Vector Boson Scattering and Anomalous Gauge Couplings

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ATLAS EXPERIMENT

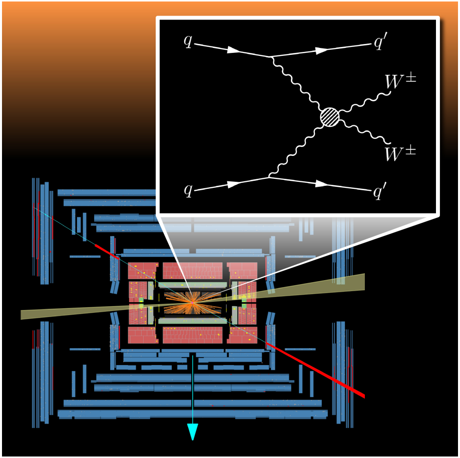
TECHNISCHE UNIVERSITÄT DRESDEN

GEFÖRDERT VOM Bundesministerium für Bildung und Forschung

FSP 101 ATLAS

Outline

1. Introduction & Motivation
2. Vector Boson Scattering at the LHC
3. Look at Physics beyond the Standard Model
4. Summary and Outlook

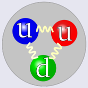


The Standard Model of particle physics (SM)

The **Standard Model** explains 3 of the 4 fundamental interactions

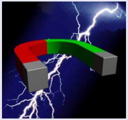
- Each interaction is mediated by exchanging **gauge bosons**

Strong interaction



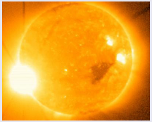
Gluons g

Electromagnetism



Photons γ

Weak interaction



W, Z bosons

- All of them arise from **local gauge symmetries**,

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

generated by three types of **charges**

- The gauge bosons only couple to particles carrying the charge of the respective interaction

The Standard Model – electroweak symmetry breaking

The symmetry of the electroweak interaction forbids that elementary particles have mass

$\lightning$ This is not what we observe!

The Standard Model – electroweak symmetry breaking

The symmetry of the electroweak interaction forbids that elementary particles have mass

↯ This is not what we observe!

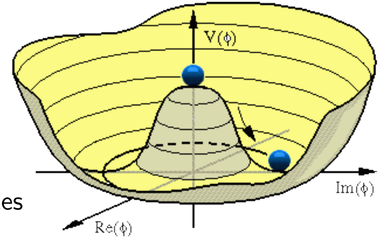
⇒ Solution: spontaneous electroweak symmetry breaking (EWSB) via **Brout-Englert-Higgs mechanism**

after EWSB:

→ massless γ

→ massive $W^{\pm}$ and Z bosons and their longitudinal polarization states

→ physical Higgs boson H^0



$$V(\phi) = -\mu^2\phi^\dagger\phi - \lambda(\phi^\dagger\phi)^2$$

The Higgs boson

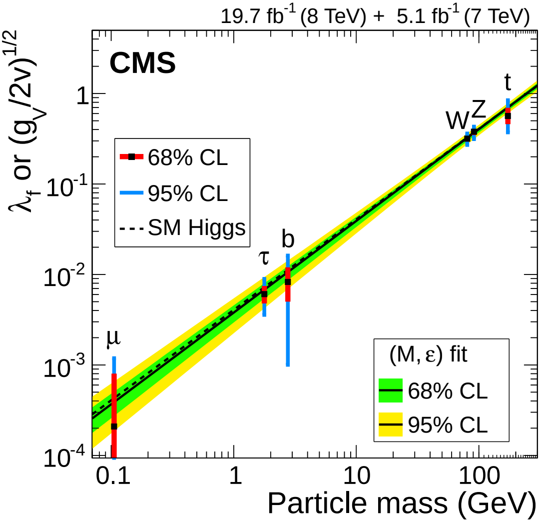
arXiv:1412.8662

Combined ATLAS and CMS Higgs mass measurement:

$$m_H = 125.09 \pm 0.24\,\mathrm{GeV}$$

Phys. Rev. Lett. 114, 191803

5154 authors!



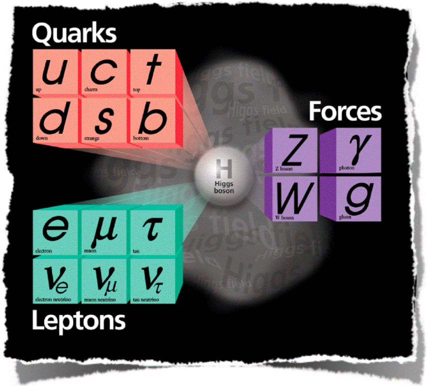
Particle content of the Standard Model

- Matter particles (fermions):
  - 6 quarks
  - 6 leptons

  in 3 generations

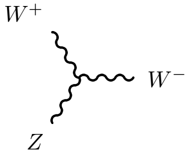
- Force mediators (gauge bosons):
  - Photon γ
  - $W^{\pm}, Z$ bosons
  - Gluons g

- Higgs boson H^0

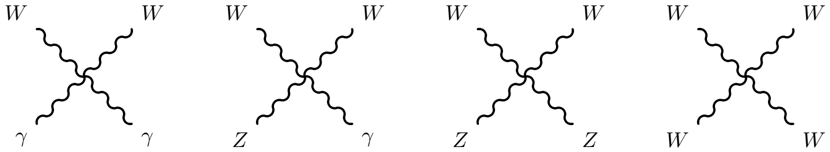


SM – Electroweak gauge boson self-interactions

- Electroweak gauge bosons carry weak charge
  $\Rightarrow$ their self-interactions should exist
- **Triple gauge couplings (TGC)**

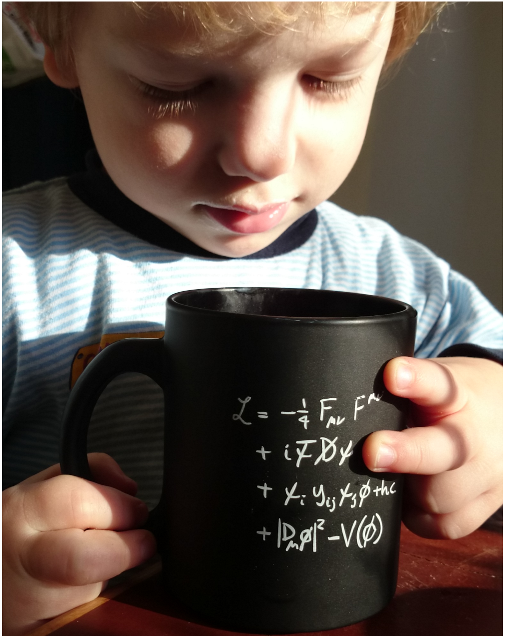


- **Quartic gauge couplings (QGC)**

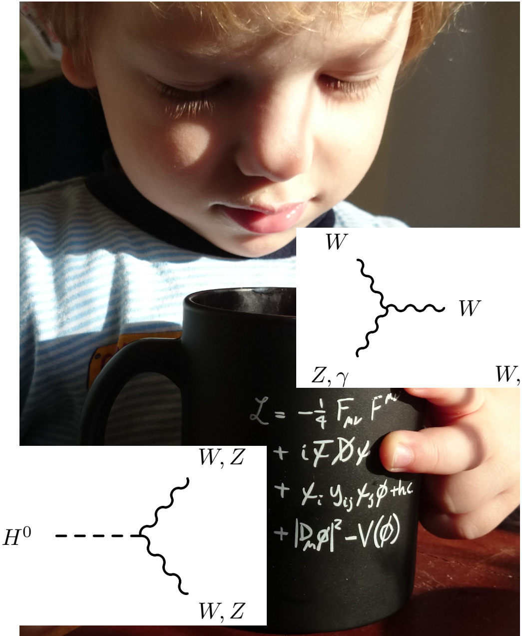


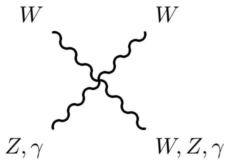
- No neutral self-couplings

The Standard Model

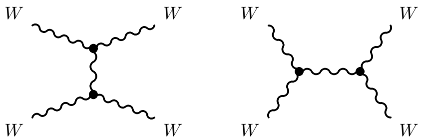


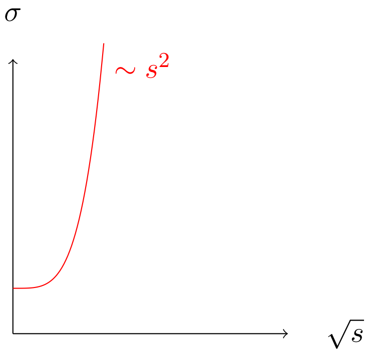
The Standard Model



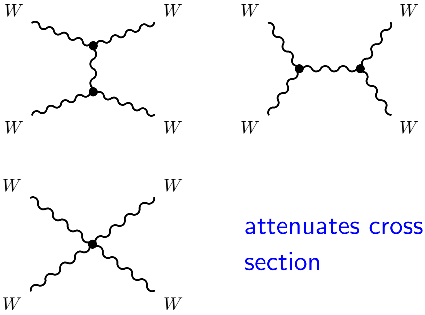


Vector boson scattering and the role of the Higgs boson

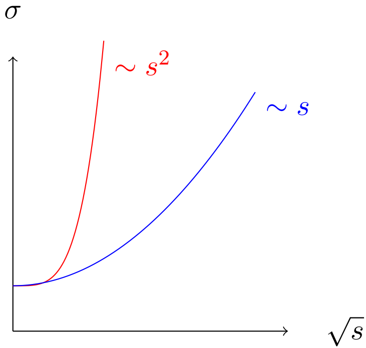




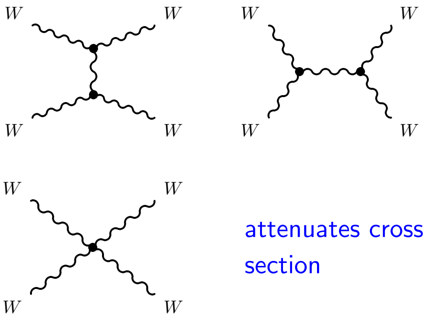
Vector boson scattering and the role of the Higgs boson



