Multiboson Production at ATLAS

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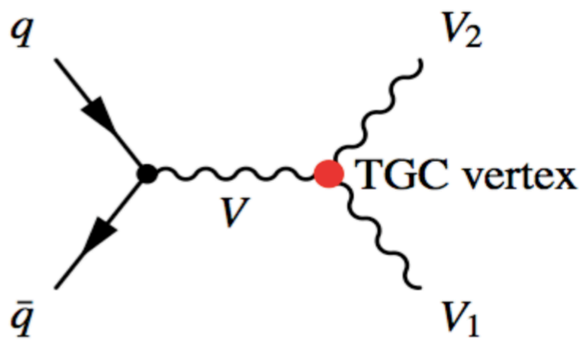
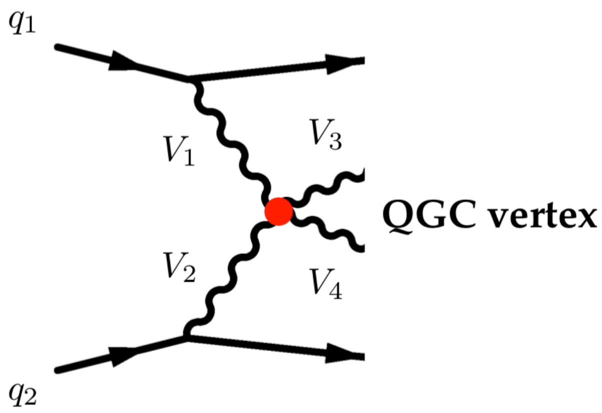
for the ATLAS Collaboration

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Electroweak Precision and New Physics

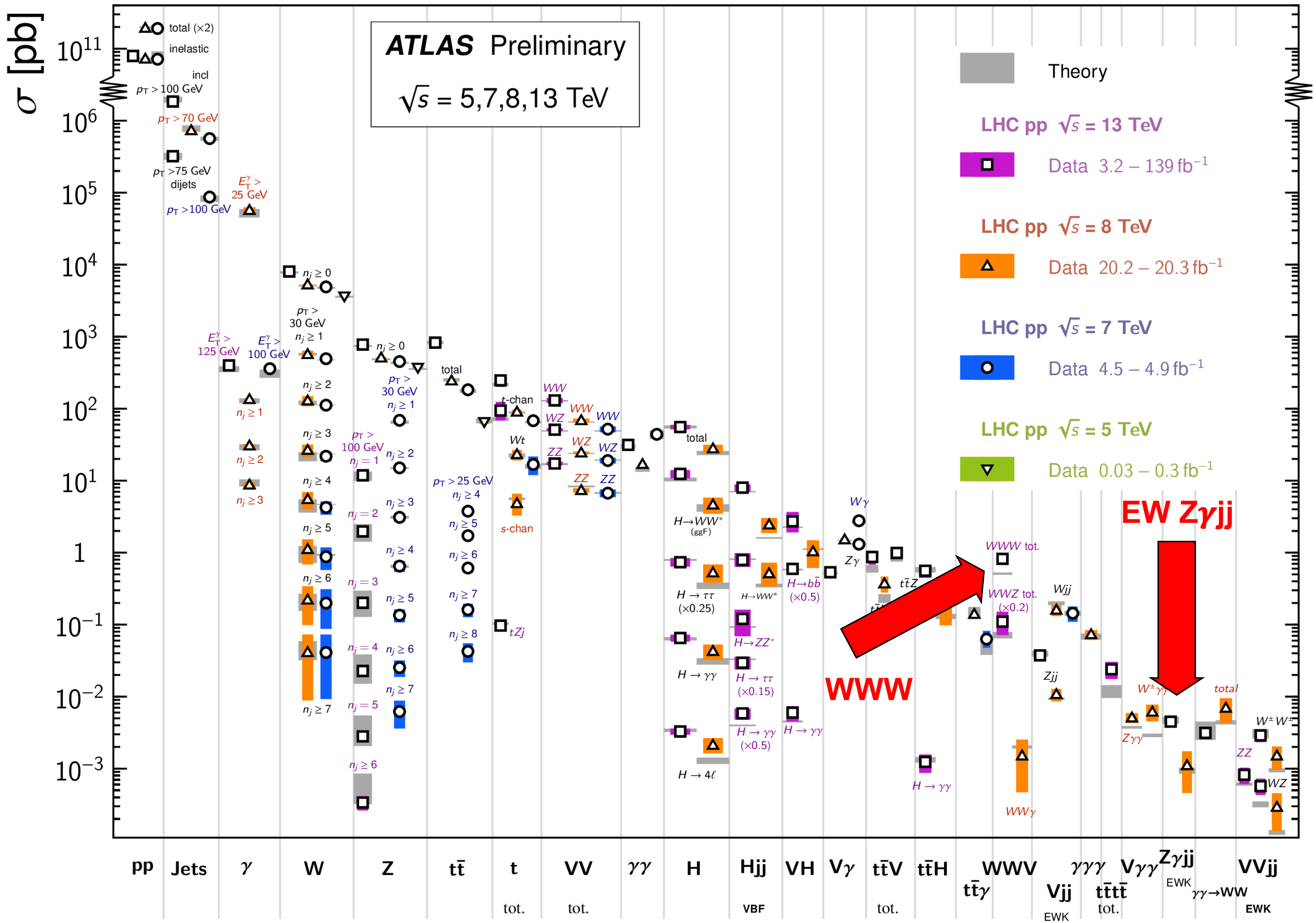
- Precision test of higher order predictions
  - higher order corrections more important at higher center of mass energies
  - recently available NNLO QCD and NLO EWK theoretical calculations.
- Study of triple and quartic gauge boson couplings (TGC and QGC)
  - Gauge boson couplings fixed within the standard model (SM).
  - Strong test of the SM couplings
  - Indirect search for new physics via anomalous gauge boson couplings
- Search for multiboson final states never observed before.



