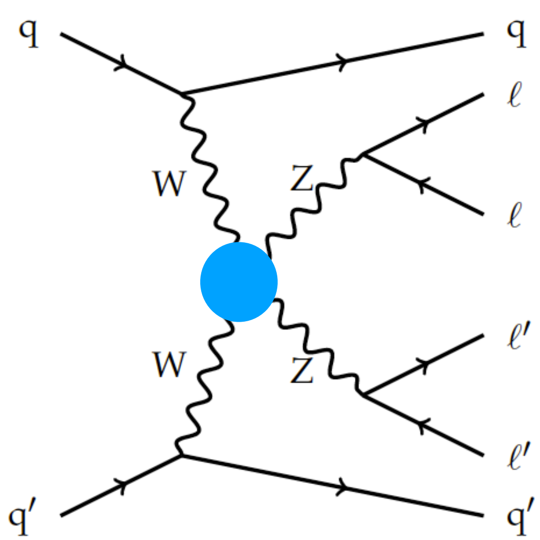
$$\mathcal{L}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right]$$

Anomalous Quartic Couplings ZZ (fully leptonic)

https://arxiv.org/pdf/1708.02812.pdf





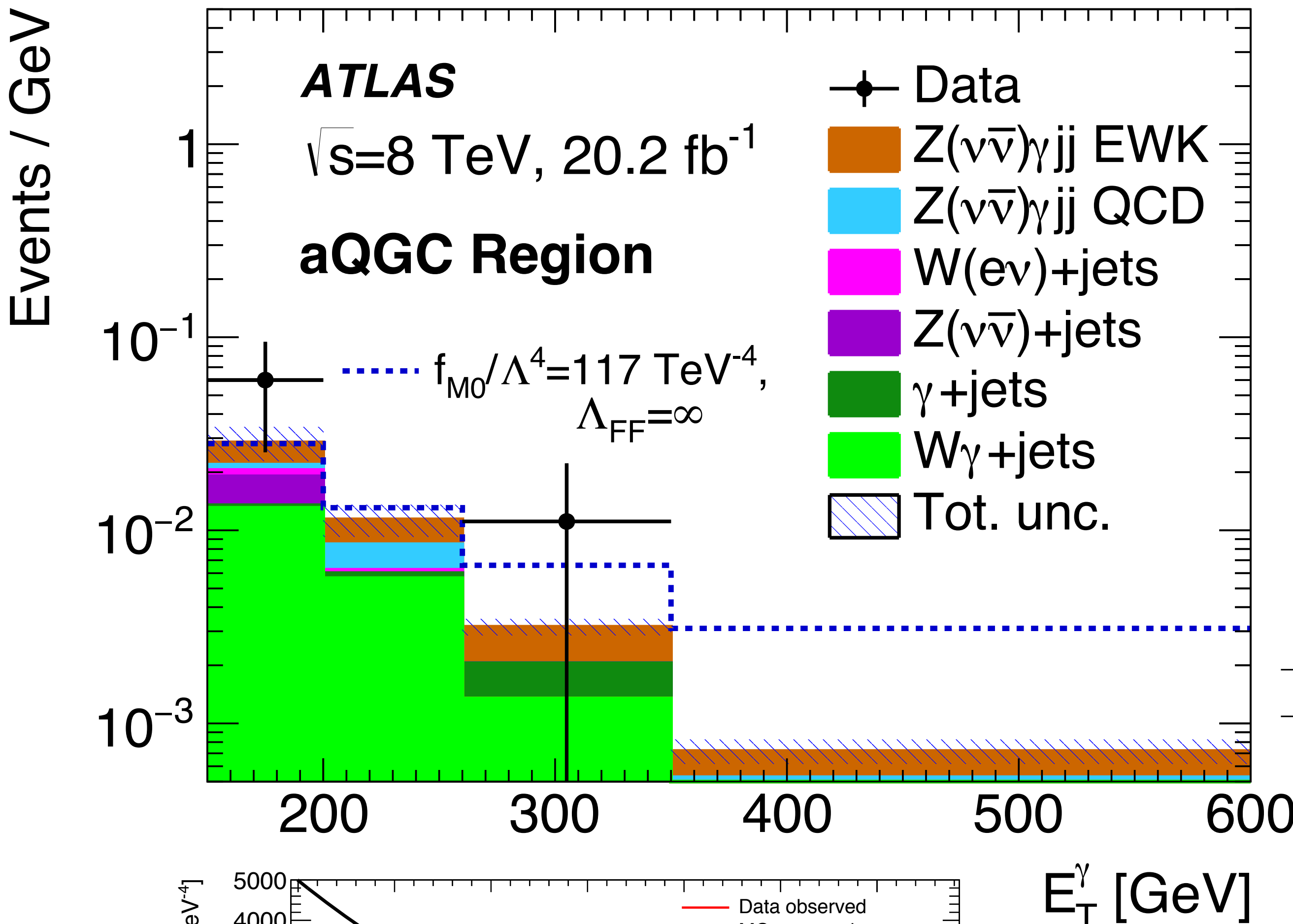


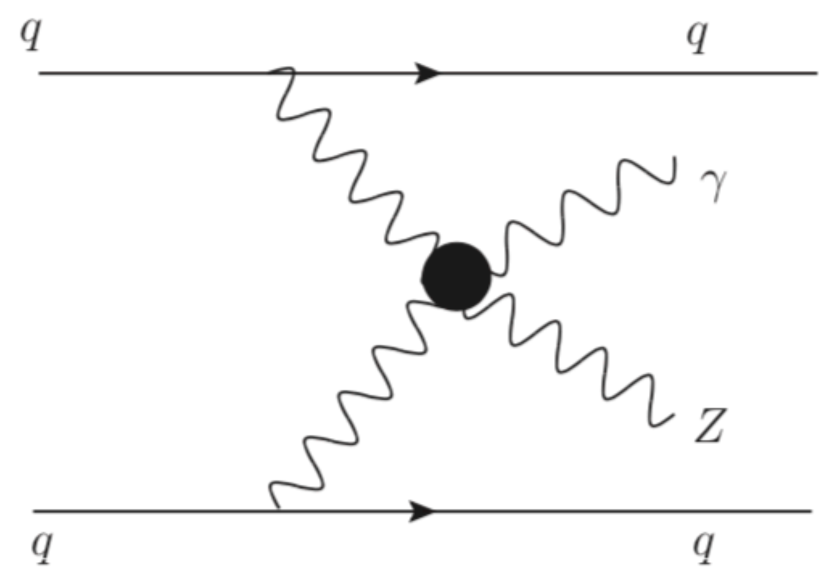
M_{ZZ} used to set limits on anomalous quartic couplings

