EFT re-interpretation of WZjj Vector Boson Scattering production

Eirini Kasimi

Aristotle University of Thessaloniki

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Motivation

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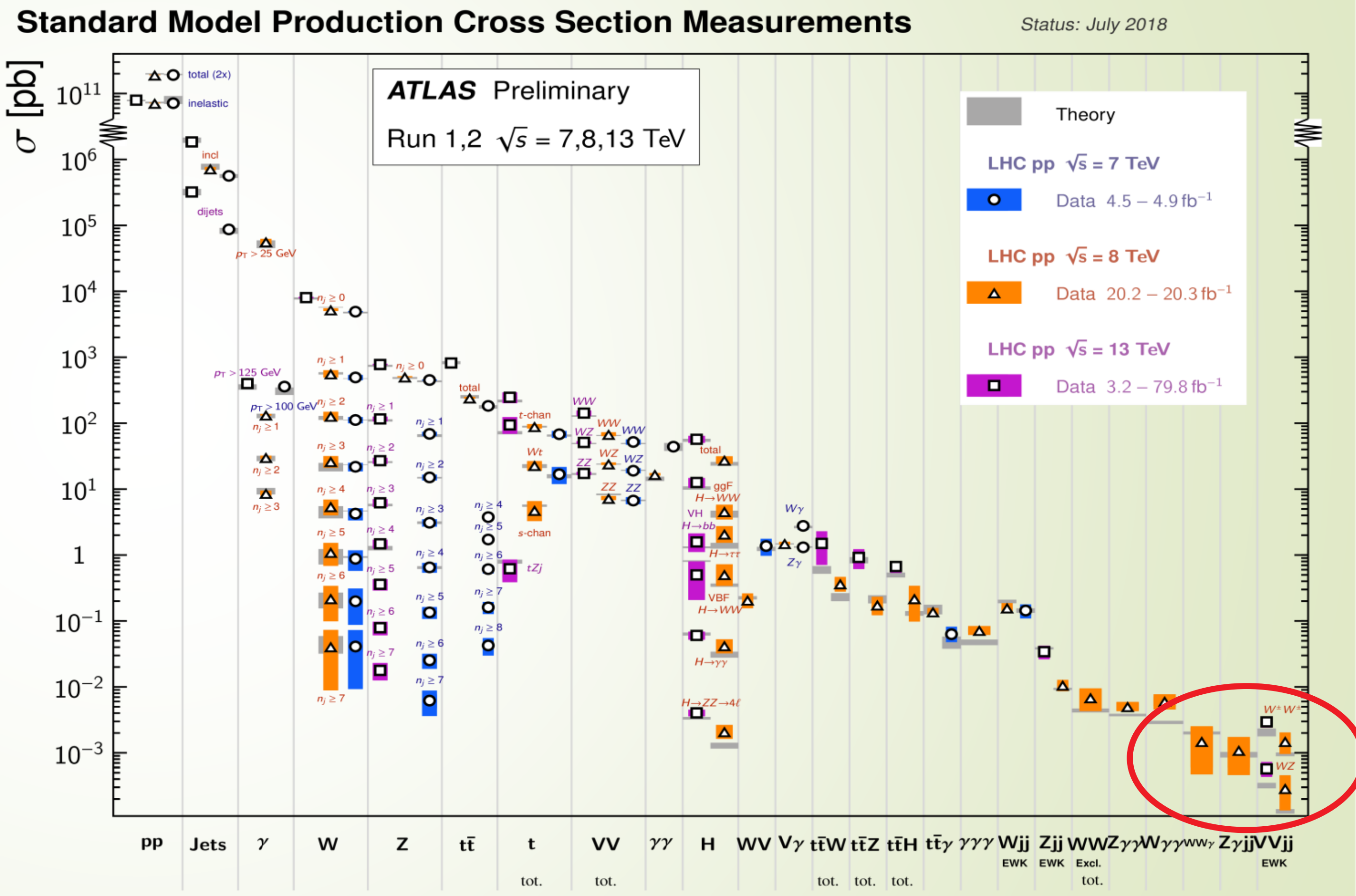
- WZjj VBS process is a rare process
- Vector Boson Scattering (VBS) provides an alternative way to study the mechanism of electroweak symmetry breaking (EWSB)
- VBS probes information on vector boson self-couplings
- Explore the existence of New Physics through deviations from SM



