Anomalous gauge couplings: Status of triple and quartic gauge couplings

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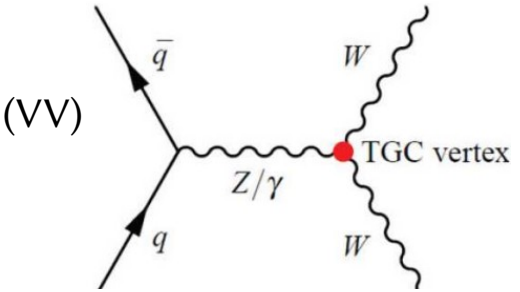
Overview

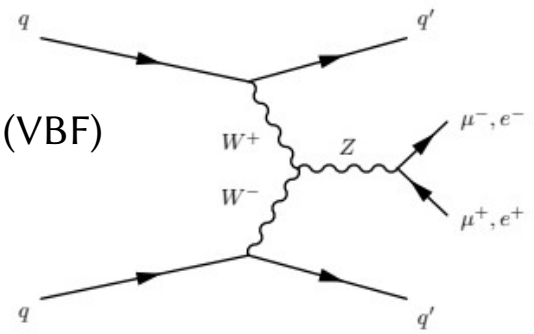
- Electroweak sector is a key area for checking Standard Model prediction
  - Especially that decades of measurements are consistent with the SM
- Searches for deviation from the SM performed during Run-1 and Run-2
  - Can be performed without choosing a specific model
  - Capture wide range of possible new physics

Anomalous triple gauge coupling (aTGC)

Diboson production (VV)
$\sigma \sim \mathcal{O}(10\ \text{pb})$

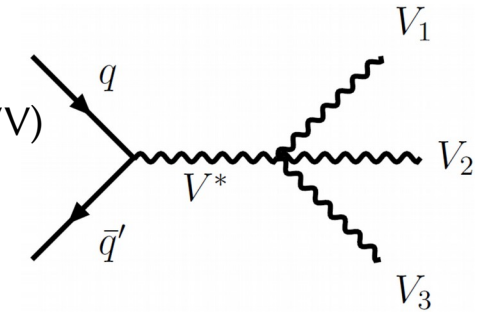


Vector boson fusion (VBF)
$\sigma \sim \mathcal{O}(0.1\ \text{pb})$

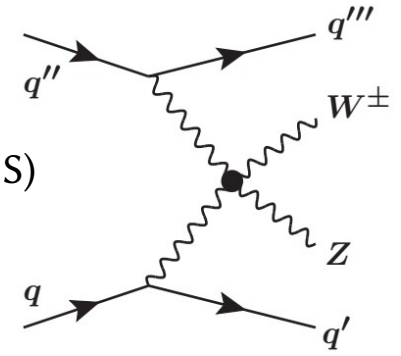


Anomalous quartic gauge coupling (aQGC)

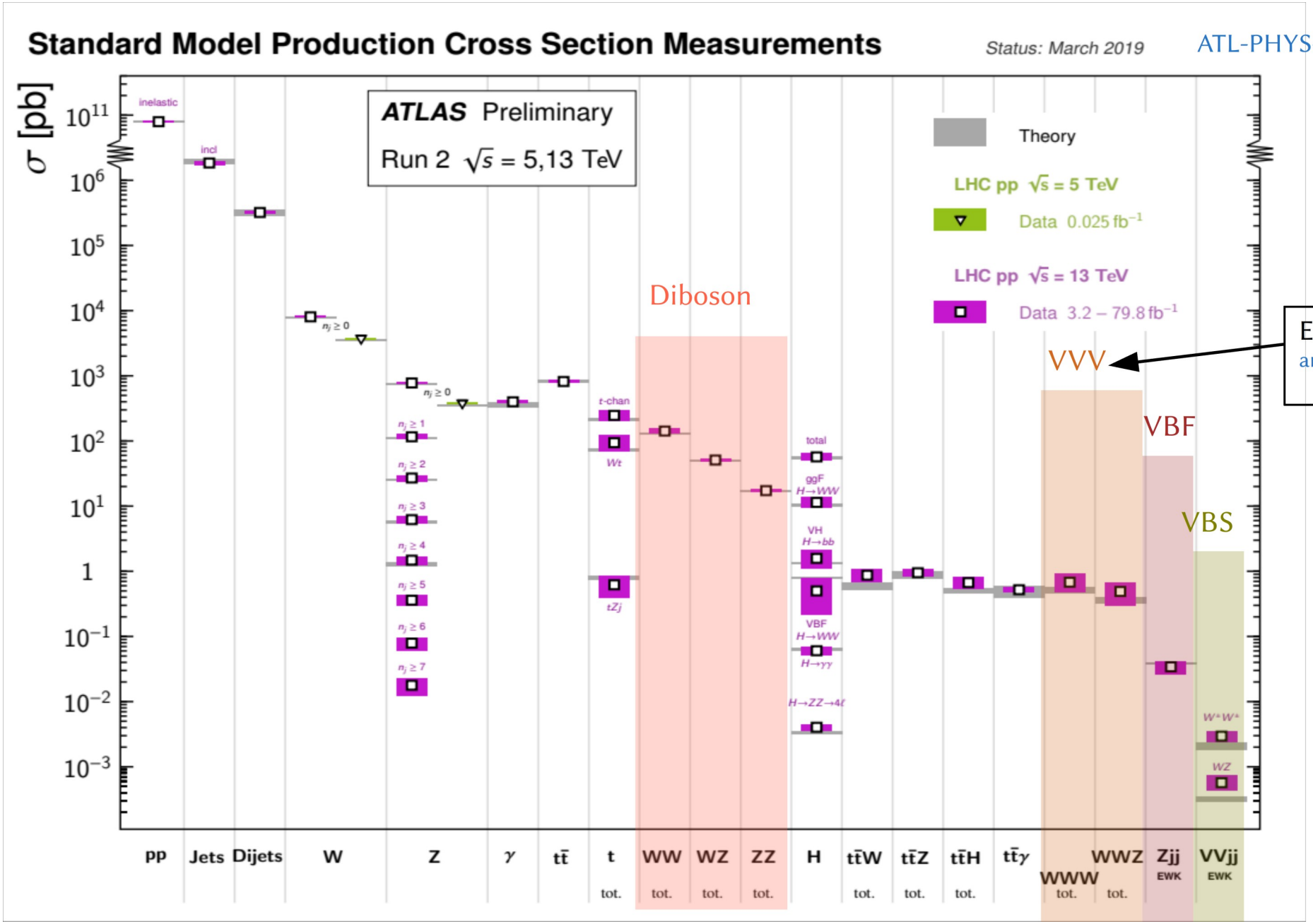
Triboson production (VVV)
$\sigma \sim \mathcal{O}(1\ \text{pb})$



Vector boson scattering (VBS)
$\sigma \sim \mathcal{O}(1\ \text{fb})$



Some processes sensitive to aGCs



Extension of the Standard Model

- Can add new degrees of freedom in the SM Lagrangian (vertex approach)
  - For example, adding new interaction term to introduce anomalous triple gauge couplings (aTGCs) $\Delta\kappa^V$, Δg_1^V, λ^V CERN-96-01-V-1
  - Can compare directly to LEP and Tevatron results

- Also possible to extend the SM using Effective Field Theory (EFT) with operators of dimension six, dimension eight, ... (Phys.Rev. D74 (2006) 073005):

Dim-6 Dim-8

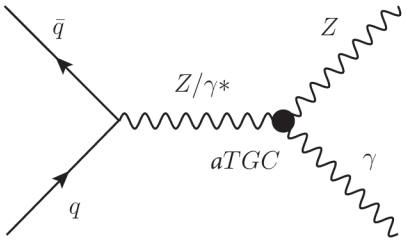
$$\mathcal{L} = \mathcal{L}_{SM} + \Sigma_i \frac{c_i}{\Lambda^2} O_i + \Sigma_j \frac{f_j}{\Lambda^4} O_j + \dots$$

