TECHNISCHE UNIVERSITÄT DRESDEN

Review of EW WG Conventions

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on behalf of the LHCEWMB group

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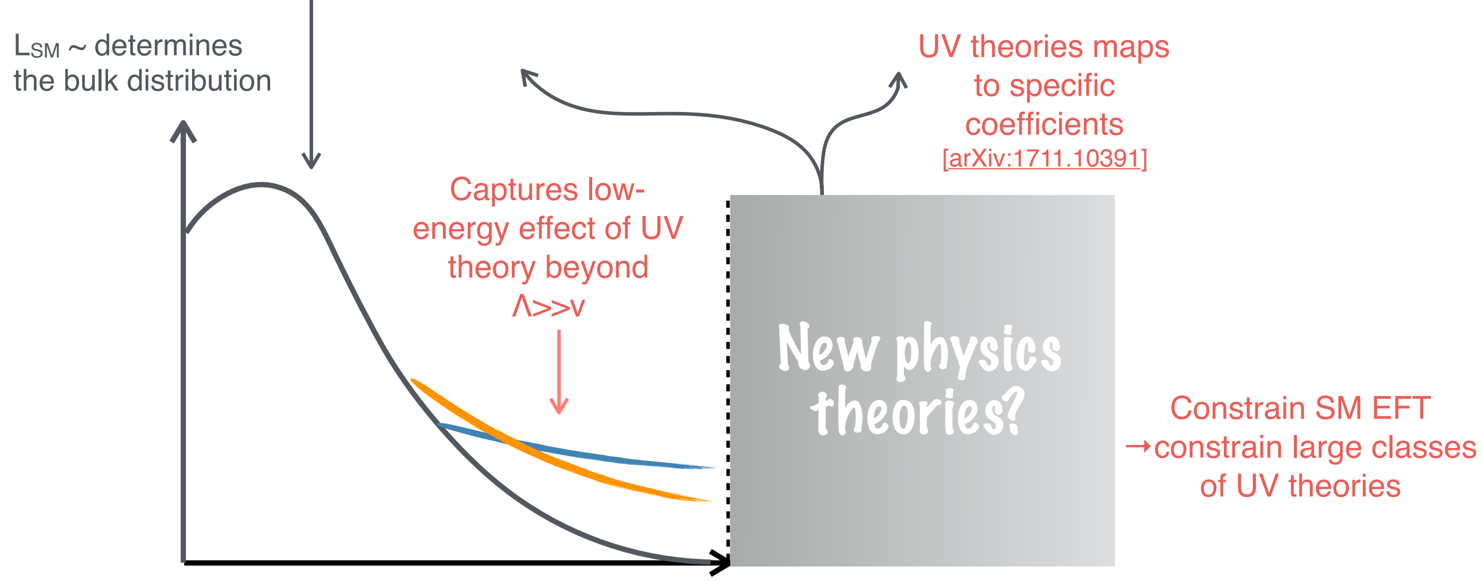
Review of conventions? Which conventions?

- The aim of the EFT studies is to make best use of SM measurements to constrain new physics
- EFT expansion of new physics in inverse of energy scale $1/\Lambda$
  - Lagrangian (without L and B violating operators)

$$L_{EFT} = L_{SM} + \sum_i \frac{c_i}{\Lambda^2} O_{i,dim\text{-}6} + \sum_j \frac{c_j}{\Lambda^4} O_{j,dim\text{-}8}$$



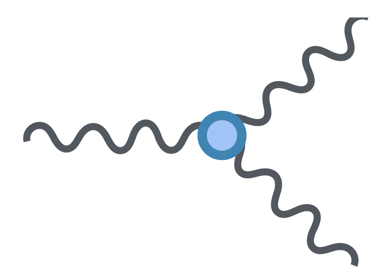
  - Operator basis not unique, different conventions in use, the most used are Warsaw, HISZ and SILH
  - Growth of amplitude with $\sqrt{s}$ can violate unitarity, different unitarisation schemes exist
  - Huge number of free parameters → some assumptions needed in order to be able to use measurements for constrains

What I will be reviewing: EFT bases/unitarisation schemes/assumptions that have been used (or have been considered) for LHC results

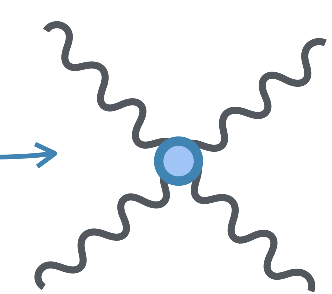
The anomalous Gauge Coupling Measurements

- In SM precision measurements at the LHC EFT constraints almost exclusively from anomalous gauge coupling measurements
    - Anomalous triple gauge couplings (aTGCs): Dibosons (WW, WZ, Wγ) and VBF production (Zjj, Wjj)
    - Neutral triple gauge couplings (nTGCs): ZZ and Zγ
    - Anomalous quartic gauge couplings (aQGCs): Triboson, VBS production of boson pairs, exclusive γγ→WW

Triple gauge couplings



$$L_{EFT} = L_{SM} + \sum_i \frac{c_i}{\Lambda^2} O_{i,\text{dim-6}} + \sum_j \frac{c_j}{\Lambda^4} O_{j,\text{dim-8}}$$

