Vector Boson Scattering at the LHC: towards an EFT interpretation of the measurements

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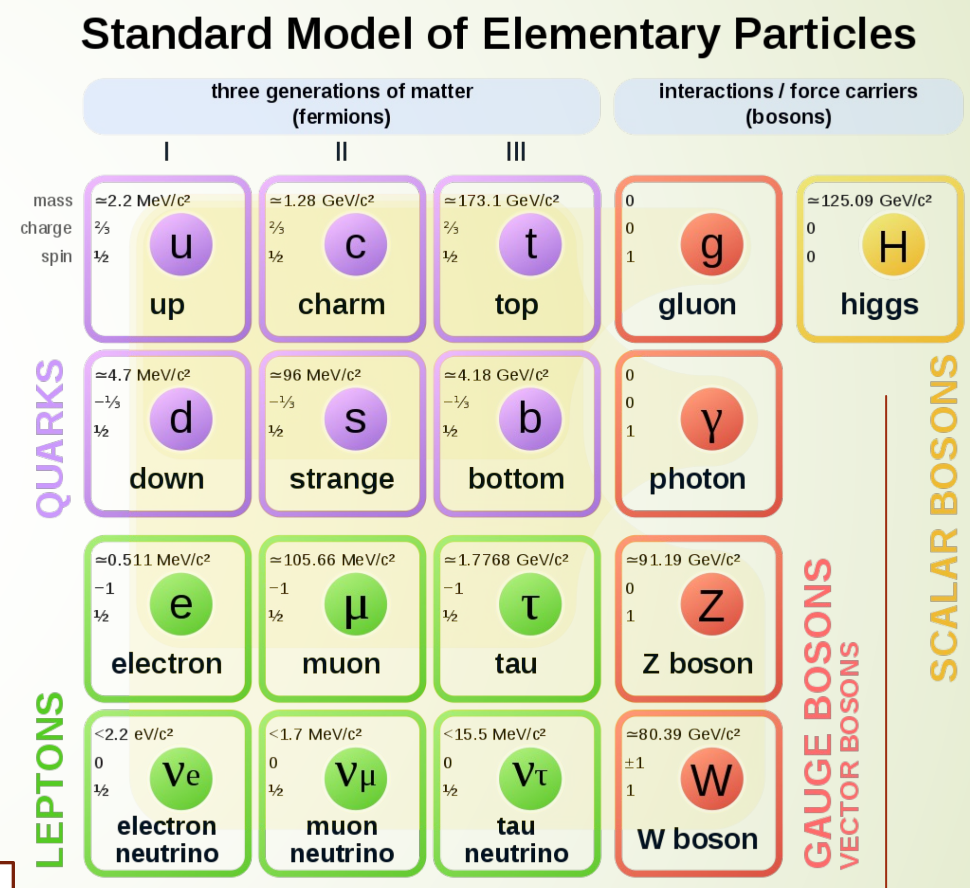
ATLAS EXPERIMENT

Theory part

The Standard Model of Particle Physics

- Standard Model is a highly successful quantum field theory that describes the fundamental particles and their interactions
- Base on the symmetry group $SU(3)\times SU(2)\times U(1)$
  - $SU(3)$ group describes the strong interaction
  - $SU(2)\times U(1)$ group describes the unified electroweak interaction
- SM has limitations
  - Hierarchy problem
  - Incorporation of gravity
  - Dark matter – dark energy
  - Masses of neutrinos

Extensions to the SM

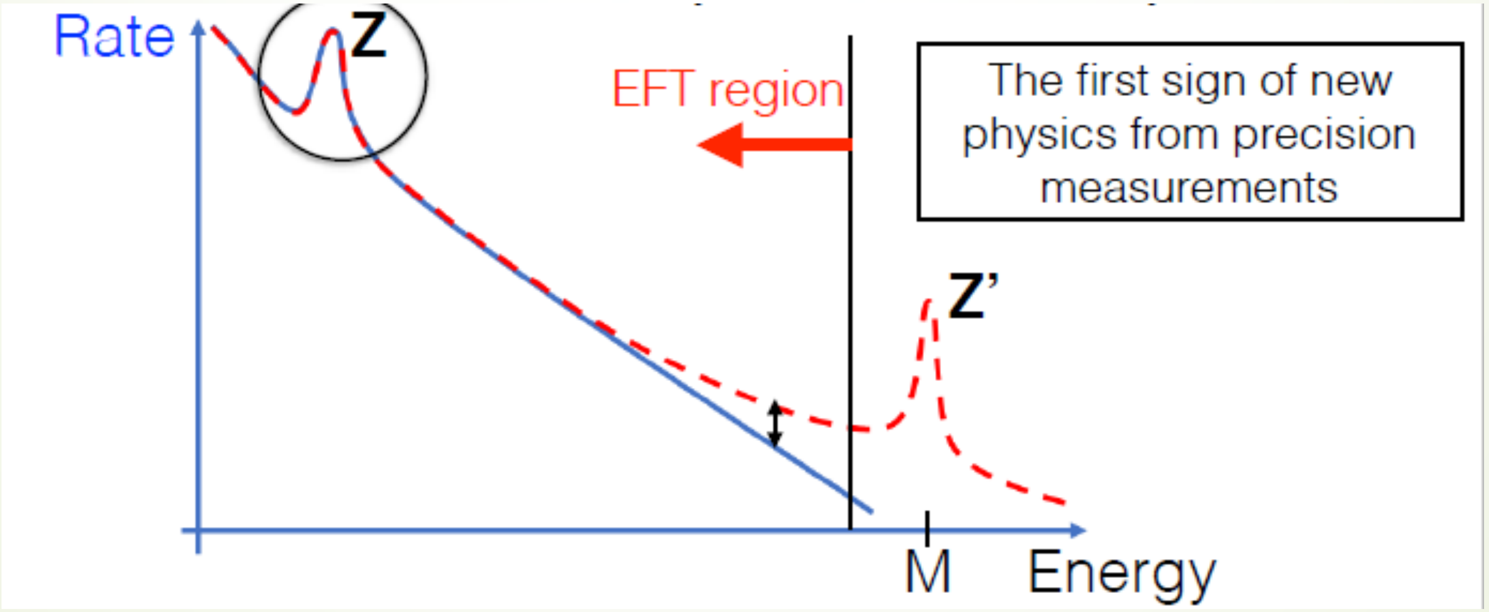


Physics beyond the SM

Electroweak symmetry breaking

Effective Field Theory: Overview (1)

- There are two methods to look for physics beyond the Standard Model (BSM).
  - Look for new particles (model-dependent)
  - Look for new interactions of SM particles (model-independent)
- We use the second method and we try to notice deviations in the tails of the distributions of some kinematical variables.



Effective Field Theory: Overview (2)

- The Effective Field Theory (EFT) is the natural way to expand the SM such that the gauge symmetries are respected
- The EFT provides a way to search for effects of BSM
- Construction of an EFT Lagrangian:
  - SM: general theory of quark and lepton fields and their interactions with vector boson and the Higgs fields
  - Extend the theory: Add operators of higher dimension
- The EFT Lagrangian can be expressed as:

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda_i^2} O_i^{(6)} + \sum_i \frac{c_i^{(8)}}{\Lambda_i^4} O_i^{(8)} + \ldots$$

Where: Λ is the scale of new physics

$O_i^{(6)}$, $O_i^{(8)}$ are the Lorentz and gauge invariant dimension-6 and dimension-8 operators

$c_i^{(6)}$, $c_i^{(8)}$ are the dimensionless Wilson coefficients of the dimension-6 and 8 effective operators

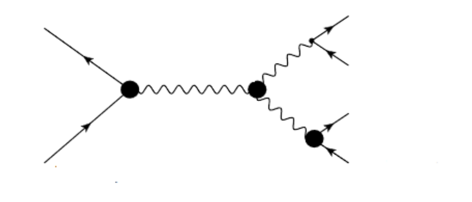
- Λ can be assumed as common to all the coefficients, the Wilson coefficients can be written as:

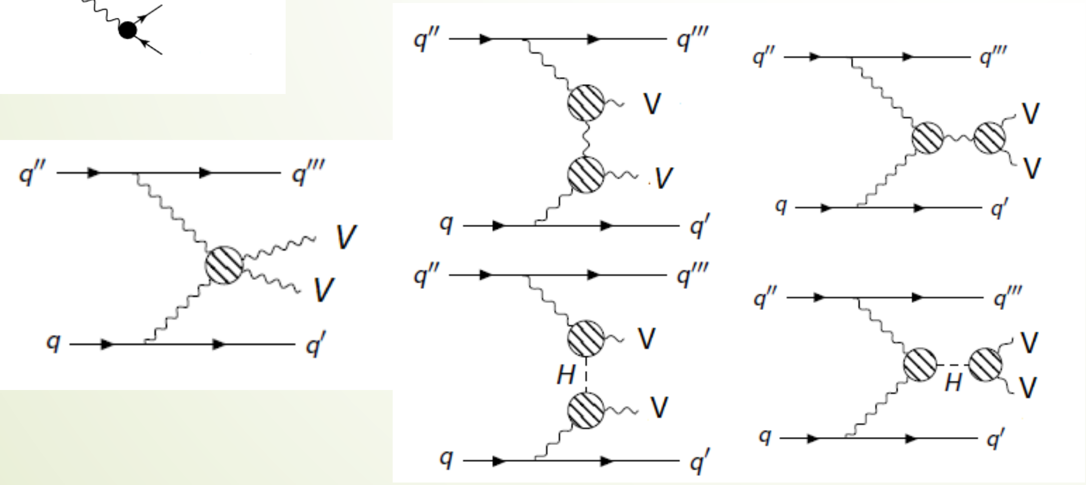
$$f_i^{(6)} = \frac{c_i^{(6)}}{\Lambda^2}, f_i^{(8)} = \frac{c_i^{(8)}}{\Lambda^4}, \ldots$$

Energy scale of the
interaction must be
$E < \Lambda$

Effective Field Theory: dimension-6 operators

- Dimension-6 operators are dominant in anomalous Triple Gauge Couplings (aTGCs)
- After flavor symmetry assumptions, the Warsaw basis is used
  - minimal set of non-redundant dimension-6 operators
  - Includes bosonic, boson to fermion and four-fermion operators

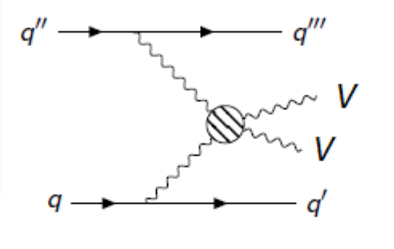




$\mathcal{L}_6^{(1)} - X^3$		$\mathcal{L}_6^{(6)} - \psi^2 X H$		$\mathcal{L}_6^{(8b)} - (\bar{R}R)(\bar{R}R)$	
Q_G	$f^{abc} G_\mu^{a\nu} G_\nu^{b\rho} G_\rho^{c\mu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \sigma^i H W_{\mu\nu}^i$	Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{\widetilde{G}}$	$f^{abc} \widetilde{G}_\mu^{a\nu} G_\nu^{b\rho} G_\rho^{c\mu}$	Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$	Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$
Q_W	$\varepsilon^{ijk} W_\mu^{i\nu} W_\nu^{j\rho} W_\rho^{k\mu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^a u_r) \widetilde{H}\, G_{\mu\nu}^a$	Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{\widetilde{W}}$	$\varepsilon^{ijk} \widetilde{W}_\mu^{i\nu} W_\nu^{j\rho} W_\rho^{k\mu}$	Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \sigma^i \widetilde{H}\, W_{\mu\nu}^i$	Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$
$\mathcal{L}_6^{(2)} - H^6$		Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \widetilde{H}\, B_{\mu\nu}$	Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$
Q_H	$(H^\dagger H)^3$	Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^a d_r) H\, G_{\mu\nu}^a$	$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$
$\mathcal{L}_6^{(3)} - H^4 D^2$		Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \sigma^i H\, W_{\mu\nu}^i$	$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^a u_r)(\bar{d}_s \gamma^\mu T^a d_t)$
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$		
Q_{HD}	$(D^\mu H^\dagger H)\,(H^\dagger D_\mu H)$				
$\mathcal{L}_6^{(4)} - X^2 H^2$		$\mathcal{L}_6^{(7)} - \psi^2 H^2 D$		$\mathcal{L}_6^{(8c)} - (\bar{L}L)(\bar{R}R)$	
Q_{HG}	$H^\dagger H\, G_{\mu\nu}^a G^{a\mu\nu}$	$Q_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$	Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^a G^{a\mu\nu}$	$Q_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^i H)(\bar{l}_p \sigma^i \gamma^\mu l_r)$	Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^i W^{I\mu\nu}$	Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$	Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^i W^{i\mu\nu}$	$Q_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$	Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$	$Q_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^i H)(\bar{q}_p \sigma^i \gamma^\mu q_r)$	$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$	$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^a q_r)(\bar{u}_s \gamma^\mu T^a u_t)$
Q_{HWB}	$H^\dagger \sigma^i H\, W_{\mu\nu}^i B^{\mu\nu}$	Q_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$	$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{H\widetilde{W}B}$	$H^\dagger \sigma^i H\, \widetilde{W}_{\mu\nu}^i B^{\mu\nu}$	Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$	$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^a q_r)(\bar{d}_s \gamma^\mu T^a d_t)$
$\mathcal{L}_6^{(5)} - \psi^2 H^3$		$\mathcal{L}_6^{(8a)} - (\bar{L}L)(\bar{L}L)$		$\mathcal{L}_6^{(8d)} - (\bar{L}R)(\bar{R}L), (\bar{L}R)(\bar{L}R)$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$	Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$	Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$	$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$	$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r) \varepsilon_{jk} (\bar{q}_s^k d_t)$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$	$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \sigma^i q_r)(\bar{q}_s \gamma^\mu \sigma^i q_t)$	$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^a u_r) \varepsilon_{jk} (\bar{q}_s^k T^a d_t)$
		$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$	$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r) \varepsilon_{jk} (\bar{q}_s^k u_t)$
		$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \sigma^i l_r)(\bar{q}_s \gamma^\mu \sigma^i q_t)$	$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r) \varepsilon_{jk} (\bar{q}_s^k \sigma^{\mu\nu} u_t)$

Effective Field Theory: dimension-8 operators

- The dimension-8 operators are dominant in anomalous Quartic Gauge Couplings (aQGCs)



They are divided into three categories: Longitudinal (L_S), transverse (L_T) and mixed (L_M)

$$\mathcal{L}_{S,0} = \frac{c_{S,0}}{\Lambda^4}\left[(D_\mu\Phi)^\dagger (D_v\Phi)\right] \times \left[(D^\mu\Phi)^\dagger (D^v\Phi)\right]$$
$$\mathcal{L}_{S,1} = \frac{c_{S,1}}{\Lambda^4}\left[(D_\mu\Phi)^\dagger (D^\mu\Phi)\right] \times \left[(D_v\Phi)^\dagger (D^v\Phi)\right]$$
$$\mathcal{L}_{S,2} = \frac{c_{S,2}}{\Lambda^4}\left[(D_\mu\Phi)^\dagger (D_v\Phi)\right] \times \left[(D^v\Phi)^\dagger (D^\mu\Phi)\right]$$

Scalar operators: Pure Higgs field

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

Tensor operators: field strength tensor

Mixed operators

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

	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

Effective Field Theory: Unitarity bounds

- aTGCs/aQGC terms: disturb the cancellation between different contributions to the scattering amplitude of longitudinally polarized, massive electroweak gauge bosons
- Cross section for the scattering of massive electroweak gauge bosons is rising with increasing centre-of-mass energy but it cannot exceed the physical upper bound
- Range of validity of the specific EFT model: $E^2 < \Lambda \leq s^U$, where $s^U \equiv s^U(f_i)$ is the unitarity bound

Wilson coefficient	Bound
$\lvert\frac{f_{M0}}{\Lambda^4}\rvert$	$\frac{32}{\sqrt{6}}\pi s^{-2}$
$\lvert\frac{f_{M1}}{\Lambda^4}\rvert$	$\frac{128}{\sqrt{6}}\pi s^{-2}$
$\lvert\frac{f_{M2}}{\Lambda^4}\rvert$	$\frac{16}{\sqrt{2}}\pi s^{-2}$
$\lvert\frac{f_{M3}}{\Lambda^4}\rvert$	$\frac{64}{\sqrt{2}}\pi s^{-2}$
$\lvert\frac{f_{M4}}{\Lambda^4}\rvert$	$32\pi s^{-2}$
$\lvert\frac{f_{M5}}{\Lambda^4}\rvert$	$64\pi s^{-2}$
$\lvert\frac{f_{M7}}{\Lambda^4}\rvert$	$\frac{256}{\sqrt{6}}\pi s^{-2}$

Wilson coefficient	Bound
$\lvert\frac{f_{S0}}{\Lambda^4}\rvert$	$32\pi s^{-2}$
$\lvert\frac{f_{S1}}{\Lambda^4}\rvert$	$\frac{96}{7}\pi s^{-2}$
$\lvert\frac{f_{S2}}{\Lambda^4}\rvert$	$\frac{96}{5}\pi s^{-2}$

Wilson coefficient	Bound
$\lvert\frac{f_{T0}}{\Lambda^4}\rvert$	$\frac{12}{5}\pi s^{-2}$
$\lvert\frac{f_{T1}}{\Lambda^4}\rvert$	$\frac{24}{5}\pi s^{-2}$
$\lvert\frac{f_{T2}}{\Lambda^4}\rvert$	$\frac{96}{13}\pi s^{-2}$
$\lvert\frac{f_{T5}}{\Lambda^4}\rvert$	$\frac{8}{\sqrt{3}}\pi s^{-2}$
$\lvert\frac{f_{T6}}{\Lambda^4}\rvert$	$\frac{48}{7}\pi s^{-2}$
$\lvert\frac{f_{T7}}{\Lambda^4}\rvert$	$\frac{32}{\sqrt{3}}\pi s^{-2}$
$\lvert\frac{f_{T8}}{\Lambda^4}\rvert$	$\frac{3}{2}\pi s^{-2}$
$\lvert\frac{f_{T9}}{\Lambda^4}\rvert$	$\frac{24}{7}\pi s^{-2}$

https://journals.aps.org/prd/abstract/10.1103/PhysRevD.101.113003

Effective Field Theory: Decomposition method

- MC samples for the effect of higher dimension operators in many values of the coefficients
- In order to avoid the production of large amounts of Monte Carlo samples, we will profit from the decomposition method

