



# **Vector Boson Scattering**

#### as a portal to new physics

Iro Koletsou

Laboratoire d'Annecy de Physique des Particules

#### Introduction

- Already many years of proton-proton collisions in LHC
- Higgs discovery in 2012
- Deep study of the electroweak symmetry breaking



#### higgs decay ratios



#### https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults



• What else is out there?

## Introduction

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https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

• What else is out there?

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					$\int \mathcal{L} dt =$	(3.2 - 37.0) fb <sup>-*</sup>	$v_{5} = 8, 13 \text{ lev}$
Model	ί,γ.	Jets† I	E <sup>miss</sup>	∫£ dt[fb <sup>-1</sup>	Limit		Reference
$ \begin{array}{c} \text{ADD } G_{KK} + g/q \\ \text{ADD non-resonant } _{YY} \\ \text{ADD } \text{ADD } \text{ADD } \text{H} \\ \text{ADD } \text{BH } \text{high } \Sigma  p_T \\ \text{ADD } \text{BH } \text{multijet} \\ \text{BR } \text{BSI } G_{KK} \rightarrow YY \\ \text{Bulk } \text{BS } G_{KK} \rightarrow YWV \rightarrow qq\ell_Y \\ \text{2UED } / \text{RPP} \end{array} $	$\begin{array}{c} 0 \ e, \mu \\ 2 \ \gamma \\ - \\ \geq 1 \ e, \mu \\ - \\ 2 \ \gamma \\ 1 \ e, \mu \\ 1 \ e, \mu \end{array} \ge$	1 - 4 j 2 j ≥ 2 j ≥ 3 j - 1 J 2 b, ≥ 3 j	Yes - - - Yes Yes	36.1 36.7 37.0 3.2 3.6 36.7 36.1 36.1	7.75 TeV 8.6 TeV 8.5 TeV 8.2 TeV 9.55 Te 4.1 TeV 1.5 TeV 1.5 TeV	$\begin{array}{l} n=2 \\ n=3 \ \text{HLZ NLO} \\ n=6 \\ n=6, \ M_D=3 \ \text{TeV, rot BH} \\ \forall  n=6, \ M_D=3 \ \text{TeV, rot BH} \\ \lambda/\overline{M}_{PI}=0.1 \\ \lambda/\overline{M}_{PI}=1.0 \\ \text{Tier} (1,1), \mathcal{B}(A^{(1,1)} \rightarrow tt)=1 \end{array}$	ATLAS-CONF-2017-06 CERN-EP-2017-132 1703.09217 1606.02265 1512.02586 CERN-EP-2017-132 ATLAS-CONF-2017-05 ATLAS-CONF-2016-10
$\begin{array}{llllllllllllllllllllllllllllllllllll$	$2 e, \mu$ $2 \tau$ - $1 e, \mu \ge 1$ $1 e, \mu$ $3 0 e, \mu$ multi-channel $1 e, \mu = 1$ $0 e, \mu = 2$	- 2 b 1 b, ≥ 1J/2 - 2 J 2 b, 0-1 j ≥ 1 b, 1 J	- Yes Yes - Yes -	36.1 3.2 3.2 36.1 3.2 36.1 36.7 36.1 20.3 20.3	4.5 TeV 2.4 TeV 1.5 TeV 2.0 TeV 5.1 TeV 3.5 TeV 2.93 TeV 1.02 TeV 1.76 TeV	$\Gamma/m = 3\%$ $g_V = 3$ $g_V = 3$	ATLAS-CONF-2017-023 ATLAS-CONF-2017-064 1603.08791 ATLAS-CONF-2016-01- 1706.04786 CERN-EP-2017-147 ATLAS-CONF-2017-053 1410.4103 1408.0806
Cl qqqq Cl (l qq Cl uutt	_ 2 e,μ 2(SS)/≥3 e,μ ≩	2j 1b, ≥1j	- - Yes	37.0 / 36.1 / 20.3 /	4.9 TeV	21.8 TeV $\eta_{LL}^-$ 40.1 TeV $\eta_{LL}^-$ $ C_{RR}  = 1$	1703.09217 ATLAS-CONF-2017-02 1504.04605
Axial-vector mediator (Dirac DM) Vector mediator (Dirac DM) VVχχ EFT (Dirac DM)	0 e, μ 0 e, μ, 1 γ 0 e, μ	1 – 4 j ≤ 1 j 1 J, ≤ 1 j	Yes Yes Yes	36.1 36.1 3.2	1.5 TeV 1.2 TeV 700 GeV	$\begin{array}{l} g_q{=}0.25,  g_{\chi}{=}1.0,  m(\chi) < 400 \; {\rm GeV} \\ g_q{=}0.25,  g_{\chi}{=}1.0,  m(\chi) < 480 \; {\rm GeV} \\ m(\chi) < 150 \; {\rm GeV} \end{array}$	ATLAS-CONF-2017-060 1704.03848 1608.02372
