Study of Multiboson Production with the ATLAS detector

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on behalf of the ATLAS Collaboration

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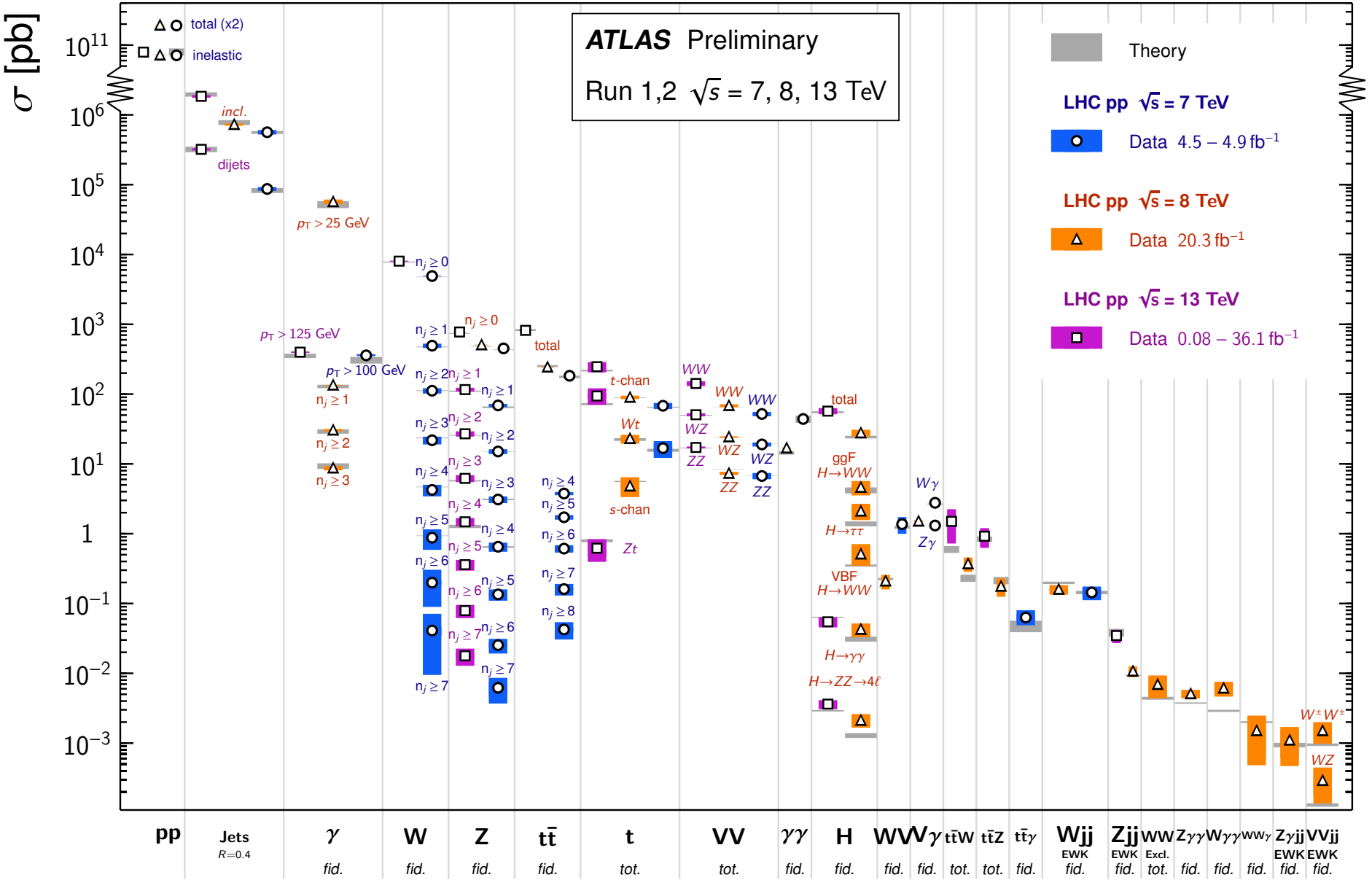
ARC Centre of Excellence for Particle Physics at the Terascale

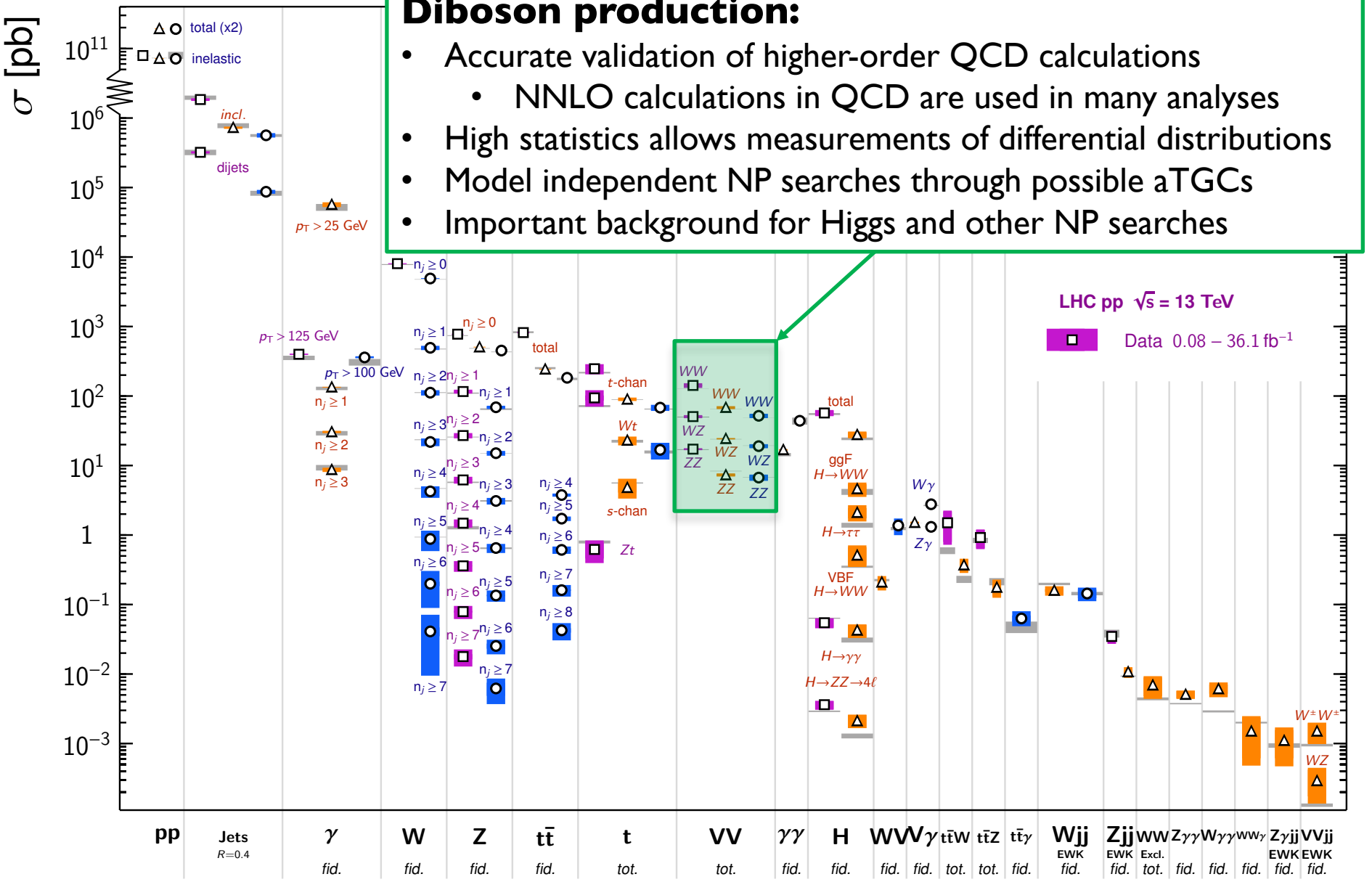
Multiboson Production in ATLAS: Stringent Test of the Electroweak Structure



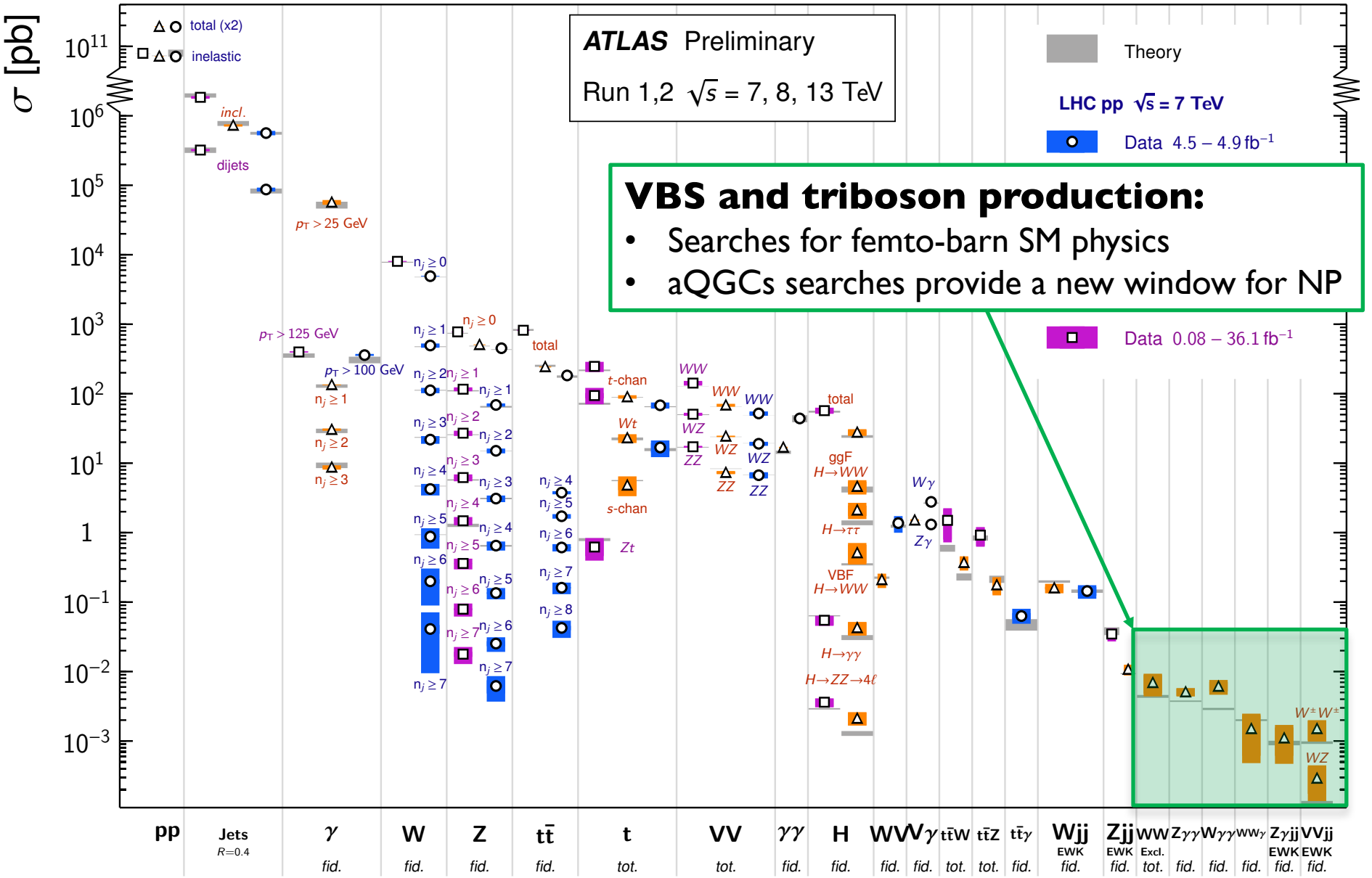
Multiboson Production in ATLAS: Stringent Test of the Electroweak Structure

Diboson production:

- Accurate validation of higher-order QCD calculations
  - NNLO calculations in QCD are used in many analyses
- High statistics allows measurements of differential distributions
- Model independent NP searches through possible aTGCs
- Important background for Higgs and other NP searches



Multiboson Production in ATLAS: Stringent Test of the Electroweak Structure



VBS and triboson production:

- Searches for femto-barn SM physics
- aQGCs searches provide a new window for NP

