SM EFT effects in Vector Boson Scattering at the LHC

(with focus on the same-sign WW process)

*** Recent experimental progress in setting limits on dim-8 operators**
(work done within the CMS Collaboration)

*** Considerations about dim-6 operators in same-sign WW**
(based on arXiv:2011.07367 by A. Dedes and P. Kozów (+MS))

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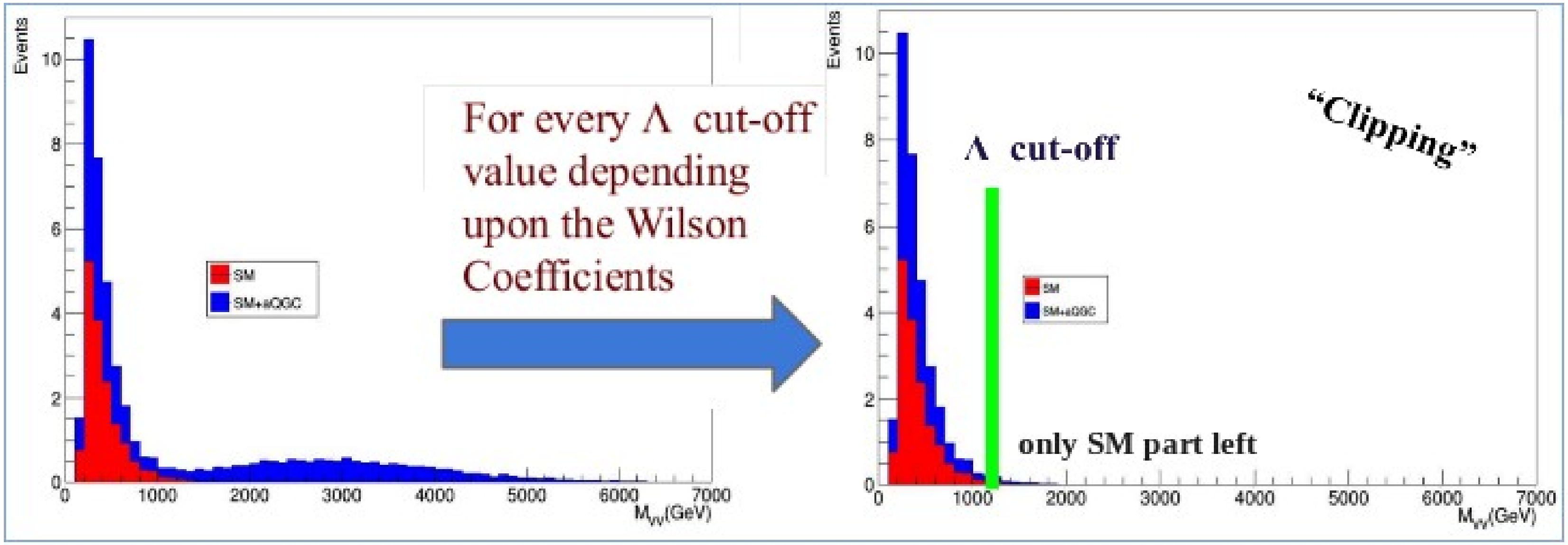
Winter 2021 topical meeting on VBS: VBS at Snowmass, January 28, 2021

Latest news on setting limits on dim-8 SMEFT operators – CMS, full Run 2 data



Without "clipping"

	Observed ($W^{\pm}W^{\pm}$) (TeV^{-4})	Expected ($W^{\pm}W^{\pm}$) (TeV^{-4})
f_{T0}/Λ^4	[-0.28, 0.31]	[-0.36, 0.39]
f_{T1}/Λ^4	[-0.12, 0.15]	[-0.16, 0.19]
f_{T2}/Λ^4	[-0.38, 0.50]	[-0.50, 0.63]
f_{M0}/Λ^4	[-3.0, 3.2]	[-3.7, 3.8]
f_{M1}/Λ^4	[-4.7, 4.7]	[-5.4, 5.8]
f_{M6}/Λ^4	[-6.0, 6.5]	[-7.5, 7.6]
f_{M7}/Λ^4	[-6.7, 7.0]	[-8.3, 8.1]
f_{S0}/Λ^4	[-6.0, 6.4]	[-6.0, 6.2]
f_{S1}/Λ^4	[-18, 19]	[-18, 19]

With "clipping"

	Observed ($W^{\pm}W^{\pm}$) (TeV^{-4})	Expected ($W^{\pm}W^{\pm}$) (TeV^{-4})
f_{T0}/Λ^4	[-1.5, 2.3]	[-2.1, 2.7]
f_{T1}/Λ^4	[-0.81, 1.2]	[-0.98, 1.4]
f_{T2}/Λ^4	[-2.1, 4.4]	[-2.7, 5.3]
f_{M0}/Λ^4	[-13, 16]	[-19, 18]
f_{M1}/Λ^4	[-20, 19]	[-22, 25]
f_{M6}/Λ^4	[-27, 32]	[-37, 37]
f_{M7}/Λ^4	[-22, 24]	[-27, 25]
f_{S0}/Λ^4	[-35, 36]	[-31, 31]
f_{S1}/Λ^4	[-100, 120]	[-100, 110]

Limits weaker by a factor ~4-5 by only considering unitarity, similar for WZ (CMS Collaboration, *arXiv:2005.01173*)

New developments: "full clipping" under implementation (work in progress)

- **Limits on f as a function of Λ.**
- **Obtained limit can be compared to theoretical limit (unitarity condition).**
- **Observed limit is physically meaningful if stronger than theoretical limit.**

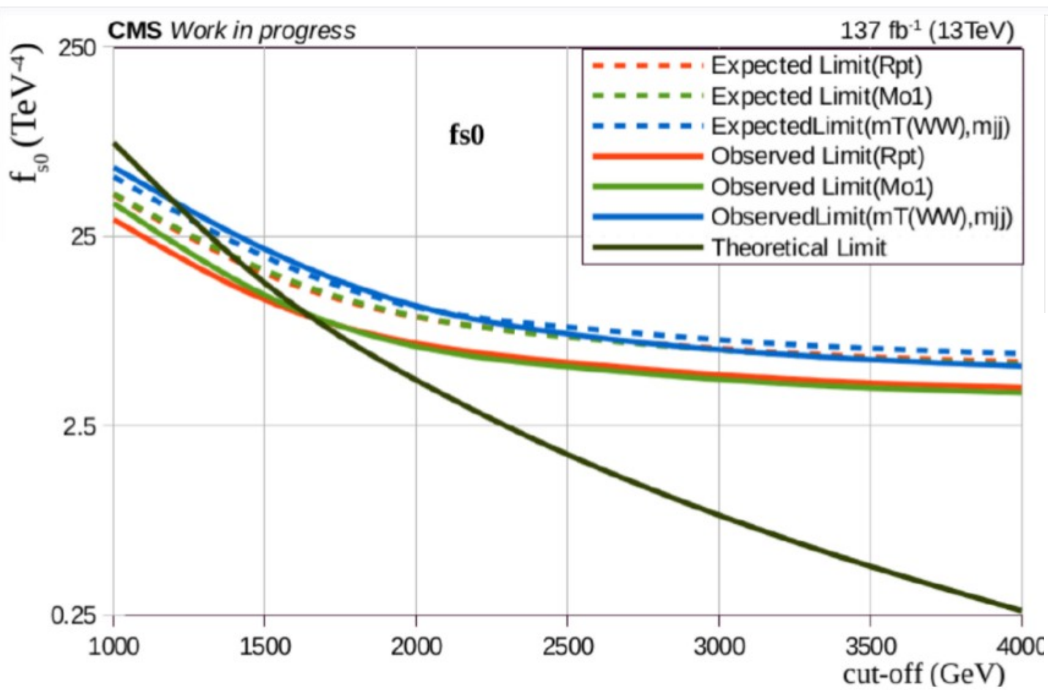
  \+ study of new variables to improve sensitivity to BSM effects.