Vector Boson Scattering (VBS)

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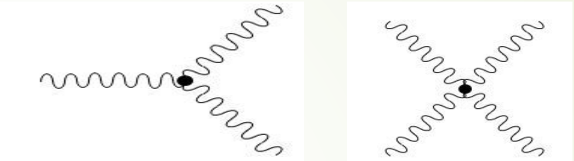
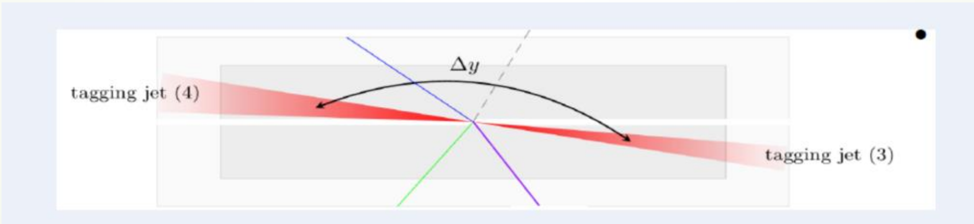
- Standard Model predicts self-interactions between the electroweak gauge bosons
- These self-couplings can involve either three or four gauge bosons at a single vertex, known as triple and quartic gauge couplings, respectively.

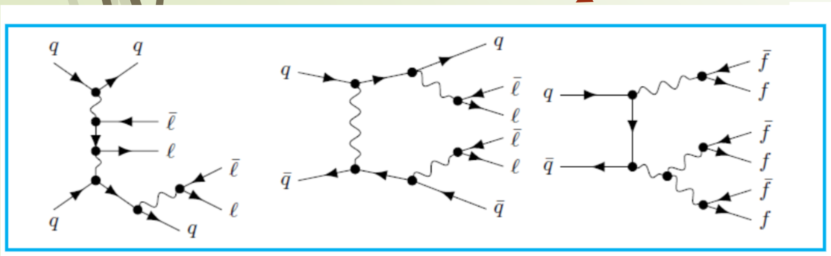


- Two Vector Bosons radiated from the two initial state quarks are scattered (VBS)
- VBS has a very characteristic final state with the two boson's products generally central and two forward jets with large spatial separation in rapidity and a high invariant mass

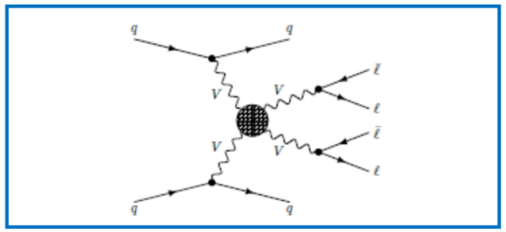


- We study the WZjj VBS fully leptonic process. Leptons are allowed to be electrons or muons. Thus the final state contains two same flavor opposite charged leptons from the Z and a lepton (plus neutrino) from the W

