$WW/WZ/ZZ$ scattering at high energy at LHC

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on behalf of the ATLAS and CMS collaborations

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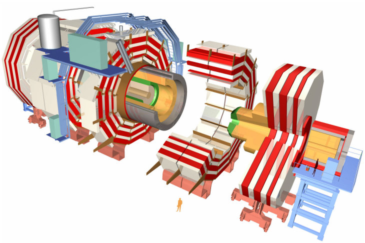

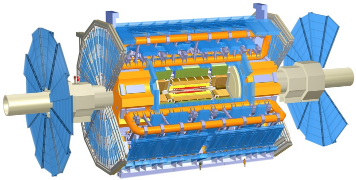

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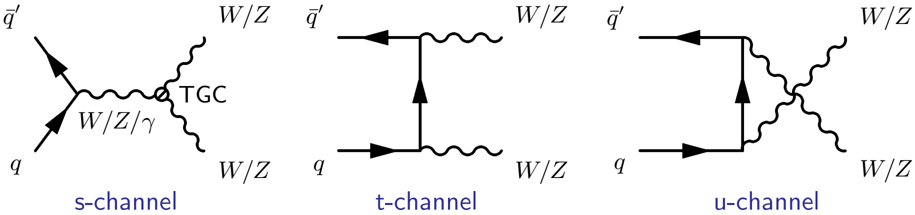
Introduction

- Electroweak diboson measurements
  - test of the electroweak sector of the SM at the TeV scale
  - sensitive to anomalous triple gauge couplings (aTGC)
  - irreducible background to Higgs searches
- *WW*/*WZ*/*ZZ* scattering → (massive, weak) vector boson scattering (VBS)
  - measurable key process inextricably linked with EWSB:
    the EWSB mechanism
    - must regulate $\sigma(V_L V_L \rightarrow V_L V_L)$ in order to restore unitarity above $\sim 1 - 2\ \mathrm{TeV}$
    - must thus be experimentally observable in VBS at the TeV scale
  - sensitive to anomalous quartic gauge couplings (aQGC)
  - final state: diboson $+ \geq 2$ jets
- VBS at the LHC at high energy ($14\ \mathrm{TeV}$) is the key process to experimentally probe the SM nature of EWSB, complementary to direct Higgs measurements

WW/WZ/ZZ production at the LHC

- Measuring *WW/WZ/ZZ* production is an evident prerequisite for VBS measurements
- LO diagrams for *WW/WZ/ZZ* production:

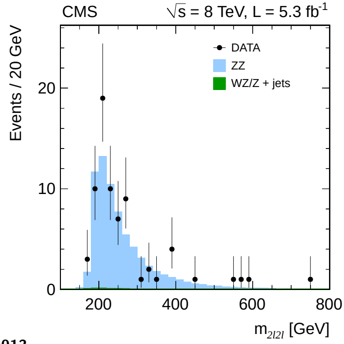


- Cross sections calculated to NLO (using MCFM with PDF set CT10 or MSTW08)
  $\rightarrow$ gluon-gluon enters at NLO, $< 10\%$ of the cross-section
- Access to triple gauge couplings (TGC)
  $\rightarrow$ new physics may show up as anomalous ($=$ non-SM) TGCs
- Important background to Higgs and beyond-SM searches
  $\rightarrow$ precise knowledge of cross-sections and kinematic distributions needed

$ZZ^{(*)} \rightarrow llll$ and $ll\nu\nu$

	$\sqrt{s}$	$\int \mathcal{L}dt$	measured cross section (pb)	theory (pb)	reference
ATLAS	7 TeV	4.6 fb^{-1}	6.7 $\pm$0.7(stat)$^{+0.4}_{-0.3}$(sys)$\pm$0.3(lumi)	5.89$^{+0.22}_{-0.18}$	arXiv:1211.6096
CMS	7 TeV	5.0 fb^{-1}	6.24 $^{+0.68}_{-0.80}$(stat)$^{+0.41}_{-0.32}$(sys)$\pm$0.14(lumi)	6.3$\pm$0.4	JHEP 1301 (2013) 063
ATLAS	8 TeV	20 fb^{-1}	7.1 $^{+0.5}_{-0.4}$(stat)$\pm$0.3(sys)$\pm$0.2(lumi)	7.2$^{+0.3}_{-0.2}$	ATLAS-CONF-2013-020
CMS	8 TeV	5.3 fb^{-1}	8.4 $\pm$1.0(stat)$\pm$0.7(sys)$\pm$0.4(lumi)	7.7$\pm$0.4	arXiv:1301.4698

- four high p_T, isolated leptons
- two opposite-sign same-flavor lepton pairs, each (8 TeV) within
  $66\text{ GeV} < m_Z < 116\text{ GeV}$ (ATLAS)
  $60\text{ GeV} < m_Z < 120\text{ GeV}$ (CMS)
- CMS includes $ee\tau\tau$ and $\mu\mu\tau\tau$ channels



