Measurement of di- and tri-boson cross sections and differential distributions and EFT interpretations, where available

Multi-Boson results and anomalous couplings at the LHC

Marc-André Pleier

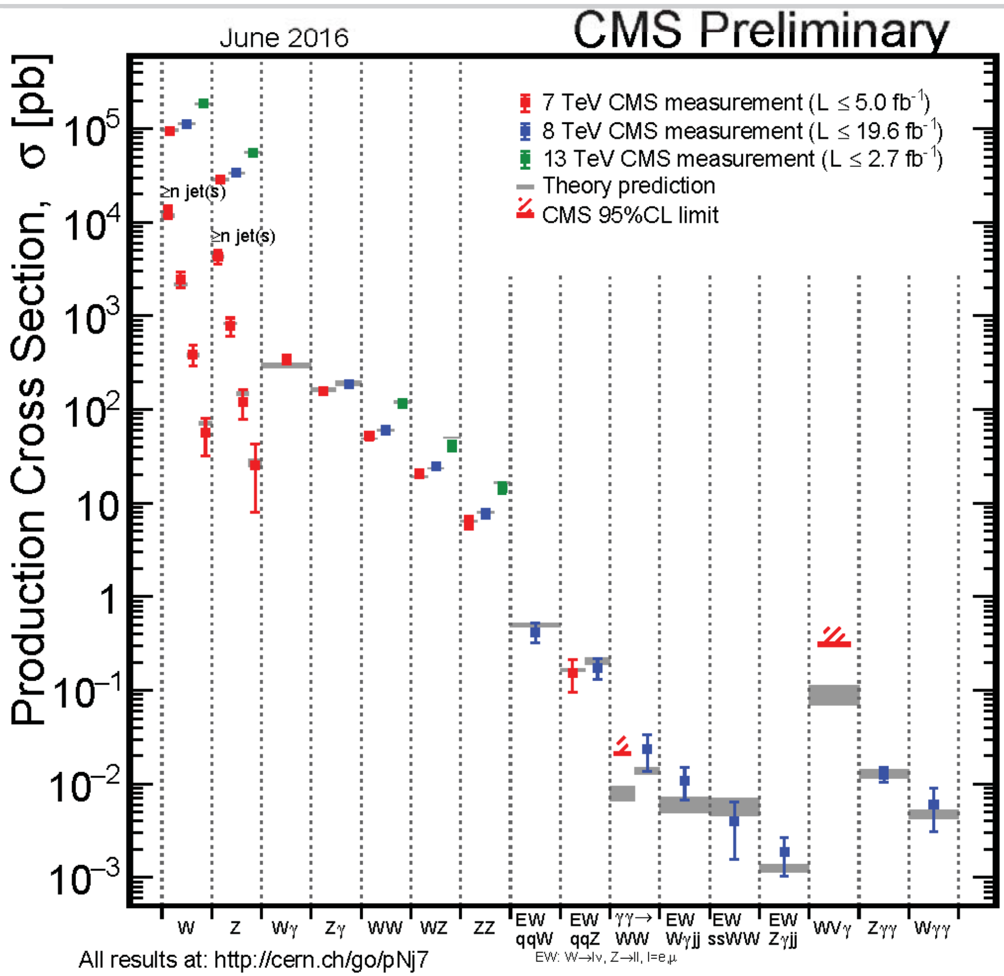
BROOKHAVEN NATIONAL LABORATORY

ATLAS EXPERIMENT

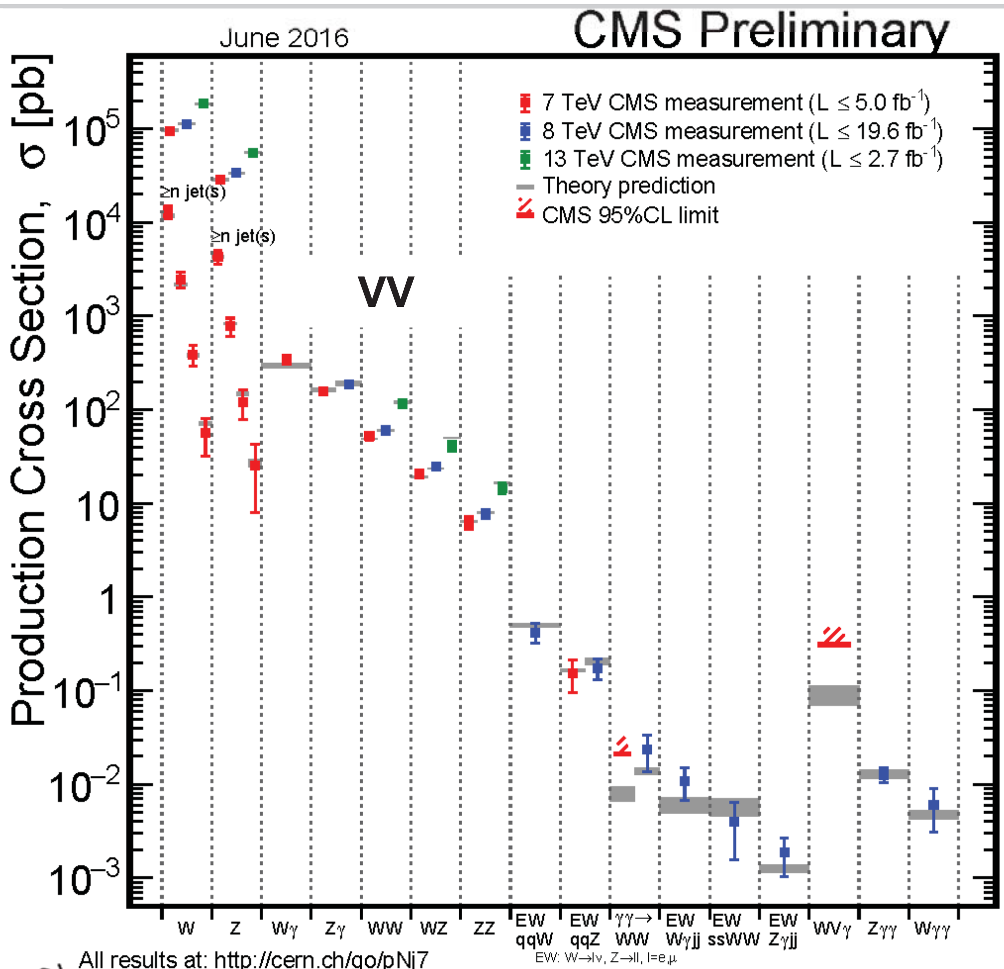
CMS

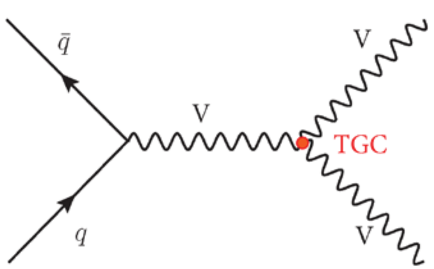
HEFT2016, October 28 2016

(Multi-) V Production



(Multi-) V Production





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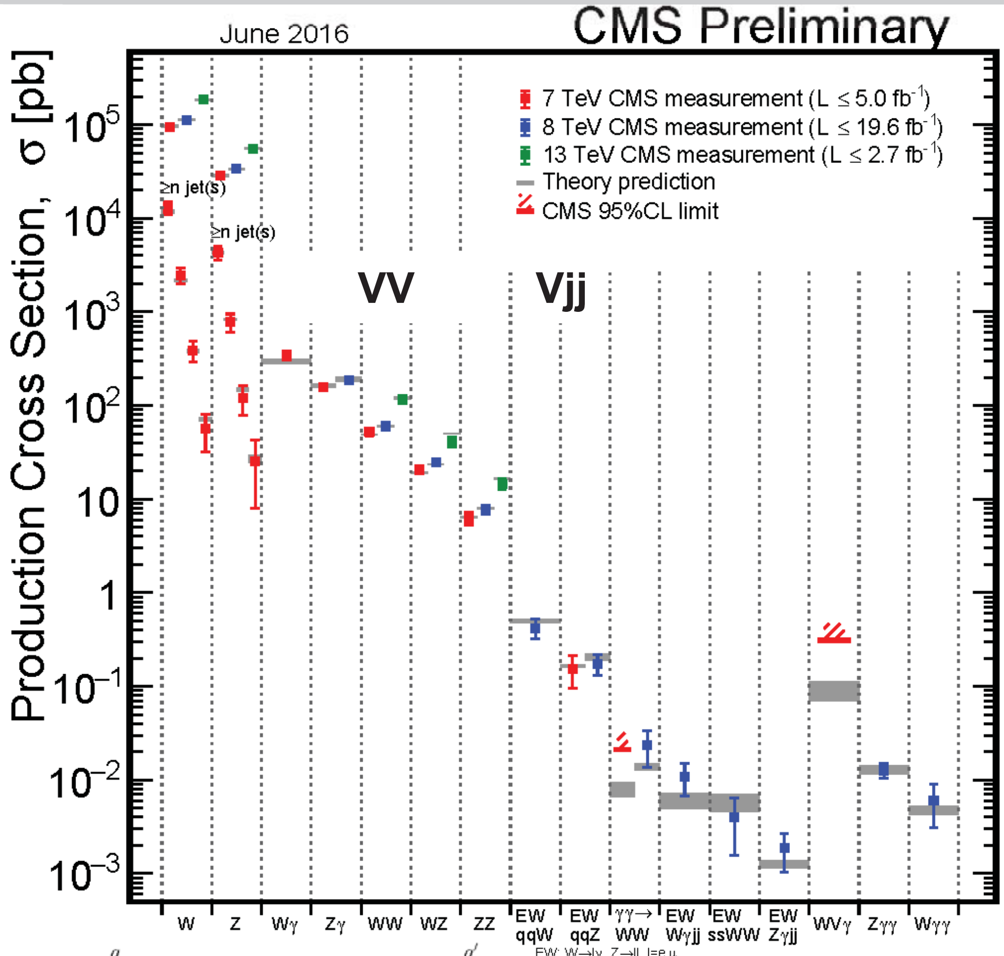

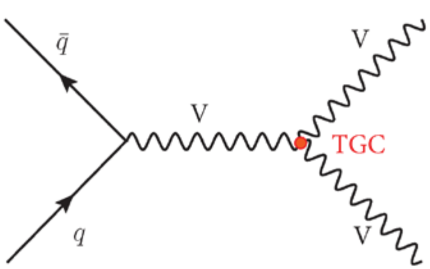

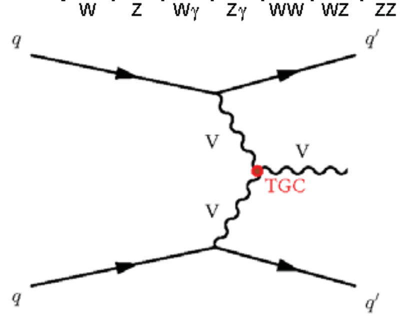

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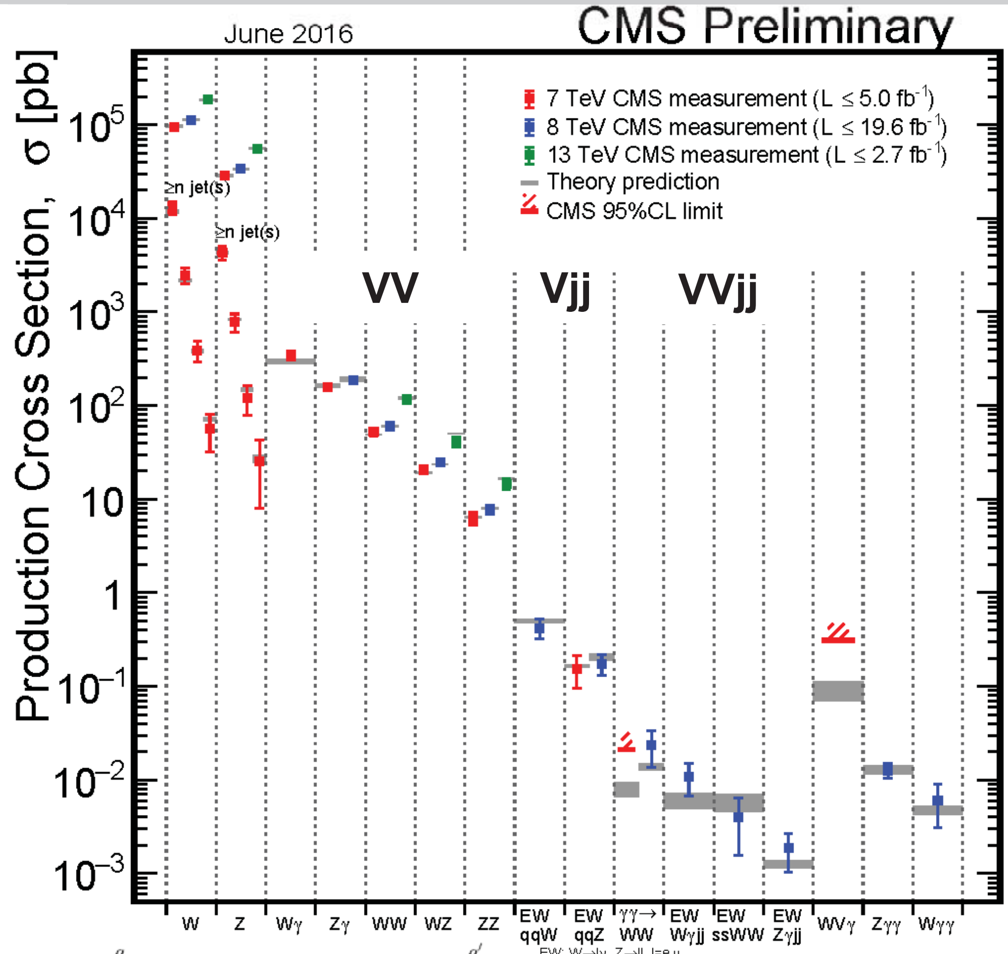
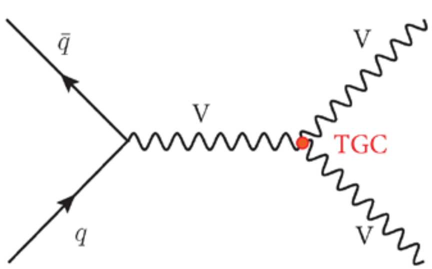
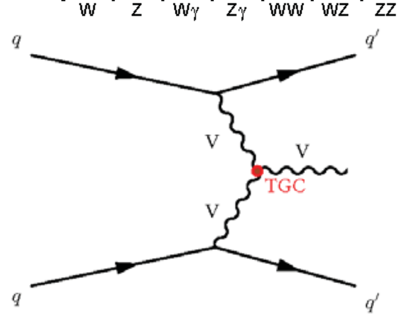
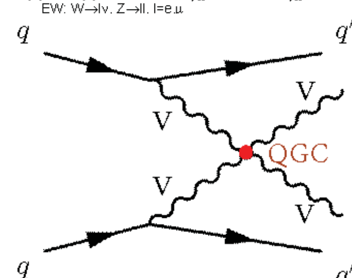
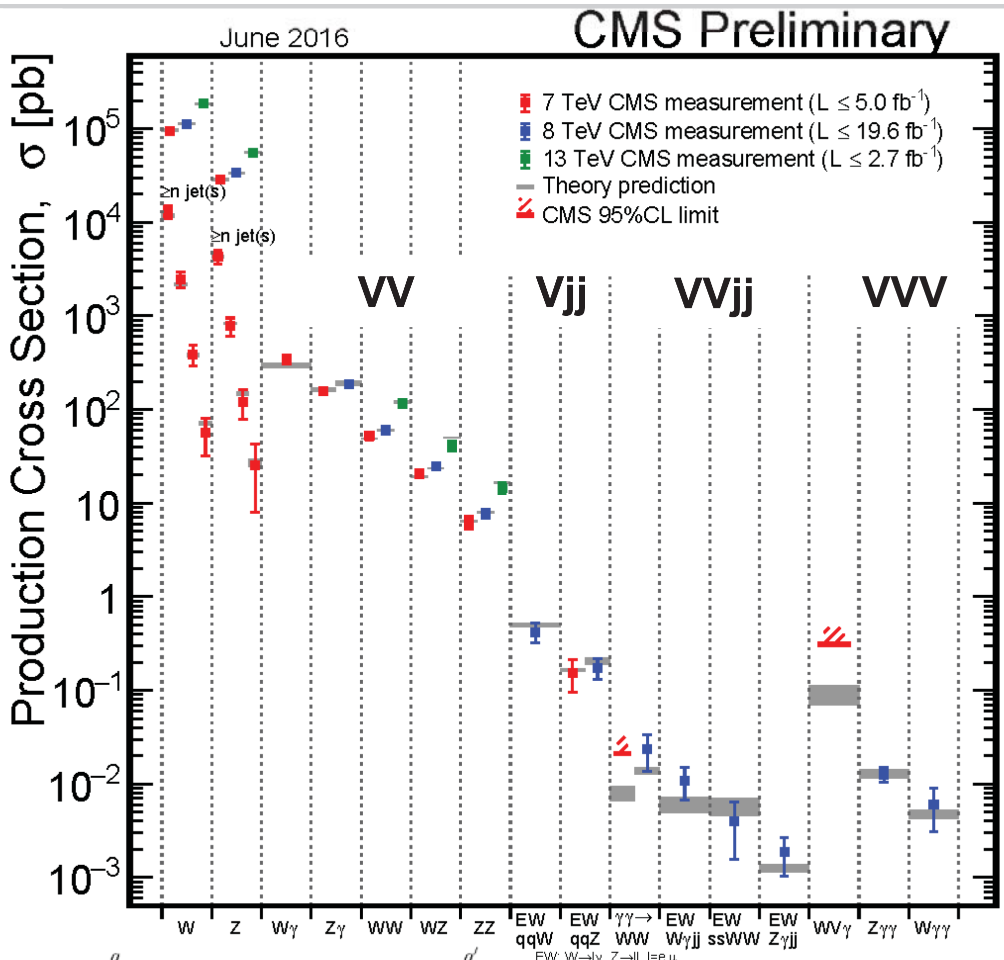