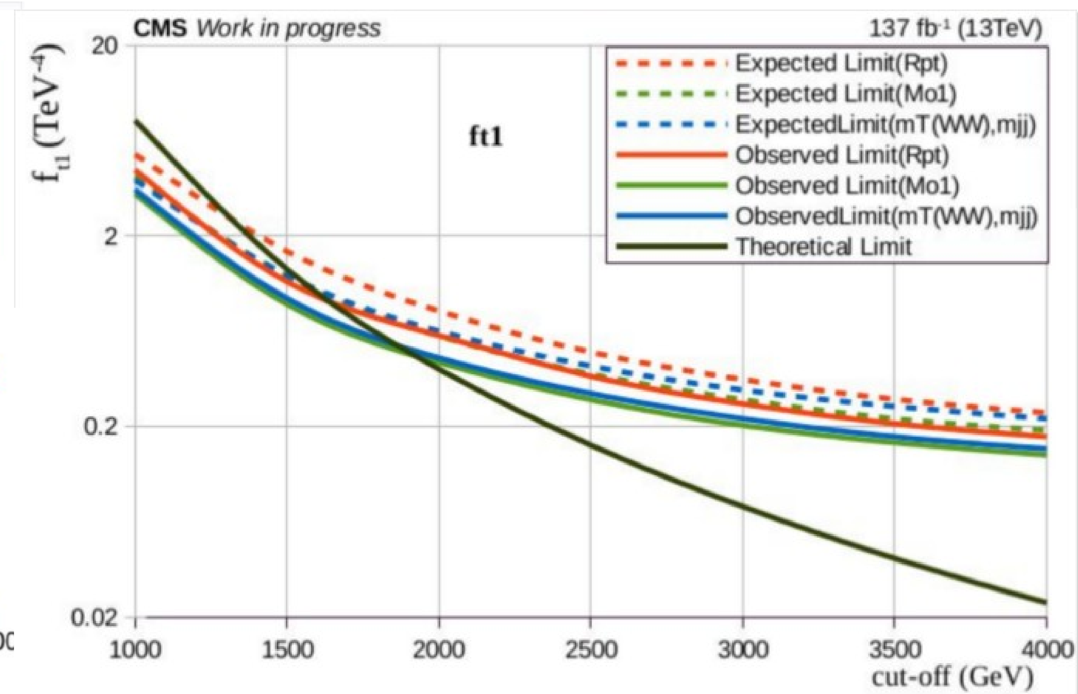
$$R_{pt} = (p_T^{l1} * p_T^{l2})/(p_T^{j1} * p_T^{j2})$$

$$M_{o1} \equiv \sqrt{(|\vec{p}_T^{\,l1}| + |\vec{p}_T^{\,l2}| + |\vec{p}_T^{\,miss}|)^2 - (\vec{p}_T^{\,l1} + \vec{p}_T^{\,l2} + \vec{p}_T^{\,miss})^2}$$

$$m_T(VV) = \sqrt{(\textstyle\sum_i E_i)^2 - (\sum_i p_{z,i})^2}$$

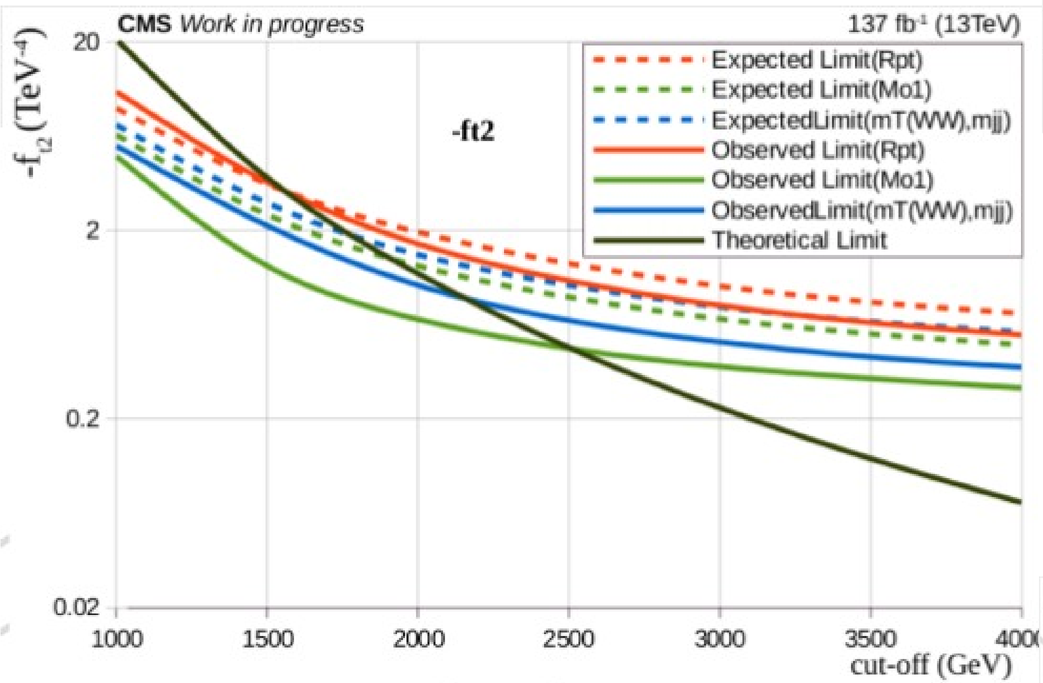
Two examples:

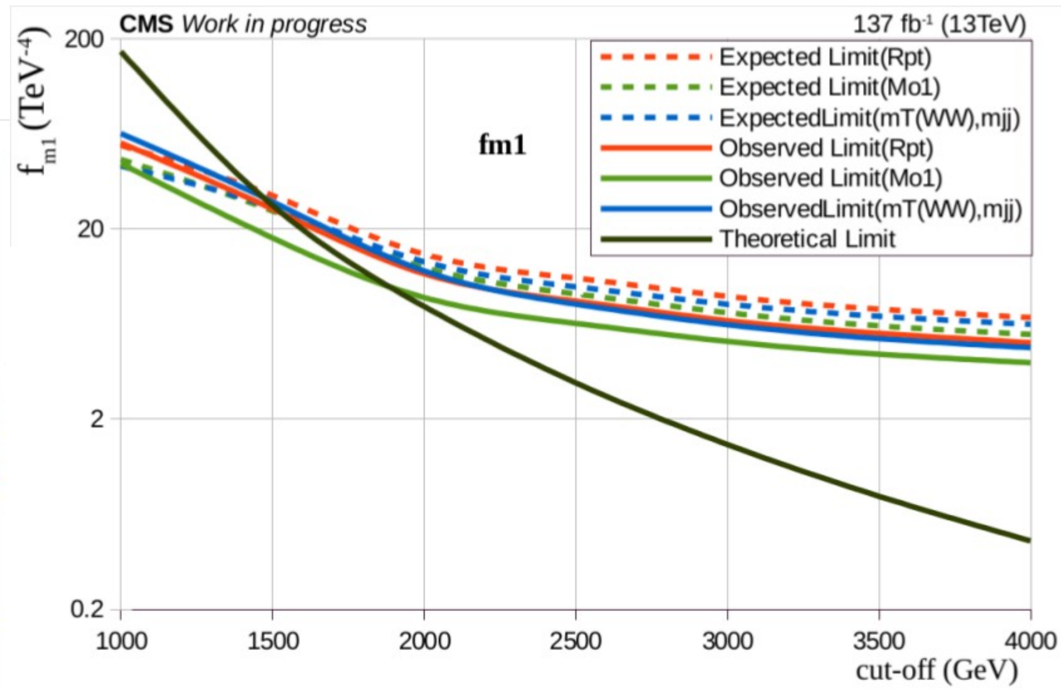


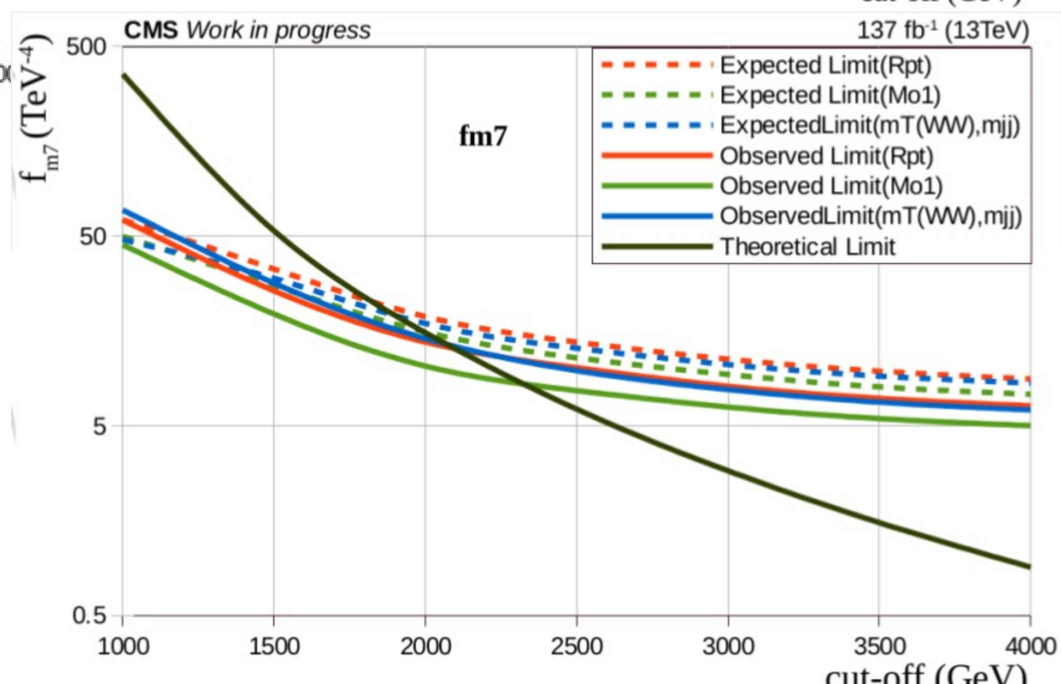


We can already place some meaningful limits on fS0 and fT1 if Λ is less than 1.7-1.8 TeV

