Multiboson production at LHC

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Multiboson physics

Cross-section measurements:

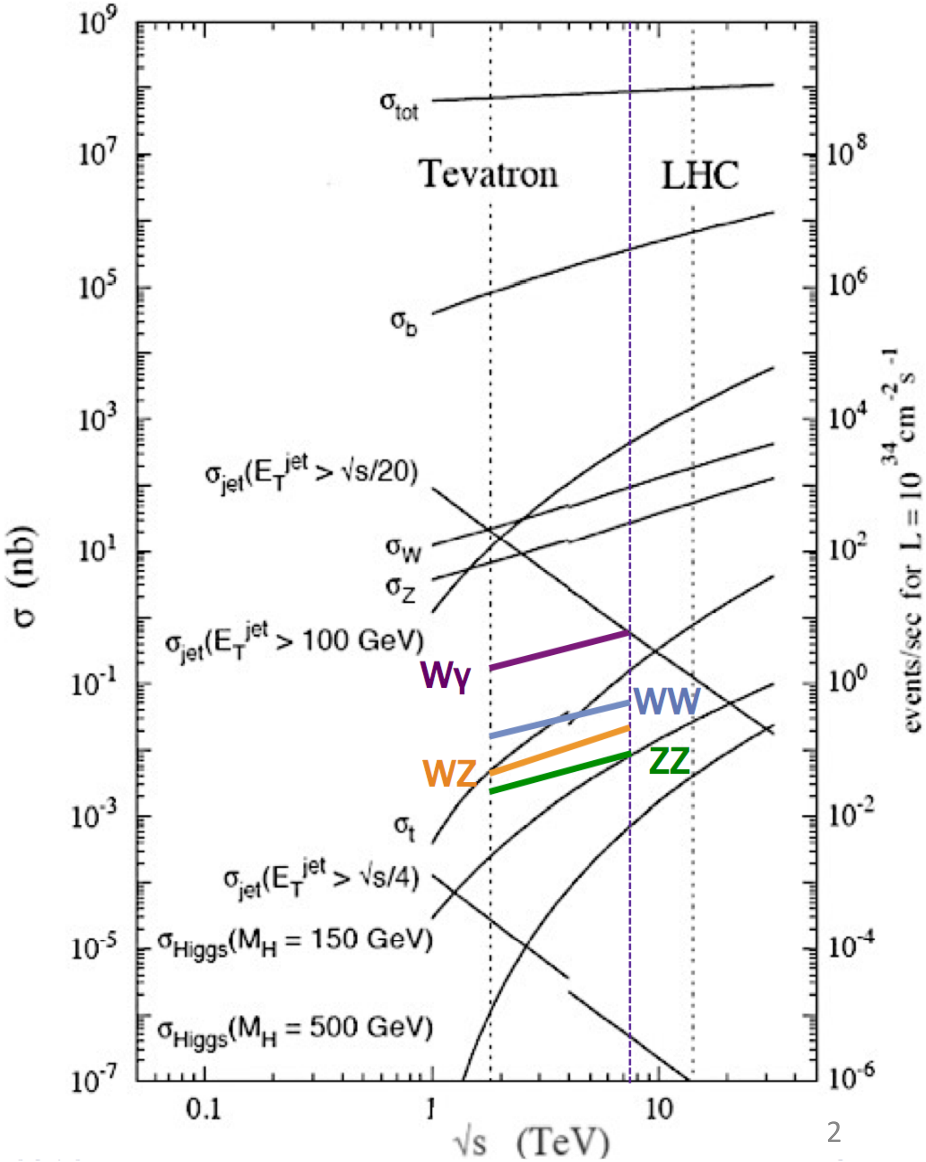
- precise test of Standard Model (SM)
- irreducible background to Higgs
- sensitivity to new particles

Triple/quartic gauge couplings:

- precision study of V self-couplings
- probe new physics through anomalous couplings (aTGCs, aQGCs)

At LHC:

- small cross-sections, between 1-100pb



Signature

Multiboson final states: combination of photons, W, Z

- γγ, Wγ, Zγ, WW, WZ, ZZ + three bosons (Wγγ….)
- σ(γ)>σ(W)>σ(Z)

At LHC measured mainly through leptonic final states:

- relatively low background
- small branching ratios
  - BR (W->lν) = 0.108, BR (Z->ll) = 0.034

Semileptonic or invisible channels also studied

- to get complementary sensitivity
- to cover a larger kinematic region
  - but with larger experimental systematics

How the final state looks like:

- high p_T isolated photons, electrons, muons (taus)
- Z channels: dilepton invariant mass peak at Z mass
  - m(ll) selection
- W channels: large missing transverse energy from undetected neutrinos
  - E_T^{miss} or $m_T(W)$ selection

Main backgrounds

V + jets:
- high p_T prompt leptons from boson decay
- non prompt leptons from heavy flavour decays
- fake leptons / photons from misidentified jets
- E_T^{miss} from particles outside acceptance

Top (ttbar, single top):
- high p_T prompt leptons from W decay
- E_T^{miss} from W

Data-driven techniques

Drell-Yan:
- high p_T prompt leptons from Z decay
- E_T^{miss} from particles outside acceptance, detector effects

Other di-boson processes:
- background for each other

Estimated from MC

Run1 results overview

xsec: cross-section measurement
aGC: anomalous gauge couplings measurement

	ATLAS 7TeV, xsec	ATLAS 8TeV, xsec	ATLAS 7TeV, aGC	ATLAS 8TeV, aGC	CMS 7TeV, xsec	CMS 8TeV, xsec	CMS 7TeV, aGC	CMS 8TeV, aGC
WW(llνν)	X	X	X		X	X	X	X
ZZ (4l)	X	X	X		X	X	X	X
ZZ (2l2ν)	X		X		X	X	X	X
WZ (3l)	X	X	X		X	X		
Wγ (lν)	X		X		X		X	
Zγ (ll)	X		X		X	X	X	X
Zγ (νν)	X		X		X	X	X	X
VW or Z (jj)	X		X		X	X	X	
γγ	X				X			
Wγγ		X		X				
WWγ +WZγ						X		X
Ewk WW+2jets		X		X		X		X
Ewk Zγ+2jets						X		X

Selected results presented here (mainly 8TeV)

Cross-section experimental measurements

N_{data}: cut-and-count or max.likelihood

N_{bkg}: data-driven or from MC

$$\sigma^{tot} = \frac{N_{data} - N_{bkg}}{A \cdot C \cdot Br \cdot \int \mathcal{L} dt}$$

$$A = \frac{N^{fid}_{MC,gen}}{N^{tot}_{MC,gen}}$$

acceptance: theory only

$$C = \frac{N^{Selected}_{Reco}}{N^{fid}_{MC,gen}}$$

efficiency: detector effects

- cross-section in the fiducial region (FR):
  - defined by detector acceptance and selection requirements
  - minimizes extrapolation to unmeasured regions
- production cross-section:
  - extrapolated from FR to the total phase space
- differential cross-sections in the fiducial region

WW -> 2l2ν

Signature: 2 isolated leptons + E_T^{miss}

Relatively large cross-section

Main challenge: large background

Main backgrounds rejection:

- W+jets => tight lepton selection
- Top => anti b-tagging and jet veto
- Drell-Yan => Z mass veto and E_T^{miss}
- WZ, ZZ => third lepton veto

Uncertainty dominated by systematics:

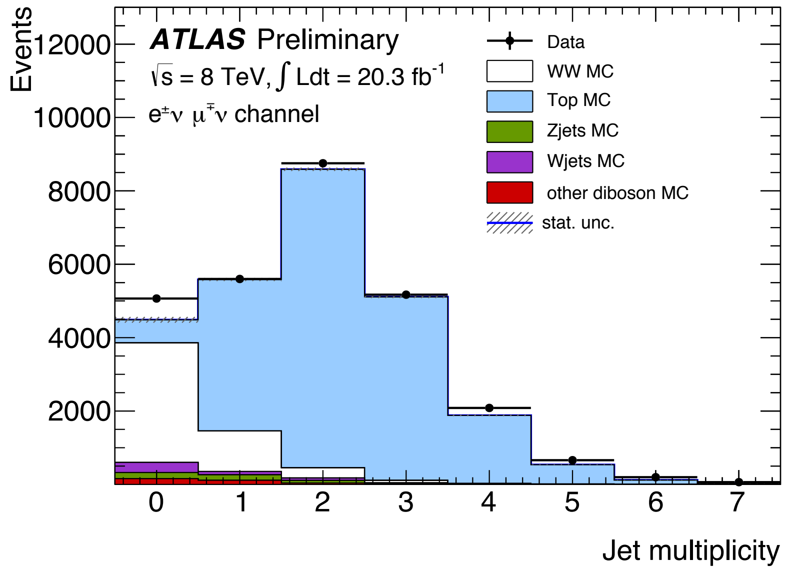
- jet veto (theory)
- background estimates (experimental)
- lepton selection (experimental)

ATLAS: 0 jets only

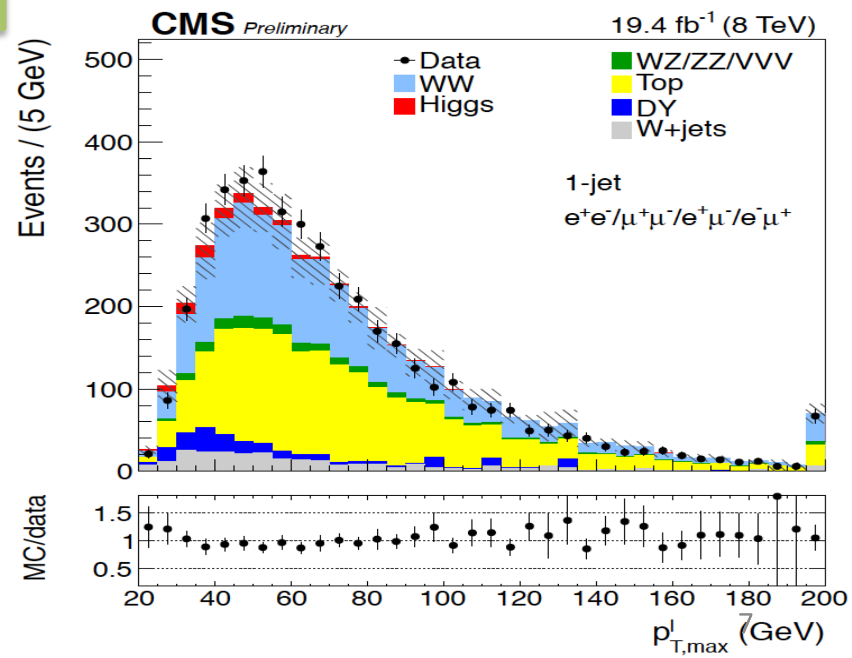
CMS: 0-1 jets

Categorization based on lepton flavours

ATLAS-CONF-2014-033



SMP-14-016 (submitted to EPJC)



WW -> 2l2ν, results

total σ [pb] 8TeV	theory
CMS: 60.1 ± 0.9 (stat) ± 3.2 (exp) ± 3.1(th) ± 1.6 (lumi)	$59.8^{+1.3}_{-1.1}$ (NNLO)
Atlas: $71.4^{+1.2}_{-1.2}$ (stat) $^{+5.0}_{-4.4}$ (syst) $^{+2.2}_{-2.1}$ (lumi)	$58.7^{+3.0}_{-2.7}$ (qq NLO, gg LO) H->WW included

ATLAS / CMS 7 TeV
ATLAS 8 TeV
→ Excess over NLO predictions

CMS 8TeV: good agreement with theory

Might be explained by

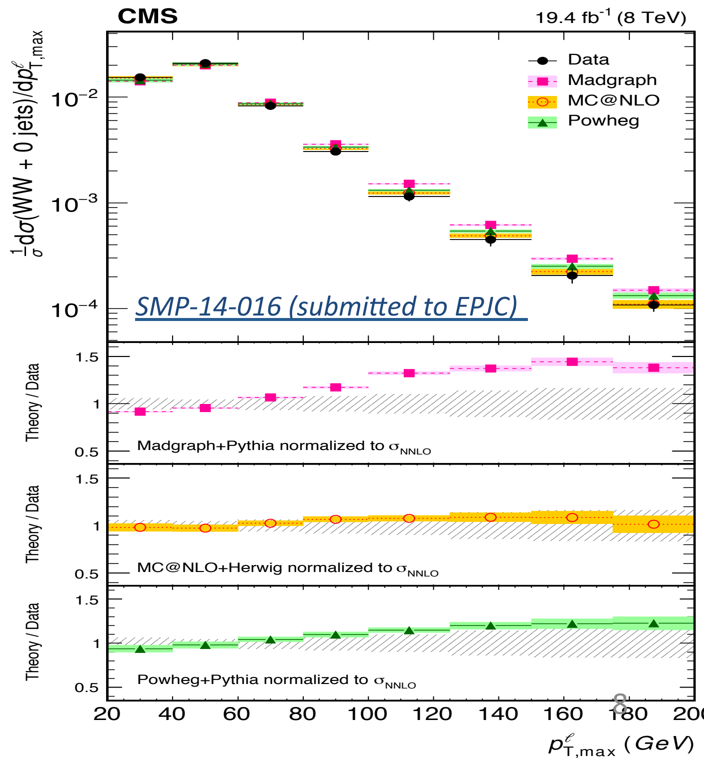
- NNLO contributions, ~10%
- Gluon resummation effects
  - correlated with jet veto efficiency