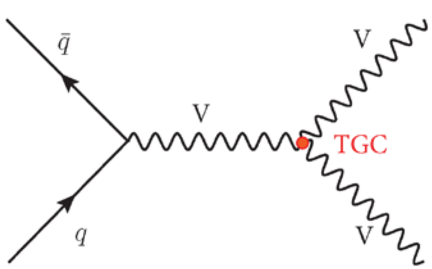


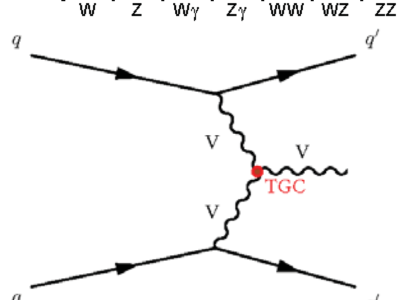


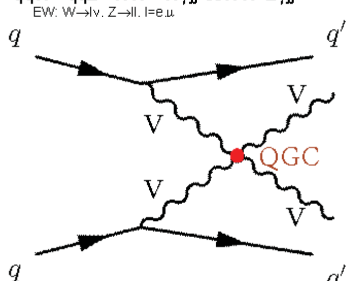


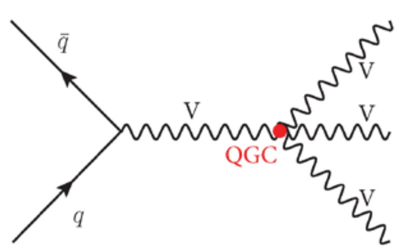
(Multi-) V Production



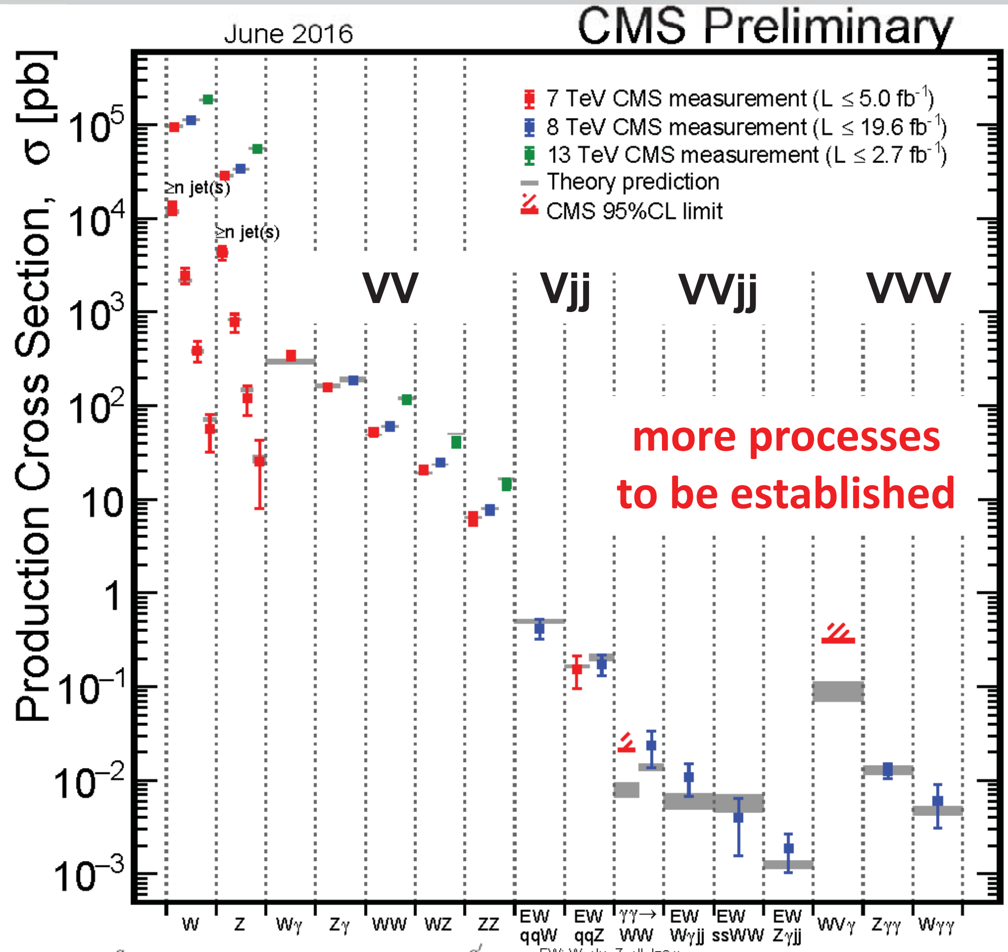


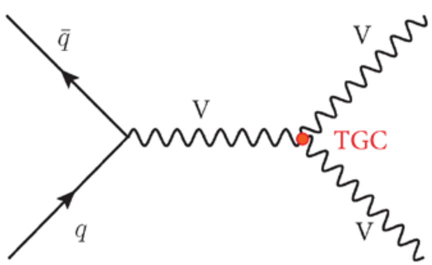


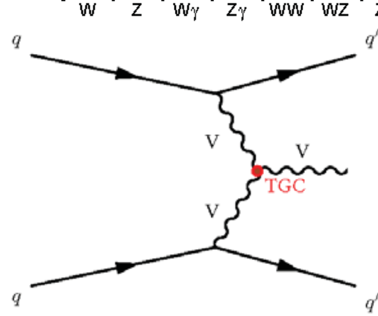


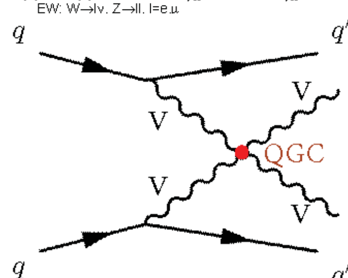


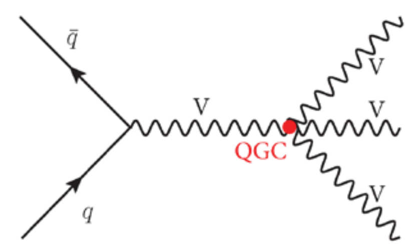
(Multi-) V Production





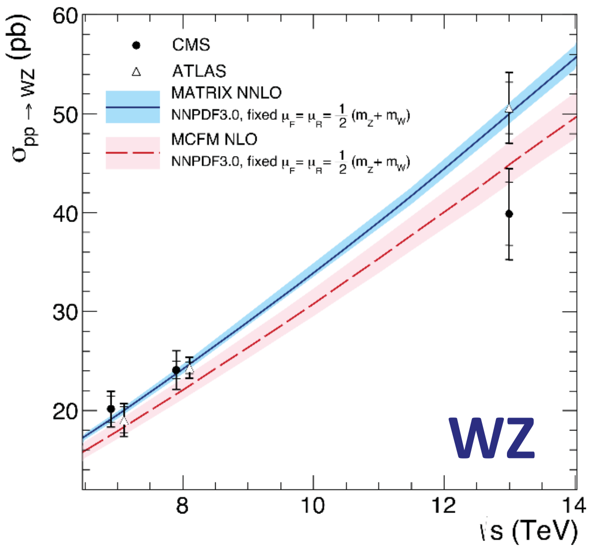


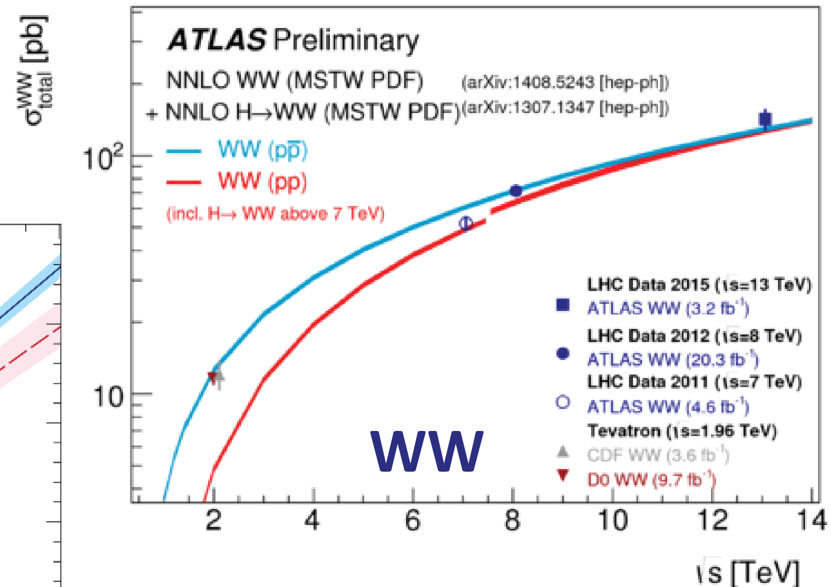


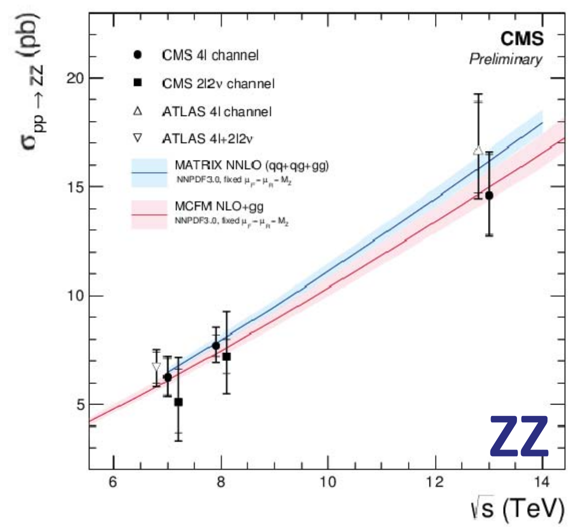


Run II Results

❖ First 13 TeV multi-V results available[ATLAS, CMS]…







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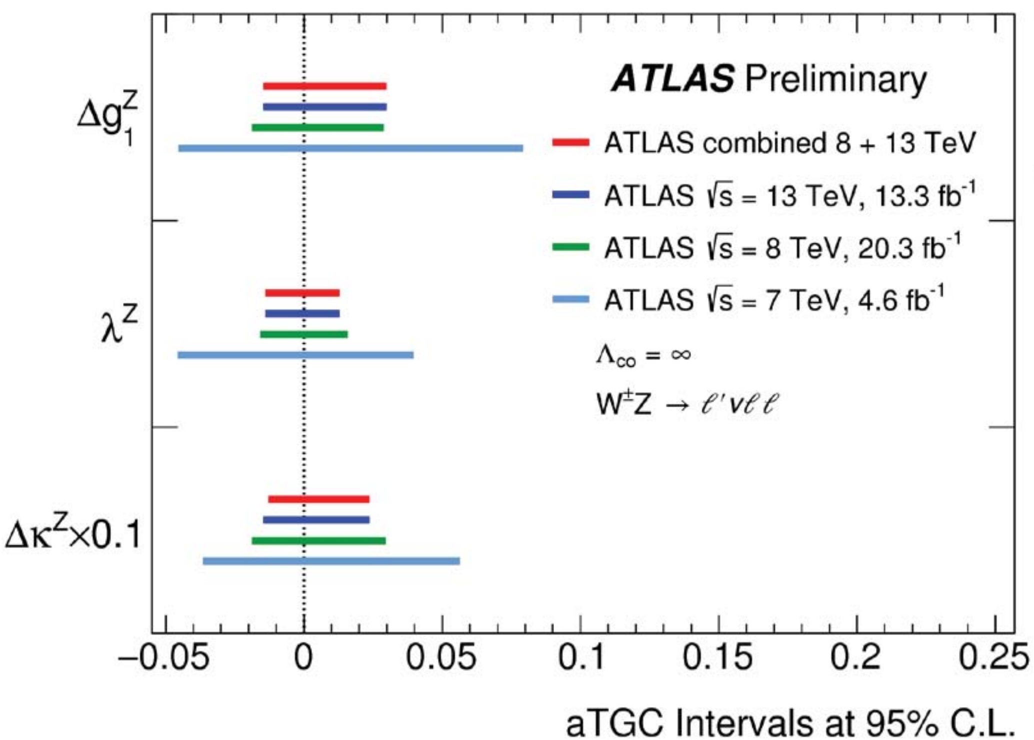
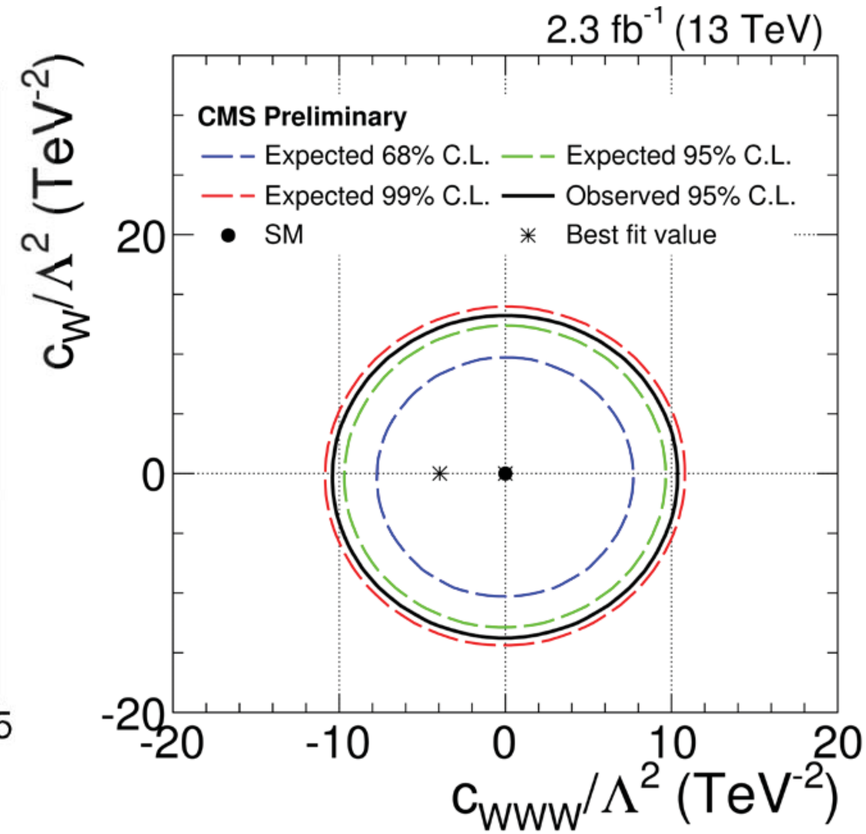




❖ … but only few preliminary results on anomalous couplings

Recent VBF/VV results

Recent VV results

VBF/VV Production and aTGCs

- Overview of studied aTGCs:

Coupling	Parameters	Channel
$WW\gamma$	$\Delta\kappa_\gamma, \lambda_\gamma$	$WW, W\gamma$, VBF-W
WWZ	$\Delta g_1^Z, \Delta\kappa_Z, \lambda_Z$	WW, WZ, VBF-W, VBF-Z
$Z\gamma\gamma$	h_3^γ, h_4^γ	$Z\gamma$
$Z\gamma Z$	h_3^Z, h_4^Z	$Z\gamma$
$ZZ\gamma$	f_4^γ, f_5^γ	ZZ
ZZZ	f_4^Z, f_5^Z	ZZ

f_4^V violate CP

SM expectation for all these parameters = 0.

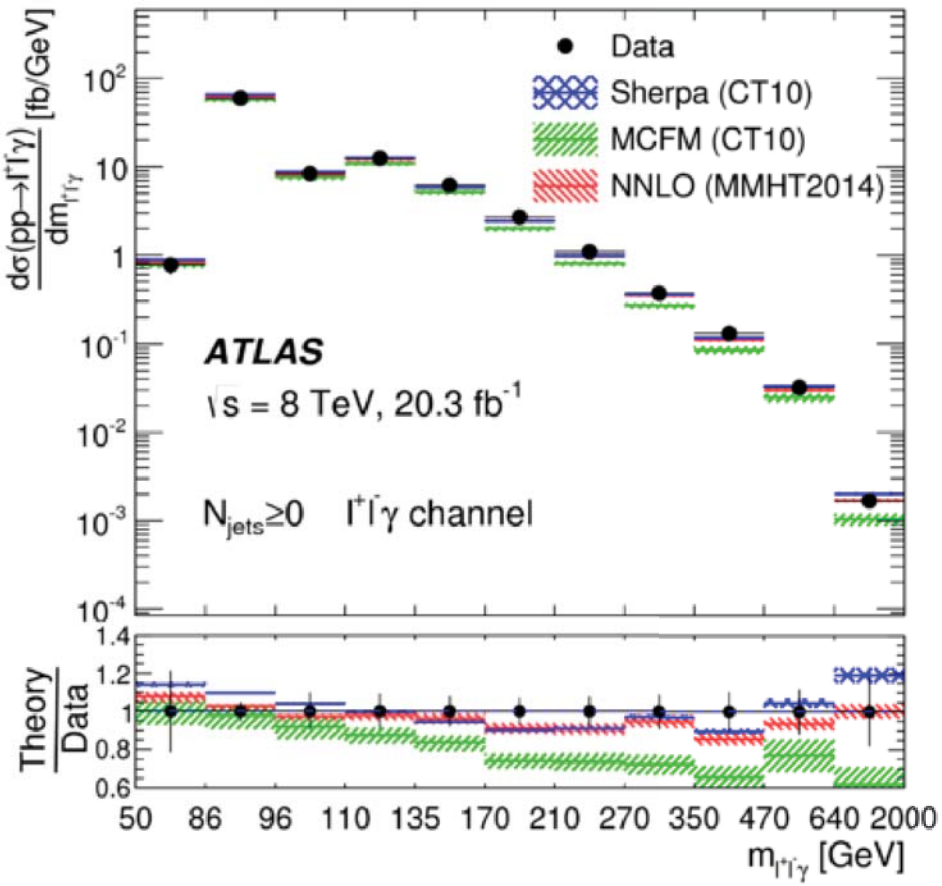
- Experimental access: aTGCs modify total production rate as well as event kinematics
  - Use cross-section measurement or kinematics to constrain aTGCs
- A suppression factor depending on a scale Λ_{FF} ensures conservation of unitarity (divergent xsecs at high $\sqrt{s}$):

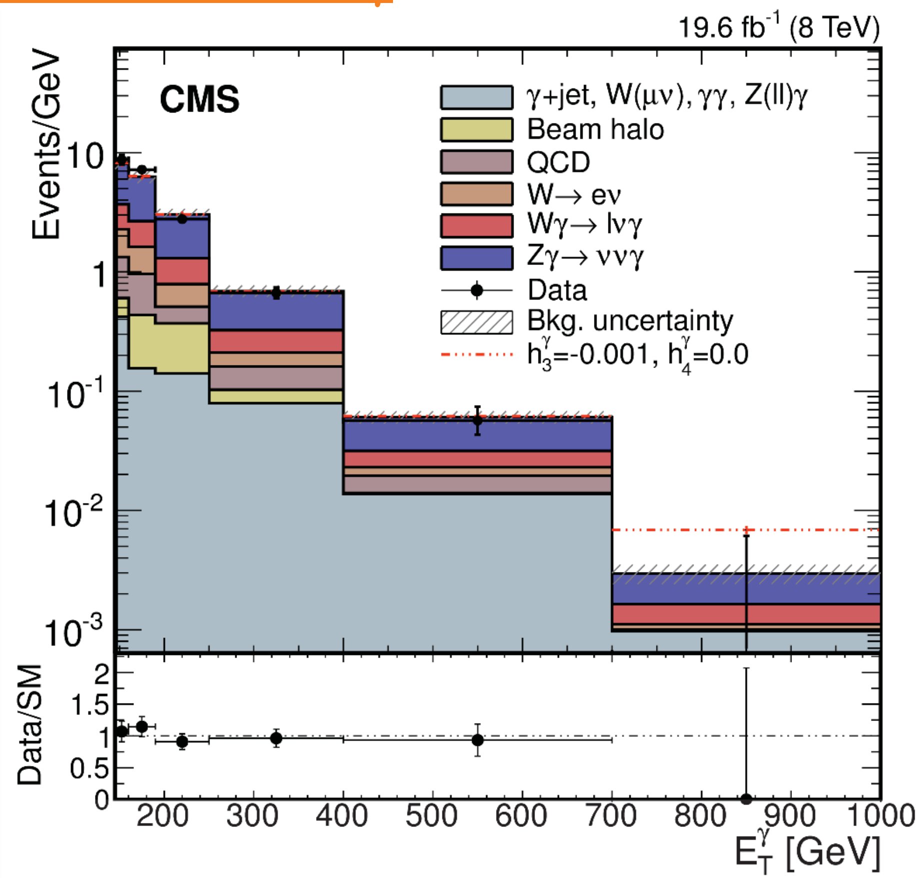
$$\lambda(\hat{s}) = \frac{\lambda_0}{(1+\hat{s}/\Lambda_{FF}^2)^n}$$

Zγ → ℓℓγ, ννγ @ 8 TeV

PRD 93, 112002 (2016) PLB 760 (2016) 448

- e^+e^- / $\mu^+\mu^-$ (ATLAS only) or MET plus isolated photon(s)
- Early NNLO fully differential calculation for Zγ in 2013





