# Multiboson production in ATLAS and CMS

SUSY 2018

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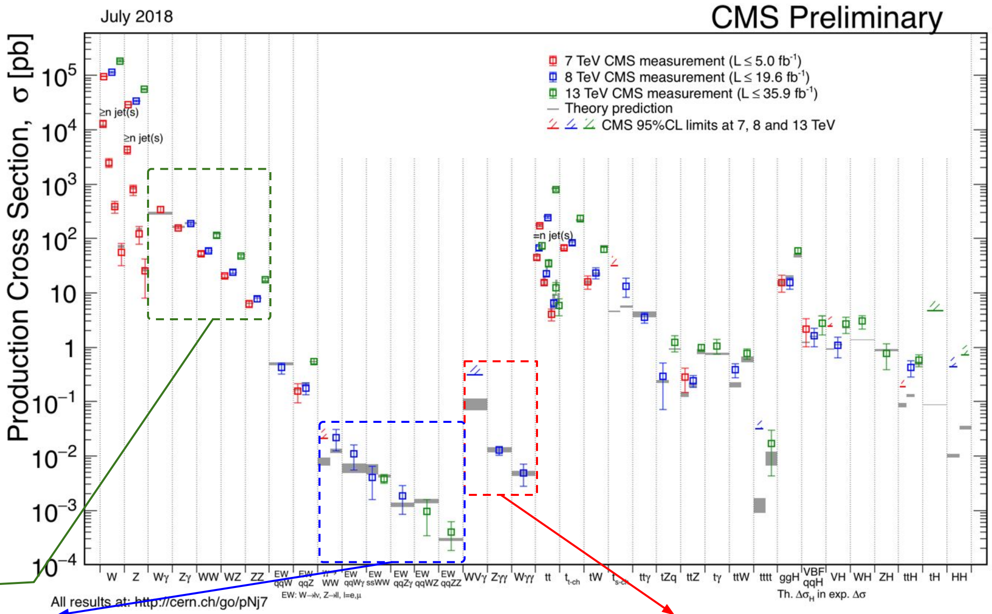
# Motivation

⇢ Multiboson production provides a unique probe to the electroweak sector of the SM. Provide further insight in the vector bosons' self interactions.

⇢ Great sensitivity to different BSM physics. Any deviation on the measurements can be pointing to new physics!




## Diboson production (inclusive)

⇢ Higher cross-sections.
⇢ Era of **precision measurements**.
⇢ Differential measurements.
⇢ Sensitive to anomalies in triple gauge couplings (TGC).

## VBS/VBF production

⇢ Very low cross-sections.
⇢ First **observations** at 13 TeV**.**
⇢ Sensitivity to both triple and quartic gauge couplings**.**
⇢ Discussed in next talk.

## Triboson production

⇢ Very rare processes. Final states usually overlapping with diboson processes.
⇢ Starting to see **observations** or **evidences**.

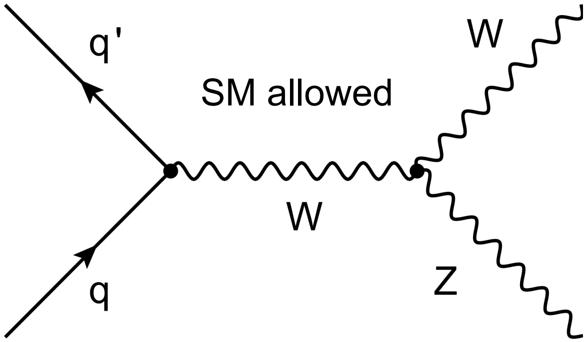
# Anomalous gauge couplings

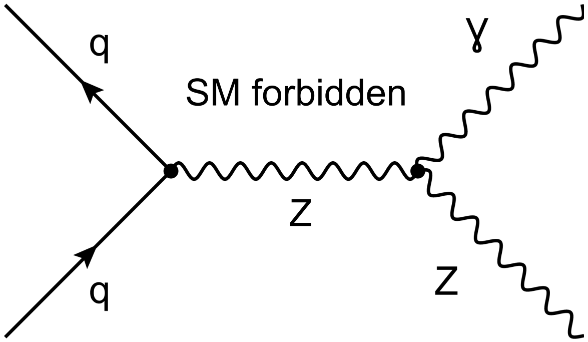
⇢ Most multiboson channels are sensitive to BSM processes through what effectively are “anomalous” alterations of the triple and quadruple gauge couplings (aTGC and aQGC).

⇢ Most measurements are complemented with searches for anomalous couplings. Sensitivity is increased at higher effective energies, i.e., high values of $m_{VV}$ , $m_{VVV}$.

⇢ Different approaches (~different BSM lagrangian terms) are used in each analysis.

⇢ Both variations of couplings allowed and forbidden in the SM:



# Recent results in multiboson measurements

- Multiboson production is currently a very active area of research both at ATLAS and CMS.

- Today we focus on the most recent results from both collaborations:

Most recent results (ICHEP)

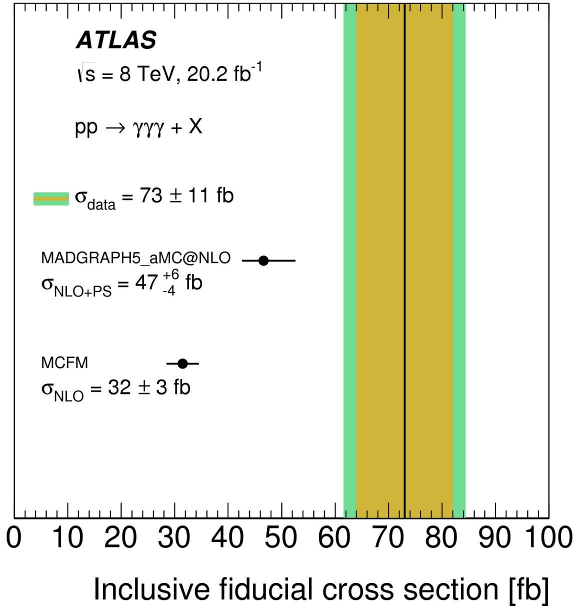
  - $pp \rightarrow WZ \rightarrow 3l\nu$ (13 TeV, L=35.9 $fb^{-1}$) **SMP-PAS-18-002**
  - $pp \rightarrow WZ \rightarrow 3l\nu$ (13 TeV, L=35.9 $fb^{-1}$) **CONF-2018-034**
  - $pp \rightarrow ZZ \rightarrow 4l$ (13 TeV, L=35.9 $fb^{-1}$) **Eur. Phys. J. C 78 (2018) 165**
  - $pp \rightarrow ZZ + jets \rightarrow 4l + jets$ (8TeV,19.7 $fb^{-1}$ + 13 TeV,35.9 $fb^{-1}$) **SMP-17-005** (submitted to Phys.Lett.B)
  - $pp \rightarrow ZZ \rightarrow 4l$ (13 TeV, L=35.9 $fb^{-1}$) **Phys. Rev. D 97 (2018), 032005**
  - $pp \rightarrow Z\gamma \rightarrow \nu\nu\gamma$ (13 TeV, L=35.9 $fb^{-1}$) **CONF-2018-035**
  - $pp \rightarrow \gamma\gamma\gamma$ (8 TeV, L=35.9 $fb^{-1}$) **Phys. Lett. B 781 (2018) 55**

# γγγ production at ATLAS (8 TeV)

Phys. Lett. B 781 (2018) 55

⇢ Selected based on the "clean" final state with 3 isolated photons. Main backgrounds arise from misidentified objects.

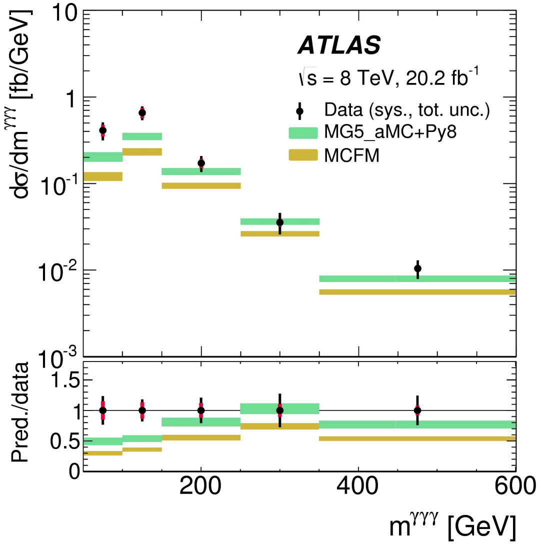
| Requirements on | Phase-space region |
|---|---|
| $E_{\mathrm{T}}^{\gamma}$ | $E_{\mathrm{T}}^{\gamma 1} > 27$ GeV, $E_{\mathrm{T}}^{\gamma 2} > 22$ GeV, $E_{\mathrm{T}}^{\gamma 3} > 15$ GeV |
| $m^{\gamma\gamma\gamma}$ | $m^{\gamma\gamma\gamma} > 50$ GeV |
| $\Delta R^{\gamma\gamma}$ | $\Delta R^{\gamma\gamma} > 0.45$ |
| $\lvert\eta^{\gamma}\rvert$ | $\lvert\eta^{\gamma}\rvert < 2.37$ (excluding $1.37 < \lvert\eta^{\gamma}\rvert < 1.56$) |
| Isolation | $E_{\mathrm{T}}^{\mathrm{iso}} < 10$ GeV |




⇢ Excess over SM predictions. Expect sizable NNLO corrections (as for γγ).