Recent ATLAS multiboson measurements

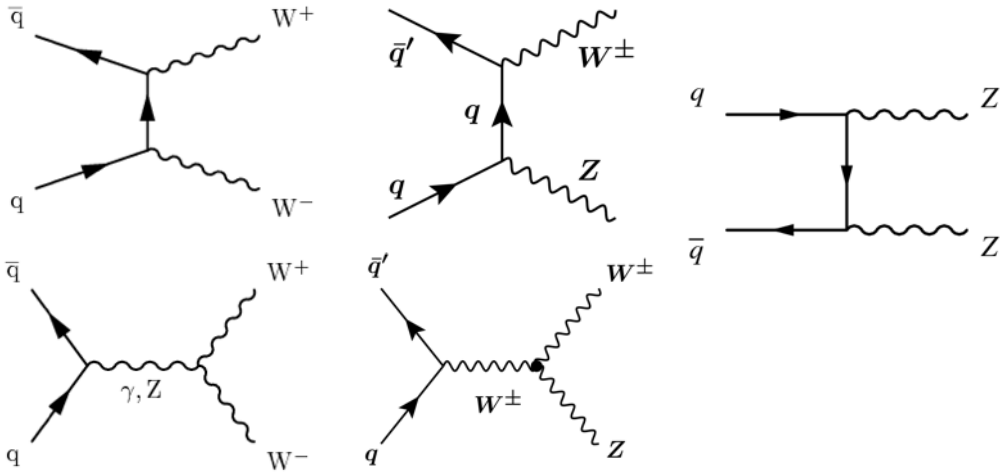
- Diboson Production
  - ZZ leptonic decay @ 13 TeV (ATLAS-CONF-2017-031)
  - WZ leptonic decay @ 13 TeV (ATLAS-CONF-2016-043, Phys.Lett.B 762 (2016)1)
  - WW leptonic decay @ 13 TeV (arXiv: 1702.04519)
  - WW/WZ semi-leptonic decay @ 8 TeV (arXiv: 1706.01702)

- Vector Boson Scattering and triboson production
  - VBS Zγjj production @ 8 TeV (JHEP07(2017)107)
  - WVγ production @ 8 TeV (arXiv: 1707.05597)

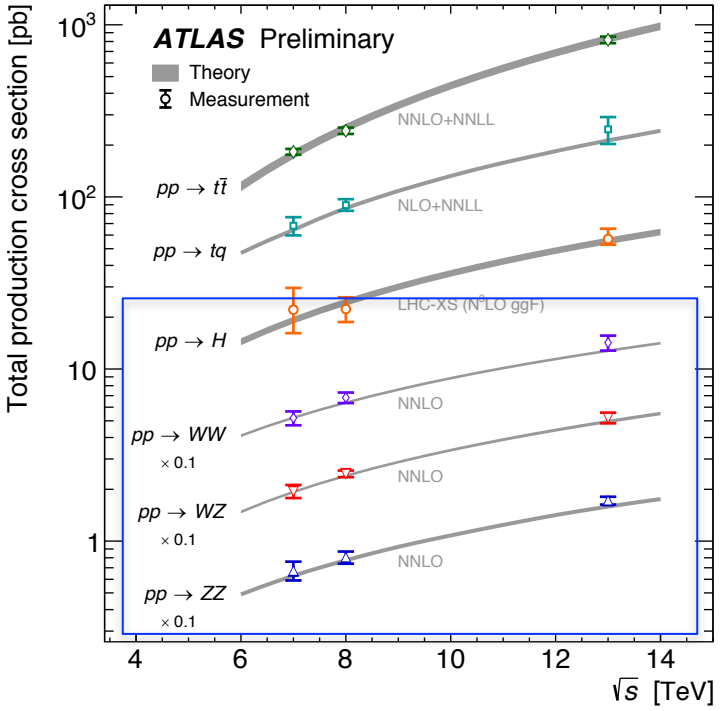
Diboson measurements

- WW, WZ and ZZ production
  - ZZ: smallest cross-section but clean 4ℓ signature : statistics dominant
  - WW: largest cross-section but difficult $2\ell 2\nu$ final state: systematics dominant
  - WZ: nice balance
- First step are measurements of **full-leptonic** decay modes
  - 13 TeV results are published with all channels
- Then, analyses of **semi-leptonic** decay modes
  - More stat. gives us higher sensitivity to NP
  - 8 TeV result of WW/WZ production

WW WZ ZZ

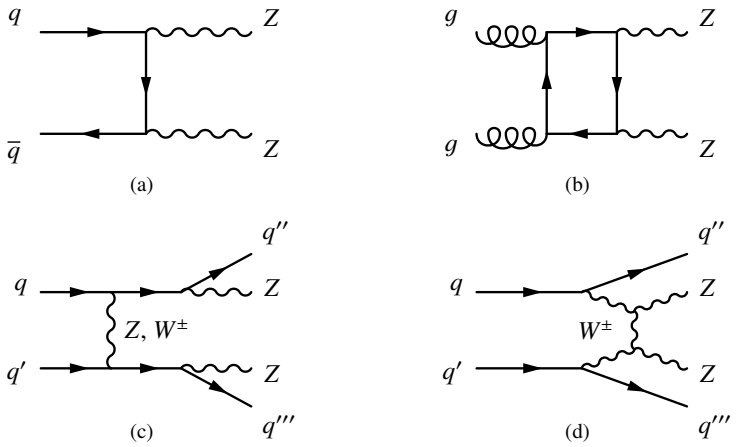


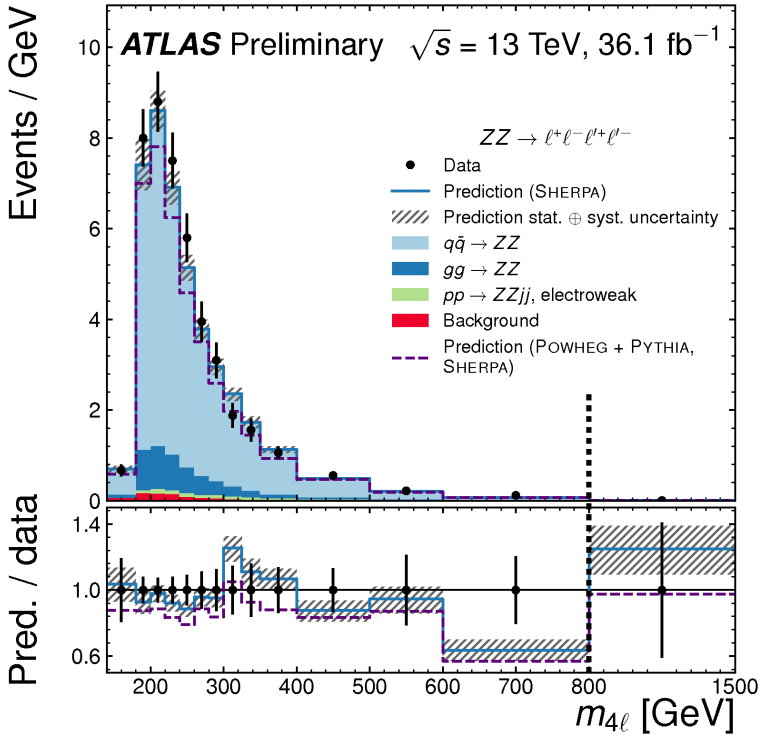
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults



ZZ full-leptonic @ 13 TeV

- $ZZ \to l^+l^-l'^+l'^-$ signal (Nominal: Sherpa)
  - qq/gg processes are dominant
  - EW $ZZjj$ (including VBS) is included
    - Also $ZZV \to l^+l^-l'^+l'^-jj$ is included
- Compared two generators
  - Powheg: NLO ME calculation up to 1-jet
  - Sherpa: + LO ME calculation for 2, 3-jets
- 2 same-flavour opposite-sign e/μ pairs
  - Only on-shell: 66 < m_{ll} < 116 GeV
  - Main background: fake-lepton
  - Main systematics: lepton ID



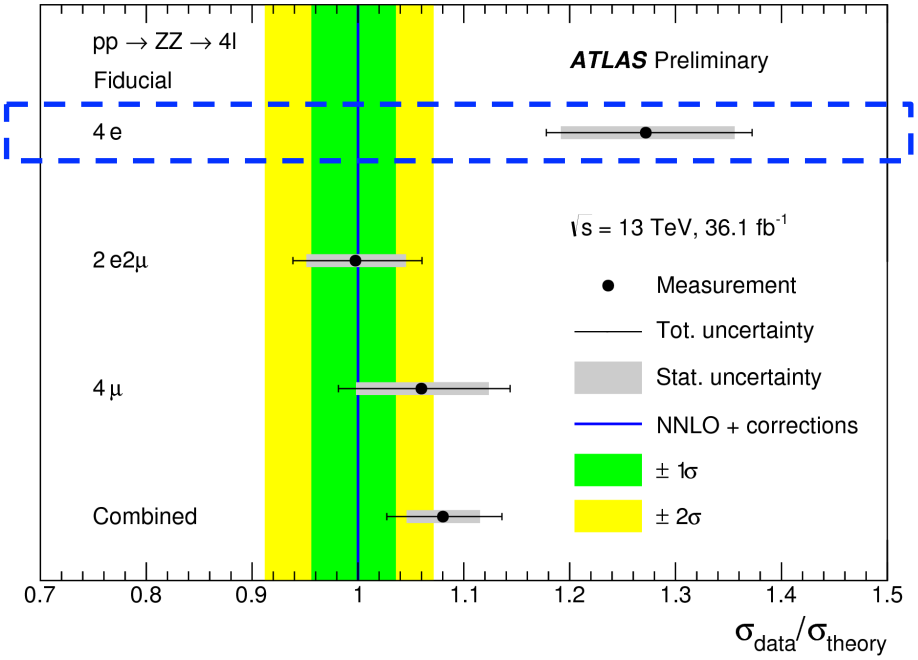


ZZ full-leptonic @ 13 TeV

- Fiducial cross-section is measured with ~5% uncertainty (combined)

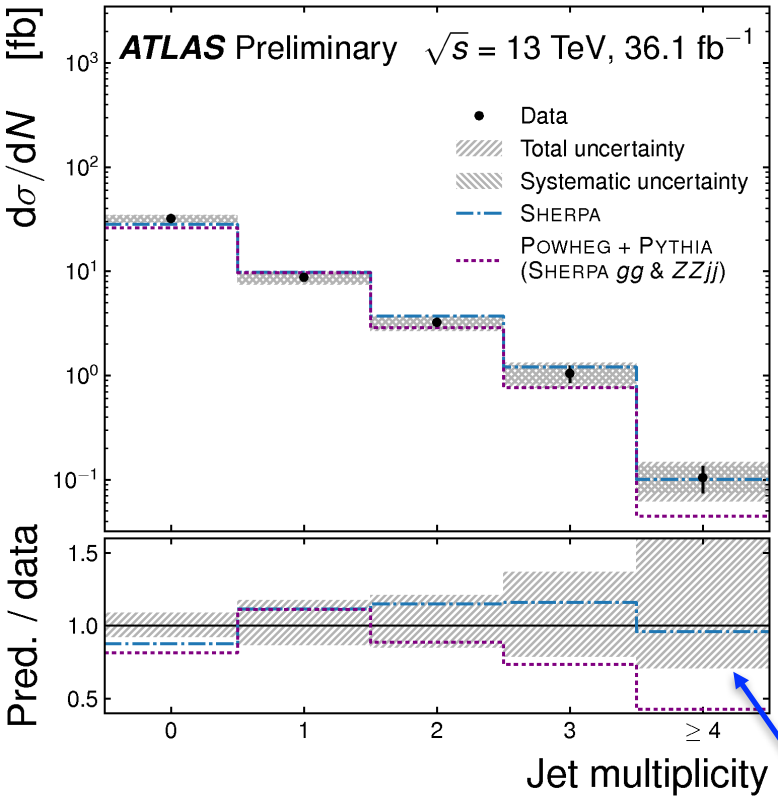
Channel	Measurement [fb]	Prediction [fb]
$4e$	$13.8^{+1.1}_{-1.0}$ $\left[\pm 0.9\ (\text{stat.})\ \pm 0.3\ (\text{syst.})\ ^{+0.5}_{-0.4}\ (\text{lumi.})\right]$	$10.9^{+0.5}_{-0.4}$
$2e2\mu$	$21.1^{+1.3}_{-1.2}$ $\left[\pm 1.0\ (\text{stat.})\ ^{+0.5}_{-0.4}\ (\text{syst.})\ ^{+0.7}_{-0.6}\ (\text{lumi.})\right]$	$21.2^{+0.9}_{-0.8}$
4μ	$11.5^{+0.9}_{-0.8}$ $\left[\pm 0.7\ (\text{stat.})\ \pm 0.4\ (\text{syst.})\ ^{+0.4}_{-0.3}\ (\text{lumi.})\right]$	$10.9^{+0.5}_{-0.4}$
Combined	$46.4^{+2.4}_{-2.2}$ $\left[\pm 1.5\ (\text{stat.})\ \pm 1.0\ (\text{syst.})\ ^{+1.5}_{-1.4}\ (\text{lumi.})\right]$	$42.9^{+1.9}_{-1.5}$

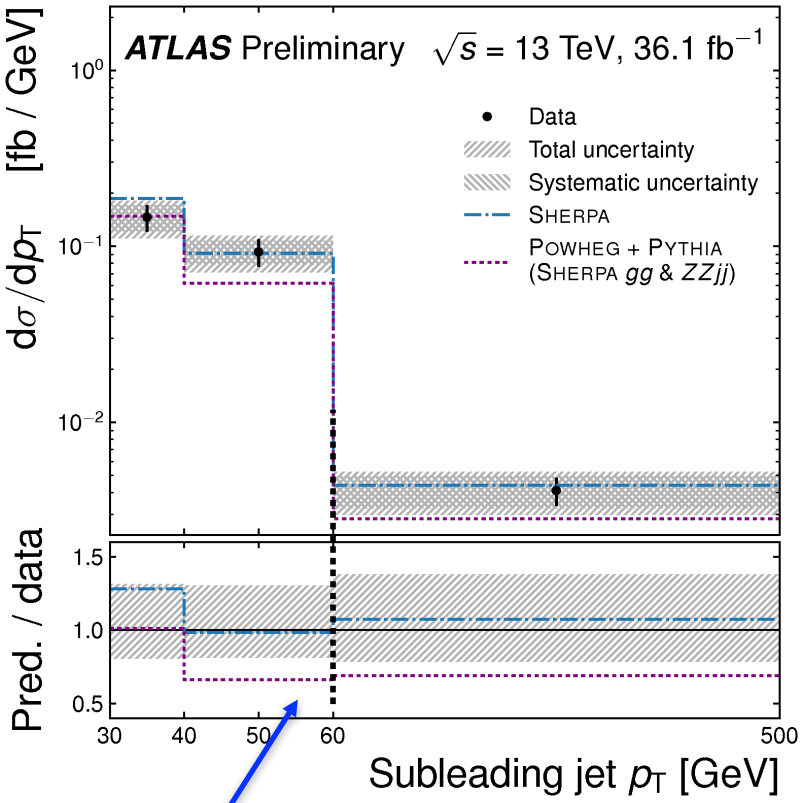
- Good agreement with MATRIX NNLO calculation
  - 2.7 σ tension in 4e channel



ZZ full-leptonic @ 13 TeV

- 20 differential cross-sections are measured



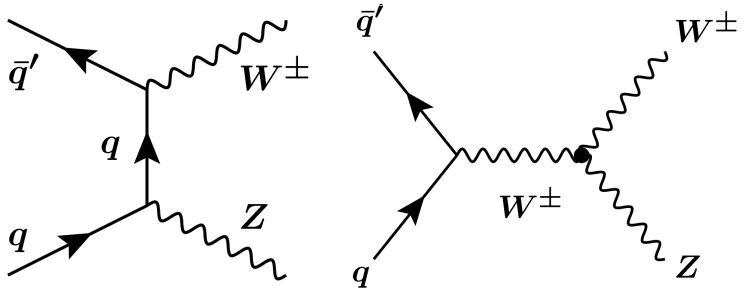


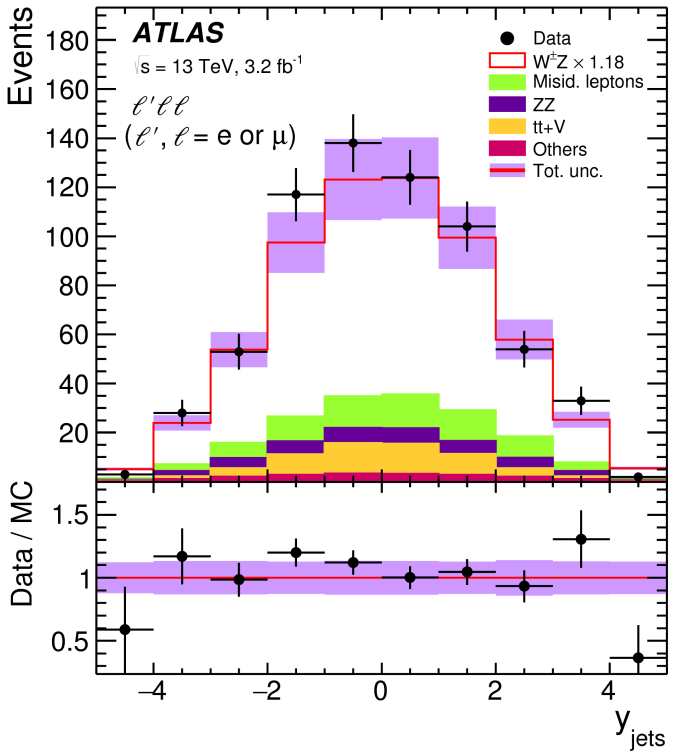
Sherpa models better

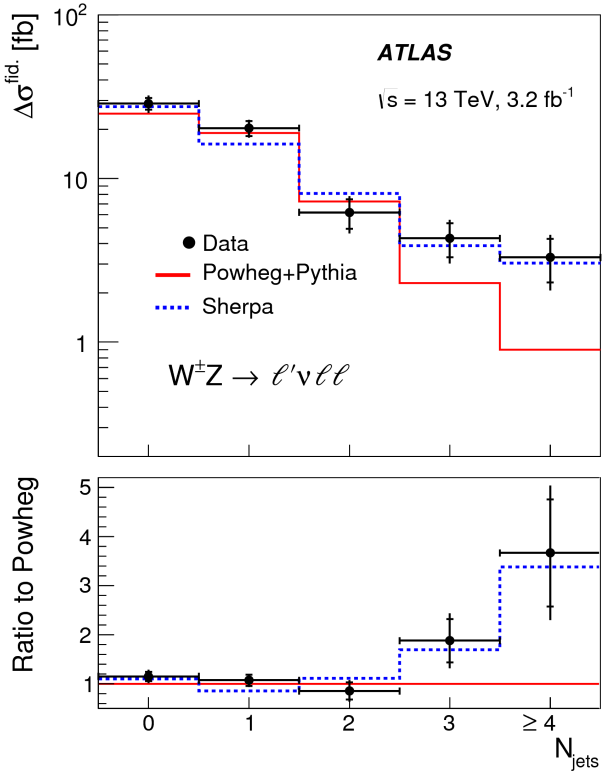
Phys.Lett.B 762 (2016)1

WZ full-leptonic @ 13 TeV

- WZ→l'νl⁺l⁻ signal (Nominal: Powheg+Pythia)
- Three high-p_T e or μ
  - On-shell Z boson: $|M_{ll} - M_Z| < 10$ GeV
  - W boson selection: $m_T^W > 30$ GeV
- Main background: mis-identified leptons
- Main systematics: Fake factor, lepton ID, luminosity





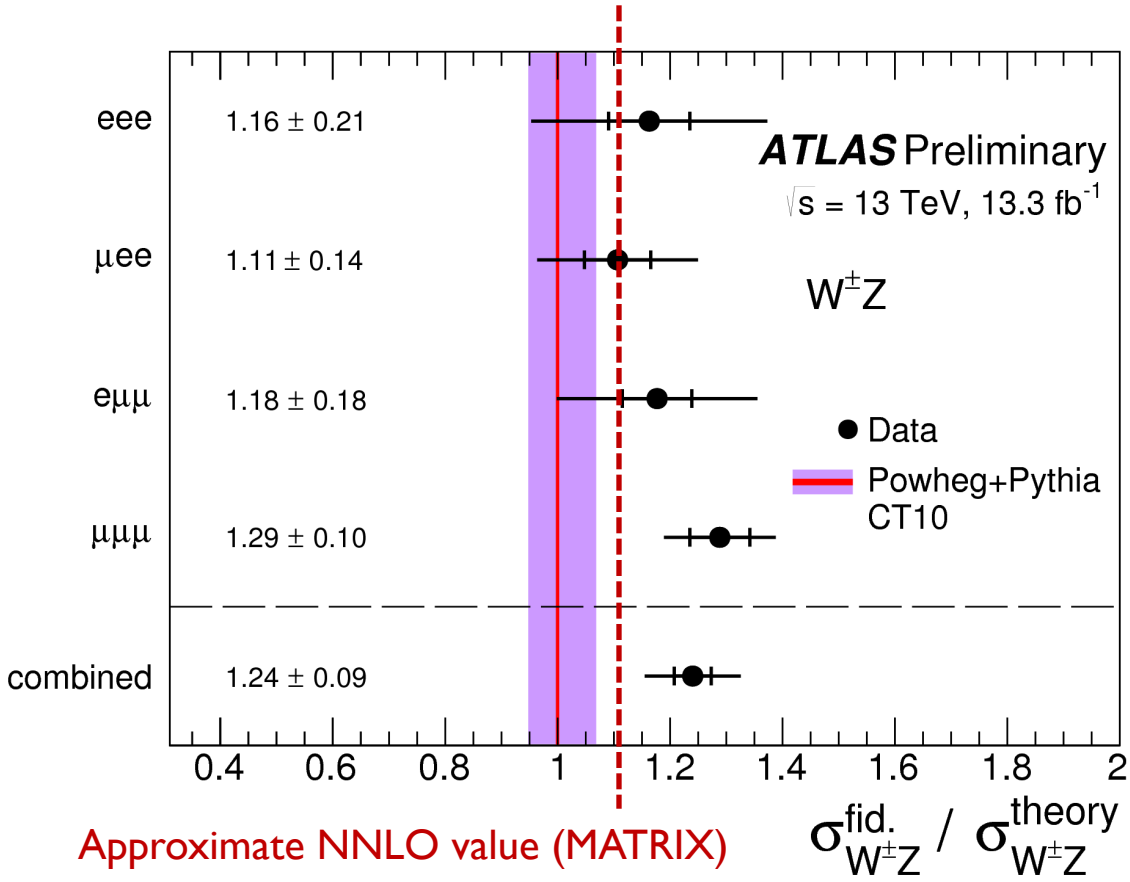


WZ full-leptonic @ 13 TeV

- Fiducial cross-section measured with ~7% uncertainty

$$\sigma^{\text{fid.}}_{W^{\pm}Z\to\ell'\nu\ell\ell} = 66.2 \pm 1.8\,(\text{stat.}) \pm 3.6\,(\text{sys.}) \pm 2.1\,(\text{lumi.})\ \text{fb}.$$

- Good agreement with Powheg+Pythia prediction
  - Even better with approximate scale factor of 1.11 to MATRIX NNLO

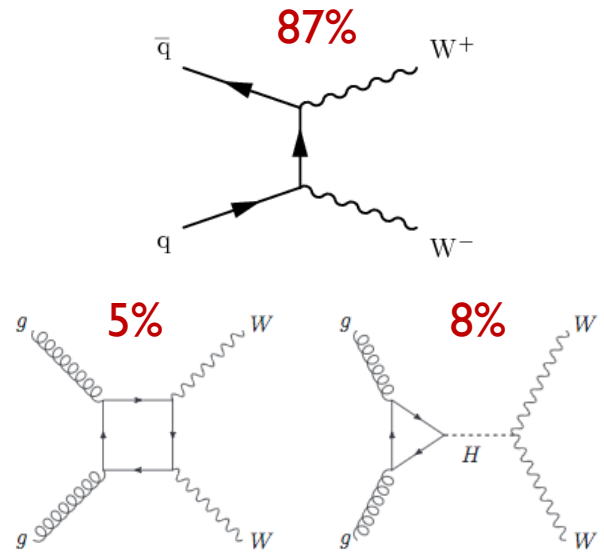


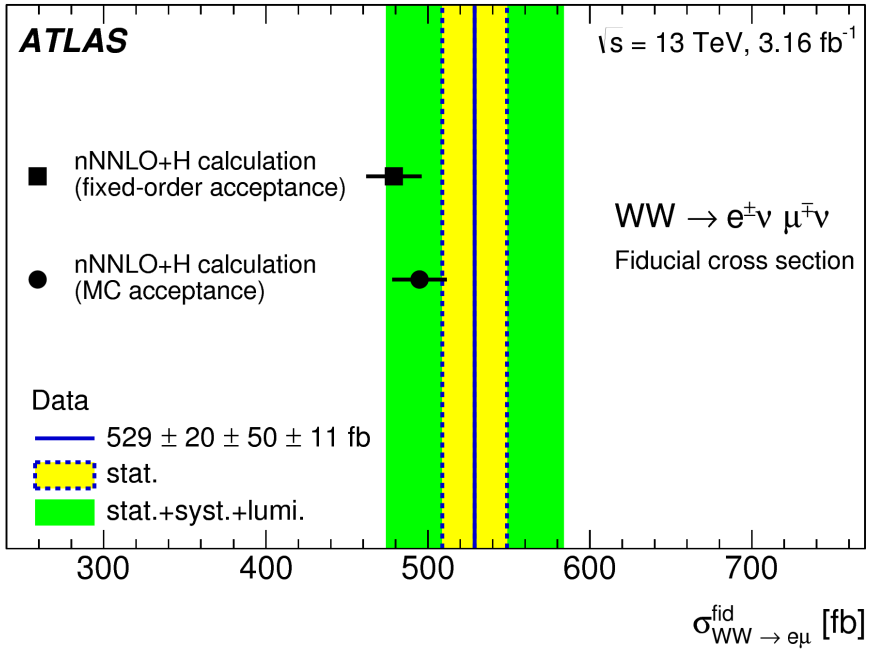
WW full-leptonic @ 13 TeV

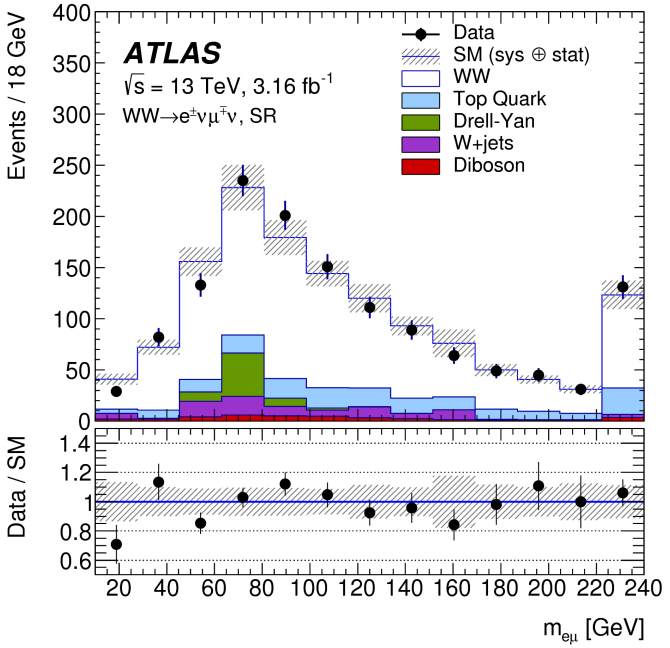
arXiv: 1702.04519

- $WW \to e\nu\mu\nu$ signal (nNNLO+H)
  - qq → WW (Powheg norm. to $O(\alpha_S^2)$)
  - gg → WW (Sherpa norm. to $O(\alpha_S^3)$)
  - gg → H → WW (Powheg norm. to $O(\alpha_S^3)$)
- High-p_T $e\mu$ pair with E_T^{miss} and no jet
  - Major systematics: Jet energy scale, fake factor
- Fiducial cross section measured with ~10% uncert.

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



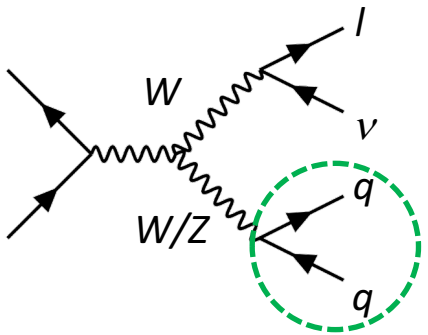


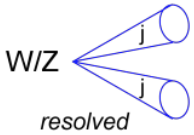


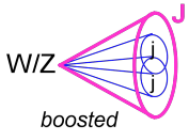
arXiv: 1706.01702

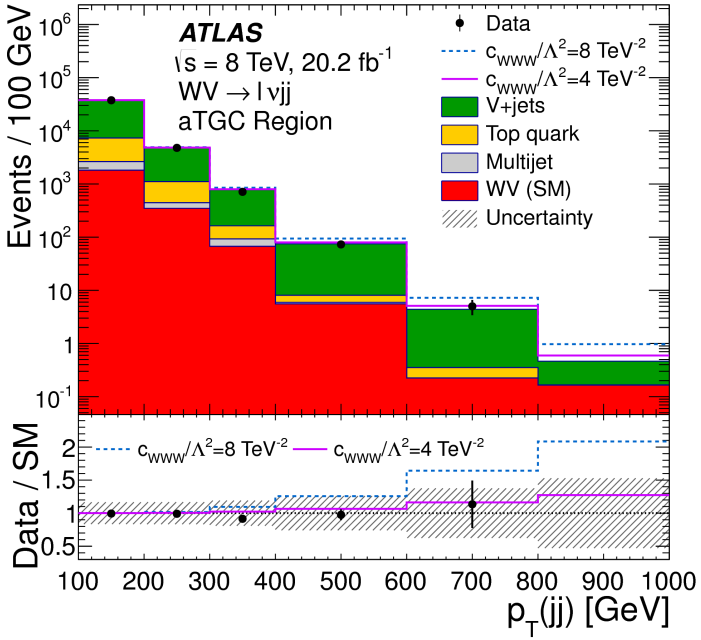
WZ/WW semi-leptonic @ 8 TeV

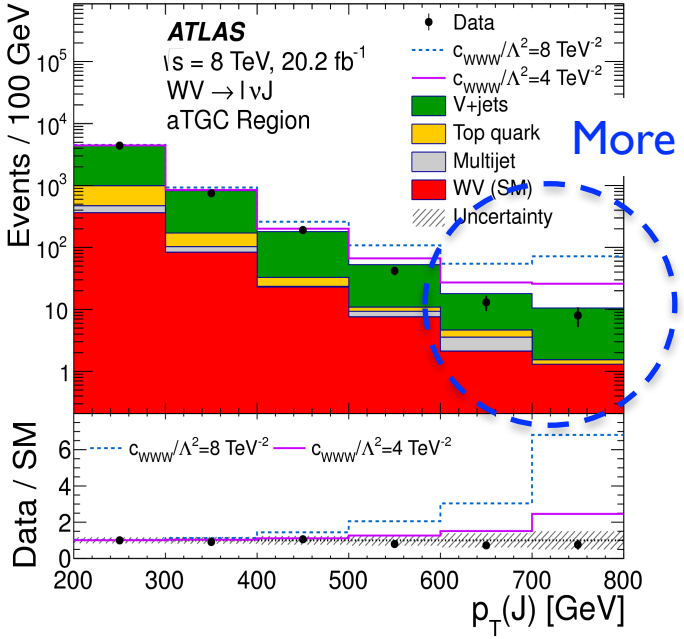
- Extend out sensitivity to NP
  - 6x BR than full-leptonic mode
  - Better kinematics reconstruction in WW
- Two jet reconstruction approaches
  - Resolved jet (lnjj): two jets with anti-kt (R=0.4)
  - Boosted jet (lnJ): one jet with anti-kt with R=1.0 and jet grooming









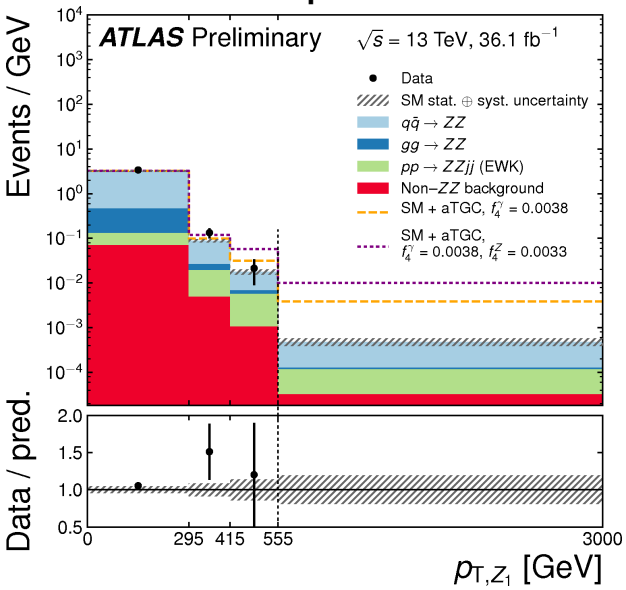


More sensitivity to NP!

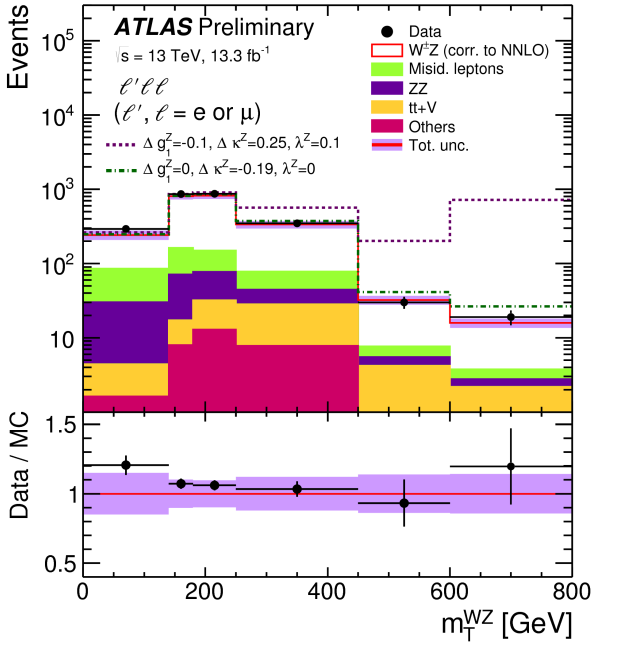
aTGC search inputs

- Extract constraints on aTGC parameters in high $\hat{s}$ regions

ZZ leptonic

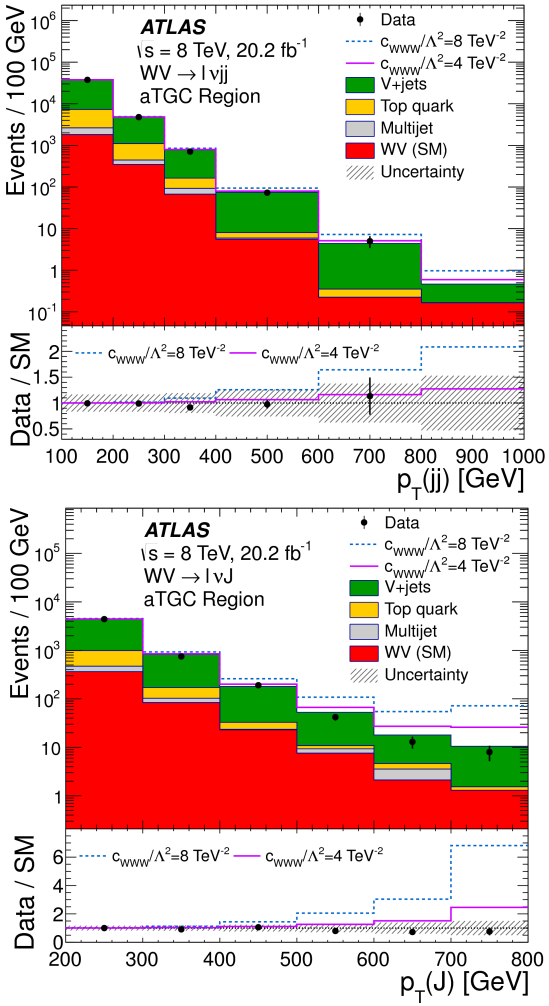


WZ leptonic



$$m_{\mathrm{T}}^{WZ} = \sqrt{\left(\sum_{\ell=1}^{3} p_{\mathrm{T}}^{\ell} + E_{\mathrm{T}}^{\mathrm{miss}}\right)^2 - \left[\left(\sum_{\ell=1}^{3} p_x^{\ell} + E_x^{\mathrm{miss}}\right)^2 + \left(\sum_{\ell=1}^{3} p_y^{\ell} + E_y^{\mathrm{miss}}\right)^2\right]}.$$

WW/WZ semi-leptonic



ATLAS-CONF-2017-031 ATLAS-CONF-2016-043 arXiv: 1706.01702

aTGC constraints

- Results with effective Lagrangian approach are shown
  - Results with EFT approach are also available

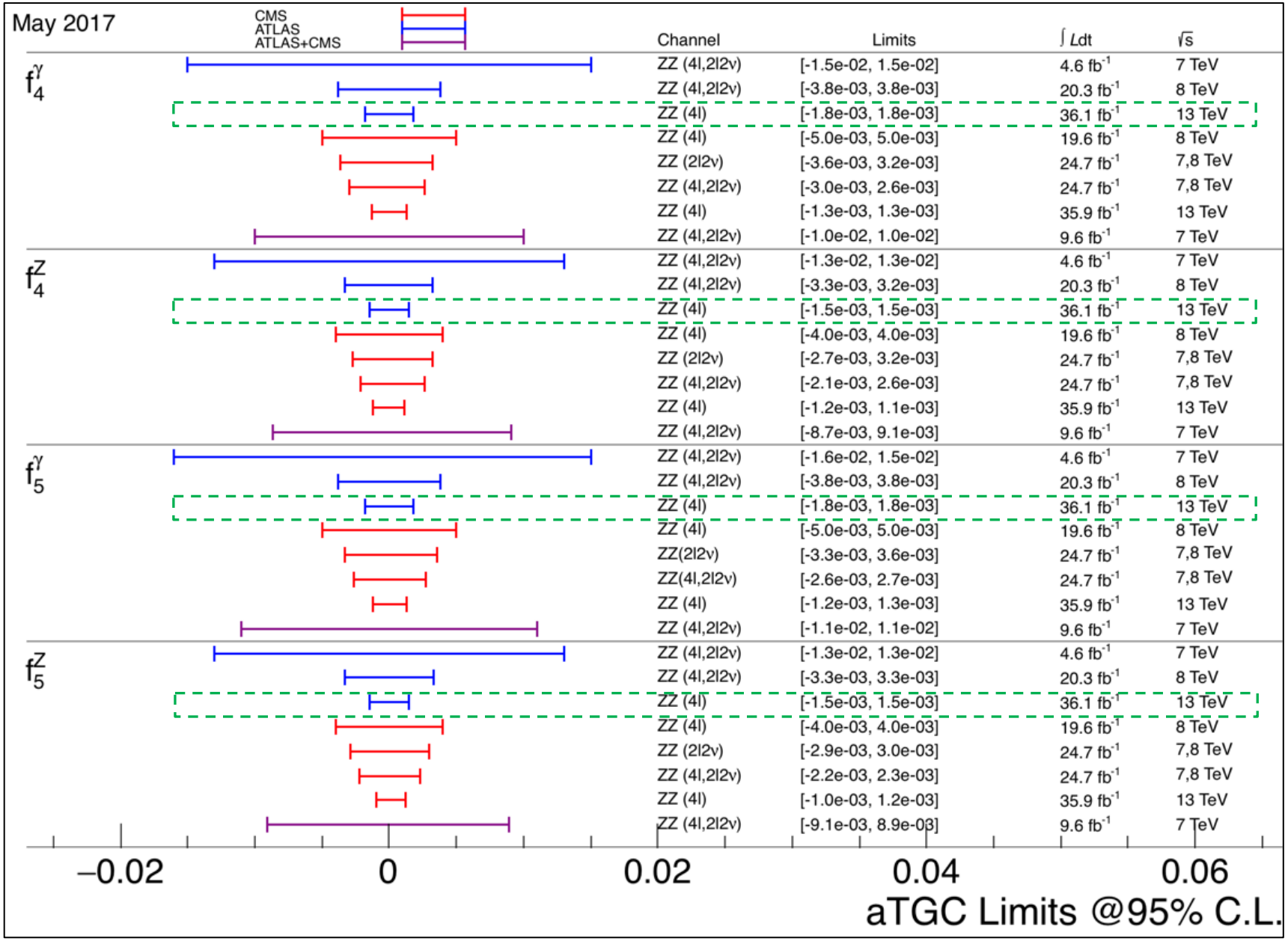
$$\mathcal{L}_{ZZV} = -\frac{e}{M_Z^2}\left(f_4^V(\partial_\mu V^{\mu\beta})Z_\alpha(\partial^\alpha Z_\beta) + f_5^V(\partial^\sigma V_{\sigma\mu})\tilde{Z}^{\mu\beta}Z_\beta\right)$$

$$\frac{\mathcal{L}_{WWV}}{g_{WWV}} = ig_1^V(W^+_{\mu\nu}W^\mu V^\nu - W^+_\mu V_\nu W^{\mu\nu}) + i\kappa_V W^+_\mu W_\nu V^{\mu\nu} + \frac{i\lambda_V}{m_W^2}W^+_{\lambda\mu}W^\mu_\nu V^{\nu\lambda}$$

= 1 in SM

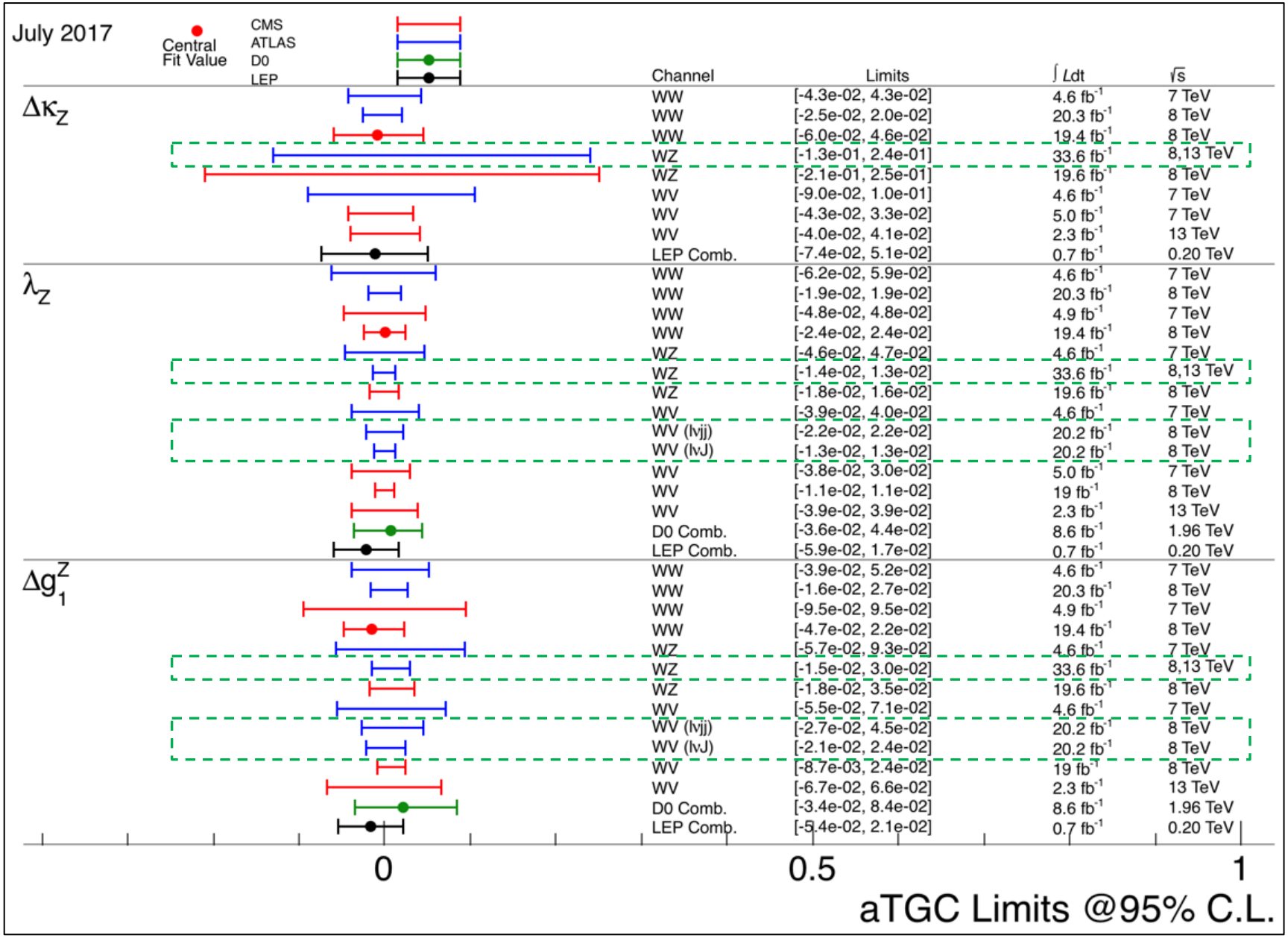
= 0 in SM

$$\mathcal{L}_{ZZV} = -\frac{e}{M_Z^2}\left(f_4^V(\partial_\mu V^{\mu\beta})Z_\alpha(\partial^\alpha Z_\beta) + f_5^V(\partial^\sigma V_{\sigma\mu})\tilde{Z}^{\mu\beta}Z_\beta\right)$$



https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

$$\frac{\mathcal{L}_{WWV}}{g_{WWV}} = ig_1^V (W^+_{\mu\nu} W^\mu V^\nu - W^+_\mu V_\nu W^{\mu\nu}) + i\kappa_V W^+_\mu W_\nu V^{\mu\nu} + \frac{i\lambda_V}{m_W^2} W^+_{\lambda\mu} W^\mu_\nu V^{\nu\lambda}$$



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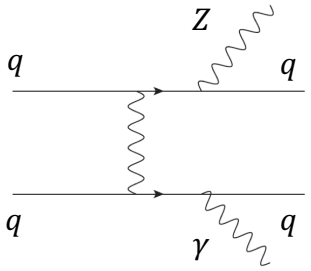
JHEP07(2017)107

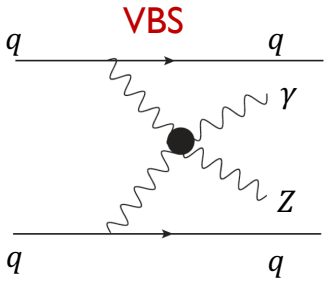
$Z\gamma jj$ production @ 8 TeV

- EWK and QCD processes with Sherpa
- Clean $\ell\ell\gamma jj$ channel for fiducial σ
  - Same-flavour opposite-sign lepton pair
  - One isolated γ
- EWK processes: energetic forward di-jet
  - m_{jj} and $\zeta^{Z\gamma}$ to separate from QCD bkg.

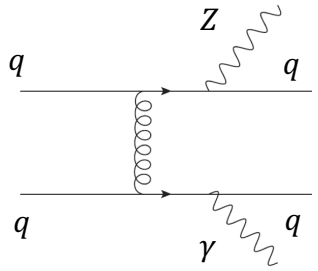
EW non-VBS

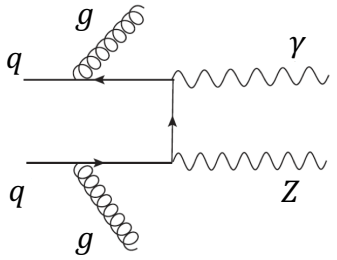


VBS

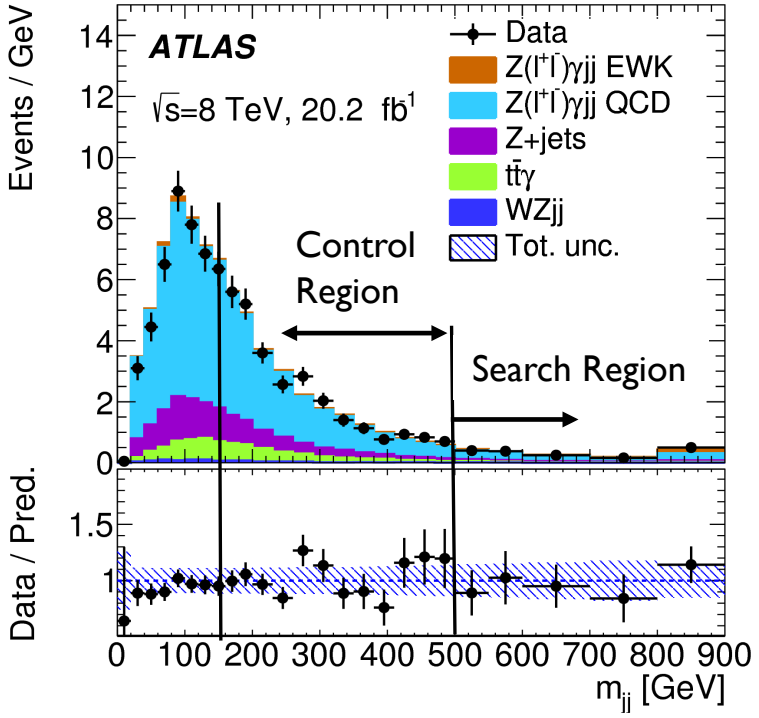


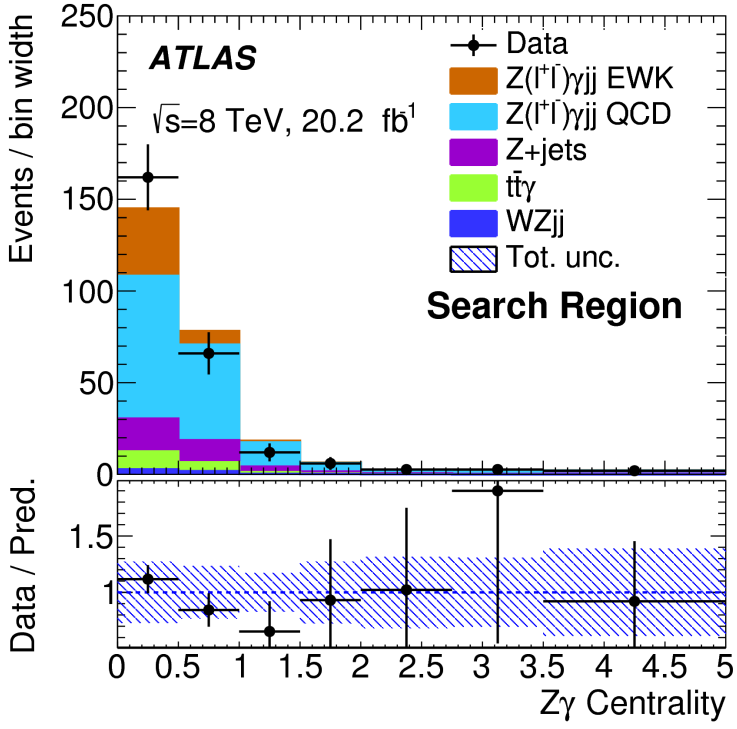
QCD backgrounds





gluon radiation





$$\zeta \equiv \left| \frac{\eta - \bar{\eta}_{jj}}{\Delta\eta_{jj}} \right|$$

$$\bar{\eta}_{jj} = \frac{\eta_{j_1} + \eta_{j_2}}{2}, \quad \Delta\eta_{jj} = \eta_{j_1} - \eta_{j_2}$$

JHEP07(2017)107

$Z\gamma jj$ production @ 8 TeV

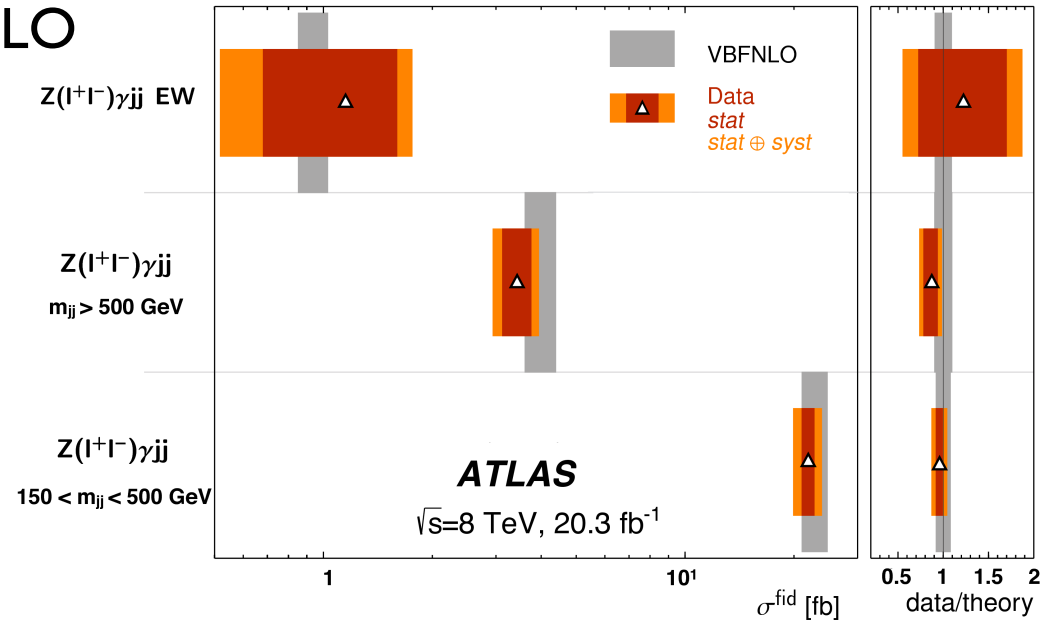
- Fiducial cross-section measured with $\ell\ell\gamma jj$

2 σ significance

Channel	Phase-space region	Process type	Measured cross-section [fb]	Predicted cross-section [fb]
$Z(\ell^+\ell^-)\gamma jj$	Search region	EWK	1.1 ± 0.5 (stat) ± 0.4 (syst)	0.94 ± 0.09
$Z(\ell^+\ell^-)\gamma jj$	Search region	EWK+QCD	3.4 ± 0.3 (stat) ± 0.4 (syst)	4.0 ± 0.4
$Z(\ell^+\ell^-)\gamma jj$	Control region	EWK+QCD	21.9 ± 0.9 (stat) ± 1.8 (syst)	22.9 ± 1.9

- Good agreement with VBFNLO

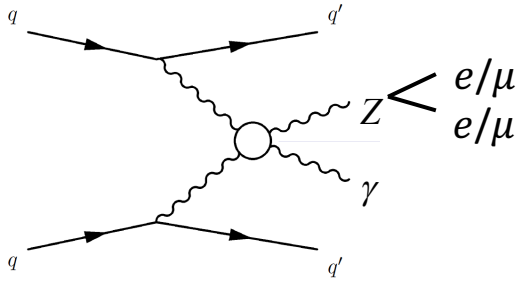
- Main uncertainties on σ_{EW}
  - Statistical uncertainty: 40%
  - Jet energy scale: 36%
  - Sherpa modeling: 10%

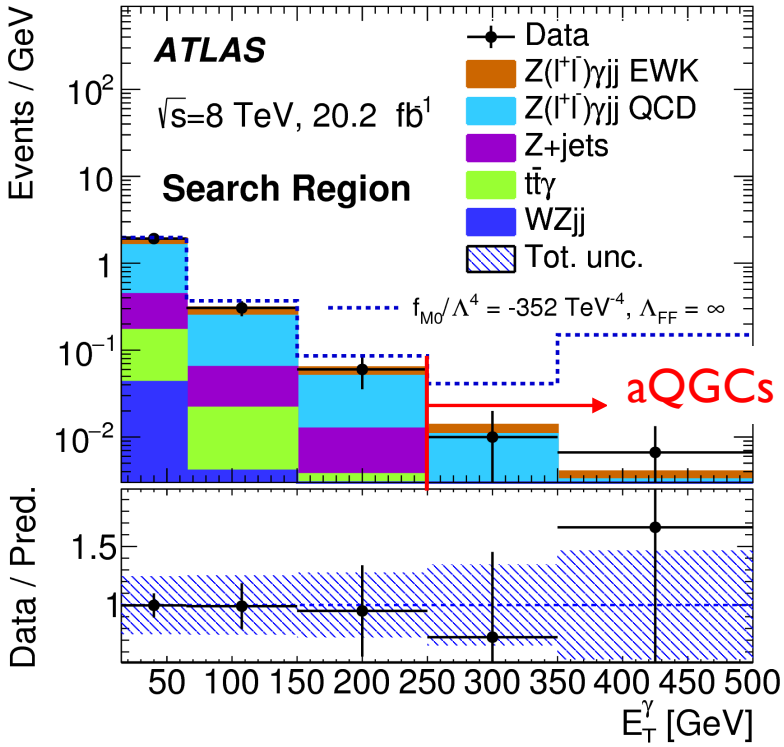


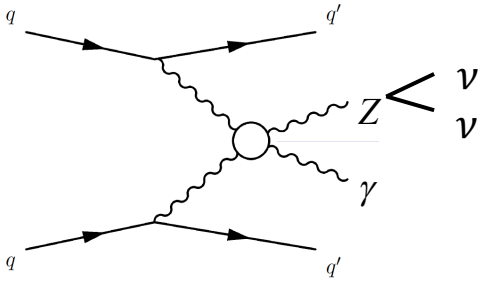
JHEP07(2017)107

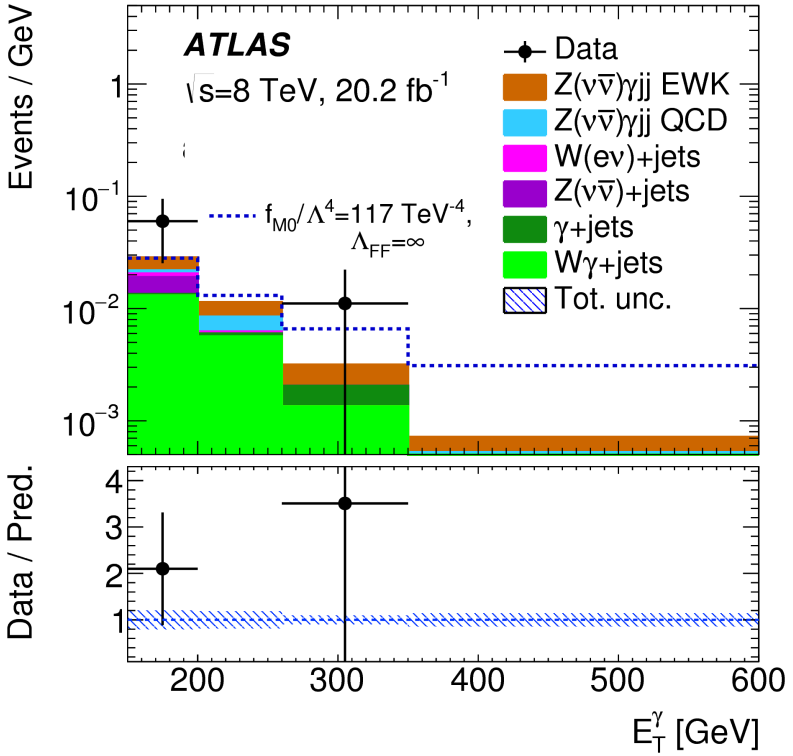
$Z\gamma jj$ production @ 8 TeV

- E_T^{γ} distributions to constrain aQGCs are obtained both in $\ell\ell\gamma jj$ and $\nu\nu\gamma jj$ samples



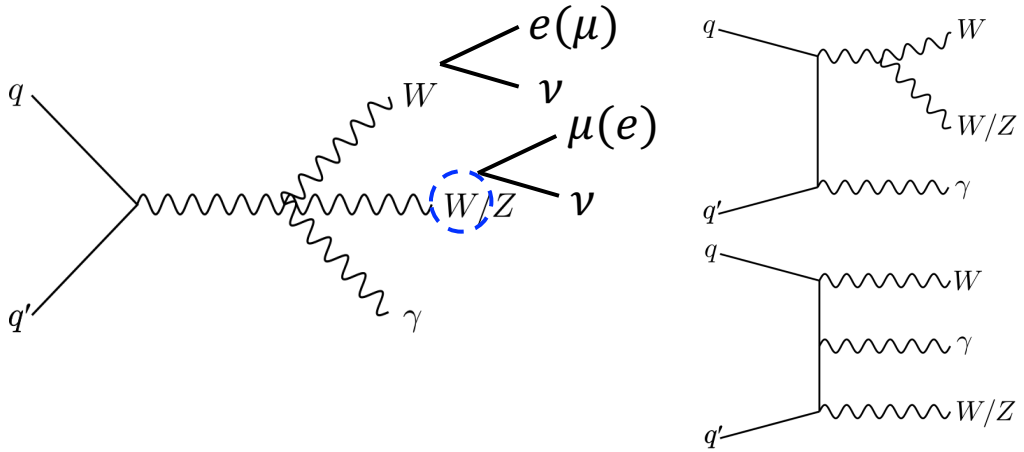


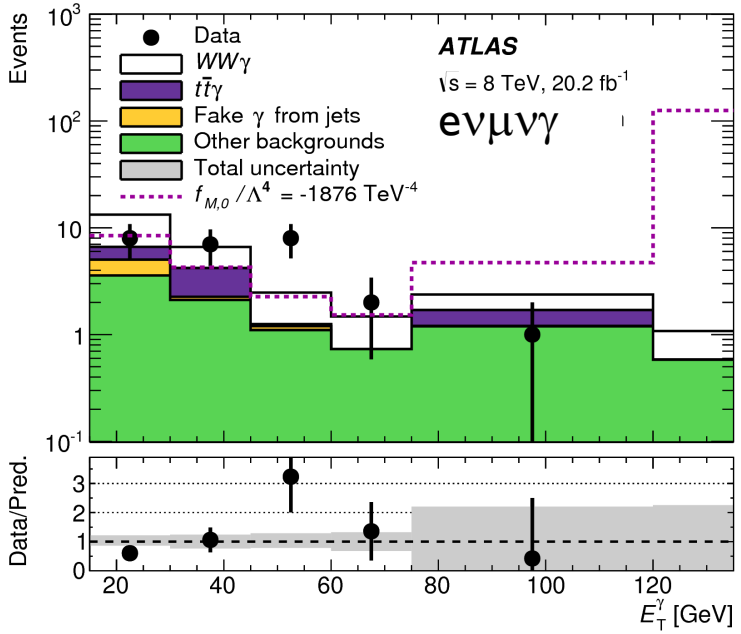




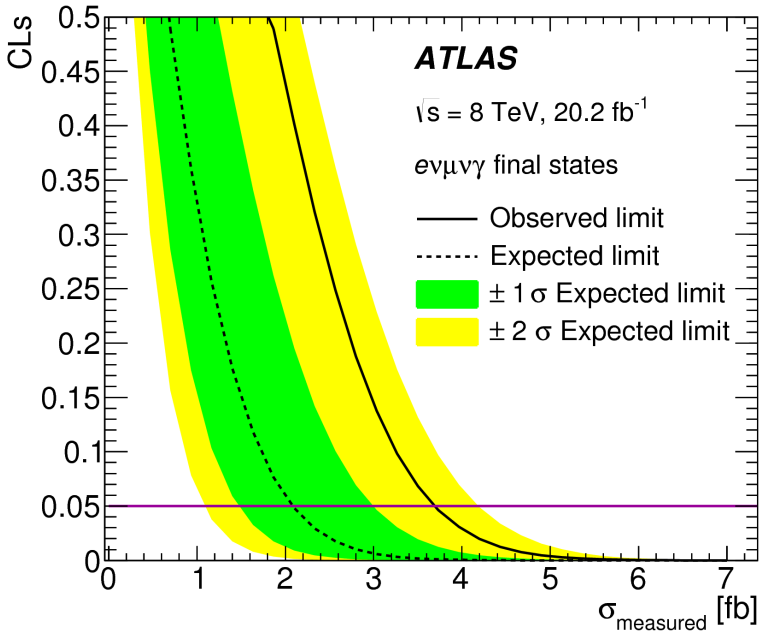
arXiv: 1707.05597

WVγ production @ 8 TeV

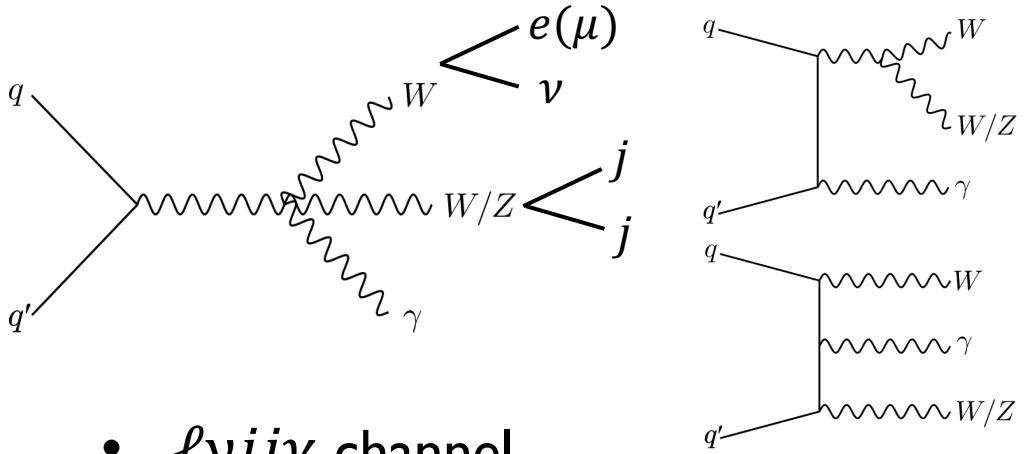




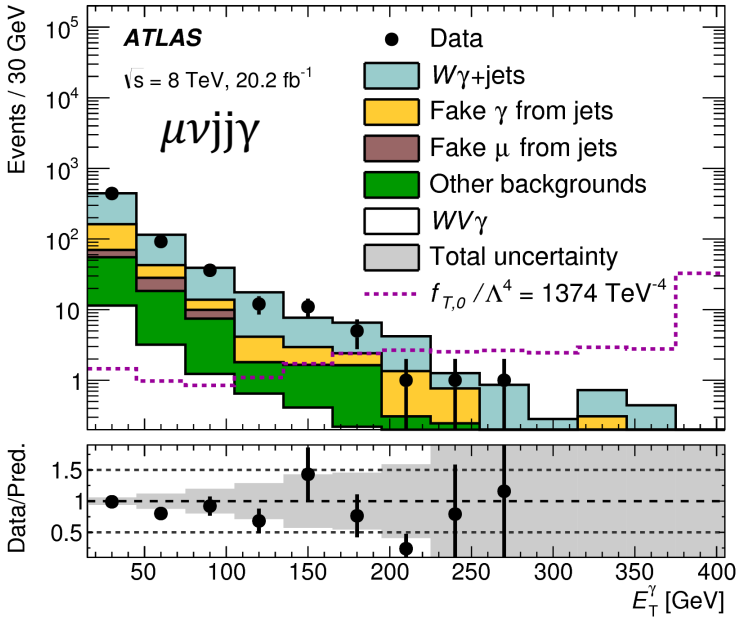
- Modelled with Sherpa (LO + 1 parton)
- $e\nu\mu\nu\gamma$ channel
  - Opposite-sign $e\mu$ pair
  - One isolated γ
  - E_T^{miss} from neutrinos
  - Only N_{jet} = 0 bin
- Fiducial cross section
  - σ_{fid} = 1.5 ± 0.9 (stat.) ± 0.5 (syst.) fb
    - 1.4 σ significance
    - 2.0 fb (theory: VBFNLO)
  - Observed limit (95% CL): 3.7 fb
    - $2.1^{+0.9}_{-0.6}$ fb (expected)

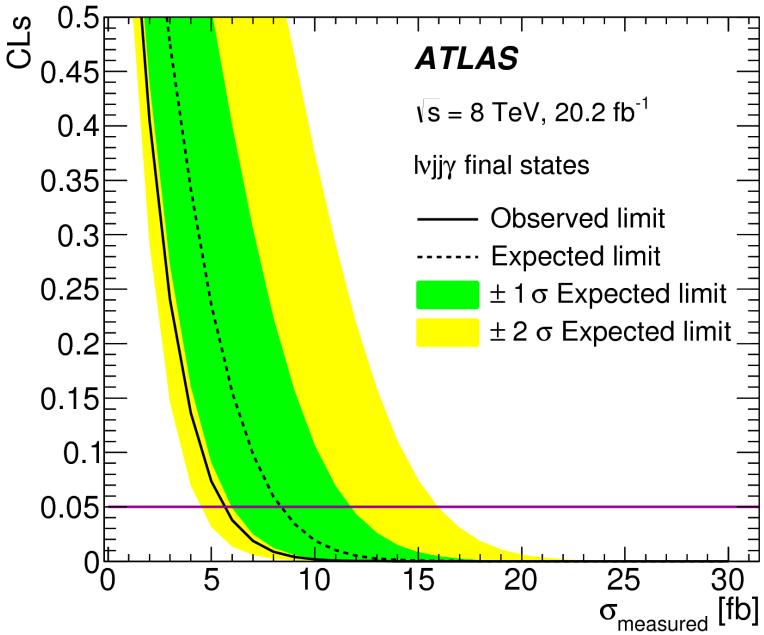


WVγ production @ 8 TeV



- $\ell\nu jj\gamma$ channel
  - One high-p_T e or μ
  - One isolated γ
  - E_T^{miss} from neutrinos
  - $\geq$ 2 jet with 70 < m_{jj} < 100 GeV
- Fiducial cross section
  - Observed limit (95% CL): 6 fb
    - $8.4^{+3.4}_{-2.4}$ fb (expected: VBFNLO)
    - Most stringent limit to date!





arXiv: 1707.05597

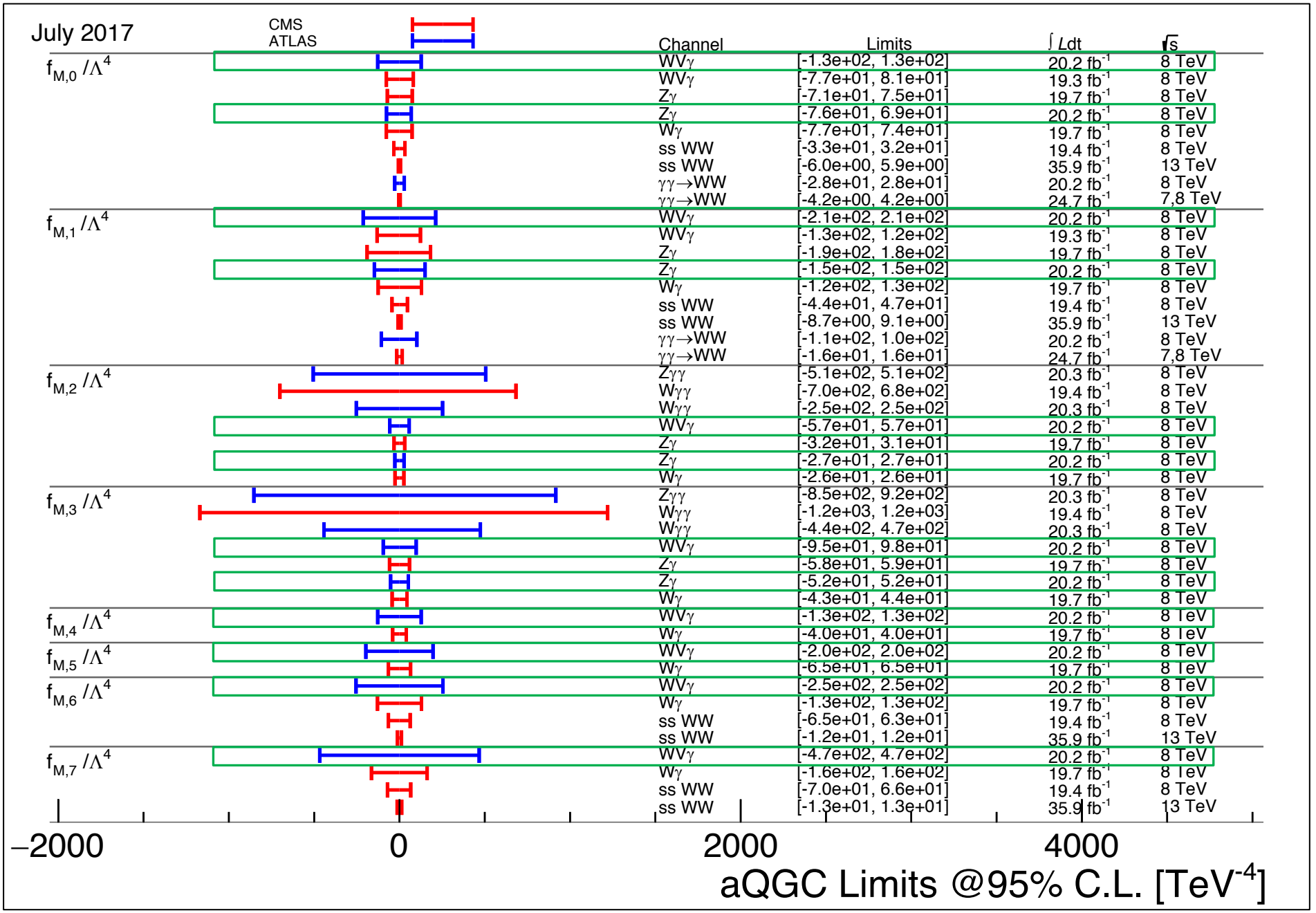
aQGC constraints

- 18 dim-8 aQGC parameters are assessed with an effective theory (Eboli *et al.*, Phys.Rev. D 74, 073005 (2006))

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{j=0}^{1} \frac{f_{S,j}}{\Lambda^4} \mathcal{O}_{S,j} + \sum_{j=0}^{7} \frac{f_{M,j}}{\Lambda^4} \mathcal{O}_{M,j} + \sum_{j=0,1,2,5,6,7} \frac{f_{T,j}}{\Lambda^4} \mathcal{O}_{T,j}$$

3,4 and 6 vanished to respect gauge invariance

  - $f_{S,j}$: only cov. derivatives of Higgs field
  - $f_{M,j}$: only field strength tensors
  - $f_{T,j}$: field strength tensors and cov. derivatives of Higgs field



