



# Anomalous coupling sensitivity study of Vector Boson Scattering(VVjj) with Effective Field Theory operators

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On behalf of  
Snowmass EWK VBS/Triboson Group

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J. Metcalfe, M-A. Pleier, C. Pollard)

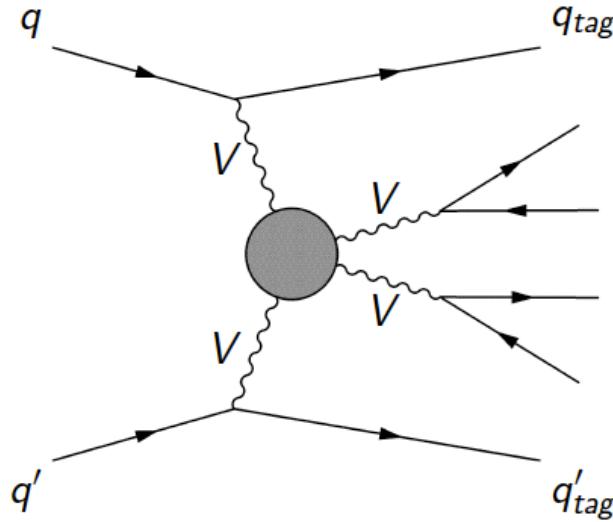
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# Outline

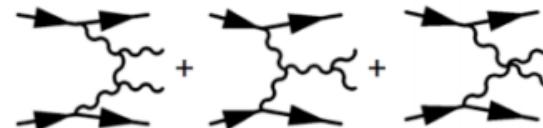
- Introduction to Vector Boson Scattering
  - Anomalous coupling and Effective Field Theory(EFT) approach with high dimension operators
  - VBS VV(+jj) sensitivity studies with EFT high dimension operators using ATLAS/SnowMass Parametrized Simulations
  - Summary
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# Vector Boson Scattering (VBS)

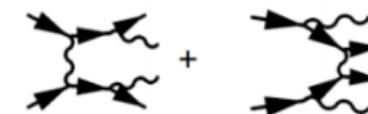
- TeV scale Unitarity Violation(UV) if NO higgs boson
- Probe of the mechanism of electroweak symmetry breaking(EWSB) regardless of the underlying physics
  - Higgs boson couplings (e.g. to gauge bosons and fermions)
  - CP properties
- Can be enhanced by Higgs or extra resonances, alternative mechanism, **anomalous gauge couplings**, etc.



VV Scattering (TGC, QGC, Higgs)  $O(EW)=6$



non-VV Scattering  $O(EW)=6$



$O(EW)=4$   $O(QCD)=2$ , Other backgrounds

# EFT with high dimension operators

- Dimension N of the new operators should be  $> 4$
- New physics suppression:  $1/\Lambda^{N-4}$

$$\mathcal{L} = \mathcal{L}^{SM} + \sum \frac{c_i}{\Lambda^2} \mathcal{O}_i + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

- ❖ Dim6 operators:
  - ❖ Unique to VBS
  - ❖ Not constrained by inclusive diboson
  - ❖ Fully gauge invariant

$$\begin{aligned} \mathcal{O}_{\phi d} &= \partial_\mu (\phi^\dagger \phi) \partial^\mu (\phi^\dagger \phi) \\ \mathcal{O}_{\phi W} &= (\phi^\dagger \phi) \text{Tr}[W^{\mu\nu} W_{\mu\nu}] \\ \mathcal{O}_{\phi B} &= (\phi^\dagger \phi) B^{\mu\nu} B_{\mu\nu} \end{aligned}$$

[Celine Degrande's talk at BNL WS](#)

- ❖ Dim8 operators:
  - ❖ the **lowest dimension operators** exhibiting QGC in VBS
  - ❖ NOT in two or three gauge boson vertices

[O.J.P. Eboli, et. al. Phys.Rev.D74:073005,2006](#)

	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

# Analysis framework

- Generator choice:
  - MadGraph5 with EFT operators supported by our theorist colleagues (Celine Degrande, Oscar Eboli, Olivier Mattelaer, etc.)
  - Cross checked by VBF@NLO
- Signal: VBS Same Sign(SS) WWjj, VBS WZjj and VBS ZZjj
- Background: WZ+QCD jets, ZZ+QCD jets, SS WW+QCD jets, charge flips, mis-ID
- Analysis cuts: (same cuts for ssWWjj, WZjj and ZZjj)
  - Lepton:  $pT > 25\text{GeV}$ ,
  - Electron:  $| \eta | < 2.47$  (excluding crack region), Muon:  $| \eta | < 2.4$
  - Jets:  $pT > 50\text{GeV}$ ,  $| \eta | < 5$
  - $M(jj) > 1\text{TeV}$  (optimized for VVjj)
  - M(VV) cutoff at UV boundaries
    - <http://www.itp.kit.edu/~vbfnloweb/wiki/doku.php?id=download:formfactor>
- Sensitivities are studied for:
  - 300, 3000  $\text{fb}^{-1}$  @ 14 TeV using ATLAS Upgrade Parametrized Simulations (Approved as a [ATLAS PUB note result](#))
  - 3000  $\text{fb}^{-1}$  @ 14TeV(140Pileup) and 33TeV(225Pileup) using [SnowMass Delphes Parametrized FastSim](#) (Work in progress...)