Scalar LQ 1 <sup>st</sup> gen Scalar LQ 2 <sup>rd</sup> gen Scalar LQ 3 <sup>rd</sup> gen	2 e 2 μ 1 e,μ	≥ 2 j ≥ 2 j :1 b, ≥3 j	- - Yes	3.2 L 3.2 L 20.3 L	1.1 TeV 1.05 TeV 640 GeV	$\beta = 1$ $\beta = 1$ $\beta = 0$	1605.06035 1605.06035 1508.04735
$ \begin{array}{l} VLQ\ TT \rightarrow Ht + X \\ VLQ\ TT \rightarrow Zt + X \\ VLQ\ TT \rightarrow Wb + X \\ VLQ\ BB \rightarrow Hb + X \\ VLQ\ BB \rightarrow Db + X \\ VLQ\ BB \rightarrow Wt + X \\ VLQ\ BB \rightarrow Wt + X \\ VLQ\ QQ \rightarrow WqWq \end{array} $	$\begin{array}{l} 0 \text{ or } 1 e, \mu \geq \\ 2 / \geq 3 e, \mu \\ 1 e, \mu \geq \\ 1 e, \mu \geq \\ 1 e, \mu \end{array}$	$2 b, \ge 3 j$ $1 b, \ge 3 j$ $1 b, \ge 1 J/2 j$ $2 b, \ge 3 j$ $\ge 2/\ge 1 b$ $1 b, \ge 1 J/2 j$ $\ge 2/\ge 1 b$ $2 b, \ge 1 J/2 j$ $\ge 4 j$	Yes Yes Yes Yes Yes Yes	13.2 36.1 36.1 20.3 20.3 36.1 20.3	1.2 TeV 1.16 TeV 1.35 TeV 700 GeV 700 GeV 700 GeV 1.25 TeV 690 GeV	$\begin{split} \mathcal{B}(T \to Ht) &= 1 \\ \mathcal{B}(T \to Zt) &= 1 \\ \mathcal{B}(T \to Wb) &= 1 \\ \mathcal{B}(B \to Hb) &= 1 \\ \mathcal{B}(B \to Hb) &= 1 \\ \mathcal{B}(B \to Zb) &= 1 \\ \mathcal{B}(B \to Wt) &= 1 \end{split}$	ATLAS-CONF-2016-10- 1705.10751 CERN-EP-2017-094 1505.04306 1409.5500 CERN-EP-2017-094 1509.04261
Excited quark $q^* \rightarrow qg$ Excited quark $q^* \rightarrow q\gamma$ Excited quark $b^* \rightarrow bg$ Excited quark $b^* \rightarrow Wr$ Excited quark $b^* \rightarrow Wr$ Excited lepton $r^*$	- 1 γ - 1 or 2 e, μ 3 e, μ 3 e, μ, τ	2j 1j 1b,1j 1b,20j -	- - Yes -	37.0 36.7 13.3 20.3 20.3 20.3	6.0 TeV 5.3 TeV 2.3 TeV 1.5 TeV 3.0 TeV 1.6 TeV	only $a^{\circ}$ and $d^{\circ}$ , $\Lambda = m(q^{\circ})$ only $a^{\circ}$ and $d^{\circ}$ , $\Lambda = m(q^{\circ})$ $f_{e} = f_{c} = f_{H} = 1$ $\Lambda = 3.0 \text{ TeV}$ $\Lambda = 1.6 \text{ TeV}$	1703.09127 CERN-EP-2017-148 ATLAS-CONF-2016-060 1510.02664 1411.2921 1411.2921
LRSM Majorana v Higgs triplet H <sup>+2</sup> → ℓℓ Higgs triplet H <sup>+2</sup> → ℓr Monetop (non-res prod) Multi-charged particles Magnetic monopoles	2 e, μ 2,3,4 e, μ (SS) 3 e, μ, τ 1 e, μ - - -	2j - 1b - -	- Yes - TeV	20.3 36.1 20.3 20.3 20.3 7.0	2.0 TeV a 400 GeV autor particle mater egy particle mater article particle mater article particle mater T 25 GeV article particle mater T 25 GeV article particle mater T 25 GeV article particle material T 25 GeV article particle partic	$\begin{split} m(W_{\rm R}) &= 2.4 \text{ TeV}, \text{no mixing} \\ DY production, \\ DY production, \\ S(H_{\rm L}^{\rm IX} \to \ell \tau) &= 1 \\ a_{\rm monorm} &= 0.2 \\ DY production, \\  g  &= 1 \\ g_D, \\ \text{spin} \ 1/2 \end{split}$	1506.06020 ATLAS-CONF-2017-05 1441.2921 1410.5404 1504.04188 1509.08059

