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

Zhijun Liang
University of California,Santa Cruz
on behalf of ATLAS and CMS collaborations

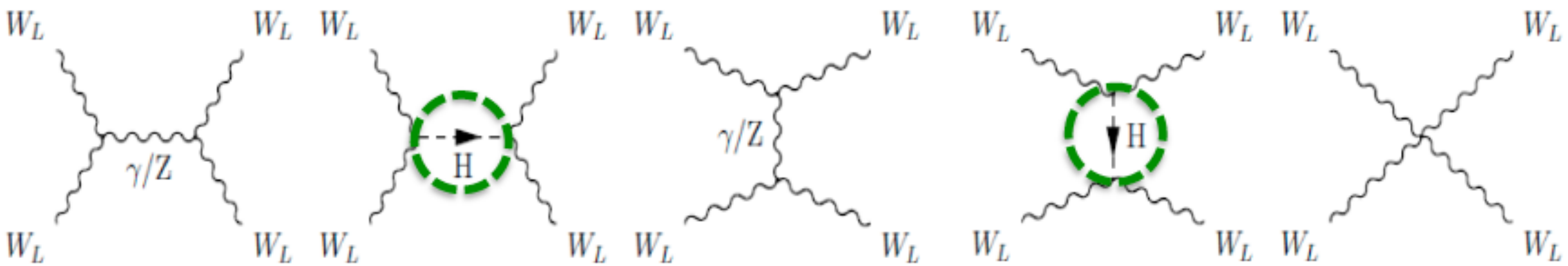
Presented in SM@LHC Conference 2015 at Galileo Galilei Institute

Outline

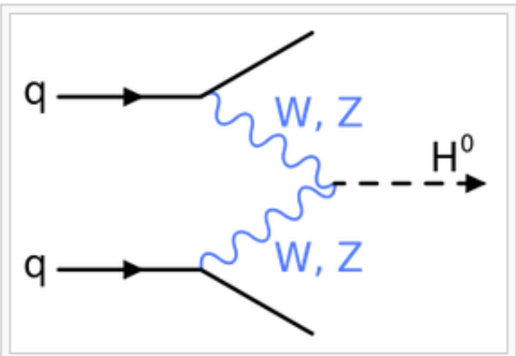
- Vector boson fusion (VBF):
  - VBF Z+2jets
    - ATLAS: JHEP 04 (2014) 031
    - CMS: Eur. Phys. J. C 75 (2015) 66
- Vector boson scattering (VBS):
  - $W^{\pm}W^{\pm}jj$
    - ATLAS: Phys. Rev. Lett. 113, 141803 (2014)
    - CMS: Phys. Rev. Lett. 114, 051801 (2015)
- Triboson measurements
  - $WW\gamma/WZ\gamma$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

Introduction

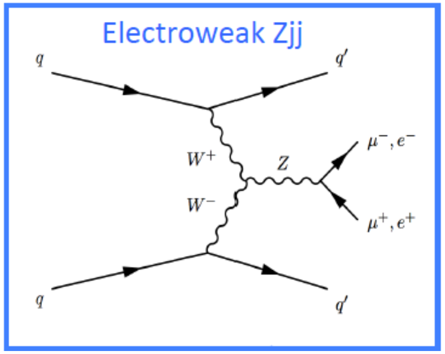
- **The Higgs mechanism ≠ a Higgs boson !**
- Vector boson self-coupling is a fundamental prediction of the Electroweak Sector of SM
- Its study is important to understanding electroweak symmetry breaking mechanism

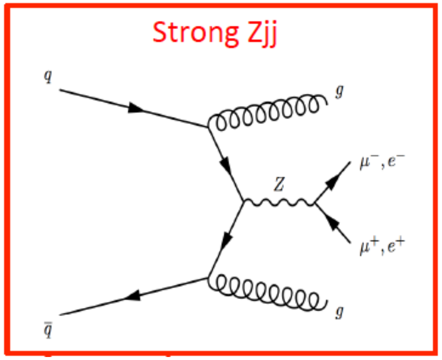


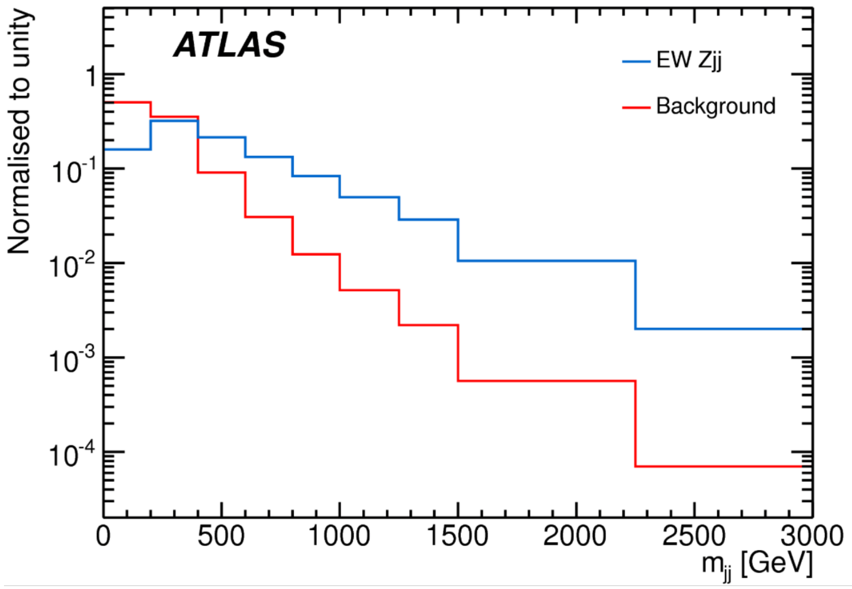
VBF Z



- Two main Higgs production mechanism
  - Gluon-gluon fusion
  - 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

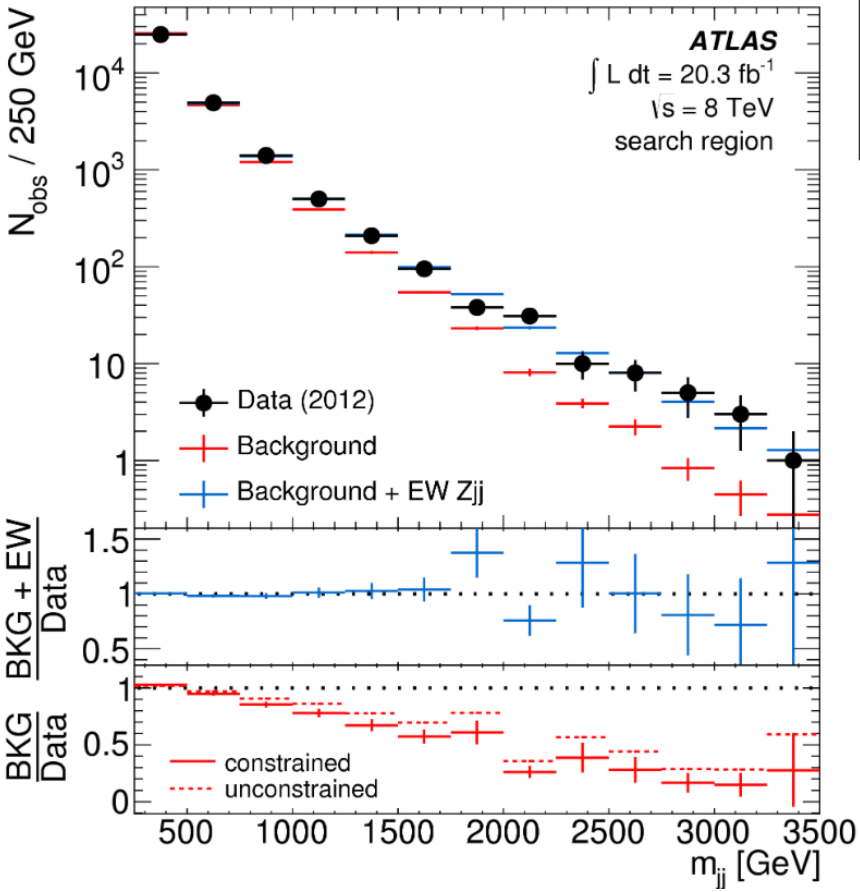






VBF Z (ATLAS)

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

Measured EWK Zjj cross section

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

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

.

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

VBF Z (CMS)

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

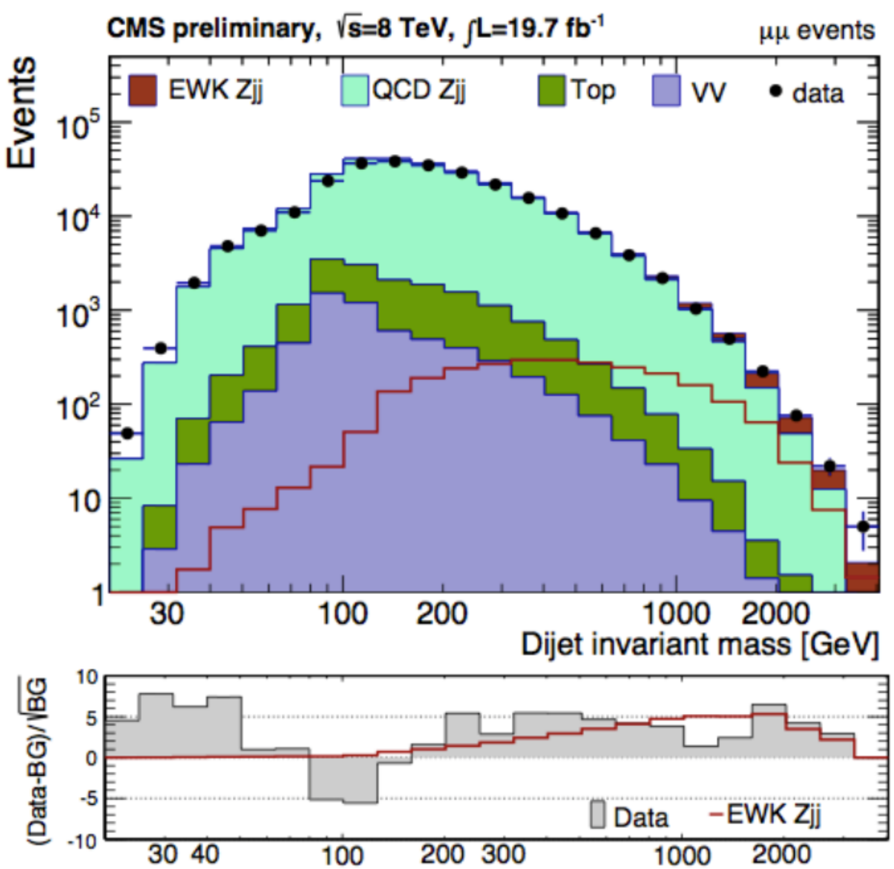
- Use boosted decision tree (BDT) technique to improve sensitivity

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

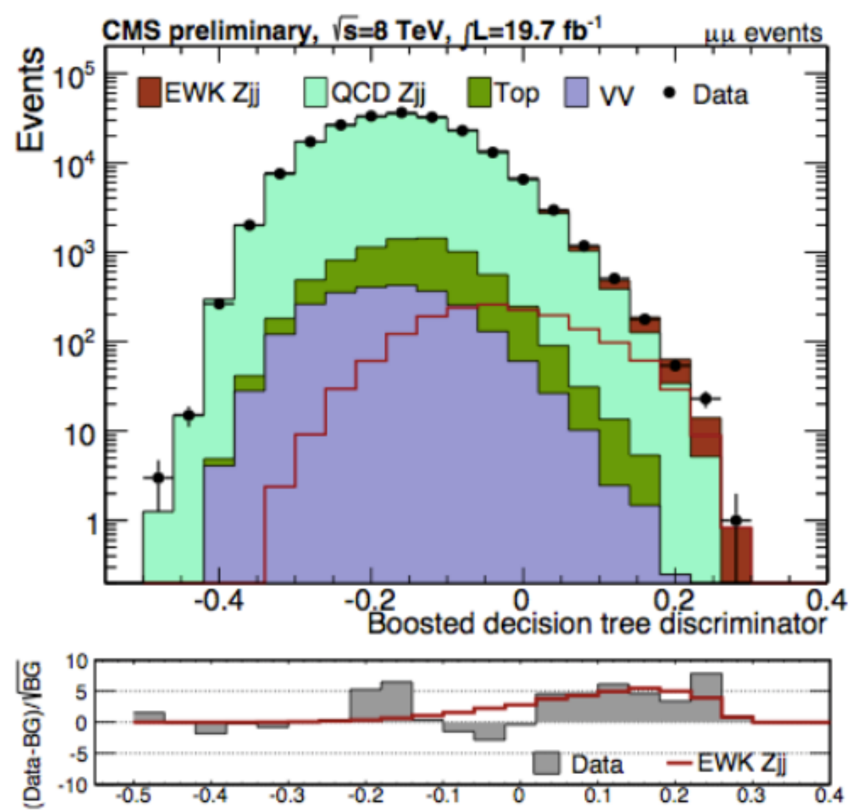
Measured σ_{EW}(lljj)=174± 15 (stat) ± 40 (syst) fb

5σ significance

Mjj spectrum

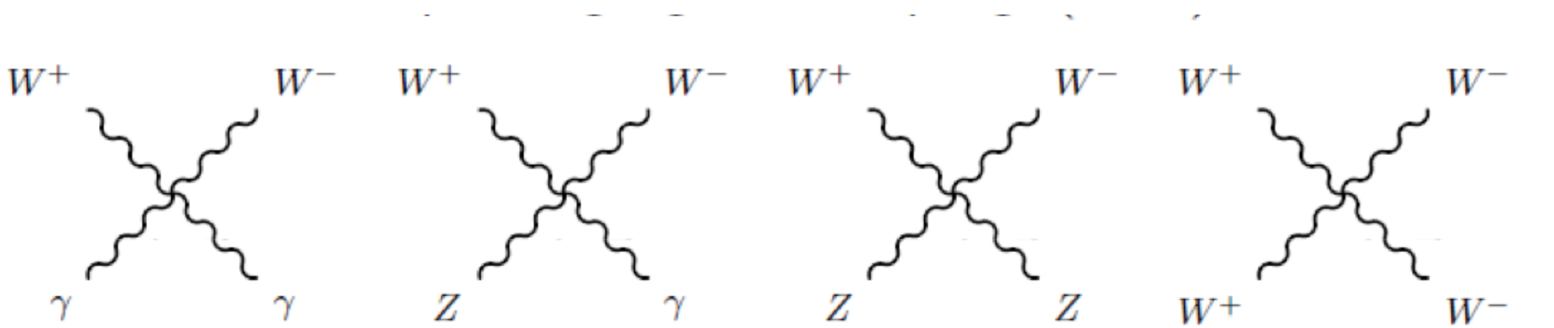


BDT output spectrum



Quartic Gauge Boson Couplings

- Reminder of **Quartic Gauge Boson Couplings (QGCs)**
  - SM model predicts gauge boson self coupling
    - Four gauge boson vertex:
      - $WW\gamma\gamma$, $WWZ\gamma$, WWWW, WWZZ, ZZZZ …



- QGCs can be studied in
  - Tri-boson processes
  - Vector boson scattering processes
  - Exclusive $\gamma\gamma$->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)

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

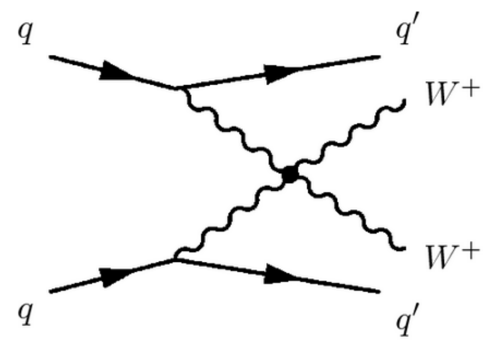
VVjj final state	ZZ	Zγ γγ	W^+W^- WZ	$W^\pm W^\pm$	Wγ	
VVV final state	ZZZ	ZZγ Zγγ	WWZ WZZ	WWW	WVγ	γγγ
$f_{S,0}$, $f_{S,1}$	✔		✔	✔		
$f_{M,0}$, $f_{M,1}$, $f_{M,6}$, $f_{M,7}$	✔	✔	✔	✔	✔	
$f_{M,2}$, $f_{M,3}$, $f_{M,4}$, $f_{M,5}$	✔	✔	✔		✔	
$f_{T,0}$, $f_{T,1}$, $f_{T,2}$	✔	✔	✔	✔	✔	✔
$f_{T,5}$, $f_{T,6}$,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

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

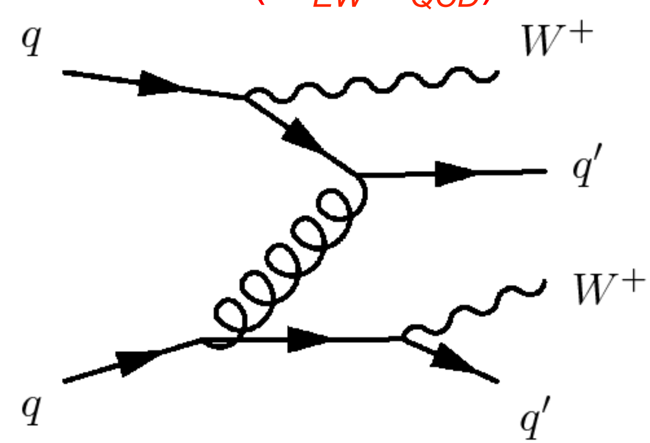
The measurement of Vector boson scattering processes

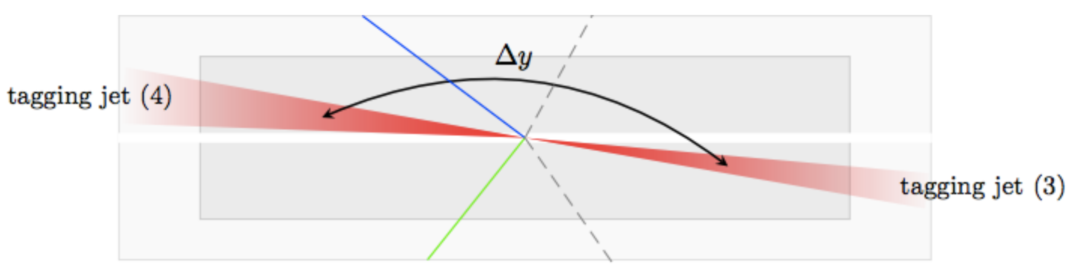
- Vector boson scattering (VBS) is one of the most promising process to study QGCs.
  - Diboson + two forward jets in event topology
- The scattering of longitudinally polarized vector bosons
  - violates unitarity at ~1TeV without higgs
- Important to check
  - whether Higgs boson unitarizes it fully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

Electroweak $W^\pm W^\pm jj$ $O(\alpha^6_{EW})$



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

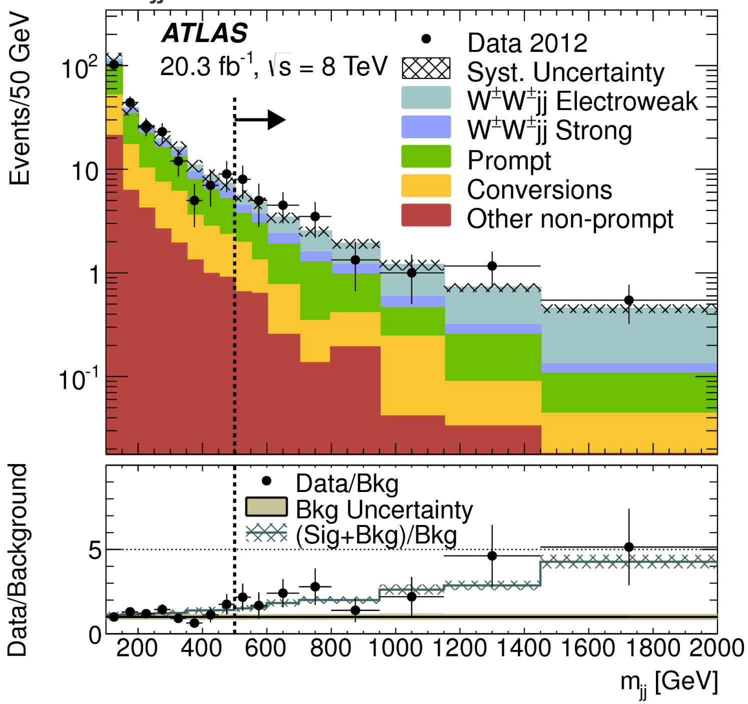




Electroweak W±W±jj (ATLAS)

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

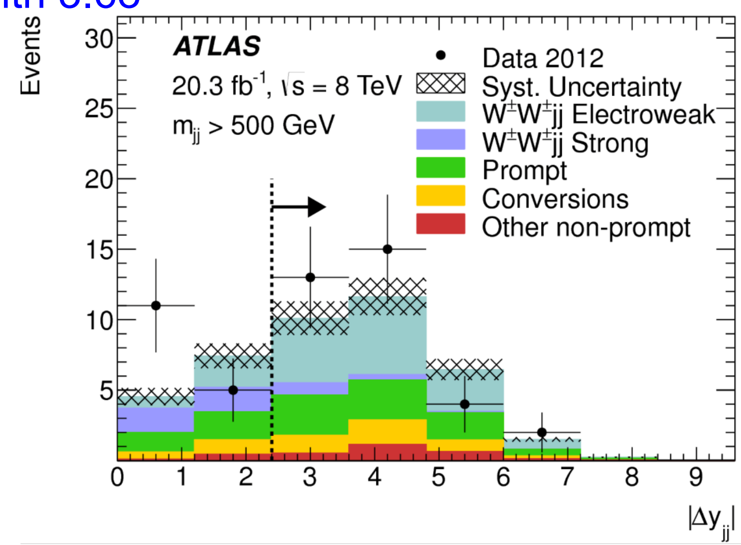
Inclusive QCD+EWK W±W±jj measurement
- M_{ll}>20GeV
- $|M_{ee}-M_Z|$>10GeV
- M_{jj}>150GeV



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

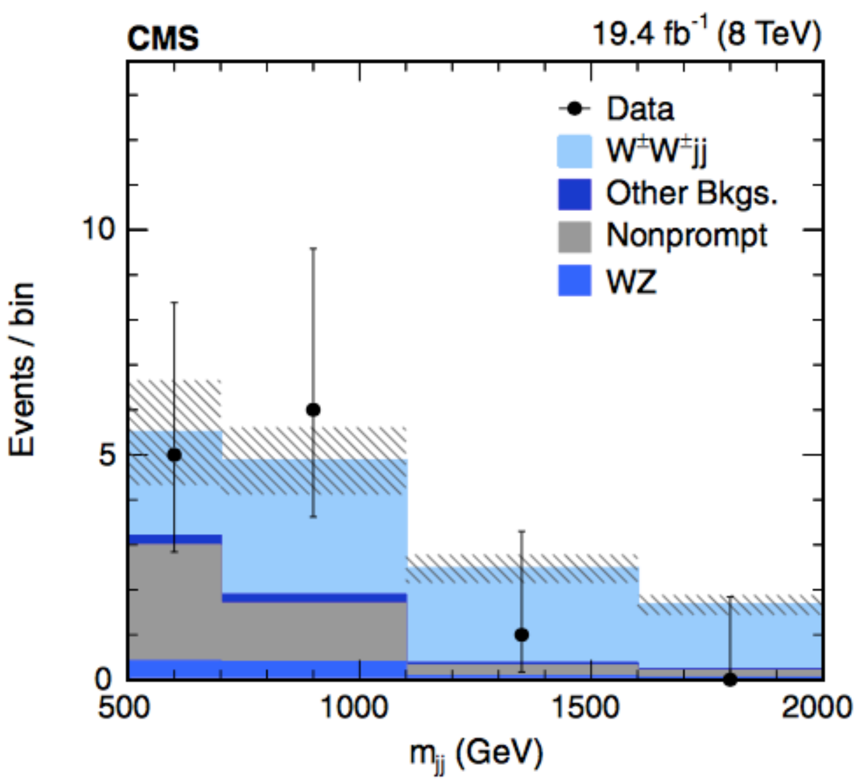
Measured σ_{EW}(W±W±jj)=1.3 ± 0.4(stat) ± 0.2(syst) fb
Predicted σ_{EW}(W±W±jj)=0.95 ± 0.06 fb
Observed with 3.6σ



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

Electroweak W±W±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

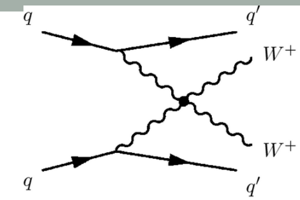
EWK signal region

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

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

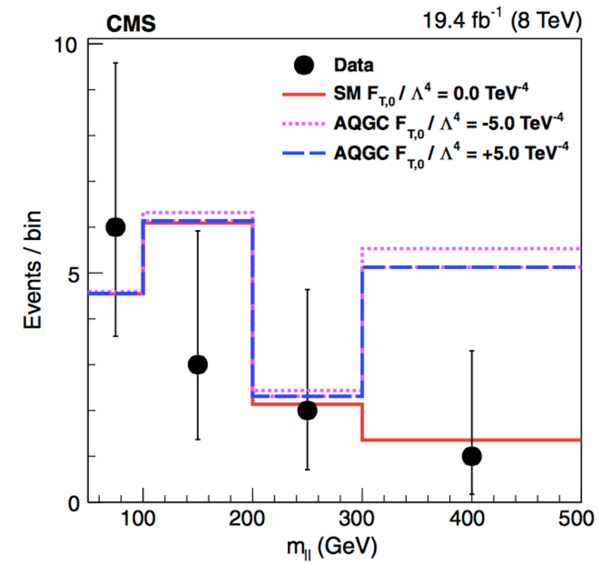
Predicted σ_{EW}(W±W±jj)=5.8 ± 1.2 fb.
Observed with 2.0 σ

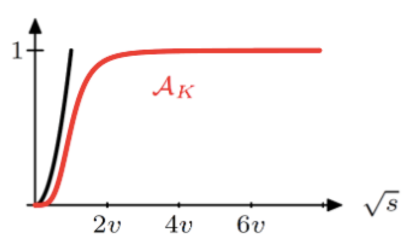
aQGCs limits from VBS process

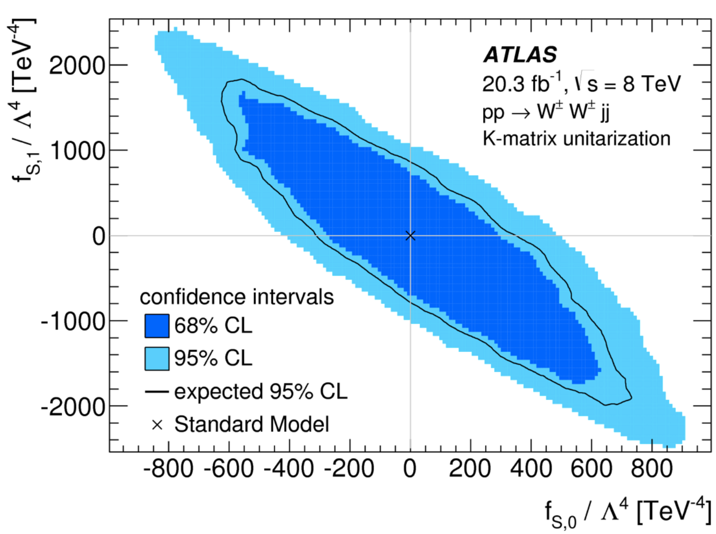


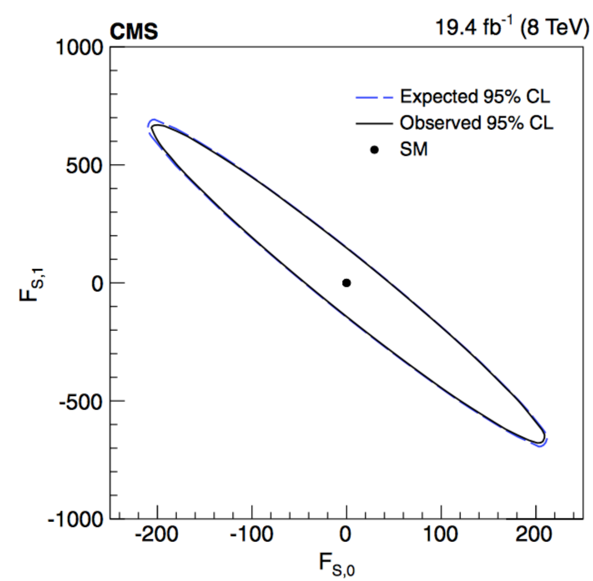
- FS0 and FS1 in Dim 8 EFT model is related to the Higgs field
- Naive EFT-predicted aTGC/aQGCs amplitudes
  - disrespect the gauge symmetry
  - and violate the unitarity once the √s goes sufficiently
- CMS result is not unitarized
- ATLAS use K matrix unitarization
  - Preserve unitarity in high sqrt(s)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

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





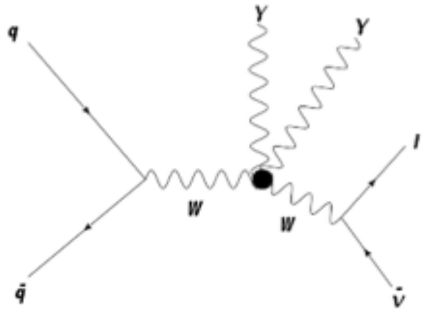


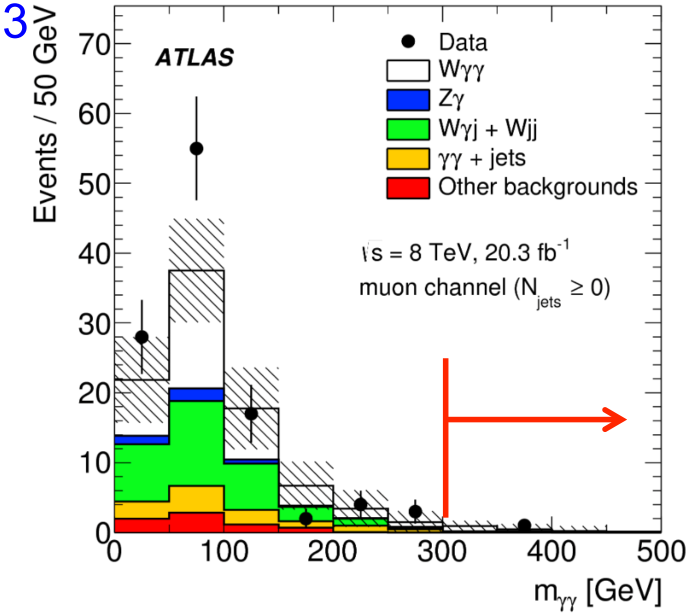


Wγγ (ATLAS)

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

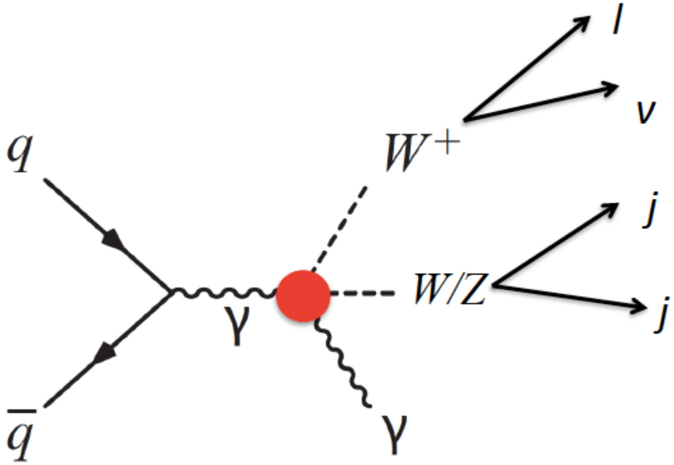
	Measured cross section (fb)	SM prediction (fb)
Inclusive Wγγ	6.1 ± 1.1(stat) ± 1.2(syst)+- 0.2 (lumi)	2.90±0.16
Exclusive Wγγ With hard jet veto	2.9 ± 0.8(stat) ± 1.0(syst)+- 0.1 (lumi)	1.88±0.2

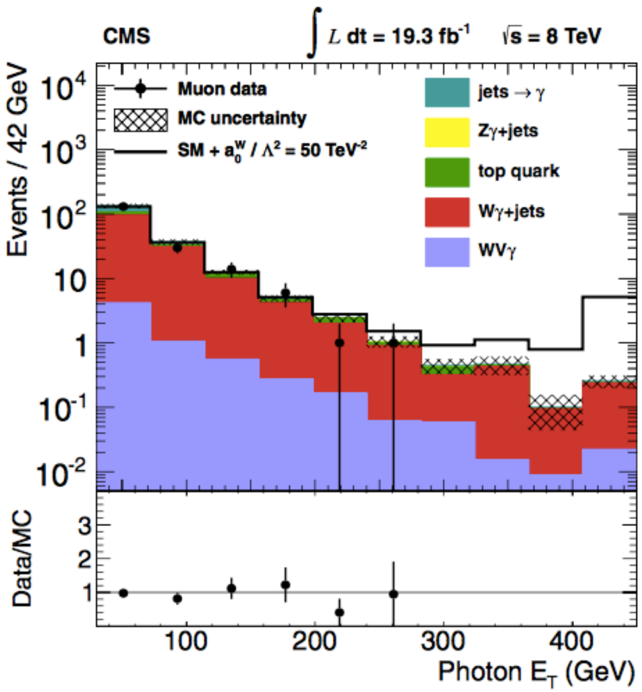
See Vasiliki's talk on Wednesday electroweak physics sections for more details

Wγ (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

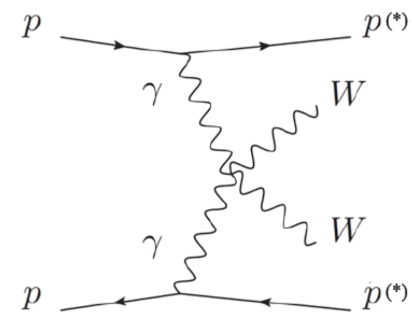
Major BG in WVγ

Wγ+jets

WV +jet , jet fake as γ

Multijets

Exclusive γγ->WW (CMS)



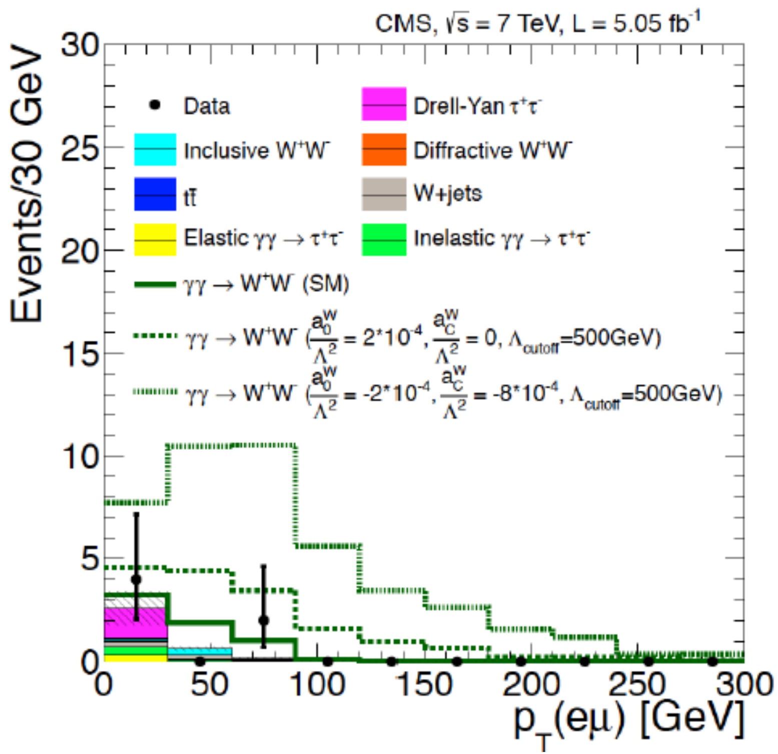
- Exclusive γγ production without color exchange
  - Very clean event signature (two tracks vertex)
  - Require No extra track on di-lepton vertex

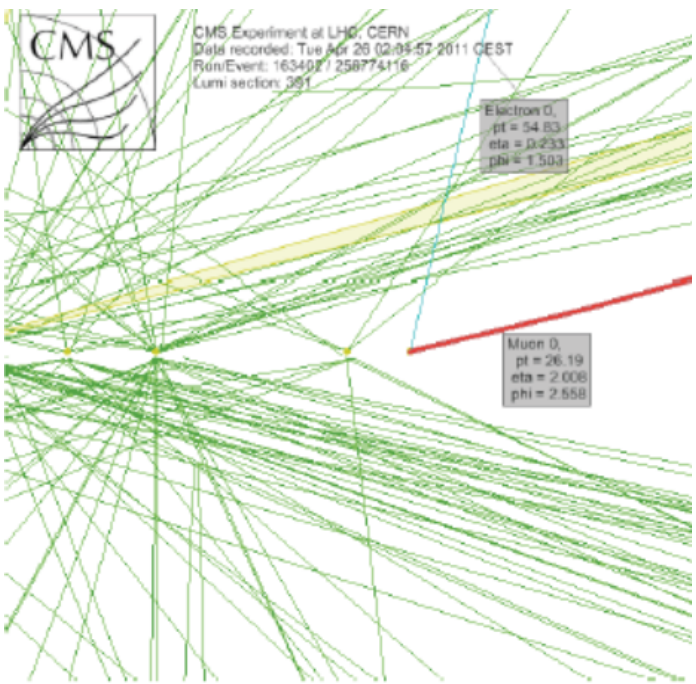
$$\sigma(\mathrm{pp} \rightarrow \mathrm{p}^{(*)}\mathrm{W}^{+}\mathrm{W}^{-}\mathrm{p}^{(*)} \rightarrow \mathrm{p}^{(*)}\mu^{\pm}\mathrm{e}^{\mp}\mathrm{p}^{(*)}) = 2.2^{+3.3}_{-2.0}\,\mathrm{fb}$$

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

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

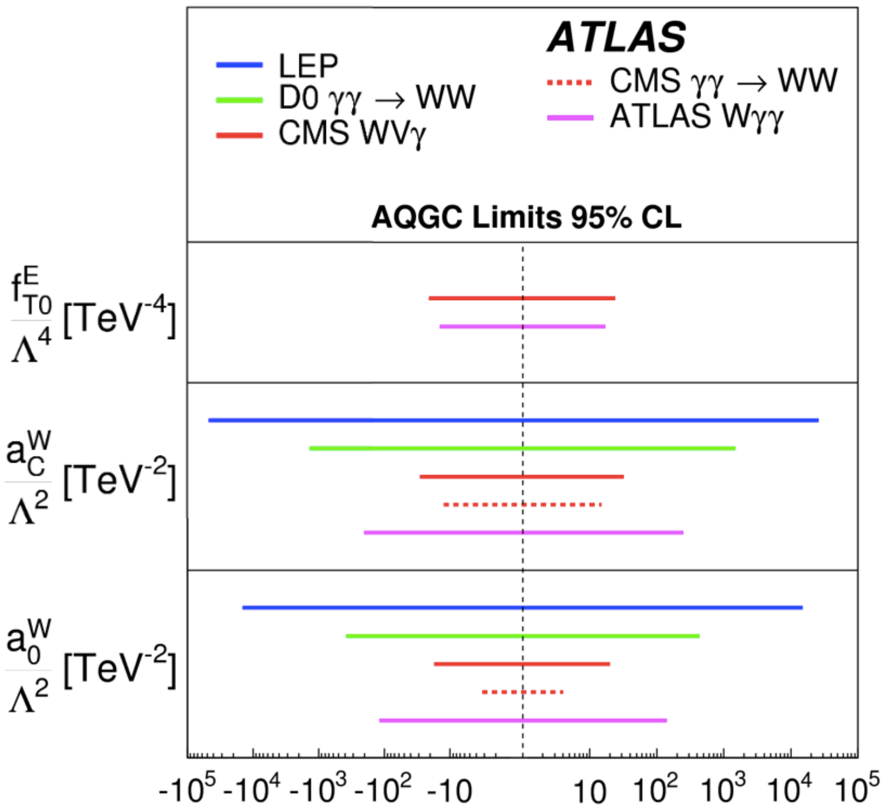
1σ significance





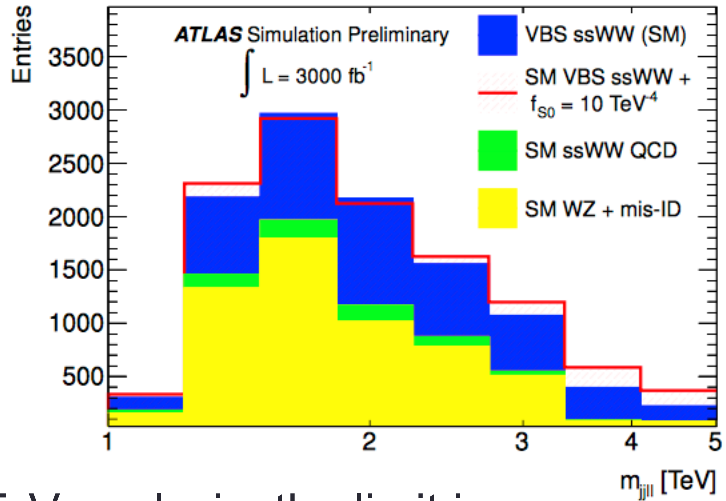
aQGCs limits from tri-boson and Exclusive γγ->WW processes

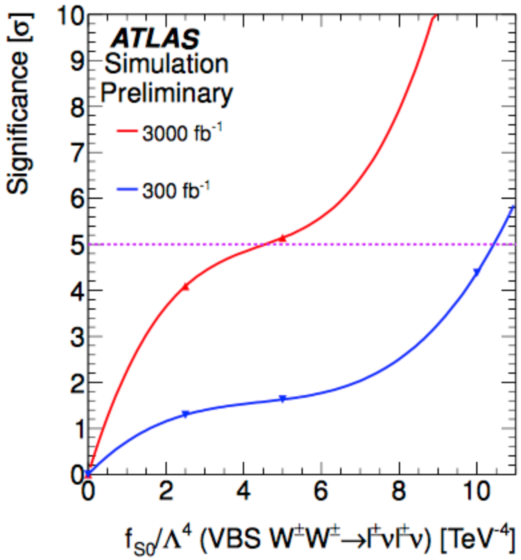
- Tri-boson processes and γγ->WW are sensitive to
  - F_T operators (Gauge boson field)
  - F_M operators (Higgs-Gauge field)
    - $F_{M,2}$, $F_{M,3}$ can be converted to LEP convention a_C^W a_0^W



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

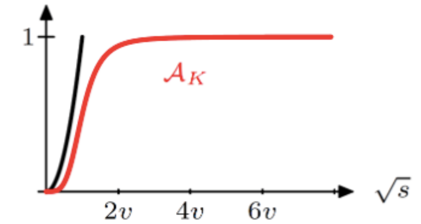
- Observation of electroweak Zjj production at LHC
  - A benchmark process for future studies of VBF processes at LHC
  - Background only hypothesis rejected at greater than 5 σ in both ATLAS and CMS

- 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: : $f_S/\Lambda 4$ ~O(1000), $f_T/\Lambda 4$ ~O(10)
    - expected limits with 300 fb^{-1} data at 14TeV : $f_S/\Lambda 4$ ~O(10), $f_T/\Lambda 4$ ~O(1)
    - expected limits with 3000 fb^{-1} data at 14TeV: $f_S/\Lambda 4$ ~O(1), $f_T/\Lambda 4$ ~O(1)

backup

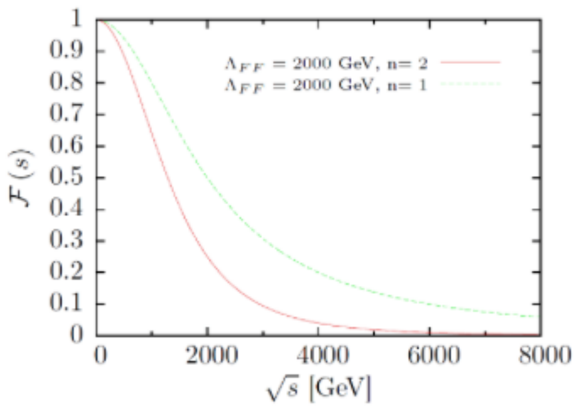
Unitarity violation treatment

- 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

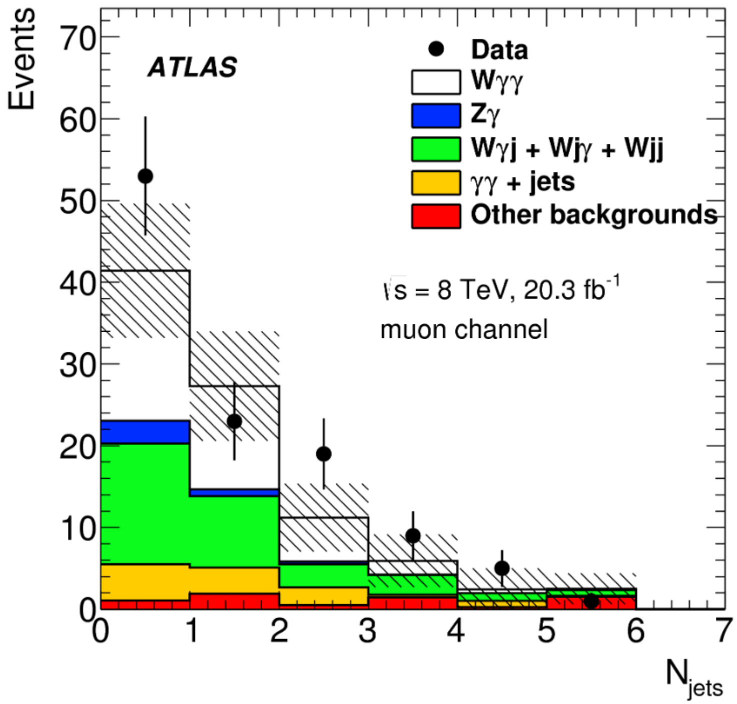
$$\mathcal{F}(s) = \frac{1}{(1+\frac{s}{\Lambda_{FF}^2})^n}$$



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 $p_T^{\text{jet}} > 30\,GeV$, $\lvert\eta^{\text{jet}}\rvert < 4.4$

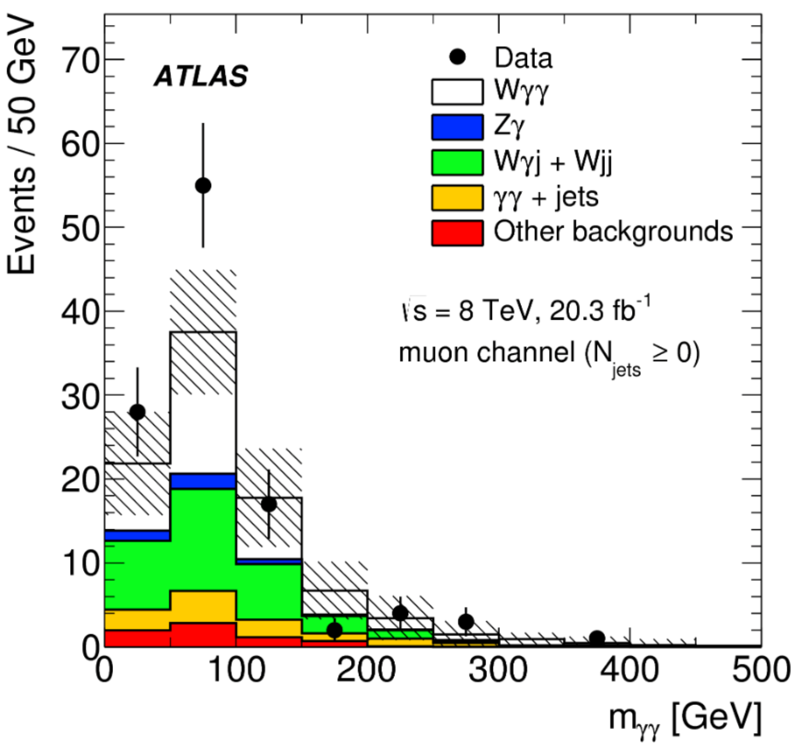
More than 3 σ significance

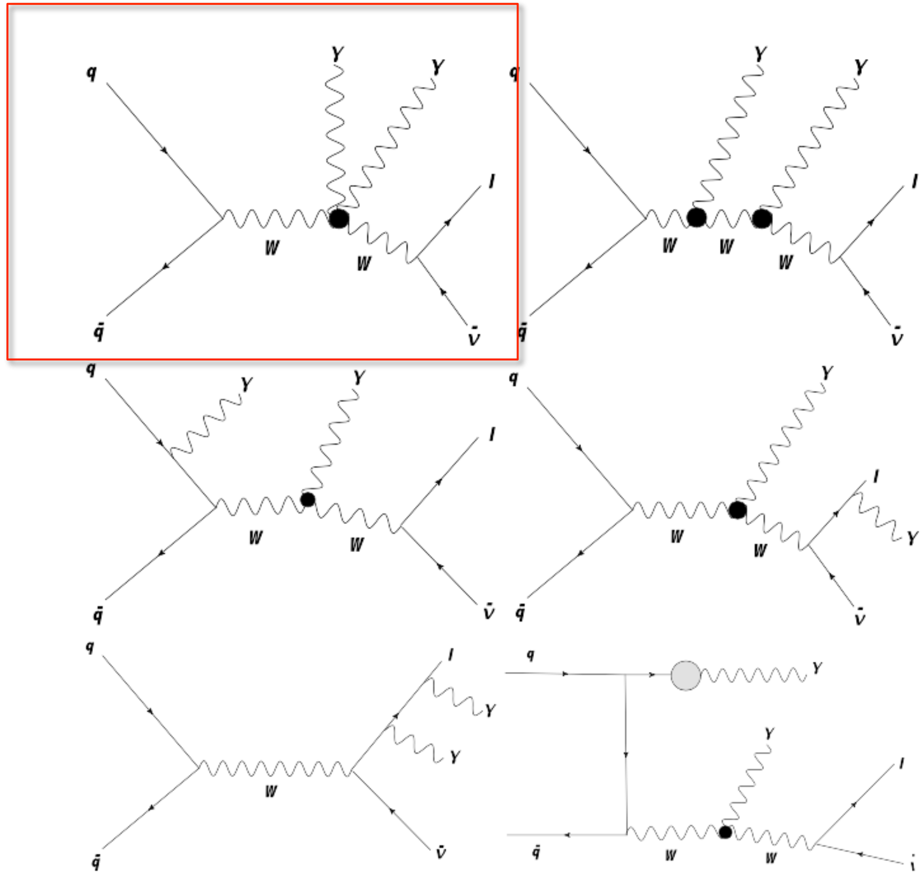
	Measured cross section (fb)	SM prediction (fb)
Inclusive Wγγ	6.1 ± 1.1(stat) ± 1.2(syst)+- 0.2 (lumi)	2.90±0.16
Exclusive Wγγ	2.9 ± 0.8(stat) ± 1.0(syst)+- 0.1 (lumi)	1.88±0.2

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





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