# ZZjj: ATLAS Upgrade Parametrized Simulation

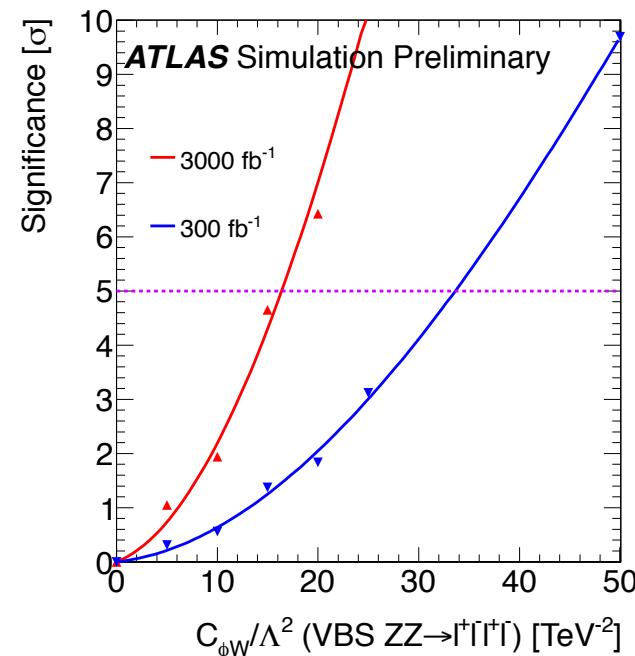
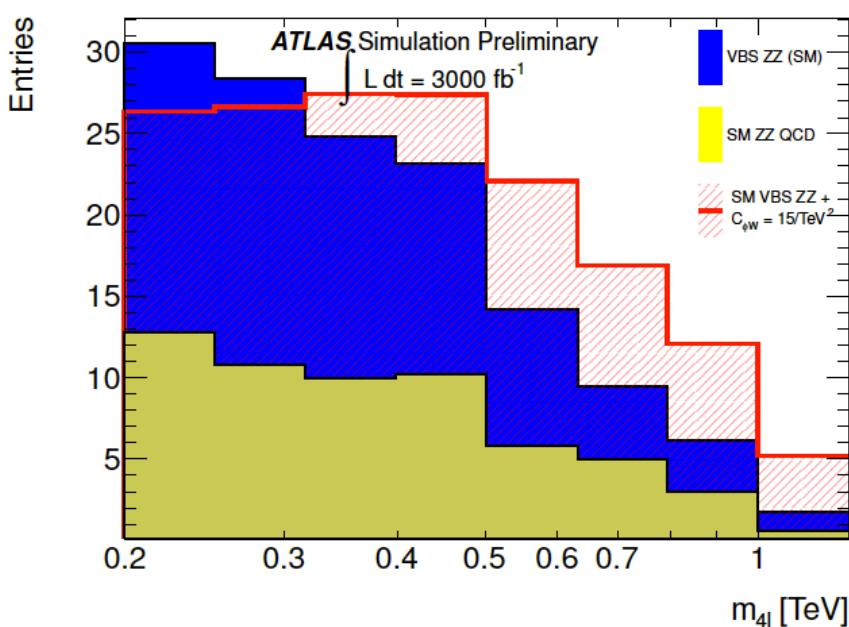
- Sensitivity accessed with M\_ZZ spectrum

- dim6 operator  $C_{\varphi W}$ :

$$\mathcal{L}_{\varphi W} = \frac{c_{\varphi W}}{\Lambda^2} Tr(W^{\mu\nu}W_{\mu\nu})\phi^\dagger\phi$$

- 14 TeV results with ATLAS Upgrade Param Sim in fully leptonic channels

ATLAS-PHYS-PUB-2013-006



5- $\sigma$  discovery value:

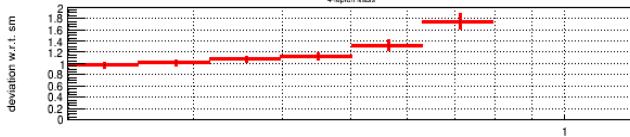
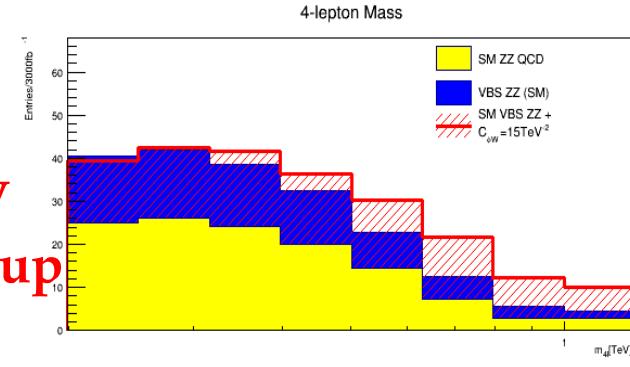
Model	300 fb <sup>-1</sup>	3000 fb <sup>-1</sup>
$C_{\varphi W}/\Lambda^2$	$34 \text{ TeV}^{-2}$	$16 \text{ TeV}^{-2}$

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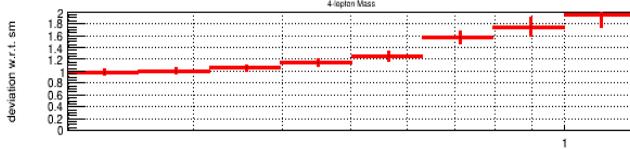
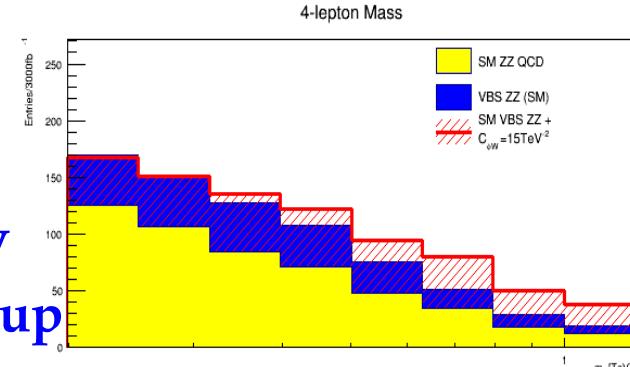
# ZZjj: SnowMass EF Delphes3 Parametrized FastSim