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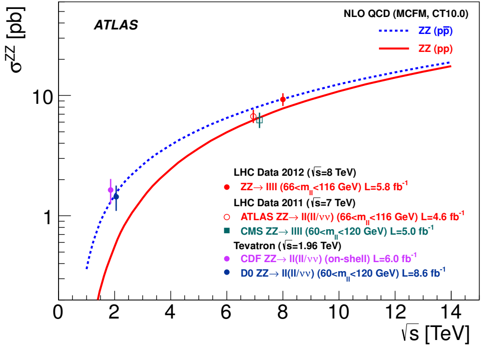

$WZ \rightarrow l\nu ll$

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CMS	7 TeV	1.1 fb^{-1}	17.0 $\pm$2.4(stat)$\pm$1.1(sys)$\pm$1.1(lumi)	19.8 $\pm$0.1	CMS-PAS-EWK-11-010
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- opposite-sign lepton pair forming Z within

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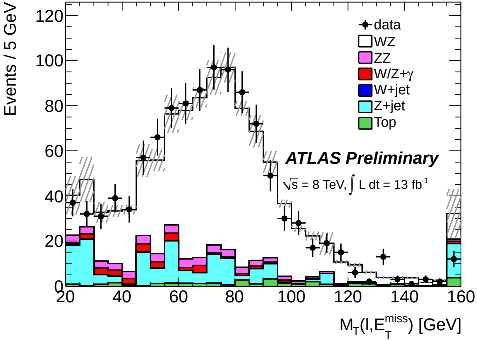
- lepton + $E_{\mathrm{T}}^{\mathrm{miss}}$ forming W
- (leading syst error: Z+jets background estimate)



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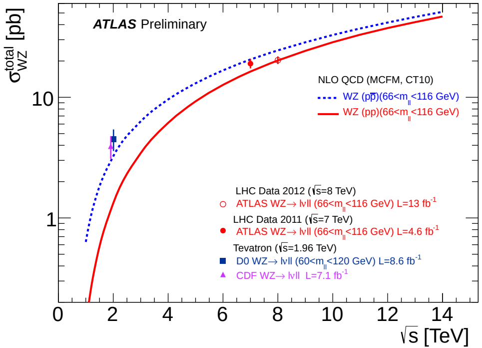

$WW \to l\nu l\nu$

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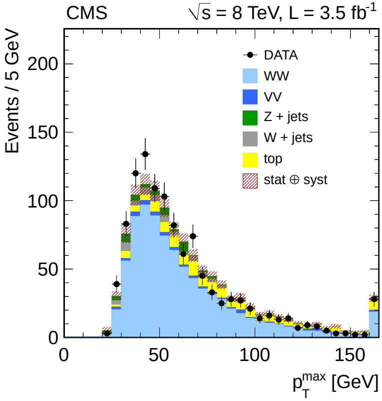
ATLAS	7 TeV	4.6 fb^{-1}	51.9 $\pm$2.0(stat)$\pm$3.9(sys)$\pm$2.0(lumi)	44.7 $^{+2.1}_{-1.9}$	arXiv:1210.2979
CMS	7 TeV	4.9 fb^{-1}	52.4 $\pm$2.0(stat)$\pm$4.5(sys)$\pm$1.2(lumi)	47.0 $\pm$2.0	CMS-PAS-SMP-12-005
CMS	8 TeV	3.5 fb^{-1}	69.9 $\pm$2.8(stat)$\pm$5.6(sys)$\pm$3.1(lumi)	57.3 $^{+2.4}_{-1.6}$	arXiv:1301.4698

- tight event selection needed against background:
  - opposite-sign high p_T isolated leptons
  - $E_{\mathrm{T}}^{\mathrm{miss}}$(against Z+jets)
  - jet veto (against $t\bar{t}$)
- cross sections at the LHC are slightly larger than the SM prediction



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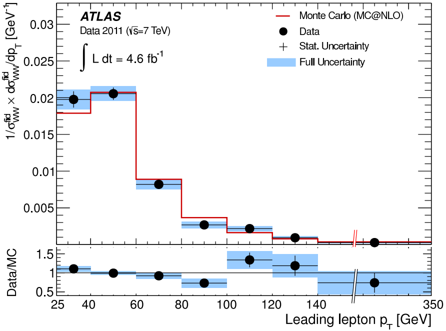
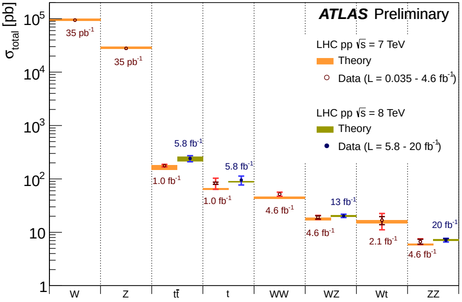
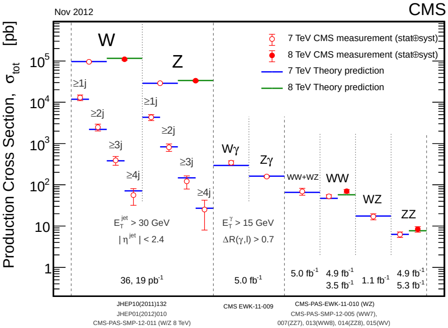