Full production

Interference term between SM-EFT (Linear term)

Pure EFT contribution (Quadratic term)

Interference term between EFT operators (Cross term)

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

SM term

Hands on

An EFT reinterpretation analysis from scratch

- 1st step
  - Produce EFT samples and validate the decomposition method
- 2nd step
  - Find the most sensitive operators
- 3rd step
  - Build the analysis phase space using an analysis framework e.g., Rivet framework for truth level measurements
- 4th step
  - Use the outputs from the analysis framework as inputs to the fitting framework in order to compute the confidence intervals for the EFT parameters

All number and plots used in this tutorial come from this thesis: https://ikee.lib.auth.gr/record/349124/files/thesis_kasimi-1.pdf

1st step: Production of EFT dimension-6 or 8 samples

- production of the WZjj EWK process
  - Madgraph5_aMC@NLO generator for hard process
  - UFO models
    - Eboli-Garcia model for EFT dimension-8 operators at LO
    - SMEFTSim model for EFT dimension-6 operators at LO
    - SMEFT@NLO model for EFT dimension-6 operators at NLO (only the full production at NLO)
    - SmeftFR v3 model for both dimension-6 and dimension-8 operators (very preliminary)

- Production of dimension-8 samples with the Eboli-Garcia model:
  - SM: p p > l+ l- l+ v j j QCD=0 T0==0
  - Interference term: p p > l+ l- l+ v j j QCD=0 T0^2==1
  - Quadratic term: p p > l+ l- l+ v j j QCD=0 T0^2==2
  - Cross term: p p > l+ l- l+ v j j QCD=0 T0^2==1 T1^2==1
  - Full production(SM+EFT parts): p p > l+ l- l+ v j j QCD=0 T0=1

- Production of dimension-6 samples with the SMEFT@NLO model:
  - SM: p p > l+ l- l+ v j j QCD=0 NP^2==0
  - Interference term: p p > l+ l- l+ v j j QCD=0 NP^2==2
  - Quadratic term: p p > l+ l- l+ v j j QCD=0 NP^2==4
  - Cross term: p p > l+ l- l+ v j j QCD=0 T0^2==1 NP^2==4
  - Full production(SM+EFT parts): p p > l+ l- l+ v j j QCD=0 NP=2

1st step: Building the JobOption

Eboli-Garcia model

```
if eft_order == "interference":
    runName = 'lllvjj_Eboli_int'
    description = 'MadGraph_lllvjj_Eboli_int'
    mgproc = """
generate p p > mu+ mu- e- ve~ j j QCD=0 T0^2==1 @0"""
elif eft_order == "quadratic":
    runName = 'llajj_Eboli_quad'
    description = 'MadGraph_llajj_Eboli_quad'
    mgproc = """
generate p p > mu+ mu- e- ve~ j j QCD=0 T0^2==2 @0"""
elif eft_order == "cross":
    runName = 'llajj_Eboli_cross'
    description = 'MadGraph_llajj_Eboli_cross'
    mgproc = """
generate p p > mu+ mu- e- ve~ j j QCD=0 T0^2==1 T1^2==1 @0"""
elif eft_order == "full":
    runName = 'llajj_Eboli_full'
    description = 'MadGraph_llajj_Eboli_full'
    mgproc = """generate p p > mu+ mu- e- ve~ j j QCD=0 T0=1 @0"""
    pass
else:
    raise RuntimeError(
        "EFT-order %i not recognised in these jobOptions" % eft_order)
```

```
import model QAll_5_Aug21v2
define l+ = e+ mu+
define vl = ve vm
define l- = e- mu-
define vl~ = ve~ vm~
define p = g u c d s b u~ c~ d~ s~ b~
define j = g u c d s b u~ c~ d~ s~ b~
```

SMEFT@NLO model

```
if eft_order == "interference":
    runName = 'lllv_SMEFTatNLO_int'
    description = 'MadGraph_lllv_SMEFTatNLO_int'
    mgproc = """
generate p p > l+ l- l+ vl QCD=0 QED=4 NP^2==2 @0
add process p p > l+ l- l- vl~ QCD=0 QED=4 NP^2==2 @0"""
elif eft_order == "quadratic_cross":
    runName = 'lllv_SMEFTatNLO_quad'
    description = 'MadGraph_lllv_SMEFTatNLO_quad'
    mgproc = """
generate p p > l+ l- l+ vl QCD=0 QED=4 NP^2==4 @0
add process p p > l+ l- l- vl~ QCD=0 QED=4 NP^2==4 @0"""
elif eft_order == "full":
    runName = 'lllv_SMEFTatNLO_full'
    description = 'MadGraph_lllv_SMEFTatNLO_full'
    mgproc = """
generate p p > l+ l- l+ vl QCD=0 QED=4 NP=2 @0
add process p p > l+ l- l- vl~ QCD=0 QED=4 NP=2 @0"""
elif eft_order == "sm":
    runName = 'lllv_SMEFTatNLO_sm'
    description = 'MadGraph_lllv_SMEFTatNLO_sm'
    mgproc = """
generate p p > l+ l- l+ vl QCD=0 QED=4 NP^2==0 @0
add process p p > l+ l- l- vl~ QCD=0 QED=4 NP^2==0 @0"""
    pass
```

```
import model SMEFTatNLO-LO
define all = g ghg ghg~ u c d s b u~ c~ d~ s~ b~ a gha gha~ ve vm vt e- mu- ta- ve~ vm~ vt~ e+ mu+ ta+ t t~ z w+ ghz ghwp ghwm h w- ghz~ ghwp~ ghwm~
%s
output -f
```

1st step: Building the JobOption (2)

```
extras = {
    'dynamical_scale_choice': 2,
    'ptl': 4.0,
    'mmll': 0.0,
    'drll': 0.2,
    'etal': 5.0,
    'maxjetflavor': 5,
    'event_norm': 'average',
}
```

SMEFT@NLO model

```
Block dim62f
    1 1.000000e-05 # cpl1
    2 1.000000e-05 # cpl2
    3 1.000000e-05 # cpl3
    4 1.000000e-05 # c3pl1
    5 1.000000e-05 # c3pl2
    6 1.000000e-05 # c3pl3
    7 1.000000e-05 # cpe
    8 1.000000e-05 # cpmu
    9 1.000000e-05 # cpta
   10 1.000000e-00 # cpqMi
   11 1.000000e-05 # cpq31
   12 1.000000e-05 # cpQ3
   13 1.000000e-05 # cpQM
   14 1.000000e-05 # cpu
   15 1.000000e-05 # cpt
   16 1.000000e-05 # cpd
   19 1.000000e-05 # ctp
   22 1.000000e-05 # ctZ
   23 1.000000e-05 # ctW
   24 1.000000e-05 # ctG
```

Eboli-Garcia model

```
###################################
## INFORMATION FOR ANOINPUTS
###################################
Block anoinputs
    1 0.000000e-12 # FS0
    2 0.000000e-12 # FS1
    3 0.000000e-12 # FS2
    4 0.000000e-12 # FM0
    5 0.000000e-12 # FM1
    6 0.000000e-12 # FM2
    7 0.000000e-12 # FM3
    8 0.000000e-12 # FM4
    9 0.000000e-12 # FM5
   10 0.000000e-12 # FM6
   11 0.000000e-12 # FM7
   12 1.000000e-12 # FT0
   13 0.000000e-12 # FT1
   14 0.000000e-12 # FT2
   15 0.000000e-12 # FT3
   16 0.000000e-12 # FT4
   17 0.000000e-12 # FT5
   18 0.000000e-12 # FT6
   19 0.000000e-12 # FT7
   20 0.000000e-12 # FT8
   21 0.000000e-12 # FT9
```

Parameter card

```
if operator == "cpqMi":
    param_card_name='param_card_cpqMi_1.dat'
    modify_param_card(param_card_input=param_card_name,process_dir=process_dir,param_card_backup='param_card_cpqMi_1_backup.dat')
elif operator == "sm":
    param_card_name='param_card_sm.dat'
    modify_param_card(param_card_input=param_card_name,process_dir=process_dir,param_card_backup='param_card_sm_backup.dat')
    pass
```

1st step: Building the configuration file

```
eft_order="quadratic"
operator="T0"
include('MadGraphControl_NNPDF30NLO_lllvjj_dim8.py')
```

- Commands to run the configuration files:
  - setupATLAS
  - asetup 21.6.99,AthGeneration
  - Gen_tf.py --ecmEnergy=13000. --maxEvents=1 --firstEvent=1 --outputEVNTFile=EVNT.root --jobConfig=./

1st step: Validation of the decomposition method

- In order to use the decomposition method to generate samples, we have to prove that the method works well even for coefficient values very far from the Standard Model

	value	SM xsec(fb)	INT xsec(fb)	QUAD xsec(fb)	FULL xsec(fb)	SUM xsec(fb)	Difference %
$cWWW$	-26.5	74.41	81.44	90330	90340	90490	0.16
$cpDC$	-41.2	74.41	-66.7	6519	5879	2260	0.5

Validation of the decomposition method by comparing the full production with the sum of the decomposed samples

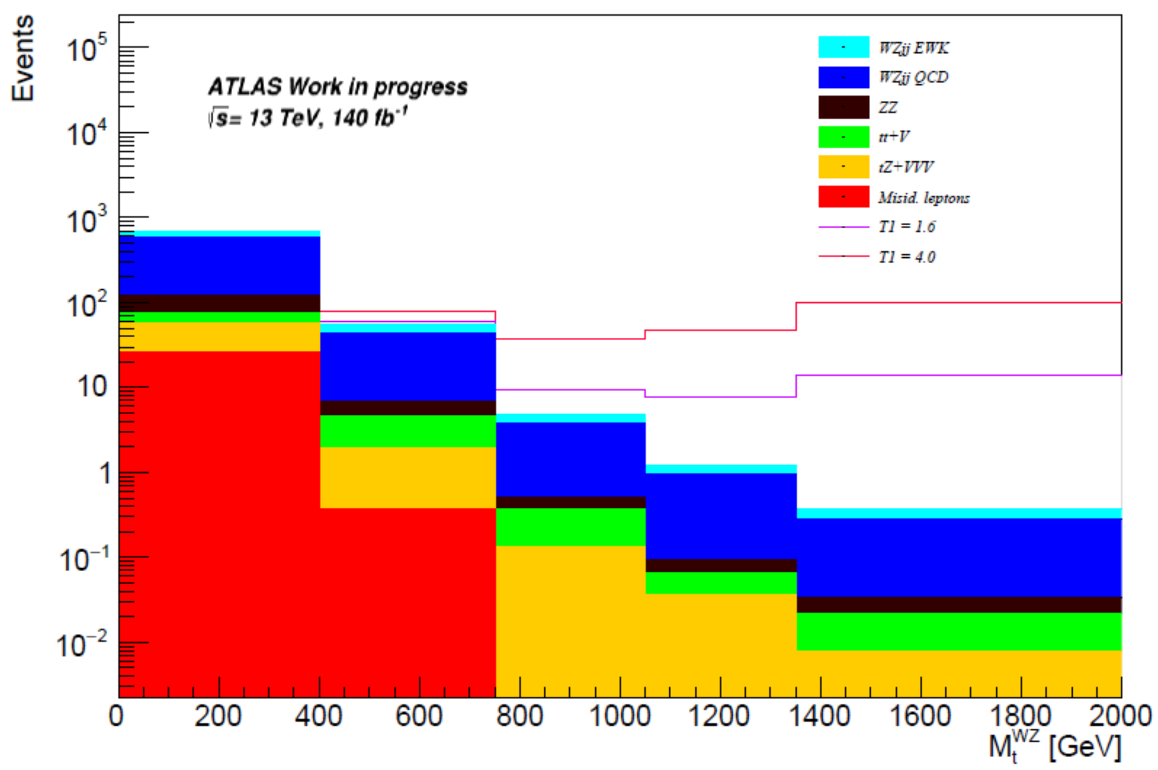
Arbitrary values

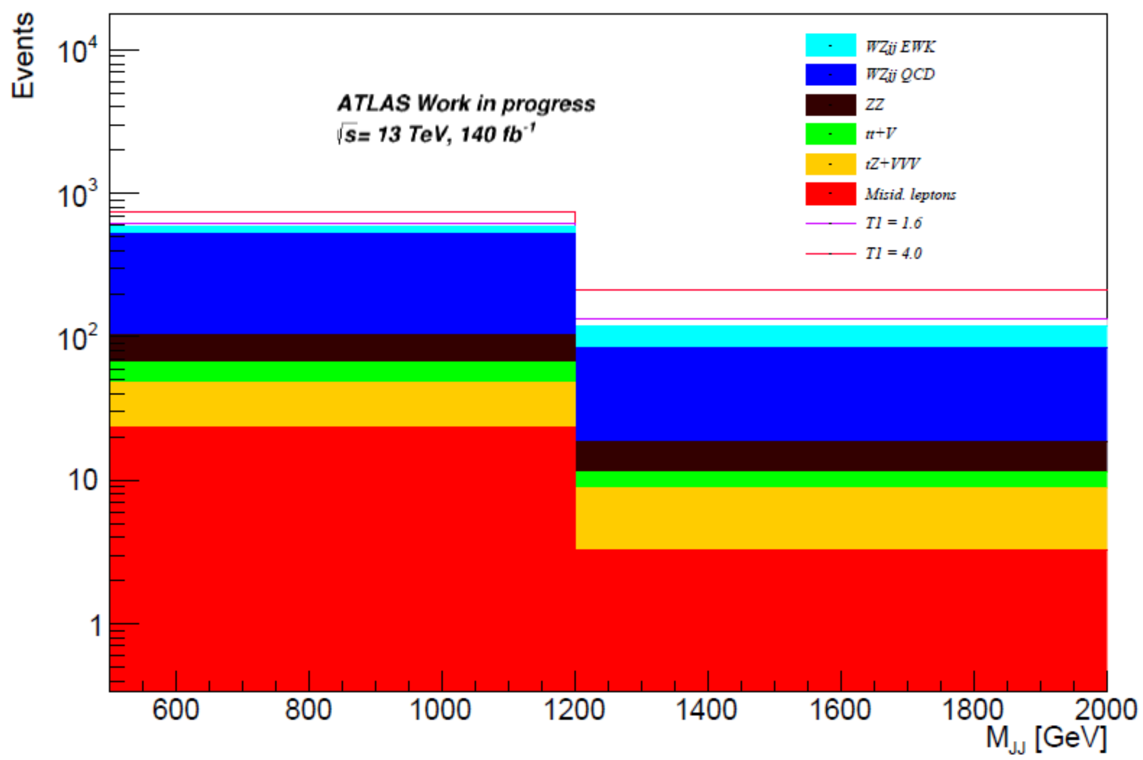
Good agreement between full and sum

Within the statistical error

	value	SM xsec(fb)	INT xsec(fb)	QUAD xsec(fb)	FULL xsec(fb)	SUM xsec(fb)	Difference %
f_{S0}	-26.5	1.049	0.00168	0.02421	1.0750	1.0749	0.09
f_{S1}	-41.2	1.049	0.00167	0.03005	1.0810	1.0804	0.05
f_{M3}	-43.0	1.049	-0.00140	0.12300	1.160	1.1706	0.91
f_{M7}	-13.0	1.049	-0.0004	0.01541	1.061	1.0640	0.28
f_{T2}	-1.2	1.049	0.00476	0.01095	1.070	1.0647	0.50
f_{T6}	3.0	1.049	0.00429	0.06548	1.111	1.1188	0.70

1st step: EFT contribution to kinematical variables





2nd step: Sensitive operatos

- Effects of aTGCs/aQGCs on
  - the cross section measurement
  - The shape of the relevant kinematical distributions

Both criteria have to be fulfilled in order to characterize an operator as "sensitive"

- Generate a Standard Model sample and full samples for some operators
- 3x the existing limits for the coefficients that have one and c=1 or 3 for those which have not a limit
- In order to detect the effect of dimension-6 or dimension-8 operators on the SM cross section experimentally, the deviation from the SM has to be larger than the cross section error, which is of the order of 8-9% (for fullRun2 statistics)
- Perform the study using the fiducial phase space

WZjj VBS Phase Space	
p_T of Z leptons	> 20 GeV
p_T of W leptons	> 30 GeV
$\|\eta\|$ of leptons	< 2.5
m_Z range $[GeV]$	$\|m_Z - m_Z^{PDG}\| < 10$
$m_T^W [GeV]$	> 30
Jet multiplicity	≥ 2
p_T of two tagging jets	> 40 GeV
$\|\eta\|$ of two tagging jets	< 4.5
η of two tagging jets	opposite sign
m_{jj}	> 500 GeV

2nd step: Sensitive operators (2)

- WZjj VBS production is mostly affected by the dimension-8 operators → ideal ground for search for aQGCs
- However, both WZjj EWK and WZjj-QCD are also affected by the dimension-6 operators → search of aTGCs
- MadGraph5_aMC@NLO 2.7.3 version and SMEFT@NLO model are used for the generation of LO for dimension-6 operators at parton level
- MadGraph5_aMC@NLO 2.7.3 version and Eboli & Co model are used for the generation of LO events for dimension-8 operators at parton level
- The generated process is: $p\,p > \mu^+\mu^-e^+\nu_e\,j\,j$