EWK WZjj productions



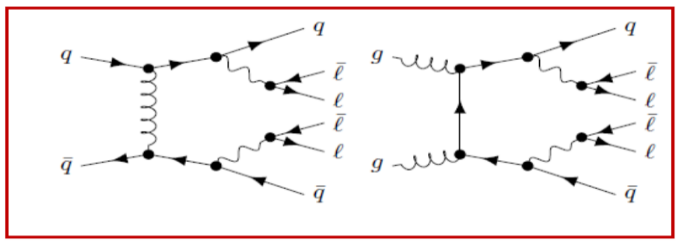
VBS



Study of electroweak symmetry breaking through the vector boson self-couplings

Main background

QCD VVjj

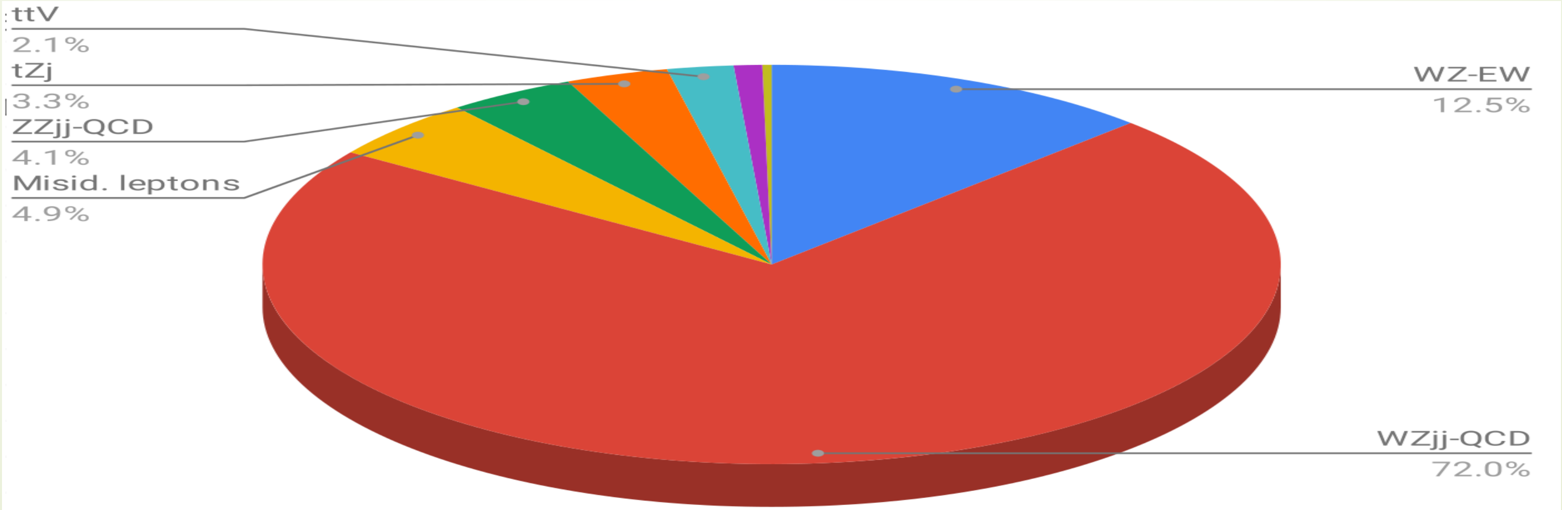


Vector Boson Scattering(VBS) (2)

- Other background sources:
  - Reducible background: $Z + jets,\ Z\gamma,\ t\bar{t}$ and Wt
  - Irreducible background: $WZjj - QCD,\ t\bar{t}V,\ tZ,\ VVV,\ ZZjj - QCD$ and $ZZjj - EWK$

- At least one "fake" lepton
- Matrix method technique

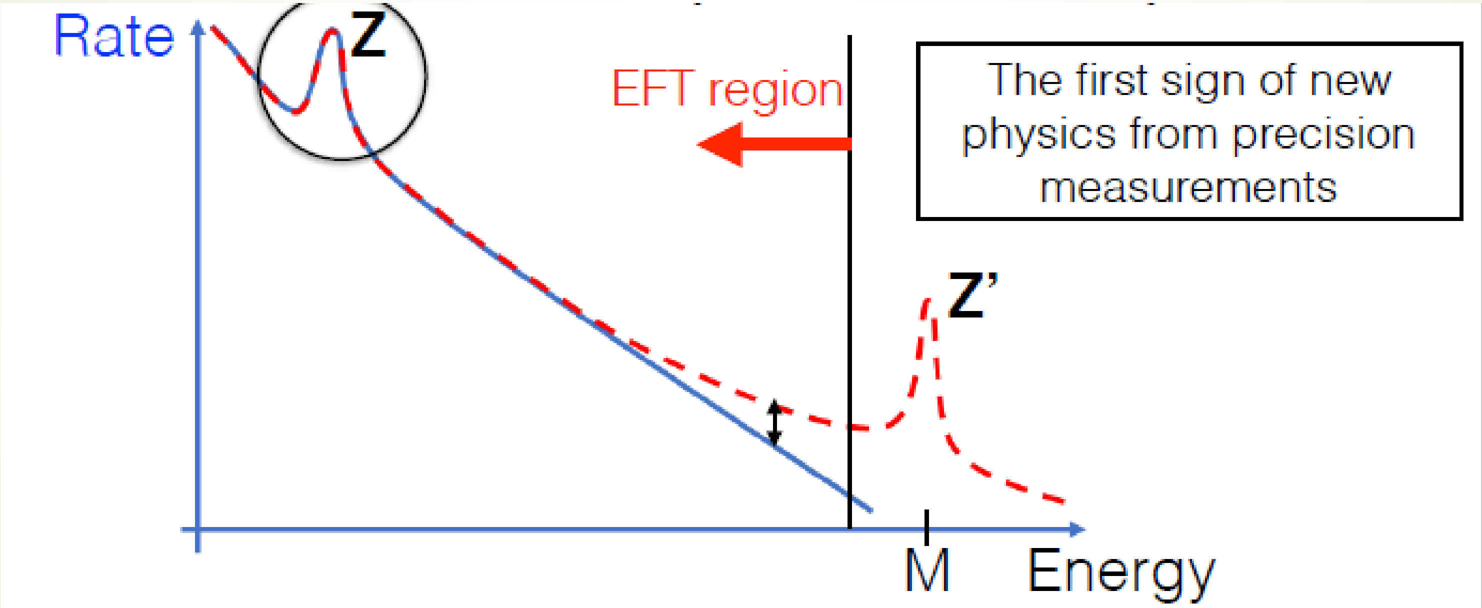
- At least three prompt leptons in the final state
- Simultaneous fit in dedicated CRs