- Sensitivity results at both 14 TeV and 33 TeV scenarios with pileup

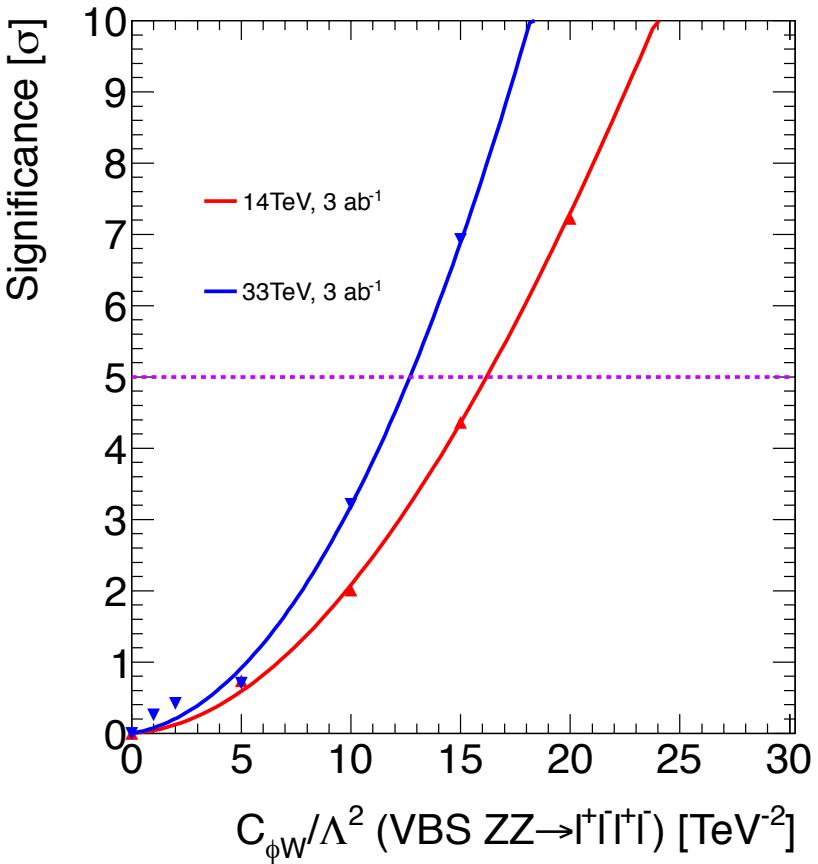
14TeV  
140 Pileup



33TeV  
225 Pileup



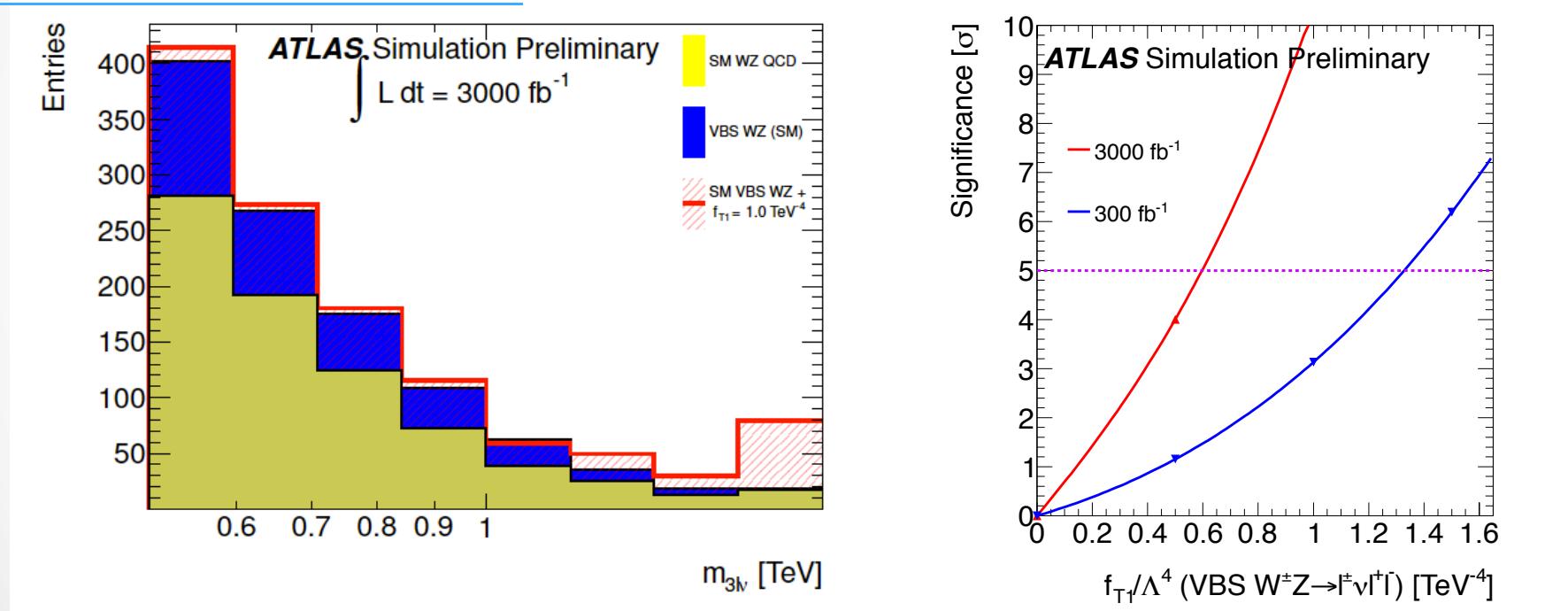
$$\mathcal{L}_{\phi W} = \frac{c_{\phi W}}{\Lambda^2} Tr(W^{\mu\nu}W_{\mu\nu})\phi^\dagger\phi$$