Summary of (diboson) cross sections at the LHC

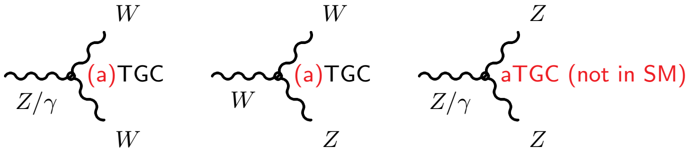
Standard Model total production cross-sections corrected for leptonic branching fractions, compared to theoretical expectations:





- No significant deviation from the SM observed
- (Massive) diboson measurements:
  - unfolded differential cross sections by ATLAS for all results at 7 TeV
  - jet multiplicity bins not yet measured (→ VBS)

Anomalous triple gauge couplings



- WWV ($V = Z/\gamma$) couplings $\longleftrightarrow$ WW and WZ (also $W\gamma$)

$$\frac{\mathcal{L}_{WWV}}{g_{WWV}} = ig_1^V(W_{\mu\nu}^+ W^\mu V^\nu - W_\mu^+ V_\nu W^{\mu\nu}) + i\kappa_V W_\mu^+ W_\nu V^{\mu\nu} + \frac{i\lambda_V}{m_W^2} W_{\lambda\mu}^+ W_\nu^\mu V^{\nu\lambda}$$

5 parameters: Δg_1^Z ($= g_1^Z - 1$), $\Delta\kappa_Z$ ($= \kappa_Z - 1$), $\Delta\kappa_\gamma$ ($= \kappa_\gamma - 1$), λ_Z, λ_γ

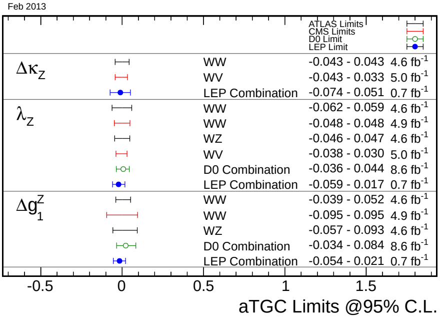
- ZZV ($V = Z/\gamma$) couplings $\longleftrightarrow$ ZZ (also $Z\gamma$)

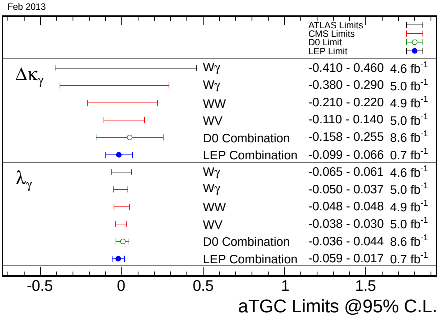
$$\mathcal{L}_{ZZV} = -\frac{e}{M_Z^2}\left(f_4^V(\delta_4^V V^{\mu\beta})Z_\alpha(\delta^\alpha Z_\beta) + f_5^V(\delta^\sigma V_{\sigma\mu})\tilde{Z}^{\mu\beta}Z_\beta\right)$$

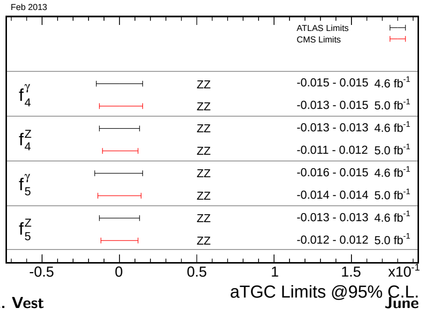
4 parameters: f_4^Z, f_4^γ, f_5^Z, f_5^γ

- Parameters in red (aTGCs) are zero in the SM
- Unitarization via energy-dependent form factors

aTGC results overview







- 8 TeV data not yet included
- TGCs consistent with the SM
- four of the *WWZ* and *WWγ* couplings constrained to $\mathcal{O}(0.05)$ (LEP scenario)
- *ZZZ/γ* couplings constrained to $\mathcal{O}(0.01)$

  e.g. f_4^Z (CMS): [-0.011, 0.012], f_4^Z (LEP): [-0.28, 0.32]

