



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

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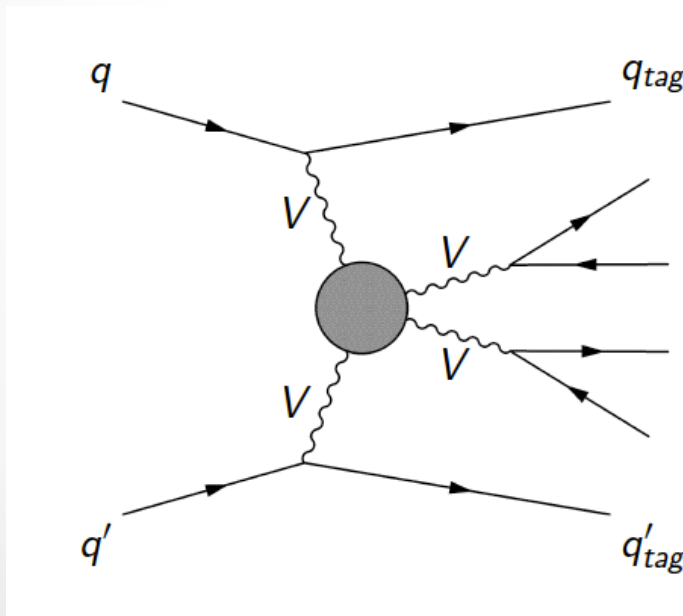
On behalf of
Snowmass EWK VBS/Triboson Group
(S. Hsu, A. Kotwal, S. Li, M. Marx, J. Metcalfe, M-A. Pleier, C. Pollard)

Outline

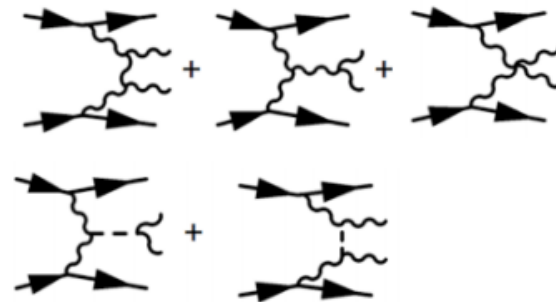
- Introduction to Vector Boson Scattering
- Anomalous coupling and Effective Field Theory(EFT) approach with high dimension operators
- VBS VV(+jj) sensitivity studies with EFT high dimension operators using ATLAS/SnowMass Parametrized Simulations
- Summary
-

Vector Boson Scattering (VBS)

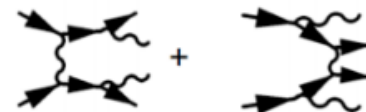
- TeV scale Unitarity Violation (UV) if NO higgs boson
- probe of the mechanism of electroweak symmetry breaking (EWSB) regardless of the underlying physics
 - Higgs boson couplings (e.g. to gauge bosons and fermions)
 - CP properties
- Can be enhanced by Higgs or extra resonances, alternative mechanism,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

$$\mathcal{O}_{\phi d} = \partial_\mu (\phi^\dagger \phi) \partial^\mu (\phi^\dagger \phi)$$

$$\mathcal{O}_{\phi W} = (\phi^\dagger \phi) \text{Tr}[W^{\mu\nu} W_{\mu\nu}]$$

$$\mathcal{O}_{\phi B} = (\phi^\dagger \phi) B^{\mu\nu} B_{\mu\nu}$$

[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

[Q.I.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, misID
- Analysis cuts: (same cuts for ssWWjj, WZjj and ZZjj)
 - Lepton: $p_T > 25 \text{ GeV}$,
 - Electron: $|\eta| < 2.47$ (excluding crack region), Muon: $|\eta| < 2.4$
 - Jets: $p_T > 50 \text{ GeV}$, $|\eta| < 5$
 - $M(jj) > 1 \text{ TeV}$ (optimized for VVjj)
 - **$M(VV)$ cutoff at UV boundaries**
 - <http://www.itp.kit.edu/~vbfnlweb/wiki/doku.php?id=download:formfactor>
- Sensitivities are studied for:
 - 300, 3000 fb^{-1} @ 14 TeV using ATLAS Upgrade Parametrized Simulations (Approved as a ATLAS PUB note result)
 - 3000 fb^{-1} @ 14 TeV (140Pileup) and 33 TeV (225Pileup) using SnowMass Delphes Parametrized FastSim (Work in progress...)