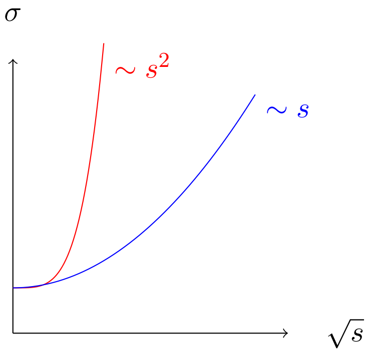
attenuates cross section



Vector boson scattering and the role of the Higgs boson

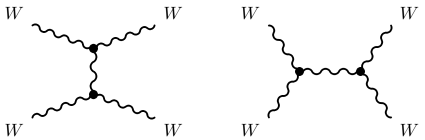


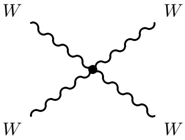
attenuates cross section



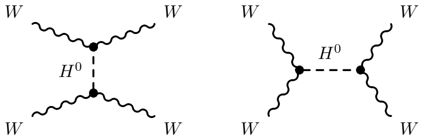
Some mechanism must regulate the WW scattering cross section to restore unitarity (probability conservation) $\rightarrow$ scalar particle needed

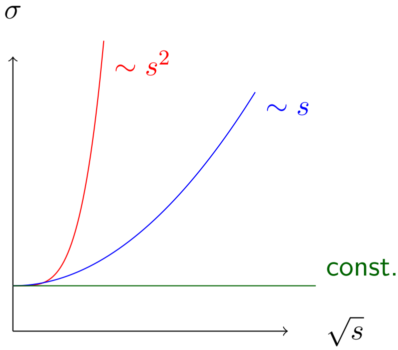
Vector boson scattering and the role of the Higgs boson





attenuates cross section

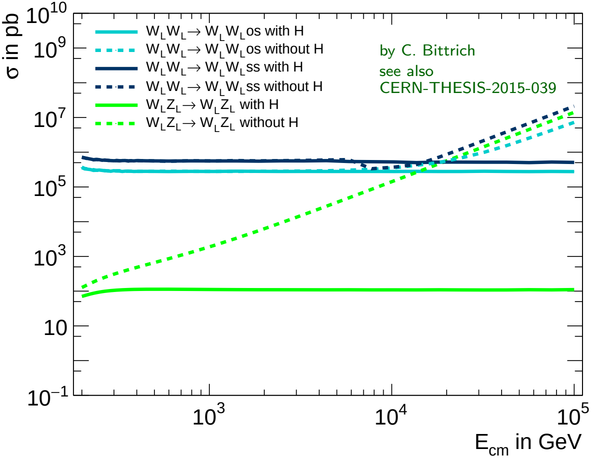




A light SM Higgs boson cancels increase for large energies ($M_H \leq \sqrt{\frac{8\pi\sqrt{2}}{3G_F}} \approx 1$ TeV)

Vector boson scattering and the role of the Higgs boson

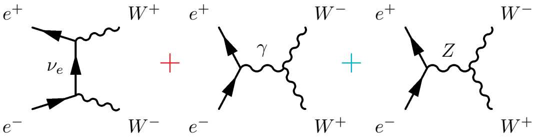
Total cross sections as a function of the $V_L V_L$ center-of-mass energy:

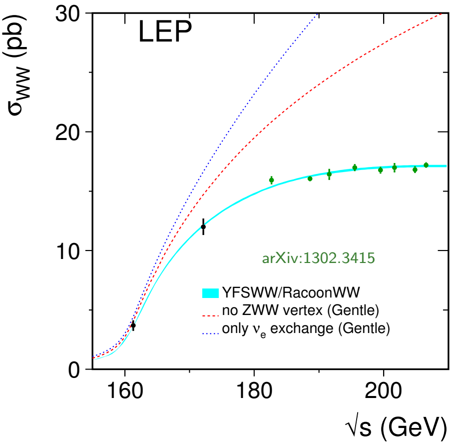


⇒ VV scattering is a key process to experimentally probe the SM nature of EWSB!

Experimental tests of the EW theory at LEP

- EW interactions measured extensively by the LEP experiments
- Triple gauge boson couplings validated by $e^+e^- \to W^+W^-$ cross section measurements
- SM confirmed at very high precision

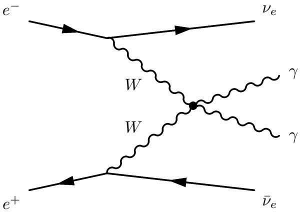


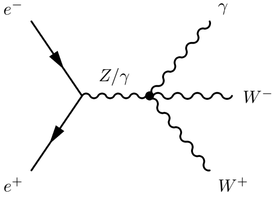


Experimental tests of the EW theory at LEP

Measured processes with **QGC** vertices at LEP:

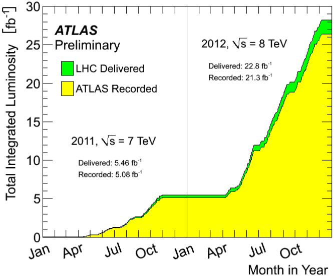
- Significant observation of $e^+e^- \rightarrow \nu\nu\gamma\gamma$ and $e^+e^- \rightarrow W^+W^-\gamma$ with very small background
  OPAL, L3, OPAL, DELPHI
- **Consistent with ISR/FSR processes**
- No real observation of any process including QGC vertices at LEP (nor at Tevatron)





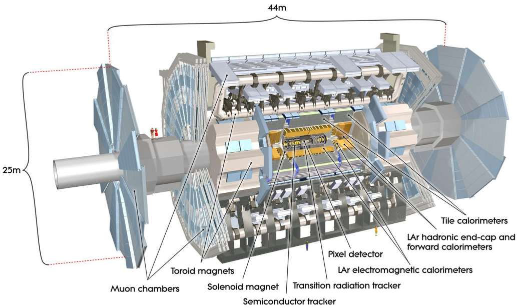
Large Hadron Collider (LHC) at CERN

- pp collisions in 27 km circumference ring
- centre-of-mass energy:
  - $\sqrt{s} = 7$ TeV in 2010/2011
  - $\sqrt{s} = 8$ TeV in 2012
  - $\sqrt{s} = 13$ TeV about to start

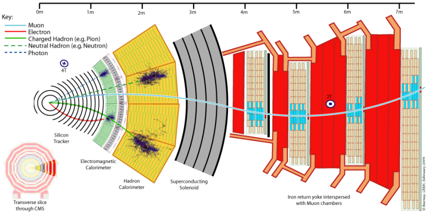


The multi-purpose detectors ATLAS & CMS

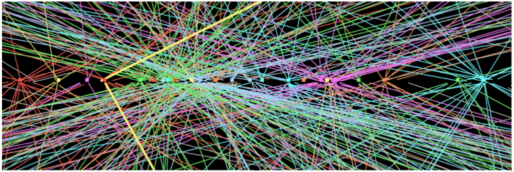
ATLAS



CMS



Candidate $Z \to \mu\mu$ event with high pile-up



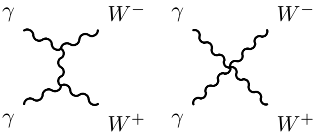
ATLAS Experiment © 2013 CERN

Particles from interaction of interest must be separated from "pile-up"

At $\sqrt{s} = 13$ TeV: up to ~ 130 interactions per bunch crossing

Vector boson scattering at the LHC

Vector boson scattering in “exclusive” $\gamma\gamma \to WW$



- **First $VV \to VV$ analysis at the LHC!**

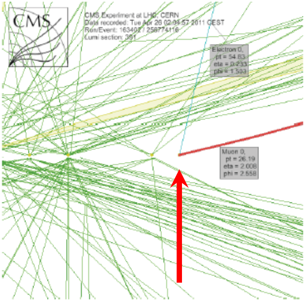
  CMS, $\sqrt{s} = 7$ TeV, $\mathcal{L} = 5$ fb^{-1} JHEP 07 (2013) 116

  $$pp \to p^{(*)}W^+W^-p^{(*)} \to p^{(*)}e^+\bar{\nu}\mu^-\nu p^{(*)}$$

  both very forward-scattered protons escape detection

- Event selection:
  - 2 high p_T isolated opposite charge μe
  - $m(\mu^\pm e^\mp) > 20$ GeV, $p_T(\mu^\pm e^\mp) > 30$ GeV
  - **0 extra tracks from primary vertex**
- 2 events observed