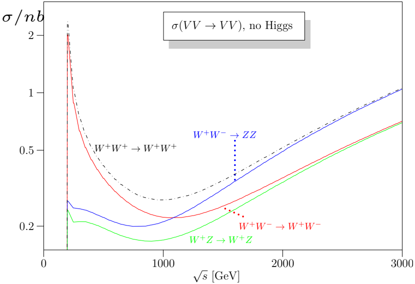
arxiv.org/abs/1302.3415v2

WW/WZ/ZZ scattering introduction

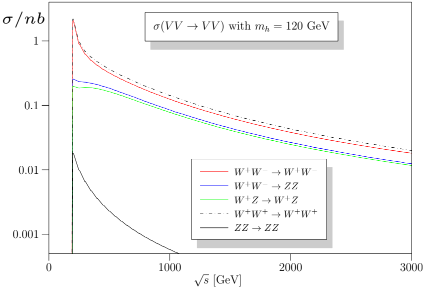
- A measurable key process inextricably linked with EWSB is the scattering of massive, weak vector bosons (*WW/WZ/ZZ*) → "VBS"
- Without a light SM Higgs boson ($m_H \lesssim 850$ GeV) VBS would violate unitarity, → Higgs contribution exactly cancels increase for large s for SM-HWW coupling

$$\mathcal{A}(W_L W_L \to W_L W_L) \propto \frac{g_W^2}{v^2}\left[-s - t + \frac{s^2}{s - m_H^2} + \frac{t^2}{t - m_H^2}\right]$$

VBS cross sections as a function of the VBS center-of-mass energy (arXiv:0806.4145):



SM without a Higgs boson

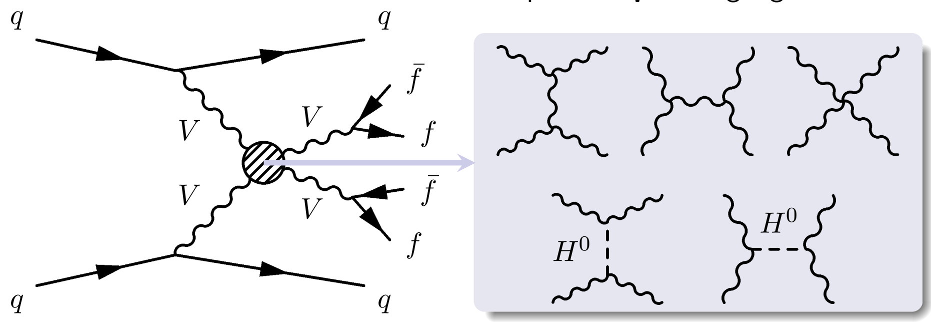


SM with a 120 GeV Higgs boson

WW/WZ/ZZ scattering at LHC

WW/WZ/ZZ scattering at LHC is characterized by VVjj final state:

triple and **quartic** gauge vertices



Higgs exchange and Higgs production via vector boson fusion

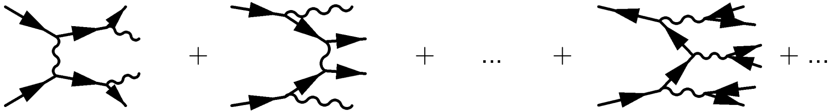
Sensitivity to QGC (only occur in few channels besides VBS)
$\rightarrow$ setting exclusion limits on aQGC

WW/WZ/ZZ scattering at LHC

Further non-*WW/WZ/ZZ* scattering contributions to the VVjj final state:

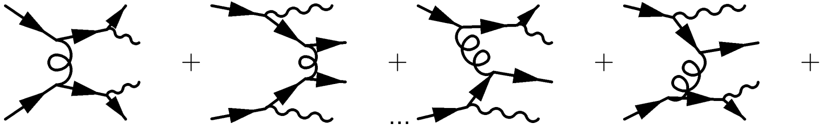
- EW $= \mathcal{O}(\alpha_{EW}^6)$

  not gauge invariantly separable: gauge invariantly separable:



  can be suppressed by VBS topology cuts

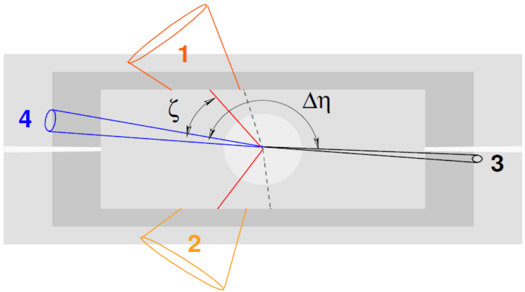
- QCD $= \mathcal{O}(\alpha_s^2 \alpha_{EW}^4)$



  gauge invariantly separable: can be suppressed by VBS topology cuts

WW/WZ/ZZ scattering event topology

Example:



- high p_T central leptons (1, 2) (decay products of the vector bosons)
- two hard, forward tagging jets (3, 4) with large m_{jj} and well separated in η
- missing transverse energy due to the neutrinos from W decays
- to extract the EW contribution from the total EW+QCD process: cut on $|\Delta\eta_{jj}|$ and m_{jj}

VVjj final states

Most promising measurable VVjj final states in terms of *WW/WZ/ZZ* scattering :

- fully leptonic final states

$W^{\pm}W^{\pm}$jj	$\rightarrow$	$l^{\pm}\nu l^{\pm}\nu$jj	equally charged leptons, best σ_{EW} to σ_{QCD} ratio
$W^{\pm}W^{\mp}$jj	$\rightarrow$	$l^{\pm}\nu l^{\mp}\nu$jj	oppositely charged leptons, huge $t\bar{t}$ background
$W^{\pm}Z$jj	$\rightarrow$	$l^{+}l^{-}l^{\pm}\nu$jj	clean channel due to three lepton final state
ZZjj	$\rightarrow$	$l^{+}l^{-}l^{+}l^{-}$jj	very clean channel due to four lepton final state
ZZjj	$\rightarrow$	$l^{+}l^{-}\nu\nu$jj	more difficult to measure, but higher BR

