Vector Boson Scattering, Triboson and Quartic Gauge Couplings with ATLAS at the LHC

Konstantinos Bachas[1]

HEP 2015, 15-18 April, Athens

OPERATIONAL PROGRAMME EDUCATION AND LIFELONG LEARNING
investing in knowledge society
MINISTRY OF EDUCATION, LIFELONG LEARNING AND RELIGIOUS AFFAIRS
MANAGING AUTHORITY
European Union
European Social Fund
Co- financed by Greece and the European Union
NSRF 2007-2013
programme for development
EUROPEAN SOCIAL FUND

[1]Aristotle University of Thessaloniki

Contents

- **Motivation for studying VBS, Tribosons and QGCs**
- **What have we measured so far with ATLAS?**
- **What are the prospects during Run-2 and beyond?**

The Standard Model of particle physics

- **Our current understanding of the world lies in the SM of particle physics**

- **Already before the start of the LHC program in 2009 the SM had been extremely successful**
  - Describes extremely well a wide range of precise experimental measurements

- **Electroweak Symmetry Breaking: The discovery of the Higgs boson in July 2012 indicated that it proceeds according to the Higgs mechanism**
  - Represents one of the triumphs of the SM and modern particle physics

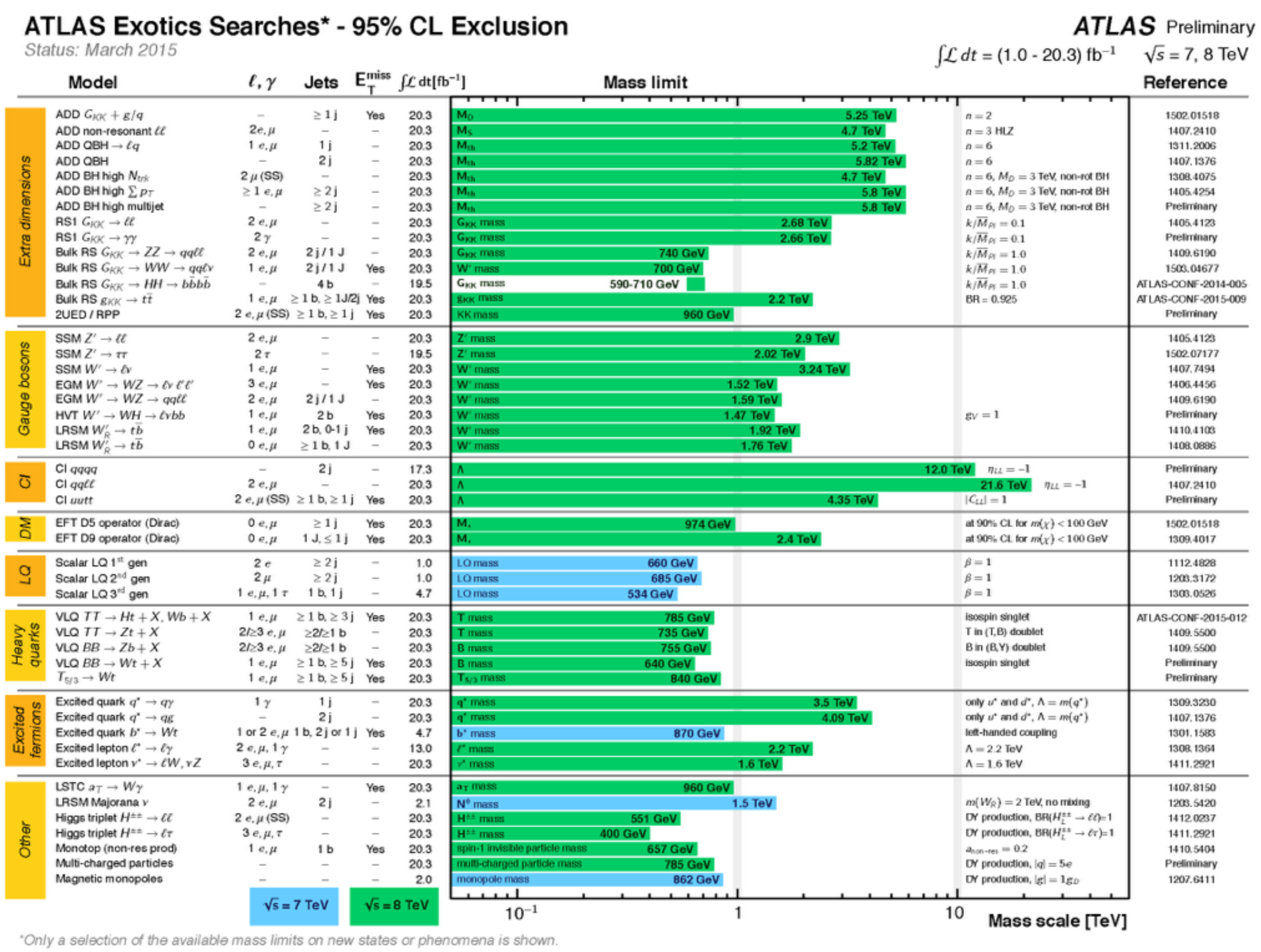
State of the art

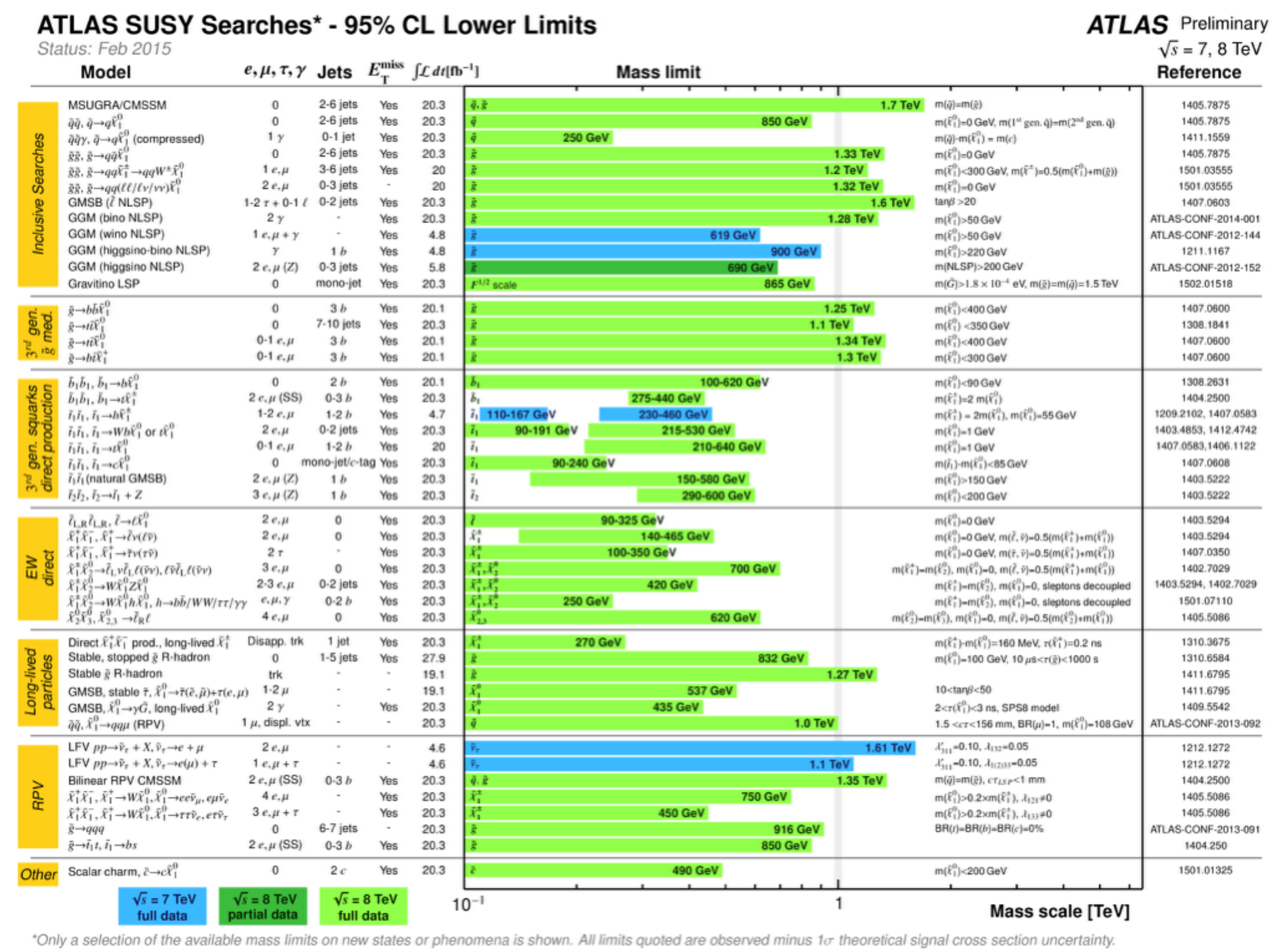
- **High-energy physics stands now at another turning point as in 2009**
  - Despite its huge success, the SM is not the ultimate theory
- **There are still open questions that the SM cannot accommodate**
  - The difference between the strength of electroweak and gravity forces, known as the hierarchy problem
  - The origin and composition of dark matter, which is five times as prevalent as normal matter in the universe, remains unknown.
  - The apparent matter-antimatter asymmetry in the universe
- **There should be a more fundamental theory that incorporates New Physics.**
- **The SM should be a low energy approximation and new physics should be present at the TeV energy scale → Physics Beyond SM (BSM) !**
  - Little Higgs models, supersymmetry, new gauge bosons, technicolour, compositeness, leptoquarks, hidden valley physics, etc
  - all targeted processes being model dependent

Lessons from Run-1 of LHC

1. No evidence for New Physics has been observed.

- **Several targeted searches to look for signals from various extensions of the SM**