ZZjj: ATLAS Upgrade Parametrized Simulation

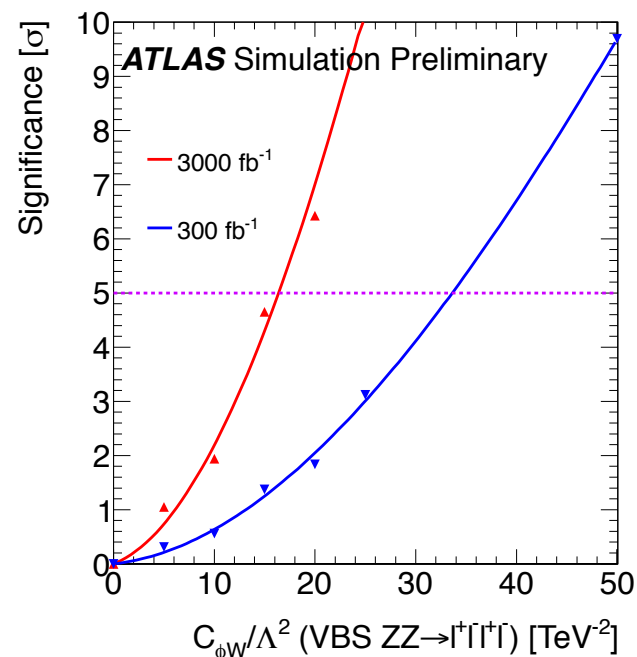
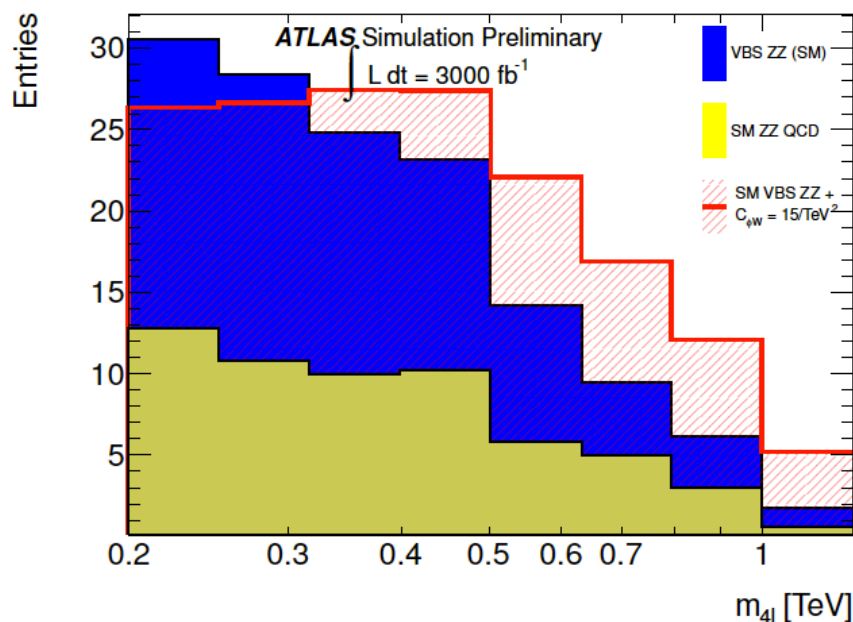
- ♦ Sensitivity accessed with M_{ZZ} spectrum

- ♦ dim6 operator $C_{\phi W}$:

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

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

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



5- σ discovery value:

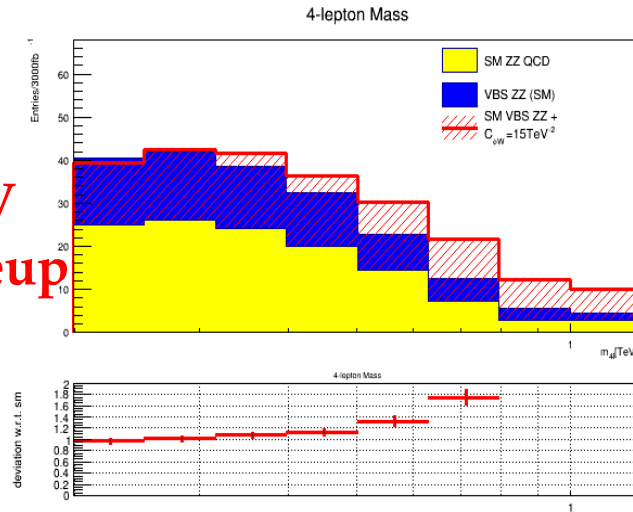
Model	300 fb^{-1}	3000 fb^{-1}
$C_{\phi W}/\Lambda^2$	34 TeV^{-2}	16 TeV^{-2}

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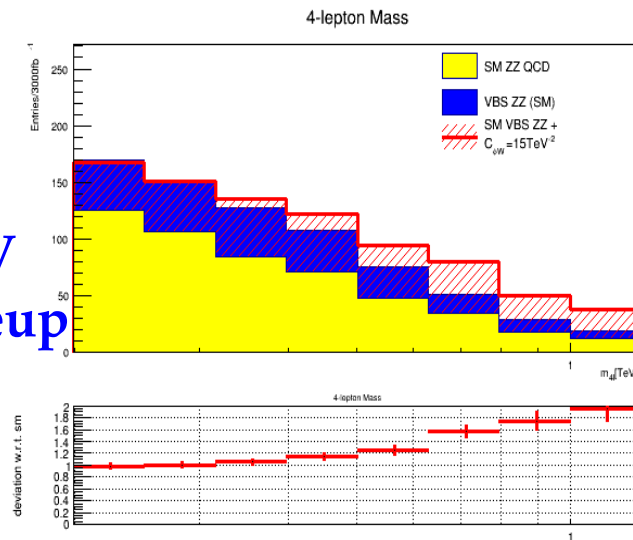
ZZjj: SnowMass EF Delphes3 Parametrized FastSim