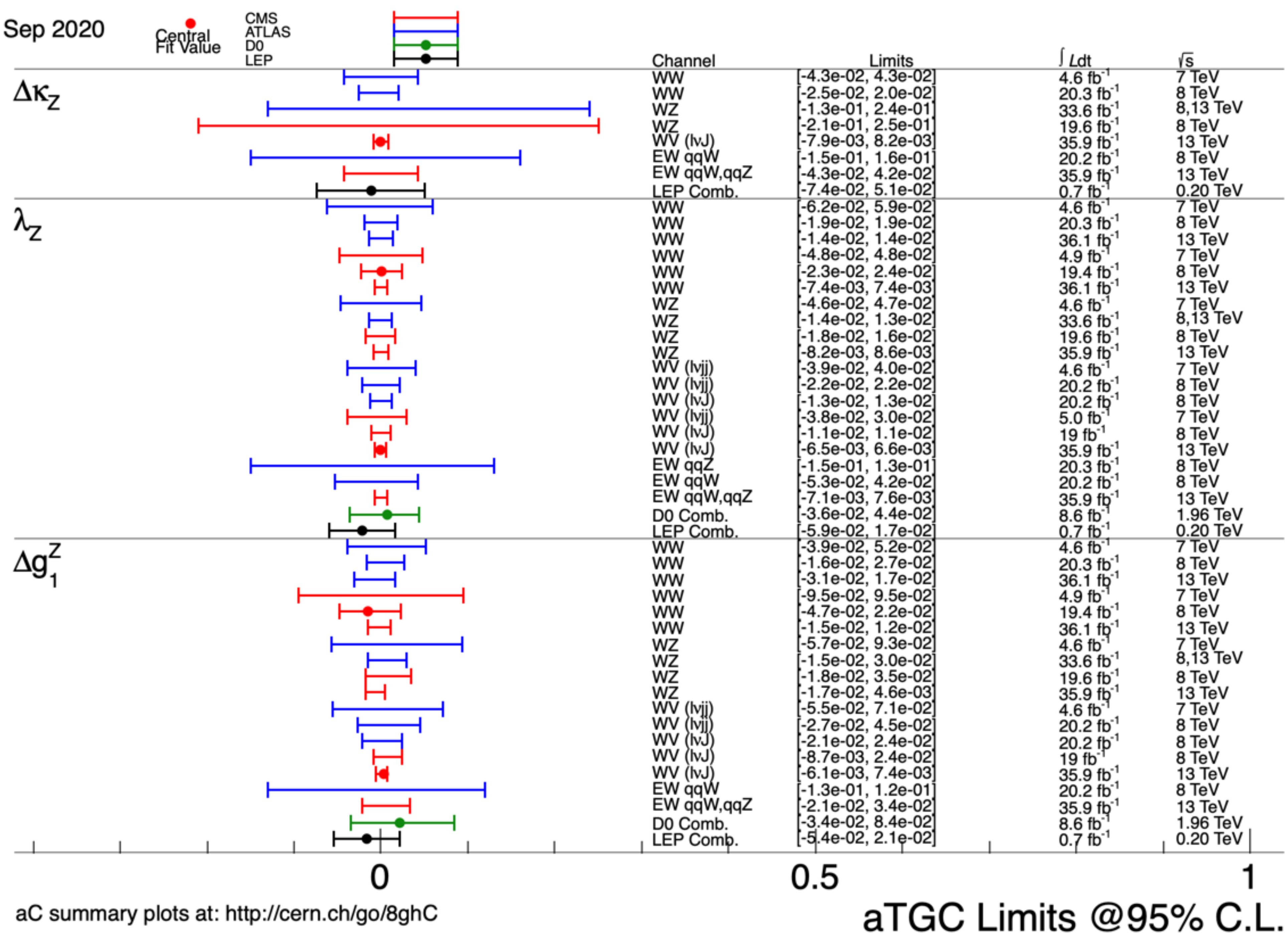


Quartic gauge couplings

- There is so far not a common framework to get MC predictions for both dim-6 and dim-8 operators

Anomalous Gauge Coupling Measurements:
The basis

- Many un(co)rrelated constrains
  - **Triple Gauge Couplings:** limits on both anomalous couplings and EFT (HISZ basis commonly used for 8TeV results) → *Warsaw basis becoming the standard?*



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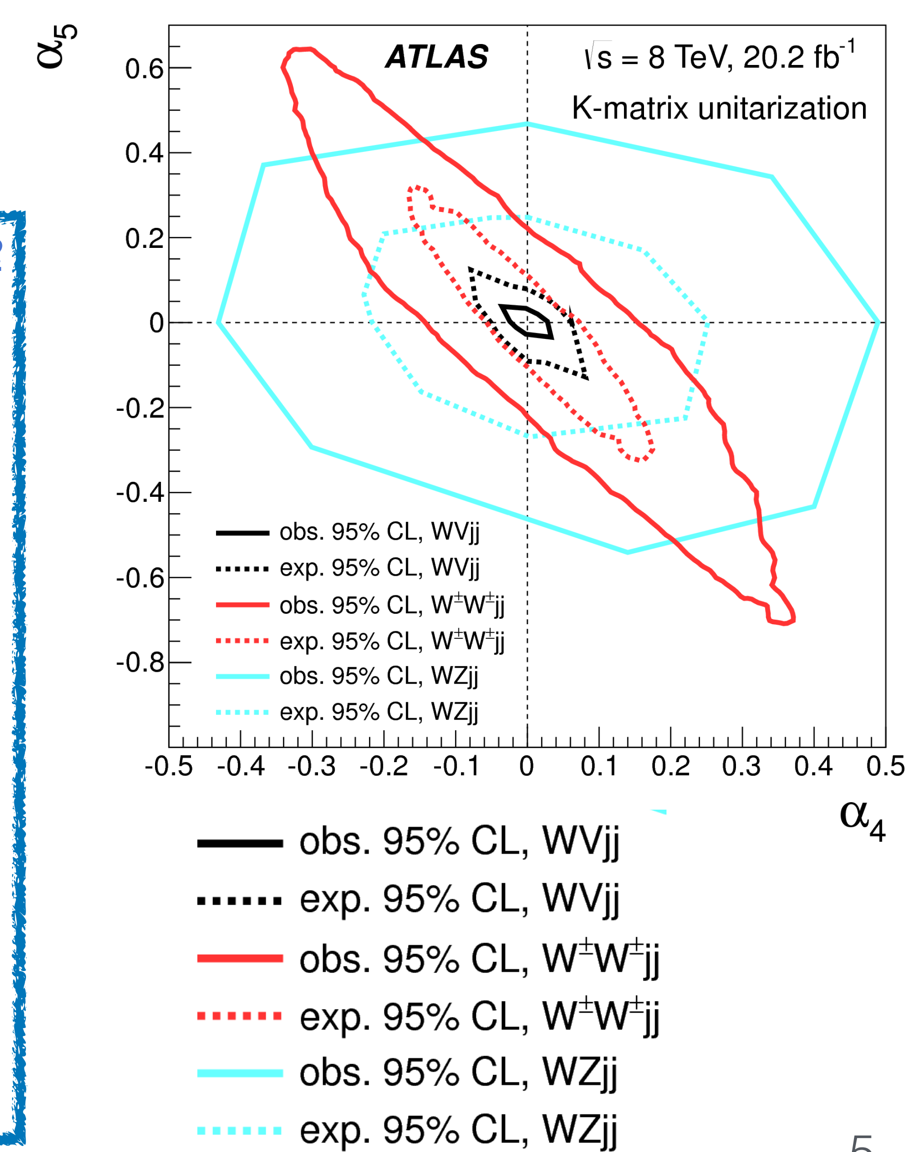
Sometimes 1-1 translation between models not easy