"Full clipping" first results – some optimistic examples





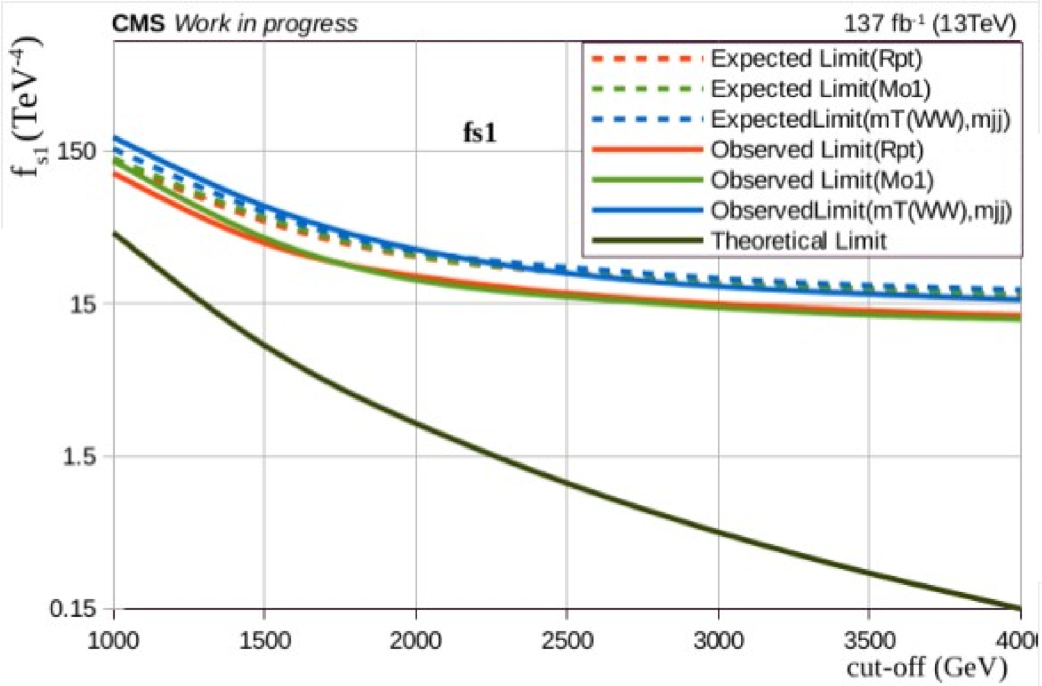


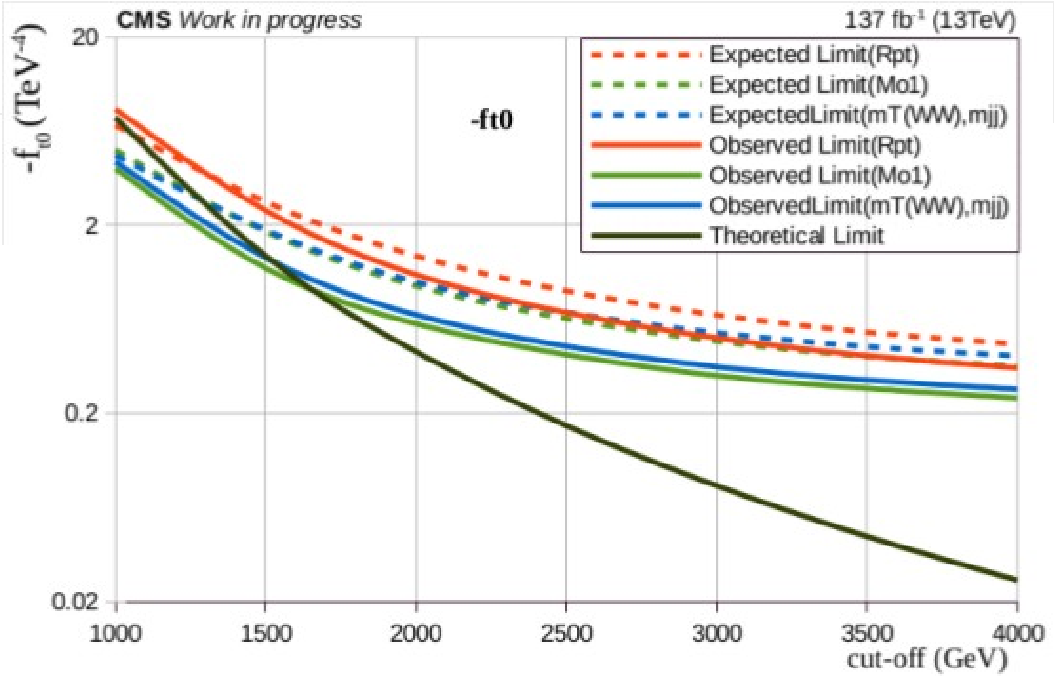
Observed limits are physical for

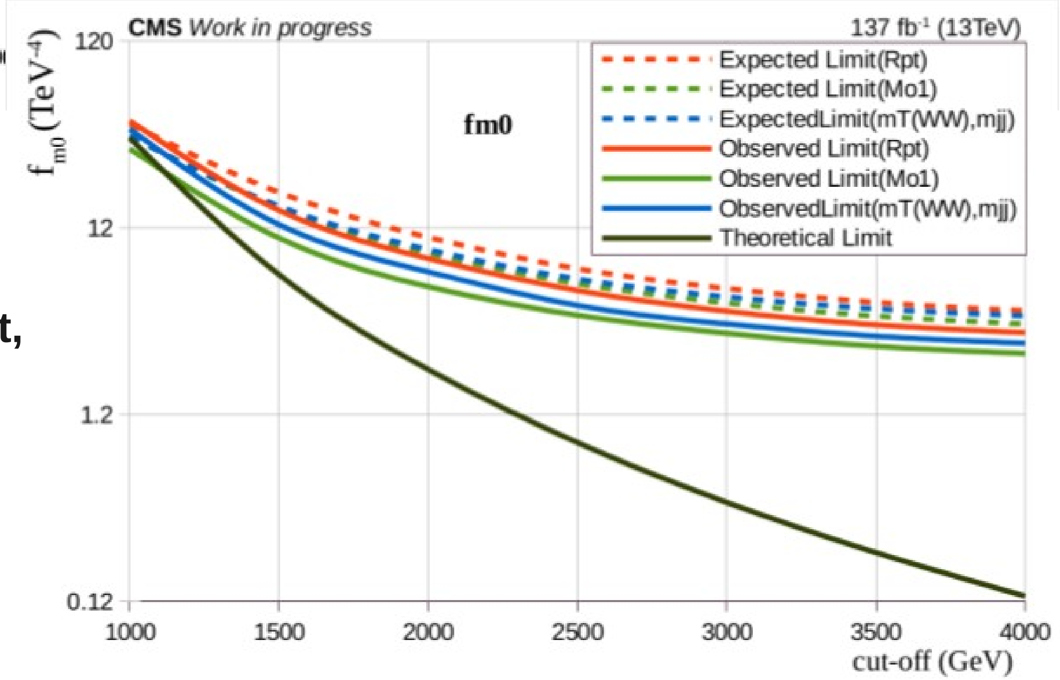
fT2 (negative values only), fM1 and fM7

as long as Λ < 2-2.5 TeV

"Full clipping" results – some not so optimistic examples







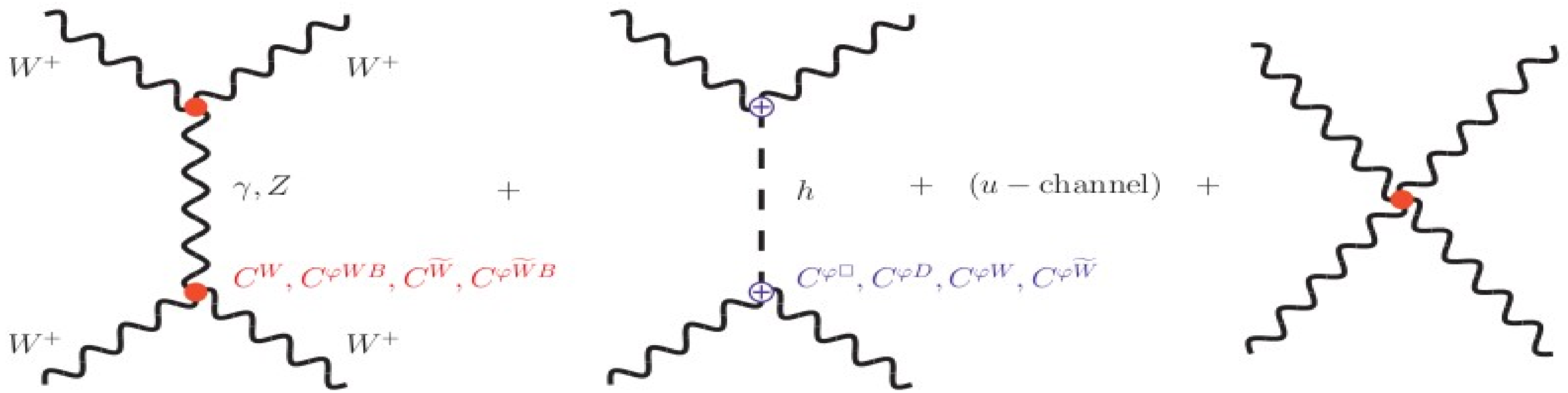
fT0 – meaningful limits only for negative values.

fM0 – no meaningful limits at the present moment, but will improve at HL-LHC.

Little hope for fS1.

Dim-6 SMEFT operators in same-sign WW

	X^3	$\varphi^4 D^2$	$X^2\varphi^2$
CPC	$Q_W = \epsilon^{IJK} W_\mu^{\nu\, I} W_\nu^{\rho\, J} W_\rho^{\mu\, K}$	$Q_{\varphi\Box} = (\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$ $Q_{\varphi D} = (\varphi^\dagger D^\mu \varphi)^* (\varphi^\dagger D_\mu \varphi)$	$Q_{\varphi W} = \varphi^\dagger \varphi W^I_{\mu\nu} W^{\mu\nu\, I}$ $Q_{\varphi WB} = \varphi^\dagger \tau^I \varphi W^I_{\mu\nu} B^{\mu\nu}$
CPV	$Q_{\widetilde{W}} = \epsilon^{IJK} \widetilde{W}_\mu^{\nu\, I} W_\nu^{\rho\, J} W_\rho^{\mu\, K}$		$Q_{\varphi\widetilde{W}} = \varphi^\dagger \varphi \widetilde{W}^I_{\mu\nu} W^{\mu\nu\, I}$ $Q_{\varphi\widetilde{W}B} = \varphi^\dagger \tau^I \varphi \widetilde{W}^I_{\mu\nu} W^{\mu\nu\, I}$



Decompose W+W+ → W+W+ process into helicity amplitudes and derive analytic expressions for cross sections in the presence of dim-6 operators (on-shell approximation)

$$\sigma_{TTTT} : \sigma_{LLLL} : \sigma_{LTLT} : \sigma_{TLTL} : \sigma_{TLLT} : \sigma_{LTTL} \approx 1 : \frac{1}{8.5} : \frac{1}{8.0} : \frac{1}{8.0} : \frac{1}{8.0} : \frac{1}{8.0}$$

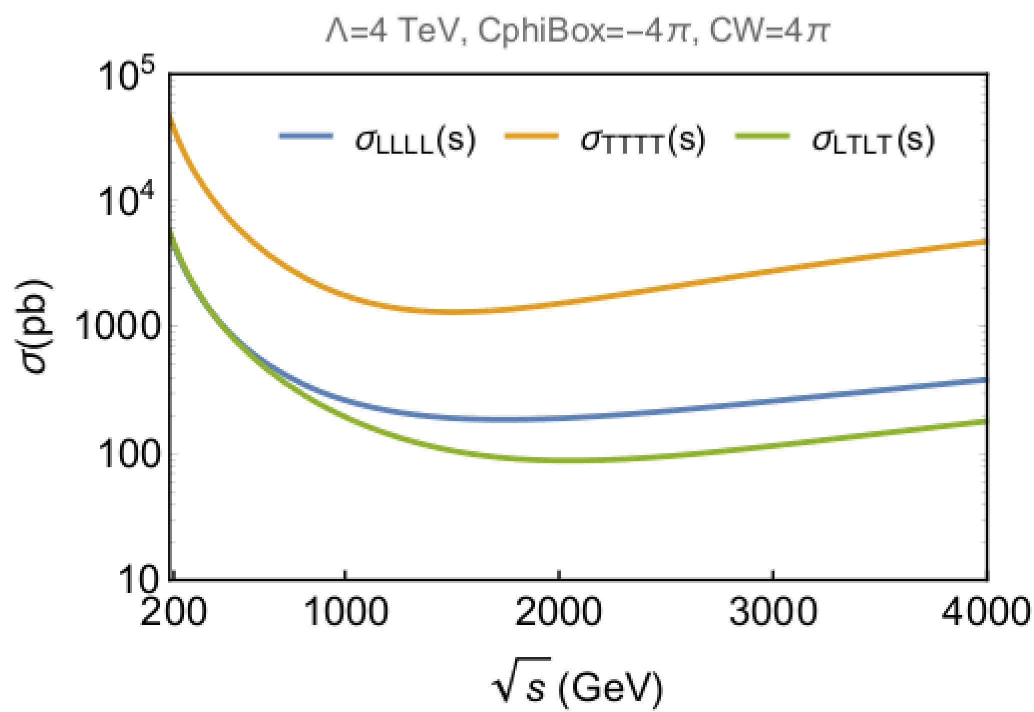
The effect of dim-6 operators on the W+W+ → W+W+ process