Differential cross-sections also measured

- in fiducial region with zero jets
- after unfolding

Good agreement between data and theory

- few differences depending on generator/variable



ZZ -> 4leptons

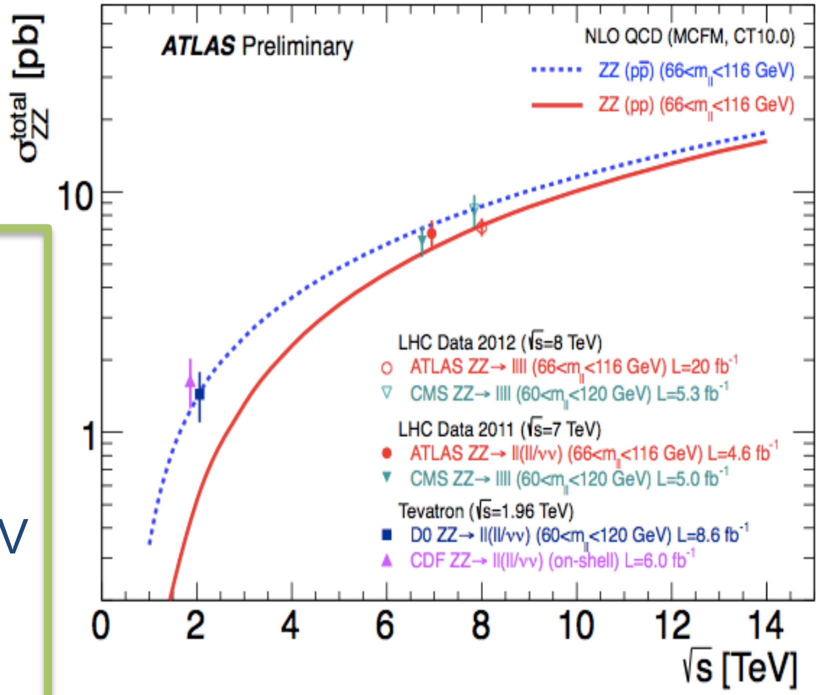
ZZ->2l2v also measured
WZ->3l

Signature: 4 isolated leptons
Low rate, low background.
Challenge: optimize efficiency

Selection:
- p_T(l)>20-25(10) GeV [leading (other)]
- m(ll) window
  - defining the fiducial region
  - ATLAS: 66-116 GeV; CMS: 60-120 GeV

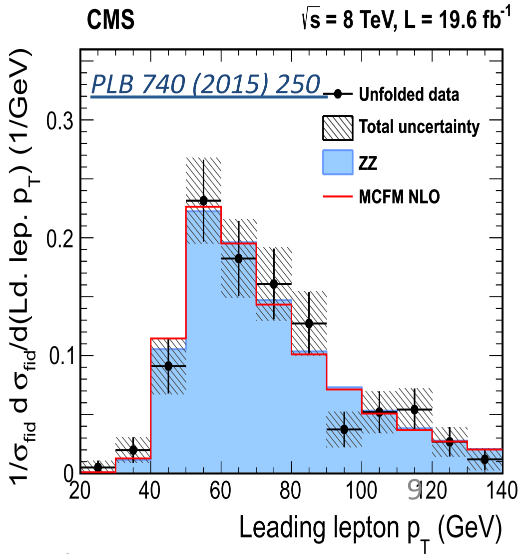
Main backgrounds:
- misidentified jets in Z+jets and WZ.

ATLAS-CONF-2013-020



Good agreement with NLO predictions
Differential results also available

σ (fiducial) [pb] 8TeV	MCFM
CMS: 7.7±0.5(stat)$^{+0.5}_{-0.4}$(syst)±0.4(theo)±0.2(lumi)	7.7 ± 0.6
Atlas: 7.1$^{+0.5}_{-0.4}$(stat) ± 0.3 (syst) ± 0.2(lumi)	7.2$^{+0.3}_{-0.2}$

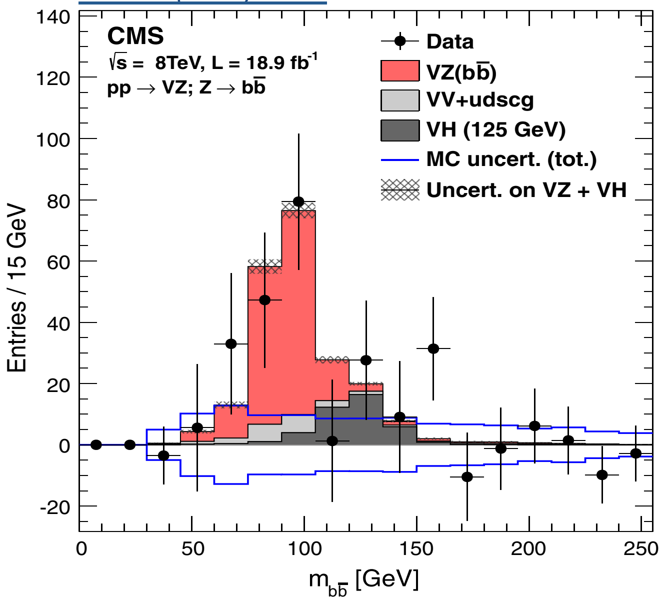


Semileptonic W and Z decays

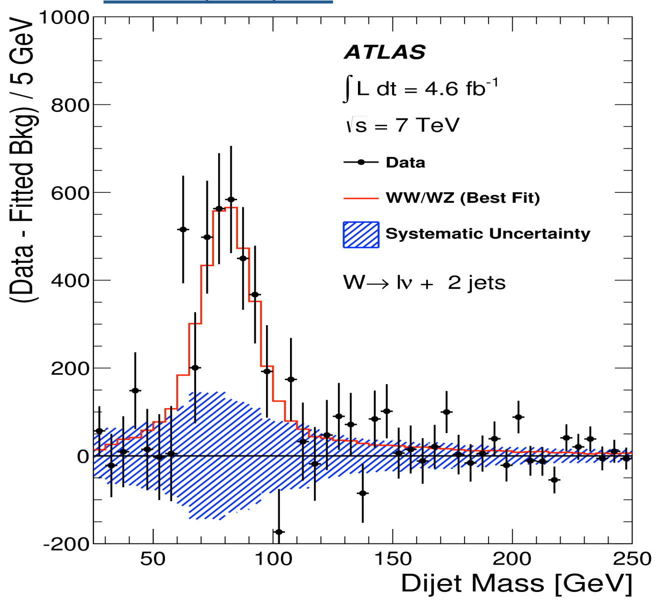
Semileptonic channels with W and Z also studied at 7 and 8TeV:
- VW (V=W or Z), W->jj, V->leptons (CMS 7TeV)
- VZ (V=W or Z), V->jj, W->lν (ATLAS 7TeV)
- VZ (V=W or Z), Z->bb (CMS, 8TeV)

Pros: large BR => more events, access to higher boson p_T
Cons: large backgrounds, worse S/B
Challenge: background modeling for signal extraction

EPJC 74 (2014) 2973



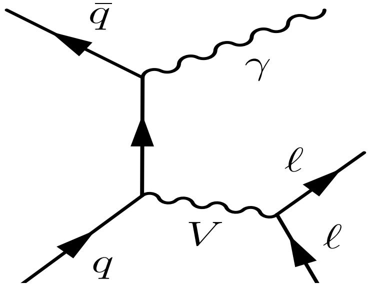
JHEP 01 (2015) 049



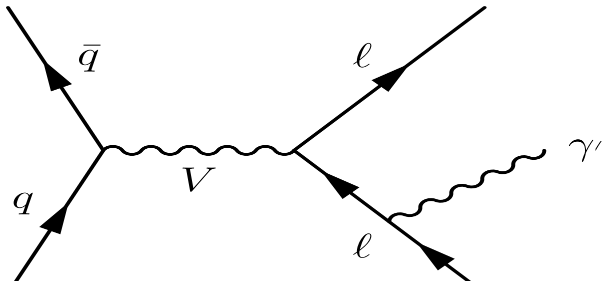
- VZ->Vbb observed with significance 6.3σ
- σ(pp->WZ) and σ(pp->ZZ) consistent with NLO expectations

- WW+WZ measured with significance 3.4σ
- σ(WW+WZ) consistent with NLO expectations

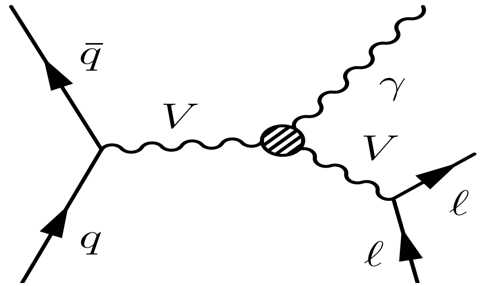
Wγ and Zγ production



ISR



FSR



TGC (Wγ only)

Final states: ννγ, lνγ, llγ

Signature: 1 photon, 0-1-2 isolated leptons, (E_T^{miss})

lνγ, llγ

Selection:

- lepton p_T>20-35GeV
- photon E_T>15GeV
- m_T^W>40-70GeV
- $|m_{e\gamma}-m_Z|$>15GeV
- m(ll)>40-50GeV

Main background:

- V+jets

ννγ

Selection:

- photon p_T>100-145GeV
- E_T^{miss} > 35–130 GeV
- lepton/jet veto

Main background:

- Wγ->lνγ, W->eν
- instrumental/non-collision effects

Wγ and Zγ cross-section results

	channel	σ (fiducial) [pb]	NLO [pb]
CMS 7TeV	Wγ -> lνγ	37.0±0.8(stat)±4.0(syst)±0.8(lumi)	31.81±1.80
	Zγ -> llγ	5.33 ± 0.08 ± 0.25 ± 0.12	5.45 ± 0.27
	Zγ -> ννγ	21.1 ± 4.2 ± 4.3 ± 0.5 [fb]	21.9 ± 1.1 [fb]
ATLAS 7TeV	Wγ -> lνγ	2.77 ± 0.03 ± 0.33 ± 0.14	1.96 ± 0.17
	Zγ->llγ	1.31 ± 0.02 ± 0.11 ± 0.05	1.18 ± 0.05
	Zγ->ννγ	0.133 ± 0.013 ± 0.020 ± 0.005	0.156 ± 0.012
CMS 8TeV	Zγ->llγ	2.063 ± 0.019 ± 0.098 ± 0.054	2.100 ± 0.120
	Zγ -> ννγ	**NEW!** 52.7 ± 2.1 ± 6.4 ± 1.4	50.0 + 2.4 – 2.2 [fb,NNLO]

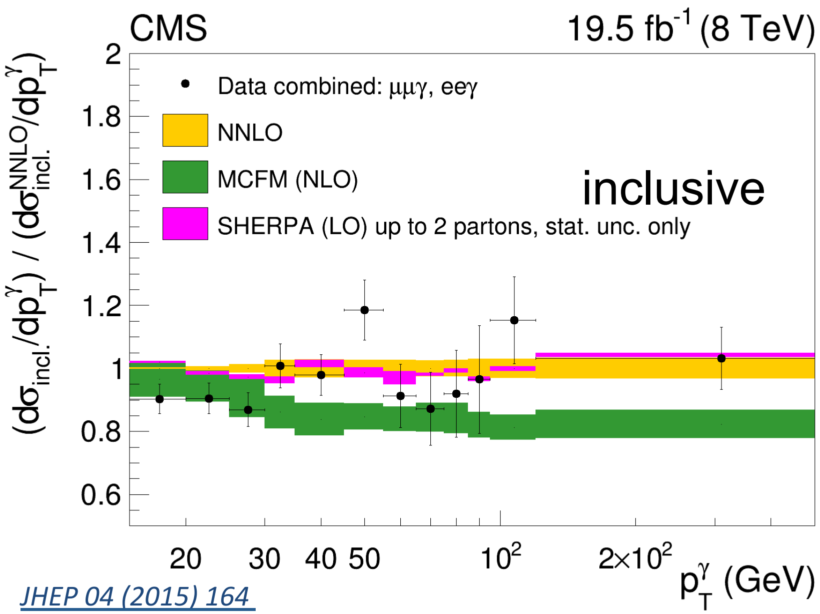
ATLAS/CMS,
different fiducial regions:
not comparable results

- ✓ Overall good agreement with NLO predictions **(MCFM)**
- ✓ Small excess in Wγ for both experiments
  - ✓ Discrepancy worse at high $p_T(\gamma)$ and jet multiplicity

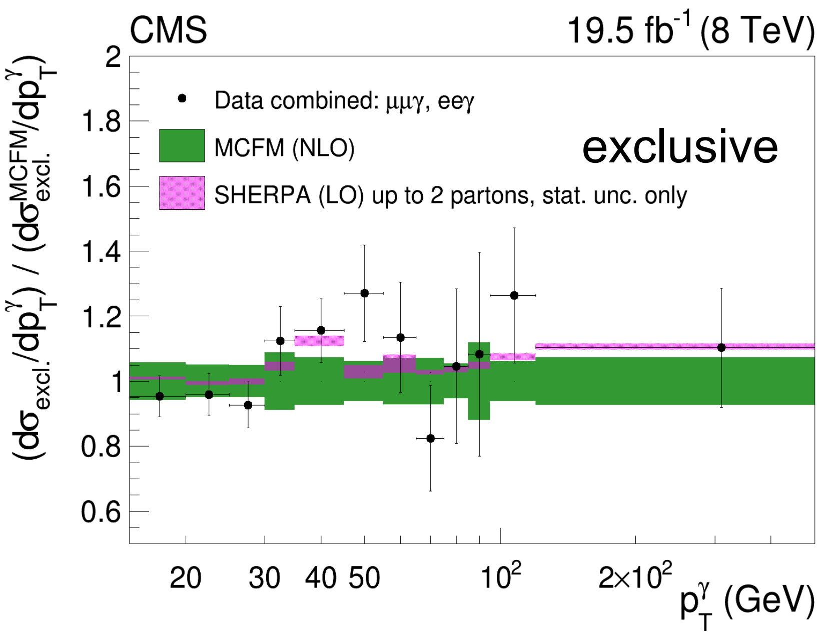
NNLO [fb]	2453 ± 4.1%
ATLAS [fb]	2770 ± 30 ± 330 ± 140

Cured when QCD NNLO corrections are included
(Grazzini, hep-ph:1407.1618
Grazzini et al., hep-ph:1504.01330)