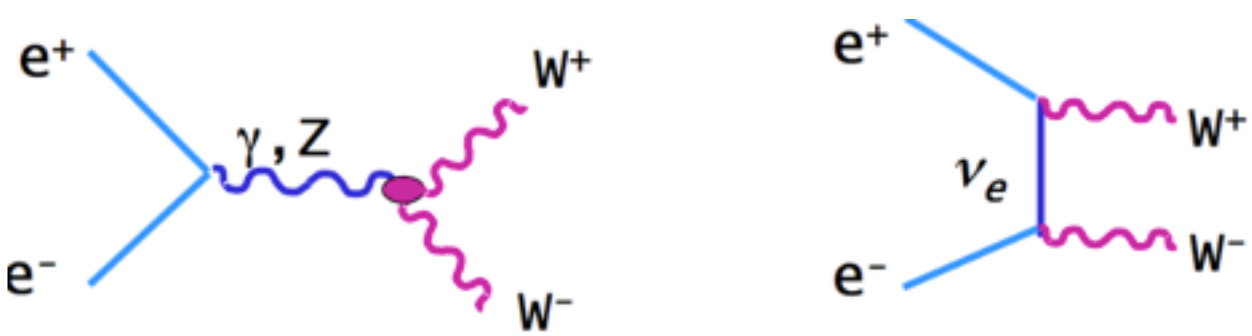


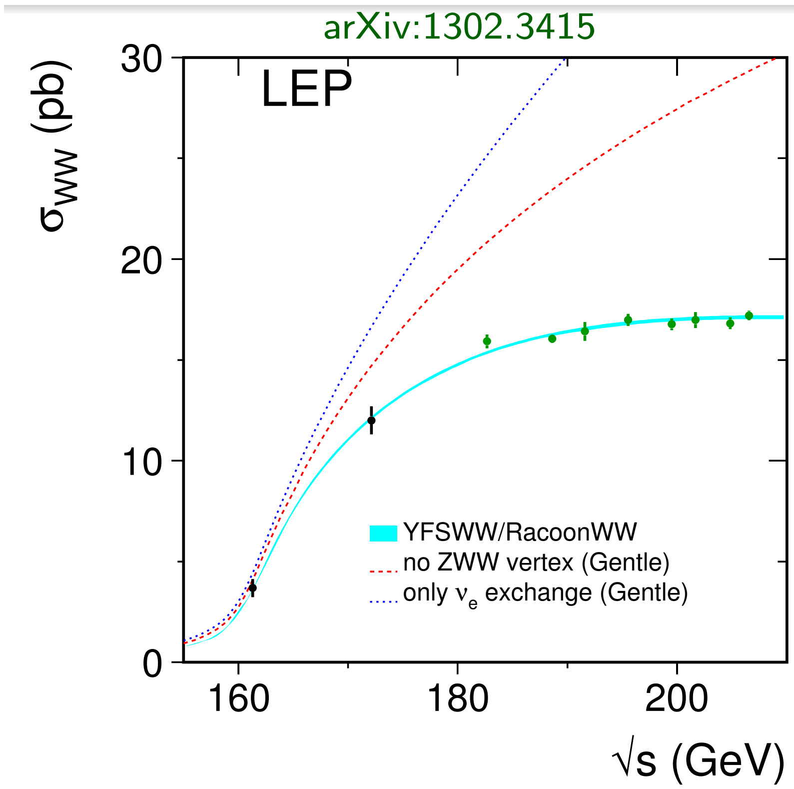
2. Evidence for SM Vector Boson Scattering and Triboson production

- First evidence for Vector Boson Scattering (VBS) has been reported by both ATLAS and CMS experiments in the same charge WW+2jets scattering process and in the Z and two jets production mode respectively

Motivation

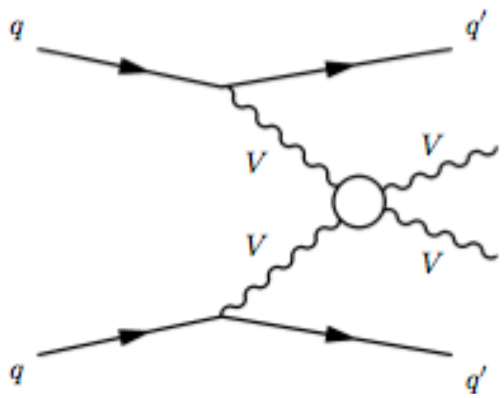
- **The non-abelian nature of the SM allows for the self-coupling of the vector bosons**
  - In the form of triple and quartic gauge boson couplings (TGC and QGC)
- **Already at LEP II it became apparent the importance of the precise contribution of the γWW and the ZWW vertices**
  - Cancels the t-channel neutrino exchange diagram
  - Prevents the WW cross section to violate unitarity

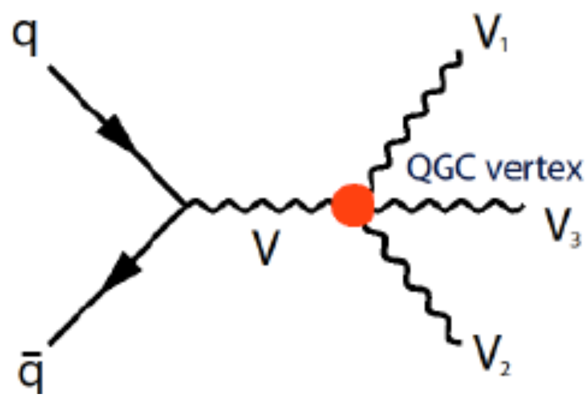




- **The exact cancellations would not have happened if the tree vertices γWW and ZWW were not "exactly" SM**
  - Sets thus limits on anomalous couplings…

At LHC: Processes with QGCs - VBS and Triboson





- **Two measurable classes of processes exist where a QGC vertex (VV→VV and V→VVV) contributes: VBS as VV+2jets and triple gauge boson production (VVV).**
- **If we assume there was no SM Higgs boson, the VBS amplitude would increase as a function of the center-of-mass energy and would violate unitarity at energies around 1 TeV.**
- **Many physics scenarios predict enhancements in VBS**
  - either from additional resonances
  - or if the observed SM-like Higgs boson only partially unitarizes the VBS .

Probing for deviations from SM

- **The SM is assumed to be a low energy effect of new physics at scales beyond the current kinematic reach**
- **Deviations from SM are parametrized using effective Lagrangian**
- **Traditional approach: parametrize deviations from SM values for TGC and QGC as anomalous couplings.**

Coupling	Parameter	Channel
WWγ	$\lambda_\gamma, \Delta\kappa_\gamma$	WW,Wγ
WWZ	$\lambda_Z, \Delta\kappa_Z, \Delta g_1^Z$	WW,WZ
ZZγ	h_3^Z, h_4^Z	Zγ
Zγγ	h_3^γ, h_4^γ	Zγ
ZγZ	f_{40}^Z, f_{50}^Z	ZZ
ZZZ	$f_{40}^\gamma, f_{50}^\gamma$	ZZ

Characteristics
Anomalous couplings can manifest as increase cross sections and modification of kinematic distributions

Coupling	Parameter	Channel
WWZZ,WWWW	$\alpha 4, \alpha 5$	WW,WZ

Alternative approach: Effective Field Theories(EFT)

- **Alternative approach is to use EFT, expanding deviations from the SM Lagrangian in higher dimension operators**

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{\text{dimension } d} \sum_{i} \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

Λ: scale of New Physics

- **EFT provides the means to conduct indirect searches for signals of BSM physics when the energy for directly producing new particles does not suffice.**
- **Additional advantage with EFT approach is greater predictive power**
- **In the framework of an EFT these operators are organized in order of increasing dimensionality.**
  - The SM Lagrangian contains dimension-4 operators.
  - Multi-boson production is modified by certain dimension-6 and dimension-8 operators containing the Higgs and/or gauge boson fields.

Dimension 8 QGC operators with no effect on TGC

	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$	X	X	X						
$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$, $\mathcal{O}_{M,6}$, $\mathcal{O}_{M,7}$	X	X	X	X	X	X	X		
$\mathcal{O}_{M,2}$, $\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$, $\mathcal{O}_{M,5}$		X	X	X	X	X	X		
$\mathcal{O}_{T,0}$, $\mathcal{O}_{T,1}$, $\mathcal{O}_{T,2}$	X	X	X	X	X	X	X	X	X
$\mathcal{O}_{T,5}$, $\mathcal{O}_{T,6}$, $\mathcal{O}_{T,7}$		X	X	X	X	X	X	X	X
$\mathcal{O}_{T,8}$, $\mathcal{O}_{T,9}$			X			X	X	X	X

Alternative approach: Effective Field Theories(EFT)

- **Alternative approach is to use EFT, expanding deviations from the SM Lagrangian in higher dimension operators**

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{\text{dimension } d} \sum_{i} \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

Λ: scale of New Physics

- **EFT provides the means to conduct <u>indirect searches</u> for signals of BSM physics when the energy for directly producing new particles does not suffice.**
- **Additional advantage with EFT approach is greater predictive power**
- **In the framework of an EFT these operators are organized in order of increasing dimensior**
  - The SM
  - Multi-b ... ining the Higgs a

$\mathcal{O}_{M,0}$

$\mathcal{O}_{M,2}$

$\mathcal{O}$

$\mathcal{O}$

A

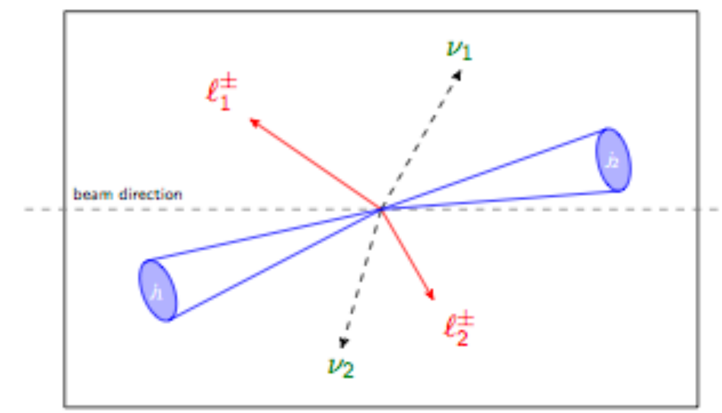
VBS and Triboson processes are an excellent probe for New Physics and one of the core reasons for the LHC energy upgrade