$Z\gamma \rightarrow \ell\ell\gamma, \nu\nu\gamma$ @ 8 TeV

PRD 93, 112002 (2016)   PLB 760 (2016) 448

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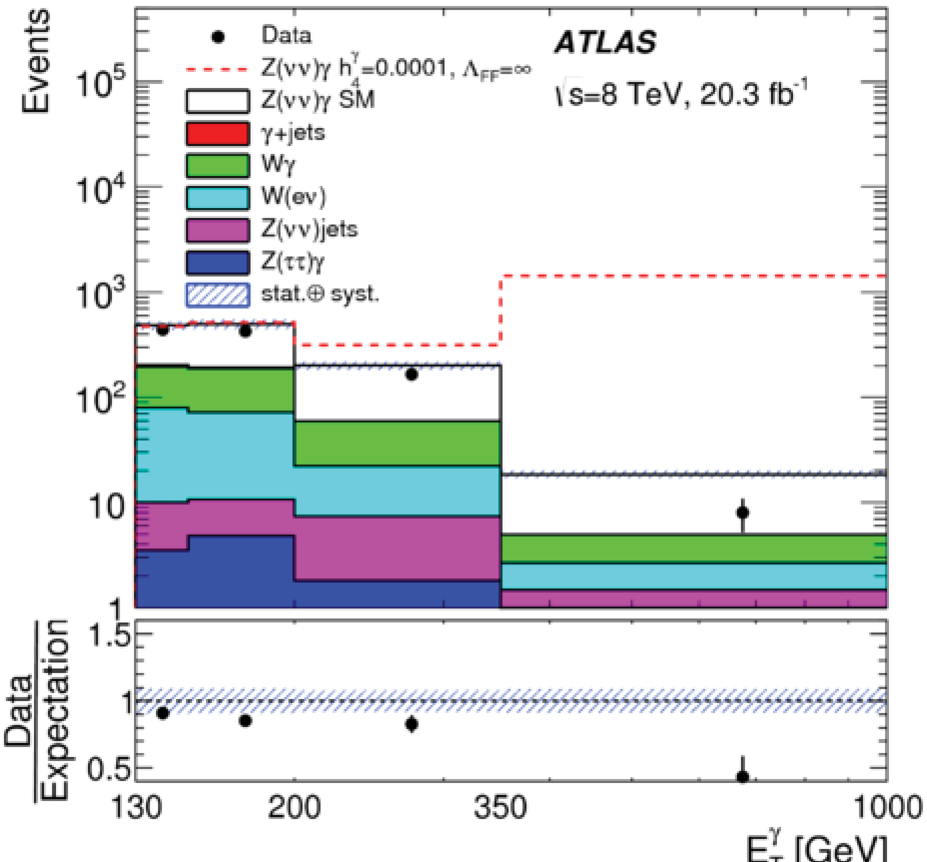
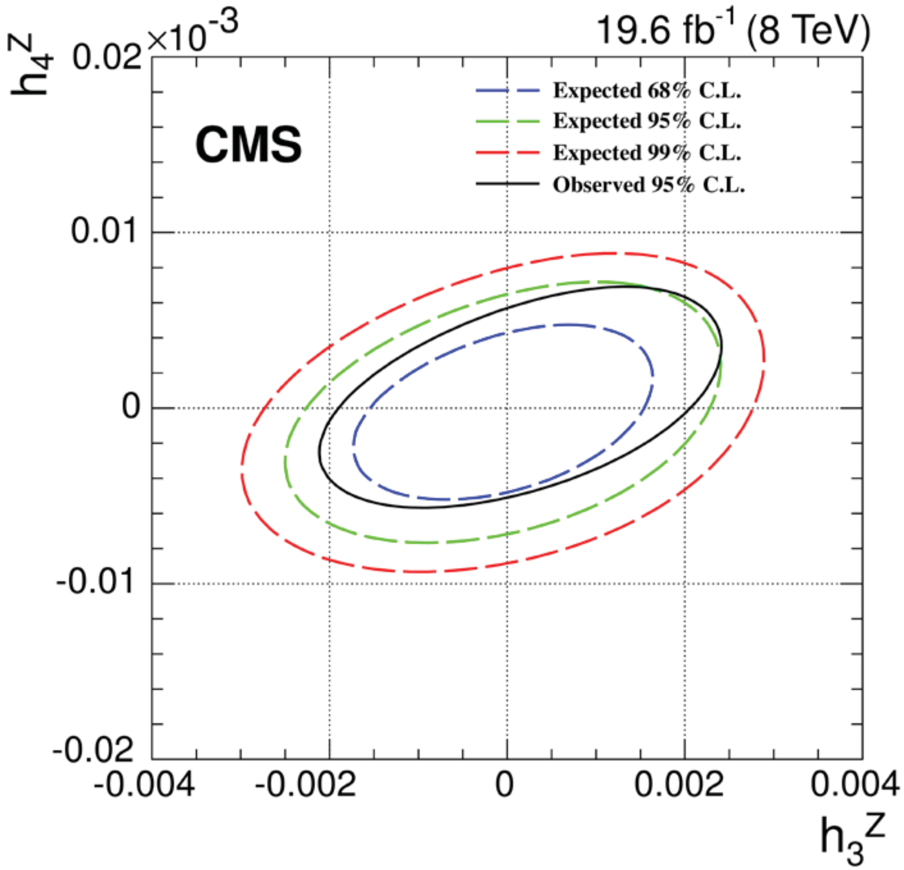


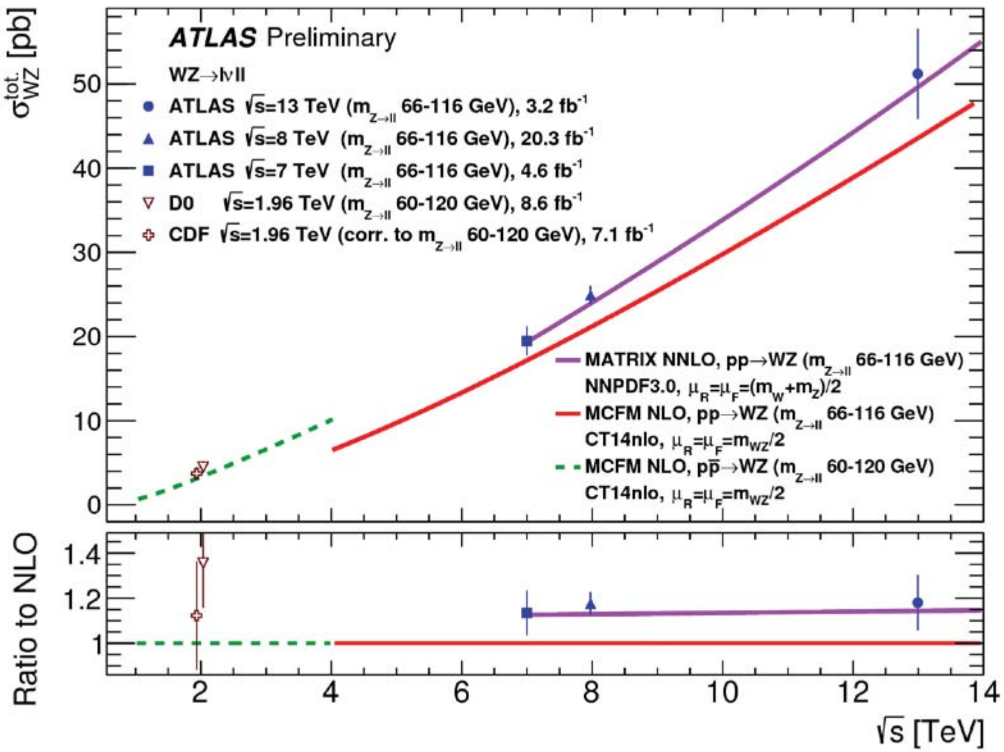


- N_{jets}=0 for aTGC limits (ATLAS); NLO ewk corrections not included

WZ → $\ell\nu\ell\ell$ @ 8 TeV

PRD 93, 092004 (2016)

- 3 isolated leptons (e or μ), MET
- Inclusive NNLO QCD calculation recently became available

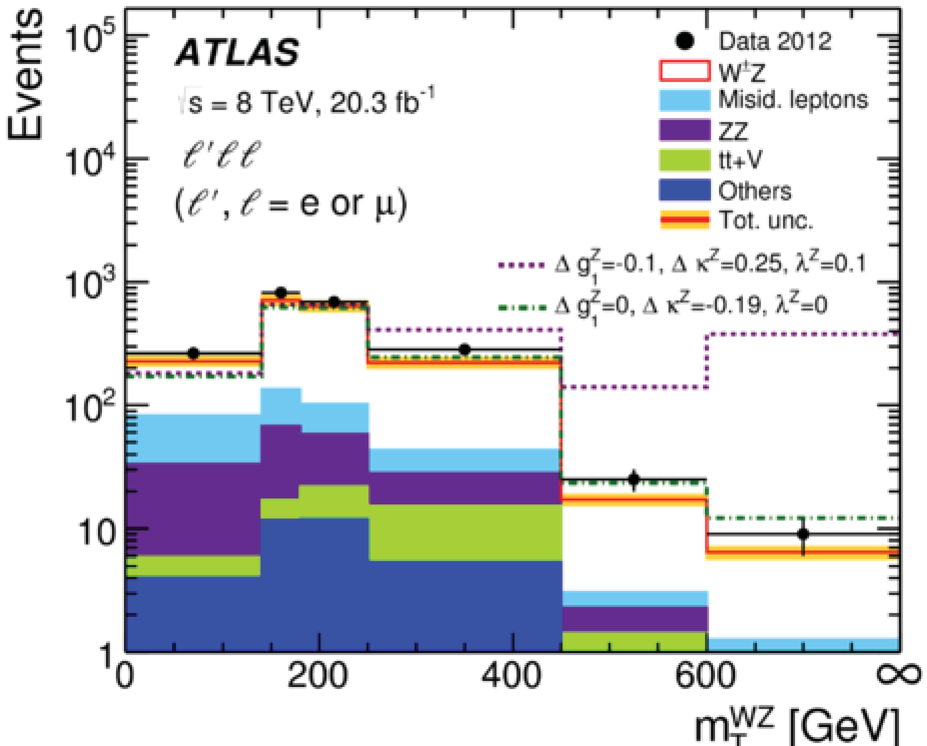


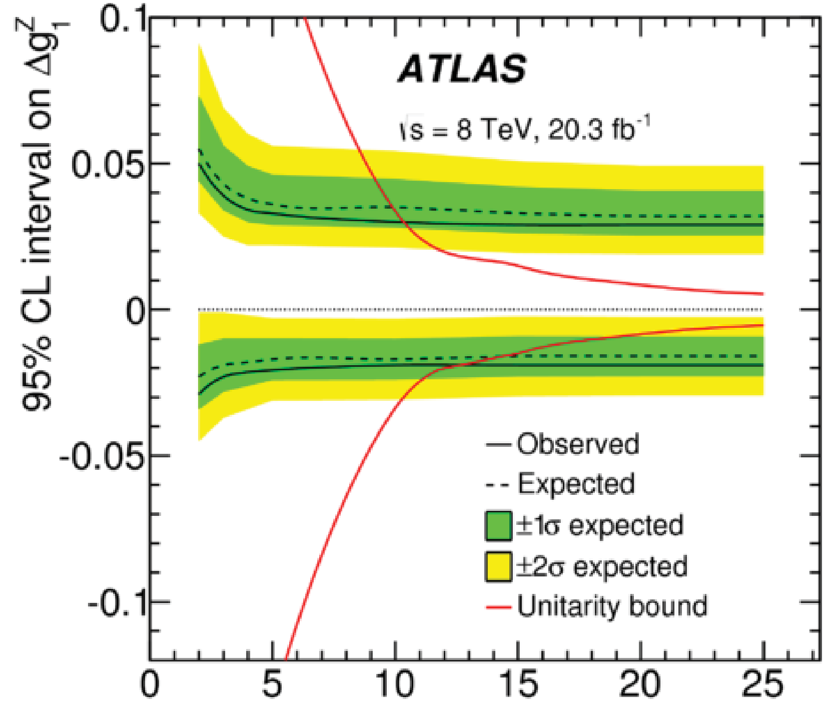
- Inclusive fiducial xsec precision: 4.2% (ATLAS)! Provided as well:
  - Unfolded differential cross sections (ATLAS, CMS)
  - Ratio of W^+Z, W^-Z cross sections, also as function of kinematic vars (ATLAS)

$WZ \to \ell\nu\ell\ell$ @ 8 TeV

PRD 93, 092004 (2016)

- 3 isolated leptons (e or μ), MET
- Inclusive NNLO QCD calculation recently became available





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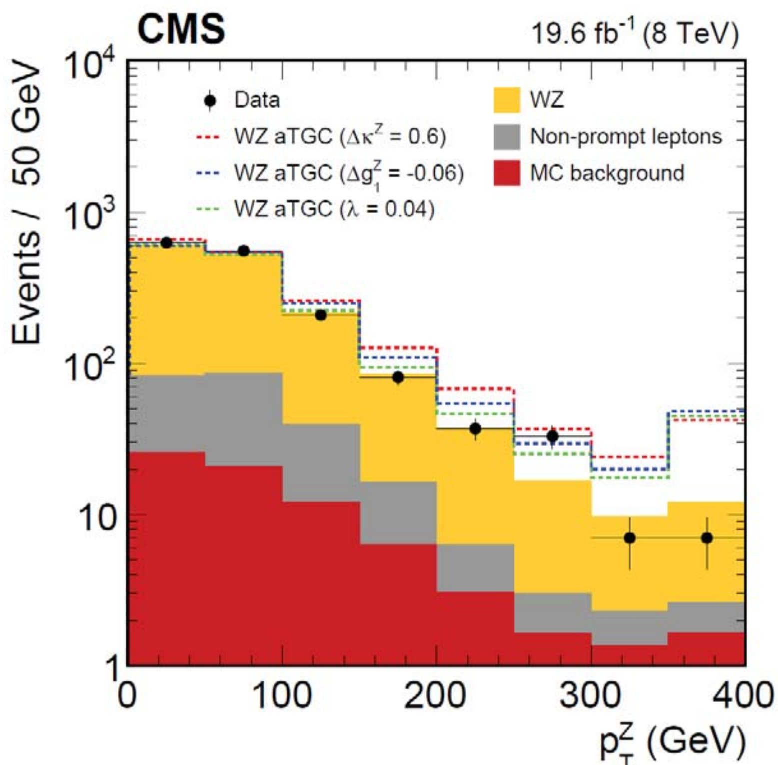
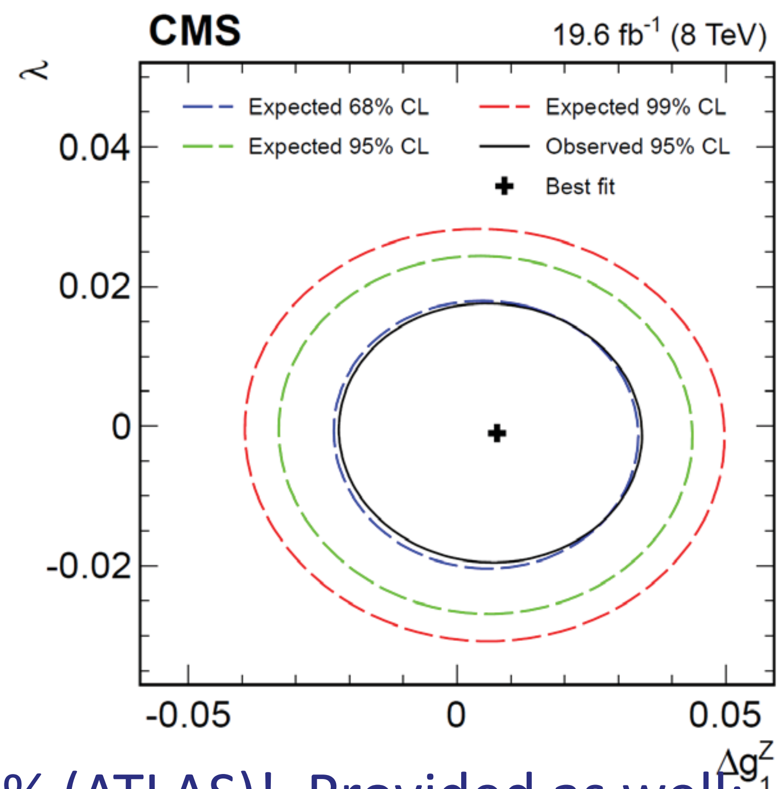
WZ → ℓνℓℓ @ 8 TeV

arXiv:1609.05721

- 3 isolated leptons (e or μ), MET
- Inclusive NNLO QCD calculation recently became available



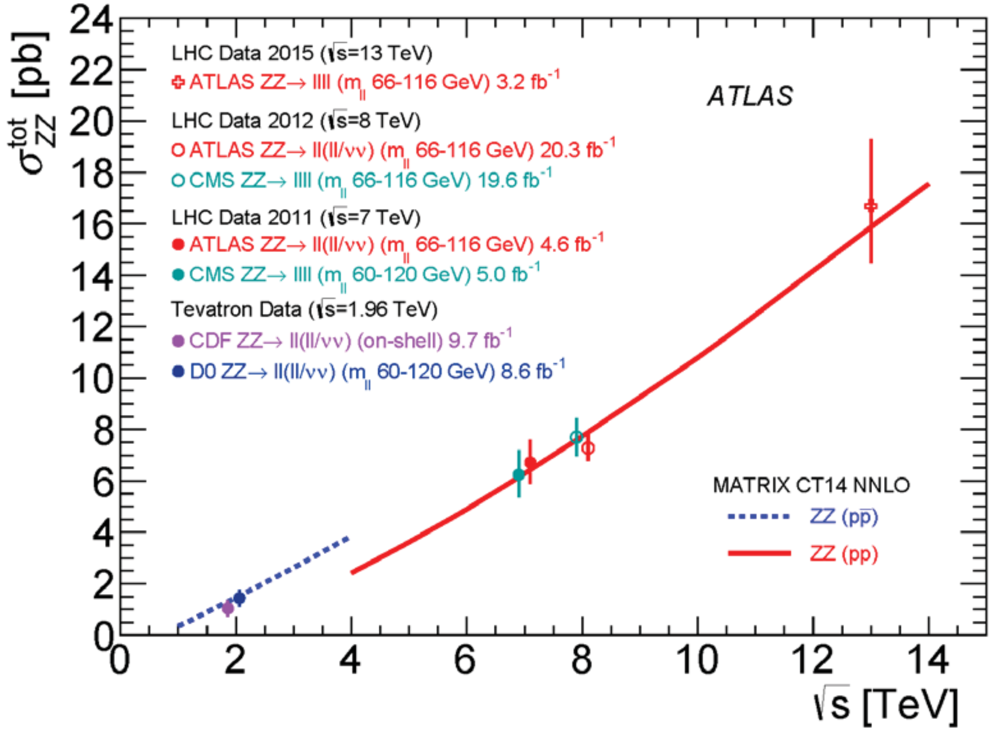


- Inclusive fiducial xsec precision: 4.2% (ATLAS)! Provided as well:
  - Unfolded differential cross sections (ATLAS, CMS)
  - Ratio of W^+Z, W^-Z cross sections, also as function of kinematic vars (ATLAS)

$ZZ \rightarrow 4\ell/2\ell2\nu$ @ 8 TeV

arXiv:1610.07585

- 4 (2) isolated leptons (e or μ), (MET)
- Inclusive NNLO QCD calculation available