Zγ differential distributions



[JHEP 04 (2015) 164]



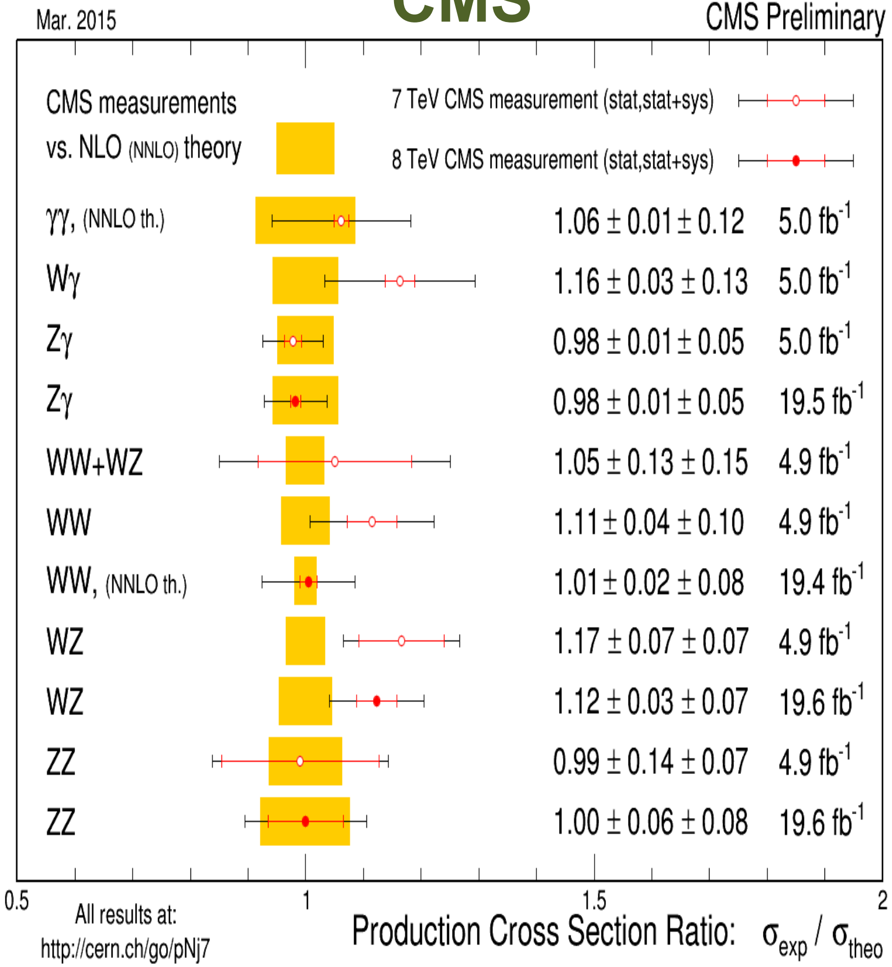
First comparison with NNLO predictions
[Grazzini et al., arXiv hep-ph 1309.7000]

Inclusive measurement:
SHERPA in better agreement at high $p_T(\gamma)$ with NNLO than MCFM

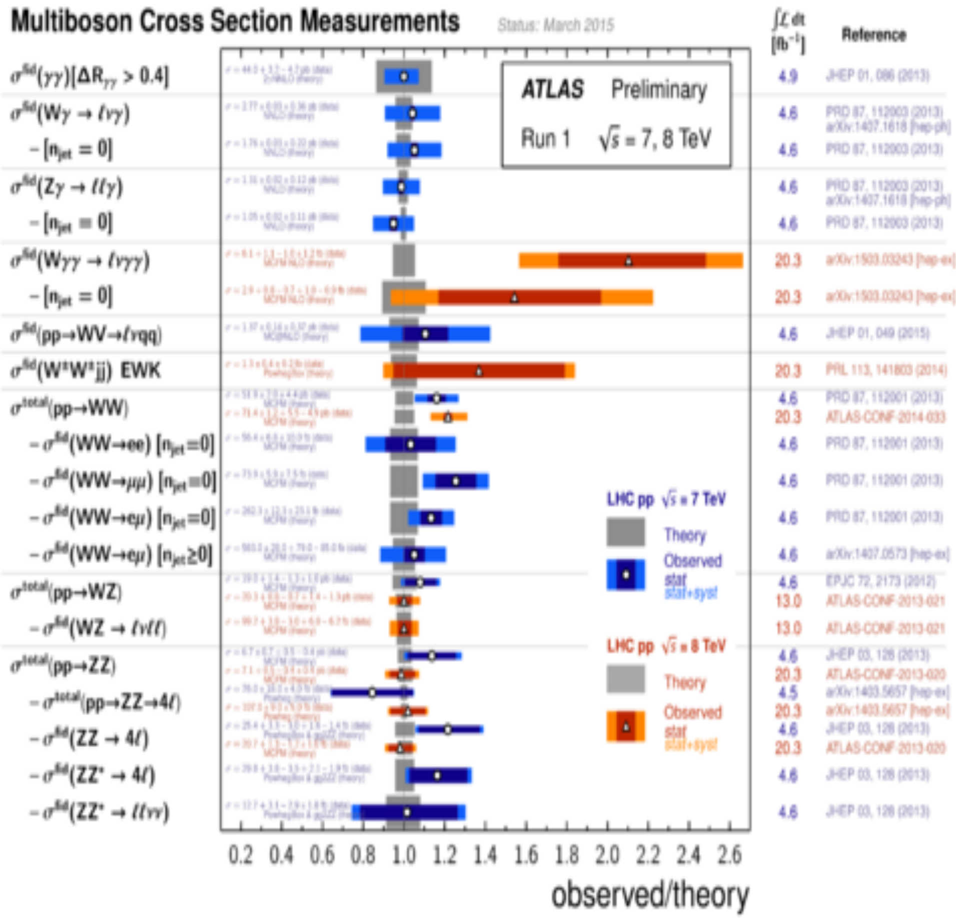
Exclusive measurement
(= no jet with p_T>30GeV and $|\eta|$<2.4):
reduced difference between MCFM and SHERPA at high $p_T(\gamma)$

Cross-sections summary

CMS



ATLAS



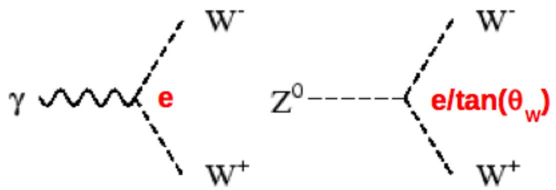
Good agreement between experiments and theory in most channels

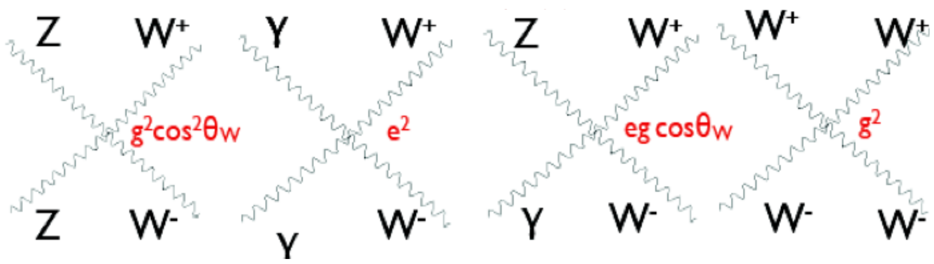
Gauge Couplings in SM

Gauge bosons couplings:

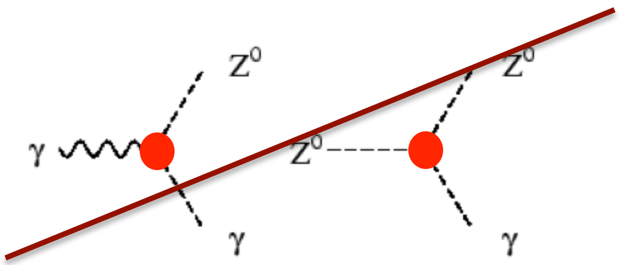
- fundamental prediction of SM
- consequence of SU(2) x U(1) structure of EWK sector

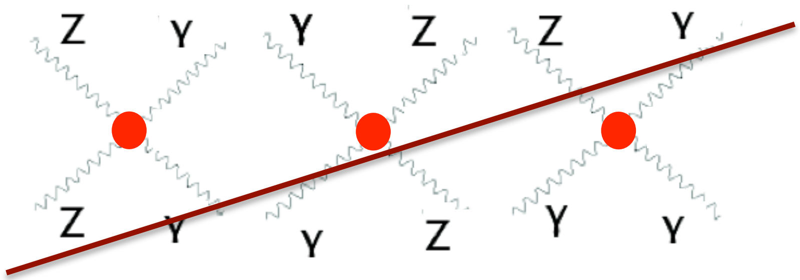
Have exact values in SM





Charged couplings only allowed at tree level, neutral couplings forbidden

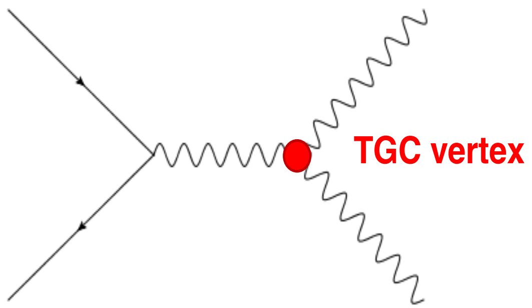




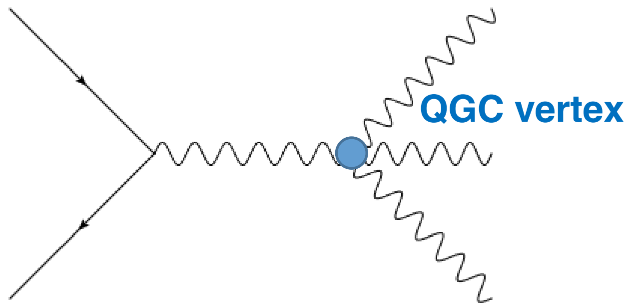
Anomalous Gauge Couplings (aGCs)

Deviation from prediction
Observation of a forbidden coupling → Anomalous coupling

aGCs predicted by many SM extensions
Measurement of aGCs => indirect search for new physics



- Diboson production
- Single boson EWK production
    - not covered



- Triboson production
- Diboson EWK production

Most of ATLAS/CMS analyses measure together cross-section and aGCs

Experimental searches for aGCs

Anomalous coupling => cross-section increase at high energies

Probed looking at:

- measured cross-section wrt expectations
- deviations in the spectrum of sensitive variables
  - eg boson p_T, diboson invariant mass, …
  - different observables for different analyses

Signal model:

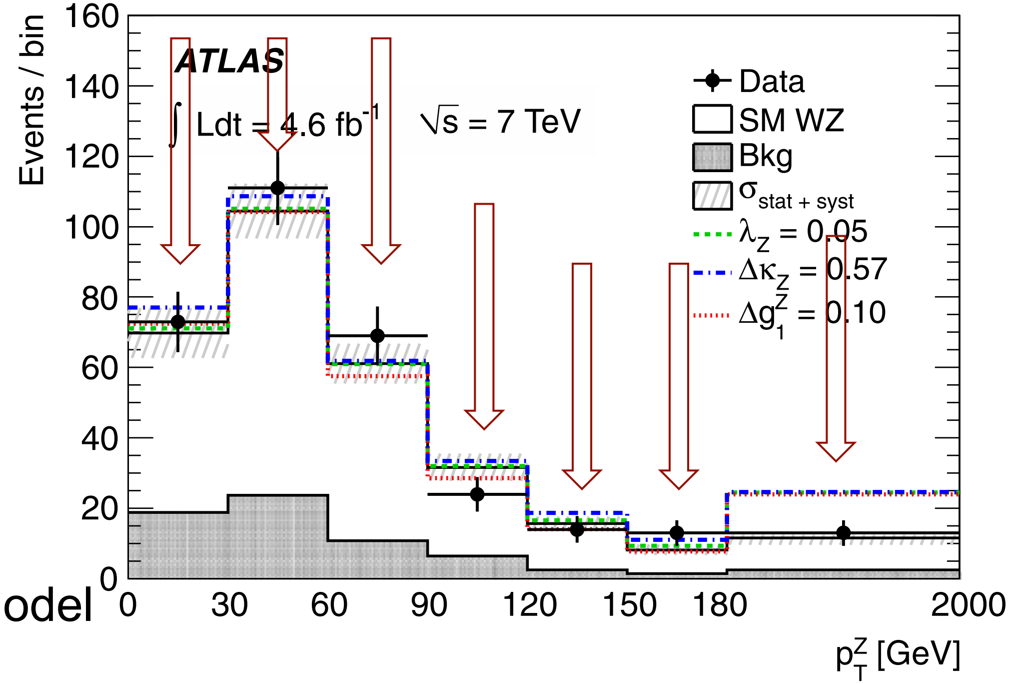
- Expected distributions derived for different parameter values (MC)
- Fit as a function of parameters in each observable bin
  - uncertainties included here

=> 1D or 2D measurement by fitting parameters of interests

Limiting factors:

- observed statistics in the tails
- stat+syst uncertainty on the signal model

Eur.Phys.J.C (2012) 72:2173



aTGC parameterizations

A few parameterizations in usage:

- SM + additional terms up to a fixed energy scale Λ
- as much as possible model independent
- limit number of free parameters imposing symmetries

Effective Lagrangian approach

Charged couplings (WWγ and WWZ vertices)

- 7 parameters each
- C+P conservation: 5 parameters
  - $\Delta\kappa_\gamma = (\kappa_\gamma-1)$, λ_γ, $\Delta g_1^Z = (g_1^Z-1)$, $\Delta\kappa_Z = (k_z-1)$, λ_Z
- C+P+ SU(2)xU(1) gauge invariant Lagrangian with dim6:
  - $\Delta\kappa_\gamma$, $\lambda_\gamma = \lambda_Z$, Δg_1^Z (LEP)