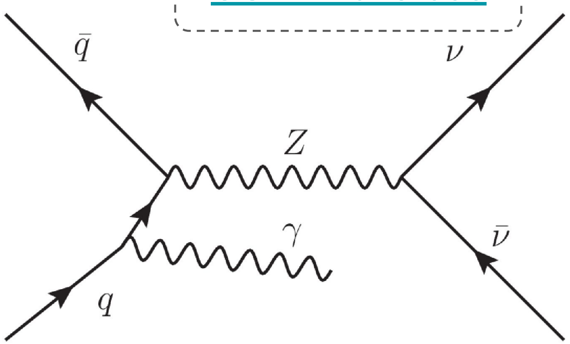
⇢ Dominated by uncertainties in photon identification and isolation.

⇢ Differential measurements for multiple kinematical variables of the photons.



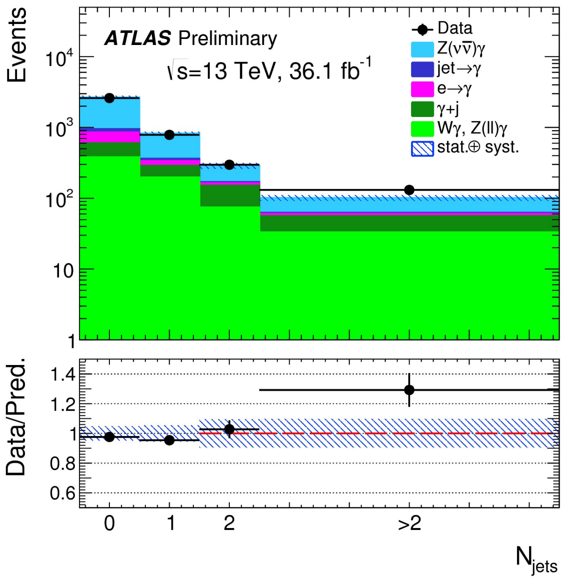
# $Z\gamma$ ($\nu\nu\gamma$) production at ATLAS (13 TeV)

CONF-2018-035




- Select exactly 1 isolated photon and high $p_T^{miss}$ > 150 GeV. Further criteria:
  - Reduce the "fake" $p_T^{miss}$: **$(p_T^{miss})^2/[(p_T^{jet})^2+(p_T^{\gamma})^2]$ > 110 GeV**
  - Reduce W+$\gamma$ backgrounds: **0 leptons**, **$\Delta\phi(\gamma, p_T^{miss})$ > $\pi/2$**

- Measurement in exclusive ($N_J$=0) and inclusive ($N_J \geq 0$) categories.




| $\sigma^{\text{ext.fid.}}$ [fb] Measurement | $\sigma^{\text{ext.fid.}}$ [fb] NNLO MCFM Prediction |
|---|---|
| $N_{\text{jets}} \geq 0$ | |
| $83.7^{+3.6}_{-3.5}$ (stat.)$^{+6.9}_{-6.2}$ (syst.)$^{+1.7}_{-2.0}$ (lumi.) | $78.1 \pm 0.2$(stat.)$\pm 4.4$(syst.) |
| $N_{\text{jets}} = 0$ | |
| $52.4^{+2.4}_{-2.3}$ (stat.)$^{+4.0}_{-3.6}$ (syst.)$^{+1.2}_{-1.1}$ (lumi.) | $55.9 \pm 0.1$(stat.)$\pm 2.5$(syst.) |

- Good agreement with NNLO predictions.

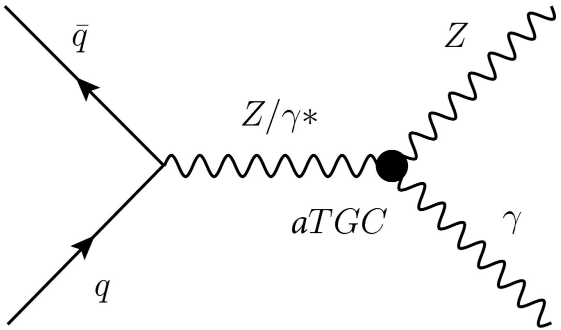
- Dominated by photon isolation and identification efficiency uncertainties.

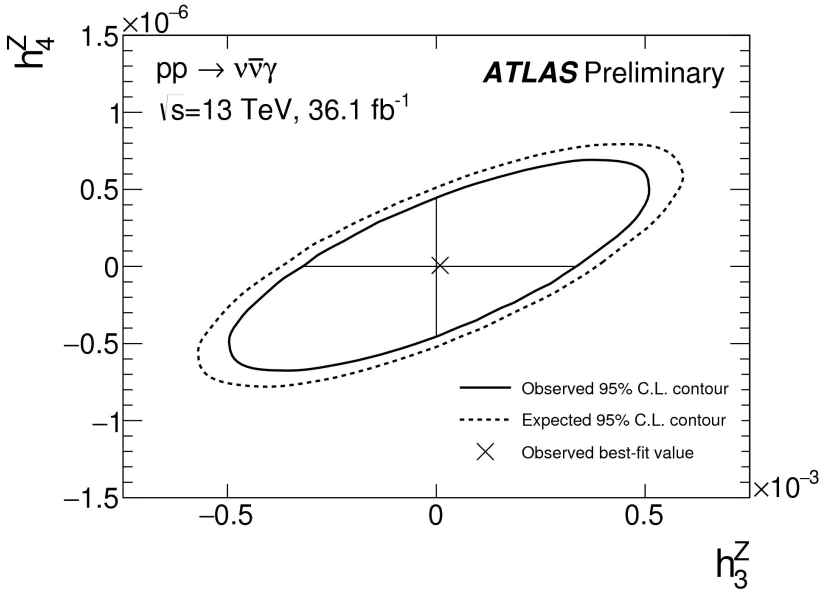
- Also measured differential results in $p_T^{\gamma}$, $p_T^{\nu\nu}$, $N_{Jet}$ in good agreement with NNLO predictions.

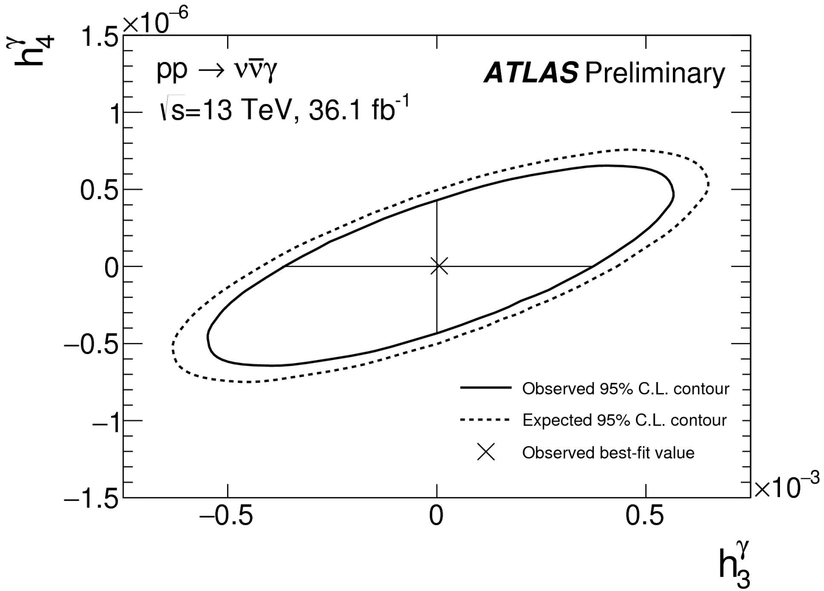
# $Z\gamma$ ($\nu\nu\gamma$) aQGC at ATLAS (13 TeV)

CONF-2018-035

- Restricting selection to $p_T^{\gamma}$ > 600 GeV.
- Using the effective vertex approach.
- CL are set based on the predicted cross-section (yields) for each configuration of aQGC parameters.



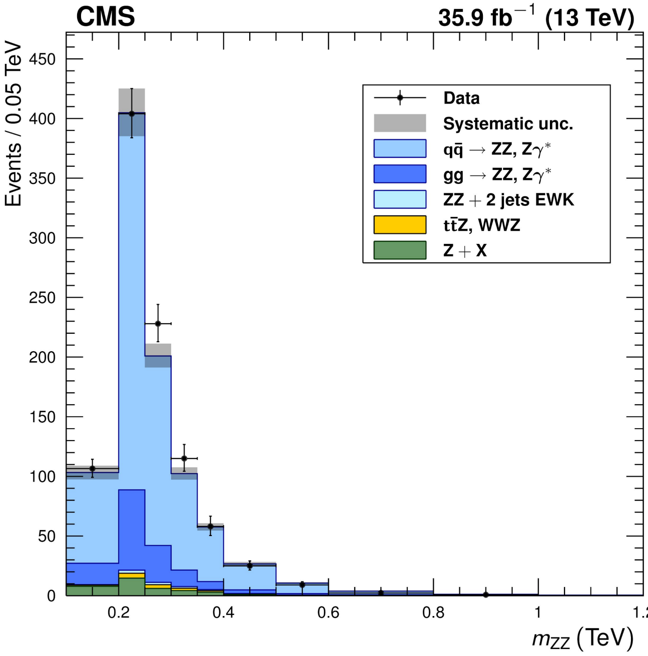



# ZZ (+jets) production (CMS, 8+13 TeV)

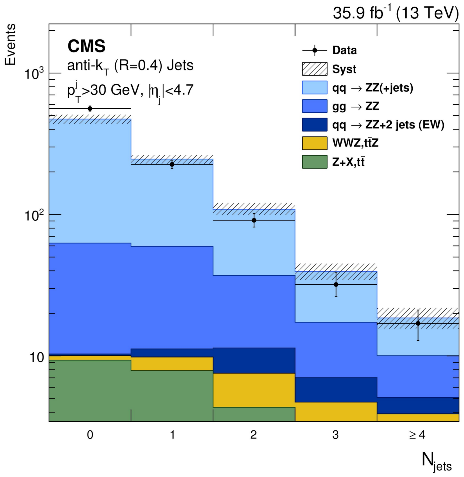
Eur. Phys. J. C 78 (2018) 165 (SMP-17-005)

- Selection based on 4 leptons that reconstruct 2 Z candidates: 60 GeV < m(Z1), m(Z2) < 120 GeV.
- Very "clean" final state with few contributions from ttV and triboson background processes.
- Measurements are dominated by the uncertainty in the total lepton identification efficiency.