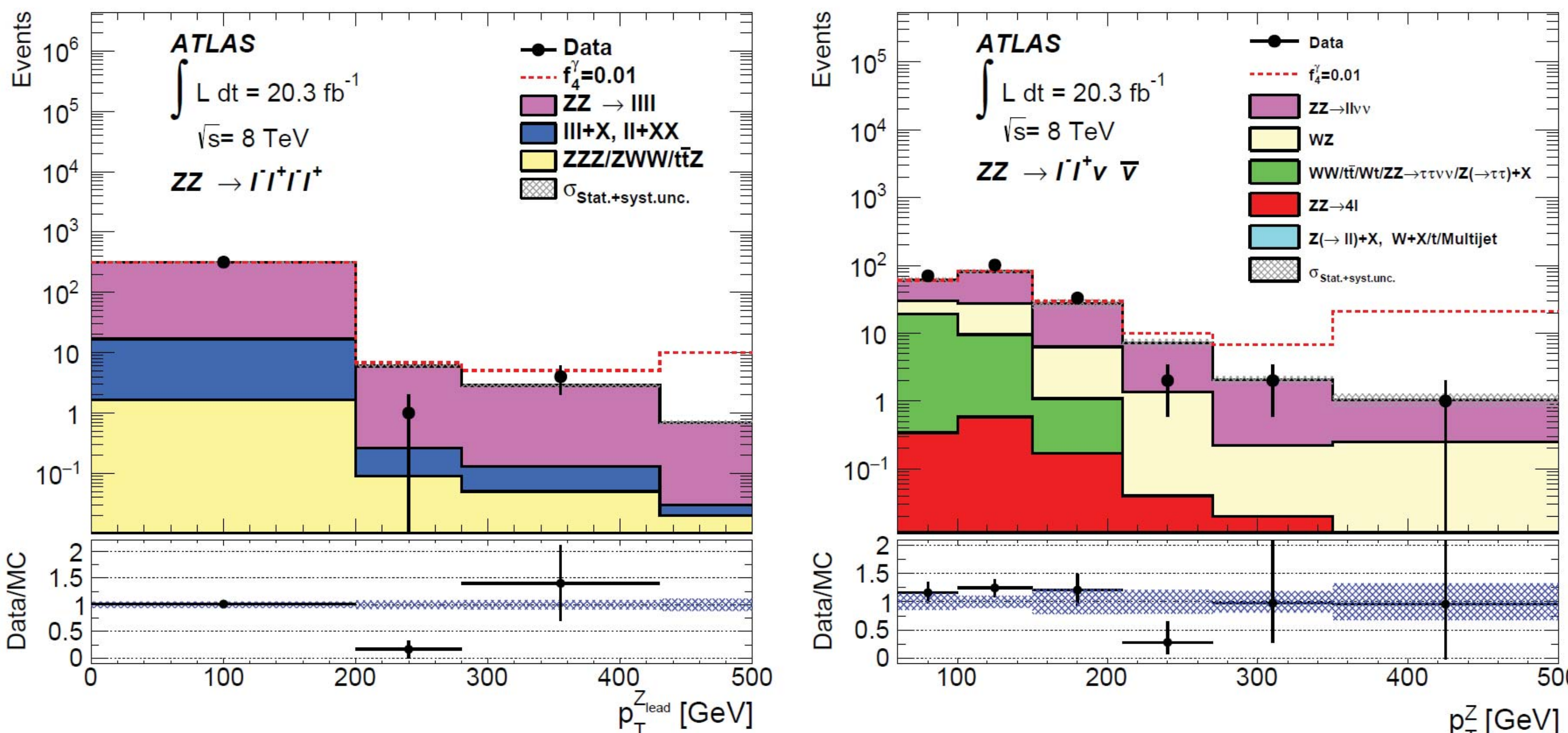


- NLO EWK corrections are taken into account
- Unfolded differential cross sections are provided as well

ZZ → 4ℓ/2ℓ2ν @ 8 TeV

arXiv:1610.07585

- 4 (2) isolated leptons (e or μ), (MET)
- Inclusive NNLO QCD calculation available

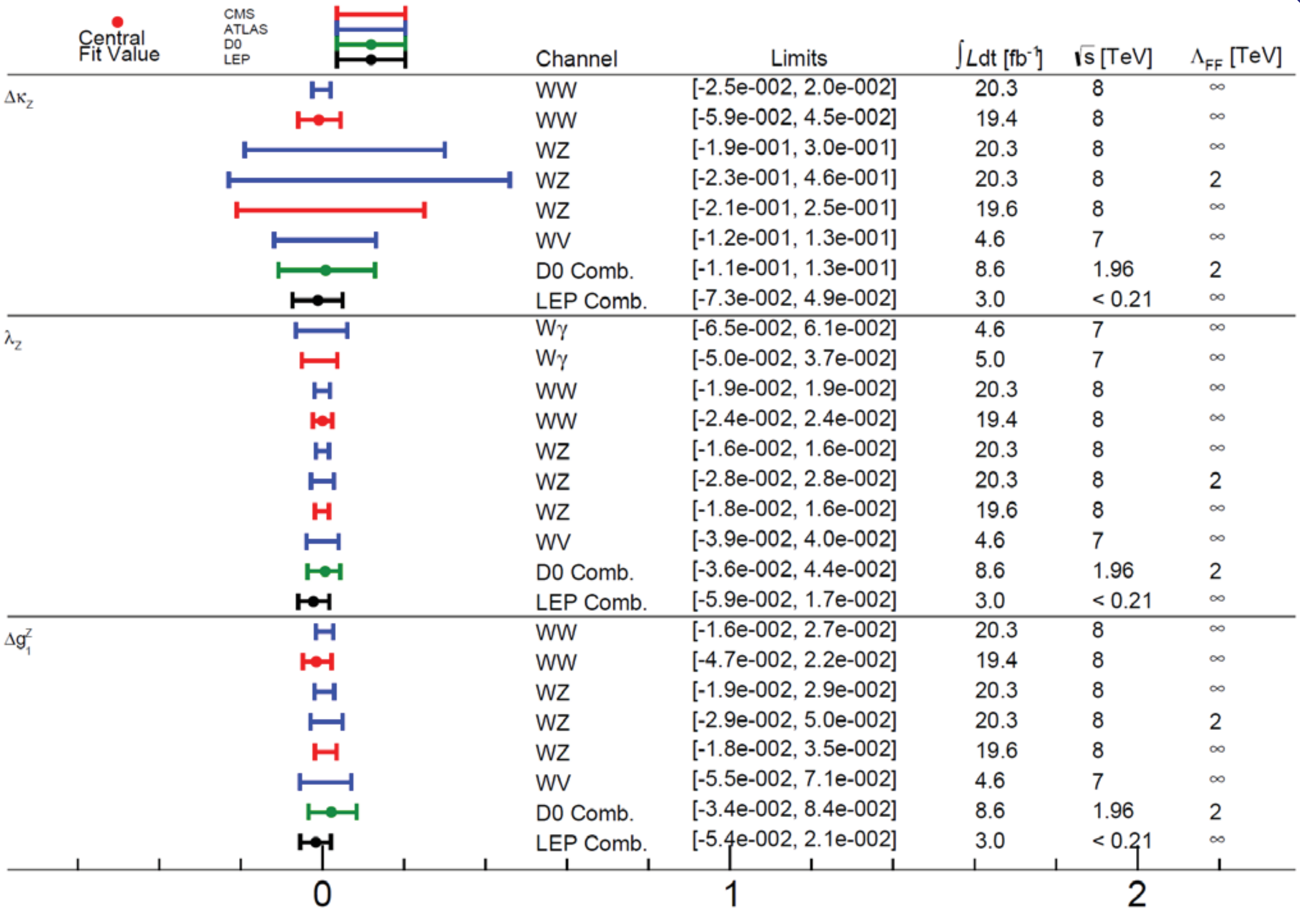


- NLO EWK corrections are taken into account
- Unfolded differential cross sections are provided as well

aTGC status

arXiv:1610.07572

❖ Most stringent limits on WWγ, WWZ from WZ and WW

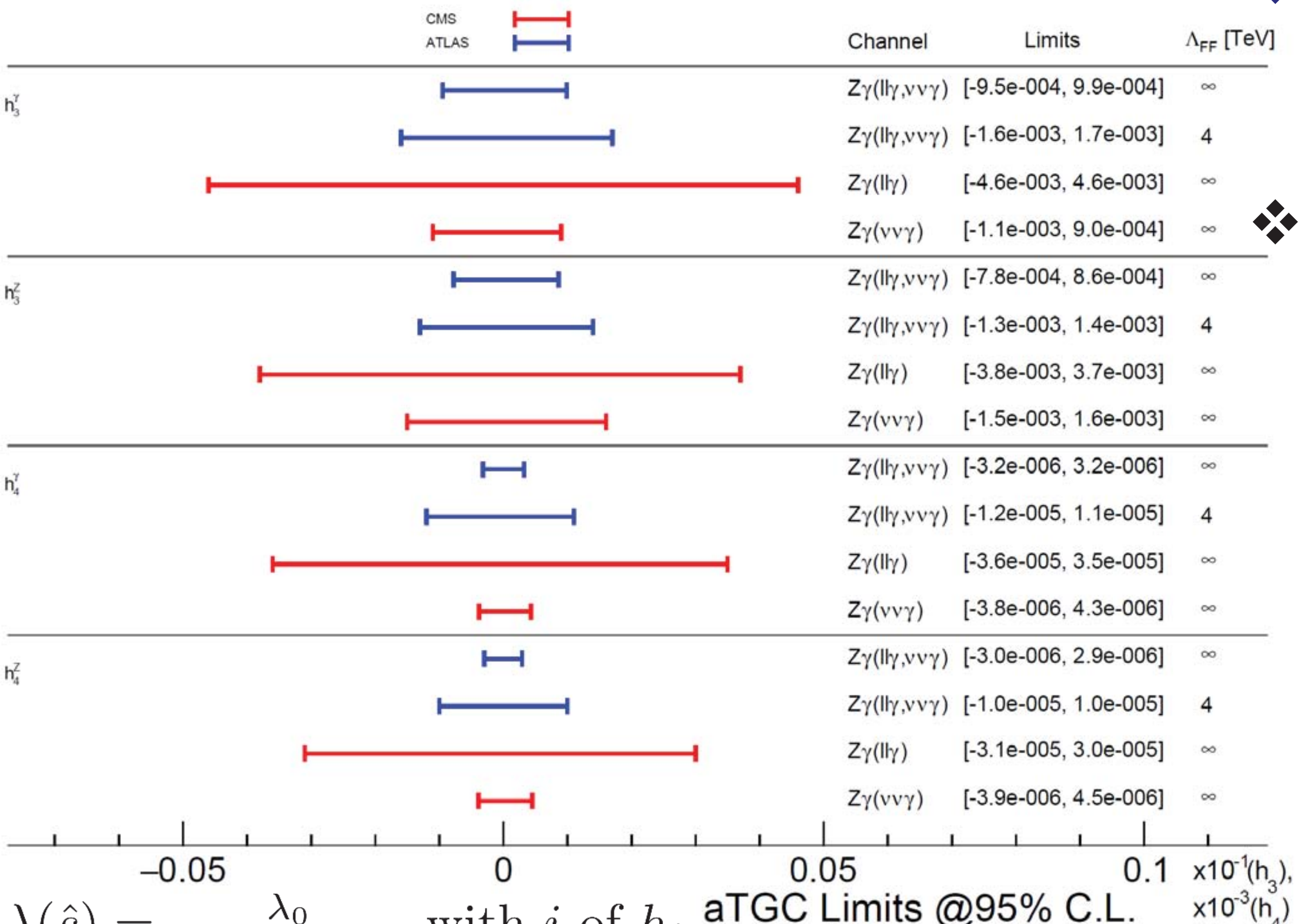


	Channel	Limits	$\int Ldt$ [fb^{-1}]	$\sqrt{s}$ [TeV]	Λ_{FF} [TeV]
$\Delta\kappa_Z$	WW	[-2.5e-002, 2.0e-002]	20.3	8	∞
	WW	[-5.9e-002, 4.5e-002]	19.4	8	∞
	WZ	[-1.9e-001, 3.0e-001]	20.3	8	∞
	WZ	[-2.3e-001, 4.6e-001]	20.3	8	2
	WZ	[-2.1e-001, 2.5e-001]	19.6	8	∞
	WV	[-1.2e-001, 1.3e-001]	4.6	7	∞
	D0 Comb.	[-1.1e-001, 1.3e-001]	8.6	1.96	2
	LEP Comb.	[-7.3e-002, 4.9e-002]	3.0	< 0.21	∞
λ_Z	Wγ	[-6.5e-002, 6.1e-002]	4.6	7	∞
	Wγ	[-5.0e-002, 3.7e-002]	5.0	7	∞
	WW	[-1.9e-002, 1.9e-002]	20.3	8	∞
	WW	[-2.4e-002, 2.4e-002]	19.4	8	∞
	WZ	[-1.6e-002, 1.6e-002]	20.3	8	∞
	WZ	[-2.8e-002, 2.8e-002]	20.3	8	2
	WZ	[-1.8e-002, 1.6e-002]	19.6	8	∞
	WV	[-3.9e-002, 4.0e-002]	4.6	7	∞
	D0 Comb.	[-3.6e-002, 4.4e-002]	8.6	1.96	2
	LEP Comb.	[-5.9e-002, 1.7e-002]	3.0	< 0.21	∞
Δg_1^Z	WW	[-1.6e-002, 2.7e-002]	20.3	8	∞
	WW	[-4.7e-002, 2.2e-002]	19.4	8	∞
	WZ	[-1.9e-002, 2.9e-002]	20.3	8	∞
	WZ	[-2.9e-002, 5.0e-002]	20.3	8	2
	WZ	[-1.8e-002, 3.5e-002]	19.6	8	∞
	WV	[-5.5e-002, 7.1e-002]	4.6	7	∞
	D0 Comb.	[-3.4e-002, 8.4e-002]	8.6	1.96	2
	LEP Comb.	[-5.4e-002, 2.1e-002]	3.0	< 0.21	∞

$$\lambda(\hat{s}) = \frac{\lambda_0}{(1+\hat{s}/\Lambda_{FF}^2)^2}$$

aTGC status

arXiv:1610.07572



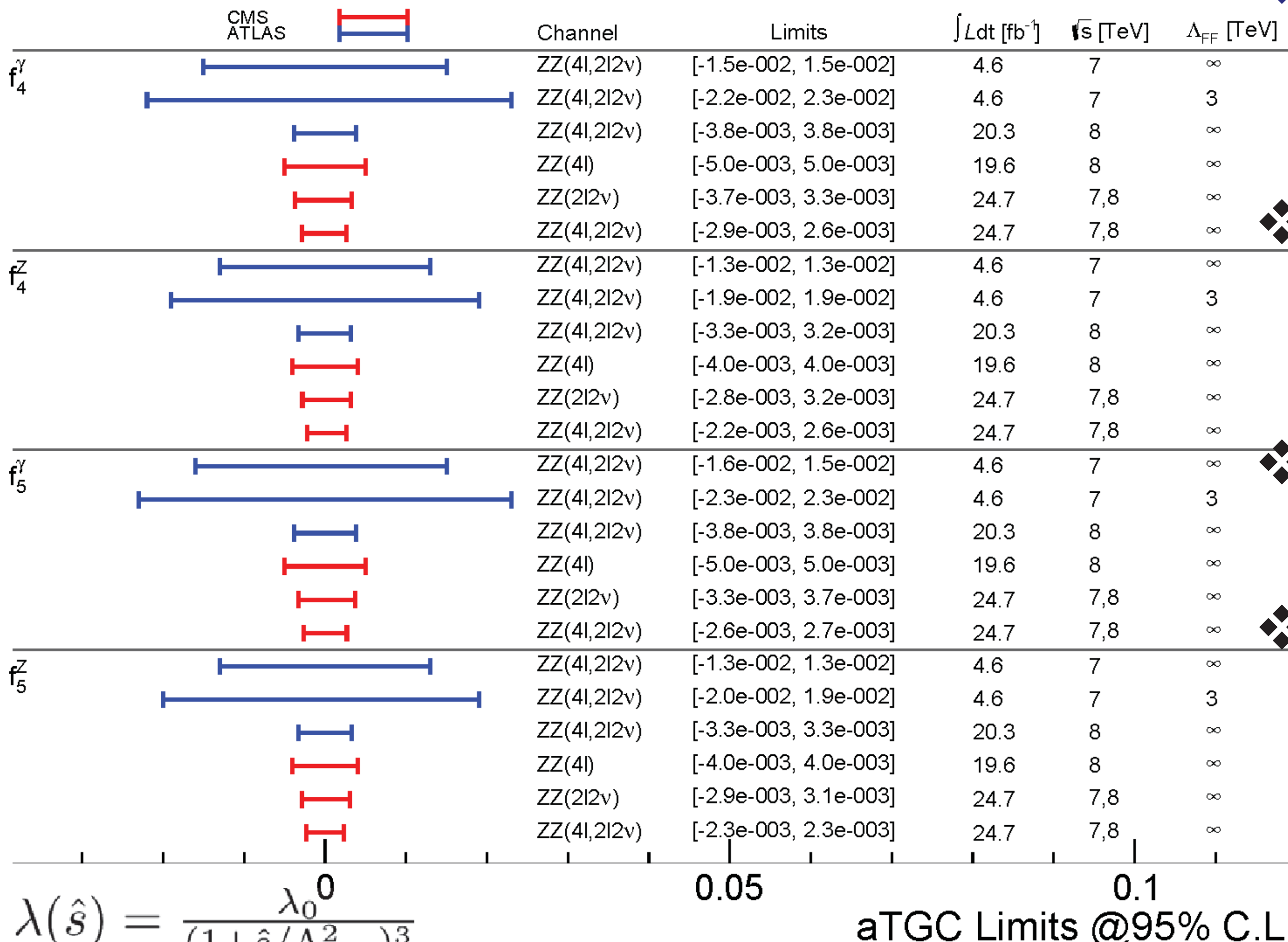
$$\lambda(\hat{s}) = \frac{\lambda_0}{(1+\hat{s}/\Lambda_{FF}^2)^i} \text{ with } i \text{ of } h_i$$

$$\sqrt{s} = 8 \text{ TeV}$$

- Most stringent limits on WWγ, WWZ from WZ and WW
- Best constraints so far on $h_{3,4}^{\gamma,Z}$, driven by ννγ

