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HL-LHC Sensitivity Studies

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Outline

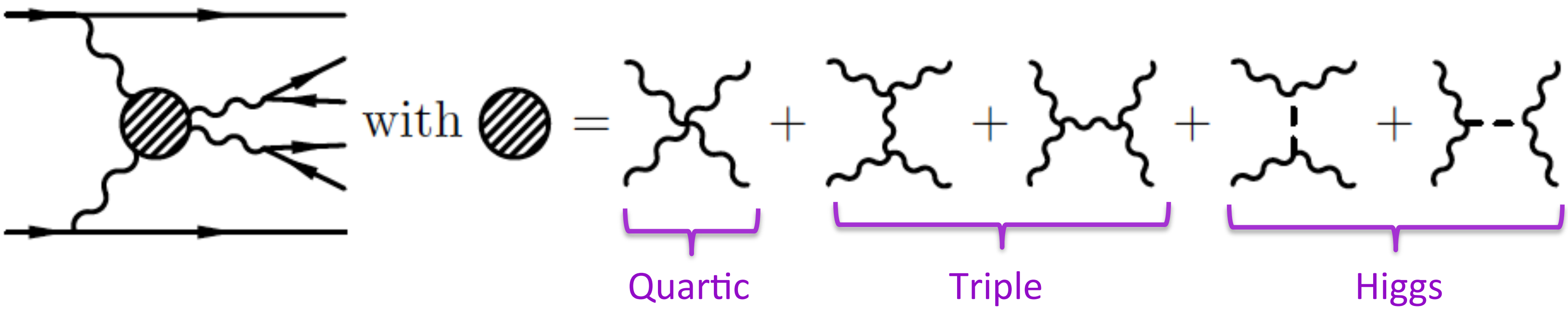
➔ Anomalous triple and quartic gauge boson couplings in VBS and tri-boson processes for a high luminosity LHC (HL-LHC): pp collider at 14 TeV

- Reminder of EFT's
- Survey of HL-LHC studies
  - Chiral Lagrangian variables
  - Dim-6 operators
  - Dim-8 operators
- Channels
  - WW
  - same-sign (ss)WW
  - WZ
  - ZZ
  - WWW
  - Zγγ

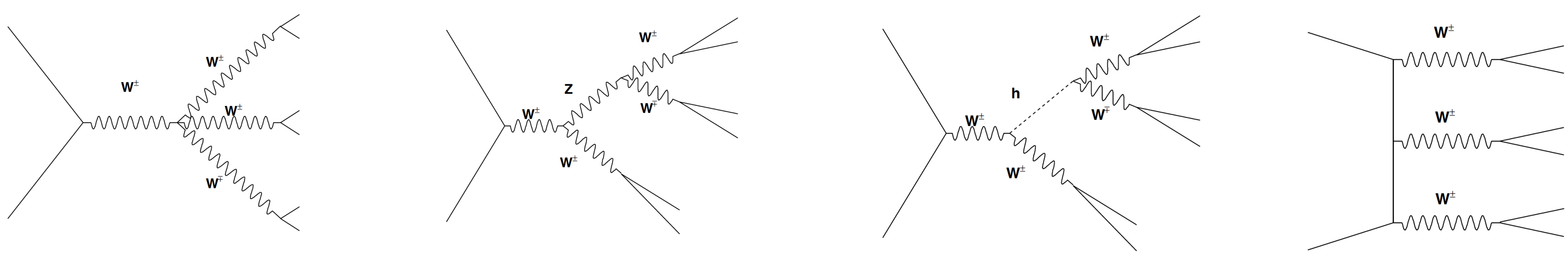
VBS and Tri-boson Production

Relevant diagrams include:

Vector Boson Scattering:



Tri-boson Processes:



EFT

EFT to look for aQGC's and aTGC's:

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \underbrace{\sum_{i=WWW,W,B,\Phi W,\Phi B} \frac{c_i}{\Lambda^2}\mathcal{O}_i}_{\text{Dimension-6}} + \underbrace{\sum_{j=0,1} \frac{f_{S,j}}{\Lambda^4}\mathcal{O}_{S,j} + \sum_{j=0,\ldots,9} \frac{f_{T,j}}{\Lambda^4}\mathcal{O}_{T,j} + \sum_{j=0,\ldots,7} \frac{f_{M,j}}{\Lambda^4}\mathcal{O}_{M,j}}_{\text{Dimension-8}}$$

- Dimension-6 operators affect triple and quartic gauge vertices
- Dimension-8 operators affect only quartic vertices

[1] Snowmass EWK arXiv:1310.6708

EFT Dim-6

Dimension-6

$$\mathcal{O}_{WWW} = \mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W_{\rho}^{\mu}]$$
$$\mathcal{O}_{W} = (D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi)$$
$$\mathcal{O}_{B} = (D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi),$$
$$\mathcal{O}_{\Phi d} = \partial_\mu\left(\Phi^\dagger\Phi\right)\partial^\mu\left(\Phi^\dagger\Phi\right)$$
$$\mathcal{O}_{\Phi W} = \left(\Phi^\dagger\Phi\right)\mathrm{Tr}[W^{\mu\nu}W_{\mu\nu}]$$
$$\mathcal{O}_{\Phi B} = \left(\Phi^\dagger\Phi\right)B^{\mu\nu}B_{\mu\nu}$$

CP conserving

$$\mathcal{O}_{\tilde{W}WW} = \mathrm{Tr}[\tilde{W}_{\mu\nu}W^{\nu\rho}W_{\rho}^{\mu}]$$
$$\mathcal{O}_{\tilde{W}} = (D_\mu\Phi)^\dagger \tilde{W}^{\mu\nu}(D_\nu\Phi)$$
$$\mathcal{O}_{\Phi d} = \partial_\mu\left(\Phi^\dagger\Phi\right)\partial^\mu\left(\Phi^\dagger\Phi\right)$$
$$\mathcal{O}_{\Phi W} = \left(\Phi^\dagger\Phi\right)\mathrm{Tr}[W^{\mu\nu}W_{\mu\nu}]$$
$$\mathcal{O}_{\Phi B} = \left(\Phi^\dagger\Phi\right)B^{\mu\nu}B_{\mu\nu}$$

CP violating

Φ = Higgs doublet field
W = SU(2)
B = U(1)

[1] Snowmass EWK
arXiv:1310.6708

EFT Dim-6

Dimension-6:

$$\sum_{i=WWW,W,B,\Phi W,\Phi B} \frac{c_i}{\Lambda^2} \mathcal{O}_i$$

X = evaluated
o = not evaluated
- = does not apply

Coupling Parameter:	Vector Boson Scattering: ssWW l±vl±v	WW lvlv	WW lvjj	WZ lvll	ZZ llll	Tri-Boson Processes: WWW lvlvlv	WWW lvlvjj	Zγγ llγγ
CWWW	o	o	o	o	-	X	o	-
CW	o	o	o	o	o	o	o	-
CB	o	o	o	-	o	o	o	-
CΦd	o	o	o	**X**	o	o	o	-
CΦW	o	o	o	-	**X**	o	o	-
CΦB	-	-	-	-	o	-	-	-
CŴWW	o	o	o	o	-	o	o	-
CŴ	o	o	o	-	o	o	o	-
CŴW	o	o	o	-	o	o	o	-
CBB	-	-	-	-	o	-	-	-

EFT Dim-8

Effective Field Theory Dimension-8 Operators: $\sum_{j=0,1} \frac{f_{S,j}}{\Lambda^4} \mathcal{O}_{S,j} + \sum_{j=0,\ldots,9} \frac{f_{T,j}}{\Lambda^4} \mathcal{O}_{T,j} + \sum_{j=0,\ldots,7} \frac{f_{M,j}}{\Lambda^4} \mathcal{O}_{M,j}$

Higgs Field

$$\mathcal{O}_{S,0} = \left[(D_\mu \Phi)^\dagger D_\nu \Phi \right] \times \left[(D^\mu \Phi)^\dagger D^\nu \Phi \right]$$

$$\mathcal{O}_{S,1} = \left[(D_\mu \Phi)^\dagger D^\mu \Phi \right] \times \left[(D_\nu \Phi)^\dagger D^\nu \Phi \right]$$

Gauge Boson Fields

$$\mathcal{O}_{T,0} = \mathrm{Tr}\left[W_{\mu\nu} W^{\mu\nu} \right] \times \mathrm{Tr}\left[W_{\alpha\beta} W^{\alpha\beta} \right]$$

$$\mathcal{O}_{T,1} = \mathrm{Tr}\left[W_{\alpha\nu} W^{\mu\beta} \right] \times \mathrm{Tr}\left[W_{\mu\beta} W^{\alpha\nu} \right]$$

$$\mathcal{O}_{T,2} = \mathrm{Tr}\left[W_{\alpha\mu} W^{\mu\beta} \right] \times \mathrm{Tr}\left[W_{\beta\nu} W^{\nu\alpha} \right]$$

$$\mathcal{O}_{T,5} = \mathrm{Tr}\left[W_{\mu\nu} W^{\mu\nu} \right] \times B_{\alpha\beta} B^{\alpha\beta} ,$$

$$\mathcal{O}_{T,6} = \mathrm{Tr}\left[W_{\alpha\nu} W^{\mu\beta} \right] \times B_{\mu\beta} B^{\alpha\nu} ,$$

$$\mathcal{O}_{T,7} = \mathrm{Tr}\left[W_{\alpha\mu} W^{\mu\beta} \right] \times B_{\beta\nu} B^{\nu\alpha} ,$$

$$\mathcal{O}_{T,8} = B_{\mu\nu} B^{\mu\nu} B_{\alpha\beta} B^{\alpha\beta}$$

$$\mathcal{O}_{T,9} = B_{\alpha\mu} B^{\mu\beta} B_{\beta\nu} B^{\nu\alpha} .$$

Higgs and Gauge Boson Fields

$$\mathcal{O}_{M,0} = \mathrm{Tr}\left[W_{\mu\nu} W^{\mu\nu} \right] \times \left[(D_\beta \Phi)^\dagger D^\beta \Phi \right]$$

$$\mathcal{O}_{M,1} = \mathrm{Tr}\left[W_{\mu\nu} W^{\nu\beta} \right] \times \left[(D_\beta \Phi)^\dagger D^\mu \Phi \right]$$

$$\mathcal{O}_{M,2} = \left[B_{\mu\nu} B^{\mu\nu} \right] \times \left[(D_\beta \Phi)^\dagger D^\beta \Phi \right] ,$$

$$\mathcal{O}_{M,3} = \left[B_{\mu\nu} B^{\nu\beta} \right] \times \left[(D_\beta \Phi)^\dagger D^\mu \Phi \right] ,$$

$$\mathcal{O}_{M,4} = \left[(D_\mu \Phi)^\dagger W_{\beta\nu} D^\mu \Phi \right] \times B^{\beta\nu} ,$$

$$\mathcal{O}_{M,5} = \left[(D_\mu \Phi)^\dagger W_{\beta\nu} D^\nu \Phi \right] \times B^{\beta\mu} ,$$

$$\mathcal{O}_{M,6} = \left[(D_\mu \Phi)^\dagger W_{\beta\nu} W^{\beta\nu} D^\mu \Phi \right] ,$$

$$\mathcal{O}_{M,7} = \left[(D_\mu \Phi)^\dagger W_{\beta\nu} W^{\beta\mu} D^\nu \Phi \right] ,$$

[1] Snowmass EWK
arXiv:1310.6708

EFT Dim-8

Coupling Parameter:	VBS: ssWW l±vl±v	WW lvlv	WW lvjj	WZ lvll	ZZ llll	Tri-boson: WWW lvlvlv	WWW lvlvjj	Zγγ llγγ
FS0	X	o	o	o	o	X	X	-
FS1	o	o	o	o	o	X	X	-
FT0	o	o	o	o	o	X	X	o
FT1	X	o	o	X	o	o	o	o
FT2	o	o	o	o	o	o	o	o
FT6	-	-	-	o	o	-	-	o
FT7	-	-	-	o	o	-	-	o
FT8	-	-	-	-	X	-	-	X
FT9	-	-	-	-	X	-	-	X
FM0	o	o	o	o	o	o	o	X
FM1	o	o	o	o	o	o	o	X
FM2	-	-	-	o	o	-	-	X
FM3	-	-	-	o	o	-	-	X
FM4	-	-	-	o	o	-	-	o
FM5	-	-	-	o	o	-	-	o
FM6	o	o	o	o	o	o	o	o
FM7	o	o	o	o	o	o	o	o