[CMS-SMP-19-012](CMS-SMP-19-012)

CMS EFT dim-8 parameters from ssWW @13 TeV

	Observed ($W^{\pm}W^{\pm}$) (TeV^{-4})	Expected ($W^{\pm}W^{\pm}$) (TeV^{-4})
f_{T0}/Λ^4	[-0.28, 0.31]	[-0.36, 0.39]
f_{T1}/Λ^4	[-0.12, 0.15]	[-0.16, 0.19]
f_{T2}/Λ^4	[-0.38, 0.50]	[-0.50, 0.63]
f_{M0}/Λ^4	[-3.0, 3.2]	[-3.7, 3.8]
f_{M1}/Λ^4	[-4.7, 4.7]	[-5.4, 5.8]
f_{M6}/Λ^4	[-6.0, 6.5]	[-7.5, 7.6]
f_{M7}/Λ^4	[-6.7, 7.0]	[-8.3, 8.1]
f_{S0}/Λ^4	[-6.0, 6.4]	[-6.0, 6.2]
f_{S1}/Λ^4	[-18, 19]	[-18, 19]



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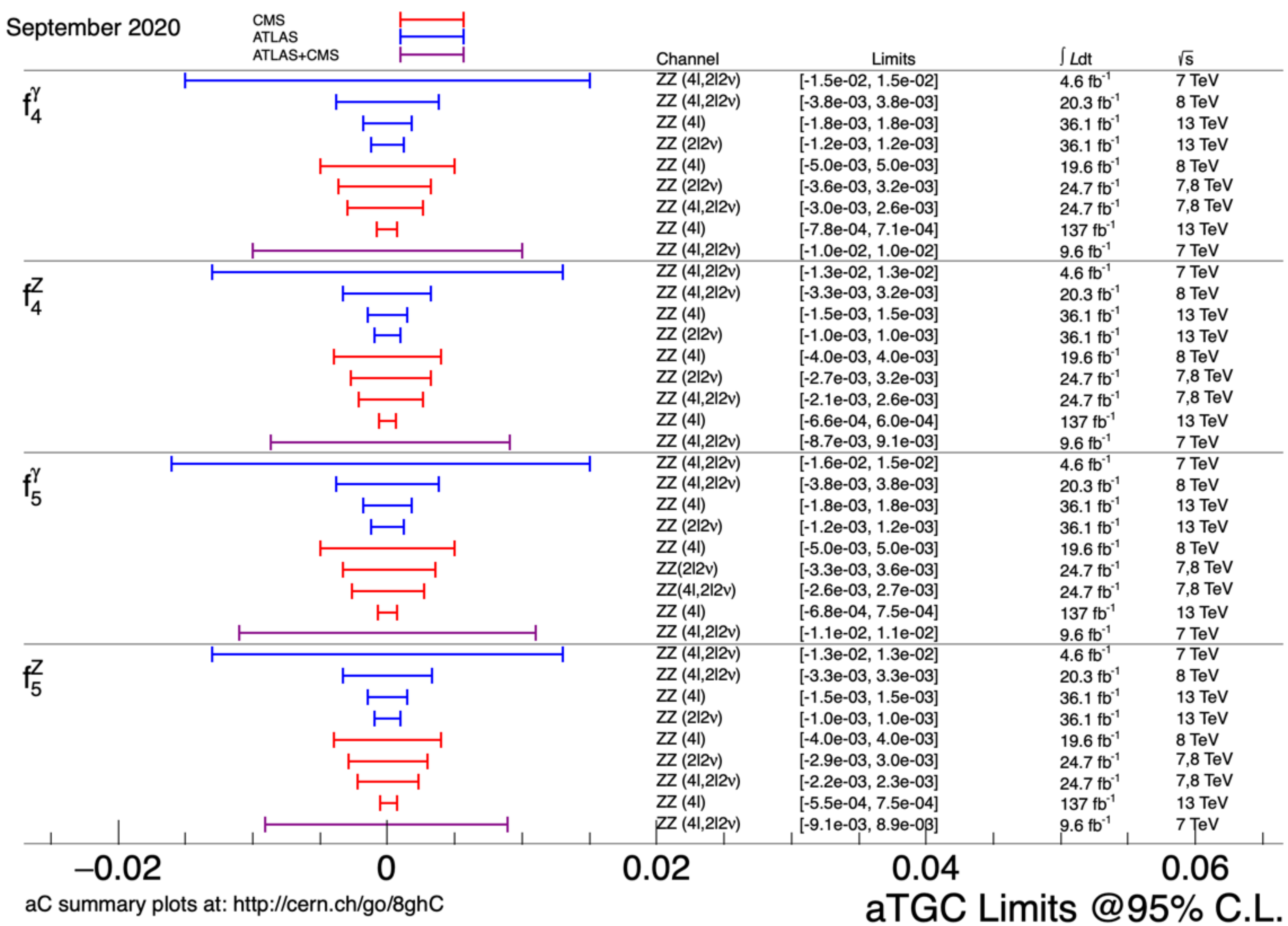
  - **Quartic Gauge Couplings:** anomalous couplings and Eboli model → *Eboli model the standard for run-2 results*
  - Interesting to combine several channels sensitive to the same parameter