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

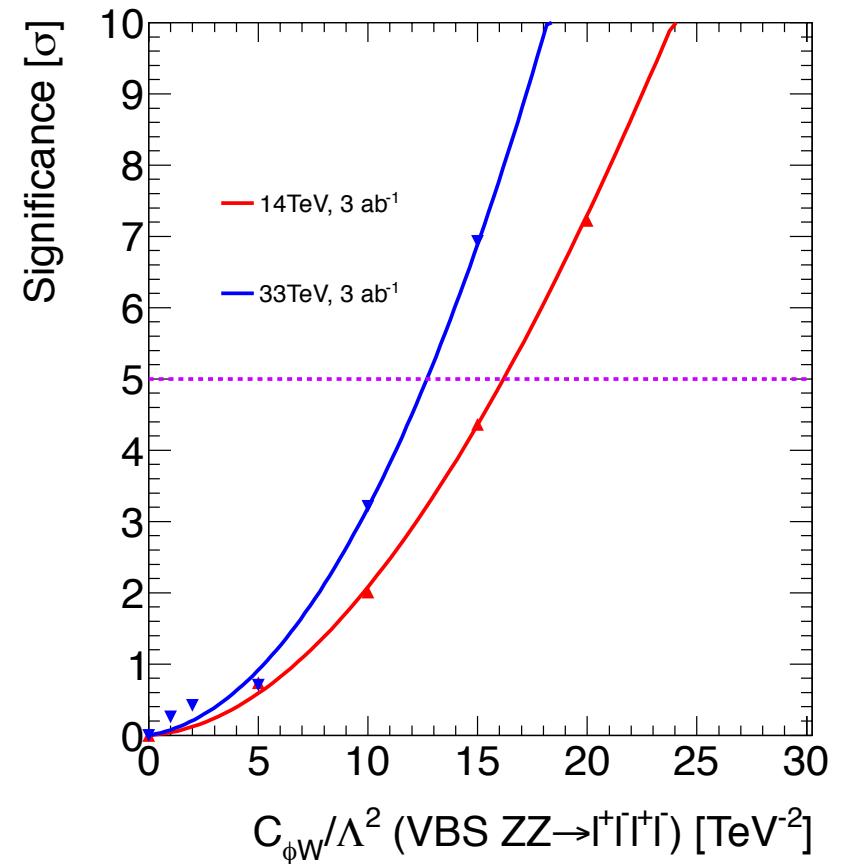
14TeV
140 Pileup



33TeV
225 Pileup



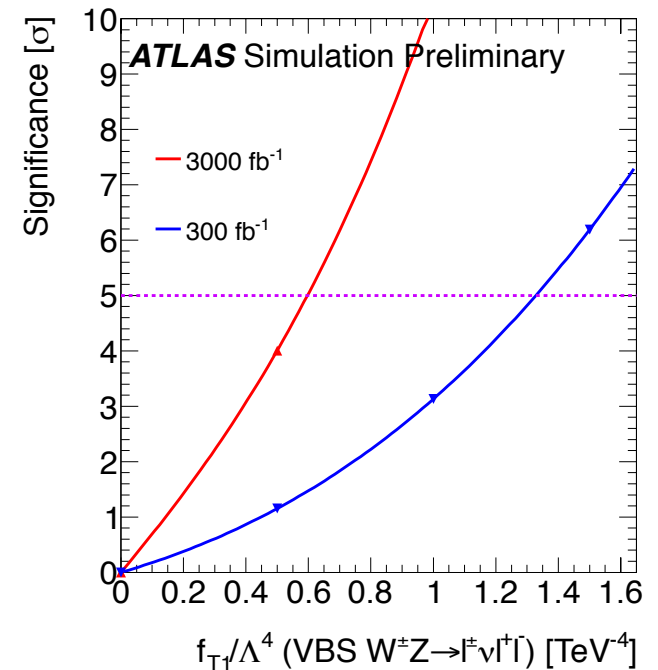
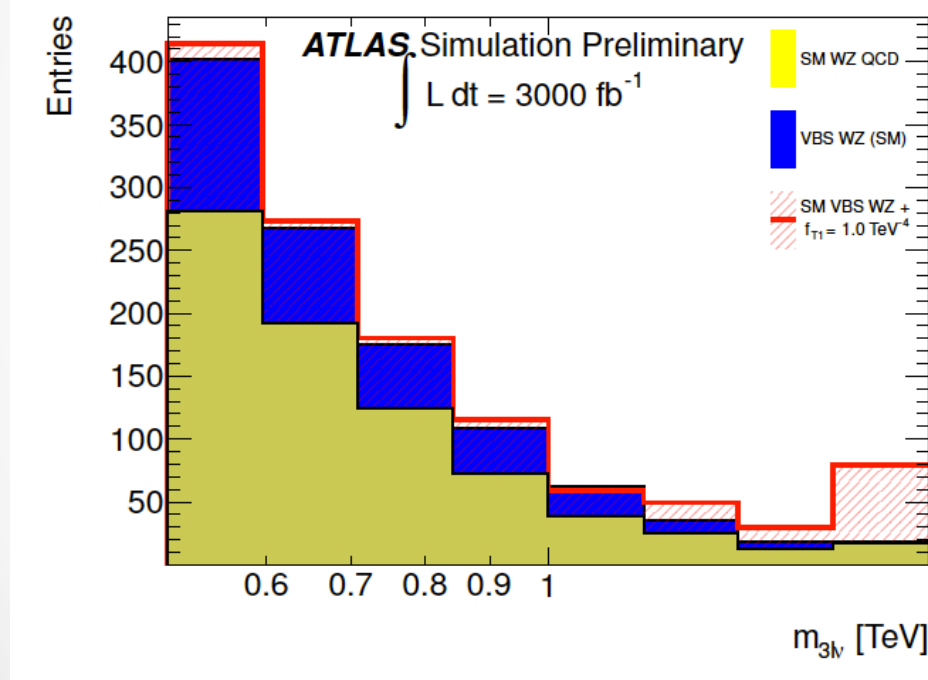
$$\mathcal{L}_{\phi W} = \frac{c_{\phi W}}{\Lambda^2} \text{Tr}(W^{\mu\nu} W_{\mu\nu}) \phi^\dagger \phi$$