#### Introduction

- Already many years of proton-proton collisions in LHC
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https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults



Could it be... nothing?

• What else is out there?

#### Time for rare processes



## Vector Boson Scattering: EW symmetry breaking

- The cross section computation includes interactions with the Higgs boson
- These interactions unitarize the scattering amplitude

>Important test of the *EW* symmetry breaking

Complementary to direct Higgs studies



# VBS: Quartic Gauge boson Couplings (QGC)

- VBS process can give us access to quartic gauge boson couplings
- Anomalous QGCs could lead to deviation in the VBS cross section
- ≻and allow new physics to appear



## VBS: Quartic Gauge boson Couplings (QGC)

• Anomalous QGC in a EFT framework:

$$\mathcal{L} = \mathcal{L}^{SM} + \sum_{i} \frac{c_i}{\Lambda^2} \mathcal{O}_i + \sum_{j} \frac{f_j}{\Lambda^4} \mathcal{O}_j.$$

SM effective Lagrangian

Gauge boson interactions as described by the SM

Valid below an energy scale  $\Lambda$ 

**dim-6** : operators describing aTGCs and aQGCs

VBS processes not really competitive for their constraint **dim-8** : lowest order operators describing only aQGCs

Can be constrained by VBS

arXiv:1310.6708v1 [hep-ph] 24 Oct 2013

## VBS: Quartic Gauge boson Couplings (QGC)

• Three different types of parameters:

$$\mathcal{L}_{T,0} = \operatorname{Tr} \left[ \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \right] \times \operatorname{Tr} \left[ \hat{W}_{\alpha\beta} \hat{W}^{\alpha\beta} \right]$$
$$\mathcal{L}_{T,1} = \operatorname{Tr} \left[ \hat{W}_{\alpha\nu} \hat{W}^{\mu\beta} \right] \times \operatorname{Tr} \left[ \hat{W}_{\mu\beta} \hat{W}^{\alpha\nu} \right]$$
$$\mathcal{L}_{T,2} = \operatorname{Tr} \left[ \hat{W}_{\alpha\mu} \hat{W}^{\mu\beta} \right] \times \operatorname{Tr} \left[ \hat{W}_{\beta\nu} \hat{W}^{\nu\alpha} \right]$$
$$\mathcal{L}_{T,3} = \operatorname{Tr} \left[ \hat{W}_{\alpha\mu} \hat{W}^{\mu\beta} \hat{W}^{\nu\alpha} \right] \times B_{\beta\nu}$$
$$\mathcal{L}_{T,4} = \operatorname{Tr} \left[ \hat{W}_{\alpha\mu} \hat{W}^{\alpha\mu} \hat{W}^{\beta\nu} \right] \times B_{\beta\nu}$$
$$\mathcal{L}_{T,5} = \operatorname{Tr} \left[ \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \right] \times B_{\alpha\beta} B^{\alpha\beta}$$
$$\mathcal{L}_{T,6} = \operatorname{Tr} \left[ \hat{W}_{\alpha\mu} \hat{W}^{\mu\beta} \right] \times B_{\mu\beta} B^{\alpha\nu}$$
$$\mathcal{L}_{T,7} = \operatorname{Tr} \left[ \hat{W}_{\alpha\mu} \hat{W}^{\mu\beta} \right] \times B_{\beta\nu} B^{\nu\alpha}$$
$$\mathcal{L}_{T,8} = B_{\mu\nu} B^{\mu\nu} B_{\alpha\beta} B^{\alpha\beta}$$
$$\mathcal{L}_{T,9} = B_{\alpha\mu} B^{\mu\beta} B_{\beta\nu} B^{\nu\alpha}$$