aTGC status

arXiv:1610.07572



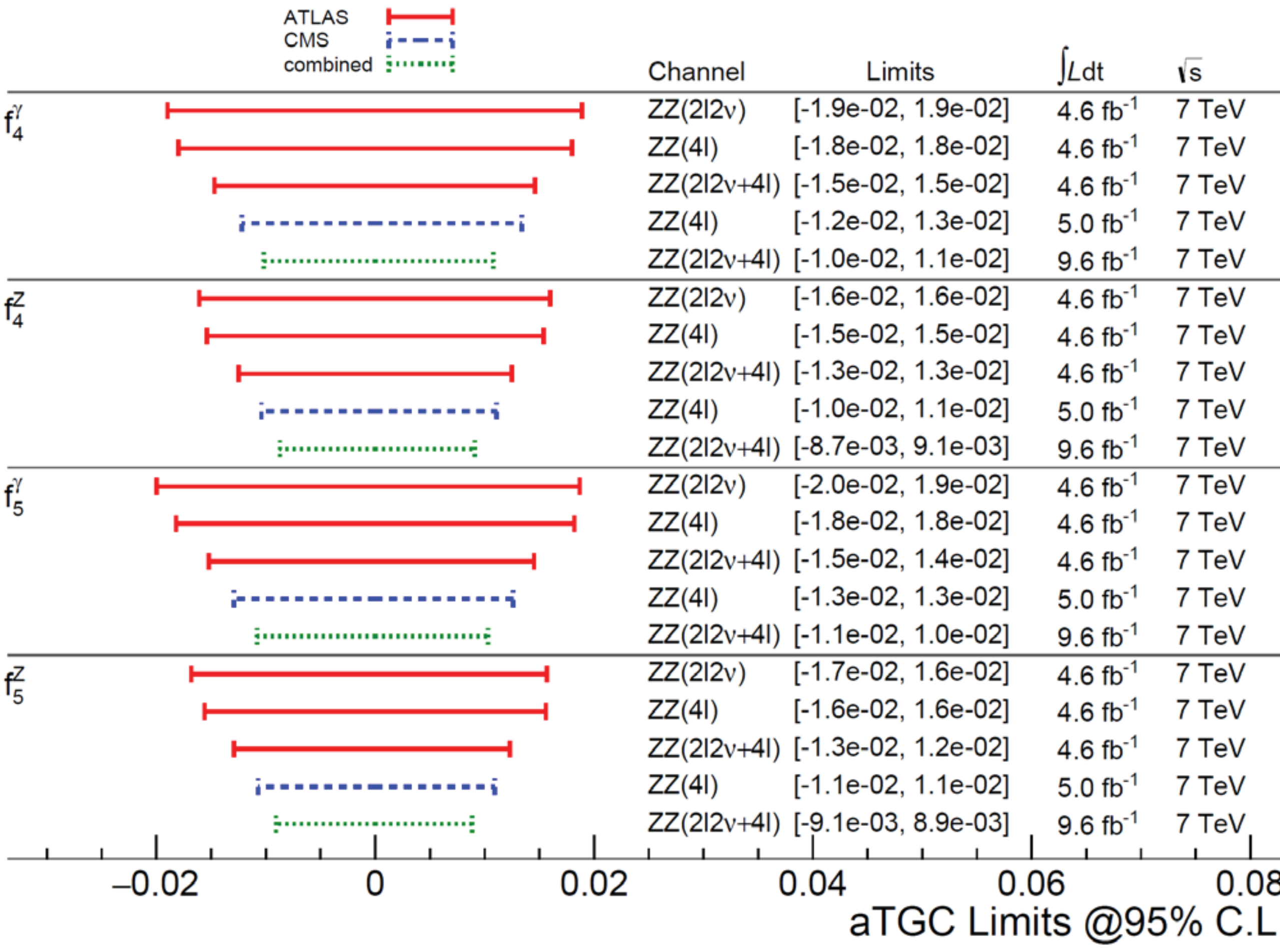
	Channel	Limits	$\int L dt$ [fb^{-1}]	$\sqrt{s}$ [TeV]	Λ_{FF} [TeV]
f_4^γ	ZZ(4l,2l2ν)	[-1.5e-002, 1.5e-002]	4.6	7	∞
	ZZ(4l,2l2ν)	[-2.2e-002, 2.3e-002]	4.6	7	3
	ZZ(4l,2l2ν)	[-3.8e-003, 3.8e-003]	20.3	8	∞
	ZZ(4l)	[-5.0e-003, 5.0e-003]	19.6	8	∞
	ZZ(2l2ν)	[-3.7e-003, 3.3e-003]	24.7	7,8	∞
	ZZ(4l,2l2ν)	[-2.9e-003, 2.6e-003]	24.7	7,8	∞
f_4^Z	ZZ(4l,2l2ν)	[-1.3e-002, 1.3e-002]	4.6	7	∞
	ZZ(4l,2l2ν)	[-1.9e-002, 1.9e-002]	4.6	7	3
	ZZ(4l,2l2ν)	[-3.3e-003, 3.2e-003]	20.3	8	∞
	ZZ(4l)	[-4.0e-003, 4.0e-003]	19.6	8	∞
	ZZ(2l2ν)	[-2.8e-003, 3.2e-003]	24.7	7,8	∞
	ZZ(4l,2l2ν)	[-2.2e-003, 2.6e-003]	24.7	7,8	∞
f_5^γ	ZZ(4l,2l2ν)	[-1.6e-002, 1.5e-002]	4.6	7	∞
	ZZ(4l,2l2ν)	[-2.3e-002, 2.3e-002]	4.6	7	3
	ZZ(4l,2l2ν)	[-3.8e-003, 3.8e-003]	20.3	8	∞
	ZZ(4l)	[-5.0e-003, 5.0e-003]	19.6	8	∞
	ZZ(2l2ν)	[-3.3e-003, 3.7e-003]	24.7	7,8	∞
	ZZ(4l,2l2ν)	[-2.6e-003, 2.7e-003]	24.7	7,8	∞
f_5^Z	ZZ(4l,2l2ν)	[-1.3e-002, 1.3e-002]	4.6	7	∞
	ZZ(4l,2l2ν)	[-2.0e-002, 1.9e-002]	4.6	7	3
	ZZ(4l,2l2ν)	[-3.3e-003, 3.3e-003]	20.3	8	∞
	ZZ(4l)	[-4.0e-003, 4.0e-003]	19.6	8	∞
	ZZ(2l2ν)	[-2.9e-003, 3.1e-003]	24.7	7,8	∞
	ZZ(4l,2l2ν)	[-2.3e-003, 2.3e-003]	24.7	7,8	∞

$$\lambda(\hat{s}) = \frac{\lambda_0}{(1+\hat{s}/\Lambda_{FF}^2)^3}$$

- Most stringent limits on WWγ, WWZ from WZ and WW
- Best constraints so far on $h_{3,4}^{\gamma,Z}$, driven by $\nu\nu\gamma$
- Constraints on $f_{3,4}^{\gamma,Z}$ driven by $\ell\ell\nu\nu$
- Generally modest impact of unitarisation

aTGC status

arXiv:1610.07572



- Most stringent limits on WWγ, WWZ from WZ and WW
- Best constraints so far on $h_{3,4}^{\gamma,Z}$, driven by $\nu\nu\gamma$
- Constraints on $f_{3,4}^{\gamma,Z}$ driven by $\ell\ell\nu\nu$
- Generally modest impact of unitarisation
- First ATLAS/CMS aTGC combination released!

Recent VBS/VVV results

VBS/VVV Production and aQGCs

❖ Overview of studied aQGCs:

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

Vertex-specific conversions from WHIZARD α_4, α_5 exist, e.g. for WWWW:

$$\alpha_4 = \frac{f_{S,0}}{\Lambda^4}\frac{v^4}{8}, \alpha_4 + 2\cdot\alpha_5 = \frac{f_{S,1}}{\Lambda^4}\frac{v^4}{8}$$

❖ Experimental access: aQGCs modify total production rate as well as event kinematics

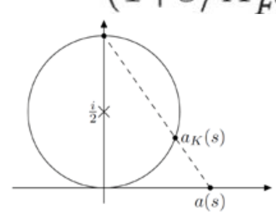
- Use cross-section measurement or kinematics to constrain aQGCs

❖ Unitarisation methods:

- Form factor

$$\lambda(\hat{s}) = \frac{\lambda_0}{(1+\hat{s}/\Lambda_{FF}^2)^n}$$

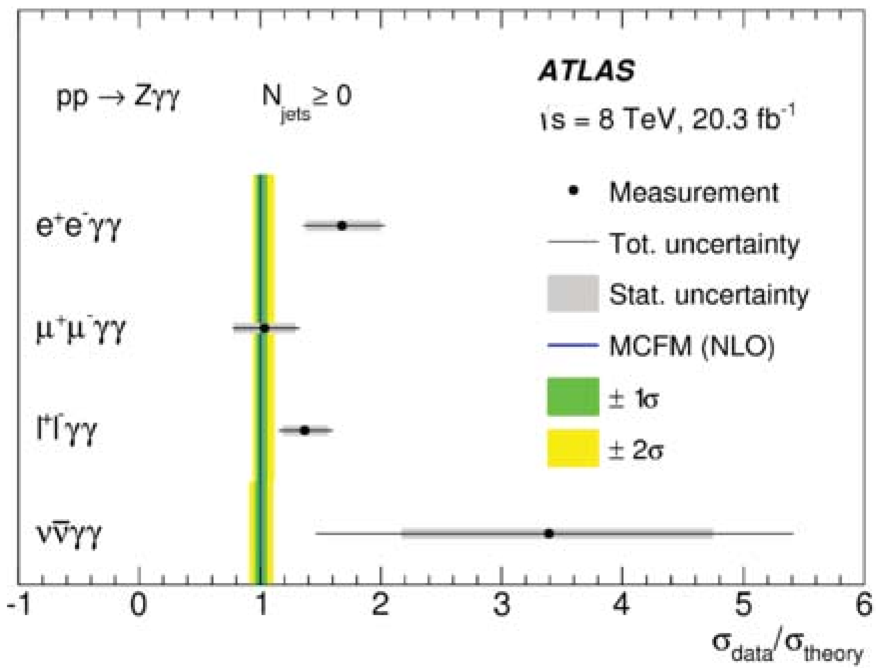
- K-matrix unitarisation

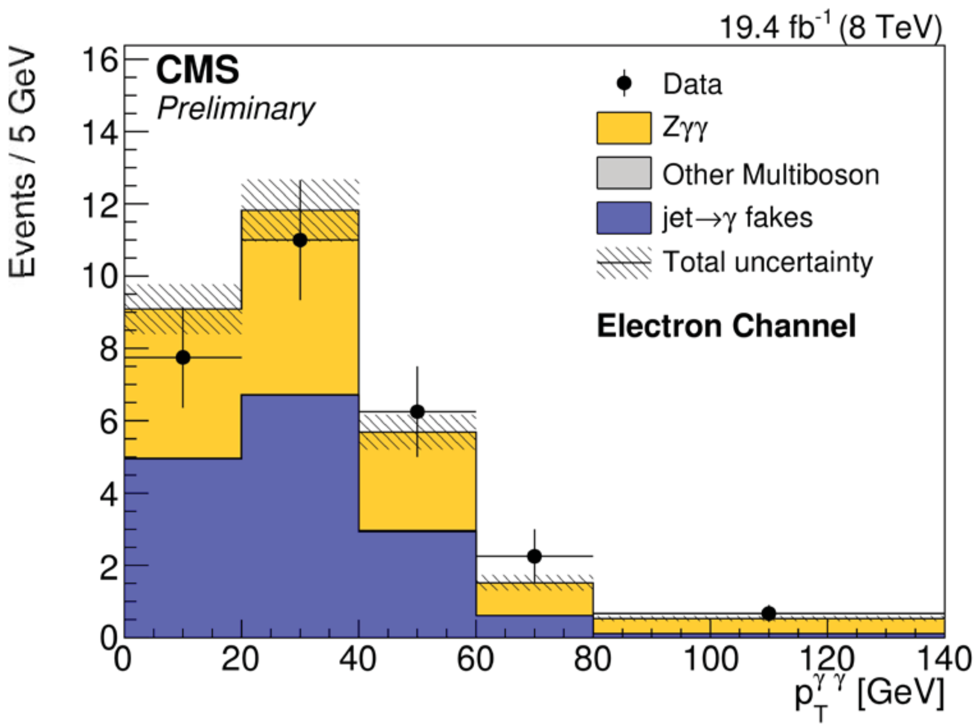


$Z\gamma\gamma \rightarrow \ell\ell\gamma\gamma, \nu\nu\gamma\gamma$

PRD 93, 112002 (2016) CMS-PAS-SMP-15-008

- e^+e^- / $\mu^+\mu^-$ or MET (ATLAS only) plus isolated photons
- Signal @ >5σ. NLO prediction is still state-of-the-art for signal!





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PRD 93, 112002 (2016)

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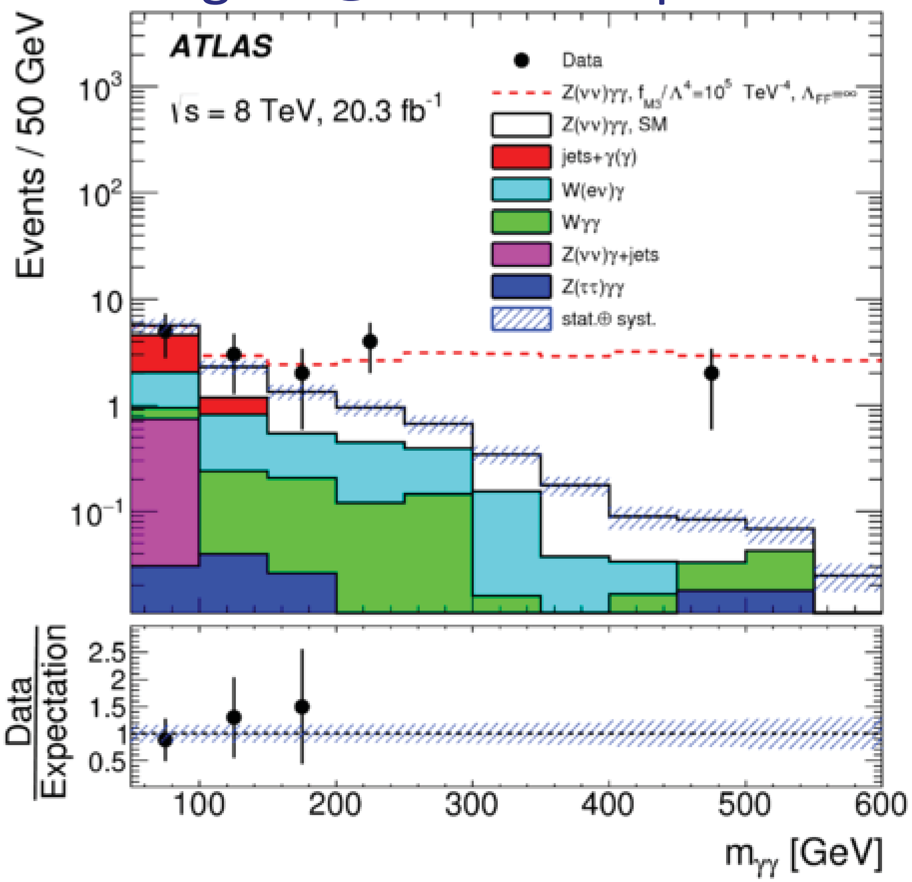
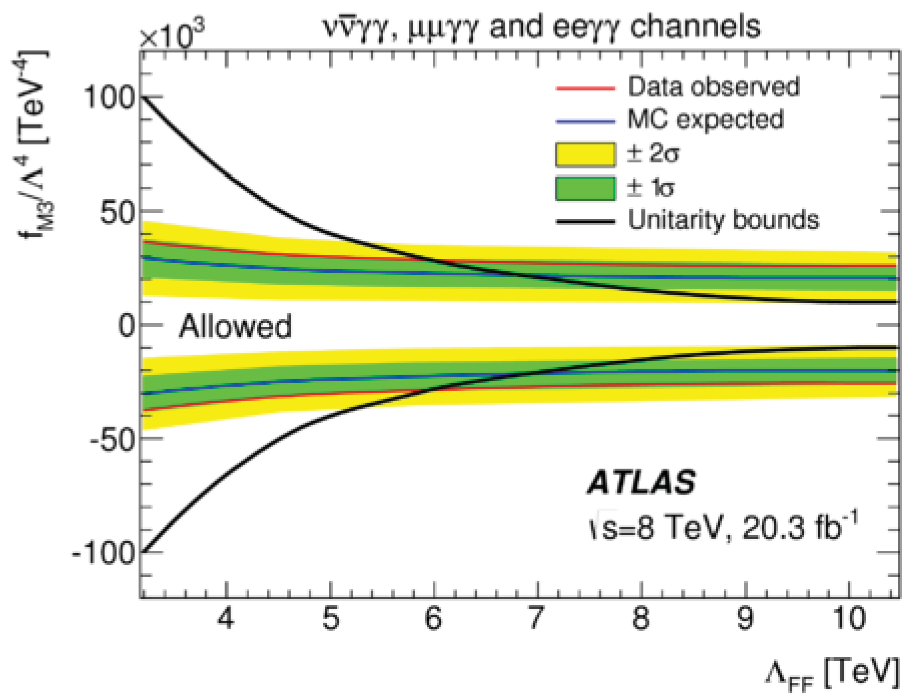


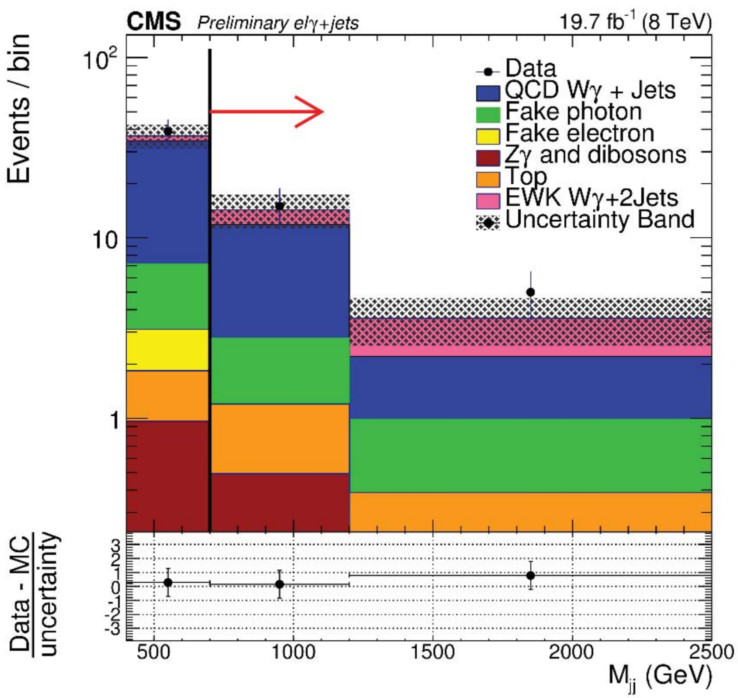


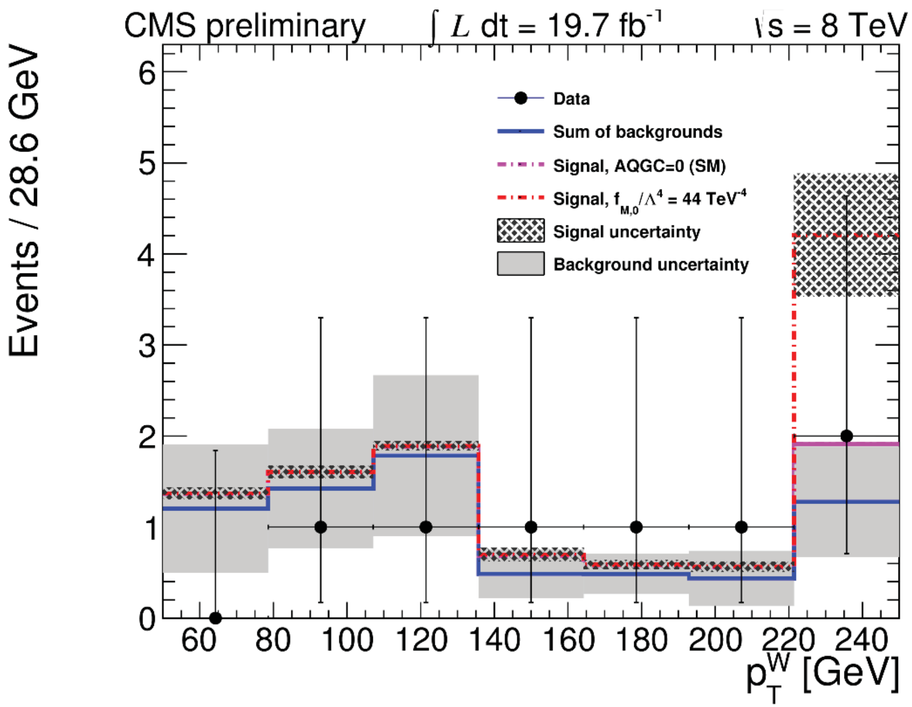
- N_{jets}=0, high-$m\gamma\gamma$ fiducial xsecs used for aQGC limits

$W\gamma jj \to \ell\nu\gamma jj$ @ 8 TeV

CMS-PAS-SMP-14-011

- 1 isolated lepton (e or μ), MET, isolated photon, two tagging jets
- SM EW signal significance: 2.7σ; EW+QCD well-described @NLO



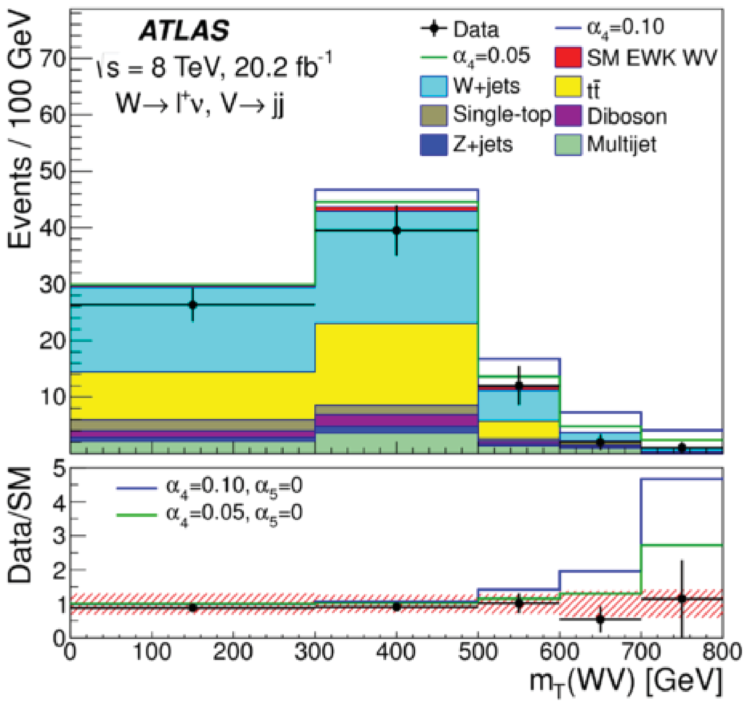


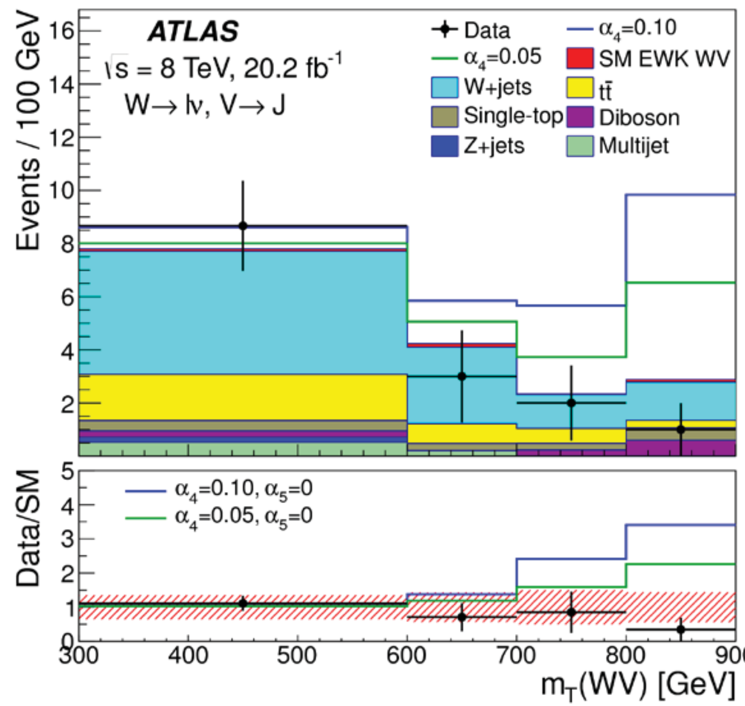
- aQGC limits: require $p_T^\gamma > 200$ GeV & harsher tagging jets cuts
- use shape of p_T^W distribution to provide limits on $f_{M,0..7}$, $f_{T,0..2,5..7}$ (!)