- Dim-8 operators affect QGCs, while dim-6 can affect both TGC and QGC

Classification of dim-8 operators

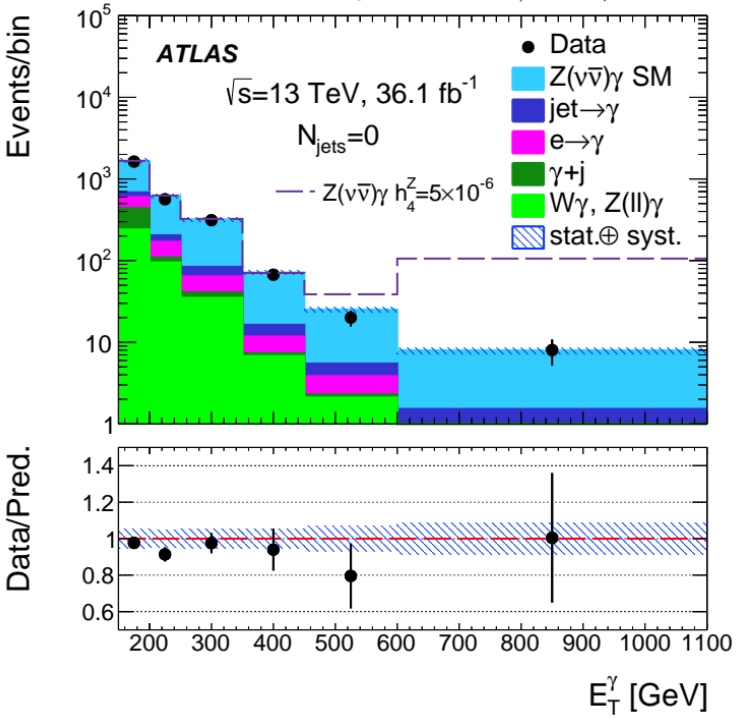
	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$	X	X	X						
$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$,$\mathcal{O}_{M,6}$,$\mathcal{O}_{M,7}$	X	X	X	X	X	X	X		
$\mathcal{O}_{M,2}$,$\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$,$\mathcal{O}_{M,5}$		X	X	X	X	X	X		
$\mathcal{O}_{T,0}$,$\mathcal{O}_{T,1}$,$\mathcal{O}_{T,2}$	X	X	X	X	X	X	X	X	X
$\mathcal{O}_{T,5}$,$\mathcal{O}_{T,6}$,$\mathcal{O}_{T,7}$		X	X	X	X	X	X	X	X
$\mathcal{O}_{T,8}$,$\mathcal{O}_{T,9}$			X			X	X	X	X

Analysis strategy



- $Z\gamma$ production is sensitive to $ZZ\gamma$ and $Z\gamma\gamma$ aTGCs
  - Neutral TGCs forbidden at tree level in the SM
- Search for enhancement at high-energy region
  - In this case, the region E_T of the photon > 600 GeV
- Adding new terms to the Lagrangian leads to cross-section rising at high energies, violating unitarity
  - Many measurements report limits both with and without a factor to restore unitary
  - Unitarization has bigger effect on aQGC limits

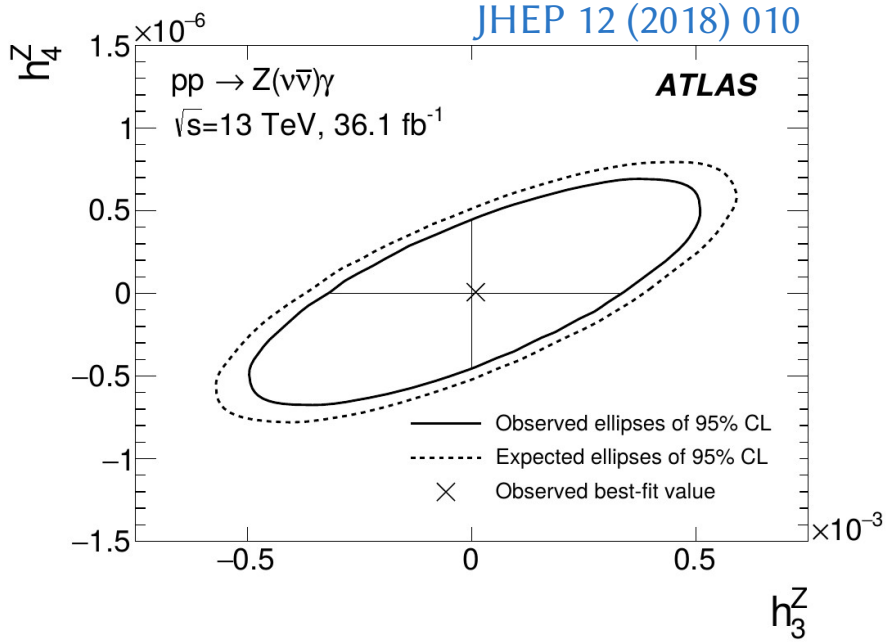
JHEP 12 (2018) 010



- No unitarization
- Set limit on aTGCs and translate to limits on EFT too.

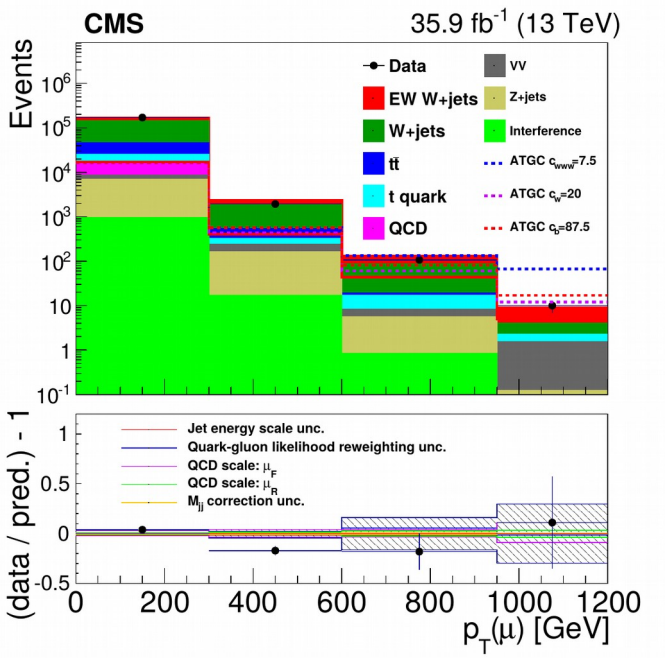
Limit setting

- One dimension:
  - Limits at 95% C.L. are set on an aTGC parameter while the other parameters are set to the SM prediction
- Two dimension:
  - likelihood fit is performed as function of the two aGC parameters
- A linear relation can be derived to convert between the two approaches (between the vertex parameterization and EFT parameterization)



Some recent probes of TGC

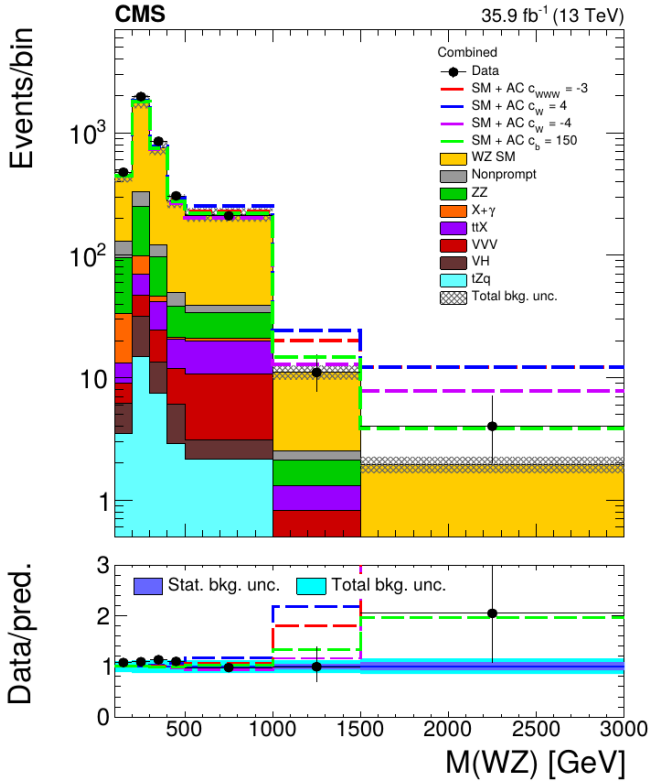
CMS electroweak *W*+jj



- Significance of EW W+jj > 5σ
- Limits on dim-6 c_W, c_B, c_{WWW} parameters
- Limits on $\Delta\kappa^Z$, Δg_1^Z, λ^Z