W[±]Zjj

- ♦ 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- σ discovery value:

Model	300 fb ⁻¹	3000 fb ⁻¹
f_{T1}/Λ^4	1.3 TeV ⁻⁴	0.6 TeV ⁻⁴

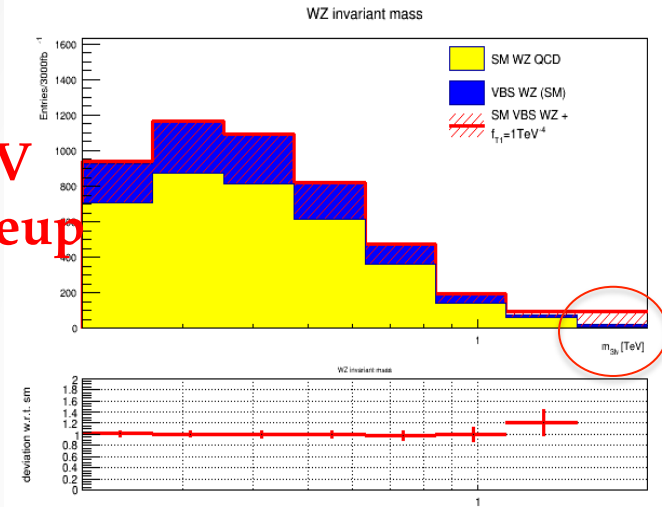
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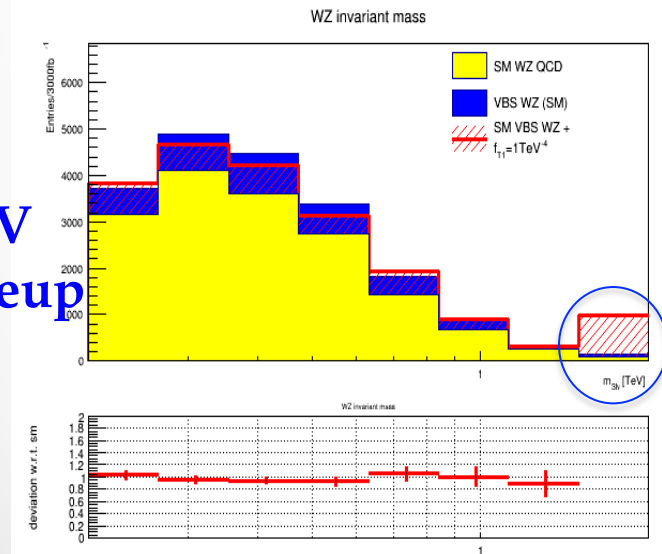
$W^\pm Z j j$: SnowMass EF Delphes3 Parametrized FastSim