Effective Field Theory

Effective Field Theory (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 tails of the distributions of some kinematical variables.



Effective Field Theory (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 guidance as to the most probable place to see the effects of BSM
- Construction of an EFT of the SM:
  - SM: general theory of quark and lepton fields and the Higgs field
  - Extend the theory: Add operators of higher dimension
- The Lagrangian of the EFT of the SM is

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \sum \frac{f_i O_i}{\Lambda^4}$$

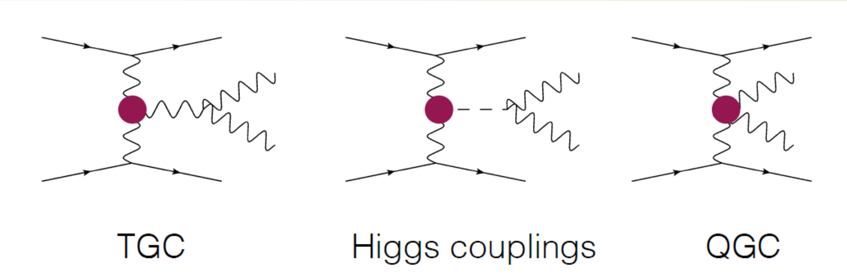
Where: Λ is the scale of new physics

$\mathcal{O}_i$ O_i are the dimension-6 and dimension-8 operators

c_i f_i are the dimensionless Wilson coefficients of the dimension-6 and 8 effective operators

Effective Field Theory (3)

- The VBS process is interesting as it probes:



- We use the dimension-8 operators because they are dominant in anomalous QGC

	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

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

- In order to avoid the production of large amounts of Monte Carlo samples, we will profit from the decomposition method

Interference term between SM-EFT (Linear term)

Pure EFT contribution (Quadratic term)

Interference term between EFT operators (Cross term)