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

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

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

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

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

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

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

 ${\cal L}_{M,6} \;=\; \left[ \left( D_\mu \Phi 
ight)^\dagger \hat{W}_{eta 
u} \hat{W}^{eta 
u} D^\mu \Phi 
ight]$ 

 $\mathcal{L}_{S,0} = \left[ \left( D_{\mu} \Phi \right)^{\dagger} D_{\nu} \Phi \right] \times \left[ \left( D^{\mu} \Phi \right)^{\dagger} D^{\nu} \Phi \right]$  $\mathcal{L}_{S,1} = \left[ \left( D_{\mu} \Phi \right)^{\dagger} D^{\mu} \Phi \right] \times \left[ \left( D_{\nu} \Phi \right)^{\dagger} D^{\nu} \Phi \right]$ 

pure Higgs field ( $f_s$ ) (cannot induce couplings with photons)

-								
VVjj final state	ZZ	Zy yy	W+W- WZ	W±W±	Wy			
f <sub>5,0</sub> , f <sub>5,1</sub>	1		~	٢				
f <sub>M,0</sub> , f <sub>M,1</sub> , f <sub>M,6</sub> , f <sub>M,7</sub>	~	~	~	~	~			
f <sub>M,2</sub> , f <sub>M,3</sub> , f <sub>M,4</sub> , f <sub>M,5</sub>	>	~	~		~			
f <sub>T,0</sub> , f <sub>T,1</sub> , f <sub>T,2</sub>	~	~	~	~	~			
f <sub>T,5</sub> , f <sub>T,6</sub> , f <sub>T,7</sub>	>	~	~		~			
f <sub>T,8</sub> , f <sub>T,9</sub>	~	~						

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# **VBS:** a challenging process

- Very low cross section ( $\sim fb$ ) with a high background
- Electroweak diboson production (signal)



can be enhanced with an optimal choice of analysis phase space

• QCD diboson production



## With a clear cinematic signature

• Two forward jets and suppressed hadronic activity in between (absence of color flow between interacting partons)



Cinematic discriminative variables (D. Zeppenfeld et al.)



arXiv:hep-ph/9605444

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#### **Diboson final states**

- https://twiki.cern.ch/twiki/bin/view/ CMSPublic/PhysicsResultsSMP
- https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults

8 TeV	ATLAS	CMS	
WWss	limits on QGCs	only dim-6	most optimal S/B
WZ	limits on QGCs	No ew	
ZZ	-	No ew	low reducible background
Ζγ	limits on QGCs	limits on QGCs	
Wγ	-	limits on QGCs	largest cross section

13 TeV	ATLAS	CMS	
WWss	?	limits on QGCs	first EW production observation
ZZ	?	limits on QGCs	

#### **Diboson final states**

- https://twiki.cern.ch/twiki/bin/view/ CMSPublic/PhysicsResultsSMP
- https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults

8 TeV	ATLAS	CMS	
WWss	limits on QGCs	only dim-6	most optimal S/B
WZ	limits on QGCs	No ew	
ZZ	-	No ew	low reducible background
Zγ ATLAS	limits on QGCs	limits on QGCs	
Wγ	-	limits on QGCs	largest cross section

13 TeV	ATLAS	CMS	
WWss ATLAS	?	limits on QGCs	first EW production observation
ZZ	?	limits on QGCs	

• M<sub>ii</sub> variable used to

#### define a QCD control region Create a VBS enriched phase space



Events / GeV

Data / Pred.