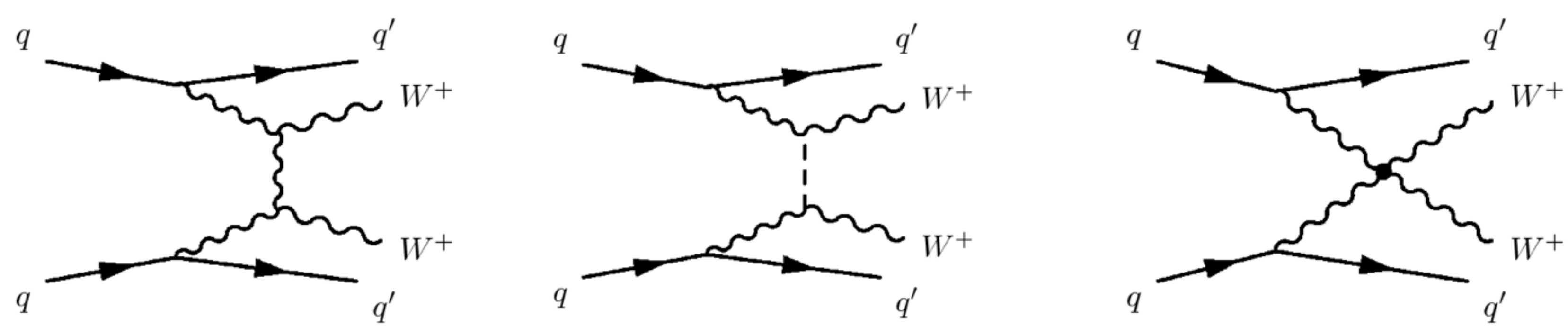
PRL 113, 141803 (2014)

$W^{\pm}W^{\pm}$+2jets production (1/3)

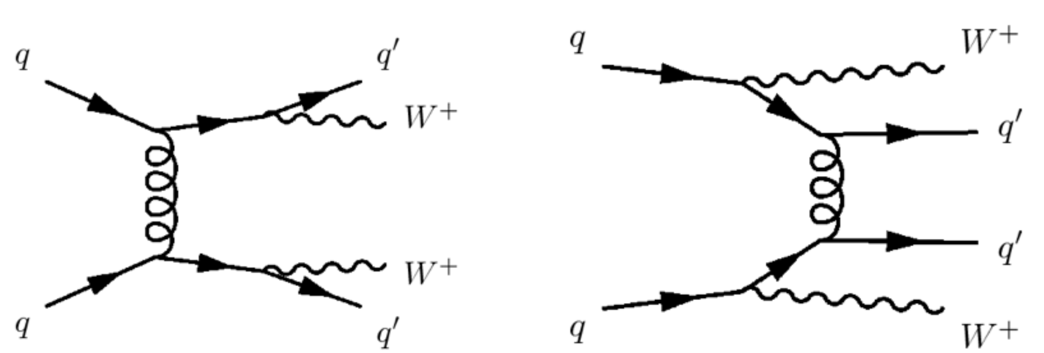
- **Same charge WWjj scattering (VBS) is a key process to experimentally probe the SM nature of EWSB**
- **WWjj production process classification**
  - Pure EWK WWjj production (VBS contribution)
  - Strong + Ewk WWjj production (inclusive)

Characteristic signature
2 forward jets with high dijet mass
Jets well separated in rapidity





WWjj-Ewk

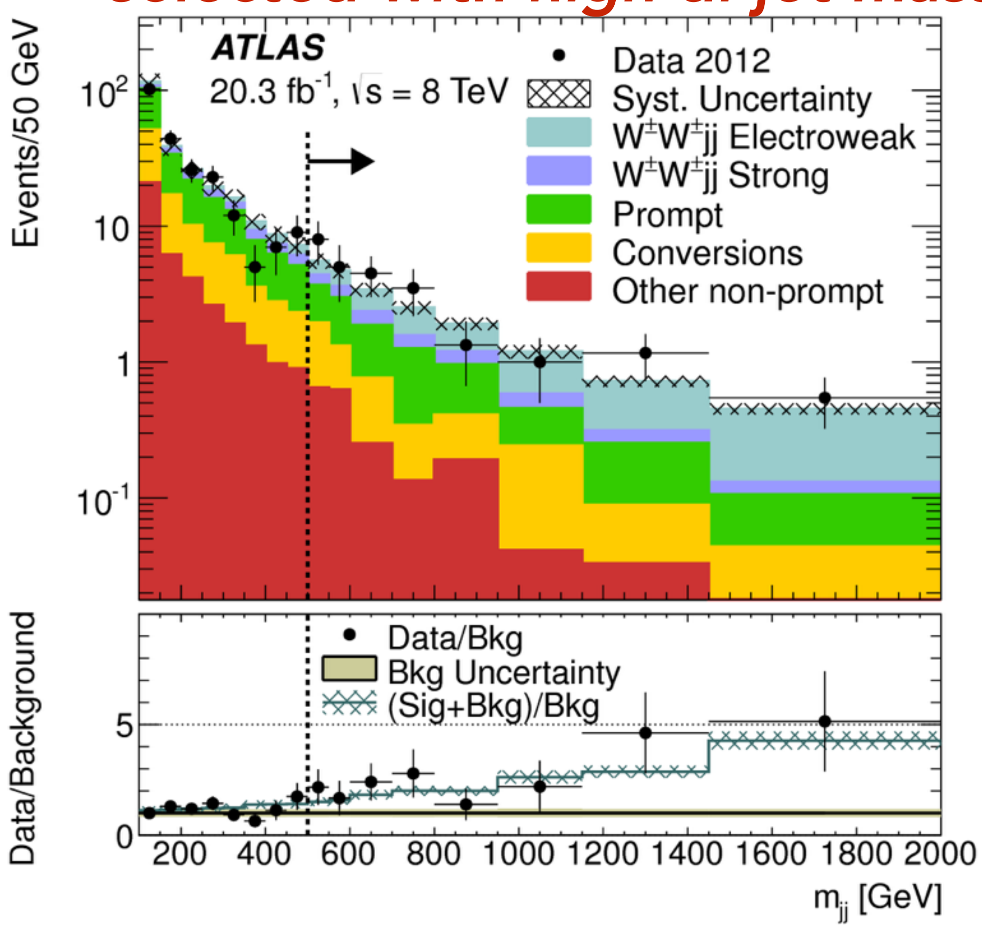


WWjj-strong

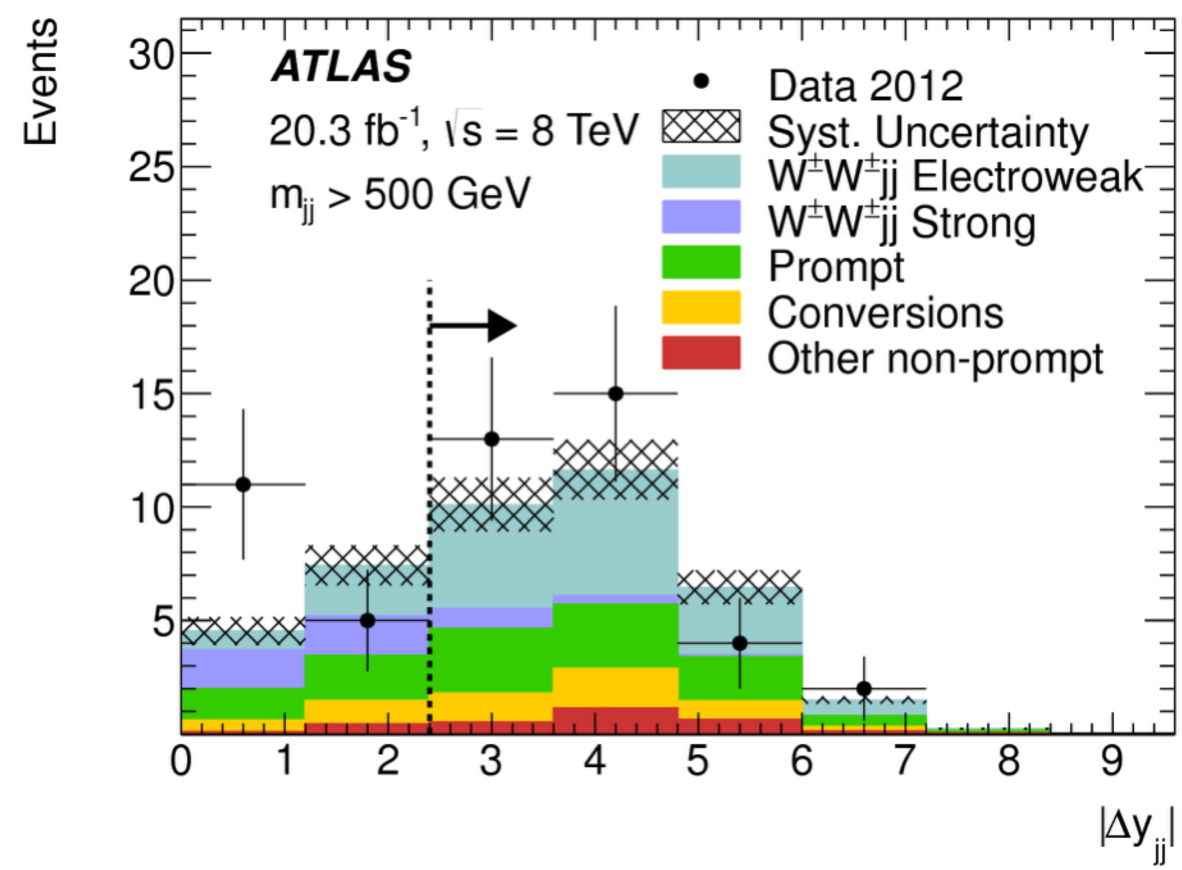
W±W±+2jets production (2/3)

