Triboson Production at the LHC

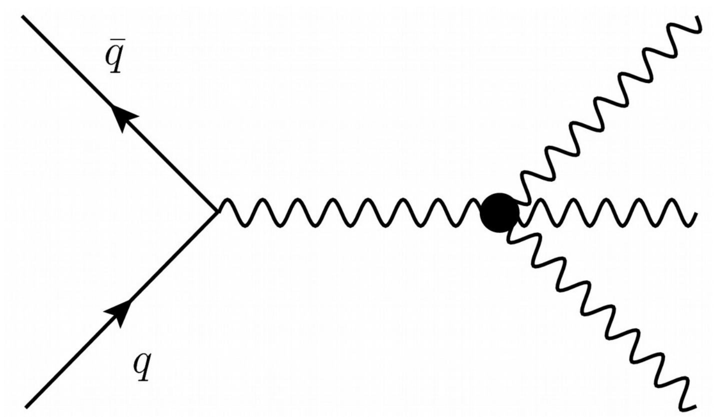
Julia I. Djuvsland

KIP – Heidelberg University

WWγ & WZγ, W$\gamma\gamma$, Z$\gamma\gamma$ and WWW

Motivation

- Measure quartic gauge couplings
  Fixed by gauge structure in SM → Test of electroweak sector
- Complementary to the VBS analyses
  Advantage: 3 particles of the vertex are identified
- Model independent search for new physics
  Interpreted in terms of anomalous quartic gauge couplings
- Charged processes accessible for the first time
  $W\gamma\gamma$ and WWW



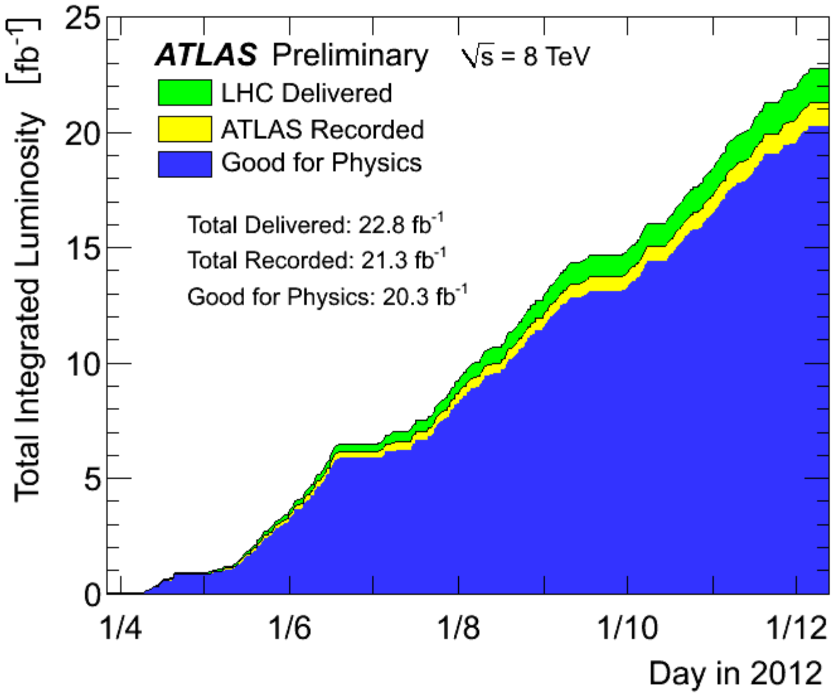
Overview

In order of appearance: $WW\gamma$ &$WZ\gamma$, $W\gamma\gamma$, $Z\gamma\gamma$, WWW

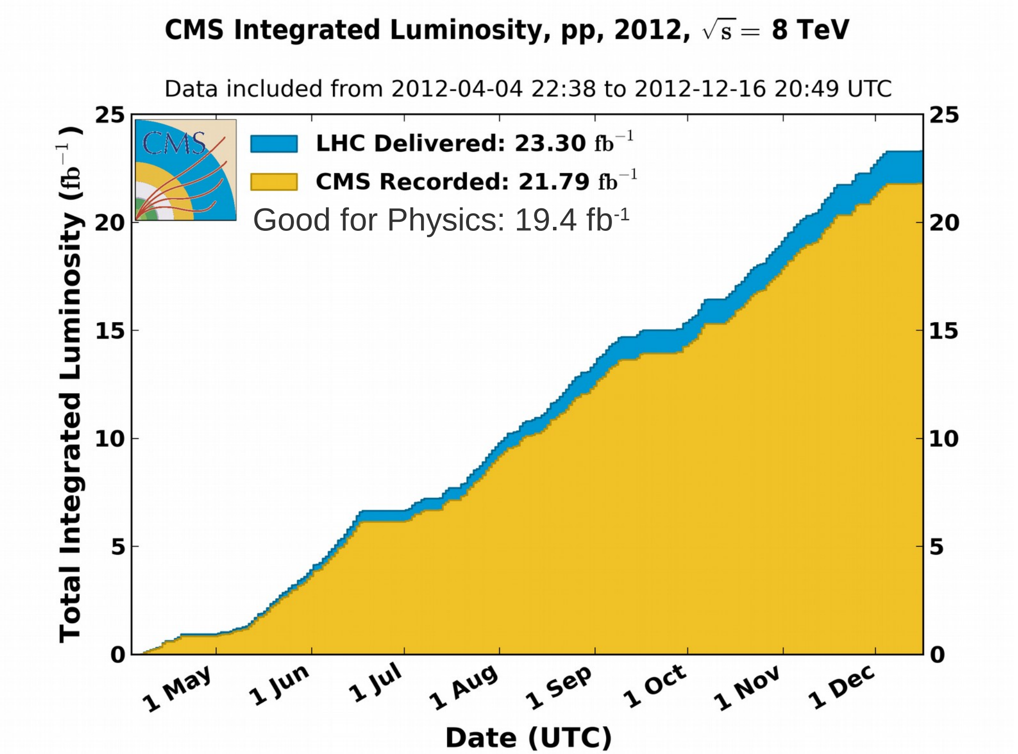
→ First discuss SM measurements, then BSM limits

Typically low cross section → need large data sets

All measurements use full Run 1 statistics at 8 TeV



https://atlas.web.cern.ch/Atlas/GROUPS/DATAPREPARATION/PublicPlots/2011-2012/Luminosity/intlumivstime2012DQ.png



http://cms-service-lumi.web.cern.ch/cms-service-lumi/publicplots/int_lumi_per_day_cumulative_pp_2012.png

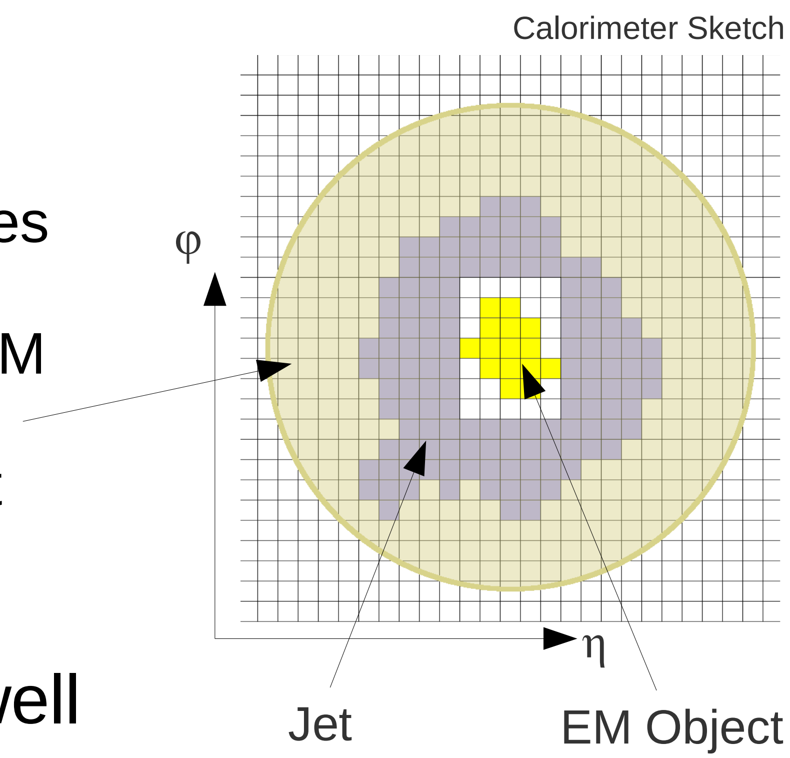
Generals

Challenge: Isolate signal from backgrounds

- Backgrounds from detector effects (misidentified or mismeasured objects) sizeable due to low signal statistics
  → Usually not well modelled
  → Use data driven methods:

  e. g. exploit difference in shower shapes

  - Hadronic showers much wider than EM
  - Good discriminator: isolation energy = energy deposited around EM object