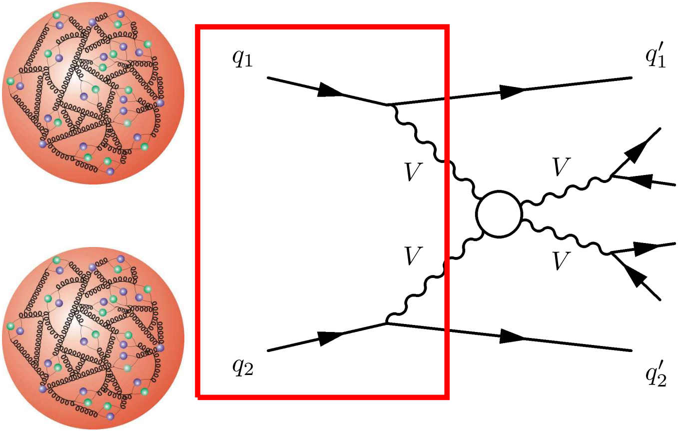
  2.2 ± 0.4 signal and 0.84 ± 0.15 background expected



- Measured cross section: $\sigma = 2.2^{+3.3}_{-2.0}$ fb ($\sim 1\sigma$) (predicted: $\sigma = 4.0 \pm 0.7$ fb)

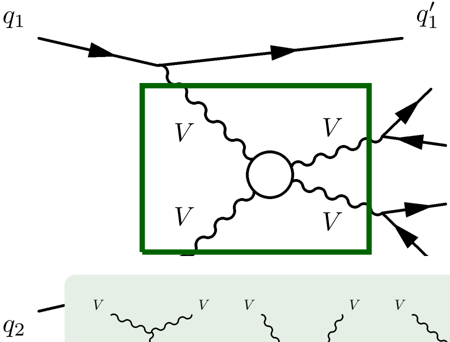
  $\to$ upper limit: $\sigma < 10.6$ fb @ 95% C.L.

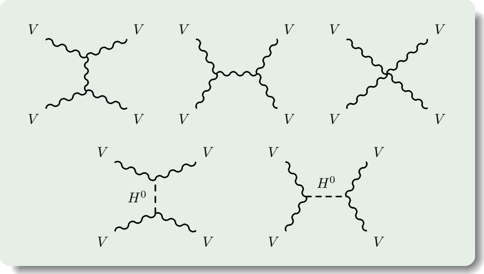
Vector boson scattering in $VVjj$ final states



Initial state: protons in LHC serve as source of vector boson beams

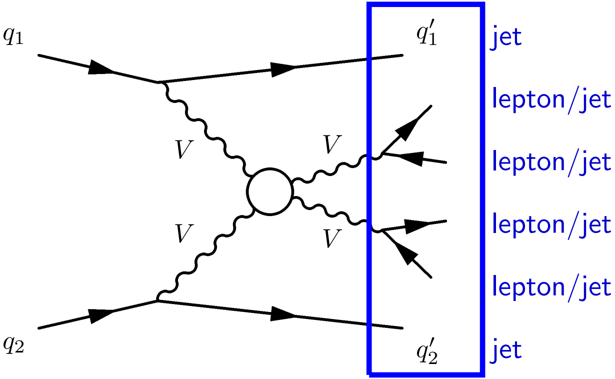
Vector boson scattering in $VVjj$ final states





Process of interest:
vector boson scattering

Vector boson scattering in $VVjj$ final states



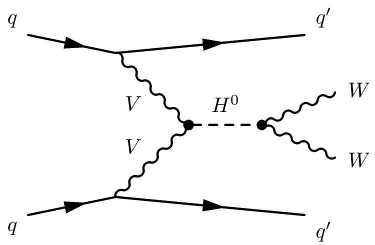
Final state: measurable signature in the detectors:

$\rightarrow$ decay products of 2 electroweak gauge bosons + 2 "tagging" jets

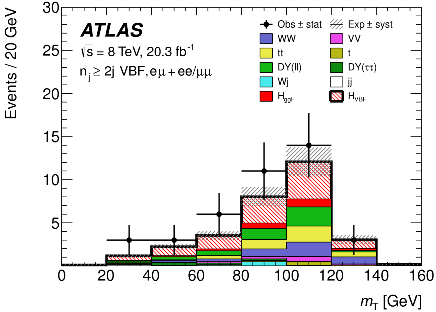
VBF and Higgs boson decays to WW^*

arXiv:1412.2641

Evidence for VBF Higgs production in $H^0 \to WW^* \to \ell\nu\ell\nu$!



Transverse mass distributions for $N_j \geq 2$ after the $O_{\mathrm{BDT}} > 0.3$ requirement

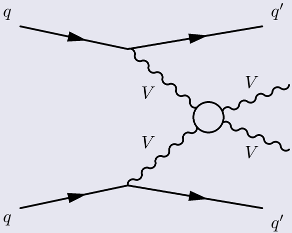


→ Significance: 3.2 s.d. (expected: 2.7 s.d.)

$VVjj$ production process classification

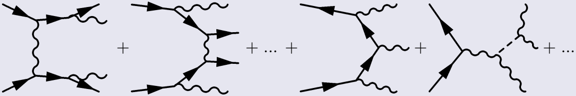
Electroweak $VVjj$ production: $\mathcal{O}(\alpha_w^6)$ @ LO

VBS diagrams



non-VBS EW diagrams, gauge invariantly

not separable: separable:

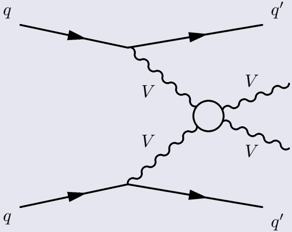


suppressed by
VBS topology cuts

$VVjj$ production process classification

Electroweak $VVjj$ production: $\mathcal{O}(\alpha_w^6)$ @ LO

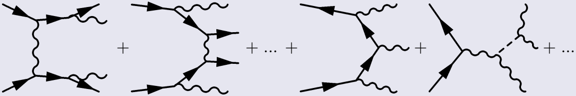
VBS diagrams



non-VBS EW diagrams, gauge invariantly

not separable:

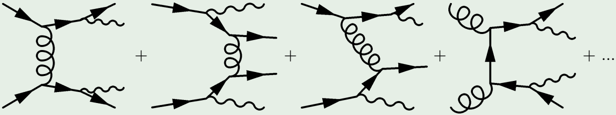
separable:



suppressed by
VBS topology cuts

Strong $VVjj$ production: $\mathcal{O}(\alpha_w^4 \alpha_s^2)$ @ LO

gauge invariantly separable: suppressed by VBS topology cuts



VBS processes (heavy vector bosons only)

Leading order cross sections (SHERPA) at $\sqrt{s} = 8$ TeV:

final state	sensitive to $VV \to$	σ^{EW}[fb]	σ^{strong}[fb]	$\sigma^{\mathrm{EW}}/\sigma^{\mathrm{strong}}$
$\ell^\pm\ell^\pm\nu\nu' jj$	$W^\pm W^\pm$	19.5	18.8	$\sim$ **1:1**
$\ell^+\ell^-\nu\nu' jj$	$W^\pm W^\mp$, ZZ	93.7	3192	$\sim$ 1:35
$\ell^+\ell^-\ell'^\pm\nu' jj$	$W^\pm Z$	30.2	687	$\sim$ 1:20
$\ell^+\ell^-\ell'^+\ell'^- jj$	ZZ	1.5	106	$\sim$ 1:70*

numbers by P. Anger

* includes γ^*, would be also 1:20 – 1:30 with higher m_{ll} cut

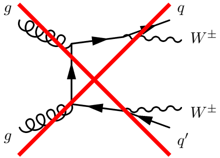
(generator cuts: $m_{\ell\ell} > 4$ GeV, $p_T^l > 5$ GeV, $p_T^j > 15$ GeV)

$\Rightarrow$ Most promising measurable $VVjj$ final state in terms of VBS:

same electric charge-sign ("same-sign") $W^\pm W^\pm jj$

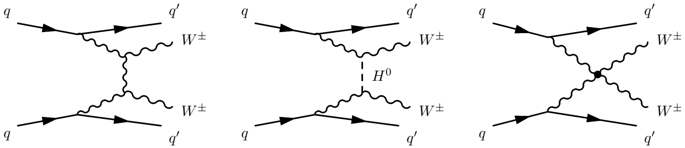
$\rightarrow$ no LO gg or gq initial state

$\Rightarrow$ strong $W^\pm W^\pm jj$ contributions very small



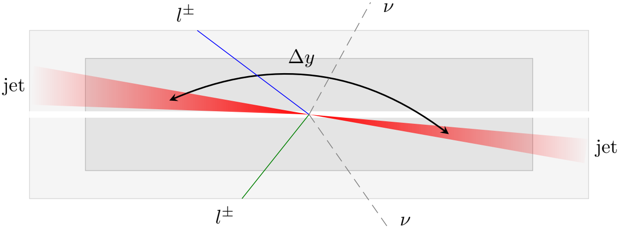
Same-sign $W^\pm W^\pm jj$ production at the LHC

- $W^\pm W^\pm jj$ VBS: no s-channel diagrams



lowest order: $W^\pm W^\pm + 2$ jets, there is no SM inclusive $W^\pm W^\pm$ production!