- Variables related to kinematics vector bosons
  - m_Z, m_W invariant mass of the Z and W bosons
  - p_T^Z, p_T^W, transverse momentum of the Z and W bosons
  - η_Z, η_W, pseudorapidity of the Z and W boson
  - m_T^W, transverse mass of W boson
  - m_{WZ}, invariant mass of WZ system
  - m_T^{WZ}, transverse mass of WZ system
  - $m_{3leptons}$, $p_T^{3leptons}$, invariant mass and transverse momentum of the three leptons
  - $|y_{l,W} - y_Z|$, difference of rapidity of the lepton of W boson and the Z boson
  - $\Delta\varphi(l1\_Z, l\_W)$, difference of φ angle of the first lepton of Z boson and the lepton of W boson
  - $\Delta\varphi(l2\_Z, l\_W)$, difference of φ angle of the second lepton of Z boson and the lepton of W boson
  - $\Delta\varphi(Z, l\_W)$, difference of φ angle of the Z boson and the lepton of W boson
- Variables related to the kinematics of tagging jets
  - m_{jj}, invariant mass of the two tagging jets
  - $\Delta\eta(j1, j2)$, difference of pseudorapidity of the two tagging jets
  - $\Delta\varphi(j1, j2)$, difference of φ angle of the two tagging jets
- Variables related both to jets and leptons kinematics:
  - $\Delta R(j1, Z)$, $\Delta R = \sqrt{\Delta\eta^2 + \Delta\varphi^2}$ distance between of the jet with the highest transverse momentum and Z boson
  - $R_{p_T}^{hard}$, transverse component of the vectorial sum of the momentum of the three leptons and the two tagging jets divided by the sum of their transverse momentum $R_{p_T}^{hard} = \frac{\sqrt{(\Sigma_i p_x^i)^2 + (\Sigma_i p_y^i)^2}}{\Sigma_i p_T^i}$, where *i* is: the two leptons of Z boson, the lepton of W boson and the two tagging jets.
  - ζ_{lep},, lepton centrality $j_{lep} = \min(\Delta\eta_-, \Delta\eta_+)$ where

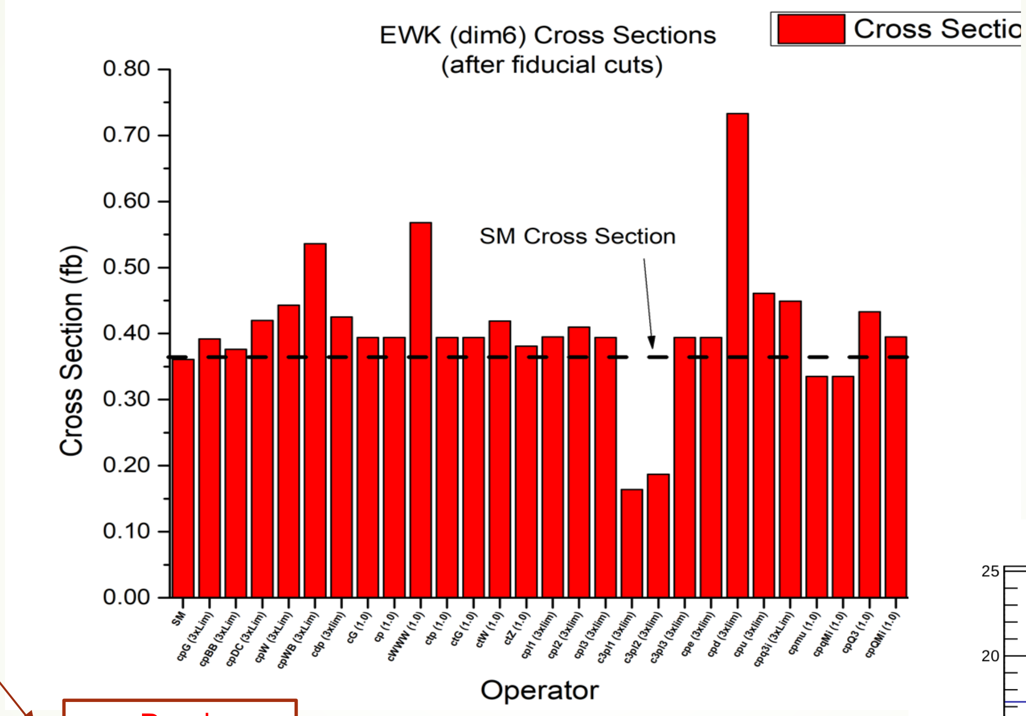
$\Delta\eta_- = \min(\eta_l^W, \eta_{l1}^Z, \eta_{l2}^Z) - \min(\eta_{j1}, \eta_{j2})$, *and* $\Delta\eta_+ = \max(\eta_{j1}, \eta_{j2}) - \max(\eta_l^W, \eta_{l1}^Z, \eta_{l2}^Z)$

2^{nd} step: Sensitive dimension-6 operators for EWK WZjj VBS case

- The sensitive operators with either a positive or negative effect are:
  - cpWB (16% diff. from SM)
  - cpW (72% diff. from SM)
  - cdp (39% diff. from SM)
  - cWWW (31% diff. from SM)
  - ctW (15% diff. from SM)
  - c3pl1 (56% diff. from SM)
  - c3pl2 (57% diff. from SM)
  - cpmu (22% diff. from SM)
  - cpu (205% diff. from SM)
  - cpd (24% diff. from SM)
  - cpQ3 (23% diff. from SM)

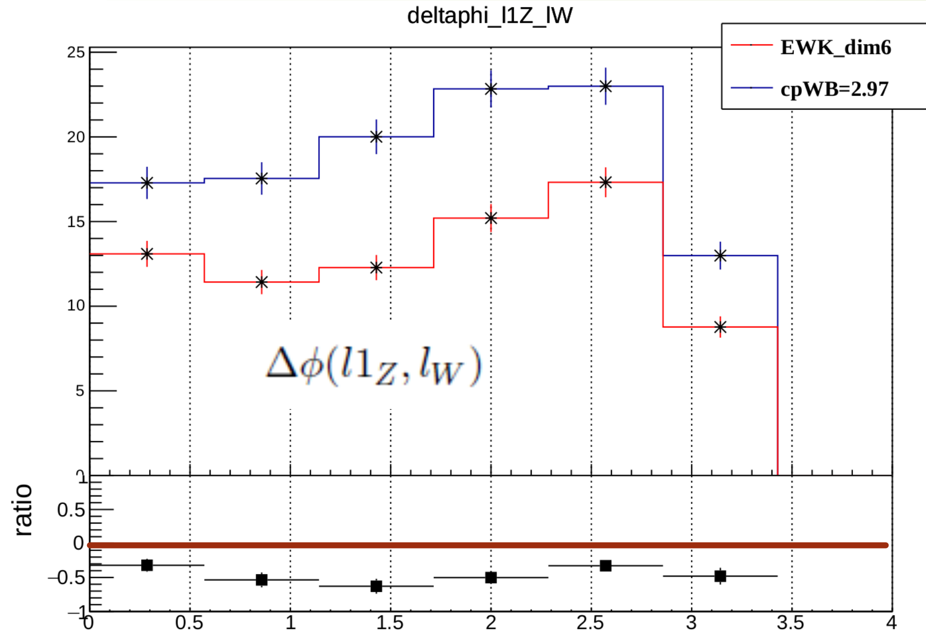
Differences before the fiducial cuts

- There are operators which have an effect to SM cross section after the WZjj VBS SR cuts (mjj>500GeV)
  - cpDC (16% diff. from SM)
  - cpl2 (13% diff. from SM)



Red: operators which do not have limits (maybe unphysical values)

Sensitive kinematical variables	
$cpWB$	$\Delta\phi(l1_Z, l_W)$
cpW	$\Delta\phi(l1_Z, l_W)$
cdp	m_T^{WZ}
$cWWW$	m_T^{WZ}
ctW	$\Delta\phi(l2_Z, l_W)$
$c3pl1$	$\Delta\phi(j_1, j_2)$
$c3pl2$	$\Delta\phi(j_1, j_2)$
$cpmu$	$\Delta\phi(l2_Z, l_W)$
cpd	$\Delta\phi(l1_Z, l_W)$
$cpQ3$	$\Delta\phi(l1_Z, l_W)$
$cpDC$	$\Delta\phi(l2_Z, l_W)$
$cpl2$	$\Delta\phi(j_1, j_2)$

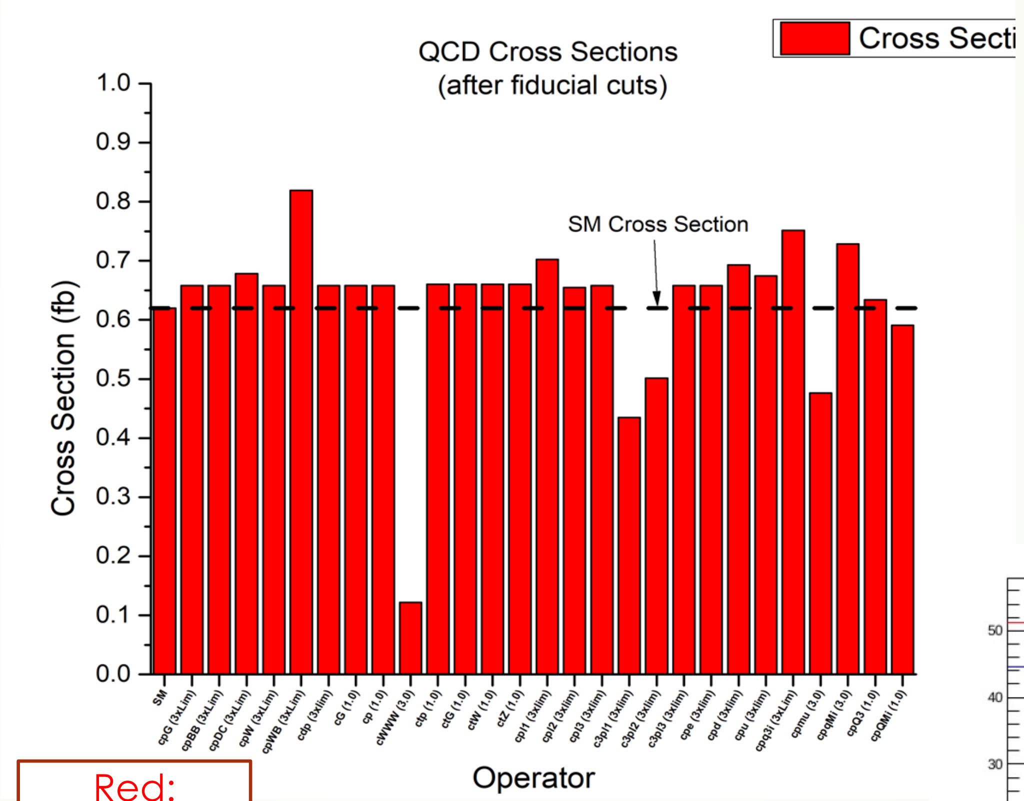


2^{nd} step: Sensitive dimension-6 operators for QCD WZjj VBS case

- The sensitive operators with either a positive or negative effect are:
  - cWWW (74% diff. from SM)
  - c3pl1 (31% diff. from SM)
  - c3pl2 (36% diff. from SM)
  - cpmu (20% diff. from SM)
  - cpq3i (21% diff. from SM)

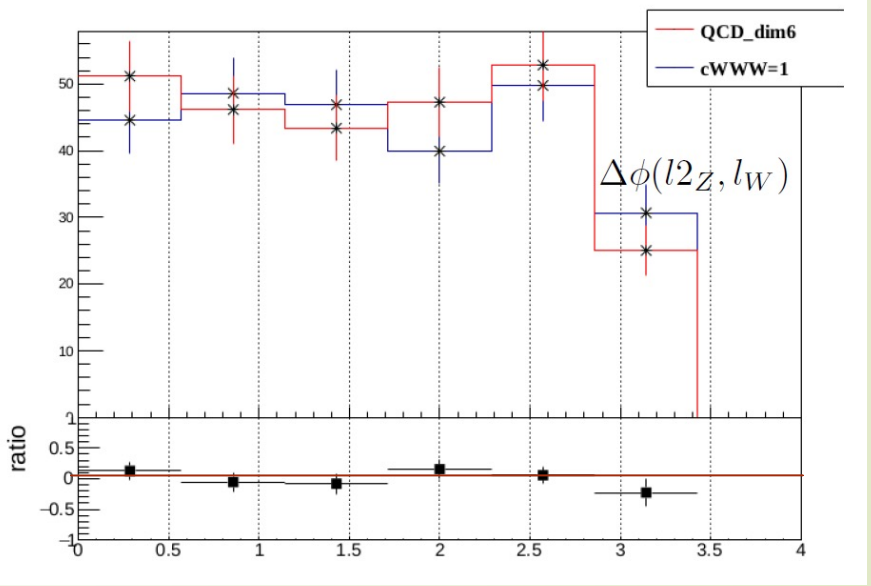
Differences before the fiducial cuts

- There are operators which have an effect to SM cross section after the WZjj VBS SR cuts (mjj>500GeV)
  - cpWB (31% diff. from SM)
  - cpl1 (13% diff. from SM)
  - cpd (11% diff. from SM)
  - cpqMi (46% diff. from SM)



Red: operators which do not have limits (maybe unphysical values)

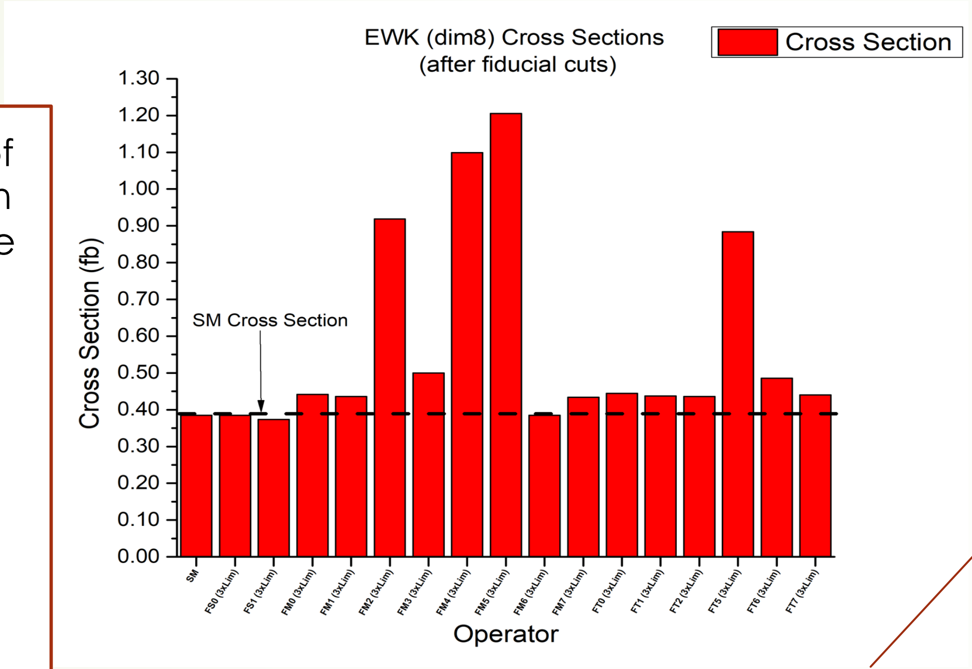
Sensitive kinematical variables	
$cWWW$	$\Delta\phi(l2_Z, l_W)$
$c3pl1$	$\Delta\phi(Z, l_W)$
$c3pl2$	$\Delta\phi(Z, l_W)$
$cpmu$	$\Delta\phi(l1_Z, l_W)$
$cpq3i$	m_T^{WZ}
$cpWB$	$\Delta\phi(l1_Z, l_W)$
$cpl1$	$\Delta\phi(j_1, j_2)$
cpd	$\Delta\phi(l1_Z, l_W)$
$cpqMi$	$\Delta\phi(l2_Z, l_W)$



2^{nd} step: Sensitive dimension-8 operators for EWK WZjj VBS case

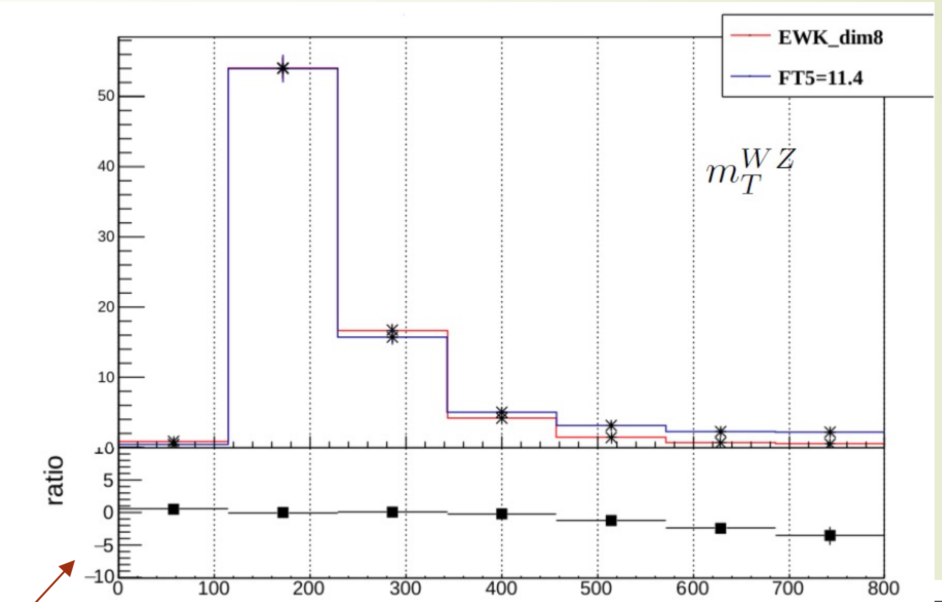
For dim-8 operators, the effect of the operators on SM cross section cannot been showed without use the fiducial cuts. The sensitive operators are:

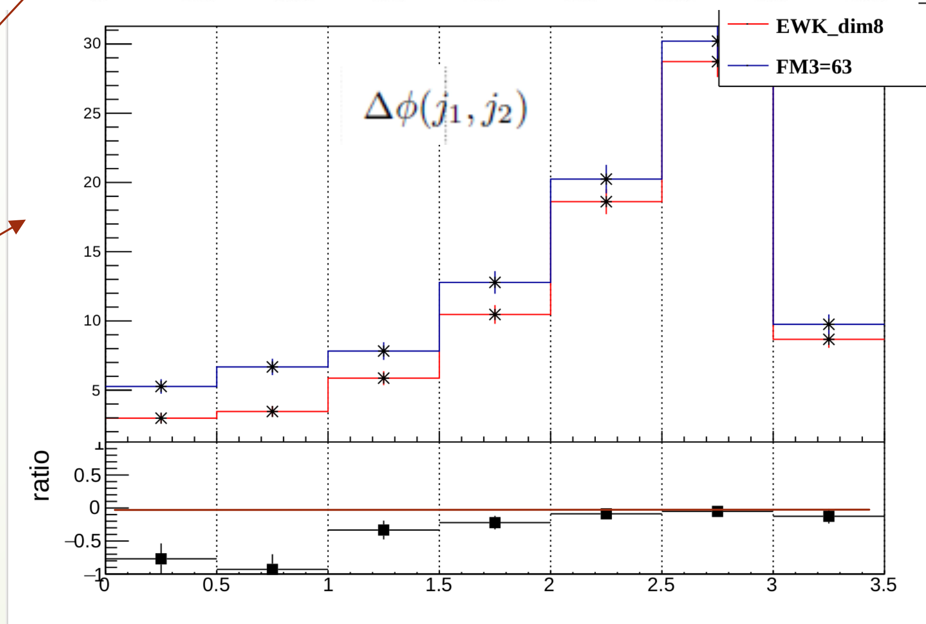
- FM0 (15% diff from SM)
- FM1 (13% diff from SM)
- FM2 (139% diff from SM)
- FM3 (30% diff from SM)
- FM4 (185% diff from SM)
- FM5 (213% diff from SM)
- FM7 (13% diff from SM)
- FT0 (16% diff from SM)
- FT1 (14% diff from SM)
- FT2 (13%diff from SM)
- FT5 (129% diff from SM)
- FT6 (26% diff from SM)
- FT7 (15% diff from SM)



Red: operators which do not have limits (maybe unphysical values)

Most sensitive kinematical variables for all the operators: m_T^{WZ} and $\Delta\varphi(j1, j2)$





1st and 2nd steps: Exercises

- Download the folder gif_school from this link:
  - https://drive.google.com/file/d/1gAWEk_C7gEsqUXmudw7HjGxU6HYcFEaP/view?usp=sharing
- Copy it in your home directory
- Two folders: JOs_dim6 and JOs_dim8
  - Only JOs_dim6 today
- 1st task: find the most sensitive dimension-6 operators (only cross section comparison)
  - Generate the SM sample
  - Generate the full samples for the following operators:
    - cpDC (existing expected limits: [-0.43, 0.45])
    - cpWB (existing expected limits: [-1.09, 0.99])
    - cWWW (No existing limits)
    - c3pl1 (existing expected limits: [-0.33, 0.32])
    - c3pl2 (existing expected limits: [-0.33, 0.32])
    - cpq3i (existing expected limits: [-0.080, 0.052])
    - cpmu (No existing limits)
    - cpqMi (No existing limits)
    - cpW (existing expected limits: [-02.9, 1.6])
    - cdp (existing expected limits: [-4.9, 9.8])

Compare the cross section of the full sample with the SM cross section.