Neutral couplings:

- ZZV vertices:
  - f_4^V : CP-violating, f_5^V : CP-conserving
- ZγV vertices:
  - h_i, i=3 and 4 => CP-conserving

Mostly used so far

Coupling	Parameters	Channel
WWγ	$\Delta\kappa_\gamma$, λ_γ	WW, Wγ
WWZ	Δg_1^Z, $\Delta\kappa_Z$, λ_Z	WW, WZ
ZγZ	h_3^Z, h_4^Z	Zγ
Zγγ	h_3^γ, h_4^γ	Zγ
ZZZ	f_4^Z, f_5^Z	ZZ
ZZγ	f_4^γ, f_5^γ	ZZ

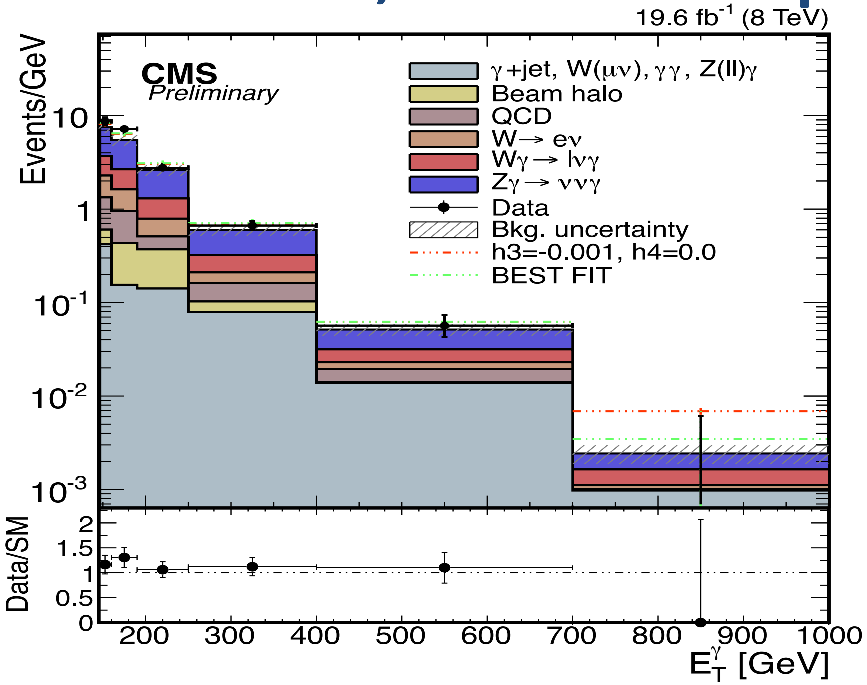
Effective Field theory approach

$$\mathcal{L}_{\text{eff}} = \sum_{n=1}^{\infty} \sum_i \frac{f_i^{(n)}}{\Lambda^n} \mathcal{O}_i^{(n+4)}$$

- higher order operators, valid for sqrt(s) << Λ

Phys.Rev.D41 (1990) 2113
Nucl.Phys. B282 (1987) 253
Phys. Rev. D 47 (1993) 4889
Phys.Rev.D48 (1993) 2182

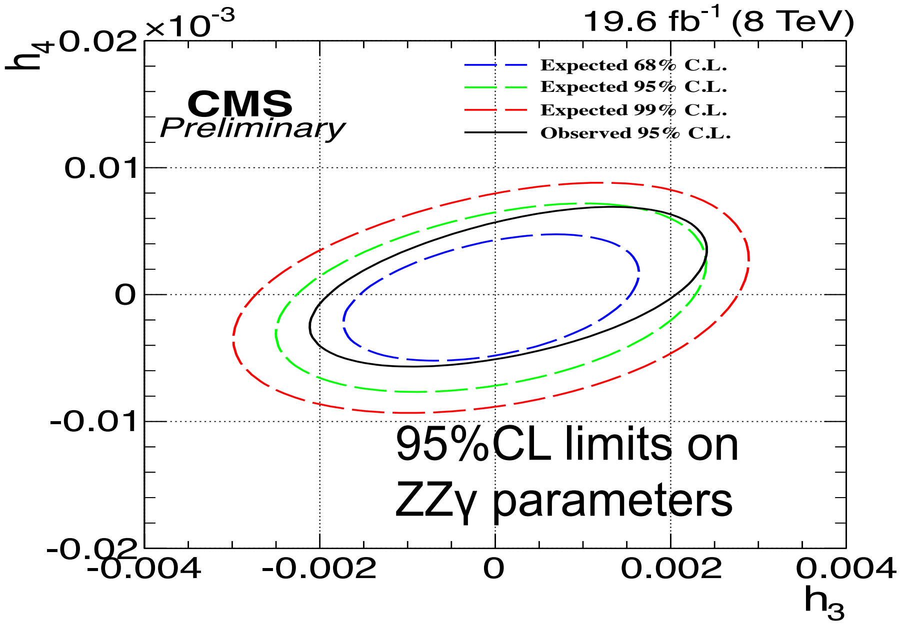
aTGC, an example: Zγ->ννγ at 8TeV **NEW**

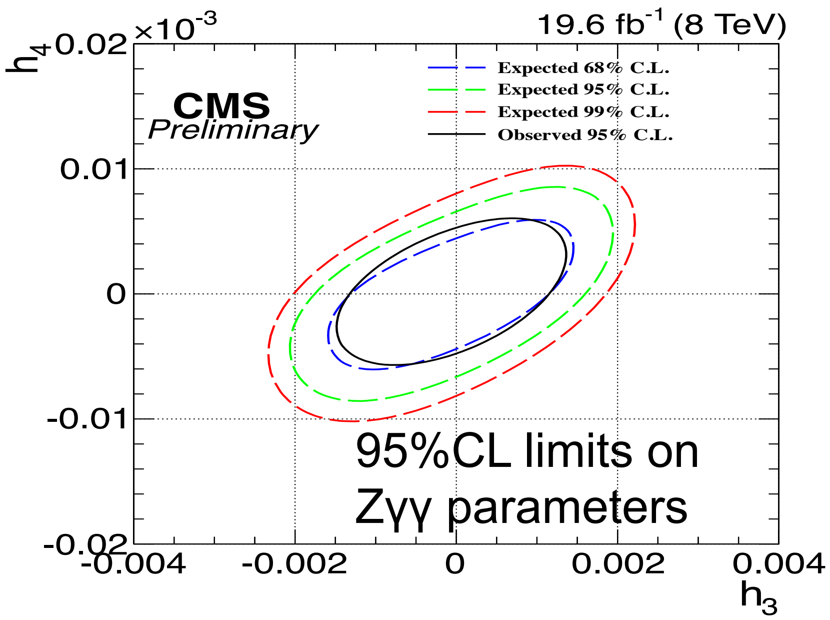


- aTCG signal generated with Sherpa
- Binned fit to $E_T(\gamma)$ spectrum
- No significant deviation in the high $E_T(\gamma)$ tail => limits on parameters

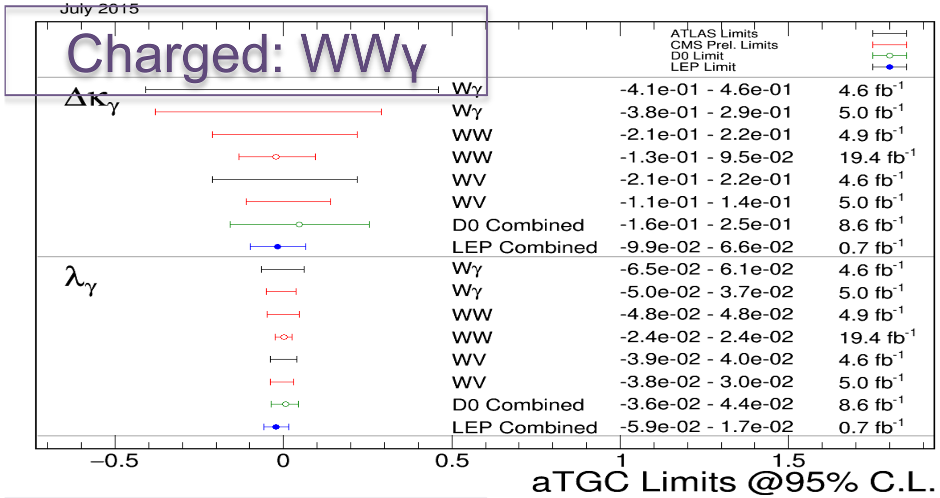
Limit uncertainties statistically dominated

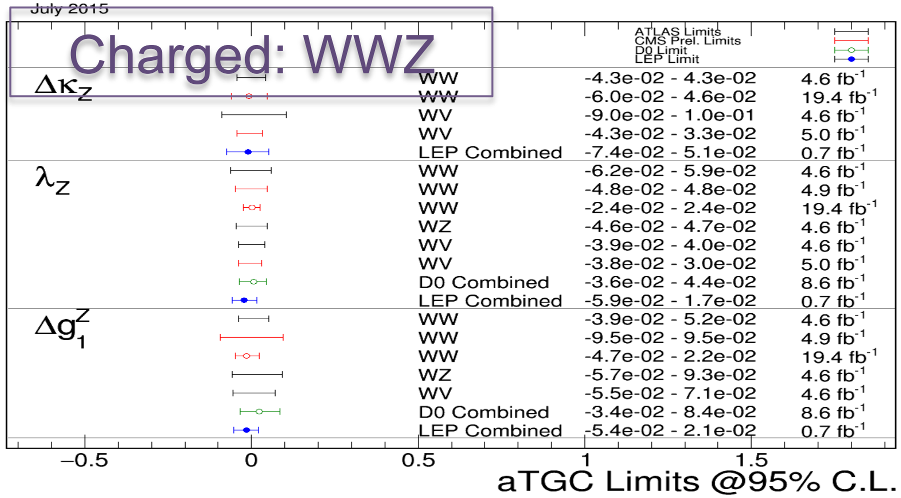
CMS PAS SMP-14-019

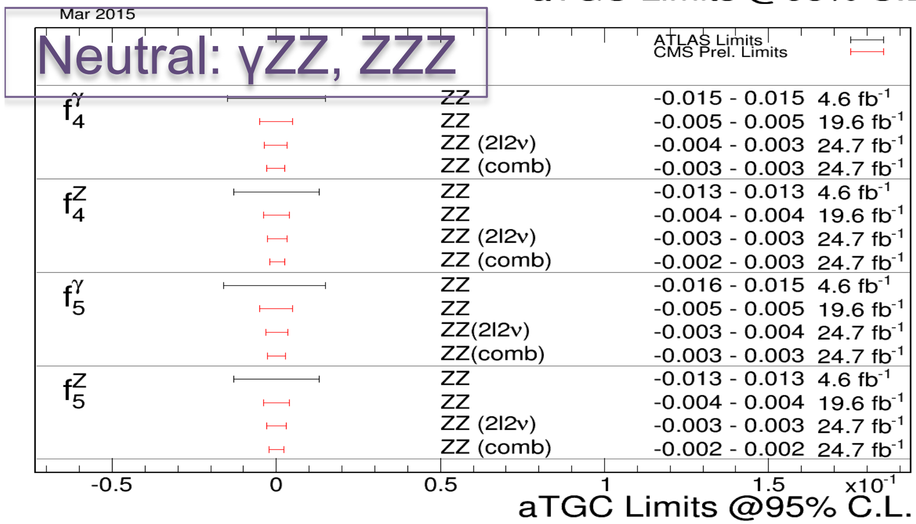


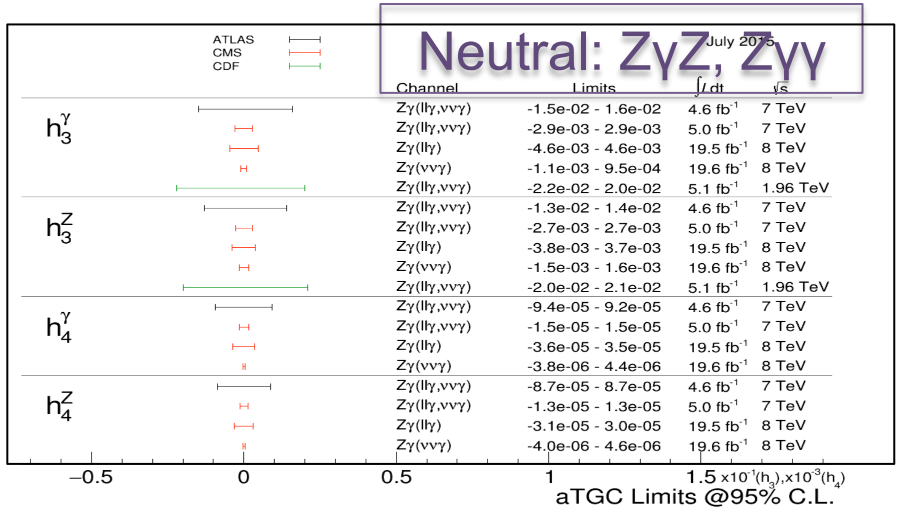


aTGC results









No deviation from SM predictions observed
Sensitivity close to LEP, better than Tevatron
Results at 8TeV improves a lot sensitivity

Channels with a lot of background
(eg Z->2l2v, Zγ->ννγ) very sensitive
(larger BR, higher reach in kinematics)

aQGC parameterizations

$$\mathcal{L}_{\text{eff}} = \sum_{n=1}^{\infty} \sum_i \frac{f_i^{(n)}}{\Lambda^n} \mathcal{O}_i^{(n+4)}$$

Higher order operators respecting symmetries
Assumption: CP conservation

Two formalisms used for quartic couplings:

Non linear

- Spontaneous symmetry breaking without Higgs scalar
- Non-decoupling: valid below ~3TeV scale
- dim6 operators
- **Used by LEP and currently to compare with previous results**

Eur.Phys.J.C13:283-293,2000

Linear:

- Spontaneous symmetry breaking with Higgs
- Decoupling: arbitrary scale of new physics
- Lowest independent aQGC operators: dim8
  - Not affecting aTGCs

Phys.Rev.D74:073005,2006

Mostly used now

Non linear operators: a_0^W/Λ^2, a_c^W/Λ^2, k_0^W/Λ^2, k_c^W/Λ^2…
Linear operators: $f_{T,0}/\Lambda^4$, $f_{M,0}/\Lambda^4$, $f_{M,1}/\Lambda^4$…

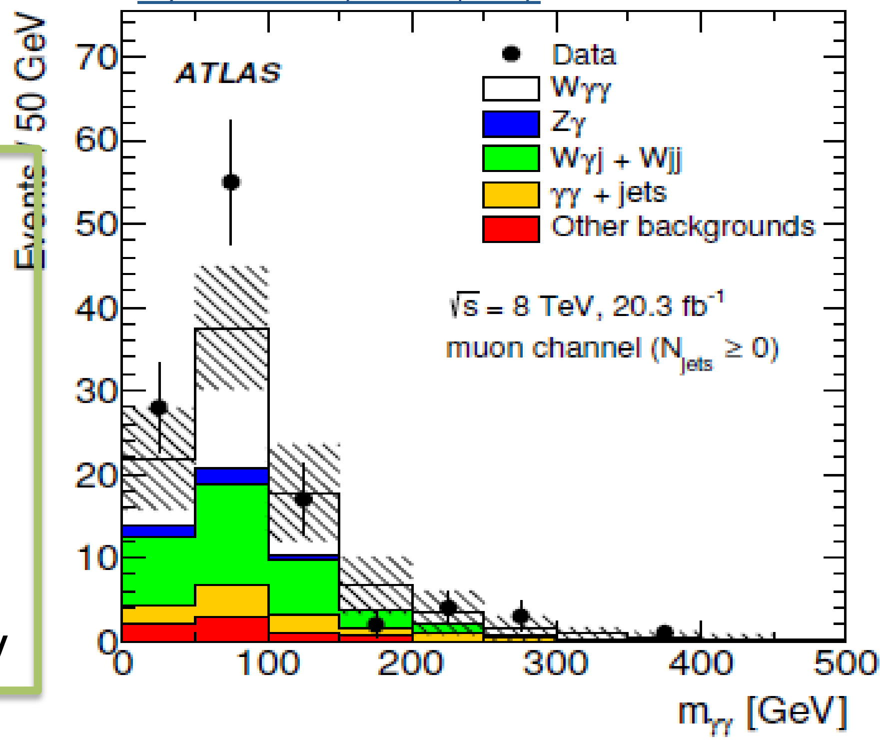
Triboson: Wγγ

Final state: W(->lν)γγ
Inclusive and #jets=0 analysis

Selection:
- lepton/photon p_T>20GeV
- E_T^{miss}>25GeV
- m_T^W>40GeV

Backgrounds:
- fake photon (Wγj+Wjj) and fake lepton (γγ+jets)
  - dominating systematic uncertainty

Phys.Rev.Lett.115, 031802 (2015)



Total significance: 3.7σ (inclusive), 2.1σ (exclusive)
Cross-section larger than MCFM NLO predictions

First evidence of Wγγ

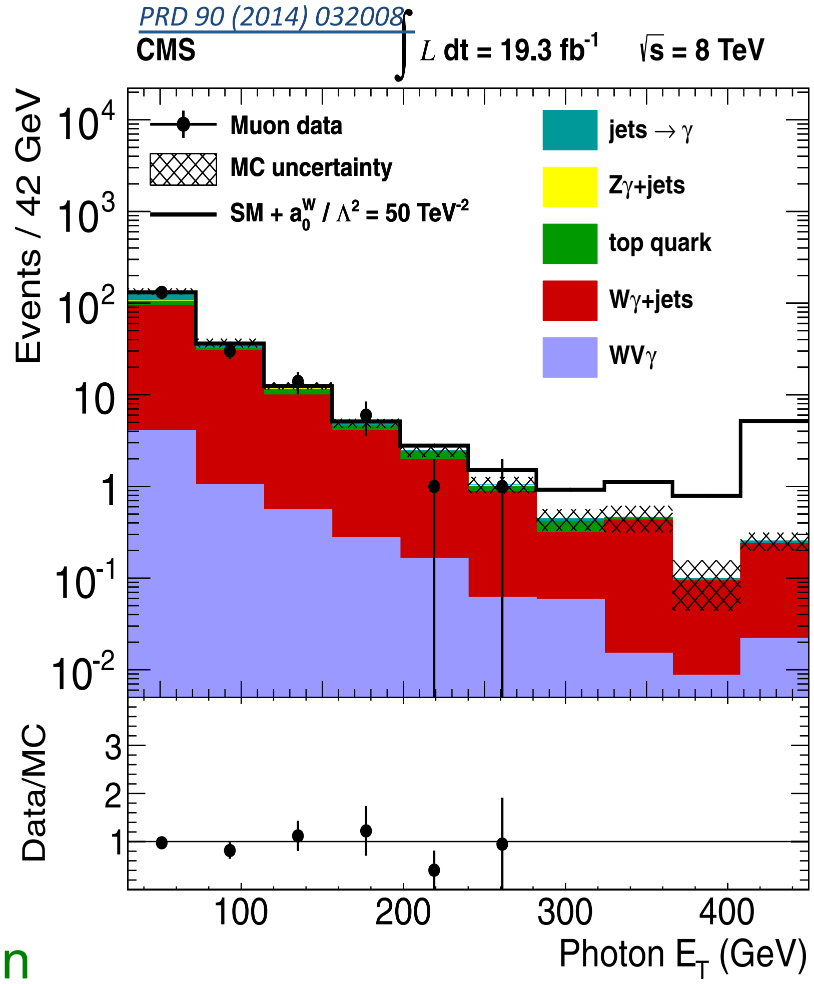
	σ (fiducial) [fb]	MCFM [fb]
Njets>=0	$6.1^{+1.1}_{-1.0}$(stat) ± 1.2(syst) ± 0.2(lumi)	2.90 ± 0.16
Njets=0	$2.9^{+0.8}_{-0.7}$(stat) $^{+1.0}_{-0.9}$(syst) ± 0.1(lumi)	1.88 ± 0.20

Triboson: WVγ->lνjjγ

W -> lν
V (= W or Z) -> jj
Signature: lepton + photon + E_T^{miss} + jets

Selection:
- $p_T(\gamma)$>30GeV
- $p_T(l)$>30/25 GeV
- E_T^{miss}>35GeV, m_T^W>30GeV
- 70<m_{jj}<120GeV
- p_T(jets)>30GeV, btag veto

Backgrounds:
- Wγ+jets (dominant)
- Top, Zγ+jets, jet->γ misidentification



Upper limit at 95%CL on WVγ cross-section
(photon p_T>30GeV and |η|<1.44) = 311fb
- ~3.4 larger than NLO SM predictions (91.6 ± 21.7fb)

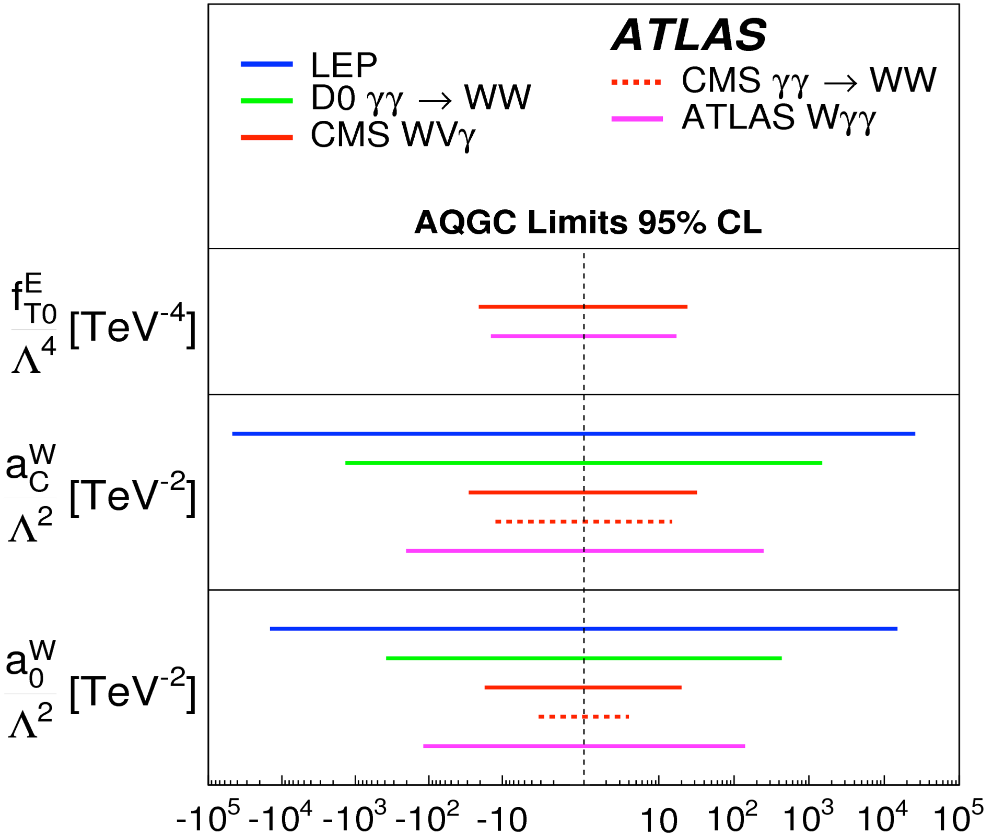
aQGC from triboson channels

(ATLAS) Wγγ

- sensitive to WWγγ
- exclusive xsec with $m_{\gamma\gamma}$>300 GeV used
- form factor computed with VBFNLO

(CMS) WVγ

- sensitive to WWγγ and WWZγ
- photon E_T distribution used
- no form factor



[Phys.Rev.Lett.115, 031802 (2015)](#)
[supporting public material](#)

- Stringent aQGC limits set
- LEP / Tevatron results improved
- Wγγ quite sensitive to T0 operator
- VWγ (and γγ->WW) more sensitive to other operators

No form factor [needed to avoid unitarity violation] applied here

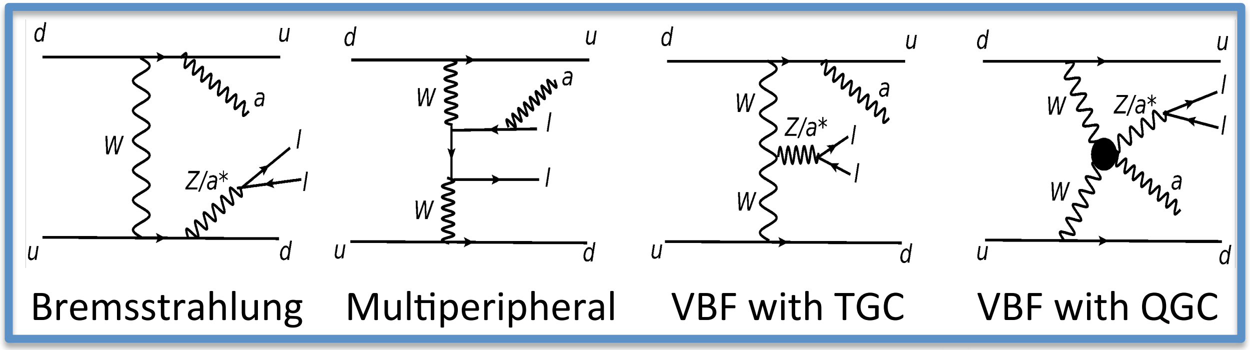
NEW

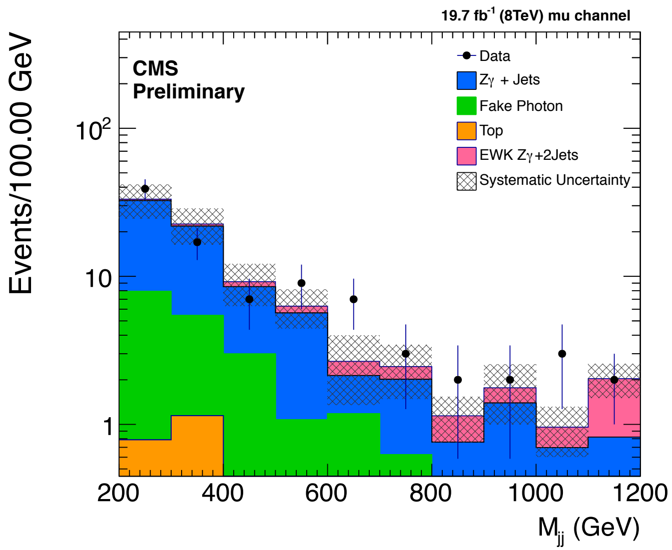
CMS PAS SMP 14-018

Electroweak Zγ+jj

Selection:
$p_T(l)>20$ GeV, $|\eta|<2.4$
$70 < M_{ll}<110$ GeV
$p_T(\gamma)>20$ GeV, $|\eta|<1.44$
p_T (jets)>30 GeV, $|\eta|<4.7$
$M_{jj}>400$ GeV
$|\Delta\eta_{jj}|>2.5$
$|\Delta\varphi_{Z\gamma,jj}|>2.0$ (x-sec)

Main backgrounds:
QCD Zγ+2jets
Z+jets with fake γ





combined measurement, single processes can not be isolated

Good agreement with theory

Mjj> [GeV]	Fiducial σ_{EWK} [fb] 8TeV	Madgraph LO [fb]	Evidence
400	$1.86^{+0.89}_{-0.75}$(stat) $^{+0.41}_{-0.27}$(syst) ± 0.05(lumi)	1.26 ± 0.11(scale) ± 0.05(PDF)	3.0σ
800	1.00 ± 0.43(stat) ± 0.26(syst) ± 0.03(lumi)	0.78 ±0.09(scale) ± 0.02(PDF)	4.3σ