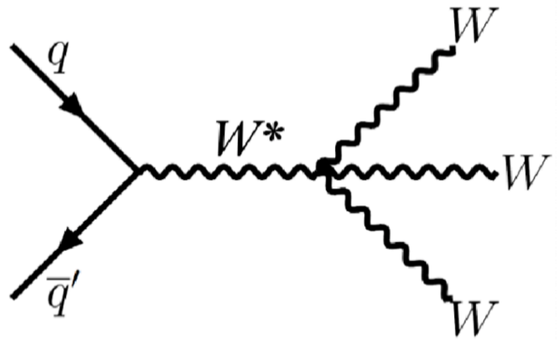


Standard Model Production Cross Section Measurements

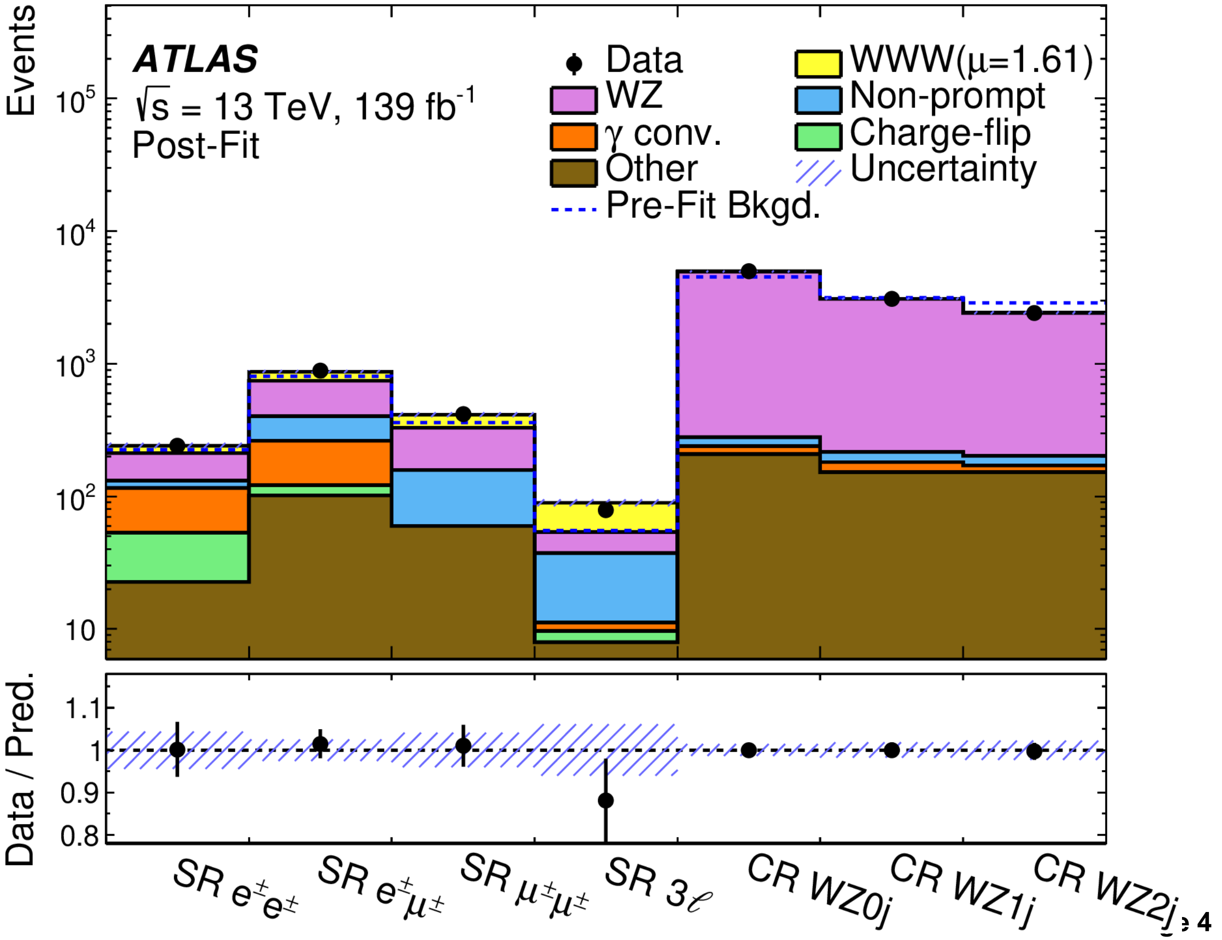
Status: February 2022



Observation of WWW production

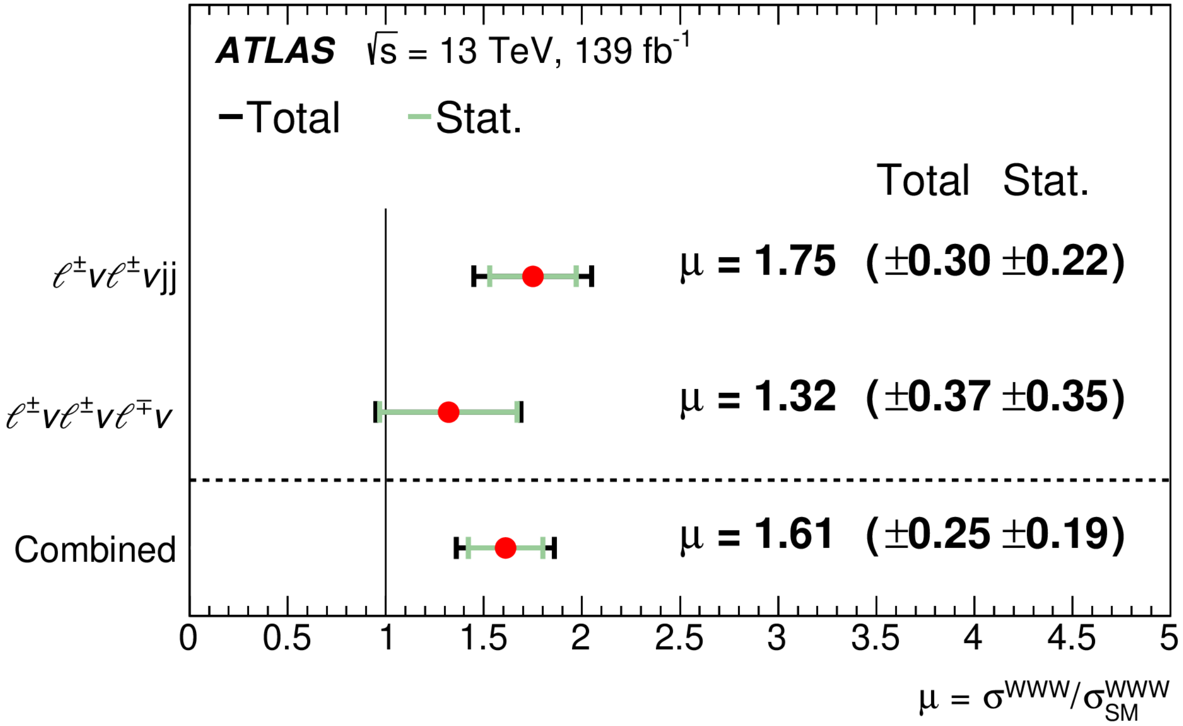


- Unexplored at the LHC, provides direct Test of gauge boson self-coupling
- Final States Considered
  - $WWW \to l^{\pm}\nu l^{\pm}\nu qq$ and $WWW \to l^{\pm}\nu l^{\pm}\nu l^{\mp}\nu$ with l = e or μ
- Main Backgrounds : WZ, non-prompt leptons (mainly ttbar)
- Data-driven estimates for non-prompt leptons and charge mis-identified leptons backgrounds
- Two BDTs used to improve signal to background separation in 2l and 3l signal regions
- Binned maximum-likelihood fit performed on BDT distributions in signal regions and m_{lll} distribution in WZ Control regions