1. Are they have a difference of 8-9%?
2. Is your operator sensitive?

Don't forget the instructions in Slide 19!!!!!

1st and 2nd steps: Exercises (2)

- 2nd task: validate the decomposition method
  - Generate the quadratic and interference terms for the previous sensitive operators
  - Add the SM, quadratic and interference cross sections and compare the sum with the full cross section

In order the samples to be comparable, the parameter value must be the same for all of them!!!!

1. Are the sum and the full comparable?
2. Can we use the decomposition method for our studies?

  - Try the same comparison using for the full and decomposed samples a "crazy" parameter value

1. Can we use the decomposition method even for values very far from a "reasonable" value?

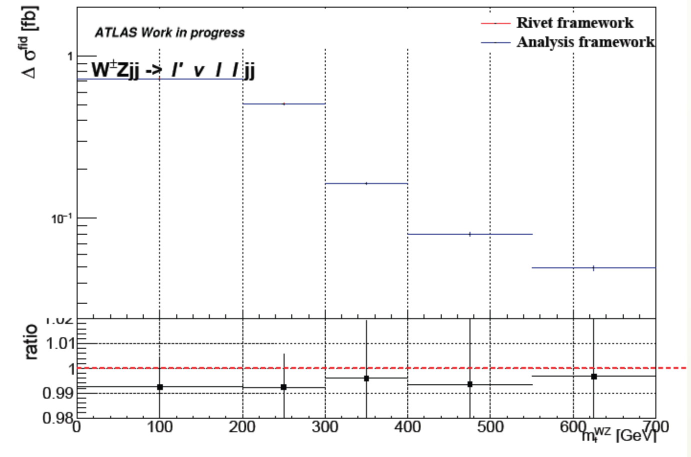
3rd step: Fiducial phase space and Rivet routine

Variable	Fiducial inclusive	Fiducial $WZjj$−EW
Lepton $\|\eta\|$	< 2.5	< 2.5
p_T of ℓ_Z, p_T of ℓ_W [GeV]	$> 15, > 20$	$> 15, > 20$
m_Z range [GeV]	$\|m_Z - m_Z^{PDG}\| < 10$	$\|m_Z - m_Z^{PDG}\| < 10$
m_T^W [GeV]	> 30	> 30
$\Delta R(\ell_Z^-, \ell_Z^+)$, $\Delta R(\ell_Z, \ell_W)$	$> 0.2, > 0.3$	$> 0.2, > 0.3$
p_T two leading jets [GeV]	–	> 40
$\|\eta_j\|$ two leading jets	–	< 4.5
Jet multiplicity	–	≥ 2
$\eta_{j1} \cdot \eta_{j1}$	–	< 0
m_{jj} [GeV]	–	> 500
$\Delta R(j, \ell)$	–	> 0.3
$N_{b-\text{quark}}$	–	$= 0$

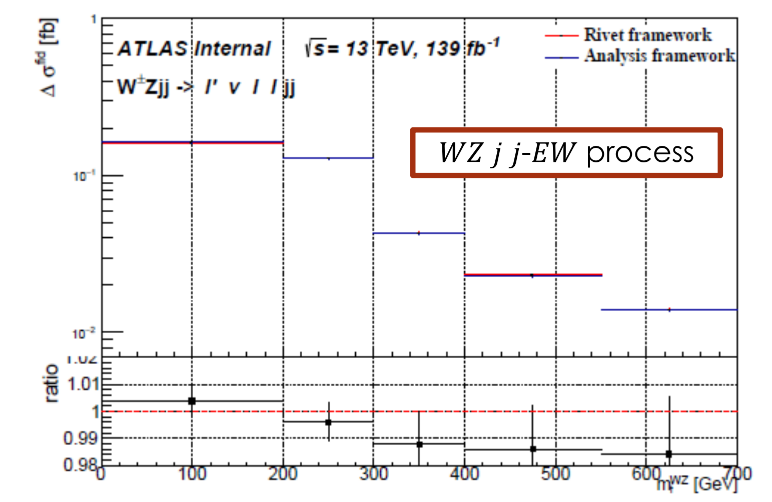
- Fiducial WZjj-EW phase space: subset of the fiducial inclusive phase space
  - Extra jet-related cuts are added
  - Selected to closely match the detector acceptance and the analysis selection

- Rivet framework:
  - definition of the exact fiducial phase space of an analysis
  - make the results exploitable for interpretation studies
- comparison between rivet framework and analysis framework
  - compare integrated cross sections:
    - $WZjj\_EW$ process:
      - Rivet routine: 0.3705 fb
      - Analysis framework: 0.3697 fb
      - Difference: 0.2%
    - $WZjj\_QCD$ process:
      - Rivet routine: 1.5283 fb
      - Analysis framework: 1.5145 fb
      - Difference: 0.9%
  - compare the differential distributions of some kinematical variables

$WZjj$-QCD process



$WZjj$-EW process



4th step: Fitting framework

- Use a fitting framework to perform the fit and to extract the confidence intervals for the coefficients of the sensitive operators
- Many likelihood-based fitting frameworks in the market that can incorporate the EFT parametrization
  - EFTFun tool
  - TRExFitter
  - HistFactory
  - pyhf
- In our examples, the EFTFun tool by Hannes Mildner is used
  - Not an open-source framework but just to see how a fitting framework works
  - Only available to those who have a CERN account

4th step: Statistical method used for the extraction of the truth level confidence intervals for the EFT parameters

- The probability density function based on a multivariate Gaussian distribution is used in the reinterpretation of the unfolded measurements for the WZjj process.

predicted fiducial cross section

$$x_b^{\text{pred}}\left(f, \boldsymbol{\theta}_{\text{theo syst}}\right) = x_b^{\text{SM}}\left(1 + \sum_i \frac{f_i x_i^{int}(\theta)}{x_b^{\text{SM}}} + \sum_i \frac{f_i^2 x_i^{quad}(\theta)}{x_b^{\text{SM}}} + \sum_{i \neq j} \frac{f_i f_j x_{ij}^{cross}(\theta)}{x_b^{\text{SM}}}\right) \times \prod_i^{n_{\text{theo syst}}} \left(1 + \theta_j u_j^b\right)$$

measured cross section

$$x_b^{\text{meas}}\left(\boldsymbol{\theta}_{\text{exp syst}}\right) = x_b \times \prod_j^{n_{\text{exp syst}}} \left(1 + \theta_{\text{exp syst},j} \nu_{b,j}\right)$$

$$\Delta x^b\left(\boldsymbol{f}, \boldsymbol{\theta}\right) = x_b^{\text{meas}} - x_{\text{pred}}^b\left(\boldsymbol{f}, \boldsymbol{\theta}\right)$$

likelihood function

$$L\left(\boldsymbol{x} | \boldsymbol{f}, \boldsymbol{\theta}\right) = \frac{1}{\sqrt{(2\pi)^{n_{\text{bins}}} \det(C)}} \exp\left(-\frac{1}{2} \Delta \boldsymbol{x}^T \left(\boldsymbol{f}, \boldsymbol{\theta}\right) C^{-1} \Delta \boldsymbol{x}\left(\boldsymbol{f}, \boldsymbol{\theta}\right)\right) \times \prod_i^{n_{\text{syst}}} d_i\left(\theta_i\right)$$

profile likelihood ratio test statistics

$$\lambda\left(f_i\right) = -2 \log \frac{L\left(f_i, \hat{\hat{\boldsymbol{\theta}}}\right)}{L\left(\hat{f}_i, \hat{\boldsymbol{\theta}}\right)}.$$

Confidence intervals are derived using Wilks' theorem, assuming that λ (fi) is χ2 distributed

$$t_\mu = \left(\chi^2\right)^{-1}(0.950, 1) = 3.84 \text{ (corresponding to a 95\% confidence level)}$$
$$t_\mu = \left(\chi^2\right)^{-1}(0.683, 1) = 1.00 \text{(corresponding to a 68.3\% confidence level)}.$$

4th step: Fitting procedure

- Need for two configuration file
  - 1st configuration file: Use it to run the main configuration file

```
[General]
# Name of the combination (mandatory)
name = Tutorial

# Coefficients of the theory, other than nuisance parameters (optional)
coeffs = T0 S1 S02 M1 M7 T1 T2 M0

# List of measurement configurations to be included, separated by space (mandatory)
measurement_configs = Measurement_Tutorial.cfg

# Default parameter range, if not specified otherwise below
default_range = -1000 1000
```

  - 2nd configuration file: this is the main configuration file
    - Add the central measurement values, most common in HEPdata format

```
# Central measurement values, in hepdata yaml format or simply as a list of numbers separated by space (mandatory)
measured = hepdata/Sample_YAML/data11.yaml
```

    - Add the correlation of the measurement

```
# Correlation of measurement, in hepdata yaml format or as list of numbers with rows separated by comma (optional)
# Can be used in combination with 'correlated uncertainty' instead of 'covariance'
correlation = hepdata/Sample_YAML/data12.yaml

# Measurement uncertainties that will be combined with correlation to covariance matrix (optional)
# In hepdata yaml format or list of numbers
# If only one of the errors should be used write as filename:error_label, otherwise errors will be summed
# Should not contain the 'Measurement Uncertainties' given below
correlated_uncertainty = hepdata/Sample_YAML/data11.yaml:all
```

The combination of correlation and correlated uncertainty serves the purpose of the covariance matrix

    - Add the SM prediction

```
sm = histos/WZ_histos_140/SM.root:/ATLAS_WZ_VBS_2021/d06-x01-y01
```

    - Add the theory uncertainties

```
{sm} pdf = {abs lin} 0.0041727225 0.004699368 0.004685235 0.0038039975
{sm} scale = {abs lin} -0.038460150,+0.027204925 -0.04327890,+0.02661370 -0.04110267,+0.02281349 -0.028669375,+0.019575000
```

4^{th} step: Fitting procedure (2)

- 2^{nd} configuration file: this is the main configuration file
  - Add the experimental uncertainties of our measurement in a different way

```
stat =  {uncorr} hepdata/Sample_YAML/data11.yaml:stat
uncor = {uncorr} hepdata/Sample_YAML/data11.yaml:sys,uncor
unfold = {corr} hepdata/Sample_YAML/data11.yaml:sys,unfold
electrons = {corr} hepdata/Sample_YAML/data11.yaml:sys,Electrons
muons = {corr} hepdata/Sample_YAML/data11.yaml:sys,Muons
jets = {corr} hepdata/Sample_YAML/data11.yaml:sys,Jets
Red_background = {corr} hepdata/Sample_YAML/data11.yaml:sys,Red. Background
Irred_background = {corr} hepdata/Sample_YAML/data11.yaml:sys,Irred. Background
pileup = {corr} hepdata/Sample_YAML/data11.yaml:sys,Pileup
lumi = {corr} hepdata/Sample_YAML/data11.yaml:sys,lumi
```

!!! We use either the combination of correlation and correlated uncertainty or this method to add the experimental uncertainties!!!

  - Add the EFT templates for the interference, the quadratic and the cross terms

```
M0 = histos/WZ_histos_140/M0_inter.root:/ATLAS_WZ_VBS_2021/d06-x01-y01
M1 = histos/WZ_histos_140/M1_inter.root:/ATLAS_WZ_VBS_2021/d06-x01-y01
S1 = histos/WZ_histos_140/S1_inter.root:/ATLAS_WZ_VBS_2021/d06-x01-y01
T0 = histos/WZ_histos_140/T0_inter.root:/ATLAS_WZ_VBS_2021/d06-x01-y01
T1 = histos/WZ_histos_140/T1_inter.root:/ATLAS_WZ_VBS_2021/d06-x01-y01
T2 = histos/WZ_histos_140/T2_inter.root:/ATLAS_WZ_VBS_2021/d06-x01-y01
```

→ Interference terms

```
M0 M0 = histos/WZ_histos_140/M0_quad.root:/ATLAS_WZ_VBS_2021/d06-x01-y01
M1 M1 = histos/WZ_histos_140/M1_quad.root:/ATLAS_WZ_VBS_2021/d06-x01-y01
S1 S1 = histos/WZ_histos_140/S1_quad.root:/ATLAS_WZ_VBS_2021/d06-x01-y01
T0 T0 = histos/WZ_histos_140/T0_quad.root:/ATLAS_WZ_VBS_2021/d06-x01-y01
T1 T1 = histos/WZ_histos_140/T1_quad.root:/ATLAS_WZ_VBS_2021/d06-x01-y01
T2 T2 = histos/WZ_histos_140/T2_quad.root:/ATLAS_WZ_VBS_2021/d06-x01-y01
```

→ Quadratic terms

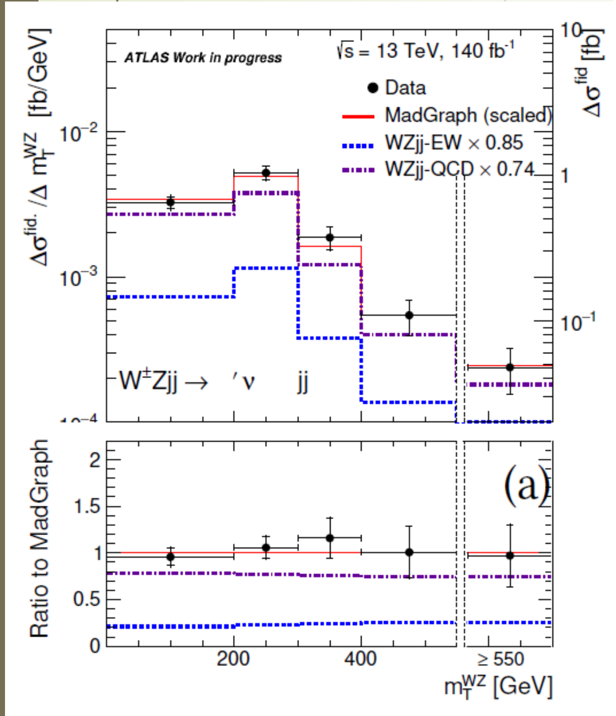
```
M0 M1 = histos/WZ_histos_140/M0_M1_cross.root:/ATLAS_WZ_VBS_2021/d06-x01-y01
T0 T1 = histos/WZ_histos_140/T0_T1_cross.root:/ATLAS_WZ_VBS_2021/d06-x01-y01
T0 T2 = histos/WZ_histos_140/T0_T2_cross.root:/ATLAS_WZ_VBS_2021/d06-x01-y01
T1 T2 = histos/WZ_histos_140/T1_T2_cross.root:/ATLAS_WZ_VBS_2021/d06-x01-y01
```

→ Cross terms

4^{th} step: Procedure for the extraction of truth level limits for dimension-8 operators

- Differential cross section distributions used for the extraction of the truth level limits
  - Used for combination with other channels
  - Easier to be used by theoreticians
- Limits are extracted using seven different kinematical variables trying one kinematical variable at a time in order to define the most sensitive to dimension-8 operators
- The binning used for each kinematical variable is the one used in the respective differential distribution which is guided by the minimum required statistics for each bin
- Extraction of expected and observed 95% CL lower and upper limits on the aQGC for two different cases:
  - 1) using one aQGC operator at a time setting all the other anomalous couplings to the SM value and
  - 2) using simultaneously two aQGC operators of the same family and setting all the other anomalous couplings to SM value