- semi-leptonic final states

$W^{\pm}Z$jj, ZZjj $\rightarrow$ $l^{+}l^{-}$jjj$_{\text{tag}}$j$_{\text{tag}}$
$W^{\pm}W^{\pm}$jj, $W^{\pm}Z$jj, $W^{\pm}W^{\mp}$jj $\rightarrow$ $l^{\pm}\nu$jjj$_{\text{tag}}$j$_{\text{tag}}$

$\rightarrow$ more difficult distinguish from hadronic background

Modeling of anomalous quartic gauge couplings (VBS)

Extension of the effective SM-Lagrangian by introducing additional dimension-8 operators for QGCs (no effect on TGCs):

arXiv:hep-ph/0606118

electroweak chiral Lagrangian approach (e.g. in WHIZARD)

- operators:
  $\mathcal{L}_4 = \alpha_4 (tr[\mathbf{V}_\mu \mathbf{V}_\nu])^2$
  $\mathcal{L}_5 = \alpha_5 (tr[\mathbf{V}_\mu \mathbf{V}^\mu])^2$
- aQGC parametrizations: α_4 and α_5

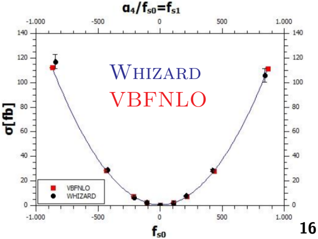
effective field theory approach (e.g. in VBFNLO)

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

$\alpha_{4/5}$ and $f_{S,0/1}$ can be converted into each other for $W^\pm W^\pm$jj production:

$\alpha_4 \approx \frac{1}{2176} \cdot \tilde{f}_{S,0}$ and $\alpha_5 \approx \frac{1}{2176} \cdot \frac{1}{2}(\tilde{f}_{S,1} - \tilde{f}_{S,0})$

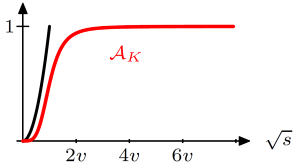
(with $\tilde{f}_{S,0/1} = \frac{f_{S,0/1}}{\Lambda^4}\ \text{TeV}^4$)



Unitarization

- Unitarization with the **k-matrix method** (WHIZARD arXiv:0806.4145)
  - unitarization by infinitely heavy and wide resonance

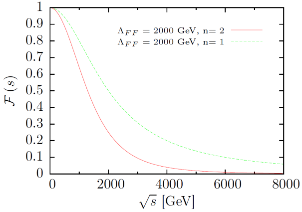
    k-matrix amplitude: $|\mathcal{A}_K(s)|^2 \xrightarrow{s\to\infty} 1$
  - allows arbitrary number of resonances with free couplings g and free widths Γ



- Unitarization via **form factors** (VBFNLO arXiv:1205.4231)
  - regime where unitarity is violated depends on the operators and their coupling strengths
  - energy-dependent form factors

    $\mathcal{F}(s) = \frac{1}{(1+\frac{s}{\Lambda^2_{\text{FF}}})^n}$

    Λ_{FF}: scale above which unitarity is violated



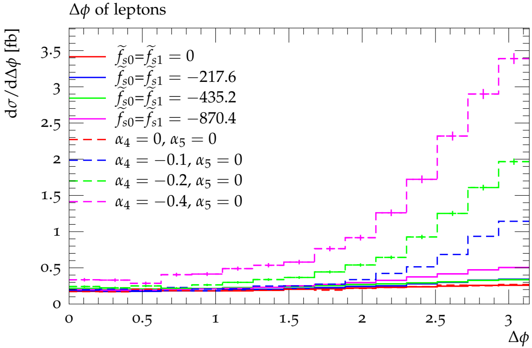
Shape of $\mathcal{F}(s)$ with $\Lambda_{\text{FF}} = 2$ TeV

Kinematic distributions, unitarized

Comparison of unitarization with k-matrix method (WHIZARD, $\alpha_{4/5}$) and form factors (VBFNLO, $\tilde{f}_{S,0/1}$) at generator level

Example process: $pp \to qqe^+\nu e^+\nu$

$\Delta\phi$(leptons) differential cross-sections with unitarization:



$$\tilde{f}_{S,0} = \tilde{f}_{S,1} \approx 2176 \cdot \alpha_4, \quad \alpha_5 = 0$$

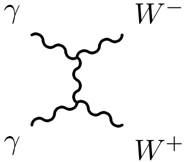
First LHC limits on aQGCs

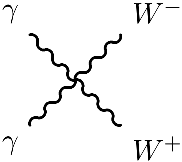
CMS PAS FSQ-12-010

First limits on anomalous quartic gauge couplings (CMS) from exclusive or quasi-exclusive (“inelastic” or “proton dissociative”) W^+W^- production