WVjj → $\ell\nu$(jj/J) jj @ 8 TeV

arXiv:1609.05122

- 1 isolated lepton (e or μ), MET, jj/J **hadronic** V, two tagging jets
- Not sensitive to SM xsec yet, but optimized for aQGC



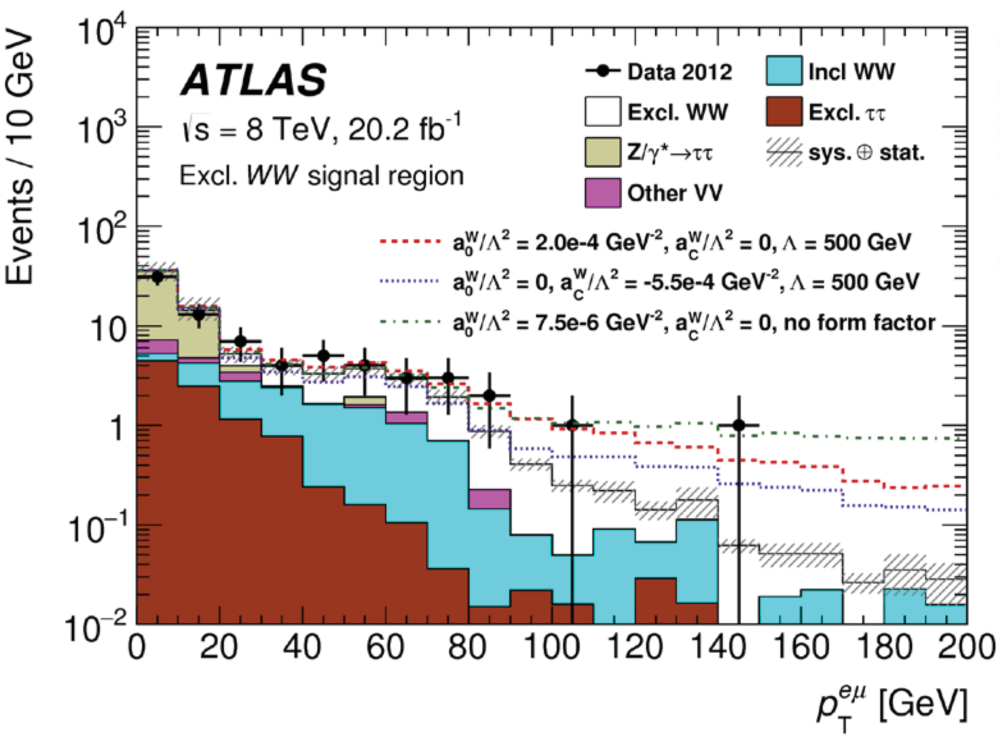


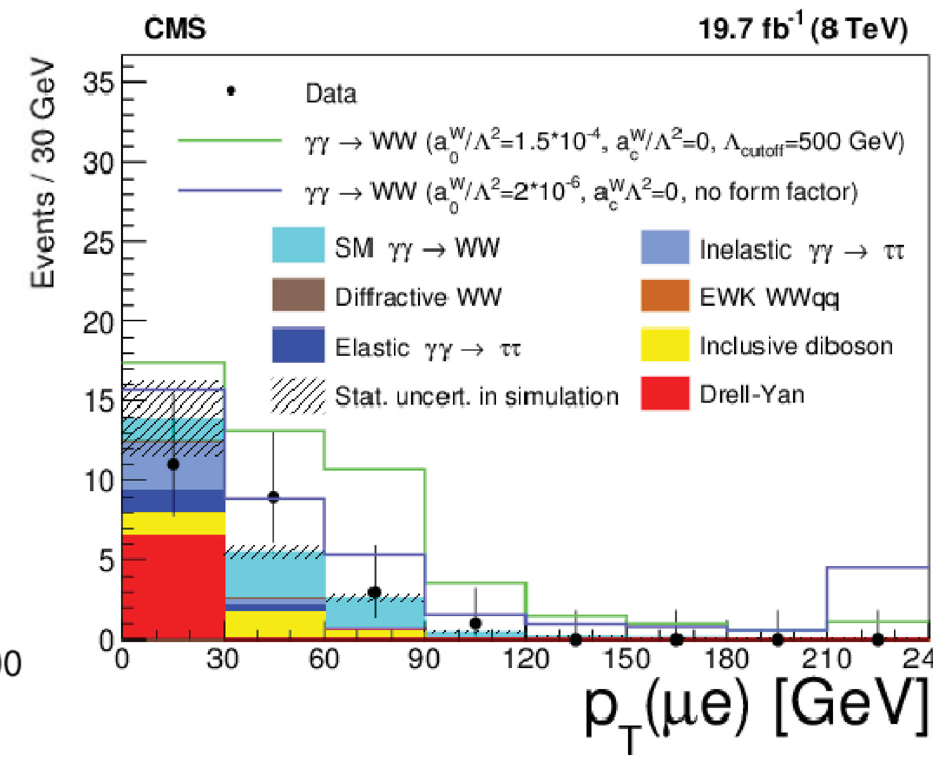
- Merged (J) category improves expected sensitivity by 40%
- No conversion $\alpha_{4,5}$ to $f_{s0,1}$ since WWjj *and* WZjj contribute

$\gamma\gamma \rightarrow$ WW

PRD 94, 032011 (2016) JHEP 08 (2016) 119

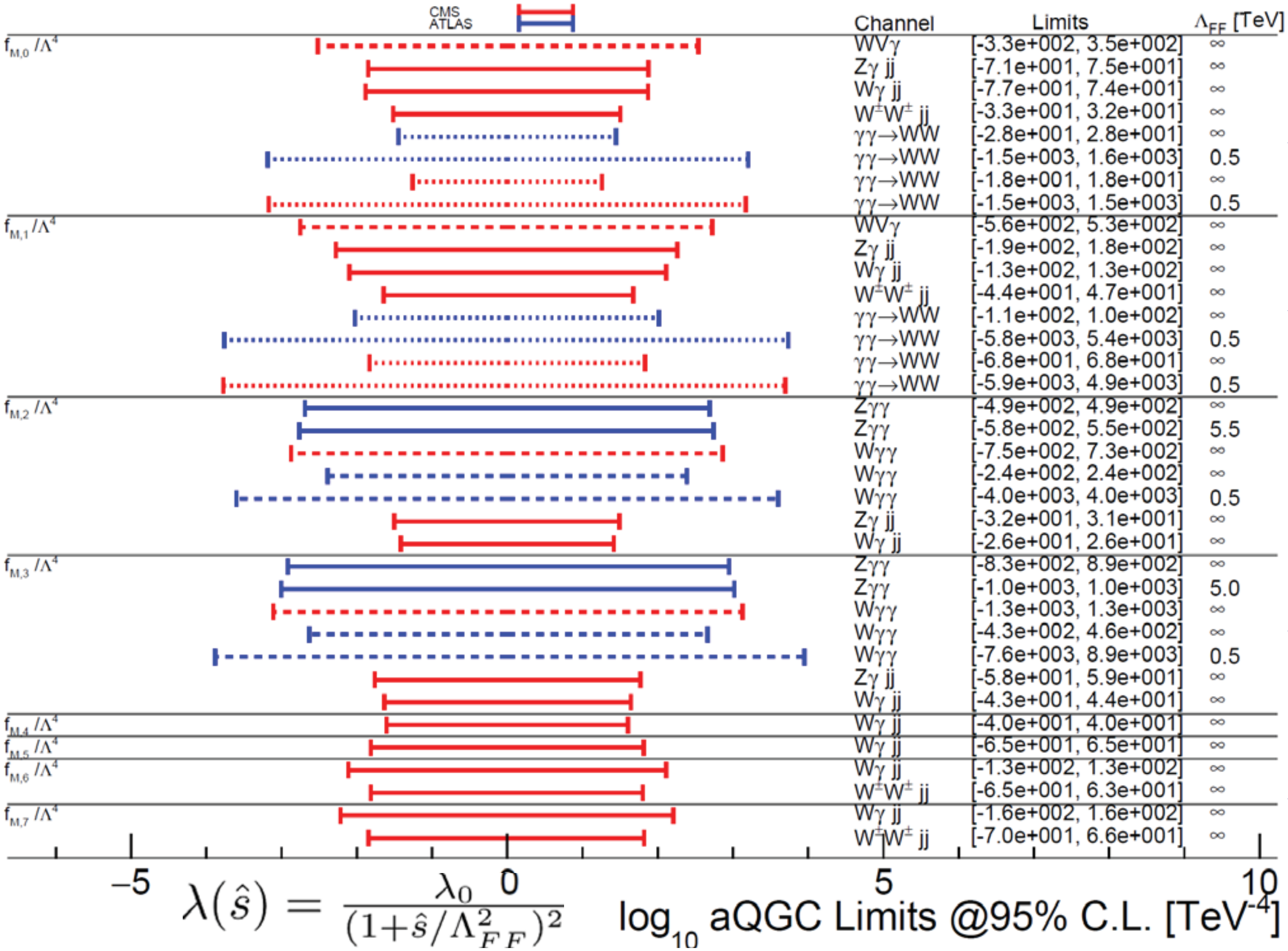
- eμ pair with large pT, no other charged particles @ vertex
- 1st *SM signal* evidence: ATLAS: 3.0σ (8TeV), CMS: 3.4σ (7,8TeV)





- aQGC limits placed using dilepton pT distribution
- No tag jets -> suppressed WWWW, WWZZ, WWZγ contributions

aQGC status



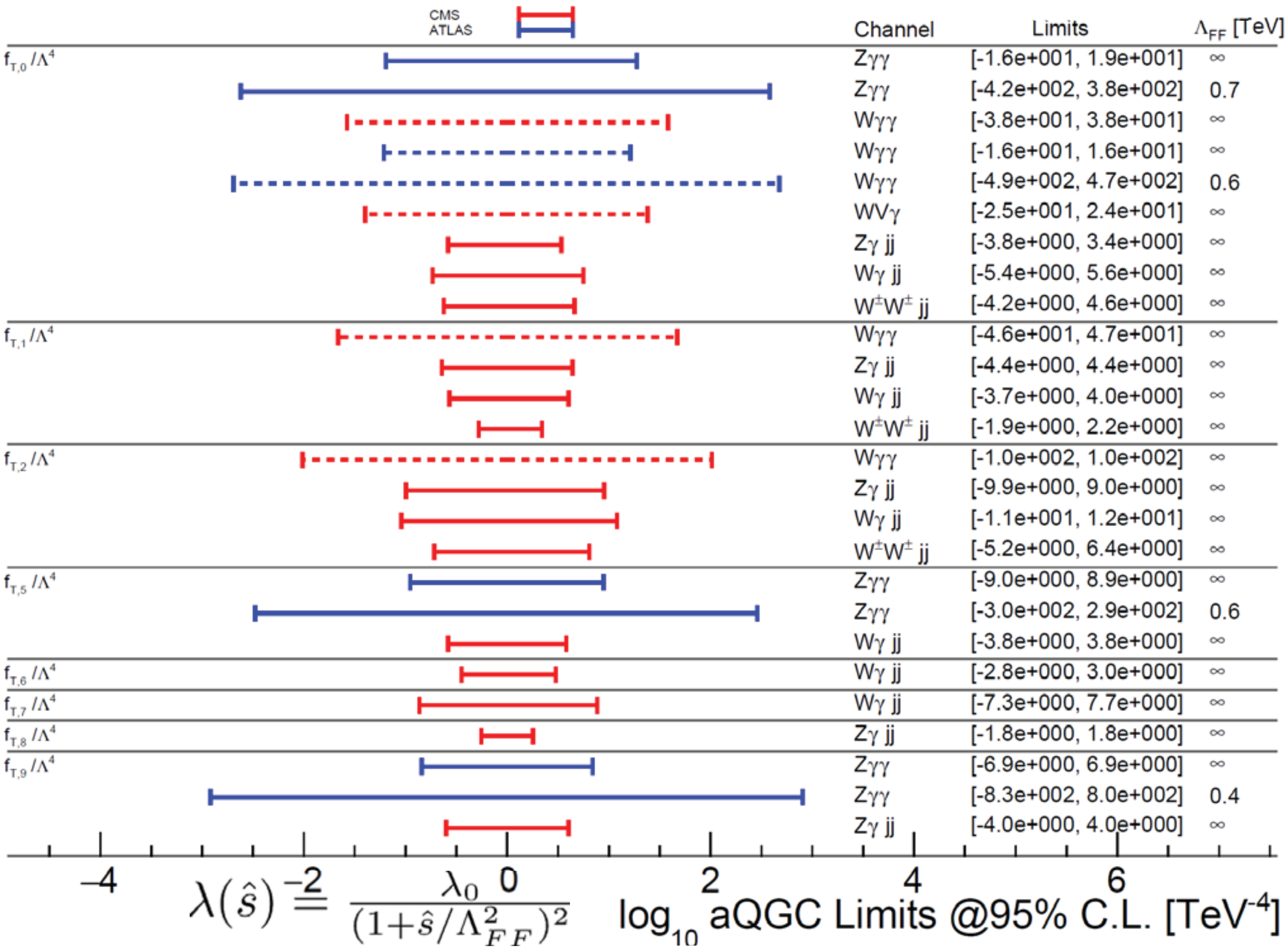
$$\lambda(\hat{s}) = \frac{\lambda_0}{(1+\hat{s}/\Lambda_{FF}^2)^2}$$

arXiv:1610.07572

- All results use full 8 TeV datasets
- Trend that exclusive outperforms VBS, which is better than VVV
- Note **strong** impact of unitarisation
- Fair comparison requires some work

- ATLAS Vγγ limits (VBFNLO) converted to CMS notation (MG5)
- WVγ and γγ→WW converted from $a_{0,C}^W$ limits to std. MG5 as CMS implemented their own Lagrangians in MG5 for $f_{M,i}$
- Checking $a_{0,C}^W$ consistent implementation b/w ATLAS/CMS

aQGC status



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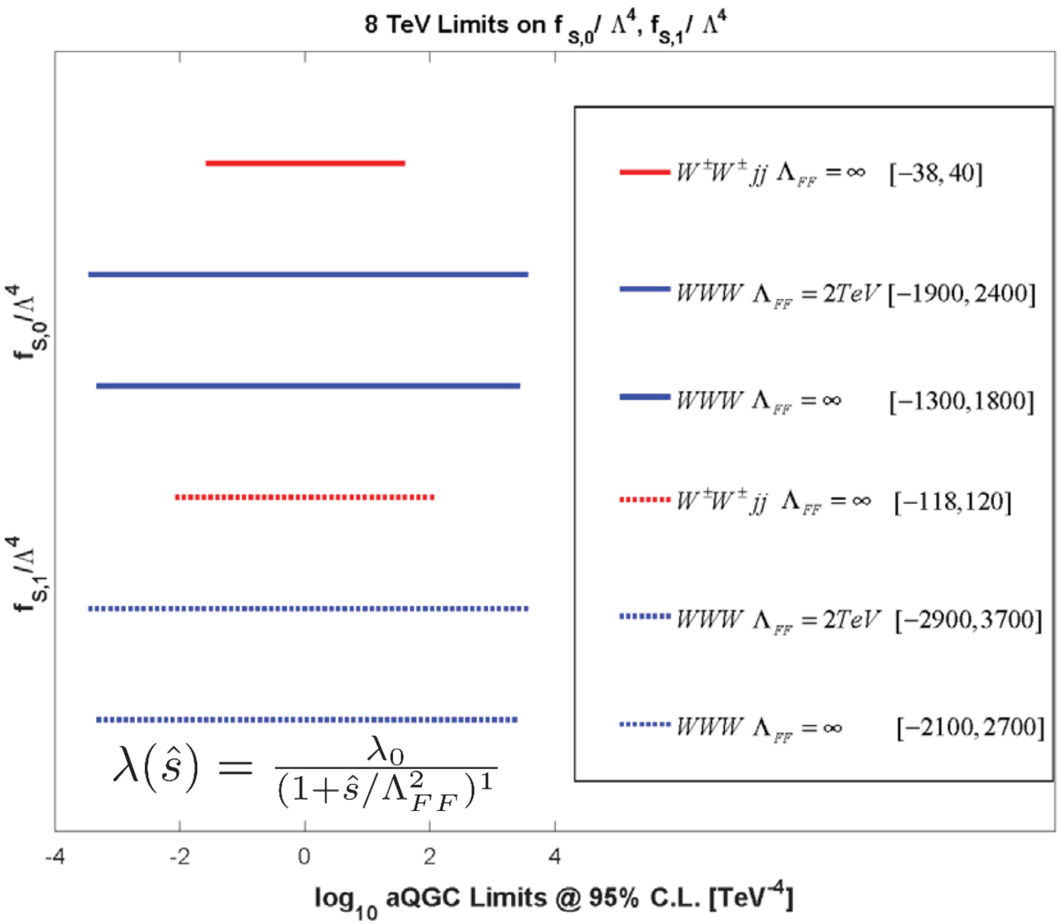