NEW

CMS PAS SMP 14-018

Electroweak Zγ+jj

Selection:

$p_T(l)$>20 GeV, $|\eta|$<2.4

70 < M_{ll}<110 GeV

$p_T(\gamma)$>60 GeV, $|\eta|$<1.44 (aQGC)

p_T (jets)>30 GeV, $|\eta|$<4.7

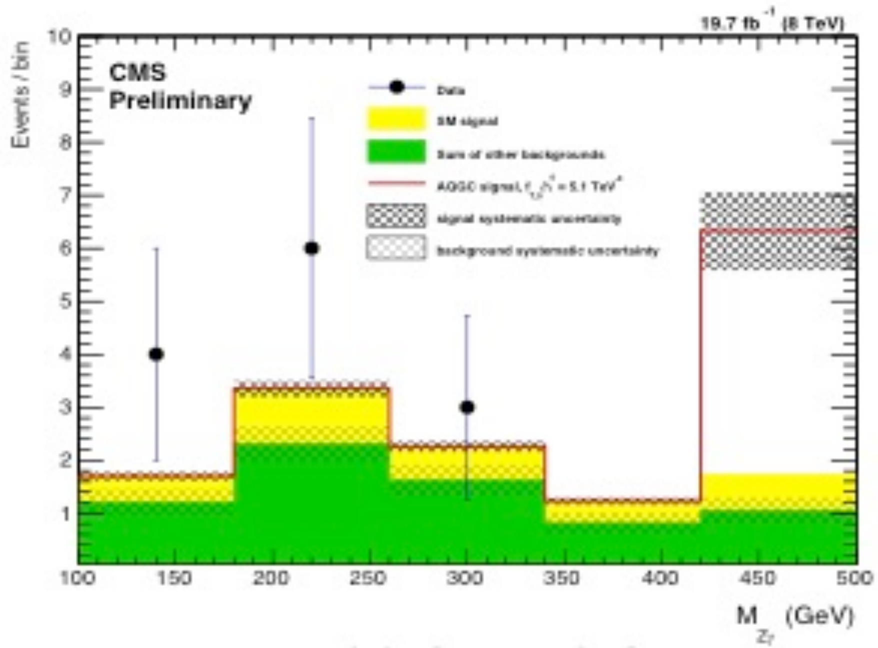
M_{jj}>400 GeV

$|\Delta\eta_{jj}|$>2.5

Main backgrounds:

QCD Zγ+2jets

Z+jets with fake γ

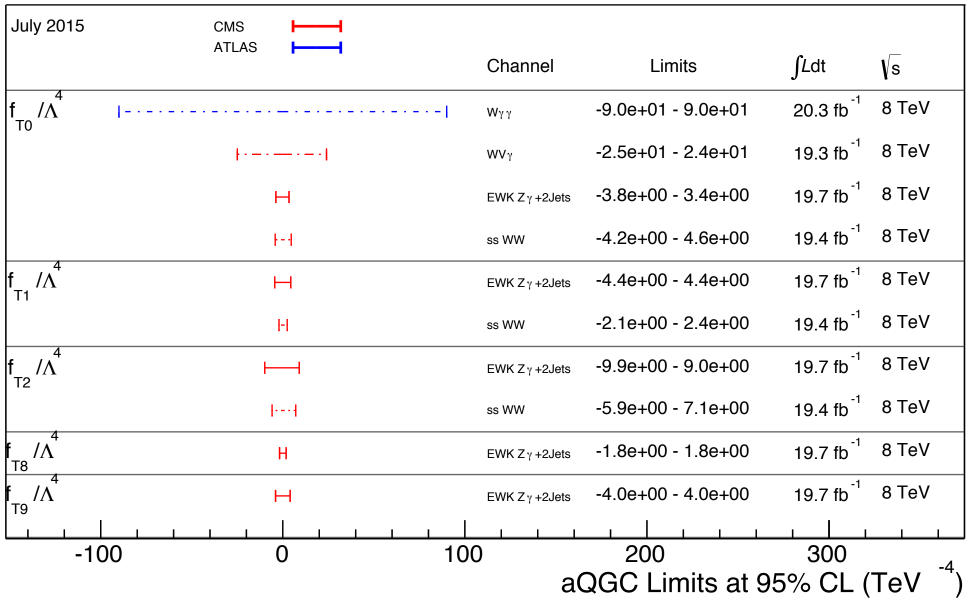


M(Zγ) used to extract aQGC limits

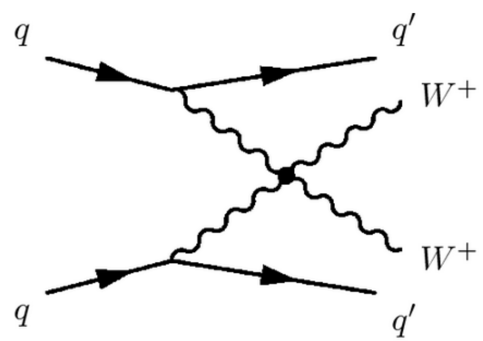
No form-factor applied

Competitive limits set on fM0, fM1, fM2, fM3, fT0, fT1, fT2

First limits set on the neutral couplings fT8 and fT9



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



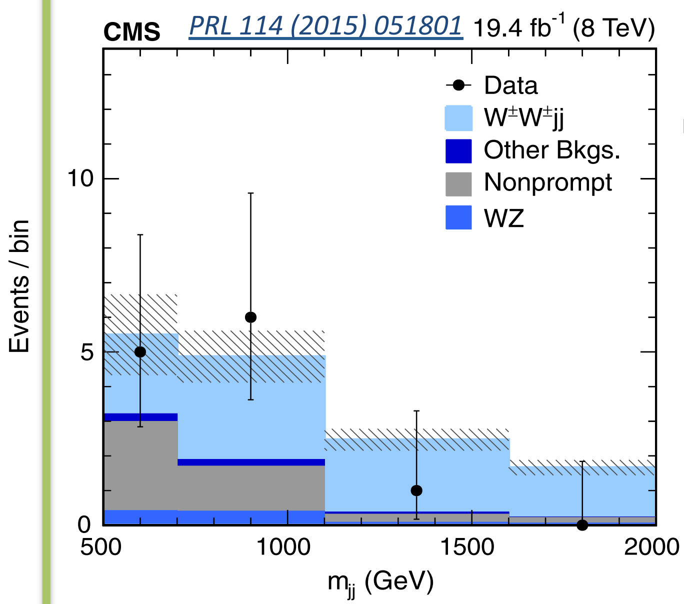
First VBF analysis at LHC: sensitive to WWWW vertex

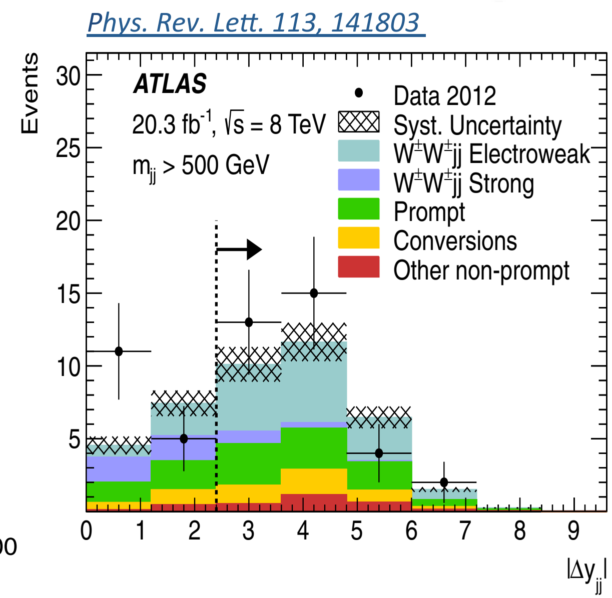
Selection:

Same sign dileptons
$p_T(l)>25$ (20)GeV
Two high p_T jets (30GeV)
$M_{ll}>20$ (50) GeV
$|M_{ll}-M_Z|>10$ (15)GeV
[third lepton veto]
[E_T^{miss} >40GeV]
$M_{jj}>500$ GeV
$|\Delta\eta_{jj}|>2.4$ (2.5)

Main backgrounds:

Non prompt, WZ





	Measured σ_{EWK} [fb] 8TeV	Predicted [fb]	Significance
ATLAS	$1.3 \pm 0.4(stat) \pm 0.2(syst)$	0.95 ± 0.06	3.6σ
CMS	$4.0^{+2.4}_{-2.0}(stat)\ ^{+1.1}_{-1.0}(syst)$	5.8 ± 1.2	2.0σ

ATLAS/CMS, different fiducial regions: not comparable results

Electroweak $W^{\pm}W^{\pm}jj$: aQGCs

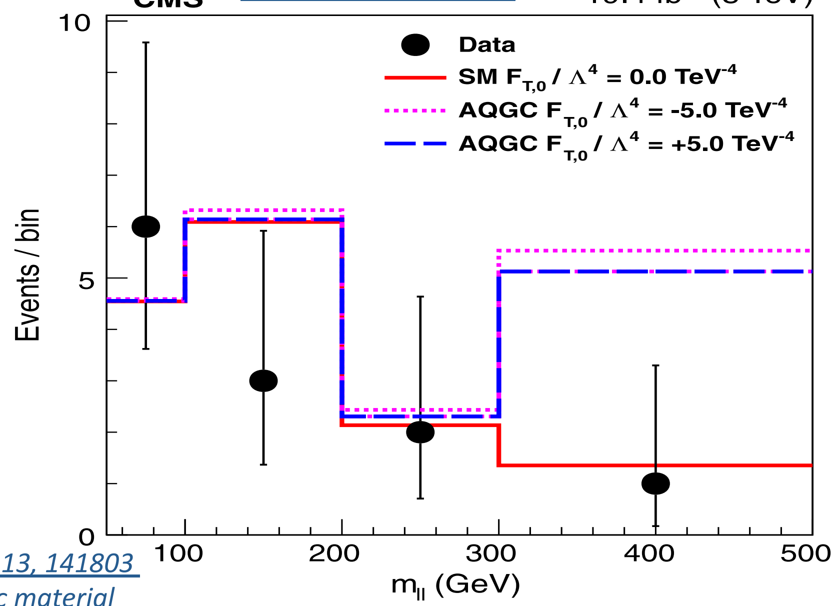
Measurement of QGCs:
ATLAS: measured fiducial xsec in VBS region
CMS: deviations in m_{ll} spectrum

ATLAS: aQGC generated with whizard
- k-matrix unitarization

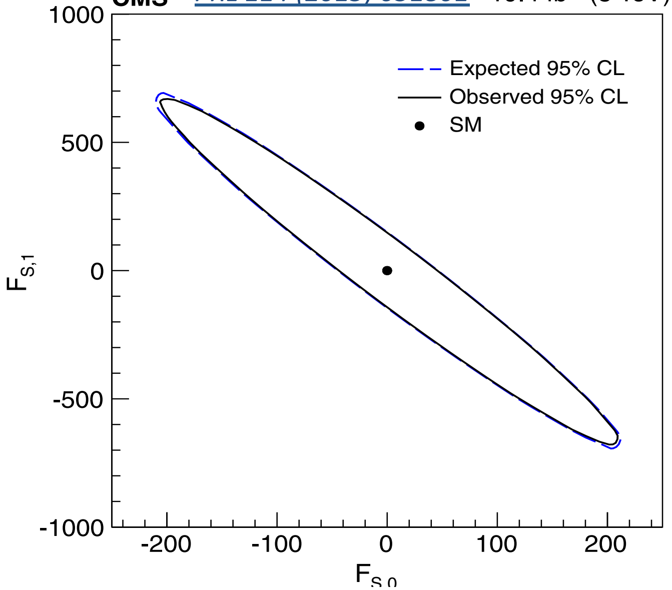
CMS: Madgraph
- no form factors

First WWWW limits set!