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

$$\gamma\gamma \to W^+W^- \to l^+\bar{\nu}l^-\nu$$





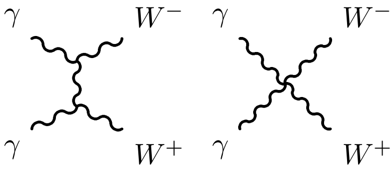
- both very forward-scattered protons escape detection
- process characterized by
  - a primary vertex with only one l^+l^- pair associated to it
  - 0 extra tracks from this primary vertex
  - large pair transverse momentum $p_T(l^+l^-)$ and invariant mass $m_{l^+l^-}$
  - exclusive $\mu^+\mu^-$ production used as benchmark to validate efficiency of vertexing and exclusivity selection, and pileup dependence

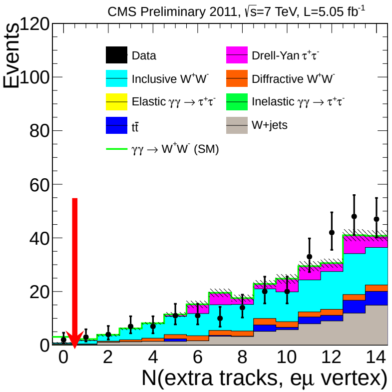
First LHC limits on aQGCs

CMS PAS FSQ-12-010

- 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
    (suppresses $\tau^+\tau^-$ background)
  - no other tracks from primary vertex
- Results (5.05 fb^{-1}, 7 TeV):
  - 2 events observed
  - expected signal: 2.2 ± 0.5
  - expected background: 0.84 ± 0.13
  - total cross-section

    $\sigma(pp \to p^{(*)}WWp^{(*)} \to p^{(*)}\mu\nu e\nu p^{(*)})$
    - measured: $2.1\ ^{+3.0}_{-1.9}$ fb
    - SM prediction: 3.8 ± 0.9 fb





First LHC limits on aQGCs

CMS PAS FSQ-12-010

- 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
    (suppresses $\tau^{+}\tau^{-}$ background)
  - no other tracks from primary vertex
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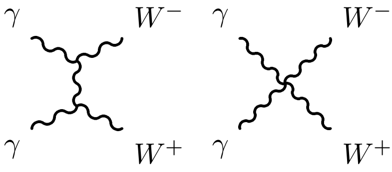
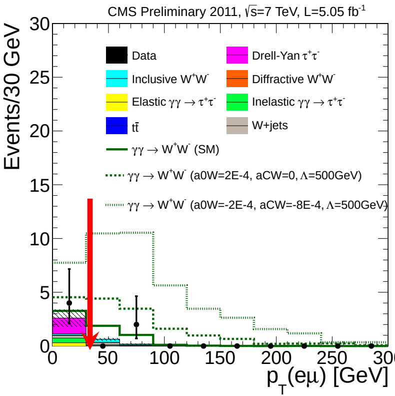
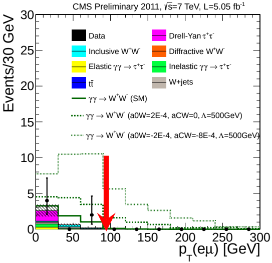


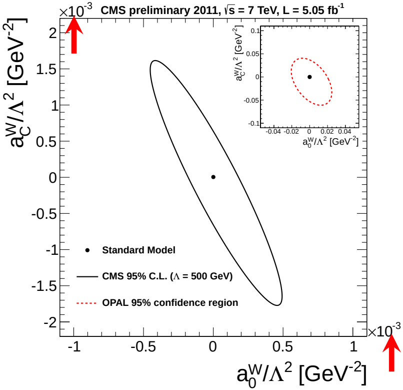


First LHC limits on aQGCs

- Two dimension-6 terms in effective Lagrangian → parameters a_0^W, a_c^W
- Limits (95% C.L.) set from number of events with $p_T(\mu e) > 100$ GeV:

$$|a_0^W/\Lambda^2|/\ \text{GeV}^{-2} < 0.00017$$
$$|a_c^W/\Lambda^2|/\ \text{GeV}^{-2} < 0.0006$$
$$\Lambda_{\text{FF}} = 500\ \text{GeV},\ n = 2$$





LHC limits two orders of magnitude more stringent than LEP combined limit (corresponding to one order of magnitude better sensitivity in Λ)

Prospects for VBS at high energy at the LHC

$\sqrt{s} = 14$ TeV CERN-ESG-005, ATLAS-PHYS-PUB-2012-005

$\rightarrow$ VBS centre-of-mass energy of $\sim 1 - 2$ TeV

- unitarization only guaranteed for explicitly included resonance(s) at unique values of the coupling g arXiv:0806.4145

	$J = 0$	$J = 1$	$J = 2$
$I = 0$	σ^0 (Higgs)	ω^0 (γ'/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?)		$t^{\pm\pm}, t^{\pm}, t^0$