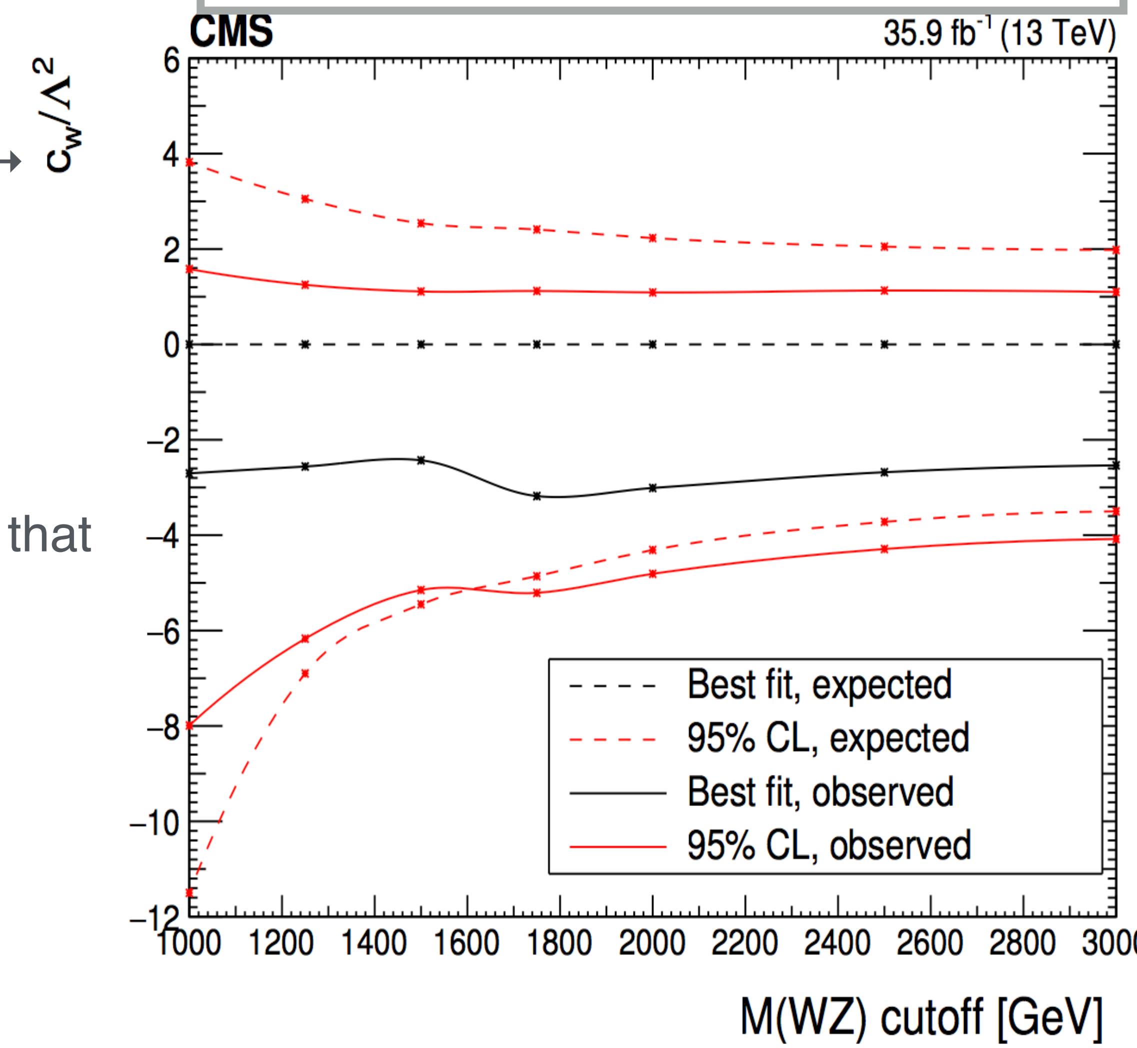
Unique ATLAS+CMS combination made by the ZZ→4l using 7 TeV data

Anomalous Gauge Coupling Measurements: Unitarisation

With EFT the growth of amplitude with $\hat{s}$ can violate unitarity → we *need to make sure we are in a valid range of the theory*

- For **aTGCs** unitarisation generally only has a mild effect
  - Run-1 analyses provided non-unitarised limits. ATLAS also used dipole form factors, with a Λ_{FF} being the largest value that guarantees unitarity (considered now over-conservative)
- For **aQGC** unitarisation can have a very large effect. Non-unitarised aQGC models often exceed unitarity bounds.
  - No consensus on the method in Run-1 (non-unitarisation, K/T-matrix, form factors and clipping scan)

WZ limits on C_w/Λ^2 vs clipping value



- For Run-II results clipping seems to be so far the preferred approach for both dim-6 and dim-8 limits

Clipping approach

- Use the EFT prediction only up to a clipping energy $\sqrt{s} = E_{clip}$ and set any contribution from this theory to 0 beyond this energy
- The clipping is done at parton level
- The SM predictions as well as the data remain untouched
- Derive limits for various E_{clip}
- Considering to use: Last data point can be use as reference point to start clipping scan

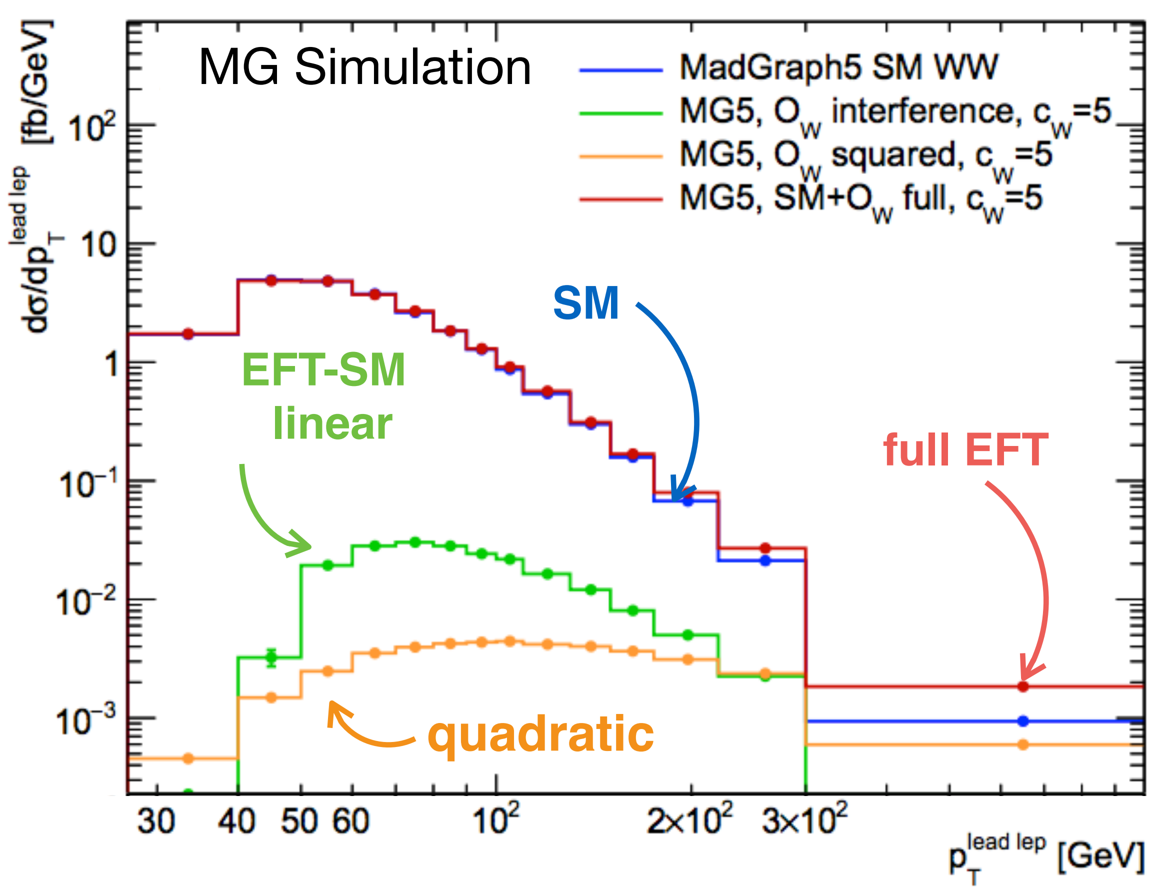
Anomalous Gauge Coupling Measurements:
Some assumptions

