The EFT Interpretations in WZ production with Dim-6 and Dim-8 operators

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ATLAS

Overview

- Effective Field Theories
- Vector Boson Scattering
- WZ fully leptonic inclusive and WZ VBS
- Dim-6 Operators
  - WZ Inclusive
  - WZ VBS
- Dim-8 Operators
  - WZ VBS

Effective Field Theories

- Since there are no hints for New Physics through direct searches➔ increased interest for indirect searches
- Assuming New Physics is heavy ➔EFTs emerge as the tool to look for deviations from the SM
- Low energy parametrization for unknown physics that can become reachable at very High Energy
- BSM terms added to the SM Lagrangian

$$L = L^{SM} + \sum_i \frac{c_i}{\Lambda^2} O_i + \sum_j \frac{c_j}{\Lambda^4} O_j$$

Effective Field Theories -II

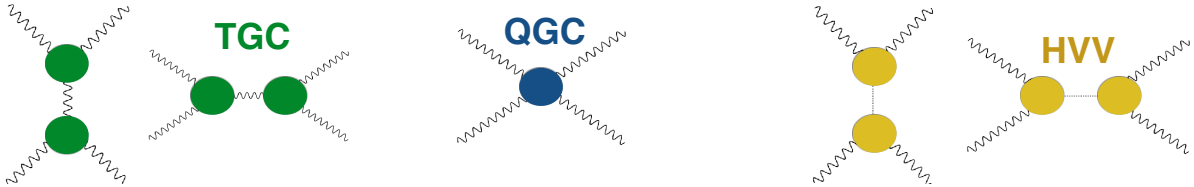
- First to look for Dim-6 and Dim-8 operators

Dim-6 **Dim-8**

$$L_{EFT} = L_{SM} + \sum_{i=WWW,W,B,\Phi W,\Phi B} \frac{c_i}{\Lambda^2} O_i + \sum_{j=1,2} \frac{f_{S,j}}{\Lambda^4} O_{S,j} + \sum_{j=0,\ldots,9} \frac{f_{T,j}}{\Lambda^4} O_{T,j} + \sum_{j=0,\ldots,7} \frac{f_{M,j}}{\Lambda^4} O_{M,j}$$

Pure Higgs field **Pure Field-strength tensor** **Mixed Higgs Field-strength**

- Experimental strategy: Associate Dim-6 and Dim-8 operators to vertices in forms of anomalous couplings



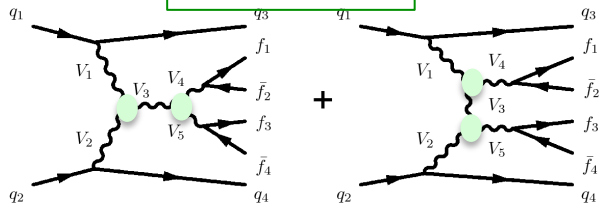
Previous approach: anomalous couplings parametrization
New approach: EFT parametrization

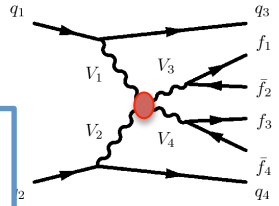
Effective Field Theories : Experimental strategy

- So far, no theory model includes both Dim6 and Dim8 operators
- Study the effect individually for Dim6 and Dim8
- In both cases, we aim to a combination of the EFT parameter limits
- How we plan to search:
  1. MC Modelling
  2. Data
  3. Limit setting on individual channels and by combining channels
- Where we should search:
  - Diboson processes→ Could be sensitive to Dim-6 operators
  - VBS processes→ Could be sensitive to Dim-6 and Dim-8 operators

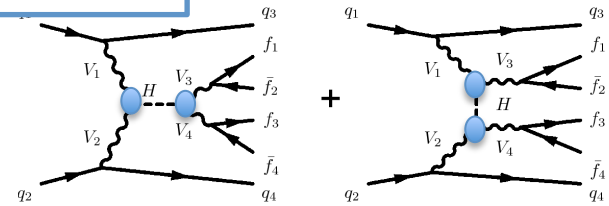
WZ serves as a good candidate

TGCs→Dim6





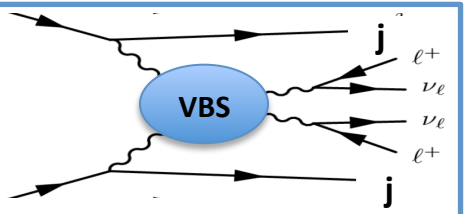
QGCs→ Dim6, Dim8



HVV→Dim6, Dim8

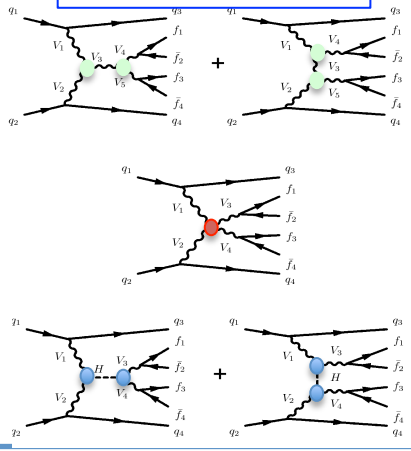
Vector Boson Scattering

- Vector Boson Scattering: interaction of two vector bosons radiated from the initial-state quarks, yielding a final state with two bosons and two jets, VVjj, in a purely electroweak process

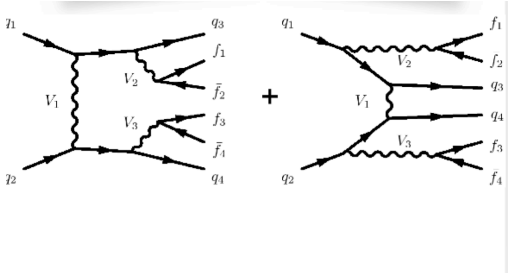


EWK production contains both VBS and non-VBS processes that cannot be dissociated