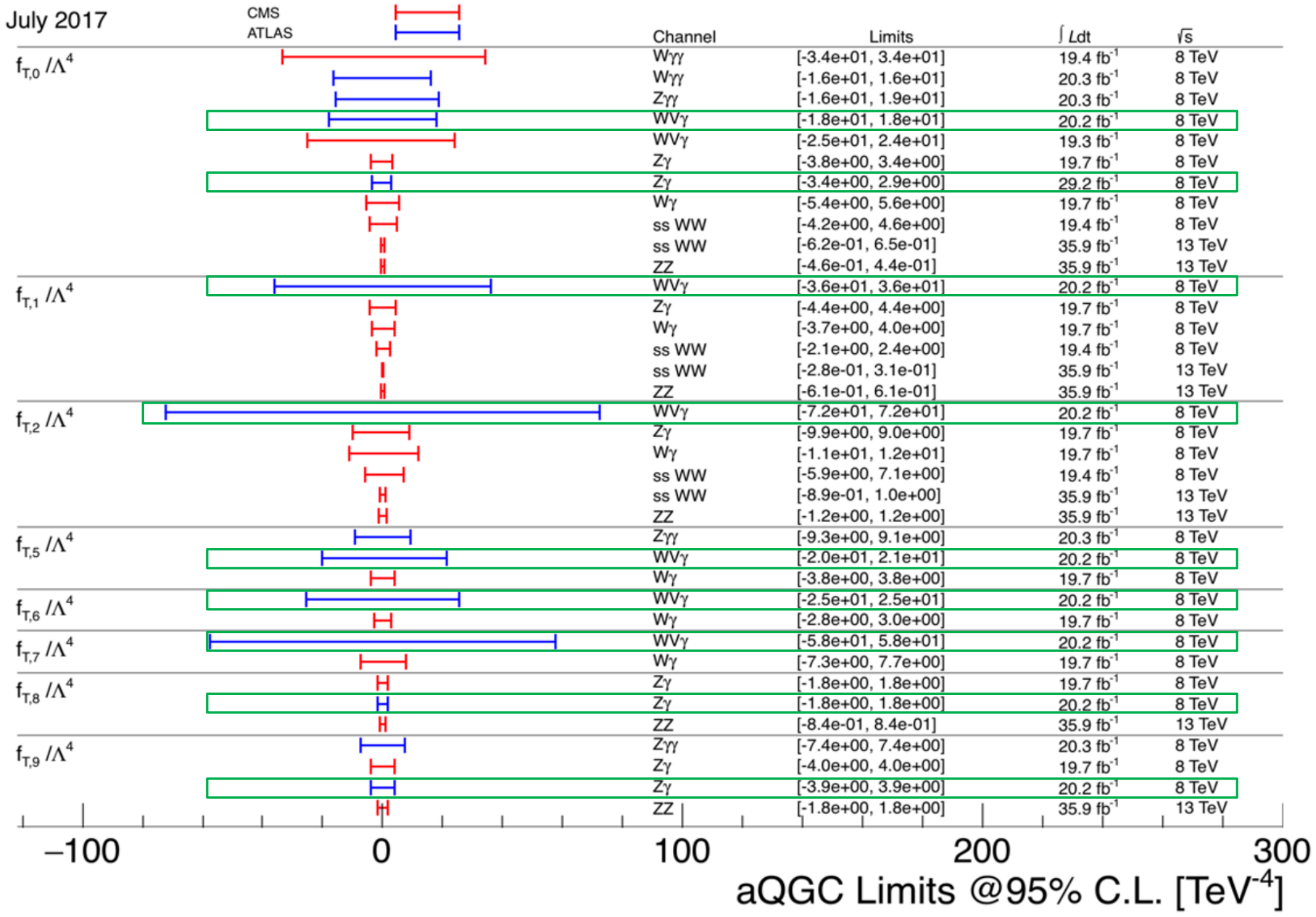
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC#aQGC_Results

JHEP07(2017)107

aQGC constraints with $Z\gamma jj$ analysis

- Madgraph formalism with $\Lambda_{FF} = \infty$

	Limits 95% CL	Measured [TeV^{-4}]	Expected [TeV^{-4}]
ATLAS $Z(\to \ell\bar{\ell}/\nu\bar{\nu})\gamma$-EWK	f_{T9}/Λ^4	$[-3.9, 3.9]$	$[-2.7, 2.8]$
	f_{T8}/Λ^4	$[-1.8, 1.8]$	$[-1.3, 1.3]$
	f_{T0}/Λ^4	$[-3.4, 2.9]$	$[-3.0, 2.3]$
	f_{M0}/Λ^4	$[-76, 69]$	$[-66, 58]$
	f_{M1}/Λ^4	$[-147, 150]$	$[-123, 126]$
	f_{M2}/Λ^4	$[-27, 27]$	$[-23, 23]$
	f_{M3}/Λ^4	$[-52, 52]$	$[-43, 43]$
CMS $Z(\to \ell\bar{\ell})\gamma$-EWK	f_{T9}/Λ^4	$[-4.0, 4.0]$	$[-6.0, 6.0]$
	f_{T8}/Λ^4	$[-1.8, 1.8]$	$[-2.7, 2.7]$
	f_{T0}/Λ^4	$[-3.8, 3.4]$	$[-5.1, 5.1]$
	f_{M0}/Λ^4	$[-71, 75]$	$[-109, 111]$
	f_{M1}/Λ^4	$[-190, 182]$	$[-281, 280]$
	f_{M2}/Λ^4	$[-32, 31]$	$[-47, 47]$
	f_{M3}/Λ^4	$[-58, 59]$	$[-87, 87]$
CMS $W(\to \ell\nu)\gamma$-EWK	f_{T0}/Λ^4	$[-5.4, 5.6]$	$[-3.2, 3.4]$
	f_{M0}/Λ^4	$[-77, 74]$	$[-47, 44]$
	f_{M1}/Λ^4	$[-125, 129]$	$[-72, 79]$
	f_{M2}/Λ^4	$[-26, 26]$	$[-16, 15]$
	f_{M3}/Λ^4	$[-43, 44]$	$[-25, 27]$



https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC#aQGC_Results

Conclusions

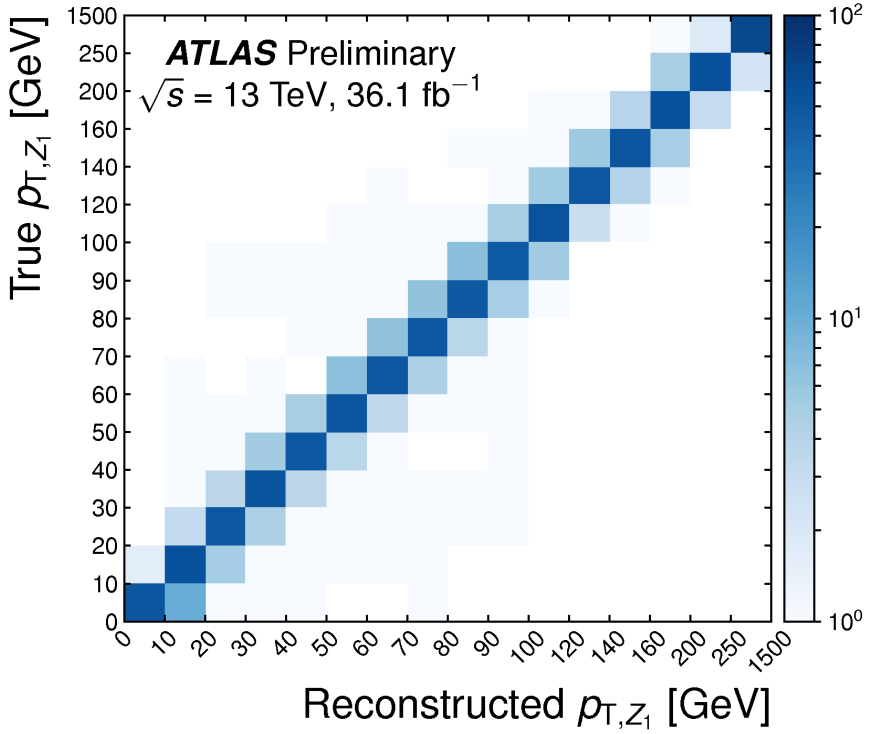
- Showcased the full ATLAS multiboson programme
- Diboson productions:
  - 13 TeV analysis for ZZ, WZ and WW with full-leptonic modes
    - Accurate validations of SM at NNLO with ≤10% precision
  - Adding sensitivity, in particular to aTGCs, with semileptonic modes
    - Developing new analysis technique (boosted jet reconstruction)
- Triboson productions and VBS:
  - ATLAS has more > 3.0 σ evidence
    - SM VBS ssWW (Phys. Rev. D 96, 012007)
    - Exclusive $\gamma\gamma \rightarrow$ WW (Phys.Rev.D 94, 032011(2016)
    - Triboson W$\gamma\gamma$ (Phys.Rev.Lett. 115 (2015) 3, 031802)
  - ATLAS measurements started setting stringent constraints on aQGCs
- No evidence for the BSM physics yet
  - Continue setting ever more stringent constraints on aTGCs/ aQGCs

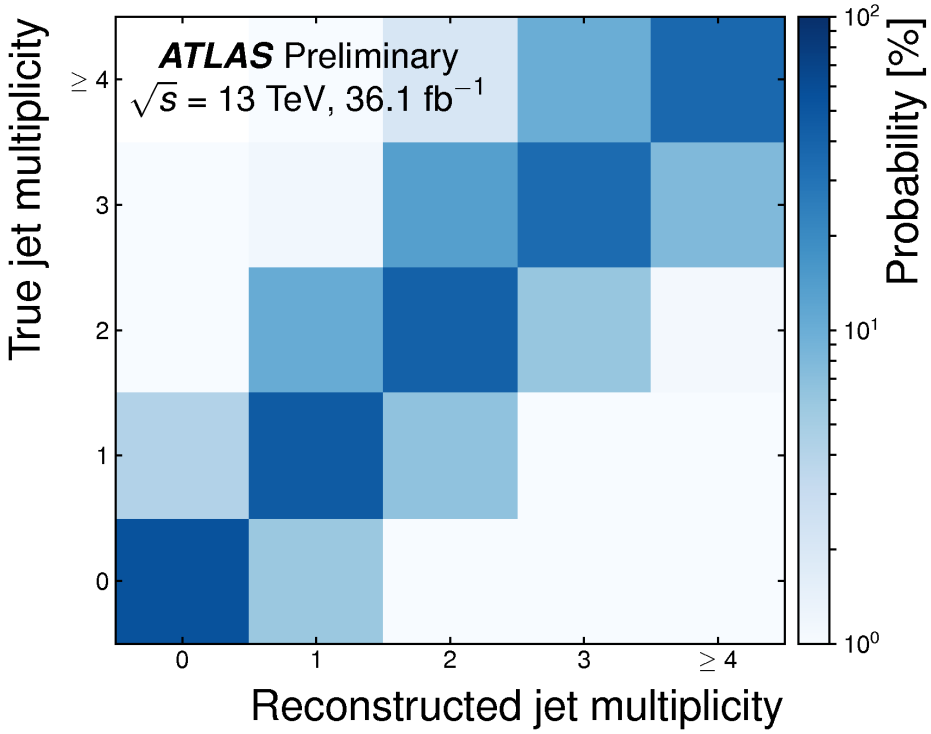
Back up

ZZ full-leptonic @ 13 TeV

- R*ij* are defined as the probability of an event in true bin *j* being observed with the detector in bin *i*

$$m_i = R_{ij} t_j.$$





arXiv: 1702.04519

WW full-leptonic @ 13 TeV

$pp \to WW$ sub-process	Order of α_s	σ^{tot}_{WW} [pb]	A [%]	$\sigma^{fid}_{WW\to e\mu}$ [fb]
$q\bar{q}$ [9,13]	$\mathcal{O}(\alpha_s^2)$	111.1 ± 2.8	16.20 ± 0.13	$422 \,^{+12}_{-11}$
gg (non-resonant) [33]	$\mathcal{O}(\alpha_s^3)$	$6.82 \,^{+0.42}_{-0.55}$	$28.1 \,^{+2.7}_{-2.3}$	44.9 ± 7.2
$gg \to H \to WW$ [67][30]	$\mathcal{O}(\alpha_s^5)$ tot. / $\mathcal{O}(\alpha_s^3)$ fid.	$10.45 \,^{+0.61}_{-0.79}$	4.5 ± 0.6	11.0 ± 2.1
$q\bar{q}$ + gg (non-resonant) + $gg \to H \to WW$	nNNLO+H	$128.4 \,^{+3.5}_{-3.8}$	$15.87 \,^{+0.17}_{-0.14}$	478 ± 17