1. What kind of effects should we look for? Linear or quadratic?

- Comparison of size of terms linear ($\propto c/\Lambda^n$) and quadratic ($\propto c^2/\Lambda^{2n}$) in EFT coefficients can be a test of convergence of EFT expansion
- The dim-6 cross section example:

$$\sigma = \underbrace{\sigma_{SM}}_{\text{SM}} + \underbrace{\sum_i \frac{c_i}{\Lambda^2}\sigma_{SM,i}^{interf}}_{\substack{\text{EFT-SM interference} \\ \text{(linear in } c_i \propto 1/\Lambda^2)}} + \underbrace{\sum_i \frac{c_i^2}{\Lambda^4}\sigma_i^{NP} + \sum_{ij,\, i\neq j} \frac{c_i c_j}{\Lambda^4}\sigma_{ij}^{NP\text{-}interf}}_{\substack{\text{Pure EFT terms} \\ \text{(quadratic in } c_i \propto 1/\Lambda^4)}}$$

WW example introducing c_W operator



- Expectation: EFT-SM interference (“linear term” $\propto 1/\Lambda^2$) leading contribution → Should we look first for the linear term?

  → For most of 8 TeV analysis we have used variables where most of the sensitivity is actually on the quadratic term!

  → New results from ATLAS and CMS are exploring the sensitivity to each term and the change on the limits is sizable!

Anomalous Gauge Coupling Measurements:
Some assumptions

arXiv:2006.15458

1. What kind of effects should we look for? Linear or quadratic?

Example from ATLAS Z VBF:

Quadratic: $|\mathcal{M}_{d6}|^2$

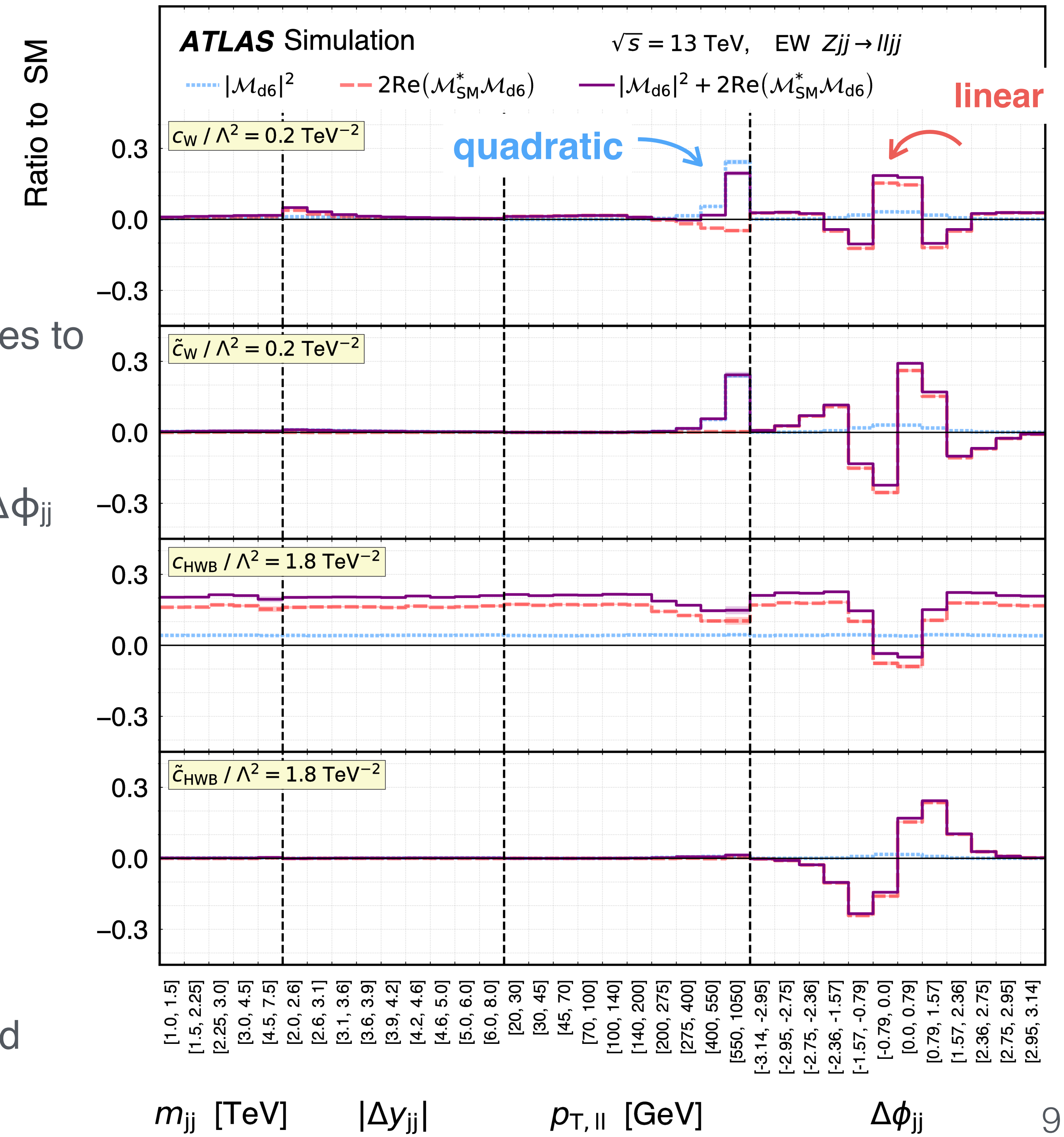
EFT-SM linear: $2\mathrm{Re}(\mathcal{M}^*_{SM}\mathcal{M}_{d6})$

full EFT: $|\mathcal{M}_{d6}|^2 + 2\mathrm{Re}(\mathcal{M}^*_{SM}\mathcal{M}_{d6})$