1.5

0

 $^{14}$  ATLAS

√s=8 TeV, 20.2 fb<sup>1</sup>

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10-

initial S/B

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m<sub>ii</sub> [GeV]

🔶 Data

tτγ WZji

100 200 300 400 500 600 700 800 900

Tot. unc. **Inclusive Region** 

Z(l⁺ĺ)γjj EWK

Z(I<sup>+</sup>I)yjj QCD Z+jets

M<sub>ii</sub> variable used to

#### define a QCD control region Create a VBS enriched phase space

Control region

Inclusive region



2 leptons:  $P_T^{\gamma}$ >25 GeV,  $|\eta|$ <2.47 (2.5 for  $\mu$ )

	$Z(\ell^+\ell^-)\gamma$	$+ \geq 2$ jets	$150 < m_{j_{1}}$	$_j < 500 \mathrm{GeV}$	$m_{jj} > $	$500{ m GeV}$			m <sub>II</sub> >40 Ge	₽V, m <sub>IIγ</sub> >182 GeV	
	$e^+e^-\gamma jj$	$\mu^+\mu^-\gamma jj$	$e^+e^-\gamma jj$	$\mu^+\mu^-\gamma jj$	$e^+e^-\gamma jj$	$\mu^+\mu^-\gamma jj$			<b>2 jets:</b> <i>P</i> <sub>T</sub>	>30 GeV,  η <4.5	
Data	781	949	362	421	58	72					
Z+jets bkg.	$134\pm36$	$154\pm42$	$57\pm16$	$67 \pm 18$	$8.5\pm2.5$	$9.4\pm2.7$	$\longrightarrow$	Reducible	e background:	extracted from da	ita
Other bkg. $(t\bar{t}\gamma, WZ)$	$88\pm17$	$91\pm18$	$47\pm9$	$46\pm9$	$5.8\pm1.1$	$5.0\pm1.0$					_
$N_{Z\gamma \text{ QCD}}$ (Sherpa MC)	$583 \pm 41$	$671\pm47$	$249\pm24$	$290\pm26$	$37\pm5$	$41\pm5$	$\rightarrow$	Irreducibl	e background:	normalized in CR	
$N_{Z\gamma \text{ EWK}}$ (Sherpa MC)	$25.4 \pm 1.5$	$27.3 \pm 1.7$	$8.6\pm0.6$	$9.3\pm0.6$	$11.2\pm0.8$	$11.6\pm0.7$		Signal			
31/03/2018	initia	IS/B			HEP 2	2018 NTUA				15	

Search region

Centrality variable used as « template »

Negative Log Likelihood ratio minimization parameter of interest:  $\mu = \frac{\sigma^{meas.}}{\sigma^{MC}}$ 

$$-\ln(\lambda(\mu)) = -\ln\frac{L(\mu,\hat{\theta})}{L(\hat{\mu},\hat{\theta})}$$

 $\geq \theta$ : nuisance parameters (systematics)

$$\sigma_{Z\gamma jj}^{\text{EWK}} = 1.1 \pm 0.5 \text{ (stat)} \pm 0.4 \text{ (syst) fb}$$



•  $E_T(\gamma)$  variable used to probe the QGC

High energy tails would be modified if aQGC
7 effective operators varied one by one

95% CL intervals	Measured $[\text{TeV}^{-4}]$	
$f_{T9}/\Lambda^4$	$[-6.9, 6.9] \times 10^4$	Non
$f_{T8}/\Lambda^4$	$[-3.4, 3.3] \times 10^4$	NOT
$f_{T0}/\Lambda^4$	$[-7.2, 6.1]  imes 10^1$	
$f_{M0}/\Lambda^4$	$[-1.0, 1.0] \times 10^3$	
$f_{M1}/\Lambda^4$	$[-1.6, 1.7] \times 10^3$	
$f_{M2}/\Lambda^4$	$[-1.1, 1.1] \times 10^4$	
$f_{M3}/\Lambda^4$	$[-1.6, 1.6] \times 10^4$	



on-zero  $f_{T,8-9}$  only accessible by Zy and ZZ channels

$$\mathcal{L}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta}$$
$$\mathcal{L}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}$$

