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Vector Boson Scattering and Measurement of Electroweak Production of two Like-Charge W Bosons and two Jets at the ATLAS detector

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GRADUIERTEN KOLLEG Masse-Spektrum-Symmetrie

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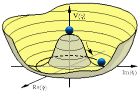
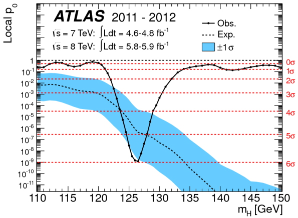
FSP 101 ATLAS

After the first run of the LHC

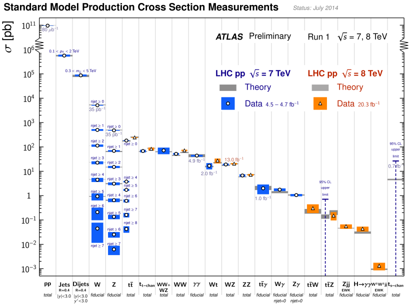
LHC Run 1:

- Start to investigate the nature of electroweak symmetry breaking after Higgs discovery





- Great experimental support for the Standard Model

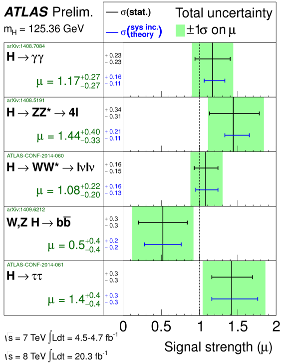


The more we know, the more we don't know

Many issues remain:

- properties of the Higgs
- is there new physics beyond the Standard Model?
  - in the electroweak symmetry breaking sector
  - elsewhere

... to explain hierarchy problem, dark matter, ...



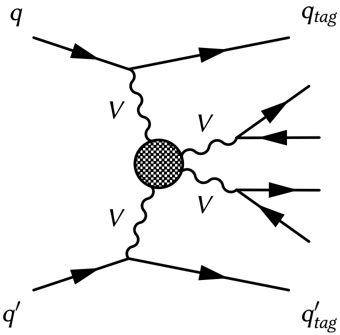
One process to address remaining questions on the electroweak symmetry breaking mechanism and the nature of gauge interactions:

Electroweak vector boson scattering

Outline of this talk

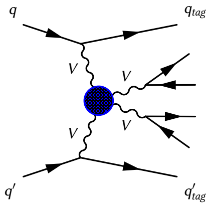
Scattering of electroweak gauge bosons

Process definition of electroweak gauge boson scattering at the LHC:



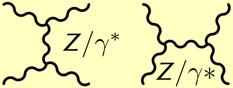
$V = W, Z$

Scattering of electroweak gauge bosons



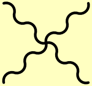
$VV \to VV$

● contains:



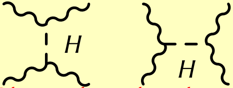
Diagrams with triple gauge couplings

Constrained by diboson production



Quartic gauge boson vertex

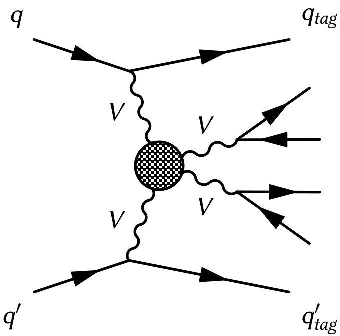
First observation via $W^{\pm}W^{\pm}jj$-EW production



Higgs exchange

Observed in other channels

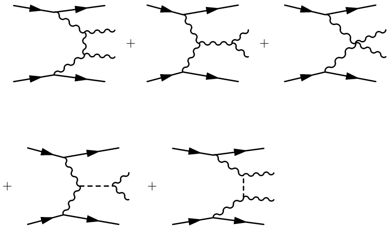
Vector Boson Scattering (VBS)



- Contains VVVV vertex (predicted by the SM) $\Rightarrow$ probe self-interactions of the electroweak gauge bosons
- Contains scattering of longitudinal components of the gauge bosons $\Rightarrow$ Probe electroweak symmetry breaking mechanism