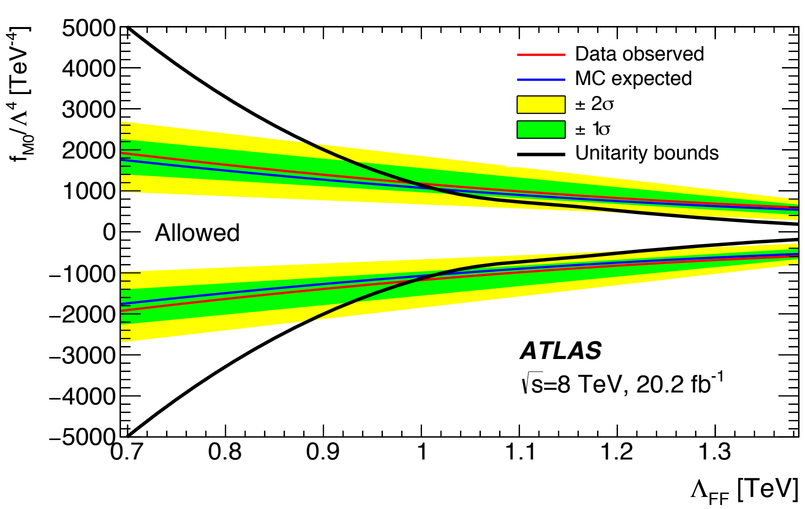
Coupling	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unitarity bound
f_{T0}/Λ^4	−0.53	0.51	−0.46	0.44	2.5
f_{T1}/Λ^4	−0.72	0.71	−0.61	0.61	2.3
f_{T2}/Λ^4	−1.4	1.4	−1.2	1.2	2.4
f_{T8}/Λ^4	−0.99	0.99	−0.84	0.84	2.8
f_{T9}/Λ^4	−2.1	2.1	−1.8	1.8	2.9

Anomalous Quartic Couplings: $Z\gamma$ ($Z \rightarrow \nu\bar{\nu}$)