4th step: WZjj VBS production: Results for truth level limits



Input measurements: unfolded distributions

Work in progress

	Variable	Expected (TeV^{-4})	Observed (TeV^{-4})
f_{M0}/Λ^4	M_T^{WZ}	[-12.5, 12.4]	[-12.6, 12.5]
	$\sum P_T^{Lep}$	[-14.1, 14.0]	[-13.0, 12.9]
	$\Delta\phi_{WZ}$	[-25.2, 24.8]	[-20.1, 19.9]
	m_{jj}	[-26.0, 24.9]	[-25.3, 24.2]
	$\Delta\phi_{jj}$	[-29.7, 29.8]	[-38.1, 37.6]
	Δy_{jj}	[-30.6, 29.5]	[-34.6, 33.5]
	N_{jets}	[-32.2, 31.1]	[-22.8, 21.7]
f_{M1}/Λ^4	M_T^{WZ}	[-19.1, 19.5]	[-19.2, 19.5]
	$\sum P_T^{Lep}$	[-21.9, 22.2]	[-20.1, 20.4]
	$\Delta\phi_{WZ}$	[-37.7, 38.2]	[-30.0, 30.4]
	m_{jj}	[-39.0, 40.2]	[-37.9, 39.1]
	$\Delta\phi_{jj}$	[-46.8, 47.4]	[-59.5, 60.4]
	Δy_{jj}	[-45.3, 46.6]	[-47.8, 49.1]
	N_{jets}	[-48.5, 49.8]	[-33.7, 35.0]
f_{M7}/Λ^4	M_T^{WZ}	[-24.0, 24.0]	[-24.1, 24.1]
	$\sum P_T^{Lep}$	[-27.2, 27.2]	[-25.0, 25.0]
	$\Delta\phi_{WZ}$	[-49.2, 49.2]	[-39.9, 39.9]
	m_{jj}	[-51.5, 51.5]	[-51.3, 51.3]
	$\Delta\phi_{jj}$	[-55.0, 55.0]	[-71.5, 71.5]
	Δy_{jj}	[-65.7, 65.7]	[-72.3, 72.3]
	N_{jets}	[-63.9, 63.9]	[-45.8, 45.8]

Expected and observed lower and upper 95% CL limits on the Wilson coefficients

Work in progress

	Variable	Expected (TeV^{-4})	Observed (TeV^{-4})
f_{S02}/Λ^4	M_T^{WZ}	[-23.7, 24.2]	[-23.8, 24.4]
	$\sum P_T^{Lep}$	[-28.0, 28.3]	[-25.8, 26.1]
	$\Delta\phi_{WZ}$	[-42.4, 43.3]	[-32.5, 33.4]
	m_{jj}	[-40.9, 41.9]	[-37.9, 38.8]
	$\Delta\phi_{jj}$	[-57.7, 58.2]	[-73.7, 74.7]
	Δy_{jj}	[-44.1, 45.4]	[-53.5, 54.8]
	N_{jets}	[-53.5, 55.0]	[-35.8, 37.3]
f_{S1}/Λ^4	M_T^{WZ}	[-68.2, 68.8]	[-68.6, 69.3]
	$\sum P_T^{Lep}$	[-80.7, 81.0]	[-74.6, 74.9]
	$\Delta\phi_{WZ}$	[-121.7, 123.0]	[-93.8, 95.0]
	m_{jj}	[-115.3, 117.3]	[-106.1, 107.9]
	$\Delta\phi_{jj}$	[-162.5, 161.4]	[-208.2, 209.3]
	Δy_{jj}	[-125.5, 127.9]	[-152.0, 154.6]
	N_{jets}	[-151.2, 154.6]	[-101.4, 104.8]

The transverse mass of the diboson system M_T^{WZ} gives the best expected limits for all the operators

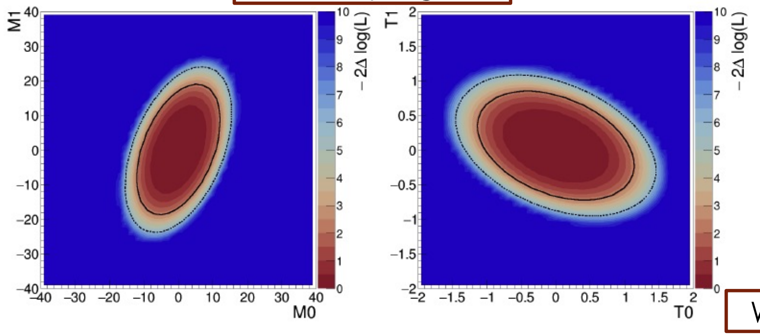
Work in progress

	Variable	Expected (TeV^{-4})	Observed (TeV^{-4})
f_{T0}/Λ^4	M_T^{WZ}	[-1.17, 1.24]	[-1.18, 1.25]
	$\sum P_T^{Lep}$	[-1.33, 1.37]	[-1.22, 1.25]
	$\Delta\phi_{WZ}$	[-2.46, 2.58]	[-1.98, 2.10]
	m_{jj}	[-2.63, 2.72]	[-2.66, 2.76]
	$\Delta\phi_{jj}$	[-2.92, 2.97]	[-3.71, 3.77]
	Δy_{jj}	[-3.39, 3.43]	[-3.49, 3.51]
	N_{jets}	[-3.28, 3.38]	[-2.43, 2.55]
f_{T1}/Λ^4	M_T^{WZ}	[-0.77, 0.90]	[-0.78, 0.90]
	$\sum P_T^{Lep}$	[-0.89, 1.00]	[-0.81, 0.91]
	$\Delta\phi_{WZ}$	[-1.56, 1.71]	[-1.22, 1.37]
	m_{jj}	[-1.84, 2.01]	[-1.88, 2.07]
	$\Delta\phi_{jj}$	[-2.06, 2.18]	[-2.59, 2.73]
	Δy_{jj}	[-2.35, 2.50]	[-2.41, 2.55]
	N_{jets}	[-2.24, 2.41]	[-1.62, 1.82]
f_{T2}/Λ^4	M_T^{WZ}	[-2.15, 2.69]	[-2.16, 2.69]
	$\sum P_T^{Lep}$	[-2.52, 2.97]	[-2.30, 2.73]
	$\Delta\phi_{WZ}$	[-4.47, 5.18]	[-3.51, 4.18]
	m_{jj}	[-5.17, 5.89]	[-5.27, 6.04]
	$\Delta\phi_{jj}$	[-5.86, 6.37]	[-7.41, 8.00]
	Δy_{jj}	[-6.73, 7.30]	[-6.93, 7.45]
	N_{jets}	[-6.36, 7.11]	[-4.55, 5.41]

4^{th} step: WZjj VBS production: 2-D truth level limits

- Limits on aQGC Wilson coefficients are also derived fitting two parameters simultaneously
- The M_T^{WZ} gives the best expected limits

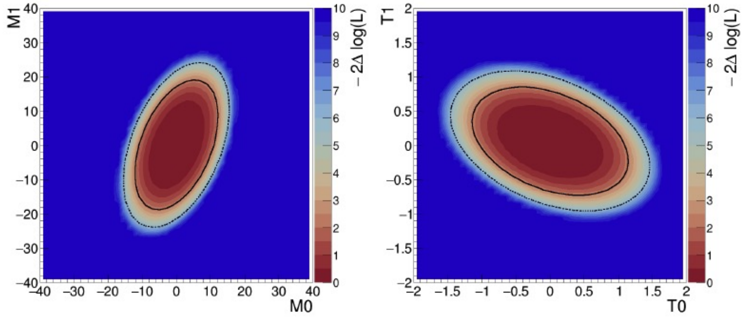
Work in progress



Work in progress

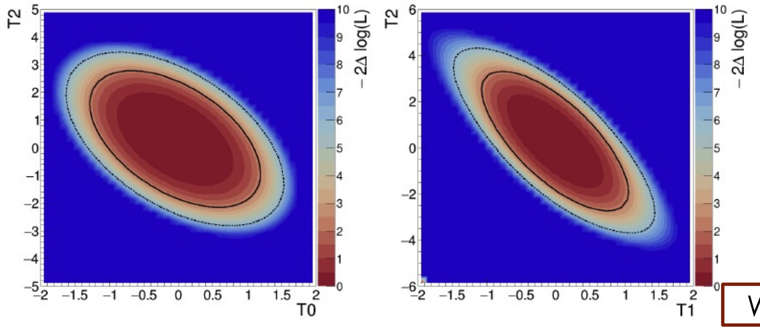
	Variable	Expected (TeV^{-4})	Observed (TeV^{-4})
f_{M0}/Λ^4, f_{M1}/Λ^4	M_T^{WZ}	[-15.5, 15.5], [-23.8, 24.2]	[-15.6, 15.6], [-23.9, 24.2]
	$\sum P_T^{Lep}$	[-17.6, 17.6], [-27.5, 27.8]	[-16.4, 16.4], [-25.6, 25.8]
	$\Delta\phi_{WZ}$	[-30.6, 30.3], [-46.0, 46.3]	[-25.0, 24.9], [-37.5, 37.8]
	m_{jj}	[-29.0, 27.9], [-43.6, 44.8]	[-28.3, 27.2], [-42.5, 43.7]
	$\Delta\phi_{jj}$	[-37.0, 37.3], [-58.5, 59.2]	[-48.4, 47.9], [-60.1, 61.2]
	Δy_{jj}	[-36.7, 35.9], [-55.0, 55.8]	[-40.9, 39.9], [-61.6, 62.5]
	N_{jets}	[-39.5, 38.6], [-60.3, 61.0]	[-40.9, 39.9], [-44.3, 45.0]

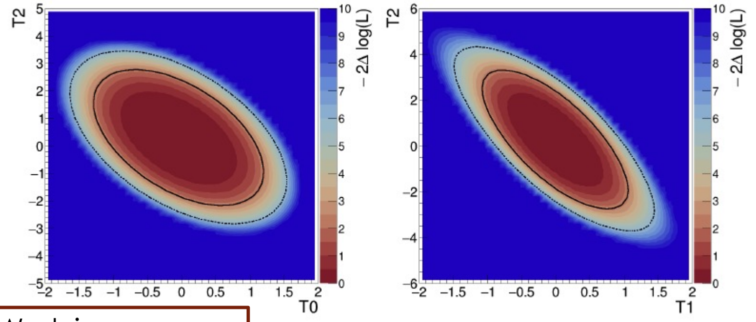
Work in progress



Work in progress

	Variable	Expected (TeV^{-4})	Observed (TeV^{-4})
f_{T0}/Λ^4, f_{T1}/Λ^4	M_T^{WZ}	[-1.45, 1.45], [-0.95, 1.09]	[-1.46, 1.46], [-0.96, 1.09]
	$\sum P_T^{Lep}$	[-1.63, 1.61], [-1.08, 1.19]	[-1.51, 1.49], [-1.00, 1.10]
	$\Delta\phi_{WZ}$	[-3.04, 3.07], [-1.91, 2.06]	[-2.55, 2.58], [-1.57, 1.71]
	m_{jj}	[-3.17, 3.18], [-2.20, 2.37]	[-3.20, 3.21], [-2.24, 2.43]
	$\Delta\phi_{jj}$	[-3.49, 3.48], [-2.45, 2.57]	[-4.30, 4.30], [-3.00, 3.16]
	Δy_{jj}	[-4.07, 4.05], [-2.81, 2.96]	[-4.17, 4.12], [-2.87, 3.01]
	N_{jets}	[-3.98, 3.99], [-2.69, 2.86]	[-3.13, 3.15], [-2.08, 2.26]





Work in progress

	Variable	Expected (TeV^{-4})	Observed (TeV^{-4})
f_{T0}/Λ^4, f_{T2}/Λ^4	M_T^{WZ}	[-1.63, 1.53], [-2.82, 3.46]	[-1.64, 1.54], [-2.84, 3.46]
	$\sum P_T^{Lep}$	[-1.82, 1.72], [-3.30, 3.86]	[-1.69, 1.59], [-3.05, 3.59]
	$\Delta\phi_{WZ}$	[-3.28, 3.20, [-5.78, 6.56]	[-2.73, 2.66], [-4.70, 5.44]
	m_{jj}	[-3.59, 3.45], [-6.83, 7.69]	[-3.65, 3.51], [-6.98, 7.91]
	$\Delta\phi_{jj}$	[-3.88, 3.77], [-7.66, 8.29]	[-4.75, 4.64], [-9.36, 10.08]
	Δy_{jj}	[-4.53, 4.40], [-8.78, 9.51]	[-4.63, 4.49], [-9.00, 9.69]
	N_{jets}	[-4.39, 4.26], [-8.29, 9.18]	[-3.45, 3.33], [-6.29, 7.27]

Work in progress

	Variable	Expected (TeV^{-4})	Observed (TeV^{-4})
f_{T1}/Λ^4, f_{T2}/Λ^4	M_T^{WZ}	[-1.48, 1.44], [-3.69, 4.32]	[-1.49, 1.44], [-3.72, 4.33]
	$\sum P_T^{Lep}$	[-1.50, 1.50], [-4.08, 4.54]	[-1.39, 1.38], [-3.77, 4.22]
	$\Delta\phi_{WZ}$	[-2.62, 2.59], [-7.29, 8.06]	[-2.17, 2.14], [-6.00, 6.74]
	m_{jj}	[-2.98, 2.98], [-8.22, 8.93]	[-3.08, 3.08], [-8.42, 9.19]
	$\Delta\phi_{jj}$	[-3.29, 3.26]], [-9.10, 9.68]	[-4.21, 4.16], [-11.48, 12.74]
	Δy_{jj}	[-3.76, 3.77], [-10.67, 11.43]	[-3.83, 3.84], [-11.01, 11.72]
	N_{jets}	[-3.62, 3.61, [-10.08, 10.99]	[-2.82, 2.81], [-11.01, 11.72]

The limits for each operators are worse when extracted in pairs than when extracted one by one

4th step: Useful commands

- Command to run the EFTFun tool:
  - In the main directory of EFTFun:
    - source setup.sh
    - ./bin/eftfun.py -i configs/ecole_de_gif/Tutorial.cfg -m scan -p T0 -c all -o example (for observed limits)
    - ./bin/eftfun.py -i configs/ecole_de_gif/Tutorial.cfg -m scan -p T0 -c all --asimov-o example (for expected limits)
    - Useful extra commands
      - Add a range in the corresponding operator: -r -2:2
      - Disable all the uncertainties except the statistical uncertainty: -d all
    - For two operators simultaneously:
      - ./bin/eftfun.py -i configs/ ecole_de_gif/Tutorial.cfg -m scan -p M0,M1 -c all -r -40:40,-40:40 --asimov –o example
      - ./bin/eftfun.py -i configs/ ecole_de_gif/Tutorial.cfg -m scan -p M0 -c T0,T1,T2,S02,S1 -r -40:40 --asimov -o example --conts2d
      - ./bin/eftfun.py -i configs/ ecole_de_gif/Tutorial.cfg -m scan -p M1 -c T0,T1,T2,S02,S1 -r -40:40 --asimov -o example --conts2d

Exercises from 4th step

- Go to the eft-fun folder in gif_school
- 1st task: Find the operator that give the best expected and observed limits
  - 1st configuration file (Tutorial.cfg): Choose an operator to test
    - Available dimension-8 operators: T0, T1, T2, M0, M1, S1 and S02
  - 2nd configuration file (Measurement_Tutorial.cfg): Add all the needed information in order to extract the limits
    - Add the measurement
    - Add the covariance matrix
    - Add the sm prediction
    - Add a relative flat uncertainty of 2% to all contributions
    - Add the interference term
    - Add the quadratic term

In this step, we will use only the MtWZ
See in Slide

Don't forget the instructions in Slide 30!!!!!

1. Which is the operator that gives the "stricter" limits?
2. What do we mean with the term "stricter"? What means a limit close to zero?
3. What is the effect of a bigger flat uncertainty on the limits?

Exercises from 4th step (2)

- 2nd task: Find the kinematical variable that gives the ”stricter” limits for every operator
  - 2nd configuration file (Measurement_Tutorial.cfg): Add all the needed information in order to extract the limits with different kinematical variable
    - Add the measurement
    - Add the covariance matrix
    - Add the sm prediction
    - Add a relative flat uncertainty of 2% to all contributions
    - Add the interference term
    - Add the quadratic term

1. Which variable gives the stricter limits for every operator?
2. What does this mean?
3. Do we take the “stricter” limits for every operator using the same variable?

Don't forget the instructions in Slide 30!!!!!