$$|\mathcal{A}_{\rm SM} + \sum_i c_i \mathcal{A}_i|^2$$

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

SM term

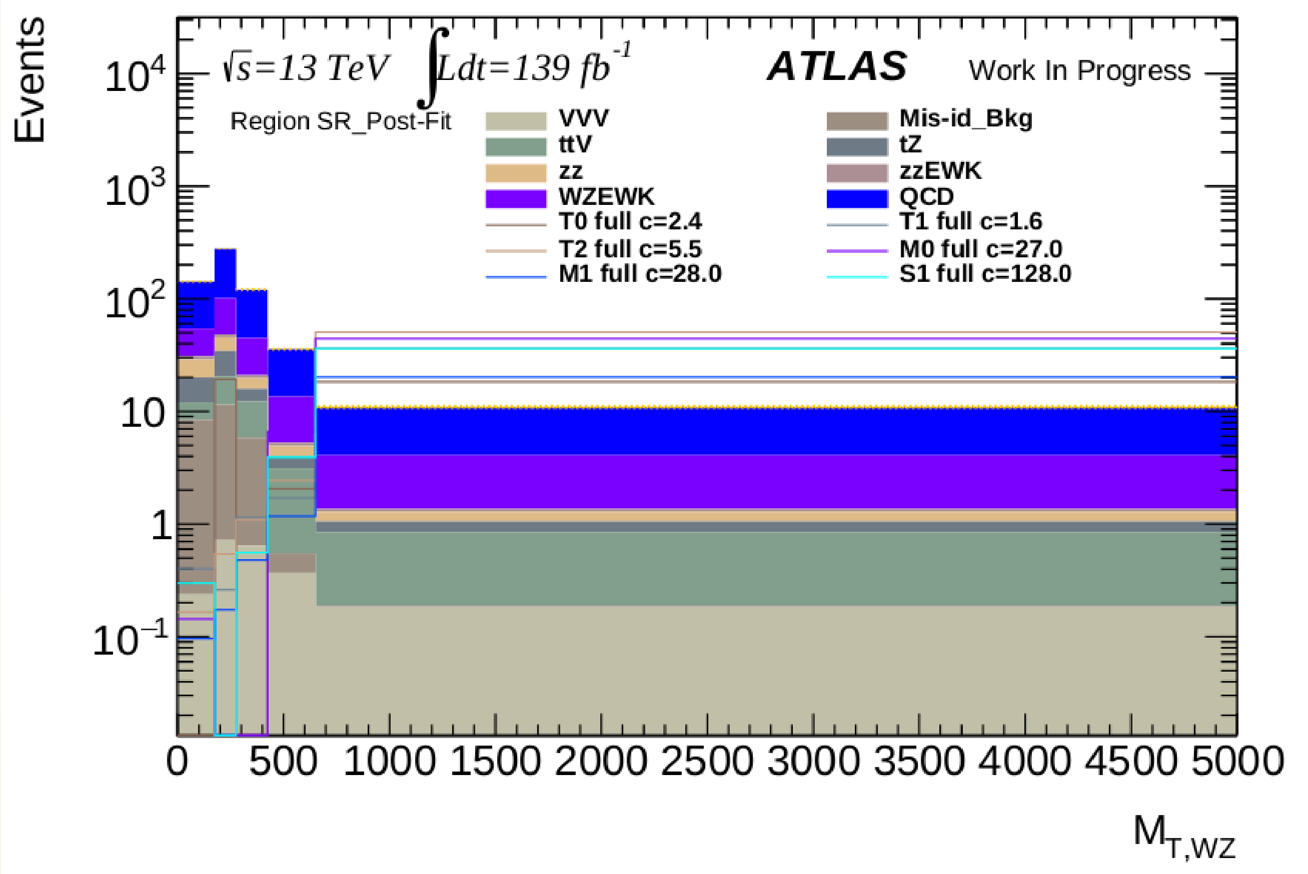
Results

Introduction

- The following results are divided into two parts:
  - Extraction and comparison of single operator 95% C.L. expected truth and reco level limits for some dimension-8 operators corresponding to full Run2 luminosity (139 fb^{-1})
  - Extraction of single operator 95% expected reco level limits using two kinematical variables simultaneously for some dimension-8 operators corresponding to full Run2 luminosity (139 fb^{-1})
- The fitting framework used in this study is the EFTfun for both truth and reco level measurements
  - The probability density function based on a multivariate Gaussian distribution is used for the re-interpretation of the WZjj Vector Boson Scattering process
  - The uncertainties are parametrized by nuisance parameters
- In our results, only the experimental systematic uncertainties are considered, as the theoretical uncertainties are under investigation. Our next step is to add them too
- Also, only expected unfolded and reco level limits are presented, as we are still blinded to the data
- The truth analysis is performed using our new validated Rivet routine for the WZjj production

Introduction (2)

- An example of the effect of the dimension-8 operators on the transverse mass of the diboson system (m_T^{WZ}) in the WZjj VBS fully leptonic channel is presented