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2015-21/



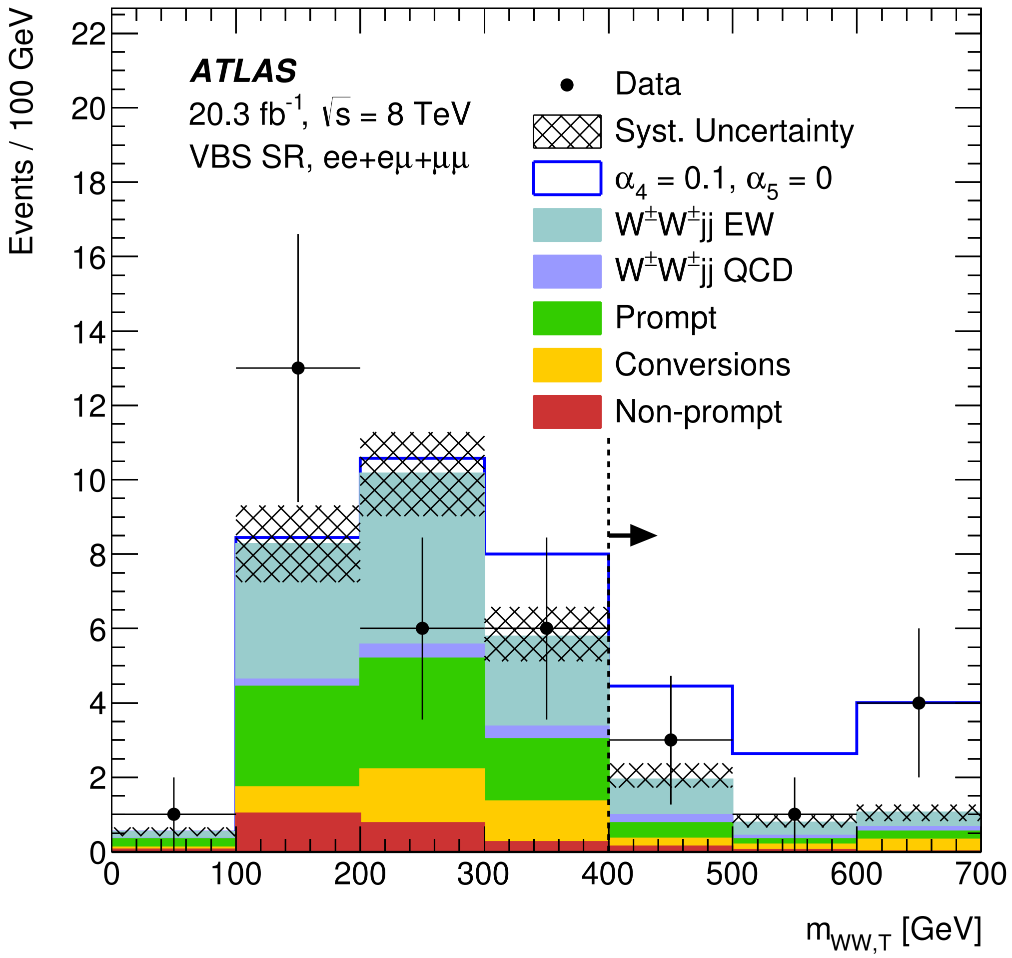


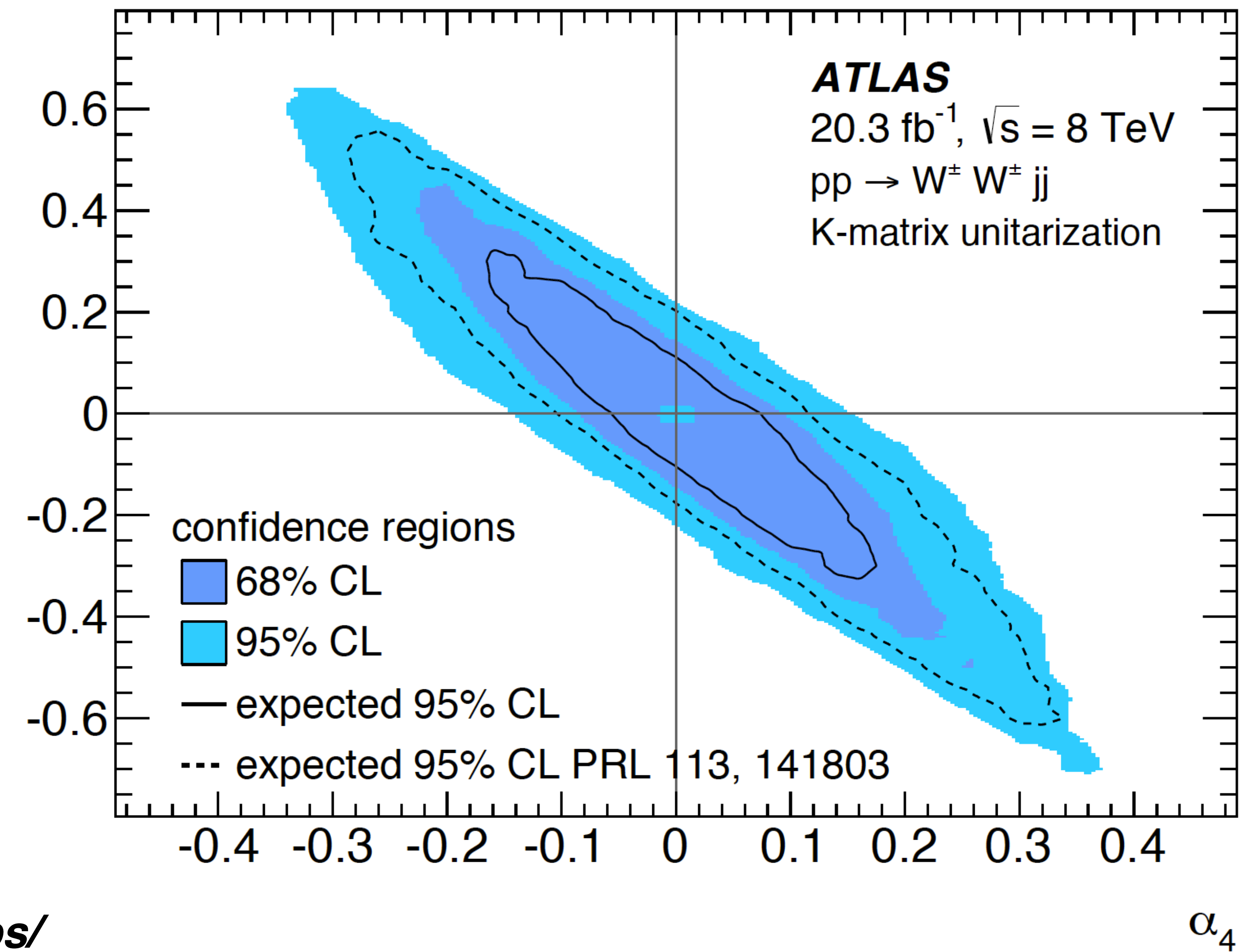


	Limits 95% CL	Measured [TeV^{-4}]	Expected [TeV^{-4}]	Λ_{FF} [TeV]
$n=0$	f_{T9}/Λ^4	$[-4.6, 4.6] \times 10^3$	$[-3.9, 3.9] \times 10^3$	$\Lambda_{FF} = \infty$
	f_{T8}/Λ^4	$[-2.2, 2.2] \times 10^3$	$[-1.8, 1.9] \times 10^3$	
	f_{T0}/Λ^4	$[-2.2, 2.1] \times 10^1$	$[-1.9, 1.8] \times 10^1$	
	f_{M0}/Λ^4	$[-2.0, 2.0] \times 10^2$	$[-1.7, 1.7] \times 10^2$	
	f_{M1}/Λ^4	$[-4.4, 4.5] \times 10^2$	$[-3.7, 3.7] \times 10^2$	
	f_{M2}/Λ^4	$[-1.1, 1.1] \times 10^3$	$[-9.5, 9.5] \times 10^2$	
	f_{M3}/Λ^4	$[-2.1, 2.1] \times 10^3$	$[-1.8, 1.8] \times 10^3$	
$n=2$	f_{T9}/Λ^4	$[-7.6, 7.6] \times 10^4$	$[-6.3, 6.2] \times 10^4$	0.7
	f_{T8}/Λ^4	$[-3.6, 3.6] \times 10^4$	$[-3.0, 3.0] \times 10^4$	0.7
	f_{T0}/Λ^4	$[-8.6, 7.8] \times 10^1$	$[-7.3, 6.5] \times 10^1$	1.7
	f_{M0}/Λ^4	$[-1.2, 1.1] \times 10^3$	$[-9.7, 9.4] \times 10^2$	1.0
	f_{M1}/Λ^4	$[-2.0, 2.0] \times 10^3$	$[-1.6, 1.7] \times 10^3$	1.2
	f_{M2}/Λ^4	$[-1.3, 1.3] \times 10^4$	$[-1.1, 1.1] \times 10^4$	0.7
	f_{M3}/Λ^4	$[-2.0, 1.9] \times 10^4$	$[-1.6, 1.6] \times 10^4$	0.8