EWK VVjj VBS



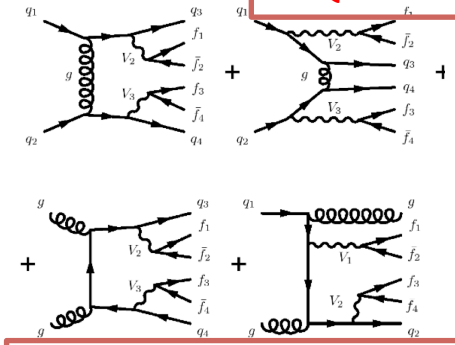
EWK VVjj non-VBS



EWK: QED<=6, QCD=0

Main background:
Diboson QCD production in association with two jets

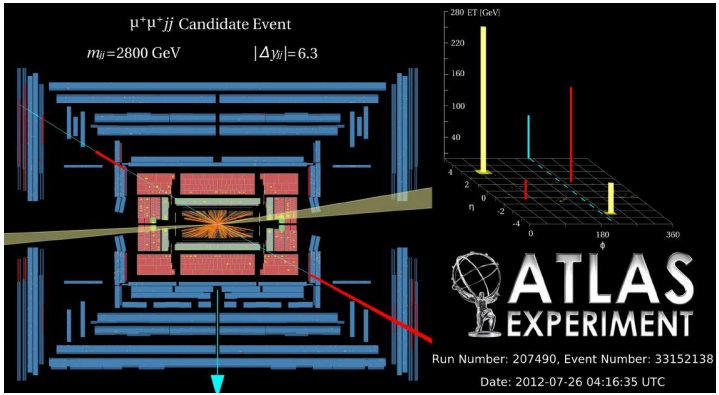
QCD VVjj

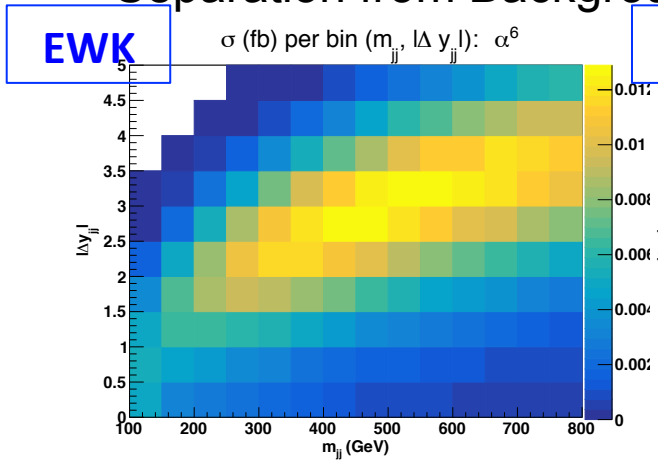


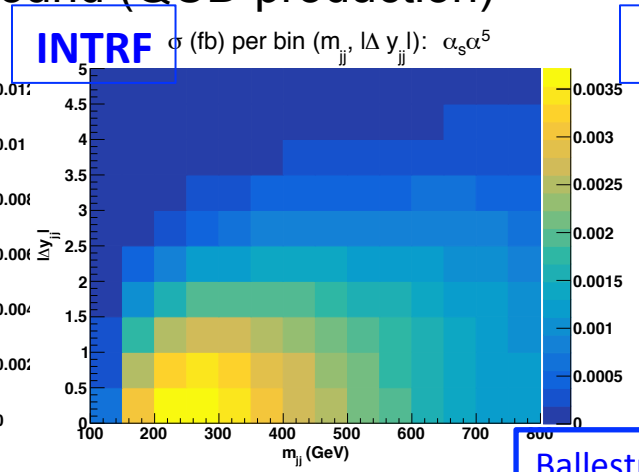
QCD: QCD=2, QED=4

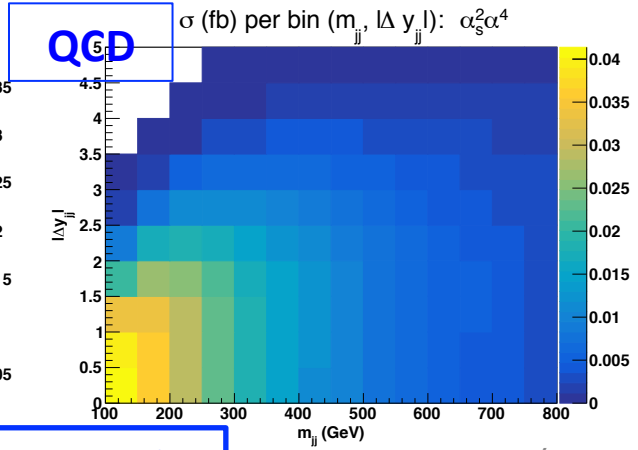
VBS phenomenology

- VBS events at LHC have distinct event topology: VVjj
  - Two energetic jets with large di-jet mass (m_{jj}) and high rapidity separation
  - diboson system, centrally produced with respect to the two forward jets
- Separation from Background (QCD production)





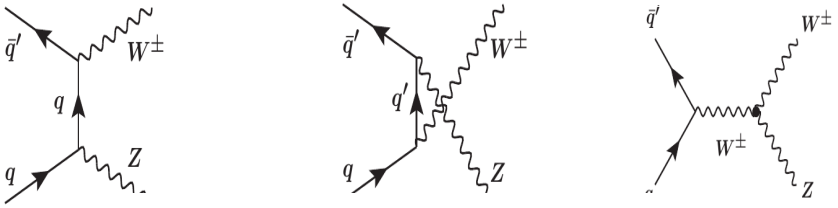


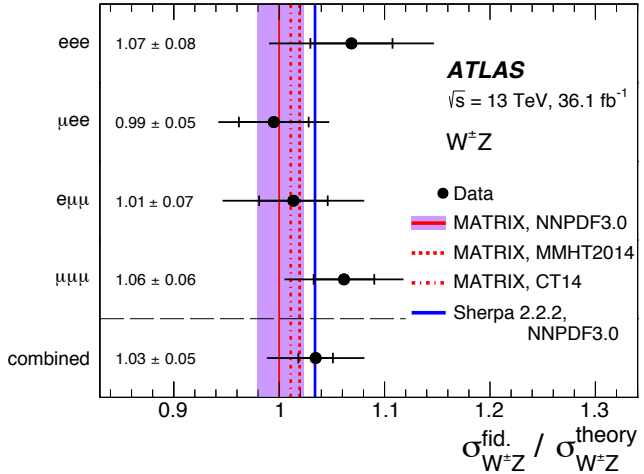


Ballestrero et al.

Current Status in WZ Inclusive from ATLAS

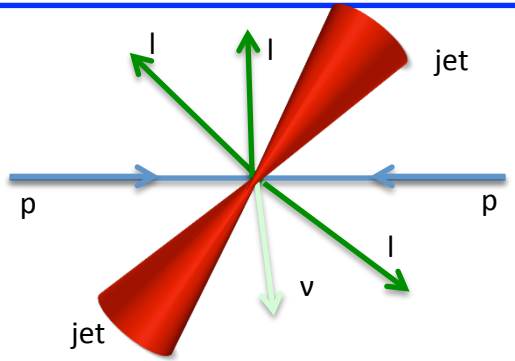
- Latest Publication on 13 TeV using 2015+2016 data
- Search for WZ leptonic decays
- Electrons and muons only
- Z -> ee,μμ: 2 high-p_T, isolated leptons with their invariant mass consistent with Z mass
- W -> eν, μν: 1 high-p_T, isolated and well-identified lepton and MET, with their transverse mass consistent with W
- Four final states: eeeν, eμμν, μeeν, μμμν
- Unfolded distributions to variable sensitive to EFTs provided, but not limits





$$\sigma^{\text{fid.}}_{W^\pm Z \to \ell' \nu \ell \ell} = 63.7 \pm 1.0\,(\text{stat.}) \pm 2.3\,(\text{exp. syst.}) \pm 0.3\,(\text{mod. syst}) \pm 1.4\,(\text{lumi.})\ \text{fb},$$

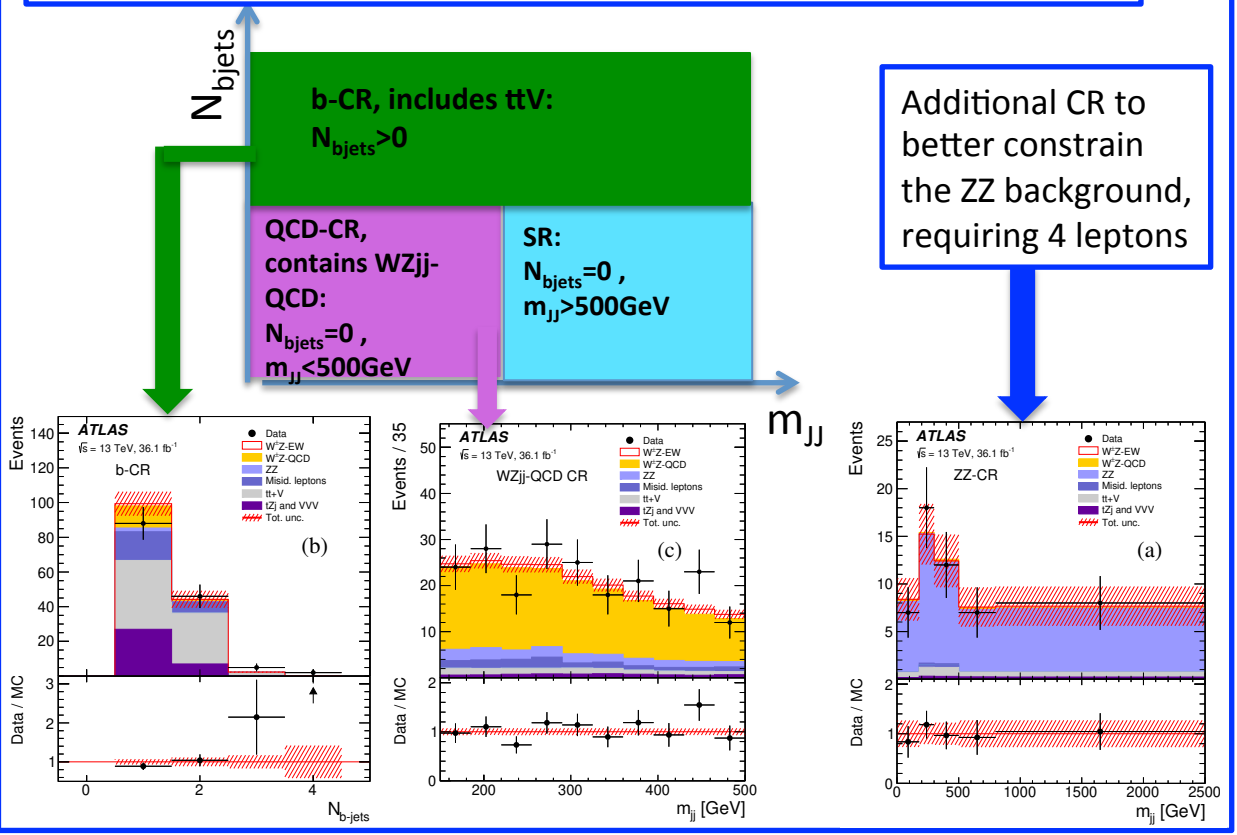
Current status in WZjj from ATLAS: Event Selection