CMS-SMP-17-011

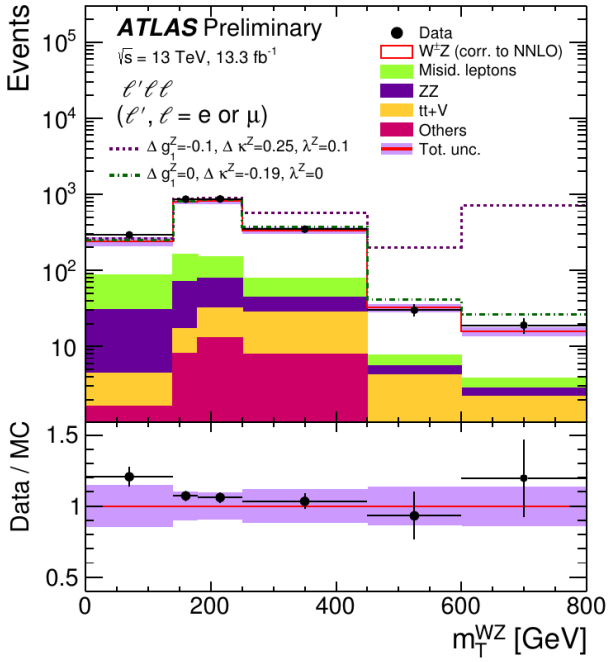
CMS *WZ* production



- Limits on dim-6 c_W, c_B, c_{WWW} parameters

CMS-SMP-18-002

ATLAS *WZ* production

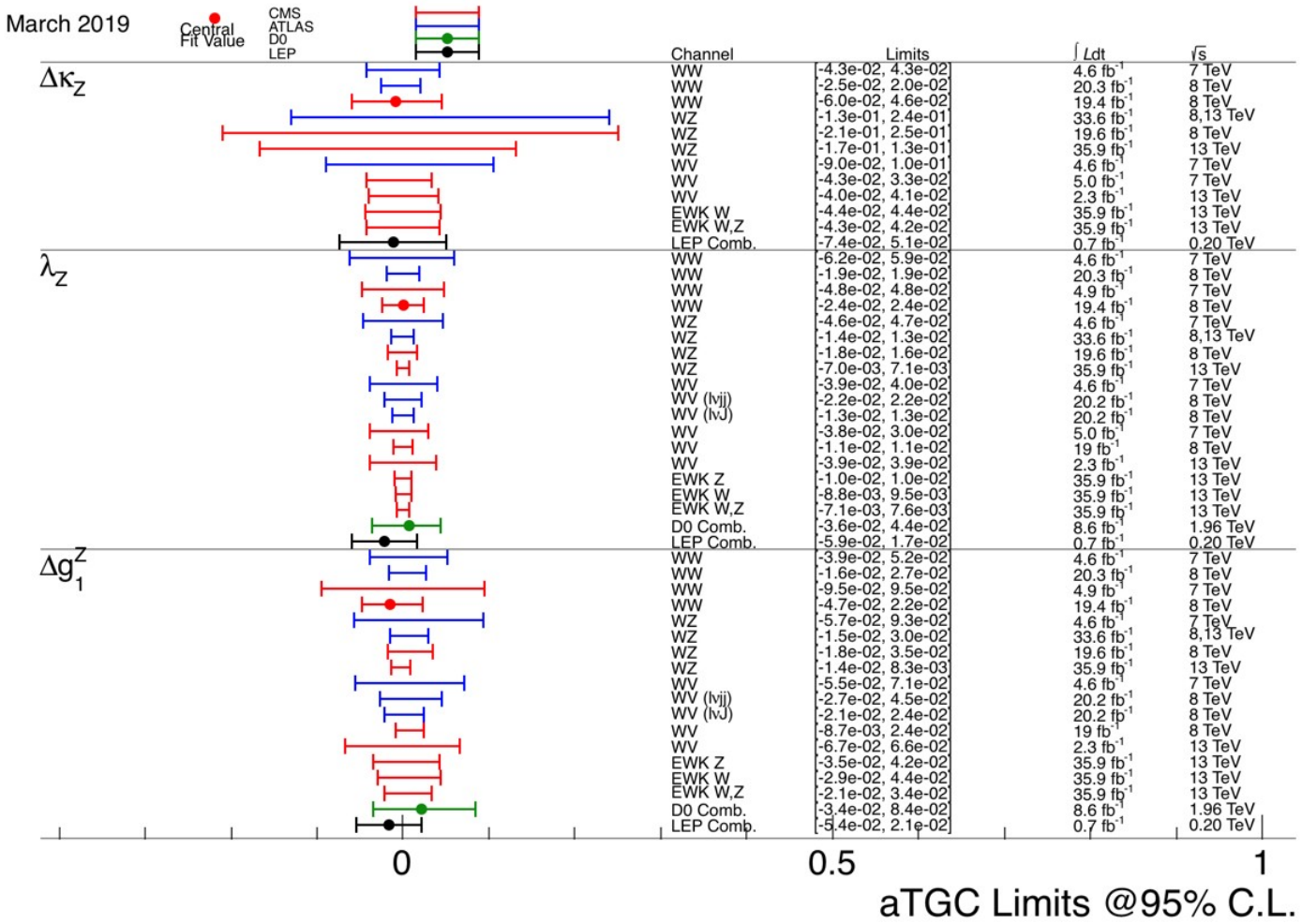


- Limits on dim-6 c_W, c_B, c_{WWW} parameters
- Limits on $\Delta\kappa^Z$, Δg_1^Z, λ^Z

ATLAS-CONF-2016-043

Limits on charged aTGCs

- Sensitivity improved with the increase of integrated luminosity
- Limits set at 95% CL are reported on both aTGCs and EFT
  - Few channels are combined for better sensitivity such as CMS VBF W + VBF Z