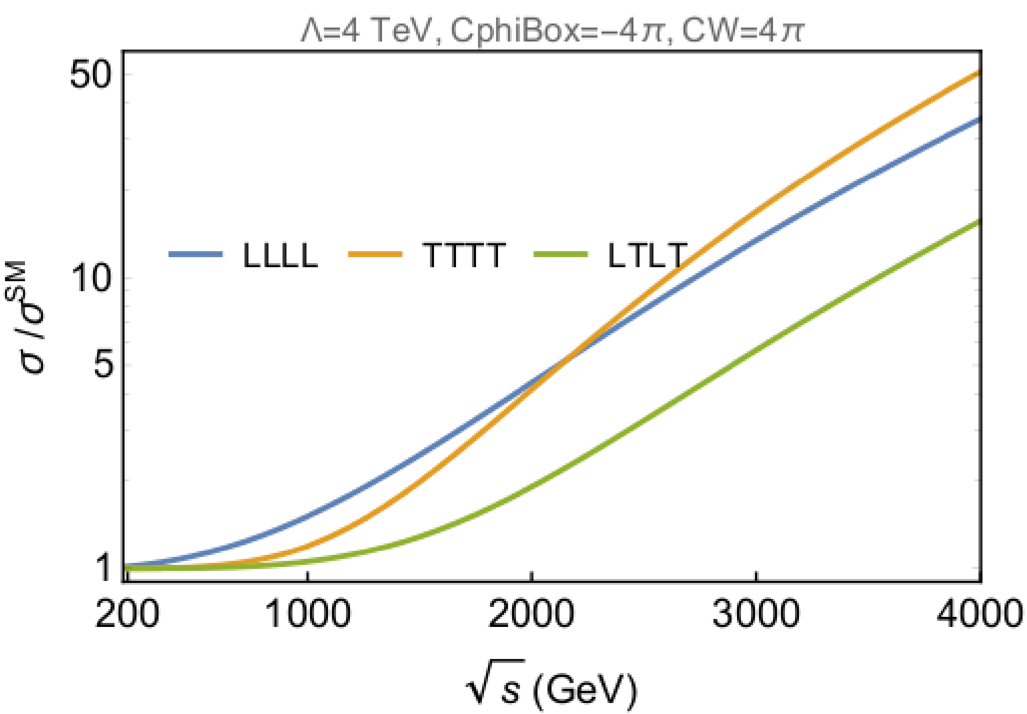
Analytic expressions at leading order in s from *arXiv:2011.07367*:

$$\sigma_{TTTT}(s) \approx \frac{\bar{g}^4}{s}\left[\frac{A_T}{1-c^2} + B_T \cdot 0 + \Gamma_T\, \bar{g}^2 \left(\frac{|C^W|}{\bar{g}^2}\right)^2 \left(\frac{s}{\Lambda^2}\right)^2 + \cdots\right],$$

$$\sigma_{LLLL}(s) \approx \frac{\bar{g}^4}{s}\left[\frac{A_L}{1-c^2} + B_L \left(\frac{C^{\varphi\Box}}{\bar{g}^2}\right)\left(\frac{s}{\Lambda^2}\right) + \Gamma_L \left(\frac{C^{\varphi\Box}}{\bar{g}^2}\right)^2 \left(\frac{s}{\Lambda^2}\right)^2 + \cdots\right]$$