- Exactly 3 leptons:
  - $|\eta|<2.5$
  - $p_T^{l,Z}>15$GeV
  - $|M_Z-M_Z^{PDG}|<10$ GeV
  - $m_T^W>30$ GeV
- At least 2 jets:
  - $|\eta|<4.5$
  - opposite hemispheres
  - $p_T^j>40$GeV
  - $m_{jj}>150$ GeV

arxiv.org/abs/1812.09740

- Selection separated in 3 orthogonal regions



Current status in WZjj: Background estimation and cross section measurement

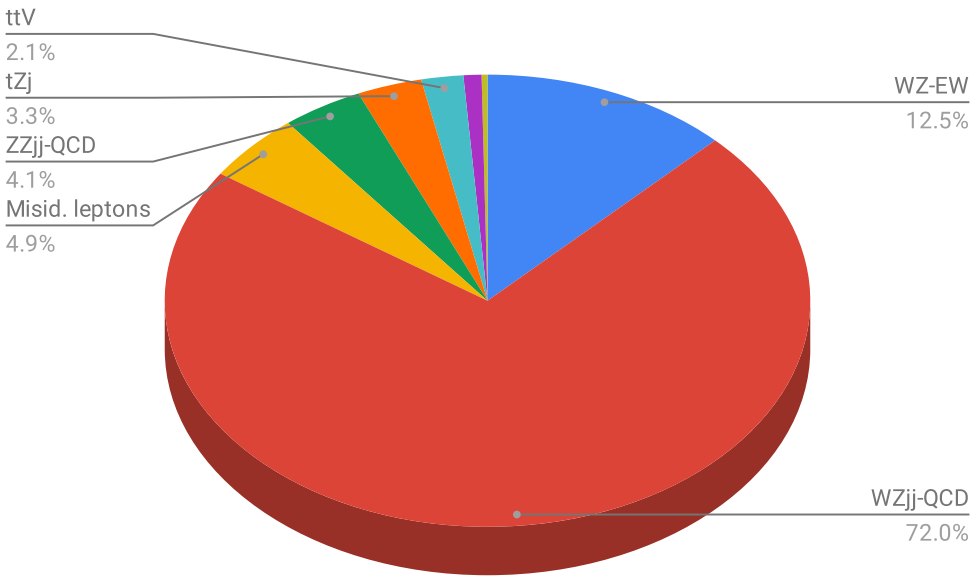
arxiv.org/abs/1812.09740

Irreducible Background

- WZjj-QCD, ZZjj, ttV: Use MC simulation and control regions to better constrain them
  - QCD: dominant background
  - ZZjj: second dominant background
- VVV, tZj: Use MC simulation to model them

Reducible Background

- Z+j, Zγ, ttbar, Wt, WW for prompt and fake leptons



- The electroweak production of *W*±*Z* bosons in association with two jets is measured with observed significance of 5.3σ.

$$\sigma_{WZjj-\mathrm{EW}} = 0.57\ ^{+0.14}_{-0.13}\,(\mathrm{stat.})\ ^{+0.05}_{-0.04}\,(\mathrm{exp.\ syst.})\ ^{+0.05}_{-0.04}\,(\mathrm{mod.\ syst.})\ ^{+0.01}_{-0.01}\,(\mathrm{lumi.})\ \mathrm{fb}$$

Dim-6 Operators

SMEFT

- The model: SMEFT
- The most general set of dimension-6 operators respecting the SM symmetries has 81 operators
- Can be reduced to 59 using the equivalence theorem
- These 59 operators, have 76 free parameters, if we consider only one generation of fermions. If we consider three independent generations, the number grows up to 2499 free parameters.
- The minimal basis of gauge-invariant non-redundant operators is called the "Warsaw Basis" *arXiv: 1008.4884*
- There are also other possible parameterizations: SILH, HISZ

R.Gomez-Ambrosio

Dim-6 operators

- Dim-6 operators in Warsaw basis excluding the 4-fermion ones
- Operators contributing across various channels
- Eventually aiming for a global fit across channels

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

SM

Higgs

Higgs

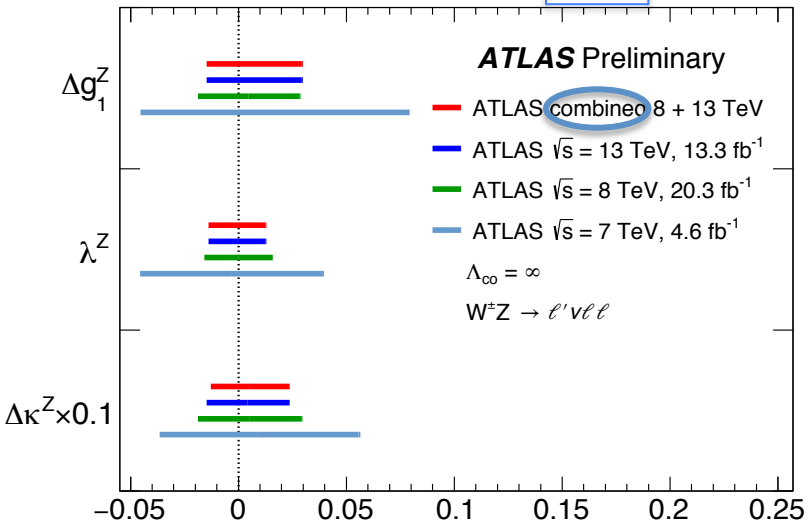
Top

H.Mildner

Current Picture in ATLAS in WZ

- Latest results for WZ Inclusive in aTGCs in ATLAS
- Results for both parametrizations:
  a. anomalous couplings aproach
  b. EFT approach
- So far the results are in HISZ basis

a.



b.

Dataset	Coupling	Expected [TeV^{-2}]	Observed [TeV^{-2}]
13 TeV	$c_W/\Lambda^2_{\rm NP}$	[-4.1; 7.6]	[-3.8; 8.6]
	$c_B/\Lambda^2_{\rm NP}$	[-261; 193]	[-280; 163]
	$c_{WWW}/\Lambda^2_{\rm NP}$	[-3.6; 3.4]	[-3.9; 3.7]
8 and 13 TeV	$c_W/\Lambda^2_{\rm NP}$	[-3.4; 6.9]	[-3.6; 7.3]
	$c_B/\Lambda^2_{\rm NP}$	[-221; 166]	[-253; 136]
	$c_{WWW}/\Lambda^2_{\rm NP}$	[-3.2; 3.0]	[-3.3; 3.2]

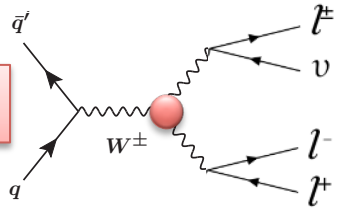
aTGC Intervals at 95% C.L.

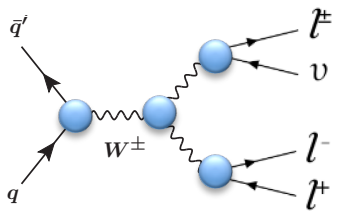
Dataset	Coupling	Expected	Observed
13 TeV	Δg_1^Z	[-0.017; 0.032]	[-0.016; 0.036]
	$\Delta\kappa_1^Z$	[-0.18; 0.24]	[-0.15; 0.26]
	λ^Z	[-0.015; 0.014]	[-0.016; 0.015]
8 and 13 TeV	Δg_1^Z	[-0.014; 0.029]	[-0.015; 0.030]
	$\Delta\kappa_1^Z$	[-0.15; 0.21]	[-0.13; 0.24]
	λ^Z	[-0.013; 0.012]	[-0.014; 0.013]

Dim-6 operators in WZ Inclusive

- HISZ Vs. Warsaw basis➔ Different operators and different associated vertices

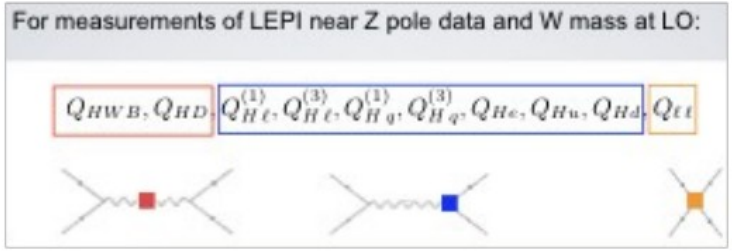
HISZ





Warsaw

- Since moving to Warsaw basis, need to test sensitivities of the operators
- Already there are constraints from electroweak precision data