- Irreducible backgrounds typically well described and measured
  → Estimated using Monte Carlo

CMS - WWγ & WZγ production

Phys. Rev. D 90, 032008 - Published 25 August 2014

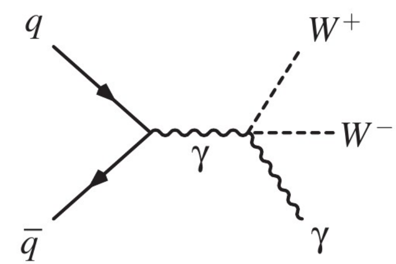
First triboson analysis at the LHC:

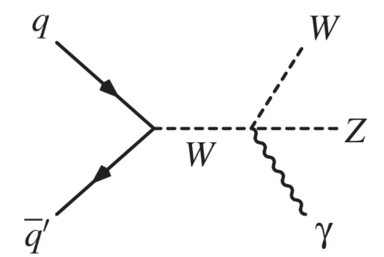
→ Semi-leptonic WVγ final states: eνjjγ & μνjjγ

- Hadronic V-Boson decay yields larger branching ratio
- No distinction between hadronic W and Z

Event Selection

- Exactly 1 lepton $p_T^e > 30$ GeV / $p_T^\mu > 25$ GeV
- 1 photon $p_T > 30$ GeV
- ≥ 2 jets $E_T > 30$ GeV, no b-tag, 70 GeV $\leq m_{jj} \leq$ 100 GeV
- $E_T^{miss} > 35$ GeV
- $m_T > 30$ GeV
- Z rejection cuts in electron channel





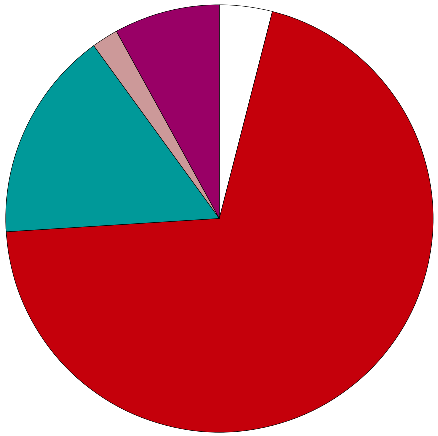
$m_T = \sqrt{p_T^{lep} E_T^{miss} (1 - \cos \Delta\Phi^{lep.,ETmiss})}$

CMS - WWγ & WZγ production

Phys. Rev. D 90, 032008 - Published 25 August 2014

Background estimation:

- Wγ + jets BG: m_{jj} sideband fit
- Jets misidentified as photons: extrapolated from shower shapes
- Jets misidentified as leptons: 2-component fit to E_T^{miss} fit
- Other BG: Monte Carlo



Averaged expectations

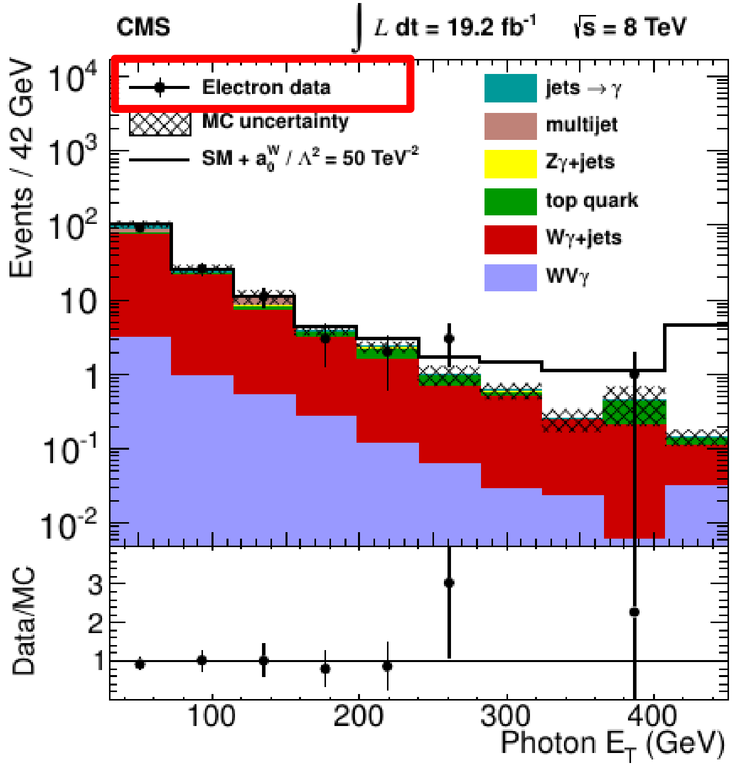
- Signal
- Wγ + jets
- WV + jets (jet → γ)
- Multijets (jet → l)
- Other BG (ttγ, single top, Zγ + jets)

→ 95% C.L. limits on cross section

σ = 311 fb using profile likelihood

Expected: σ = (91.6 fb ± 21.7) fb

→ Good agreement with SM



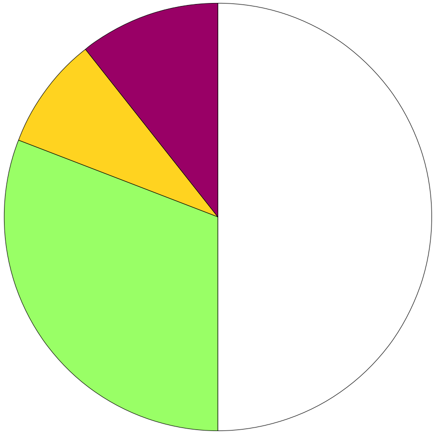
ATLAS - Wγγ production

Phys. Rev. Lett. 115, 031802 - Published 16 July 2015

First evidence of process: $pp \rightarrow W^{\pm}\gamma\gamma \rightarrow l^{\pm}\nu\gamma\gamma$ ($l = e/\mu$)

Event Selection

- Exactly 1 lepton $p_T > 20$ GeV
- 2 photons $p_T > 20$ GeV
- $E_T^{miss} > 25$ GeV
- $m_T > 40$ GeV
- Z rejection cuts in e^- channel

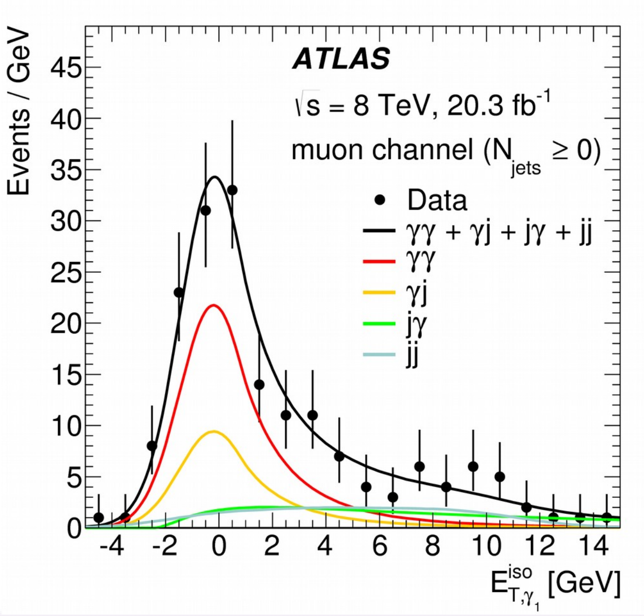


Averaged expectations

- Signal
- W + jets & Wγ + jets (jet → γ)
- γγ + jet (jet → l)
- Other BG: Zγ, ...

