Probing quartic gauge boson couplings at the LHC with the vector boson fusion, vector boson scattering and triboson processes

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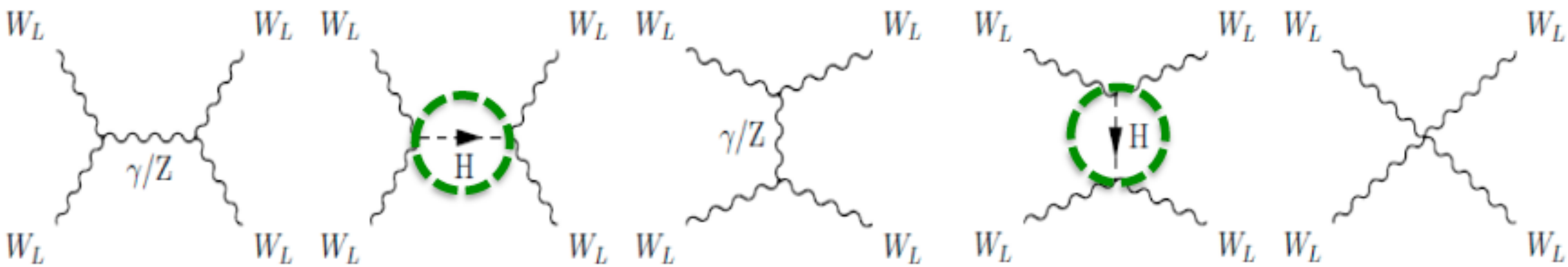
Outline

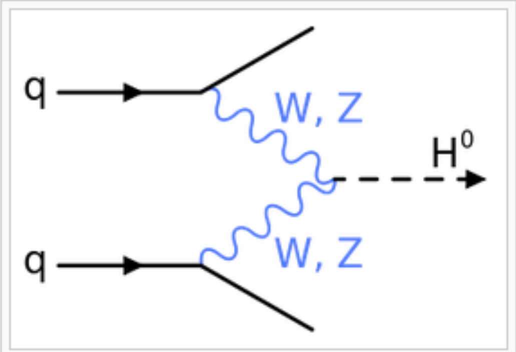
- Vector boson fusion (VBF):
  - VBF Z+2jets
    - ATLAS: JHEP 04 (2014) 031
    - CMS: Eur. Phys. J. C 75 (2015) 66
- Vector boson scattering (VBS):
  - $W^{\pm}W^{\pm}jj$
    - ATLAS: Phys. Rev. Lett. 113, 141803 (2014)
    - CMS: Phys. Rev. Lett. 114, 051801 (2015)
- Triboson measurements
  - $WW\gamma/WZ\gamma$ (CMS: Phys. Rev. D 90, 032008 (2014))
  - $W\gamma\gamma$ (ATLAS: arXiv:1503.03243)
- Exclusive WW
  - CMS: JHEP 1307 (2013) 116

Introduction

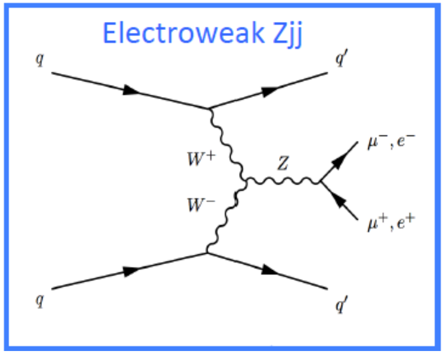
- **The Higgs mechanism ≠ a Higgs boson !**
- Vector boson self-coupling is a fundamental prediction of the Electroweak Sector of SM
- Its study is important to understanding electroweak symmetry breaking mechanism

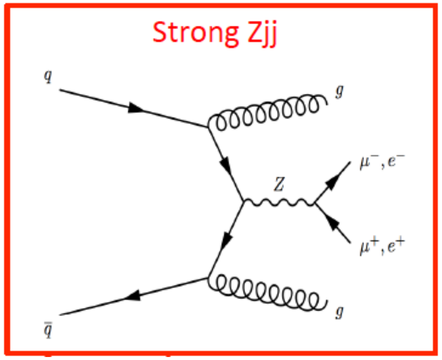


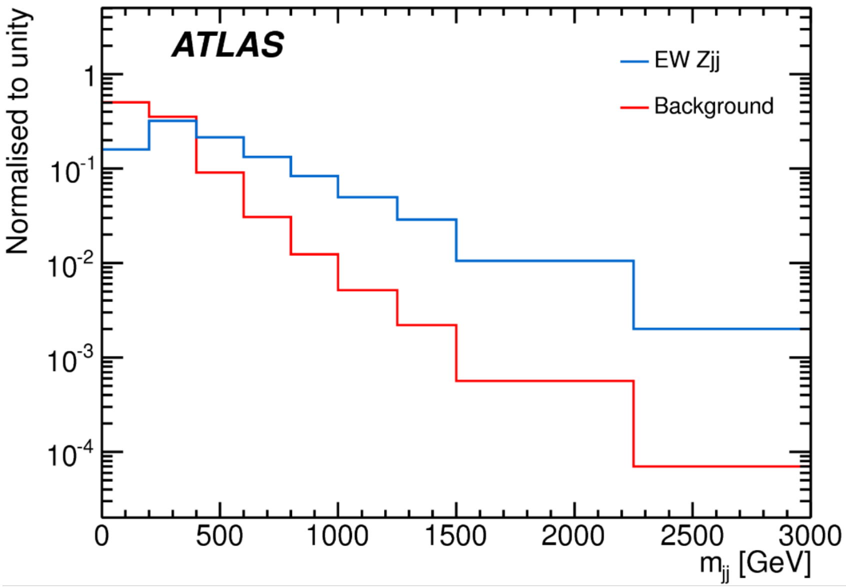
VBF Z



- Two main Higgs production mechanism
  - Gluon-gluon fusion 4
  - Vector boson fusion (VBF)
  - Higgs VBF production mechanism has not been confirmed by experimental measurements with 5 sigma significance
  - Important to confirm VBF production mechanism in VBF Z+2jets channel

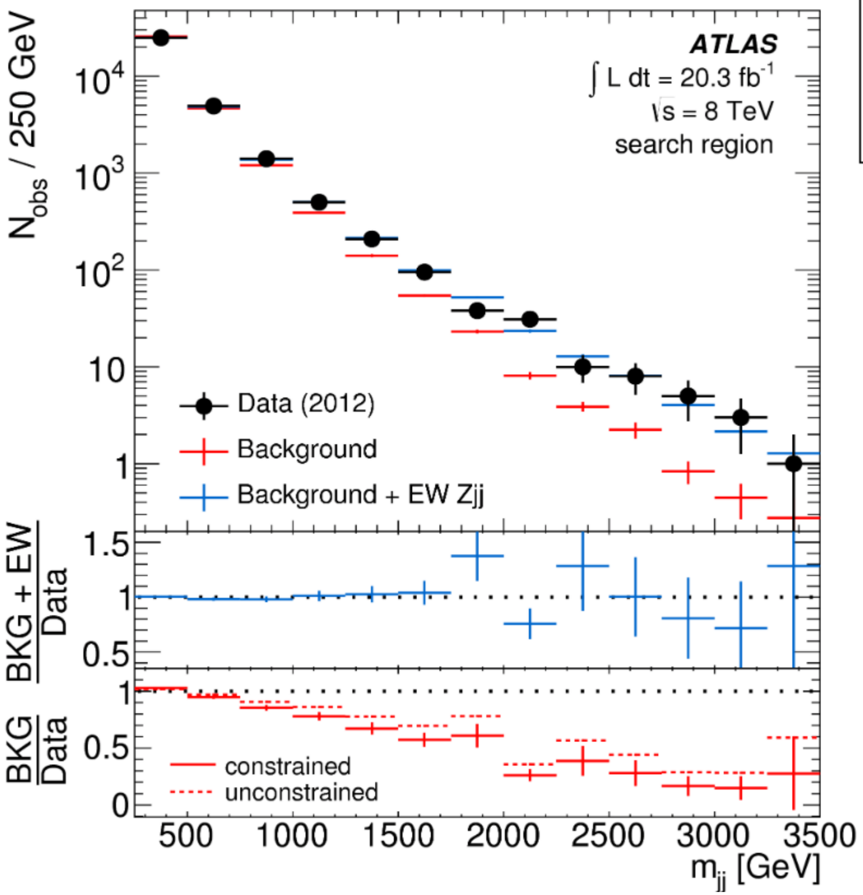






VBF Z (ATLAS)