WZ Inclusive:Setup

Generator:	• Madgraph 2.6.5
Model:	• SMEFTSim
Process:	$pp \to e + e - \mu - \bar{\nu_\mu}$
Number of events	• 5k
Level:	• generator level only
Method:	• “Decomposition” of the total sample

Decomposition method

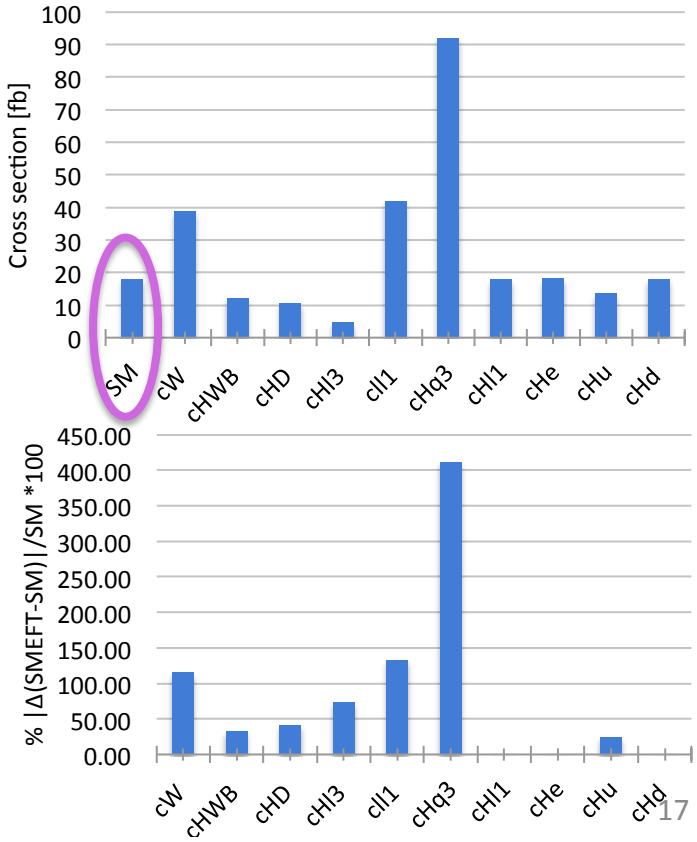
- Need to produce big number of samples on various values of EFT parameters
- So far, reweighting was used
- Now, Madgraph gives the opportunity to decompose the samples production to terms:
  - SM term
  - SM-EFT interference terms
  - pure EFT terms
  - cross EFT terms

$$|\mathcal{A}_{\mathrm{SM}} + \sum_i c_i \mathcal{A}_i|^2 = |\mathcal{A}_{\mathrm{SM}}|^2 + \sum_i c_i 2\mathrm{Re}\left(\mathcal{A}^\star_{\mathrm{SM}} \mathcal{A}_i\right) + \sum_i c_i^2 |\mathcal{A}_i|^2 + \sum_{ij, i \neq j} c_i c_j 2\mathrm{Re}\left(\mathcal{A}_i^\star \mathcal{A}_j\right)$$

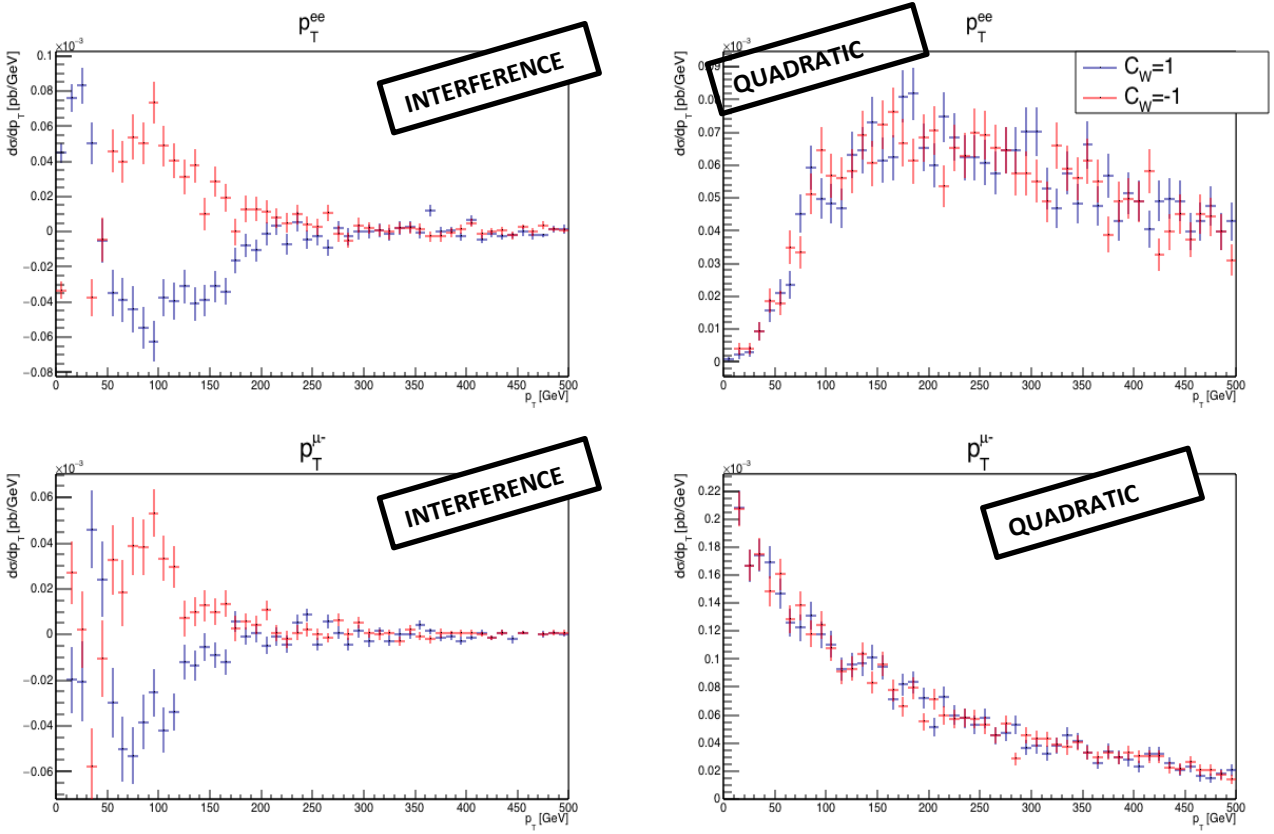
SMEFT Operators in WZ Inclusive

- Comparative study of the effect of Dim-6 operators (SMEFT model) on inclusive cross section for c_i=3, Λ=1TeV

Operators	Cross section [fb]	Effect [%]	Effect> 10%
cW	38.8	115.56	X
cHWB	12.1	32.78	X
cHD	10.48	41.78	X
cHl3	4.769	73.51	X
cll1	41.89	132.72	X
cHq3	92.05	411.39	X
cHl1	17.89	0.61	
cHe	18.16	0.89	
cHu	13.51	24.94	X
cHd	17.91	0.50	



C_W: Distributions



- Effect on SM cross section for c_W=3: 115.1%
- Here, c_W=1, -1
- 5k Events
- p_T of the di-electron system and the W-muon
- Interference affects low pt bins
- Increase in the cross section comes from the quadratic term

SMEFT operators in WZ VBS

- Dim-6 operators (SMEFT) operators expected to contribute in VBS processes

Corrections to SM couplings/propagators

$\mathcal{Q}_{HD} = (H^\dagger D_\mu H)^*(H^\dagger D^\mu H)$	🟡 🟢 🔴 🔵	$\mathcal{Q}_{Hl}^{(1)} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}\gamma^\mu l)$	🟡
$\mathcal{Q}_{H\Box} = (H^\dagger H)(H^\dagger \Box H)$	🔴	$\mathcal{Q}_{Hl}^{(3)} = (H^\dagger i \overleftrightarrow{D}^i_\mu H)(\bar{l}\sigma^i\gamma^\mu l)$	🟡 🟢 🔴 🔵
$\mathcal{Q}_W = \varepsilon_{ijk} W^i_{\mu\nu} W^{j\nu\rho} W^{k\mu}_\rho$	🟢	$\mathcal{Q}_{Hq}^{(1)} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q)$	🟡
$\mathcal{Q}_{HB} = (H^\dagger H) B_{\mu\nu} B^{\mu\nu}$	🔴	$\mathcal{Q}_{Hq}^{(3)} = (H^\dagger i \overleftrightarrow{D}^i_\mu H)(\bar{q}\sigma^i\gamma^\mu q)$	🟡
$\mathcal{Q}_{HW} = (H^\dagger H) W^i_{\mu\nu} W^{i\mu\nu}$	🔴	$\mathcal{Q}_{He} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}\gamma^\mu e)$	🟡
$\mathcal{Q}_{HWB} = (H^\dagger \sigma^i H) W^i_{\mu\nu} B^{\mu\nu}$	🟡 🟢 🔴 🔵	$\mathcal{Q}_{Hu} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u)$	🟡
$\mathcal{Q}_{ll} = (\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$	🟡 🟢 🔵	$\mathcal{Q}_{Hd} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)$	🟡