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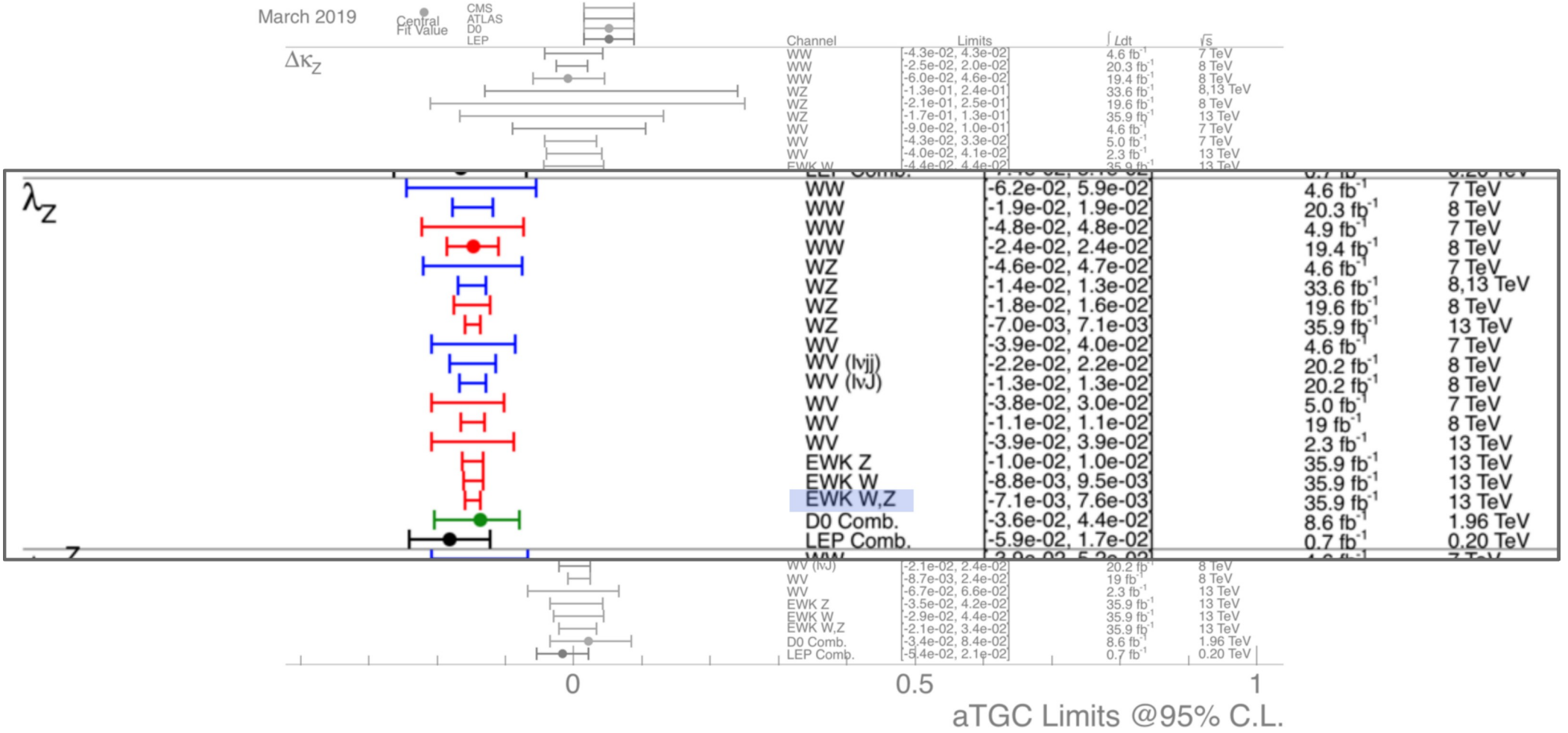
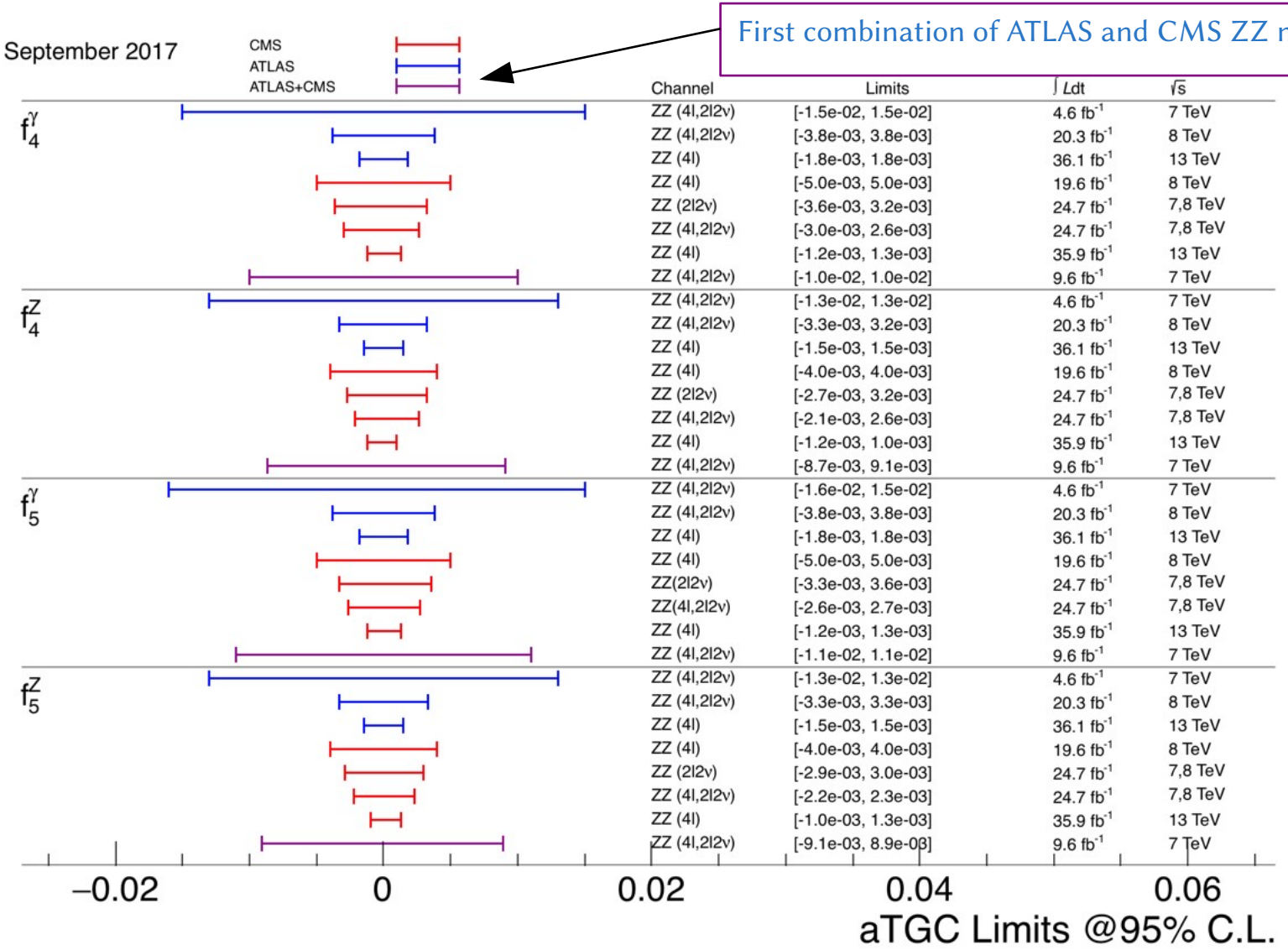


Limits on neutral TGCs

- No indication of neutral TGCs so far
- aGCs summary plots at https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

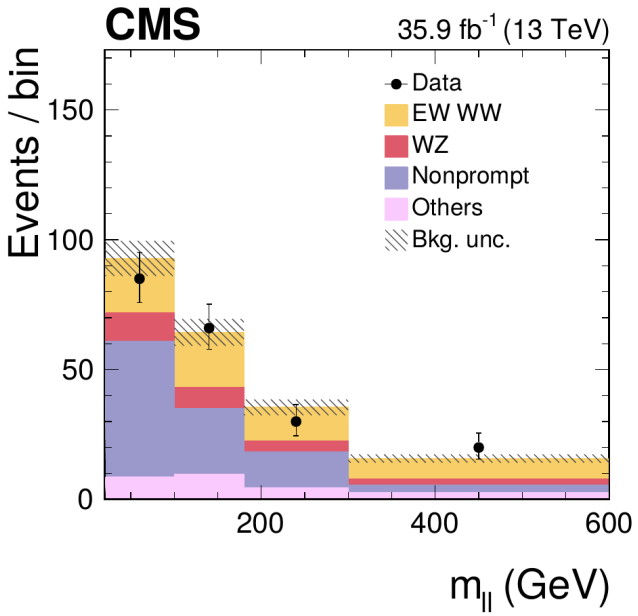


Some recent probes of QGC

- Electroweak component is much smaller than the QCD-initiated component
- Both systematic and statistical uncertainties are large:
  - Renormalization and factorization scales
  - Normalization of QCD background (especially in signal region)
  - Jet-related uncertainties (jet energy scale)