Observation of WWW production

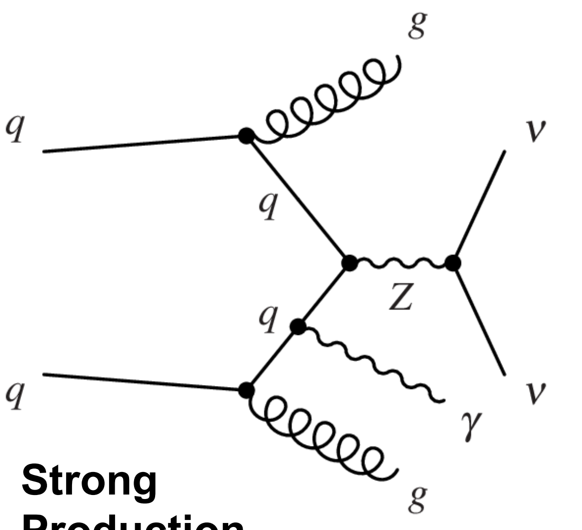
WWW production observed with significance 8.0σ (expected 5.4σ)!



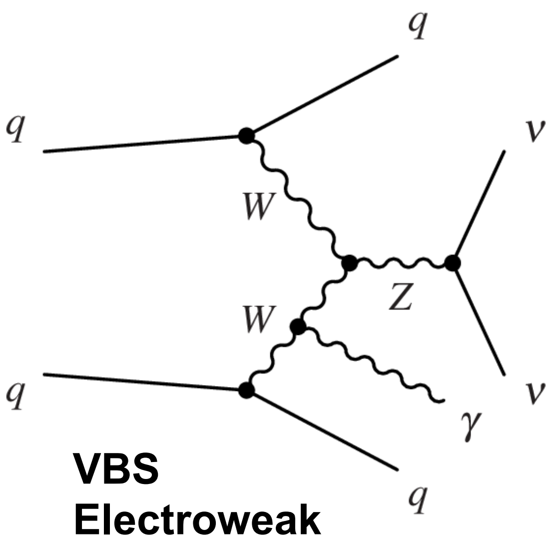
Fit	$\mu(WWW)$	Significance observed (expected)
$e^\pm e^\pm$	1.54 ± 0.76	$2.2\ (1.4)\ \sigma$
$e^\pm \mu^\pm$	1.44 ± 0.39	$4.1\ (3.0)\ \sigma$
$\mu^\pm \mu^\pm$	2.23 ± 0.46	$5.6\ (2.7)\ \sigma$
2ℓ	1.75 ± 0.30	$6.6\ (4.0)\ \sigma$
3ℓ	1.32 ± 0.37	$4.8\ (3.8)\ \sigma$
Combined	$\mathbf{1.61 \pm 0.25}$	$\mathbf{8.0\ (5.4)\ \sigma}$

- Uncertainty on the signal strength is mainly statistical
- Largest systematic uncertainties
  - uncertainty on data-driven background estimates (6%)
  - WZ theory uncertainties