🟡 = Vff ($\Gamma_{W,Z}$) 🟢 = TGC/QGC 🔴 = hVV (Γ_h) 🔵 = m_W

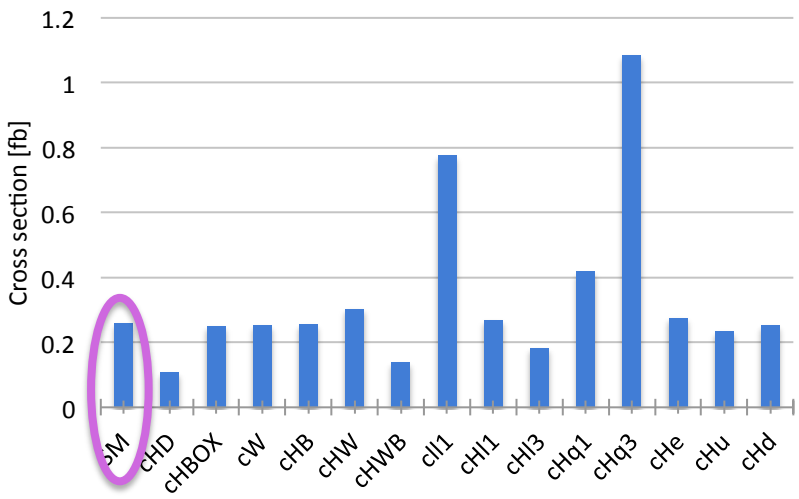
WZ VBS: Setup

Generator:	• Madgraph 2.6.5
Model:	• SMEFTSim
Process:	$pp \to W^- Zjj$
Number of events	• 5k
Level:	• generator level only
Method:	• “Decomposition” of the total sample

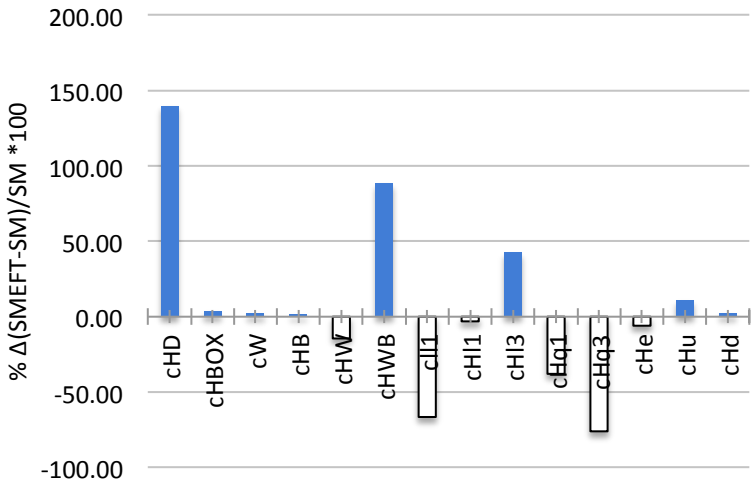
SMEFT operators in WZ VBS

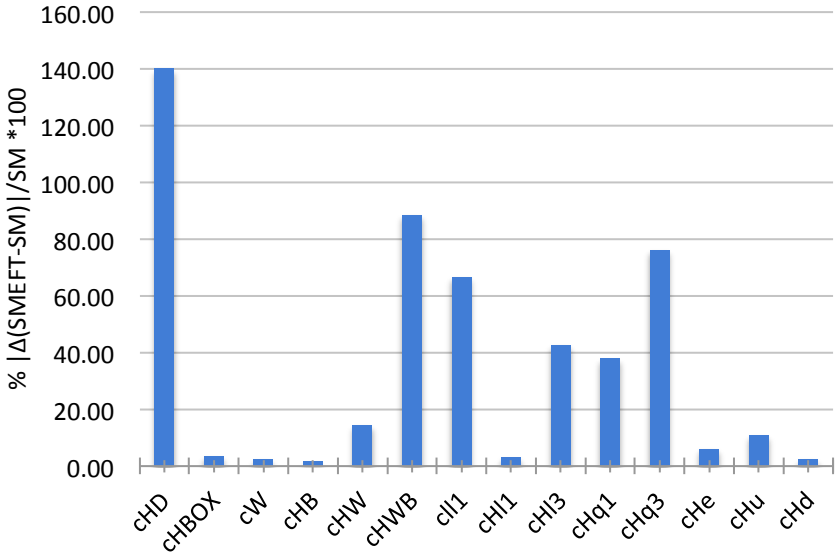
- Cross section results for SM+ 1 non-zero EFT operator
- Increase and decrease to cross section
- Decrease due to interference
- SM cross section: 0.22 fb

Coefficients	xsection (fb)	Effect>5%	Effect>10%	Effect>15%
cHD	0.1082	X	X	X
cHBOX	0.251			
cW	0.2535			
cHB	0.2558			
cHW	0.3034	X	X	
cHWB	0.1378	X	X	X
cll1	0.7754	X	X	X
cHl1	0.2679			
cHl3	0.1821	X	X	X
cHq1	0.4181	X	X	X
cHq3	1.083	X	X	X
cHe	0.2761	X		
cHu	0.2339	X	X	
cHd	0.2535			



SMEFT operators in WZ VBS





- The effect on the cross section can be positive or negative
- Negative due to interference
- Constraints from EWPD not taken into account here

Dim-8 Operators

Dim-8 Operators Theory Framework

- aQGCs can be parametrized in terms of Dimension-8 operators by the assumption that the Dimension-6 can already by constrained elsewhere
- Use EFT parametrization from Eboli, Gonzales-Garcia model
- Measurements of aQGC → constrain the following operators
  - Effort to combine limits from ATLAS and CMS within the VBSCan network

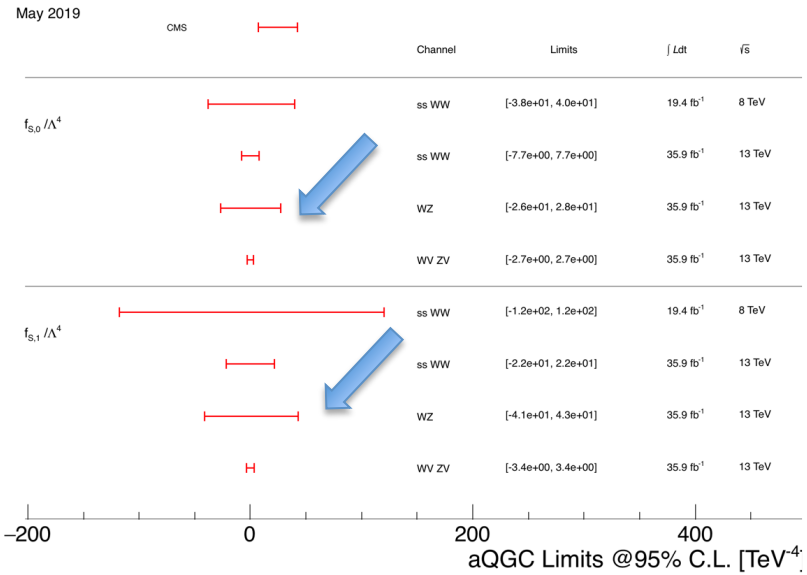
	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{L}_{S,0}$, $\mathcal{L}_{S,1}$	X	X	X	O	O	O	O	O	O
$\mathcal{L}_{M,0}$, $\mathcal{L}_{M,1}$,$\mathcal{L}_{M,6}$,$\mathcal{L}_{M,7}$	X	X	X	X	X	X	X	O	O
$\mathcal{L}_{M,2}$,$\mathcal{L}_{M,3}$, $\mathcal{L}_{M,4}$,$\mathcal{L}_{M,5}$	O	X	X	X	X	X	X	O	O
$\mathcal{L}_{T,0}$,$\mathcal{L}_{T,1}$,$\mathcal{L}_{T,2}$	X	X	X	X	X	X	X	X	X
$\mathcal{L}_{T,5}$,$\mathcal{L}_{T,6}$,$\mathcal{L}_{T,7}$	O	X	X	X	X	X	X	X	X
$\mathcal{L}_{T,9}$,$\mathcal{L}_{T,9}$	O	O	X	O	O	X	X	X	X