Longitudinal VBS

The scattering of longitudinal vector bosons violates unitarity in the absence of a SM Higgs boson:



Gauge bosons:

$$\mathcal{M}^{gauge} = -\frac{g_w^2}{4m_W^2}u + \mathcal{O}\left(\frac{E}{m_W}^0\right)$$

$\Rightarrow \sim E^2$, violates unitarity

Higgs exchange: (s, t, u $>> m_W^2, m_H^2$)

$$\mathcal{M}^{\text{Higgs}} = \frac{g_w^2}{4m_W^2}u$$

$\Rightarrow$ **terms cancel**

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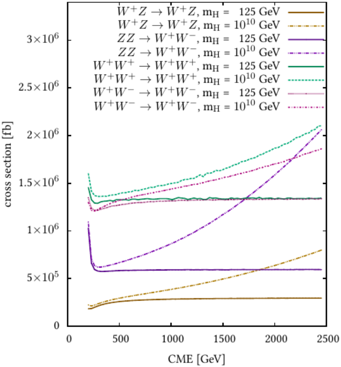

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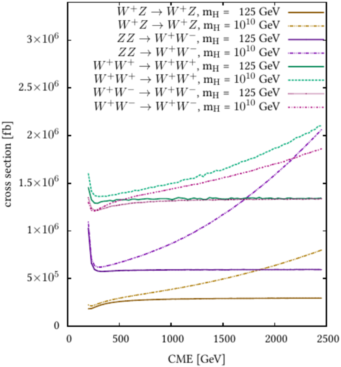

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$\Rightarrow$ **terms cancel**

$\Rightarrow$ Probing the Higgs properties through the scattering of electroweak gauge bosons

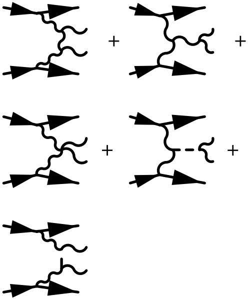
Scattering of two like-charge W bosons

$W^{\pm}W^{\pm}$ scattering analysis at 8 TeV published by the ATLAS collaboration in
Phys. Rev. Lett. 113, 141803 [1]

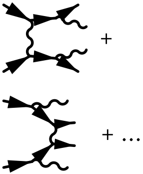
VBS signal definition

VVjj-EW: $\mathcal{O}(EW) = 6$ (incl. decays)

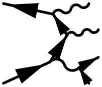
VBS



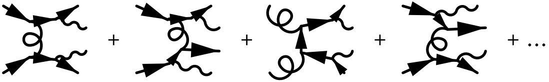
irreducible EW



VVV



VVjj-QCD: $\mathcal{O}(EW) = 4$, $\mathcal{O}(QCD) = 2$ (incl. decays)



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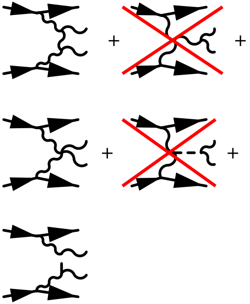
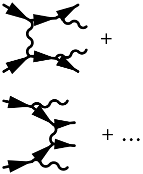
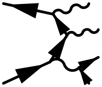


irreducible EW



VVV



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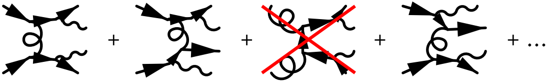

x... not included in $W^{\pm}W^{\pm}jj$

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VBS in $W^{\pm}W^{\pm}jj$ channel

Cross sections in various VV channels at 8 TeV:

Final state	Process	VVjj-EW	VVjj-QCD	Ratio
$\ell^{\pm}\nu\ell'^{\pm}\nu' jj$	$W^{\pm}W^{\pm}$	19.5 fb	18.8 fb	1:1
$\ell^{\pm}\nu\ell^{\mp}\nu jj$	$W^{\pm}W^{\mp}$ + ZZ	93.7 fb	3192 fb	1:30
$\ell^{\pm}\ell^{\mp}\ell'^{\pm}\nu' jj$	$W^{\pm}Z$	30.2 fb	687 fb	1:20
$\ell\ell\ell\ell jj$	ZZ	1.5 fb	106 fb	1:70