Background-only hypothesis
Rejected at greater than
5σ significance



Object selections:

- two electron/muon
- two high-p_T forward jets

Kinematic selections:

- $81 < m_{ll} < 101$ GeV
- $p_T^{ll} > 20$ GeV
- $p_T^{balance} < 0.15$
- $N_{jet}^{gap} = 0$
- $m_{jj} > 250$ GeV

	Electron+muon
Data	32186
MC predicted $N_{\rm bkg}$	$32600 \pm 2600 \,^{+3400}_{-4000}$
MC predicted $N_{\rm EW}$	$1333 \pm 50 \pm 40$
Fitted $N_{\rm bkg}$	$30530 \pm 216 \pm 40$
Fitted $N_{\rm EW}$	$1657 \pm 134 \pm 40$

Measured EWK Zjj cross section

$$\sigma_{\rm EW} = 54.7 \pm 4.6\,({\rm stat})\,^{+9.8}_{-10.4}\,({\rm syst}) \pm 1.5\,({\rm lumi})\ {\rm fb}.$$

Powheg Box predictions at next-to-leading-order (NLO) accuracy in perturbative QCD

.

$$46.1 \pm 0.2\,({\rm stat})\,^{+0.3}_{-0.2}\,({\rm scale}) \pm 0.8\,({\rm PDF}) \pm 0.5\,({\rm model})\ {\rm fb},$$

VBF Z (CMS)

Eur. Phys. J. C 75 (2015) 66,

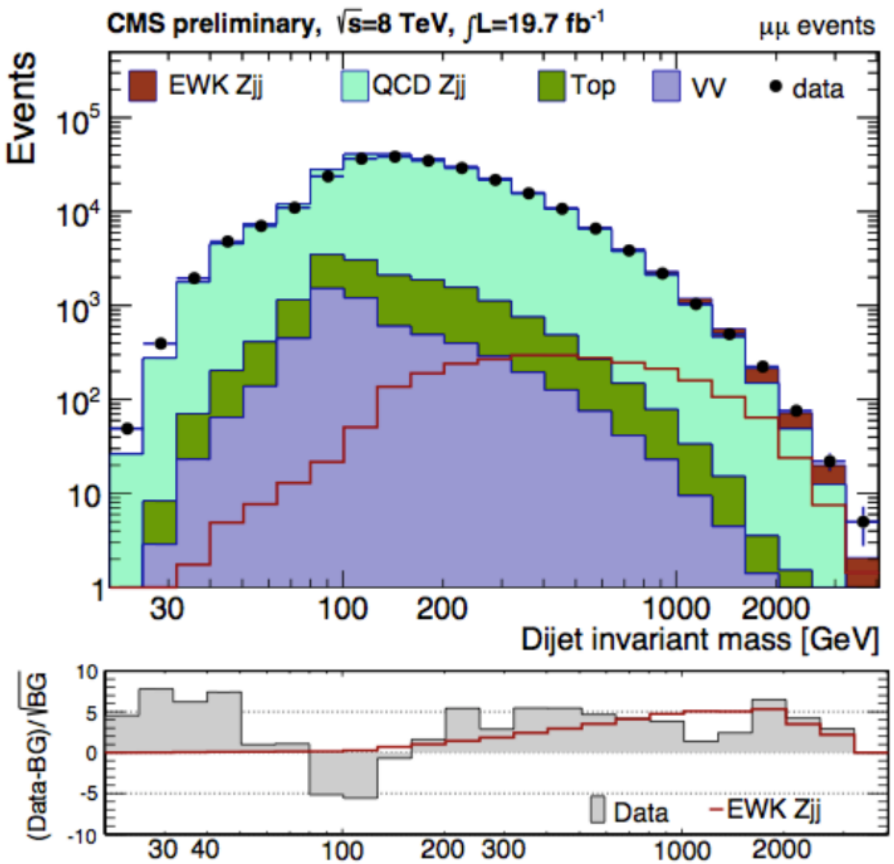
- Use boosted decision tree (BDT) technique to improve sensitivity

M_{ll}>50 GeV,
p_{Tj}>25 GeV, and $|\eta_j|$<5, M_{jj}>120 GeV,

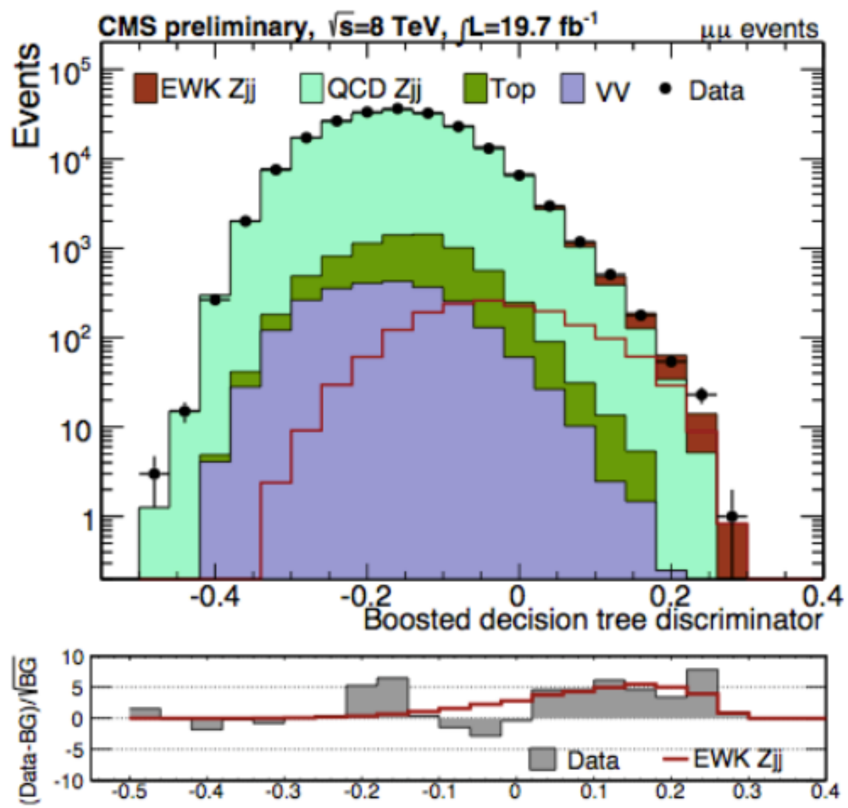
Measured σ_{EW}(lljj)=174± 15 (stat) ± 40 (syst) fb

5σ significance

Mjj spectrum

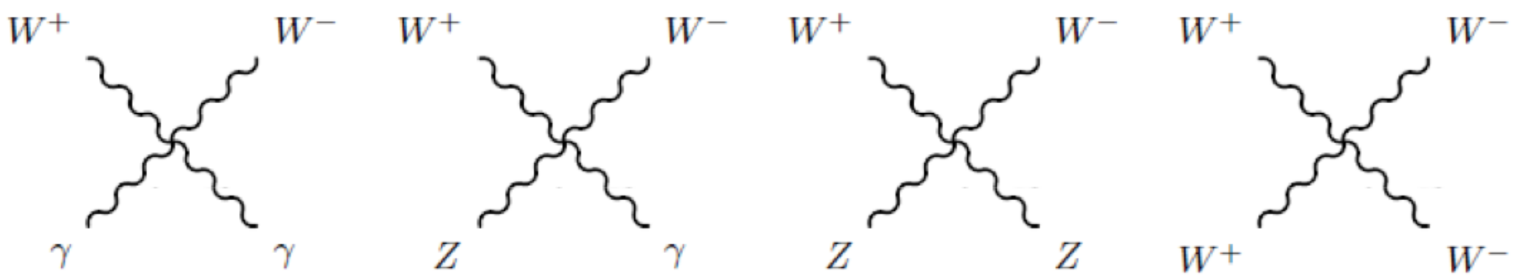


BDT output spectrum



Quartic Gauge Boson Couplings

- Reminder of **Quartic Gauge Boson Couplings (QGCs)**
  - SM model predicts gauge boson self coupling
    - Four gauge boson vertex:
      - WWγγ , WWZγ , WWWW, WWZZ, ZZZZ …



- QGCs can be studied in
  - Tri-boson processes
  - Vector boson scattering processes
  - Exclusive γγ->WW process

Modeling of aQGCs: Dim 8 EFT models

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

Higgs field

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

Higgs - Gauge boson field(L_M)

$$\mathcal{L}_{M,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$
$$\mathcal{L}_{M,1} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$
$$\mathcal{L}_{M,2} = \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$
$$\mathcal{L}_{M,3} = \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$
$$\mathcal{L}_{M,4} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\mu\Phi\right] \times B^{\beta\nu}$$
$$\mathcal{L}_{M,5} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\nu\Phi\right] \times B^{\beta\mu}$$
$$\mathcal{L}_{M,6} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\nu} D^\mu\Phi\right]$$
$$\mathcal{L}_{M,7} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu} D^\nu\Phi\right]$$

Gauge boson field (L_T)

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

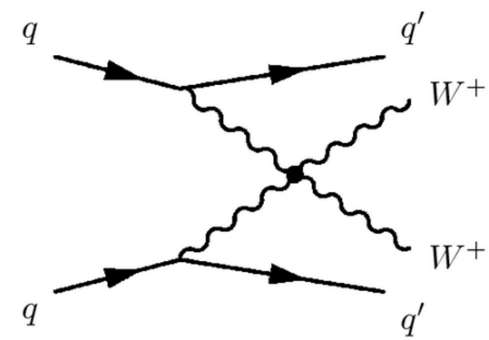
VVjj final state	ZZ	Zγ γγ	W+W- WZ	W±W±	Wγ	
VVV final state	ZZZ	ZZγ Zγγ	WWZ WZZ	WWW	WVγ	γγγ
$f_{S,0}$, $f_{S,1}$	✔		✔	✔		
$f_{M,0}$, $f_{M,1}$, $f_{M,6}$, $f_{M,7}$	✔	✔	✔	✔	✔	
$f_{M,2}$, $f_{M,3}$, $f_{M,4}$, $f_{M,5}$	✔	✔	✔		✔	
$f_{T,0}$, $f_{T,1}$, $f_{T,2}$	✔	✔	✔	✔	✔	✔
$f_{T,5}$, $f_{T,6}$, $f_{T,7}$	✔	✔	✔		✔	✔
$f_{T,8}$, $f_{T,9}$	✔	✔				✔

O.J.P.Eboli, et.al. Phys.Rev.D74:073005,2006

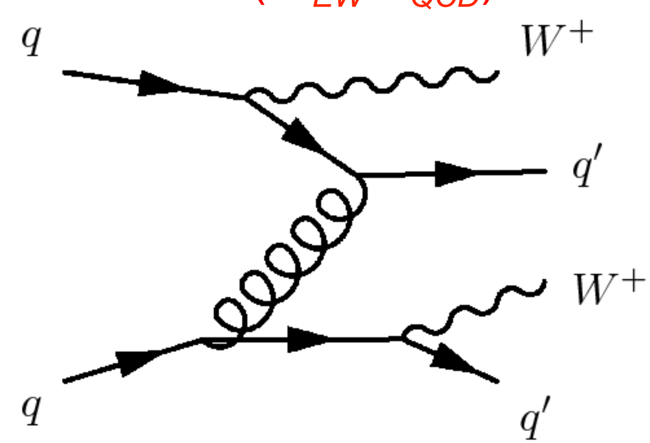
The measurement of Vector boson scattering processes

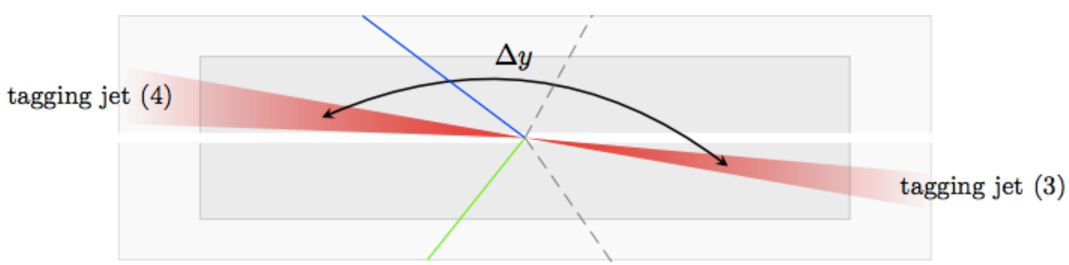
- Vector boson scattering (VBS) is one of the most promising process to study QGCs.
  - Diboson + two forward jets in event topology
- The scattering of longitudinally polarized vector bosons
  - violates unitarity at ~1TeV without higgs
- Important to check
  - whether Higgs boson unitarizes it fully or only partially
- The first VBS analysis :Same sign WW
  - Sensitive to WWWW vertex
  - Final state: W^+W^+jj or W^-W^-jj

Electroweak
W±W±jj $O(\alpha^6_{EW})$



QCD W±W±jj
$O(\alpha^4_{EW}\alpha^2_{QCD})$





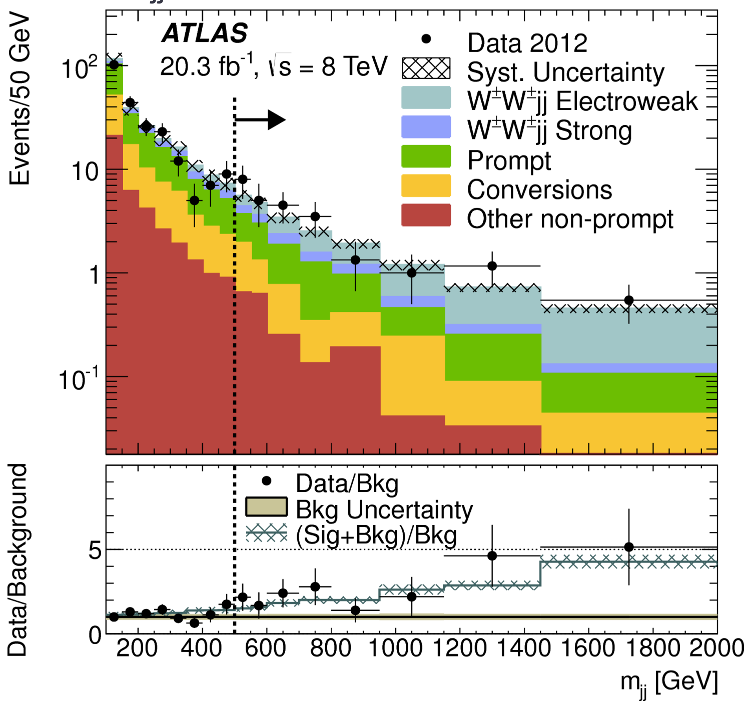
Electroweak W±W±jj (ATLAS)

Object selection

- same sign di-leptons
- $p_{T,l}$>25 GeV
- Two high pT jets

Inclusive QCD+EWK W±W±jj measurement

- M_{ll}>20GeV
- $|M_{ee}-M_Z|$>10GeV
- M_{jj}>150GeV

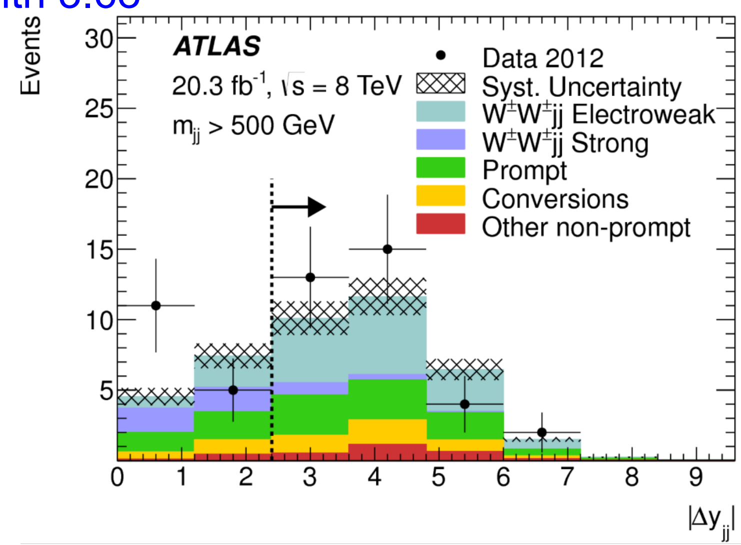


Measured σ_{EW+QCD}(W±W±jj)=2.1 ± 0.5(stat) ± 0.3(syst) fb
Predicted σ_{EW+QCD}(W±W±jj)=1.52 ± 0.11fb
Observed with 4.5σ

EWK signal only measurement

- M_{ll}>20GeV
- $|M_{ee}-M_Z|$>10GeV
- M_{jj}>500 GeV
- $|\Delta\eta_{jj}|$ >2.4

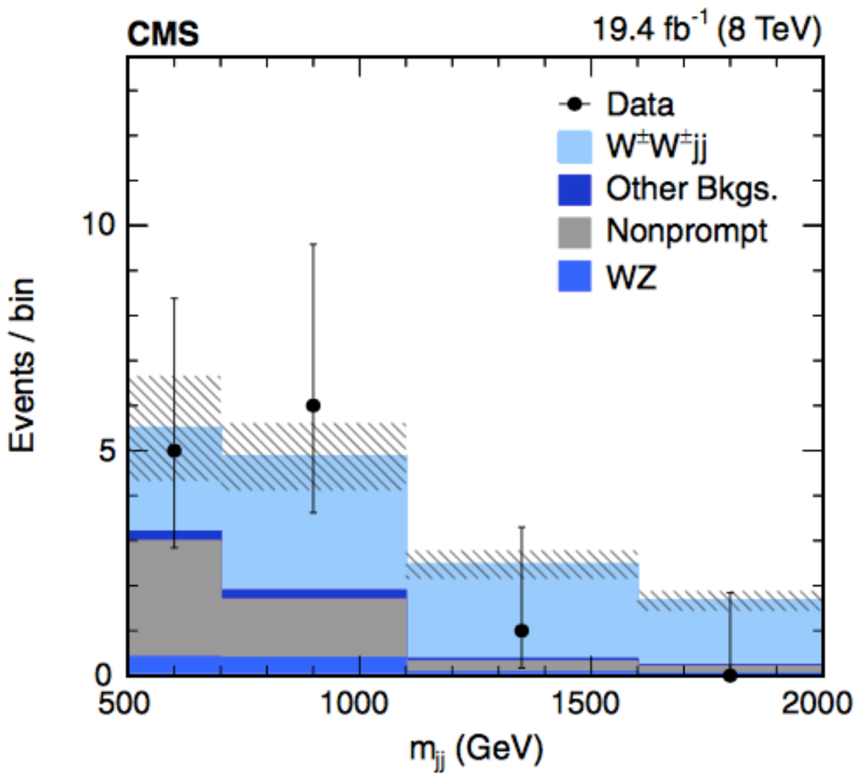
Measured σ_{EW}(W±W±jj)=1.3 ± 0.4(stat) ± 0.2(syst) fb
Predicted σ_{EW}(W±W±jj)=0.95 ± 0.06 fb
Observed with 3.6σ



SM predictions are calculated using PowhegBox at NLO accuracy in perturbative QCD

Electroweak $W^{\pm}W^{\pm}jj$ (CMS)

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



Object selection

- same sign di-leptons
- p_{Tj}>25 GeV, and $|\eta_j|$<5
- Two high pT forward jets
- $E_{T,miss}$ >40GeV

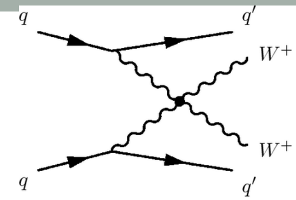
EWK signal region

- M_{ll}>20GeV
- $|M_{ee}-M_Z|$>10GeV
- M_{jj}>500 GeV
- $|\Delta\eta_{jj}|$ >2.4

Measured $\sigma_{EW}(W^{\pm}W^{\pm}jj)$= $4.0^{+2.4}_{-2.0}\,(\text{stat})^{+1.1}_{-1.0}\,(\text{syst})\,\text{fb}$

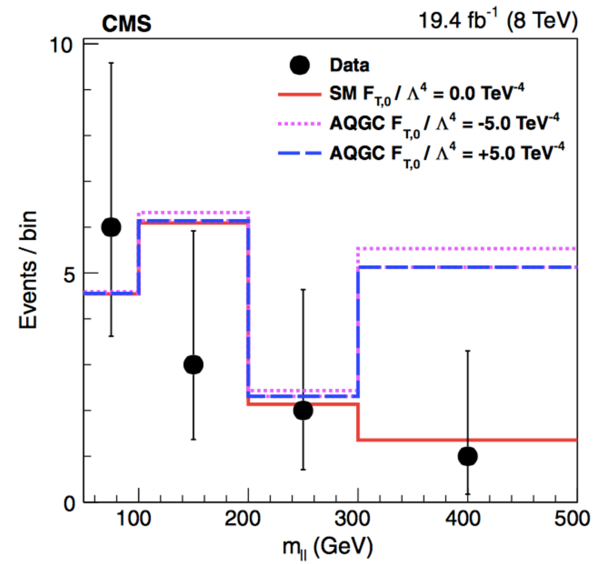
Predicted $\sigma_{EW}(W^{\pm}W^{\pm}jj)$=5.8 ± 1.2 fb.
Observed with 2.0 σ

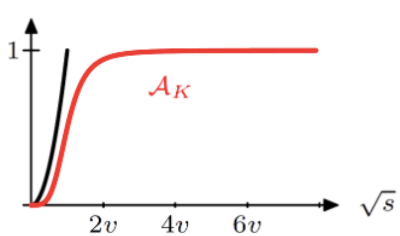
aQGCs limits from VBS process

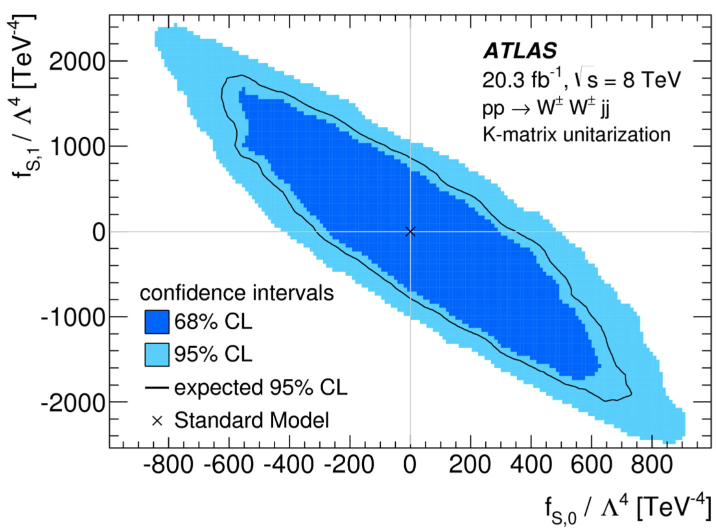


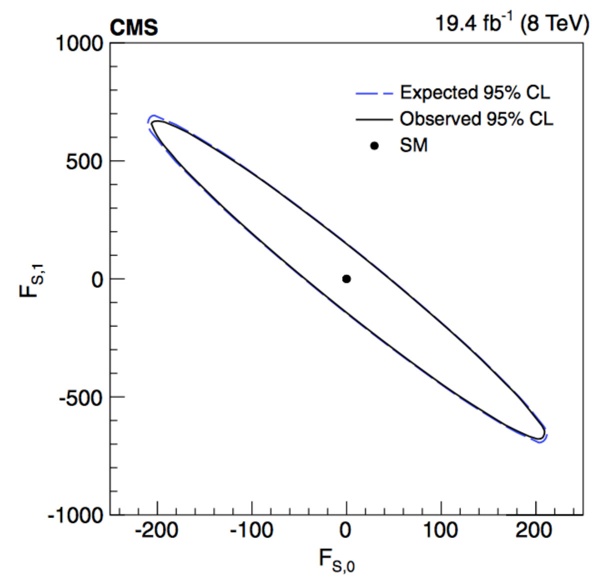
- FS0 and FS1 in Dim 8 EFT model is related to the Higgs field
- Naive EFT-predicted aTGC/aQGCs amplitudes
  - disrespect the gauge symmetry
  - and violate the unitarity once the √s goes sufficiently
- CMS result is not unitarized
- ATLAS use K matrix unitarization
  - Preserve unitarity in high sqrt(s)
  - Unitarization with the k-matrix approach (arxiv: 0806.4145)
  - K-matrix amplitude

$$|\mathcal{A}_K(s)|^2 \xrightarrow{s\to\infty} 1$$





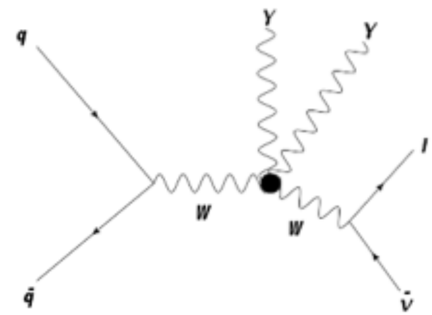


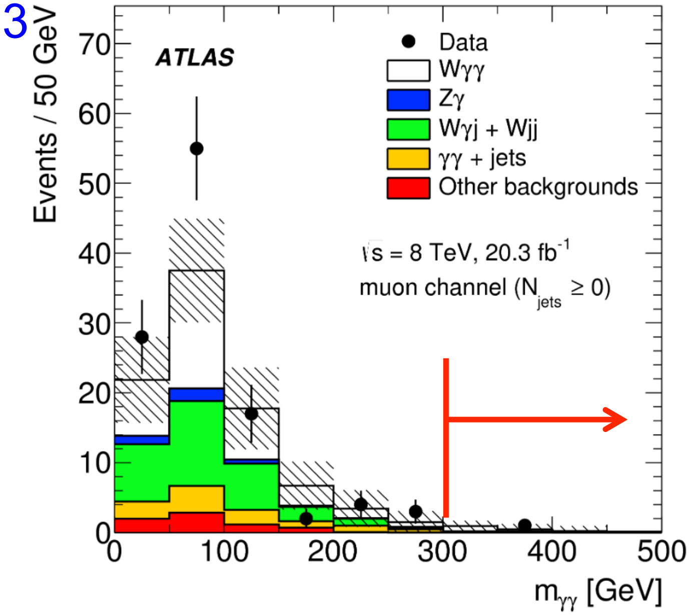


Wγγ (ATLAS)

arXiv:1503.03243

- Wγγ process is sensitive to WWγγ QGCs Vertex.
- Other contributions from:
  - ISR photons
  - FSR photons
  - Photon from TGC vertex
  - Photon from jet fragmentations





- MCFM is used for NLO Wγγ SM predicted cross section.
  - The measured cross section in inclusive case is 1.9 σ higher than predictions
  - Better agreement in exclusive case

*veto events with hard jets with pT>30GeV in exclusive measurement

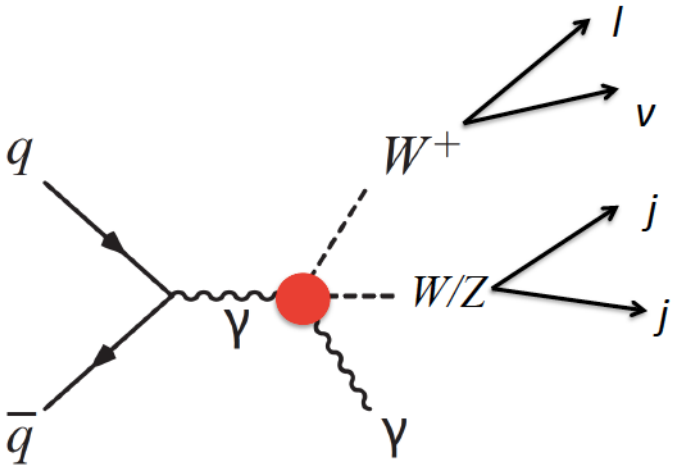
	Measured cross section (fb)	SM prediction (fb)
Inclusive Wγγ	6.1 ± 1.1(stat) ± 1.2(syst)+- 0.2 (lumi)	2.90±0.16
Exclusive Wγγ With hard jet veto	2.9 ± 0.8(stat) ± 1.0(syst)+- 0.1 (lumi)	1.88±0.2

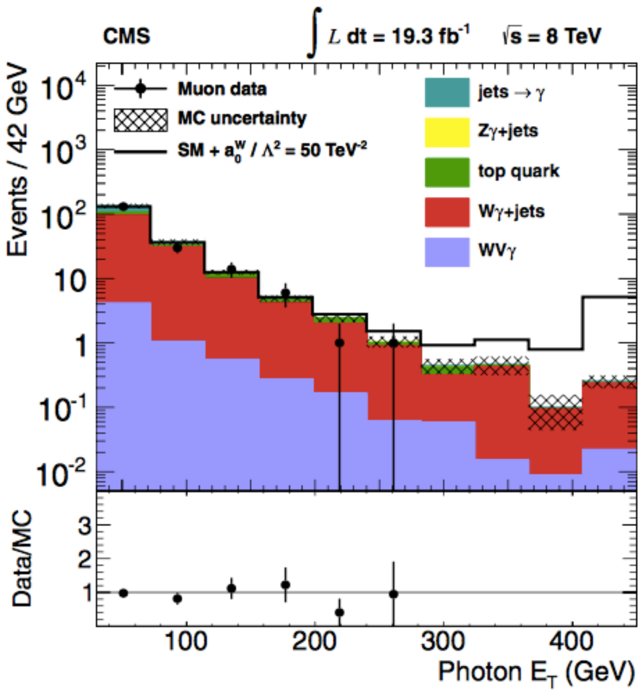
See Vasiliki's talk on Wednesday electroweak physics sections for more details

WVγ (CMS)

Phys. Rev. D 90, 032008 (2014)

- The selected data events is dominated by Wγ+jets
  - not enough signal statistics for measurements
- 95% CL cross section upper limit is set at 311 fb
  - The limit is 3.4 times larger than SM predictions





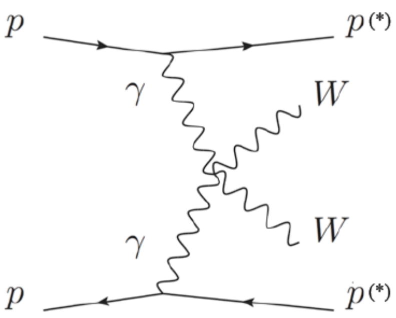
Event selection highlight

- ❑ One good lepton
- ❑ One good photon
- ❑ Two high pT jets
- ❑ 70GeV <Mjj<100GeV

Major BG in WVγ

Wγ+jets
WV +jet , jet fake as γ
Multijets

Exclusive γγ->WW (CMS)

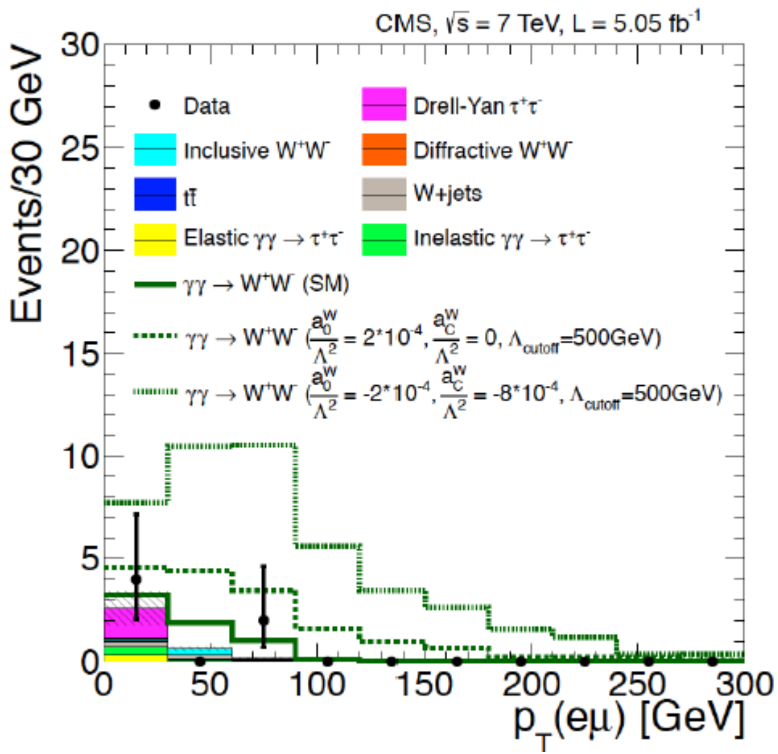


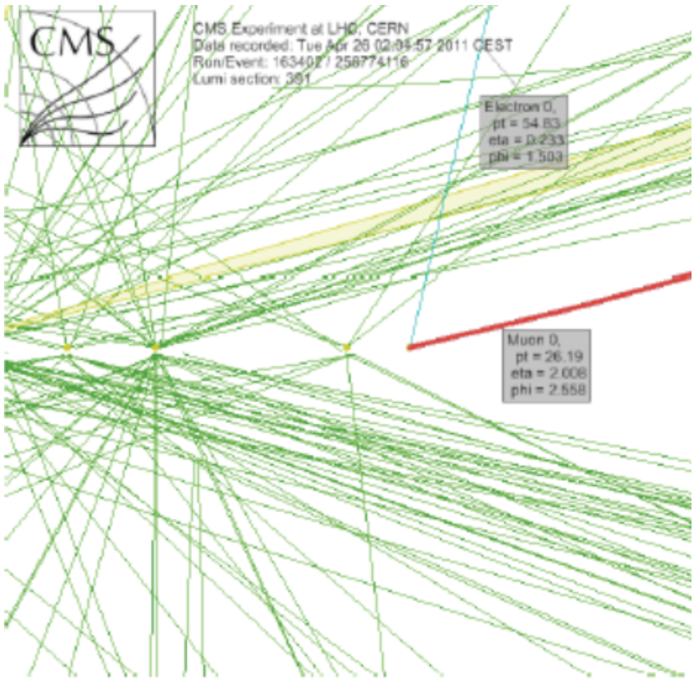
- Exclusive γγ production without color exchange
  - Very clean event signature (two tracks vertex)
  - Require No extra track on di-lepton vertex

$$\sigma(\mathrm{pp} \to \mathrm{p}^{(*)}\mathrm{W}^+\mathrm{W}^-\mathrm{p}^{(*)} \to \mathrm{p}^{(*)}\mu^\pm \mathrm{e}^\mp \mathrm{p}^{(*)}) = 2.2^{+3.3}_{-2.0}\,\mathrm{fb}$$

$$-4.0 \times 10^{-6} < a_0^W/\Lambda^2 < 4.0 \times 10^{-6}\,\mathrm{GeV}^{-2}$$
$$-1.5 \times 10^{-5} < a_C^W/\Lambda^2 < 1.5 \times 10^{-5}\,\mathrm{GeV}^{-2}$$

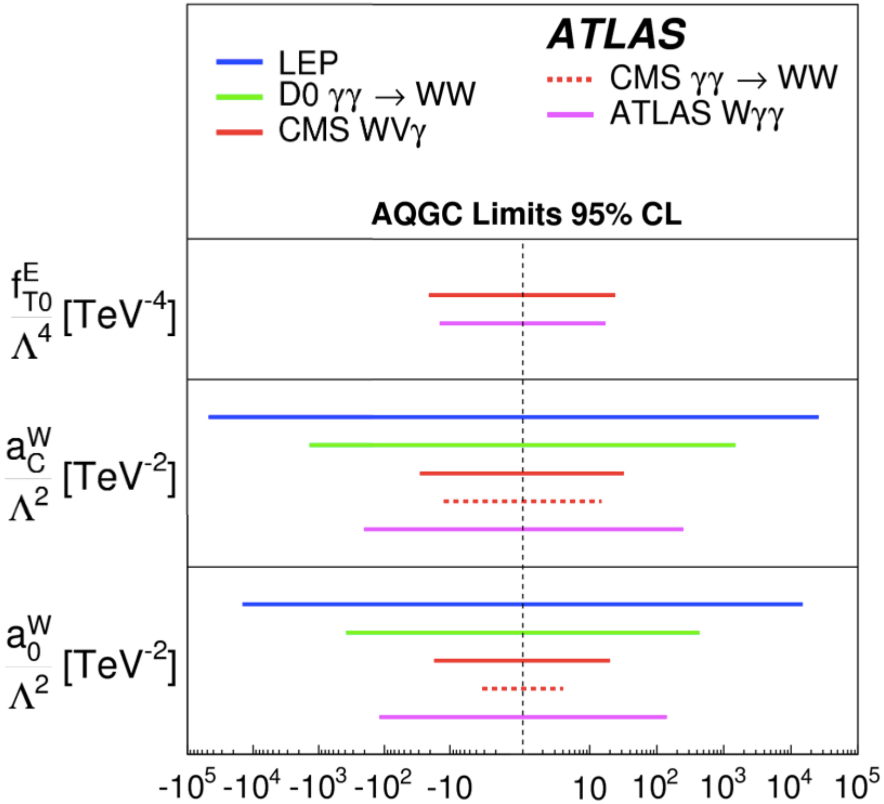
1σ significance





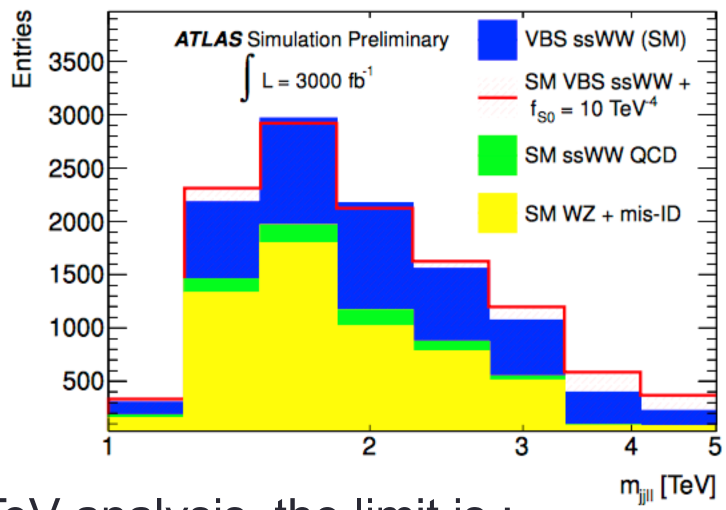
aQGCs limits from tri-boson and Exclusive γγ->WW processes

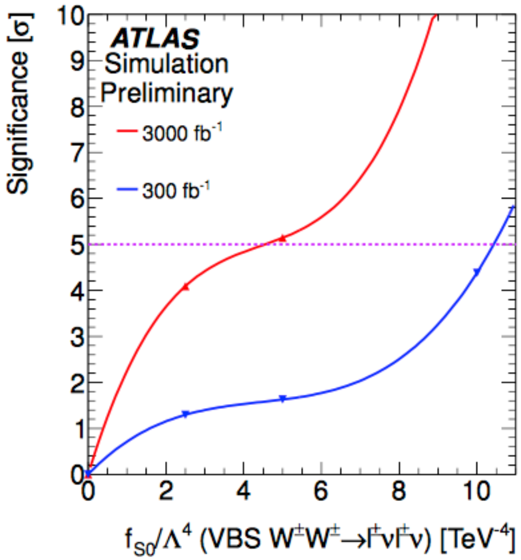
- Tri-boson processes and γγ->WW are sensitive to
  - F_T operators (Gauge boson field)
  - F_M operators (Higgs-Gauge field)
    - $F_{M,2}$, $F_{M,3}$ can be converted to LEP convention a_C^W a_0^W



aQGCs limits obtained by ATLAS/CMS are orders of magnitude more stringent than the best limits obtained at LEP.

Prospects for LHC upgrade





- At 8TeV analysis, the limit is :
  - $f_S/\Lambda 4$ ~O(1000), $f_T/\Lambda 4$ ~O(10)
- aQGCs sensitivity is orders of magnitudes better in 13TeV and in HI-LHC upgrade

Channel	Parameter	(95% CL limits) 14TeV, 300 fb^{-1}	(95% CL limits) 14TeV, 3000 fb^{-1}
$W^\pm W^\pm jj$	$f_{S,0}/\Lambda^4(TeV^{-4})$	[−6.8, 6.8]	[−0.8, 0.8]
WZ jj	$f_{T,1}/\Lambda^4(TeV^{-4})$	[−0.7, 0.7]	[−0.3, 0.3]
Zγγ	$f_{T,9}/\Lambda^4(TeV^{-4})$	[−0.9, 0.9]	[−0.3, 0.3]

Summary

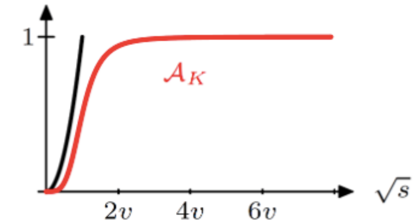
- Observation of electroweak Zjj production at LHC
  - A benchmark process for future studies of VBF processes at LHC
  - Background only hypothesis rejected at greater than 5 σ in both ATLAS and CMS

- First evidence of tri-boson and Vector boson scattering production processes.
  - Contributions of aQGCs not observed
    - limits are set on aQGCs using Dimension 8 EFT models
  - Expect aQGCs limits will improve with the upcoming 13 TeV data by order of magnitudes.
    - limits with 8TeV 20 fb^{-1} data: : $f_S/\Lambda4$ ~O(1000), $f_T/\Lambda4$ ~O(10)
    - expected limits with 300 fb^{-1} data at 14TeV : $f_S/\Lambda4$ ~O(10), $f_T/\Lambda4$ ~O(1)
    - expected limits with 3000 fb^{-1} data at 14TeV: $f_S/\Lambda4$ ~O(1), $f_T/\Lambda4$ ~O(1)

backup

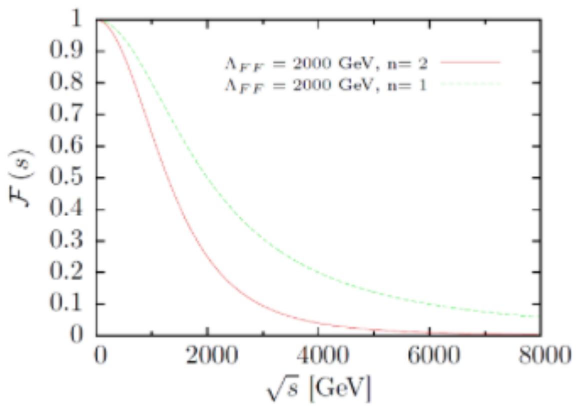
Unitarity violation treatment

- EFT-predicted aTGC/aQGCs amplitudes
  - disrespect the gauge symmetry
  - and violate the unitarity once the √s goes sufficiently high
- Unitarization with the k-matrix approach (arxiv: 0806.4145)
  - Unitarization by infinitely heavy and wide resonance
  - K-matrix amplitude $|\mathcal{A}_K(s)|^2 \xrightarrow{s\to\infty} 1$



- Form factor approach (arxiv:1205. 4231)
  - Unitarity can be preserved by introducing form-factor (FF)
  - energy-dependent form factors

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

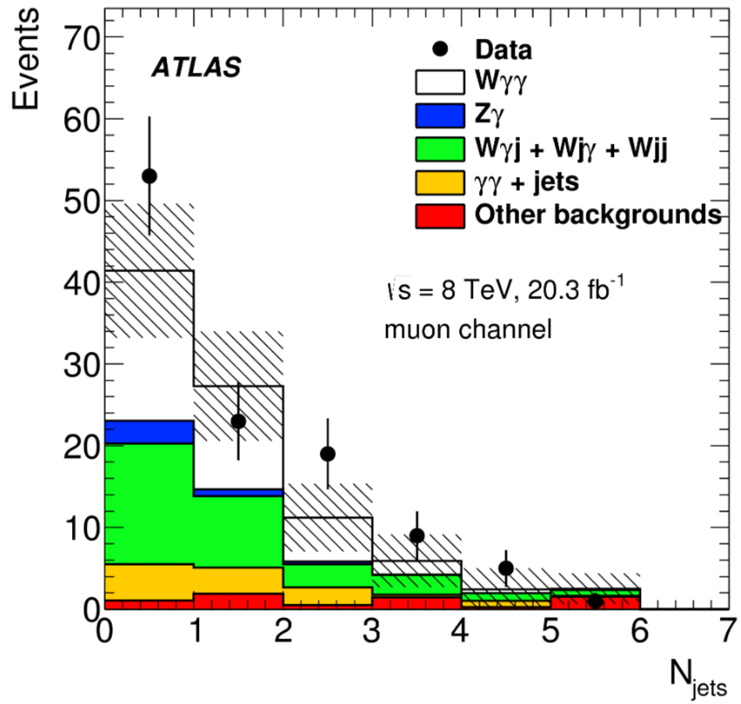


Wγγ (ATLAS)

- MCFM is used for NLO Wγγ SM predicted cross section.
  - The measured cross section in inclusive case is 1.9 σ higher than predictions
  - Better agreement in exclusive case

- Exclusive measured cross section is used for aQGCs study

Definition of the fiducial region
$p_T^\ell > 20\,GeV$, $p_T^\nu > 25\,GeV$, $\lvert\eta_\ell\rvert < 2.5$
$m_T > 40\,GeV$
$E_T^\gamma > 20\,GeV$, $\lvert\eta^\gamma\rvert < 2.37$, iso. fraction $\epsilon_h^p < 0.5$
$\Delta R(\ell,\gamma) > 0.7$, $\Delta R(\gamma,\gamma) > 0.4$, $\Delta R(\ell/\gamma,\text{jet}) > 0.3$
Exclusive: no anti-k_t jets with $p_T^{\text{jet}} > 30\,GeV$, $\lvert\eta^{\text{jet}}\rvert < 4.4$



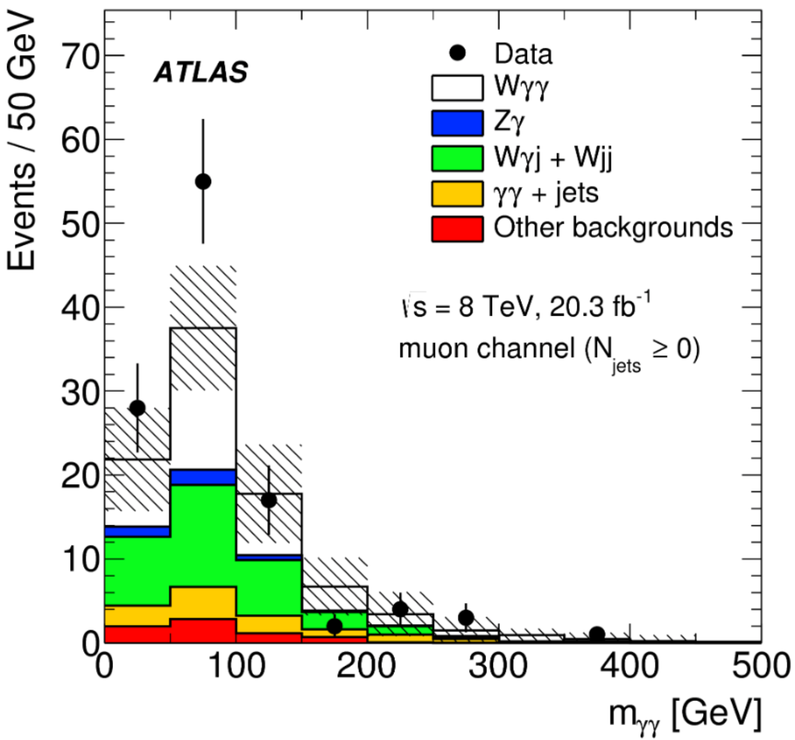
More than 3 σ significance

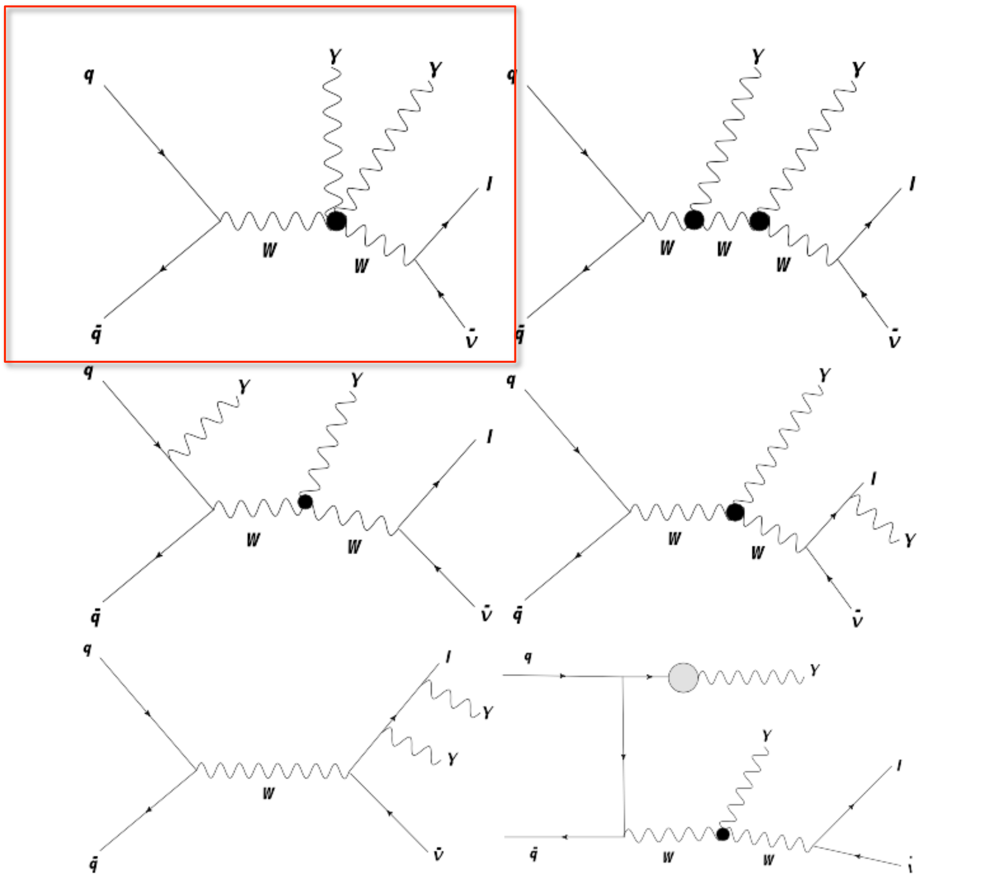
	Measured cross section (fb)	SM prediction (fb)
Inclusive Wγγ	6.1 ± 1.1(stat) ± 1.2(syst)+- 0.2 (lumi)	2.90±0.16
Exclusive Wγγ	2.9 ± 0.8(stat) ± 1.0(syst)+- 0.1 (lumi)	1.88±0.2

Wγγ (ATLAS)

arXiv:1503.03243

- Wγγ process is sensitive to WWγγ and WZγγ QGCs Vertex.
- Other contributions from:
  - ISR photons
  - FSR photons
  - Photon from TGC vertex
  - Photon from jet fragmentations





Definition of the fiducial region
$p_T^\ell > 20\,GeV$, $p_T^\nu > 25\,GeV$, $\lvert\eta_\ell\rvert < 2.5$
$m_T > 40\,GeV$
$E_T^\gamma > 20\,GeV$, $\lvert\eta^\gamma\rvert < 2.37$, iso. fraction $\epsilon_h^p < 0.5$
$\Delta R(\ell,\gamma) > 0.7$, $\Delta R(\gamma,\gamma) > 0.4$, $\Delta R(\ell/\gamma,\text{jet}) > 0.3$
Exclusive: no anti-k_t jets with $p_T^{jet} > 30\,GeV$, $\lvert\eta^{jet}\rvert < 4.4$