- Event selection according to signature:
  - → exactly 2 same-sign leptons, $p_T^\ell > 25$ GeV ($e^\pm e^\pm$, $e^\pm \mu^\pm$, and $\mu^\pm \mu^\pm$)
  - → $E_\mathrm{T}^\mathrm{miss} > 40$ GeV
  - → ≥ 2 jets with $p_T^\mathrm{jet} > 30$ GeV



$W^{\pm}W^{\pm}jj$: Background suppression cuts

Phys. Rev. Lett. 113, 141803

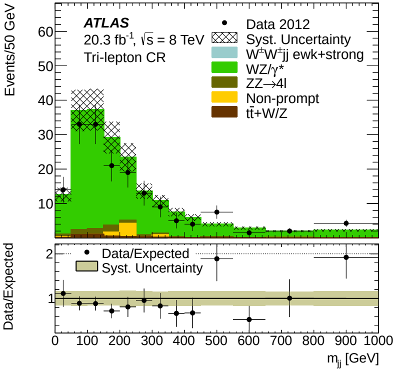
- Uncertainty on the modeling of low mass Drell-Yan processes
  $\Rightarrow m_{\ell\ell} > 20$ GeV
- Prompt background (3 or more prompt leptons)
  $\rightarrow$ WZ/γ^* and ZZ +jets, $t\bar{t} + W/Z$, tZj
  $\Rightarrow$ veto events with any additional $e(\mu)$ with $p_T > 7(6)$ GeV
- Conversions
  $\rightarrow$ prompt photon conversion: $W\gamma$
  $\rightarrow$ charge mis-ID due to bremsstrahlung with conversion (data driven): Z/γ^*+jets, di-leptonic $t\bar{t}$ decays, $W^{\pm}W^{\mp}$+jets
  $\Rightarrow$ Z-veto in ee channel: $|m_{ee} - m_Z| > 10$ GeV
- Other non-prompt background: (data driven)
  $\rightarrow$ leptons from hadron decays in jets: W+jets, semi-leptonic $t\bar{t}$ decays, dijet events
  $\Rightarrow$ veto events containing b-jets (reduces $t\bar{t}$)

$W^{\pm}W^{\pm}jj$ production – control regions

Phys. Rev. Lett. 113, 141803

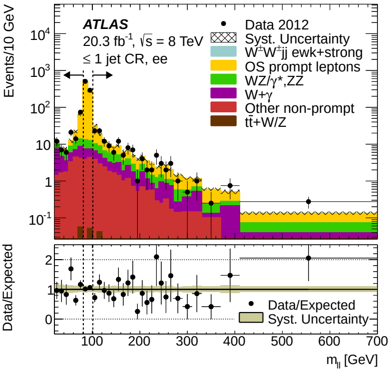
Trilepton control region:

→ prompt



≲ 1 jet control region:

→ conversions (ee), prompt ($\mu\mu$)



Control Region		Trilepton	≤ 1 jet	b-tagged	Low m_{jj}
$e^{\pm}e^{\pm}$	exp.	36 ± 6	278 ± 28	40 ± 6	76 ± 9
	data	40	288	46	78
$e^{\pm}\mu^{\pm}$	exp.	110 ± 18	288 ± 42	75 ± 13	127 ± 16
	data	104	328	82	120
$\mu^{\pm}\mu^{\pm}$	exp.	60 ± 10	88 ± 14	25 ± 7	40 ± 6
	data	48	101	36	30

$W^{\pm}W^{\pm}jj$ production

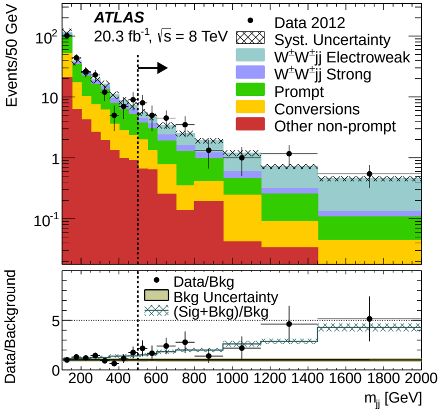
Phys. Rev. Lett. 113, 141803

EW+strong measurement

("Inclusive signal region")

→ $m_{jj} > 500$ GeV (jets with largest p_T)

invariant mass of the 2 tagging jets



$W^{\pm}W^{\pm}jj$ production

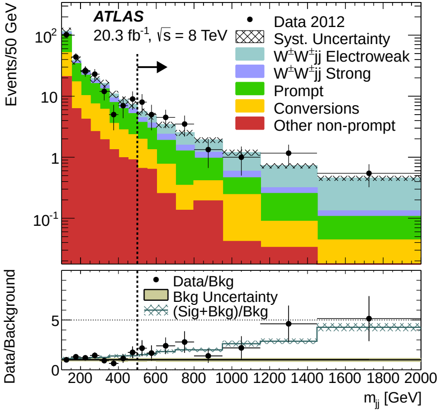
Phys. Rev. Lett. 113, 141803

EW+strong measurement

("Inclusive signal region")

→ $m_{jj} > 500$ GeV (jets with largest p_T)

invariant mass of the 2 tagging jets

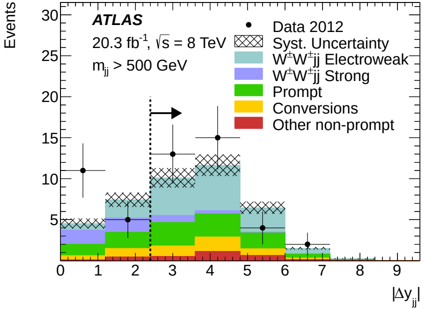


EW measurement

("VBS signal region")

→ additional cut on $|\Delta y_{jj}| > 2.4$

$|\Delta y_{jj}|$ between the 2 tagging jets

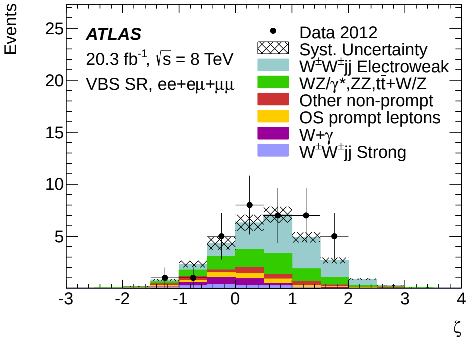


Main uncertainties from jet energy scales (up to ∼15%) and theory modelling (up to ∼8%)

$W^\pm W^\pm jj$: Lepton centrality

Phys. Rev. Lett. 113, 141803

$$\zeta = \min\left[\min(\eta_{\ell 1}, \eta_{\ell 2}) - \min(\eta_{j1}, \eta_{j2}), \max(\eta_{j1}, \eta_{j2}) - \max(\eta_{\ell 1}, \eta_{\ell 2})\right]$$



→ Both leptons between tagging jets (in η): $\zeta > 0$

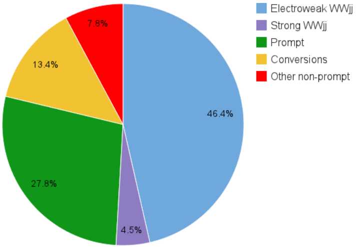
→ One or both leptons with larger η than closest jet: $\zeta < 0$

$W^{\pm}W^{\pm}jj$ event yields

Phys. Rev. Lett. 113, 141803

VBS Signal Region				
	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	Total
$W^{\pm}W^{\pm}$jj Electroweak	2.55 ± 0.25	7.3 ± 0.6	4.0 ± 0.4	13.9 ± 1.2
$W^{\pm}W^{\pm}$jj Strong	0.25 ± 0.06	0.71 ± 0.14	0.38 ± 0.08	1.34 ± 0.26
$WZ/\gamma^*, ZZ, t\bar{t} + W/Z$	2.2 ± 0.5	4.2 ± 1.0	1.9 ± 0.5	8.2 ± 1.9
$W + \gamma$	0.7 ± 0.4	1.3 ± 0.7	–	2.0 ± 1.0
OS prompt leptons	1.39 ± 0.27	0.64 ± 0.24	–	2.0 ± 0.5
Other non-prompt	0.50 ± 0.26	1.5 ± 0.6	0.34 ± 0.19	2.3 ± 0.7
Total Predicted	7.6 ± 1.0	15.6 ± 2.0	6.6 ± 0.8	29.8 ± 3.5
Data	6	18	10	34

$W^{\pm}W^{\pm}jj$ sample composition
in VBS signal region (all channels combined)



$W^{\pm}W^{\pm}jj$ candidate event

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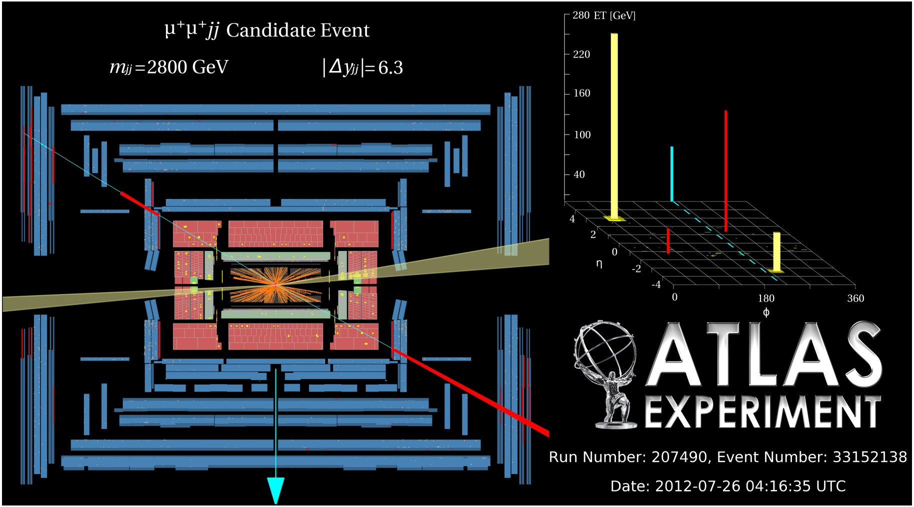


Jets: $p_T^{j1} = 271$ GeV, $p_T^{j2} = 54$ GeV, $\eta^{j1} = 2.9$, $\eta^{j2} = -3.4$

Muons: $p_T^{\mu 1} = 180$ GeV, $p_T^{\mu 2} = 38$ GeV, $\eta^{\mu 1} = 1.4$, $\eta^{\mu 2} = -1.3$

$E_T^{miss} = 75$ GeV

$W^\pm W^\pm jj$ production cross sections

	Measurement	Theory prediction POWHEGBOX+PYTHIA8
Inclusive signal region (EW+strong $W^\pm W^\pm jj$ production)		
Cross section [fb]	2.1 ± 0.5(stat) $\pm$ 0.3(syst)	1.52 ± 0.11
Significance	4.5 s.d.	3.4 s.d.
VBS signal region (EW $W^\pm W^\pm jj$ production)		
Cross section [fb]	1.3 ± 0.4(stat) $\pm$ 0.2(syst)	0.95 ± 0.06
Significance	3.6 s.d.	2.8 s.d.

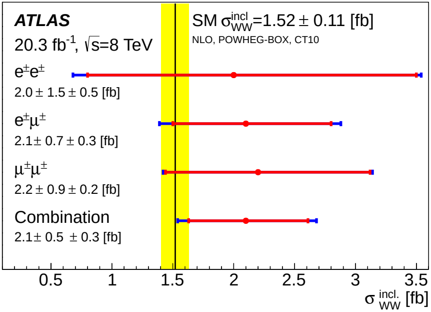
→ Interference between EW and strong $W^\pm W^\pm jj$ production: $\sim 7 \pm 4$ % (LO, evaluated with SHERPA), included in EW signal

First evidence of a process dominated by VBS and containing a quartic electroweak gauge boson vertex!

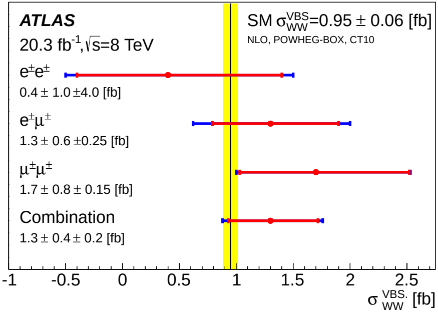
$W^{\pm}W^{\pm}jj$ production cross sections

Phys. Rev. Lett. 113, 141803

Inclusive phase space
(EW+strong measurement)

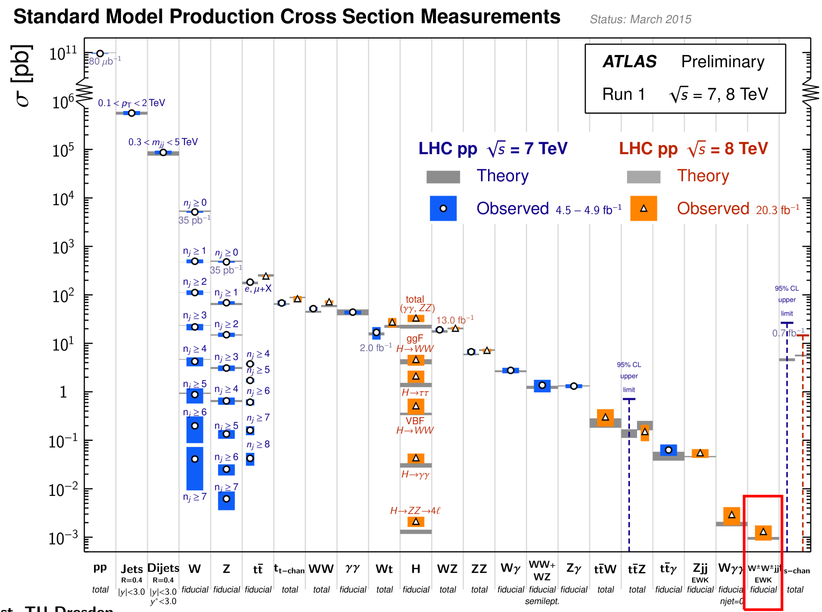


VBS phase space
(EW measurement)



Overview of ATLAS SM cross sections

TWiki StandardModelPublicResults

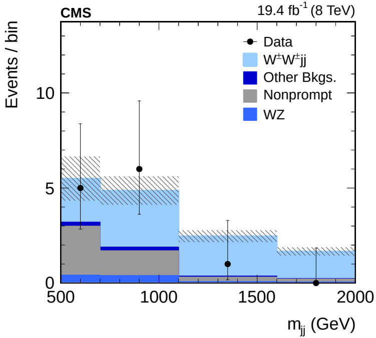


$W^{\pm}W^{\pm}jj$ production – CMS

Phys. Rev. Lett. 114 (2015) 051801

EW+strong measurement

invariant mass of the 2 tagging jets:



Backgrounds:

- non-prompt
  - → leptonic decays of heavy quarks, hadrons misidentified as leptons, electrons from photon conversions in $t\bar{t}$ decays
  - ⇒ veto events with any b-jets (reduces $t\bar{t}$)
- $WZjj$: 3 or more prompt leptons
  - ⇒ veto events with any additional lepton with loose criteria

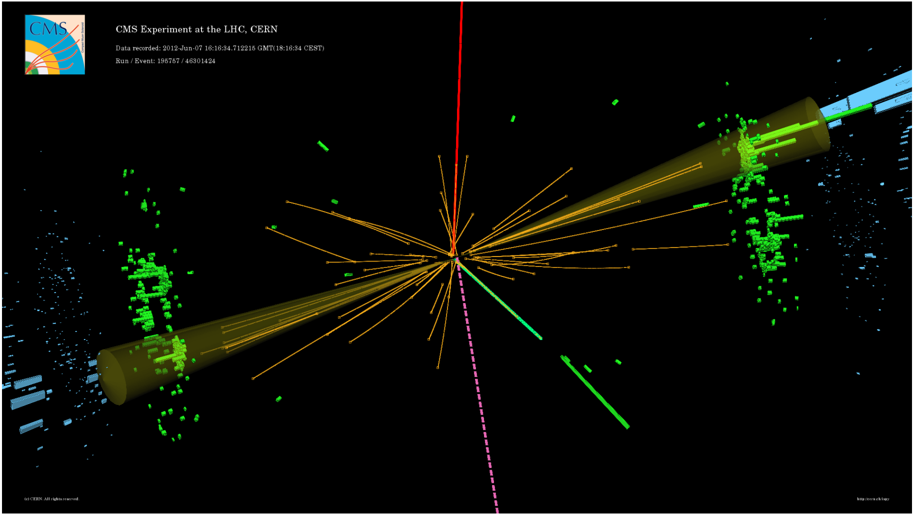
Cross section in **extended** fiducial phase space:

($p_T^{\ell} > 10$ GeV, $|\eta_\ell| < 2.5$, $p_T^{j} > 20$ GeV, $|\eta_j| < 5.0$, $m_{jj} > 300$ GeV, $|\Delta\eta_{jj}| > 2.5$)

- measured: $\sigma = 4.0\,^{+2.4}_{-2.0}(\text{stat})\,^{+1.1}_{-1.0}(\text{syst})$ fb (expected: $\sigma = 5.8 \pm 1.2$ fb)
- significance: 2.0 s.d. (expected: 3.1 s.d.)

$W^{\pm}W^{\pm}jj$ candidate event

Phys. Rev. Lett. 114 (2015) 051801



Jets: $p_T^{j1} = 73$ GeV, $p_T^{j2} = 61$ GeV,
Leptons: $p_T^{\mu} = 114$ GeV, $p_T^{e} = 33$ GeV

$E_{\mathrm{T}}^{\mathrm{miss}} = 95$ GeV
$m_{jj} = 596$ GeV

Look at physics beyond the SM

Look at physics beyond the SM

- The SM may be considered as a low-energy effective theory of a more complete but unknown theory
- Model independent approach: effective Lagrangian
  (SM + higher-dimension operators):

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

  → valid only, if new physics out of direct LHC reach, $s \ll \Lambda^2$

- New physics in EW sector modify gauge boson self-interactions
  → VBS could still be strong and differ from SM predictions
- Look at genuine dimension 8 QGC operators with no effect on TGC

Look at physics beyond the SM

- Relevant effective aQGC parametrizations (examples):

EW chiral Lagrangian approach (non-linear representation, dim 4)	Effective Field Theory description (linear representation, dim 8)
$WWWW$, $WWZZ$	all $VVVV$
α_4, α_5	$f_{S,i}/\Lambda^4$, $f_{M,i}/\Lambda^4$, $f_{T,i}/\Lambda^4$
Appelquist et al. (1980)	Eboli et al. (2006), arXiv:hep-ph/0606118

- EWchL approach can be translated in EFT description and vice versa

  $\rightarrow$ switch of operator basis, dependent on vertex

  $\rightarrow$ $\alpha_{4/5} \leftrightarrow \frac{f_{S,0/1}}{\Lambda^4}$ conversion arXiv:1309.7890, arXiv:1310.6708

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

Unitarization

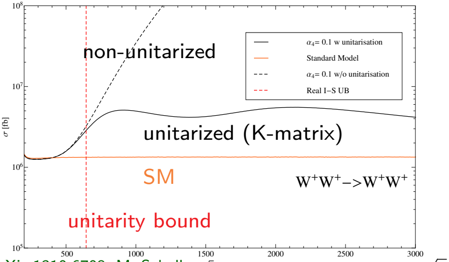
- With aQGCs unitarity may be violated even in presence of a SM Higgs

  $\Rightarrow$ unitarization scheme needed!

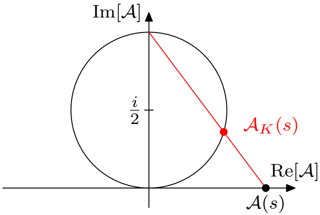
  $\rightarrow$ **all unitarization schemes are arbitrary and introduce model dependence!**

- **K-matrix** method (WHIZARD arXiv:0806.4145)
  - scattering amplitude $\mathcal{A}(s)$ projected on Argand

    $\rightarrow$ saturation of the amplitude



arXiv:1310.6708, M. Sekulla



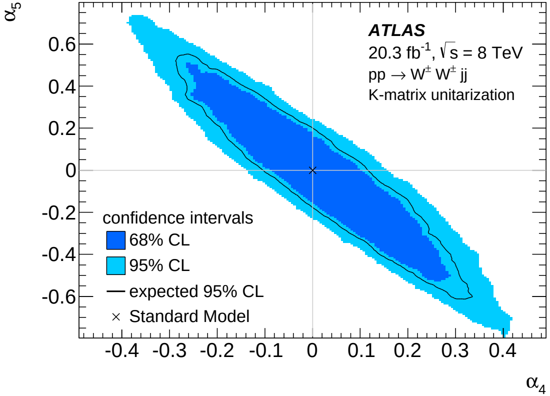
$\rightarrow$ allows for probing the entire kinematic phase space without being unphysical

Constraints on aQGCs from $W^{\pm}W^{\pm}jj$

Phys. Rev. Lett. 113, 141803

Exclusion limits on α_4 and α_5 extracted from cross section in VBS phase space

- aQGC samples from WHIZARD+PYTHIA8 with K-matrix unitarization



observed 1-dimensional 95% confidence intervals:

$$-0.14 < \alpha_4 < 0.16$$
$$-0.23 < \alpha_5 < 0.24$$

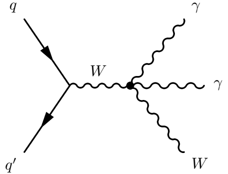
(respective other $\alpha_i = 0$)

$\hat{=}$ Scale of new physics: $\Lambda >$ 500 – 650 GeV (rule of thumb: $\Lambda = v/\sqrt{\alpha_i}$ arXiv:1307.8170)

Constraints on aQGCs from $W\gamma\gamma$ production

arXiv:1503.03243

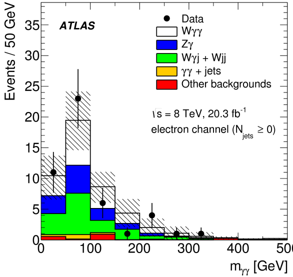
- First evidence for $W\gamma\gamma$ production!
- Constraints on aQGC parameters

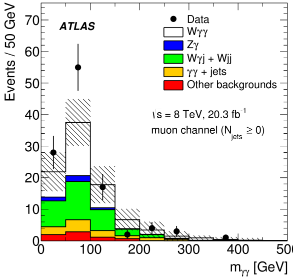


unitarization with form factors $\mathcal{F}(s) = \frac{1}{(1+\hat{s}/\Lambda^2_{\mathrm{FF}})^n}$

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

$m_{\gamma\gamma}$ distributions



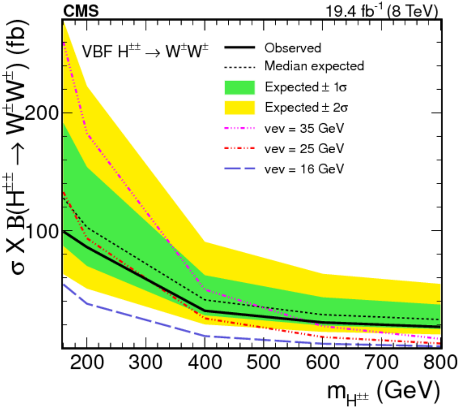


Constraints on $H^{\pm\pm} \to W^{\pm}W^{\pm}$

Phys. Rev. Lett. 114, 051801 (2015)

From $W^{\pm}W^{\pm}jj$ measurement (CMS):

$\to$ 95% CL upper limits on the cross section times branching fraction, $\sigma_{H^{\pm\pm}} \times \mathcal{B}(H^{\pm\pm} \to W^{\pm}W^{\pm})$



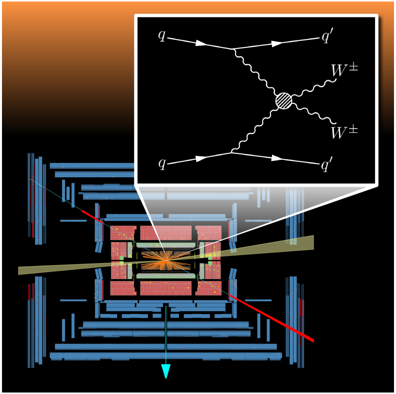
Summary

- Vector boson scattering processes provide a very important test of the EW theory and of the dynamics of EW symmetry breaking

- First LHC results:

  $\rightarrow$ $W^{\pm}W^{\pm}jj$ production:
  first evidence for a process with VBS and containing an EW quartic gauge coupling

  $\rightarrow$ exclusion limits set on anomalous QGC parameters



- Need to explore vector boson scattering at higher energies, complementary to studying Higgs boson properties

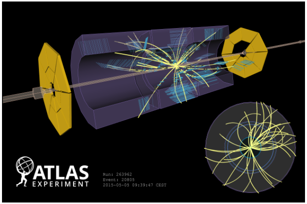
Outlook – LHC @ 13/14 TeV

- Look also at $W^\pm W^\mp jj$, $WZjj$, $ZZjj$ and $W/Z\gamma jj$ final states, ...
- Extract longitudinal polarization states V_L
- Cross sections at 8 and 13 TeV (in VBS phase space optimized for 8 TeV):

final state	sensitive to $VV \rightarrow$	σ^{EW}[fb] 8 TeV	σ^{EW}[fb] 13 TeV	σ^{strong}[fb] 8 TeV	σ^{strong}[fb] 13 TeV	background
$\ell^\pm\ell^\pm\nu\nu' jj$	$W^\pm W^\pm$	1.13	3.97	0.110	0.346	$W^\pm Z$, inst.
$\ell^+\ell^-\nu\nu' jj$	$W^\pm W^\mp$, ZZ	3.64	12.3	5.51	21.8	$t\bar{t}$ and Z+jets
$\ell^+\ell^-\ell'^\pm\nu' jj$	$W^\pm Z$	0.571	2.34	1.12	4.38	4ℓ production
$\ell^+\ell^-\ell'^+\ell'^- jj$	ZZ	0.027	0.098	0.024	0.100	inst.

by Ch. Gumpert, CERN-THESIS-2014-290

$\rightarrow$ At 13 TeV with $\sim 5\ \mathrm{fb}^{-1}$ similar significance expected than with 8 TeV data



ATLAS Experiment © 2015 CERN

Outlook – Beyond the LHC

Above $\sqrt{\hat{s}} = m_{VV} \approx 1 - 2$ TeV it will become possible to experimentally probe the SM nature of EWSB by VBS measurements

$\rightarrow$ Probing in particular unitarization of WW scattering, and explore dynamics well above EWSB

http://fcc.web.cern.ch

Backup

Unitarity

Unitarity of a theory is necessary for its consistency

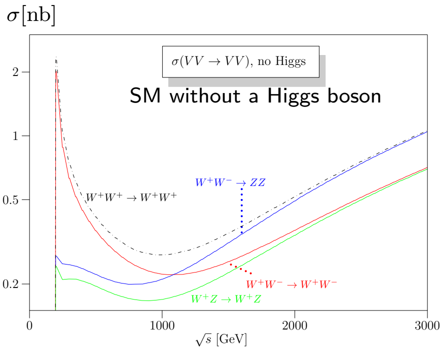
- ensures that probabilities always sum to 1
- implies the optical theorem

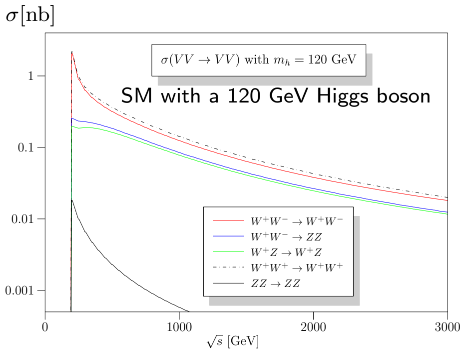
⇒ the imaginary part of a probability amplitude $\mathrm{Im}(M)$ of a 2-body forward scattering is related to the total cross section

⇒ the total cross section must not diverge

Vector boson scattering and the role of the Higgs boson

- total cross sections as a function of the VV center-of-mass energy: arXiv:0806.4145





- unitarity preservation visible only in VV scattering at large $\sqrt{\hat{s}} = m_{VV} \gtrsim$ 1 TeV

$\Rightarrow$ VV scattering is a key process to experimentally probe the SM nature of EWSB!