Anomalous Quartic Couplings: VBS

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2014-05/

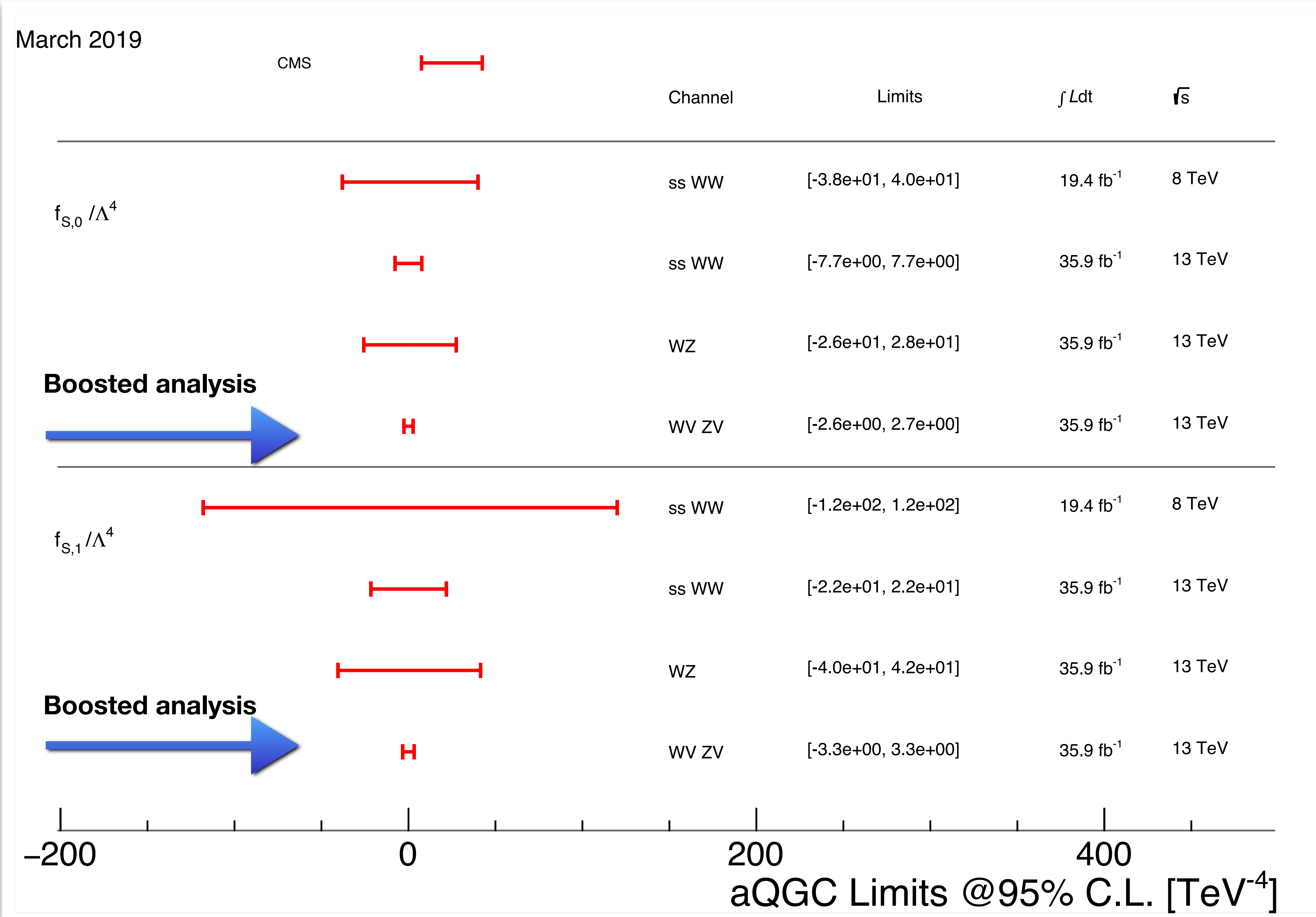




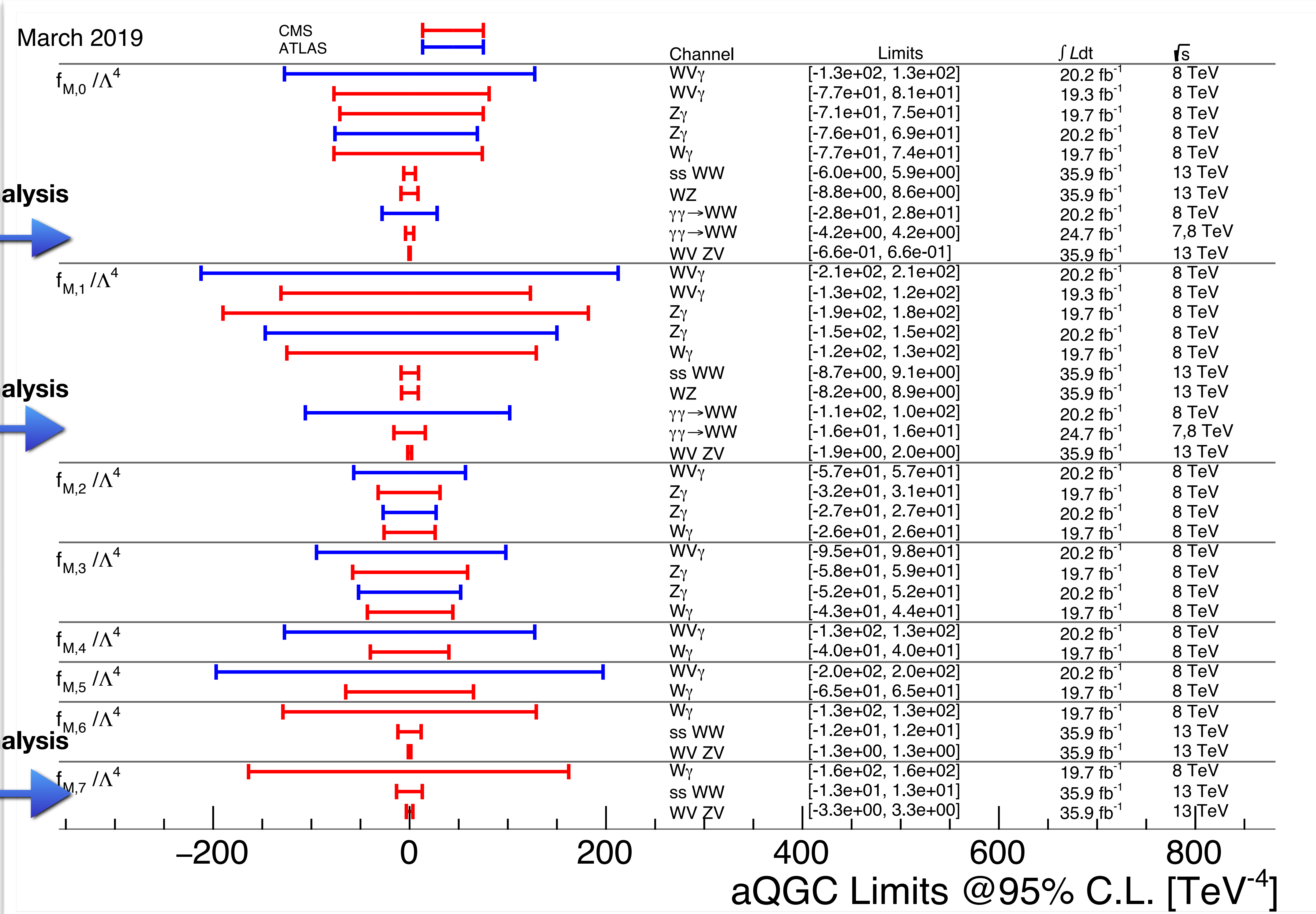
- **K-matrix unitarization based on the optical theorem *(https://arxiv.org/abs/0806.4145)***
- **Ensures projected scattering amplitude satisfies unitary condition**

$$\alpha_4 \mathcal{L}_4 = \alpha_4 \, \mathrm{tr}[\mathbf{V}_\mu \mathbf{V}_\nu] \, \mathrm{tr}[\mathbf{V}^\mu \mathbf{V}^\nu] \,,$$
$$\alpha_5 \mathcal{L}_5 = \alpha_5 \, \mathrm{tr}[\mathbf{V}_\mu \mathbf{V}^\mu] \, \mathrm{tr}[\mathbf{V}_\nu \mathbf{V}^\nu] \,,$$