JHEP07(2017)107

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# CMS WWss Run 2 Analysis

**2** same sign leptons:  $P_T^{1}>25 \text{ GeV}, P_T^{2}>20 \text{ GeV}, |\eta|<2.5 (2.4 \text{ for }\mu)$  **2** jets:  $P_T>30 \text{ GeV}, |\eta|<5.0, m_{jj}>500 \text{ GeV}, |\Delta\eta_{jj}|>2.5$ **Centrality:**  $|\eta_l - (\eta_{j1} + \eta_{j2})/2|/|\Delta\eta_{jj}|<0.75$ 



- First (and only) Run 2 VBS analysis to appear
  - >  $35.9 \text{ fb}^{-1}$  with an optimal S/B
- Main background: WZ -> measured in dedicated CR asking for a 3<sup>rd</sup> lepton

#### CMS WWss Run 2 Analysis

- Cross section extraction:
- 2-dimentionnal fit
- ➢ 2 free parameters:  $\mu_{WW}$ ,  $\mu_{WZ}$

2regions: SR and WZ CR (only m<sub>ii</sub>)



Results: 
$$\sigma_{W^{\pm}W^{\pm}}^{EWK} = 3.83 \pm 0.66 (stat) \pm 0.35 (syst) fb$$



#### CMS WWss Run 2 Analysis

#### arXiv:1709.05822v2 [hep-ex] 11 Mar 2018

• m<sub>II</sub> sensible to aQGC

> 9 effective operators varied one by one



	Observed limits
	(TeV <sup>-4</sup> )
$f_{S0}/\Lambda^4$	[-7.7,7.7]
$f_{S1}/\Lambda^4$	[-21.6, 21.8]
$f_{M0}/\Lambda^4$	[-6.0, 5.9]
$f_{M1}/\Lambda^4$	[-8.7, 9.1]
$f_{M6}/\Lambda^4$	[-11.9, 11.8]
$f_{M7}/\Lambda^4$	[-13.3, 12.9]
$f_{T0}/\Lambda^4$	[-0.62, 0.65]
$f_{T1}/\Lambda^4$	[-0.28, 0.31]
$f_{T2}/\Lambda^4$	[-0.89, 1.02]

Not accessible with Zg analysis

$$\mathcal{L}_{S,0} = \left[ \left( D_{\mu} \Phi \right)^{\dagger} D_{\nu} \Phi \right] \times \left[ \left( D^{\mu} \Phi \right)^{\dagger} D^{\nu} \Phi \right]$$
$$\mathcal{L}_{S,1} = \left[ \left( D_{\mu} \Phi \right)^{\dagger} D^{\mu} \Phi \right] \times \left[ \left( D_{\nu} \Phi \right)^{\dagger} D^{\nu} \Phi \right]$$

We need the complementarity of several analysis!