- 3rd task: extract the limits using two operators simultaneously
  - 2nd configuration file (Measurement_Tutorial.cfg): Add all the needed information in order to extract the limits with different kinematical variable
    - Add also a cross term

1. Using two operators simultaneously, are the limits “stricter”?
2. Why?

Exercises from 4th step (3)

HEPData

- m_T^{WZ}
  - Data: data1.yaml
  - Covariance matrix: data2.yaml
- $\sum pT_{3l}$
  - Data: data3.yaml
  - Covariance matrix: data4.yaml
- $\Delta\varphi(Z,W)$
  - Data: data5.yaml
  - Covariance matrix: data6.yaml
- Njets
  - Data: data7.yaml
  - Covariance matrix: data8.yaml
- m_{jj}
  - Data: data9.yaml
  - Covariance matrix: data10.yaml
- $|y_{j1} - y_{j2}|$
  - Data: data11.yaml
  - Covariance matrix: data12.yaml
- $\Delta\varphi(j1,j2)$
  - Data: data13.yaml
  - Covariance matrix: data14.yaml

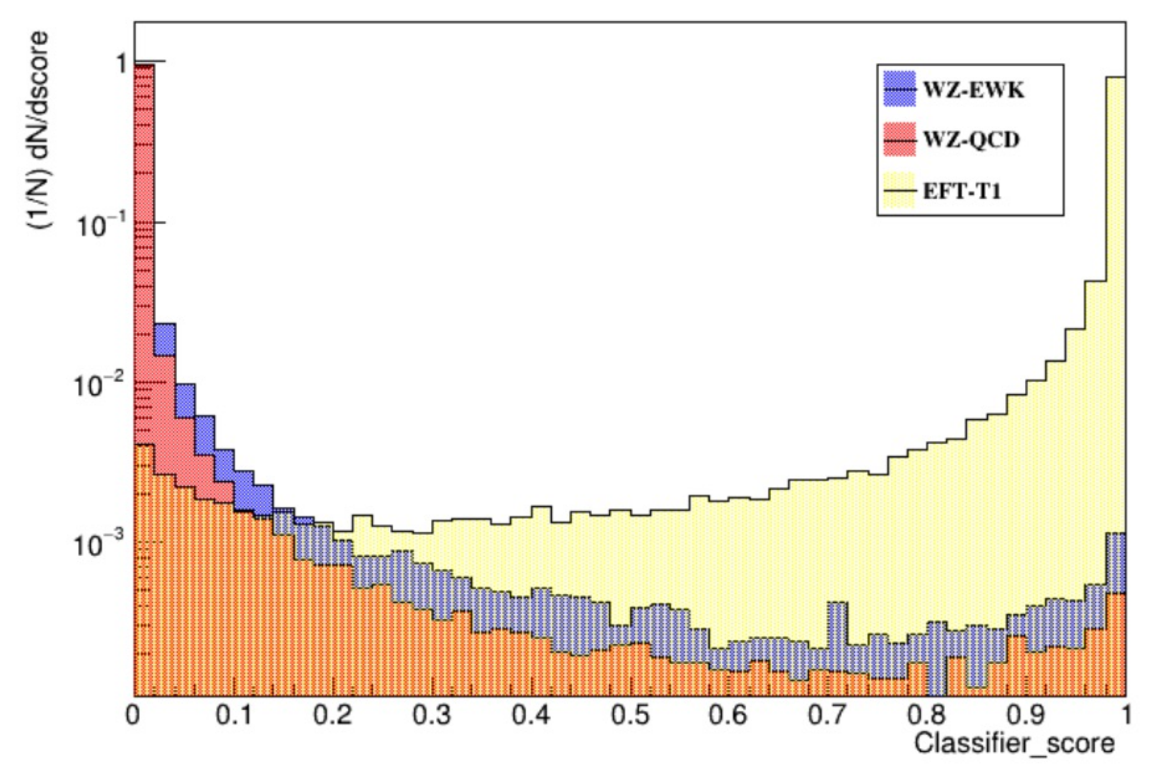
Root files

- m_T^{WZ}
  - d02-x01-y01
- $\sum pT_{3l}$
  - d03-x01-y01
- $\Delta\varphi(Z,W)$
  - d04-x01-y01
- Njets
  - d01-x01-y01
- m_{jj}
  - d05-x01-y01
- $|y_{j1} - y_{j2}|$
  - d06-x01-y01
- $\Delta\varphi(j1,j2)$
  - d07-x01-y01

Future plans

- Run2 WZ VBS analysis
  - Combination of aQGC EFT results combination among many diboson analyses
- Run3 WZ diboson and VBS analyses
  - perform a complete study of both dimension-6 and dimension-8 operators using the new SmeftFR v3
  - machine learning approach to the EFT re-interpretation of the WZ diboson and VBS productions → results appear very promising (next slide)
  - find a way to incorporate the NLO QCD and EWK effect
- HL-LHC
  - WZ VBS polarization analysis

Machine learning approach to the EFT re-interpretation of the WZ diboson and VBS productions



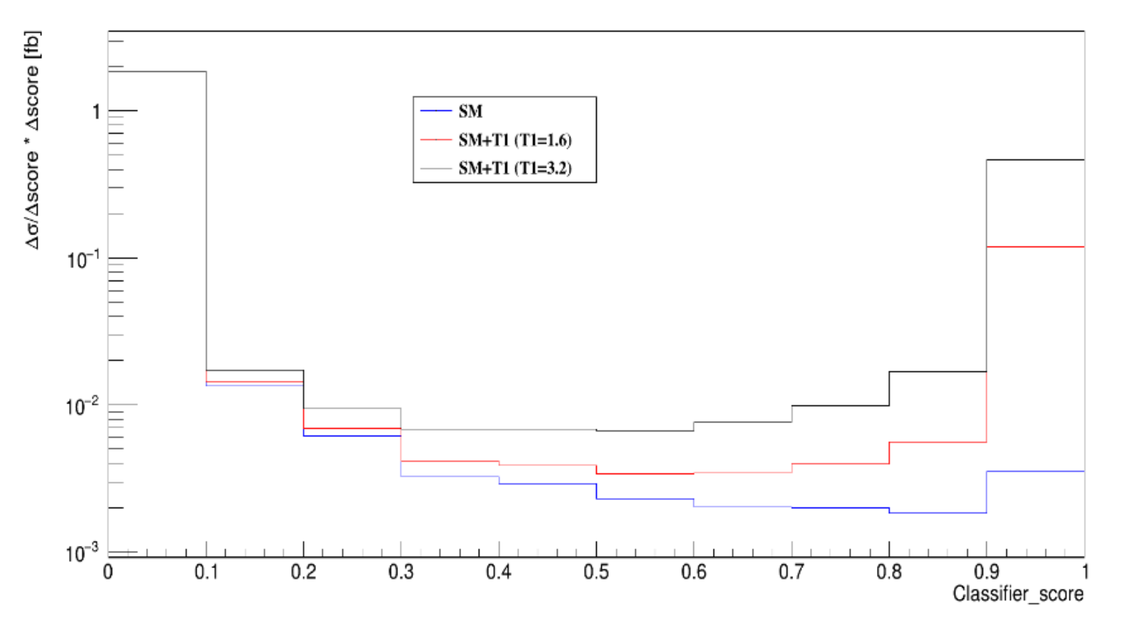


Table 2: Expected limits at $36 fb^{-1}$

Wilson coeff.	M_T^{WZ}	$\sum p_{Tl}$	$\Delta\phi(WZ)$	Δy_{jj}	ML Model
f_{S1}	$[-167.4, 167.4]$	$[-132.3, 132.3]$	$[-182.6, 182.6]$	$[-184.3, 184.3]$	$[-54.6, 54.6]$
f_{T0}	$[-2.97, 2.97]$	$[-2.21, 2.21]$	$[-3.65, 3.65]$	$[-3.97, 3.97]$	$[-1.00, 1.00]$
f_{T1}	$[-2.04, 2.04]$	$[-1.53, 1.53]$	$[-2.39, 2.39]$	$[-2.77, 2.77]$	$[-0.47, 0.47]$

Extraction of reconstructed level limits for dimension-8 operators

Motivation

- More difficult analysis than the truth level analysus BUT
  - Choose a better binning in order to have stricter limits
  - Two kinematical variables simultaneously
  - Multivariate variables like BDT scores and NN scores

WZjj VBS production: Procedure for the extraction of reconstructed level limits for dimension-8 operators

- To maximally profit from the sensitive kinematical variables two variables relatively uncorrelated are selected. This template is created by binning two kinematical variables simultaneously.
- Also a comparison between the limits derived using the two-variable fit template and the limits derived using only one kinematical variable is done
- Extraction of expected and observed 95% CL lower and upper limits on the aQGC for two different cases:
  - 1) using one aQGC operator at a time setting all the other anomalous couplings to the SM value and
  - 2) using simultaneously two aQGC operators of the same family and setting all the other anomalous couplings to SM value

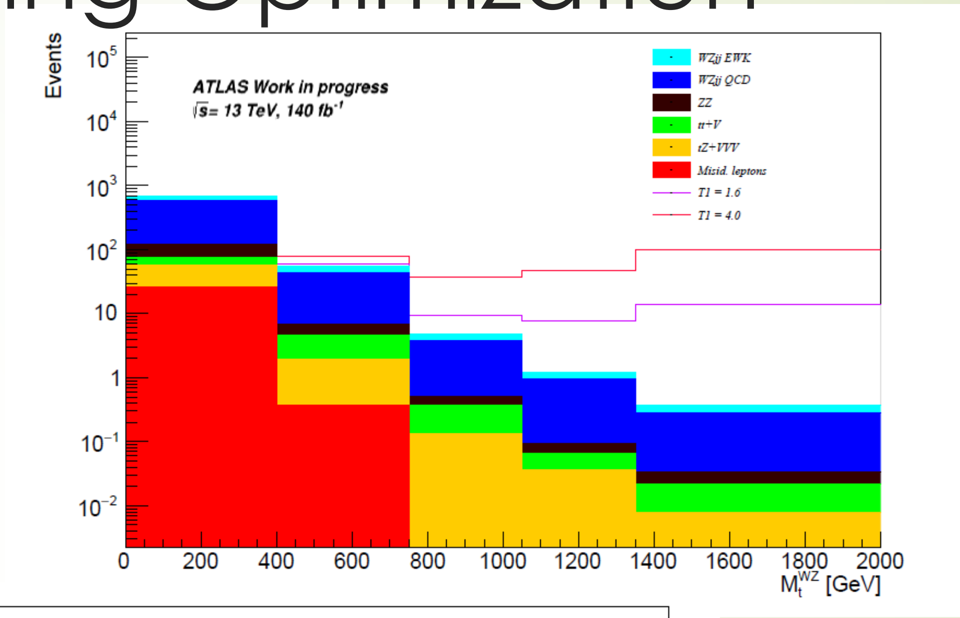
WZjj VBS production: Binning Optimization

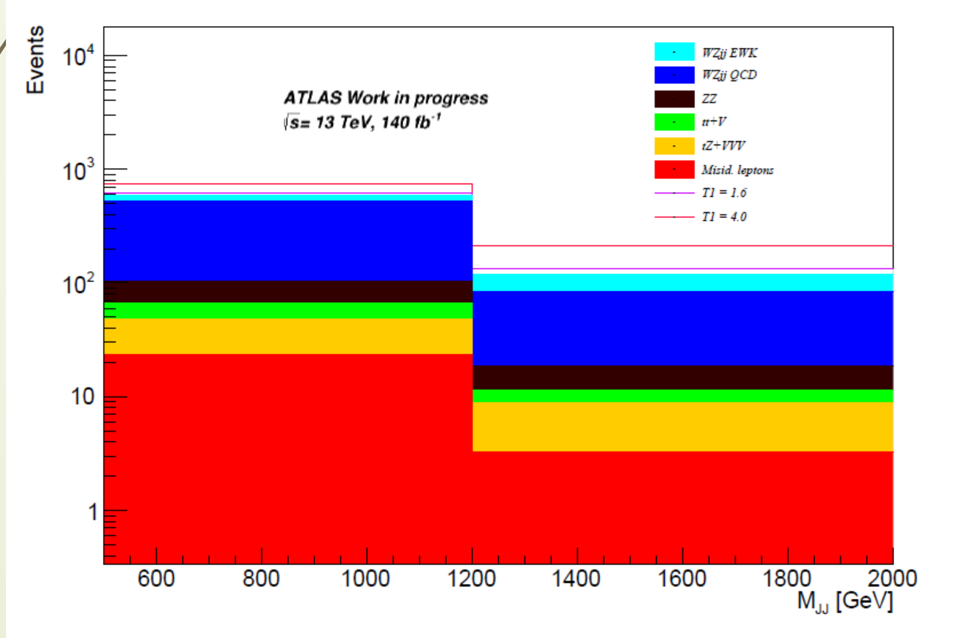
- After performing a binning optimization, the results for the optimized binnings are:

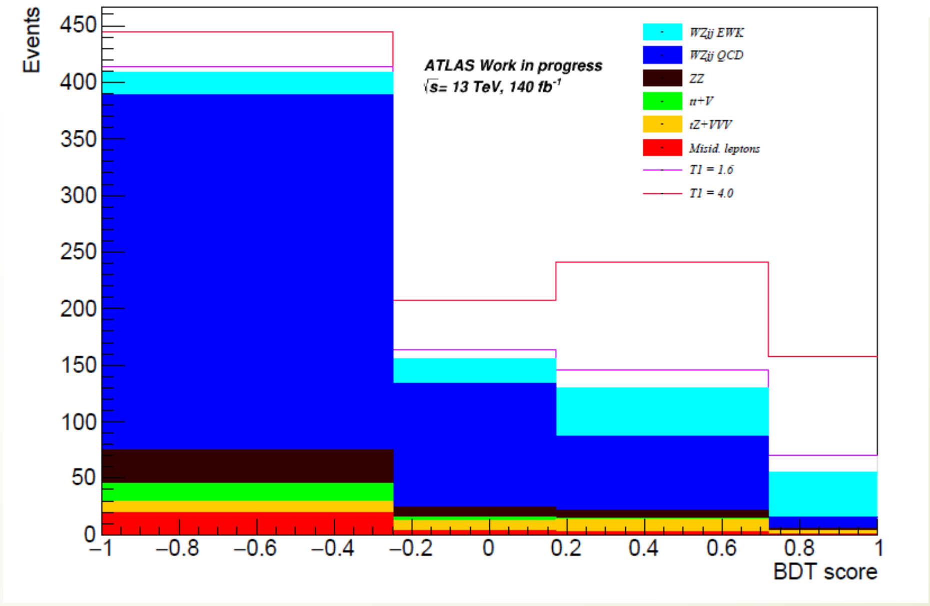
$M_T^{WZ}\ (GeV)$	[0, 450, 700, 1050, 1550, ∞]
$M_{jj}\ (GeV)$	[500, 1050, ∞]
$BDT\ Score$	[-1.0, -0.25, 0.17, 0.72, 1.0]

- For the M_T^{WZ} and the M_{jj} the CMS binning will be used for comparison reasons, as the differences in the 95 % CL limits when using either the optimized binning or this binning are negligible.

$M_T^{WZ}\ (GeV)$	[0, 400, 750, 1050, 1350, ∞]
$M_{jj}\ (GeV)$	[500, 1200, ∞]







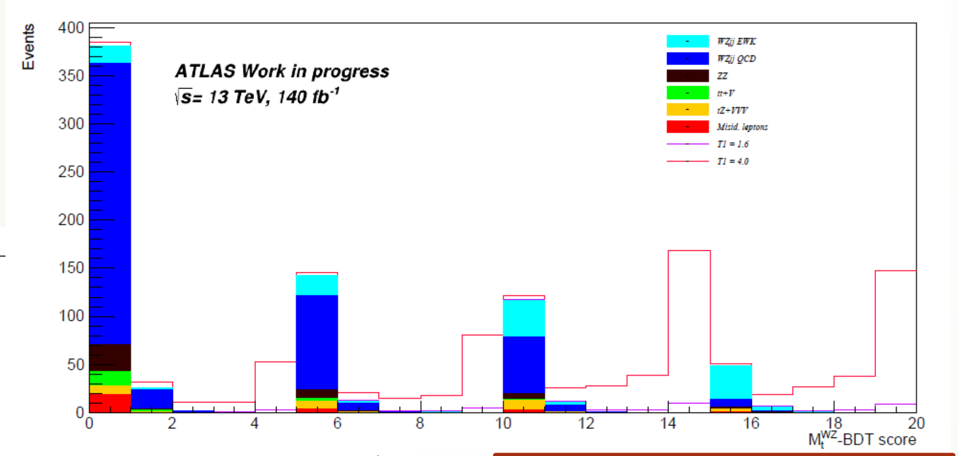
WZjj VBS production: Results for reconstructed level limits

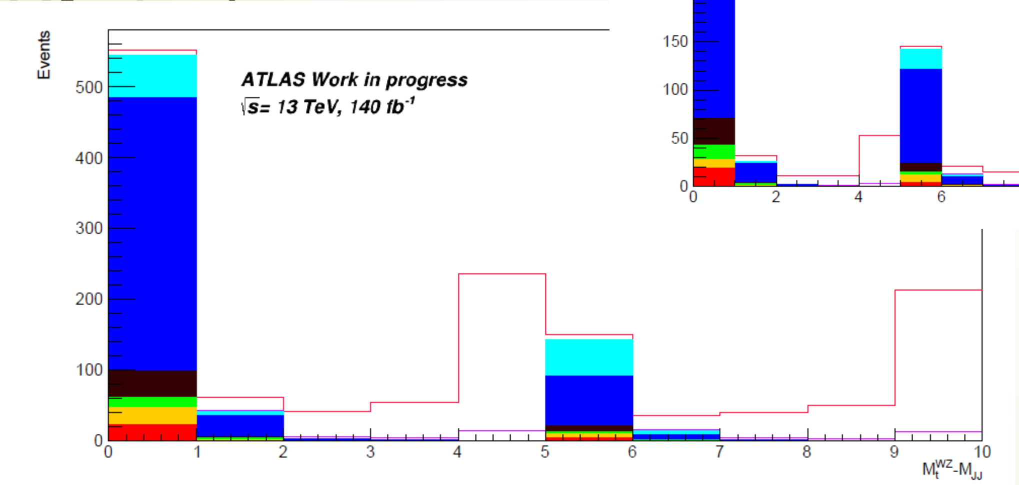
Work in progress

- Extraction of the limits using
  - one dimensional distribution (M_T^{WZ}) in the fit
  - two-dimensional distributions (M_T^{WZ}- M_{jj} and M_T^{WZ}- BDT score) in the fit
    - Create two-dimensional templates by binning two kinematic variables simultaneously
    - Create one dimension by 'unrolling' the bin contents

Expected and observed lower and upper 95% CL limits on the Wilson coefficients

	Variable	Expected (TeV^{-4})	Observed (TeV^{-4})
f_{S02}/Λ^4	M_T^{WZ}	[-16.4, 16.4]	[-10.4, 10.4]
	$M_T^{WZ} vs M_{jj}$	[-15.4, 15.4]	[-10.5, 10.5]
	$M_T^{WZ} vs BDT score$	[-14.2, 14.2]	[-10.4, 10.3]
f_{S1}/Λ^4	M_T^{WZ}	[-48.7, 48.4]	[-30.6, 30.2]
	$M_T^{WZ} vs M_{jj}$	[-45.6, 45.2]	[-30.9, 30.6]
	$M_T^{WZ} vs BDT score$	[-41.6, 41.2]	[-30.3, 29.9]
f_{T0}/Λ^4	M_T^{WZ}	[-0.82, 0.82]	[-0.57, 0.55]
	$M_T^{WZ} vs M_{jj}$	[-0.81, 0.81]	[-0.57, 0.56]
	$M_T^{WZ} vs BDT score$	[-0.80, 0.80]	[-0.57, 0.56]
f_{T1}/Λ^4	M_T^{WZ}	[-0.53, 0.51]	[-0.39, 0.35]
	$M_T^{WZ} vs M_{jj}$	[-0.53, 0.50]	[-0.39, 0.35]
	$M_T^{WZ} vs BDT score$	[-0.52, 0.49]	[-0.39, 0.35]
f_{T2}/Λ^4	M_T^{WZ}	[-1.59, 1.47]	[-1.19, 0.99]
	$M_T^{WZ} vs M_{jj}$	[-1.58, 1.46]	[-1.19, 1.00]
	$M_T^{WZ} vs BDT score$	[-1.57, 1.44]	[-1.19, 0.99]
f_{M0}/Λ^4	M_T^{WZ}	[-8.8, 8.7]	[-5.8, 5.6]
	$M_T^{WZ} vs M_{jj}$	[-8.6, 8.5]	[-5.8, 5.7]
	$M_T^{WZ} vs BDT score$	[-8.3, 8.3]	[-5.8, 5.6]
f_{M1}/Λ^4	M_T^{WZ}	[-13.0, 12.9]	[-8.6, 8.5]
	$M_T^{WZ} vs M_{jj}$	[-12.7, 12.6]	[-8.7, 8.5]
	$M_T^{WZ} vs BDT score$	[-12.3, 12.2]	[-8.6, 8.5]
f_{M7}/Λ^4	M_T^{WZ}	[-16.8, 16.8]	[-11.2, 11.2]
	$M_T^{WZ} vs M_{jj}$	[-16.6, 16.6]	[-11.2, 11.2]
	$M_T^{WZ} vs BDT score$	[-16.2, 16.2]	[-11.3, 11.3]