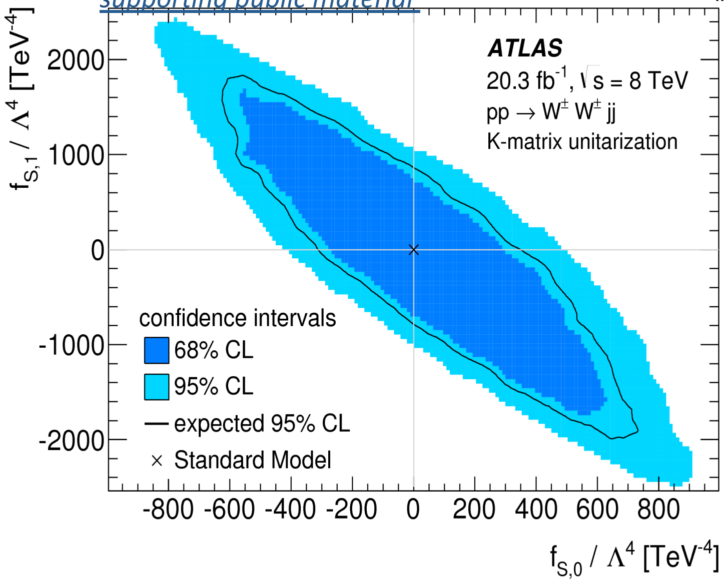
PRL 114 (2015) 051801



PRL 114 (2015) 051801



Phys. Rev. Lett. 113, 141803 supporting public material



Limits on $F_{S,0/1}/\Lambda^4$

LHC Run2 has started

Many measurements are currently statistically limited

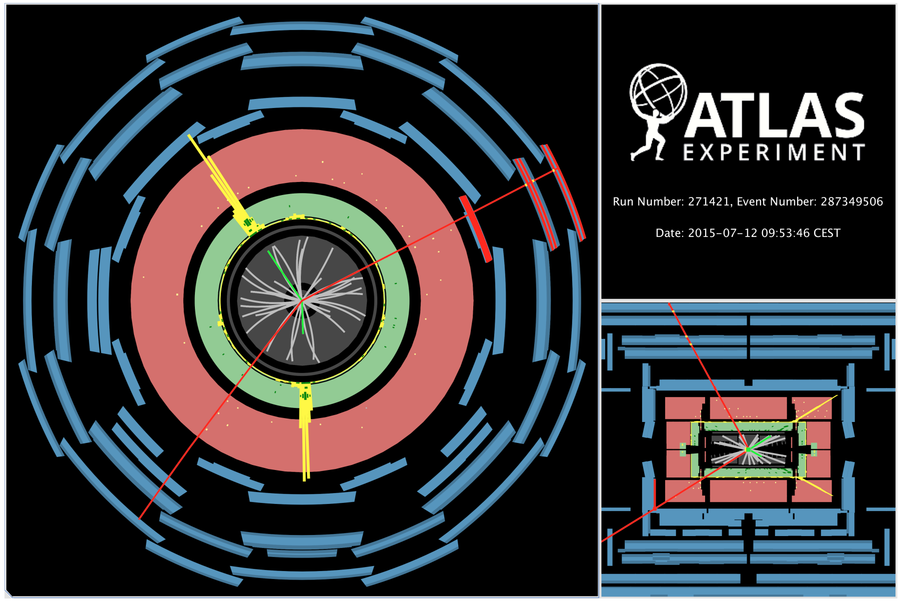
- in control region or in signal region
- in the high p_T / mass / … tail where aGC measurements are sensitive

⇒ Major improvement expected due to larger cross-section at 13 TeV

Anomalous coupling signals increase with energy

- Run2 will give soon better results

Many studies expected on VBS, triboson, aQGCs….
And (of course!) cross-section measurements at a new energy



Conclusions

Multiboson measurements allow precise comparison between data and theory

Overall good agreement observed in cross-sections

- only a few 1-2σ differences
- in some cases sensitivity to NNLO reached

8TeV LHC data: evidence for triboson production and vector boson scattering

No hint of anomalous gauge couplings so far:
strong limits on aTGCs and aQGCs set

More measurements with full 8TeV dataset coming soon…

… And interesting results expected for RunII as well!

ATLAS
CMS

Bibliography

7TeV

- γγ
  - JHEP 01 (2013) 086
  - EPJC 74 (2014) 3129
- WW (2l2ν)
  - Phys.Rev.D87,112001 (2013)
  - EPJC 73 (2013) 2610
- WZ (3lν)
  - Eur.Phys.J.C (2012) 72:2173
  - CMS PAS SMP-12-006
- ZZ (4l)
  - JHEP 03 (2013) 128
  - JHEP 01 (2013) 063
- ZZ (2l2ν)
  - SMP-12-016 (submitted to EPJC)
- Semileptonic WV
  - JHEP 01 (2015) 049
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- Wγ (lνγ)
  - Phys. Rev. D 87, 112003
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  - Phys. Rev. D 87, 112003
  - JHEP 10 (2013) 164

8TeV

- WW (2l2ν)
  - ATLAS-CONF-2014-033
  - SMP-14-016 (submitted to EPJC)
- WZ (3lν)
  - ATLAS-CONF-2013-021
  - CMS PAS SMP-12-006
- ZZ (4l)
  - ATLAS-CONF-2013-020
  - PLB 740 (2015) 250
- ZZ (2l2ν)
  - SMP-12-016 (submitted to EPJC)
- Semileptonic WV
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- Zγ (llγ)
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- Zγ (ννγ)
  - CMS PAS SMP-14-019
- WVγ
  - PRD 90 (2014) 032008
- EWK $W^{\pm}W^{\pm}jj$
  - Phys. Rev. Lett. 113, 141803
  - PRL 114 (2015) 051801
- Wgg
  - Phys.Rev.Lett.115, 031802 (2015)
- EWK Zγjj
  - CMS PAS SMP-14-018

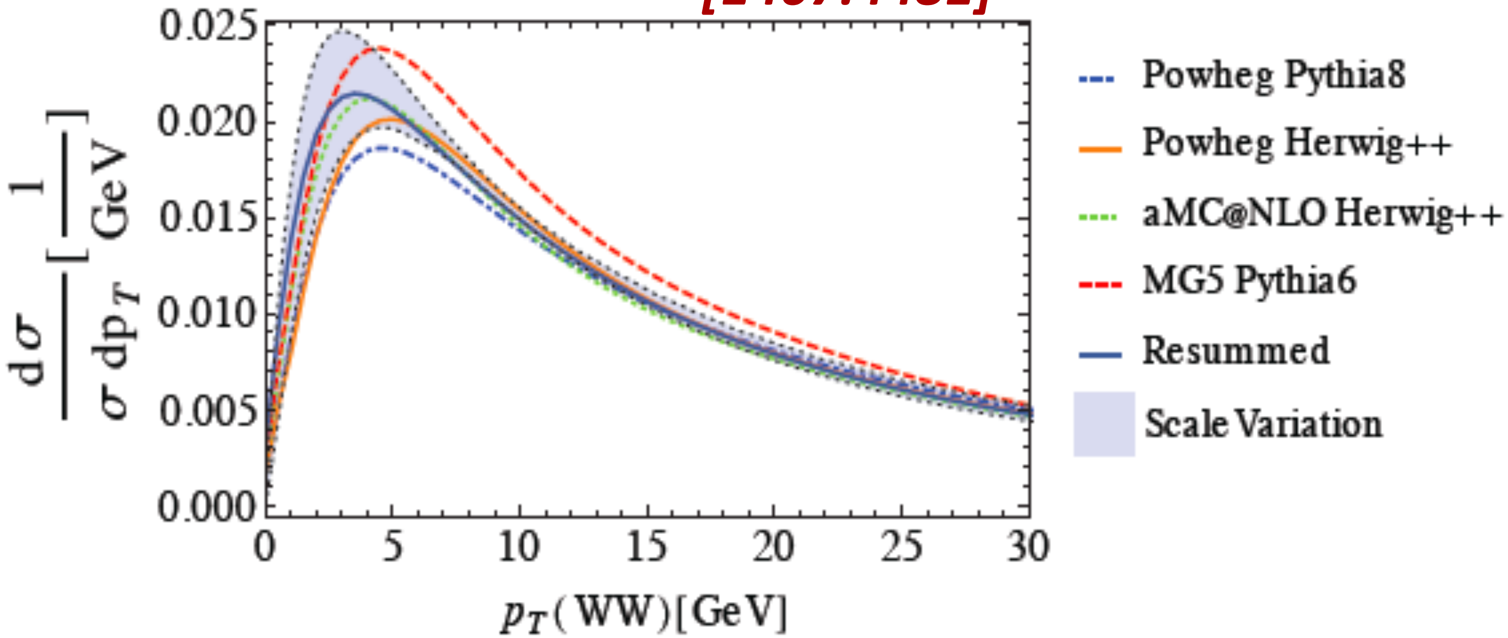
Backup

WW – gluon resummation

The 0-1 jet bin applied in the analysis makes the kinematical distributions sensitive to higher order QCD corrections

CMS:
To improve the modeling of gluon resummation:
reweight p_T(WW) of qq->WW MC to a NLO+NNLL p_T resummation calculation
$\Rightarrow$ strongly correlated with jet veto because of the p_T of jets

[1407.4481]



WW theoretical cross-section

Process	Cross section [pb]	Scale [pb]	PDF+α_s [pb]	Branching fraction [pb]	Calculation	Total [pb]
$q\bar{q} \to WW$	53.2	$^{+2.3}_{-1.9}$	$^{+1.0}_{-1.1}$	-	NLO MCFM [1]	$^{+2.5}_{-2.2}$
$gg \to WW$	1.4	$^{+0.3}_{-0.2}$	$^{+0.1}_{-0.1}$	-	LO MCFM [1]	$^{+0.3}_{-0.2}$
$gg \to H \to WW$	4.1	$\pm$ 0.3	$\pm$0.3	$\pm$0.2	NNLO+NNLL QCD, NLO EW [3]	$\pm$0.5

qq->WW, gg->WW: PDF = CT10
gg->H->WW: PDF = MSTW2008

ATLAS

$\frac{\sqrt{s}}{\text{TeV}}$	σ_{LO}	σ_{NLO}	σ_{NNLO}	$\sigma_{gg\to H\to WW^*}$
7	$29.52^{+1.6\%}_{-2.5\%}$	$45.16^{+3.7\%}_{-2.9\%}$	$49.04^{+2.1\%}_{-1.8\%}$	$3.25^{+7.1\%}_{-7.8\%}$
8	$35.50^{+2.4\%}_{-3.5\%}$	$54.77^{+3.7\%}_{-2.9\%}$	$59.84^{+2.2\%}_{-1.9\%}$	$4.14^{+7.2\%}_{-7.8\%}$
13	$67.16^{+5.5\%}_{-6.7\%}$	$106.0^{+4.1\%}_{-3.2\%}$	$118.7^{+2.5\%}_{-2.2\%}$	$9.44^{+7.4\%}_{-7.9\%}$
14	$73.74^{+5.9\%}_{-7.2\%}$	$116.7^{+4.1\%}_{-3.3\%}$	$131.3^{+2.6\%}_{-2.2\%}$	$10.64^{+7.5\%}_{-8.0\%}$

CMS, from
Phys.Rev.Lett. 113 (2014) 212001

ABLE I. LO, NLO and NNLO cross sections (in picobarn) r on-shell W^+W^- production in the 4FNS and reference sults for $gg \to H \to WW^*$ from Ref. [75].