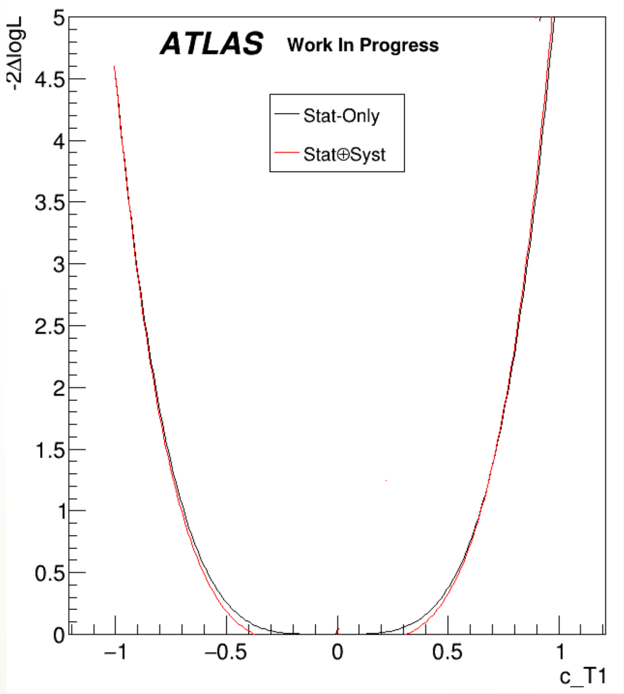


Expected truth and reco level limits for dimension-8 operators

- The transverse mass of the diboson system (m_T^{WZ}) is used in order to extract the limits
- For the results, we use the full set of the experimental systematic uncertainties

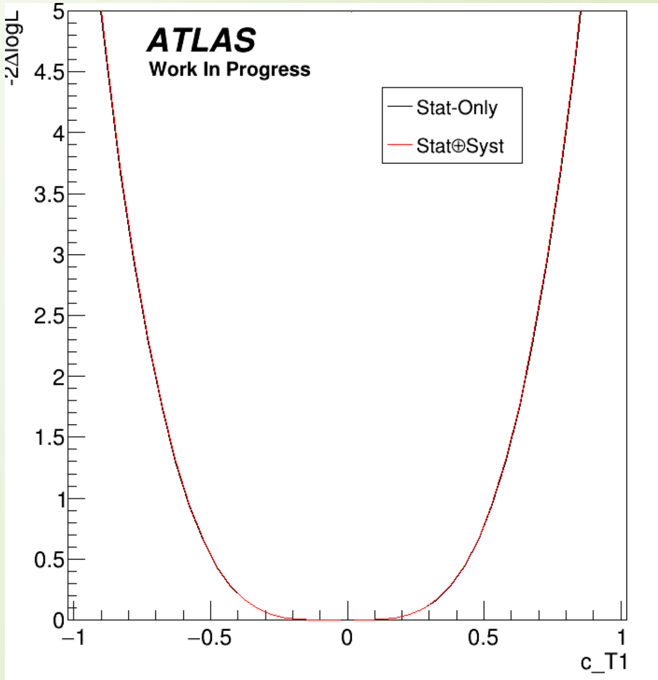
	Expected Truth (TeV^{-4})	Expected Reco (TeV^{-4})
f_{T0}/Λ^4	[-1.37, 1.36]	[-1.22, 1.19]
f_{T1}/Λ^4	[-0.96, 0.91]	[-0.84, 0.79]
f_{T2}/Λ^4	[-2.85, 2.62]	[-2.50, 2.26]
f_{M0}/Λ^4	[-14.2, 14.1]	[-12.1, 12.0]
f_{M1}/Λ^4	[-21.9, 21.9]	[-18.4, 18.3]
f_{S1}/Λ^4	[-78, 78]	[-63, 63]

For complete comparison between the two sets of limits, the theoretical uncertainties should be taken into account