- ♦ Sensitivity results at both 14 TeV and 33 TeV senario with pileups

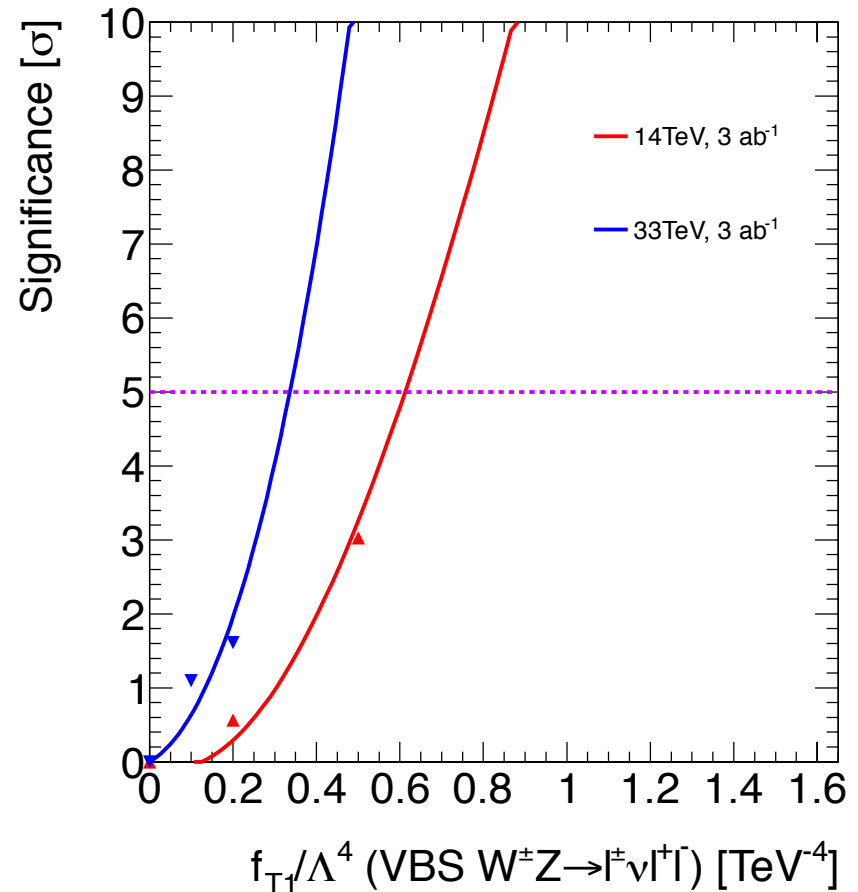
14TeV
140 Pileup



33TeV
225 Pileup



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

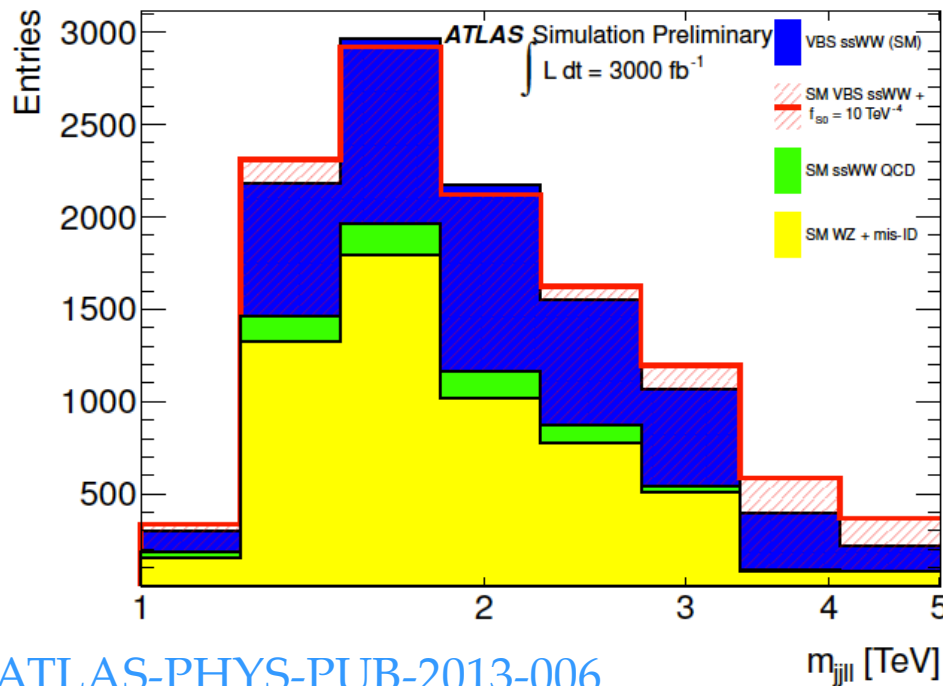


SS $W^\pm W^\pm jj$

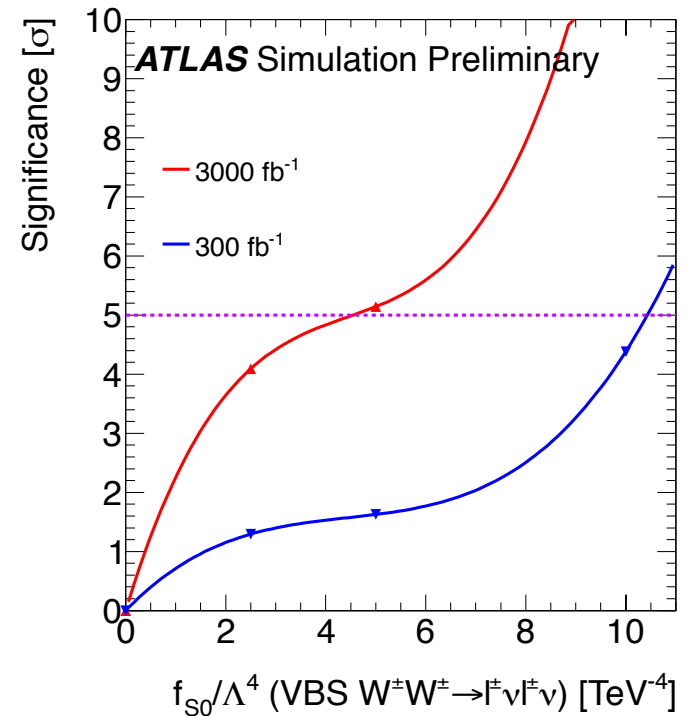
- ♦ f_{S0} correlated to α_4 in the Electroweak Chiral Lagrangian, couples to:

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

- ♦ 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- σ discovery value:

Model	300 fb ⁻¹	3000 fb ⁻¹
f_{S0}/Λ^4	10 TeV ⁻⁴	4.5 TeV ⁻⁴

J. Metcalfe
& M.-A. Pleier

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Summary

- Anomalous coupling sensitivity to new physics parameterized by EFT high dimension operators
- 300 fb⁻¹ and 3000 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	Λ_{UV} [TeV]	300 fb ⁻¹		3000 fb ⁻¹	
				5 σ	95% CL	5 σ	95% CL
$c_{\phi W}/\Lambda^2$	6	ZZ	1.9	34 TeV ⁻²	20 TeV ⁻²	16 TeV ⁻²	9.3 TeV ⁻²
f_{S0}/Λ^4	8	$W^\pm W^\pm$	2.0	10 TeV ⁻⁴	6.8 TeV ⁻⁴	4.5 TeV ⁻⁴	0.8 TeV ⁻⁴
f_{T1}/Λ^4	8	WZ	3.7	1.3 TeV ⁻⁴	0.7 TeV ⁻⁴	0.6 TeV ⁻⁴	0.3 TeV ⁻⁴
f_{T8}/Λ^4	8	$Z\gamma\gamma$	12	0.9 TeV ⁻⁴	0.5 TeV ⁻⁴	0.4 TeV ⁻⁴	0.2 TeV ⁻⁴
f_{T9}/Λ^4	8	$Z\gamma\gamma$	13	2.0 TeV ⁻⁴	0.9 TeV ⁻⁴	0.7 TeV ⁻⁴	0.3 TeV ⁻⁴

- 3000 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 σ	95% CL	5 σ	95% CL
$c_{\phi W}/\Lambda^2$	6	ZZ	16 TeV ⁻²	9.7 TeV ⁻²	13 TeV ⁻²	7.7 TeV ⁻²
f_{T1}/Λ^4	8	WZ	0.6 TeV ⁻⁴	0.4 TeV ⁻⁴	0.3 TeV ⁻⁴	0.2 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 ⁻²)	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



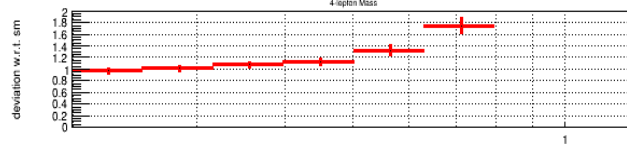
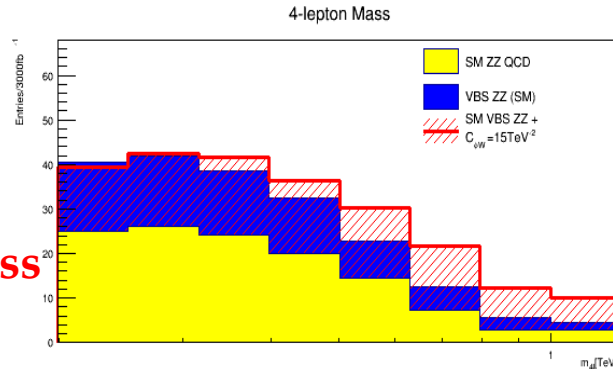
WZjj total cross section enhancements with dim8 operators

Used in current study

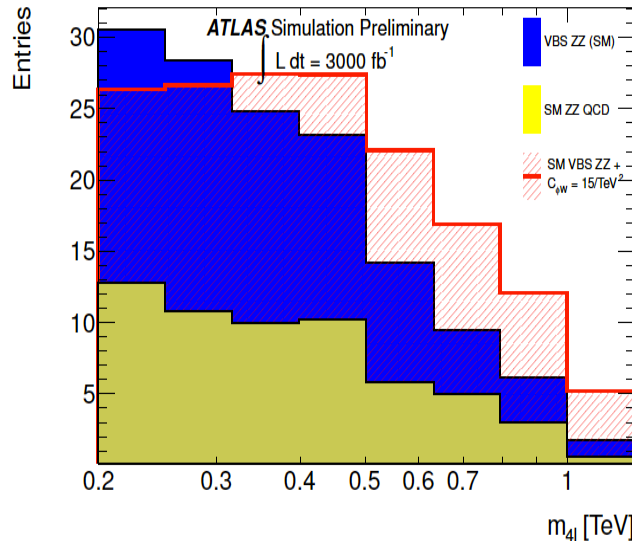
Dim8 operators(TeV ⁻⁴)	14TeV Cross section (pb)
SM	0.5367
FT0=1	0.6116
FT1=1	0.7437
FT2=1	0.5532
FM0=1	0.5386
FM1=1	0.536
FM2=1	0.5365
FM3=1	0.5386
FS0=1	0.5372
FS1=1	0.5342