- **Final states: ℓ±νℓ±ν + jj (ℓ=e,μ)**
- **Main backgrounds:**
  - WZ+2jets , Wɣ+2jets: estimated from MC
  - tt(bar) and single Z production through charge misidentification : estimated from data
- **Systematics dominated by jet energy scale and WZ+2jets normalization**

measurement of EW + strong production selected with high di-jet mass

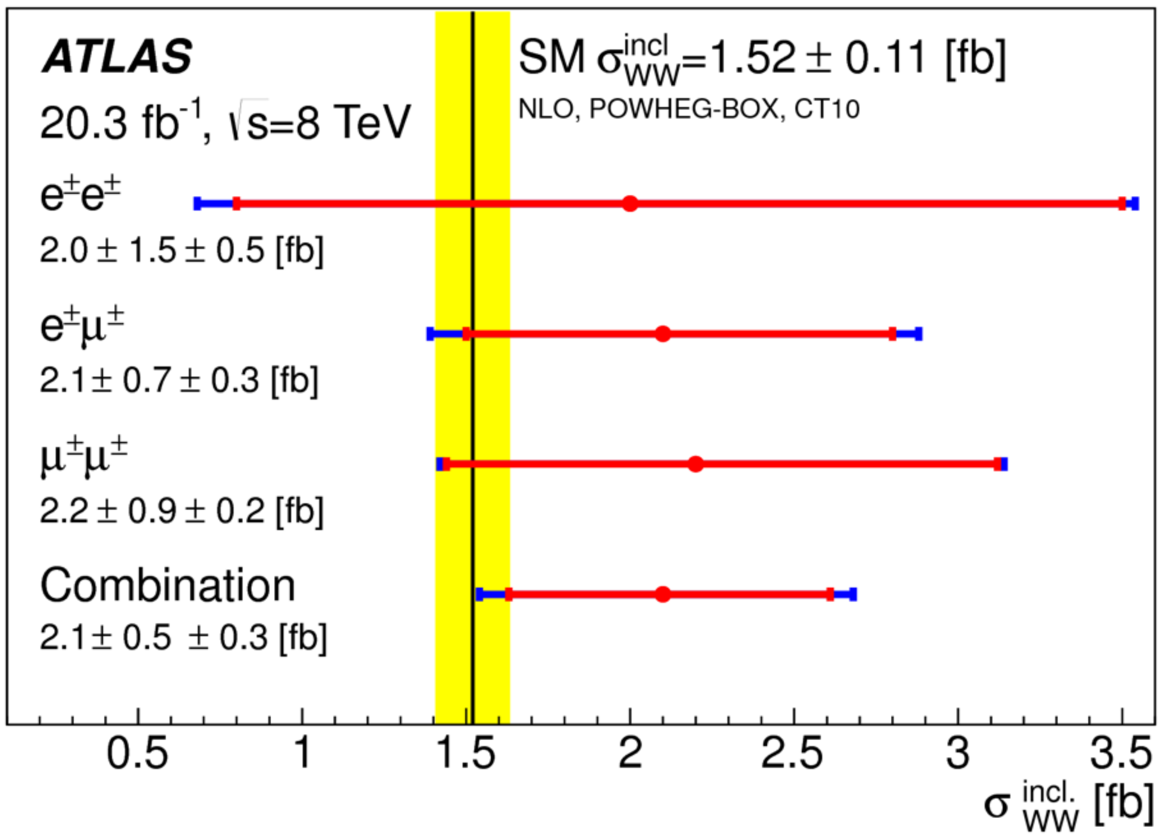


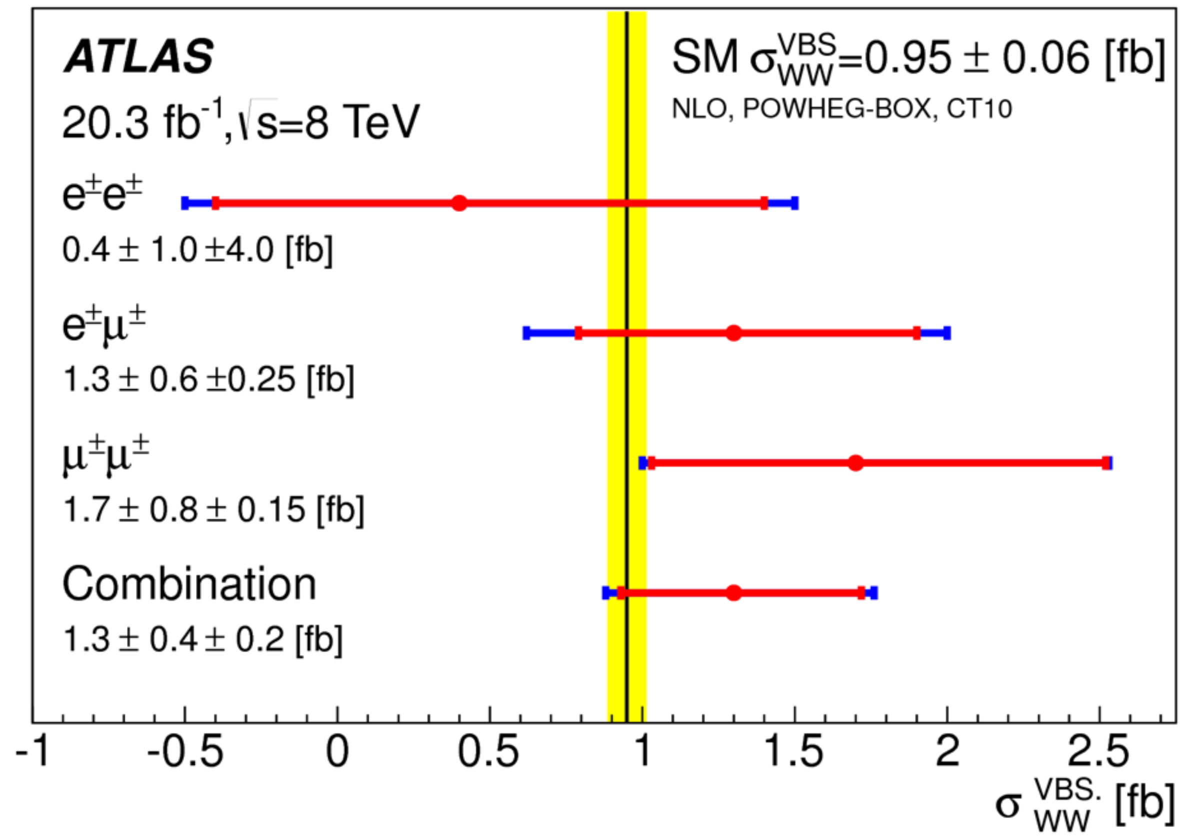
measurement of EW only selection enhanced by ΔYjj cut



PRL 113, 141803 (2014)

W±W±+2jets production (3/3)





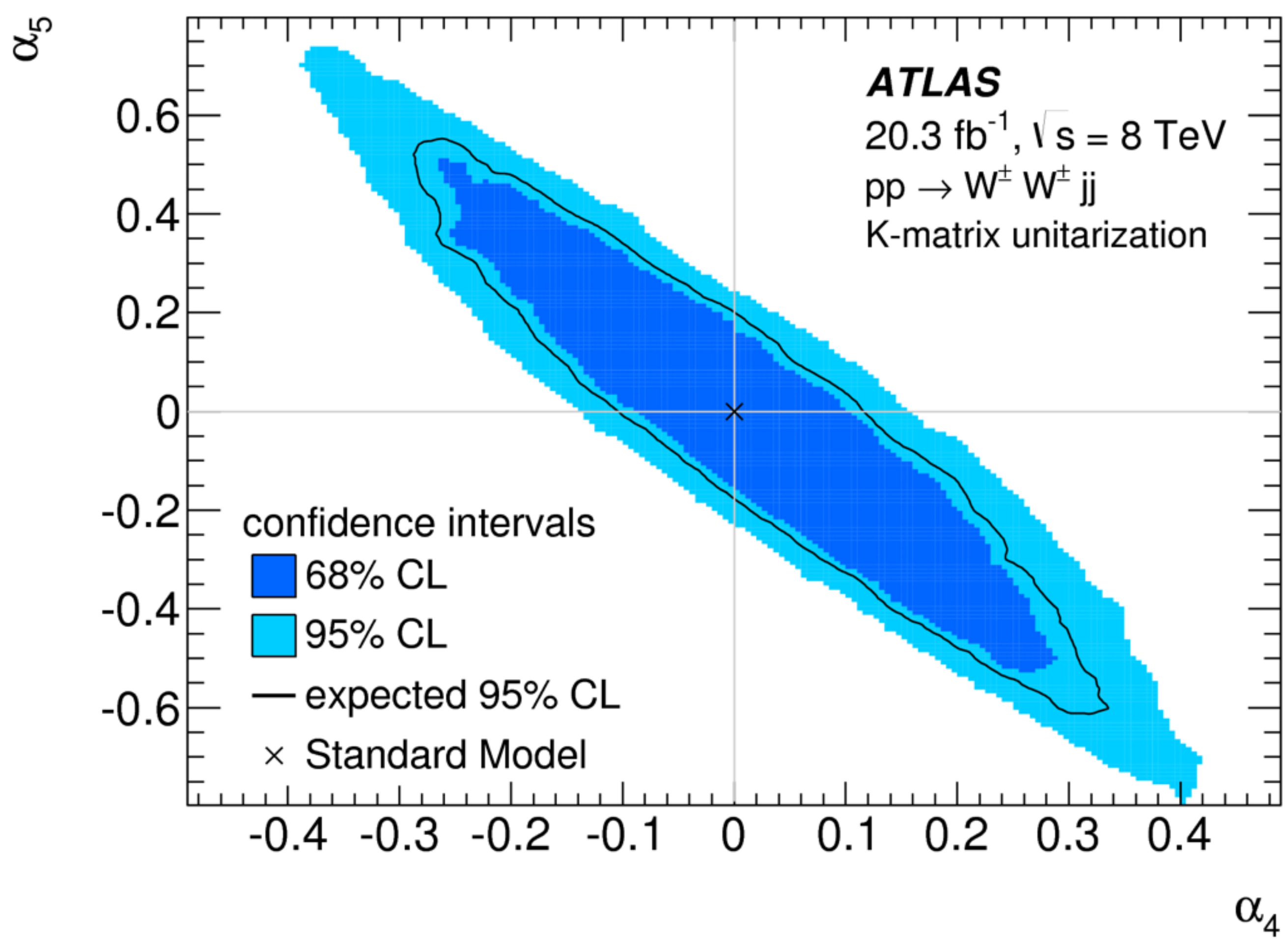
	Measurement [fb]	Theory [fb] (PowhegPythia8)	measurement significance
Inclusive	2.1 ± 0.5(stat) ± 0.3(syst)	1.5 ± 0.11	4.5
Ewk-only	1.3 ± 0.4(stat) ± 0.2(syst)	0.95 ± 0.06	3.6