# $W^\pm Z jj$

- ◆ Sensitivity accessed with  $M_{WZ}$  spectrum (neutrino  $p_Z$  with  $W$  mass constraint)
- ◆ Dim8 operator  $f_{T1}$  :  $\mathcal{L}_{T,1} = \frac{f_{T1}}{\Lambda^4} \text{Tr}[\hat{W}_{\alpha\nu} \hat{W}^{\mu\beta}] \times \text{Tr}[\hat{W}_{\mu\beta} \hat{W}^{\alpha\nu}]$
- ◆ 14 TeV results with ATLAS Upgrade Param Sim in fully leptonic channels

[ATLAS-PHYS-PUB-2013-006](#)



5- $\sigma$  discovery value:

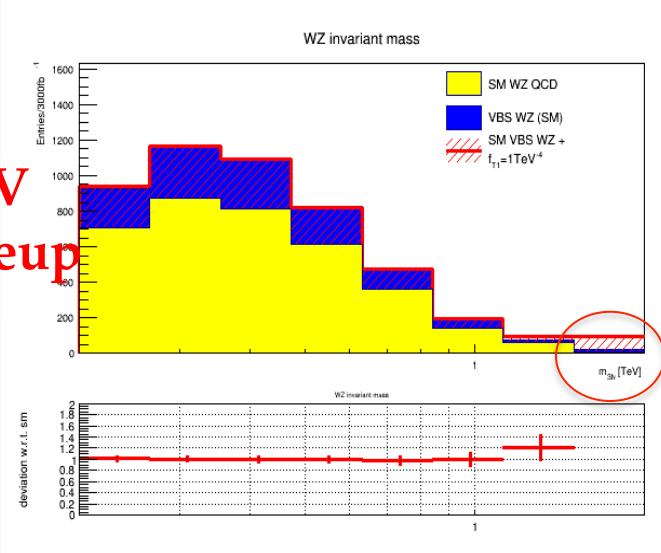
Model	$300 \text{ fb}^{-1}$	$3000 \text{ fb}^{-1}$
$f_{T1}/\Lambda^4$	$1.3 \text{ TeV}^{-4}$	$0.6 \text{ TeV}^{-4}$

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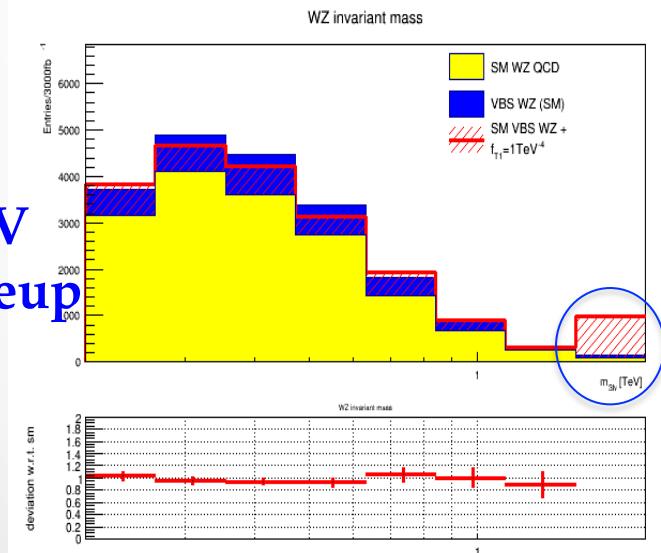
# $W^\pm Z jj$ : SnowMass EF Delphes3 Parametrized FastSim

- Sensitivity results at both 14 TeV and 33 TeV scenario with pileups

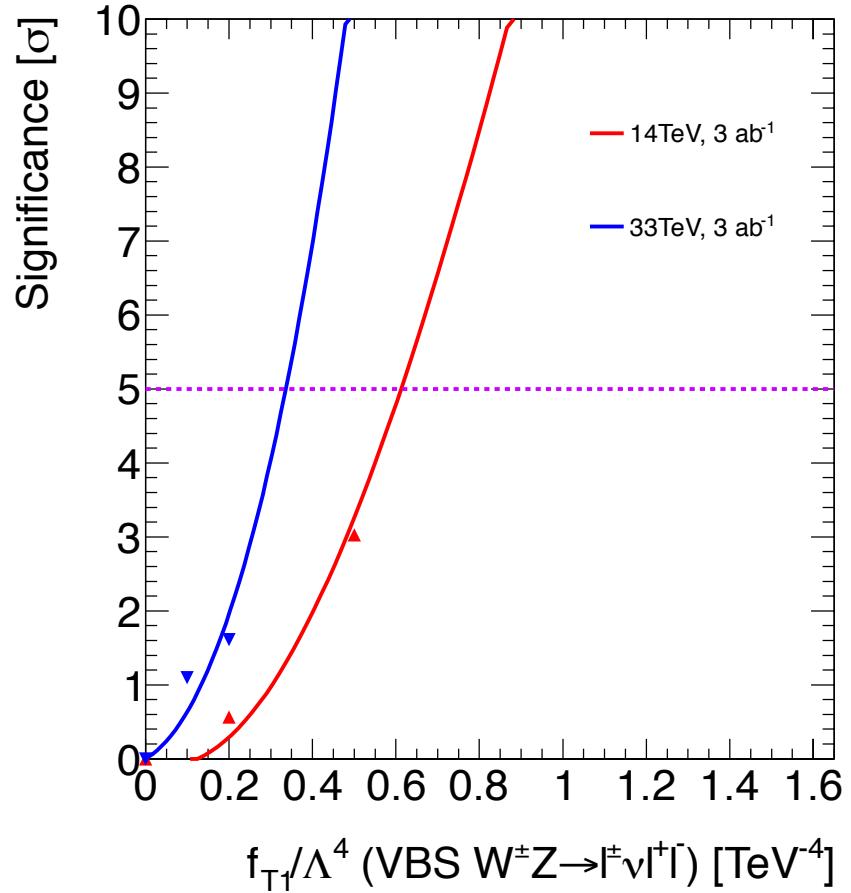
14TeV  
140 Pileup



33TeV  
225 Pileup



$$\mathcal{L}_{T,1} = \frac{f_{T1}}{\Lambda^4} \text{Tr}[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}] \times \text{Tr}[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}]$$