EFT Chiral Lagrangian

Dimension-8 Chiral Lagrangian formulation:

$$\mathcal{L}_4^{(4)} = \alpha_4 \left[\mathrm{Tr}\left(V_\mu V_\nu\right)\right]^2$$

$$\mathcal{L}_5^{(4)} = \alpha_5 \left[\mathrm{Tr}\left(V_\mu V^\mu\right)\right]^2$$

[1] Snowmass EWK
arXiv:1310.6708

where α_4 and α_5 are a function of f_{S0} and f_{S1} for a given VV process

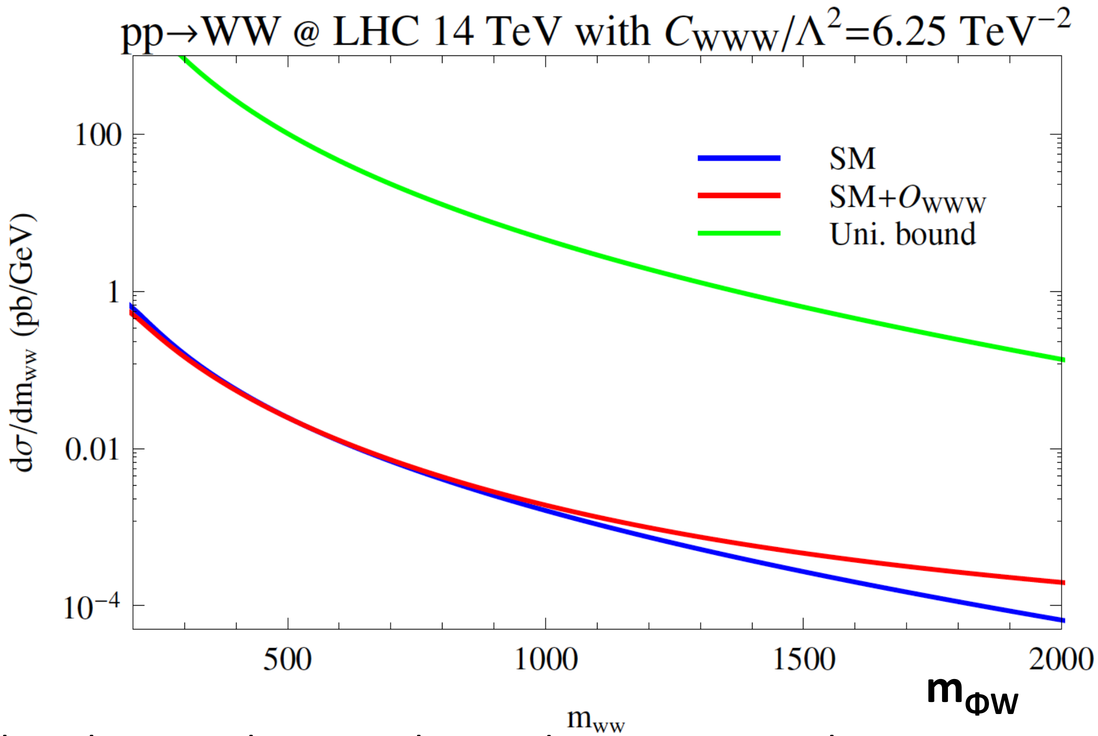
- α_4 and α_5 are the lowest dimension operators that affect aQGC
- $m_{Resonance}$ is determined by the values α_4 and α_5

	Vector Boson Scattering:					Tri-Boson Processes:		
Coupling Parameter:	ssWW l±νl±ν	WW lνlν	WW lνjj	WZ lνll	ZZ llll	WWW lνlνlν	WWW lνlνjj	Zγγ llγγ
α4	o	X	X	o	o	o	o	-
α5	o	o	X	o	o	o	o	-
m-resonance	o	o	X	o	X	o	o	o

Unitarity Bounds

Unitarity Violation:

WW



$m_{\Phi W}$

[1] Snowmass EWK arXiv:1310.6708

- EFT is valid below the new physics scale Λ and no unitarity violation occurs
- Dim-8 generally has a lower threshold in the invariant mass where UV violation occurs than dim-6 due to $1/\Lambda^4$
- Different methods were employed in different studies to cope with the UV boundary including UV cut-off, UV form-factor, and K-matrix,
- Most studies presented here are without UV treatment for consistent comparison and model independence

Channels

VBS @ HL-LHC

[2] Snowmass VBS
arXiv:1309.7452v1

- MadGaph
- Pythia8
- Delphes: generic HL-LHC detector
- 14 TeV,
- 0 PU
- $W^{\pm}W^{\pm}$: 0,50,140 PU
- no unitarization (UV cut-off from VBFNLO)

WZ->lvll
ZZ->llll
$W^{\pm}W^{\pm}$->lvlv
Zγγ->llγγ
WWW->lvlvlv

[3] ATLAS 2013
ATLAS-PHYS-PUB-2013-006

- MadGaph
- Pythia8
- TruthToReco from European Strategy
- "high pileup" (80)
- no unitarization

WZ->lvll
ZZ->llll
$W^{\pm}W^{\pm}$->lvlv
Zγγ->llγγ

[4] ATLAS 2012
ATL-UPGRADE-PUB-2012-006

- MadGaph, Whizard
- Pythia8
- TruthToReco from European Strategy
- 14 TeV
- "high pileup" (80)
- K-matrix unitarization

WW->lvlv
WW->lvjj
ZZ->llll

[5] Beijing CMS 2014
arXiv:1407.4922v1

- MadGaph
- Pythia8
- Delphes: CMS detector
- 14 TeV
- No pileup
- no unitarization
- BDT optimization

WWW->lvlvlv
WWW->lvlvjj

Coupling Parameters

ssWW

Dimension-8 parameters for ssWW:

operator	cross section ratio
$\mathcal{L}_{S,0}$	1.1
$\mathcal{L}_{S,1}$	1.0
$\mathcal{L}_{M,0}$	1.3
$\mathcal{L}_{M,1}$	1.1
$\mathcal{L}_{T,0}$	33
$\mathcal{L}_{T,1}$	150
$\mathcal{L}_{T,2}$	17

- Scan variables and compare to the SM cross-section (9 fb) for $\sqrt{s}$ = 14 TeV and coupling parameter tuned to $f_{x,i}/\Lambda^4 = 10\ \mathrm{TeV}^{-4}$
- $f_{T,1}$ shows the largest increase in cross-section
  - Select as focus for detailed studies

[2] Snowmass VBS arXiv:1309.7452v1

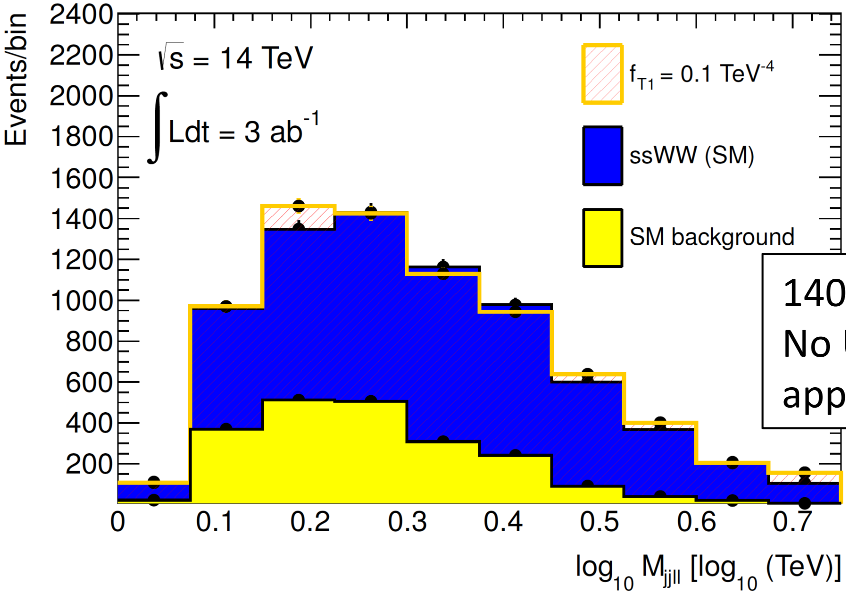
ssWW

FT1

$W^{\pm}W^{\pm}$->lvlv

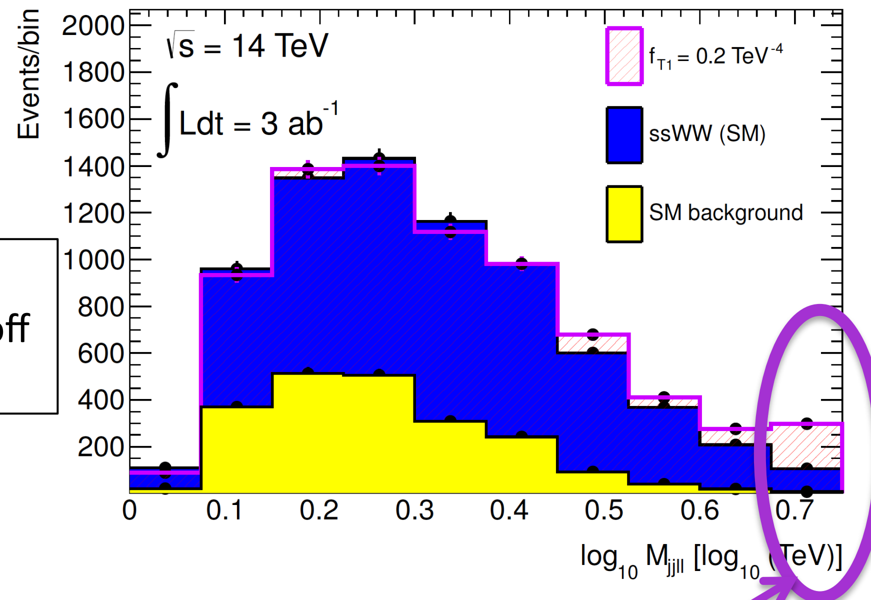
[2] Snowmass VBS arXiv:1309.7452v1

$FT1/\Lambda^4 = 0.1$ [TeV^{-4}]



140 pileup
No UV cutoff applied

$FT1/\Lambda^4 = 0.2$ [TeV^{-4}]



Significance = 4.2σ

Significance = 17σ

- As the coupling parameter FT1 is increased the new physics signature begins to emerge
- The new physics manifests in the high invariant mass bins of the two forward jets and two leptons

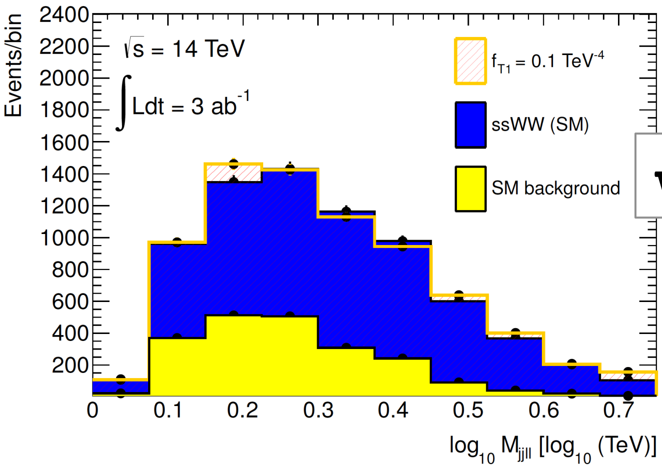
ssWW

FT1

$W^{\pm}W^{\pm} \rightarrow l\nu l\nu$

FT1/Λ^4 = 0.1 [TeV^{-4}]