ZZjj: SnowMass FastSim VS ATLAS Param Simulation

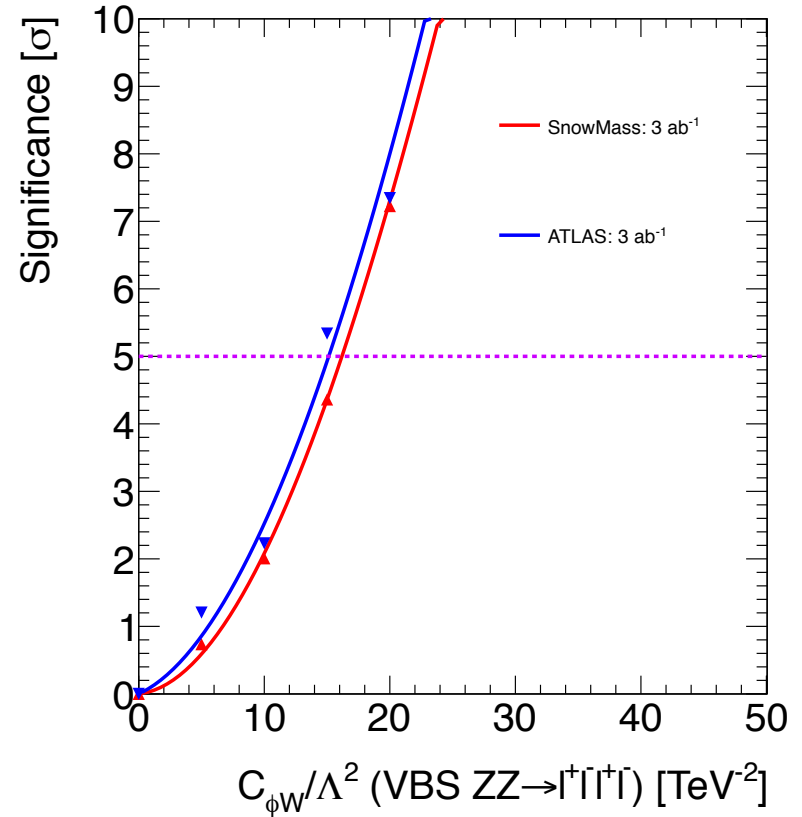
Snow Mass



ATLAS

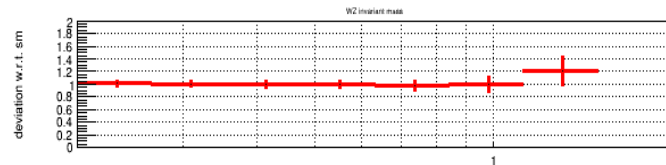
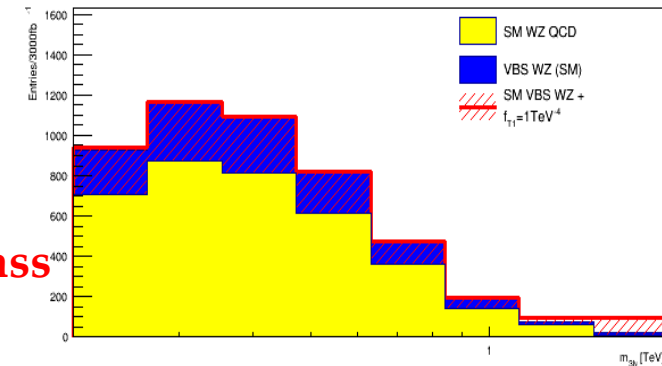