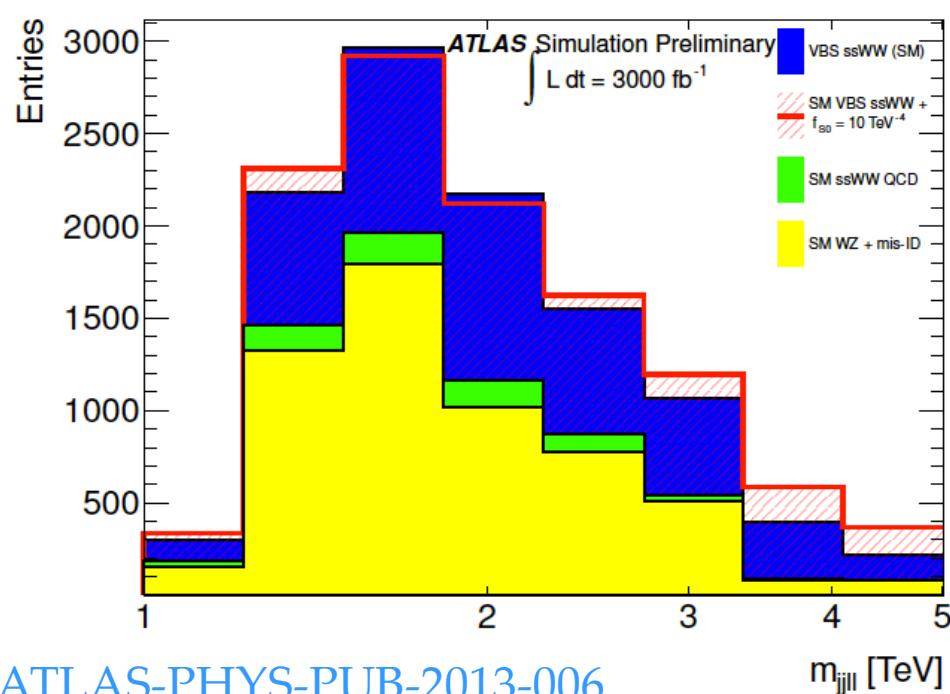


# SS $W^\pm W^\pm jj$

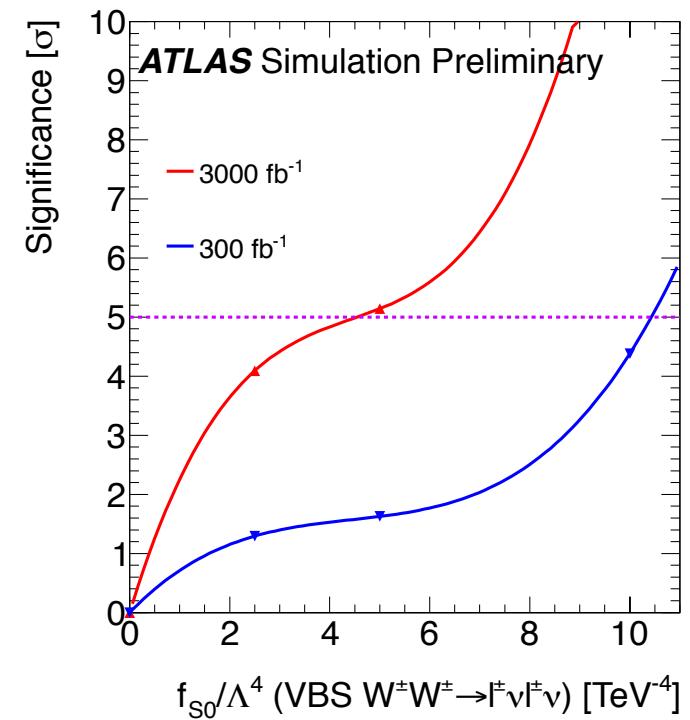
- $f_{S0}$  correlated to  $\alpha_4$  in the Electroweak Chiral Lagrangian, couples to:

$$\mathcal{L}_{S,0} = \frac{f_{S0}}{\Lambda^4} [(D_\mu \phi)^\dagger D_\nu \phi] \times [(D^\mu \phi)^\dagger D^\nu \phi]$$

- WZ background scaled by a factor of 2 to account for charge flip, mis-id, and Wgamma backgrounds
- Results for 14 TeV ATLAS Detector using fully leptonic decays:



[ATLAS-PHYS-PUB-2013-006](#)



5- $\sigma$  discovery value:

Model	$300 \text{ fb}^{-1}$	$3000 \text{ fb}^{-1}$
$f_{S0}/\Lambda^4$	$10 \text{ TeV}^{-4}$	$4.5 \text{ TeV}^{-4}$

# Summary

- Anomalous coupling sensitivity to new physics parameterized by EFT high dimension operators
- $300 \text{ fb}^{-1}$  and  $3000 \text{ fb}^{-1}$  14TeV sensitivities are studied using VBS ZZjj, WZjj and SS WWjj in fully leptonic decay channels with ATLAS Upgrade Parametrized Simulation (ATLAS approved results)