CMS same-sign *WW*

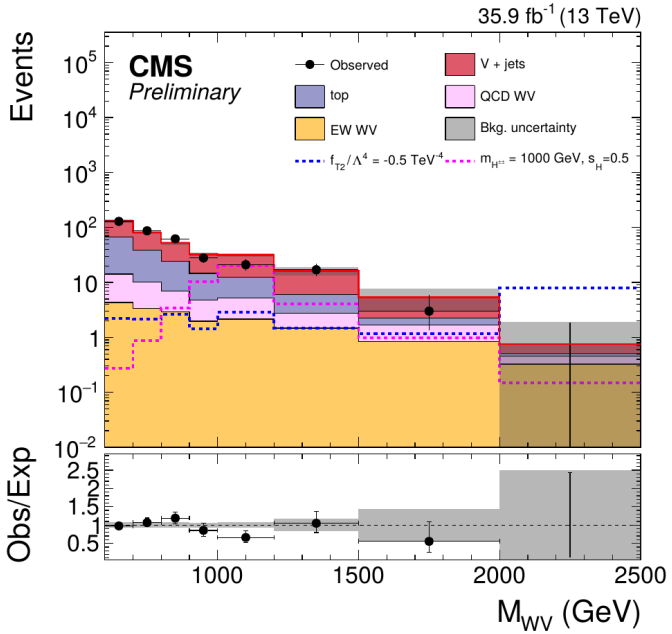
Significance of 5.5σ



Phys. Rev. Lett. 120 (2018) 081801

CMS electroweak *WV*

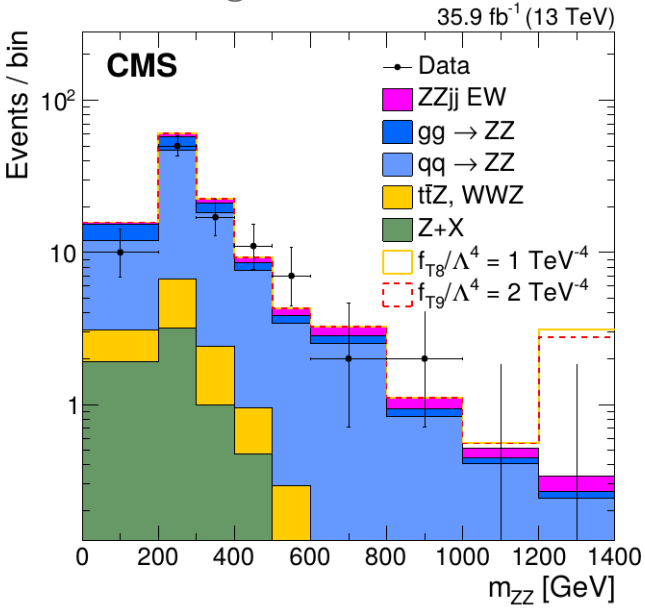
First search at 13 TeV



CMS-PAS-SMP-18-006

CMS VBS *ZZ*

Significance of 2.7σ

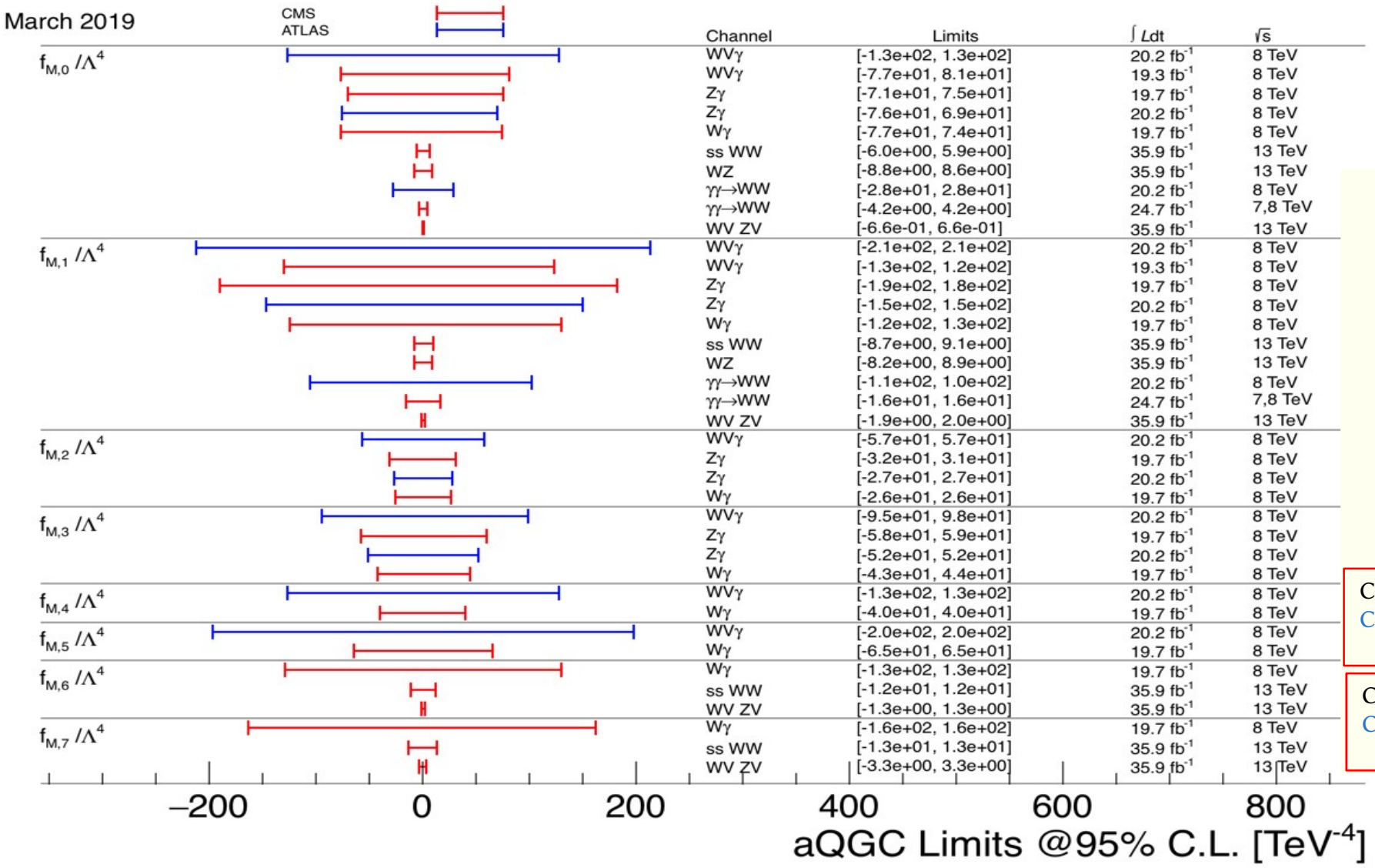


Phys. Lett. B 774 (2017) 682

Limits on aQGCs

- Limits set on both aQGCs and EFT parameters
  - Assume no enhancement due to aTGCs