(cuts: 2 leptons: $p_{\mathrm{T}} >$ 5 GeV, $m_{\ell\ell} >$ 4 GeV, 2 jets: $p_{\mathrm{T}} >$ 10 GeV)

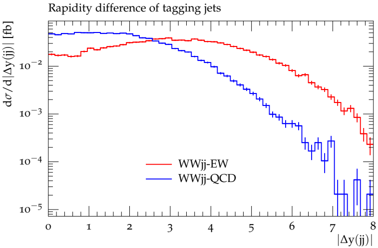
VBS by channel

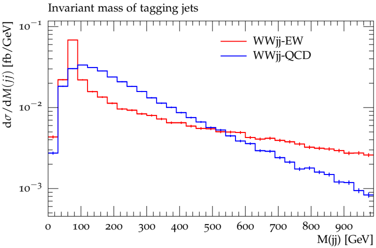
- $W^{\pm}W^{\pm}jj$ most promising: high EW/QCD ratio (no gluons in initial state)
- $W^{\pm}Zjj$ has larger QCD contribution, but profits from clean 3 lepton signature
- $W^{\pm}W^{\mp}$overwhelmed by ttbar background $\rightarrow$ use MVA methods

VVjj-EW vs. VVjj-QCD

Comparison of $W^\pm W^\pm jj$-EW and $W^\pm W^\pm jj$-QCD

Tagging the VBS process according to dijet kinematics

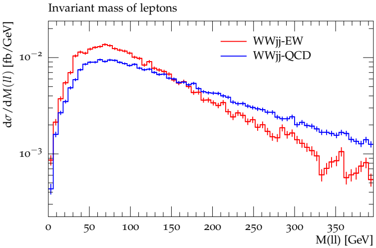


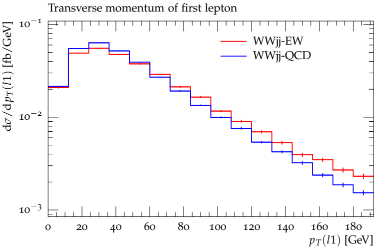


VVjj-EW vs. VVjj-QCD

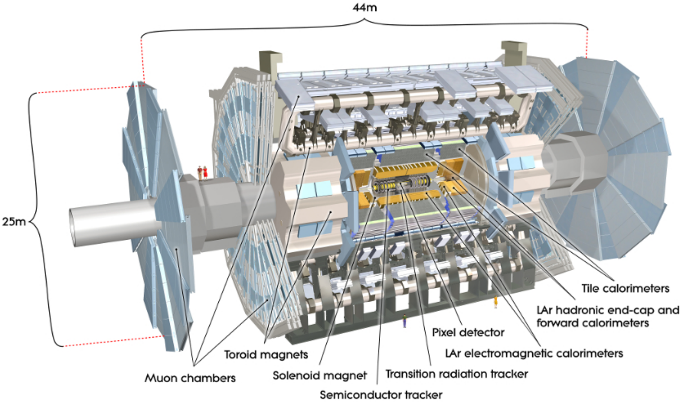
Comparison of $W^{\pm}W^{\pm}jj$-EW and $W^{\pm}W^{\pm}jj$-QCD

Kinematics of the leptons, i.e. the decay products of the W bosons:

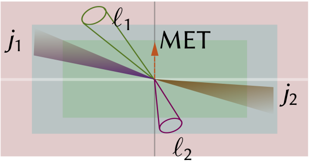




ATLAS detector



VBS topology



- two forward energetic tagging jets (initial quarks radiating off Ws)
- two central leptons (decay products of Ws)
- Missing E_T from Ws

Inclusive analysis phase space

- 2 same-sign high-p_T leptons
- at least 2 high-p_T jets
- $E_T^{miss} > 40$ GeV
- leading jets: $m_{jj} > 500$ GeV