140 PU

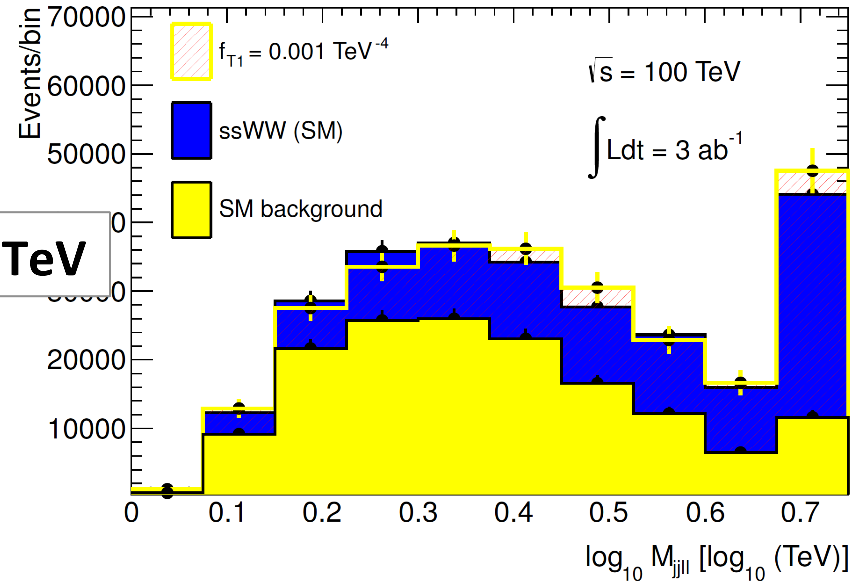


Significance = 4.2σ

√s: 14 -> 100 TeV

FT1/Λ^4 = 0.001 [TeV^{-4}]

263 PU



Significance = 4.0σ

- Higher pp center-of-mass energy enhances high m_{jjll} spectrum in SM and new physics
- Significance remains about the same ~4σ (no UV cutoff applied)
  - Different pileup scenarios
  - No selection optimization

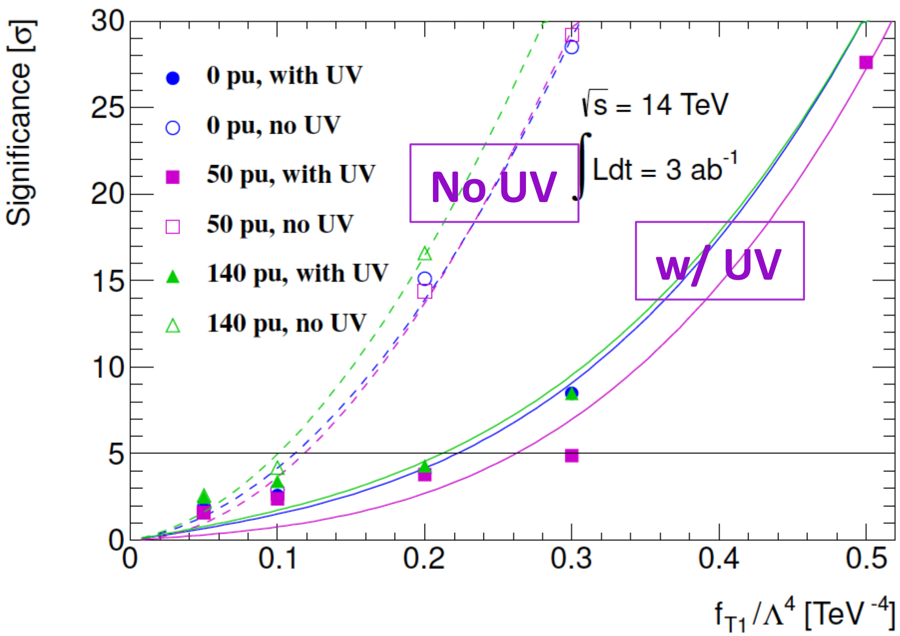
[2] Snowmass VBS arXiv:1309.7452v1

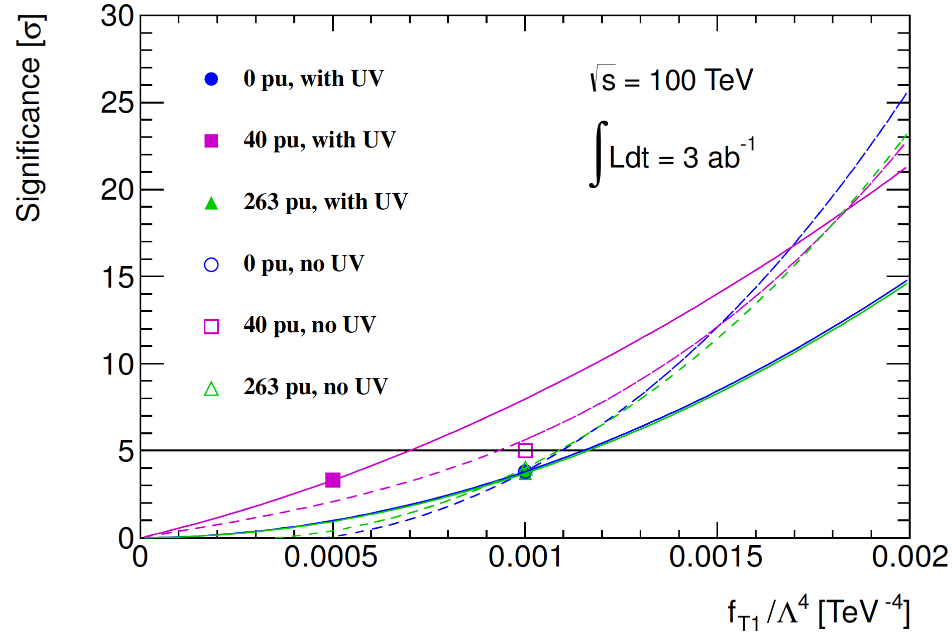
ssWW

FT1

$W^{\pm}W^{\pm}$->lνlν

[2] Snowmass VBS
arXiv:1309.7452v1





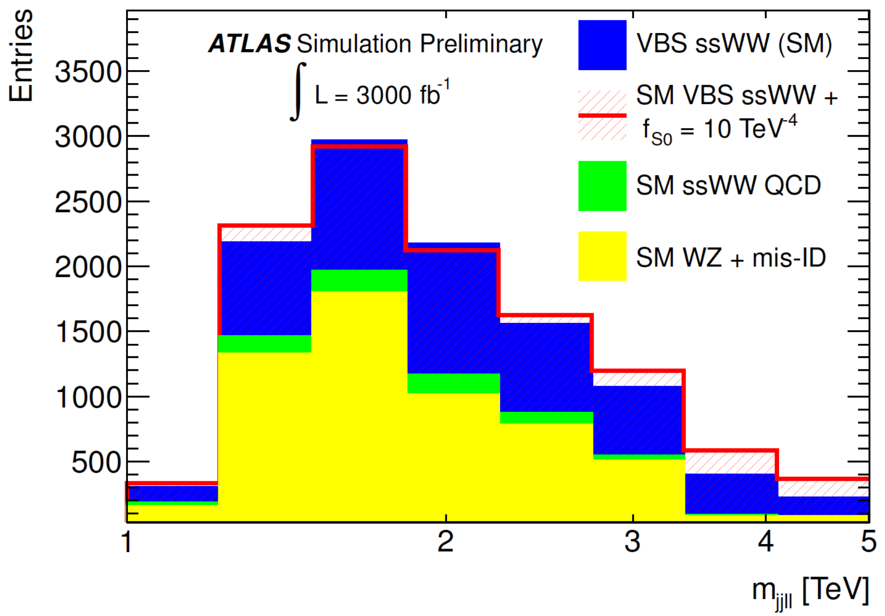
- The results shown here are fairly independent of pileup
- At √s = 14 TeV the UV cutoff makes a larger impact on the 5σ significance value by approximately a factor of 2
  - No UV and UV cutoff are extremes in the significance
- A √s = 100 TeV machine may increase the reach by a factor of 100

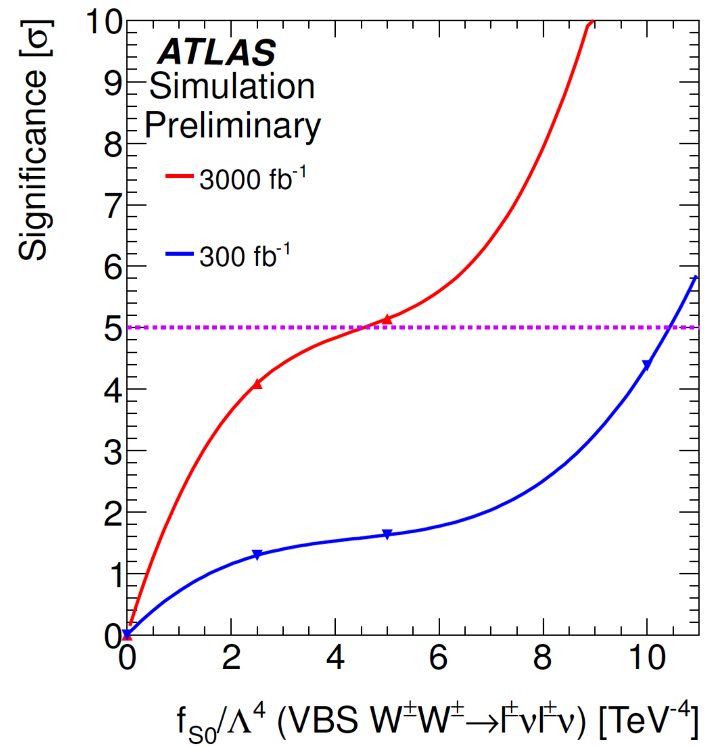
ssWW

FS0

$W^{\pm}W^{\pm}$->lνlν

[3] ATLAS 2013
ATLAS-PHYS-PUB-2013-006





5σ discovery potential:

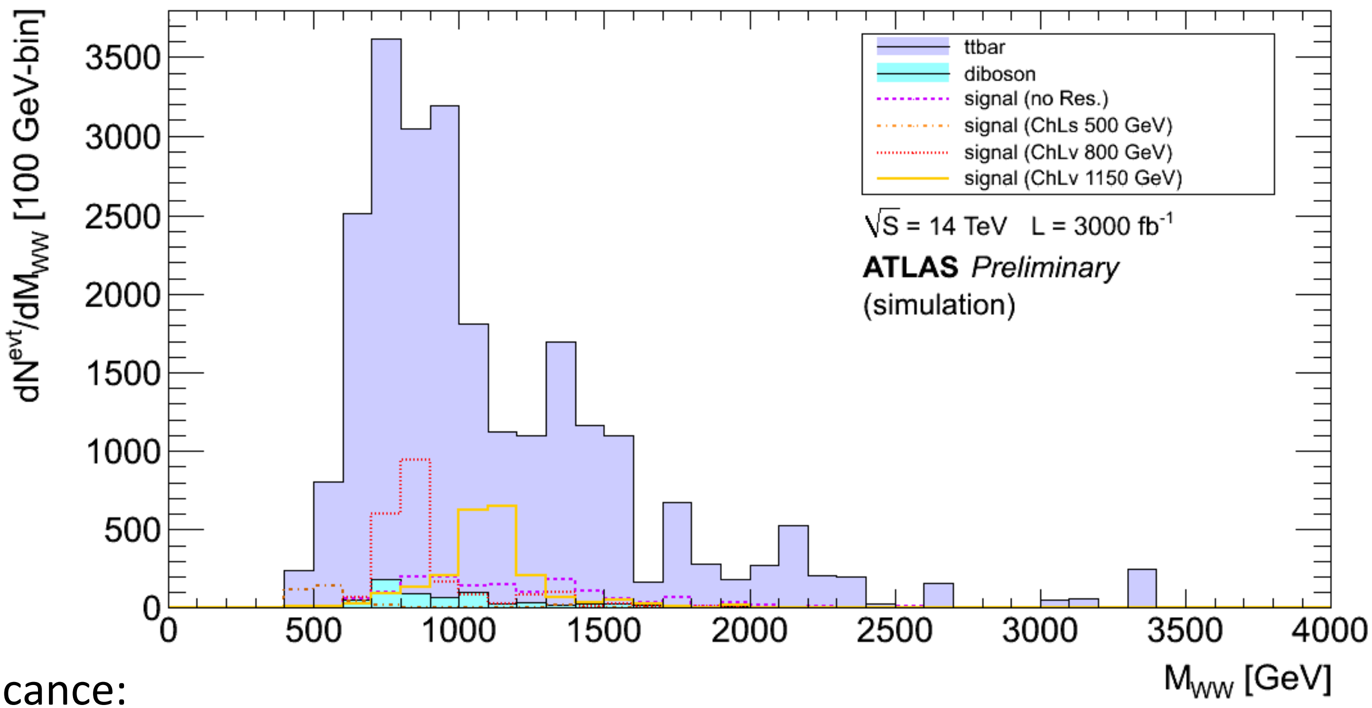
model	300 fb^{-1}	3 ab^{-1}
f_{S0}/Λ^4	10 TeV^{-4}	4.5 TeV^{-4}