- **First evidence for EWK VV → VV scattering !**

PRL 113, 141803 (2014)

First limits on aQGC

- **Measurement of VBS allows for setting limits on anomalous quartic couplings**
- **Deviations from SM parametrized in terms of parameters α4 and α5**
    - Limits on aQGCs extracted from $W^{\pm}W^{\pm}jj$ cross section in VBS phase space



parameter	observed limit	expected limit
α4	-0.139, 0.157	-0.104, 0.116
α5	-0.229, 0.244	-0.180, 0.199

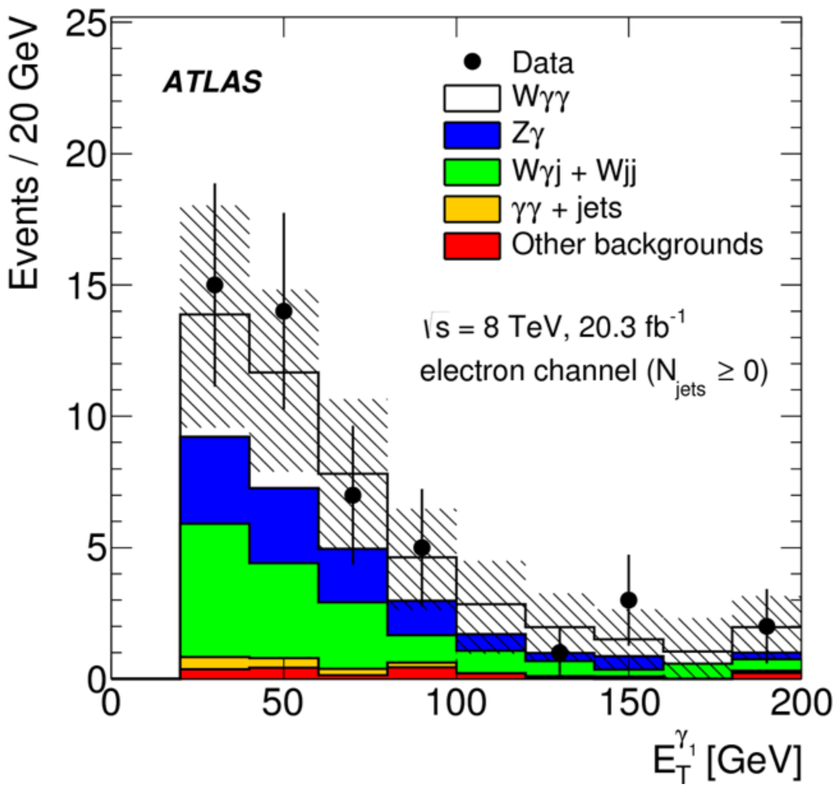
1503.03243v1 submitted to PRL

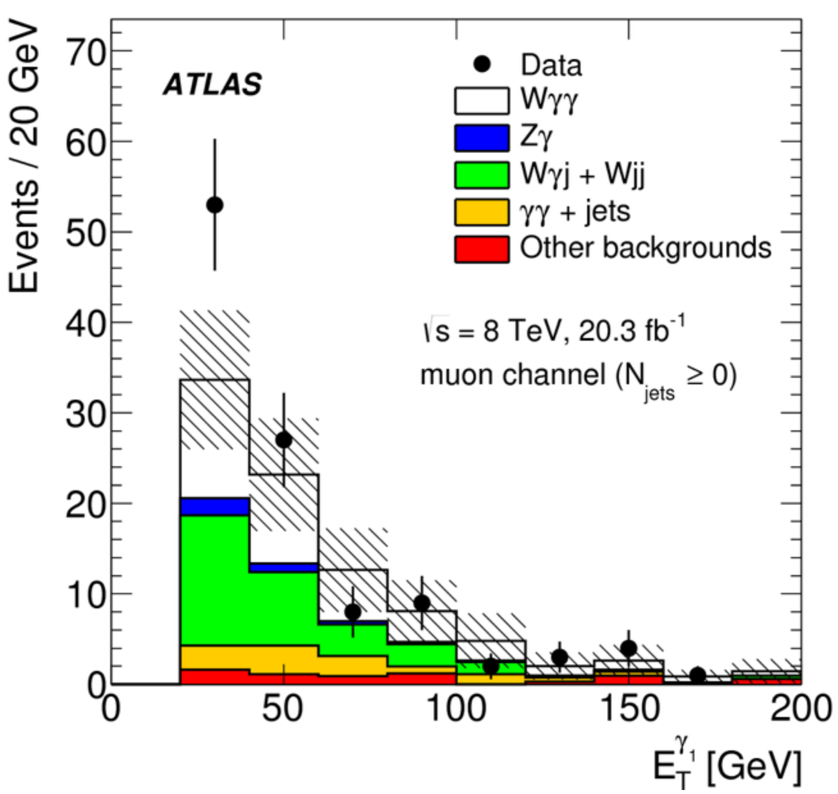
NEW!

Wγγ production (1/2)

- **Final states: ℓ±ν+γγ (ℓ=e,μ)**
- **Main backgrounds:**
  - Wγ+jets, W+2jets: estimated from data with 2-d template fit to the isolation energy distributions of the 2 photons
  - γγ+jets, Zγ, Drell-Yan
- **Systematics dominated by data-driven background (14%-23%) and jet energy scale (5%-7%)**

Selection Highlights
2 isolated high-pT photons and MissingET > 25GeV
Exclusive (Njet=0) and Inclusive (Njet>=0) measurement
Suppress final state radiation events by requiring ΔR(ℓ,γ) > 0.7.





1503.03243v1 submitted to PRL

NEW!

Wγγ production (2/2)

	Electron channel	Muon channel	Electron channel	Muon channel
	$N_{\rm jet} \geq 0$		$N_{\rm jet} = 0$	
$W\gamma$j + Wjj	15.3 ± 4.8(stat.) ± 5.3(syst.)	30.5 ± 7.7(stat.) ± 6.8(syst.)	5.8 ± 2.1(stat.) ± 2.0(syst.)	14.4 ± 4.9(stat.) ± 4.9(syst.)
$\gamma\gamma$ + jets	1.5 ± 0.6(stat.) ± 1.0(syst.)	11.0 ± 4.0(stat.) ± 4.9(syst.)	0.2 ± 0.2(stat.) ± 0.2(syst.)	6.1 ± 3.5(stat.) ± 3.1(syst.)
$Z\gamma$	11.2 ± 1.1(stat.)	3.9 ± 0.2(stat.)	2.4 ± 0.5(stat.)	2.8 ± 0.2(stat.)
Other backgrounds	2.2 ± 0.6(stat.)	6.7 ± 2.0(stat.)	0.3 ± 0.1(stat.)	1.1 ± 0.3(stat.)
Total background	30.2 ± 5.0(stat.) ± 5.4(syst.)	52.1 ± 8.9(stat.) ± 8.4(syst.)	8.7 ± 2.2(stat.) ± 2.0(syst.)	24.4 ± 6.0(stat.) ± 5.8(syst.)
Data	47	110	15	53

- **Evidence for the W(lν)γγ process is reported for the first time!**
- **In addition to the inclusive prediction, an exclusive cross section is obtained by vetoing events with an additional jet**
  - Significance of the inclusive production cross section is larger than 3 σ
- **The measured cross section is higher by 1.9σ from the SM prediction (MCFM) in the inclusive case**
- **Better agreement is seen in the exclusive case**

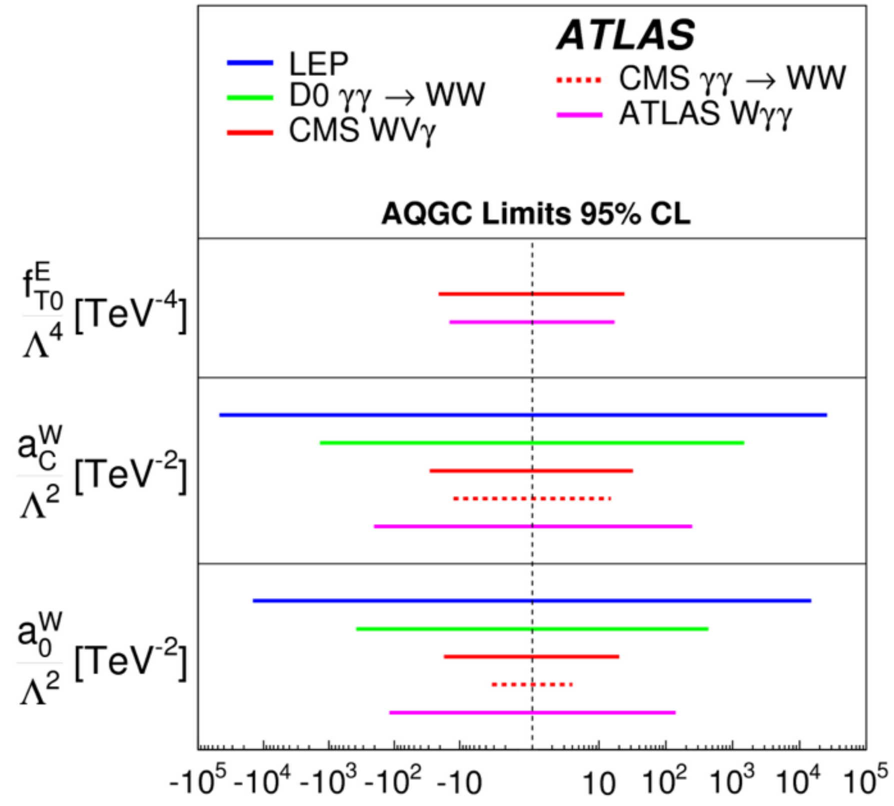
	$\sigma^{\rm fid}$ [fb]	$\sigma^{\rm MCFM}$ [fb]
Inclusive ($N_{\rm jet} \geq 0$)		
$\mu\nu\gamma\gamma$	$7.1\ ^{+1.3}_{-1.2}$ (stat.) ±1.5 (syst.) ±0.2 (lumi.)	2.90 ± 0.16
$e\nu\gamma\gamma$	$4.3\ ^{+1.8}_{-1.6}$ (stat.) $^{+1.9}_{-1.8}$ (syst.) ±0.2 (lumi.)	
$\ell\nu\gamma\gamma$	$6.1\ ^{+1.1}_{-1.0}$ (stat.) ±1.2 (syst.) ±0.2 (lumi.)	
Exclusive ($N_{\rm jet} = 0$)		
$\mu\nu\gamma\gamma$	3.5 ± 0.9 (stat.) $^{+1.1}_{-1.0}$ (syst.) ±0.1 (lumi.)	1.88 ± 0.20
$e\nu\gamma\gamma$	$1.9\ ^{+1.4}_{-1.1}$ (stat.) $^{+1.1}_{-1.2}$ (syst.) ±0.1 (lumi.)	
$\ell\nu\gamma\gamma$	$2.9\ ^{+0.8}_{-0.7}$ (stat.) $^{+1.0}_{-0.9}$ (syst.) ±0.1 (lumi.)	