More limits in backup



13 TeV results

CMS ssWW
arXiv:1709.05822

CMS WZ
arXiv:1901.04060

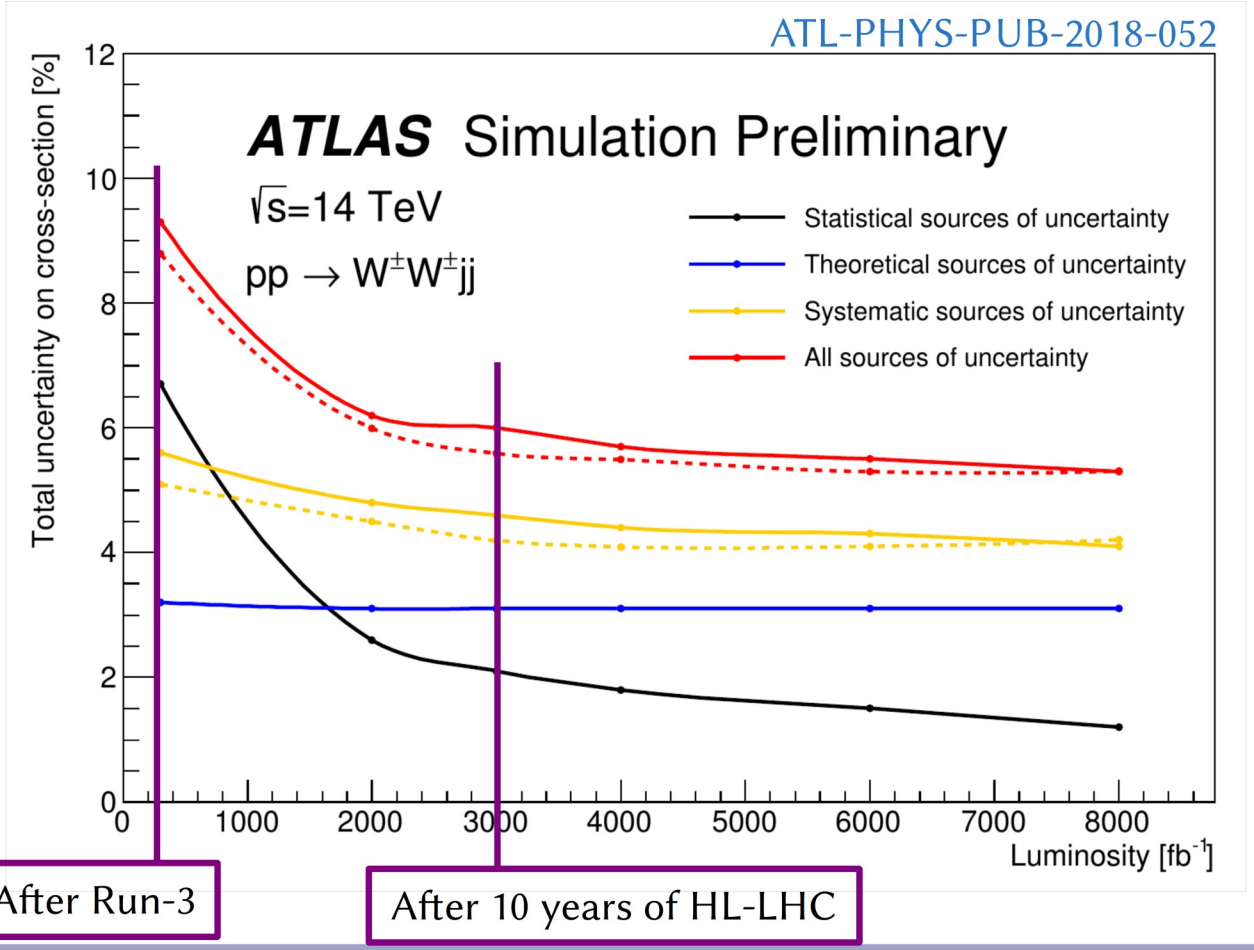
CMS ZZ
arXiv:1708.02812

CMS WV ZV
CMS-PAS-SMP-18-006

CMS WWW
CMS-PAS-SMP-17-013

Toward Run-3 and HL-LHC

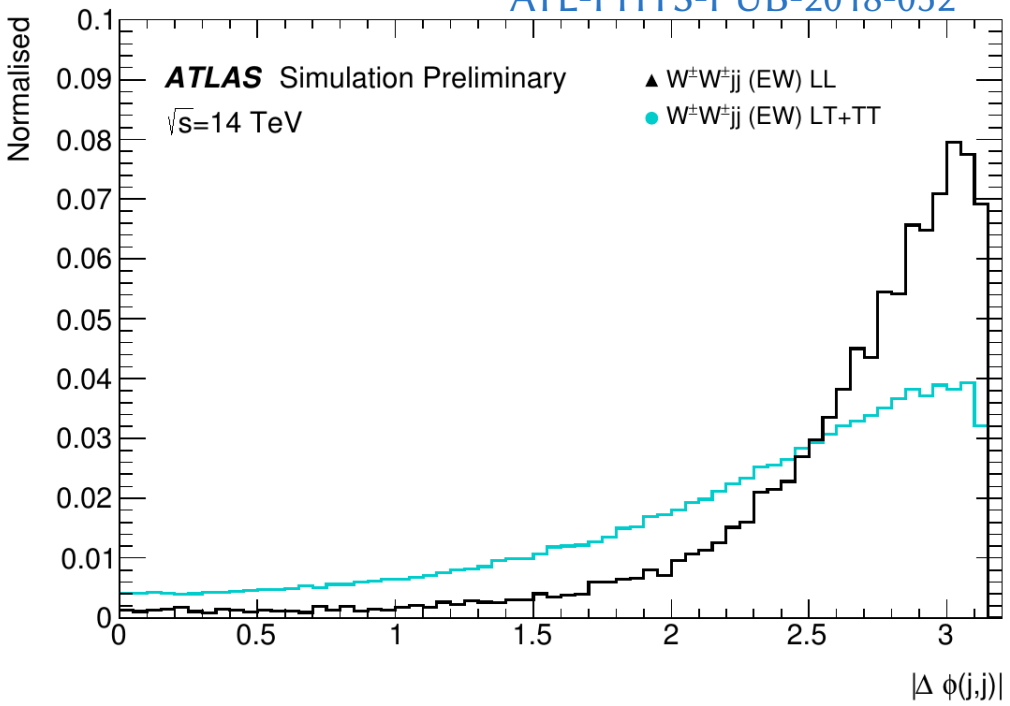
- Sensitivity to aGCs would improve with increase of integrated luminosity, 300 fb^{-1} after Run-3 and 3000 fb^{-1} at the HL-LHC
- ATLAS and CMS has studied the prospect for measuring VBS, VBF, triboson and diboson production at the HL-LHC, CERN-LPCC-2019-01



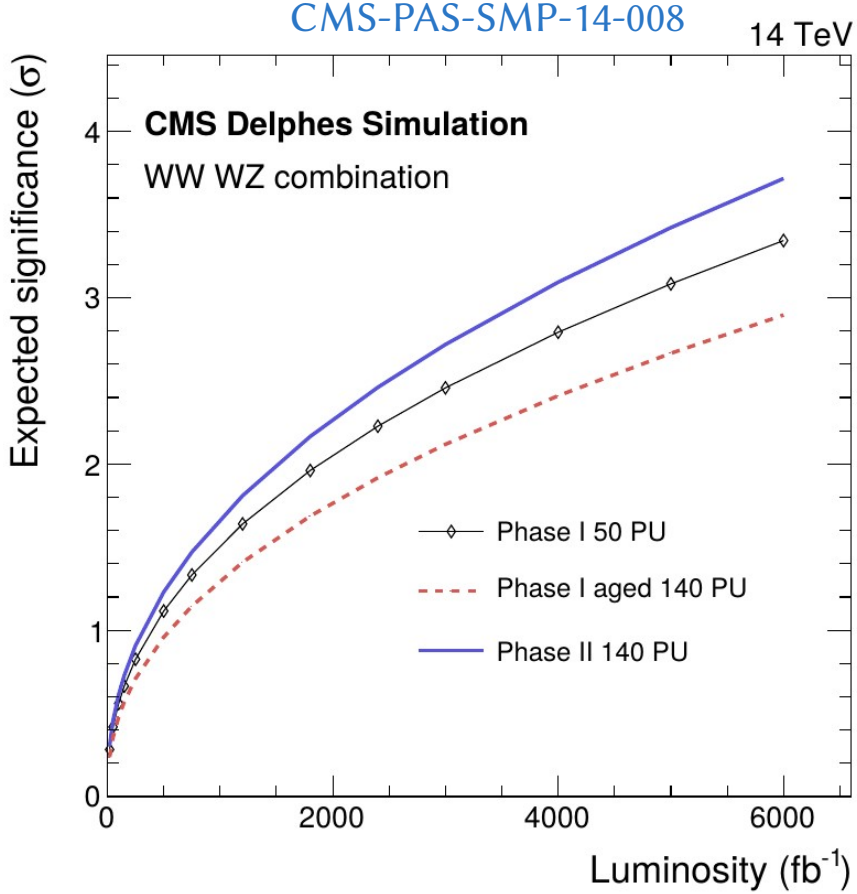
Prospect for longitudinal VBS

- Large dataset at HL-LHC would allow separation of longitudinal from transverse amplitudes in VBS
- Worthwhile to try more advanced analysis techniques
  - Machine learning techniques explored (arXiv:1510.01691, arXiv:1812.07591)