Background estimation:

- Jets misidentified as photons: 2D-template fit of isolation energy
- Jets misidentified as leptons: ABCD method using E_T^{miss} and isolation energy
- Other BG: Monte Carlo



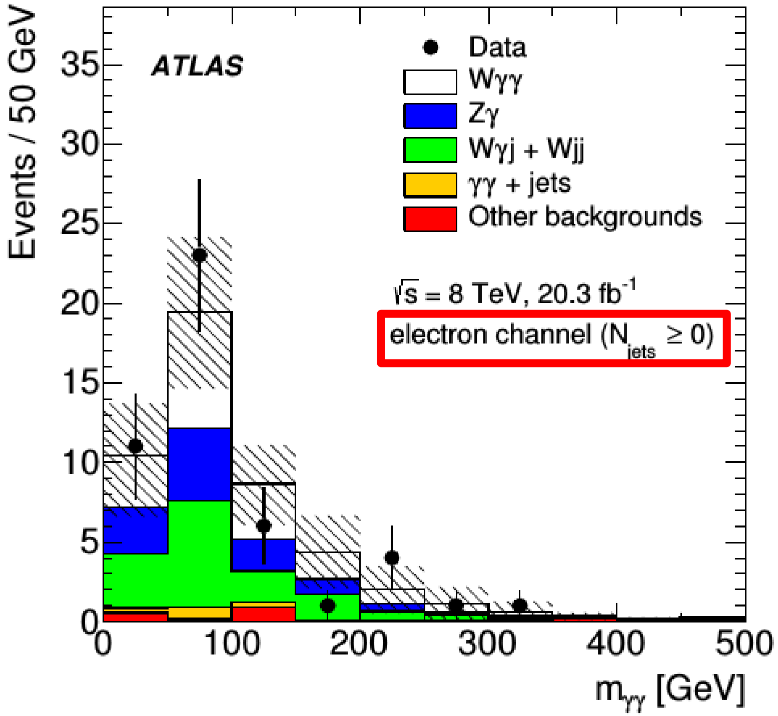
ATLAS - Wγγ production

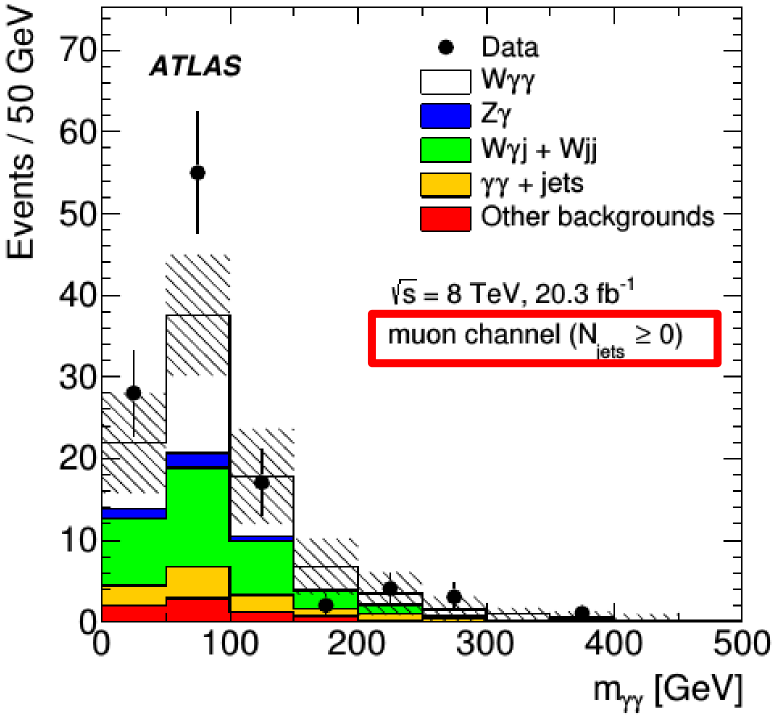
Phys. Rev. Lett. 115, 031802 - Published 16 July 2015

Inclusive and exclusive (no jets p_T > 25 GeV) measurement

	σ^{fid} [fb]	σ^{MCFM} [fb]
$N_{\text{jet}} \geq 0$	$6.1\ ^{+1.1}_{-1.0}$ (stat.) ± 1.2 (syst.) ± 0.2 (lumi.)	2.90 ± 0.16
$N_{\text{jet}} = 0$	$2.9\ ^{+0.8}_{-0.7}$ (stat.) $^{+\,1.0}_{-\,0.9}$ (syst.) ± 0.1 (lumi.)	1.88 ± 0.20

→ Observation of signal > 3 σ



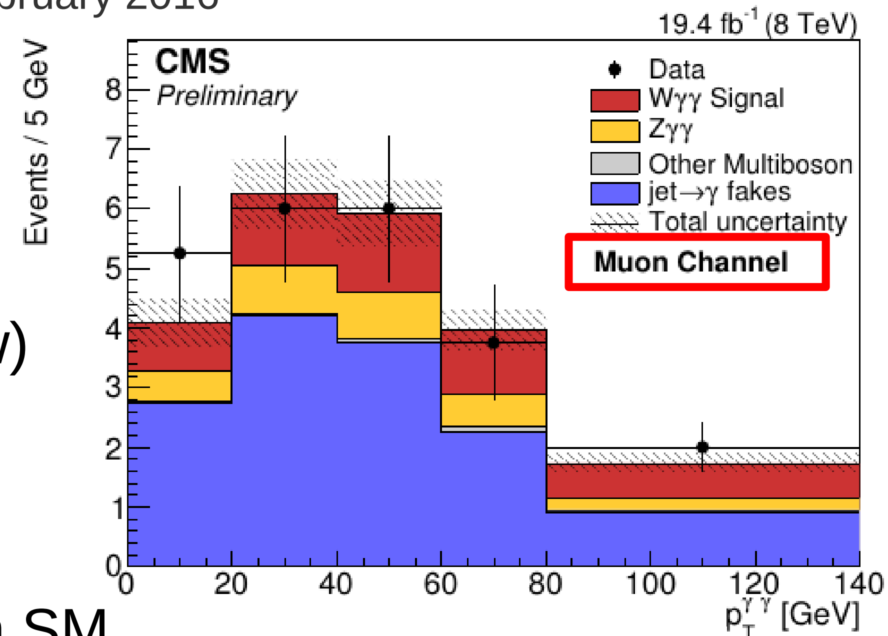


CMS - Wγγ & Zγγ production

CMS-PAS-SMP-15-008 - February 2016

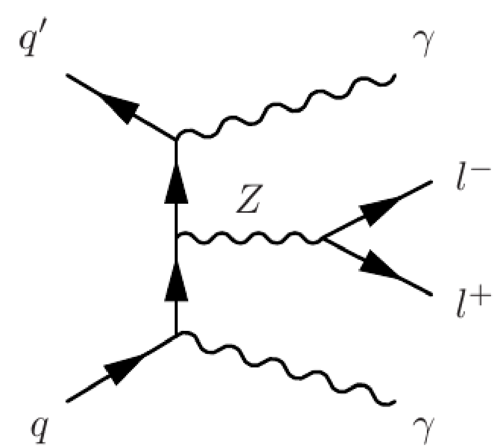
Wγγ → μνγγ:

- Muon channel analysed
- Observation of signal with 2.4 σ
- Strategy similar to Zγγ analysis (below)



Zγγ → eeγγ / μμγγ

→ No neutral triple or quartic vertices in SM
Zγγ process produced via radiation, e.g.:



Event Selection

- 2 same flavour leptons
  opposite sign p_T^{lead} > 20 GeV, $p_T^{sublead}$ > 10 GeV
- 2 photons p_T > 15 GeV, max. 1 in endcaps
- m_{ll} > 40 GeV

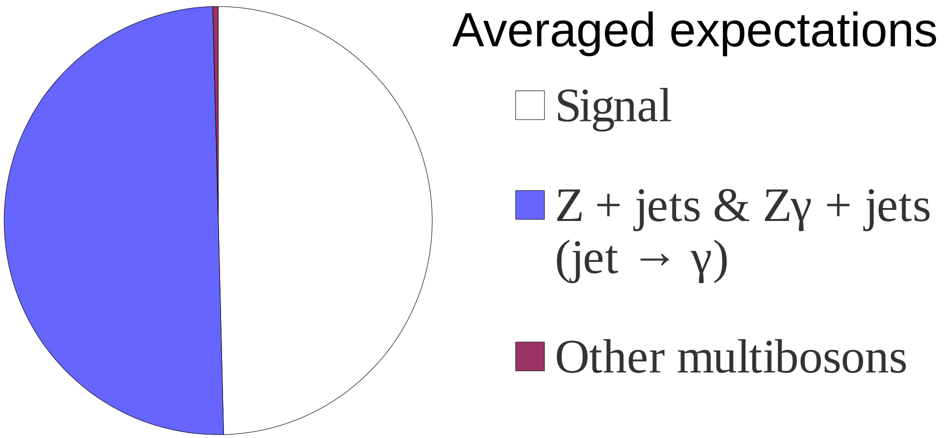
Analysis divided in categories corresponding to detector regions of photons (barrel-barrel, barrel-endcap, endcap-barrel)