Parameter	dimension	channel	$\Lambda_{UV} [\text{TeV}]$	300 $\text{fb}^{-1}$		3000 $\text{fb}^{-1}$	
				$5\sigma$	95% CL	$5\sigma$	95% CL
$c_{\phi W}/\Lambda^2$	6	ZZ	1.9	$34 \text{ TeV}^{-2}$	$20 \text{ TeV}^{-2}$	$16 \text{ TeV}^{-2}$	$9.3 \text{ TeV}^{-2}$
$f_{S0}/\Lambda^4$	8	$W^\pm W^\pm$	2.0	$10 \text{ TeV}^{-4}$	$6.8 \text{ TeV}^{-4}$	$4.5 \text{ TeV}^{-4}$	$0.8 \text{ TeV}^{-4}$
$f_{T1}/\Lambda^4$	8	WZ	3.7	$1.3 \text{ TeV}^{-4}$	$0.7 \text{ TeV}^{-4}$	$0.6 \text{ TeV}^{-4}$	$0.3 \text{ TeV}^{-4}$
$f_{T8}/\Lambda^4$	8	$Z\gamma\gamma$	12	$0.9 \text{ TeV}^{-4}$	$0.5 \text{ TeV}^{-4}$	$0.4 \text{ TeV}^{-4}$	$0.2 \text{ TeV}^{-4}$
$f_{T9}/\Lambda^4$	8	$Z\gamma\gamma$	13	$2.0 \text{ TeV}^{-4}$	$0.9 \text{ TeV}^{-4}$	$0.7 \text{ TeV}^{-4}$	$0.3 \text{ TeV}^{-4}$

- 3000  $\text{fb}^{-1}$  sensitivities are studied at both 14TeV and 33TeV using VBS ZZjj, WZjj in fully leptonic decay channels with SnowMass Delphes Parametrized FastSim

Parameter	dimension	channel	14 TeV		33 TeV	
			$5\sigma$	95% CL	$5\sigma$	95% CL
$c_{\phi W}/\Lambda^2$	6	ZZ	$16 \text{ TeV}^{-2}$	$9.7 \text{ TeV}^{-2}$	$13 \text{ TeV}^{-2}$	$7.7 \text{ TeV}^{-2}$
	8	WZ	$0.6 \text{ TeV}^{-4}$	$0.4 \text{ TeV}^{-4}$	$0.3 \text{ TeV}^{-4}$	$0.2 \text{ TeV}^{-4}$

- Work in progress towards SnowMass in Minneapolis
  - More operator choices
  - More optimal phase space for sensitivities
  - 95% CL limits
  - Better understanding of SnowMass Delphes FastSim
  - More center-of-mass energy and pileup scenarios

# Backup

# Effective Field Theory (EFT)

- Experimental challenge to Traditional anomalous coupling framework:
  - Does not incorporate  $SU(3)_C \times SU(2)_L \times U(1)_Y$  gauge symmetry
  - No well-defined prescription to employ anomalous couplings in the loop calculations describing varieties of precision electroweak processes
  - Form factor arbitrary choices at tree level
- Features of EFT:
  - Model-independent approach to BSM
  - Respect Lorentz Invariance and  $SU(3)_C \times SU(2)_L \times U(1)_Y$  gauge symmetry
  - General enough to capture new physics BSM
  - Unambiguous calculation of loop effects
  - Able to calculate radiative corrections at any order in SM/BSM interactions in the extended theory

# ZZjj total cross section enhancement with dim6 operators

Dim6 operators(TeV <sup>-2</sup> )	14TeV Cross section (pb)
SM	1.33E-01
Cphid=5	1.39E-01
Cphib=5	1.33E-01
CphiW=5	1.36E-01
Cphid=50	6.82E-01
Cphib=50	1.36E-01
CphiW=50	9.24E-01

used in  
current  
sensitivity  
study

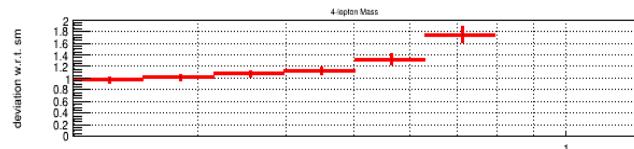
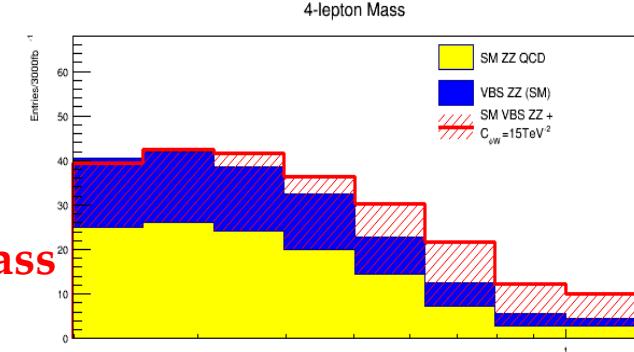


# WZjj total cross section enhancements with dim8 operators

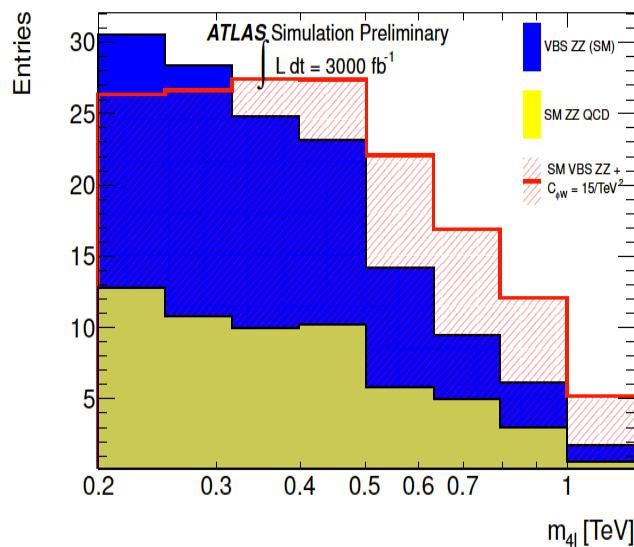
Dim8 operators(TeV <sup>-4</sup> )	14TeV Cross section (pb)
SM	0.5367
FT0=1	0.6116
<b>Used in current study</b>	<b>FT1=1</b>
FT2=1	0.5532
FM0=1	0.5386
FM1=1	0.536
FM2=1	0.5365
FM3=1	0.5386
FS0=1	0.5372
FS1=1	0.5342