ATL-PHYS-PUB-2018-052



CMS-PAS-SMP-14-008



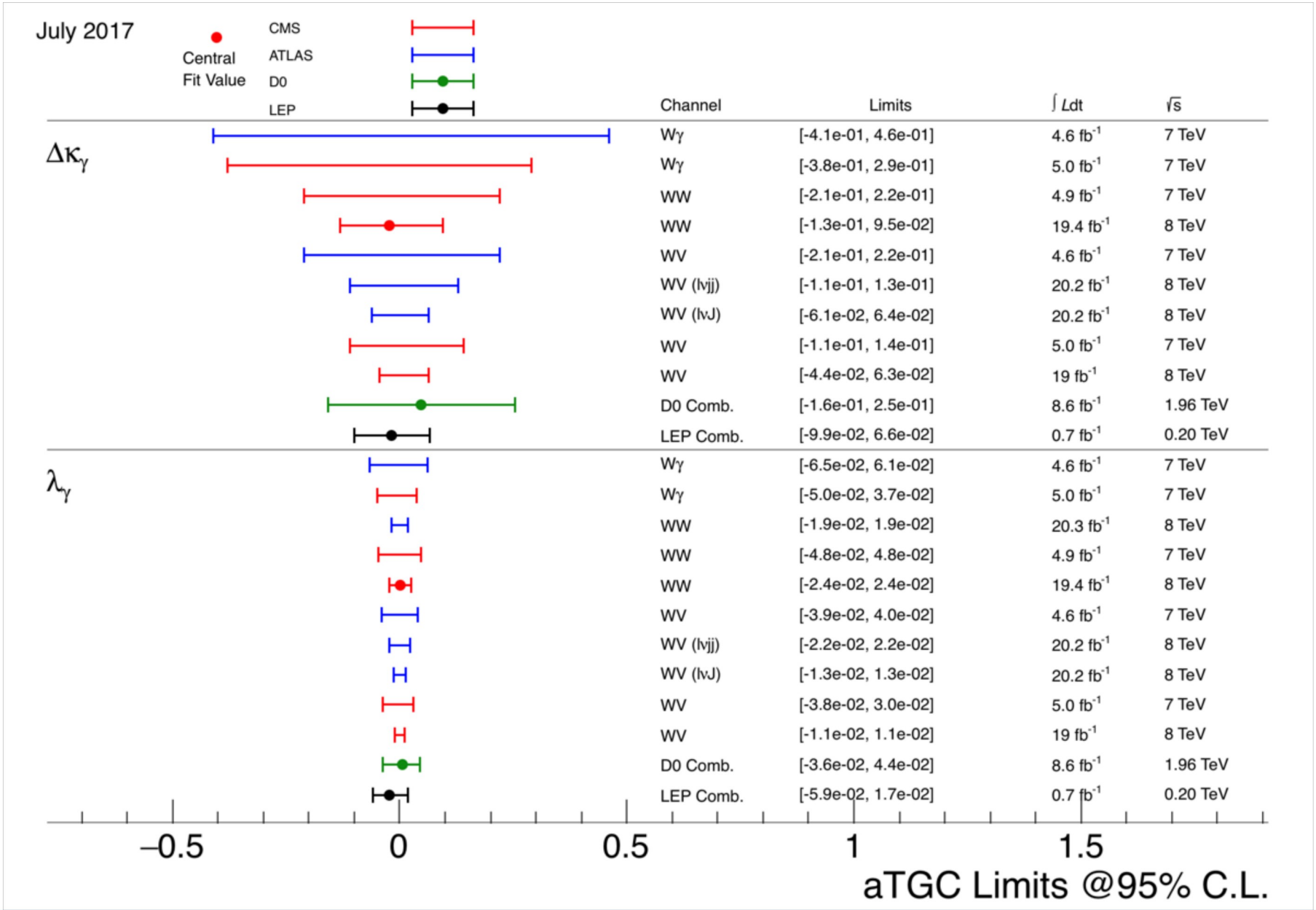
Summary

- Probe of TGC and QGC for deviation from the SM prediction has been carried out as part of many electroweak measurements at the LHC
- Measurements at 13 TeV are becoming available, reporting limits on anomalous gauge couplings that surpass previous limits set with 7 and 8 TeV data
  - Dibosons (WW, WZ, ZZ), VBF (Zjj, Wjj), VBS (WW, WZ, ZZ)
- ATLAS and CMS report the observation of VBS WW and evidence of triboson production at ATLAS
  - Processes with QGC at tree level
- More data expected at HL-LHC will improve measurement of rare VBS processes, leading to better limits on anomalous gauge couplings
- In general a EFT operator affects many channels, so combination between channels would improve sensitivity