Current results

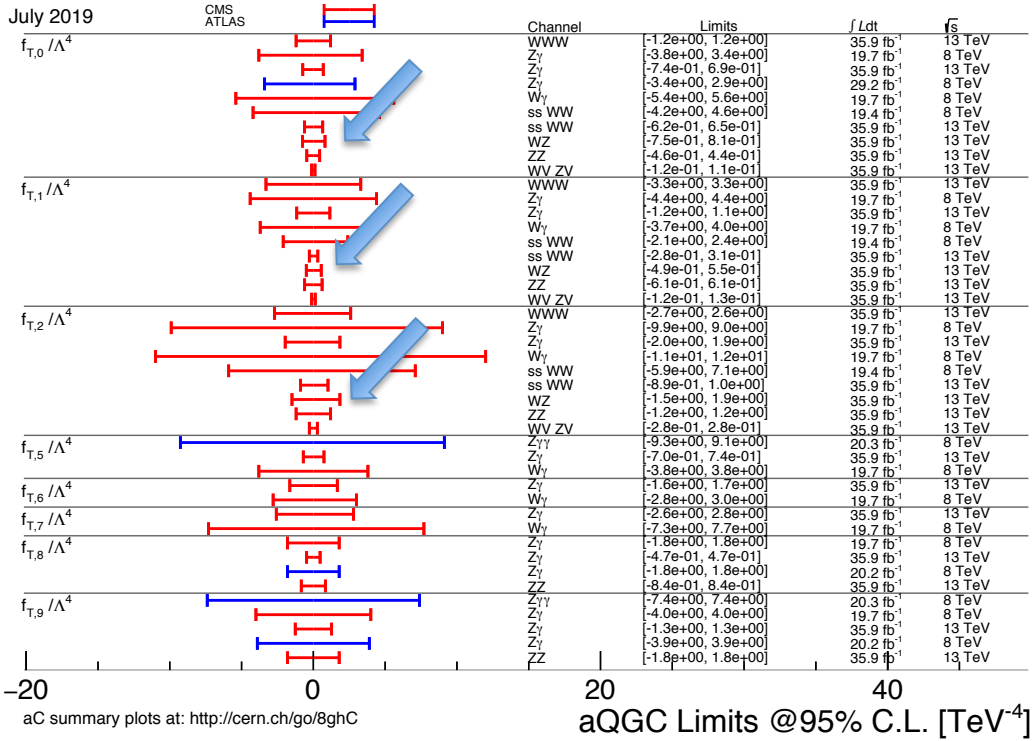
CMS
ATLAS

Published results from ATLAS and CMS on Dim-8 operators limits

f_S operators' limits



f_T operators' limits

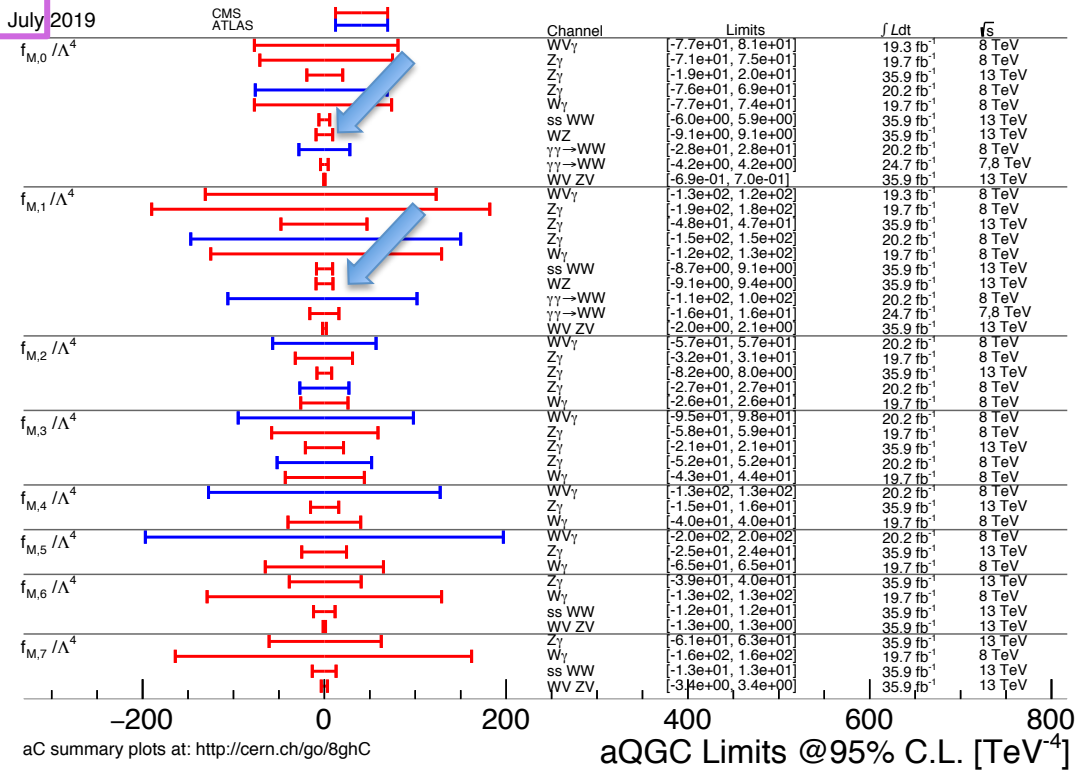


Current results

Published results from ATLAS and CMS on Dim-8 operators limits

f_M operators' limits

CMS
ATLAS



Setup

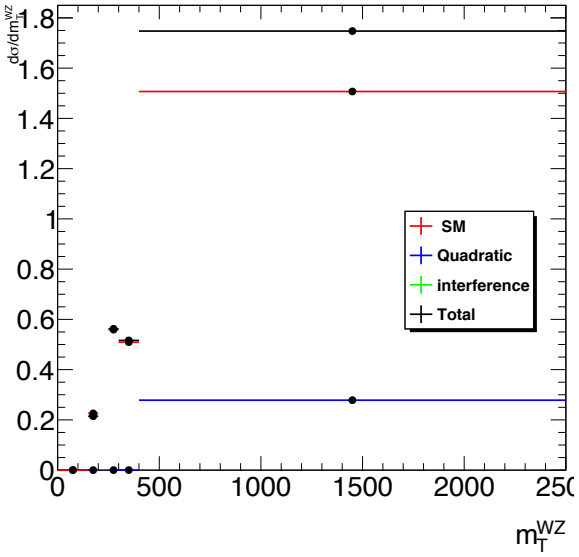
Model:	• Eboli, Gonzales-Garcia model, SM_LST
Process:	$dd \rightarrow e + e - \mu - \bar{\nu_\mu} ud$
Number of events	• 200k
Level:	• generator level only
Method:	• “Decomposition” of the total sample
EFT parameter values:	• Tested at the latest limit values for the WZjj provided by CMS **X 5**
Dynamical Scale Choice	• option 3