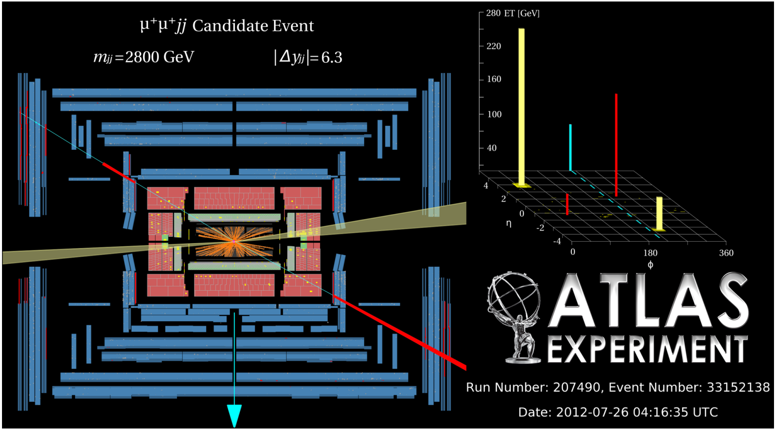
Measure $W^{\pm}W^{\pm}jj$ (incl. EW, QCD)

VBS analysis phase space

inclusive analysis phase space +

- $|\Delta y(jj)| > 2.4$

Measure $W^{\pm}W^{\pm}jj$ EW and set aQGC limits



$$p_T(\text{lep1}) = 180.2\ \text{GeV}$$
$$p_T(\text{lep2}) = 37.5\ \text{GeV}$$
$$E_T^{\text{miss}} = 74.8\ \text{GeV}$$

Phys. Rev. Lett. 113, 141803

Backgrounds to $W^{\pm}W^{\pm}jj$

Backgrounds arise due to

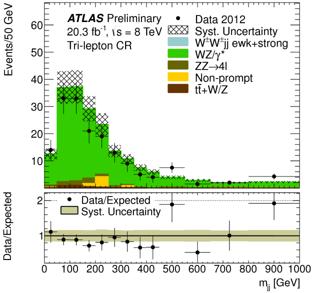
- Events with two prompt like-charge leptons in the final state
- Events with two opposite-charge leptons in the final state, if one charge is mis-measured
- Events with one charged lepton and one lepton from jet mis-identification or hadronic decays
- Double parton interaction (negligible)

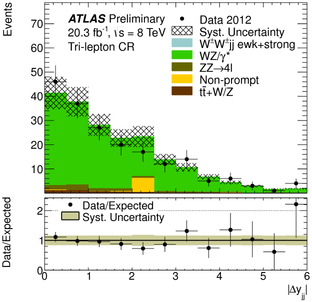
Prompt background

Containing two real prompt same-charge leptons

- WZ/γ^*+jets
- ZZ+jets
- $t\bar{t}+W/Z$, tZj

- Main contribution: WZ/γ^*+jets
- Suppressed by a veto on additional, looser leptons
- Estimated from MC and cross checked in a control region where additional lepton is required

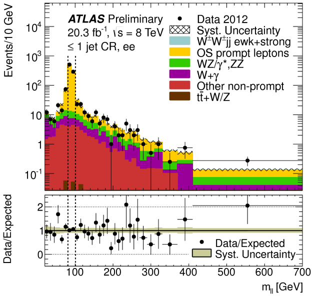


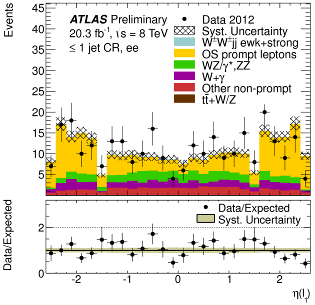


Photon conversions

Prompt photon conversion: $W\gamma$
$\rightarrow$ estimated from MC
Charge mis-identification due to bremsstrahlung with conversion: Z/γ^*+jets or $t\bar{t}$
$\rightarrow$ estimated from a control-region with two oppositely charged electrons by applying charge-flip rates determined in $Z \rightarrow ee$ events

Cross check in $\leq$ 1 jet control region:





Other non-prompt leptons

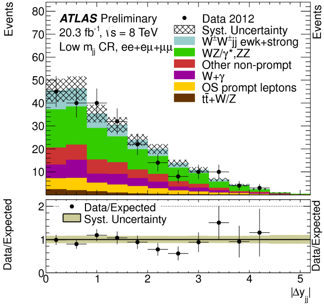
Jets mis-reconstructed as leptons

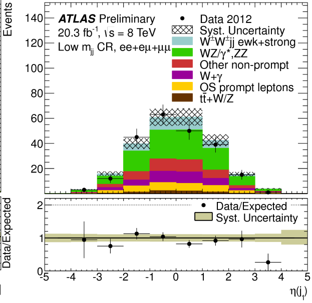
or W+jets

leptons from hadron decays in jets

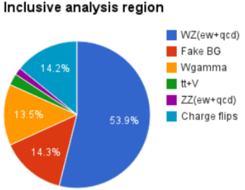
- Suppressed by requiring high quality, isolated leptons
- Contribution is estimated by applying fake rates to a dijet control region

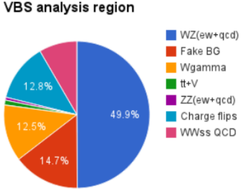
Cross check in low M_{jj} control region:





Event yields

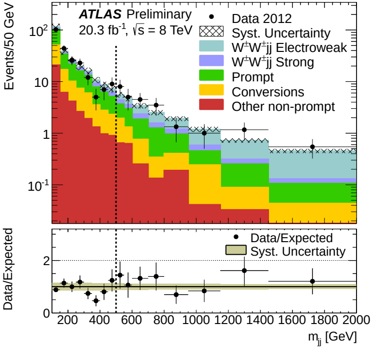




Process	Inclusive Region	VBS Region
Prompt backgrounds	11.7 ± 1.6	8.3 ± 1.3
Conversions	5.6 ± 1.1	4.0 ± 0.9
Fake leptons	2.3 ± 0.9	2.3 ± 0.7
$W^{\pm}W^{\pm}jj$-QCD	(is signal)	1.3 ± 0.1
Background total	21 ± 2.4	16 ± 2
Expected signal	22 ± 1.5	14 ± 1
Data	50	34

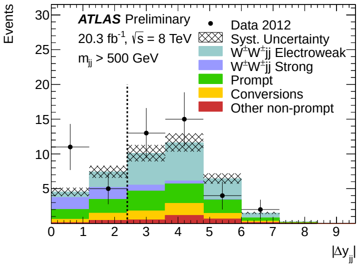
Kinematics of jets

Tagging jets invariant mass



(Inclusive region before m_{jj} cut)

Rapidity difference



(VBS signal region before Δy_{jj} cut)

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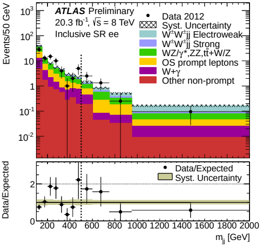
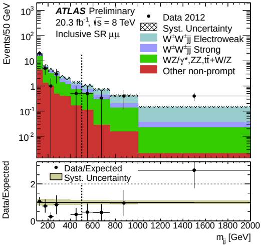
Invariant mass split by channel

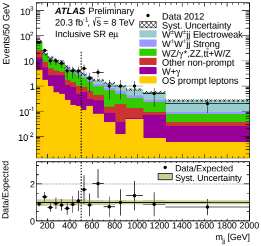
Inclusive region before M_{jj} cut



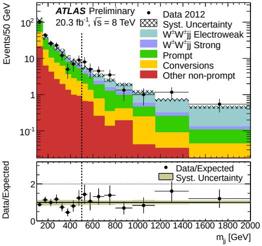
ee



$\mu\mu$



eμ



all

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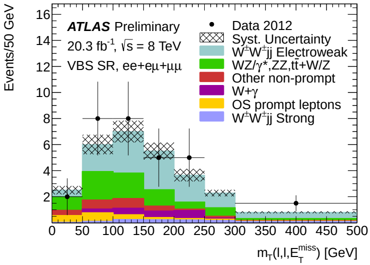
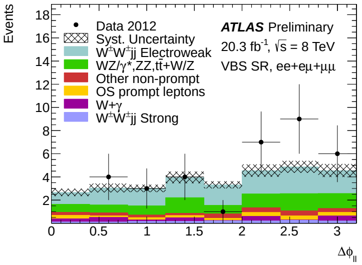
Kinematics of leptons

