# Multi-Boson results and anomalous couplings at the LHC



ATLAS EXPERIMENT

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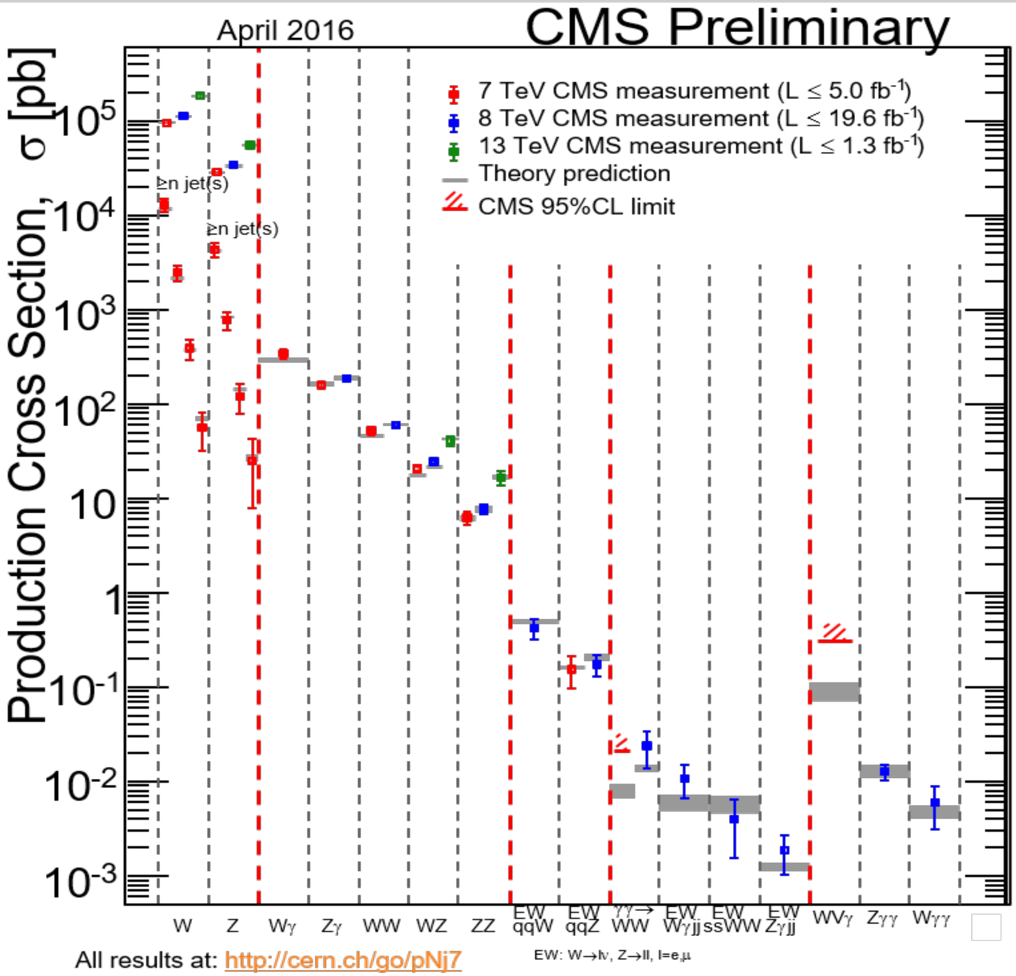
BROOKHAVEN NATIONAL LABORATORY

CMS


Stress-testing the Standard Model at the LHC, KITP, May 27 2016

# (Multi-) V Production



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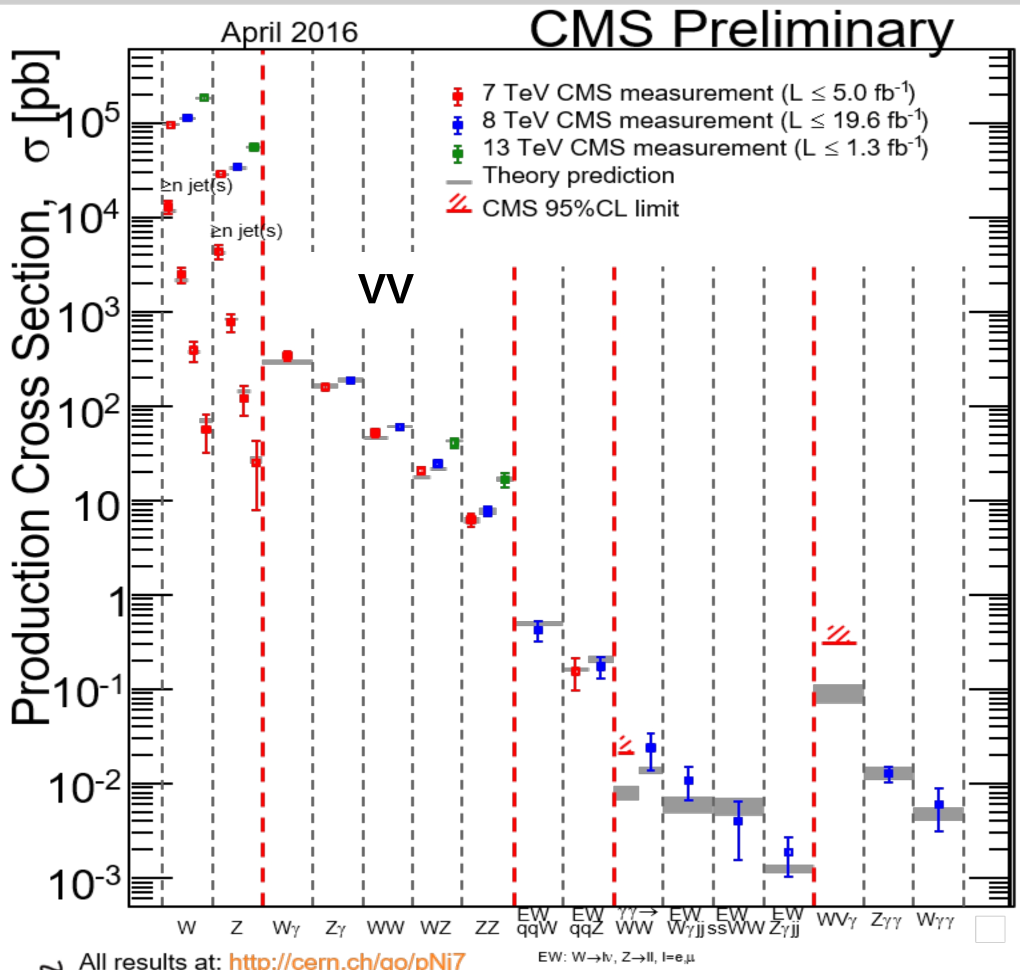


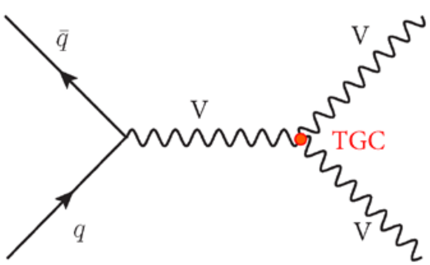

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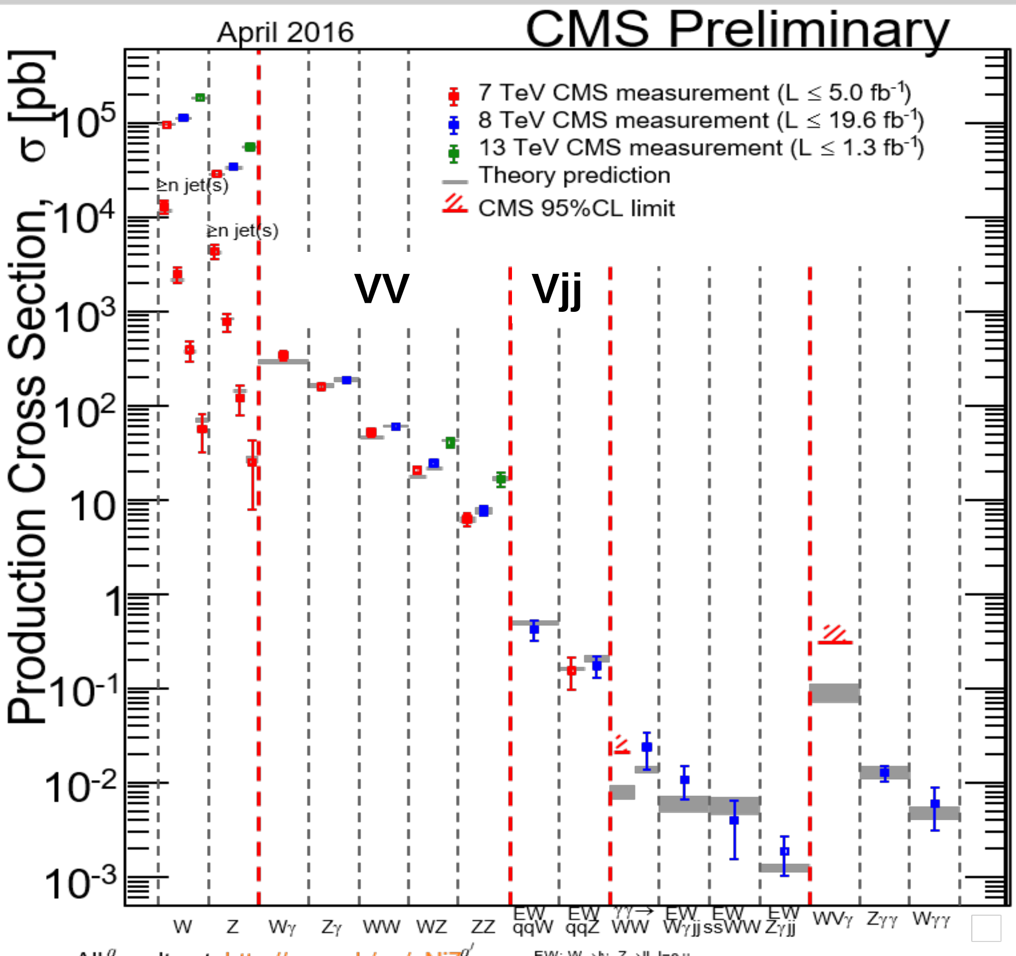
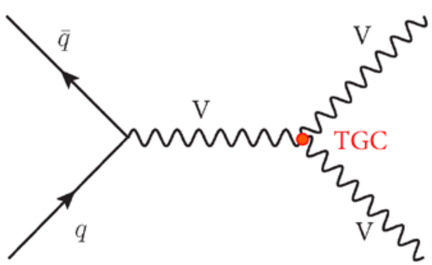
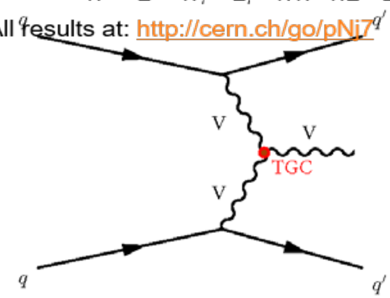



All results at: http://cern.ch/go/pNj7



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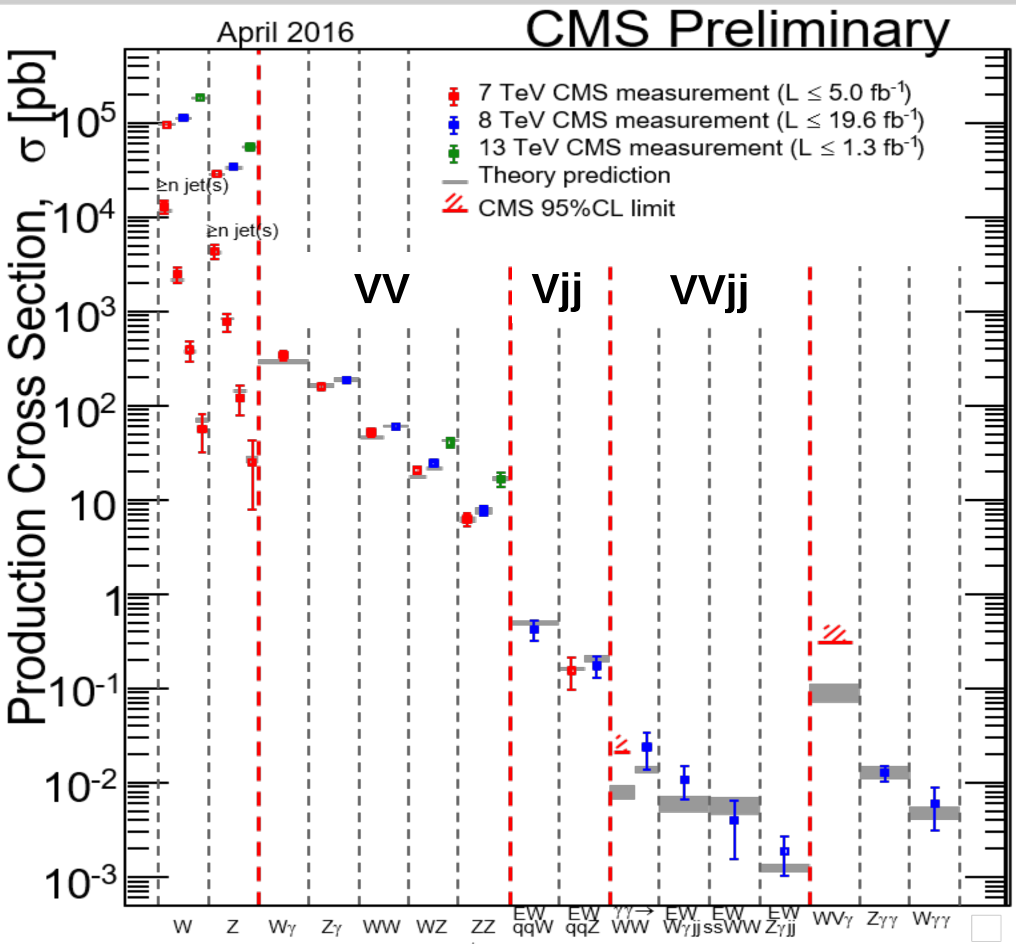


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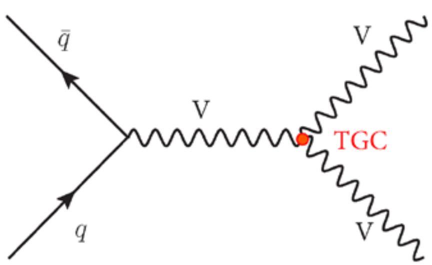


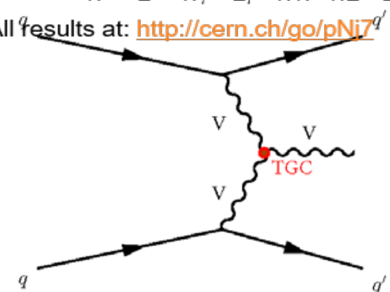


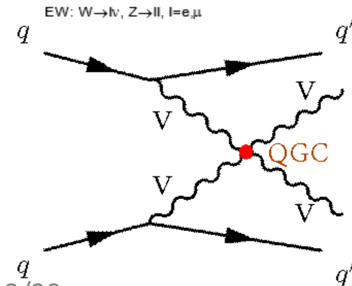

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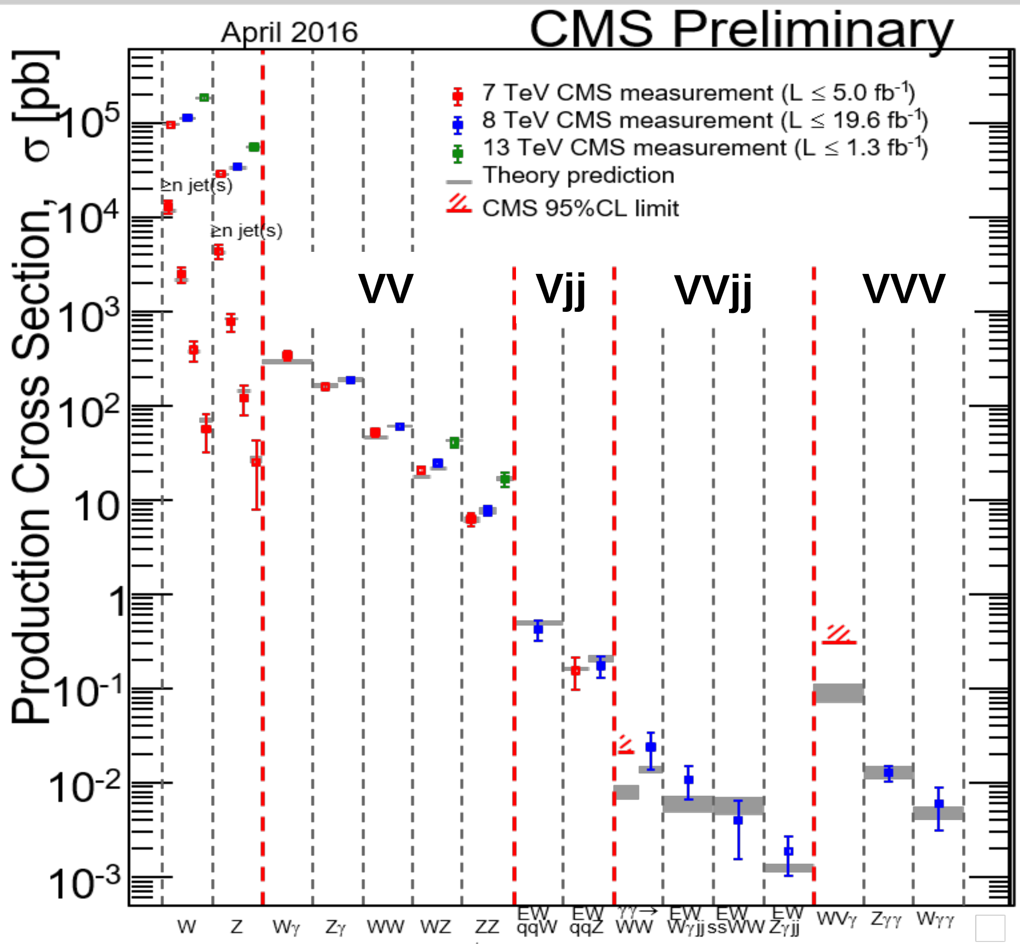


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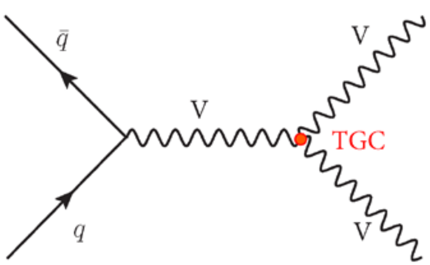


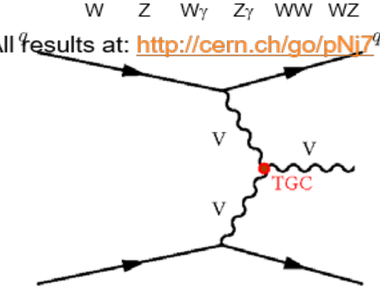


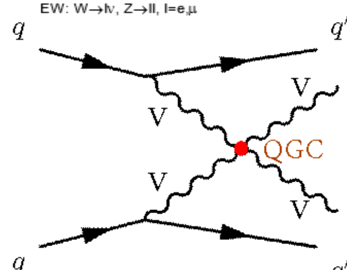


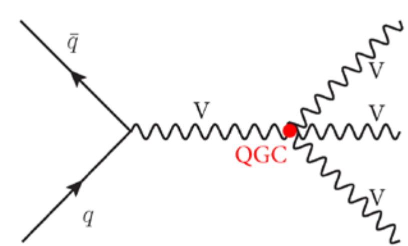

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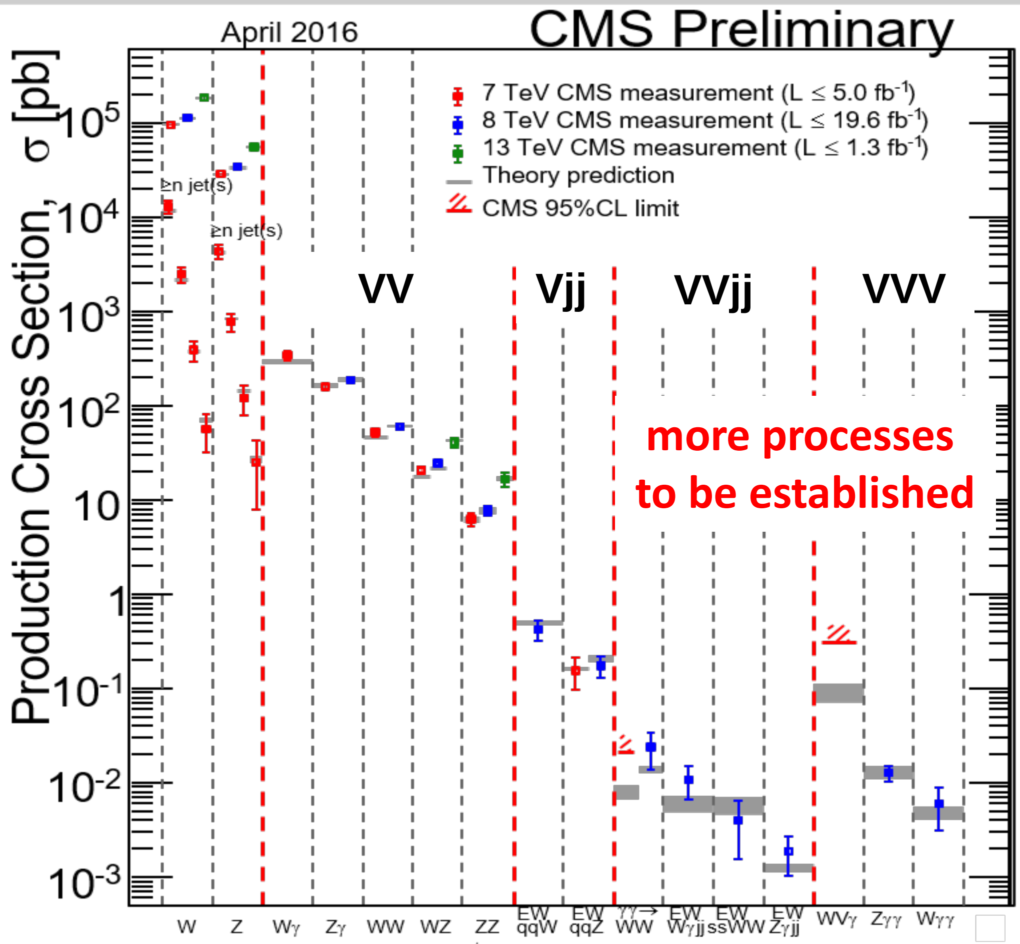
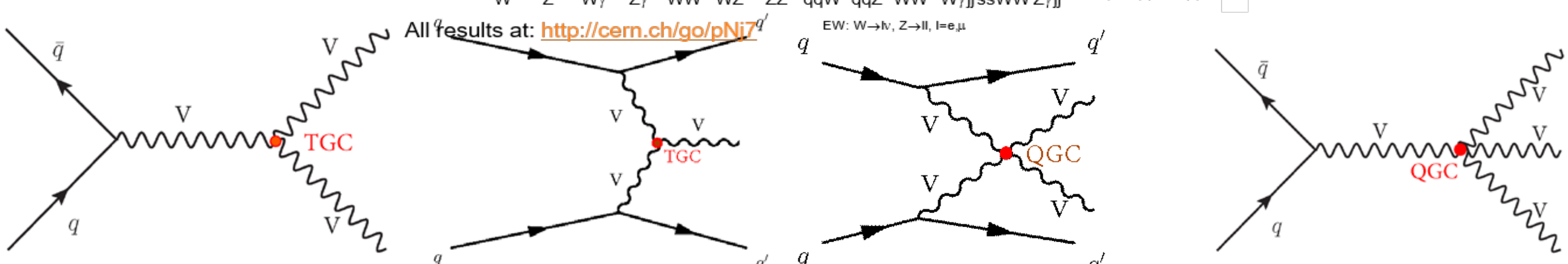
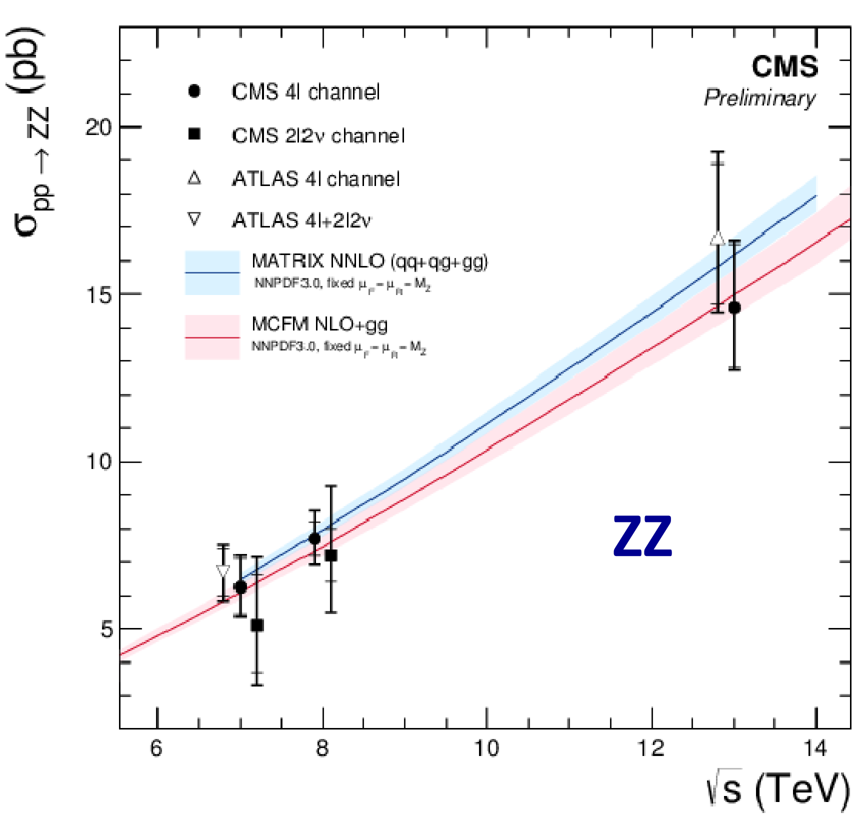
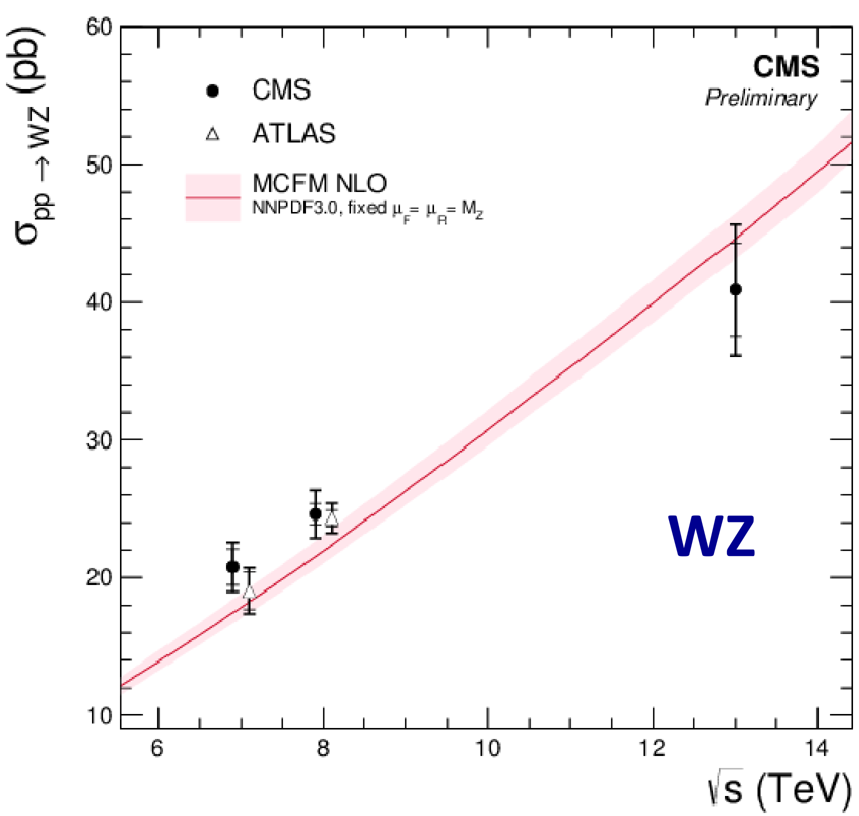


# Run II Results

❖ First 13 TeV multi-V results available…



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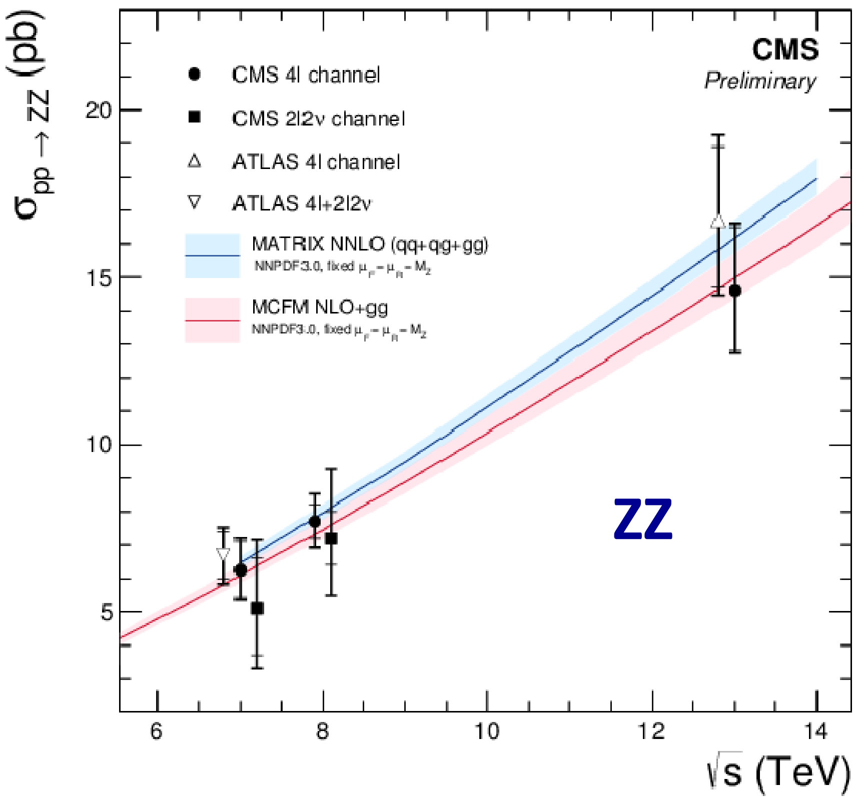


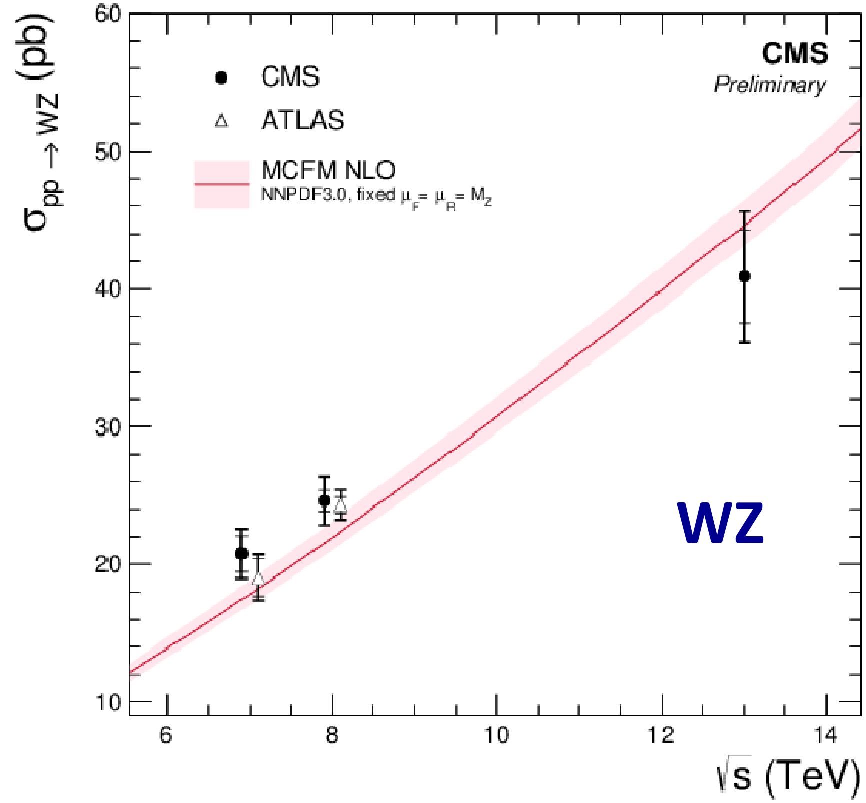


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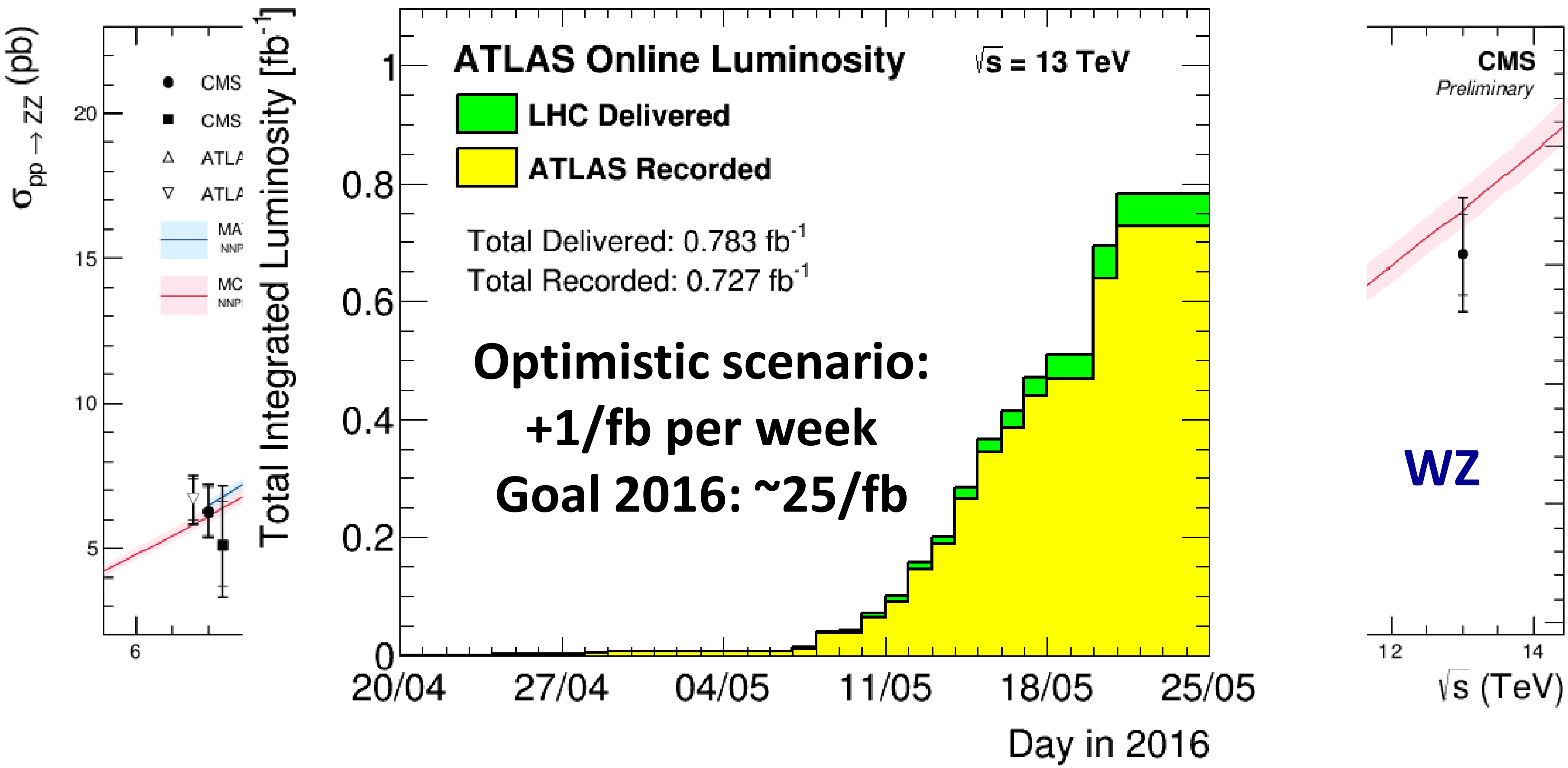


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# Introduction

- Vector boson self-interactions in the SM: study processes *including* triple and quartic gauge couplings (TGCs and QGCs)
  - Measurements allow precision tests of SM predictions @ (N)NLO
  - "Model-independent" probe for new phenomena
  - QGC processes are just being established – new territory!
  - Multi-boson production is important background for other processes
- Experimental access to probe for aGCs:
  - aTGCs: VBF Vjj and VV production
  - aQGCs: VBS VVjj and VVV production
  - Datasets so far: 7 TeV: ~5/fb, 8 TeV: ~20/fb, 13 TeV: ~3/fb in 2015
  - Rely mainly on leptonic W/Z decay channels to allow signal extraction from large BG ($\ell$= e or $\mu$)
  - Experimental signature: **isolated high $p_T$ leptons/photons, MET if $\nu$ present, "tagging jets" if VBF/VBS**

# 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-$Z$ |
| $Z\gamma\gamma$ | $h_3^\gamma, h_4^\gamma$ | $Z\gamma$ |
| $Z\gamma Z$ | $h_3^Z, h_4^Z$ | $Z\gamma$ |
| $ZZ\gamma$ | $f_4^\gamma, f_5^\gamma$ | $ZZ$ |
| $ZZZ$ | $f_4^Z, f_5^Z$ | $ZZ$ |

$f_4^V$ violate CP

SM expectation for all these parameters = 0.

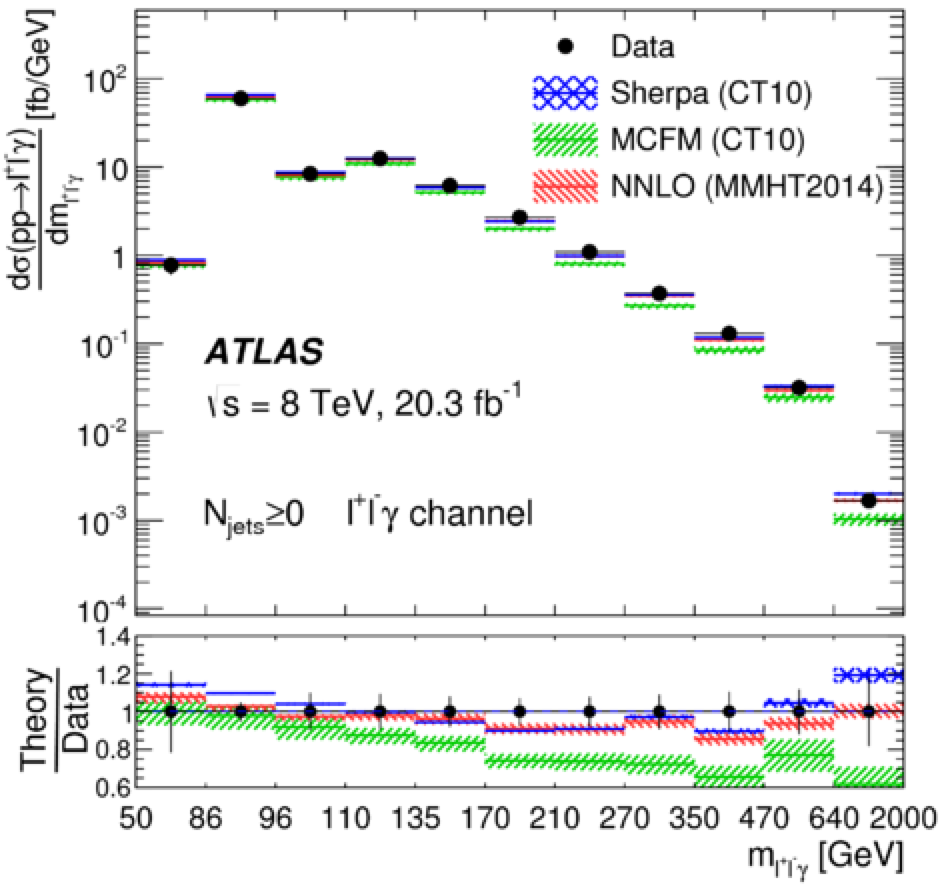
- Experimental access: aTGCs modify total production rate as well as event kinematics
  - Use cross-section measurement or kinematics to constrain aTGCs
- A suppression factor depending on a scale $\Lambda$ ensures conservation of unitarity (divergent xsecs at high $\sqrt{s}$ ):

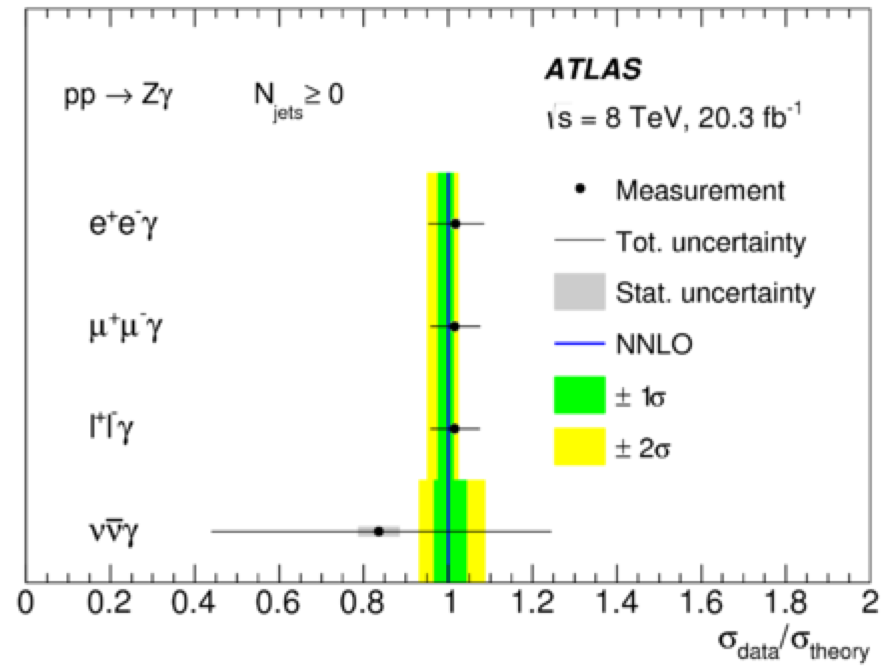
$$\lambda(\hat{s}) = \frac{\lambda_0}{(1+\hat{s}/\Lambda^2)^n}$$

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

arXiv:1604.05232

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



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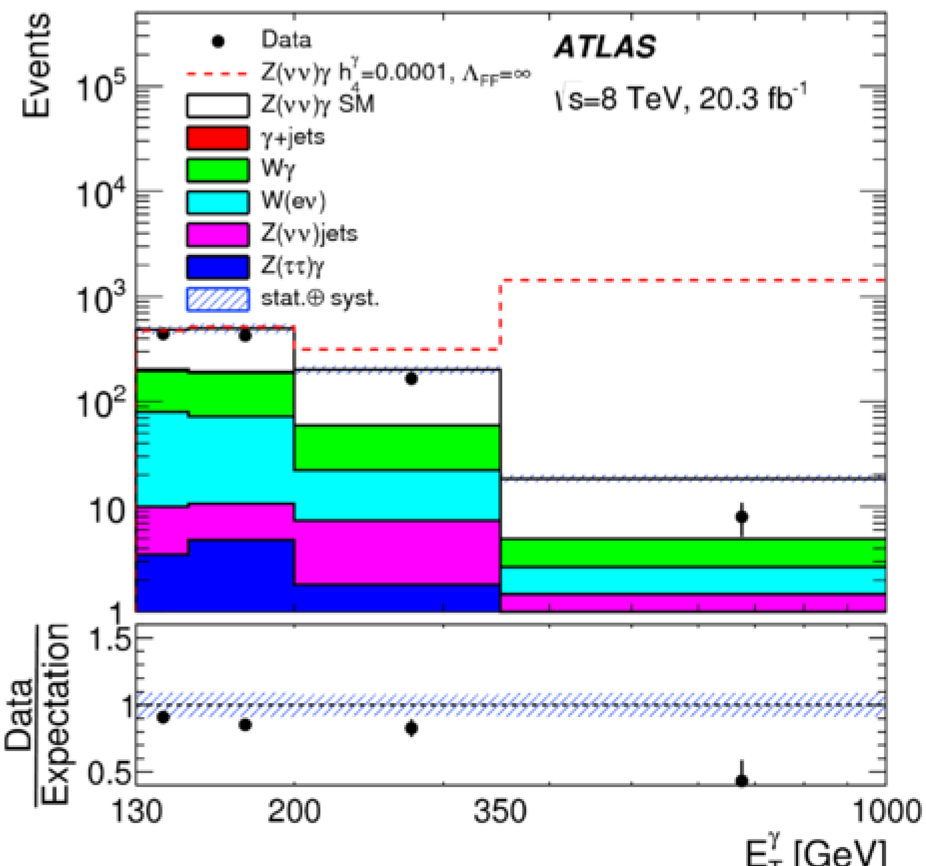
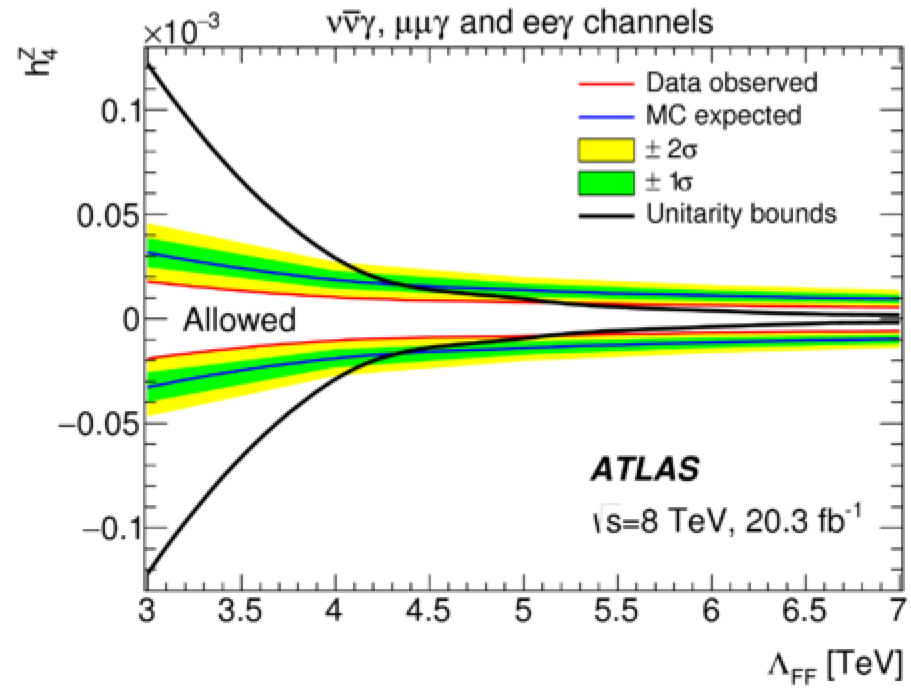


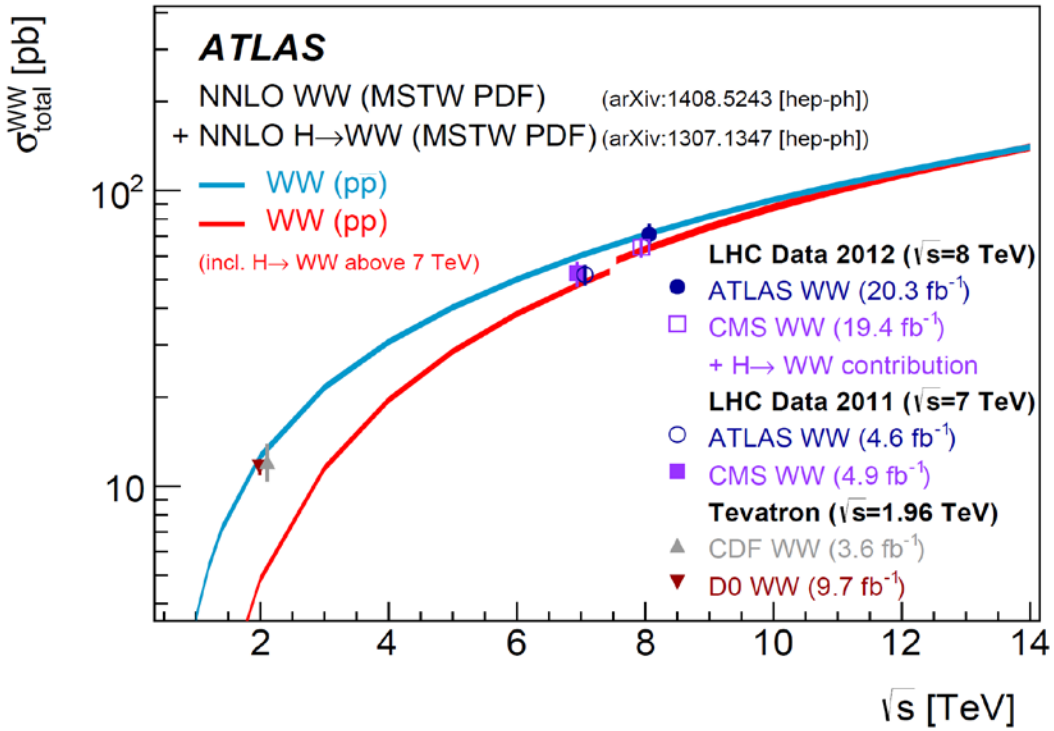




- Exclusive evts used for aTGC limits; NLO ewk corrs not included

# WW → ℓνℓν @ 8 TeV

arXiv:1603.01702

- 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

# WW → $\ell\nu\ell\nu$ @ 8 TeV

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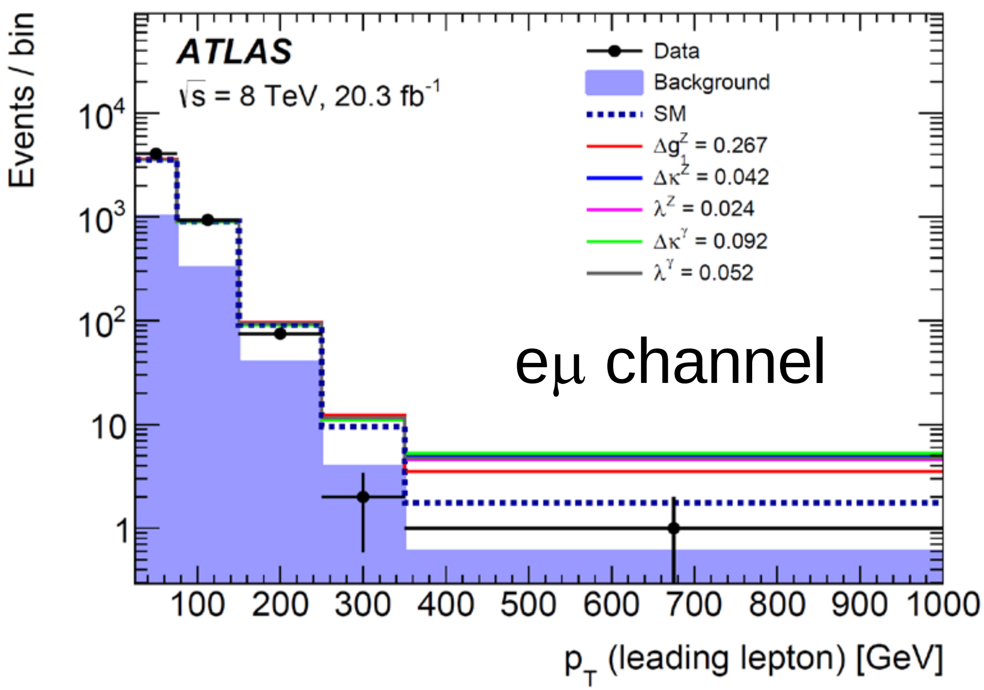
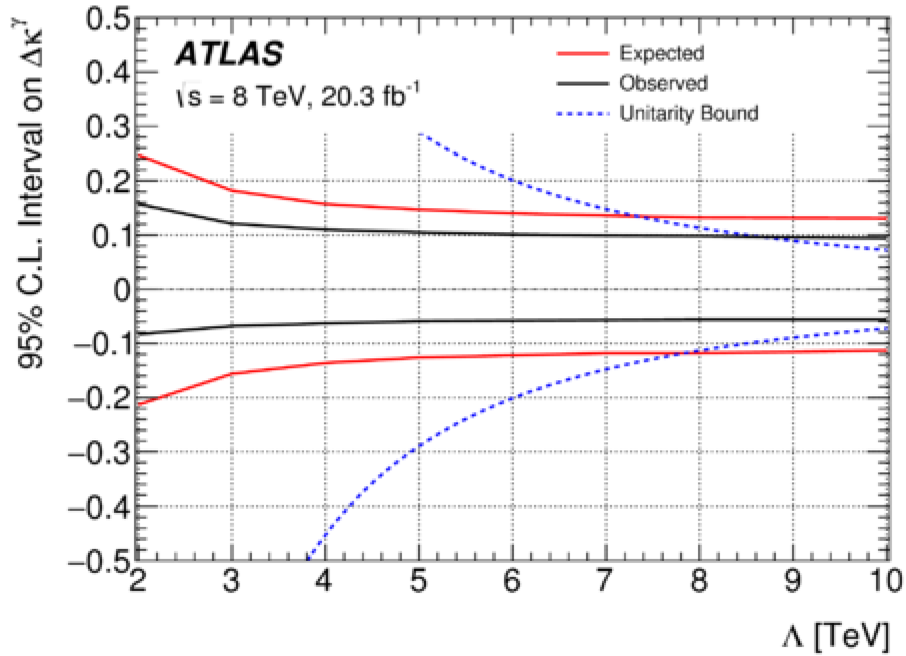


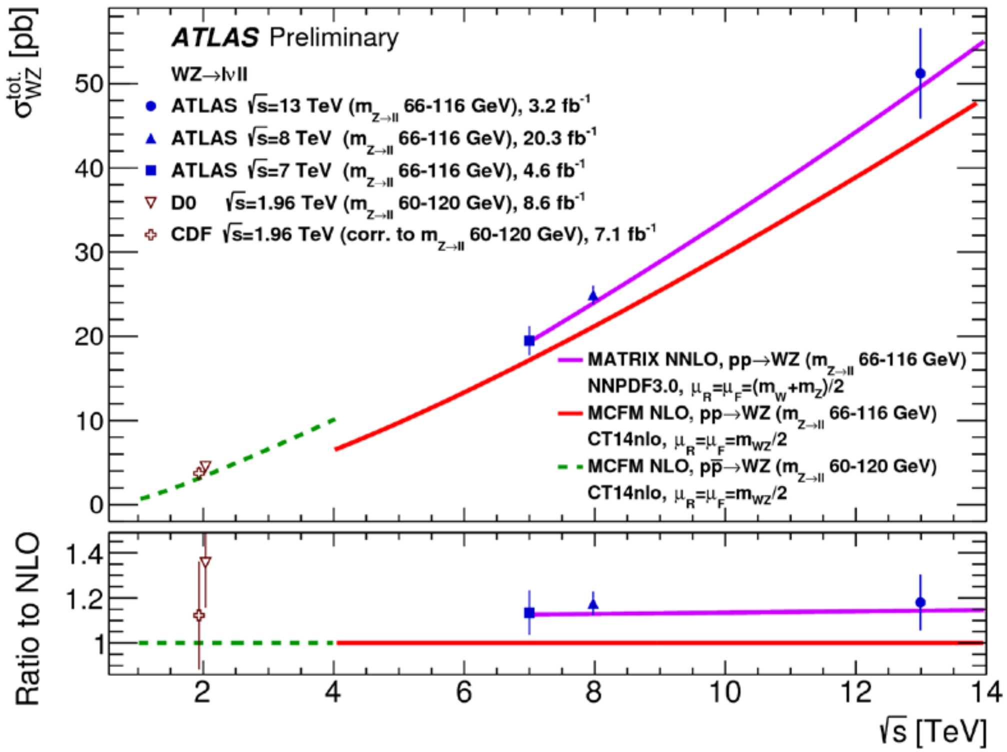




- NLO EWK corrections are taken into account

# 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% ! Provided as well:
  - Unfolded differential cross sections
  - Ratio of $W^+Z$, $W^-Z$ cross sections (also as function of kinematic vars)

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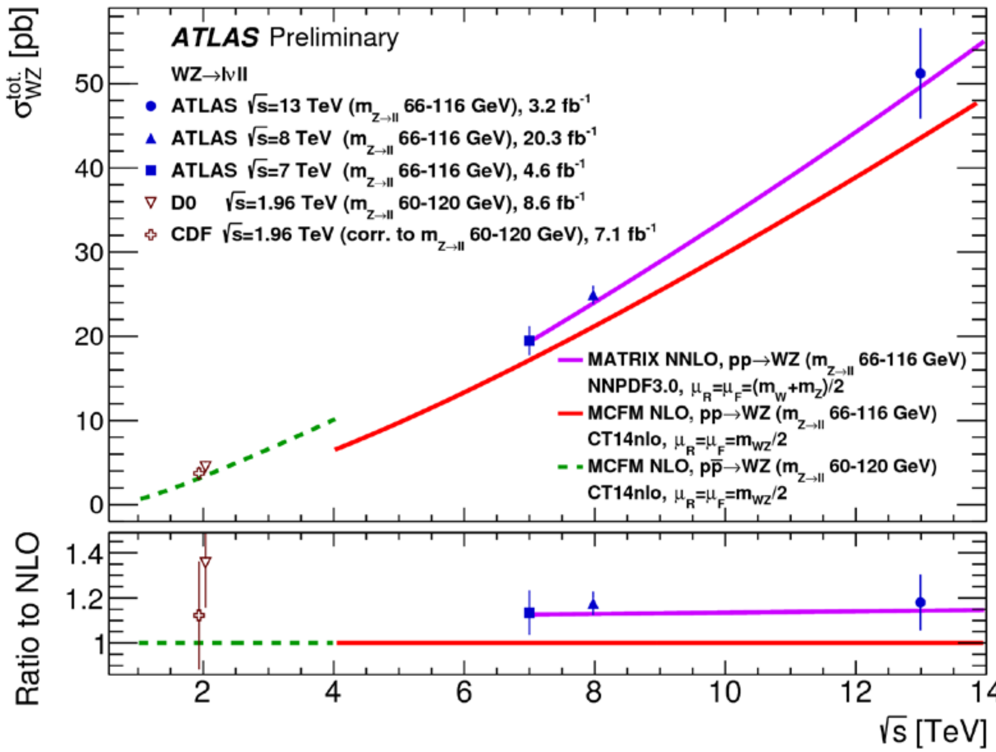


Sneak peek @ 13 TeV (3.2/fb)

- Inclusive fiducial xsec precision: 4.2% ! Provided as well:
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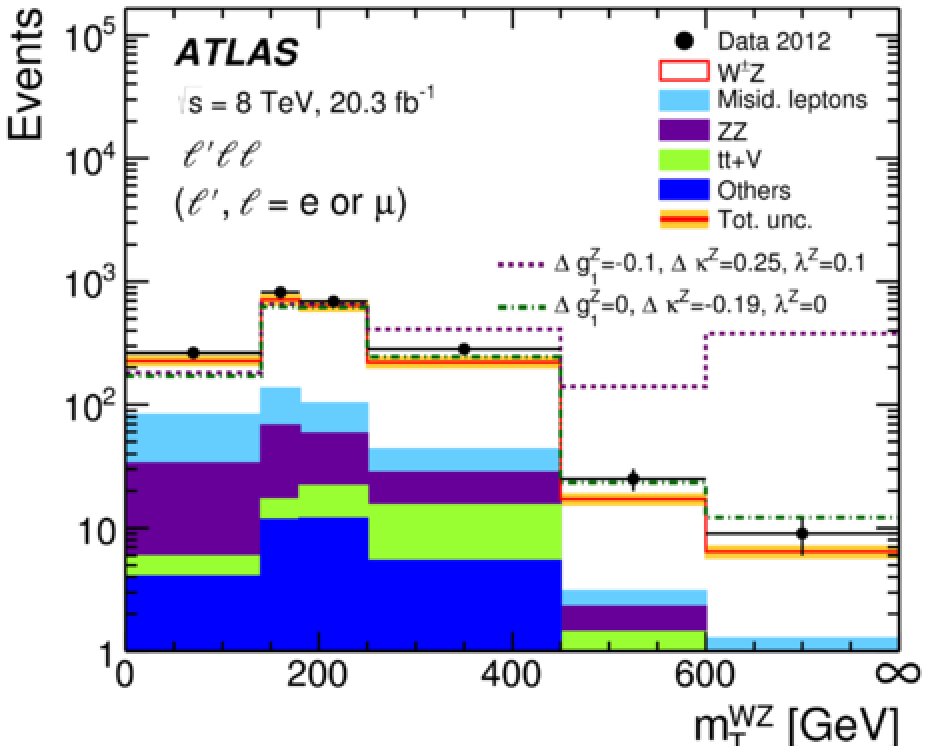


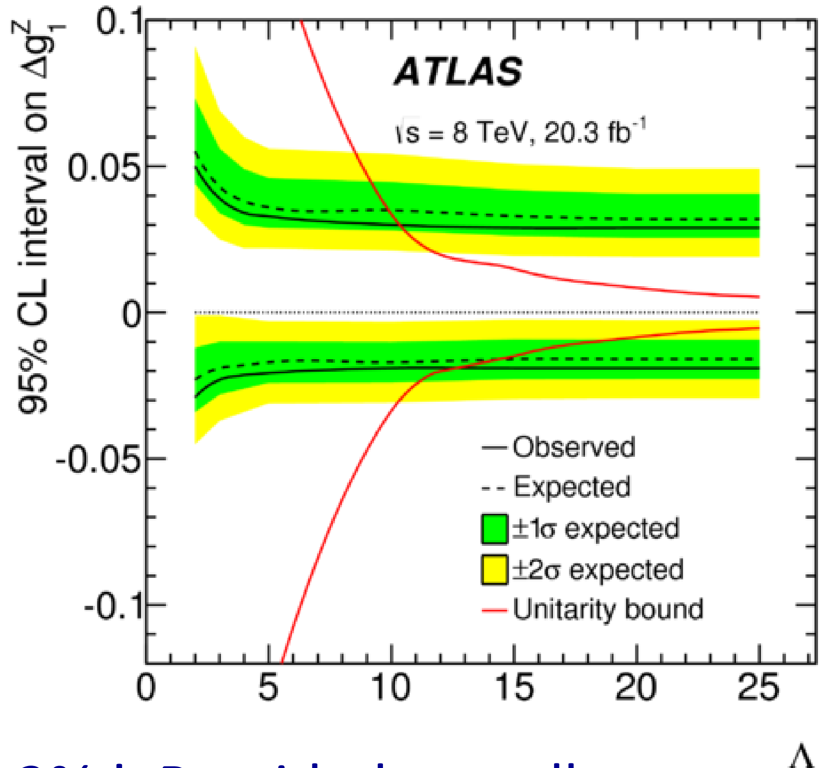


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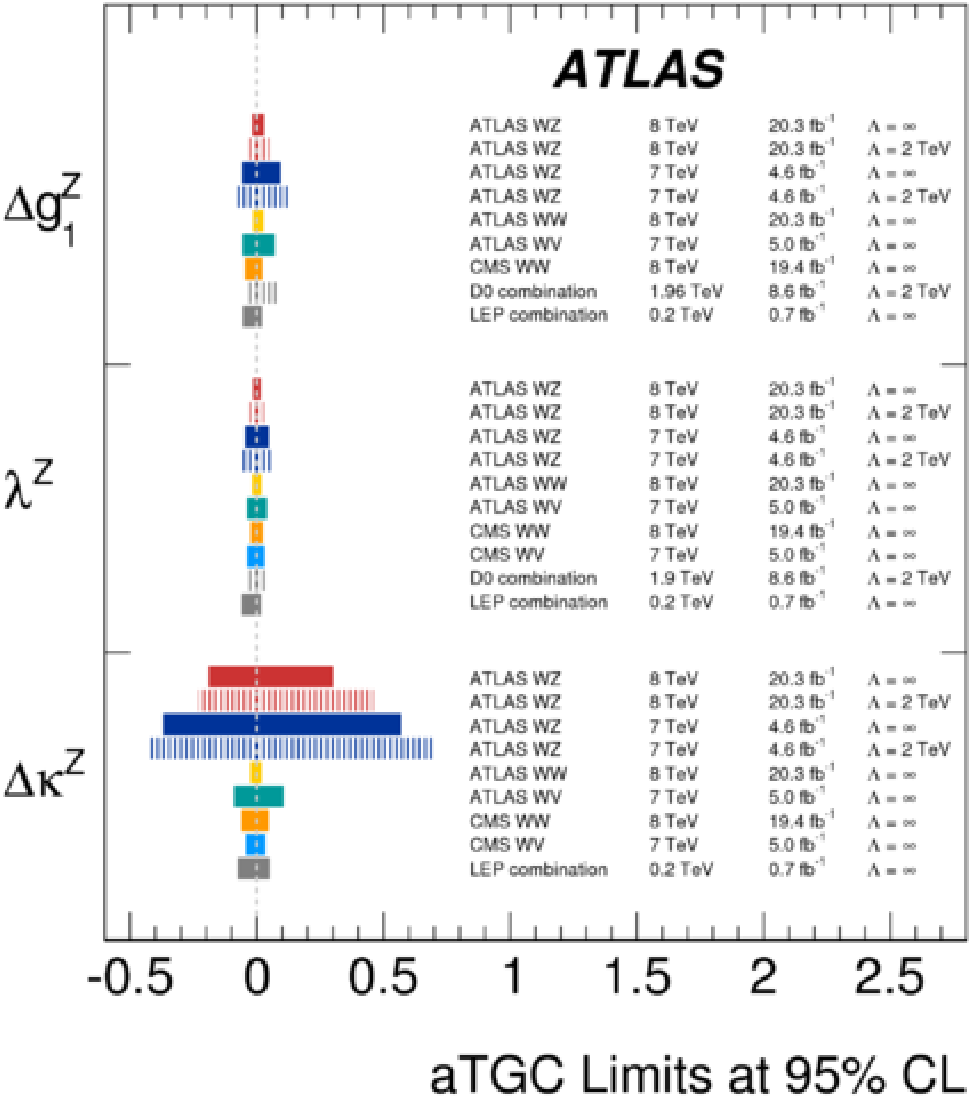
# aTGC status




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

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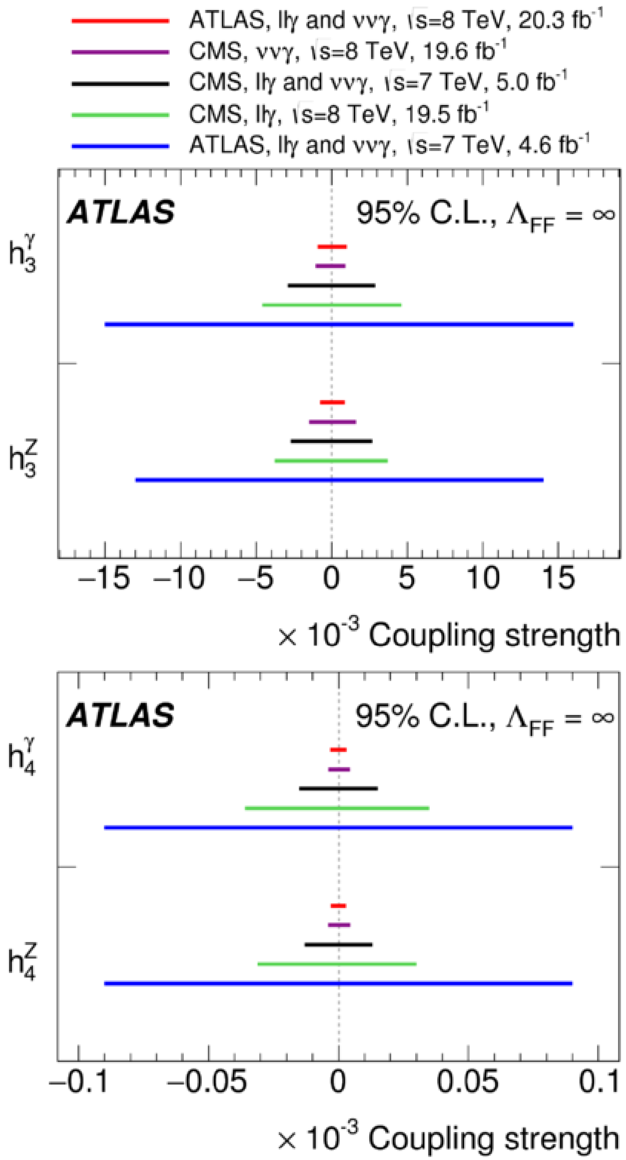


- Most stringent limits on WW$\gamma$, WWZ from WZ and WW
- Best constraints so far on $h_{3,4}^{\gamma,Z}$, driven by $\nu\nu\gamma$

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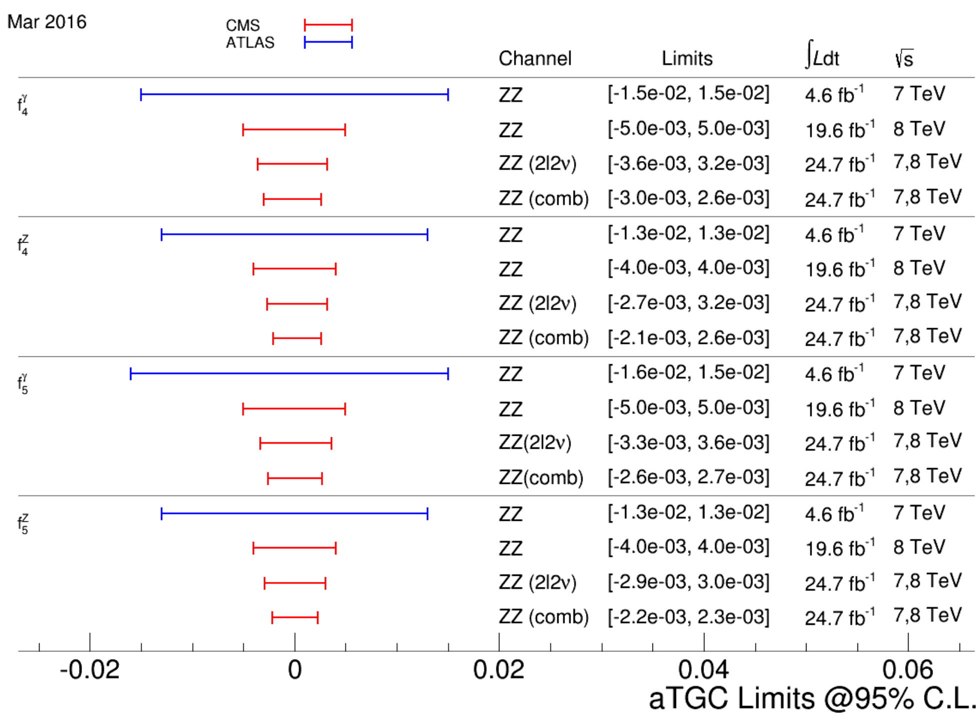



- Most stringent limits on WWγ, WWZ from WZ and WW
- Best constraints so far on $h_{3,4}^{\gamma,Z}$, driven by ννγ
- Constraints on $f_{3,4}^{\gamma,Z}$ driven by $\ell\ell\nu\nu$
- First ATLAS/CMS aTGC combination to be released soon!

# 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 $\alpha_4, \alpha_5$ exist, e.g. for WWWW:

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

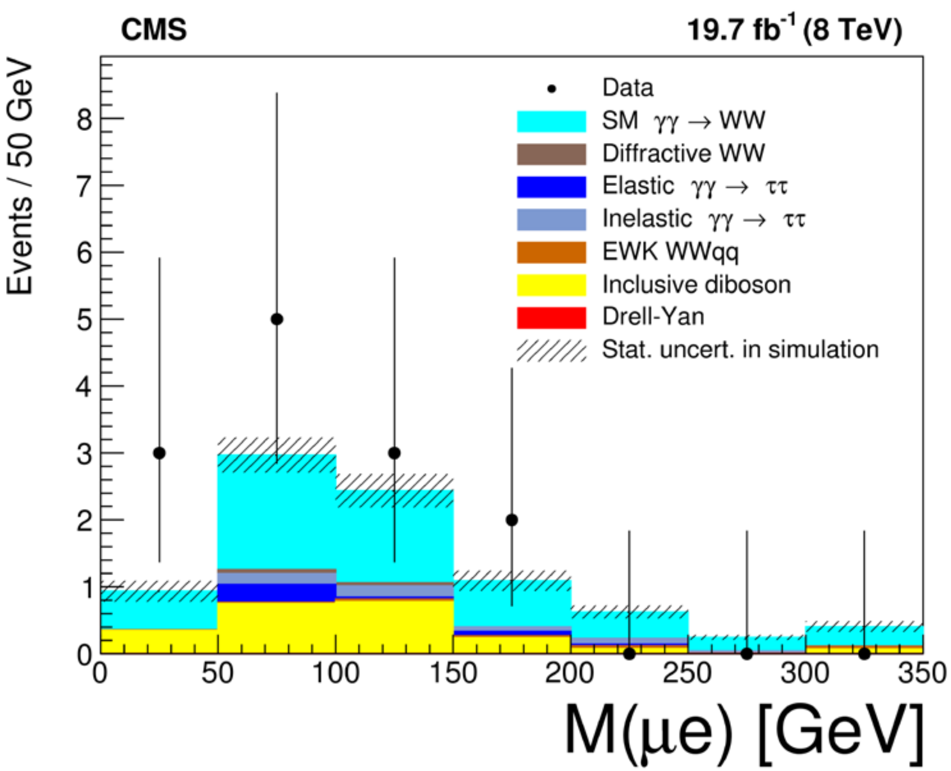
- Experimental access: aQGCs modify total production rate as well as event kinematics
  - Use cross-section measurement or kinematics to constrain aQGCs
- A suppression factor depending on a scale $\Lambda$ ensures conservation of unitarity (divergent xsecs at high $\sqrt{s}$ ):

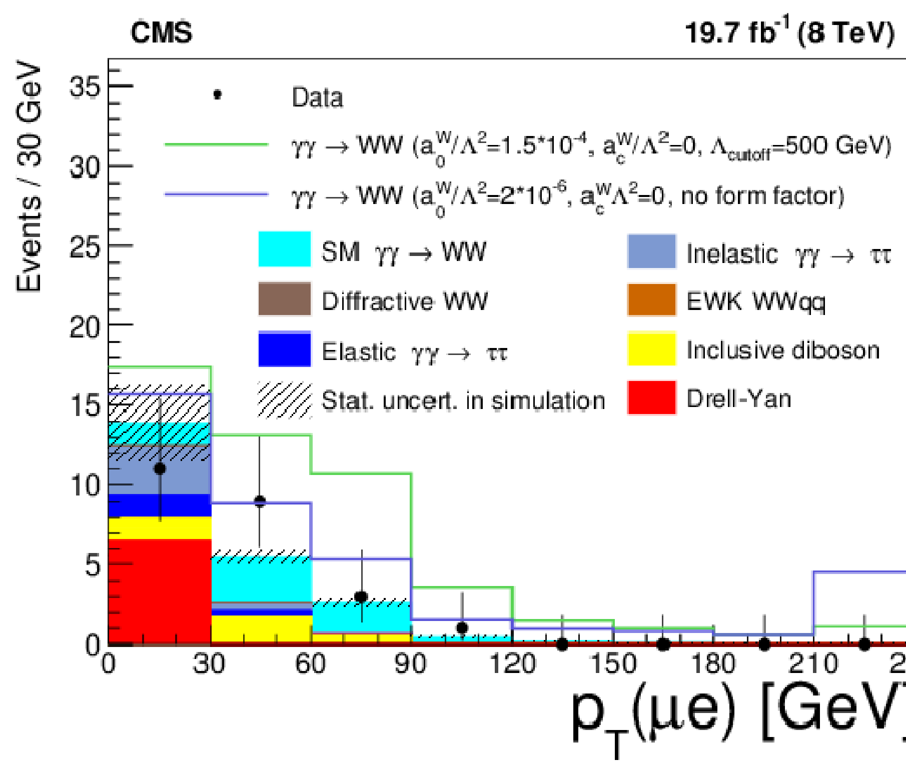
$$\lambda(\hat{s}) = \frac{\lambda_0}{(1+\hat{s}/\Lambda^2)^n}$$

# $\gamma\gamma \rightarrow$ WW

arxiv:1604.04464

- eμ pair with large pT, no other charged particles @ vertex
- First evidence for signal combining 7, 8 TeV data: 3.4σ



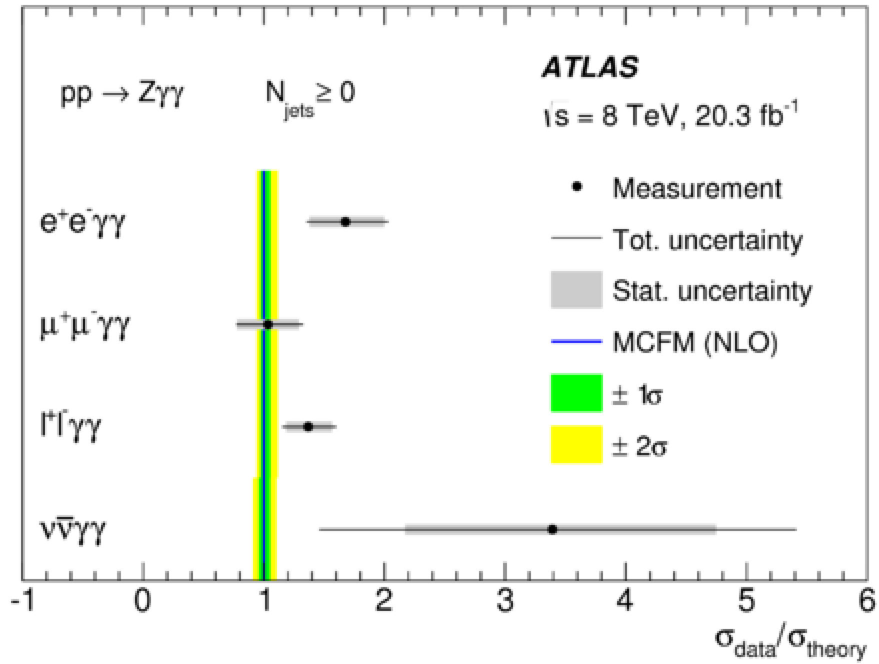




- aQGC limits placed using dilepton pT distribution
- No tag jets -> suppressed WWWW, WWZZ, WWZγ contribs

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

arXiv:1604.05232

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



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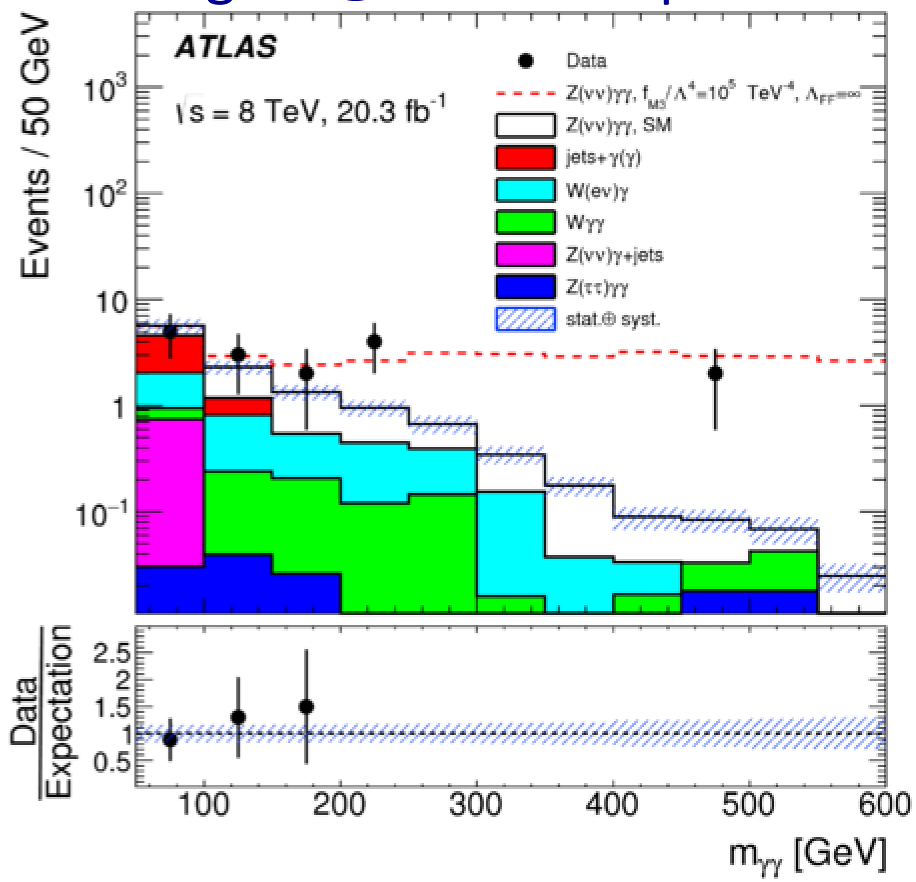
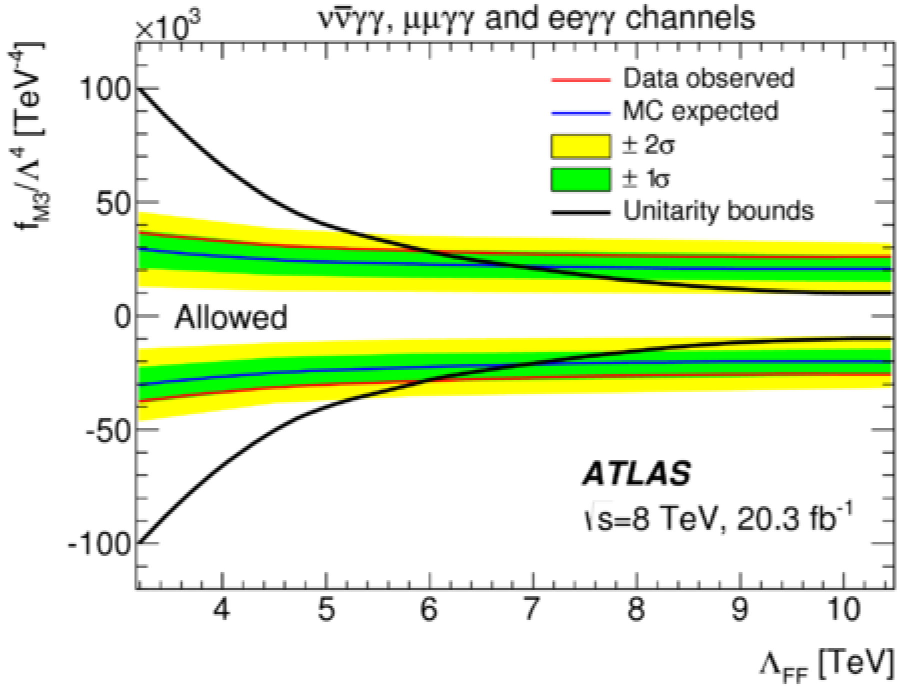


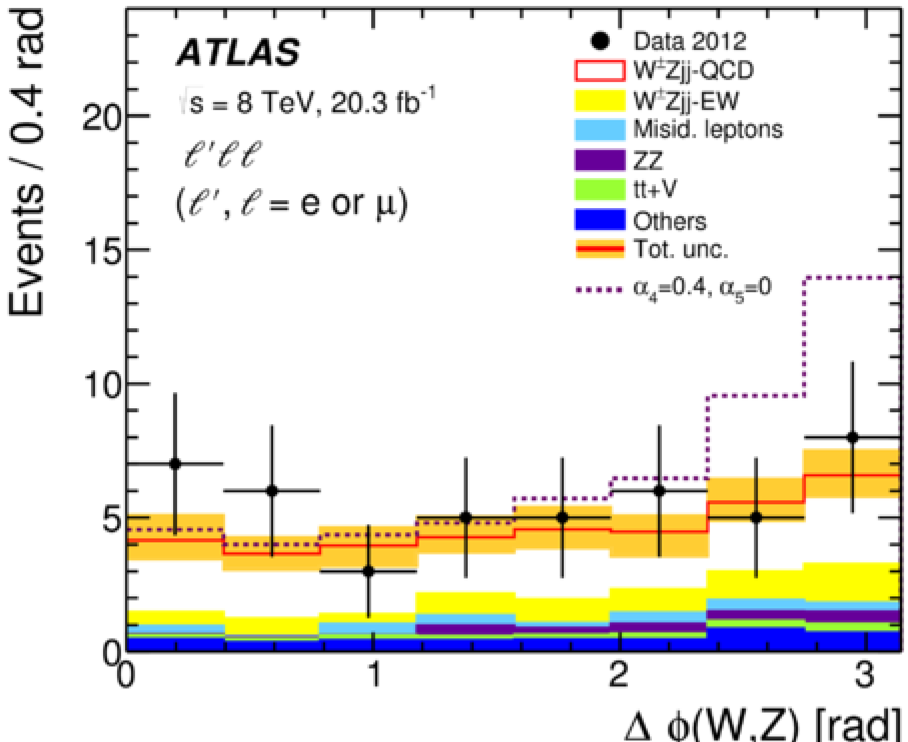



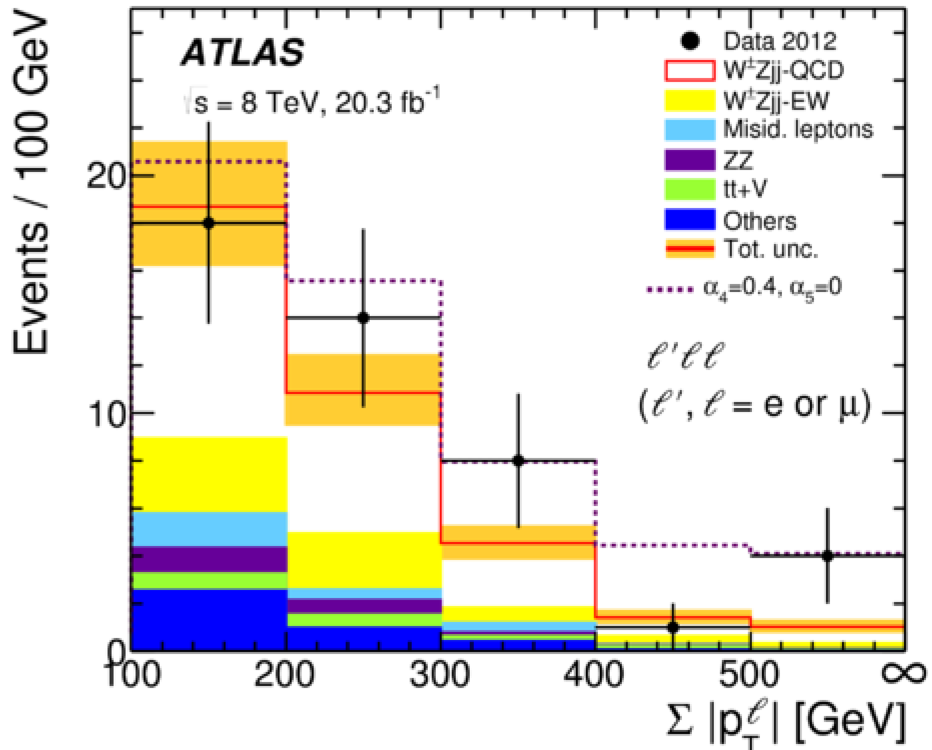

- Exclusive high-mγγ fiducial xsecs used for aQGC limits

# WZjj → ℓνℓℓjj @ 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 (*proof, anyone?*)

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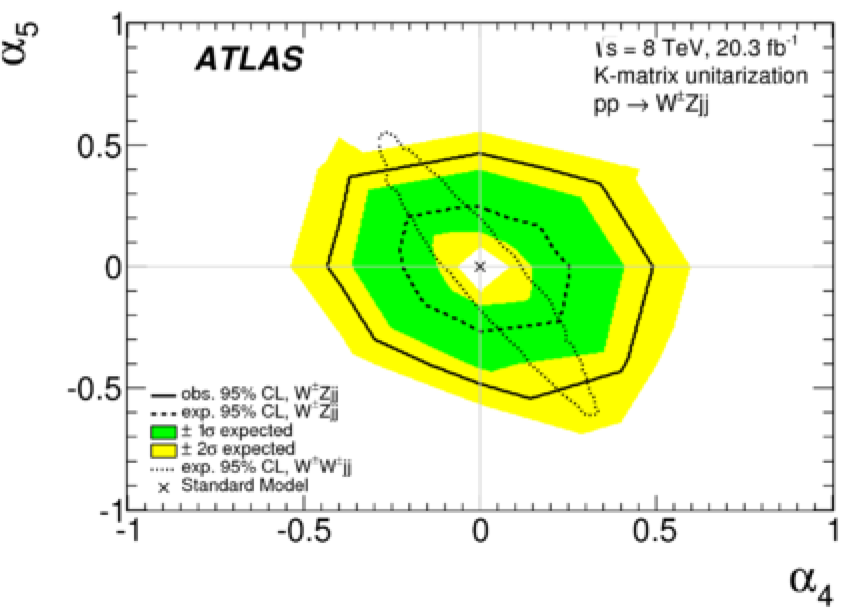
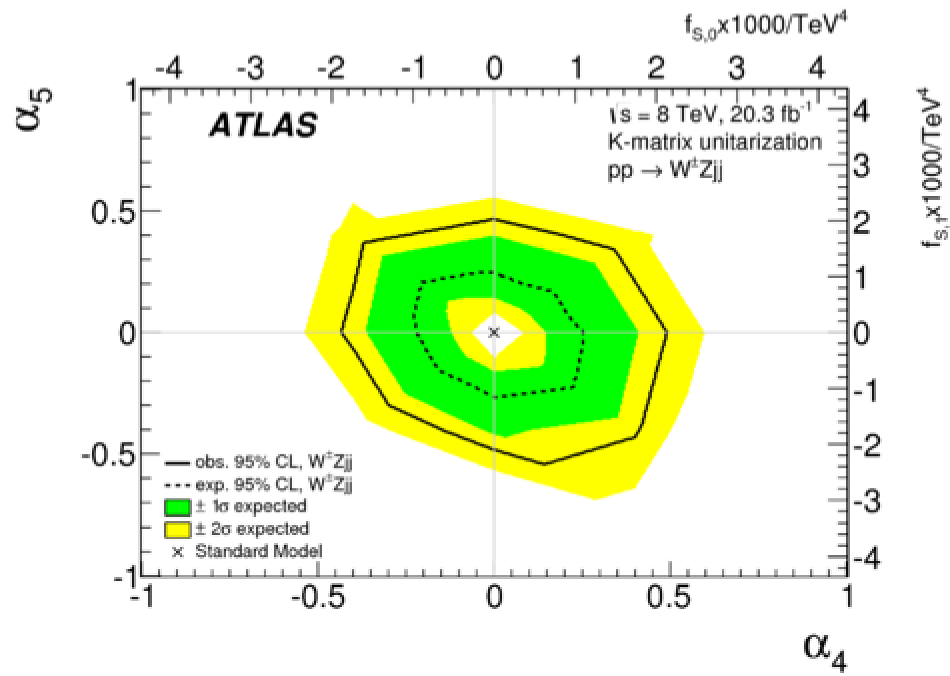


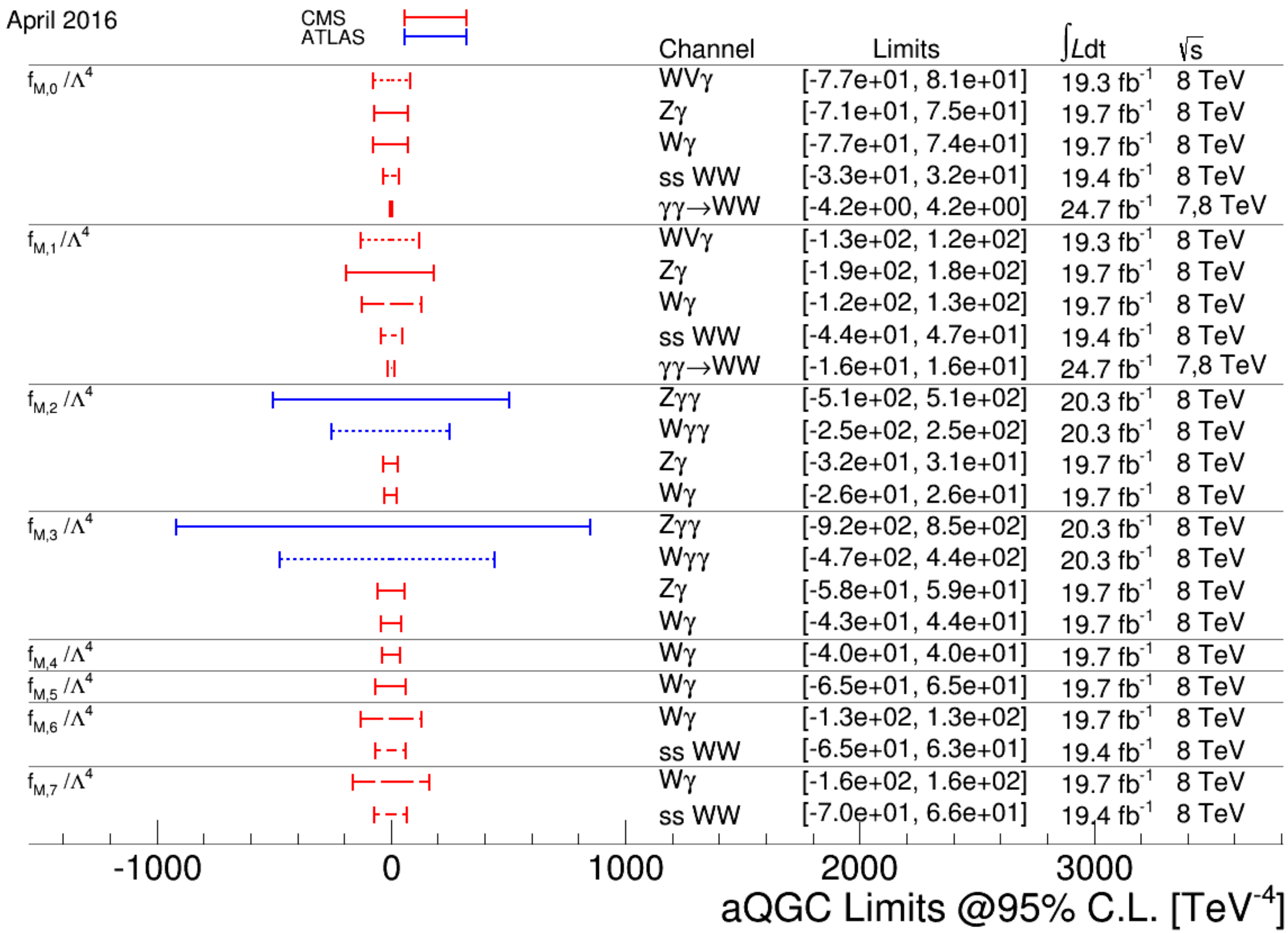




- measured fiducial xsec in aQGC phase space used for limits
- Conversion $\alpha_{4,5}$ to $f_{s0,1}$ *after* k-matrix unitarisation (*proof, anyone?*)

# aQGC limits

❖ Different processes give access to different aQGCs

- Trend that exclusive outperforms VBS, which is better than VVV
- Different parametrizations/unitarisation => no fair comparison



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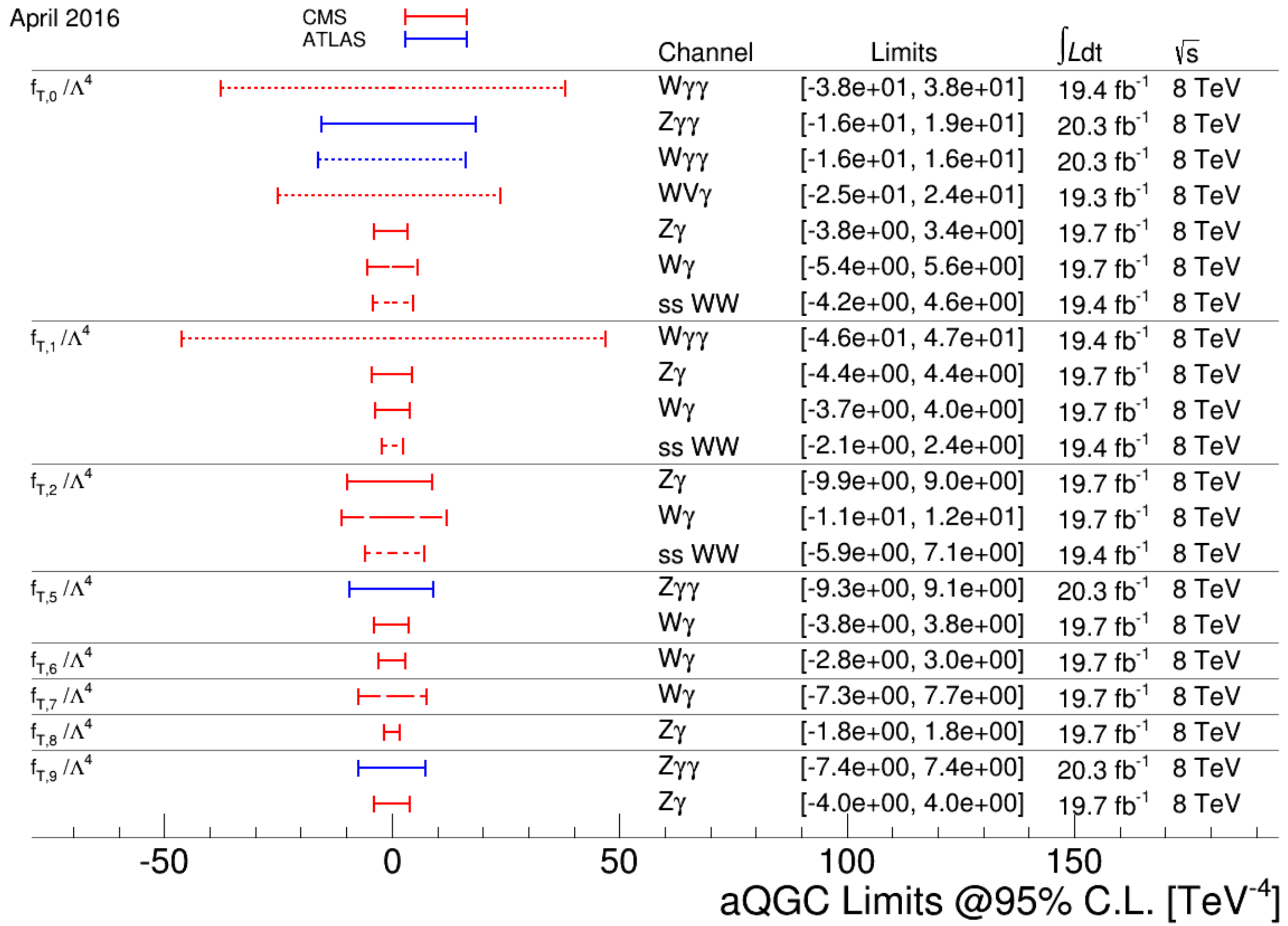

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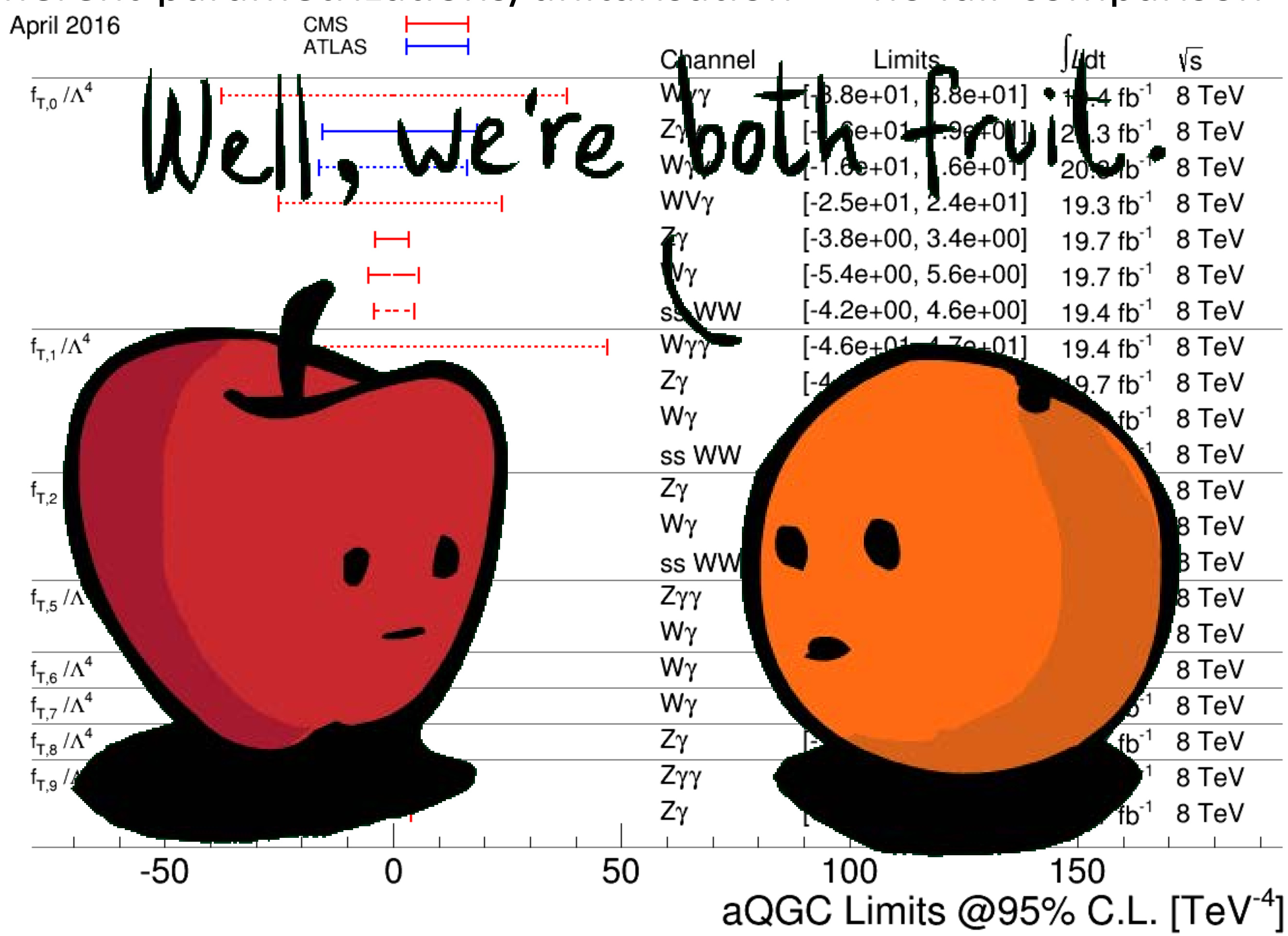
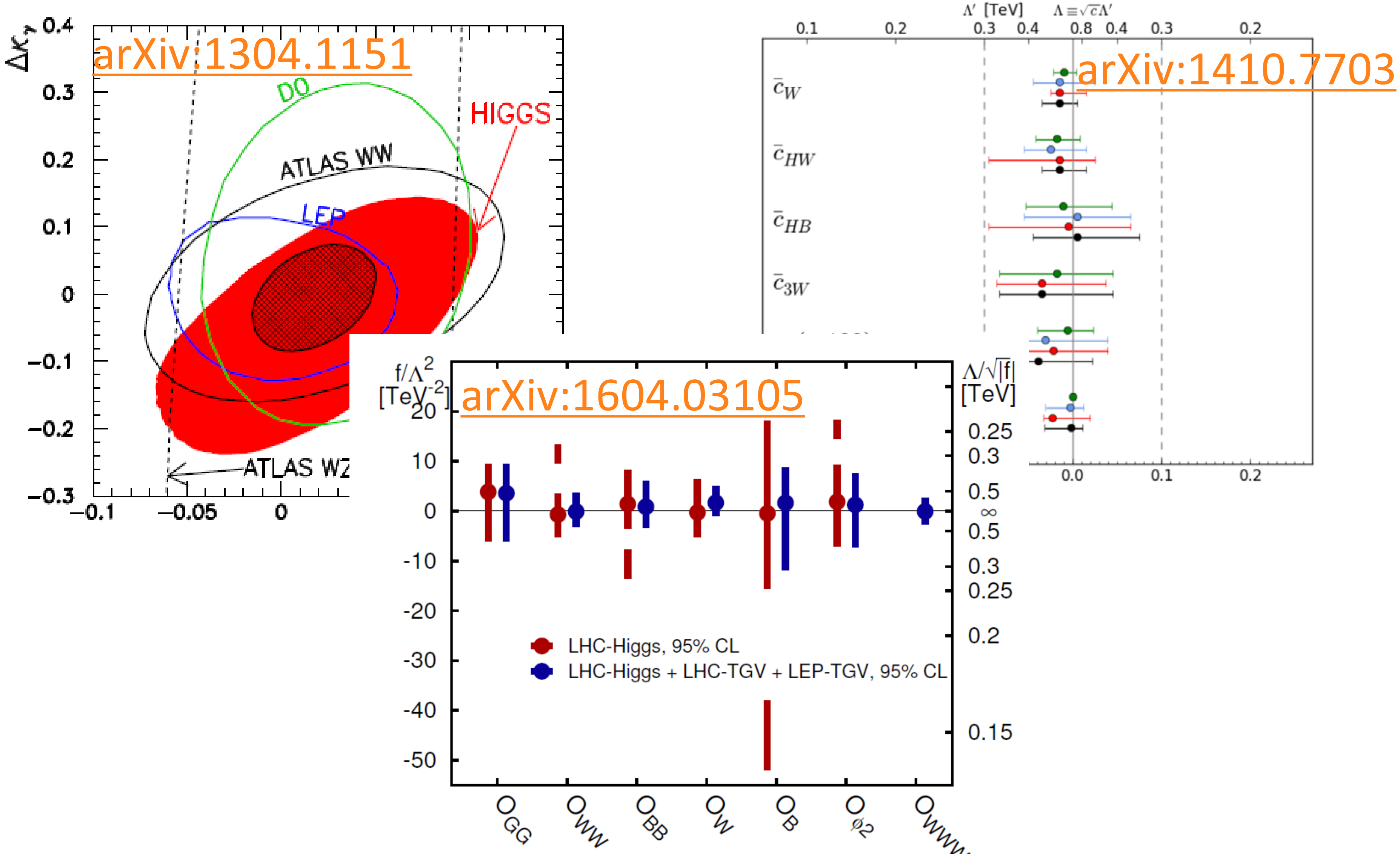


# Putting it all together…




❖ 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 H$\gamma\gamma$ 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 more stringent limits!
- 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 and match in modelling: PDF, ME, scales, PS, EW scheme, HO corrs – 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

# Outlook

August 24th to August 26th 2016:


https://agenda.hep.wisc.edu/event/965/