1503.03243v1 submitted to PRL

NEW!
Limits on aQGC from Wγγ process

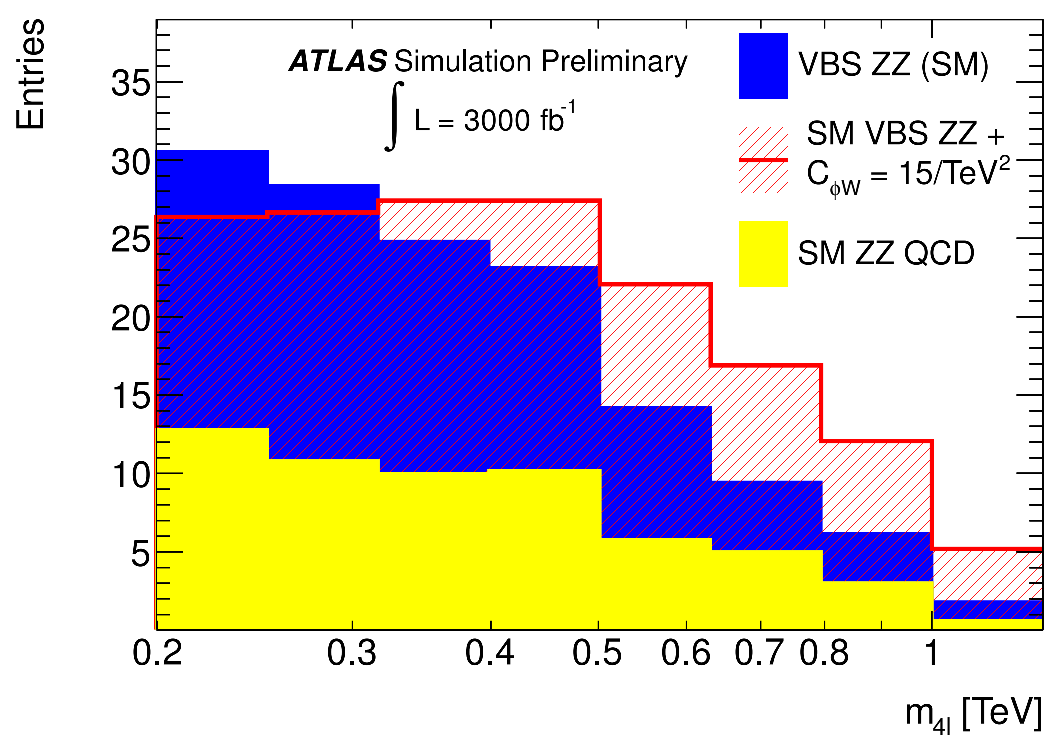
- **The aQGCs are introduced as dimension-8 operators T0, M2,M3**
- **The Wγγ final state is expected to be more sensitive to the T0 operator**
  - M2, M3 can be related to the parameters of the dimension-6 operators used at LEP and CMS
- **Best available limit on fT0/Λ4 !**

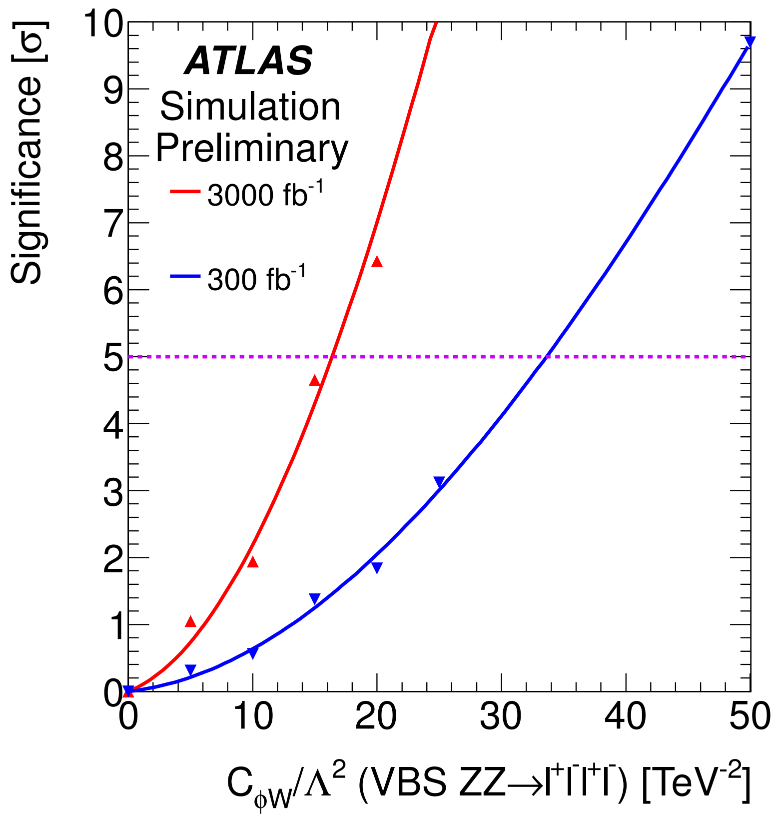
		Observed [TeV^{-4}]	Expected [TeV^{-4}]
$n = 0$	f_{T0}/Λ^4	$[-0.9, 0.9] \times 10^2$	$[-1.2, 1.2] \times 10^2$
	f_{M2}/Λ^4	$[-0.8, 0.8] \times 10^4$	$[-1.1, 1.1] \times 10^4$
	f_{M3}/Λ^4	$[-1.5, 1.4] \times 10^4$	$[-1.9, 1.8] \times 10^4$
$n = 1$	f_{T0}/Λ^4	$[-7.6, 7.3] \times 10^2$	$[-9.6, 9.5] \times 10^2$
	f_{M2}/Λ^4	$[-4.4, 4.6] \times 10^4$	$[-5.7, 5.9] \times 10^4$
	f_{M3}/Λ^4	$[-8.9, 8.0] \times 10^4$	$[-11.0, 10.0] \times 10^4$
$n = 2$	f_{T0}/Λ^4	$[-2.7, 2.6] \times 10^3$	$[-3.5, 3.4] \times 10^3$
	f_{M2}/Λ^4	$[-1.3, 1.3] \times 10^5$	$[-1.6, 1.7] \times 10^5$
	f_{M3}/Λ^4	$[-2.9, 2.5] \times 10^5$	$[-3.7, 3.3] \times 10^5$



Prospects for VBS during Run-2 and beyond (1/2)

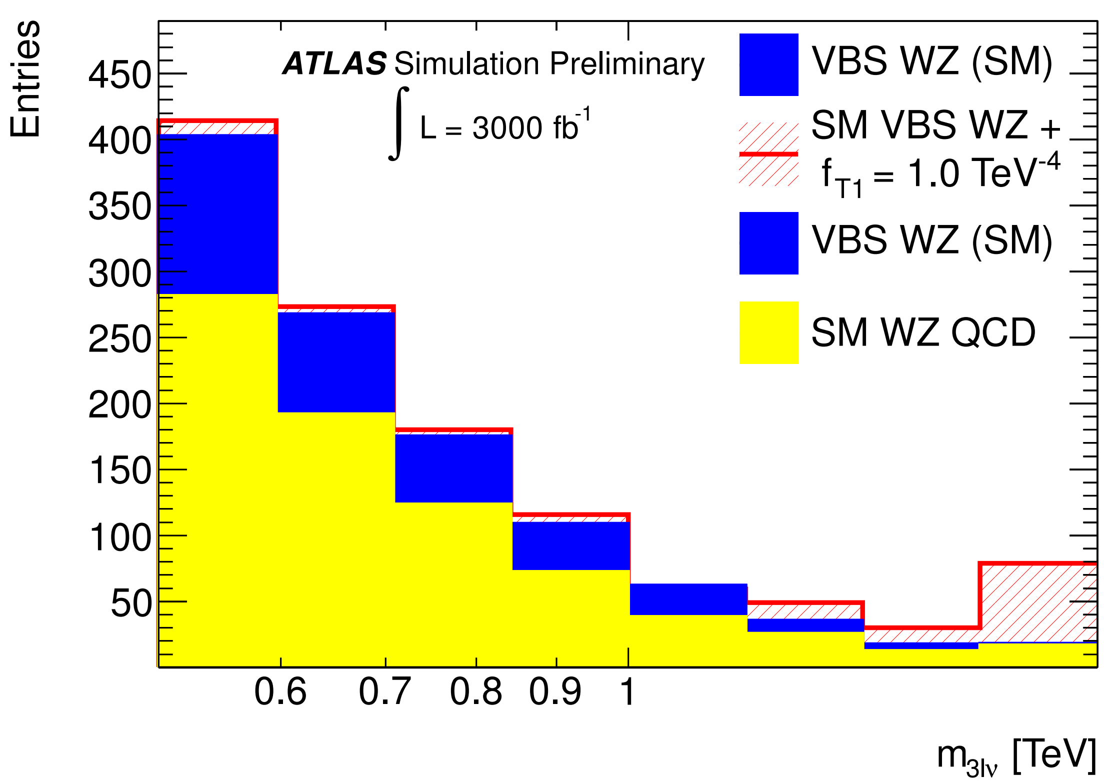
- **It is expected to greatly increase the sensitivity to an extended electroweak symmetry-breaking sector beyond the Standard Model Higgs mechanism**
- **VBS ZZjj → llllјj**
  - Deviations from SM parametrized with dimension-6 operator ($C_{\phi W}$)
  - The fully-leptonic ZZjj → llll jj channel has a small cross section but provides a clean, fully reconstructible ZZ final state.
  - A forward dijet mass requirement of 1 TeV reduces the contribution from jets accompanying non-VBS diboson production.