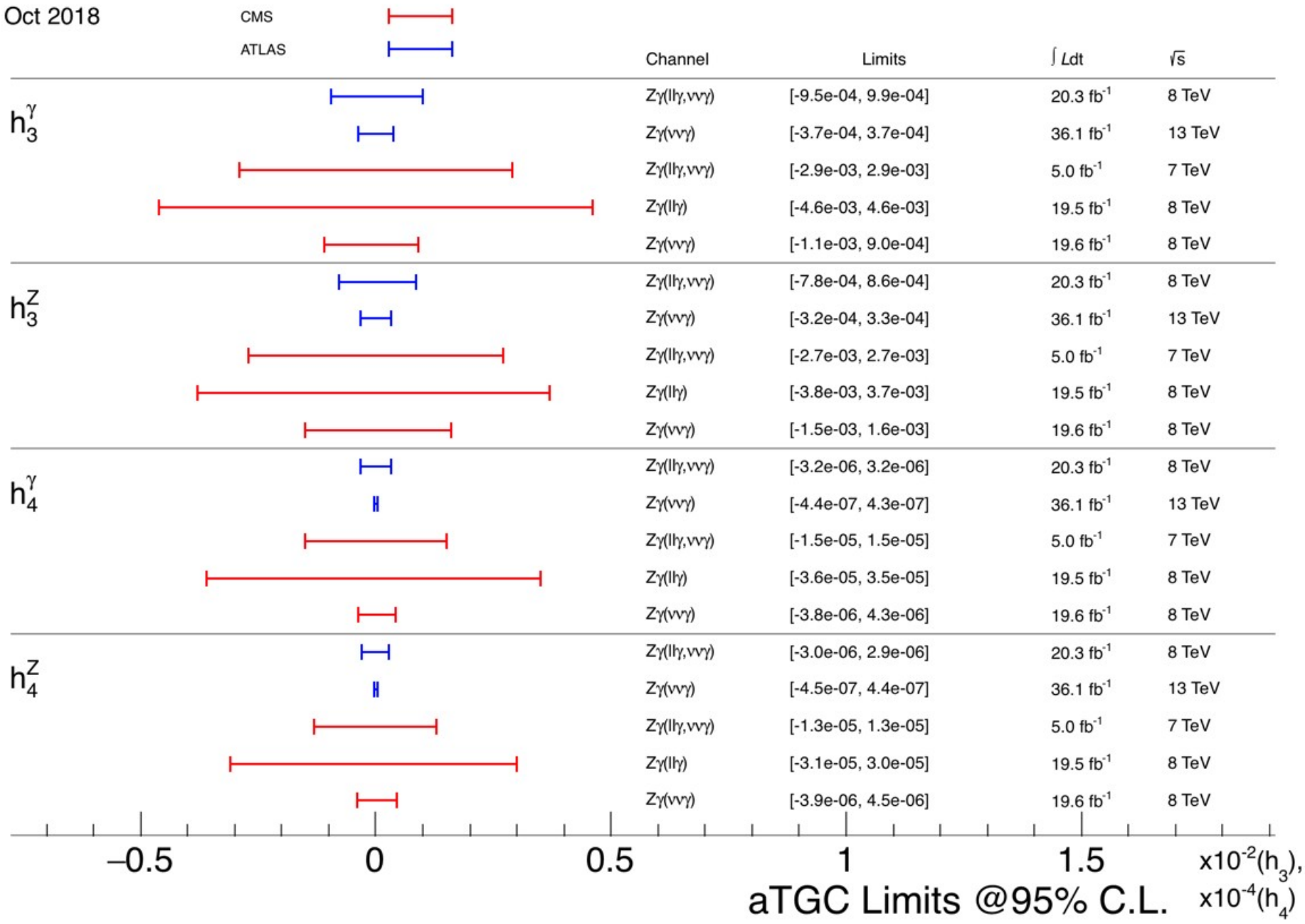
Backup

$WW\gamma$ aTGCs

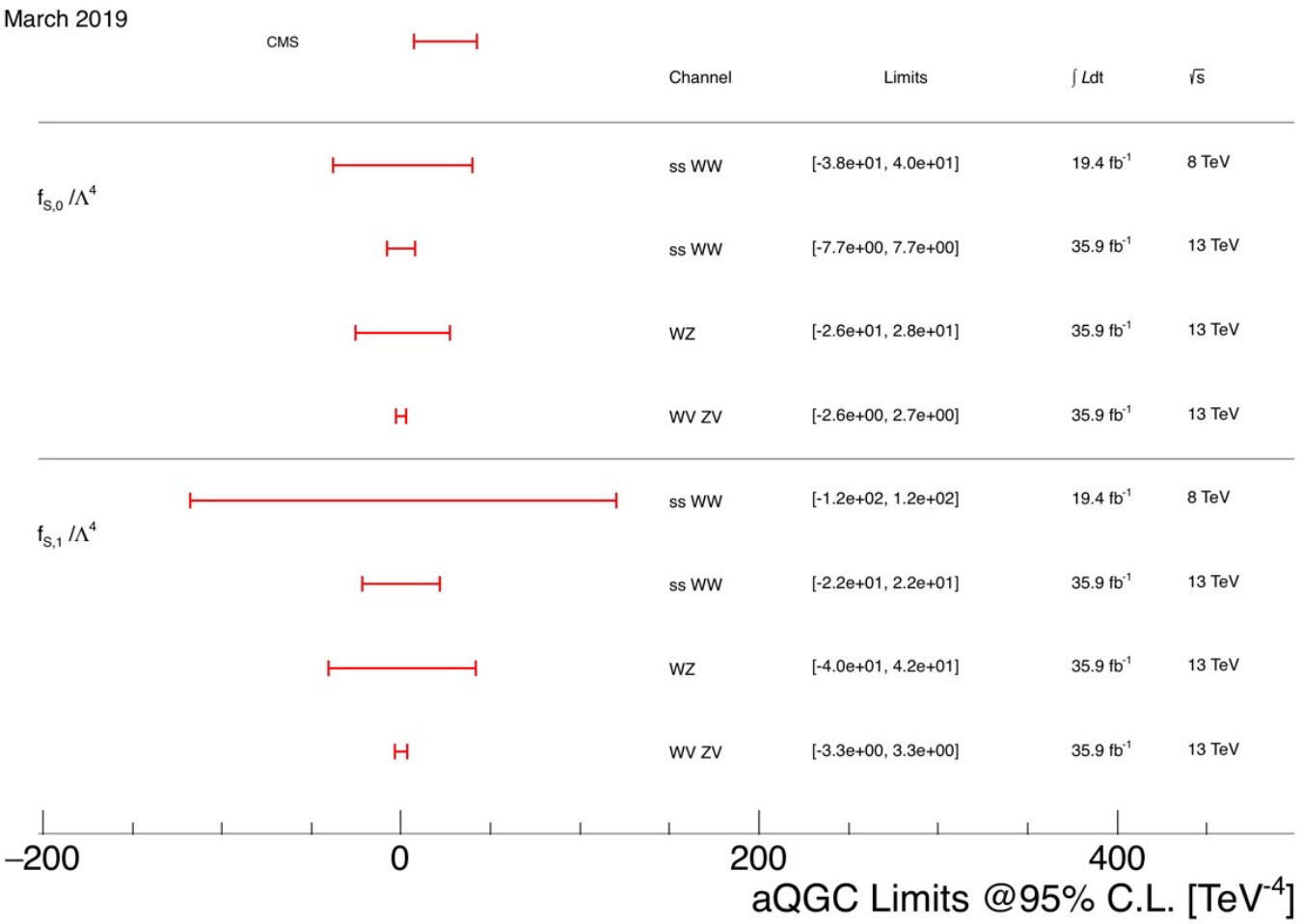
- Link to summary plots: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC



$Z\gamma\gamma$ and $ZZ\gamma$ aTGCs

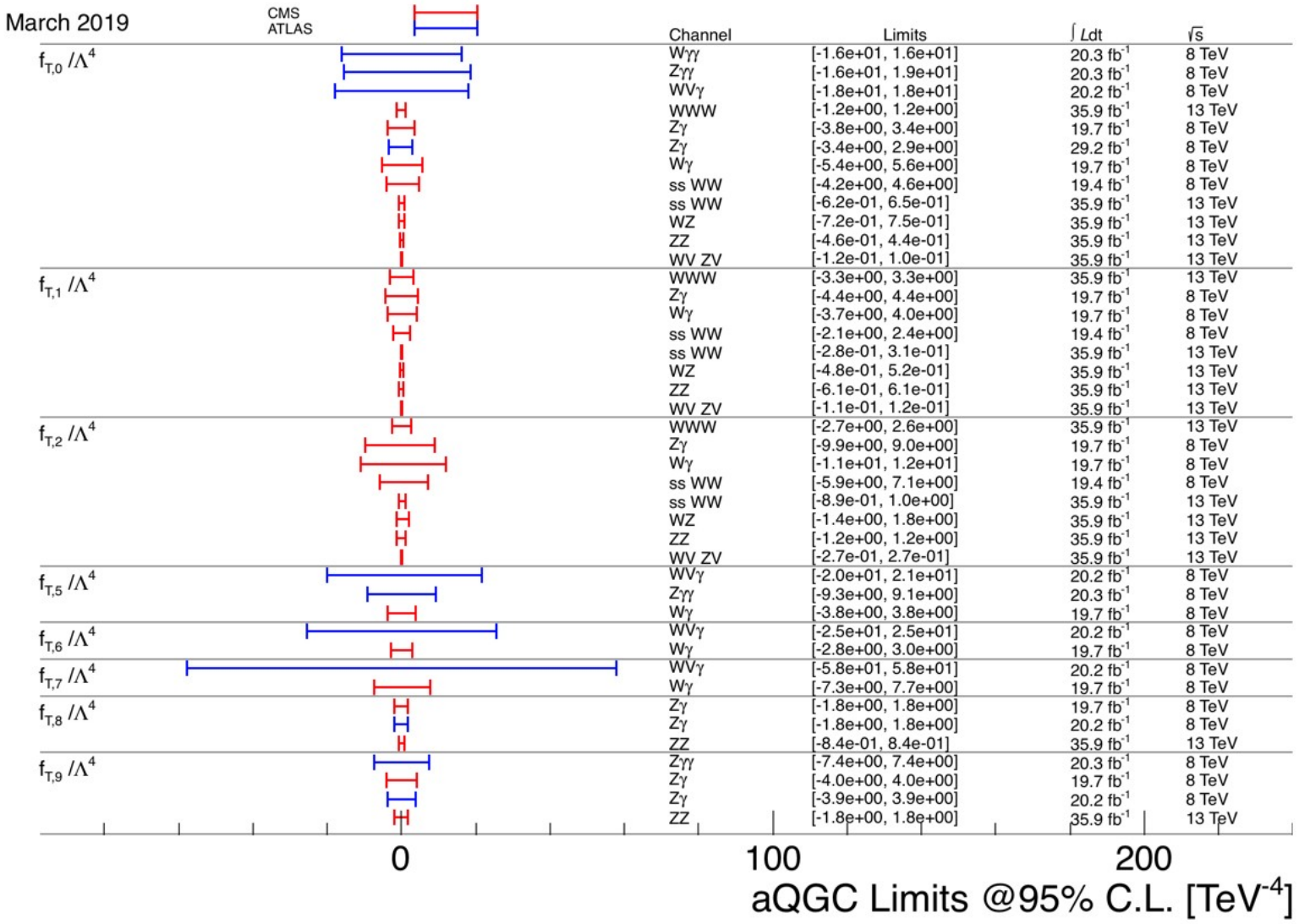


aQGC f_S parameters



More limits on aQGCs

- Unitarization can have significant effect on limits
  - Limits without unitarization reported for most channels



Longitudinal fraction

- Challenging to separate the longitudinal from the transverse states
  - A method has been developed using machine learning, see arXiv:1510.01691
  - More recent study of the prospect at the HL-LHC was done based on latest same-sign WW measurements, see arXiv:1812.07591