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# Summary of results: $f_T$

May 2017	ATLAS without FF	Channel	Limits	∫Ldt	vs
$f_{T,0} / \Lambda^4$		Wγγ	[-3.4e+01, 3.4e+01]	19.4 fb <sup>-1</sup>	8 TeV
	H	Wyy	[-1.6e+01, 1.6e+01]	20.3 fb <sup>-1</sup>	8 TeV
	H	Zyy	[-1.6e+01, 1.9e+01]	20.3 fb <sup>-1</sup>	8 TeV
		WVγ	[-2.5e+01, 2.4e+01]	19.3 fb <sup>-1</sup>	8 TeV
	<b>├</b> ──┤	Ζγ	[-3.8e+00, 3.4e+00]	19.7 fb <sup>-1</sup>	8 TeV
		Zγ	[-3.4e+00, 3.4e+00]	29.2 fb <sup>-1</sup>	8 TeV
		Wγ	[-5.4e+00, 5.6e+00]	19.7 fb <sup>-1</sup>	8 TeV
	<b>⊢</b>	ss WW	[-4.2e+00, 4.6e+00]	19.4 fb <sup>-1</sup>	8 TeV
	Н	ss WW	[-6.2e-01, 6.5e-01]	35.9 fb <sup>-1</sup>	13 TeV
	H	ZZ	[-4.6e-01, 4.4e-01]	35.9 fb <sup>-1</sup>	13 TeV
$f_{T,1}/\Lambda^4$	<b>⊢</b> −−1	Ζγ	[-4.4e+00, 4.4e+00]	19.7 fb <sup>-1</sup>	8 TeV
		Wγ	[-3.7e+00, 4.0e+00]	19.7 fb <sup>-1</sup>	8 TeV
	H	ss WW	[-2.1e+00, 2.4e+00]	19.4 fb <sup>-1</sup>	8 TeV
	I IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII	ss WW	[-2.8e-01, 3.1e-01]	35.9 fb <sup>-1</sup>	13 TeV
	H	ZZ	[-6.1e-01, 6.1e-01]	35.9 fb <sup>-1</sup>	13 TeV
$f_{T,2}/\Lambda^4$		Ζγ	[-9.9e+00, 9.0e+00]	19.7 fb <sup>-1</sup>	8 TeV
		Wγ	[-1.1e+01, 1.2e+01]	19.7 fb <sup>-1</sup>	8 TeV
		ss WW	[-5.9e+00, 7.1e+00]	19.4 fb <sup>-1</sup>	8 TeV
	H	ss WW	[-8.9e-01, 1.0e+00]	35.9 fb <sup>-1</sup>	13 TeV
	H	ZZ	[-1.2e+00, 1.2e+00]	35.9 fb <sup>-1</sup>	13 TeV
$f_{T,5} / \Lambda^4$		Ζγγ	[-9.3e+00, 9.1e+00]	20.3 fb <sup>-1</sup>	8 TeV
		Wγ	[-3.8e+00, 3.8e+00]	19.7 fb <sup>-1</sup>	8 TeV
$f_{T,6} / \Lambda^4$		Wγ	[-2.8e+00, 3.0e+00]	19.7 fb <sup>-1</sup>	8 TeV
$f_{T,7} / \Lambda^4$	<b>├───</b> ┥	Wγ	[-7.3e+00, 7.7e+00]	19.7 fb <sup>-1</sup>	8 TeV
f <sub>τ,8</sub> /Λ <sup>4</sup>	H	Zγ	[-1.8e+00, 1.8e+00]	19.7 fb <sup>-1</sup>	8 TeV
	H	Zγ	[-1.8e+00, 1.8e+00]	20.2 fb <sup>-1</sup>	8 TeV
	Н	ZZ	[-8.4e-01, 8.4e-01]	35.9 fb <sup>-1</sup>	13 TeV
f <sub>T.9</sub> /Λ <sup>4</sup>	<b>⊢−−−−</b>	Ζγγ	[-7.4e+00, 7.4e+00]	20.3 fb <sup>-1</sup>	8 TeV
		Zγ	[-4.0e+00, 4.0e+00]	19.7 fb <sup>-1</sup>	8 TeV
		Zγ	[-3.9e+00, 3.9e+00]	20.2 fb <sup>-1</sup>	8 TeV
I .	Ì	ZZ	[-1.8e+00, 1.8e+00]	35.9 fb <sup>-1</sup>	13 TeV
50		-			
-50	0	50	10	0	
		6	aQGC Limits @9	5% C.L	. [TeV⁻⁴]