Summary of limits on anomalous quartic couplings



Summary of limits on anomalous quartic couplings



Boosted analysis

Boosted analysis

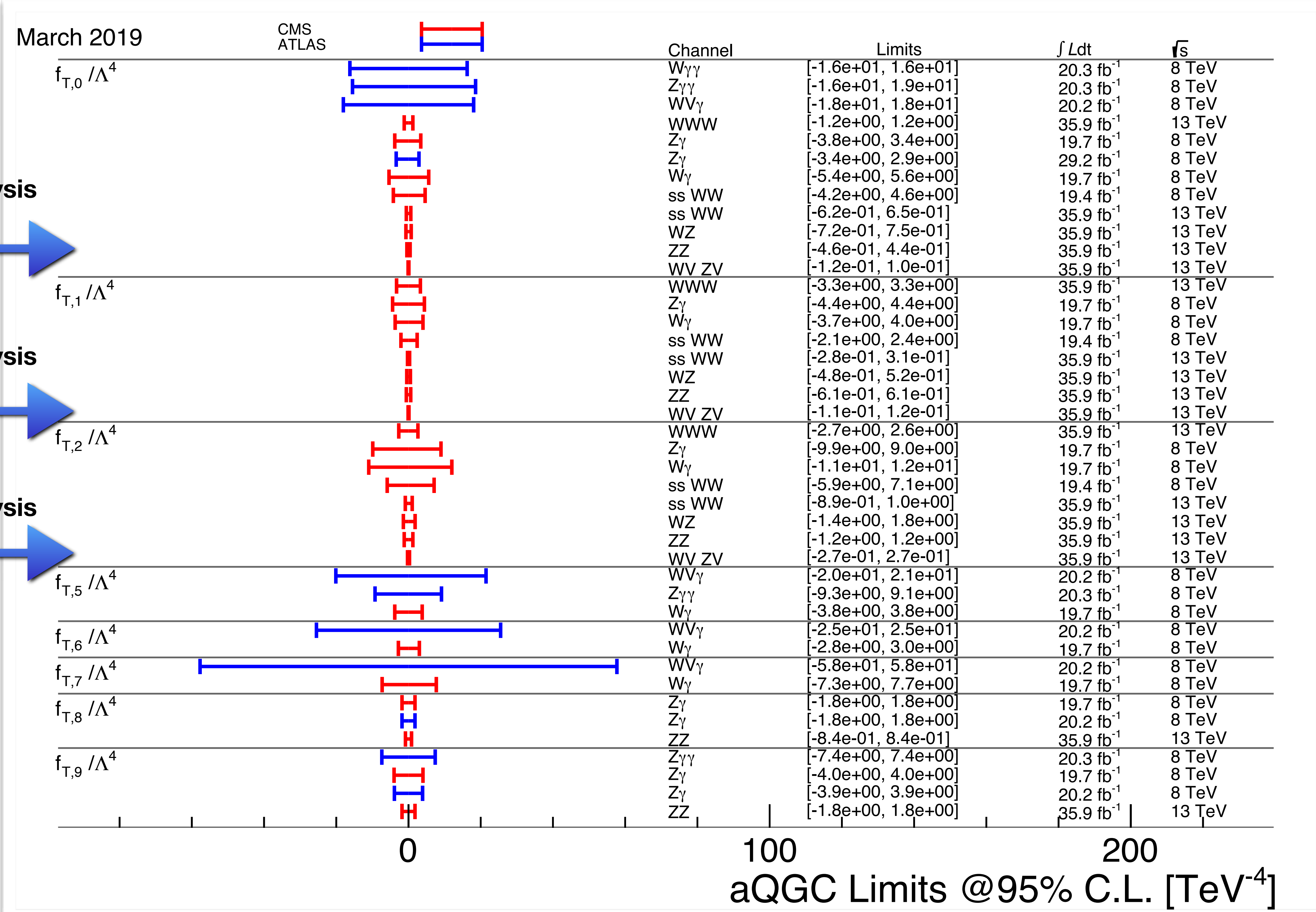
Boosted analysis

Summary of limits on anomalous quartic couplings

Boosted analysis

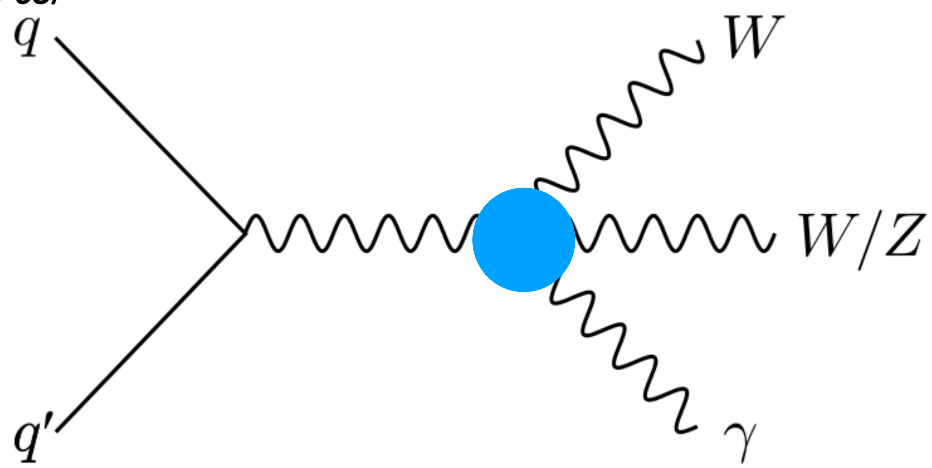
Boosted analysis

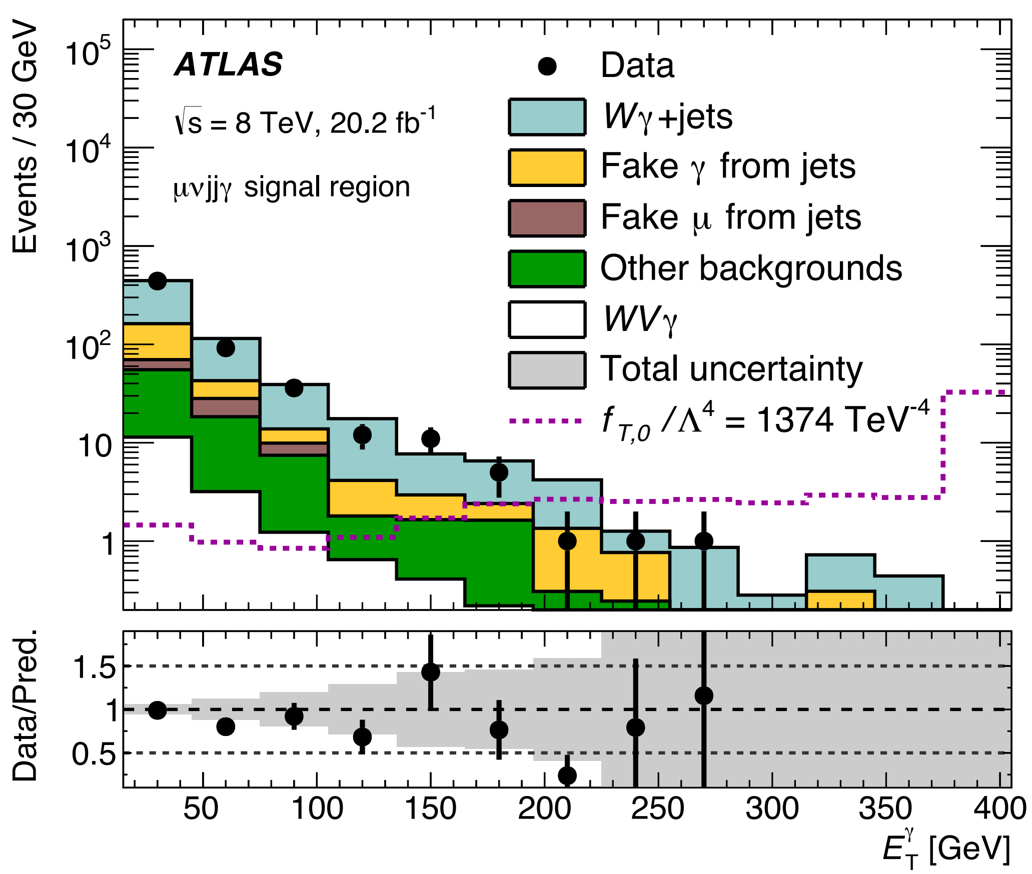
Boosted analysis

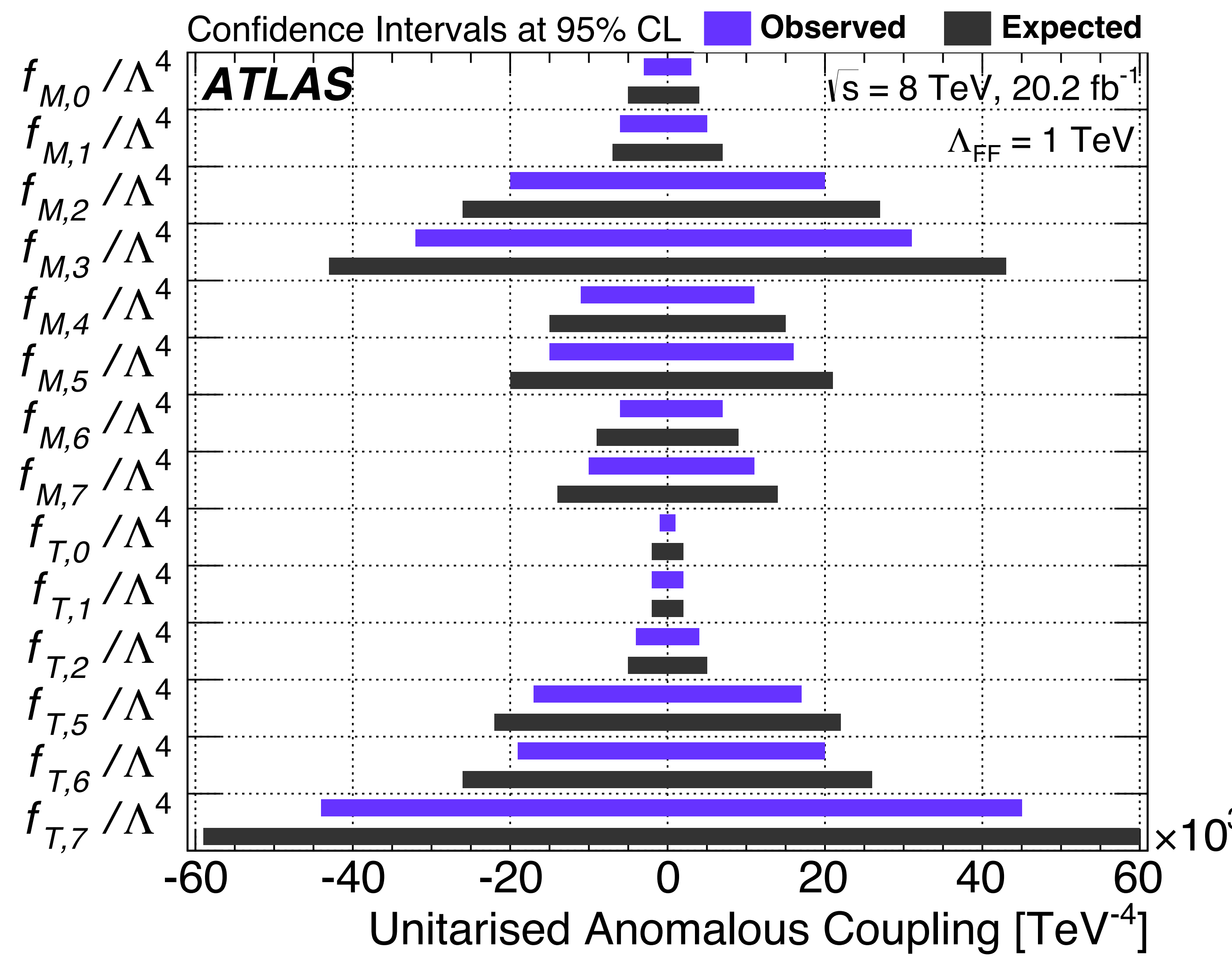


aQGCs in triboson final states

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2016-05/

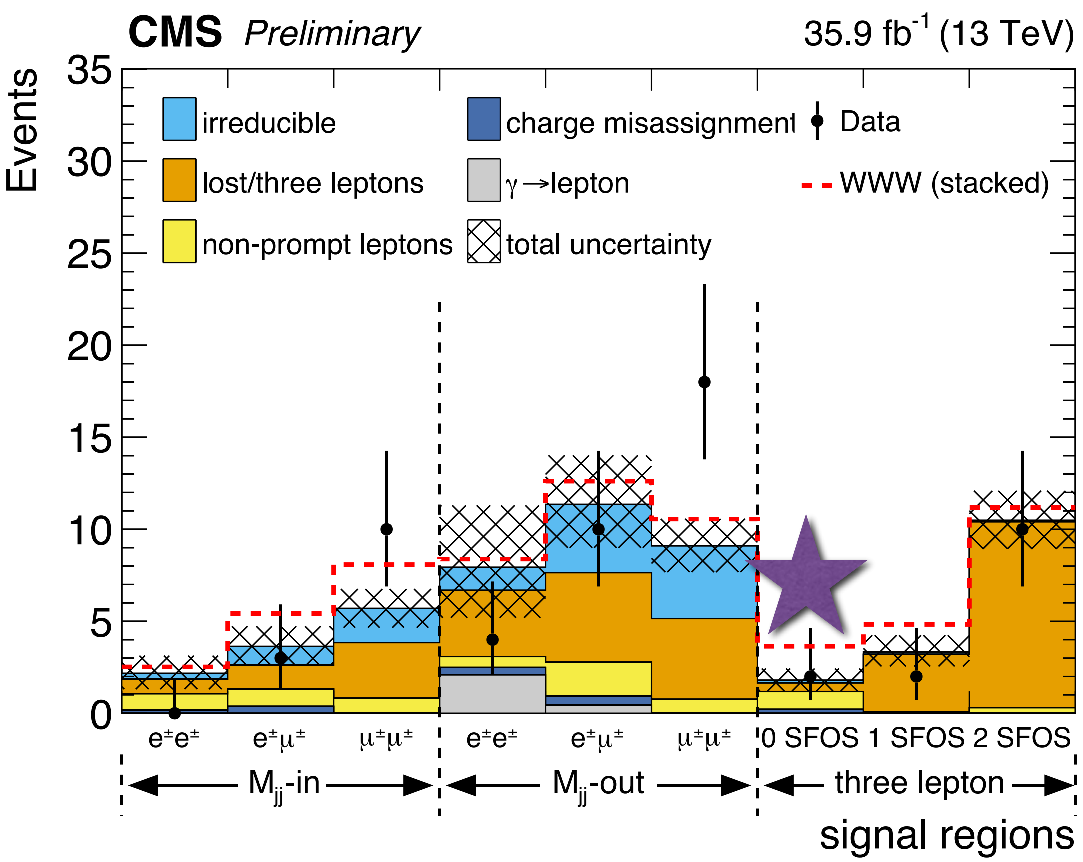






Λ_{FF} = 0.5 TeV, 1 TeV, ∞

aQGCs in triboson final states



- **Optimized cuts on S_T (= sum of all objects in an event)** lead to almost **background free environments**
- **Remaining backgrounds are irreducible** (no contamination from fakes)
- **Use simulations** to determine these **backgrounds**
- **SM WWW** is taken as a **background**

Anomalous coupling	Allowed range (TeV^{-4}) Expected	Observed
$f_{T,0}/\Lambda^4$	[-1.3, 1.3]	[-1.2, 1.2]
$f_{T,1}/\Lambda^4$	[-3.7, 3.7]	[-3.3, 3.3]
$f_{T,2}/\Lambda^4$	[-3.0, 2.9]	[-2.7, 2.6]