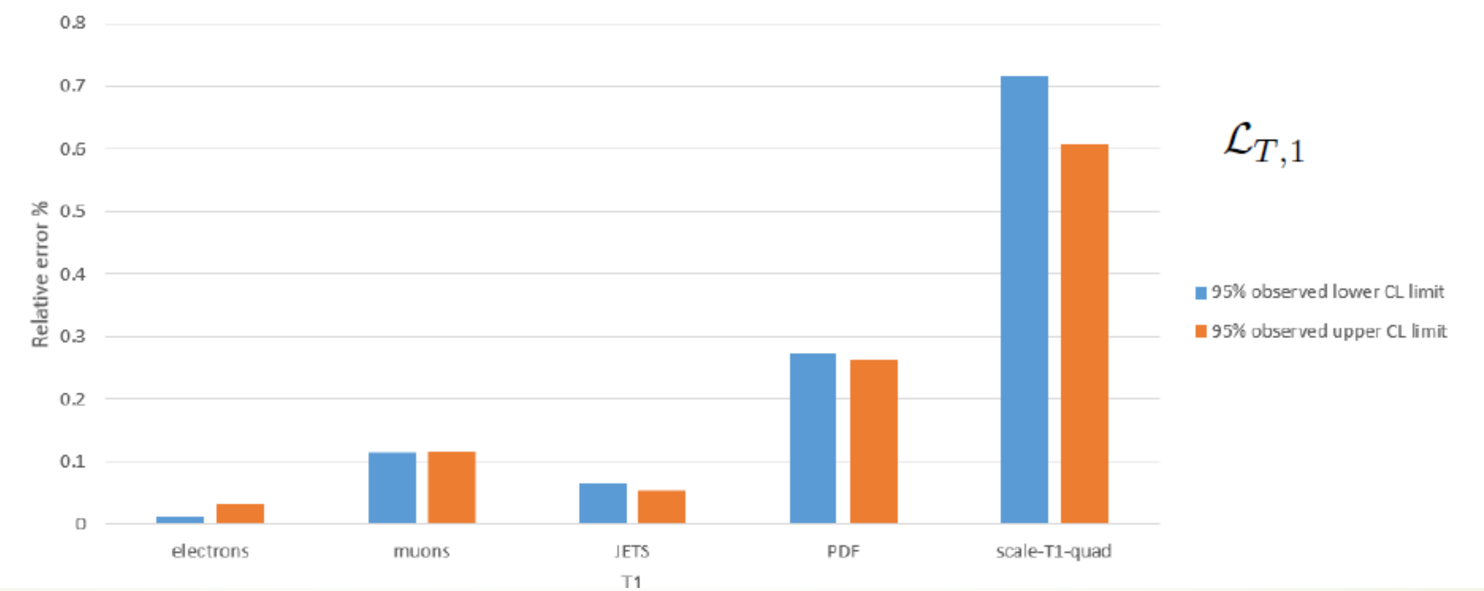




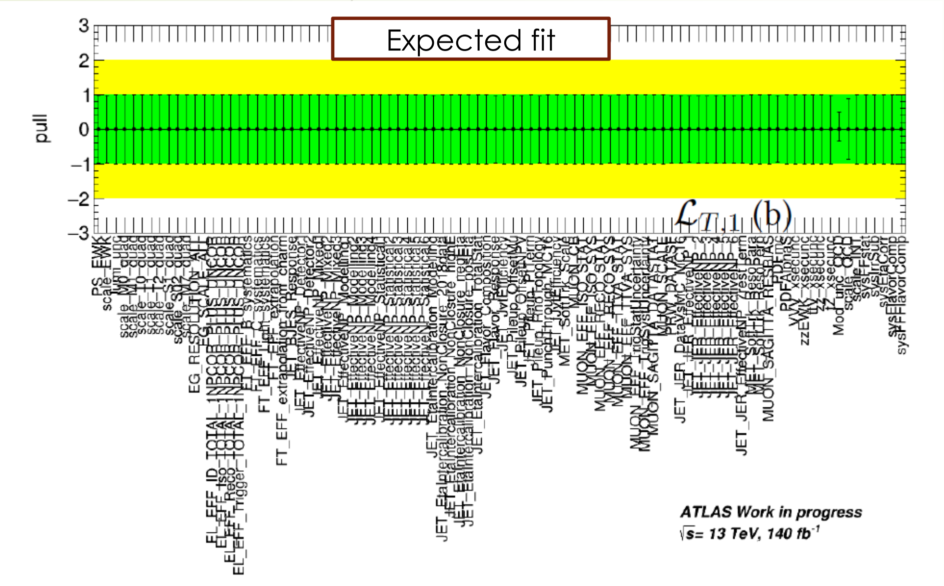
The two-dimensional template of the M_T^{WZ} with the BDT score gives the best expected limits

WZjj VBS production: Impact of the nuisance parameters on the 95% CL lower and upper expected limits

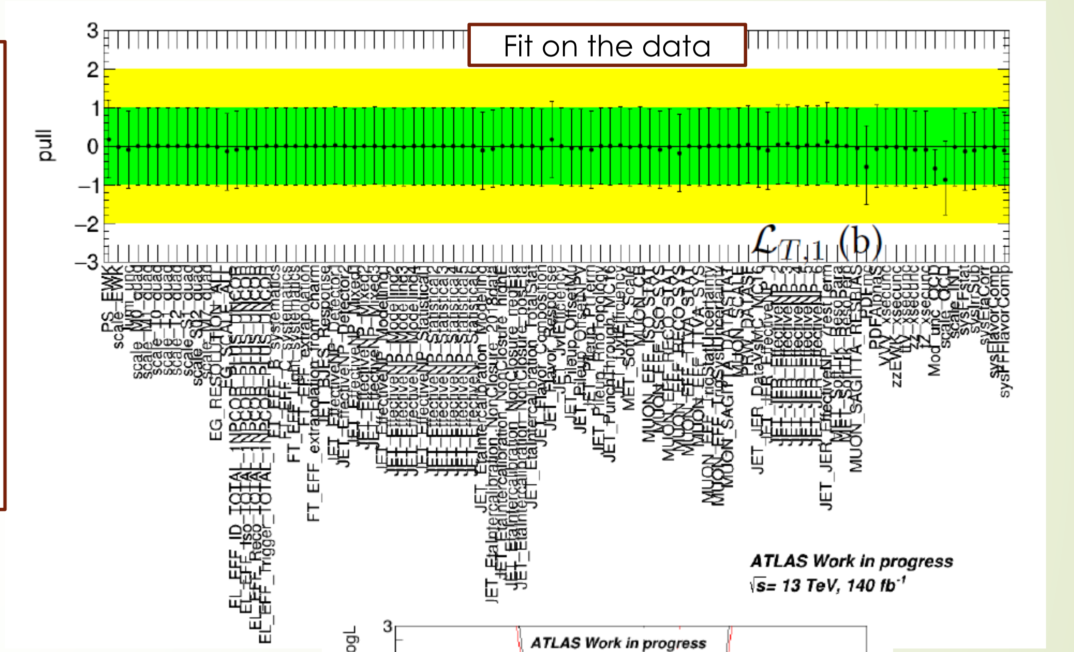
- Impact of the nuisance parameters on the 95% CL observed limits for the Wilson coefficients of the $L_{T,1}$ operator. Only the nuisance parameters that have a visible effect are shown

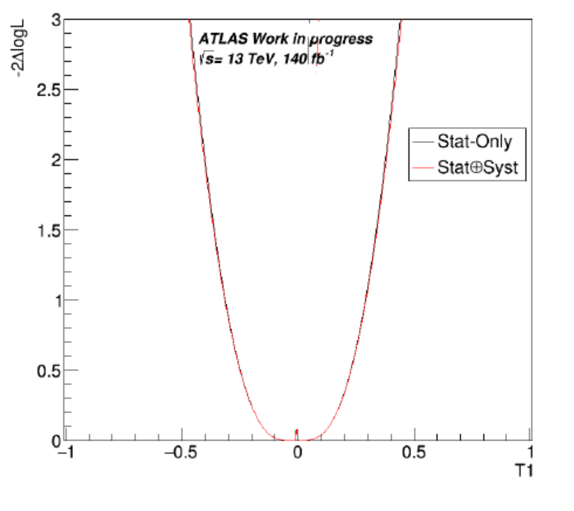


WZjj VBS production: Results for reconstructed level limits (2)

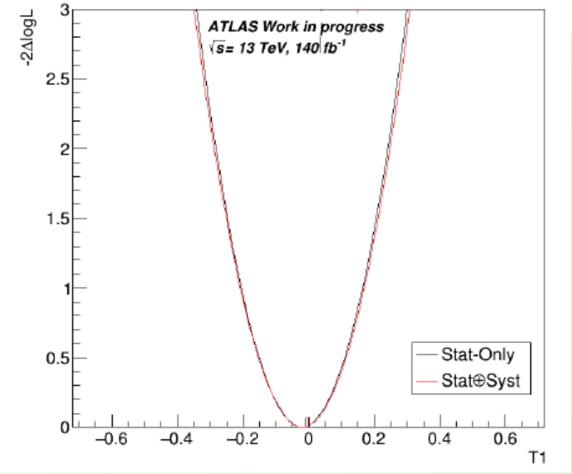


Example of the nuisance parameter pull distributions of the expected two-dimensional fit and of the fit on the data usingthe M_T^{WZ}- BDT score, for the $L_{T,1}$ operator





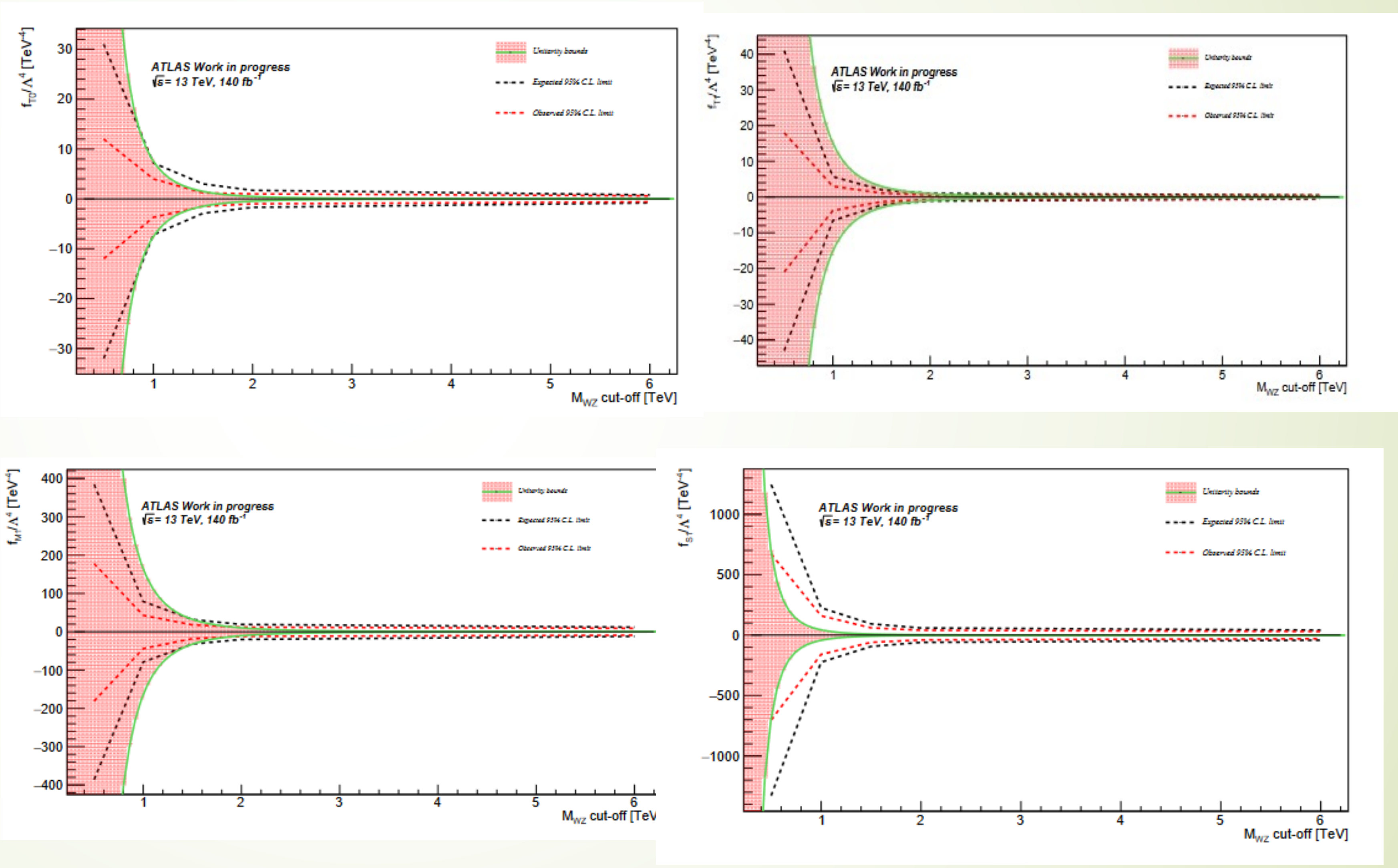
Comparison of the profile likelihood ratio curves on the Wilson coefficients of the, $L_{T,1}$ operator for the expected fit and for the fit to the data using the two dimensional distributions of the M_T^{WZ}- BDT score when only statistical uncertainties are included (black curve) are included and when experimental and theoretical uncertainty nuisance parameters (red curve) are considered



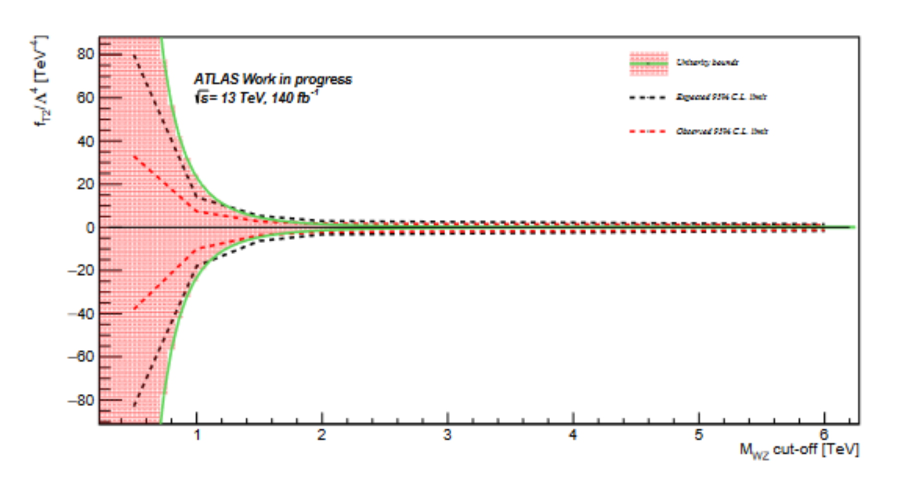
WZjj VBS production: Clipping method

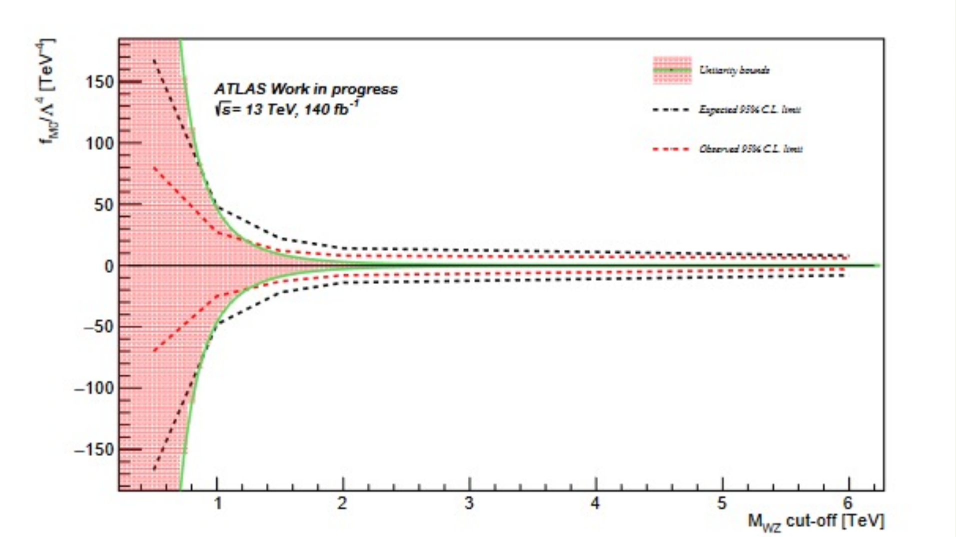
- EFT is not a complete model
  - the presence of non-zero aQGCs will violate tree-level unitarity at sufficiently high energy
- The unitarity bounds show the range of validity of the EFT approach, where a contribution of an aQGC operator will not lead to unitarity violation at high energies.
- More physical limits can be obtained using the clipping method by:
  - cutting the EFT integration at the unitarity limit and
  - keeping the SM predictions at invariant mass of parton level WZ, even above the unitarity limit