$W^{\pm}W^{\pm}jj$: fiducial phase space

Phys. Rev. Lett. 113, 141803

Inclusive signal region

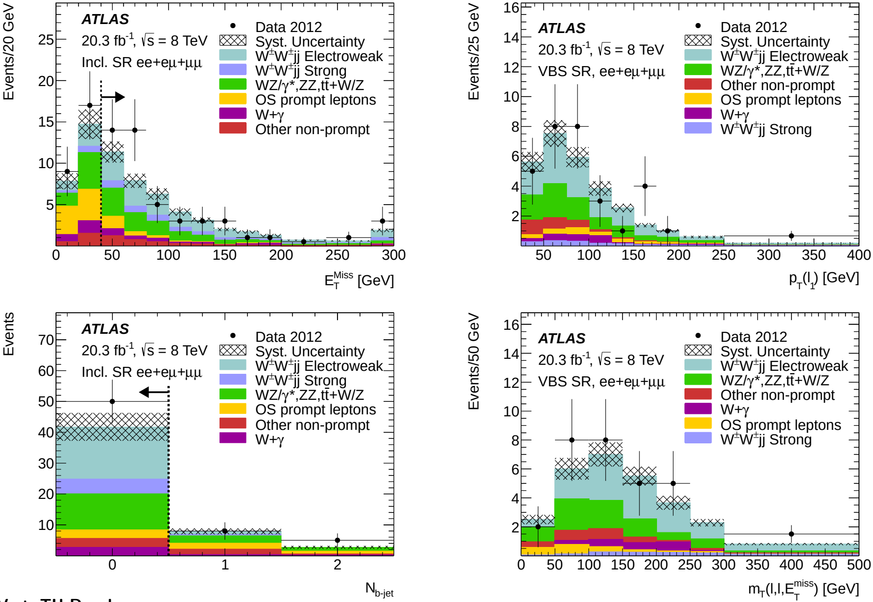
- exactly 2 leptons with same electric charge
  - $e^{\pm}e^{\pm}$, $e^{\pm}\mu^{\pm}$ and $\mu^{\pm}\mu^{\pm}$ final states
  - $p_T^{\ell} > 25$ GeV, $|\eta^{\ell}| < 2.5$
  - $m_{\ell\ell} > 20$ GeV
  - $\Delta R_{\ell\ell} > 0.3$
- ≥ 2 jets reconstructed with the anti-k$_t$ algorithm, jet size R $= 0.4$
  - $p_T^{\mathrm{jet}} > 30$ GeV, $|\eta^{\mathrm{jet}}| < 4.5$
  - $\Delta R_{j\ell} > 0.3$
- $E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV
- invariant mass of the two jets with the largest p_T: $m_{jj} > 500$ GeV

VBS signal region

- rapidity separation between these jets: $|\Delta y_{jj}| > 2.4$

$W^{\pm}W^{\pm}jj$: kinematic distributions

Phys. Rev. Lett. 113, 141803



$W^{\pm}W^{\pm}jj$ event yields

Phys. Rev. Lett. 113, 141803

	Inclusive Region		
	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$
Prompt	3.0 ± 0.7	6.1 ± 1.3	2.6 ± 0.6
Conversions	3.2 ± 0.7	2.4 ± 0.8	–
Other non-prompt	0.61 ± 0.30	1.9 ± 0.8	0.41 ± 0.22
$W^{\pm}W^{\pm}jj$ Strong	0.89 ± 0.15	2.5 ± 0.4	1.42 ± 0.23
$W^{\pm}W^{\pm}jj$ Electroweak	3.07 ± 0.30	9.0 ± 0.8	4.9 ± 0.5
Total background	6.8 ± 1.2	10.3 ± 2.0	3.0 ± 0.6
Total predicted	10.7 ± 1.4	21.7 ± 2.6	9.3 ± 1.0
Data	12	26	12

$W^\pm W^\pm jj$ – systematic uncertainties

Phys. Rev. Lett. 113, 141803

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/–	$E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction	1.1
$E_{\mathrm{T}}^{\mathrm{miss}}$ 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		

$W^{\pm}W^{\pm}jj$ production – control regions

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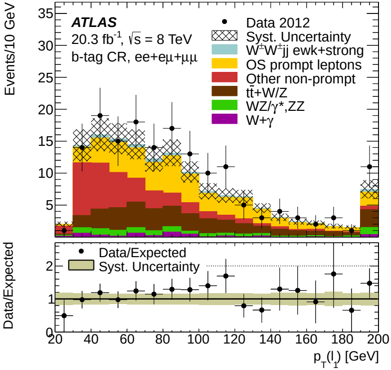
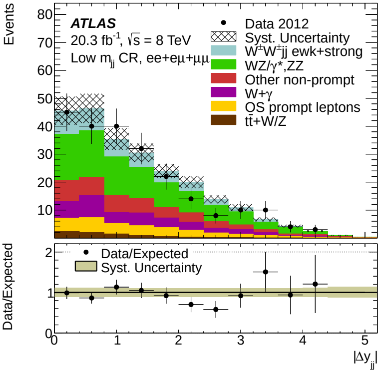
$t\bar{t}$/b-tag control region:
→ other non-prompt (b-decays)



$m_{jj} < 500$ GeV control region:
→ mix



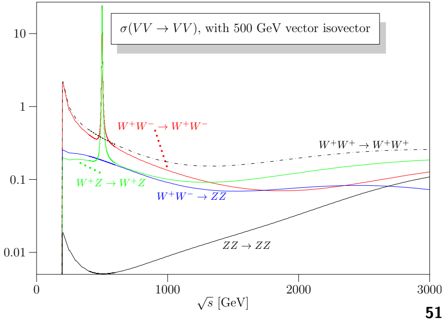
Control Region		Trilepton	$\leq$ 1 jet	b-tagged	Low m_{jj}
$e^{\pm}e^{\pm}$	exp.	36 $\pm$ 6	278 $\pm$ 28	40 $\pm$ 6	76 $\pm$ 9
	data	40	288	46	78
$e^{\pm}\mu^{\pm}$	exp.	110 $\pm$ 18	288 $\pm$ 42	75 $\pm$ 13	127 $\pm$ 16
	data	104	328	82	120
$\mu^{\pm}\mu^{\pm}$	exp.	60 $\pm$ 10	88 $\pm$ 14	25 $\pm$ 7	40 $\pm$ 6
	data	48	101	36	30

New resonances in electroweak sector

arXiv:0806.4145

	$J=0$	$J=1$	$J=2$
$I=0$	σ^0 (Higgs)	ω^0 $(\gamma'/Z'?)$	f^0 (Graviton?)
$I=1$	$\pi^\pm, \pi^0$ (2HDM?)	$\rho^\pm, \rho^0$ $(W'/Z'?)$	$a^\pm, a^0$
$I=2$	$\phi^{\pm\pm}, \phi^\pm, \phi^0$ (Higgs triplett?)	–	$t^{\pm\pm}, t^\pm, t^0$

- width Γ of the resonances for their decays into longitudinal EW gauge bosons dependent on their mass M and coupling g
- example: vector isovector resonance ρ: $\Gamma \sim g^2 M_\rho$
- α_i parametrize low-mass tail of these resonances
- unitarization only guaranteed for explicitly included resonance(s) at unique values of the coupling g

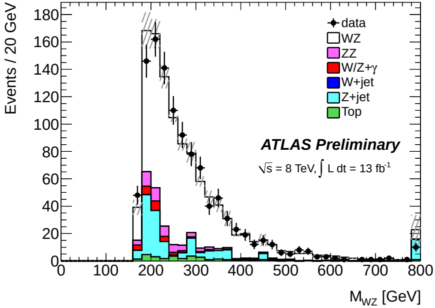


$W^{\pm}Zjj$: experimental tasks

- $W^{\pm}Z$ ($+\ n$ jets) can have **any** number of jets: $n = 0, 1, 2, 3, \ldots$
  - $\rightarrow$ lowest order: $W^{\pm}Z + 0$ jets

$\sqrt{s} = 8$ TeV, 13 fb^{-1}

- 3 high p_T, isolated leptons
- 1 opposite-sign lepton pair forming Z within 81 GeV $< m_{\ell\ell} <$ 101 GeV
- residual lepton + $E_{\mathrm{T}}^{\mathrm{miss}}$ forming W
- results:
  - 1094 events observed
  - 277 background events expected (mainly Z+jets & fake leptons)
  - $\sigma_{\mathrm{total}} = 20.3^{+0.8}_{-0.7}(\mathrm{stat})^{+1.2}_{-1.1}(\mathrm{syst})^{+0.7}_{-0.6}(\mathrm{lumi})\,\mathrm{pb}$ ($\sigma_{\mathrm{MCFM}} = 20.3 \pm 0.8\,\mathrm{pb}$)



- for $W^{\pm}Z$ VBS measurement: require additional 2 jets

Modeling of anomalous quartic gauge couplings

EW chiral Lagrangian approach (non-linear realization of the gauge symmetry)

- aQGC operators (dimension 4):

$$\mathcal{L}_4 = \alpha_4 (\mathrm{Tr}[\mathbf{V}_\mu \mathbf{V}_\nu])^2 \qquad \mathcal{L}_5 = \alpha_5 (\mathrm{Tr}[\mathbf{V}_\mu \mathbf{V}^\mu])^2$$

- $\mathbf{V}_\mu = \Sigma(D_\mu \Sigma)^\dagger$, $\Sigma = e^{-i\frac{\mathbf{w}}{v}}$, $\mathbf{w}$: goldstone scalar field triplett
- aQGC parametrizations: α_4 and α_5