- Different distributions show different sensitivities to the linear and quadratic terms
- Limits extracted using the measured EW Zjj differential cross-section as a function of the $\Delta\phi_{jj}$

Wilson coefficient	Linear EFT	95 % confidence limit Expected (Asimov)	Observed
c_W/Λ^2	yes	[−0.29, 0.29]	[−0.13, 0.44]
	no	[−0.27, 0.30]	[−0.13, 0.43]
$\tilde{c}_W/\Lambda^2$	yes	[−0.12, 0.12]	[−0.10, 0.14]
	no	[−0.12, 0.12]	[−0.10, 0.14]
c_{HWB}/Λ^2	yes	[−2.48, 2.48]	[−3.47, 1.50]
	no	[−3.08, 2.14]	[−3.61, 1.33]
$\tilde{c}_{HWB}/\Lambda^2$	yes	[−1.15, 1.15]	[0.26, 2.55]
	no	[−1.14, 1.15]	[0.26, 2.56]

Strongest limits when pure dim-6 are excluded from the theoretical prediction!

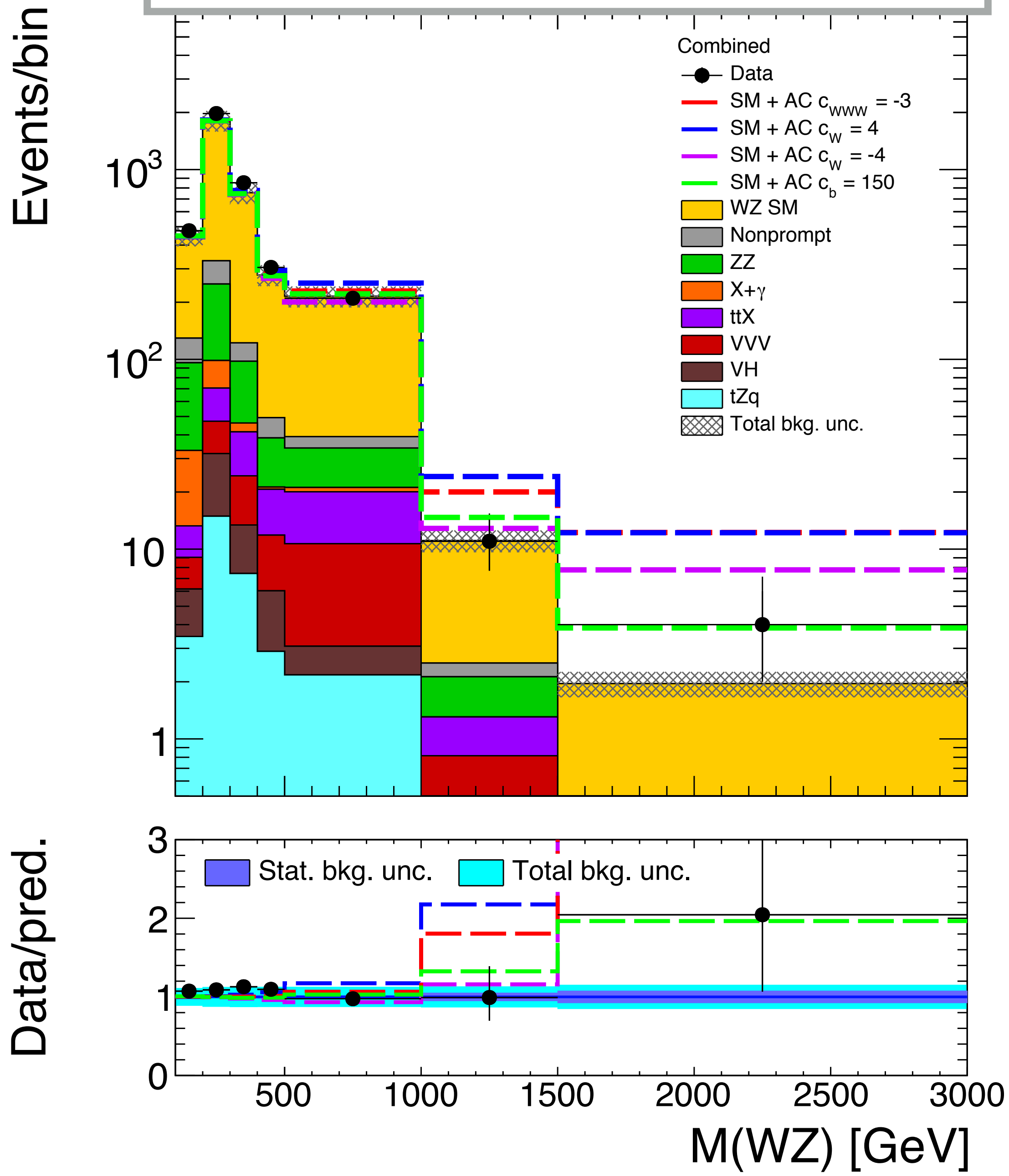


Anomalous Gauge Coupling Measurements:
Some assumptions

CMS SMP-18-002

1. What kind of effects should we look for? Linear or quadratic?

WZ invariant mass fitted for EFT limits



Example from CMS WZ:

Importance of the linear term studied by performing 2 sets of limits

- Linear term only

Parameter	95% CI (expected) $[\mathrm{TeV}^{-2}]$	95% CI (observed) $[\mathrm{TeV}^{-2}]$
c_W/Λ^2	$[-2.3, 3.4]$	$[-2.2, 2.7]$
c_{WWW}/Λ^2	$[-33.2, 28.6]$	$[-13.8, 41.2]$
c_b/Λ^2	$[-360, 300]$	$[-230, 390]$

- Linear+Quartic terms

Parameter	95% CI (expected) $[\mathrm{TeV}^{-2}]$	95% CI (observed) $[\mathrm{TeV}^{-2}]$
c_W/Λ^2	$[-3.3, 2.0]$	$[-4.1, 1.1]$
c_{WWW}/Λ^2	$[-1.8, 1.9]$	$[-2.0, 2.1]$
c_b/Λ^2	$[-130, 170]$	$[-100, 160]$

Linear vs quadratic difference not always checked → trivial to do!

Should probable keep presenting both set of results and look for observables with more discriminant power to linear terms

Anomalous Gauge Coupling Measurements:
Some assumptions

2. What about operators beyond dim-6?

- The dim-6 “quadratic terms” and the dim-8 operator interference with SM contribute at the same order $\propto 1/\Lambda^4$

Neutral Triple Gauge Couplings

- Reminder: no neutral triple gauge couplings in SM
- nTGC operators only at dim-8 in EFT expansion

$$\mathcal{O}_{\widetilde{B}W} = i H^\dagger \widetilde{B}_{\mu\nu} W^{\mu\rho} \left\{D_\rho, D^\nu\right\} H, \qquad \mathcal{O}_{WW} = i H^\dagger W_{\mu\nu} W^{\mu\rho} \left\{D_\rho, D^\nu\right\} H,$$
$$\mathcal{O}_{BW} = i H^\dagger B_{\mu\nu} W^{\mu\rho} \left\{D_\rho, D^\nu\right\} H, \qquad \mathcal{O}_{BB} = i H^\dagger B_{\mu\nu} B^{\mu\rho} \left\{D_\rho, D^\nu\right\} H.$$

Anomalous Quartic Gauge Couplings

- Only at dim-8 (or higher) operators with quartic vertices but no two or three-boson couplings
- Assumption: aQGC due to dim-6 already constrained elsewhere
- Operators affect all quartic boson couplings

$$\mathcal{L}_{S,0-1} \propto (D_\mu \Phi)^4, \qquad \mathcal{L}_{M,0-7} \propto (F^{\mu\nu})^2 (D_\mu \Phi)^2, \qquad \mathcal{L}_{T,0-9} \propto (F^{\mu\nu})^4$$

- The assumption so far is that dim-6 are already constrained elsewhere so we ignore them when doing dim-8 limits
  - Good assumption or not? Probably need to check it!
  - Considered to use the shape obtained best limits of dim-6 as an uncertainty on the dim-8

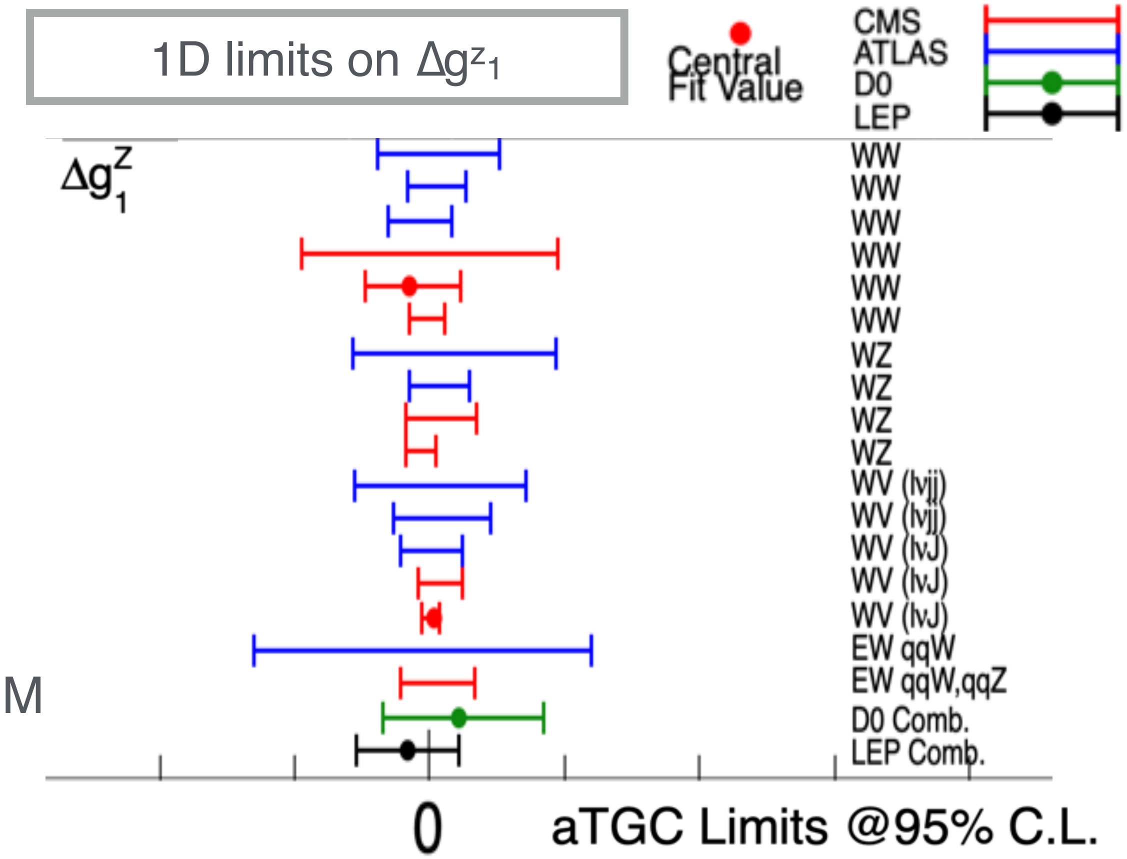
Anomalous Gauge Coupling Measurements:
Some assumptions

3. The fitting procedure

Which parameter can I fit?

- Single channels typically sensitive to more than 1 EFT parameter → statistics do not allow to fit all parameters then some assumptions need to be made:
  - 1D limits: fit 1 parameter at the time with all other set at SM
  - 2D limits: 2 free parameters and the rest fixed at SM

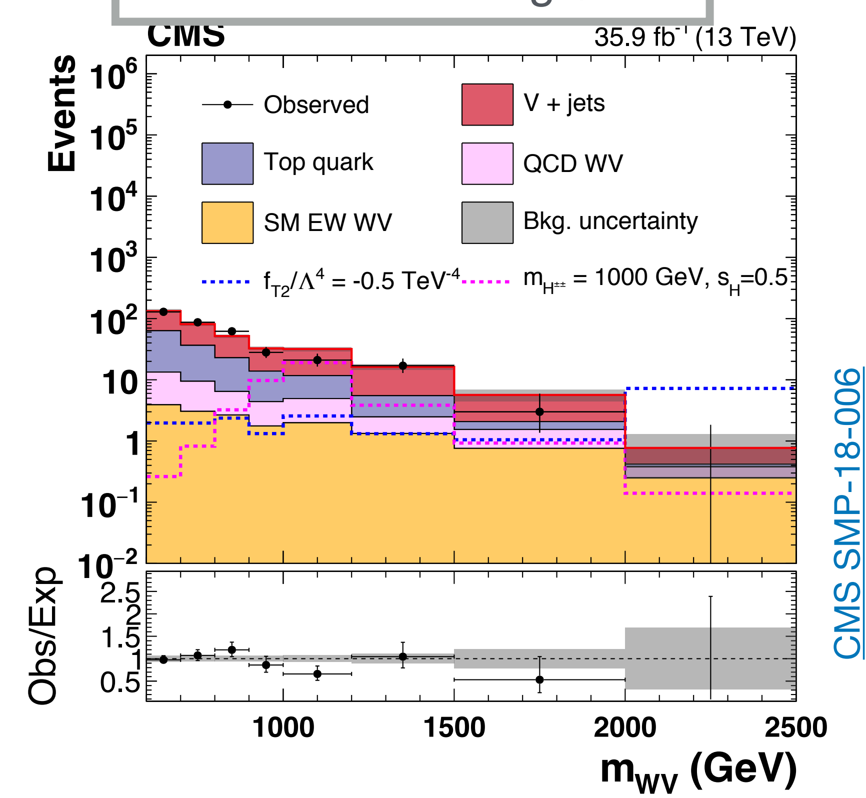
1D limits on Δg^{z}_{1}



What should I fit ?

- Two approaches have been used:
  - Fit the reconstructed level distributions: simulate the EFT effects at reco level and set limits → used for most of the Run-I results
  - Fit unfolded kinematic distributions (any way part of most of the SM results): simulate EFT in fiducial volume and set limits → becoming more common in Run-II
- Pros and cons in both approaches…

1D limits on Δg^{z}_{1}



Eur. Phys. J. C 79 (2019) 884

Anomalous Gauge Coupling Measurements:
Some assumptions

3. The fitting procedure

Using unfolded distributions

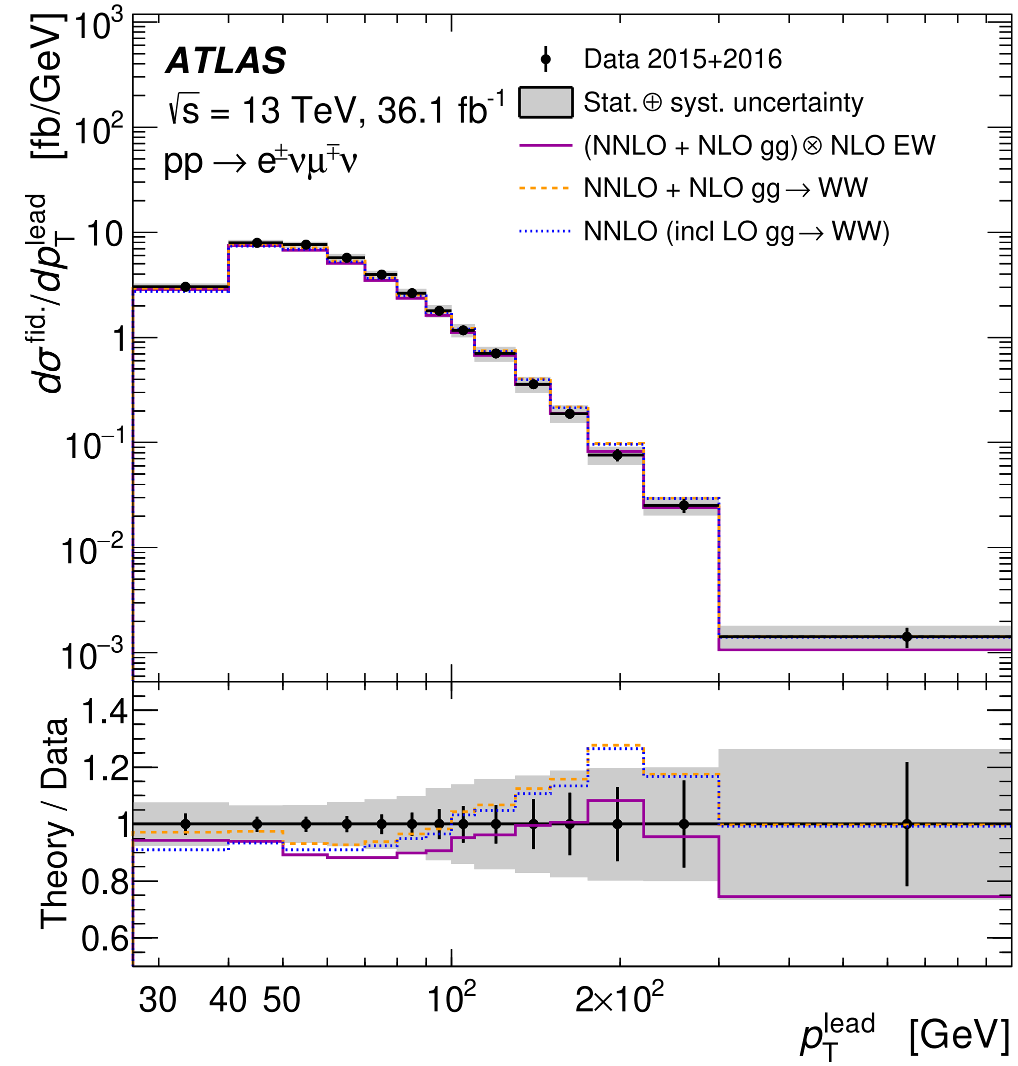
Pros

- Do not need large amount of detector simulated Monte Carlo.
- The fitting is greatly simplified.
- External members will use this procedure, easier for combinations

Cons

- Possible bias due to the unfolding procedure on the limits.
  - Reconstruction efficiencies to extrapolate from detector level to fiducial truth level might be different between BSM and SM.
- Constraining power of the unfolded result can be weaker than a fit a reconstruction level (stats in the tails)

Unfolded Leading lepton p_T from WW paper



Example of bias study for the WW publication

- Compared reconstruction efficiencies and fiducial corrections for EFT simulated sample and SM sample → no significant differences
- Limits using both reco and unfolded and get the same results to within ±1%

Summary

- At the LHC: EFT fits in EW precision measurements (so far) synonymous with anomalous gauge coupling measurements
- Many measurements are already available from Run-I and Run-II datasets (many Run-II are still under preparations) but also assumptions needed in order to produce results
- Some of the the different choices made by the collaborations in the presentation of the results were reviewed.
- Some obvious points where measurements and their interpretations can be improved
- Longer term: should move towards combinations and perform more global EFT fits and for this we need to agree in some of the assumptions we are making :)

References

- Detailed information on ATLAS and CMS analysis can be found here:
  - ATLAS https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults
  - CMS https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP
- Interesting presentations also from Pushing the Boundaries conference https://conference.ippp.dur.ac.uk/event/810/
- ATLAS EFT workshops https://indico.cern.ch/event/729117/