Transverse mass of leptons, $E_{\mathrm{T}}^{\mathrm{miss}}$



(VBS signal region)

Lepton $\Delta\phi$



(VBS signal region)

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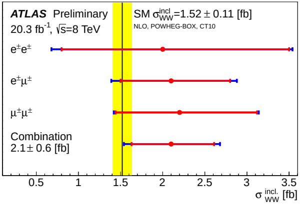
Results

Extract cross section by fitting a likelihood function to the observed data

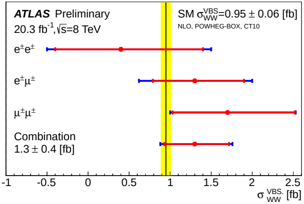
Total cross sections

	Observed	Significance
EWQCD (incl. Region)	2.1 ± 0.5 (stat.) ± 0.3 (syst.) fb	$4.5\,\sigma$
EW (VBS Region)	1.3 ± 0.4 (stat.) ± 0.2 (syst.) fb	$3.6\,\sigma$

Comparison to theory prediction:



$\sigma_{WW}^{\text{incl}}$ [fb]



σ_{WW}^{VBS} [fb]

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Anomalous quartic gauge couplings

Model effects of new physics via higher-order operators

Effective field theory ansatz:

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{d>4} \sum_{i} \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}.$$

⇒ Introduce additional higher-dimensional (d) operators $\mathcal{O}$ which modify the electroweak gauge couplings, suppressed by scale of new physics Λ

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Electroweak chiral Lagrangian

In analogy to chiral perturbation theory in QCD:
Break electroweak $SU(2)_L \otimes U(1)_Y$ to $U(1)_Q$ and custodial symmetry $SU(2)_C$

$\Rightarrow$ Electroweak chiral Lagrangian with the operators

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

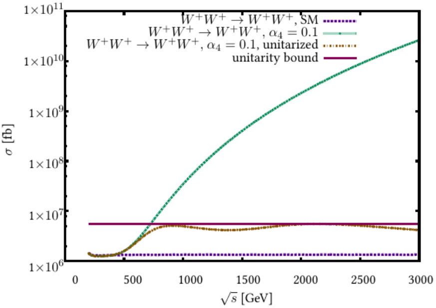
and

$$\mathcal{L}_5 = \alpha_5(\mathrm{tr}[\mathbf{V}_\mu \mathbf{V}^\mu])^2$$

with parameters α_4 and α_5

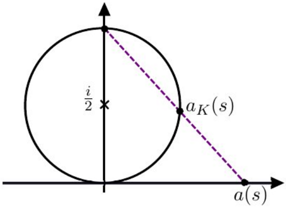
Unitarity

In general, additional operator terms lead to unitarity violation of the amplitude:



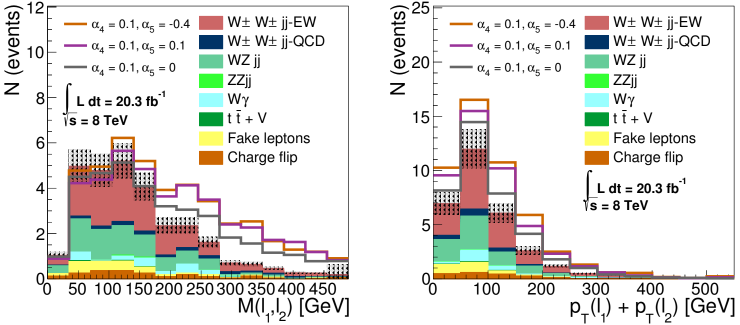
$\Rightarrow$ apply unitarization procedure to retain physical events

unitarization with K-matrix method (projection of amplitude on Argand circle) as implemented in WHIZARD [2, 3]