VBS Z(→νν)γjj production



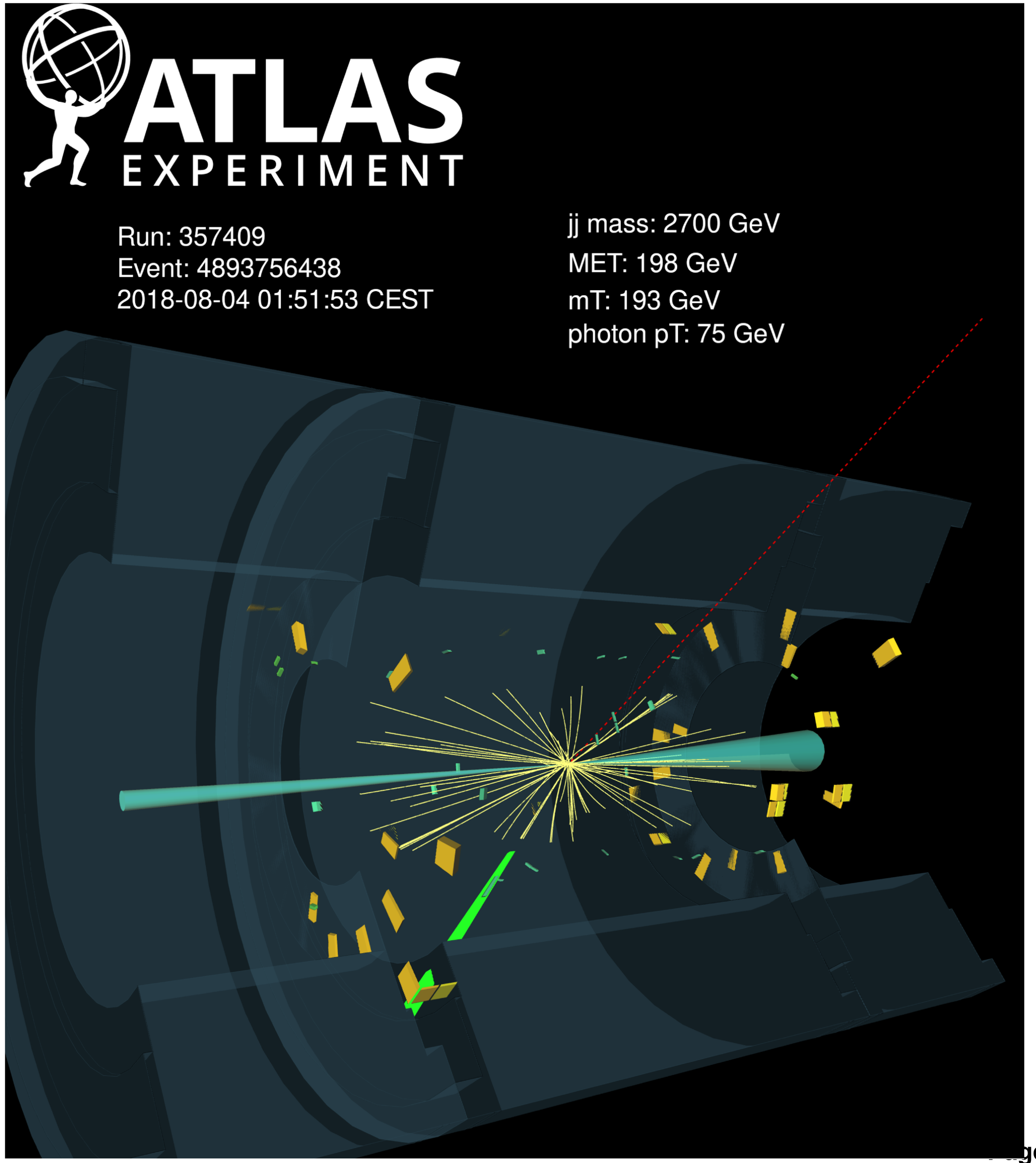
Strong Production



VBS Electroweak Production

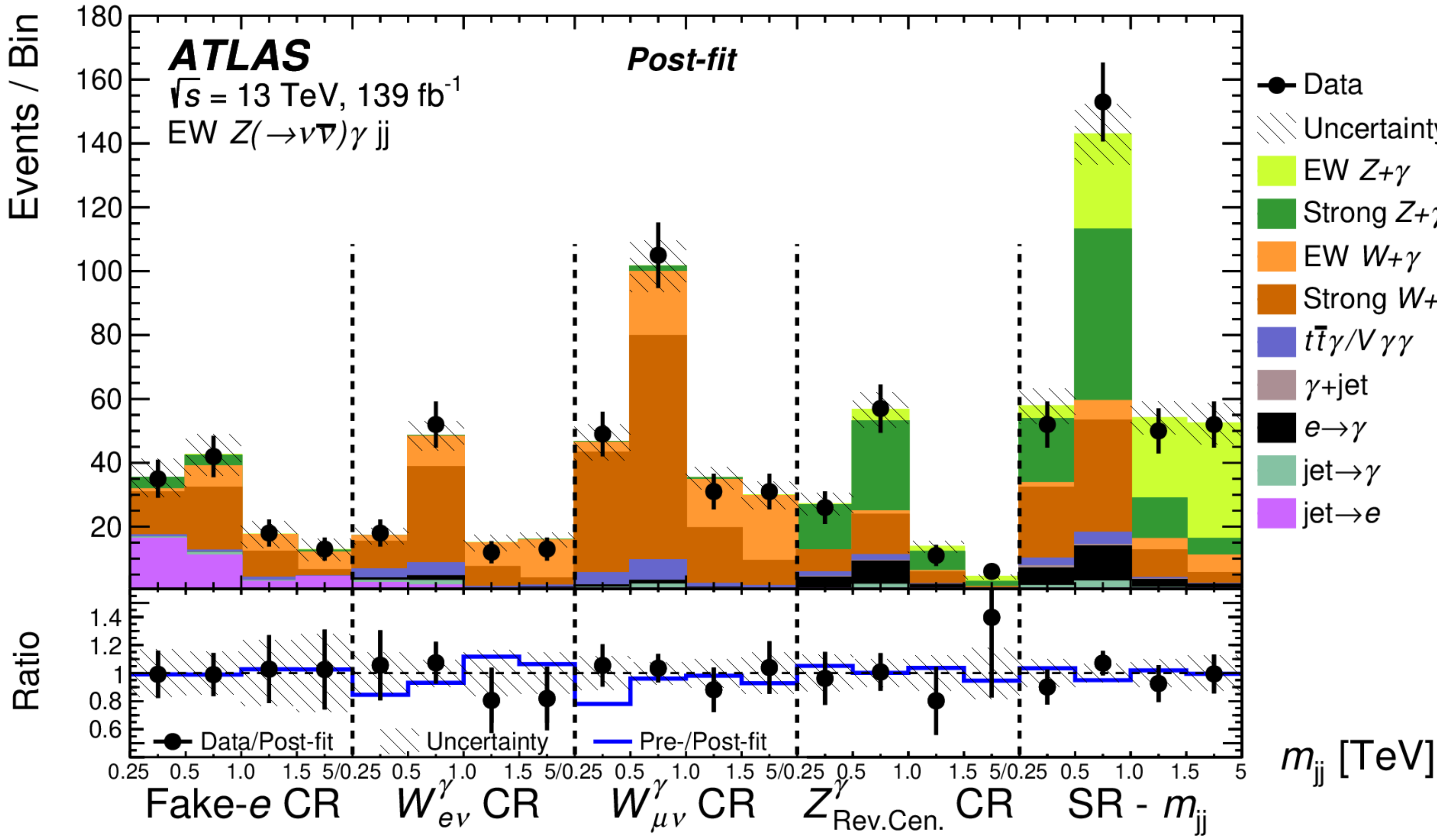
- VBF Topology
  - mjj > 250 GeV
  - $|\Delta\eta_{jj}|>3.0$, $|\Delta\phi_{jj}|<2.5$
- Large MET > 150 GeV
- one central photon
  - $15<p_T<110$ GeV
  - Centrally located wrt the jets ($C_\gamma>0.4$)