$Q_{\varphi WB}$ disappears, Q_W and $Q_{\varphi\Box}$ most promising

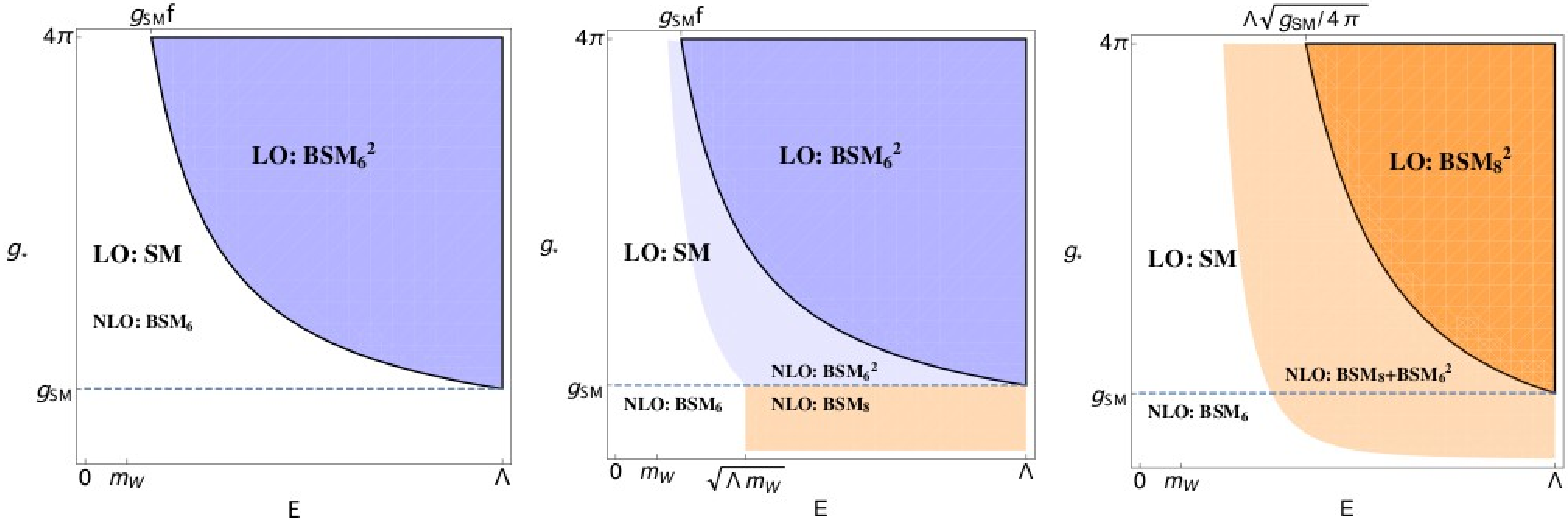




Dim-6 vs dim-8 in W+W+ → W+W+

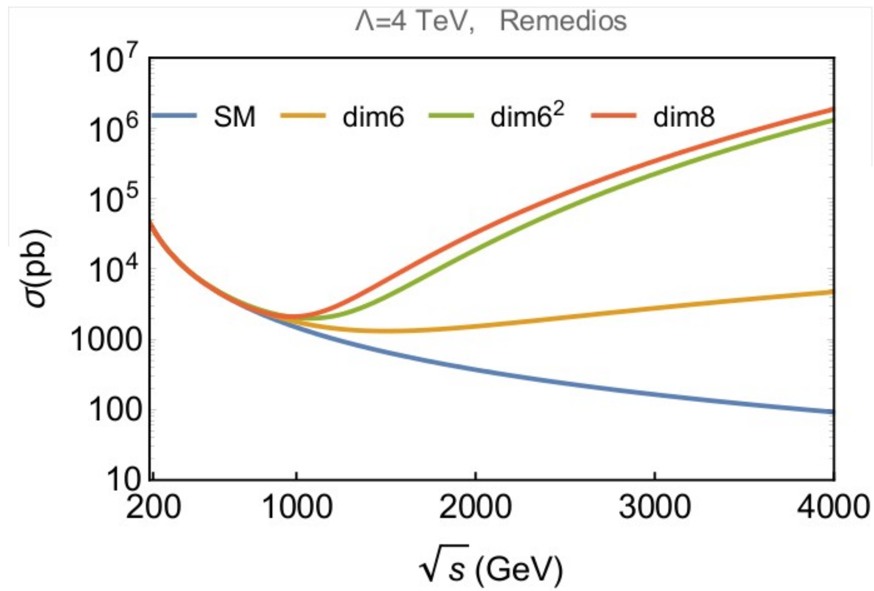
LLLL LLTT TTTT

A. Azatov, R. Contino, C. S. Machado, F. Riva, *arXiv:1607.05236*



"Remedios" (composite vectors) models of D. Liu, A. Pomarol, R. Rattazzi, F.Riva, *arXiv:1603.03064*

$$C^W \sim g_* \text{ and } C^{t0,t1,t2,t10} \sim g_*^2 \qquad g_* = 4\pi$$



Warsaw basis - all dim-6 operators potentially relevant to VBS at the LHC

from B. Grządkowski, M. Iskrzyński, M. Misiak, J.Rosiek *(arXiv:1008.4884)*

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar l_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\,\varphi)(\bar l_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar e_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I\widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar q_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\,\varphi)(\bar q_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar u_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar d_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p\gamma^\mu d_r)$

Table 2: Dimension-six operators other than the four-fermion ones.

Warsaw basis - all dim-6 operators potentially relevant to VBS at the LHC
- omit CP-violating operators

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$
		$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu \varphi\right)^\star \left(\varphi^\dagger D_\mu \varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$
		Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{\varphi}\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$
		Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{\varphi}\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
		Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$
		Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)$

Table 2: Dimension-six operators other than the four-fermion ones.

Warsaw basis - all dim-6 operators potentially relevant to VBS at the LHC - omit leptonic operators

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$		
		$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$				
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu} T^A u_r)\widetilde{\varphi}\, G_{\mu\nu}^A$		
		Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu} u_r)\tau^I\widetilde{\varphi}\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu} u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
		Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu} d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{d}_p\gamma^\mu d_r)$
		Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

Table 2: Dimension-six operators other than the four-fermion ones.

Warsaw basis - all dim-6 operators potentially relevant to VBS at the LHC
- omit operators that do not affect the W+W+ process at LO

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$				
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{\varphi}\, G_{\mu\nu}^A$		
		Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{\varphi}\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar{q}_p\gamma^\mu q_r)$
		Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\,\varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
		Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar{u}_p\gamma^\mu u_r)$
		Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar{d}_p\gamma^\mu d_r)$
		Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

Table 2: Dimension-six operators other than the four-fermion ones.

Warsaw basis - all dim-6 operators potentially relevant to VBS at the LHC
- omit gluonic operators that are well constrained by other processes

(see *arXiv:1611.00767* and *arXiv:1911.07866*)

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
		$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu \varphi\right)^\star \left(\varphi^\dagger D_\mu \varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{\varphi}\, G^A_{\mu\nu}$		
		Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{\varphi}\, W^I_{\mu\nu}$	$Q^{(1)}_{\varphi q}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$
		Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q^{(3)}_{\varphi q}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
		Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}_p \gamma^\mu u_r)$
		Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$
		Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)$

Table 2: Dimension-six operators other than the four-fermion ones.

Warsaw basis - all dim-6 operators potentially relevant to VBS at the LHC
Part 2: 4-fermion operators - omitting B-violating operators

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$		
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$		
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$		
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$		
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu} u_t)$		

Table 3: Four-fermion operators.

Warsaw basis - all dim-6 operators potentially relevant to VBS at the LHC
Part 2: 4-fermion operators - omit leptonic operators

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$		
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$		
				Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
				$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$		
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$		

Table 3: Four-fermion operators.

Simulation work: potential impact of dim-6 operators on W+W+

- **MG5 (all relevant UFOs produced) + Pythia 8 + FastJet**
  Study of BSM effects in kinematic distributions, for each operator the most sensitive variable chosen

- **Current experimental limits on dim-6 operators:**

  Non-4-fermion:
  [28] S. Dawson, S. Homiller, S. D. Lane, *arXiv:2007.01296*,
  [29] J. Ellis, C. W. Murphy, V. Sanz, T. You, *arXiv:1803.03252*
  ← include LHC Run 2 data, dim-6 only (no $(\text{dim-6})^2$ terms)

  4-fermion:
  [30] O. Domenech, A. Pomarol, J. Serra, *arXiv:1201.6510*,
  [31] CMS Collaboration, *arXiv:1703.09986*
  ← early LHC dijet data (enough)

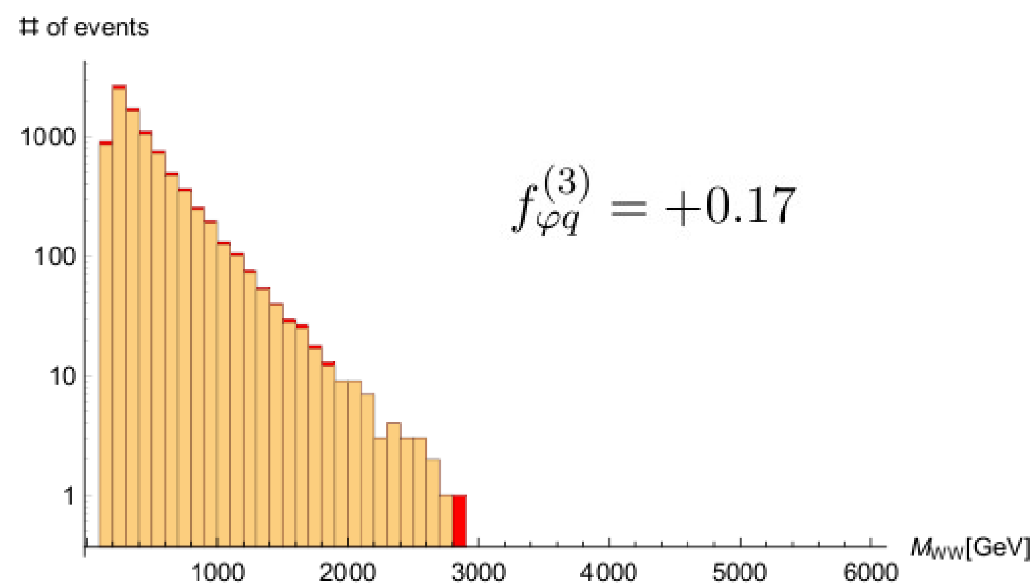
- **Operators for which experimental limits are not available:**