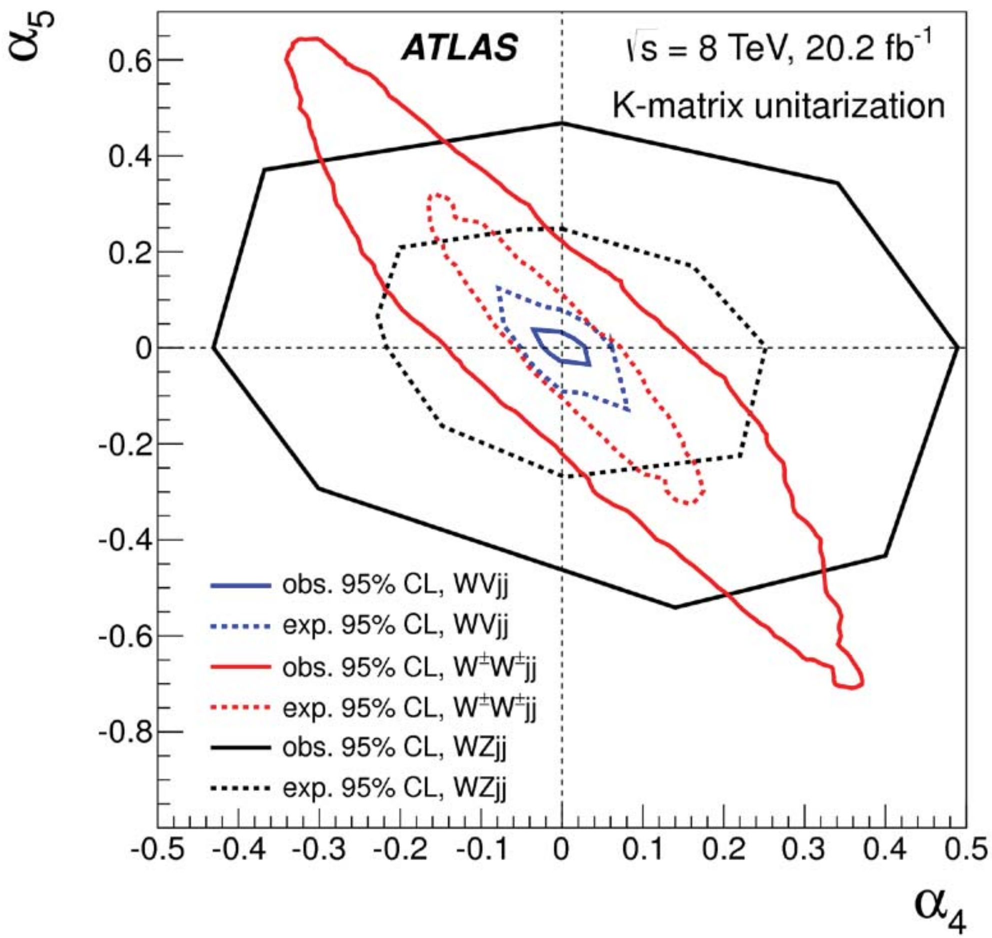
arXiv:1610.07572

- All results use full 8 TeV datasets
- Trend that exclusive outperforms VBS, which is better than VVV
- Note **strong** impact of unitarisation
- Fair comparison requires some work

- Conversion of $\alpha_{4,5}$ limits of ATLAS WVjj, ssWW, WZjj analyses not performed: vertex-dependent (missing $f_{S,2}$)

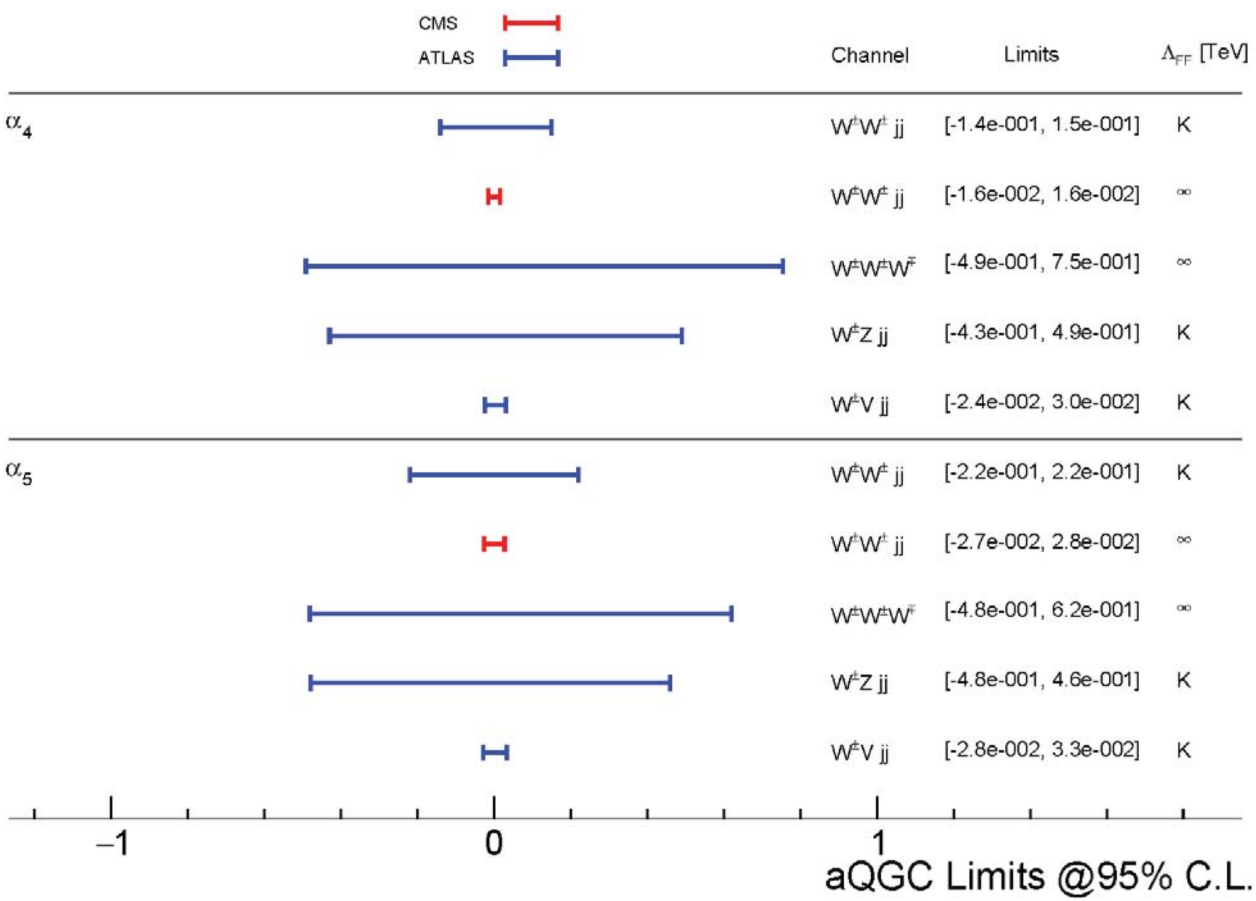
aQGC status

arXiv:1610.07572



- All results use full 8 TeV datasets
- Trend that exclusive outperforms VBS, which is better than VVV
- Note **strong** impact of unitarisation
- Fair comparison requires some work
- Semileptonic VBS analysis **very** sensitive!

aQGC status



- Conversion of $f_{S,0/1}$ limits of CMS ssWW, ATLAS WWW analyses using WWWW specific conversion formula.

arXiv:1610.07572

- All results use full 8 TeV datasets
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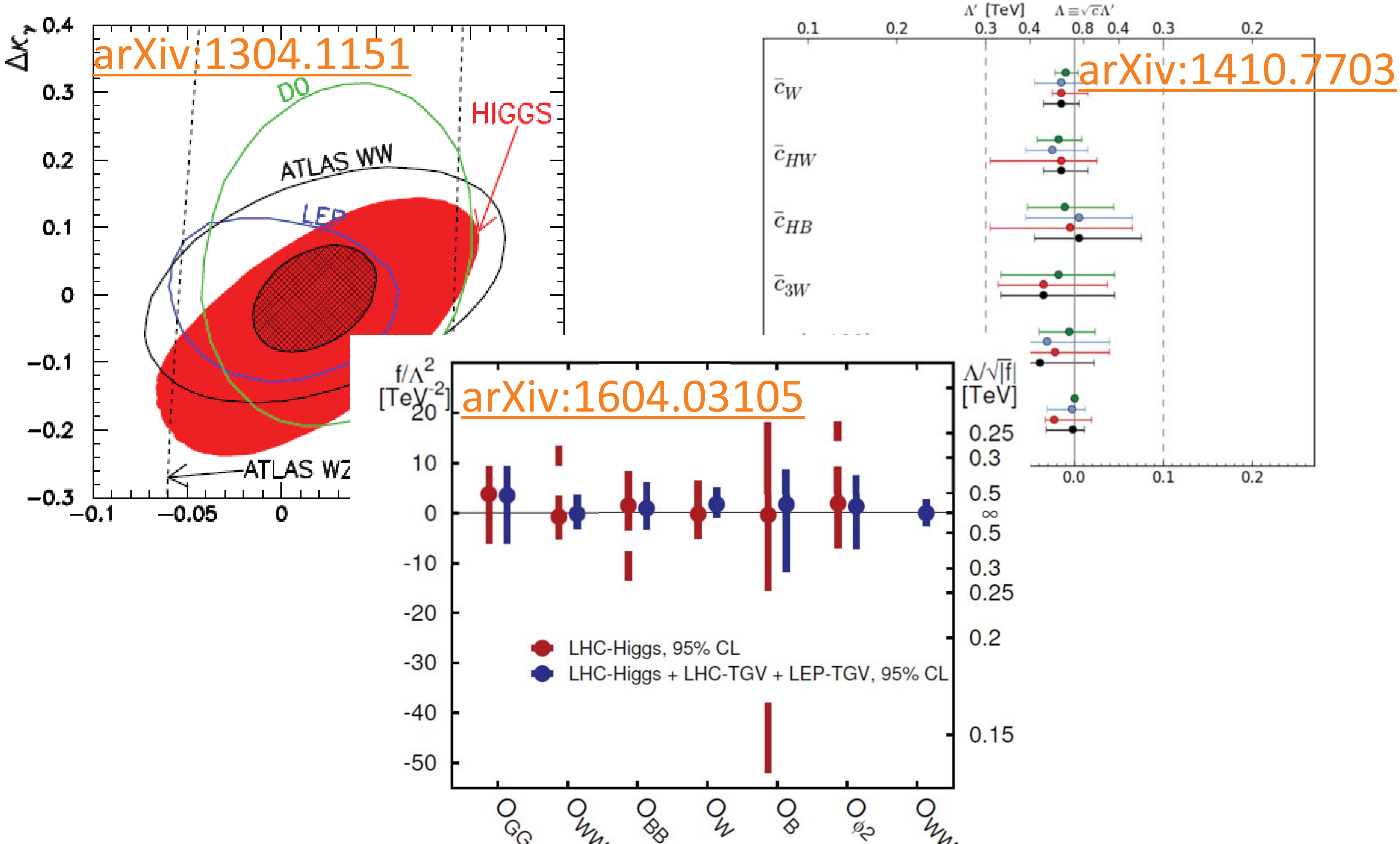
Putting it all together…



❖ VV and Higgs interactions are related in EFTs!

EFT Limit Combinations

- Higgs analyses now also moving away from μ, κ & towards EFT
  - First(?) example: ATLAS Hγγ PLB 753, 69 (2016)
- Combining constraints from
  - Higgs/SM in ATLAS
  - ATLAS and CMS
  - LHC and beyond (e.g. B-meson observables)
- Some ingredients: agree on
  - common basis, modeling choices, unitarisation method if needed, tools
  - common binning, treatment of correlations, signal/background (H/VV)
  - Smaller scale "testbench" before moving to "global fit"
    - Best observable ($\hat{s}$ sensitive)?
      Current sensitivity more from normalization than shape…
- In addition/alternatively,
  - Provide unfolded measurements w/ correlation matrix instead?
  - Provide N-dimensional limits with correlation matrix

Summary

- Harvest of Run I analyses still ongoing – establishing new processes.
- Run 2 will provide access to more processes (VBS, VVV), and better BSM sensitivity!
- Starting to prepare for combinations of limits
- THANK YOU to the MC generator + HO correction community
  - NNLO QCD predictions are very important for multi-V
  - HO EWK corrections as well, particularly for aGC limits
- Current "state of the art" ATLAS MC in multi-bosons: see "Multi-Boson Simulation for 13 TeV ATLAS Analyses"
  - Mix & match in modelling: PDF, ME, scales, PS, EW scheme, HO corrections – lots of combinations, some of which will be sub-optimal
- Wishlist:
  - NNLO (multi-leg) QCD + NLO EWK + PS event generation. ☺
  - Re-weighting functionality for PDFs, scales, EFTs/aGCs

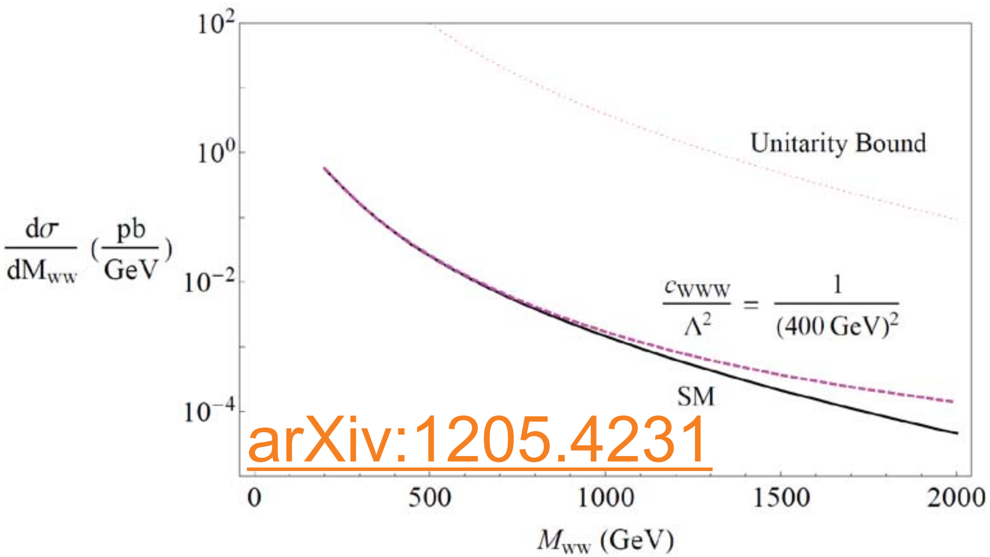
Encore!

Unitarity bounds

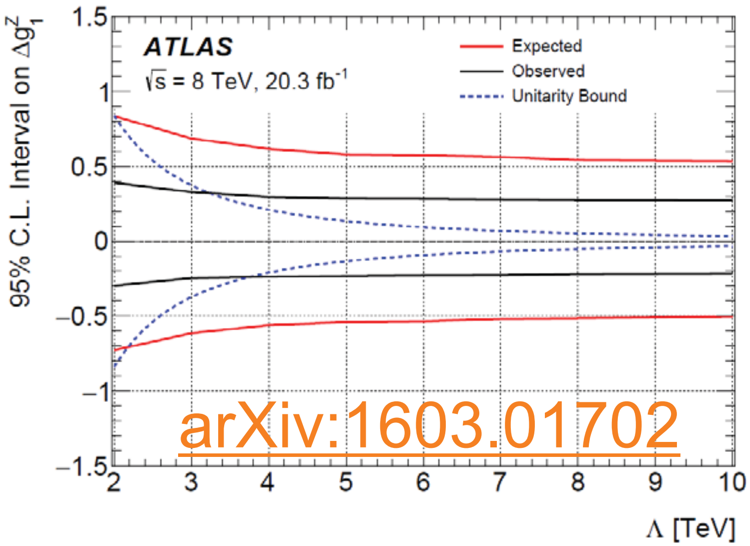
- aTGCs in LEP scenario w/o unitarisation can be directly translated into EFT coefficients:

$$\frac{c_W}{\Lambda^2} = \frac{2}{M_Z^2}\Delta g_1^Z = \frac{2}{M_Z^2}(\tan^2\theta_W \Delta\kappa_\gamma + \Delta\kappa_Z)$$
$$\frac{c_B}{\Lambda^2} = \frac{2}{M_W^2}\Delta\kappa_\gamma - \frac{2}{M_Z^2}\Delta g_1^Z$$
$$\frac{c_{WWW}}{\Lambda^2} = \frac{2}{3g^2 m_W^2}\lambda_\gamma = \frac{2}{3g^2 m_W^2}\lambda_Z$$

- No unitarity violation expected *@LHC* for dim-6:



arXiv:1205.4231

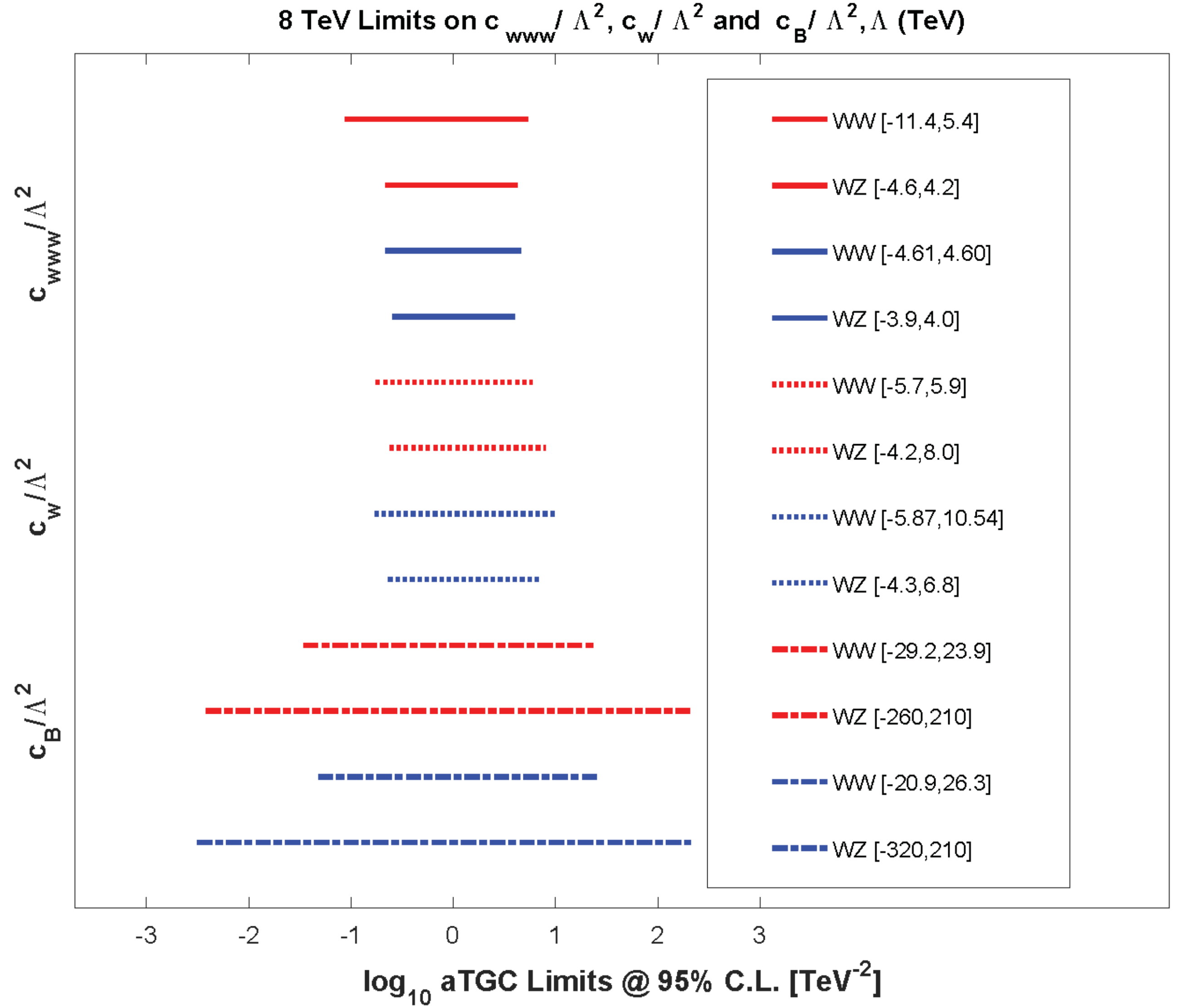


arXiv:1603.01702

- How to reconcile? ATLAS aTGC bound ensures unitarity is not violated at *arbitrary high center of mass energies.*