No UV

WW

WW -> lvjj

[4] ATLAS 2012
ATL-UPGRADE-PUB-2012-006



σ significance:

model	baseline	500 GeV scalar	800 GeV vector	1150 GeVvector
(a_4, a_5)	$(0, 0)$	$(0.01, 0.009)$	$(0.009, -0.007)$	$(0.004, -0.004)$
S/B	$(3.3 \pm 0.3)\%$	$(0.7 \pm 0.1)\%$	$(4.9 \pm 0.3)\%$	$(5.8 \pm 0.3)\%$
$S/\sqrt{B}$ $(L = 300\text{fb}^{-1})$	2.3 ± 0.3	0.6 ± 0.1	3.3 ± 0.4	3.9 ± 0.4
$S/\sqrt{B}$ $(L = 3000\,\text{fb}^{-1})$	7.2 ± 0.1	1.6 ± 0.1	10.4 ± 0.7	12.4 ± 0.7

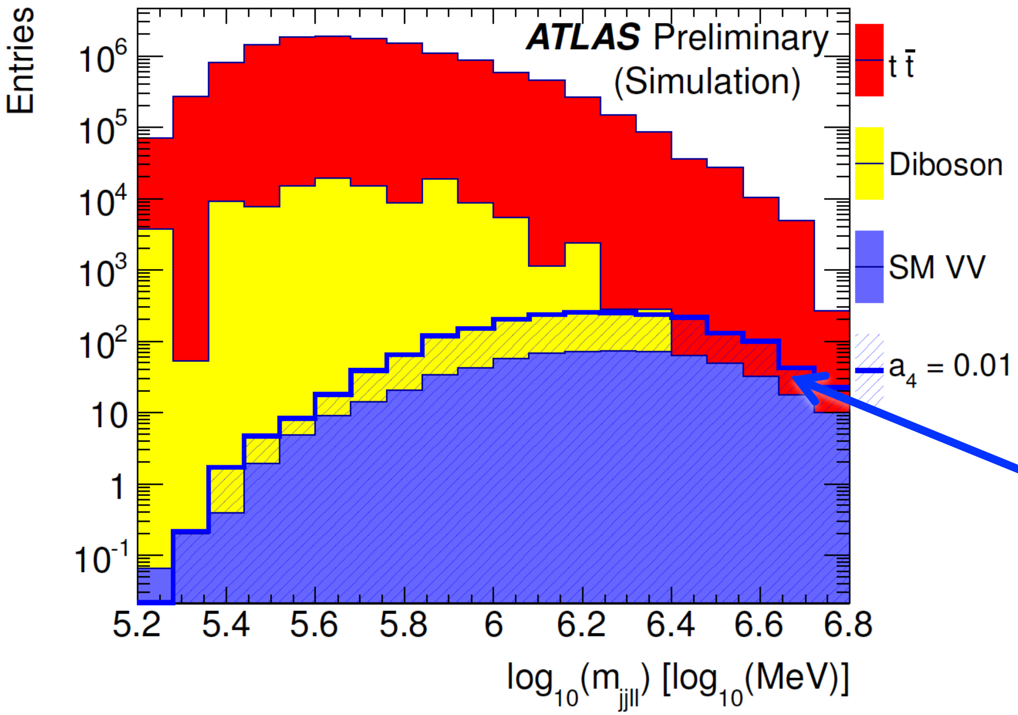
Discovery potential

WW

WW -> lνlν

[4] ATLAS 2012
ATL-UPGRADE-PUB-2012-006

3,000 fb^{-1}:



Process	σ BR (fb)
$t\bar{t}$	43.0×10^3
$a_4 = 0$	2.21
$a_4 = 0.003$	3.33
$a_4 = 0.01$	7.11
$a_4 = 0.03$	18.7

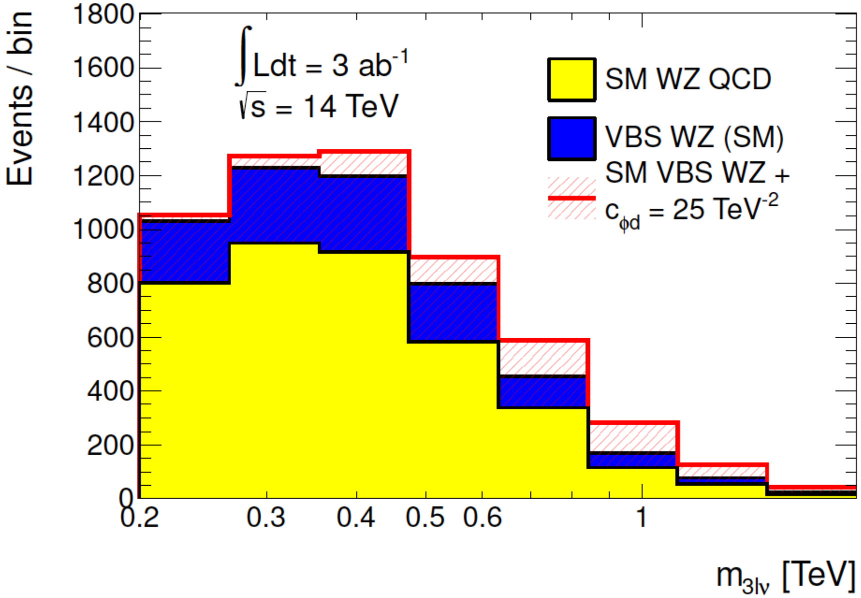
95% confidence limits:

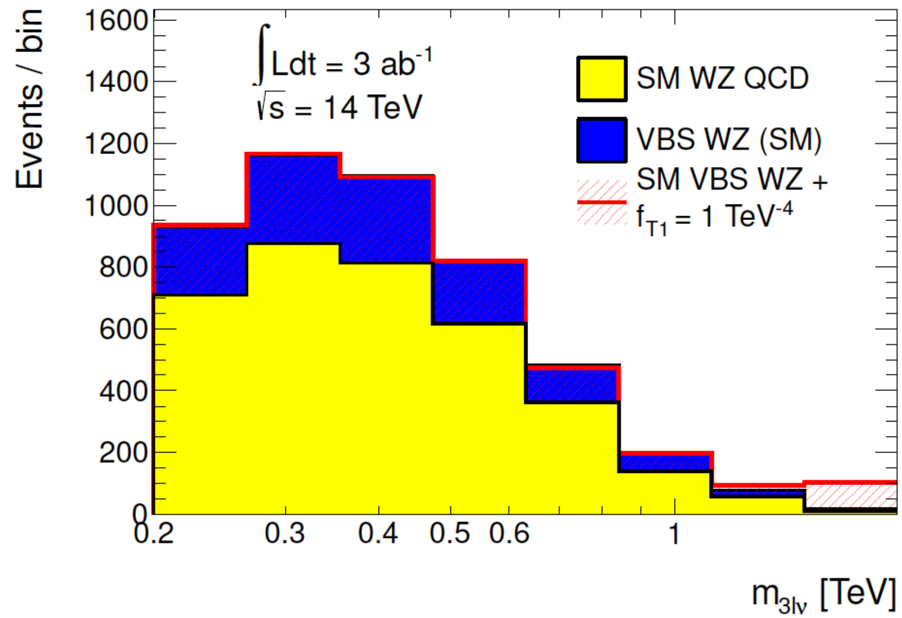
model	300 fb^{-1}	1 ab^{-1}	3 ab^{-1}
a_4	0.066	0.025	0.016

WZ

WZ -> lvll

[2] Snowmass VBS
arXiv:1309.7452v1



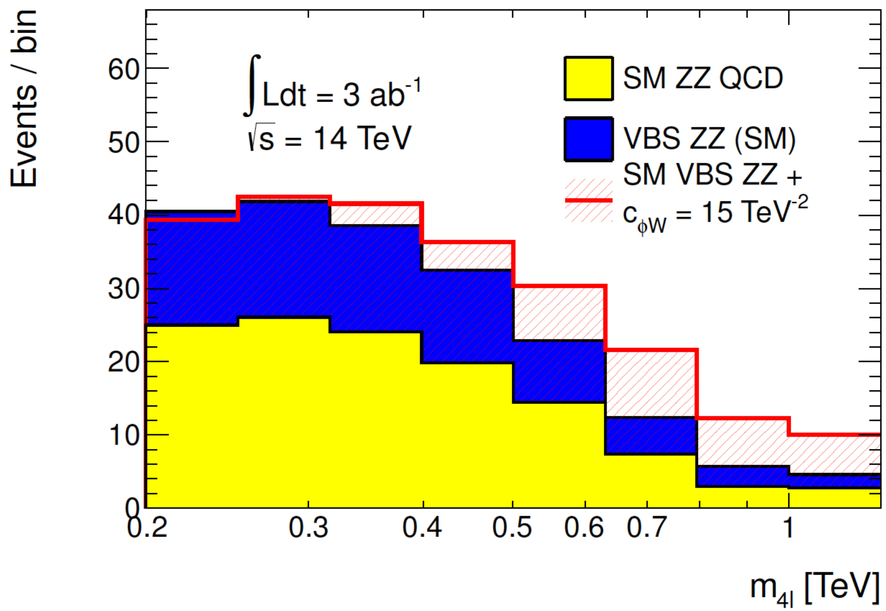


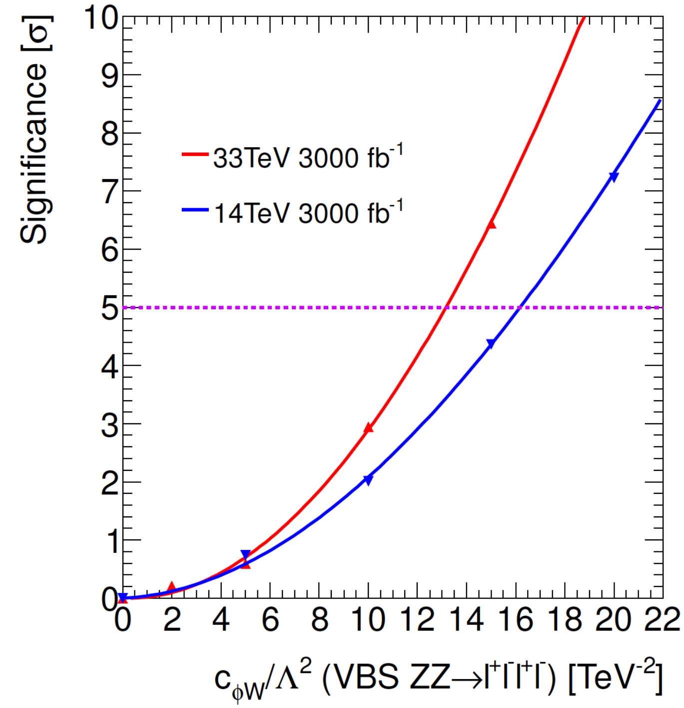
Parameter	Luminosity [fb^{-1}]	14 TeV		33 TeV	
		5σ	95% CL	5σ	95% CL
$c_{\phi d}/\Lambda^2$ [TeV^{-2}]	3000	15.2 (15.2)	9.1 (9.1)	12.6 (12.7)	7.7 (7.7)
	300	28.5 (28.7)	17.1 (17.1)	23.1 (23.3)	14.1 (14.2)
f_{T1}/Λ^4 [TeV^{-4}]	3000	0.6 (0.9)	0.4 (0.5)	0.3 (0.6)	0.2 (0.3)
	300	1.1 (1.6)	0.7 (1.0)	0.6 (0.9)	0.3 (0.6)