CMS PAS SMP 14-018

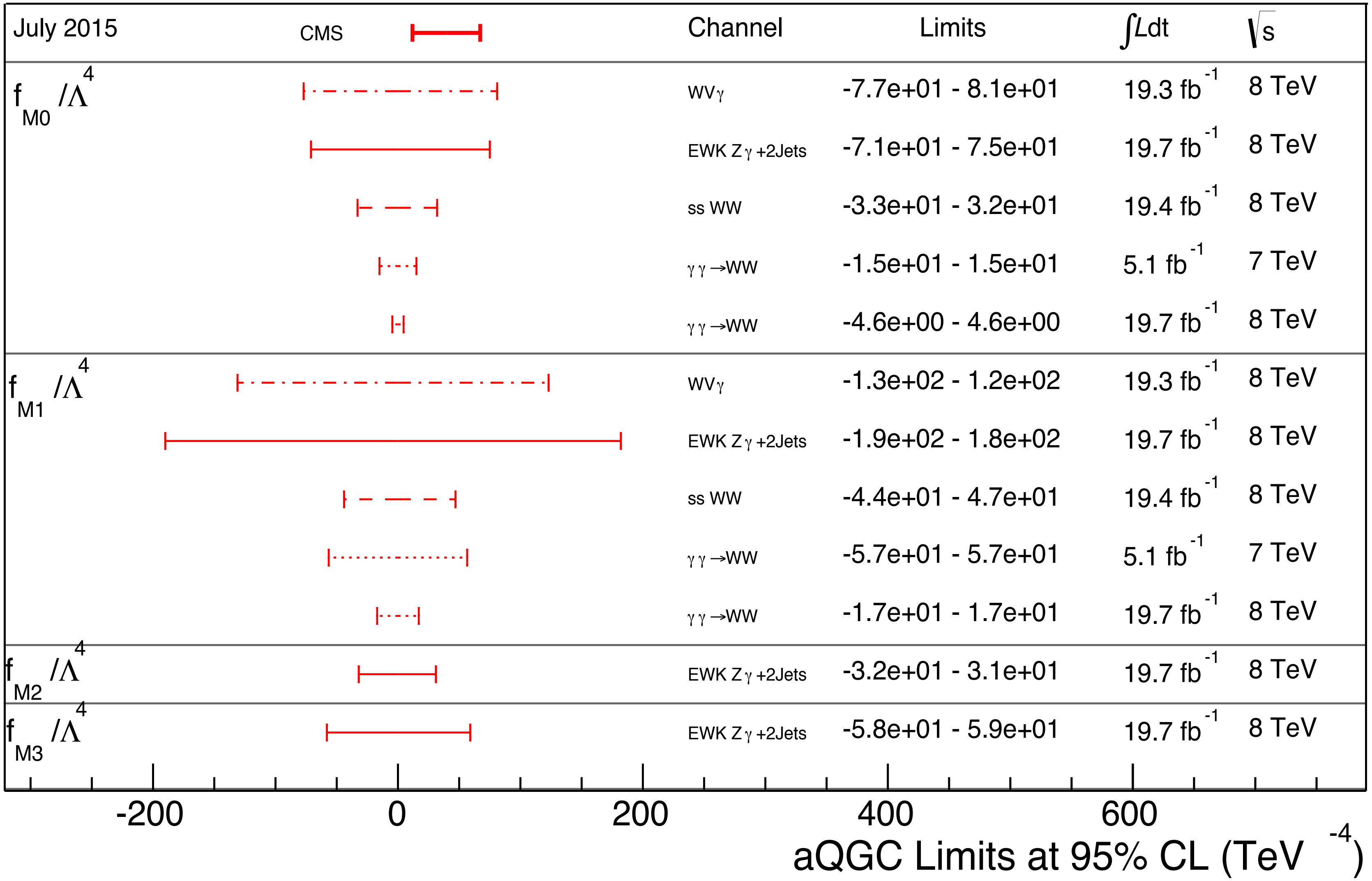
Electroweak Zγ+jj

Observed Limits	Expected Limits
$-71\ (\mathrm{TeV}^{-4}) < f_{M0}/\Lambda^4 < 75\ (\mathrm{TeV}^{-4})$	$-109\ (\mathrm{TeV}^{-4}) < f_{M0}/\Lambda^4 < 111\ (\mathrm{TeV}^{-4})$
$-190\ (\mathrm{TeV}^{-4}) < f_{M1}/\Lambda^4 < 182\ (\mathrm{TeV}^{-4})$	$-281\ (\mathrm{TeV}^{-4}) < f_{M1}/\Lambda^4 < 280\ (\mathrm{TeV}^{-4})$
$-32\ (\mathrm{TeV}^{-4}) < f_{M2}/\Lambda^4 < 31\ (\mathrm{TeV}^{-4})$	$-47\ (\mathrm{TeV}^{-4}) < f_{M2}/\Lambda^4 < 47\ (\mathrm{TeV}^{-4})$
$-58\ (\mathrm{TeV}^{-4}) < f_{M3}/\Lambda^4 < 59\ (\mathrm{TeV}^{-4})$	$-87\ (\mathrm{TeV}^{-4}) < f_{M3}/\Lambda^4 < 87\ (\mathrm{TeV}^{-4})$
$-3.8\ (\mathrm{TeV}^{-4}) < f_{T0}/\Lambda^4 < 3.4\ (\mathrm{TeV}^{-4})$	$-5.1\ (\mathrm{TeV}^{-4}) < f_{T0}/\Lambda^4 < 5.1\ (\mathrm{TeV}^{-4})$
$-4.4\ (\mathrm{TeV}^{-4}) < f_{T1}/\Lambda^4 < 4.4\ (\mathrm{TeV}^{-4})$	$-6.5\ (\mathrm{TeV}^{-4}) < f_{T1}/\Lambda^4 < 6.5\ (\mathrm{TeV}^{-4})$
$-9.9\ (\mathrm{TeV}^{-4}) < f_{T2}/\Lambda^4 < 9.0\ (\mathrm{TeV}^{-4})$	$-14.0\ (\mathrm{TeV}^{-4}) < f_{T2}/\Lambda^4 < 14.5\ (\mathrm{TeV}^{-4})$
$-1.8\ (\mathrm{TeV}^{-4}) < f_{T8}/\Lambda^4 < 1.8\ (\mathrm{TeV}^{-4})$	$-2.7\ (\mathrm{TeV}^{-4}) < f_{T8}/\Lambda^4 < 2.7\ (\mathrm{TeV}^{-4})$
$-4.0\ (\mathrm{TeV}^{-4}) < f_{T9}/\Lambda^4 < 4.0\ (\mathrm{TeV}^{-4})$	$-6.0\ (\mathrm{TeV}^{-4}) < f_{T9}/\Lambda^4 < 6.0\ (\mathrm{TeV}^{-4})$

Parameterized by Zγ mass

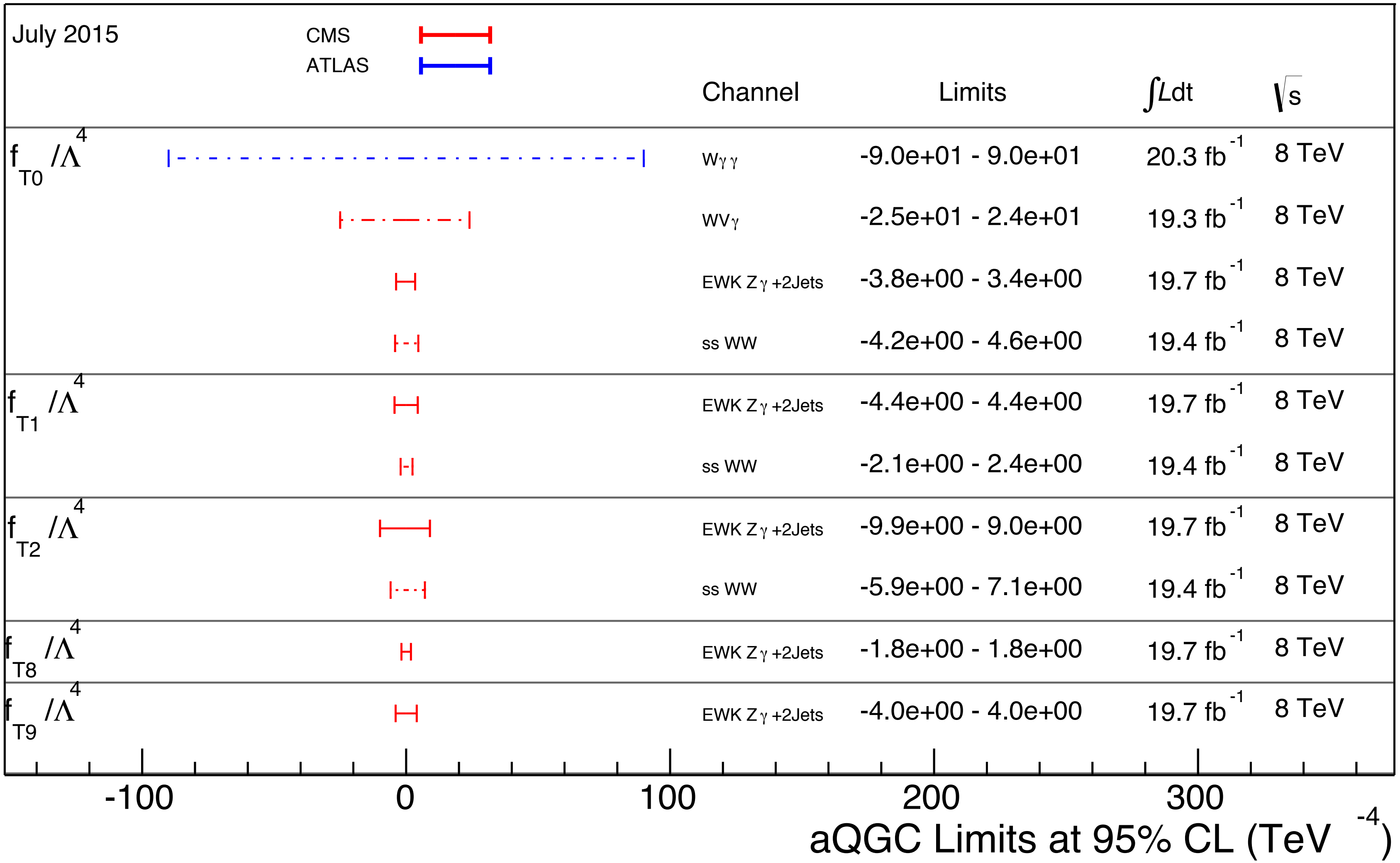
CMS PAS SMP 14-018

Electroweak Zγ+jj



CMS PAS SMP 14-018

Electroweak Zγ+jj



aTGC parameterizations

A few parameterizations in usage:

- SM + additional terms up to a fixed energy scale Λ
- as much as possible model independent

Effective Lagrangian approach

Phys.Rev.D41 (1990) 2113
Nucl.Phys. B282 (1987) 253

Charged couplings: WWγ and WWZ vertices

$$\mathcal{L}_{SM} \longrightarrow \mathcal{L}_{WWV} = -ig_{WWV}\Big\{ g_1^V \left(W^+_{\mu\nu} W^{-\mu} V^{\nu} - W^+_{\mu} V_{\nu} W^{-\mu\nu} \right) + \kappa_V W^+_{\mu} W^-_{\nu} V^{\mu\nu} + \frac{\lambda_V}{m_W^2} W^+_{\mu\nu} W^{-\nu\rho} V_{\rho}{}^{\mu} - i g_5^V \epsilon^{\mu\nu\rho\sigma} \left[W^+_{\mu} (\partial_\rho W^-_{\nu}) - (\partial_\rho W^+_{\mu}) W^-_{\nu} \right] V_\sigma \Big\} ,$$

- 7 parameters each
- imposing C and P conservation: 5 remaining parameters
  - using deviations from SM: $\Delta\kappa_\gamma = (\kappa_\gamma - 1)$, λ_γ, $\Delta g_1^Z = (g_1^Z - 1)$, $\Delta\kappa_Z = (k_z - 1)$, λ_Z
- possibility to reduce further:
  - eg LEP => SU(2)xU(1) gauge invariant Lagrangian with dim6 => 3 parameters only: $\Delta\kappa_\gamma$ $\lambda_\gamma = \lambda_Z$, Δg_1^Z

Mostly used so far

Neutral couplings:

- ZZV vertices:
  - f_4^V : CP-violating, f_5^V : CP-conserving
- ZγV vertices: Phys. Rev. D 47 (1993) 4889
  - h_i, i=1 and 2 => CP-violating
  - h_i, i=3 and 4 => CP-conserving (commonly used)

Coupling	Parameters	Channel
WWγ	$\Delta\kappa_\gamma$, λ_γ	WW, Wγ
WWZ	Δg_1^Z, $\Delta\kappa_Z$, λ_Z	WW, WZ
ZγZ	h_3^Z, h_4^Z	Zγ
Zγγ	h_3^γ, h_4^γ	Zγ
ZZZ	f_4^Z, f_5^Z	ZZ
ZZγ	f_4^γ, f_5^γ	ZZ

Effective Field theory approach

$$\mathcal{L}_{\rm eff} = \sum_{n=1}^{\infty} \sum_i \frac{f_i^{(n)}}{\Lambda^n} \mathcal{O}_i^{(n+4)}$$

Phys.Rev.D48 (1993) 2182

- higher order operators, valid for sqrt(s) << Λ

aTGCs: EFT approach

$$\mathcal{L}_{\text{eff}} = \sum_{n=1}^{\infty} \sum_{i} \frac{f_i^{(n)}}{\Lambda^n} \mathcal{O}_i^{(n+4)}$$

Coupling	Parameters
WWγ, WWZ	f_{WWW}/Λ^2, f_B/Λ^2, f_W/Λ^2 (all dim6)

- valid for sqrt(s) << Λ
- SU(3)xSU(2)xU(1) invariance by construction
- O_i = operator of energy dimension n
- f_i = adimensional couplings (~1)
- only first terms relevant because suppressed by sqrt(s)/Λ => dominant contribution dim=6

Assuming CP conservation => 3 independent parameters:

$$\mathcal{O}_{WWW} = \mathrm{Tr}[\hat{W}_{\mu\nu}\hat{W}^{\nu\rho}\hat{W}_{\rho}{}^{\mu}],$$
$$\mathcal{O}_{W} = (D_\mu\Phi)^\dagger \hat{W}^{\mu\nu}(D_\nu\Phi),$$
$$\mathcal{O}_{B} = (D_\mu\Phi)^\dagger \hat{B}^{\mu\nu}(D_\nu\Phi)\ .$$

EFT <=> Effective lagrangian

$$g_1^Z = 1 + f_W \frac{m_Z^2}{2\Lambda^2}\ ,$$
$$\kappa_Z = 1 + [f_W - s^2(f_B + f_W)] \frac{m_Z^2}{2\Lambda^2}\ ,$$
$$\kappa_\gamma = 1 + (f_B + f_W) \frac{m_W^2}{2\Lambda^2}\ ,$$
$$\lambda_\gamma = \lambda_Z = \frac{3m_W^2 g^2}{2\Lambda^2} f_{WWW} = \lambda\ ,$$

with $s = \sin\theta_W$.

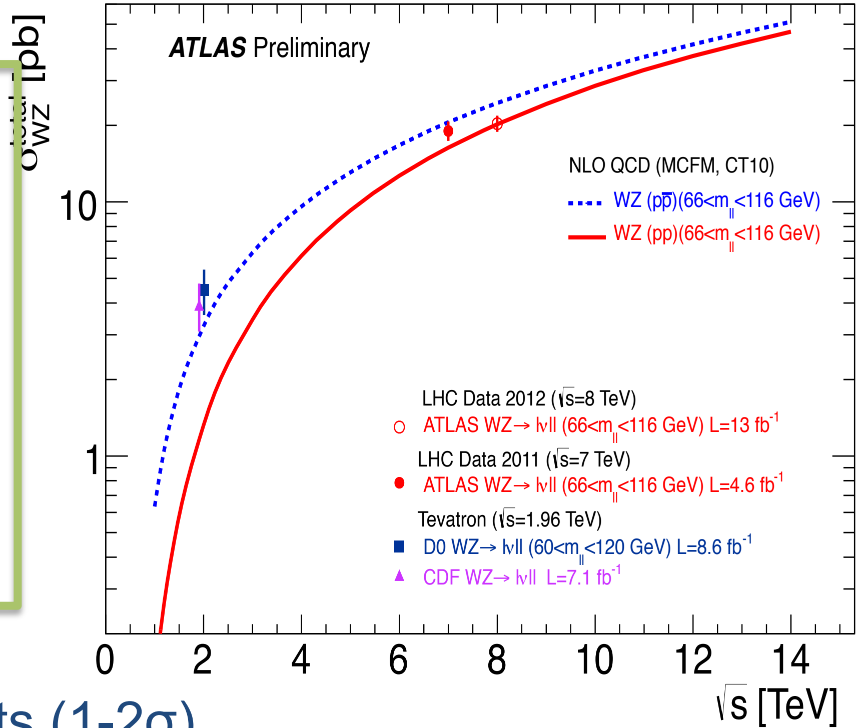
WZ-> 3leptons

Signature: 3 isolated leptons + E_T^{miss}

Selection:
- 3 leptons, p_T >20(10) GeV
- E_T^{miss}>25-30GeV (m_T^W cut)
- m_{ll} window
  - ±20GeV CMS; ±10GeV ATLAS

Main background:
- 1 fake+2 real leptons: Z+jets
  - dominating systematic uncertainty

ATLAS-CONF-2013-021



At 7/8TeV, small excess in ¾ measurements (1-2σ)

σ (fiducial) [pb] 8TeV	MCFM [pb]
CMS: 24.61±0.76(stat) ±1.13(syst) ±1.08(lumi)	$21.91^{+1.17}_{-0.88}$
Atlas: $20.3^{+0.8}_{-0.7}$(stat) $^{+1.2}_{-1.1}$(syst) $^{+0.7}_{-0.6}$(lumi)	20.3 ± 0.8

W+Z / W-Z x-sec ratio also measured

CMS: 1.81 ± 0.12 (stat) ± 0.03 (syst) (exp: 1.724 ± 0.003)