WWZ aTGC → EFT limits

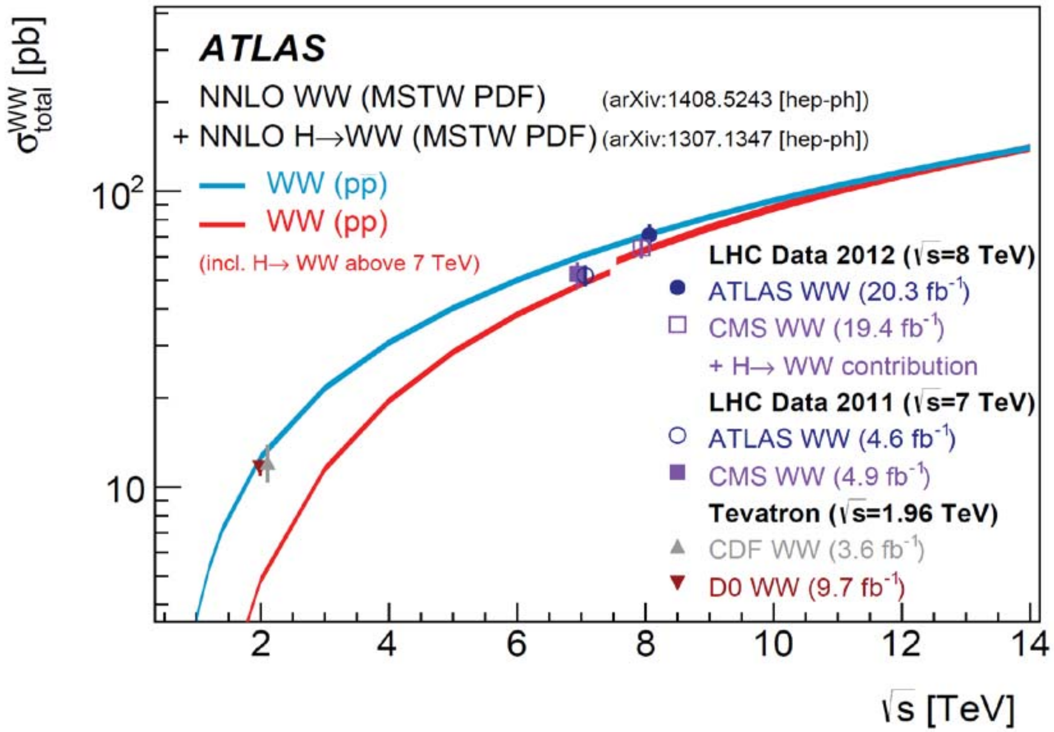
- No unitarisation here!



$W^+W^- \to \ell^+\nu\ell^-\nu$ @ 8 TeV

JHEP 09 (2016) 029

- 2 isolated leptons (e or μ) of opposite charge, MET, no jets (CMS: ≤ 1 jets)
- qq, gg, gg(H) production mechanisms (CMS subtracts gg(H))



- Unfolded differential cross sections are provided as well!
- Fully differential NNLO QCD calculation just became available

$W^+W^- \to \ell^+\nu\ell^-\nu$ @ 8 TeV

JHEP 09 (2016) 029

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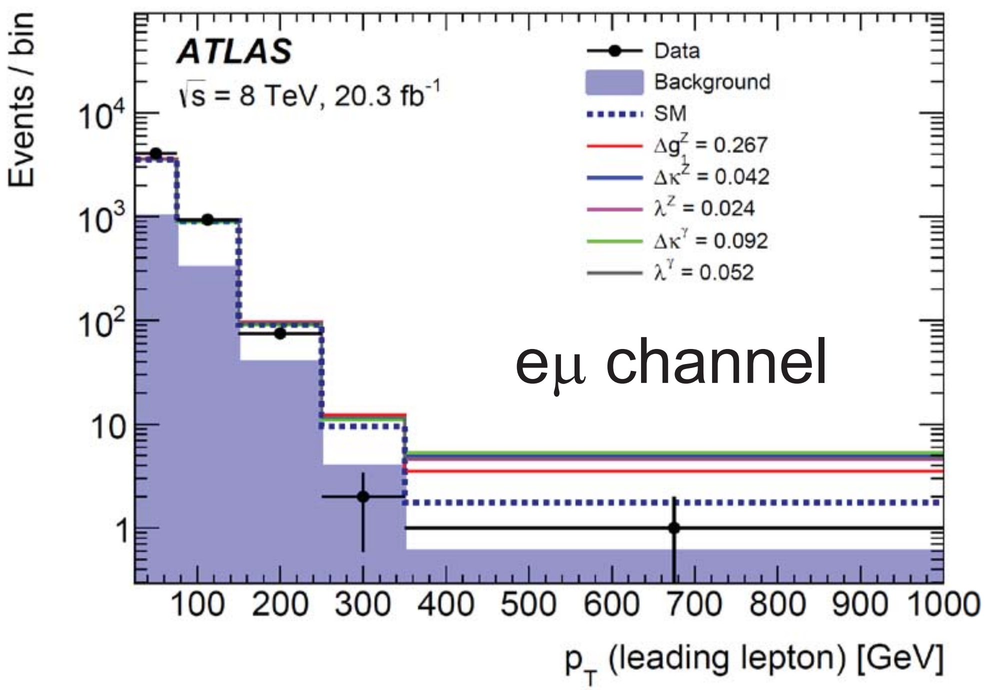
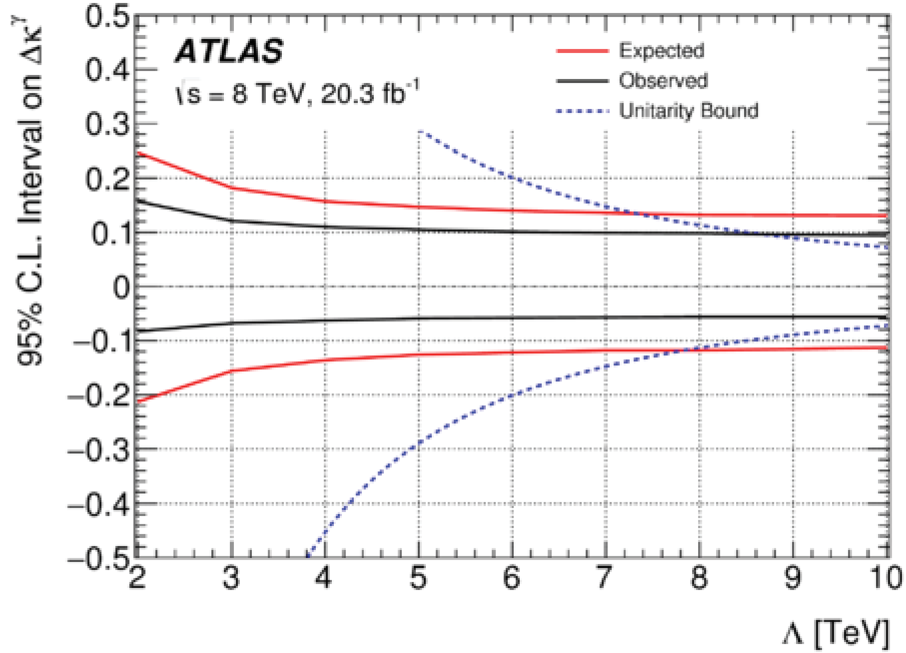


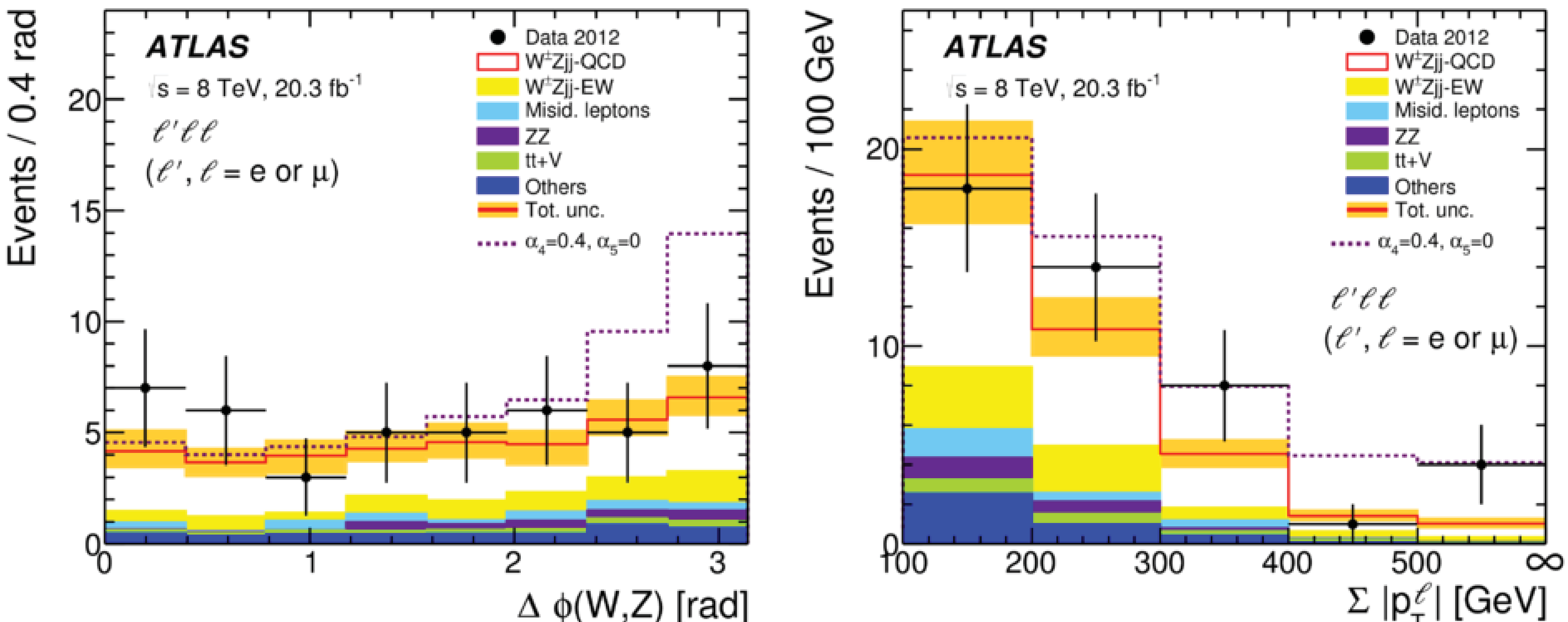


- NLO EWK corrections are taken into account

WZjj → $\ell\nu\ell\ell jj$ @ 8 TeV

PRD 93, 092004 (2016)

- 3 isolated leptons (e or μ), MET, ≥ two jets
- VBS/aQGC additional selection on m_{jj}, $\Delta\Phi(W,Z)$, $\Sigma|p_T(\ell)|$



- measured fiducial xsec in aQGC phase space used for limits
- Conversion $\alpha_{4,5}$ to $f_{s0,1}$ *after* k-matrix unitarisation

WZjj → ℓνℓℓjj @ 8 TeV

PRD 93, 092004 (2016)

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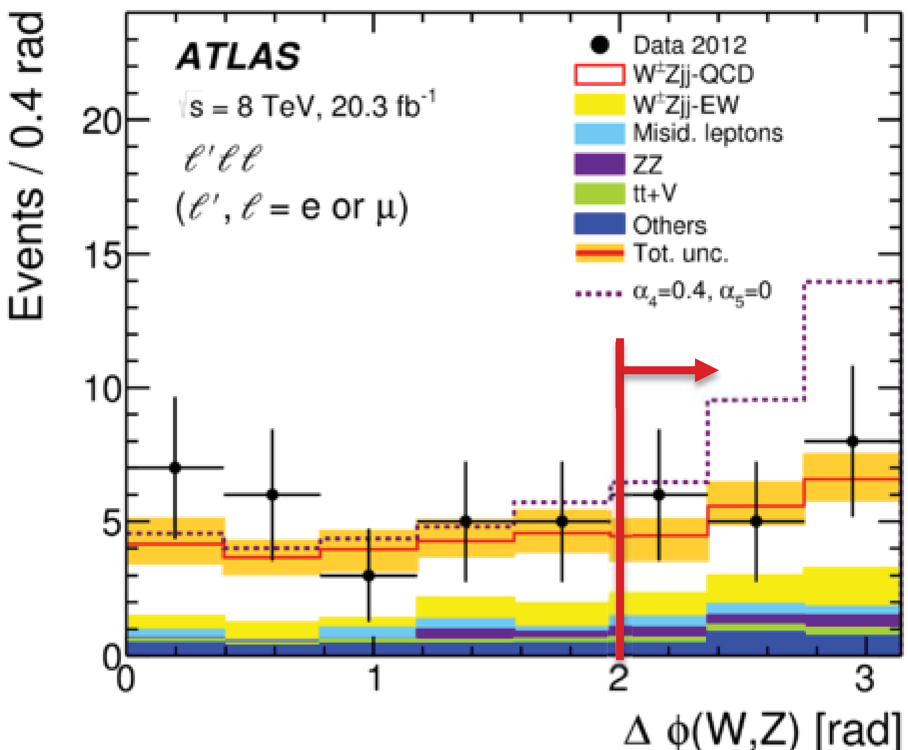

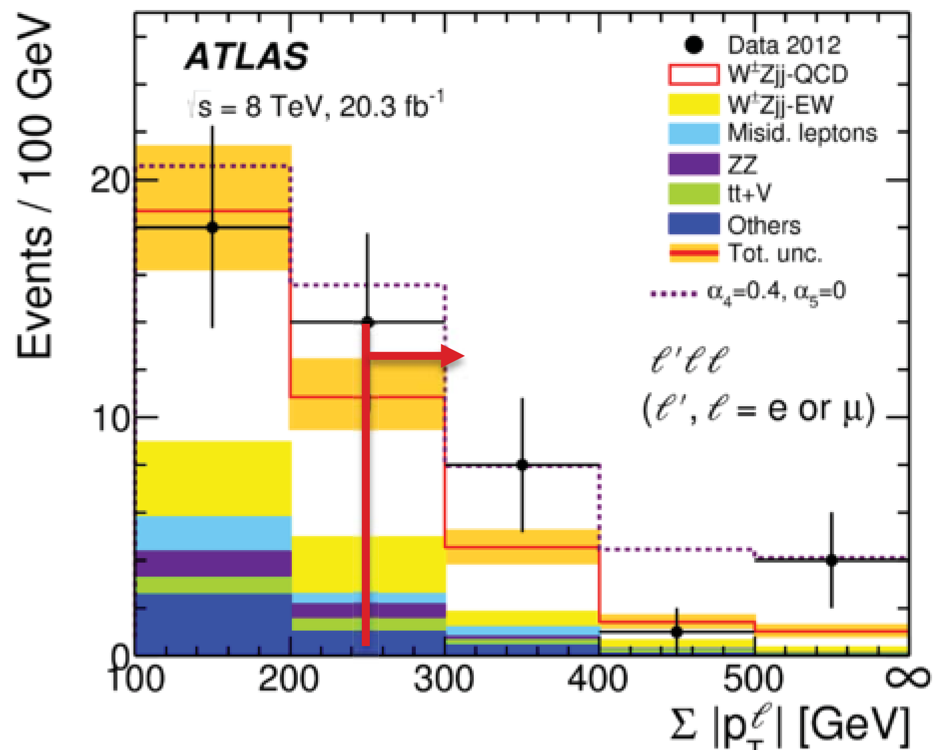

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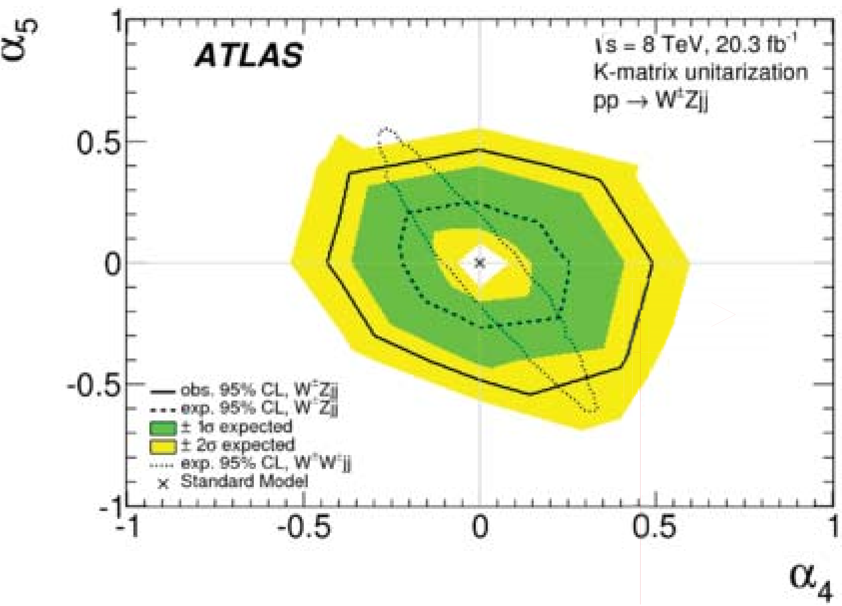

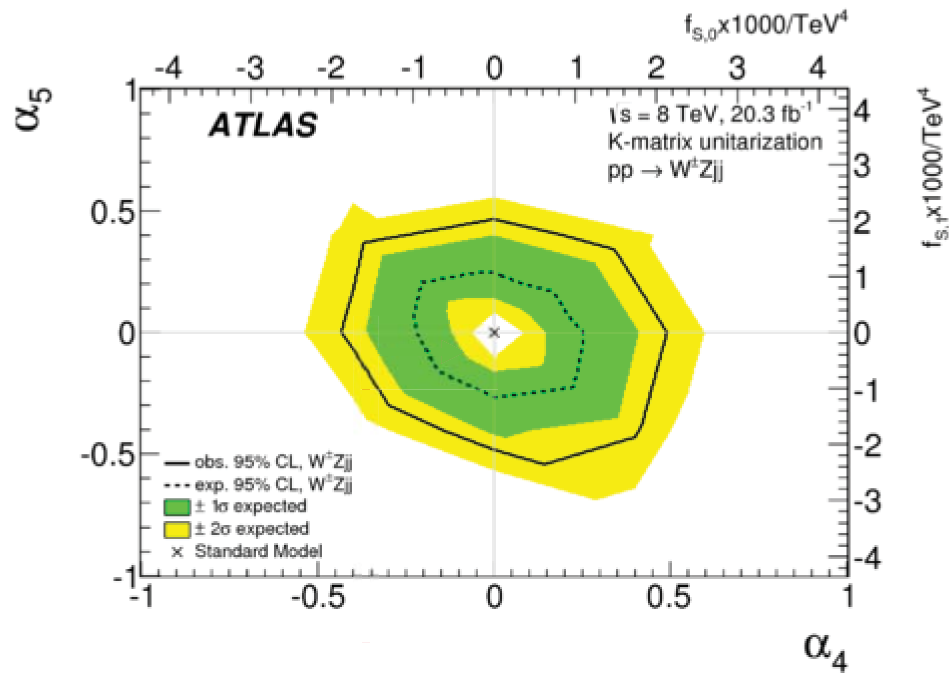

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