ZZ

[2] Snowmass VBS arXiv:1309.7452v1

ZZ -> llll



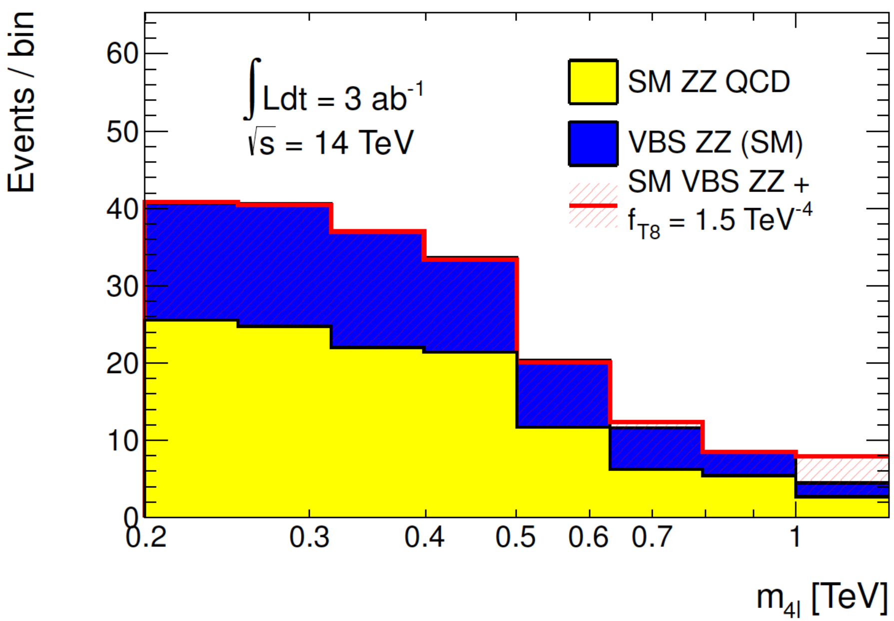


Parameter	Luminosity $[\text{fb}^{-1}]$	14 TeV		33 TeV	
		5σ	95% CL	5σ	95% CL
$c_{\phi W}/\Lambda^2$ $[\text{TeV}^{-2}]$	3000	16.2 (16.2)	9.7 (9.7)	13.2 (13.2)	8.2 (8.2)
	300	31.3 (31.5)	18.2 (18.3)	23.8 (23.8)	14.7 (14.7)

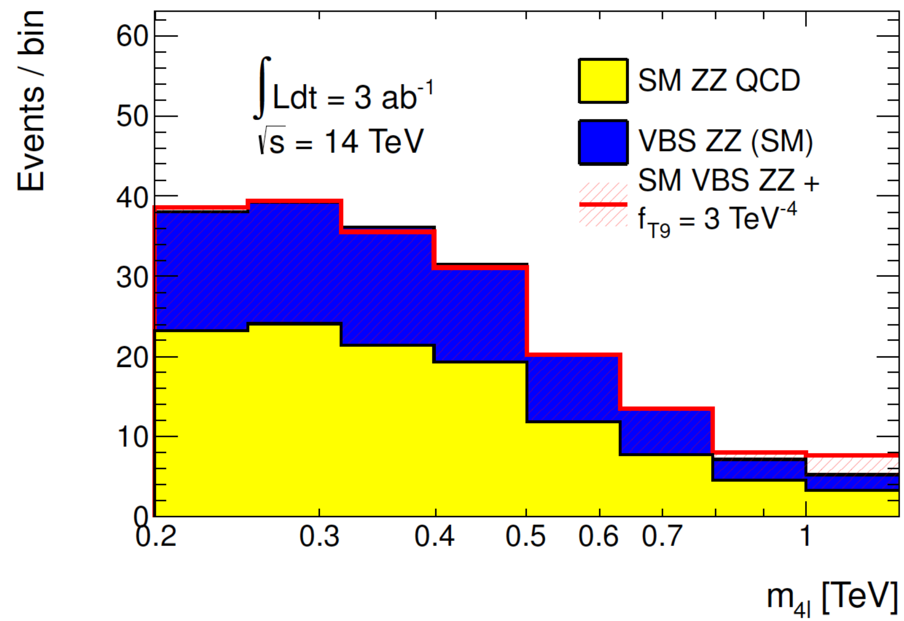
ZZ

ZZ -> llll

FT8



FT9



Parameter	Luminosity [fb^{-1}]	14 TeV		33 TeV	
		5σ	95% CL	5σ	95% CL
f_{T8}/Λ^4 [TeV^{-4}]	3000	2.9 (4.7)	1.7 (2.4)	1.6 (1.7)	1.0 (1.3)
	300	5.5 (8.4)	3.2 (5.3)	2.8 (2.3)	1.8 (1.8)
f_{T9}/Λ^4 [TeV^{-4}]	3000	5.7 (6.3)	3.9 (4.6)	3.8 (6.6)	2.5 (3.5)
	300	8.7 (9.0)	6.2 (6.7)	6.3 (10.1)	4.2 (8.2)

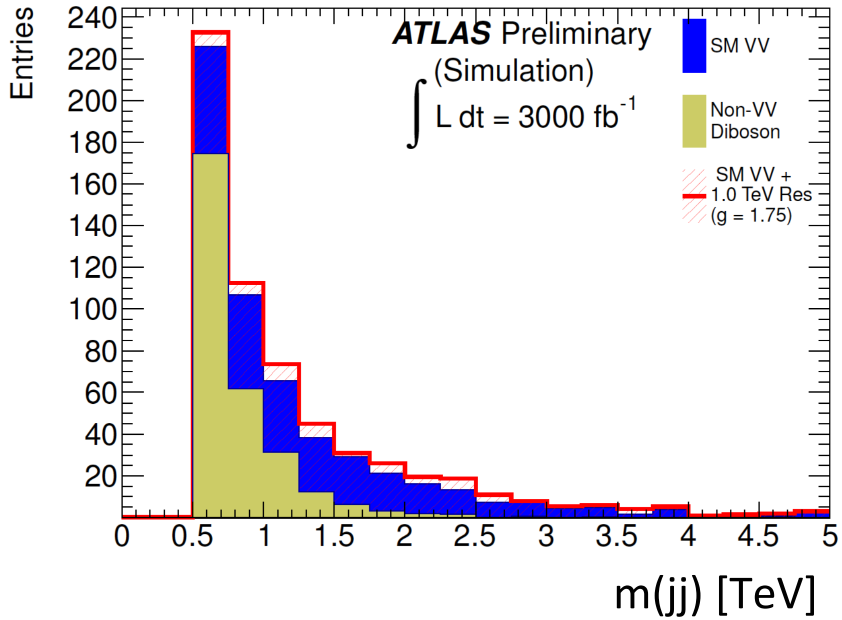
[2] Snowmass VBS
arXiv:1309.7452v1

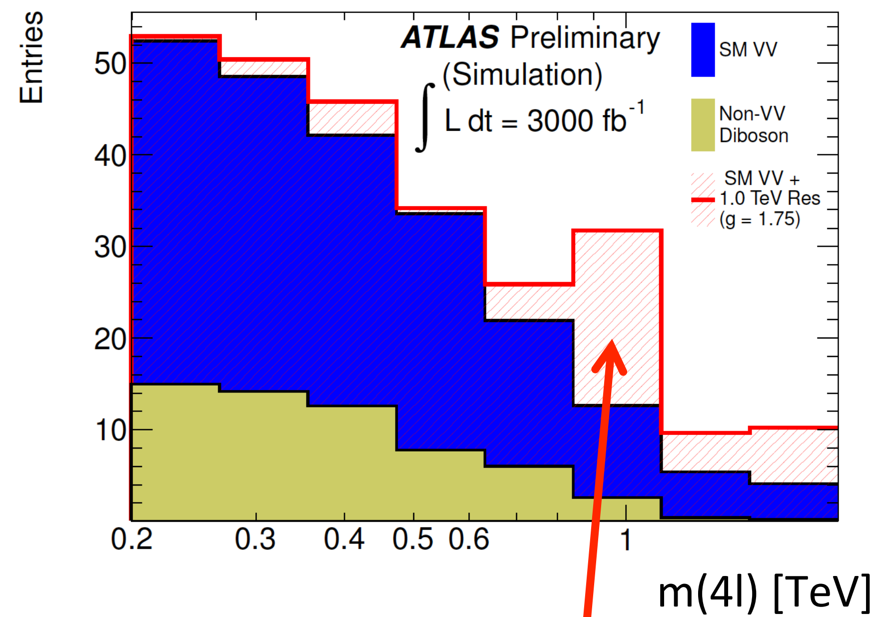
ZZ

$m_{Resonance}$

ZZ -> llll

[4] ATLAS 2012
ATL-UPGRADE-PUB-2012-006



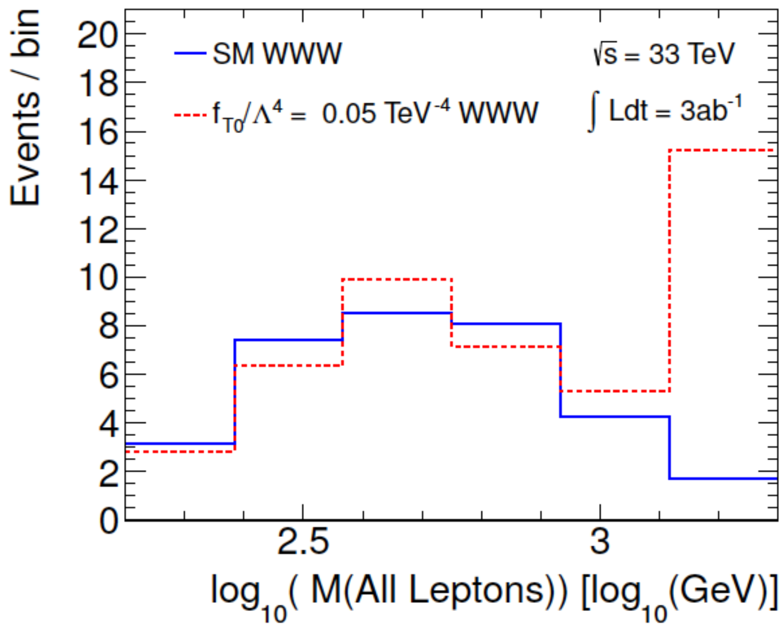


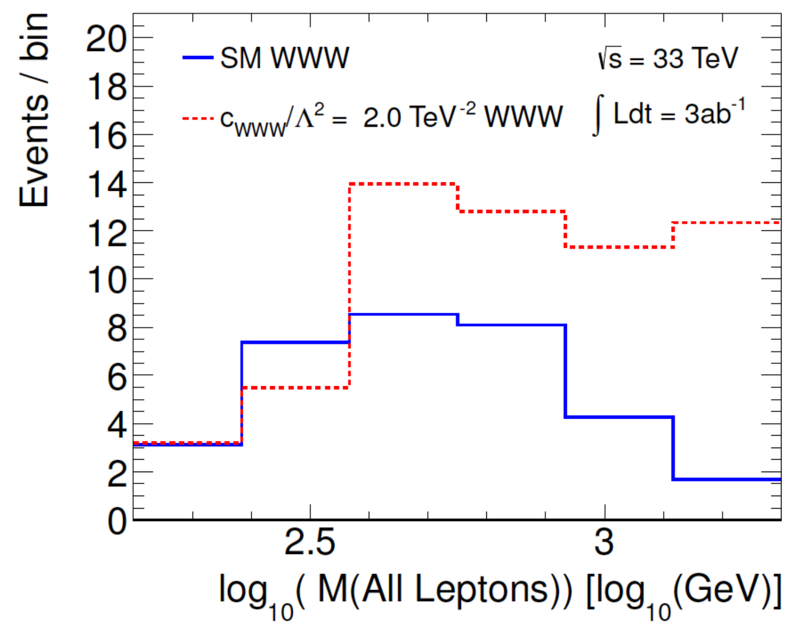
model	$300\ \text{fb}^{-1}$	$3000\ \text{fb}^{-1}$
$m_{\text{resonance}} = 500$ GeV, $g = 1.0$	2.4σ	7.5σ
$m_{\text{resonance}} = 1$ TeV, $g = 1.75$	1.7σ	5.5σ
$m_{\text{resonance}} = 1$ TeV, $g = 2.5$	3.0σ	9.4σ

WWW

WWW -> lνlνlν

(plots for √s = 33 TeV, no UV)





5σ discovery potential:

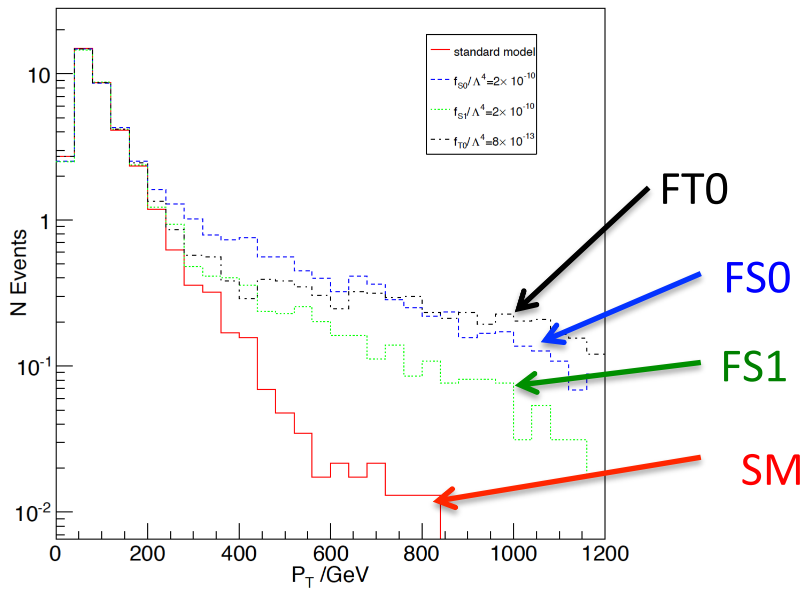
Parameter	dim.	Luminosity [fb^{-1}]	14 TeV	33 TeV	100 TeV
c_{WWW}/Λ^2 [TeV^{-2}]	6	300	4.8 (8)	-	-
		1000	-	-	1.3 (1.5)
		3000	2.3 (2.5)	1.7 (2.0)	0.9 (1.0)
f_{T0}/Λ^4 [TeV^{-4}]	8	300	1.2	-	-
		1000	-	-	0.004
		3000	0.6	0.05	0.002

[2] Snowmass VBS arXiv:1309.7452v1

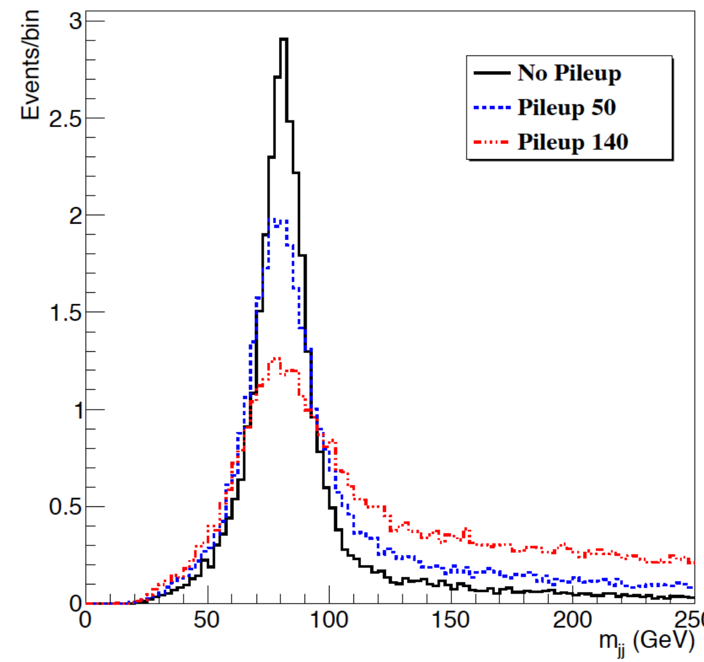
WWW

WWW -> lvlvlv

leading lepton PT



WWW -> lvlvjj



	WWW -> lvlvlv 95% CL with 100 fb^{-1}		WWW -> lvlvjj 95% CL with 100 fb^{-1}	
	lower limit	upper limit	lower limit	upper limit
$\frac{f_{S0}}{\Lambda^4}$	-1.8×10^{-10}	1.8×10^{-10}	-4.6×10^{-10}	4.6×10^{-10}
$\frac{f_{S1}}{\Lambda^4}$	-2.7×10^{-10}	2.8×10^{-10}	-9.5×10^{-10}	9.9×10^{-10}
$\frac{f_{T0}}{\Lambda^4}$	-5.8×10^{-13}	5.9×10^{-13}	-2.8×10^{-12}	2.7×10^{-12}

$$Signif=\sqrt{2ln(Q)}, Q=(1+N_s/N_b)^{N_{obs}}exp(-N_s).$$

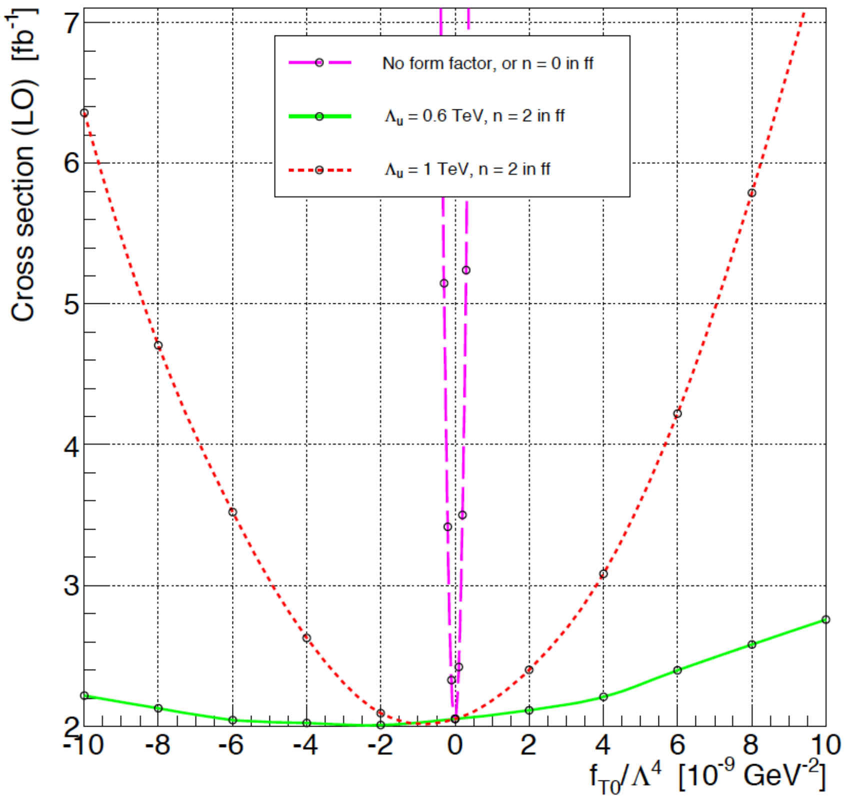
[5] Beijing CMS 2014
arXiv:1407.4922v1

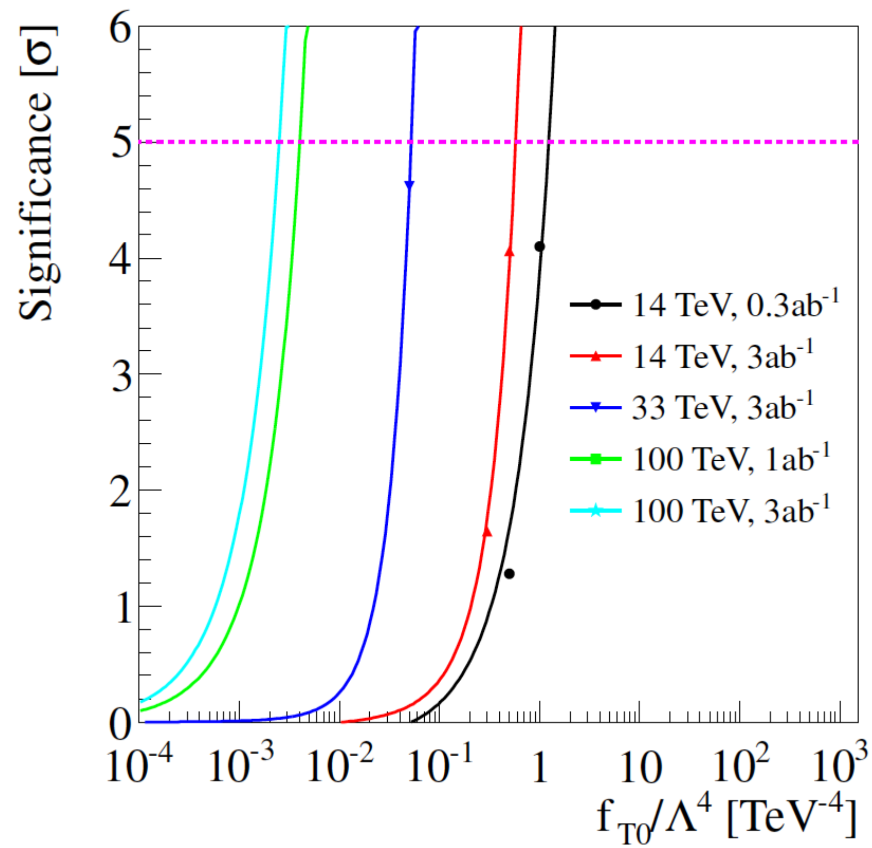
WWW

[5] Beijing CMS 2014
arXiv:1407.4922v1

WWW: FT0

[2] Snowmass VBS
arXiv:1309.7452v1





Limit FT0/Λ^4 = 0.59 TeV^{-4}
@100 fb^{-1}

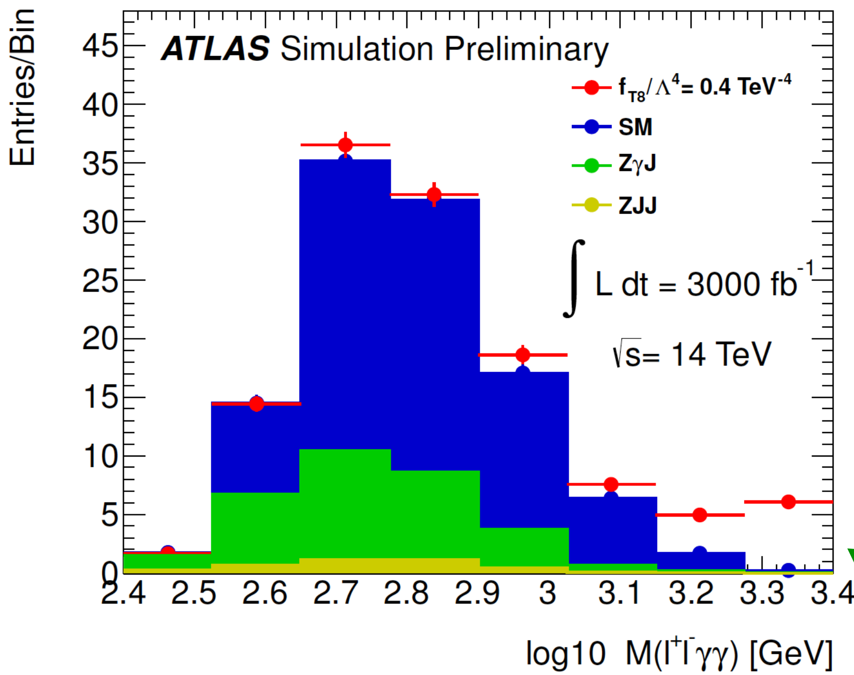
Limit FT0/Λ^4 = 1.2 TeV^{-4}
@300 fb^{-1}

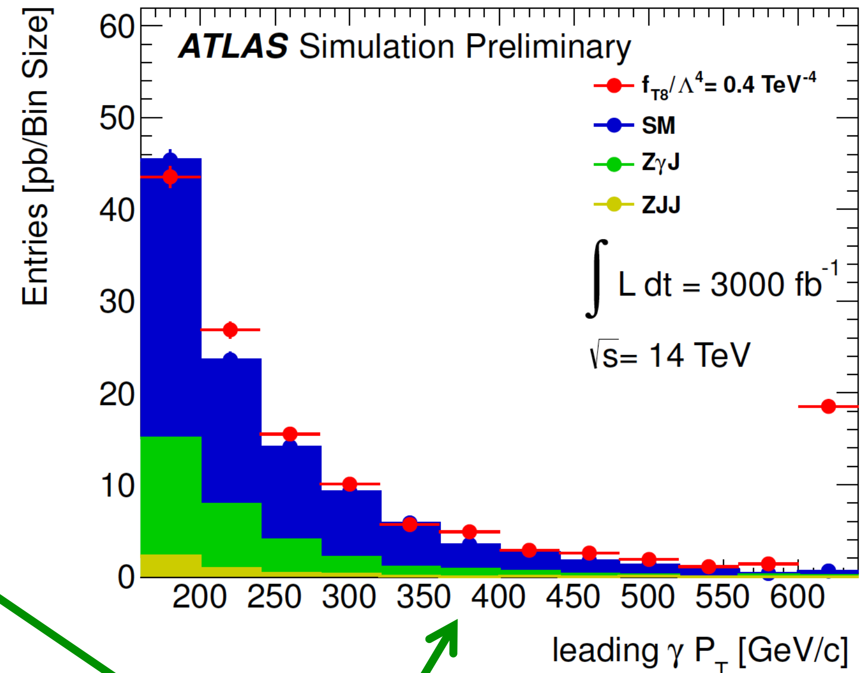
Zγγ

FT8

Zγγ -> llγγ

FT8





5σ discovery potential:

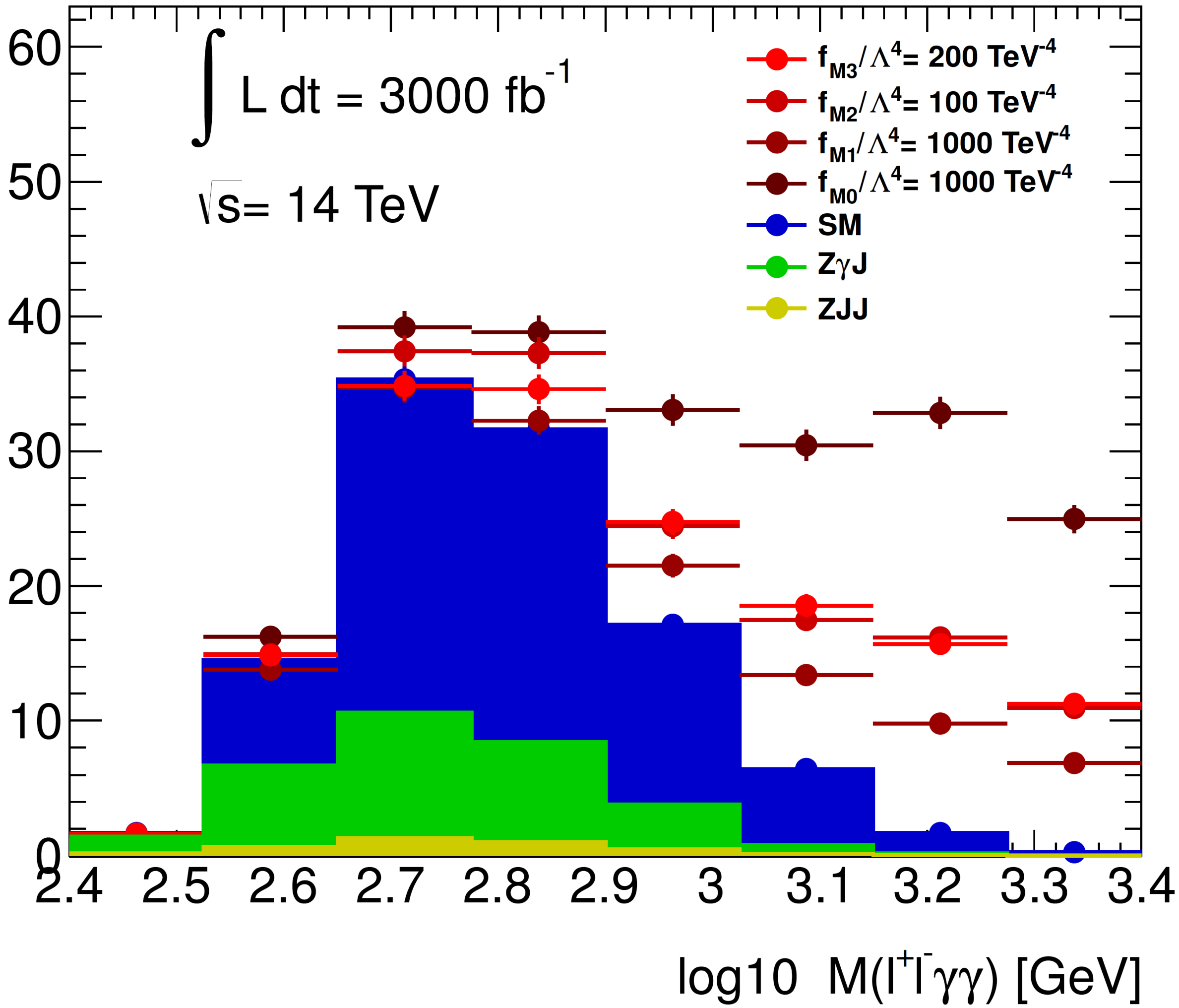
	$300\ \text{fb}^{-1}$	$3000\ \text{fb}^{-1}$
f_{T8}/Λ^4	$0.9\ \text{TeV}^{-4}$	$0.4\ \text{TeV}^{-4}$
f_{T9}/Λ^4	$2.0\ \text{TeV}^{-4}$	$0.7\ \text{TeV}^{-4}$

[3] ATLAS 2013
ATLAS-PHYS-PUB-2013-006

Zγγ

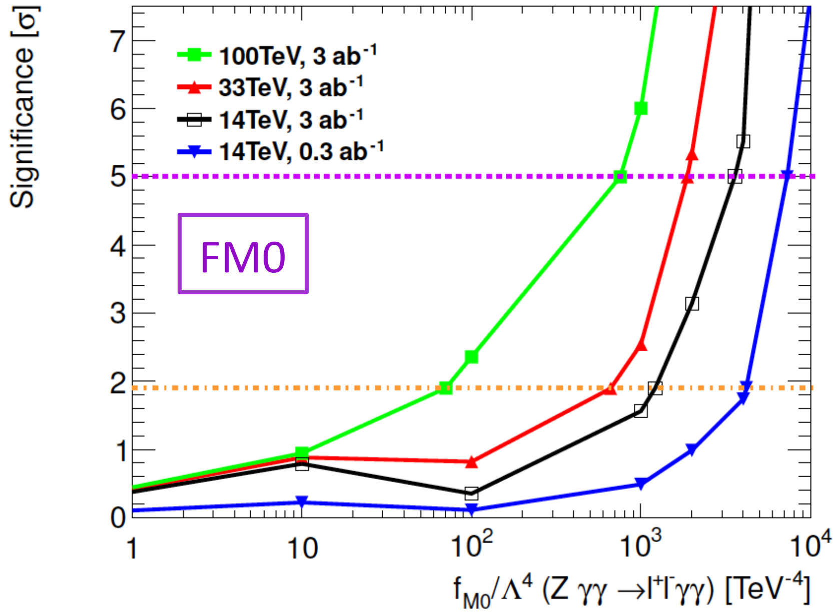
Zγγ -> llγγ

[2] Snowmass VBS
arXiv:1309.7452v1



Zγγ

Zγγ -> llγγ



[2] Snowmass VBS arXiv:1309.7452v1

(with UV cutoff)

Parameter	$\sqrt{s}$	14 TeV	14 TeV	33 TeV	100 TeV
	Lum.	300 fb^{-1}	3000 fb^{-1}		
f_{M0}/Λ^4 [TeV^{-4}]	5σ	7300 (830)	3600 (310)	1900 (190)	750 (120)
	95% CL	4200 (360)	1200 (160)	660 (120)	71 (59)
f_{M1}/Λ^4 [TeV^{-4}]	5σ	7600 (1600)	3600 (680)	2100 (340)	1000 (220)
	95% CL	4500 (800)	1200 (290)	770 (160)	240 (126)
f_{M2}/Λ^4 [TeV^{-4}]	5σ	3300 (130)	510 (48)	310 (26)	120 (16)
	95% CL	670 (56)	160 (21)	110 (13)	25 (10)
f_{M3}/Λ^4 [TeV^{-4}]	5σ	2400 (250)	720 (120)	320 (66)	180 (34)
	95% CL	820 (133)	210 (52)	130 (23)	38 (15)

x5 gain @ 100 TeV

FM2 lowest sensitivity

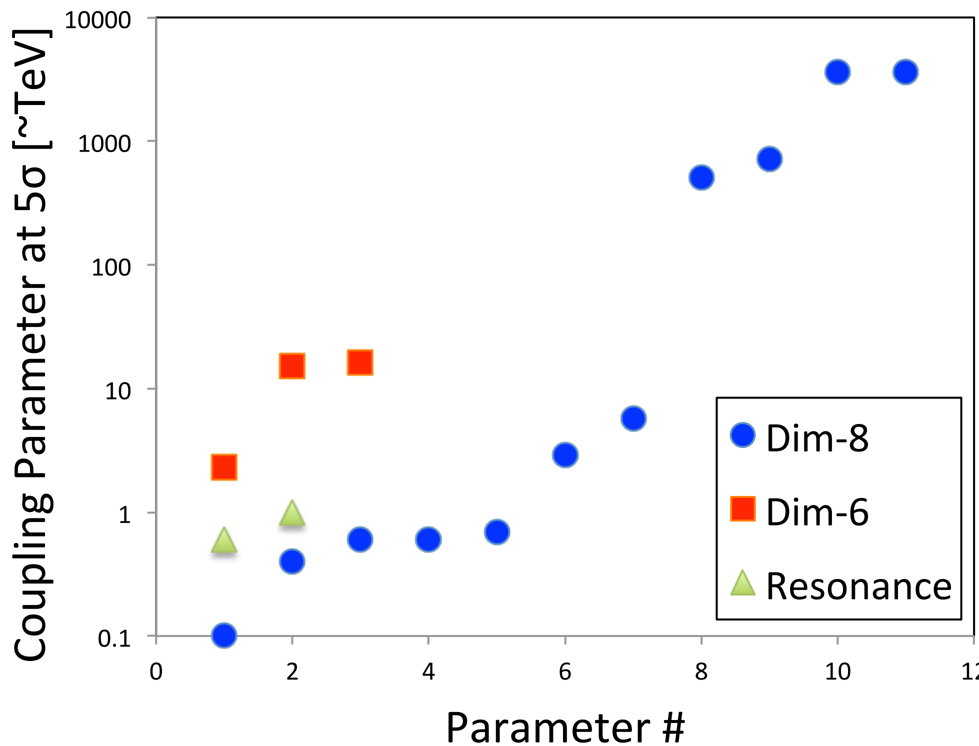
VBS @ HL-LHC

Comparison of sensitivities:

Channel	Parameter (#)	Coupling Parameter for 5σ
ssWW	FT1 (1)	0.1
Zγγ	FT8 (2)	0.4
WZ	FT1 (3)	0.6
WWW	FT0 (4)	0.6
Zγγ	FT9 (5)	0.7
WWW	CWWW (1)	2.3
ZZ	FT8 (6)	2.9
ZZ	FT9 (7)	5.7
WZ	CΦd (2)	15.2
ZZ	CΦW (3)	16.2
Zγγ	FM2 (8)	510
Zγγ	FM3 (9)	720
Zγγ	FM0 (10)	3600
Zγγ	FM1 (11)	3600
WW	m_Resonance (1)	0.6
ZZ	m_Resonance (2)	1

@ 14 TeV & 3,000 fb^{-1}

5σ Discovery Potential:



[2] arXiv:1309.7452v1
[3] ATLAS-PHYS-PUB-2013-006
[4] ATL-UPGRADE-PUB-2012-006
[5] arXiv:1407.4922v1

VBS @ HL-LHC

Summary:

- Many VBS and tri-boson channels
- Many coupling parameters
- Only a small portion of overall new physics production has been studied for HL-LHC prospects
- So far, Dimension-8 FT1 for ssWW is most sensitive to new physics
  - 5σ discovery potential at $FT1/\Lambda^4 = 0.1\ TeV^{-4}$

Backup

VBS @ HL-LHC

[1] Snowmass EWK
"Studies of Electroweak Interactions at the Energy Frontier", M. Baak, et al., arXiv:1310.6708, October 2013.

[2] Snowmass VBS
"Studies of Vector Boson Scattering and Triboson Production with DELPHES Parameterized Fast Simulation for Snowmass 2013", C. Degrande, et al., arXiv:1309.7452v1, September 2013.

[3] ATLAS 2012
"Studies of Vector Boson Scattering with an Upgraded ATLAS Detector at a High-Luminosity LHC", P. Anger, et al., ATL-UPGRADE-PUB-2012-006, December 2012.

[4] ATLAS 2013
"Studies of Vector Boson Scattering and Triboson Production with an Upgraded ATLAS Detector at a High-Luminosity LHC", The ATLAS Collaboration, ATLAS-PHYS-PUB-2013-006, June 2013.

[5] Beijing CMS 2014
"Probing Triple-W Production and Anomalous WWWW Coupling at the CERN LHC and future O(100) TeV proton-proton collider", Yiwen Wen, et al., arXiv:1407.4922v1, July 2014.

[6] "Study of vector boson scattering and search for new physics in events with two same-sign leptons and two jets", CMS Collaboration, arXiv:1410.6315, October 2014.

VBS @ HL-LHC

Dimension-8 conversions:

- for the WWWW-Vertex:

$$\alpha_4 = \frac{f_{S,0}}{\Lambda^4}\frac{v^4}{8}$$
$$\alpha_4 + 2\cdot\alpha_5 = \frac{f_{S,1}}{\Lambda^4}\frac{v^4}{8}$$

- for the WWZZ-Vertex:

$$\alpha_4 = \frac{f_{S,0}}{\Lambda^4}\frac{v^4}{16}$$
$$\alpha_5 = \frac{f_{S,1}}{\Lambda^4}\frac{v^4}{16}$$

- for the ZZZZ-Vertex:

$$\alpha_4 + \alpha_5 = \left(\frac{f_{S,0}}{\Lambda^4} + \frac{f_{S,1}}{\Lambda^4}\right)\frac{v^4}{16}$$

$$W_{\mu\nu} = \frac{i}{2} g \tau^i (\partial_\mu W^i_\nu - \partial_\nu W^i_\mu + g\epsilon_{ijk} W^j_\mu W^k_\nu)$$
$$B_{\mu\nu} = \frac{i}{2} g' (\partial_\mu B_\nu - \partial_\nu B_\mu)\ .$$

$$D_\mu \equiv \partial_\mu + i\frac{g'}{2} B_\mu + igW^i_\mu \frac{\tau^i}{2}$$

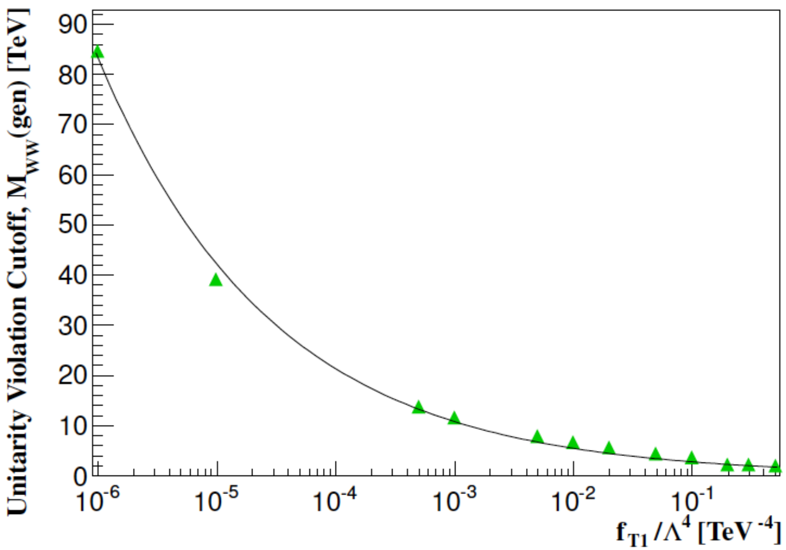
[1] Snowmass EWK
arXiv:1310.6708

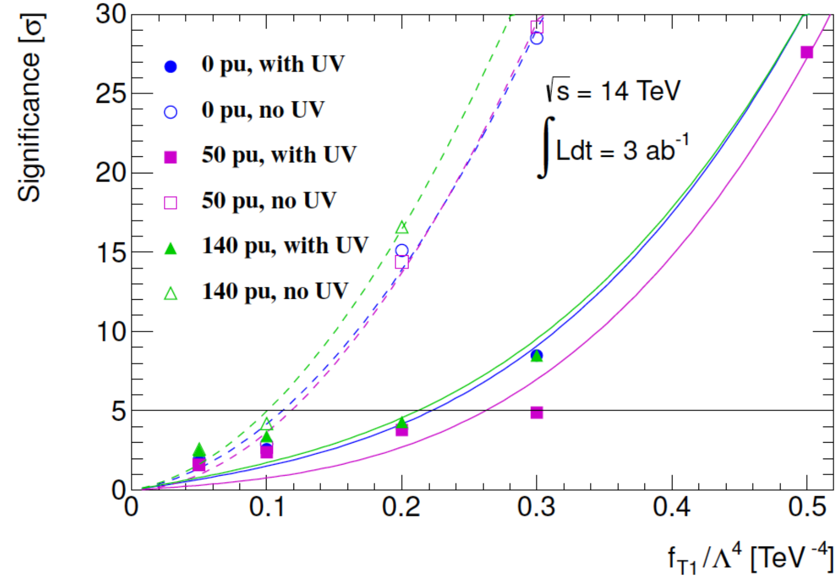
ssWW

FT1

W±W±->lνlν

[2] arXiv:1309.7452v1



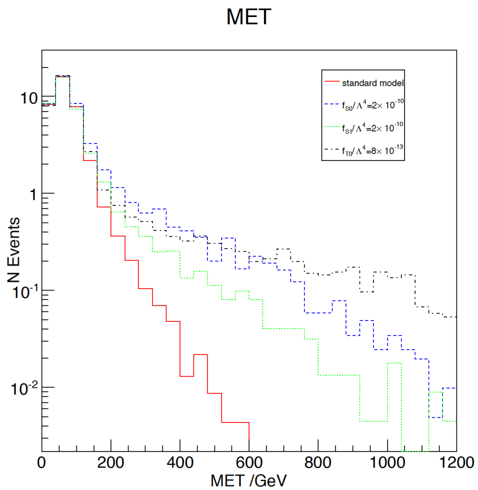


Parameter	$\sqrt{s}$ [TeV]	Luminosity [fb^{-1}]	pileup	5σ [TeV^{-4}]	95% CL [TeV^{-4}]
f_{T1}/Λ^4	14	300	50	0.2 (0.4)	0.1 (0.2)
f_{T1}/Λ^4	14	3000	140	0.1 (0.2)	0.06 (0.1)
f_{T1}/Λ^4	14	3000	0	0.1 (0.2)	0.06 (0.1)
f_{T1}/Λ^4	100	1000	40	0.001 (0.001)	0.0004 (0.0004)
f_{T1}/Λ^4	100	3000	263	0.001 (0.001)	0.0008 (0.0008)
f_{T1}/Λ^4	100	3000	0	0.001 (0.001)	0.0008 (0.0008)

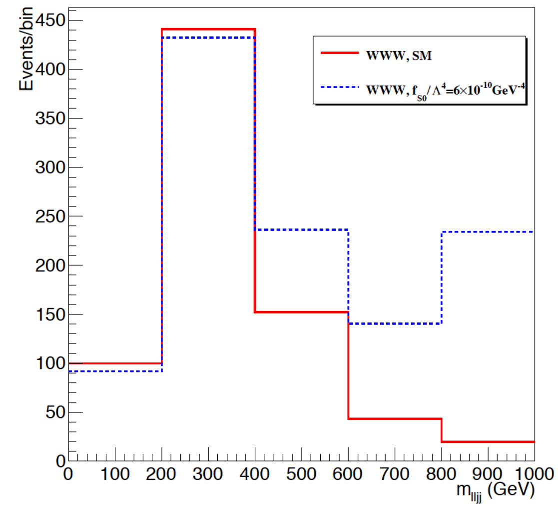
(UV)

WWW

WWW -> lvlvlv



WWW -> lvlvjj



Processes	Cross section[fb]	Events						
		cut-based						BDT
		Pileup 0		Pileup 50		Pileup 140		Pileup 0
		s1	s2	s1	s2	s1	s2	s1
WWW	2.17	21.0	6.29	20.0	5.82	17.9	5.18	20.2
WZ	412	421	6.86	429	6.72	398	6.59	337
$t\bar{t}W$	9.88	33.4	10.3	38.2	11.5	38.8	11.9	56.0
ZZ	273	40.4	1.09	98.8	1.64	107	2.73	32.7
$t\bar{t}Z$	6.35	10.8	2.78	12.6	3.46	13.3	3.60	18.5
WWZ	0.849	3.73	1.04	3.73	1.01	3.54	0.949	3.23
significance		0.922	1.28	0.822	1.14	0.751	0.989	0.946

Processes	Cross section[fb]	Events					
		Pileup 0		Pileup 50		Pileup 140	
		cut-based	BDT	cut-based	BDT	cut-based	BDT
WWW	3.586	22.1	21.9	22	20.7	21.2	39.7
$t\bar{t}W$	480.2	14.4	19.7	53.2	36.5	112.6	140.2
$WWjj$	49.15	13.3	15.5	24.4	27.9	46.7	121.8
$WZjj$	627.9	106.7	82.9	212.7	138.8	379.5	680
Significance		1.86	1.96	1.28	1.43	0.91	1.28

$$Signif = \sqrt{2ln(Q)}, Q = (1 + N_s/N_b)^{N_{obs}} exp(-N_s).$$

[5] arXiv:1407.4922v1

WWW

Use tri-boson production to probe quartic couplings

operator SM cross section [ab]	WWW 603	WWZ 124	WZZ 9.63	ZZZ 0.972
$\mathcal{L}_{S,0}/\mathrm{SM}$	1.0	1.0	1.0	1.0
$\mathcal{L}_{S,1}/\mathrm{SM}$	1.0	1.0	1.0	1.0
$\mathcal{L}_{M,0}/\mathrm{SM}$	1.46	1.09	1.05	1.02
$\mathcal{L}_{M,1}/\mathrm{SM}$	1.17	1.02	1.04	1.03
$\mathcal{L}_{M,2}/\mathrm{SM}$	1.0	1.05	1.0	1.02
$\mathcal{L}_{M,3}/\mathrm{SM}$	1.0	1.01	1.00	1.01
$\mathcal{L}_{T,0}/\mathrm{SM}$	18.31	3.96	3.38	2.90
$\mathcal{L}_{T,1}/\mathrm{SM}$	15.15	2.10	2.83	2.90
$\mathcal{L}_{T,2}/\mathrm{SM}$	4.48	1.32	1.35	1.54
$\mathcal{L}_{T,8}/\mathrm{SM}$	1.0	1.0	1.0	1.31
$\mathcal{L}_{T,9}/\mathrm{SM}$	1.0	1.0	1.0	1.08

operator SM cross section [ab]	WWW 603	WWZ 124	WZZ 9.63	ZZZ 0.972
$\mathcal{L}_{WWW}/\mathrm{SM}$	1.4	1.3	1.4	1.0
$\mathcal{L}_{W}/\mathrm{SM}$	1.1	1.1	1.2	1.1
$\mathcal{L}_{b}/\mathrm{SM}$	1.0	1.0	1.0	1.0

[2] arXiv:1309.7452v1