- unitarization with k-matrix method
- new physics signal in this study: anomalous VBS ZZ resonance f^0

$\Rightarrow$ Four lepton final state ZZjj $\rightarrow llll$jj:

- exactly four selected leptons: two opposite sign, same flavor pairs
- at least two selected jets with $m_{jj} > 1$ TeV

Prospects for VBS at high energy at the LHC

$\sqrt{s} = 14\ \mathrm{TeV}$ CERN-ESG-005, ATLAS-PHYS-PUB-2012-005

$\rightarrow$ VBS centre-of-mass energy of $\sim 1 - 2\ \mathrm{TeV}$

- signal: anomalous VBS ZZ resonance f^0 $(m = 1\ \mathrm{TeV}, g = 1.75, \Gamma = 50\ \mathrm{GeV})$

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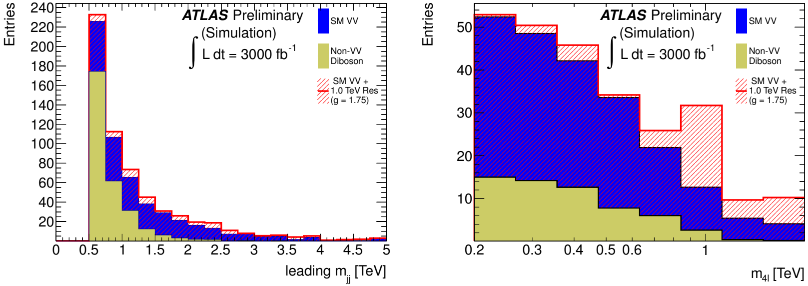

Prospects for VBS at high energy at the LHC

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  $\Rightarrow$ Four lepton final state ZZjj $\rightarrow llll$jj:

  - exactly four selected leptons: two opposite sign, same flavor pairs
  - at least two selected jets with $m_{jj} > 1$ TeV

- statistical precision for cross-section measurements in the signal-enhanced kinematic region of $m_{4l} > 200$ GeV:

  - 30% with 300 fb^{-1}
  - 10% with 3000 fb^{-1}

- statistical precision on the SM contribution for $m_{4l} > 500$ GeV:

  - 45% with 300 fb^{-1}
  - 15% with 3000 fb^{-1}

Prospects for VBS at high energy at the LHC

$\sqrt{s} = 14$ TeV

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

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- signal: anomalous VBS ZZ resonance f^0 ($m = 1$ TeV$, g = 1.75, \Gamma = 50$ GeV)

  $\Rightarrow$ Four lepton final state ZZjj $\rightarrow llll$jj:

  - exactly four selected leptons: two opposite sign, same flavor pairs
  - at least two selected jets with $m_{jj} > 1$ TeV

- sensitivity for 300 fb^{-1}and 3000 fb^{-1}:

$m_{\text{resonance}}$	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

- signal chosen is a hard benchmark, sensitivity higher for other resonances

Summary and outlook

- *WW*, *WZ* and *ZZ* measurements continue to improve
  - cross-sections measured: no significant deviations from the SM
  - limits set on aTGCs: TGCs show no deviations from the SM
- (Massive) vector boson scattering measurements started
  - cross-section measurements
  - set limits on aQGCs
- First LHC limits on aQGCs ($\gamma\gamma WW$): $\sim$ two orders of magnitude more stringent than LEP limits
- More results on full 8 TeV dataset to come
- Probing *WW*/*WZ*/*ZZ* scattering at LHC at high energy (14 TeV) promising:
  - at a VBS centre-of-mass energy of $\sim 1 - 2$ TeV it will be possible to experimentally probe the SM nature of EWSB, complementary to direct Higgs measurements
  - increase of significances for VBS anomalous resonances with high luminosity