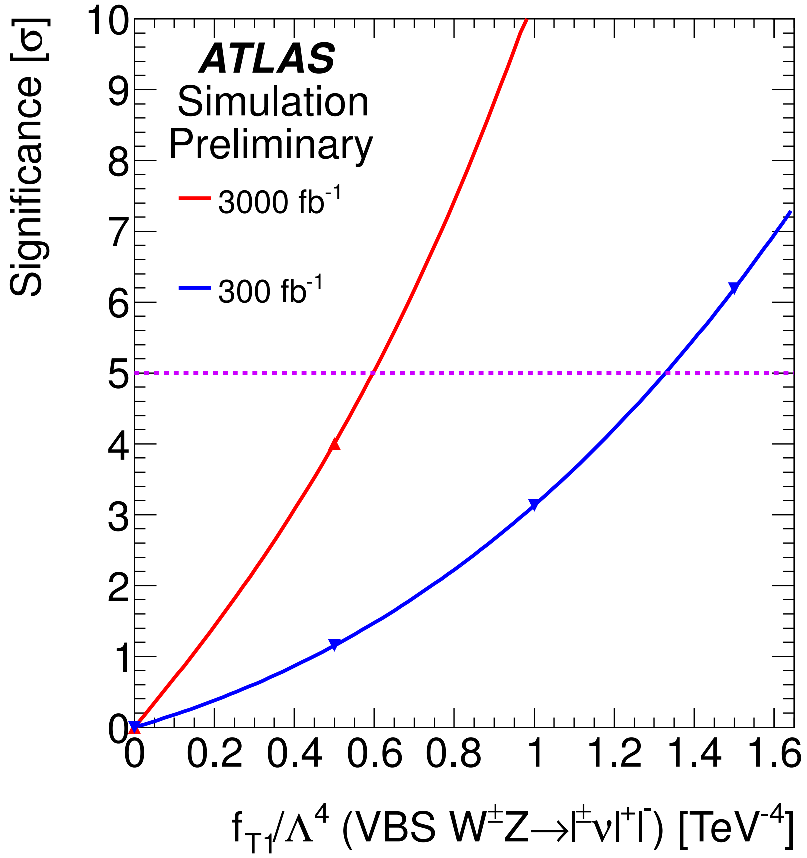




Prospects for VBS during Run-2 and beyond (2/2)

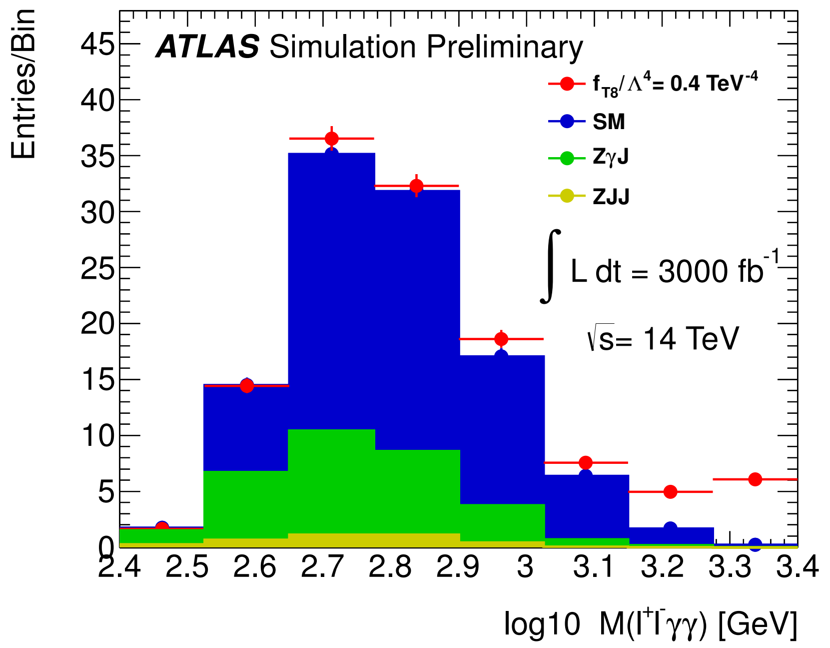
- **VBS WZjj → lνlljj**
  - Deviations from SM parametrized with dimension-8 operator (f_{T1})
  - Exactly three selected leptons (each with pT > 25 GeV)
  - At least two selected jets with pT > 50 GeV.
  - mjj > 1 TeV, where mjj is the invariant mass of the two highest- pT selected jets

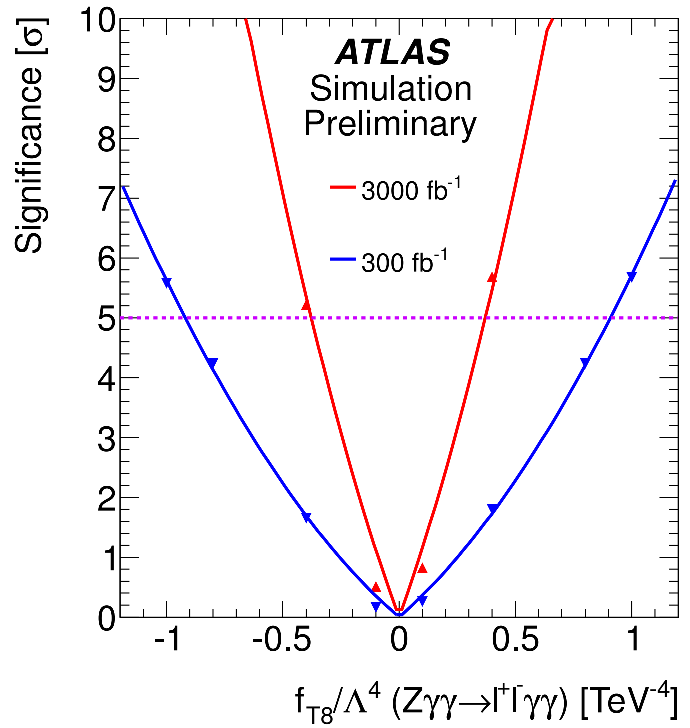


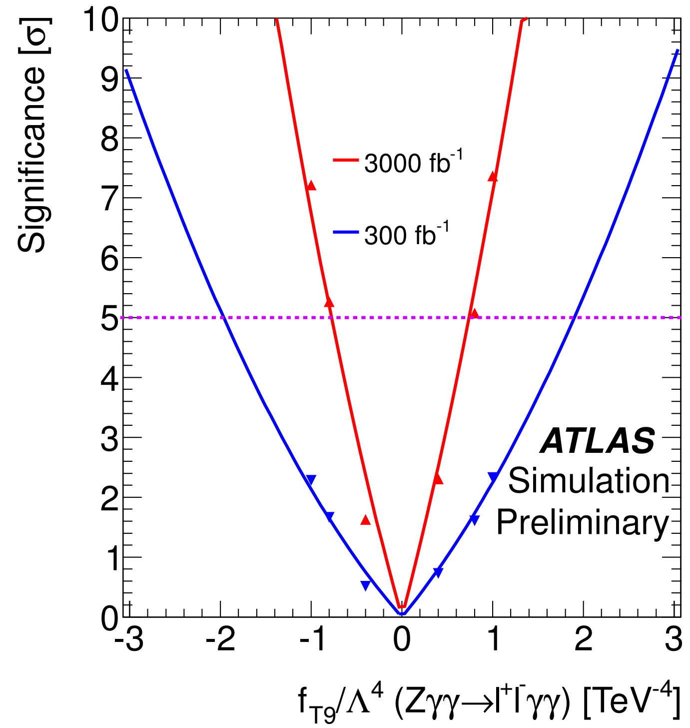


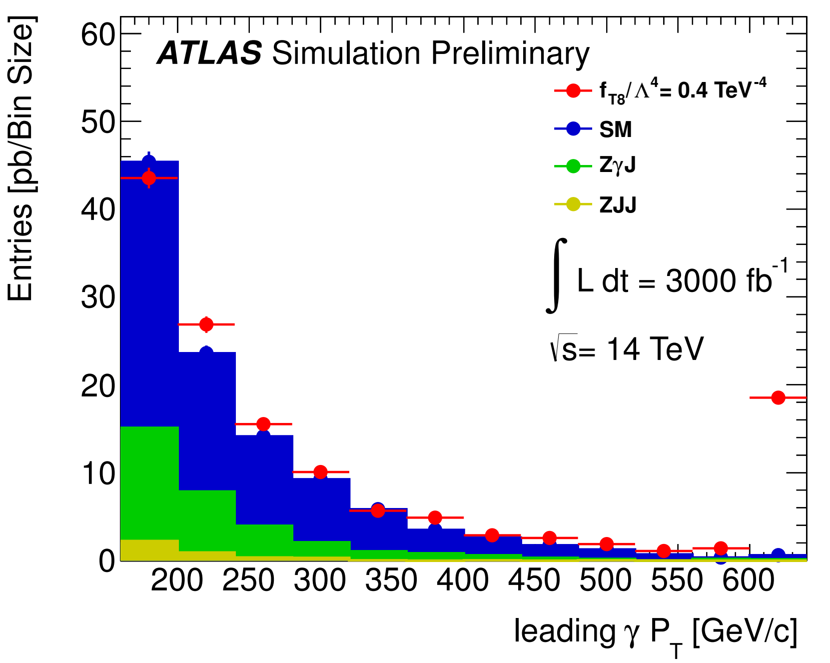
Prospects for Triboson production during Run-2 and beyond
Zγγ Example