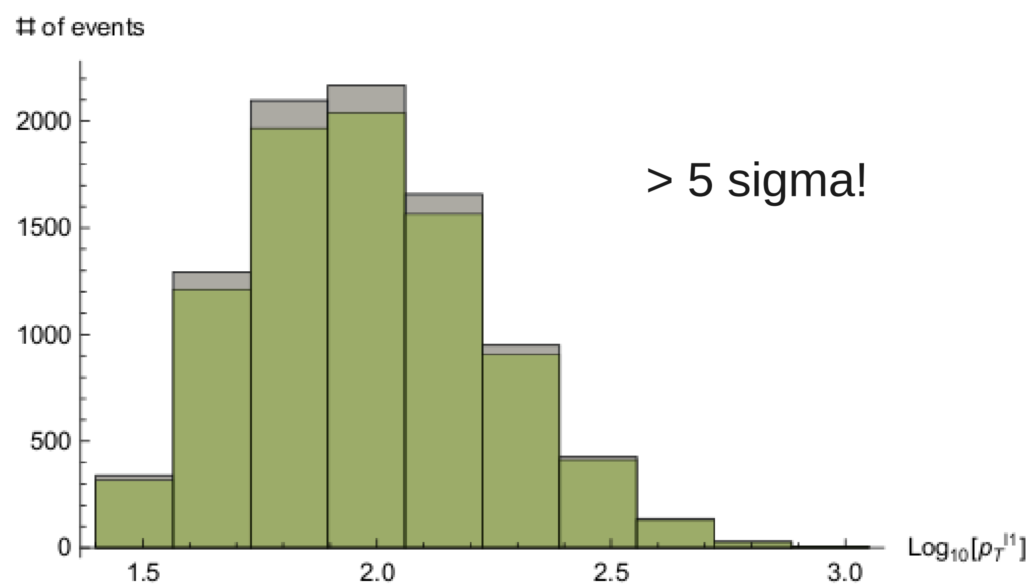
  Q_quqd(1), **Q_quqd(8)** – no sensitivity up to the strong coupling limit,
  Q_uW, **Q_uB**, **Q_dG**, **Q_dW**, **Q_dB** ("dipole operators") – claimed to be strongly constrained in [29] and A. Falkowski http://cds.cern.ch/record/2001958?ln=pl, in addition no sensitivity to **Q_uB** and **Q_dB**, while **Q_uW**, **Q_dG** and **Q_dW** affect mostly jet distributions,
  Q_phiud – affects mainly jet pT,
  Q_qq(3) is identical to **Q_qq(1)** assuming flavor-diagonal Wilson coefficients.

$\psi^2\varphi^3$ [29]		σ	$\psi^2 X\varphi$ [29]		σ
$f_{u\varphi}$	$[-120., -36.] \times y_u$	0.027	f_{uG}	$[+5, +18.] \times y_u$	5.5×10^{-3}
$f_{d\varphi}$	$[+3., +7.9] \times y_d$	0.			
$\psi^2\varphi^2 D$ [28]		σ	$(\bar{L}L)(\bar{L}L)$ [30,31]		σ
$f_{\varphi q}^{(1)}$	$[-0.23, +0.12]$	0.46	$f_{qq}^{(1)}$	$[-0.028, +0.057]$	1.1
$f_{\varphi q}^{(3)}$	$[-0.18, +0.17]$	5.7			
$f_{\varphi u}$	$[-0.79, +0.54]$	0.			
$f_{\varphi d}$	$[-0.81, +0.13]$	0.			
$(\bar{R}R)(\bar{R}R)$ [30]		σ	$(\bar{L}L)(\bar{R}R)$ [30]		σ
f_{uu}	$[-0.1, +0.23]$	0.	$f_{qu}^{(1)}$	$[-0.35, +0.35]$	0.
f_{dd}	$[-0.31, +0.44]$	0.	$f_{qu}^{(8)}$	$[-0.5, +1.]$	0.
$f_{ud}^{(1)}$	$[-0.44, +0.44]$	0.	$f_{qd}^{(1)}$	$[-0.59, +0.59]$	0.
$f_{ud}^{(8)}$	$[-0.59, +1.56]$	0.	$f_{qd}^{(8)}$	$[-1., +1.56]$	0.

Summary of "background" (non-VBS) operators

Significant effects possible from Q_phiq(3) with current bounds, but kinematics distinctly different from VBS operators.





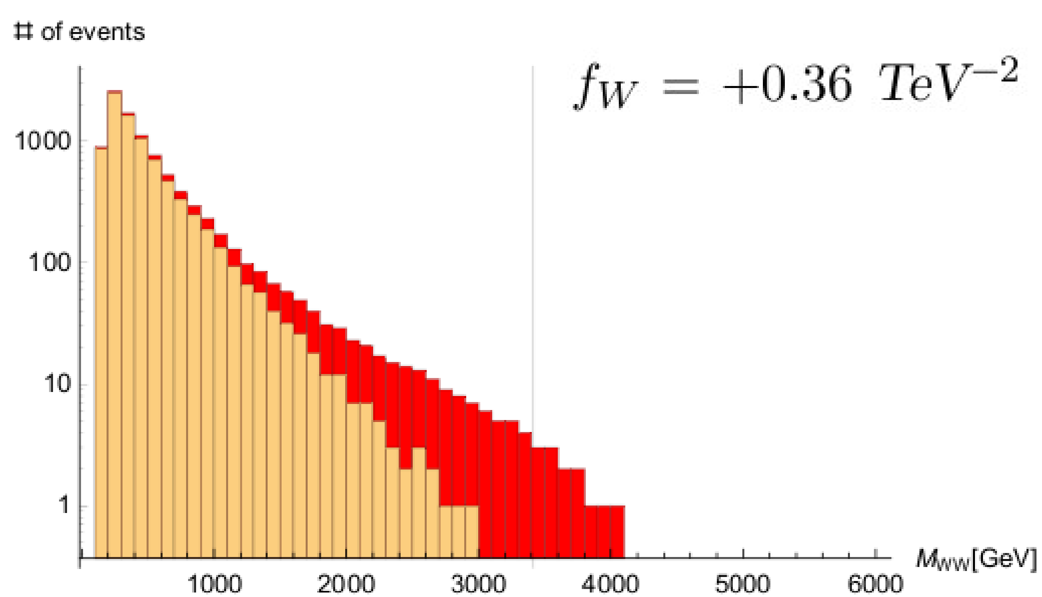
Potential impact of VBS dim-6 operators on W+W+

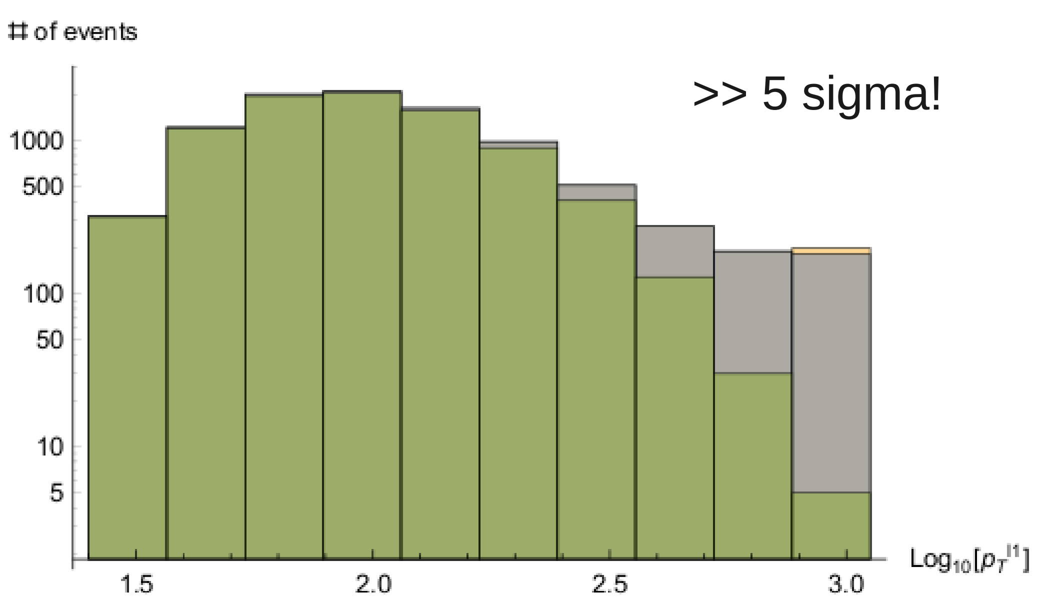
Current bounds taken from [28]:

	f_W	$f_{\varphi\Box}$	$f_{\varphi D}$	$f_{\varphi W}$
"individual"	[-0.15,+0.36]	[-0.44,+0.52]	[-0.025,+0.0015]	[-0.014,+0.0068]
"global"	[-1.3,+1.1]	[-3.4,+2.4]	[-2.7,+1.2]	[-0.14,+1.6]