CMS - (Wγγ &) Zγγ production

CMS-PAS-SMP-15-008 - February 2016

Background estimation:

- Jets misidentified as photons: 2D-template normalisation using isolation energy and photon ID individually for different detector regions
- Other multibosons: Monte Carlo



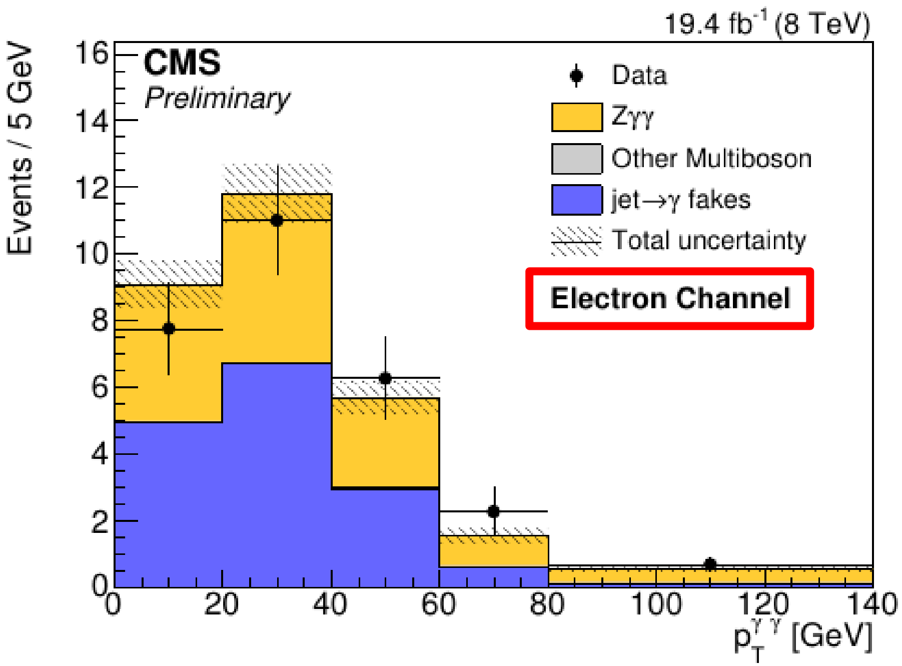
→ Observation of signal at 5.9 σ

$$\sigma^{\text{fid}}_{Z\gamma\gamma} \cdot \text{BR}\,(Z \to \ell\ell) = 12.7 \pm 1.4\,(\text{stat}) \pm 1.8\,(\text{syst}) \pm 0.3\,(\text{lumi})\,\text{fb}$$

Expected:

$$\sigma^{\text{NLO}}_{Z\gamma\gamma} \cdot \text{BR}\,(Z \to \ell\ell) = 12.95 \pm 1.47\,\text{fb}$$

→ Good agreement with SM



ATLAS - $Z\gamma\gamma$ production

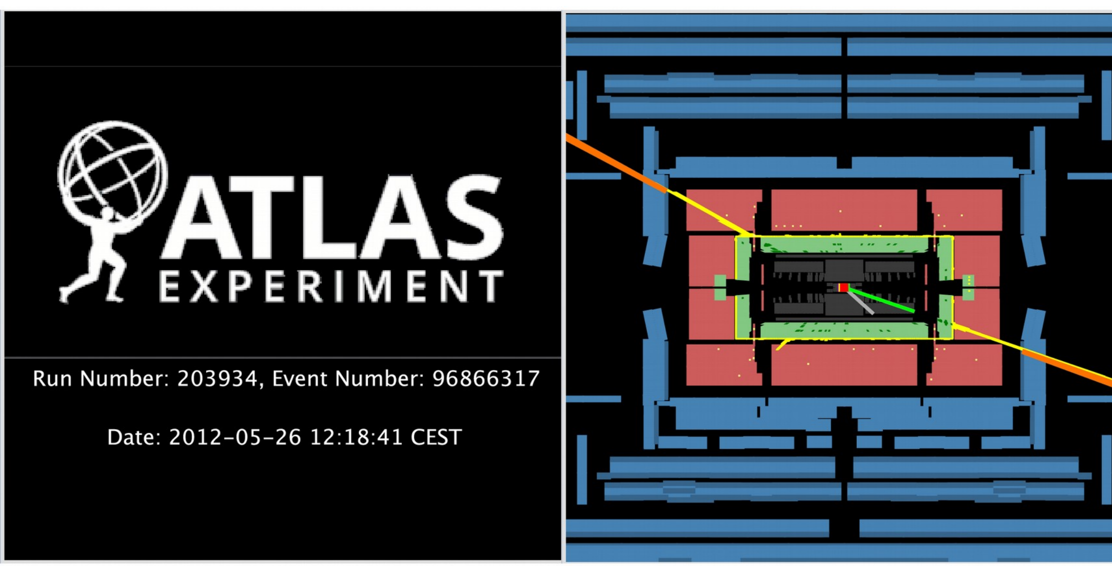
Phys. Rev. D 93, 112002 - Published 2 June 2016

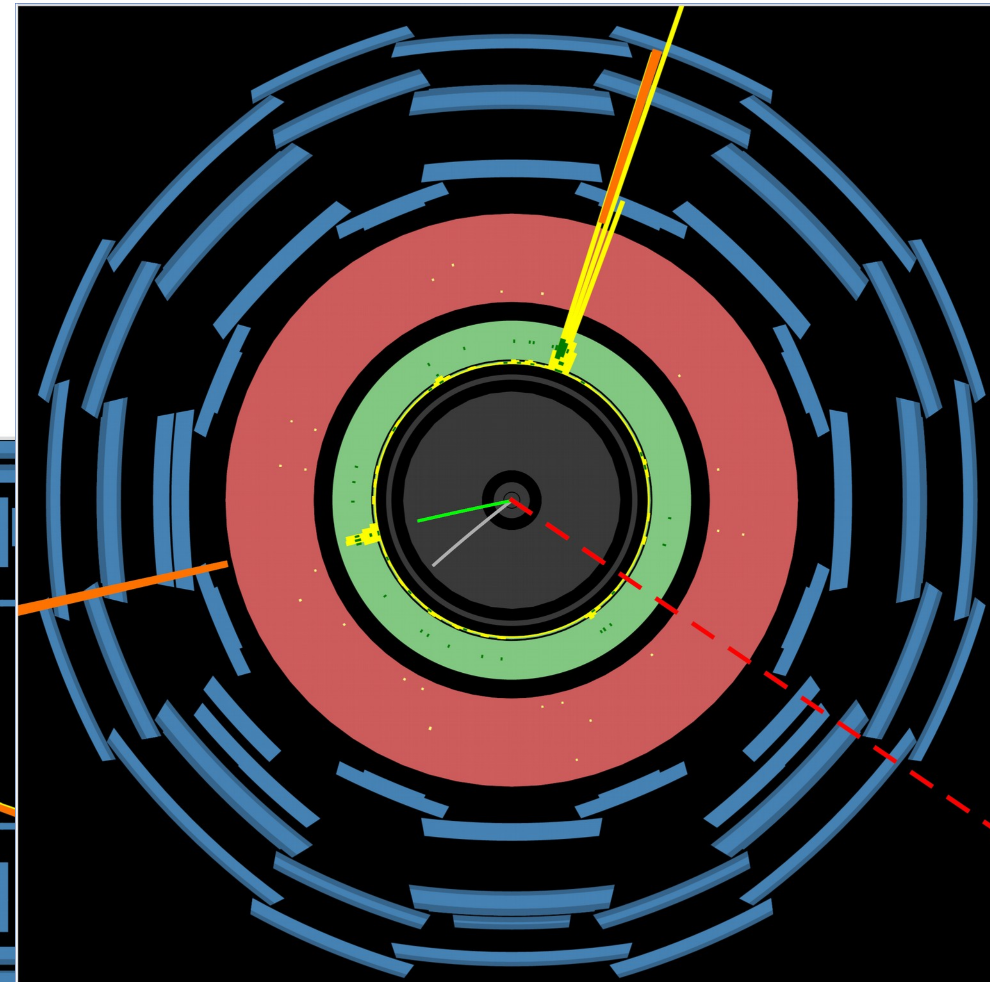
$Z\gamma\gamma \rightarrow ee\gamma\gamma$ / $\mu\mu\gamma\gamma$ / $\nu\nu\gamma\gamma$ → Also studied neutrino channel

Electron and muon channel similar as CMS analysis

$\nu\nu\gamma\gamma$ Event Selection

- E_T^{miss} > 110 GeV
- 2 photons E_T > 22 GeV
- $\Delta\Phi(p_T^{miss}, \gamma\gamma) > 5/6\ \pi$
- No lepton in event



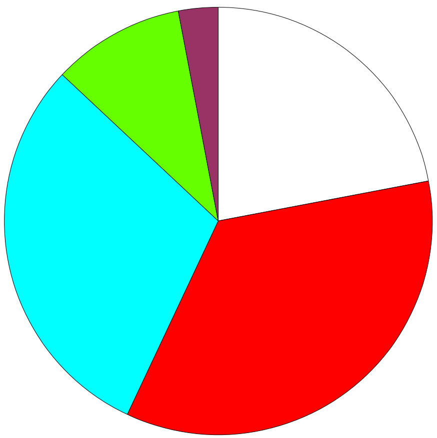


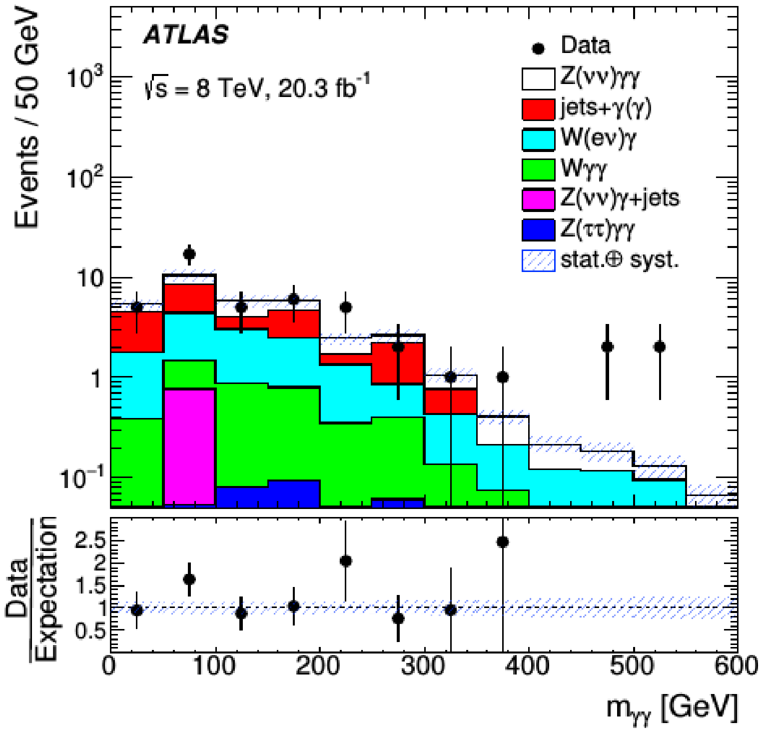
ATLAS - $Z\gamma\gamma$ production

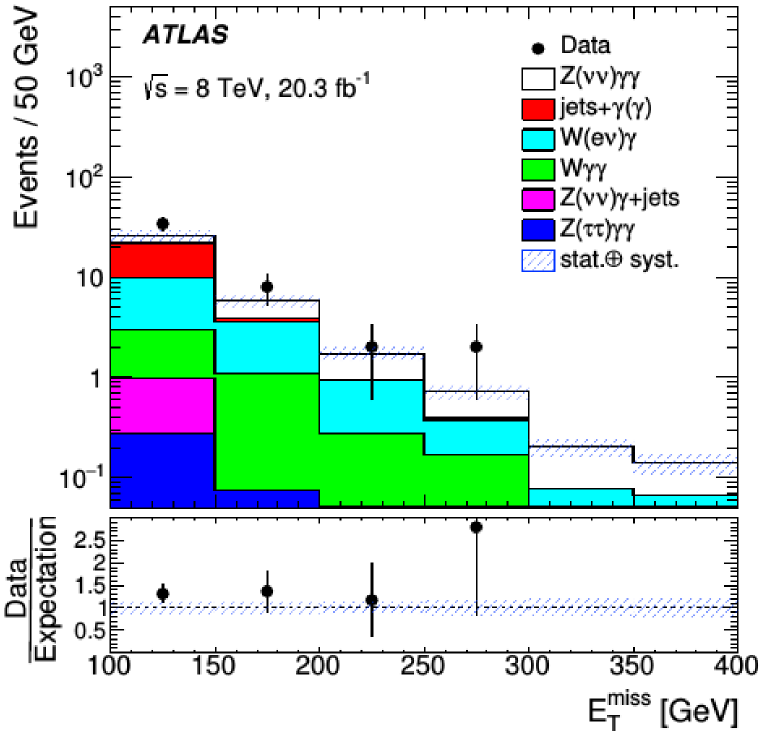
Phys. Rev. D 93, 112002 - Published 2 June 2016

$\nu\nu\gamma\gamma$ background estimation:

- Mismeasured jets: ABCD method using E_T^{miss} and photon ID
- Misidentified electrons: fake rate from $Z \rightarrow ee$
- $W\gamma\gamma$: scale factors for MC
- Other BG: Monte Carlo



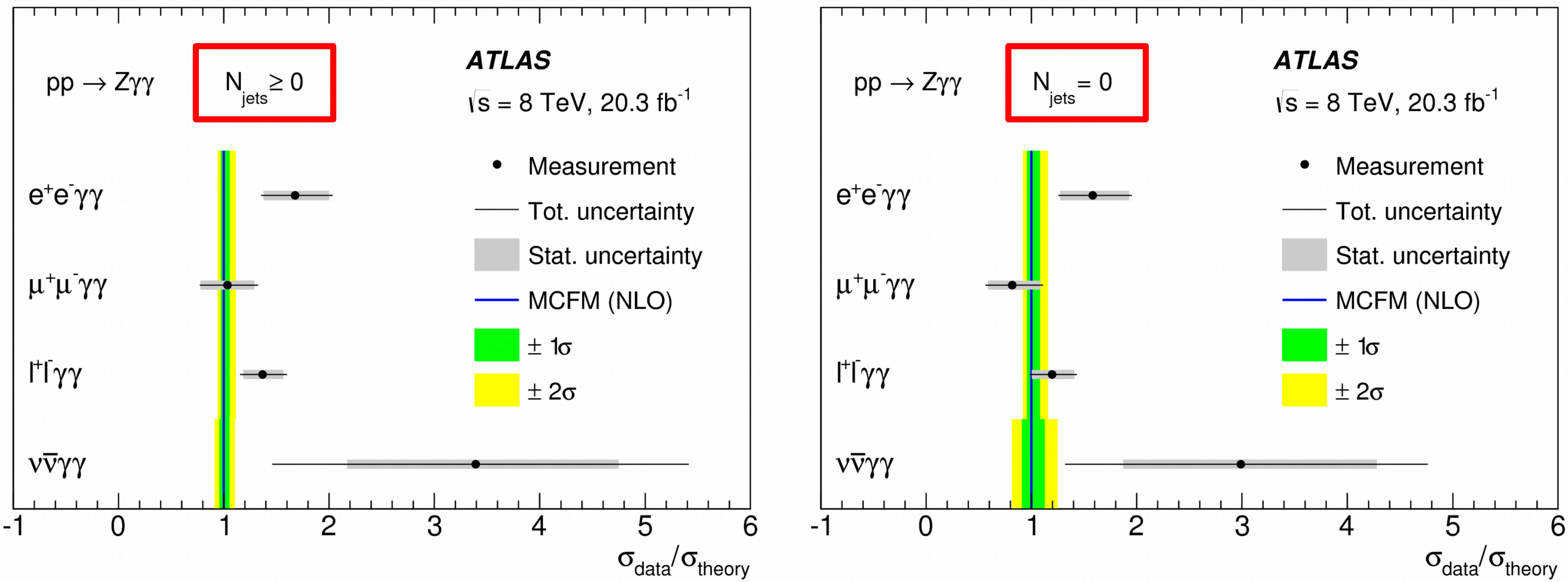




ATLAS - $Z\gamma\gamma$ production

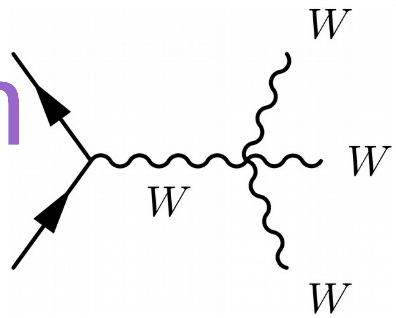
Phys. Rev. D 93, 112002 - Published 2 June 2016

Inclusive and exclusive (no jets p_T > 30 GeV) measurement



→ Good agreement with Standard Model expectations

ATLAS - WWW production



To be published

First study of: $pp \rightarrow W^{\pm}W^{\pm}W^{\mp} \rightarrow l\nu l\nu l\nu$ / $l\nu l\nu jj$ (l =e/μ)

Leptonic Selection

- Exactly 3 leptons $p_T > 20$ GeV
- Maximally 1 jet $p_T > 25$ GeV
- $\Delta\Phi(lll, p_T^{miss}) > 2.5$
- No b-jet
- Z rejection cuts on m_{ll} and E_T^{miss}

Hadronic Selection

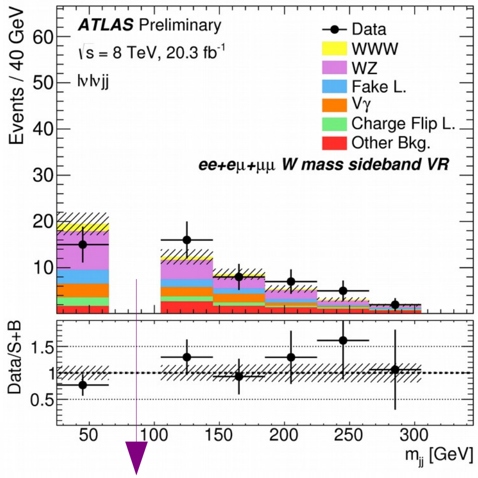
- Exactly 2 same charge leptons $p_T > 30$ GeV
- 2 jets $p_T^{lead} > 30$ GeV, $p_T^{sublead} > 30$ GeV, 65 GeV < m_{jj} < 105 GeV, $|\eta_{jj}| < 1.5$
- No b-jet
- $m_{ll} > 40$ GeV
- Z rejection cuts in channels with e^-

Backgrounds:

- Electron charge misidentification
  → From $Z \rightarrow ee$ (data)
- Leptons from misidentified jets
  → From matrix method (leptonic) and fake factor method (hadronic)
- Other BG: $WZ/\gamma^* + \text{jets}$, $W\gamma + \text{jets}$, $Z\gamma + \text{jets}$, …
  → From Monte Carlo with leptonic $WZ/\gamma^* + \text{jets}$ normalisation taken from data

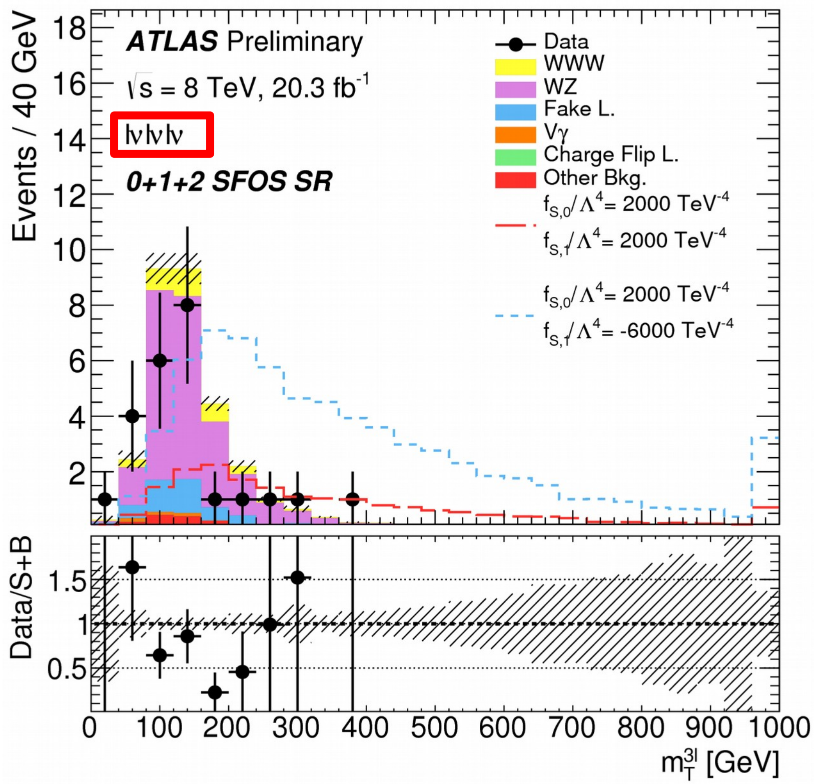
ATLAS - WWW production

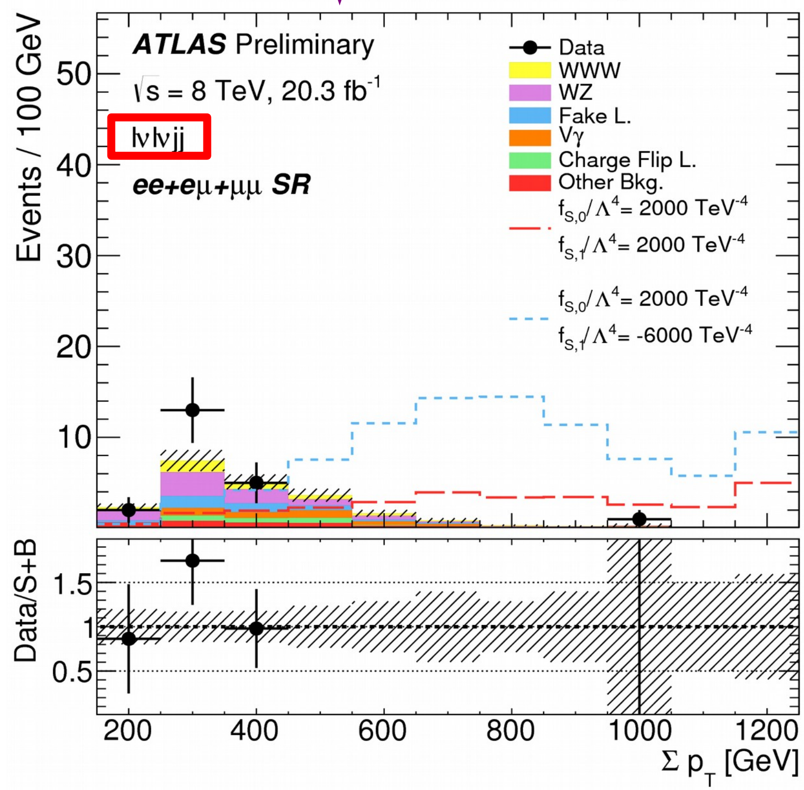
To be published



Background estimation validated
in dedicated control regions, e.g.:

Comparison to expectations:

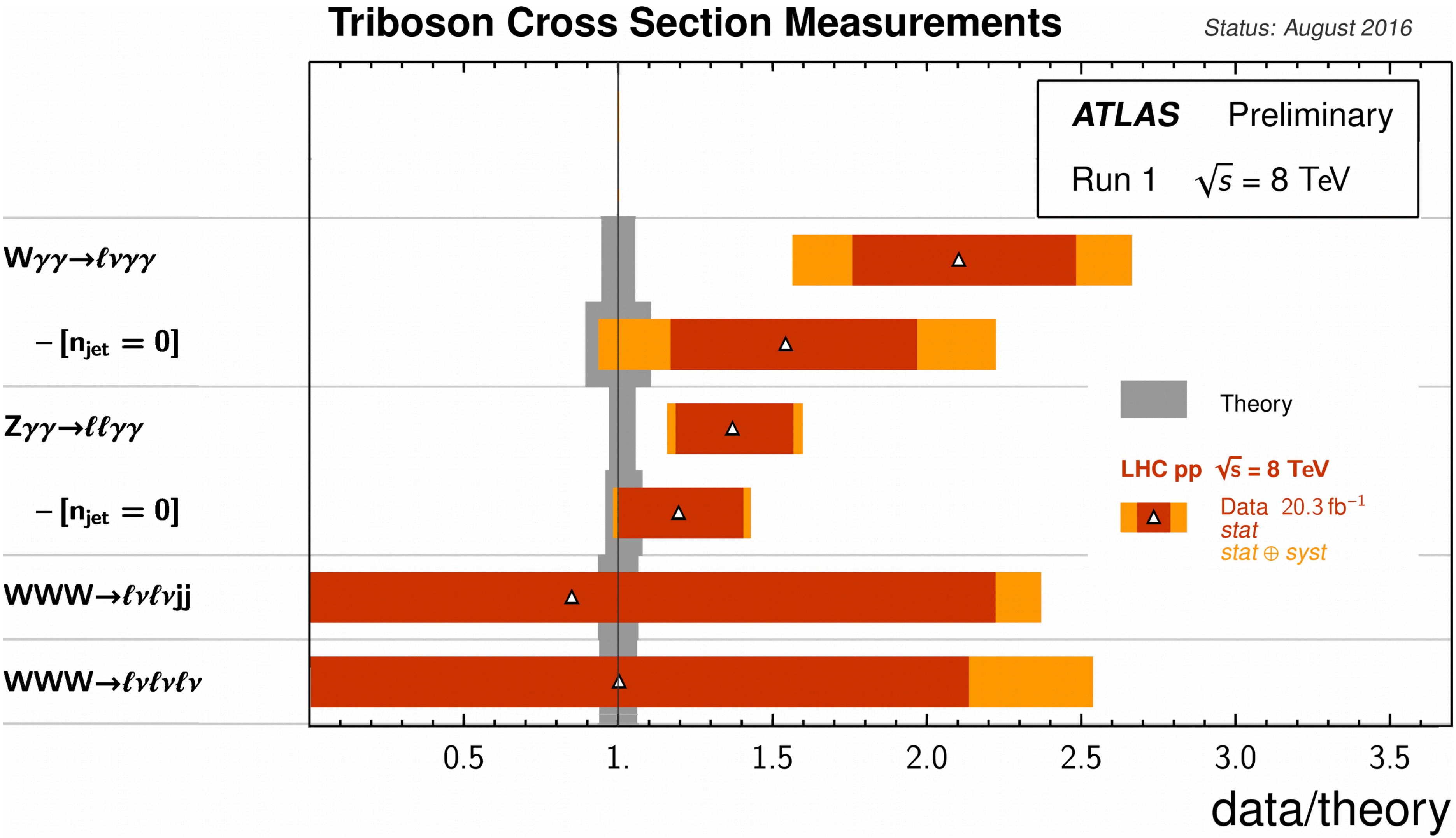




→ Good agreement with SM, low statistics

ATLAS – Tribosons Overview

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SM/ATLAS_k_SMSummary_TriBosonFiducialRatio_Simple/ATLAS_k_SMSummary_TriBosonFiducialRatio_Simple.png



→ Analyses would profit from larger data set

Limits on Anomalous Quartic Gauge Couplings

Anomalous Quartic Gauge Couplings

arXiv:1309.7890

Limits on coupling of operators of mass-dimension-8

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_{j=1,2} \frac{f_{S,j}}{\Lambda^4}\mathcal{O}_{S,j} + \sum_{j=0,\ldots,9} \frac{f_{T,j}}{\Lambda^4}\mathcal{O}_{T,j} + \sum_{j=0,\ldots,7} \frac{f_{M,j}}{\Lambda^4}\mathcal{O}_{M,j}$$

coupling
operator
new physics scale

→ 18 independent operators,
Different final states sensitive to different operators
Partly dedicated search regions defined

Limits set at 95% C.L. using profile likelihood ratio

$$\Lambda(\sigma) = \frac{\mathcal{L}(\sigma, \hat{\hat{\theta}}(\sigma))}{\mathcal{L}(\hat{\sigma}, \hat{\theta})}, \quad \mathcal{L}(\sigma, \theta) = \prod_{i}^{\text{final states}} \text{Poisson}(N_i \mid S_i(\sigma, \theta) + B_i(\theta)) \cdot \text{Gaussian}(\theta_0 \mid \theta)$$

with nuisance parameters **θ** describing systematic uncertainties

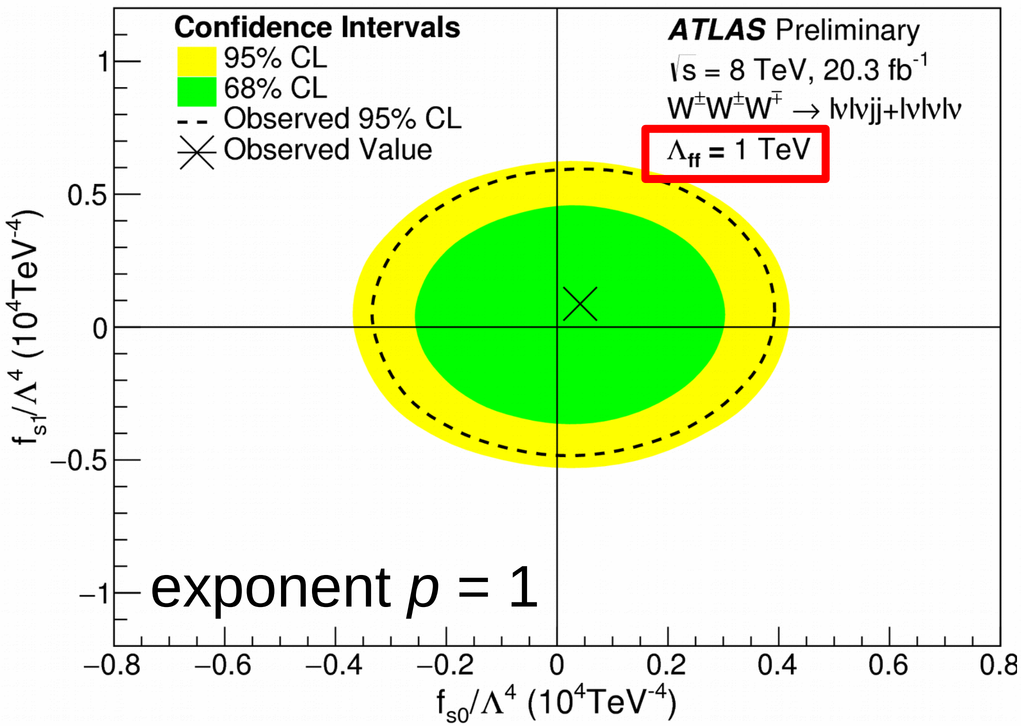
Anomalous Quartic Gauge Couplings

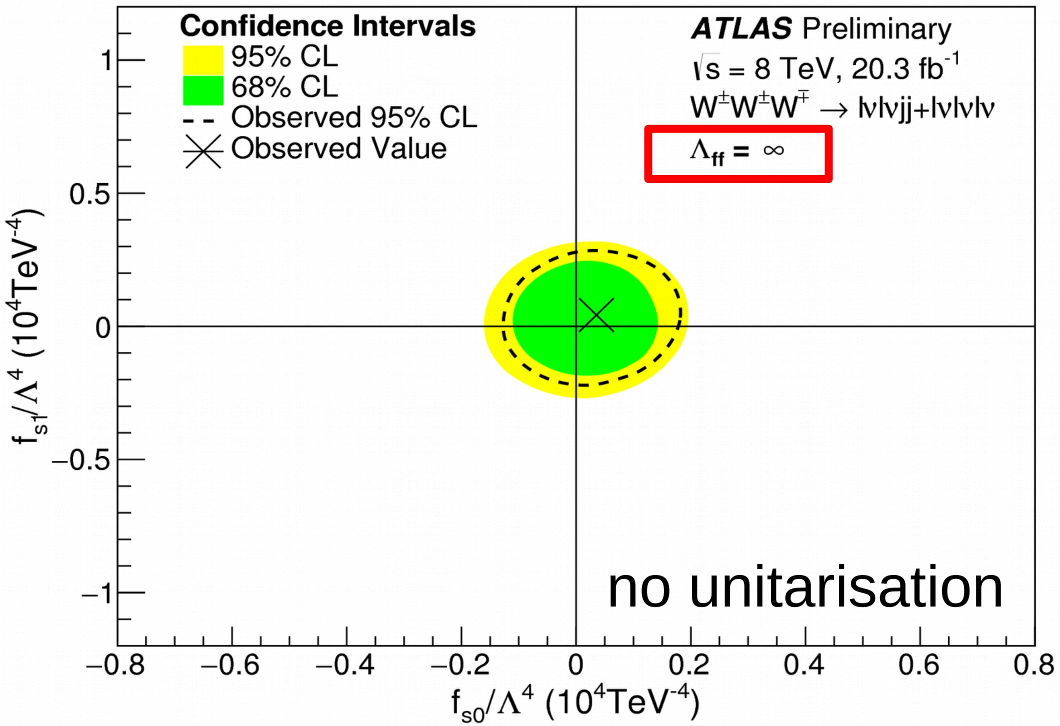
Only one or two coupling parameters ≠ 0 for limit setting