Summary of aTGC analyses

Process	Salient feature	CMS or ATLAS	Center of mass energy, $\sqrt{s}$ and data set	Reference
W^+W^- production	Uses unfolded leading lepton p_T to set limits on aTGCs	ATLAS	13 TeV, 36.1 fb^{-1}	https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2017-24/
WZ production	Uses p_T of 2 resolved jets or p_T of boosted jet	ATLAS	8 TeV, 20.1 fb^{-1}	https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2015-23/
WZ production (semileptonic decay)	Uses mass of WV system	CMS	13 TeV, 35.9 fb^{-1}	http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP-18-008/
WZ production (leptonic decay)	Uses mass of WV system	CMS	13 TeV, 35.9 fb^{-1}	http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP-18-002/

Summary of aTGC analyses

Process	Salient feature	CMS or ATLAS	Center of mass energy, √s and data set	Reference
ZZ production	Exploration of neutral aTGCs from dim-8 operators	ATLAS	13 TeV, 36.1 fb^{-1}	https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2016-15/
ZZ ($Z \to l^+l^-$, $Z \to \nu\nu$)	Exploration of neutral aTGCs from dim-8 operators; achieve higher sensitivity	ATLAS	13 TeV, 36.1 fb^{-1}	https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2017-03/
Zγ ($Z \to \nu\nu$)	Exploration of neutral aTGCs from dim-8 operators; achieve higher sensitivity	ATLAS	8 TeV, 20.1 fb^{-1}	https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2017-18/

Summary of aQGC analyses

Process	Salient feature	CMS or ATLAS	Center of mass energy, √s and data set	Reference
WZ (semileptonic)	**Use VBS topology and tag a boosted W or Z jet; sets most stringent limits**	**CMS**	**13 TeV, 35.9 fb^{-1}**	***http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP-18-006/***
WZ (leptonic)	**VBS WZ in fully leptonic channel**	**CMS**	**13 TeV, 35.9 fb^{-1}**	***http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP-18-001/***
ZZ (leptonic)	**VBS ZZ in fully leptonic channel, set limits on f_{T8}, f_{T9}**	**CMS**	**13 TeV, 35.9 fb^{-1}**	***https://arxiv.org/pdf/1708.02812.pdf***
Zγ (Z →νν)	**Limits characterized as a function of cut-off scale**	**ATLAS**	**8 TeV, 20.1 fb^{-1}**	***https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2015-21/***
VBS WW	**Analysis uses k-matrix unitarization to set limits on aQGCs**	**ATLAS**	**8 TeV, 20.1 fb^{-1}**	**https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2014-05/**

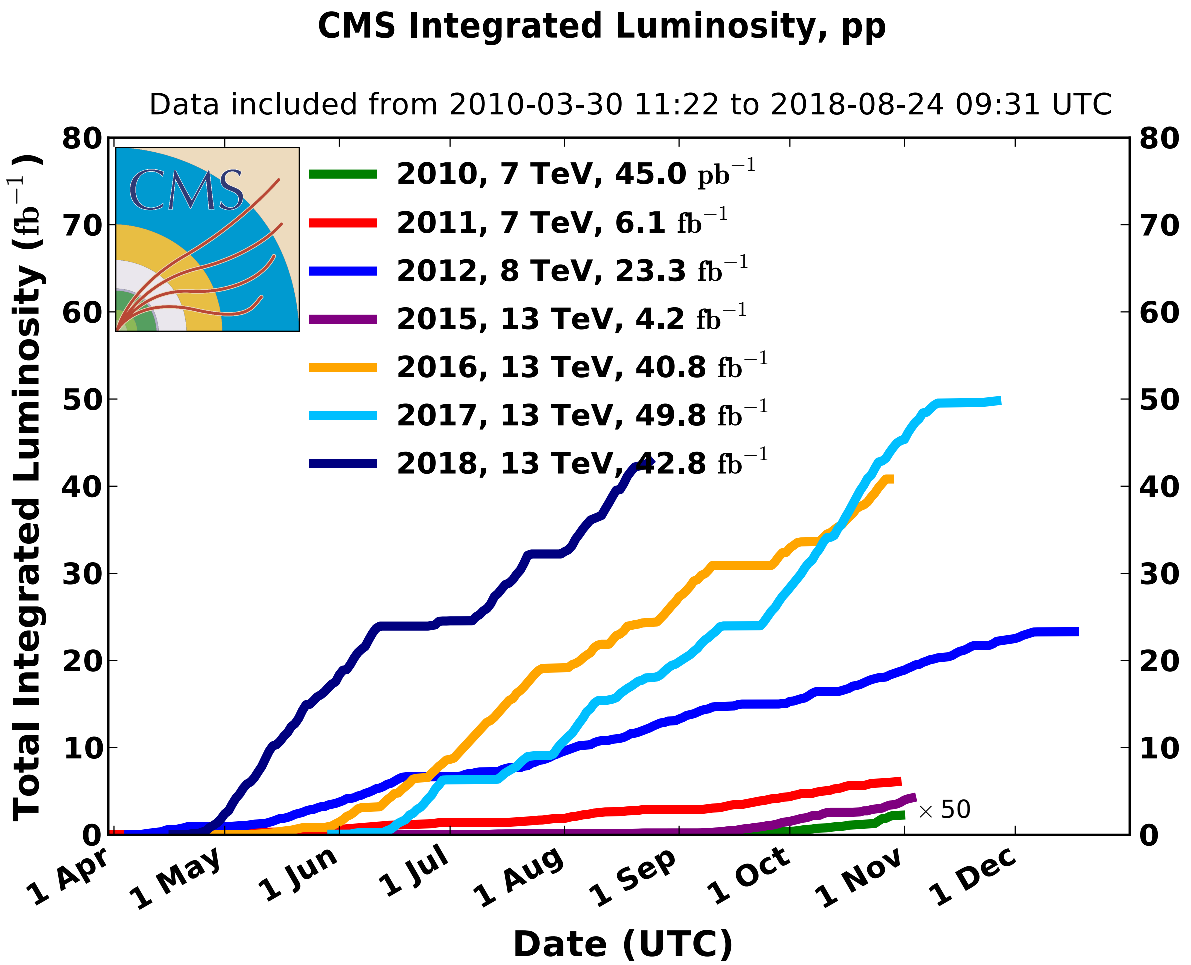
Current state of combination of CMS and ATLAS results

It is the early stages in the determination of quartic couplings by the LHC experiments. It is hoped that the two collaborations, ATLAS and CMS, will agree to use at least one common set of parameters to express these limits to enable the reader to make a comparison and allow for a possible LHC combination.

emphasis mine!

Summary and next steps

- Anomalous contributions explored in myriad final states
- Exploration of anomalous contribution to SM couplings complementary to BSM searches
- In the process of analyzing full Run 2 dataset
- Stay tuned for new results!