Correlation matrix from [29]: negligible to mild correlation between operators of interest

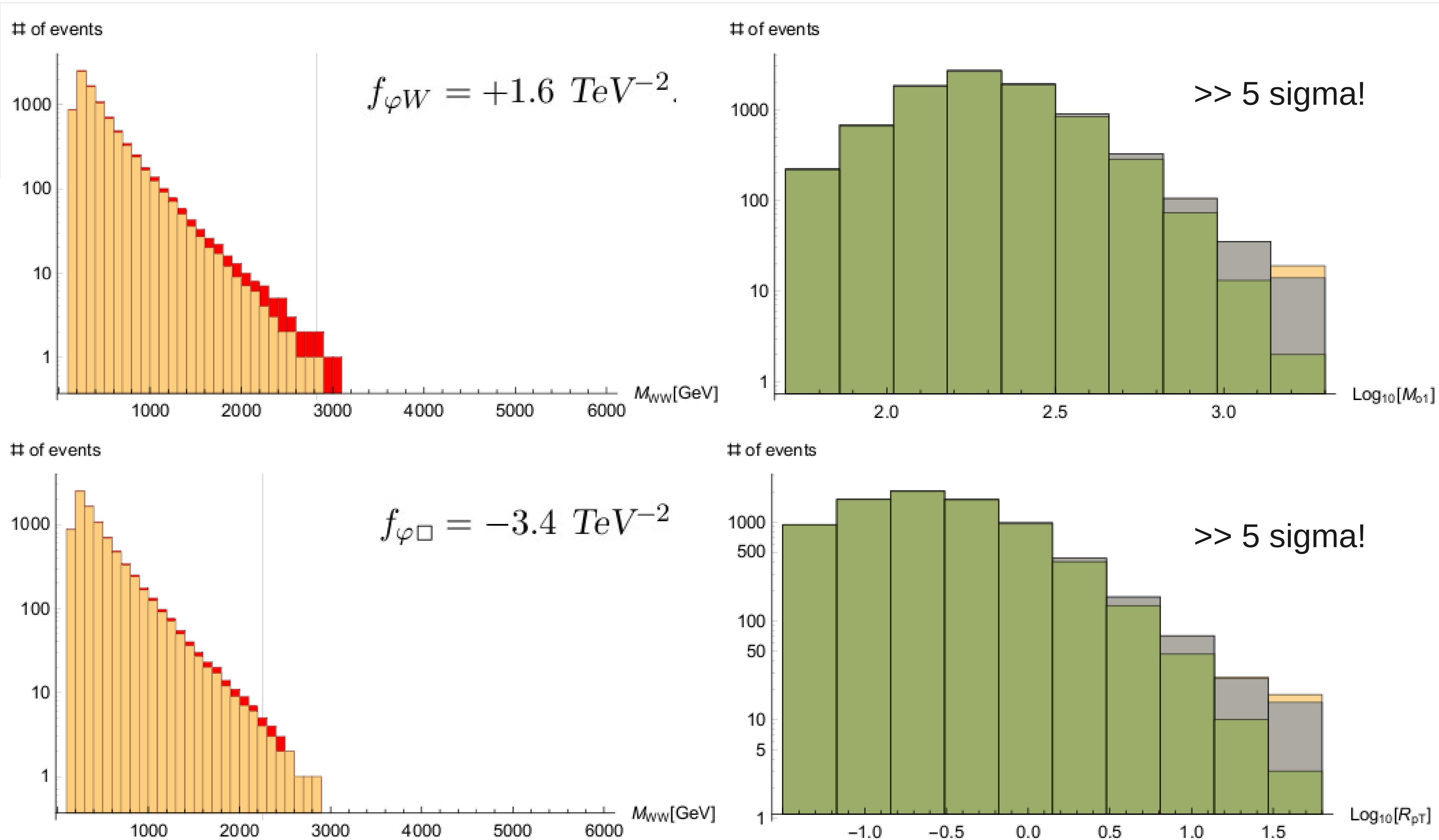
Q_W: significant effects possible at the HL-LHC even with "individual" bounds





Potential impact of VBS dim-6 operators on W+W+

Q_phiW and Q_phiBox: significant effects possible at the HL-LHC if current "global" bounds are considered



Summary and conclusions

1. "Full clipping" method to set limits on SMEFT dim-8 operators is under implementation in the analysis of Run 2 data.

2. For most dim-8 operators the limits are already physical, i.e., stronger than the limits coming from pure theory (unitarity conditions), but only for relatively low values of the cutoff parameter Λ – typically below 2 TeV.

3. The potential impact of all dimension-6 operators in the same-sign scattering process have been studied, taking into account the current experimental limits from other processes.

4. The answer to the question whether we can safely ignore dim-6 operators in VBS analyses at this point seems to be no. Particularly large effects are possible from Q_W.

Coefficient	Individual Limit (95% C.L.)	Marginalized Limit (95% C.L.)
C_{HWB}	$[-0.005, 0.0025]$	$[-0.61, 1.25]$
C_{HD}	$[-0.0253, 0.0015]$	$[-2.7, 1.24]$
$C_{H\square}$	$[-0.4390, 0.5150]$	$[-3.41, 2.44]$
C_{H}	$[-19.7, 6.2]$	$[-23.4, 20.2]$
C_{ll}	$[-0.0039, 0.0207]$	$[-0.0842, 0.0351]$
$C_{Hq}^{(1)}$	$[-0.029, 0.042]$	$[-0.228, 0.116]$
$C_{Hq}^{(3)}$	$[-0.099, 0.0146]$	$[-0.183, 0.167]$
$C_{Hl}^{(1)}$	$[-0.0043, 0.0120]$	$[-0.296, 0.689]$
$C_{Hl}^{(3)}$	$[-0.0119, 0.0029]$	$[-0.142, 0.220]$
C_{Hu}	$[-0.076, 0.087]$	$[-0.791, 0.535]$
C_{Hd}	$[-0.165, 0.0540]$	$[-0.806, 0.132]$
C_{He}	$[-0.0126, 0.0094]$	$[-0.620, 1.350]$
C_{W}	$[-0.15, 0.36]$	$[-1.28, 1.11]$
C_{HG}	$[-0.0027, 0.0032]$	$[-0.0164, 0.0083]$
C_{HW}	$[-0.0143, 0.0068]$	$[-0.141, 1.63]$
C_{HB}	$[-0.0043, 0.0020]$	$[-0.4490, 0.731]$
$C_{\tau H}$	$[-0.0154, 0.0269]$	$[-0.0297, 0.0382]$
C_{bH}	$[-0.131, 0.0723]$	$[-0.134, 0.132]$
C_{tH}	$[-1.0900, 0.625]$	$[-7.35, 3.64]$