# Summary of results: f<sub>M</sub>

May 2017	CMS ATLAS	without FF	Channel	Limits	<i>∫L</i> dt	เร
$f_{M,0} / \Lambda^4$			WVγ	[-7.7e+01, 8.1e+01]	19.3 fb <sup>-1</sup>	8 TeV
		Z. ATLAC	Ζγ	[-7.1e+01, 7.5e+01]	19.7 fb⁻¹	8 TeV
		Ζγ ΑΙ LΑ5	Wγ	[-7.7e+01, 7.4e+01]	19.7 fb⁻¹	8 TeV
	ł H		ss WW	[-3.3e+01, 3.2e+01]	19.4 fb⁻¹	8 TeV
			ss WW	[-6.0e+00, 5.9e+00]	35.9 fb⁻¹	13 TeV
		~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~	γγ→ <b>VV</b> VV	[-2.8e+01, 2.8e+01]	20.2 fb <sup>-1</sup>	8 TeV
			γγ→WW	[-4.2e+00, 4.2e+00]	24.7 fb⁻¹	7,8 TeV
$f_{M,1}/\Lambda^4$		Lânn manne an de lânn mannement a ray de lânn namer an	WVγ	[-1.3e+02, 1.2e+02]	19.3 fb <sup>-1</sup>	8 TeV
,.			Ζγ	[-1.9e+02, 1.8e+02]	19.7 fb⁻¹	8 TeV
	∮ <b>`⊢</b> −− <b> </b>	Z Y AI LAS	Wγ	[-1.2e+02, 1.3e+02]	19.7 fb <sup>-1</sup>	8 TeV
	H		ss WW 🚦	[-4.4e+01, 4.7e+01]	19.4 fb <sup>-1</sup>	8 TeV
			ss WW	[-8.7e+00, 9.1e+00]	35.9 fb⁻¹	13 TeV
		~~~~~~	γγ→WW	[-1.1e+02, 1.0e+02]	20.2 fb <sup>-1</sup>	8 TeV
	н		γγ→WW	[-1.6e+01, 1.6e+01]	24.7 fb <sup>-1</sup>	7,8 TeV
$f_{M,2}/\Lambda^4$		-	Ζγγ	[-5.1e+02, 5.1e+02]	20.3 fb <sup>-1</sup>	8 TeV
			<b>W</b> γγ	[-7.0e+02, 6.8e+02]	19.4 fb <sup>-1</sup>	8 TeV
		l	Wγγ	[-2.5e+02, 2.5e+02]	20.3 fb <sup>-1</sup>	8 TeV
		Ζν ΔΤΙ Δ ς	Ζγ	[-3.2e+01, 3.1e+01]	19.7 fb⁻¹	8 TeV
	<u></u>		Wγ	[-2.6e+01, 2.6e+01]	19.7 fb⁻¹	8 TeV
$f_{M,3} / \Lambda^4$			Ζγγ	[-8.5e+02, 9.2e+02]	20.3 fb <sup>-1</sup>	8 TeV
			Wγγ	[-1.2e+03, 1.2e+03]	19.4 fb <sup>-1</sup>	8 TeV
			Wγγ	[-4.4e+02, 4.7e+02]	20.3 fb <sup>-1</sup>	8 TeV
		7γ ΔΤΙ Δ S	Ζγ	[-5.8e+01, 5.9e+01]	19.7 fb⁻¹	8 TeV
		ΖγΗΤΕΛΟ	Wγ	[-4.3e+01, 4.4e+01]	19.7 fb⁻¹	8 TeV
$f_{M,4} / \Lambda^4$	H		Wγ	[-4.0e+01, 4.0e+01]	19.7 fb⁻¹	8 TeV
$f_{M,5} / \Lambda^4$			Wγ	[-6.5e+01, 6.5e+01]	19.7 fb <sup>-1</sup>	8 TeV
$f_{M,6} / \Lambda^4$			Wγ	[-1.3e+02, 1.3e+02]	19.7 fb⁻¹	8 TeV
			ss WW	[-6.5e+01, 6.3e+01]	19.4 fb <sup>-1</sup>	8 TeV
			ss WW	[-1.2e+01, 1.2e+01]	35.9 fb <sup>-1</sup>	13 TeV
$f_{M,7}/\Lambda^4$			Wγ 💈	[-1.6e+02, 1.6e+02]	19.7 fb⁻¹	8 TeV
			ss WW	[-7.0e+01, 6.6e+01]	19.4 fb⁻¹	8 TeV
- I	ылана на		ˈss WW 🏢	[-1.3e+01, 1.3e+01]	35.9 fb⁻¹	13 TeV
2000		₩₩₩₽₽₽₽₽₩₩₩₩₩₩₩₩₩₩₩₩₩₩₩₩₩₩₩₩₩₩₩₩₩₩₩₩₩₩	2000	)	4000	<b>_</b>
-2000	0		2000		4000	
			aQ	GC Limits @9	5% C.L.	leV <sup>4</sup>

## Summary

- *VBS* is the "new", interesting chapter of indirect new physics searches
  - First observation with same sign WW (CMS)
  - Already used in Run 1 to set limits to aQGC machinery in place
- To come:
  - New results with much more statistics and new analysis technics
  - Close ATLAS-CMS collaboration in order to combine their results
  - Close collaboration with theorists for the interpretation of the results
- We're looking forward to this