Additional Material

Definitions

- Mass drop tagger used :

$$\text{Soft Drop Condition:} \quad \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R_0} \right)^{\beta},$$

- Transverse mass of the WW system:

$$m_{WW,\mathrm{T}} = \sqrt{\left(\mathbf{P}_{\ell_1} + \mathbf{P}_{\ell_2} + \mathbf{P}_{E_{\mathrm{T}}^{\mathrm{miss}}}\right)^2}$$

$$M(WZ)^2 = [p(\ell_1) + p(\ell_2) + p(\ell_3) + p(\nu)]^2$$

$$m_{\mathrm{T}}(\mathrm{WZ}) = \sqrt{[E_{\mathrm{T}}(\mathrm{W}) + E_{\mathrm{T}}(\mathrm{Z})]^2 - [\vec{p_{\mathrm{T}}}(\mathrm{W}) + \vec{p_{\mathrm{T}}}(\mathrm{Z})]^2},$$

aTGC Modeling

$$
\begin{aligned}
F_{\text{signal}}(m_{\text{WV}}) =& N_{\text{SM}}\left(e^{a_0 m_{\text{WV}}} + e^{a_{\text{corr}} m_{\text{WV}}}\right) \\
&+ \sum_{\text{i}} \left(N_{c_{\text{i}},1} c_{\text{i}}^2 e^{a_{\text{i},1} m_{\text{WV}}} \left(\frac{1 + \text{Erf}((m_{\text{WV}} - a_{0,\text{i}})/a_{\text{w,i}})}{2} \right) + N_{c_{\text{i}},2} c_{\text{i}} e^{a_{\text{i},2} m_{\text{WV}}} \right) \\
&+ \sum_{\text{i} \neq \text{j}}^{\text{i}<\text{j}} \left(N_{c_{\text{i}},c_{\text{j}}} c_{\text{i}} c_{\text{j}} e^{a_{\text{ij}} m_{\text{WV}}} \right),
\end{aligned}
$$

EFT validity

Leptonic WZ

[Franceschini, Panico, Pomarol, Riva, AW, 2018]

The **most important plot:** reach now extends to reasonable theories !
[This is what assessing the "EFT Validity" really means]

Strongly-coupled quarks (and Higgs)

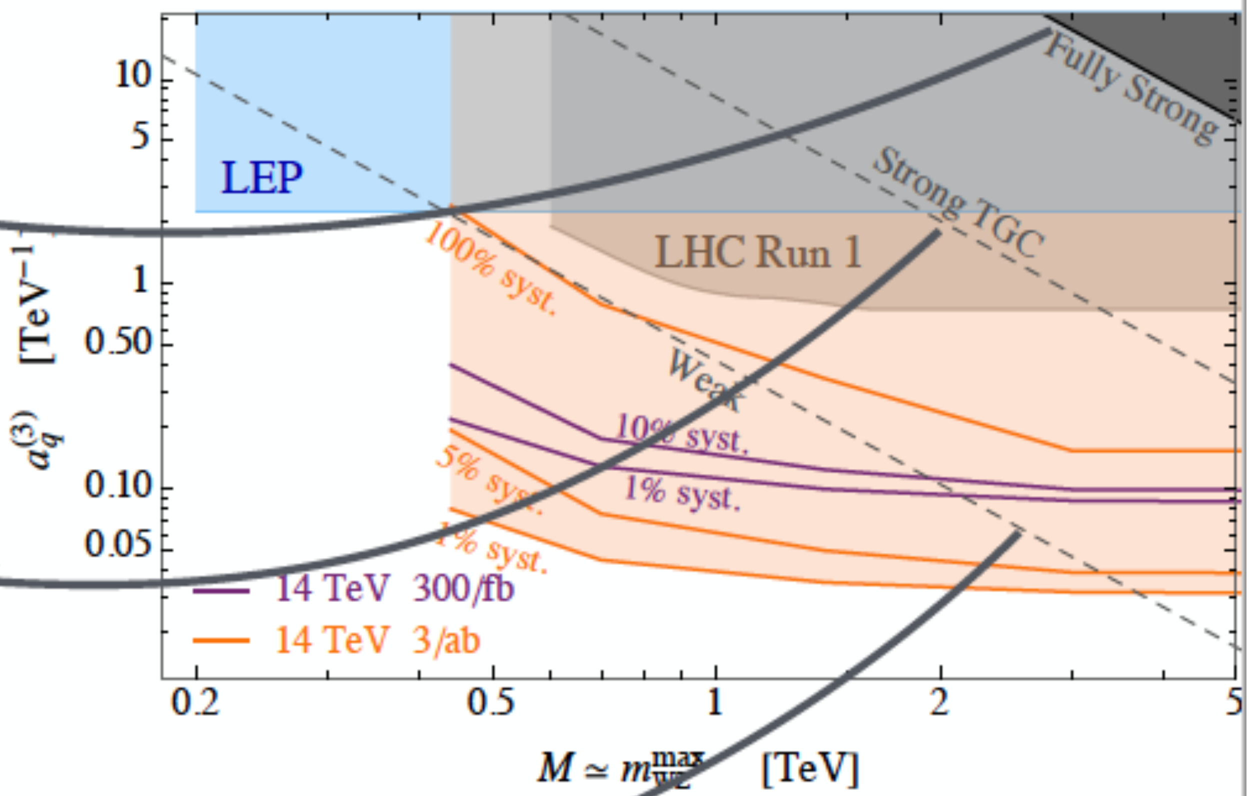
$$a_q^{(3)} = \frac{16\pi^2}{M^2}$$

Weakly-coupled quarks, **strongly coupled gauge**

$$a_q^{(3)} = \frac{4\pi g_W}{M^2}$$

Weakly-coupled quarks, **weakly coupled gauge**

$$a_q^{(3)} = \frac{g_W^2}{M^2}$$



From Andrea's Wulzer's talk given at MBI 2018

Outline of the talk

- ATLAS results:

- WW: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2017-24/: done
- 4-lepton: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2017-09/
- Zy 13TeV: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2017-18/
- WVy: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2016-05/
- semileptonic WW/WZ: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2015-23/: almost done
- Zy: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2015-21/

— ZZ production with two charged leptons and two neutrinos in the final state at 13 TeV
-- ZZ cross-section measurement and aTGC limits at 13 TeV
-- Electroweak Wjj cross section and aGC Limits at 7 and 8 TeV

Claudius' and my sources:
— https://arxiv.org/abs/1810.07698 (A Global Likelihood for Precision Constraints and Flavour Anomalies)
— http://pdg.lbl.gov/2019/reviews/rpp2018-rev-wz-quartic-couplings.pdf (pdg)
— https://www.thphys.uni-heidelberg.de/~gk_ppbsm/lib/exe/fetch.php?media=students:lectures:student_lecture_eft.pdf (Johannes intro)
— https://arxiv.org/pdf/1408.6207.pdf (Higgs EFT)
— https://arxiv.org/pdf/1205.4231.pdf (degrande)
— https://arxiv.org/pdf/1610.01618.pdf (Time to Go Beyond Triple-Gauge-Boson-Coupling Interpretation of W Pair Production)
— Claudius' previous talk: https://indico.cern.ch/event/756370/contributions/3184515/attachments/1738204/2812041/HEHL.C.Krause.pdf