VBS ZZ signal significance
comparison w/ $C_{\phi W}$ operator

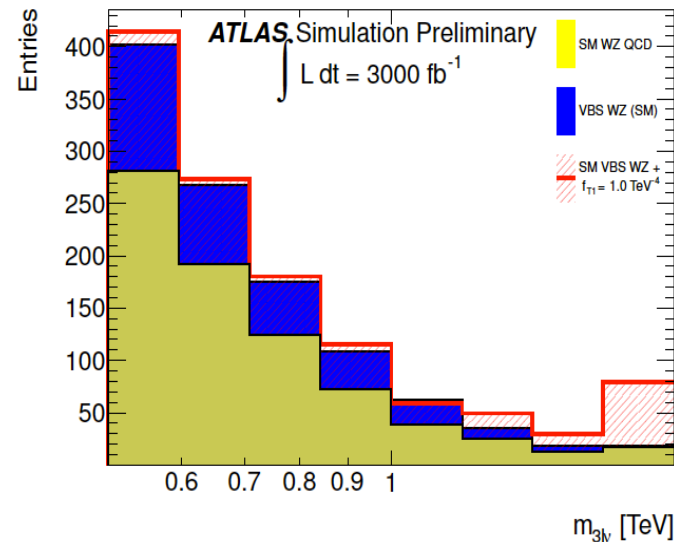


$W^\pm Z jj$: SnowMass FastSim VS ATLAS Param Simulation

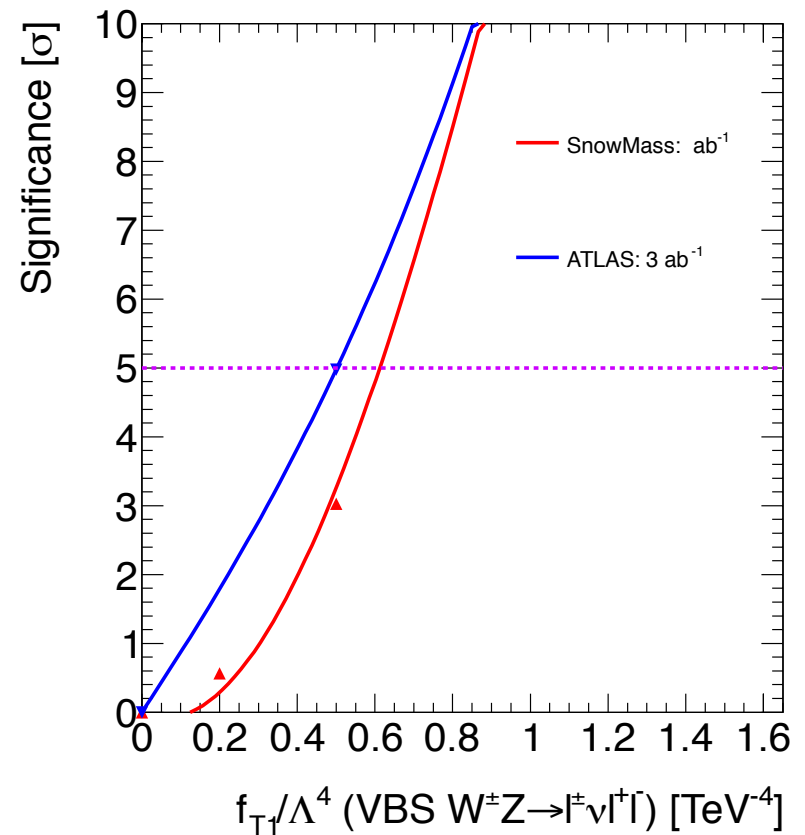
Snow Mass



ATLAS



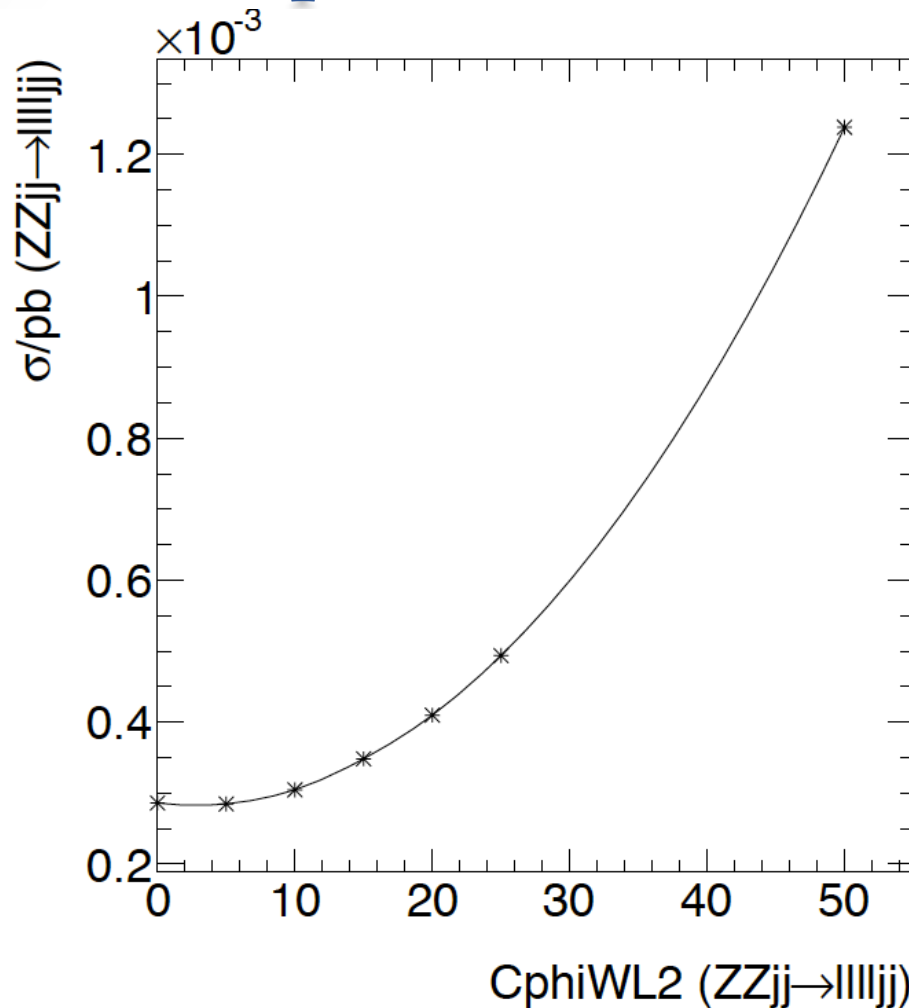
VBS WZ signal significance comparison w/ f_{T1} operator



MadGraph event generation commands

- ZZjj-EWK signal:
 - $pp > zzjj \text{ QCD}=0, z > l+l-$
- ZZjj-QCD background:
 - $pp > zzjj \text{ QCD}=2, z > l+l-$
- WZjj-EWK signal:
 - $pp > wzjj \text{ QCD}=0, w > l\nu, z > l+l-$
- WZjj-QCD background:
 - $pp > wzjj \text{ QCD}=0, w > l\nu, z > l+l-$
- Pre-definition:
 - define $l = l+l-$
 - define $\nu = \nu l \bar{\nu}$
 - define $w = w+ w-$

ZZjj cross sections as a function of dim6 operator coefficient



$WZjj$ cross sections as a function of dim8 operator coefficient