- **BSM physics are parametrized wrt dimension-8 operators T8,T9**
- **The Zγγ mass spectrum at high mass is sensitive to BSM triboson contributions**
- **Enhancement of the yield in the tail of the photon pT distribution due to anomalous QGC**
- **Sensitivity >doubled from 300 to 3000 fb-1**









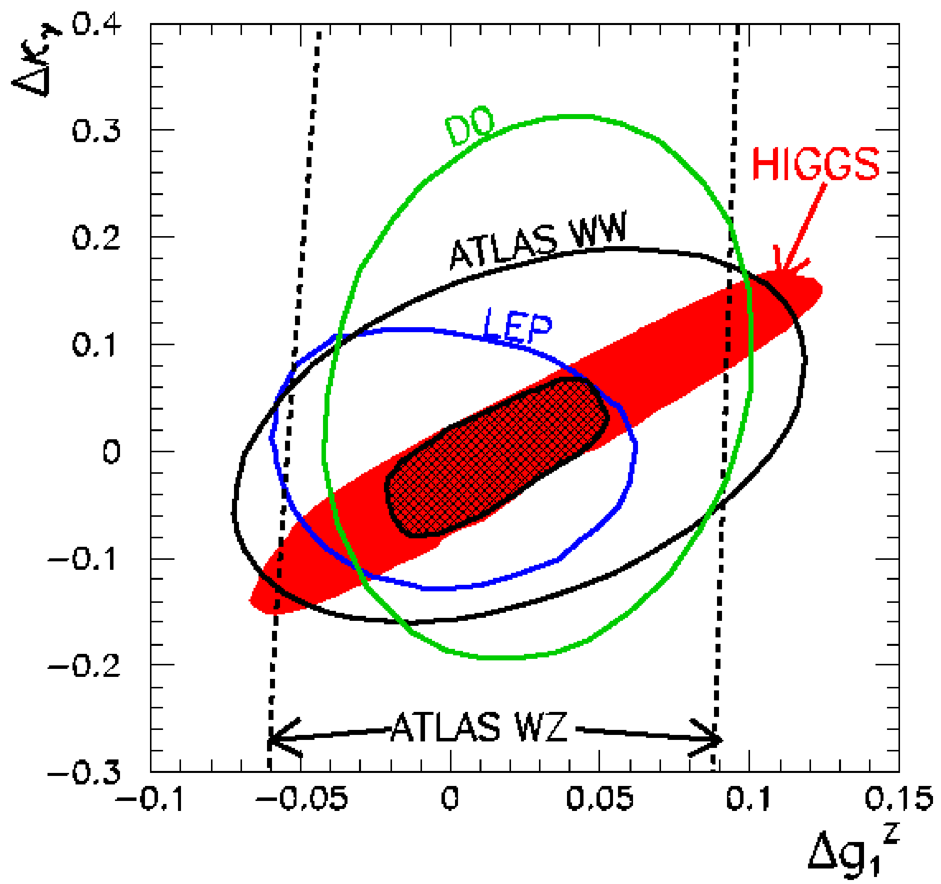
Summary

- **Higgs boson discovered, but still need to check whether this Higgs unitarizes the VBS process**
- **Evidence for the same sign WW +2jets electroweak production with a significance of 3.6 σ**
- **First limits on aQGCs and Triboson production results**
- **In Run-2 and Run-3 at 13,14 TeV, Di-boson, Tri-boson, VBS, and quartic gauge couplings will become the main probe for New Physics !**

Backup slides

EFT predictive power example

- **Example calculation (hep-ph 1304.1151), uses an EFT to relate limits on Higgs couplings to anomalous TGCs:**
  - Higgs coupling data from LHC is used to restrict the allowed range for anomalous couplings
  - Even the limited Higgs coupling data available today provides more stringent limits.



- **EFT allows combining constraints from different sets of measurements**

ssWW: selection requirements

- **Lowest order:W±W± + 2jets, there is no SM inclusive W±W±**
- **for EW+strong measurement ("inclusive signal phase space")**
  - exactly 2 high pT same-sign leptons with pT > 25 GeV in $|\eta| < 2.5$
  - $m_{\ell\ell}>20$ GeV, $\Delta R_{\ell\ell}>0.3$
  - ≥ 2 jets with $p_T>30$ GeV, $|\eta| < 4.5$
  - ETmiss > 40 GeV (from W decays)
    - *reduces Z+jets with charge mis-identification*
  - veto events containing b-jets
    - *reduces $t\bar{t}$ events (lepton from b-decays)*
  - Z-veto in ee channel: |mee – mZ | > 10 GeV
    - *reduces Z+jets with charge mis-identification*
  - mjj >500GeV
- **for EW-only measurement ("VBS signal phase space")**
  - additional cut on $|\Delta Y_{jj}| > 2.4$

ssWW: Background composition

- **prompt background:**
  - 3 or more prompt leptons
    - *$WZ/\gamma*$+jets (Sherpa) normalized to NLO with VBFNLO (uncertainty ~14% and 11% in inclusive and VBS regions respectively)*
    - *ZZ+jets (Sherpa) theory uncertainty 19%*
    - *$t\bar{t}$ + W/Z (Madgraph+Pythia8) theory uncertainty 30%*
    - *tZj (Sherpa) negligible*
- **Conversions**
  - prompt photon conversion
    - *$W\gamma$ (Alpgen+Herwig/Jimmy, Sherpa for Ewk) total theory uncertainty 17%*
  - charge mis-ID due to bremsstrahlung with conversion (data driven)
    - *$Z/\gamma*$+jets*
    - *Drell-Yan and $t\bar{t}$ decays*
- **Other non-prompt (data-driven)**
  - leptons from hadron decays in jets
    - *W+jets*
    - *semi-leptonic $t\bar{t}$ decays*
    - *di-jet events*

ssWW: Yields and interference effect

	Inclusive region			VBS region		
	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$
Prompt	3.0 ± 0.7	6.1 ± 1.3	2.6 ± 0.6	2.2 ± 0.5	4.2 ± 1.0	1.9 ± 0.5
Conversions	3.2 ± 0.7	2.4 ± 0.8	...	2.1 ± 0.5	1.9 ± 0.7	...
Other nonprompt	0.61 ± 0.30	1.9 ± 0.8	0.41 ± 0.22	0.50 ± 0.26	1.5 ± 0.6	0.34 ± 0.19
$W^{\pm}W^{\pm}jj$ Strong	0.89 ± 0.15	2.5 ± 0.4	1.42 ± 0.23	0.25 ± 0.06	0.71 ± 0.14	0.38 ± 0.08
$W^{\pm}W^{\pm}jj$ Electroweak	3.07 ± 0.30	9.0 ± 0.8	4.9 ± 0.5	2.55 ± 0.25	7.3 ± 0.6	4.0 ± 0.4
Total background	6.8 ± 1.2	10.3 ± 2.0	3.0 ± 0.6	5.0 ± 0.9	8.3 ± 1.6	2.6 ± 0.5
Total predicted	10.7 ± 1.4	21.7 ± 2.6	9.3 ± 1.0	7.6 ± 1.0	15.6 ± 2.0	6.6 ± 0.8
Data	12	26	12	6	18	10

- **Interference between electroweak and strong production is studied at leading-order accuracy using SHERPA**
- **Interference increases the combined strong and electroweak cross section by 12% in the inclusive region and 7% in the VBS region**
- **Included in EW W±W±jj prediction**

ssWW: Systematic uncertainties

Systematic Uncertainties $ee/e\mu/\mu\mu$ (%) - Inclusive SR			
Background		Signal	
Jet uncertainties	11/13/13	Jet uncertainties	5.7
Theory WZ/γ^*	5.6/7.7/11	Theory $W^{\pm}W^{\pm}jj$-ewk	4.7
MC statistics	8.2/5.9/8.4	Theory $W^{\pm}W^{\pm}jj$-strong	3.1
Fake rate	3.5/7.1/7.2	Luminosity	2.8
OS lepton bkg/ Conversion rate	5.9/4.2/–	MC statistics	3.5/2.1/2.8
Theory $W+\gamma$	2.8/2.6/–	E_T^{miss} reconstruction	1.1
E_T^{miss} reconstruction	2.2/2.4/1.8	Lepton reconstruction	1.9/1.0/0.7
Luminosity	1.7/2.1/2.4	b-tagging efficiency	0.6
Lepton reconstruction	1.6/1.2/1.2	trigger efficiency	0.1/0.3/0.5
b-tagging efficiency	1.0/1.1/1.0		
Trigger efficiency	0.1/0.2/0.4		

Systematic Uncertainties $ee/e\mu/\mu\mu$ (%) - VBS SR			
Background		Signal	
Jet uncertainties	13/15/15	Theory $W^{\pm}W^{\pm}jj$-ewk	6.0
Theory WZ/γ^*	4.5/5.4/7.8	Jet uncertainties	5.1
MC statistics	8.9/6.4/8.4	Luminosity	2.8
Fake rate	4.0/7.2/6.8	MC statistics	4.5/2.7/3.7
OS lepton bkg/ Conversion rate	5.5/4.4/–	E_T^{miss} reconstruction	1.1
E_T^{miss} reconstruction	2.9/3.2/1.4	Lepton reconstruction	1.9/1.0/0.7
Theory $W+\gamma$	3.1/2.6/–	b-tagging efficiency	0.6
Luminosity	1.7/2.1/2.4	trigger efficiency	0.1/0.3/0.5
Theory $W^{\pm}W^{\pm}jj$-strong	0.9/1.5/2.6		
Lepton reconstruction	1.7/1.1/1.1		
b-tagging efficiency	0.8/0.9/0.7		
Trigger efficiency	0.1/0.2/0.4		