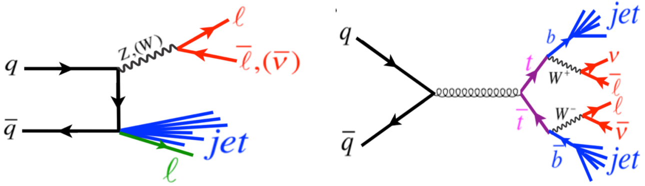
Backup

References

	Analysis	Dataset	Reference
ATLAS	$ZZ \to llll$	20 fb^{-1}, 8 TeV	ATLAS-CONF-2013-020
	$WZ \to l\nu ll$	13 fb^{-1}, 8 TeV	ATLAS-CONF-2013-021
	$WW + WZ \to l\nu jj$	4.7 fb^{-1}, 7 TeV	ATLAS-CONF-2012-157
	$ZZ \to llll, ll\nu\nu$	4.6 fb^{-1}, 7 TeV	arXiv:1211.6096
	$WW \to l\nu l\nu$	4.6 fb^{-1}, 7 TeV	arXiv:1210.2979
	$WZ \to l\nu ll$	4.6 fb^{-1}, 7 TeV	EPJC 72 (2012) 2173
	vector boson scattering	300, 3000 fb^{-1}, 14 TeV	ATLAS-PHYS-PUB-2012-005
CMS	$\gamma\gamma \to WW \to e\nu\mu\nu$	5.05 fb^{-1}, 7 TeV	CMS-PAS-FSQ-12-010
	$WW \to l\nu l\nu$ and $ZZ \to llll$	3.5 and 5.3 fb^{-1}, 8 TeV	arXiv:1301.4698
	$ZZ \to llll$	5.0 fb^{-1}, 7 TeV	JHEP 1301 (2013) 063
	$WW + WZ \to l\nu jj$	5.0 fb^{-1}, 7 TeV	EPJC 73 (2013) 2283
	$WW \to l\nu l\nu$	4.9 fb^{-1}, 7 TeV	CMS-PAS-SMP-12-005
	$WZ \to l\nu ll$	1.1 fb^{-1}, 7 TeV	CMS-PAS-EWK-11-010
Both	vector boson scattering	300, 3000 fb^{-1}, 14 TeV	CERN-ESG-005

Analysis strategy

- Common characteristics:
  - small cross-sections
  - high p_T isolated leptons (electrons or muons)
  - $E_{\mathrm{T}}^{\mathrm{miss}}$ due to neutrinos from W decays
  - two forward jets for *WW*/*WZ*/*ZZ* scattering processes
- Common backgrounds:
  - *W*+jets/*Z*+jets: data driven methods to estimate backgrounds from jets mis-reconstructed as charged leptons or $E_{\mathrm{T}}^{\mathrm{miss}}$
  - $t\bar{t}$ and single top: estimated using data driven backgrounds



  - (massive) diboson production: estimated from MC
  - other backgrounds: $Z\gamma$, $W\gamma$, *ZZZ*, *ZWW*: estimated from MC

Analysis strategy

- Cross-section measurements
  - fiducial phase space: event yields at final selection, correct for efficiency
  - extrapolation to total phase space: additionally correct for acceptance

$$\sigma_{\text{fid}} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{C \cdot \mathcal{L}}, \quad \sigma_{\text{tot}} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{A \cdot C \cdot \mathcal{L} \cdot BR}, \quad C = \frac{N_{\text{passed}}}{N_{\text{generated fid}}}, \quad A = \frac{N_{\text{generated fid}}}{N_{\text{generated all}}}$$

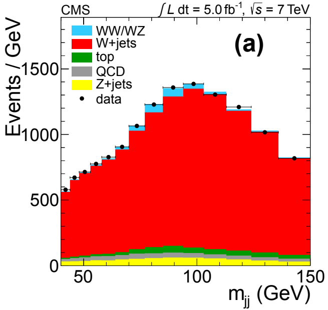
  - N_{obs}: number of observed events passing the selection
  - N_{bkg}: number of estimated background events
  - $\mathcal{L}$: integrated luminosity
  - C: efficiency correction factor in the fiducial volume
  - A: kinematic and geometric acceptance from the total phase space to the fiducial phase space
  - BR: branching ratio of bosons decaying to leptons

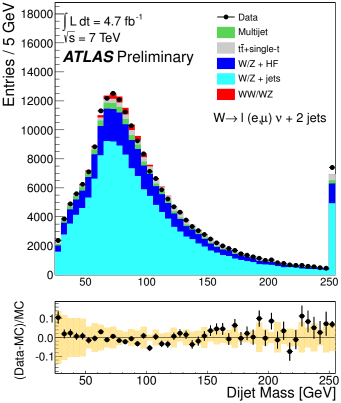
- Extraction of exclusion limits:
  - we can use the impact of anomalous couplings on both production rate and event kinematics to set limits
  - various scenarios assumed:
    - aTGC: equal couplings scenario, LEP scenario, HISZ scenario
    - aQGC: electroweak chiral Lagrangian / effective field theory approach
    - unitarization method

$WW/WZ \to l\nu jj$

	$\sqrt{s}$	$\int \mathcal{L}dt$	measured cross section (pb)	theory (pb)	reference
ATLAS	7 TeV	4.7 fb^{-1}	72 $\pm$9(stat)$\pm$15(sys)$\pm$13(MC stat)	63.4 $\pm$2.6	ATLAS-CONF-2012-157
CMS	7 TeV	5.0 fb^{-1}	68.9 $\pm$8.7(stat)$\pm$9.7(sys)$\pm$1.5(lumi)	65.6 $\pm$2.2	Eur.Phys.J. C73 (2013) 2283

- $WW/WZ \to l\nu jj$ signal also established
  - one high p_T isolated lepton
  - $E_{\mathrm{T}}^{\mathrm{miss}} > 25/30$ GeV
  - exactly two jets with $p_T > 25/35$ GeV





Phase space

Fiducial volume used in the generator level study quoted in this talk

... to suppress $V \to jj$ diagrams which are not contained in the NLO calculation

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

Event displays

Two candidate $\gamma\gamma \to W^+W^- \to l^+\bar{\nu}l^-\nu$ events: