Multi-Boson Triple/Quartic Gauge Couplings at ATLAS(+CMS)

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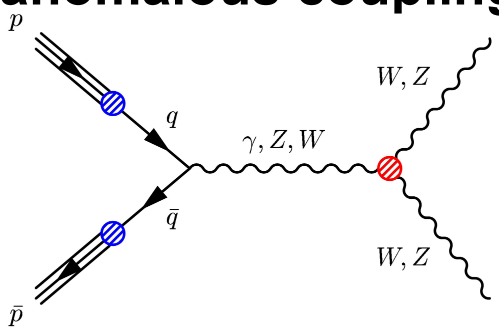
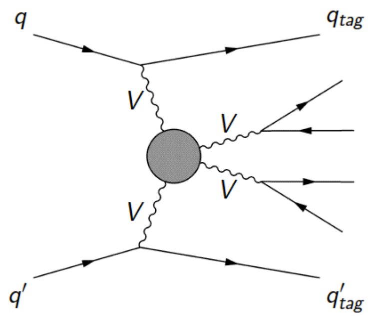
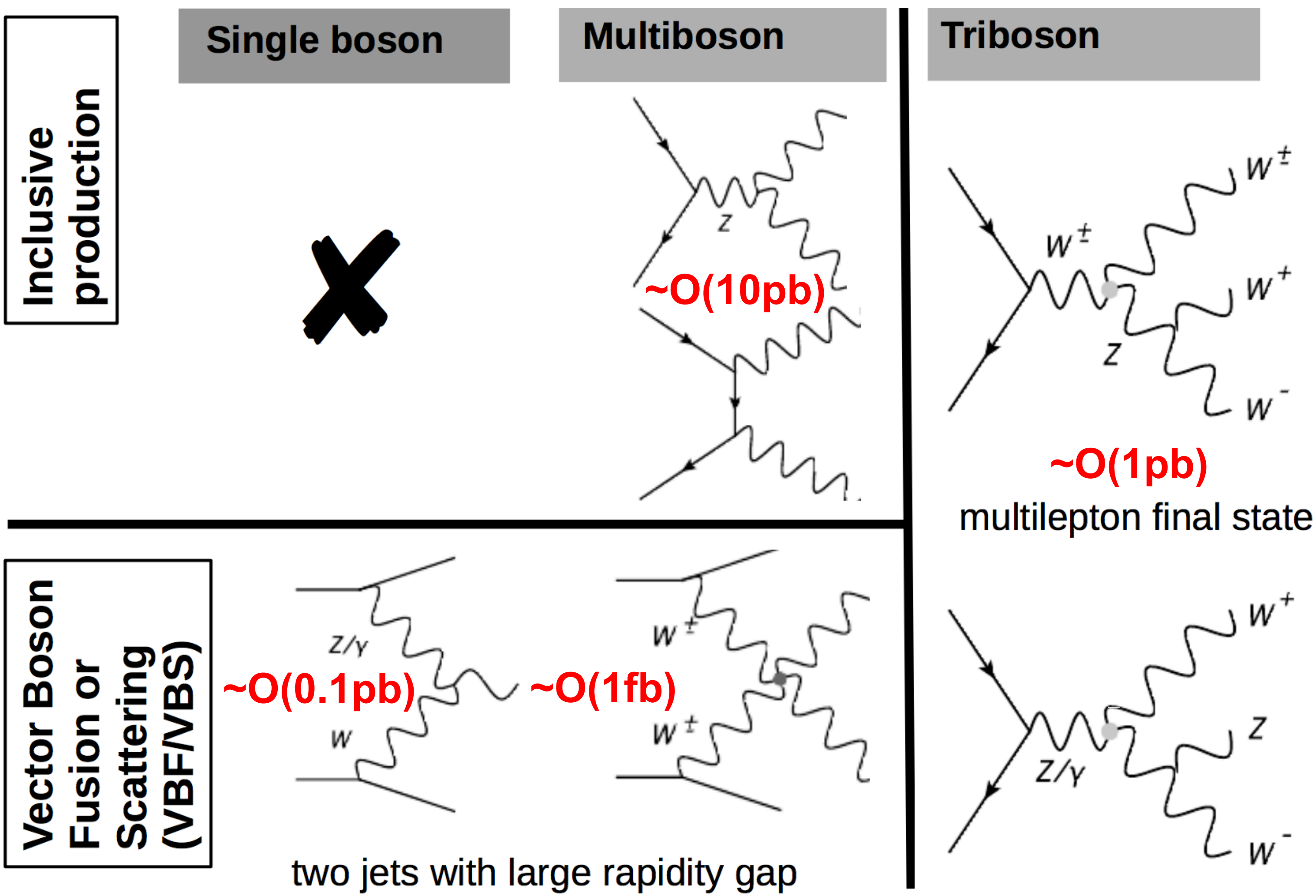
General Notes

- Electroweak is one of the key sector to check and consolidate Standard Model prediction, by far measurements are consistent with the SM in TeV colliders
- Searches for deviation from the SM performed during Run-1 and Run-2 can be performed with or without choosing a specific model to capture a wide range of possible new physics
  - **Direct search of new particles**
  - **New interactions of known particles of SM**
    - **anomalous couplings**

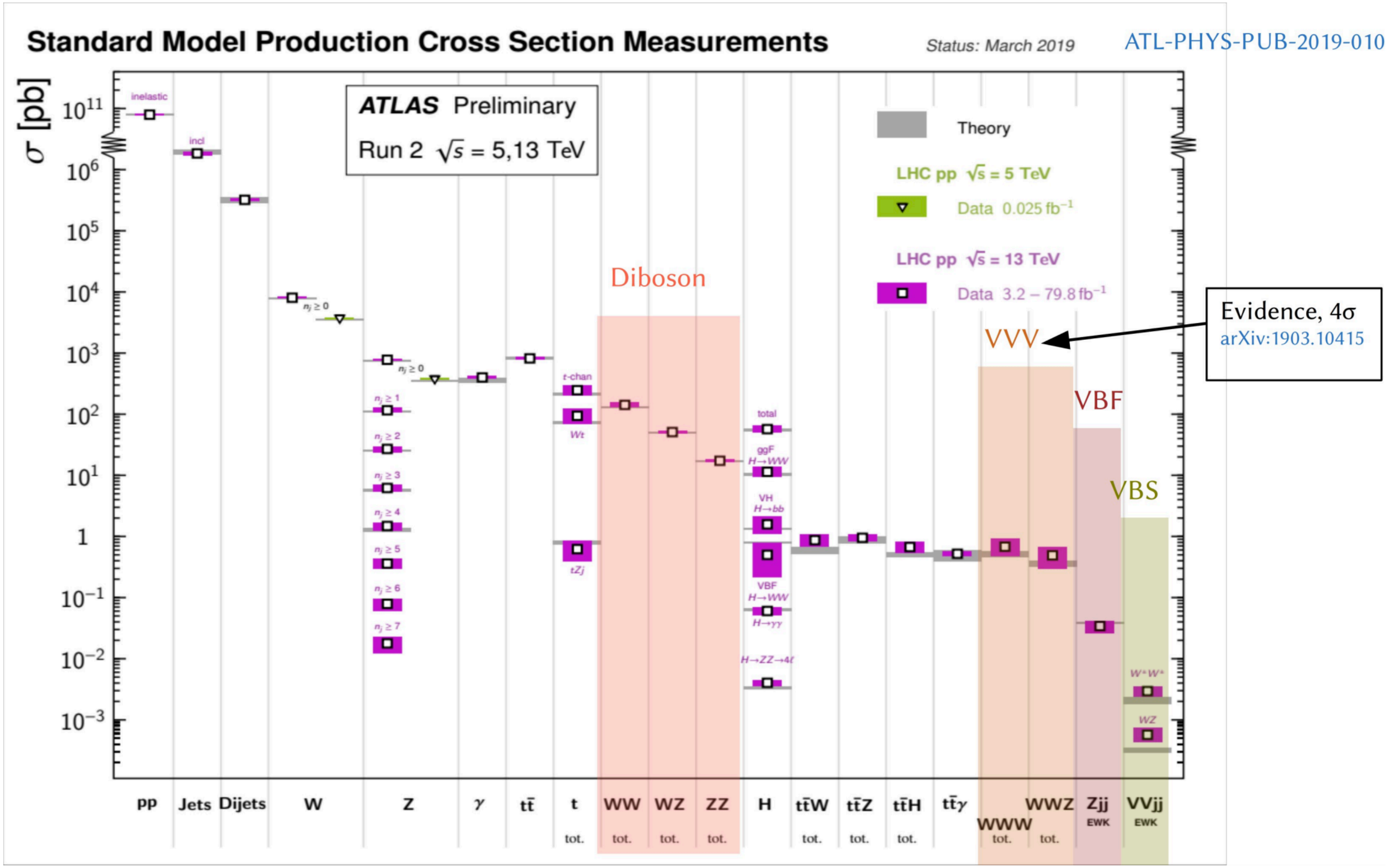


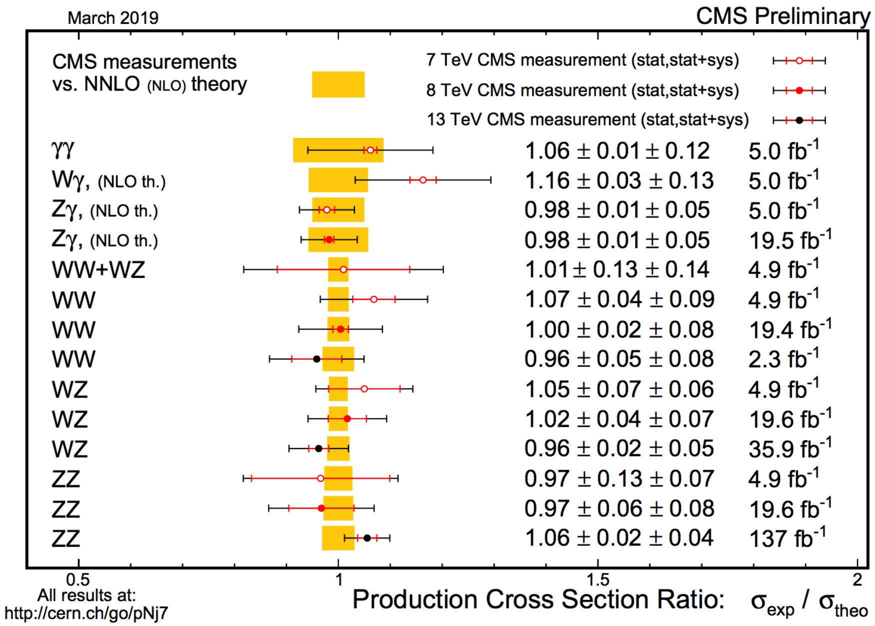


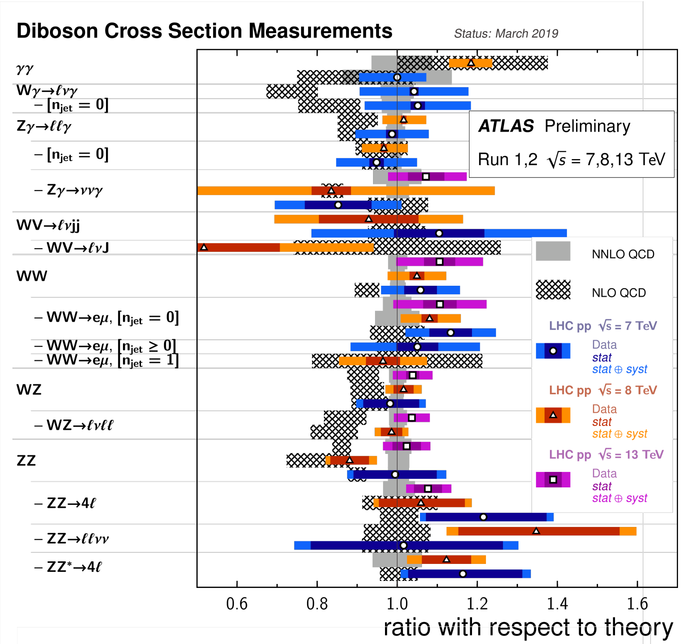
Overview of MultiBoson productions at LHC

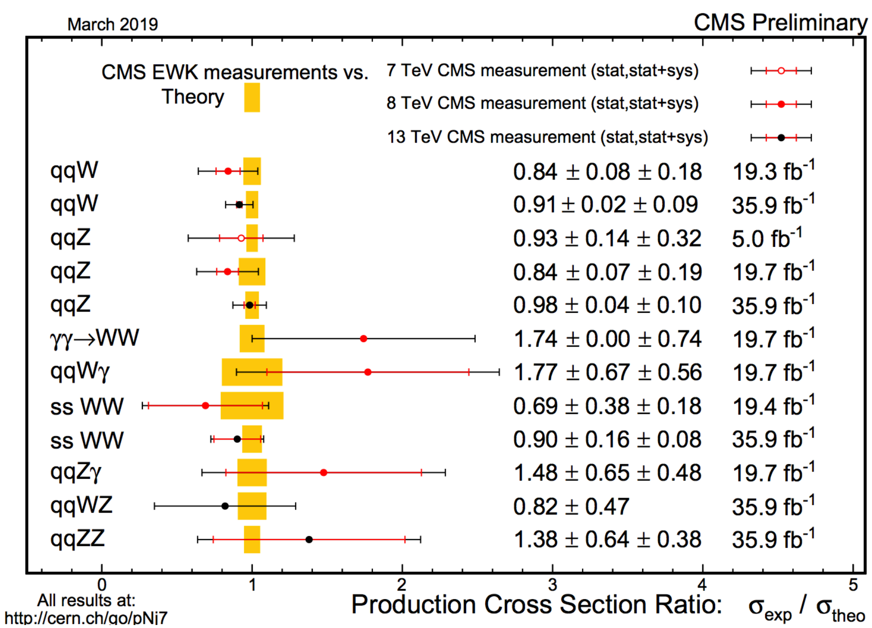


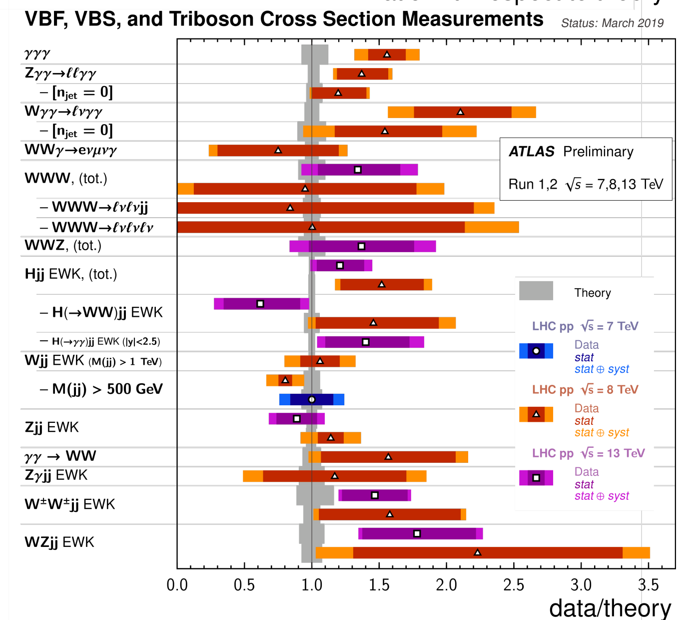
Latest SM measurement summary



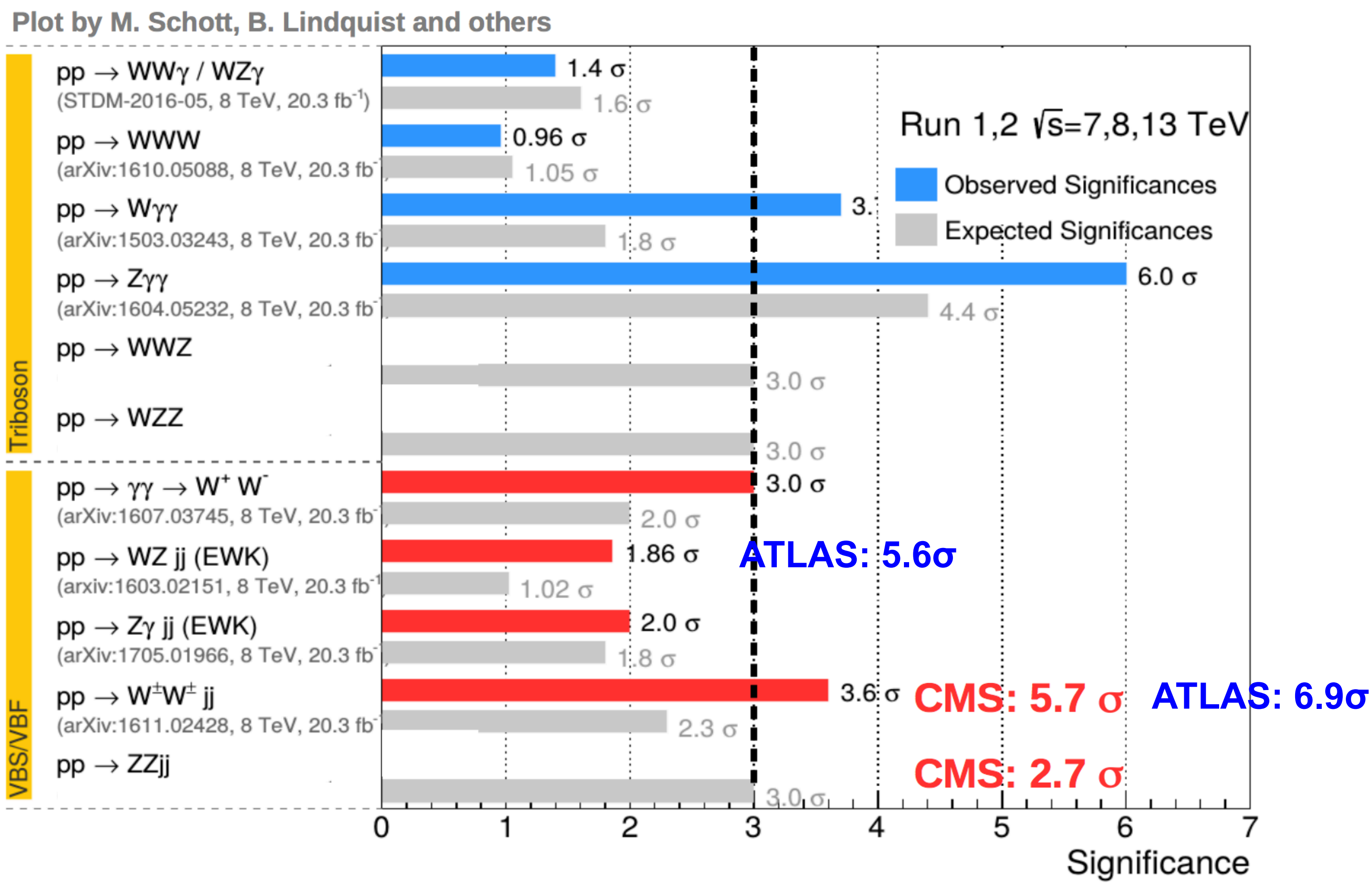

March 2019
CMS Preliminary
CMS measurements
vs. NNLO (NLO) theory
7 TeV CMS measurement (stat,stat+sys)
8 TeV CMS measurement (stat,stat+sys)
13 TeV CMS measurement (stat,stat+sys)
γγ 1.06 ± 0.01 ± 0.12 5.0 fb-1
Wγ, (NLO th.) 1.16 ± 0.03 ± 0.13 5.0 fb-1
Zγ, (NLO th.) 0.98 ± 0.01 ± 0.05 5.0 fb-1
Zγ, (NLO th.) 0.98 ± 0.01 ± 0.05 19.5 fb-1
WW+WZ 1.01 ± 0.13 ± 0.14 4.9 fb-1
WW 1.07 ± 0.04 ± 0.09 4.9 fb-1
WW 1.00 ± 0.02 ± 0.08 19.4 fb-1
WW 0.96 ± 0.05 ± 0.08 2.3 fb-1
WZ 1.05 ± 0.07 ± 0.06 4.9 fb-1
WZ 1.02 ± 0.04 ± 0.07 19.6 fb-1
WZ 0.96 ± 0.02 ± 0.05 35.9 fb-1
ZZ 0.97 ± 0.13 ± 0.07 4.9 fb-1
ZZ 0.97 ± 0.06 ± 0.08 19.6 fb-1
ZZ 1.06 ± 0.02 ± 0.04 137 fb-1
0.5 1 1.5 2
All results at:
http://cern.ch/go/pNj7
Production Cross Section Ratio: σexp / σtheo


Diboson Cross Section Measurements
Status: March 2019
γγ
Wγ→ℓνγ
– [njet = 0]
Zγ→ℓℓγ
– [njet = 0]
– Zγ→ννγ
WV→ℓνjj
– WV→ℓνJ
WW
– WW→eμ, [njet = 0]
– WW→eμ, [njet ≥ 0]
– WW→eμ, [njet = 1]
WZ
– WZ→ℓνℓℓ
ZZ
– ZZ→4ℓ
– ZZ→ℓℓνν
– ZZ*→4ℓ
ATLAS Preliminary
Run 1,2 √s = 7,8,13 TeV
NNLO QCD
NLO QCD
LHC pp √s = 7 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 8 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 13 TeV
Data
stat
stat ⊕ syst
0.6 0.8 1.0 1.2 1.4 1.6
ratio with respect to theory


March 2019
CMS Preliminary
CMS EWK measurements vs.
Theory
7 TeV CMS measurement (stat,stat+sys)
8 TeV CMS measurement (stat,stat+sys)
13 TeV CMS measurement (stat,stat+sys)
qqW 0.84 ± 0.08 ± 0.18 19.3 fb-1
qqW 0.91 ± 0.02 ± 0.09 35.9 fb-1
qqZ 0.93 ± 0.14 ± 0.32 5.0 fb-1
qqZ 0.84 ± 0.07 ± 0.19 19.7 fb-1
qqZ 0.98 ± 0.04 ± 0.10 35.9 fb-1
γγ→WW 1.74 ± 0.00 ± 0.74 19.7 fb-1
qqWγ 1.77 ± 0.67 ± 0.56 19.7 fb-1
ss WW 0.69 ± 0.38 ± 0.18 19.4 fb-1
ss WW 0.90 ± 0.16 ± 0.08 35.9 fb-1
qqZγ 1.48 ± 0.65 ± 0.48 19.7 fb-1
qqWZ 0.82 ± 0.47 35.9 fb-1
qqZZ 1.38 ± 0.64 ± 0.38 35.9 fb-1
0 1 2 3 4 5
All results at:
http://cern.ch/go/pNj7
Production Cross Section Ratio: σexp / σtheo


VBF, VBS, and Triboson Cross Section Measurements
Status: March 2019
γγγ
Zγγ→ℓℓγγ
– [njet = 0]
Wγγ→ℓνγγ
– [njet = 0]
WWγ→eνμνγ
WWW, (tot.)
– WWW→ℓνℓνjj
– WWW→ℓνℓνℓν
WWZ, (tot.)
Hjj EWK, (tot.)
– H(→WW)jj EWK
– H(→γγ)jj EWK (|y|<2.5)
Wjj EWK (M(jj) > 1 TeV)
– M(jj) > 500 GeV
Zjj EWK
γγ → WW
Zγjj EWK
W±W±jj EWK
WZjj EWK
ATLAS Preliminary
Run 1,2 √s = 7,8,13 TeV
Theory
LHC pp √s = 7 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 8 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 13 TeV
Data
stat
stat ⊕ syst
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5
data/theory

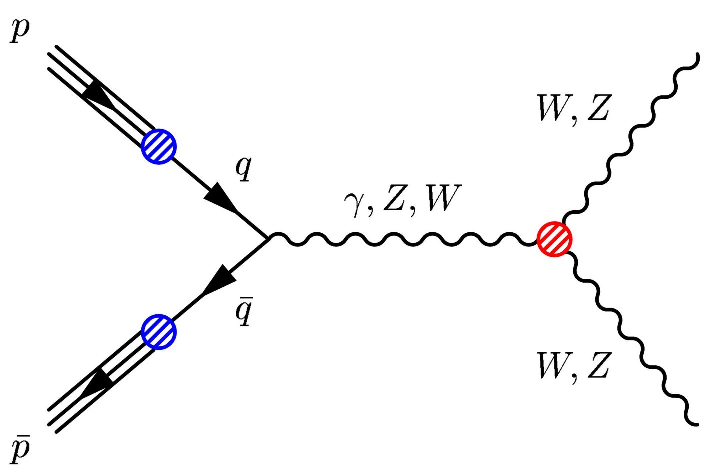
MultiBoson rare process measurement status

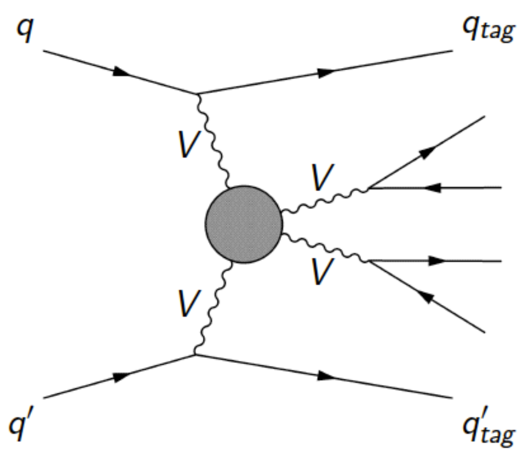


New Physics Searches at LHC

Two general ways:

- ***Direct search of new particles***
- ***New interactions of known particles of SM***
  - Traditional anomalous coupling framework, Effective field theory approach: anomalous Triple/Quartic Gauge Couplings



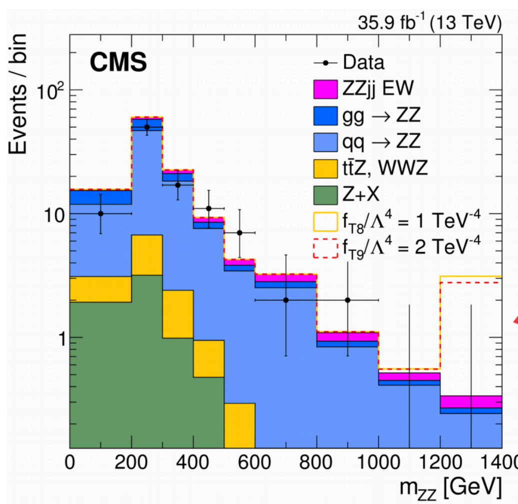


Anomalous coupling framework

- Traditional: add new degrees of freedom in the SM Lagrangian (vertex approach)
  - adding new interaction term to introduce anomalous triple gauge couplings (aTGCs) $\Delta\kappa^V$, Δg_1^V, λ^V **(CERN–96–01–V–1)**
  - Can compare directly to LEP and Tevatron results
- EFT high dimension operators

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_{d>4} \sum_{\mathrm{i}} \frac{c_{\mathrm{i}}^{d}}{\Lambda^{d-4}} \mathcal{O}_{\mathrm{i}}^{d}$$

Standard model



Adding anomalies to shatter the Standard Model with EFT high dimension operators

General extension with high dimension operators, suppressed by energy scale Λ(dimension d - 4)

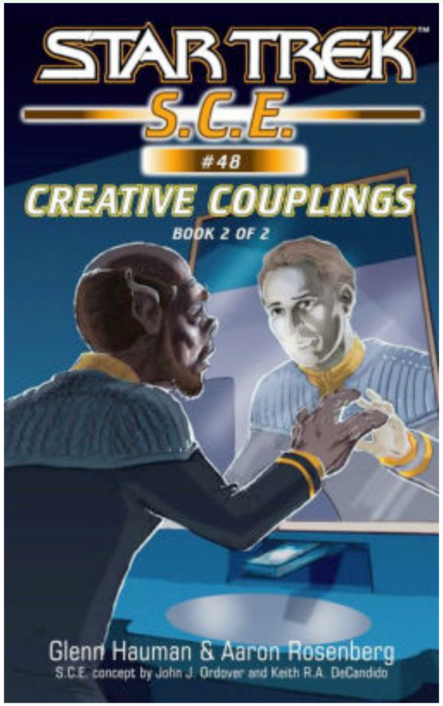
Dim-6 Dim-8

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \Sigma_i \frac{c_i}{\Lambda^2} O_i + \Sigma_j \frac{f_j}{\Lambda^4} O_j + \ldots$$

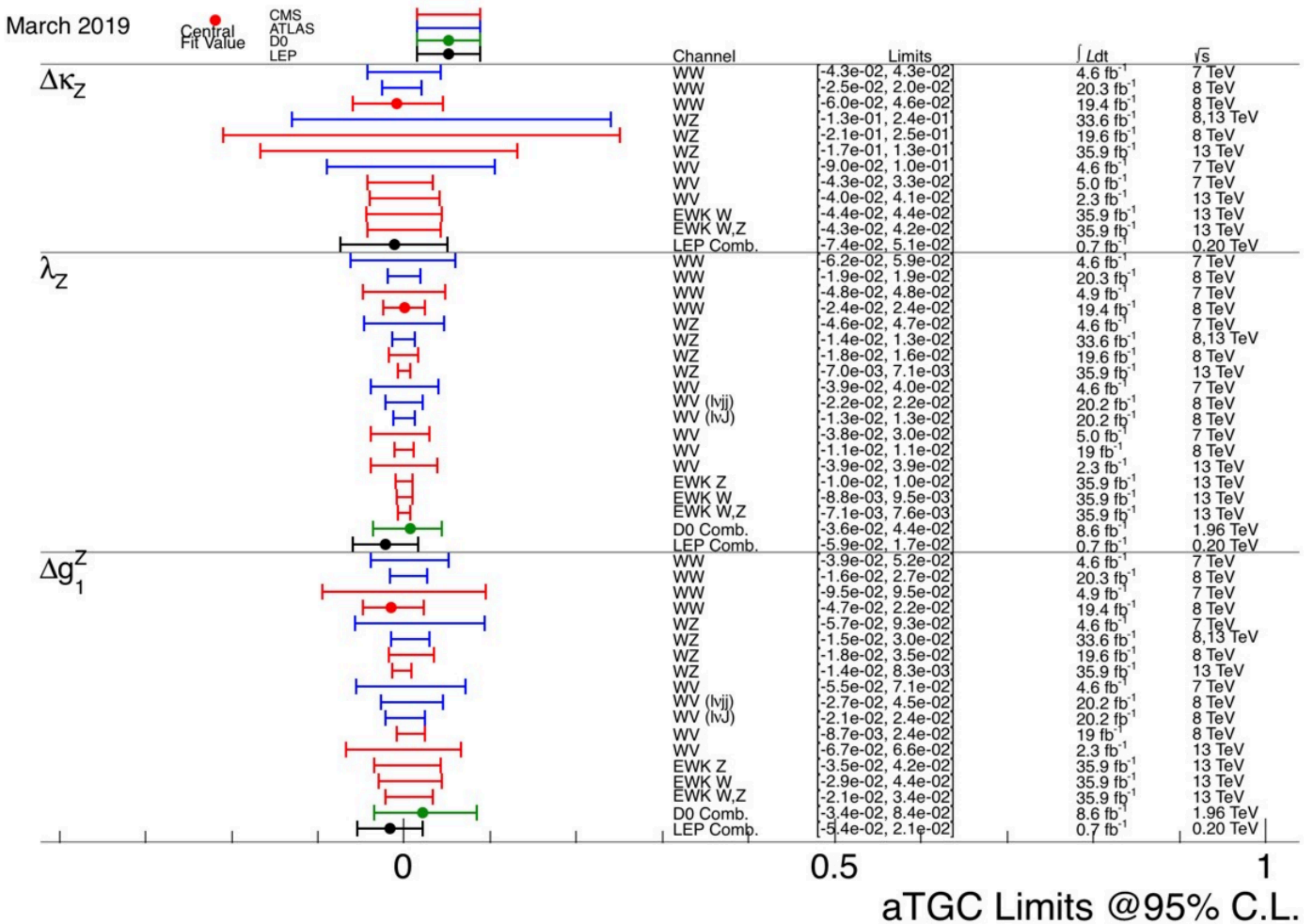
SM: d ≤ 4

Neutrino masses: d=5,

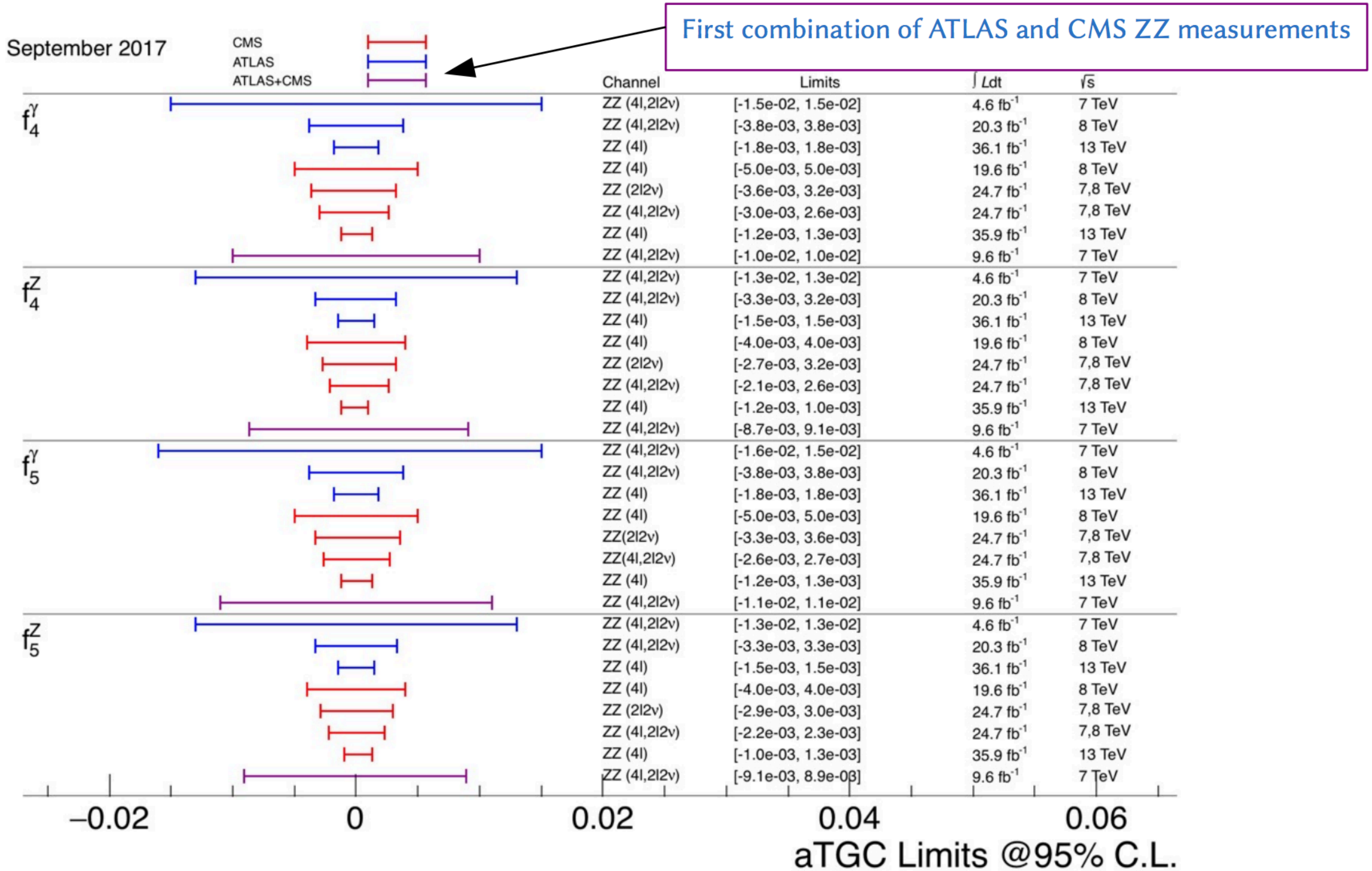
d≥ 6 → ???



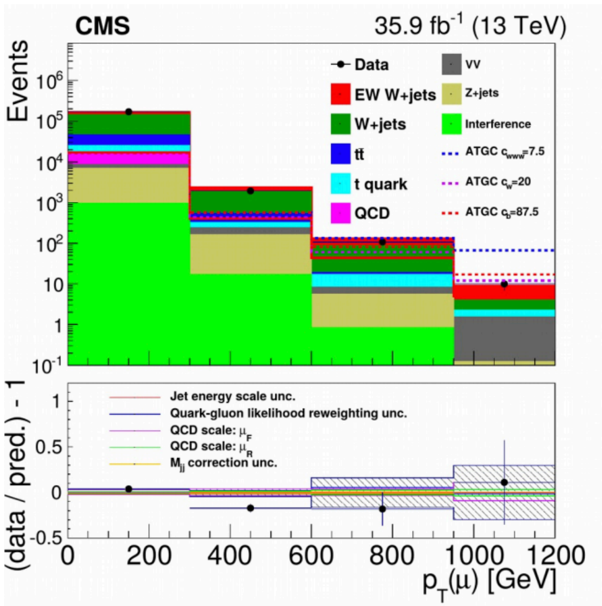
Charged TGC summary



Neutral TGC summary



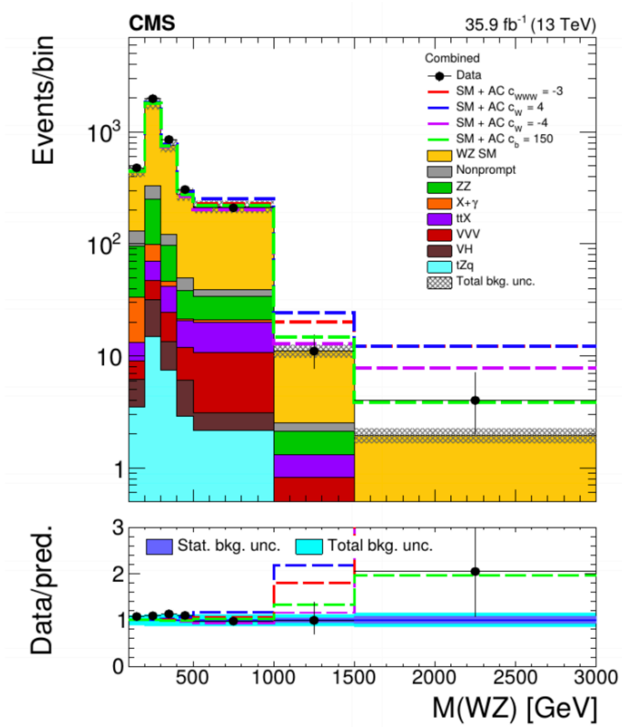
Latest TGC searches with diboson and VBF



EWK Wjj (VBF)

$\Delta\kappa^Z$, Δg_1^Z, λ^Z

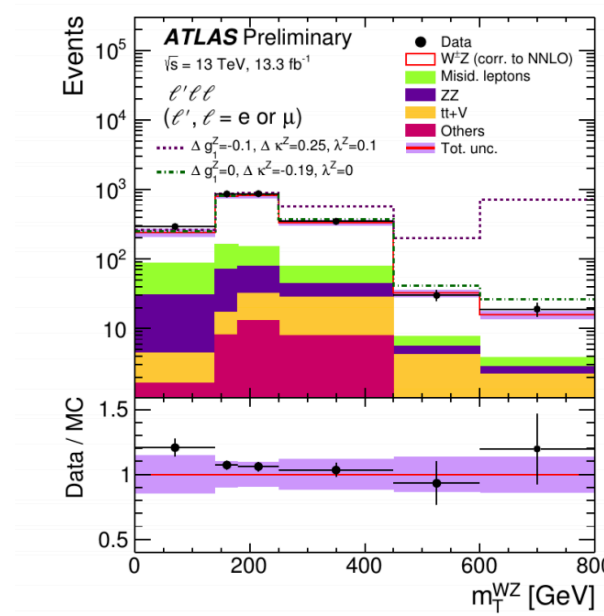
CMS_SMP_17_011



WZ inclusive

C_W, C_B, C_{WWW}

CMS_SMP_18_002



WZ inclusive

C_W, C_B, C_{WWW}

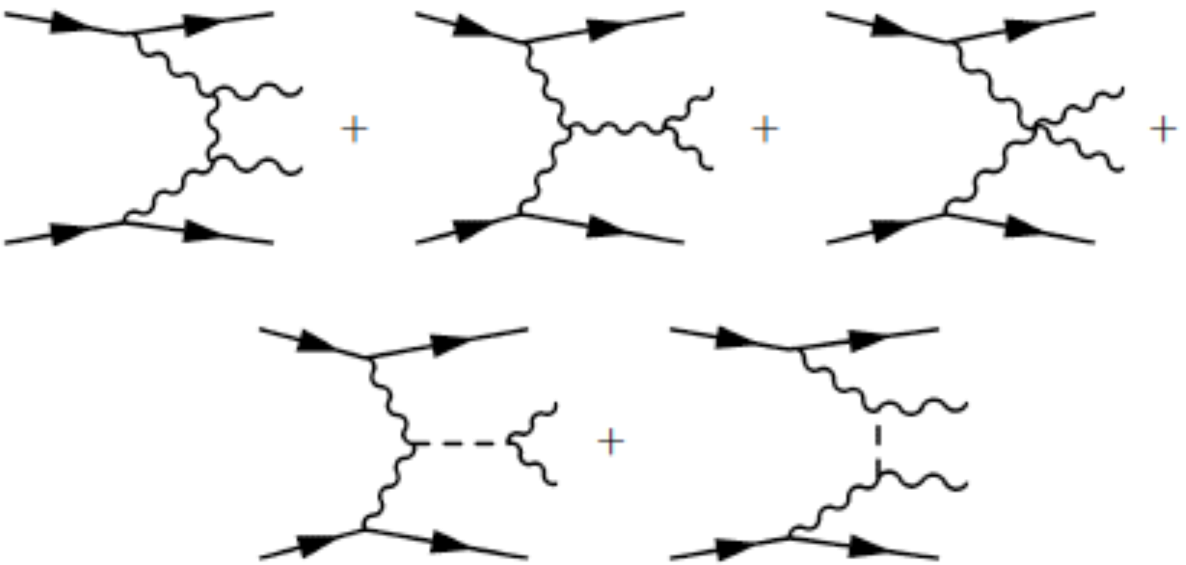
$\Delta\kappa^Z$, Δg_1^Z, λ^Z

ATLAS_CONF_2016_043

EFT with dim8 operators

- Assuming Higgs boson belongs to a $SU(2)_L$ doublet
- dimension 8: the lowest dimension operators exhibiting quartic couplings in VBS but NOT in two or three gauge boson vertices

EW signal with Vector Boson Scattering Topology:



EFT with dim8 operators

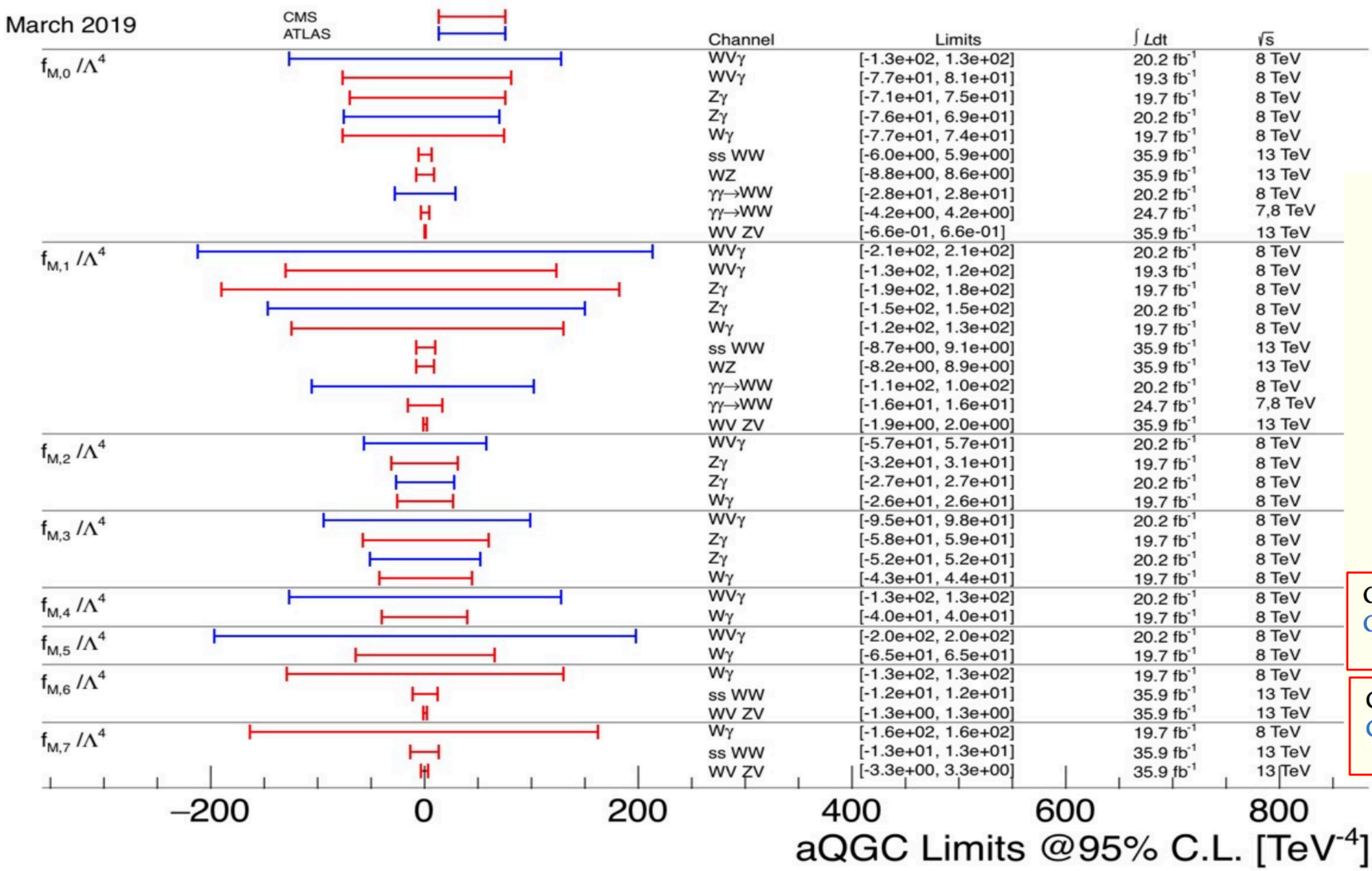
$$\mathcal{L}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right] \qquad \mathcal{L}_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]$$

$$\begin{aligned}
\mathcal{L}_{M,0} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \\
\mathcal{L}_{M,1} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \\
\mathcal{L}_{M,2} &= \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \\
\mathcal{L}_{M,3} &= \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \\
\mathcal{L}_{M,4} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\mu\Phi\right] \times B^{\beta\nu} \\
\mathcal{L}_{M,5} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\nu\Phi\right] \times B^{\beta\mu} \\
\mathcal{L}_{M,6} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\nu} D^\mu\Phi\right] \\
\mathcal{L}_{M,7} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu} D^\nu\Phi\right]
\end{aligned}$$

$$\begin{aligned}
\mathcal{L}_{T,0} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}\right] \\
\mathcal{L}_{T,1} &= \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right] \\
\mathcal{L}_{T,2} &= \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}\right] \\
\mathcal{L}_{T,5} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta} \\
\mathcal{L}_{T,6} &= \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu} \\
\mathcal{L}_{T,7} &= \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha} \\
\mathcal{L}_{T,8} &= B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta} \\
\mathcal{L}_{T,9} &= B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}
\end{aligned}$$

- Currently available dim8 operators in MadGraph
  - LS0,LS1: wwjj, wzjj, zzjj
  - LM0,LM1: wwjj, wzjj, zzjj, wajj, zajj, waa, wwa, zaa, zza, www, wwz,zzz
  - LM2,LM3: wwjj, wzjj, zzjj, wajj, zajj, waa, wwa, zaa, zza, www, wwz, zzz
  - LT012: wwjj, wzjj, zzjj, wajj, zajj, waa, wwa, zaa, zza, www, wwz, zzz
  - LT8,LT9: zzjj, zajj, zaa, zza, zzz

aQGC summary



13 TeV results

CMS ssWW
arXiv:1709.05822

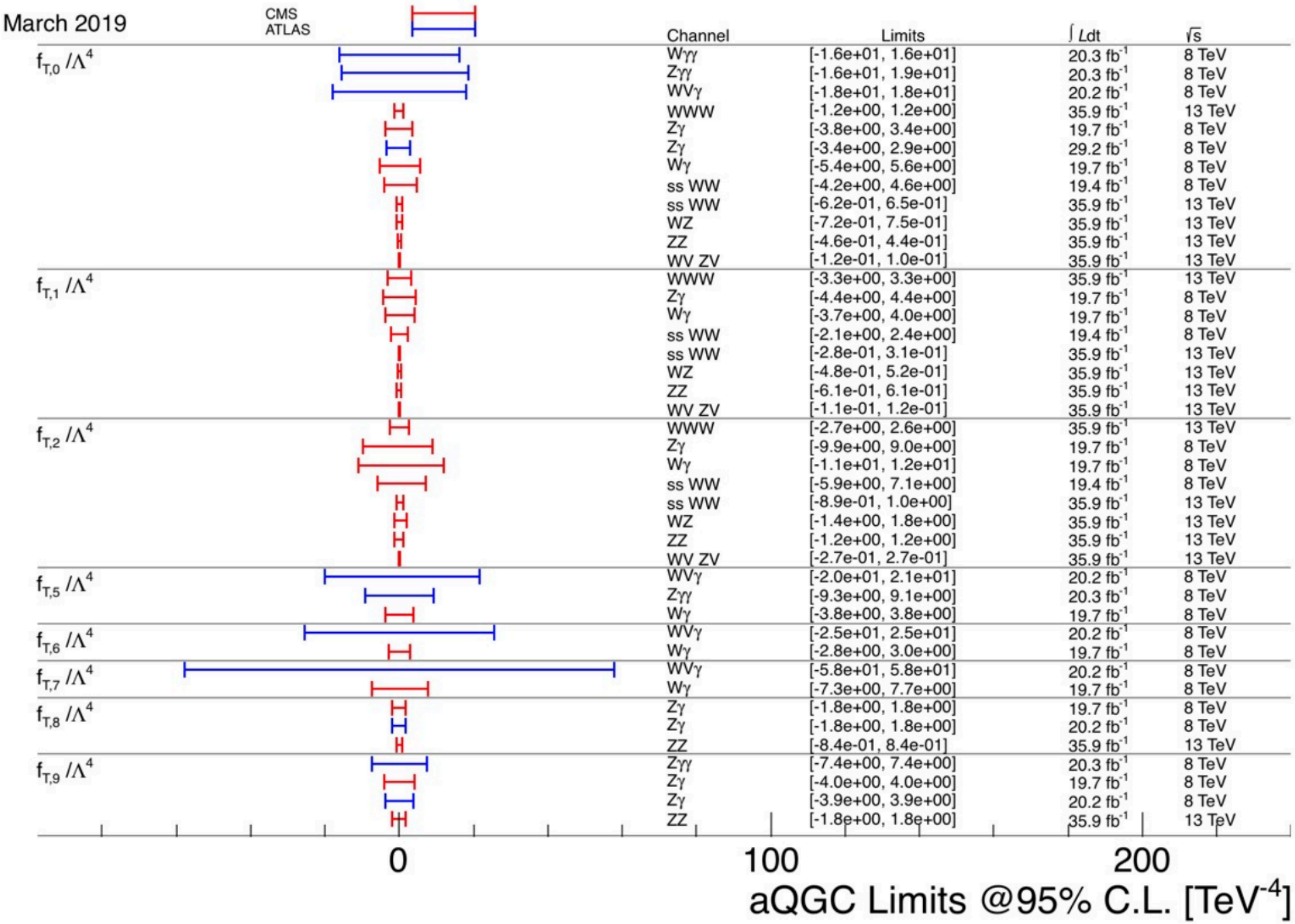
CMS WZ
arXiv:1901.04060

CMS ZZ
arXiv:1708.02812

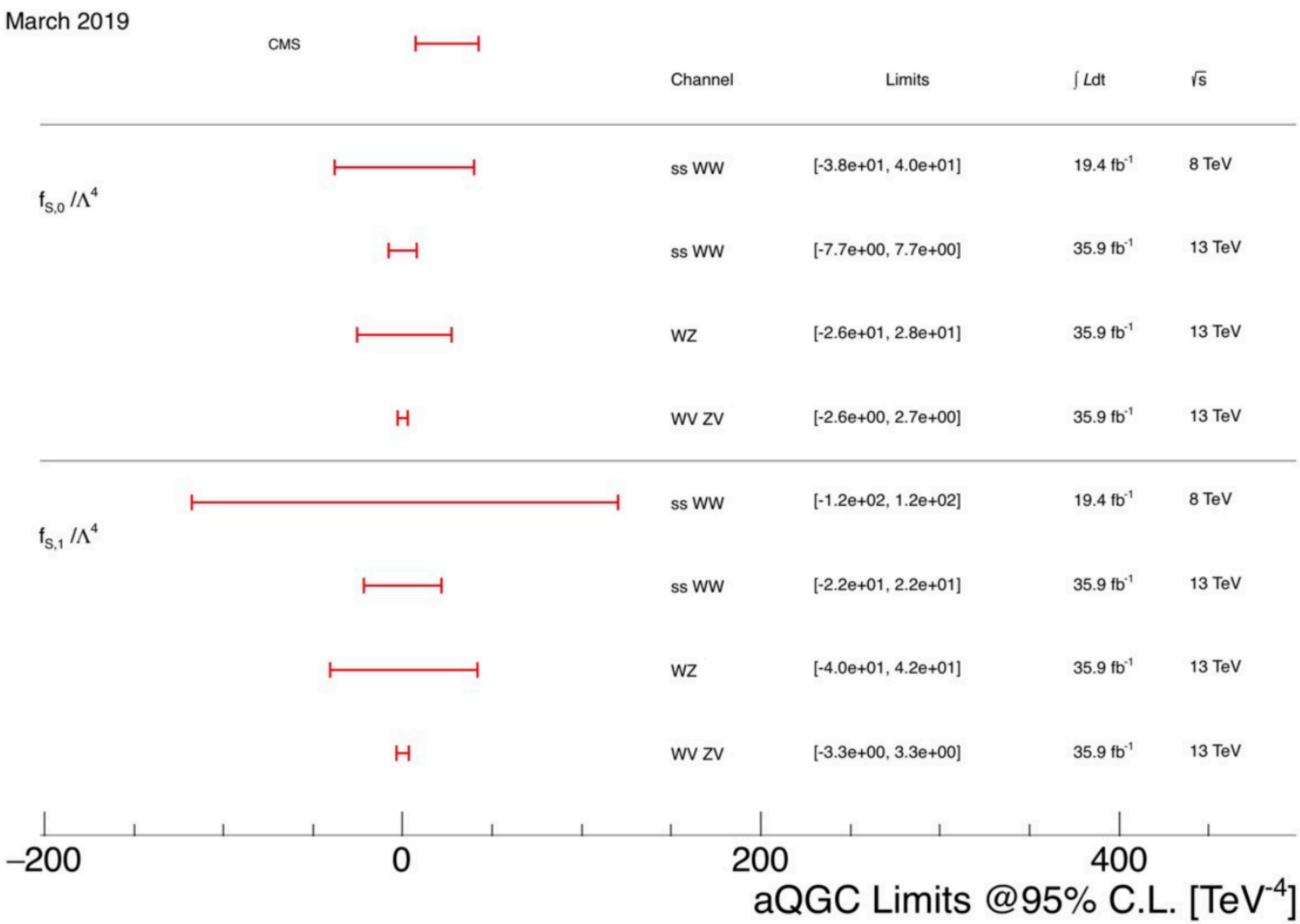
CMS WV ZV
CMS-PAS-SMP-18-006

CMS WWW
CMS-PAS-SMP-17-013

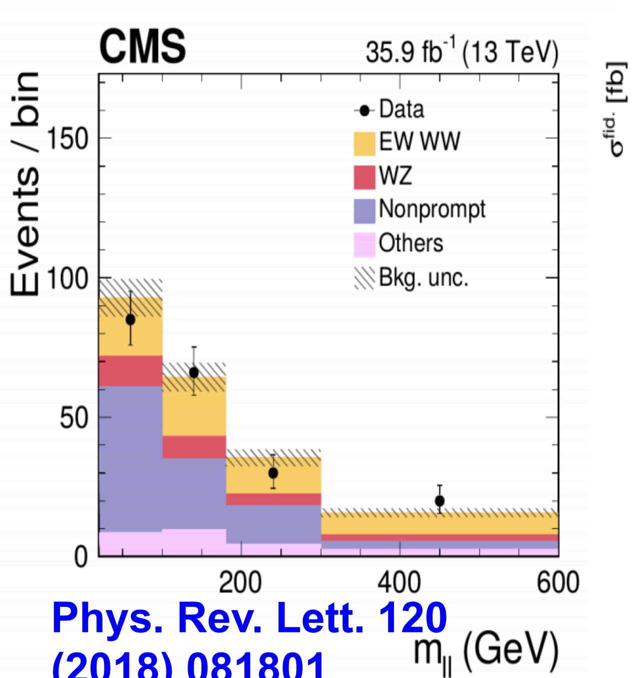
aQGC summary



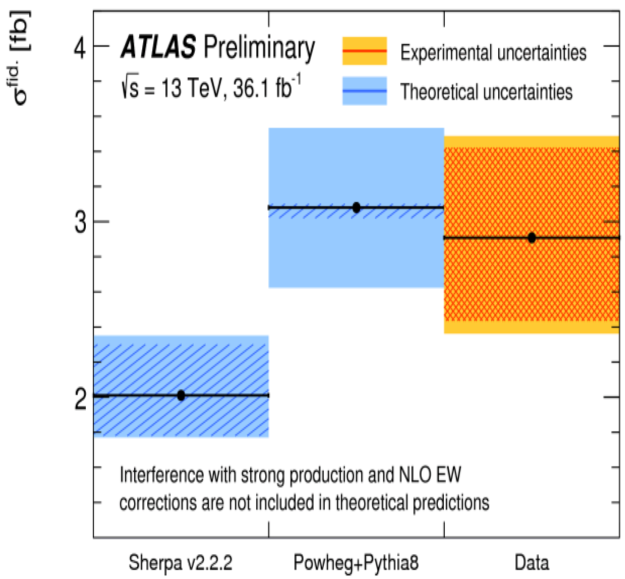
aQGC summary



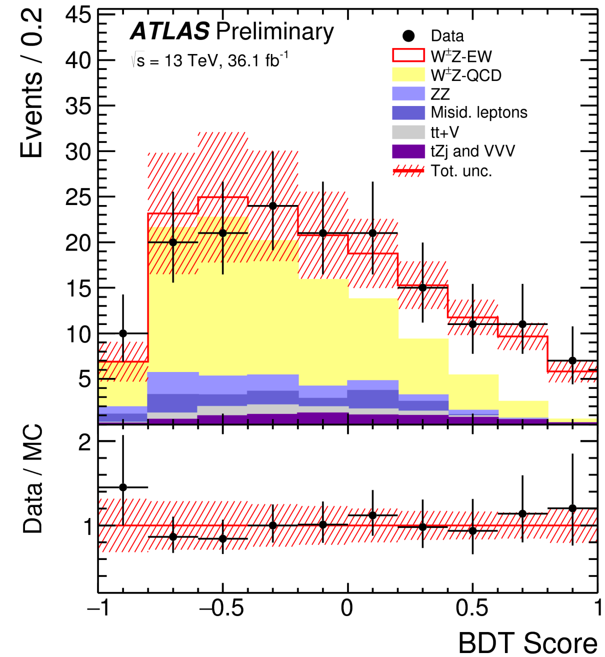
Recent Milestones in Run2 VBS measurements



Phys. Rev. Lett. 120 (2018) 081801



ATLAS-CONF-2018-030

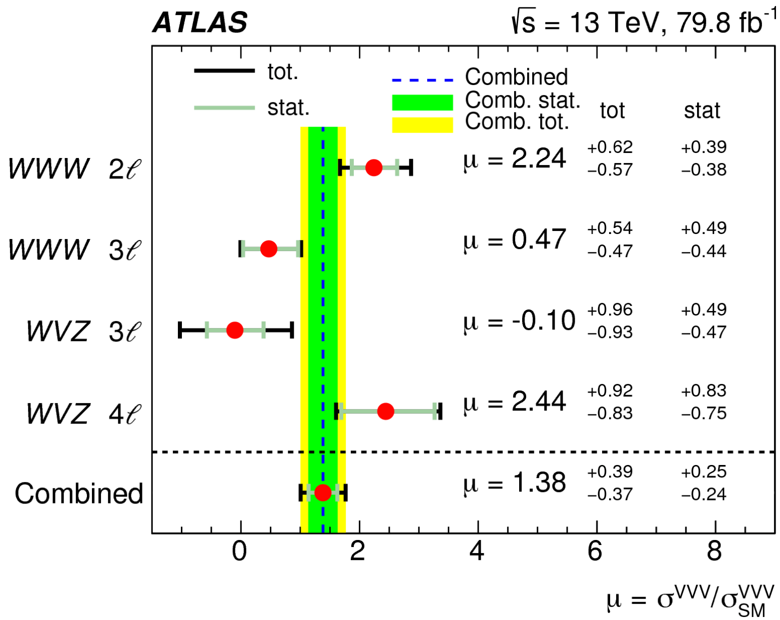


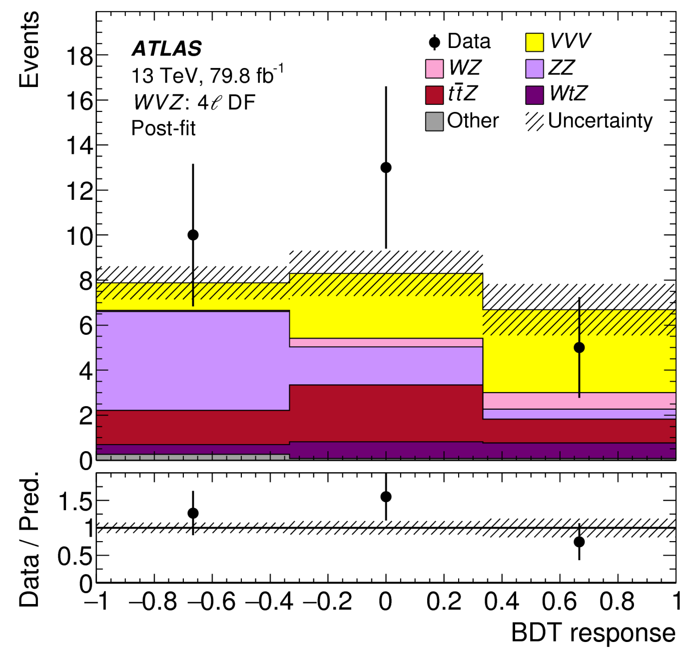
ATLAS-CONF-2018-033

- **VBS same-sign WWjj** measured with greater-than 5-σ by CMS (LHCP2017) and ATLAS (ICHEP2018)
- **VBS WZjj** measured with greater-than 5-σ by ATLAS (ICHEP2018)
- In consistency with SM prediction (interference with Strong Interactions and also NLO EWK correction would be better taken into account in measured comparisons)

Recent Milestones in Run2 Triboson measurements: evidence of VVV production

arXiv:1903.10415

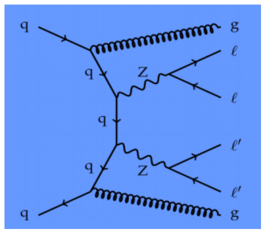




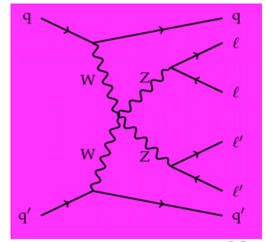
- First evidence of WVV(V=W/Z, decaying into dijets) with $80 fb^{-1}$ data by ATLAS
- **Exp. (Obs.) Significance = 3.1 (4) σ**
- Sensitive to 1→3 Quartic Coupling scenario, to be explored with next publication
- **Zγγ** measured with greater-than **5σ** by ATLAS (PRD 93 (2016) 112002) and CMS (JHEP 10 (2017) 072), **Wγγ** with greater-than 3σ by ATLAS (PRL 115 (2015) 031802) in Run1

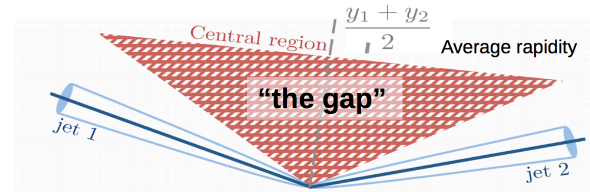
Latest VBS measurements with aQGC

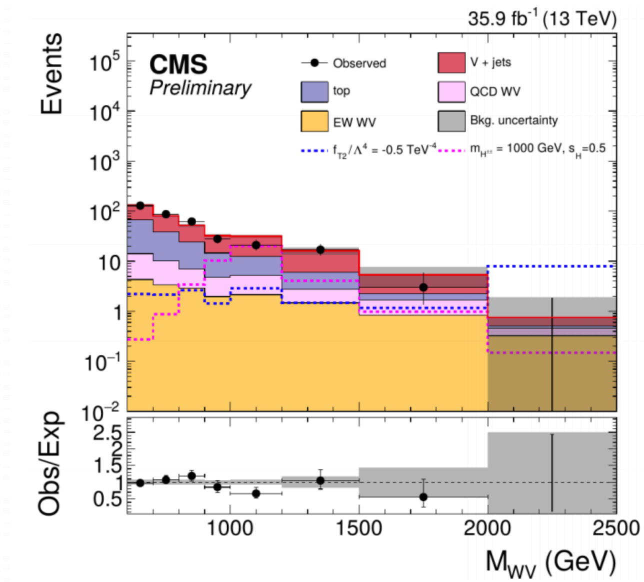
QCD VVjj
(backgrounds)



EWK VVjj
(Signals)



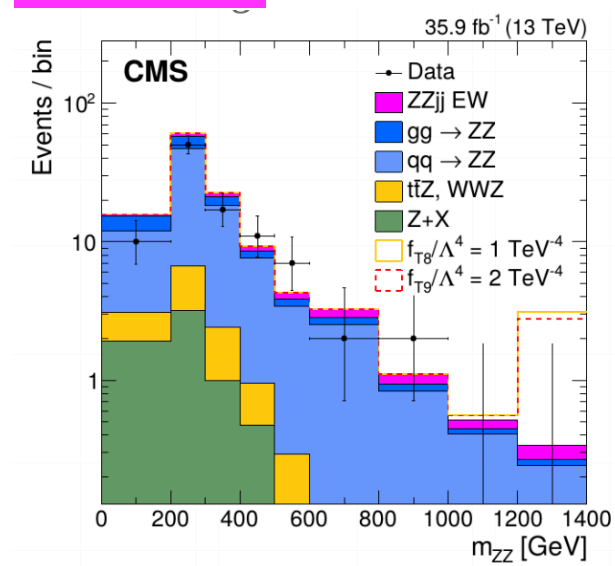




EWK WVjj (VBS)

f_{T2}, d-charged Higgs

CMS-PAS-SMP-18-006



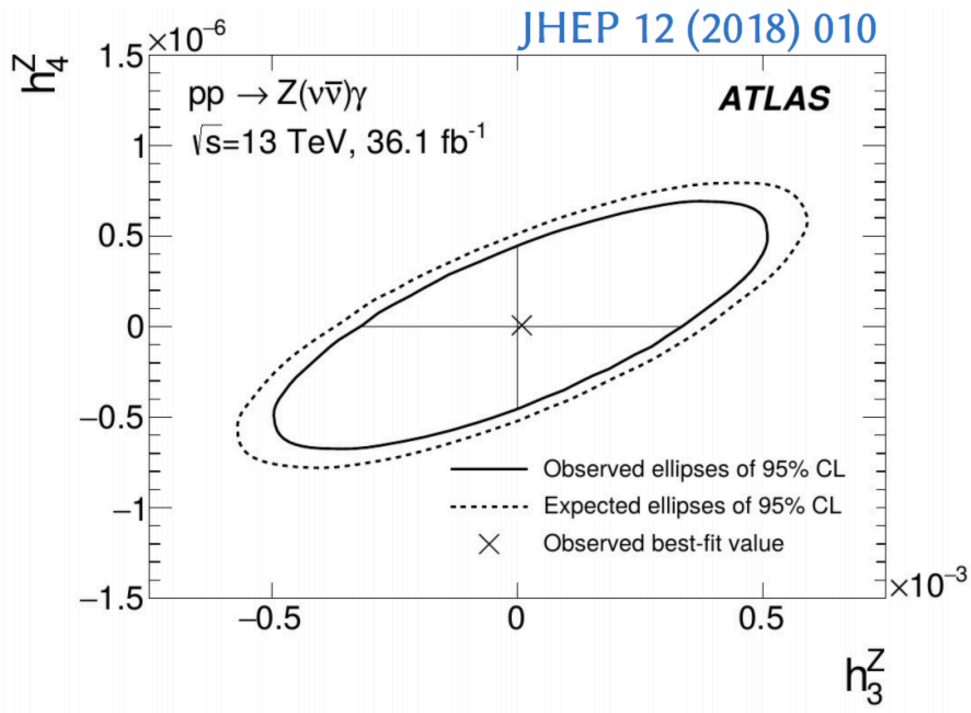
EWK ZZjj (VBS)

f_{T8}, f_{T9}

Phys. Lett. B 774 (2017) 682

Current limit setting benchmark recipe

- Typical 1-D limits are set with 95% CL limits on a given aGC parameter while other parameters are set to SM values
- Effective Lagrangian and Vertex Parameterization approach and EFT approach can be transformed via linear conversion (Vertex dependently)
- Also provide 2-D limits via likelihood fit of the two aGC parameters

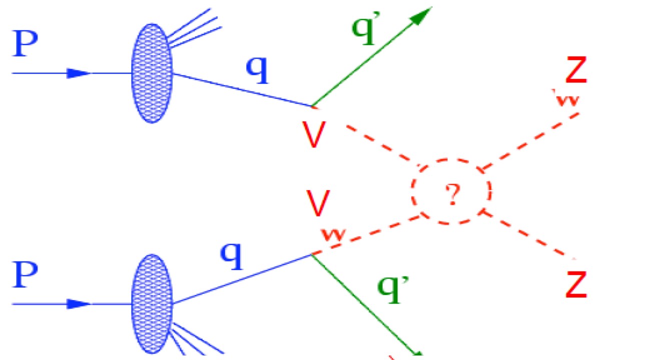


Testing Higgs unitarization mechanism and probing new interactions with SM VBS

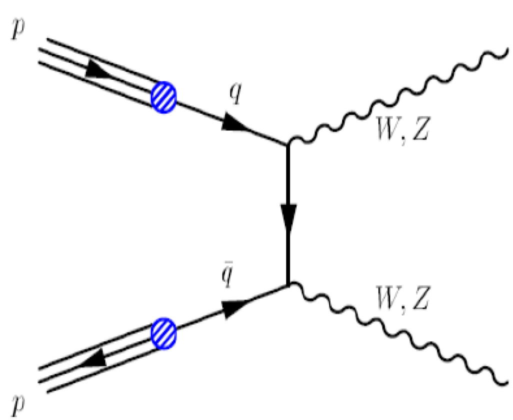
Unitarity violation of Vector Boson Scattering

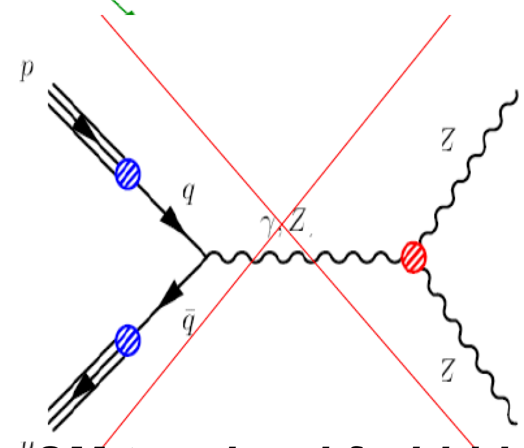
$$\mathcal{M}(W_L^+ W_L^- \rightarrow Z_L Z_L) \sim \frac{s}{M_W^2}$$

"bulk" production mode incorporating SM processes and probing high precision QCD/EWK high order calculation via measuring the decay products of bosons



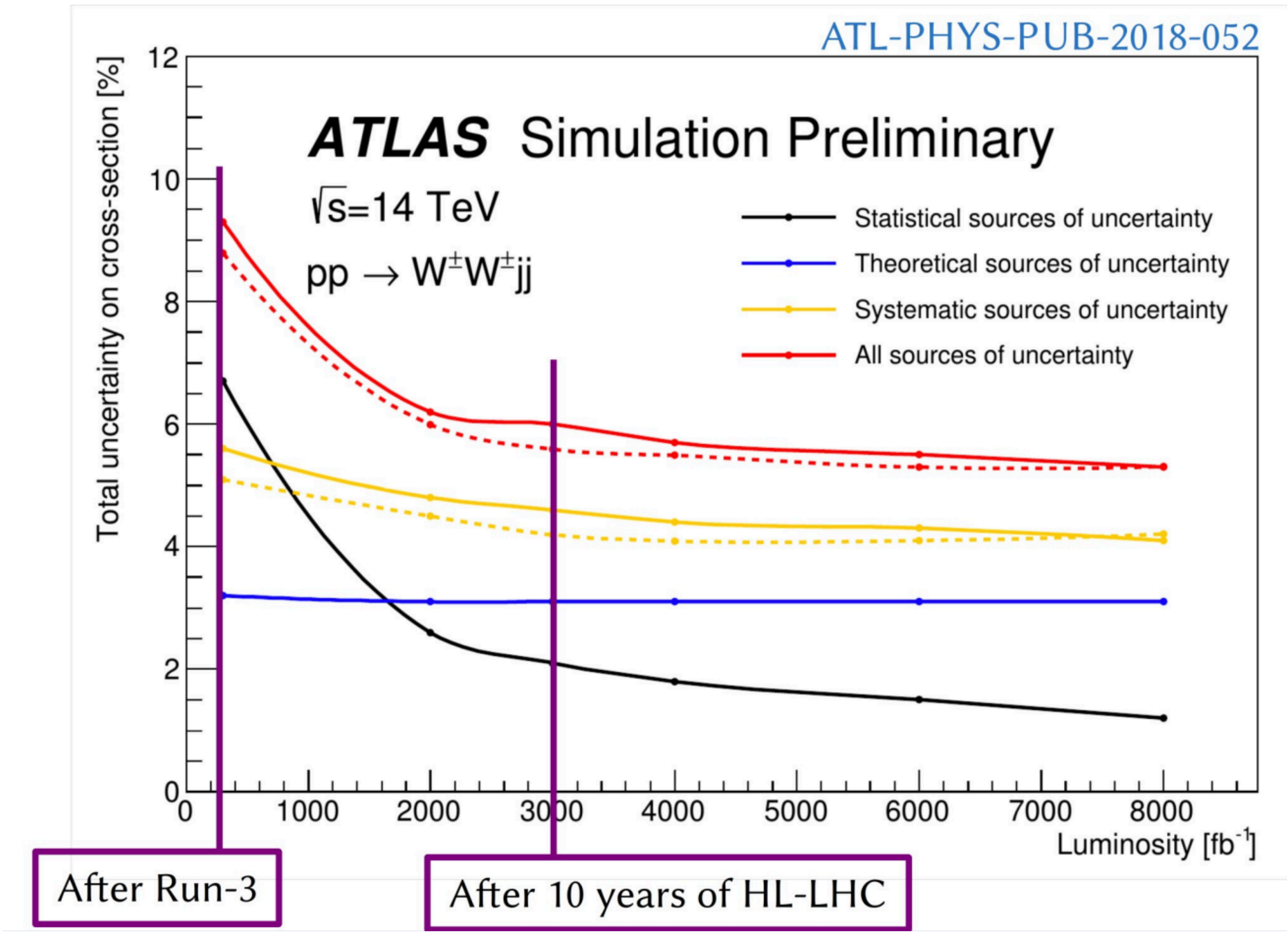
New physics show up via SM boson self-interactions, parameterized by effective lagrangians and effective field theories





SM tree-level forbidden

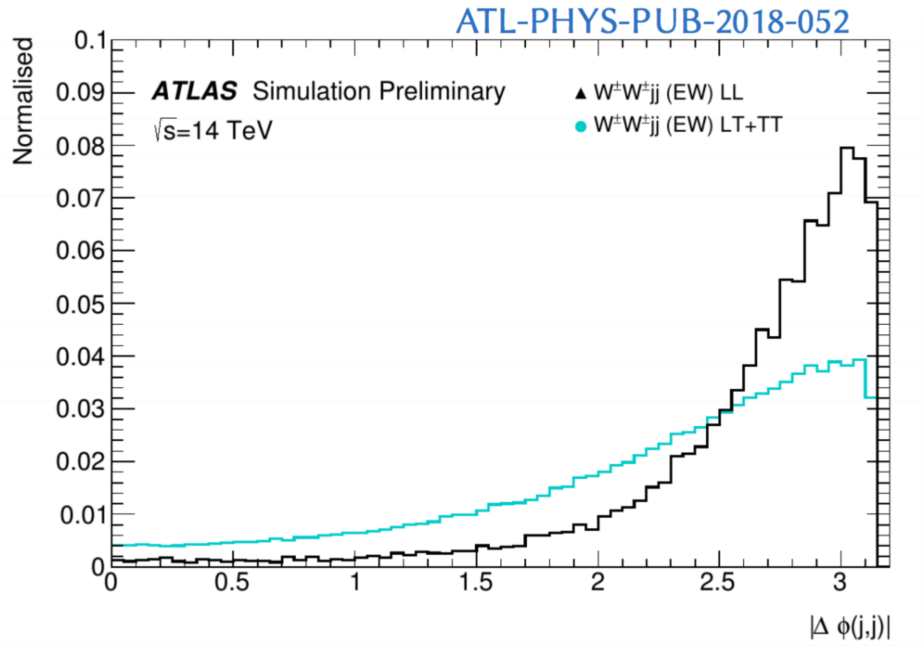
HL-LHC VBS measurement precision prospect

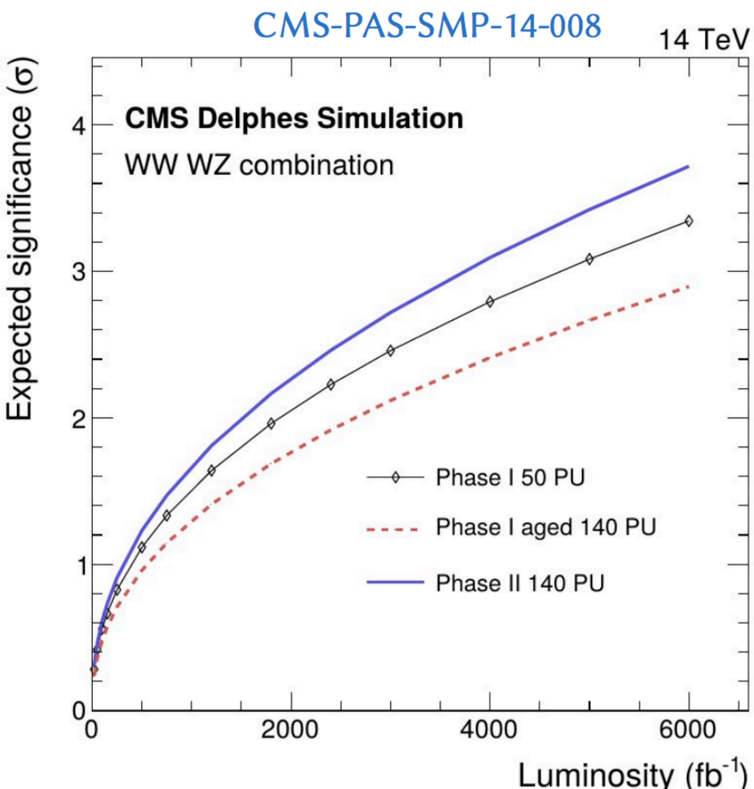


VBS processes to be measured with further improved precision at High Lumi LHC

Upgrade Physics Study by ATLAS and CMS: **CERN-LPCC-2019-01**

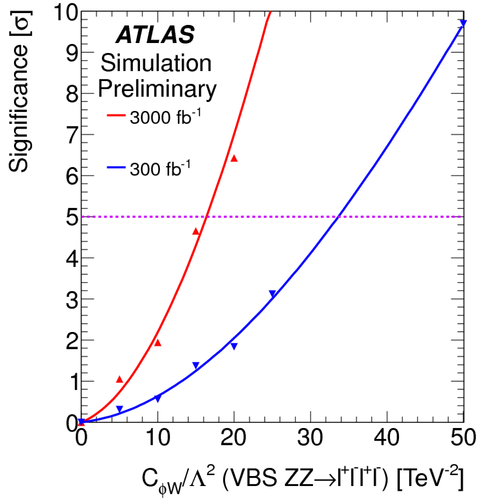
VBS Polarization extraction at HL-LHC

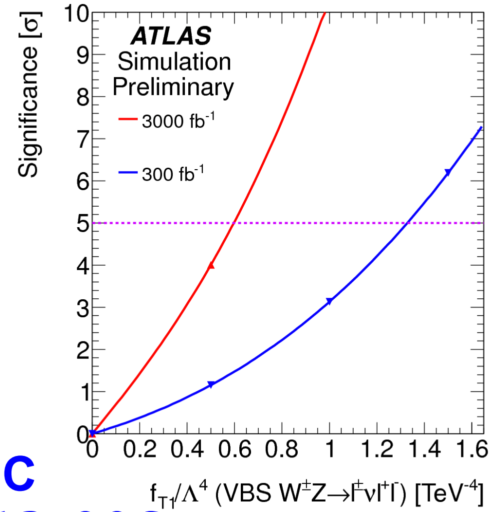




- HL-LHC allows for further attempts towards Longitudinal component separation measurement with significantly enhanced sensitivity
- Advanced machine learning techniques to be explored (arXiv:1510.01691, arXiv: 1812.07591)

aGC sensitivies at HL-LHC





aGCs at HL-LHC

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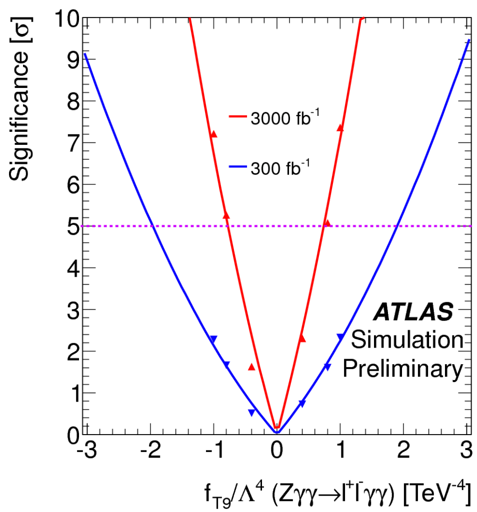

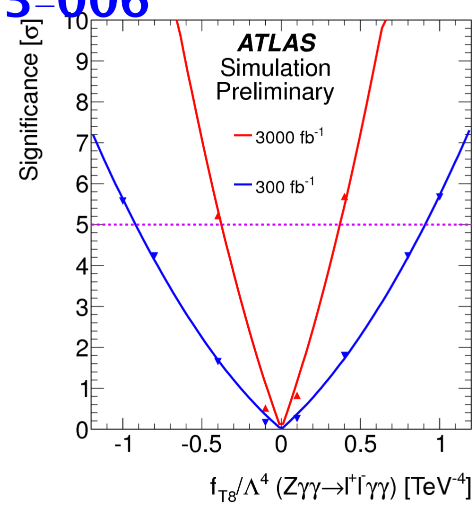

Open questions/remarks?

- Review of the aGC analysis fundamental motivations in SM measurements in general
  - In general, new physics searches consist of both new resonance searches (i.e. what SUSY, Exotics and Higgs groups of ATLAS are more into) and search for the new SM EW boson self-interactions. The aGCs are naturally motivated for the latter case and considered traditionally as the SM measurements' extension or extra theory interpretation of the extrapolated measured phase space. The famous EFT, which is philosophically considered as a theory instead of a model, was also motivated to provide a model-independent search for new SM boson interaction anomalies. However, in reality, the EFT validity is naturally challenged by UV, to unitarize which will equal to introducing extra model dependence and can strongly depend on different final states. We surely tend to pursue a better approach on if the theorists could provide any fresh ideas....

Open questions/remarks?

- Way of presenting aGCs
  - What is the best way to present the anomalous coupling results that can be useful for theorists (likelihood function, covariance matrix, multiple dimensions ?) What would be information useful to be published by the collaborations in HEPdata, are differential distributions sufficient?
  - Shouldn't we emphasize and monitor all possible Run-II analyses to pursue as much as possible the differential distributions? (though some analyses are statistically limited but need to note this well on the long-term todo list) SM analyses usually take long to get and it is better to make a very clear plan and well motivated physics goal (e.g. pursuing differential measurement as much as possible) the earlier the better for each analysis, try not to request to do this too late when it is almost the end of the nominal analysis...

Open questions/remarks?

- The effective lagrangian and EFT formalism conversions
  - Is the anomalous coupling framework (Kappa, g1Z, lambda …) for triple-boson-vertices fully compatible with the dim-6 EFT framework so that they can be converted to each other safely? This point has been examined in Run I analyses, and in most cases we convert limits derived in LEP scenario into the EFT parameter limits. This is important, since still now, many generators only implements the anomalous coupling framework.
  - It will be good if the theorists can include a summary of the practical conversions.
  - Is there any underlying assumption or approximation in going from the "Lagrangian framework" (Kappa, g_1^Z, lambda etc) to the EFT d-6 parameters?

Open questions/remarks?

- Interference between SM GCs and BSM aGCs, possible to have quantified effects and obtained limit better interpretations w.r.t. such effects? (can have model dependence when introducing more or other non-standard aGC parameterizations)
- SM high order aGC couplings (esp. tree-level forbidden neutral couplings) We are challenged by reviewers during the approval of recent neutral aGC analyses in ATLAS because of the lack of high order SM neutral couplings (e.g. high order EWK via fermion loops) theory references. It will be good to have a quantitative summary of such SM high order effects in aTGC/aQGC limit settings with explicit theory calculations. This is particularly important for tree-level forbidden neutral couplings. Currently, our intuition is that the SM high order effect, saying the fermion loop induced neutral Z/y->Zy couplings, arises from the three families of leptons and quarks, and the anomaly cancellation occurs separately inside each family.

Open questions/remarks?

- Feasibility of combining EFT high dimension operators
  - Outlook for an EFT theory that can incorporate both dimension-6 operators (for three-boson-vertices) and dimension-8 operators (for neutral vertices or four-boson-vertices)? This will be interesting in the future, if one can examine both the TGC and QGC at the same time using one final state.
  - Is it more appropriate to decouple aTGC and aQGC, that is to prefer parametrizations where aQGCs do not introduce also aTGCs. Is such an approach motivated mainly by limited statistics? Or also by complexity in extracting limits for parameters that depend from each other (aQGCs contain also functions of aTGCs)?
  - The linear Higgs-doublet dimension-8 operator representation, which is currently widely used by ATLAS and CMS for triboson and VBS aQGC analysis, are unique to aQGC without inducing any aTGCs. So that some of the dedicated physics processes such as triboson and VBS can provide more direct probe of the aQGCs while the inclusive dibosons are more dedicated to aTGCs. But if possible, we would like hear from this theory talk, a nice summary of different theorists' voices and comments on what they are more interested in getting from ATLAS analysis fruits...

Open questions/remarks?

- Unitarization treatment (long standing topic...)
  - Is Unitarization that important in this business? So far, in ATLAS, limits with anomalous coupling parameters are mostly provided as a function of form-factors. With EFT parameters, in principle, we don't need to worry about Unitarization, right? Do unitarized limits provide further information for theorists?
  - There has been always the argument that the theory predicted EFT unitarity violation (UV) bound by itself is already an intrinsic theory validity limit. Even if we don't do unitarization treatment, when we get the limit looser than the UV bound, the UV bound itself is already a "better limit". And if the limits is more stringent than the UV bound, we are safe. So in any case, our non-unitarized limits are well making physics sense. Would the unitarization still be mandatory at this point, then? We expect a good summary on this topic, i.e. what the theorists really need from the unitarized/non-unitarized limits
  - Obtaining limits in the EFT framework as a function of the scale Λ^n is it not an "intrinsic" unitarization?

Open questions/remarks?

- Generator support and readiness
  - If possible, it would be nice to review the available MC generators that implement the anomalous coupling parameters and provide some guidelines for which should be commonly used (in the point of view from the speaker).
  - It will be good to contact the cooperated generator author committee and summarize the current aGC parameterization availability (+ unitarization features). This will be very important and practical references for experimentalists and aGC analyzers.
  - It will be good to have the above together with the pros and drawbacks of these generators (in a Table type of format). Actually this Table with generators we know of, we can provide and ask for summary of their strong and weak points as well for other generators in the market, about to come.

arXiv:1803.07977 **arXiv:1803.07943**

Open questions/remarks?

- aGC correlations and combinations How can correlations between aTGC points between different measurements be determined? What are means to investigate the impact of combinations of constraints
  - Would it be possible to also help the experimentalists to summarize the *ranking* of the aGCs for different VV/VVV channels from the theory calculations? We have tons of references but not very well summarized. Experimentalists always compromise the ranking of interesting channels and realistic timescale to carry out the analyses because of corresponding production rate constraints. Also it will become interesting that the obtained limits on the same aGC but different final states, in comparison with the theorists' intuitive rankings ;-)

Open questions/remarks?

- General feeling and feedback from aTGC analyzers on the aTGC scenario choice
  - We spend a lot of time presenting aTGC limits in a variety of different "scenarios." For example, in arXiv:1210.2979, four different sets of limits are given on the charged aTGC parameters (DeltaKappaZ, DeltaKappaGamma, LambdaZ, lambdaGamma, DeltaG1Z)
  - Are we wasting our efforts by calculating so many different sets of limits? Are any of these limits other than the "LEP scenario" limits useful to theorists? Is there a more efficient way for us to present our limits to theorists?

Open questions/remarks?

- A good modelling (more precision in QCD and EW computation) of QCD VVjj, Vjj, and EW VVjj and Vjj will be very important for future VBF and VBS studies
- Further reduction of PDF uncertainties for precision V measurement, like W mass, weak mixing angles
- Theoretical motivation for photon-photon interaction