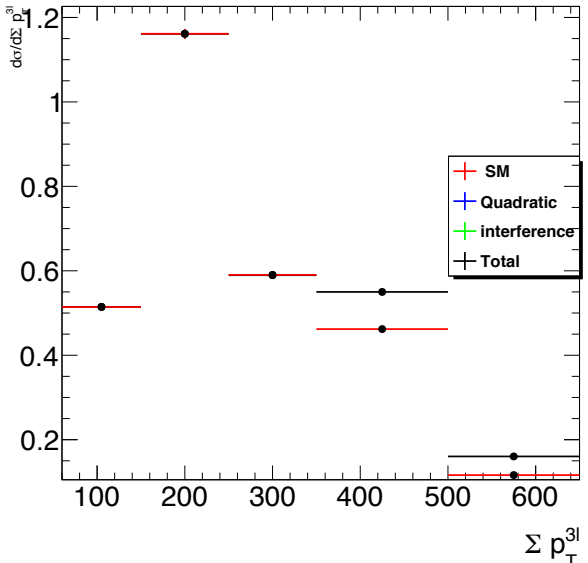
EFT Parameter: f_{S1}

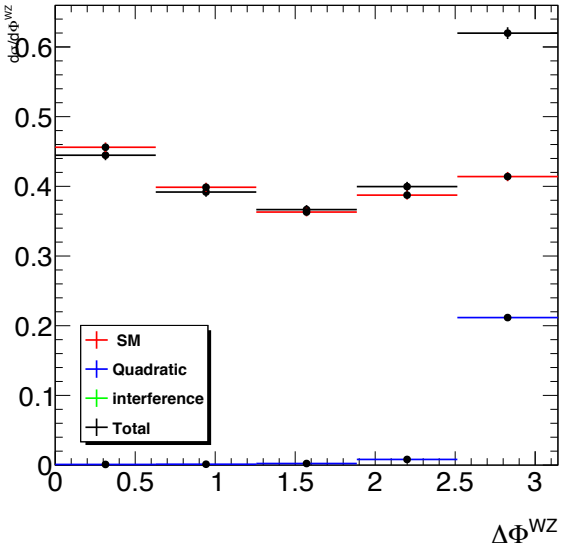
- **f_{s1}=42 TeV^{-4}**
- Decomposition Validation in the total phase space (Loose PS on WZjj final state)

SM xsec(fb)	INT xsec(fb)	QUAD xsec(fb)	TOTAL xsec(fb)	SUM xsec(fb)	Difference %
0.1065	-0.0003	0.0091	0.1151	0.1153	0.17

- Fiducial Phase space: (truth selection for WZ VBS final state)





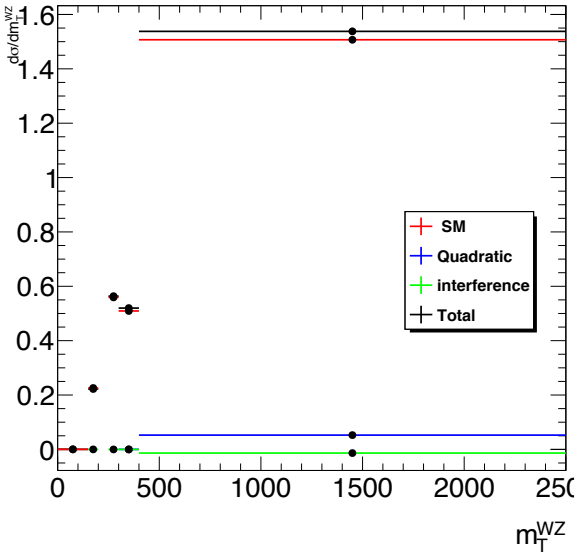


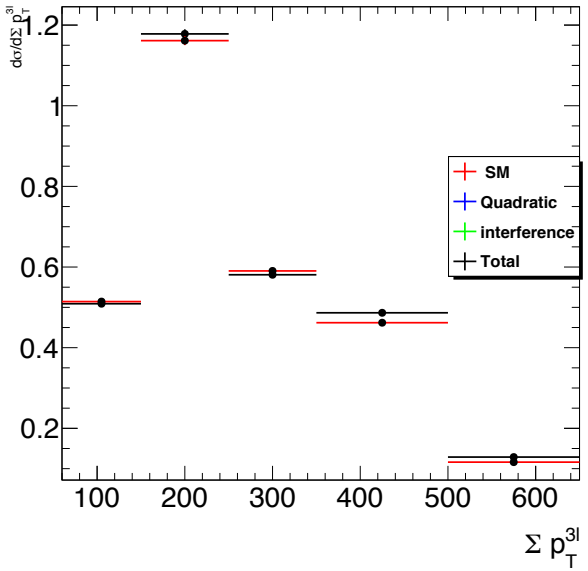
EFT Parameter: f_{T0}

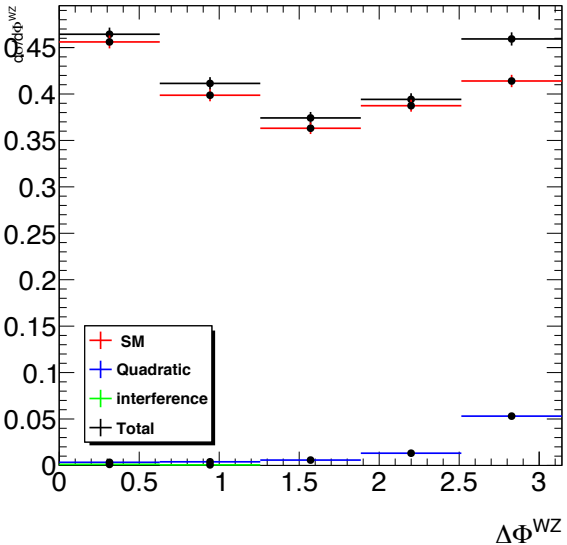
- **f_{T0}=0.8 TeV^{-4}**
- Decomposition Validation in the total phase space (Loose PS on WZjj final state)

SM	INT	QUADRATIC	TOTAL	SUM	Difference %
0.1065	-0.0004	0.0051	0.1103	0.1113	0.87

- Fiducial Phase space: (truth selection for WZ VBS final state)





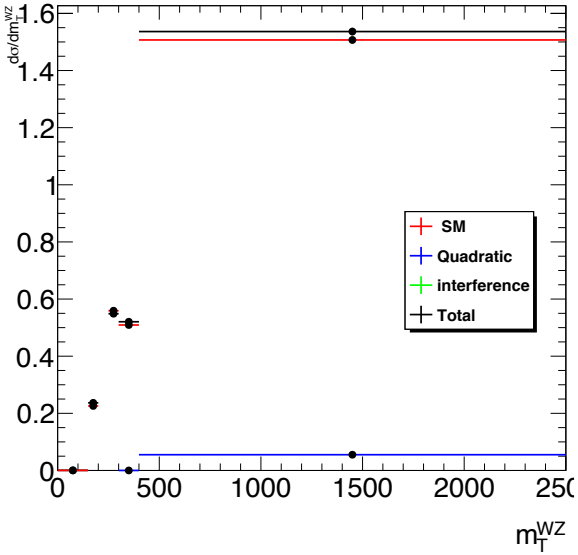


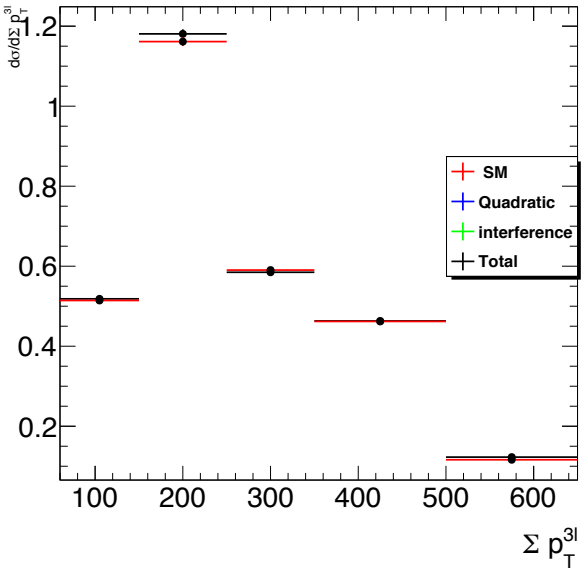
EFT Parameter: f_{T1}

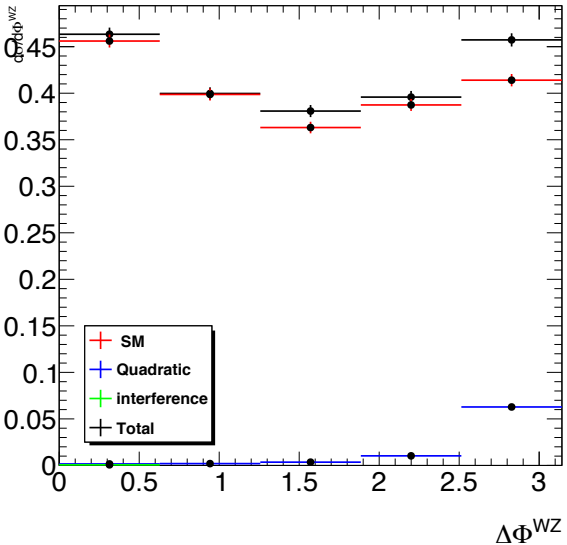
- **f_{T1}=0.55 TeV^{-4}**
- Decomposition Validation in the total phase space (Loose PS on WZjj final state)