EWchL historically motivated as a Higgs-less model, a posteriori modified to include the SM Higgs boson

EFT approach (linear realization of gauge symmetry)

- operators (dimension 8):

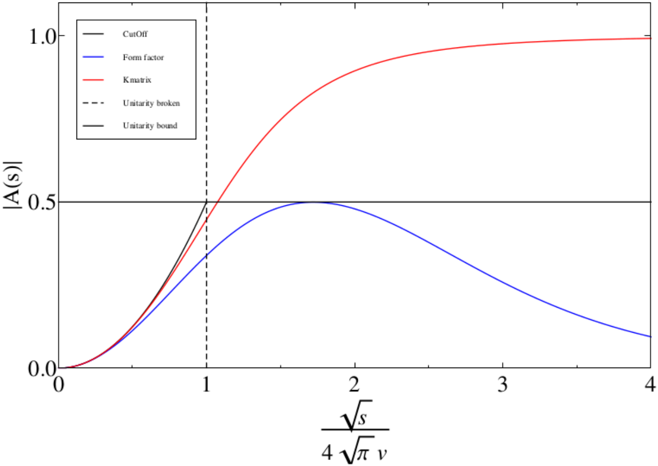
$$\mathcal{L}_{S,0} = \frac{f_{S,0}}{\Lambda^4}[(D_\mu \Phi)^\dagger D_\nu \Phi] \times [(D^\mu \Phi)^\dagger D^\nu \Phi]$$
$$\mathcal{L}_{S,1} = \frac{f_{S,1}}{\Lambda^4}[(D_\mu \Phi)^\dagger D^\mu \Phi] \times [(D_\nu \Phi)^\dagger D^\nu \Phi]$$

- parametrizations: $\frac{f_{S,0}}{\Lambda^4}$ and $\frac{f_{S,1}}{\Lambda^4}$

Unitarization schemes

K-matrix: saturation of amplitude to achieve unitarity

form factor: suppression of amplitude to get below unitarity bound



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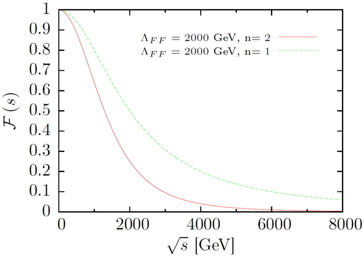
Unitarization

- With aQGCs unitarity may be violated even in presence of a SM Higgs (effective parametrization always violates unitarity at some m_{VV})
  - $\Rightarrow$ unitarization scheme needed!
  - $\rightarrow$ **all unitarization schemes are arbitrary and introduce model dependence!**

- **Form factors** $\mathcal{F}(s) = (1 + \hat{s}/\Lambda_{\mathrm{FF}}^2)^{-n}$
  - $\rightarrow$ suppression of amplitude
  - additional arbitrary parameters: exponent n and form factor scale Λ_{FF}
  - can be generally used for arbitrary anomalous operators
  - needs "fine tuning"

Feigl, Zeppenfeld, 2010

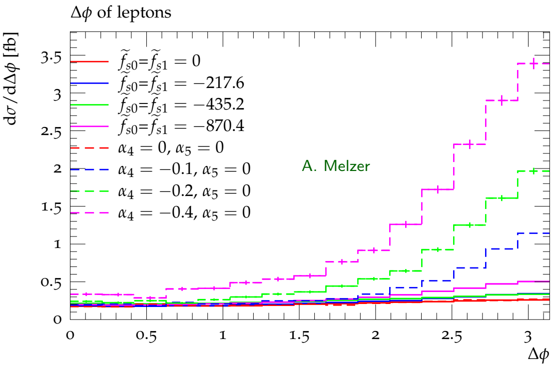


for $n = 2$ at $\Lambda_{\mathrm{FF}} = 2$ TeV: amplitude suppressed by a factor of 4

Kinematic distributions, unitarized

- comparison of unitarization with K-matrix method (WHIZARD, $\alpha_{4/5}$) and form factors (VBFNLO, $f_{S,0/1}$) at generator level
- example process: $pp \to qqe^+\nu e^+\nu$

$\Delta\phi$(leptons) differential cross-section distribution:



generator cuts:

- $p_T^\ell > 10$ GeV, $|\eta_l| < 5$
- $p_T^j > 20$ GeV, $|\eta_j| < 5$
- $|\Delta R(jj)| > 0.4$
- $m_{jj} > 150$ GeV

aQGC parameter:

- $\tilde{f}_{S,0} = \tilde{f}_{S,1} \approx 2176 \cdot \alpha_4$ (with $\tilde{f}_{S,0/1} = \frac{f_{S,0/1}}{\Lambda^4}$ TeV^4)
- $\alpha_5 = 0$

Constraints on aQGCs from $\gamma\gamma \to WW$

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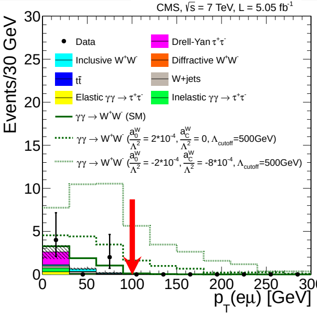
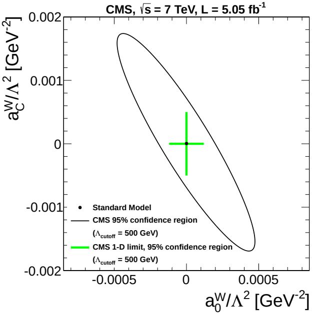
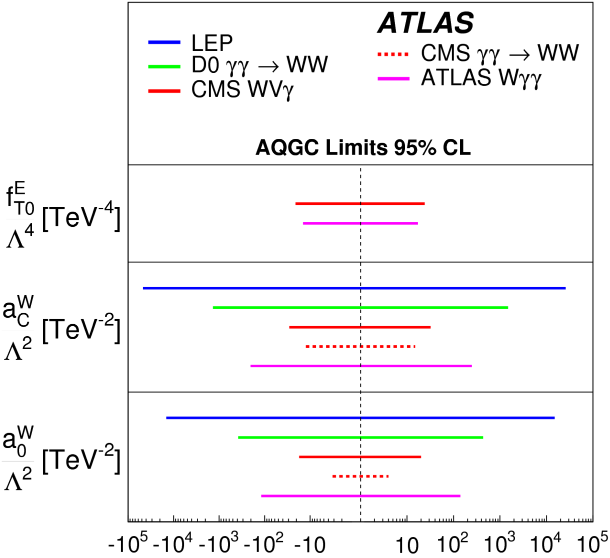
- sensitive to $WW\gamma\gamma$ vertex
- additional cut at $p_T(\mu^\pm e^\mp) > 100$ GeV:
  - $\to$ 0 events left
- 1D and 2D limits (95% CL) on aQGC parameters a_0^W/Λ^2 and a_c^W/Λ^2:
  - $|a_0^W/\Lambda^2| < 0.00015\ \mathrm{GeV}^{-2}$
  - $|a_c^W/\Lambda^2| < 0.0005\ \mathrm{GeV}^{-2}$
- unitarization with form factor with $\Lambda_{\mathrm{FF}} = 500\ \mathrm{GeV},\ n = 2$
- un-unitarized limits (without form factor):
  - 30 – 40 times better, but dominated by $\sqrt{\hat{s}}$ above unitarity
  - $\times$100 improvement wrt. D0
  - $\times$3000 improvement wrt. LEP





Limits on aQGCs for $WW\gamma\gamma$

arXiv:1503.03243



Effective QGC in VBS

arXiv:0806.4145

- non-linear realization of the gauge symmetry → chiral EW Lagrangian:

$$\mathscr{L}_4 = \alpha_4 \frac{g^2}{2} \left\{ [(W^+W^+)(W^-W^-) + (W^+W^-)^2] + \frac{2}{c_w^2}(W^+Z)(W^-Z) + \frac{1}{2c_w^4}(ZZ)^2 \right\}$$

$$\mathscr{L}_5 = \alpha_4 \frac{g^2}{2} \left\{ (W^+W^-)^2 + \frac{2}{c_w^2}(W^+W^-)(ZZ) + \frac{1}{2c_w^4}(ZZ)^2 \right\}$$

- effective parametrization of physics beyond kinematic reach, e.g. resonances at new physics scale $\Lambda = v/\sqrt{\alpha_i}$
  - wide → continuum, narrow → particles

	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$	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

Prospects for VBS at $\sqrt{s} = 14$ TeV

CERN-ESG-005, ATLAS-PHYS-PUB-2012-005

- LHC @ 14 TeV $\rightarrow \sqrt{\hat{s}} = m_{VV} \approx 1 - 2$ TeV
- signal chosen: anomalous VBS ZZ tensor singlet resonance f^0
  - $\rightarrow$ exactly four selected leptons: two opposite sign, same flavor pairs
  - $\rightarrow$ hard benchmark, sensitivity higher for other resonances

$m_{\text{resonance}}$	coupling	width	300 fb^{-1}	3000 fb^{-1}
500 GeV	$g = 1$	$\Gamma = 2$ GeV	2.4σ	7.5σ
1 TeV	$g = 1.75$	$\Gamma = 50$ GeV	1.7σ	5.5σ
1 TeV	$g = 2.5$	$\Gamma = 100$ GeV	3.0σ	9.4σ