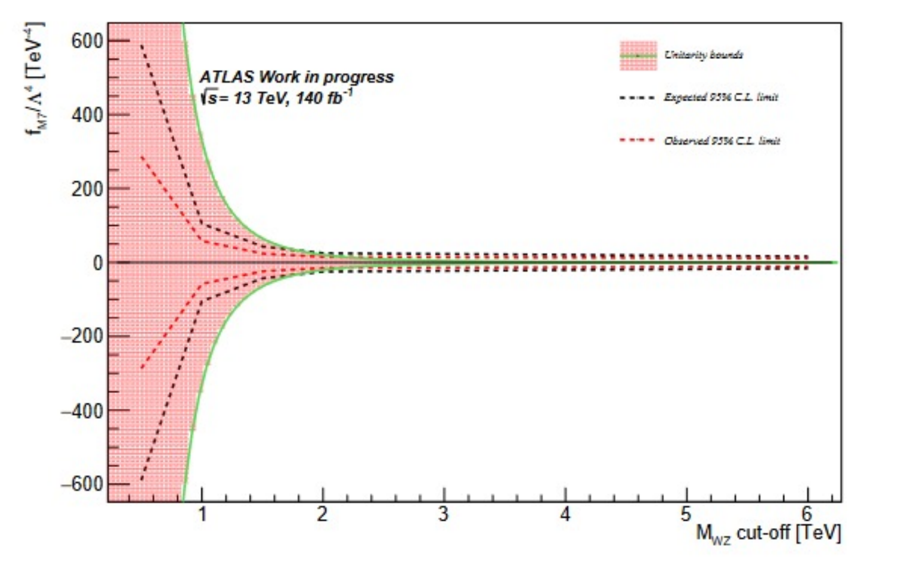
Evolution of the individual 95%C.L. expected and observed limits of the dimension-8 operators as a function of the cut-off scale

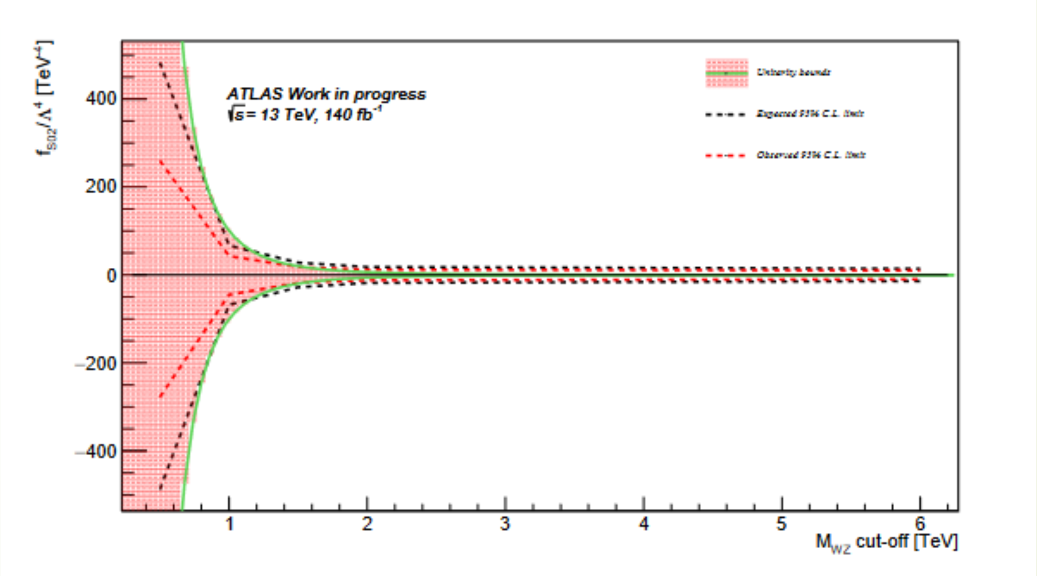


WZjj VBS production: Clipping method(2)









WZjj VBS production: 2-D reco level limits

- Limits on aQGC Wilson coefficients are also derived fitting two parameters simultaneously
- The two dimensional template of the M_T^{WZ} with the BDT score gives the best expected and observed 95% C.L. limits

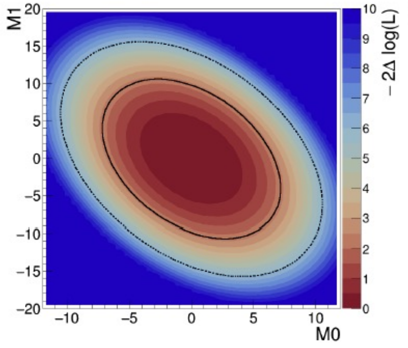
Work in progress

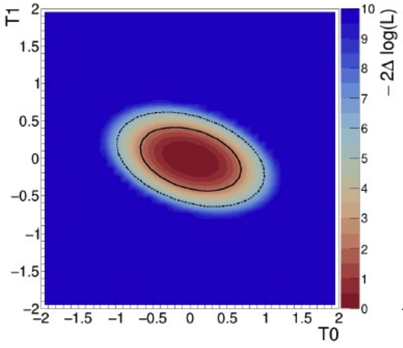
	Variable	Expected (TeV^{-4})	Observed (TeV^{-4})
f_{M0}/Λ^4, f_{M1}/Λ^4	M_T^{WZ}	[-11.1, 11.0], [-16.4, 16.3]	[-8.0, 7.8], [-11.8, 11.8]
	$M_T^{WZ} vs M_{jj}$	[-11.5, 11.9], [-16.3, 16.2]	[-7.8, 7.7], [-11.7, 11.6]
	$M_T^{WZ} vs BDT score$	[-10.5, 10.5], [-15.7, 15.6]	[-8.0, 7.7], [-11.8, 11.8]

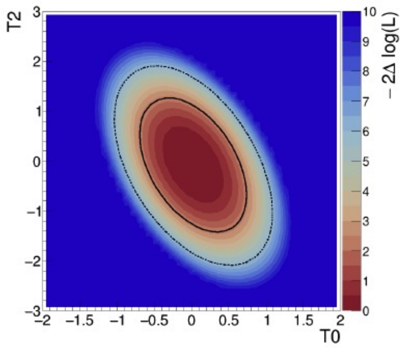
	Variable	Expected (TeV^{-4})	Observed (TeV^{-4})
f_{T0}/Λ^4, f_{T1}/Λ^4	M_T^{WZ}	[-1.00, 1.02], [-0.66, 0.63]	[-0.74, 0.75], [-0.51, 0.47]
	$M_T^{WZ} vs M_{jj}$	[-1.00, 1.02], [-0.66, 0.63]	[-0.73, 0.73], [-0.51, 0.47]
	$M_T^{WZ} vs BDT score$	[-0.99, 1.00], [-0.65, 0.62]	[-0.74, 0.75], [-0.51, 0.47]

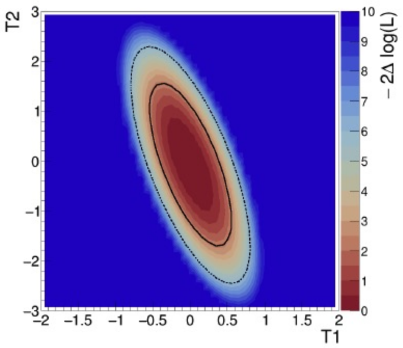
	Variable	Expected (TeV^{-4})	Observed (TeV^{-4})
f_{T0}/Λ^4, f_{T2}/Λ^4	M_T^{WZ}	[-1.06, 1.10], [-2.11, 1.94]	[-0.77, 0.82], [-1.67, 1.43]
	$M_T^{WZ} vs M_{jj}$	[-1.06, 1.10], [-2.11, 1.94]	[-0.77, 0.82], [-1.68, 1.41]
	$M_T^{WZ} vs BDT score$	[-1.04, 1.09], [-2.09, 1.91]	[-0.77, 0.82], [-1.67, 1.42]

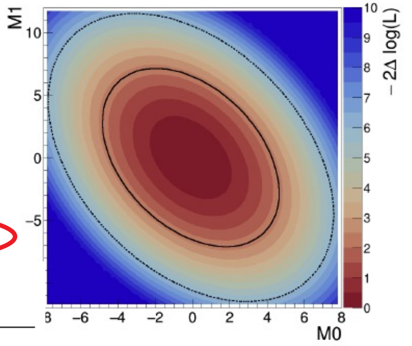
	Variable	Expected (TeV^{-4})	Observed (TeV^{-4})
f_{T1}/Λ^4, f_{T2}/Λ^4	M_T^{WZ}	[-0.91, 0.93], [-2.83, 2.62]	[-0.62, 0.63], [-1.93, 1.73]
	$M_T^{WZ} vs M_{jj}$	[-0.90, 0.93], [-2.81, 2.60]	[-0.61, 0.62], [-1.92, 1.67]
	$M_T^{WZ} vs BDT score$	[-0.89, 0.91], [-2.78, 2.56]	[-0.62, 0.63], [-1.93, 1.72]

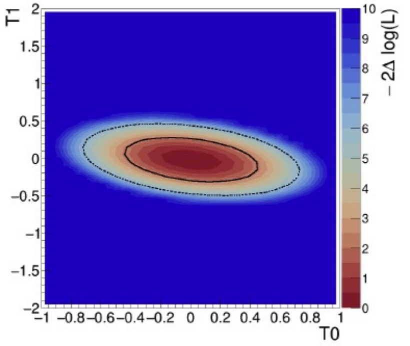


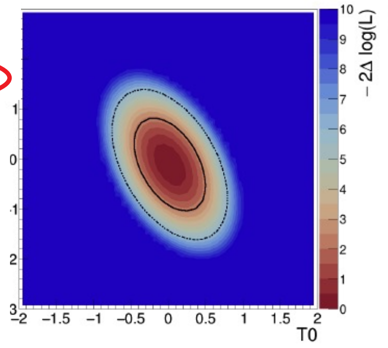


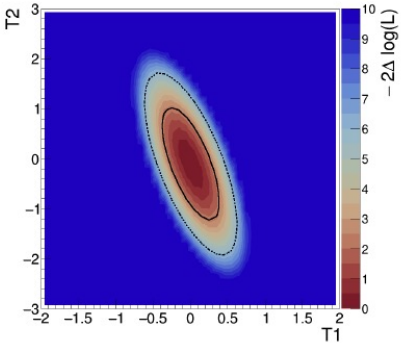








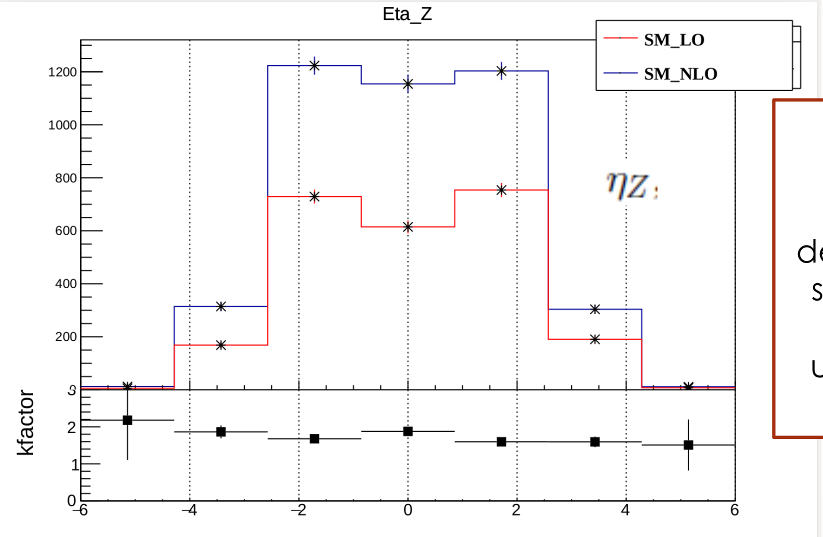




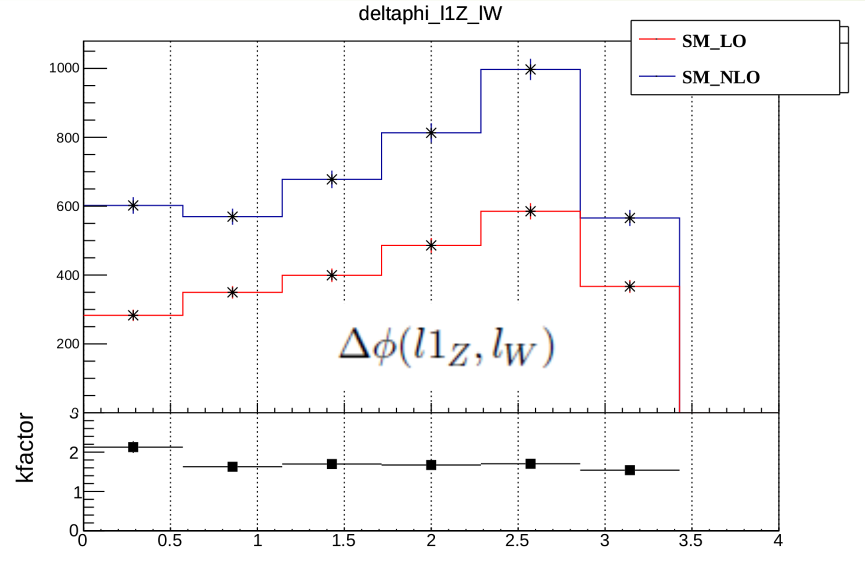
Backup

WZ diboson production: Comparison of SM_LO and SM_NLO and validation of the decomposition method

- In order to see the effect of NLO QCD corrections to the LO, we compare the SM_LO production to the SM_NLO production(It will be used for setting a systematic uncertainty)



For the Eta_Z, Mt_WZ, M_3leptons, deltaphi_l1Z_lW, deltaphi_l2Z_lW, deltaphi_Z_lW and delta_y, the k-factor seems to be almost flat and they can be used for setting a systematic uncertainty for the LO EFT distributions



- In order to use the decomposition method for our future samples, we have to prove that the method works well even for coefficient values very far from the Standard Model

Validation of the decomposition method by comparing the full production with the sum of the decomposed samples

	value	SM xsec(fb)	INT xsec(fb)	QUAD xsec(fb)	FULL xsec(fb)	SUM xsec(fb)	Difference %
$cWWW$	-26.5	74.41	81.44	90330	90340	90490	0.16
$cpDC$	-41.2	74.41	-66.7	6519	5879	2260	0.5

Arbitrary values

Good agreement between full and sum

Within the statistical error

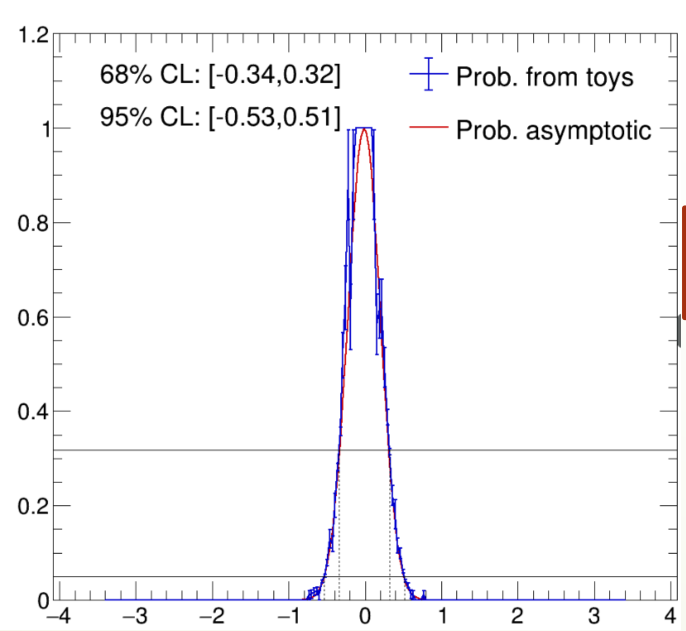
Binning Optimization (1)

- Binned Profile-likelihood fits is heavily dependent on the binning of the histogram that is used in the fit.
- The procedure to compute the optimal binning for the variables used in the Reco-level fits is as follows:
  - 1. For a given number of bins, create a large number of variable binning options for the fit histogram, while requiring > 5 events in each bin for all Standard Model processes and the quadratic term of the $L_{T,1}$ operator, which is the most sensitive operator to the WZjj process.
  - 2. The binning options are generated by splitting the initial histogram range in steps: In the first step, the range is split in n_1+1 bins. In the second step, each one of the n_1+1 bins is split in n_2+1 bins. The process continues for up to 4 steps, in which case the histogram will have 5 bins. The binning search performed in this optimization looks at 5-bin histograms, and the number of insertions at each step are: ($n_1 = 50$, $n_2 = 2$, $n_3 = 2$, $n_4 = 2$).
  - 3. Perform binned profile-likelihood fits for each binning option. The expected 95% C.L. value of the Wilson coefficient is computed using the quadratic EFT term for the $L_{T,1}$ operator.
  - 4. The binning providing the best 95% C.L. for the Wilson coefficient is chosen as the optimized binning.

WZjj VBS production: Comparison of asymptotic and toys methods

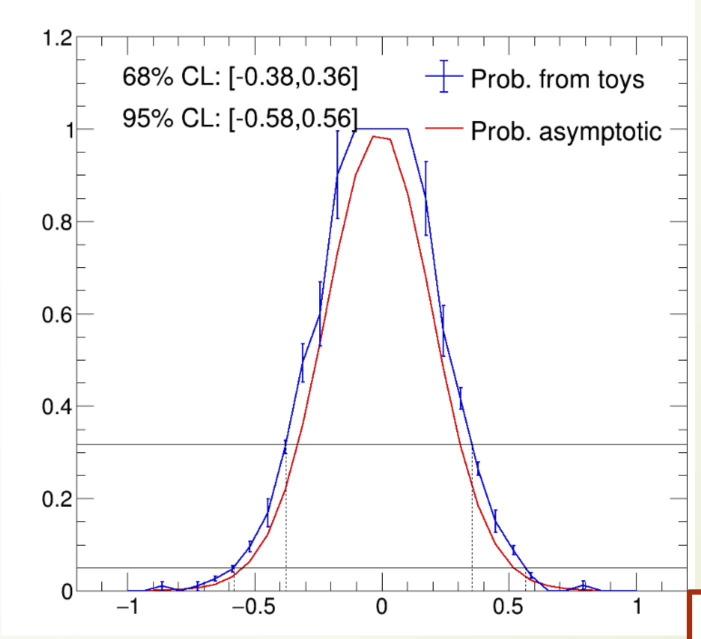
- Feldman-Cousins method uses pseudoexperiments (toys)
- Pseudoexperiments are necessary in the extraction of the reco-level expected limits because the optimized binning used contains bins with low statistics. They have been chosen to have at least 5 events each of them.
- Pseudoexperiments are very time consuming
- The asymptotic method can be used for the extraction of the limits if the results of the two methods are comparable.

Probability function



Without using NPs

T1



Using NPs

T1