SM	INT	QUADRATIC	TOTAL	SUM	Difference %
0.1065	-0.001	0.0057	0.1103	0.1112	0.83

- Fiducial Phase space: (truth selection for WZ VBS final state)



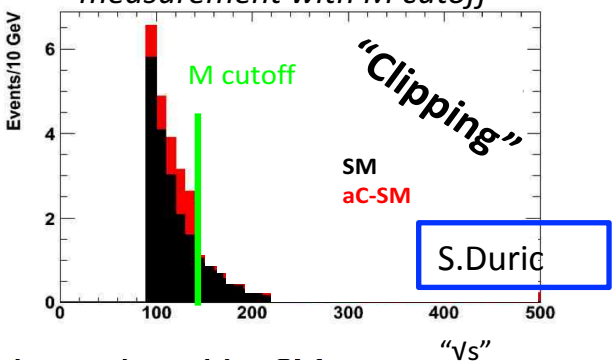


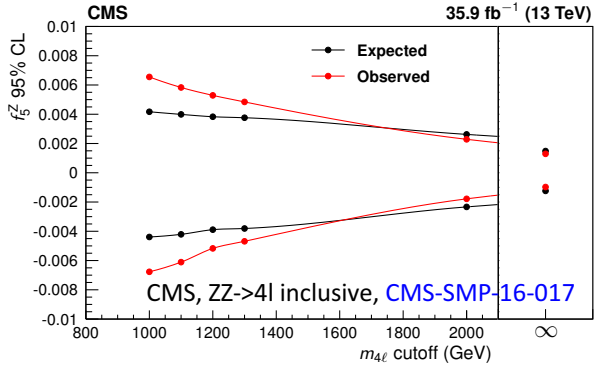


Unitarization Method: Clipping

- The cross section “explodes” for high sqrt(s-hat), violating unitarity
- Clipping: Step function form factor
  - The anomalous signal contribution is set to 0 for $\sqrt{\hat{s}} > E_c$
- Data and background remains unchanged
- Can be applied “by hand” to the BSM parts of the Monte Carlo samples. By using Decomposition method, we apply the cut to interference and quadratic terms

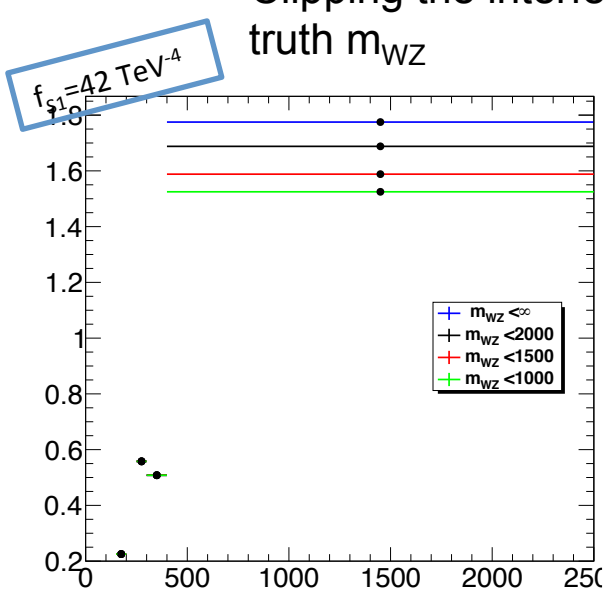
Anomalous coupling measurement with M cutoff

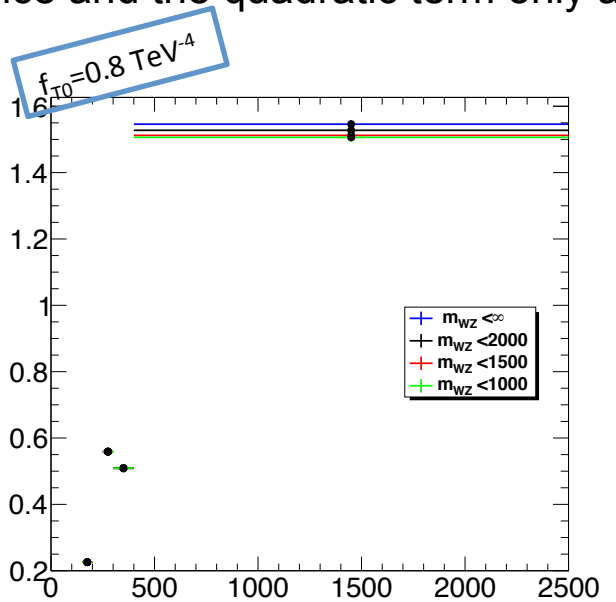


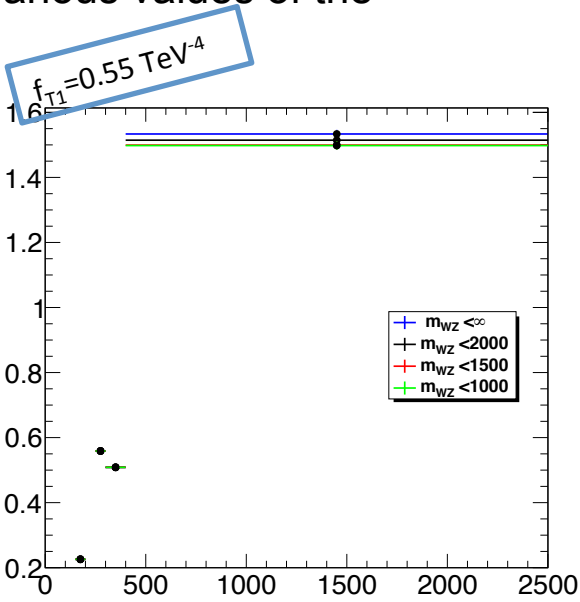


Example of clipping in m_T^{WZ}

- Comparison of the distributions of the total generated sample and the clipped distributions
  - Clipping the interference and the quadratic term only at various values of the truth m_{WZ}







Positivity Constraints

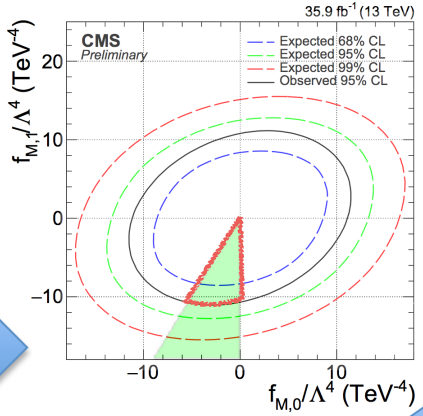
- Publication by C.Zhang
- Certain areas of the EFT parameter space are forbidden due to UV completion
- New set of theoretical constraints on the Dim-8 operators

1D

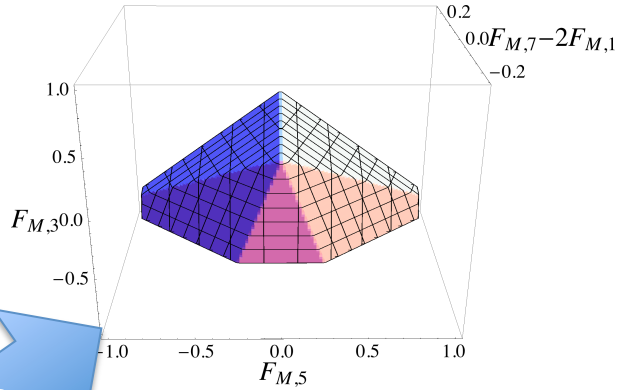
$f_{S,0}$	$f_{S,1}$	$f_{S,2}$	$f_{M,0}$	$f_{M,1}$	$f_{M,2}$	$f_{M,3}$	$f_{M,4}$	$f_{M,5}$
+	+	+	X	−	O	−	O	X
$f_{M,7}$	$f_{T,0}$	$f_{T,1}$	$f_{T,2}$	$f_{T,5}$	$f_{T,6}$	$f_{T,7}$	$f_{T,8}$	$f_{T,9}$
+	+	+	+	X	+	X	+	+

TABLE I: Positivity constraints on individual VBS operator coefficients. $+/-$ means the coefficient must be non-negative or non-positive. X means only $f = 0$ is allowed, and O means no constraints.

2D



3D



Conclusions

- EFTs is the tool to look for BSM effects
- WZ in the inclusive and the VBS phase space serves as a good candidate for the search
- Dimension-6 operators are investigated using the SMEFTSim model
- Dimension-8 operators are investigated using the Eboli,Gonzales-Garcia model
- With the full Run II data, better limits in Effective Field theory operators are expected with higher statistics and after combining the results with other final states

Thank you!