# ZZjj: SnowMass FastSim VS ATLAS Param Simulation

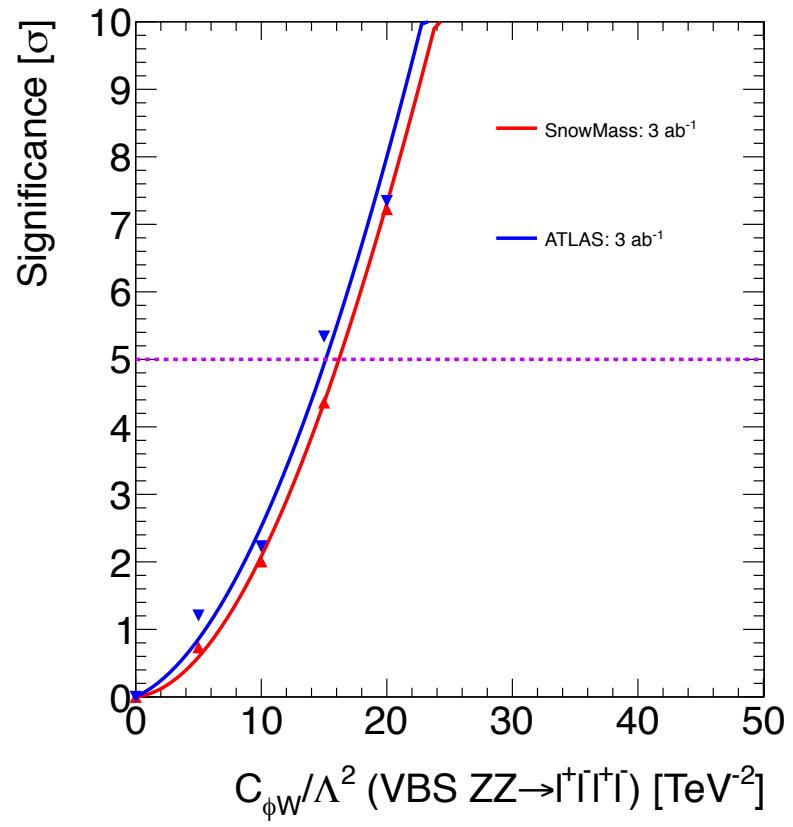
**Snow Mass**



**ATLAS**

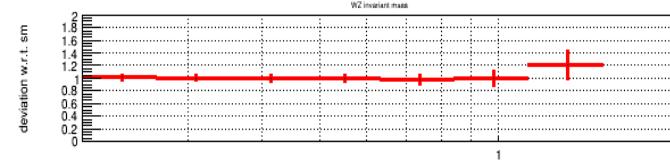
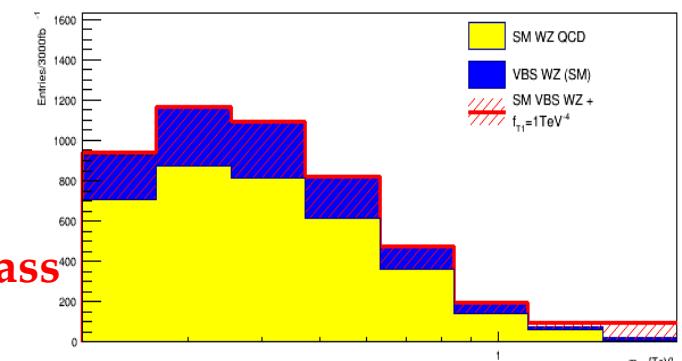