Truth level

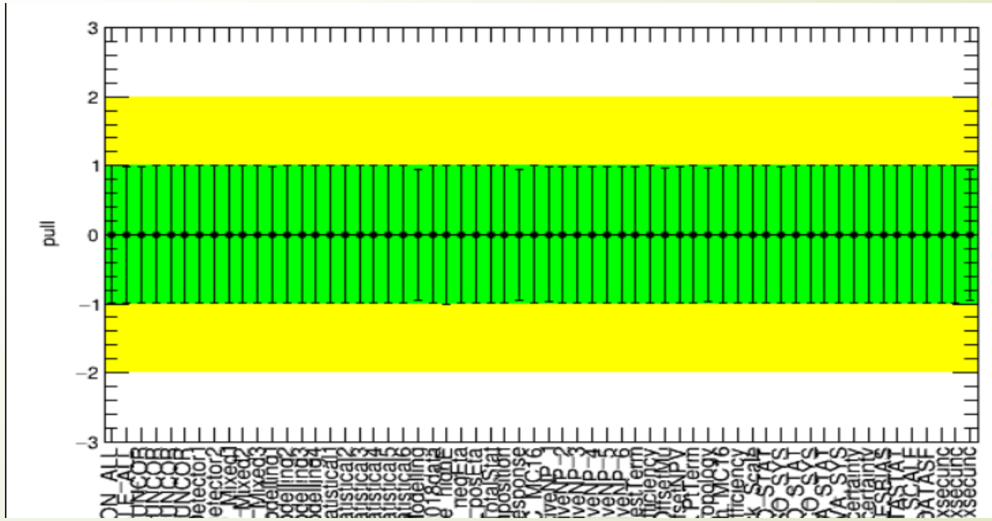
Reco level



Expected reco level limits using two kinematical variables

- We have more competitive limits by using two kinematical variables at a time by combining single-variable templates
- The two-dimensional template is transformed to one dimension by ’unrolling’ the bin contents, thus allowing it to be inserted as fit template to the fitting framework
- The two kinematical variables used by CMS are the transverse mass of the diboson system (m_T^{WZ}) and the invariant mass of the two tagging jets (m_{jj})
  - m_T^{WZ}- m_{jj} = 5 x 2 = 10 bins template
- For the results, we use the full set of the experimental systematic uncertainties, while the CMS uses the theoretical ones too

	ATLAS Expected (TeV^{-4})	CMS Expected (TeV^{-4})
f_{T0}/Λ^4	[-0.77,0.78]	[-0.82,0.85]
f_{T1}/Λ^4	[-0.50,0.48]	[-0.49,0.55]
f_{T2}/Λ^4	[-1.5,1.4]	[-1.4,1.7]
f_{M0}/Λ^4	[-8.2,8.1]	[-7.6,7.6]
f_{M1}/Λ^4	[-12,12]	[-11,11]
f_{S1}/Λ^4	[-43,43]	[-38,39]



Expected reco level limits using two kinematical variables (2)

- In order to explore which combination of kinematical variables is the most efficient, we try to combine many kinematical variables with the transverse mass of the diboson system (m_T^{WZ})
- The kinematical variables tested are:
  - $|y_{j1} - y_{j2}|$, difference of rapidity of the two tagging jets
  - $\Delta\varphi(j1, j2)$, difference of φ angle of the two tagging jets
  - $\Delta\varphi(Z, W)$, difference of φ angle of the Z and W boson
  - $\sum pT_{3l}$, sum of the transverse momentum of the three leptons
  - BDT, the signal and background BDT score

	M_T^{WZ}-m_{jj} (TeV^{-4})	M_T^{WZ}-Δy_{jj} (TeV^{-4})	M_T^{WZ}-$\Delta\phi_{jj}$ (TeV^{-4})	M_T^{WZ}-$\Delta\phi_{WZ}$ (TeV^{-4})	M_T^{WZ}-$\sum P_T^{3lep}$ (TeV^{-4})	M_T^{WZ}-BDT (TeV^{-4})
f_{T0}/Λ^4	[-0.77,0.78]	[-0.78,0.78]	[-0.79,0.78]	[-0.81,0.81]	[-0.76,0.76]	[-0.76,0.76]
f_{T1}/Λ^4	[-0.50,0.48]	[-0.50,0.48]	[-0.51,0.48]	[-0.53,0.51]	[-0.50,0.48]	[-0.50,0.47]

Conclusion

- Results on single operator 95% C.L. expected limits for some dimension-8 operators for the WZjj VBS fully leptonic channel were presented corresponding to full Run2 luminosity (139 fb^{-1})
  - Extraction and comparison of expected truth and reco level limits
  - Extraction of expected reco level limits using two kinematical variables simultaneously and comparison with the CMS results
  - Combination of various kinematical variables with the transverse mass of the diboson system (m_T^{WZ}) and extraction of expected reco level limits
- Next steps:
  - Add the theoretical systematic uncertainties to the results
  - Unblind the data and extract observed limits
  - Extract the limits using the clipping method
  - Publish the results