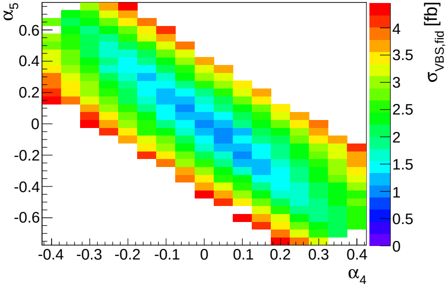
Influence on kinematics

Anomalous quartic gauge couplings modify the kinematics of the decay products of the gauge bosons:



Limits on aQGC

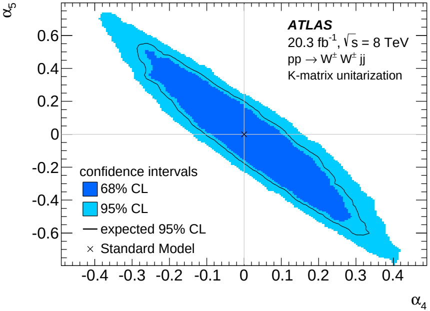
Set limits on α_4, α_5 in the VBS region of the $W^{\pm}W^{\pm}jj$-EW analysis



Use fiducial cross sections with anomalous couplings to derive confidence intervals

Limits on aQGC

Set limits on α_4, α_5 in the VBS region of the $W^\pm W^\pm jj$-EW analysis



Use fiducial cross sections with anomalous couplings to derive confidence intervals

One-dimensional limits at 95 % C.L. :

$$\alpha_4 \in [-0.139, 0.157]$$

$$\alpha_5 \in [-0.229, 0.244]$$

⇒ First limits on aQGC with massive electroweak vector bosons

Interpretation in terms of resonances

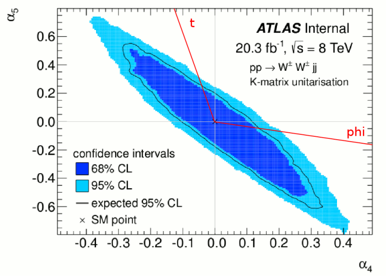
Anomalous couplings can be interpreted in terms of models such as:

- Extended Higgs sectors (2HDM, etc)
- Composite Higgs, Technicolor

or simplified models of generic resonances ordered by spin, isospin, with different masses, couplings, and widths [4]:

resonance	spin J	isospin I	Γ/Γ_0	$\Delta\alpha_4 / \alpha$	$\Delta\alpha_5 / \alpha$
ϕ	0	2	1	1/4	-1/12
t	2	2	1/30	-5/8	35/8

Interpretation in terms of resonances



- ϕ resonance (spin = 0, isospin = 2): $\frac{M}{g} < 130\,\text{GeV}$ excluded
- t resonance (spin = isospin = 2): $\frac{M}{g} < 90\,\text{GeV}$ excluded

Prospects at 14 TeV

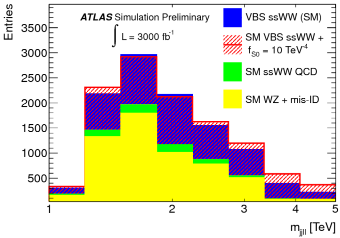
Estimate sensitivity to anomalous couplings in $W^{\pm}W^{\pm}jj$-EW at High-Luminosity LHC ($\sqrt{s} = 14\,\text{TeV}$, $\mathcal{L} = 3000\,\text{fb}^{-1}$)
$\Rightarrow$ Use performance projections for the future ATLAS detector in terms of

- efficiency (trigger, particle identification, flavor tagging)
- resolutions (momentum, energy)

Backgrounds: MC for WZ, WWss-QCD.
WZ background is scaled by a factor 2 to account for additional background contributions from charge-flip, jet fakes, photon conversion