$$C_\gamma = \exp\left[-\frac{4}{(\eta_1-\eta_2)^2}\left(\eta_\gamma - \frac{\eta_1+\eta_2}{2}\right)^2\right],$$



VBS Z(→νν)γjj production

- Main Backgrounds
  - Wγ, non prompt photons, Zγ strong production
- Cut based selection with MET triggers
- Search performed in mjj bins



- Observed Significance
  - **5.2σ** (5.1σ expected)
- Fiducial cross-section
  - **1.31 ± 0.29 fb** (theory: 1.27 ± 0.17 fb)
- Largest systematic uncertainties
  - jet energy scale, Vγ theory and normalization

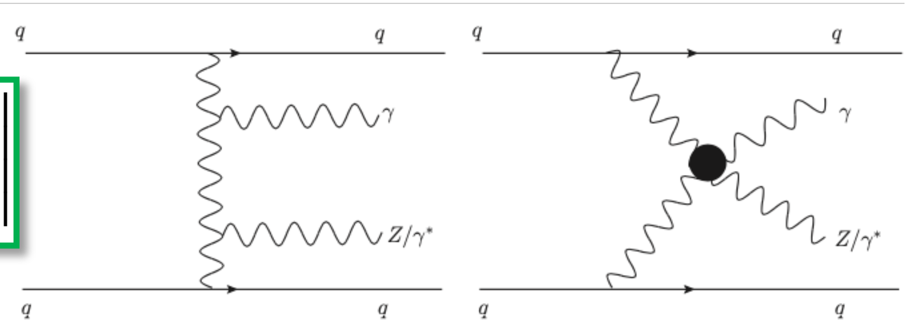
Signal Strength

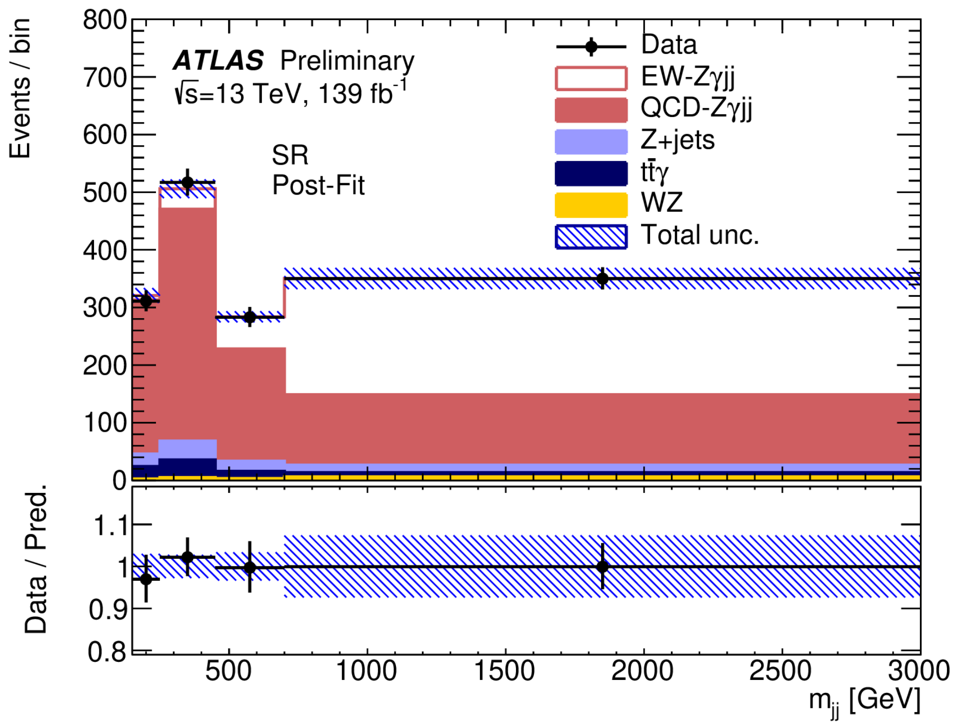
$$1.03 \pm 0.16(\text{stat}) \pm 0.19(\text{syst}) \pm 0.02(\text{lumi}).$$

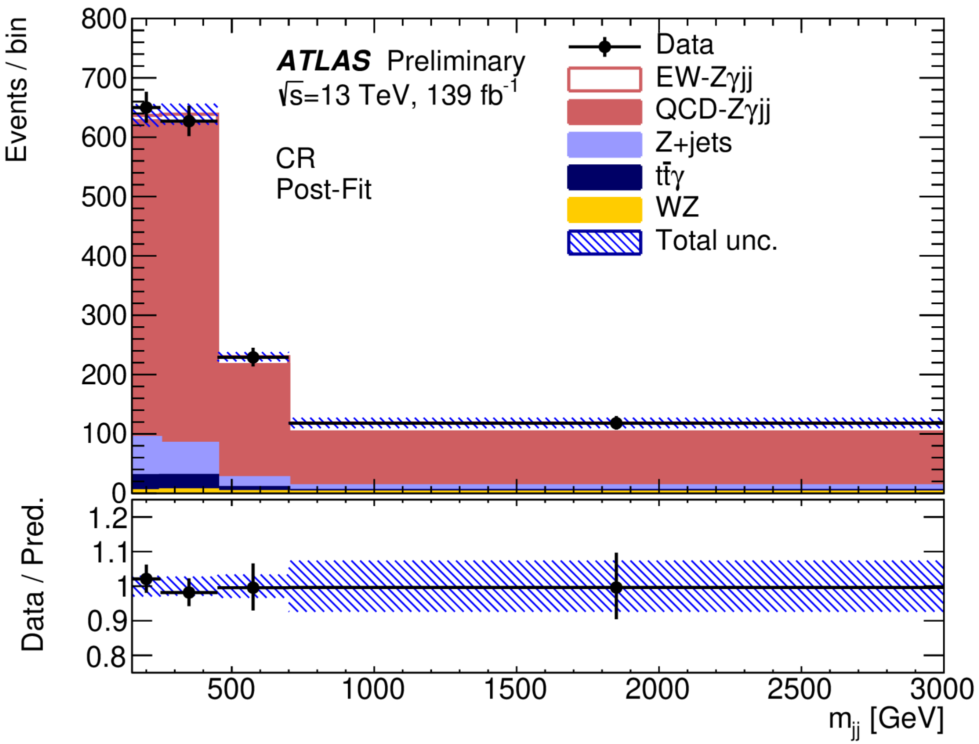
Observation of EW $Z(ll)\gamma jj$

- Measured in the $ee\gamma jj$ and $\mu\mu\gamma jj$ channels
- Main backgrounds:
  - Strong $Z\gamma jj$, fake γ, $tt\gamma$
- Key observable:
  - $Z\gamma$ centrality $\zeta ll\gamma$; **SR:** $\zeta ll\gamma < 0.4$
  - mjj > 150 GeV
- Fit performed to mjj spectrum

$$\boxed{\zeta(\ell\ell\gamma) = \left|\frac{y_{\ell\ell\gamma} - (y_{j_1} + y_{j_2})/2}{y_{j_1} - y_{j_2}}\right|}$$







Observation of EW $Z(ll)\gamma jj$

- Observation with large (10σ) *significance* as expected

$$\mu_{EW} = 0.95^{+0.14}_{-0.13}$$
$$= 0.95 \pm 0.08\ (\text{stat}) \pm 0.11\ (\text{syst}).$$

- Zy modelling uncertainty have an impact similar to the experimental uncertainties.

- Fiducial cross section is measured:
  - $\boldsymbol{\sigma_{\text{fid}} = 4.49 \pm 0.58}$ **fb**, ($\sigma_{\text{pred}} = 4.73 \pm 0.27$ fb)

	Data stat.	MC stat.	Background	Reco	EW mod.	QCD mod.	Total
$\Delta\sigma_{EW}/\sigma_{EW}$ [%]	± 9	± 1	± 1	± 5	$^{+6}_{-5}$	$^{+5}_{-4}$	± 13

- The **strong+EW** ***Zγjj*** **cross section** is measured
  - 20.6+1.4 fb (predicted: 20.4+2.6 fb)

From Cross-section Measurements to New Physics

Effective Field Theory

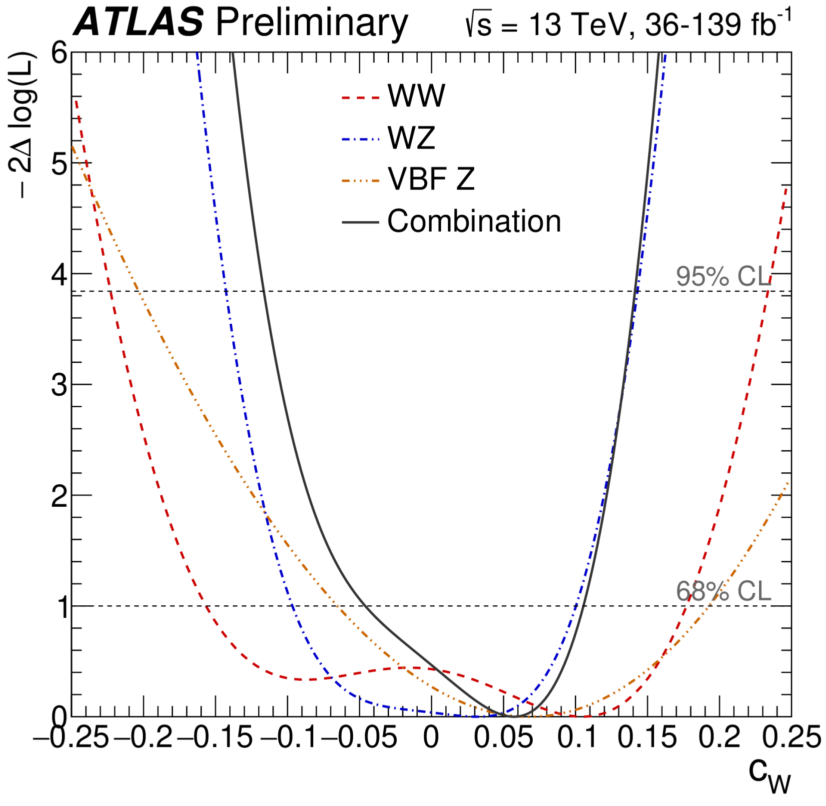
- EFT describes several possible new physics scenarios at energy scale Λ

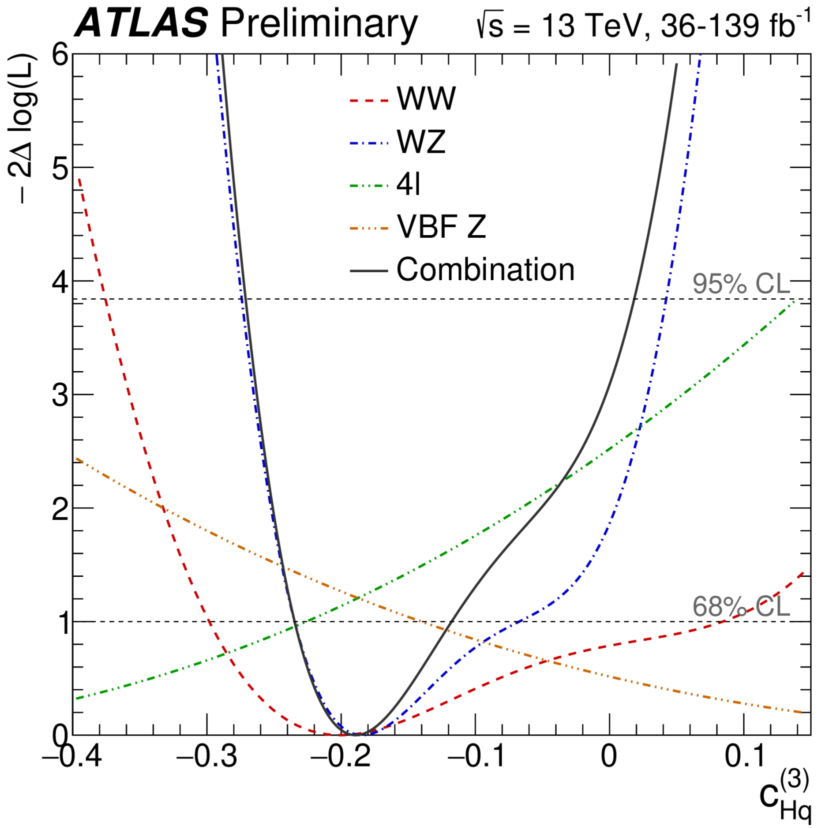
$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(5)}}{\Lambda} O_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots.$$

- Measurements sensitive to the effects of new physics → constrain the coefficients of SMEFT expression (Wilson coefficients)
- Use Run2 differential cross section measurements from various final states to test SMEFT (Λ=1 TeV)
    - **WW** (eνμν, 36 fb^{-1}) : $p_T^{\text{lead,lep}}$
    - **WZ** (36 fb^{-1}) : m_T^{WZ}
    - **$4l$** (139 fb^{-1}) : m_{Z2} in three different regions of m_{4l}
    - **Z+2j** (139 fb^{-1}) : $\Delta\phi\ j\ j$
- Constraining dim-6 operators ignoring odd-dimensional operators (lepton and baryon number violations) and non-leading terms

Combined EFT interpretation WW, WZ, 4l and Z+2j

- 33 CP-even operators are considered
- Profile likelihood ratio test scan for two Wilson coefficients (fixing other coefficients to 0)

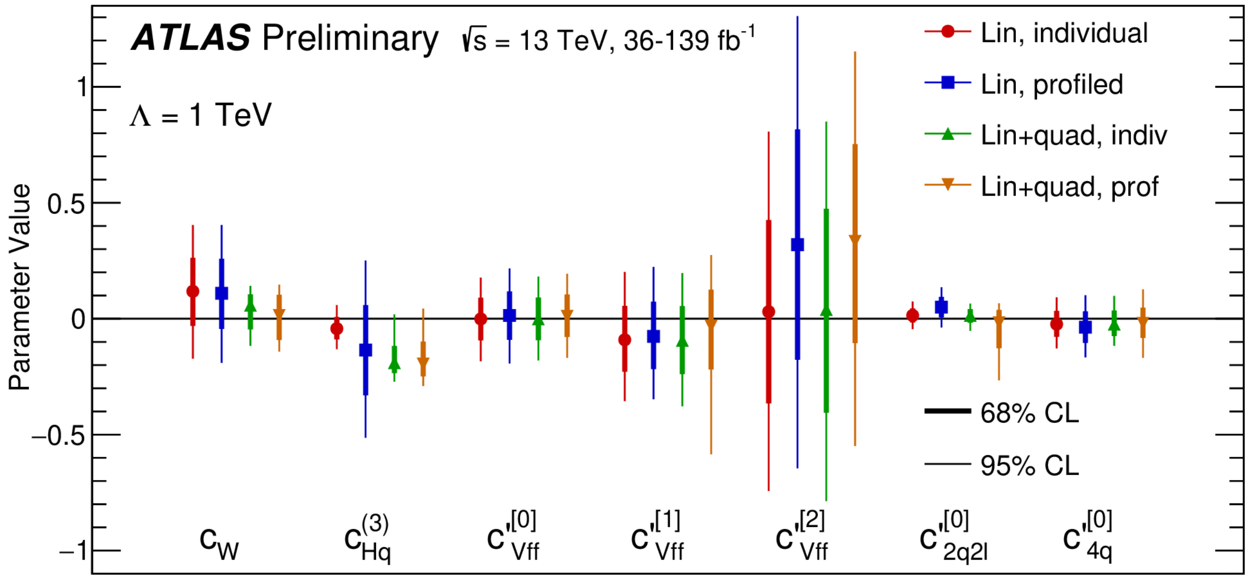




Combined EFT interpretation WW, WZ, 4l and Z+2j

- Modified basis constructed with linear combinations of the warsaw basis vectors
- Constraints obtained on further 13 linear combinations of Wilson coefficients
  - Group together Wilson coefficients with similar physics impact
- Investigate both linear $O(\Lambda^{-2})$ as well as quadratic $O(\Lambda^{-4})$ contributions

$c'^{[i]}_{Vff}$ – affect vector boson coupling to fermions
$c'^{[i]}_{2q2l}$, $c'^{[i]}_{4q}$ – four fremion coefficients



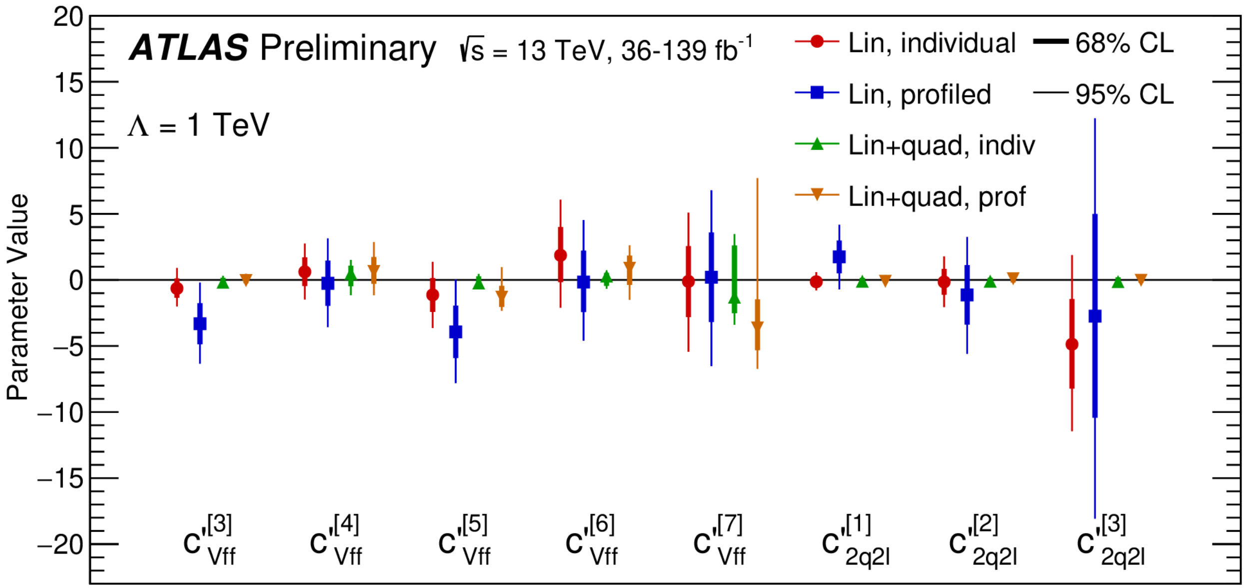
$c'^{[0]}_{Vff} \approx 0.81c_{HWB} + 0.38c_{HD} + 0.13c^{(1)}_{Hl} + 0.37c^{(3)}_{Hl} - 0.14c^{(1)}_{ll} + 0.12c^{(1)}_{Hq}$

$c'^{[1]}_{Vff} \approx 0.73c^{(1)}_{Hl} - 0.28c^{(3)}_{Hl} - 0.48c_{He} + 0.38c^{(1)}_{ll} + 0.13c^{(1)}_{Hq}$

$c'^{[2]}_{Vff} \approx 0.37c_{HWB} + 0.17c_{HD} - 0.31c^{(1)}_{Hl} - 0.53c^{(3)}_{Hl} + 0.25c_{He} + 0.59c^{(1)}_{ll} - 0.21c^{(1)}_{Hq}$

$c'^{[0]}_{2q2l} \approx -0.37c^{(1)}_{lq} + 0.89c^{(3)}_{lq} - 0.11c_{lu} - 0.21c_{eu} - 0.13c_{qe}$

$c'^{[0]}_{4q} \approx 0.11c^{(11)}_{qq} + 0.22c^{(18)}_{qq} + 0.95c^{(31)}_{qq} - 0.2c^{(38)}_{qq}$



$c'^{[3]}_{Vff} \approx -0.19c^{(1)}_{Hl} - 0.14c^{(3)}_{Hl} + 0.86c^{(1)}_{Hq} + 0.41c_{Hu} - 0.17c_{Hd}$

$c'^{[4]}_{Vff} \approx -0.35c_{HWB} + 0.49c_{HD} + 0.26c^{(1)}_{Hl} + 0.35c^{(3)}_{Hl} + 0.51c_{He} + 0.38c^{(1)}_{ll} + 0.18c^{(1)}_{Hq}$

$c'^{[5]}_{Vff} \approx 0.25c_{HD} + 0.33c^{(1)}_{Hl} - 0.22c^{(3)}_{Hl} + 0.18c_{He} - 0.35c^{(1)}_{ll} - 0.3c^{(1)}_{Hq} + 0.71c_{Hu} - 0.16c_{Hd}$

$c'^{[6]}_{Vff} \approx -0.22c^{(1)}_{Hl} + 0.52c^{(3)}_{Hl} - 0.39c_{He} + 0.44c^{(1)}_{ll} - 0.22c^{(1)}_{Hq} + 0.52c_{Hu}$

$c'^{[7]}_{Vff} \approx -0.28c_{HWB} + 0.71c_{HD} - 0.31c^{(1)}_{Hl} - 0.21c^{(3)}_{Hl} - 0.5c_{He} - 0.14c^{(1)}_{ll}$

$c'^{[1]}_{2q2l} \approx 0.56c^{(1)}_{lq} + 0.44c^{(3)}_{lq} + 0.61c_{eu} - 0.1c_{ed} + 0.34c_{qe}$

$c'^{[2]}_{2q2l} \approx 0.68c^{(1)}_{lq} + 0.15c^{(3)}_{lq} + 0.33c_{lu} - 0.51c_{eu} + 0.13c_{ed} - 0.37c_{qe}$

$c'^{[3]}_{2q2l} \approx -0.27c^{(1)}_{lq} + 0.79c_{lu} - 0.39c_{ld} + 0.26c_{eu} - 0.22c_{ed} - 0.16c_{qe}$

Summary

- Small cross-sections for multiboson production processes
  → small signal swamped by large, challenging backgrounds
- Precision analyses only recently possible.
- Most measurements are still statistics limited.
- Differential measurements made with more data → very useful for EFT interpretations
- *Looking Forward to Run3 datasets for interesting new results!*