VBS ZZ signal significance comparison w/  $C_{\phi W}$  operator

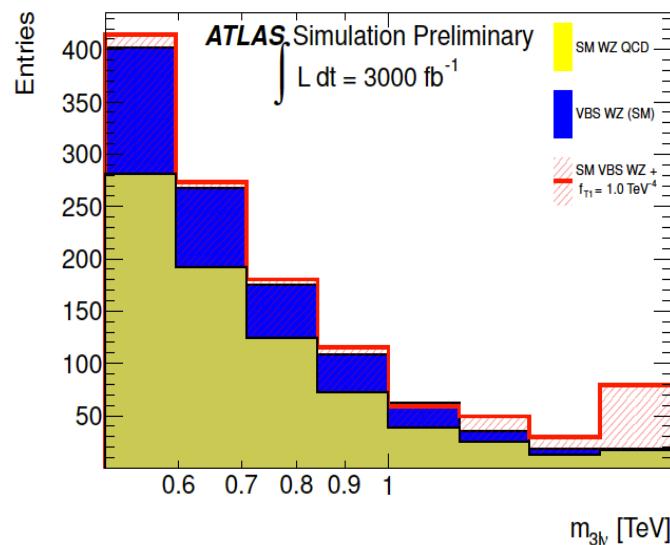


# $W^\pm Z jj$ : SnowMass FastSim VS ATLAS Param Simulation

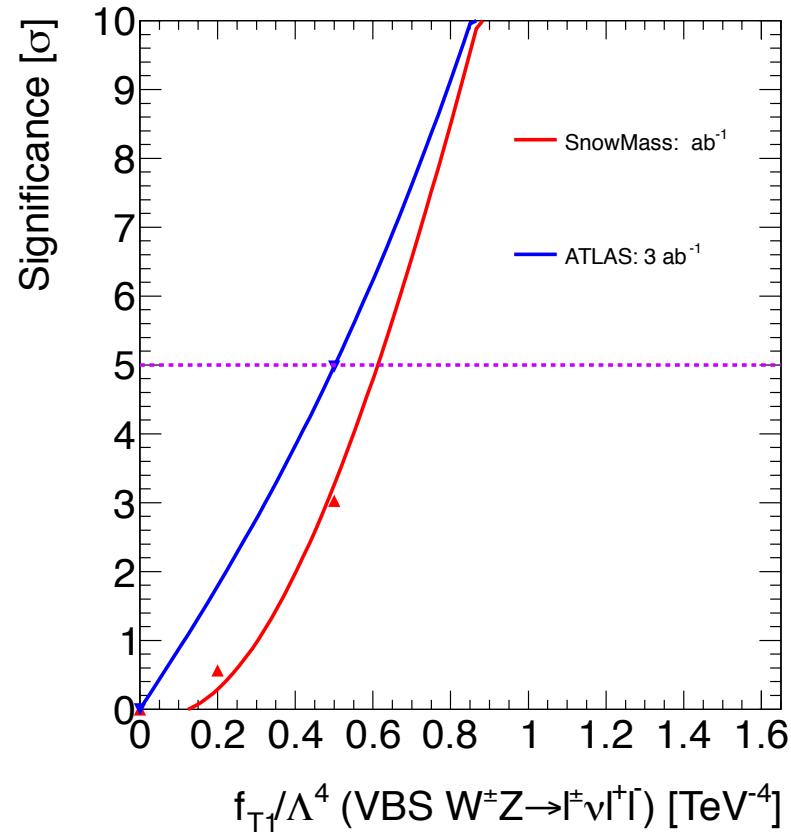
Snow Mass



ATLAS



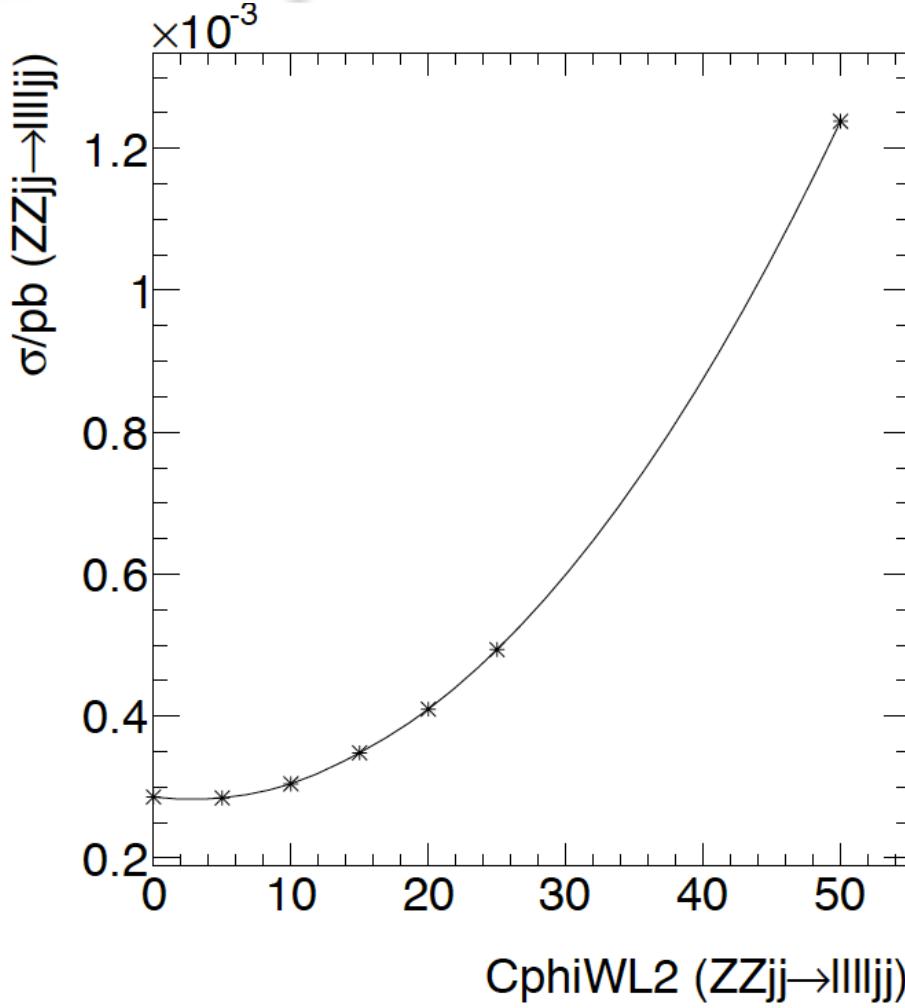
VBS WZ signal significance comparison w/  $f_{T1}$  operator



# MadGraph event generation commands

- ZZjj-EWK signal:
  - $p p \rightarrow z z j j$  QCD=0,  $z \rightarrow l^+ l^-$
- ZZjj-QCD background:
  - $p p \rightarrow z z j j$  QCD=2,  $z \rightarrow l^+ l^-$
- WZjj-EWK signal:
  - $p p \rightarrow w z j j$  QCD=0,  $w \rightarrow l v, z \rightarrow l^+ l^-$
- WZjj-QCD background:
  - $p p \rightarrow w z j j$  QCD=0,  $w \rightarrow l v, z \rightarrow l^+ l^-$
- Pre-definition:
  - define  $l = l^+ l^-$
  - define  $v = v l \bar{v} l \sim$
  - define  $w = w^+ w^-$

# $ZZjj$ cross sections as a function of dim6 operator coefficient



# WZjj cross sections as a function of dim8 operator coefficient