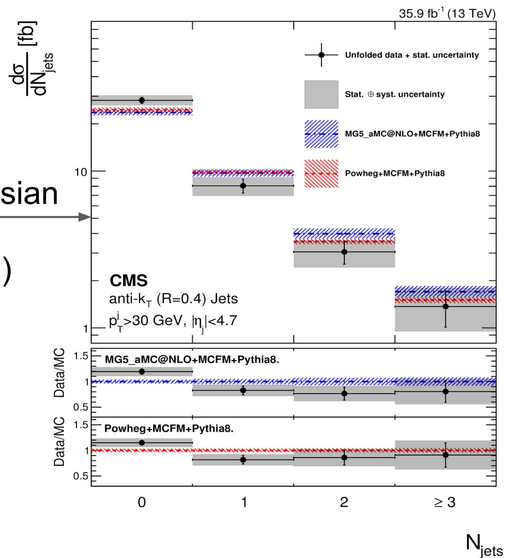



$$\sigma(\mathrm{pp} \rightarrow \mathrm{ZZ}) = 17.2 \pm 0.5\ (\mathrm{stat})\ \pm 0.7\ (\mathrm{syst})\ \pm 0.4 (\mathrm{theo}) \pm 0.4\ (\mathrm{lumi})\mathrm{pb}$$

- Results in agreement with NNLO predictions: $\sigma^{NNLO}(\mathrm{pp} \rightarrow \mathrm{ZZ}) = 16.2^{+0.6}_{-0.4}\mathrm{pb}$
- Differential results based on lepton and jets kinematics:



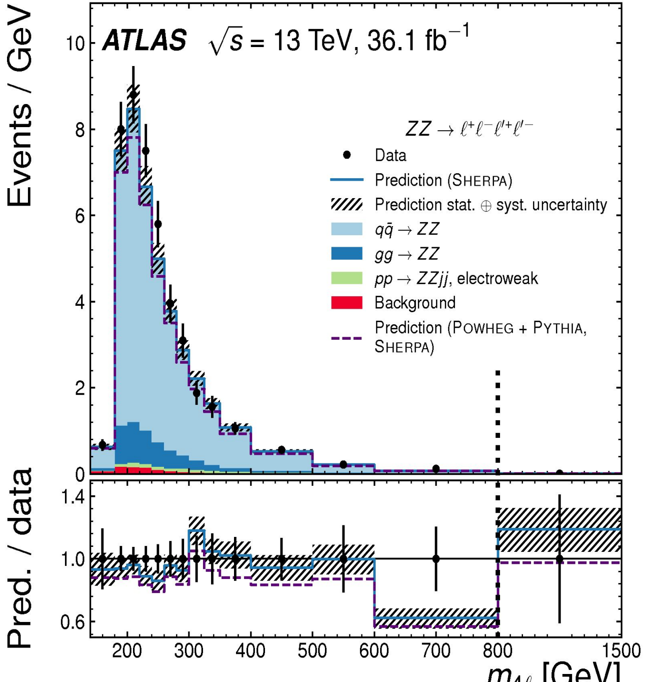

Iterative Bayesian Unfolding (d'Agostini)



# ZZ production (ATLAS, 13 TeV)

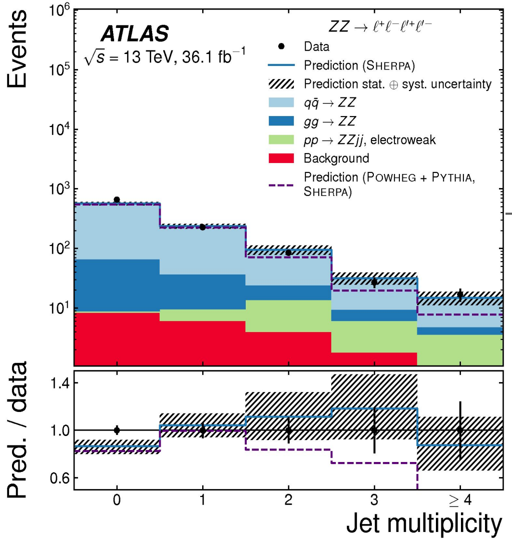
Phys. Rev. D 97 (2018), 032005

- Selection based on 4 leptons, more restricted in mass window: 66 GeV < m(Z1), m(Z2) < 116 GeV.
- Very similar strategy and final states as in the CMS analysis. Slightly different lepton $p_T$ requirements.
- Measurements are dominated by the uncertainty in the lepton identification efficiency and in luminosity.

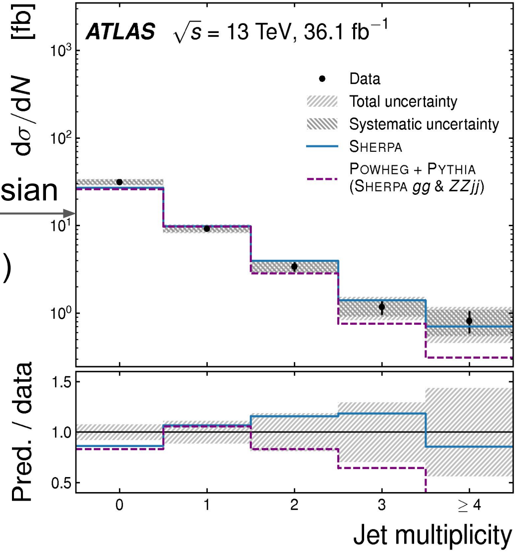



$$\boxed{\sigma(\mathrm{pp} \to \mathrm{ZZ}) = 17.3^{+0.9}_{-0.6}(\mathrm{stat.}) \pm 0.5(\mathrm{syst.}) \pm 0.6(\mathrm{lumi.})\ \mathrm{pb}}$$

- Results in agreement with NNLO predictions: $\sigma^{NNLO}(\mathrm{pp} \to \mathrm{ZZ}) = 16.9^{+0.6}_{-0.5}$ pb
- Differential results based on lepton and jets kinematics:




Iterative Bayesian Unfolding (d'Agostini)



# ZZ aTGC (ATLAS + CMS, 13 TeV)

Eur. Phys. J. C 78 (2018) 165
Phys. Rev. D 97 (2018), 032005

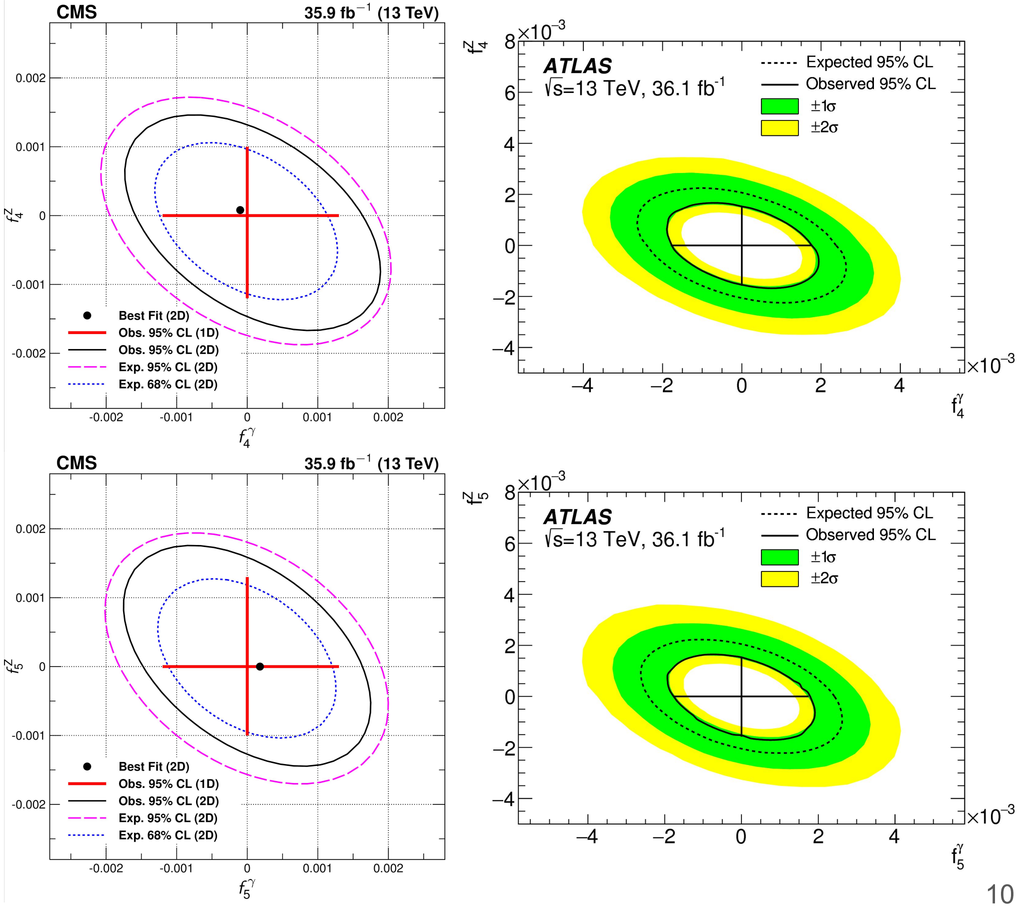
⇢ Searching for aTGC in the effective vertex approach. Based on the assumption of quadratic dependance of the expected yields on each aTGC parameter.

⇢ ATLAS: $p_T^{Z1}$ as the discrimination variable.

⇢ CMS: $m_{ZZ}$ as the discrimination variable.

⇢ Results are quite consistent between both experiments, slightly smaller confidence regions in the case of CMS.

⇢ Very good agreement with SM predictions.



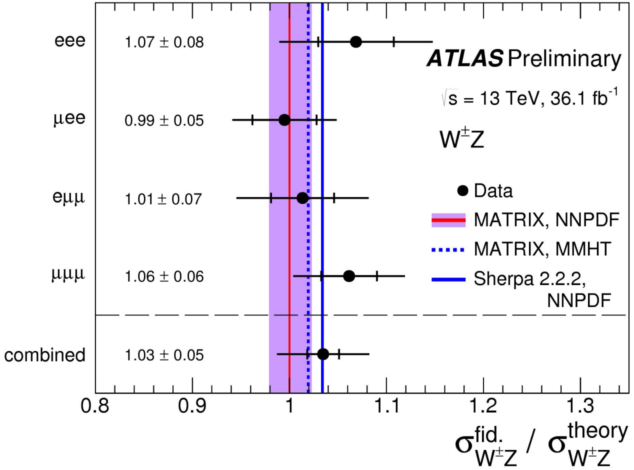
# WZ production (ATLAS, 13 TeV)

CONF-2018-034

⇢ Require exactly 3 isolated light leptons with a Z candidate: $|m_{ll} - m_Z| < 10$ GeV. Tag Z leptons based on the best reconstructed Z mass ($Z_1$, $Z_2$). The remaining lepton is tagged as W. “Reconstruct” full event.

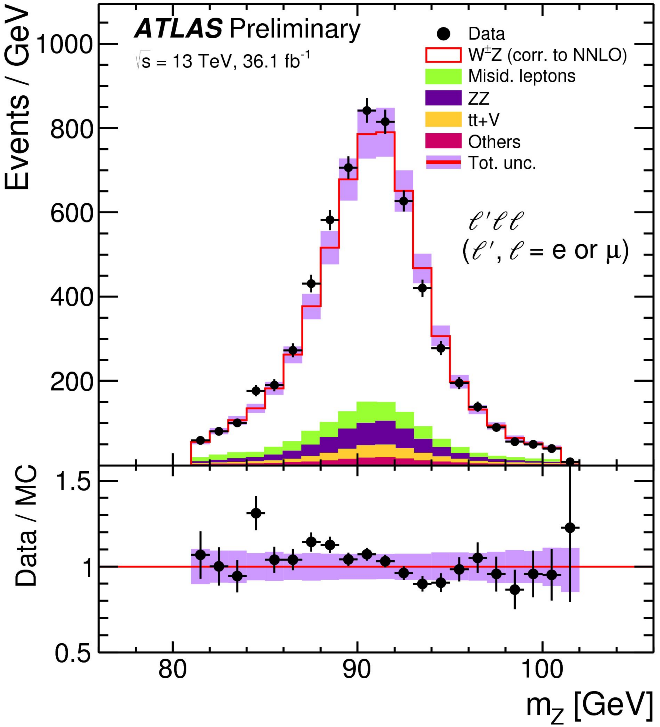
Additional background reduction criteria

- Reduce non-prompt leptons (Z+jets): $m_T^W > 30$ GeV
- Reduce non-prompt leptons: tighter W lepton.
- Reduce ZZ: veto 4th lepton.




⇢ Systematics dominated by b-tagging and lepton efficiency uncertainties.

⇢ Measurements are provided for the fiducial region.



# WZ production (CMS, 13 TeV)

SMP-PAS-18-002

⇢ Require exactly 3 isolated light leptons with a Z candidate: **$|m_{ll}$ - $m_Z| < 15$ GeV**. Tag Z leptons based on the best reconstructed Z mass ($Z_1$, $Z_2$). The remaining lepton is tagged as W. "Reconstruct" full event.

Additional background reduction criteria

- **Reduce asymmetric γ conversions (Zγ): $m_{3l} > 100$ GeV**
- Reduce non-prompt leptons (Z+jets): $p_T^{miss} > 30$ GeV
- **Reduce top-enriched processes: $N_{b\text{-}tag} = 0$**
- Reduce ZZ: veto 4th lepton.

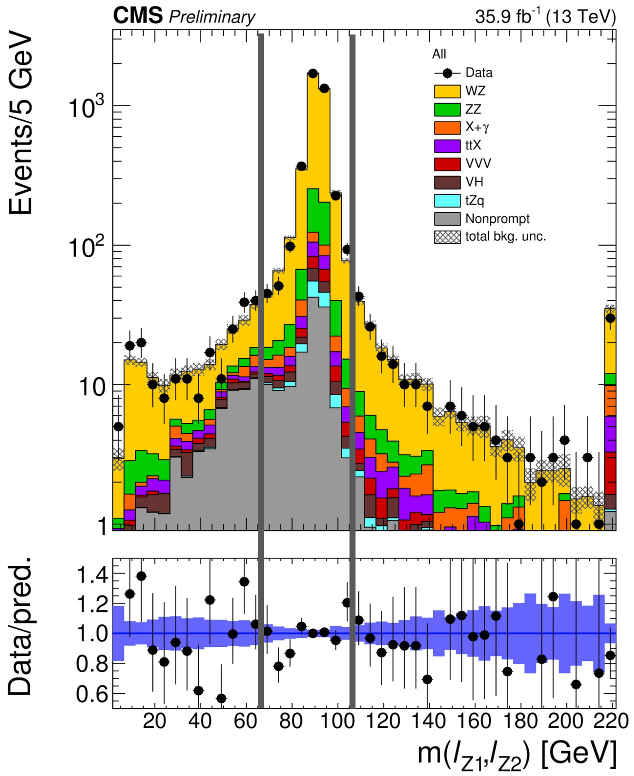
⇢ Results are dominated by uncertainties in b-tagging and lepton efficiencies.

⇢ Measurements in the mass window: 60 GeV < $|m_{ll}$ - $m_Z|$ < 120 GeV

| Category | $\sigma_{\text{tot}}(\text{pp} \to \text{WZ})$ [pb] |
|---|---|
| eee | $47.11^{+5.01}_{-4.63}\,(\text{total}) = 47.11\,^{+2.88}_{-2.79}\,(\text{stat})\,^{+0.46}_{-0.41}(\text{theo})\,^{+3.89}_{-3.47}\,(\text{syst}) \pm 1.41(\text{lumi})$ |
| $ee\mu$ | $47.16^{+3.87}_{-3.61}\,(\text{total}) = 47.16\,^{+2.31}_{-2.29}\,(\text{stat})\,^{+0.45}_{-0.38}(\text{theo})\,^{+2.83}_{-2.52}\,(\text{syst}) \pm 1.33(\text{lumi})$ |
| $e\mu\mu$ | $47.70^{+3.58}_{-3.55}\,(\text{total}) = 47.70\,^{+2.00}_{-1.96}\,(\text{stat})\,^{+0.45}_{-0.39}(\text{theo})\,^{+2.66}_{-2.61}\,(\text{syst}) \pm 1.42(\text{lumi})$ |
| $\mu\mu\mu$ | $49.00^{+3.18}_{-3.03}\,(\text{total}) = 49.00\,^{+1.57}_{-1.53}\,(\text{stat})\,^{+0.41}_{-0.35}(\text{theo})\,^{+2.42}_{-2.22}\,(\text{syst}) \pm 1.39(\text{lumi})$ |

$$\boxed{\sigma_{\text{Tot}}(\text{pp} \to \text{WZ}) = 48.09^{+2.98}_{-2.78}\ \text{pb} = 48.09\ ^{+1.00}_{-0.96}\ (\text{stat})\ ^{+0.44}_{-0.37}\ (\text{theo})\ ^{+2.39}_{-2.17}\ (\text{syst}) \pm 1.39\ (\text{lumi})\ \text{pb}}$$

⇢ In agreement with NNLO prediction: $\sigma^{NNLO}(\text{pp} \to \text{WZ}) = 49.9^{+1.1}_{-1.0}$ pb



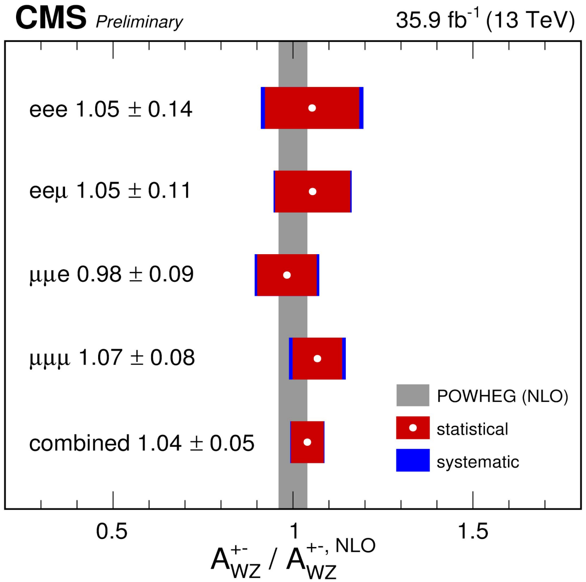
# WZ charge asymmetry (ATLAS+CMS 13 TeV)

SMP-PAS-18-002
CONF-2018-034

- Both collaborations provide results, split by flavor categories, of the charge asymmetry: $A^{+-} = \frac{\sigma(\mathrm{pp} \to \mathrm{W}^+\mathrm{Z})}{\sigma(\mathrm{pp} \to \mathrm{W}^-\mathrm{Z})}$
- Both results are in complete agreement and dominated by statistical uncertainties.

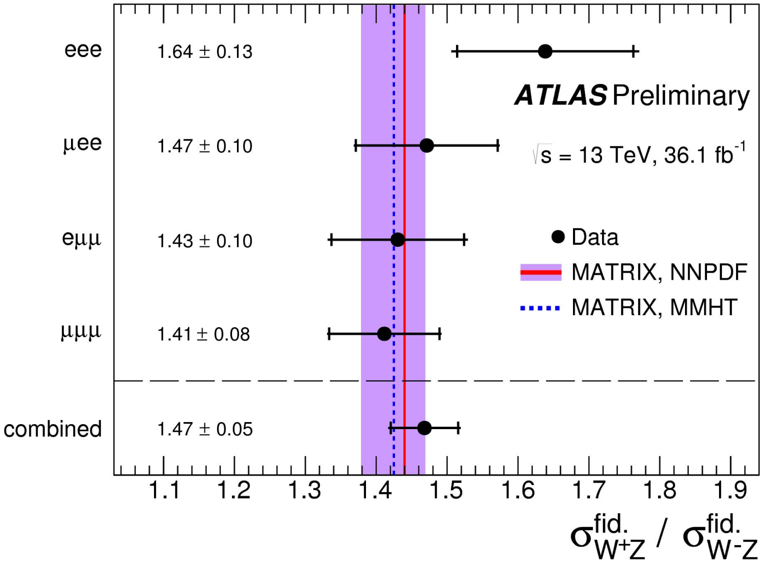
## Measured at "total" cross-section level

$$\frac{\sigma(\mathrm{pp} \to \mathrm{W}^+\mathrm{Z})}{\sigma(\mathrm{pp} \to \mathrm{W}^-\mathrm{Z})} = 1.48 \pm 0.06 \;(\mathrm{stat}) \pm 0.02 \;(\mathrm{syst}) \pm 0.01 \;(\mathrm{theo})$$




## Measured at "fiducial" cross-section level

$$\frac{\sigma^{\mathrm{fid.}}_{W^+Z\to\ell'\nu\ell\ell}}{\sigma^{\mathrm{fid.}}_{W^-Z\to\ell'\nu\ell\ell}} = 1.47 \pm 0.05\,(\mathrm{stat.}) \pm 0.02\,(\mathrm{sys.})$$



# WZ differential cross-section (ATLAS+CMS 13 TeV)

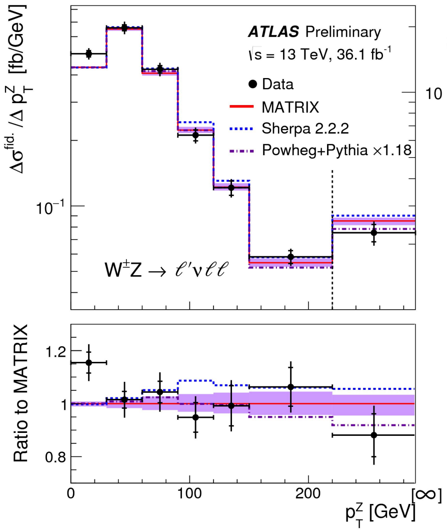
SMP-PAS-18-002
CONF-2018-034

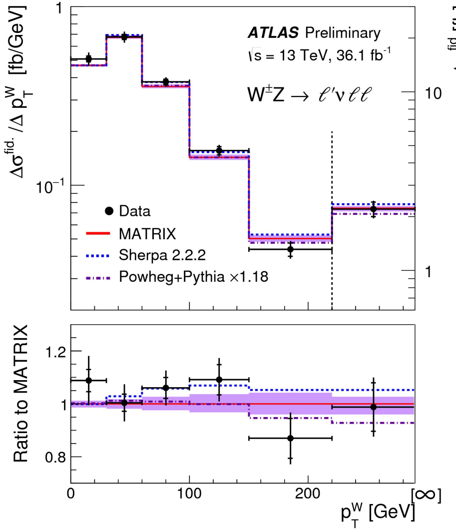
⇢ Both collaborations provide differential results in similar variables with slightly different strategies.

## ATLAS

⇢ Unfolding with iterative Bayesian (d'Agostini) algorithm. Bins are chosen based on statistical power and experimental resolution.

⇢ Providing additional angular variables.

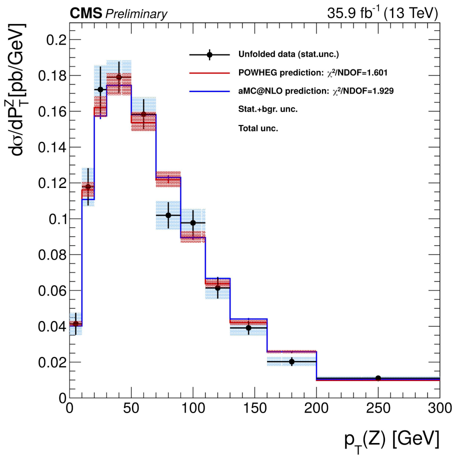


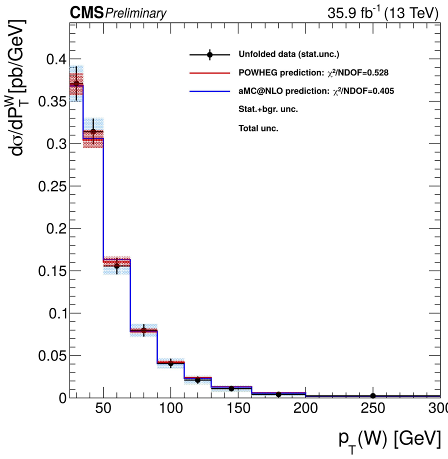




## CMS

⇢ Unfolding based on an area constrain regularization. Bins widths are chosen requiring additional stability of the unfolding procedure.

⇢ Providing measurements split by flavour.

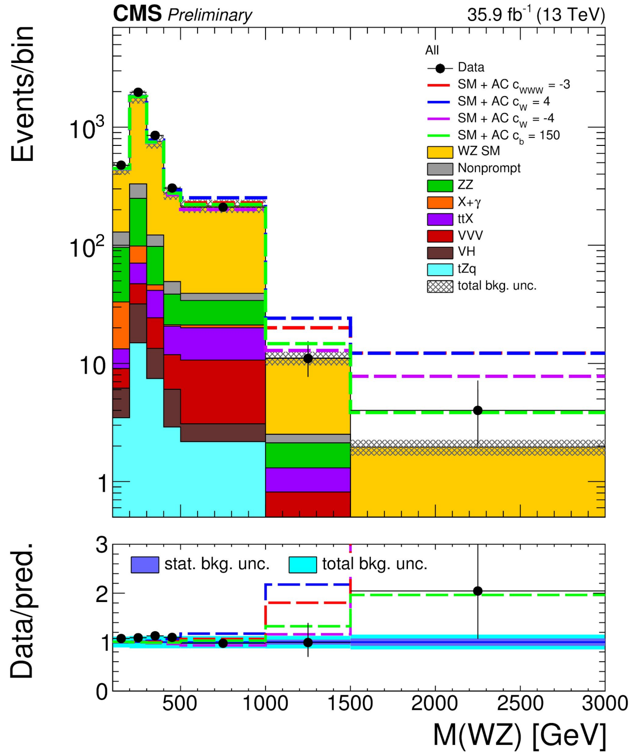


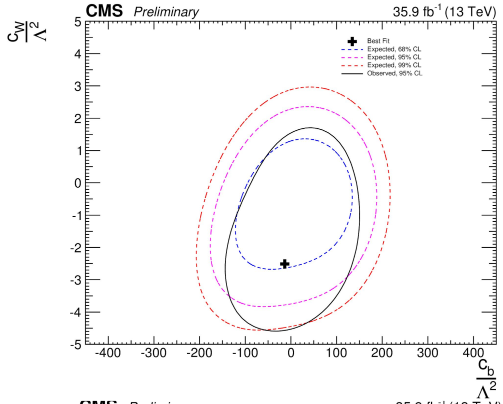



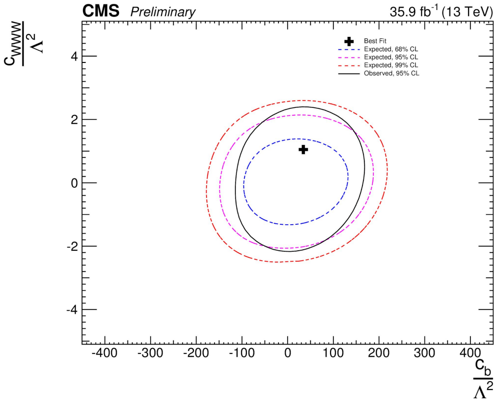
# WZ aTGC (CMS 13 TeV)

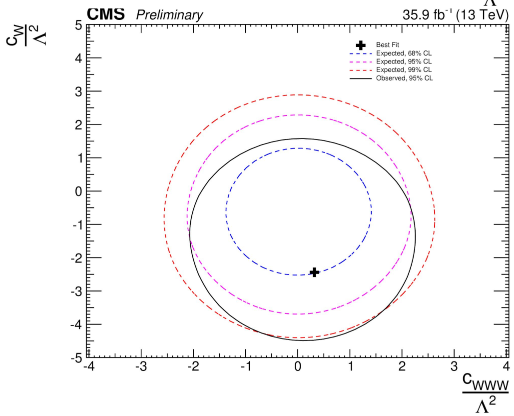
SMP-PAS-18-002

- Results at 13 TeV are only provided by CMS. Using the EFT approach.
- Signal assumptions: aTGC signal is built as a second degree polynomial on the 3 aTGC parameters.



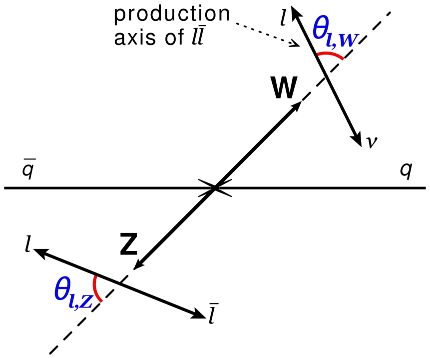




- Results are consistent with SM predictions for all sets of parameters.
- Small 1σ deviations appear due to the excess in the last bin, compatible with an statistical fluctuation.

# WZ polarization (ATLAS 13 TeV)

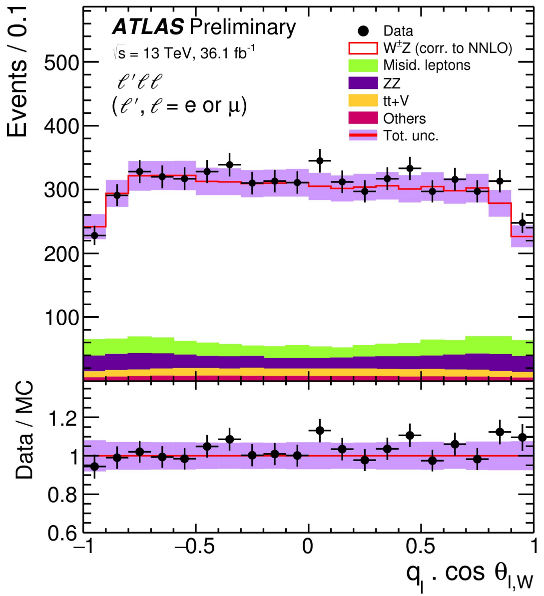
CONF-2018-034




- Results at 13 TeV are only provided by ATLAS. Measuring polarization parameters:

$$\frac{1}{\sigma_{W^\pm Z}}\frac{d\sigma_{W^\pm Z}}{d\cos\theta_{\ell,W}} = \frac{3}{8}f_L(1\mp\cos\theta_{\ell,W})^2 + \frac{3}{8}f_R(1\pm\cos\theta_{\ell,W})^2 + \frac{3}{4}f_0\sin^2\theta_{\ell,W}$$

- The neutrino's momentum is obtained applying a W mass constraint.
- $f_L$ - $f_R$ and $f_0$ measured with a binned likelihood fit to the $\cos(\theta_{l,V})$ distributions.

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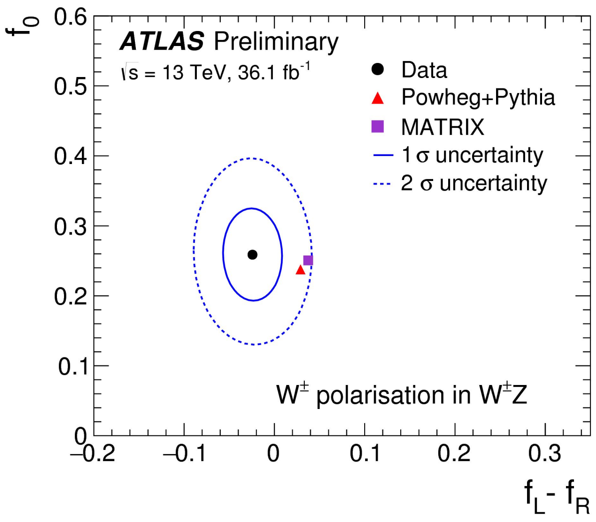



- Results are dominated by statistical uncertainties.
- Small tension but still within 2σ of SM predictions.
- Very close to observation of longitudinally polarized W bosons: 4.2 (3.8) observed (expected) significance.

# Conclusions

⇢ Multiboson production keeps providing us with new ways of exploring the properties of the SM's EWK sector with higher and higher predictions.

⇢ We are already at the precision era for diboson processes but our understanding of the SM can still increase with even better measurements.

⇢ The reach in anomalous couplings searches increases steadily, expect our sensitivity to BSM physics only to grow in the next years.

⇢ The observation frontier is now set at triboson processes. Associated production with jets is now also accessible.

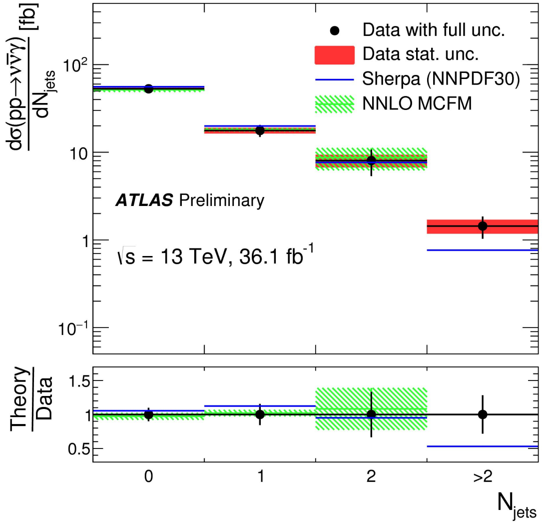
# Back-Up

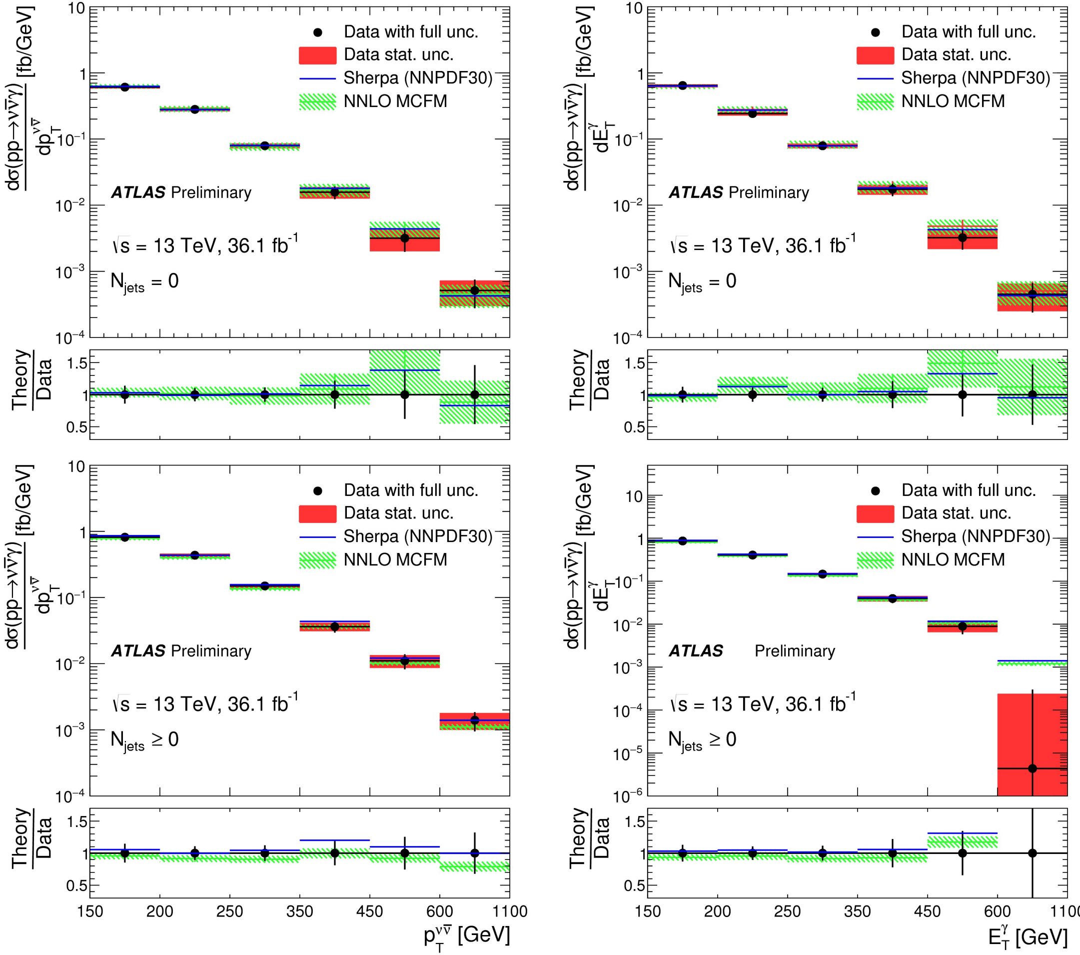
# Zγ (ννγ) (differential) at ATLAS (13 TeV)

CONF-2018-035

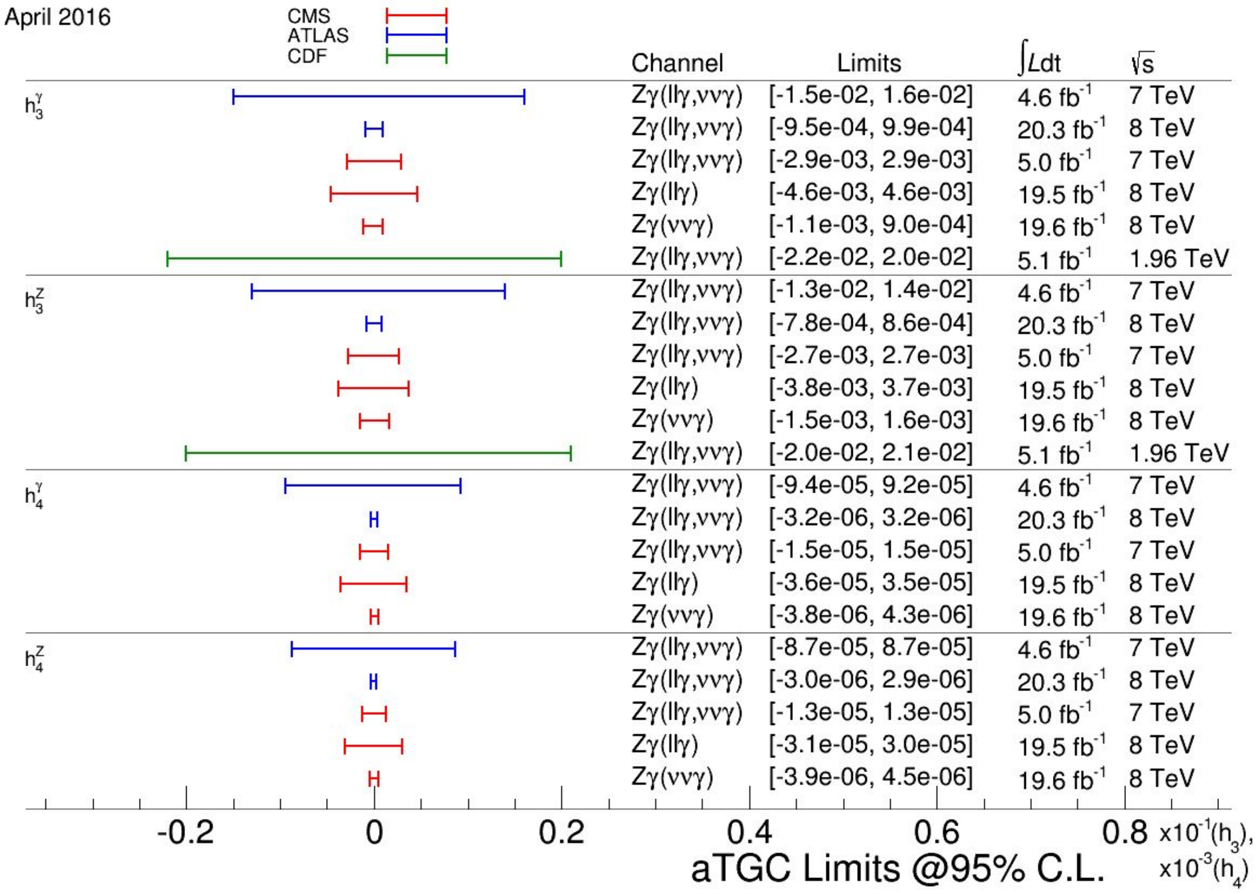
⇢ Using iterative Bayesian unfolding methods.

⇢ Good agreement with NNLO MC predictions.



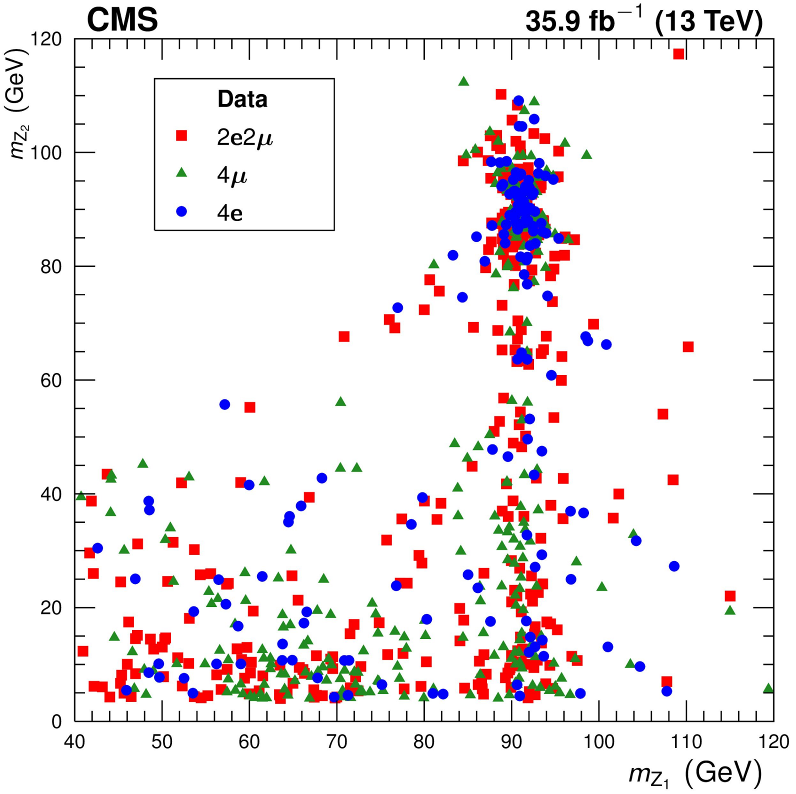



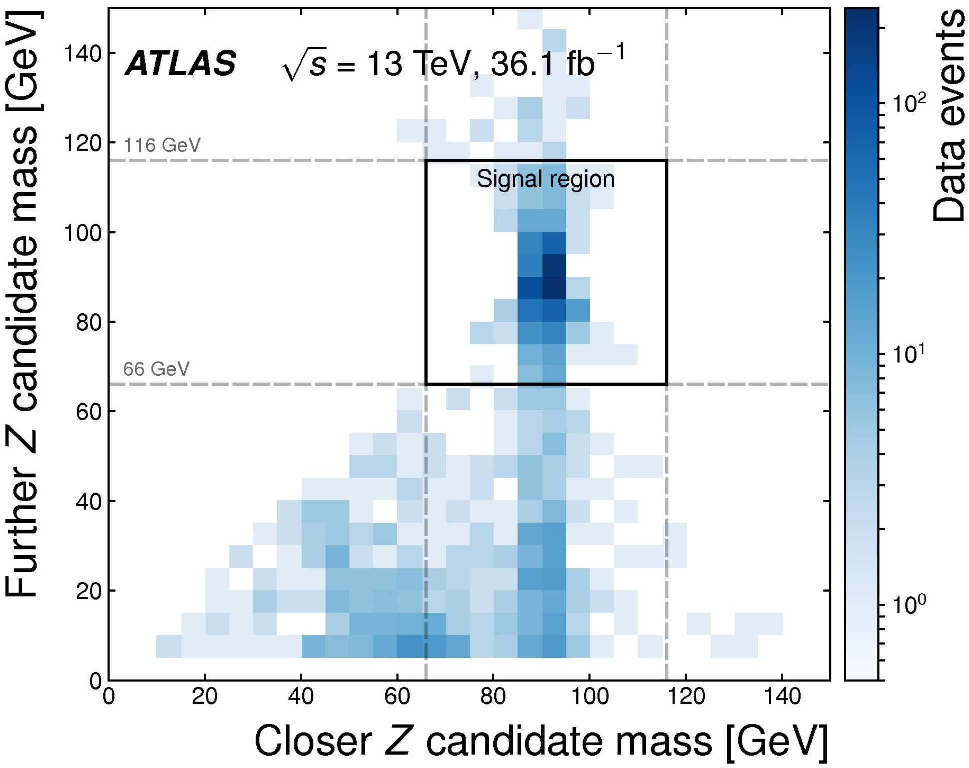
# aQGC - ZZG vertex



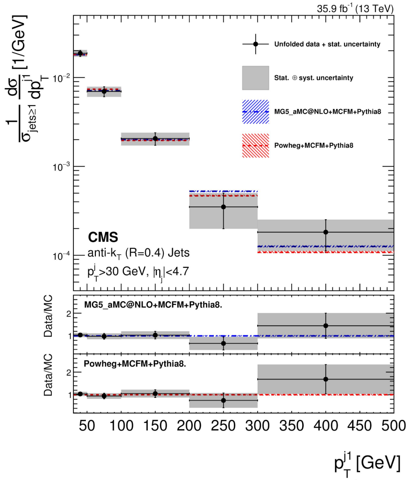

To be compared with the result in slides 6-7: **CONF-2018-035**

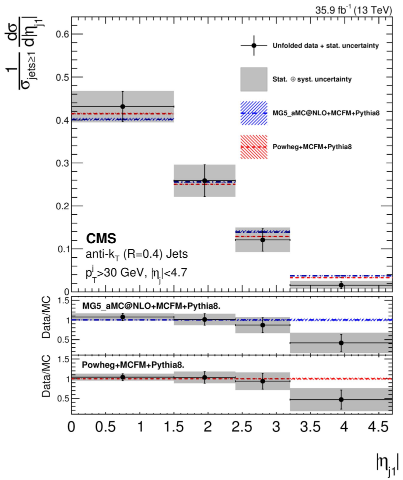
# ZZ (+jets) production, fiducial region selection (CMS, ATLAS)

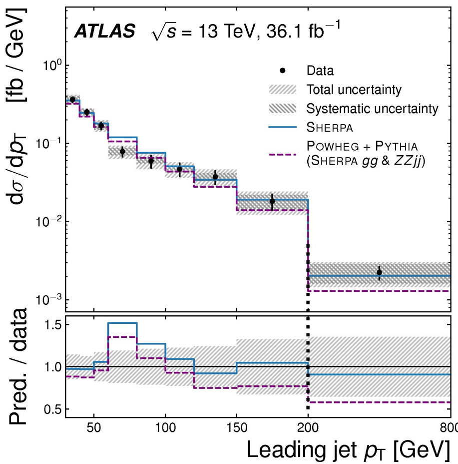


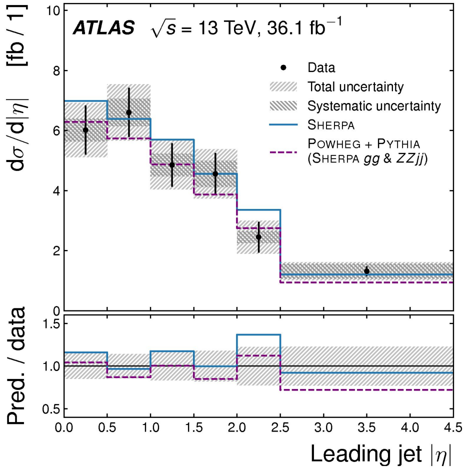



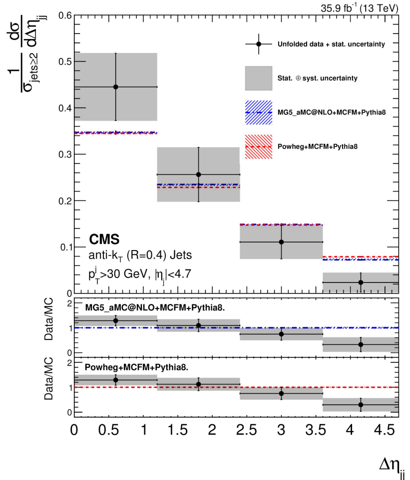
# ZZ (+jets) production, differential measurements (CMS, ATLAS)

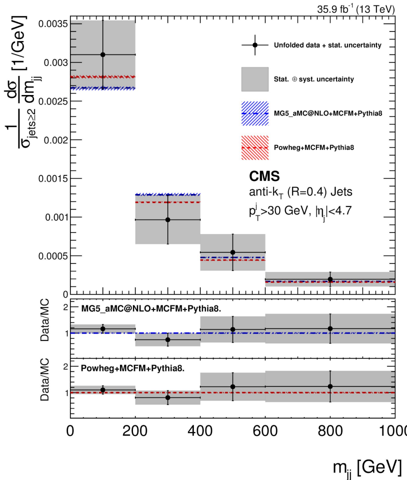


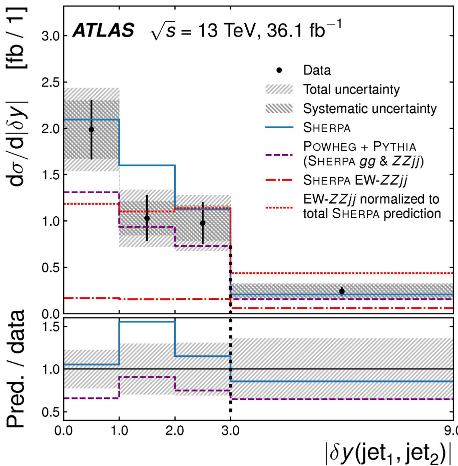



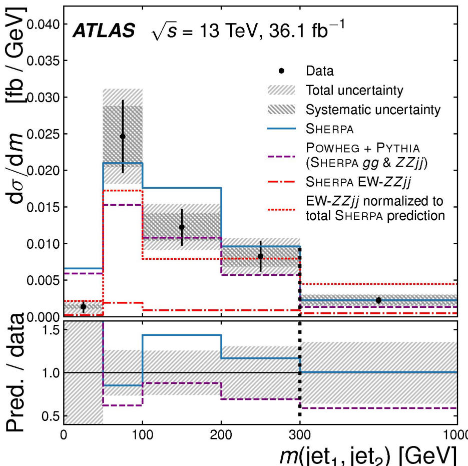



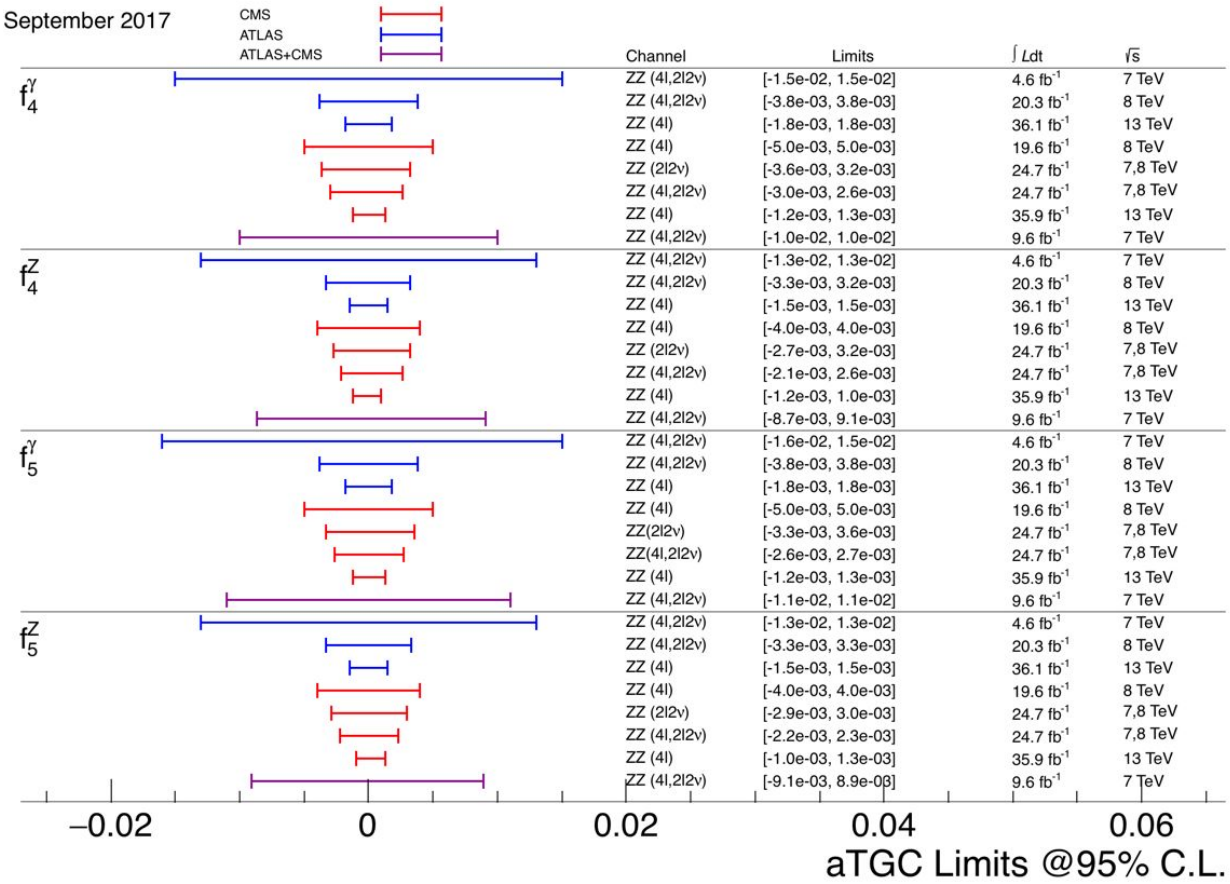



# aTGC - ZZ




To be compared with the results in slide 10.