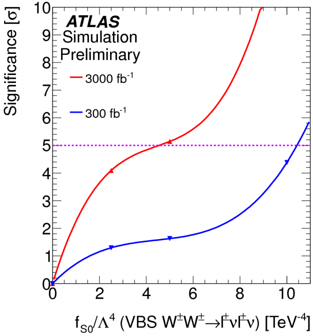
Selection:
- 2 leptons with same charge, $p_T > 25$ GeV
- ≥ 2 jets, $p_T > 50$ GeV
- $m(jj) > 1000$ GeV

Prospects at 14 TeV [5]



m_{lljj} with a signal of $f_{S,0} = 10\ \text{TeV}^{-4}$

(corresponding to $\alpha_4 = 0.0046$ and $\alpha_5 = -0.0023$ for $\Lambda = 1$ TeV)



signal significance (in standard deviations) as a function of f_{S0}

Conclusions

- Scattering of massive electroweak gauge bosons is a crucial process to study the electroweak gauge interactions and the mechanism of electroweak symmetry breaking
- First evidence of $W^{\pm}W^{\pm}$ scattering and $W^{\pm}W^{\pm}jj$ production
  $\Rightarrow$ Measurements in good agreement with the SM prediction
- First limits on anomalous couplings of massive electroweak gauge bosons of parameters α_4, α_5

Backup

References

ATLAS Collaboration, *Evidence for Electroweak Production of $W^{\pm}W^{\pm}jj$ in pp Collisions at $\sqrt{s} = 8$ TeV with the ATLAS Detector*, Phys. Rev. Lett. **113** (2014) 141803, arXiv:1405.6241 [hep-ex]. http://link.aps.org/doi/10.1103/PhysRevLett.113.141803.

W. Kilian, T. Ohl, and J. Reuter, *WHIZARD: Simulating Multi-Particle Processes at LHC and ILC*, Eur.Phys.J. **C71** (2011) 1742, arXiv:0708.4233 [hep-ph].

A. Alboteanu, W. Kilian, and J. Reuter, *Resonances and Unitarity in Weak Boson Scattering at the LHC*, JHEP **0811** (2008) 010, arXiv:0806.4145 [hep-ph].

J. Reuter, W. Kilian, and M. Sekulla, *Simplified Models for New Physics in Vector Boson Scattering - Input for Snowmass 2013*, arXiv:1307.8170 [hep-ph].

Studies of Vector Boson Scattering And Triboson Production with an Upgraded ATLAS Detector at a High-Luminosity LHC, Tech. Rep. ATL-PHYS-PUB-2013-006, CERN, Geneva, Jun, 2013.

Available experimental constraints on 4 electroweak gauge boson couplings

- No observation of processes with quartic vertex of massive electroweak gauge bosons before the presented measurement
- No constraints on massive gauge boson quartic couplings
- Constraints on anomalous quartic gauge couplings with photons exist:

Experiment	channel	Publication	year
CMS	WWγ, WZγ	CMS-PAS-SMP-13-009	2013
CMS	WW$\rightarrow \gamma\gamma$	JHEP07 (2013) 116	2013
D0	$\gamma\gamma \rightarrow WW$	Phys Rev D **88** 012005	2013
L3	$WW\gamma$	Phys. Lett. B 527:29-38, 2002	2002
OPAL	$WW\gamma$	Phys. Lett. B580:17-36, 2004	2004
DELPHI	$WW\gamma$	Eur. Phys. J C31:139-147, 2003	2003

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Analysis event selection

Leptons
- exactly 2
- well isolated, tight quality cuts
- $p_{\mathrm{T}} > 25\,\mathrm{GeV}$, $|\eta| < 2.5$
- $m_{\ell\ell} > 20\,\mathrm{GeV}$

Jets
- at least 2
- $p_{\mathrm{T}} > 30\,\mathrm{GeV}$, $|\eta| < 4.5$

$E_{\mathrm{T}}^{\mathrm{miss}} > 40\,\mathrm{GeV}$

Veto
- events with additional softer and less isolated leptons
- events with b-tagged jets

VBS cuts
- $m_{jj} > 500\,\mathrm{GeV}$
- $|\Delta y_{jj}| > 2.4$ (in VBS region)