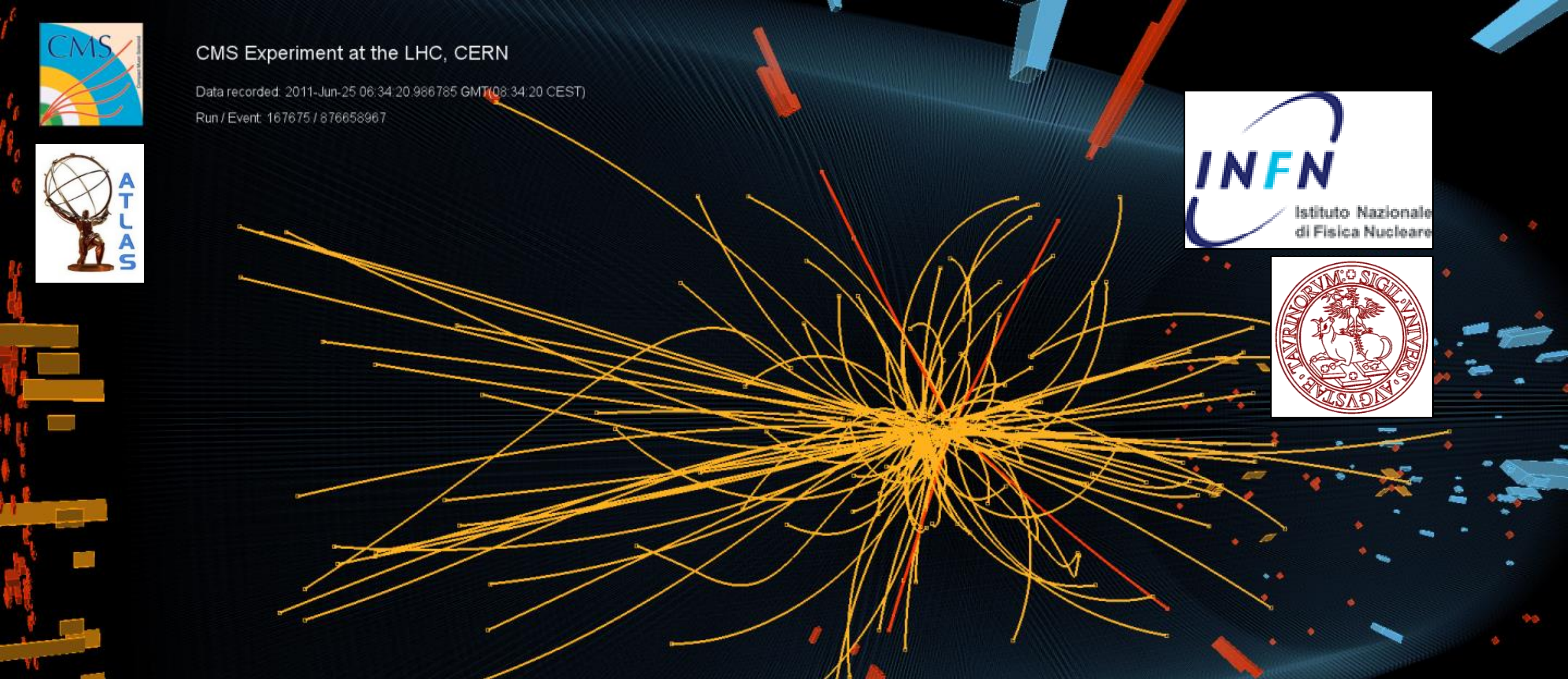


Multi-boson production at ATLAS and CMS

Roberto Covarelli (*University / INFN of Torino*)
on behalf of the CMS and ATLAS collaborations

52nd Rencontres de Moriond on QCD and High Energy Interactions
La Thuile, 25 Mar-1 Apr 2017

Multi-boson inclusive production

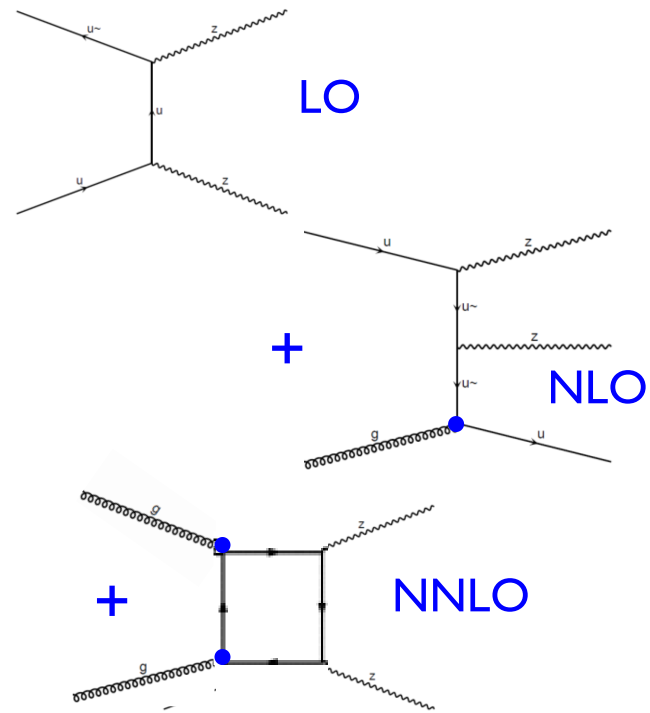
- Leading-order and with additional strong vertices
  - o(10 pb) @ LHC energies
  - High-order corrections are large because new initial states come into play
  - NLO known for years (e.g. POWHEG method)

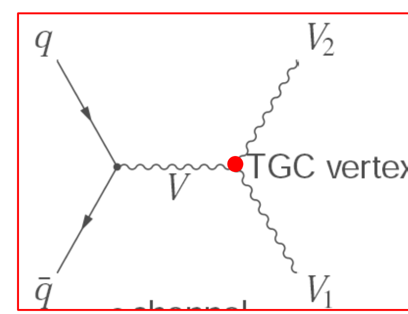
Nason and Zanderighi, *Eur.Phys.J.* **C74** (2014) 2702, etc.

  - NNLO became available very recently for basically all processes (2γNNLO, MATRIX)

Catani et al., *PRL* **108** (2012) 072001
Cascioli et al., *PLB* **735** (2015) 211, etc.

  - Consistency with SM can be translated in limits on anomalous triple gauge couplings (aTGC)





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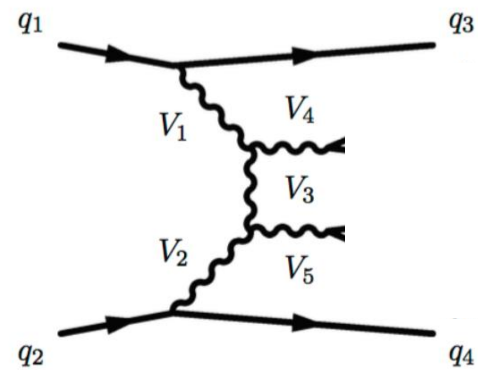
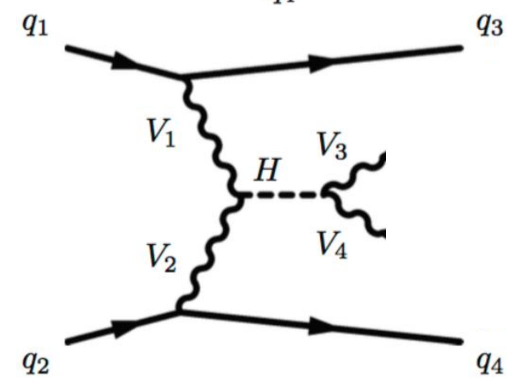
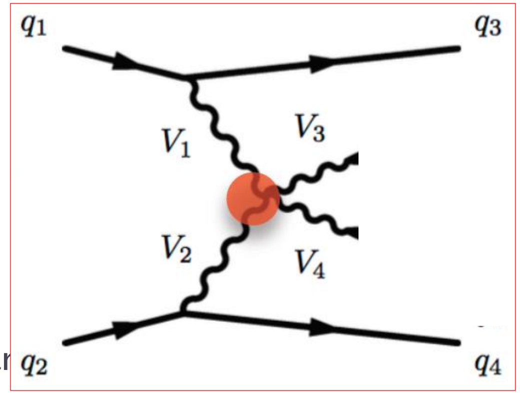
Multi-boson production with 2 jets

- Includes diagrams with gauge self-interactions («Vector-Boson Scattering», VBS)
  - o(10-100 fb) @ LHC energies, NLO QCD calculations available,

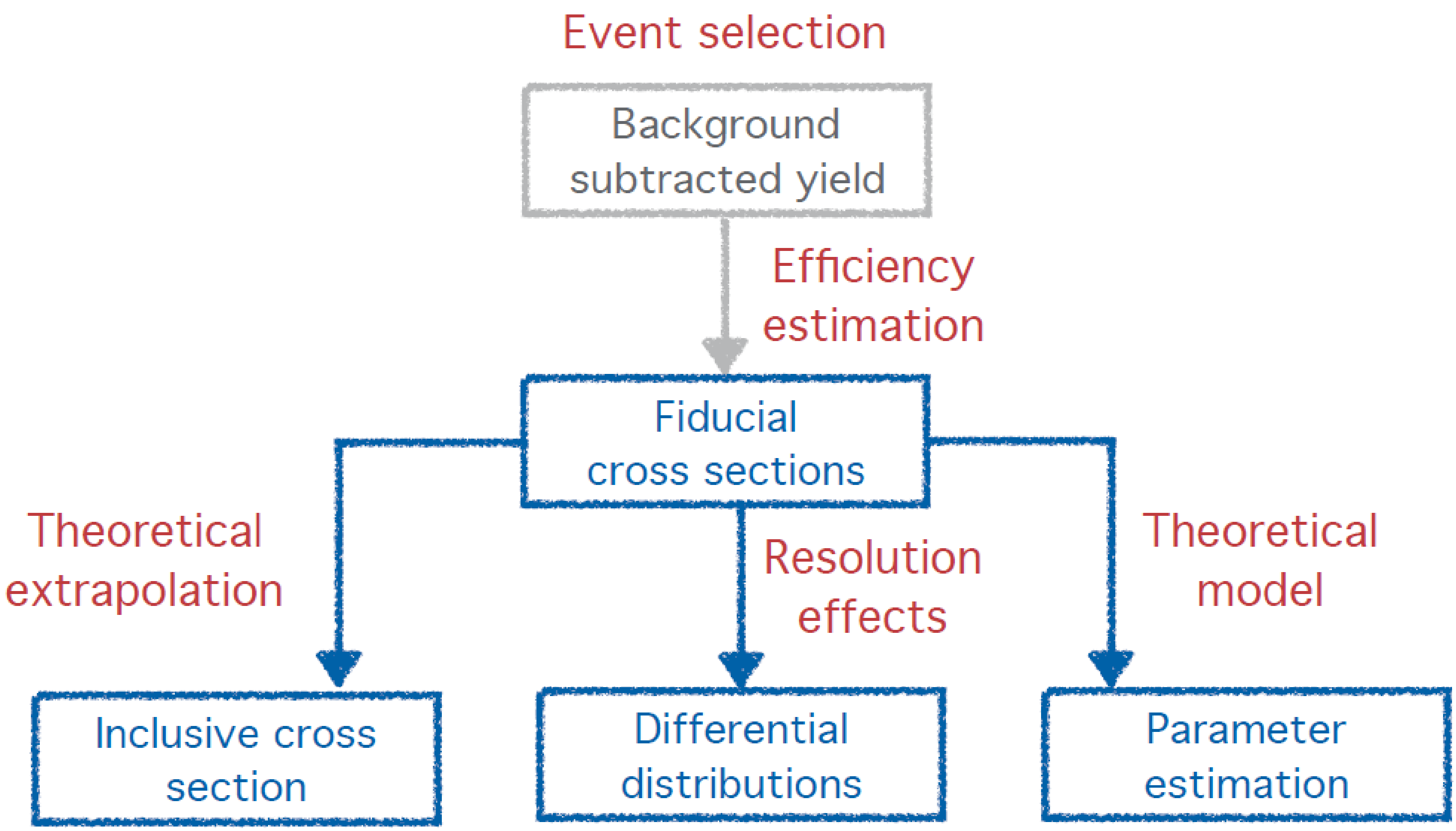
    e.g. Bozzi et al., *Phys.Rev.* **D75** (2007) 073004,
    Jaeger et al., *Phys.Rev.* **D80** (2009) 034022, etc.
  - Experimentally very challenging: large contamination from
    - QCD production + 2 jets
    - Other EWK processes (e.g. tribosons with a weak boson decaying to $q\bar{q}$)
  - Helps in understanding nature of electro-weak symmetry breaking
  - Main experimental probe of anomalous quartic gauge couplings (aQGC)





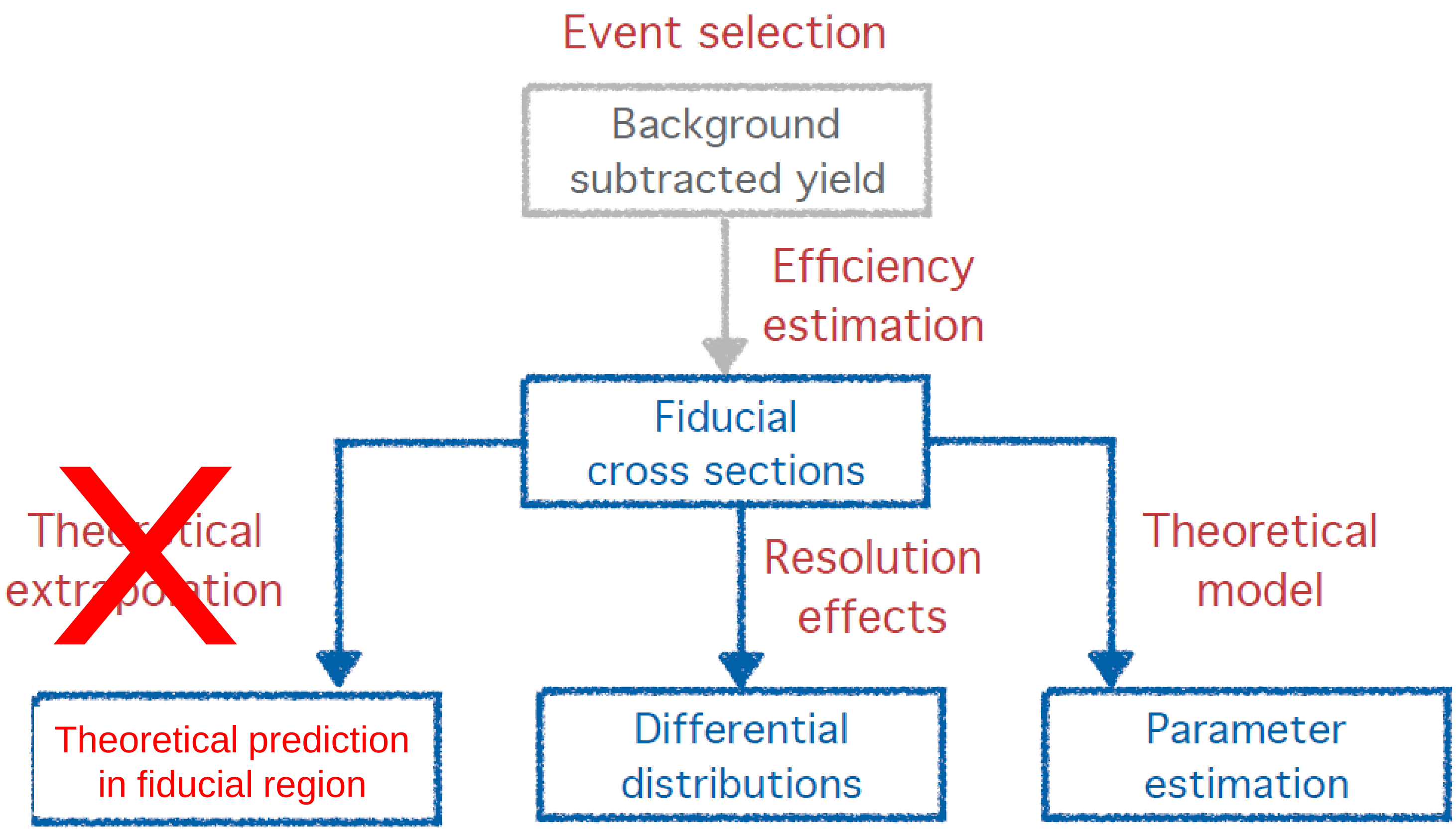


Experimental output



R. Lopes de Sà @ ICHEP2016

Experimental output



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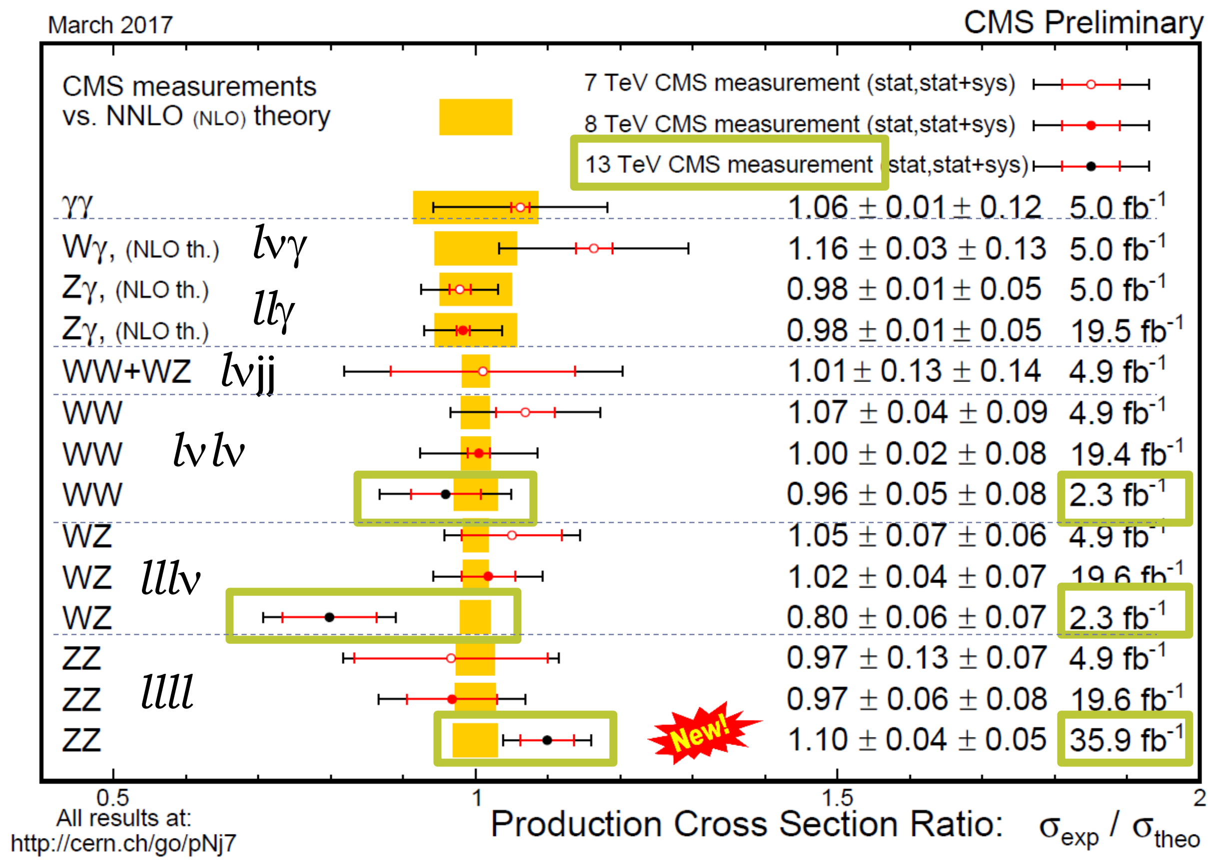
Inclusive and fiducial cross-section measurements

CMS summary

- Very good agreement with SM expectations
  - Theory uncertainties: NLO ~ 5-10%, NNLO << 5%
  - Experimental uncertainties: Systematic-to -statistical ratio depends mostly on the visible weak-boson decays (vast majority of analyses use leptonic final-states only, while semi-leptonic WW+WZ exists)



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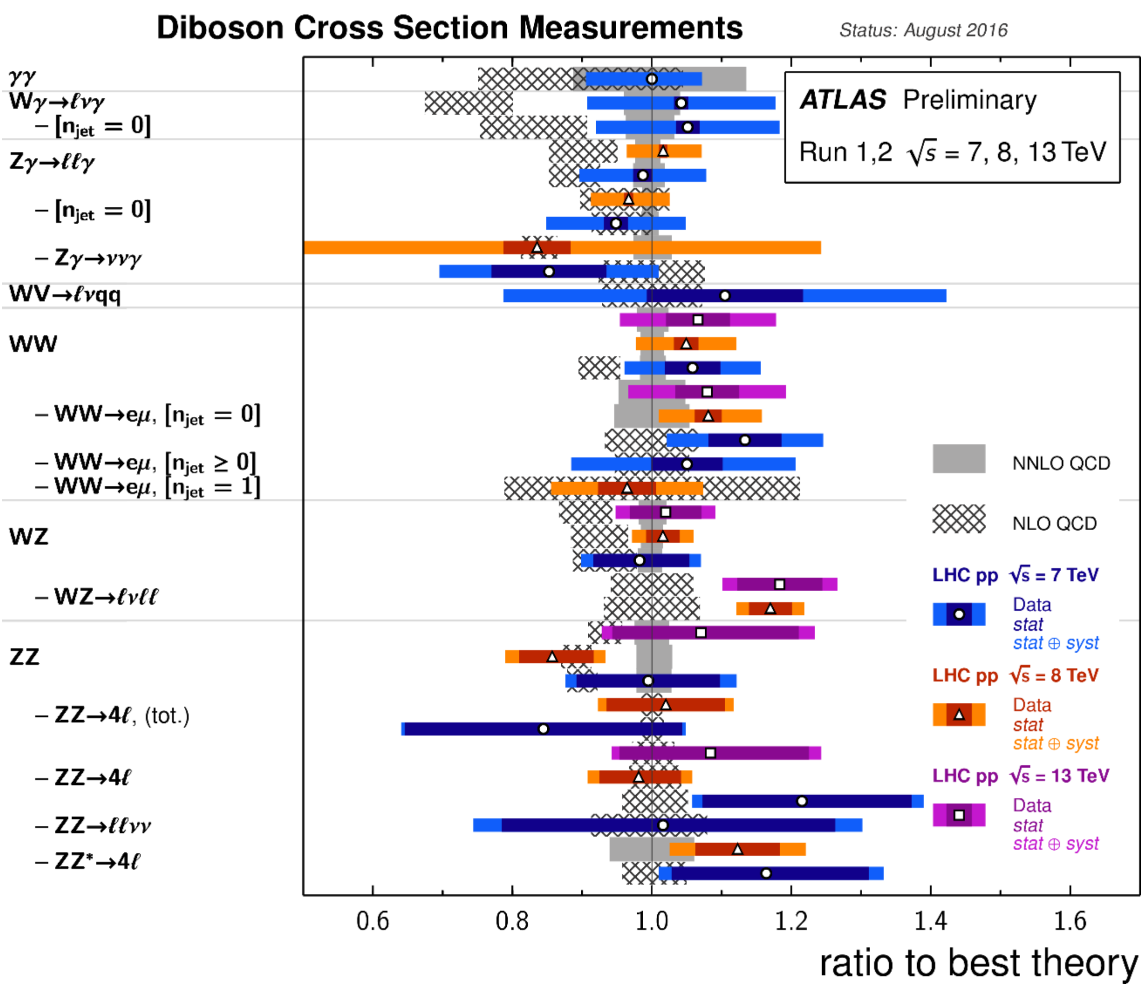
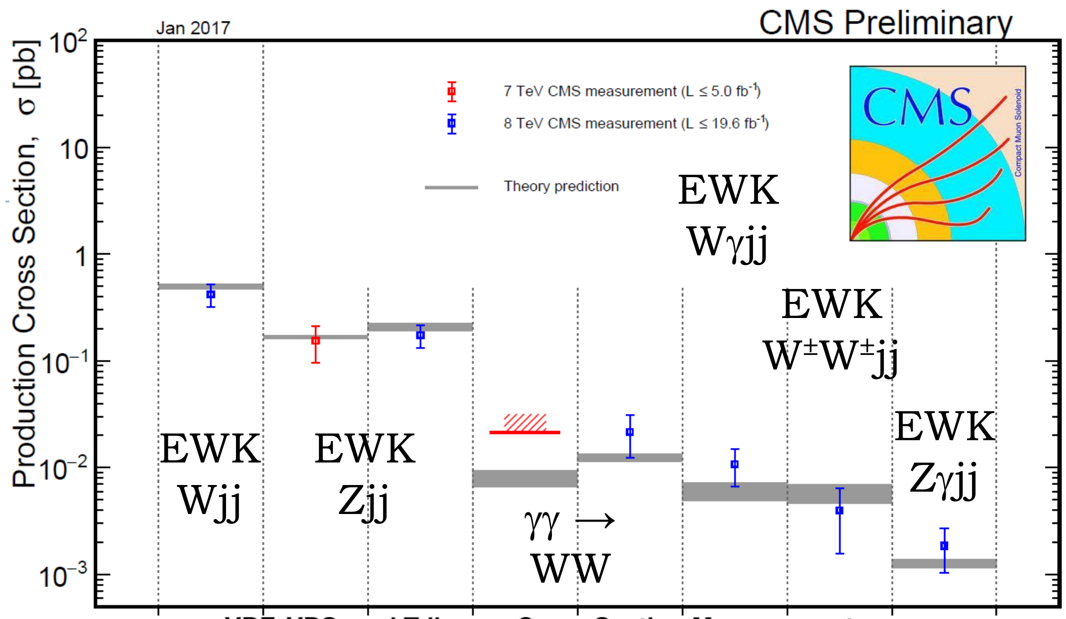
ATLAS summary



- Similar uncertainties
  - Wγ theory expectation at NNLO improves agreement with data (also true for CMS)
  - CMS WZ deficit at 13 TeV not confirmed
    - ZZ needs more data
  - $Z\to\nu\nu$ final states used: in some cases competitive with $Z\to ll$

EWK production and tri-bosons

- Several measurements without a significant observation yet
  - Mostly Run I
  - Some EWK final states missing (most notably ZZjj)



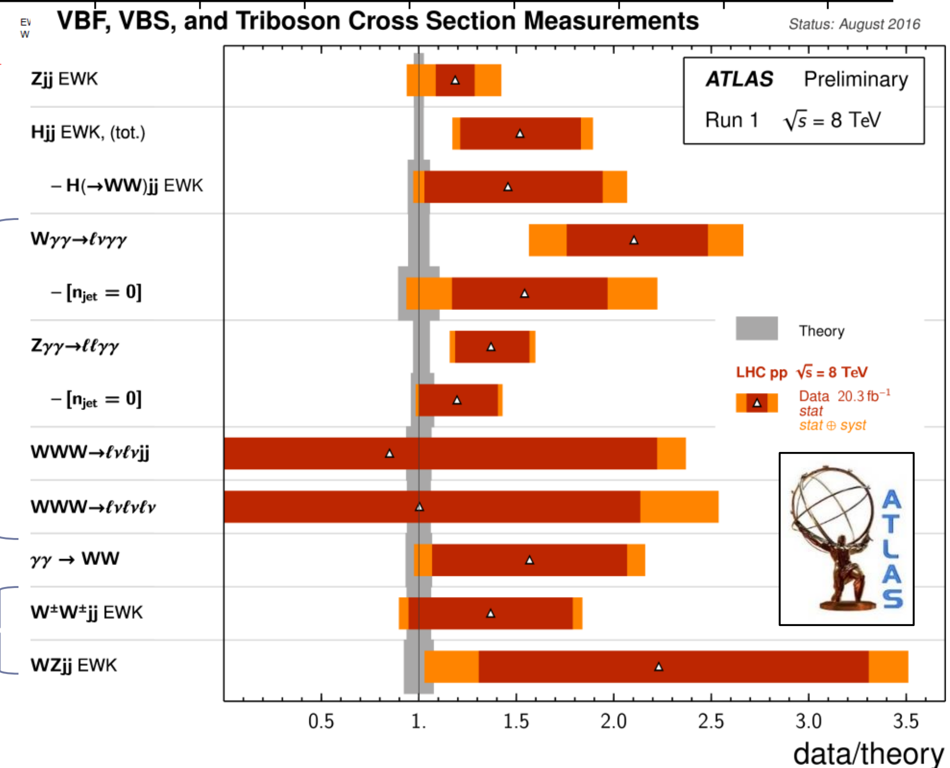
- ATLAS reports modest excesses in Vγγ (~2σ), smaller in jet-vetoed
  - CMS does not observe the same effect

New!

See M.Wolter's talk

Tri-bosons

VBS



$$\sigma^{\mathrm{fid}}_{W^\pm\gamma\gamma} \cdot \mathrm{BR}\,(W \to \ell\nu) = 6.0 \pm 1.8\,(\mathrm{stat}) \pm 2.3\,(\mathrm{syst}) \pm 0.2\,(\mathrm{lumi})\ \mathrm{fb}$$

$$\sigma^{\mathrm{NLO}}_{W^\pm\gamma\gamma} \cdot \mathrm{BR}\,(W \to \ell\nu) = 4.76 \pm 0.53\ \mathrm{fb}$$

$$\sigma^{\mathrm{fid}}_{Z\gamma\gamma} \cdot \mathrm{BR}\,(Z \to \ell\ell) = 12.7 \pm 1.4\,(\mathrm{stat}) \pm 1.8\,(\mathrm{syst}) \pm 0.3\,(\mathrm{lumi})\ \mathrm{fb}$$

$$\sigma^{\mathrm{NLO}}_{Z\gamma\gamma} \cdot \mathrm{BR}\,(Z \to \ell\ell) = 12.95 \pm 1.47\ \mathrm{fb}$$

CMS-PAS-SMP-15-008

Results on anomalous gauge couplings

Anomalous gauge couplings

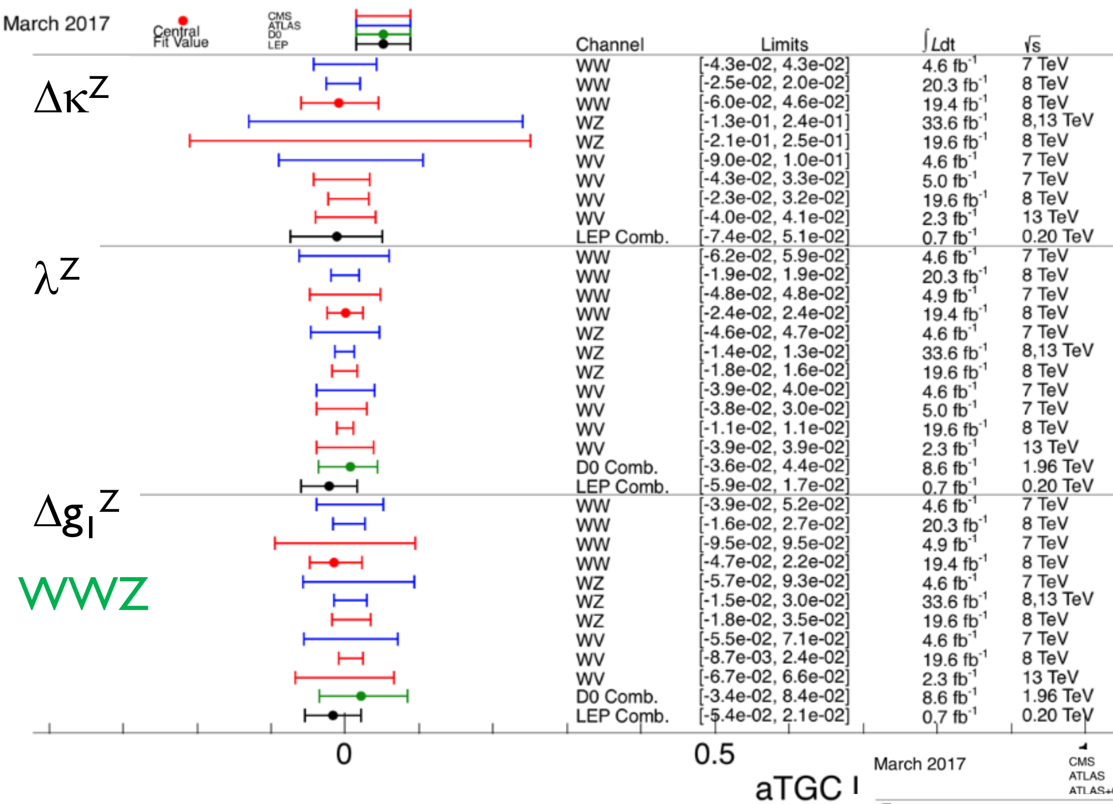
- Triple and quartic gauge couplings
  - Non-zero in SM: WWγ / WWZ / WW$\gamma\gamma$ … etc.
  - Zero in SM: Z$\gamma\gamma$ / ZZγ / ZZZ / ZZ$\gamma\gamma$ … etc.

- Anomalous couplings defined in different approaches:
  - Modifying couplings in SM Lagrangian (Δg_1^V, $\Delta\kappa^V$, λ^V) or, equivalently, introducing effective extra vertices (h_3^V, h_4^V / f_4^V, f_5^V)
  - In effective field theory, in terms of Wilson coefficients c_i and New Physics scales

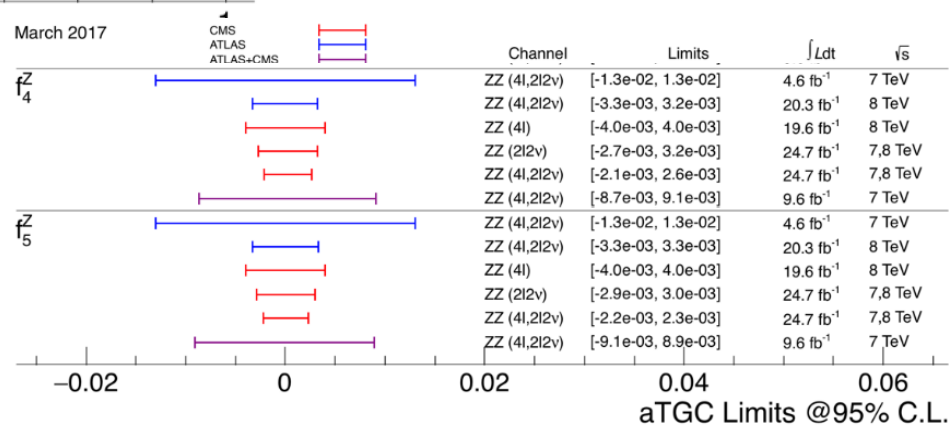
See e.g.: Degrande et al., *Ann. Phys.* **335** (2013) 21

  - Caveat: need for a form factor $\alpha_s(\hat{s}) = \frac{\alpha_s(0)}{(1+\hat{s}/\Lambda_{FF})^n}$ to preserve tree-level unitarity. Often set $\Lambda_{FF} \to \infty$ in comparing experimental results for consistency → can have a substantial weakening effect on aGC limits if Λ_{FF} = o(TeV)

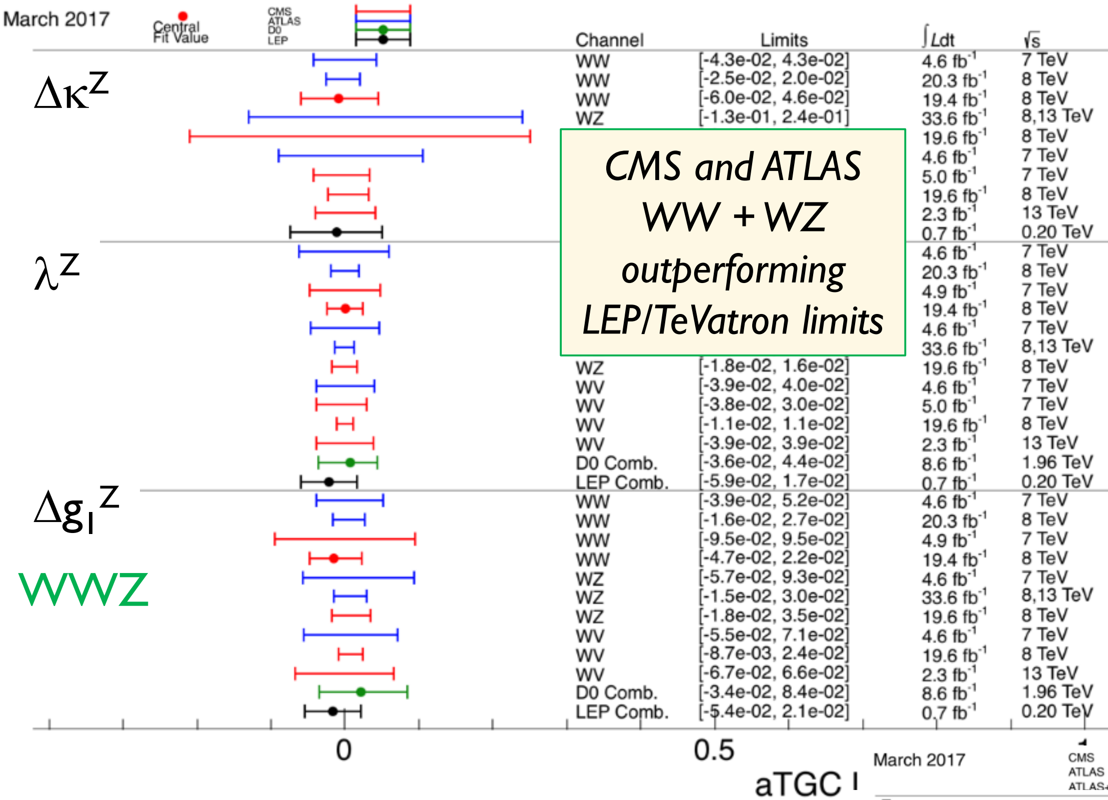
Example of results (aTGC)



ZZZ



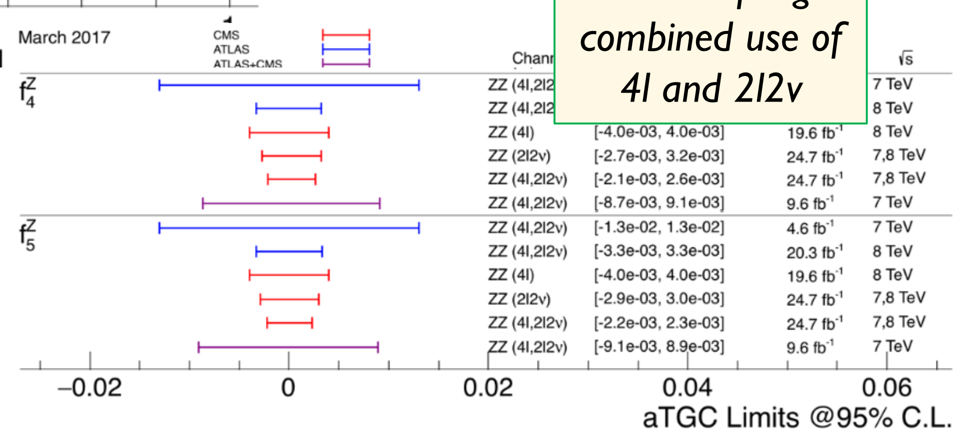
Example of results (aTGC)



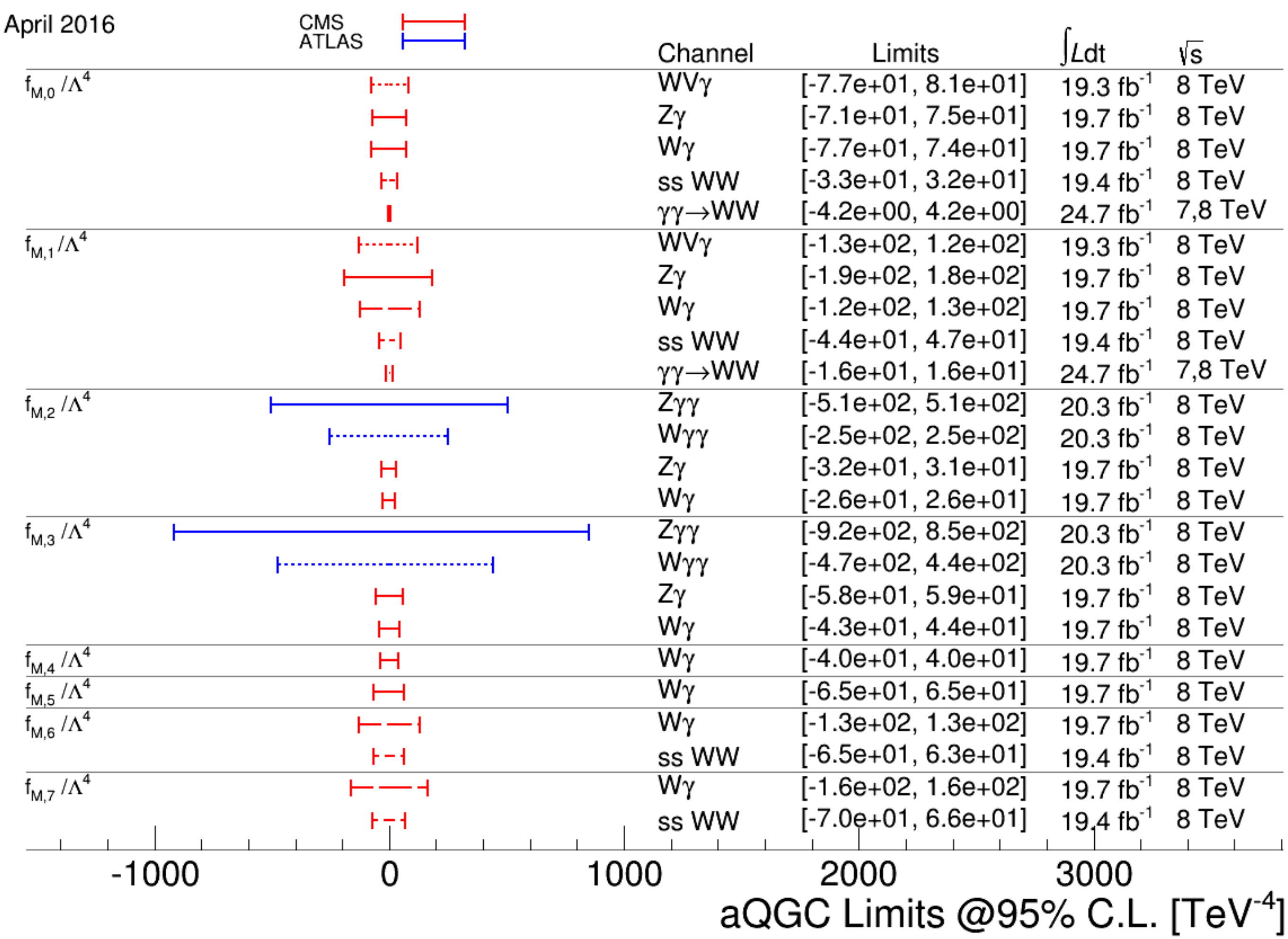
CMS and ATLAS WW + WZ outperforming LEP/TeVatron limits

ZZZ

ZZ only probe of ZZZ coupling: combined use of 4l and 2l2ν



Example of results (aQGC)



Dimension-8 mixed longitudinal and transverse coefficients ($f_{M,i}$)

Largest sensitivity from WW exclusive production, EWK $W^{\pm}W^{\pm}$ and $V\gamma$

Little or no sensitivity to sign

Selected recent results

EWK-produced Wγ and Zγ

- CMS: 8 TeV

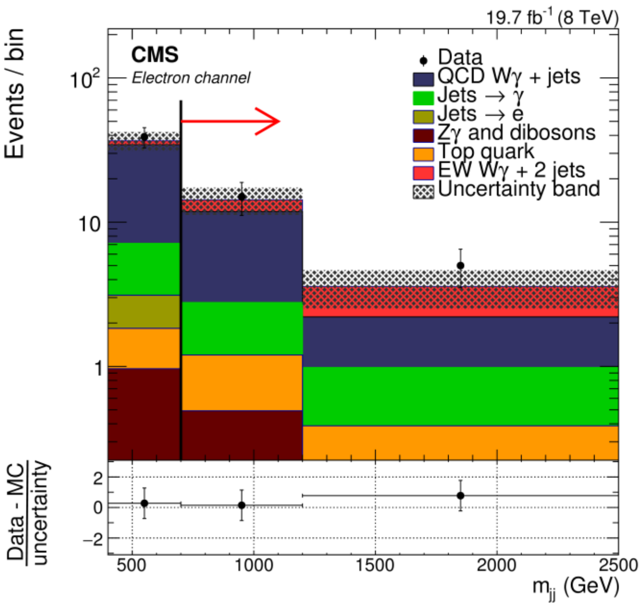
arXiv:1612.09256 (submitted to *JHEP*)
arXiv:1702.03025 (submitted to *PLB*)

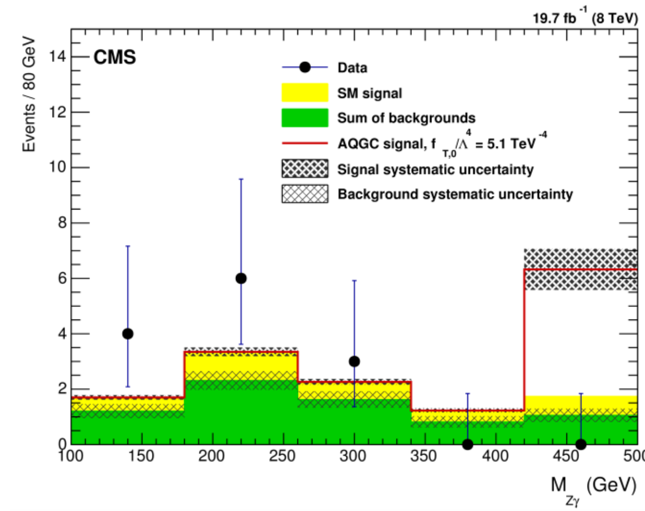
  - Select events with two jets at high invariant mass (m_{jj})
  - Backgrounds other than QCD Vγ production → data-driven methods
  - Extract aQGC limits from $p_T(W)$ (Wγ) or $m_{Z\gamma}$ (Zγ) distributions

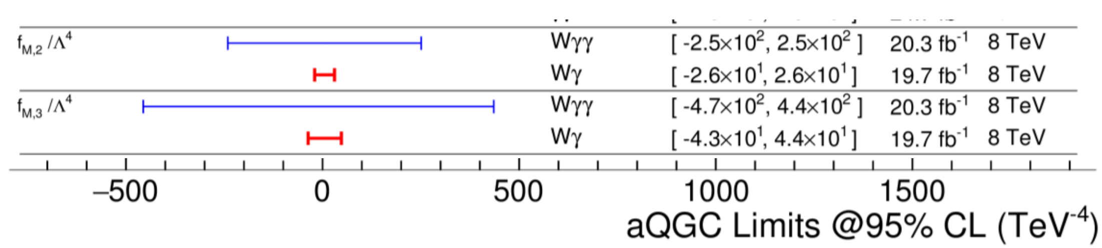
Fiducial cross sections (EWK production)

Wγ: $10.8 \pm 4.1\,(\mathrm{stat}) \pm 3.4\,(\mathrm{syst}) \pm 0.3\,(\mathrm{lumi})$ fb VBFNLO: 6.1±1.2 fb

Zγ: $1.86^{+0.90}_{-0.75}\,(\mathrm{stat})^{+0.34}_{-0.26}\,(\mathrm{syst}) \pm 0.05\,(\mathrm{lumi})$ fb MadGraph LO: 1.27±0.13 fb





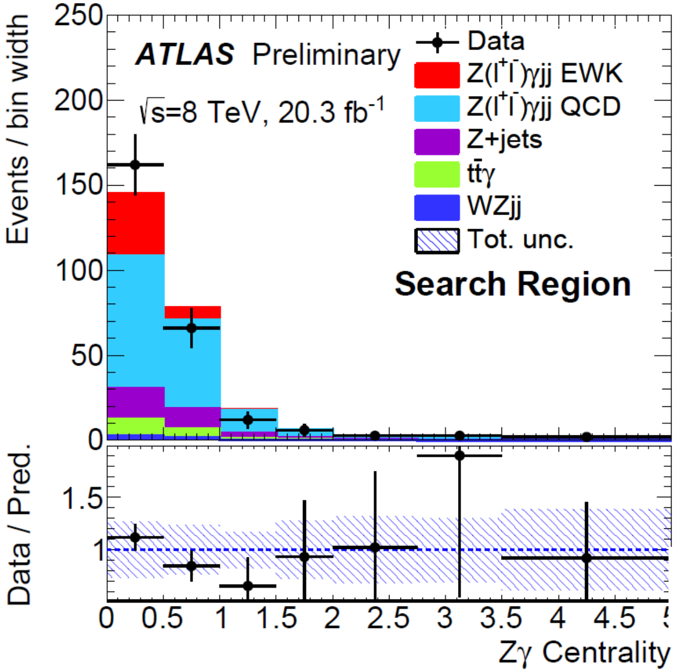


EWK-produced Zγ

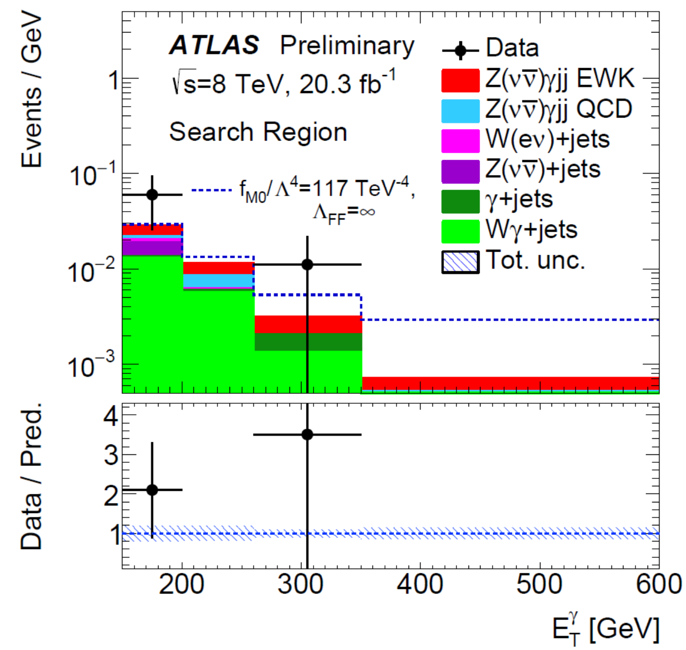
New!

- ATLAS 8 TeV: combination of llγjj and ννγjj channels
  - Fiducial cross-section extracted from Zγ centrality distributions: $\zeta = \left|\frac{\eta_{Z\gamma} - \bar{\eta}_{jj}}{\Delta\eta_{jj}}\right|$
  - aQGCs: look for excesses in E_T^{γ}

ATLAS-STDM-2015-21
(paper in preparation)



Most stringent limits on f_{2M} and f_{3M} (not accessible by EWK $W^{\pm}W^{\pm}$)



$$\sigma^{EWK}_{Z\gamma jj} = 1.1 \pm 0.5\ (\mathrm{stat}) \pm 0.4\ (\mathrm{syst})\ \mathrm{fb}$$

2σ significance

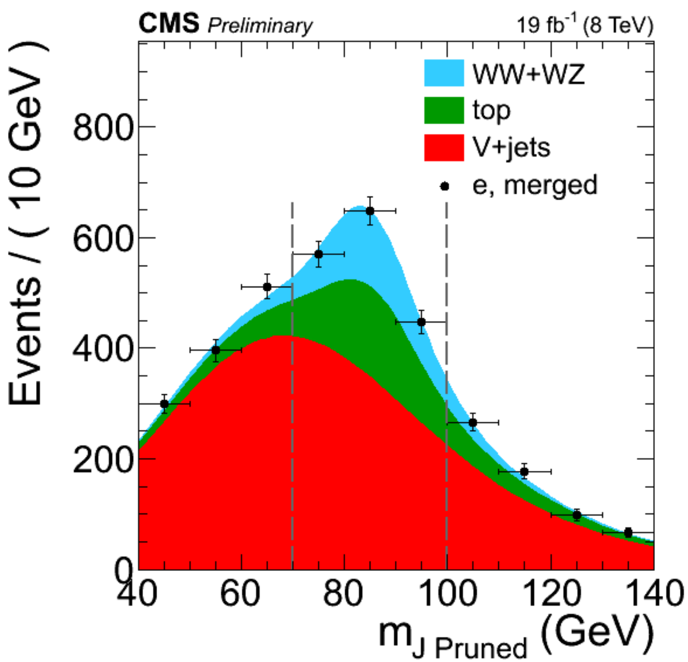
$$\sigma^{\mathrm{VBFNLO},EWK}_{Z\gamma jj} = 0.94 \pm 0.09\ (\mathrm{theo})\ \mathrm{fb}.$$

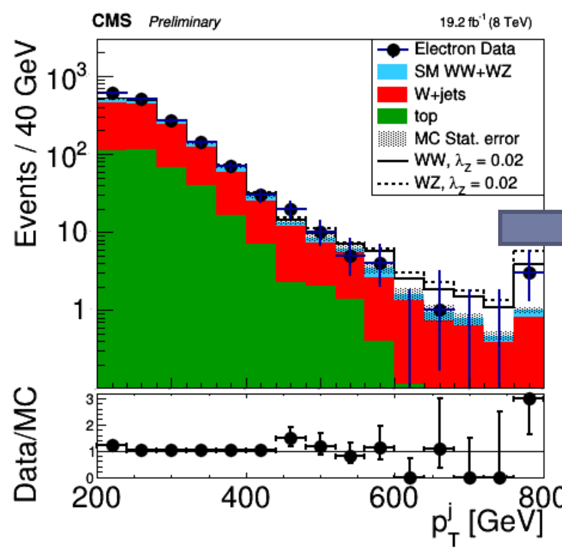
WW and WZ with a merged jet

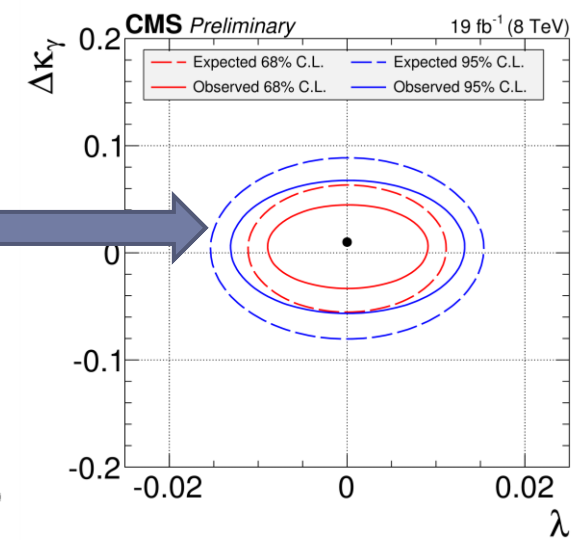
- CMS: semi-leptonic $l\nu q\bar{q}$ channel at 8 TeV

arXiv:1702.06095 (submitted to *PLB*)

  - At high W/Z p_T, quarks from boson decays merge into a single, large-radius jet J
    - «Pruned» invariant mass of jet constituents and jet substructure reducing huge W+jets and $t\bar{t}$ backgrounds
    - aTGC limits extracted from p_T(J) distributions





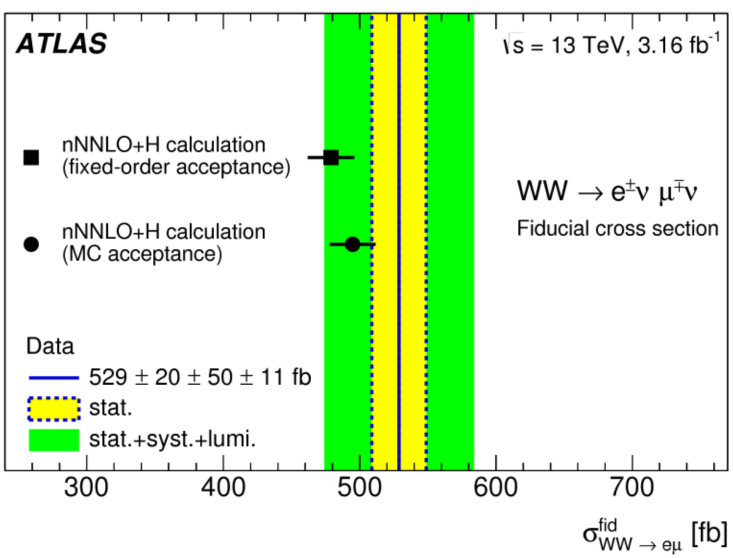


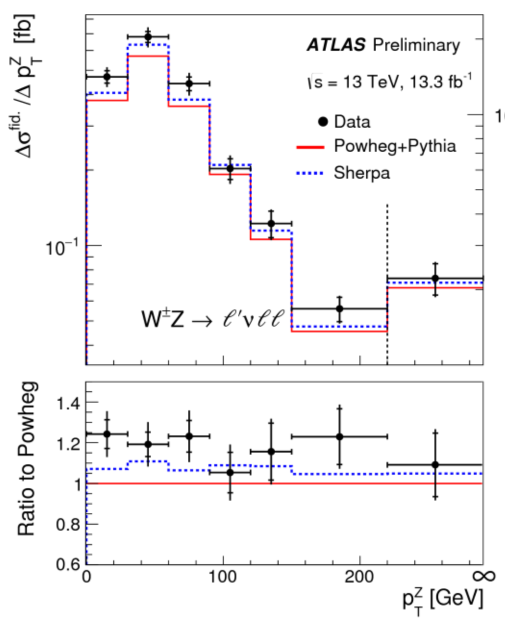
WW and WZ at 13 TeV

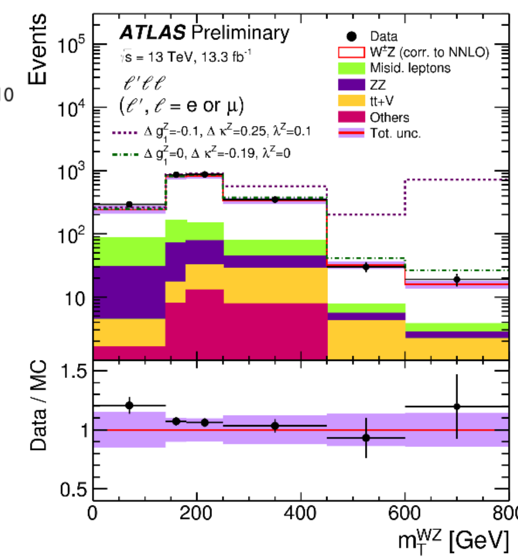
- ATLAS: fully leptonic $e\nu\mu\nu$ and $lll\nu$ at 13 TeV
- Both very pure signals (S/B ~ 4)
  - WW: compute inclusive fiducial cross-section, compare to NNLO calculations
  - WZ: fiducial cross-section, differential in $p_T(W)$ and $m_T(WZ)$, updated aTGC limits

ATLAS-CONF-2016-043
arXiv:1702.04519 (submitted to *PLB*)

$$\sigma^{\mathrm{fid}}_{WW\to e\mu} = 529 \pm 20\ (\mathrm{stat.}) \pm 50\ (\mathrm{syst.}) \pm 11\ (\mathrm{lumi.})\ \mathrm{fb}.$$

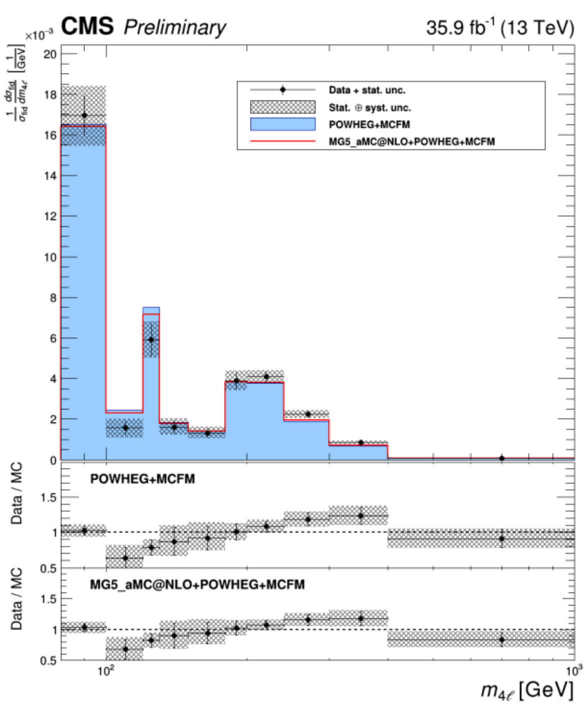


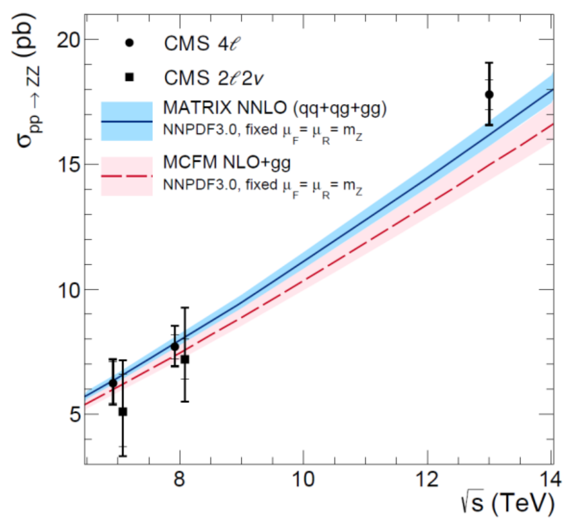


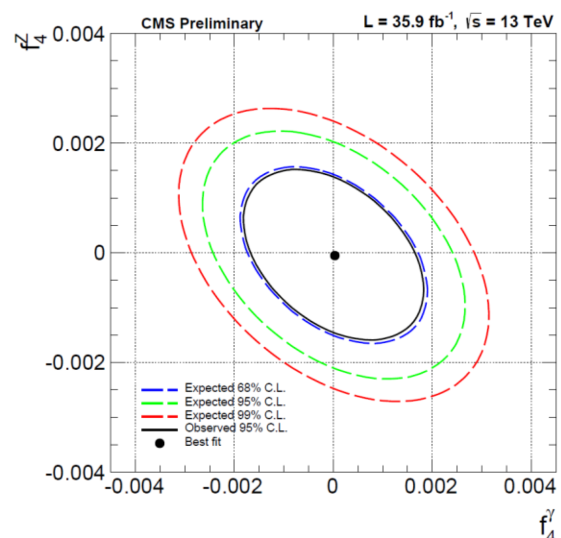


ZZ at 13 TeV

- First diboson result with full 2016 dataset (35.9 fb^{-1}) at 13 TeV, using 4l final state
  - Very pure final state, larger background from Z+jets with fake leptons → estimated in control regions
  - Z resonant region → extract BR($Z \to 4l$)
  - ZZ region (including Higgs) → fiducial cross-section and aTGC limits from m_{ZZ} distribution







$$\mathcal{B}(Z \to 4\ell) = 4.74^{+0.16}_{-0.16}\,(\text{stat})^{+0.18}_{-0.17}\,(\text{syst}) \pm 0.08\,(\text{theo}) \pm 0.12\,(\text{lumi}) \times 10^{-6},$$

5% uncertainty

Conclusions

- The numerous multi-boson production measurements in ATLAS and CMS performed so far show good agreement with the SM
  - Total experimental uncertainties and statistical / systematic balance vary a lot depending on the final states
- On the way to precision measurements
  - Search for fully electro-weak diboson production in all channels
  - Search for triple weak-boson production
  - Precise differential measurements (at high invariant mass, large jet multiplicities…)
- Impressive improvements in theory tools
  - NNLO QCD calculations available for almost all processes with possibility to compare to «fiducial» experimental results
  - What else is needed from the experiments' side?
    - At which point will NLO EWK corrections start to be important?
    - VV + n jets ($n \geq 2$) in QCD: impact of parton shower choices?

Back up

Definition of aTGC/aQGC parameters

$$\mathcal{L} = ig_{WWV}\left(g_1^V(W^+_{\mu\nu}W^{-\mu} - W^{+\mu}W^-_{\mu\nu})V^\nu + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2}W^{\nu+}_\mu W^{-\rho}_{,}V^\mu_\rho \right.$$
$$\left. + ig_4^V W^+_\mu W^-_\nu(\partial^\mu V^\nu + \partial^\nu V^\mu) - ig_5^V \epsilon^{\mu\nu\rho\sigma}(W^+_\mu \partial_\rho W^-_\nu - \partial_\rho W^+_\mu W^-_\nu)V_\sigma\right)$$

$$\Gamma_V^{\alpha\beta\mu} = f_1^V(q-\bar{q})^\mu g^{\alpha\beta} - \frac{f_2^V}{M_W^2}(q-\bar{q})^\mu P^\alpha P^\beta + f_3^V(P^\alpha g^{\mu\beta} - P^\beta g^{\mu\alpha})$$
$$+ if_4^V(P^\alpha g^{\mu\beta} + P^\beta g^{\mu\alpha}) + if_5^V\epsilon^{\mu\alpha\beta\rho}(q-\bar{q})_\rho$$

$$\begin{aligned}
\mathcal{L}_{\text{aQGC}} = & \frac{f_{M,0}}{\Lambda^4}\,\text{Tr}\left[\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] + \frac{f_{M,1}}{\Lambda^4}\,\text{Tr}\left[\mathbf{W}_{\mu\nu}\mathbf{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \\
+ & \frac{f_{M,2}}{\Lambda^4}\left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] + \frac{f_{M,3}}{\Lambda^4}\left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \\
+ & \frac{f_{M,4}}{\Lambda^4}\left[(D_\mu\Phi)^\dagger\mathbf{W}_{\beta\nu}D^\mu\Phi\right] \times B^{\beta\nu} + \frac{f_{M,5}}{\Lambda^4} \times \frac{1}{2}\left[(D_\mu\Phi)^\dagger\mathbf{W}_{\beta\nu}D^\nu\Phi + (D^\nu\Phi)^\dagger\mathbf{W}_{\beta\nu}D_\mu\Phi\right] \times B^{\beta\mu} \\
+ & \frac{f_{M,6}}{\Lambda^4}\left[(D_\mu\Phi)^\dagger\mathbf{W}_{\beta\nu}\mathbf{W}^{\beta\nu}D^\mu\Phi\right] + \frac{f_{M,7}}{\Lambda^4}\left[(D_\mu\Phi)^\dagger\mathbf{W}_{\beta\nu}\mathbf{W}^{\beta\mu}D^\nu\Phi\right] \\
+ & \frac{f_{T,0}}{\Lambda^4}Tr[\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}] \times Tr[\mathbf{W}_{\alpha\beta}\mathbf{W}^{\alpha\beta}] + \frac{f_{T,1}}{\Lambda^4}Tr[\mathbf{W}_{\alpha\nu}\mathbf{W}^{\mu\beta}] \times Tr[\mathbf{W}_{\mu\beta}\mathbf{W}^{\alpha\nu}] \\
+ & \frac{f_{T,2}}{\Lambda^4}Tr[\mathbf{W}_{\alpha\mu}\mathbf{W}^{\mu\beta}] \times Tr[\mathbf{W}_{\beta\nu}\mathbf{W}^{\nu\alpha}] + \frac{f_{T,5}}{\Lambda^4}Tr[\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}] \times B_{\alpha\beta}B^{\alpha\beta} \\
+ & \frac{f_{T,6}}{\Lambda^4}Tr[\mathbf{W}_{\alpha\nu}\mathbf{W}^{\mu\beta}] \times B_{\mu\beta}B^{\alpha\nu} + \frac{f_{T,7}}{\Lambda^4}Tr[\mathbf{W}_{\alpha\mu}\mathbf{W}^{\mu\beta}] \times B_{\beta\nu}B^{\nu\alpha}, \qquad (2)
\end{aligned}$$

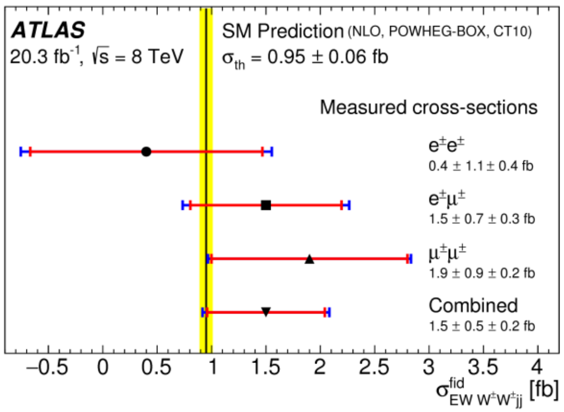
Example of aQGC change with and without form factor

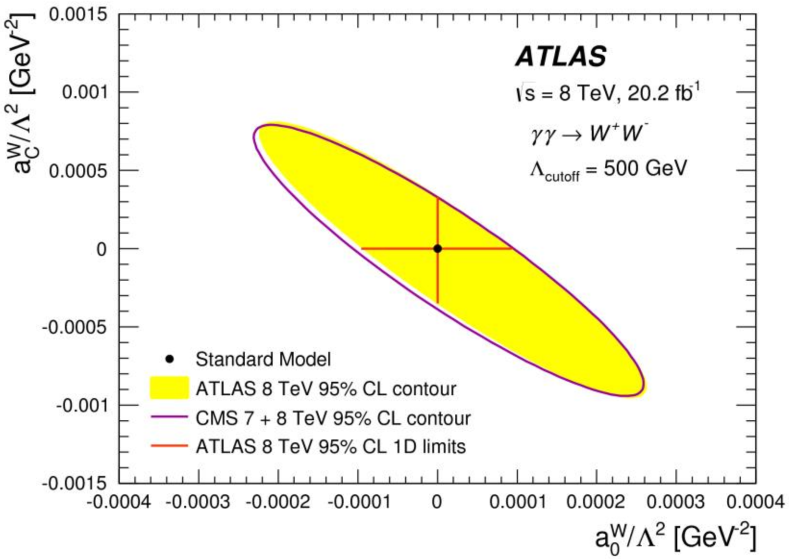
- ATLAS: Zgamma at 8 TeV

Limits 95% CL	Measured [TeV^{-4}]	Expected [TeV^{-4}]	Λ_{FF} [TeV]
f_{T9}/Λ^4	$[-5.2, 5.2] \times 10^3$	$[-3.3, 3.2] \times 10^3$	
f_{T8}/Λ^4	$[-2.4, 2.4] \times 10^3$	$[-1.5, 1.6] \times 10^3$	
f_{T0}/Λ^4	$[-2.5, 2.3] \times 10^1$	$[-1.7, 1.5] \times 10^1$	
f_{T9}/Λ^4	$[-8.6, 8.6] \times 10^4$	$[-5.8, 5.7] \times 10^4$	0.7
f_{T8}/Λ^4	$[-4.1, 4.1] \times 10^4$	$[-2.8, 2.7] \times 10^4$	0.7
f_{T0}/Λ^4	$[-9.5, 8.7] \times 10^1$	$[-6.6, 5.6] \times 10^1$	1.7

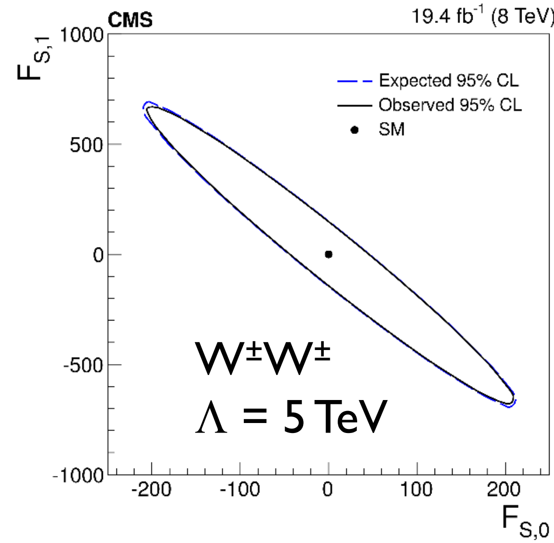
EWK and exclusive WW results

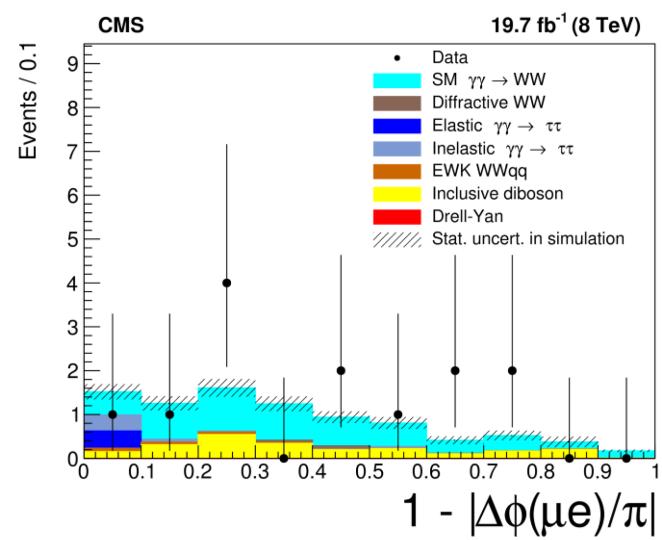
- ATLAS





CMS





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Example of systematic errors

- CMS: Zgamma EWK

Source	Uncertainty
QCD $Z\gamma$ + jets normalization	22% ($400 < M_{jj} < 800$ GeV) 24% ($M_{jj} > 800$ GeV)
Fake photon from jet (p_T^γ dependent)	15% (20–30 GeV) 22% (30–50 GeV) 49% (>50 GeV)
Trigger efficiency	1.2% ($Z \to \mu^+\mu^-$), 1.7% ($Z \to e^+e^-$)
Lepton selection efficiency	1.9% ($Z \to \mu^+\mu^-$), 1.0% ($Z \to e^+e^-$)
Jet energy scale and resolution	14% ($M_{jj} > 400$ GeV)
$t\bar{t}\gamma$ cross section	20% [?]
Pileup modeling	1.0%
Renormalization/ factorization scale (signal)	9.0% ($400 < M_{jj} < 800$ GeV), 12% ($M_{jj} > 800$ GeV) (SM) 14% (aQGC)
PDF (signal)	4.2% ($400 < M_{jj} < 800$ GeV), 2.4% ($M_{jj} > 800$ GeV) (SM) 4.3% (aQGC)
Interference (signal)	18% ($400 < M_{jj} < 800$ GeV), 11% ($M_{jj} > 800$ GeV) (SM)
Luminosity	2.6%

- ATLAS: WW

Sources of uncertainty	Relative uncertainty for $\sigma^{\text{fid}}_{WW\to e\mu}$
Jet selection and energy scale & resolution	7.3%
b-tagging	1.3%
E_T^{miss} and p_T^{miss}	1.7%
Electron	1.0%
Muon	0.4%
Pile-up	0.9%
Luminosity	2.1%
Top-quark background theory	2.4%
Drell–Yan background theory	1.5%
W+jet and multi-jet background	3.8%
Other diboson backgrounds	1.1%
Parton shower	3.1%
PDF	0.2%
QCD scale	0.2%
MC statistics	1.2%
Data statistics	3.7%
Total uncertainty	11%