Results with and without unitarisation

- form factor used for unitarisation $$F(\hat{s}) = \left(1 + \frac{\hat{s}}{\Lambda_{FF}^2}\right)^{-p}$$ ← form factor scale

E.g. from WWW:

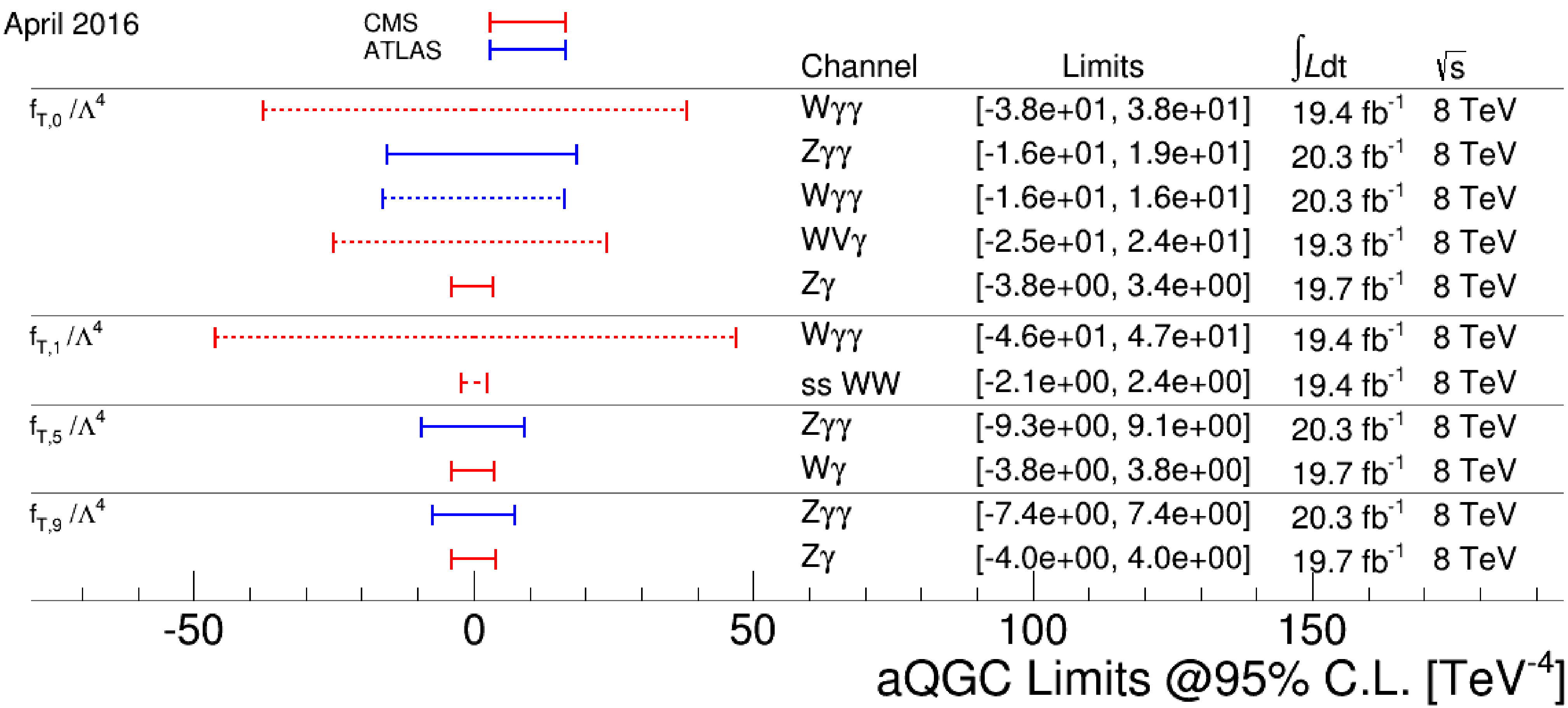




Anomalous Quartic Gauge Couplings

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

Comparison of some non-unitarised results:



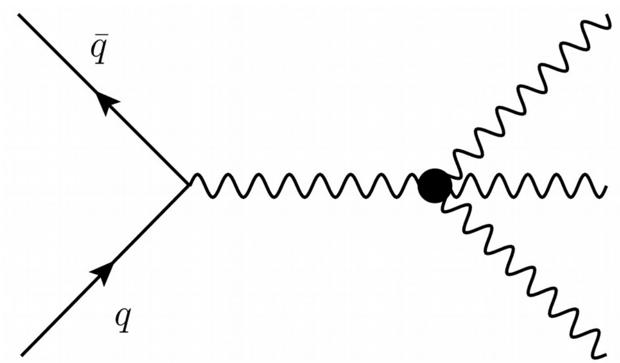
→ VBS analyses yield more stringent limits than triboson studies

Summary

Triboson processes studied at the LHC:

$W W\gamma$, $WZ\gamma$, $W\gamma\gamma$, $Z\gamma\gamma$, WWW

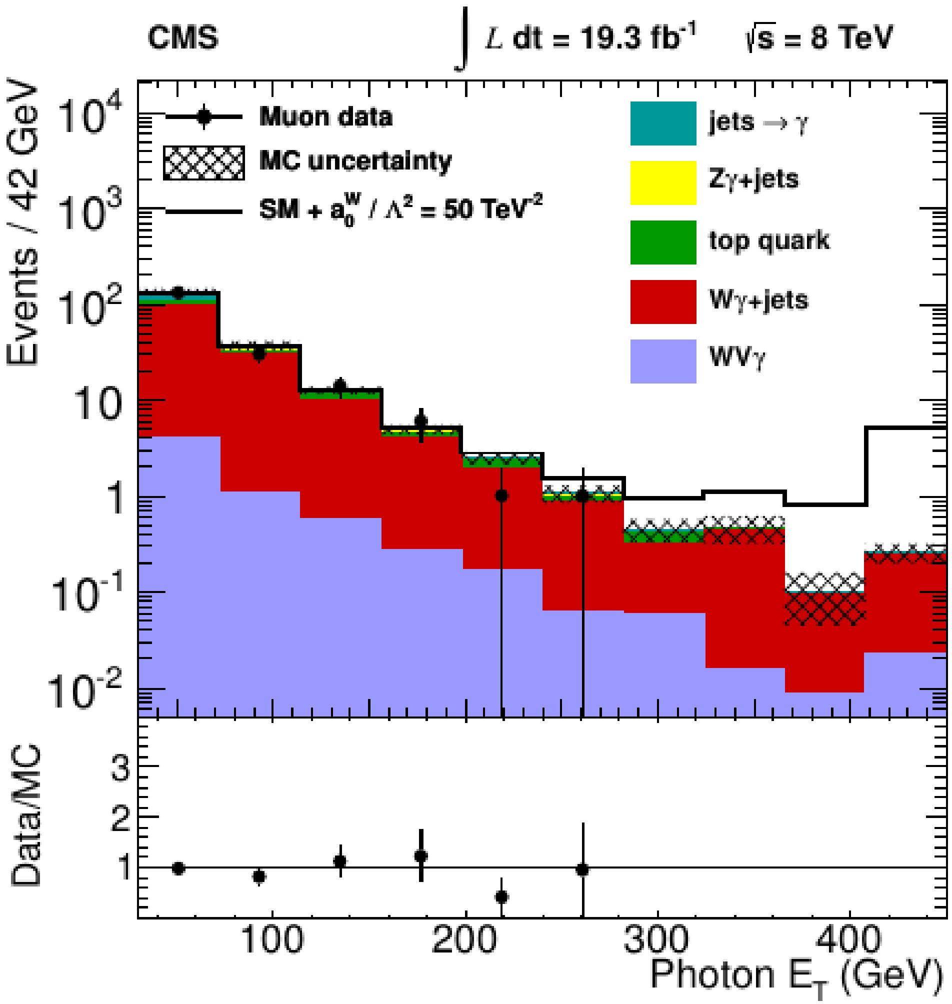
- Charged final states accessible for first time
- Good agreement with SM expectations
- Sensitive to quartic gauge couplings
- Exclusion limits set on aQGC
- 13 TeV data set luminosity starts to make triboson measurements feasible

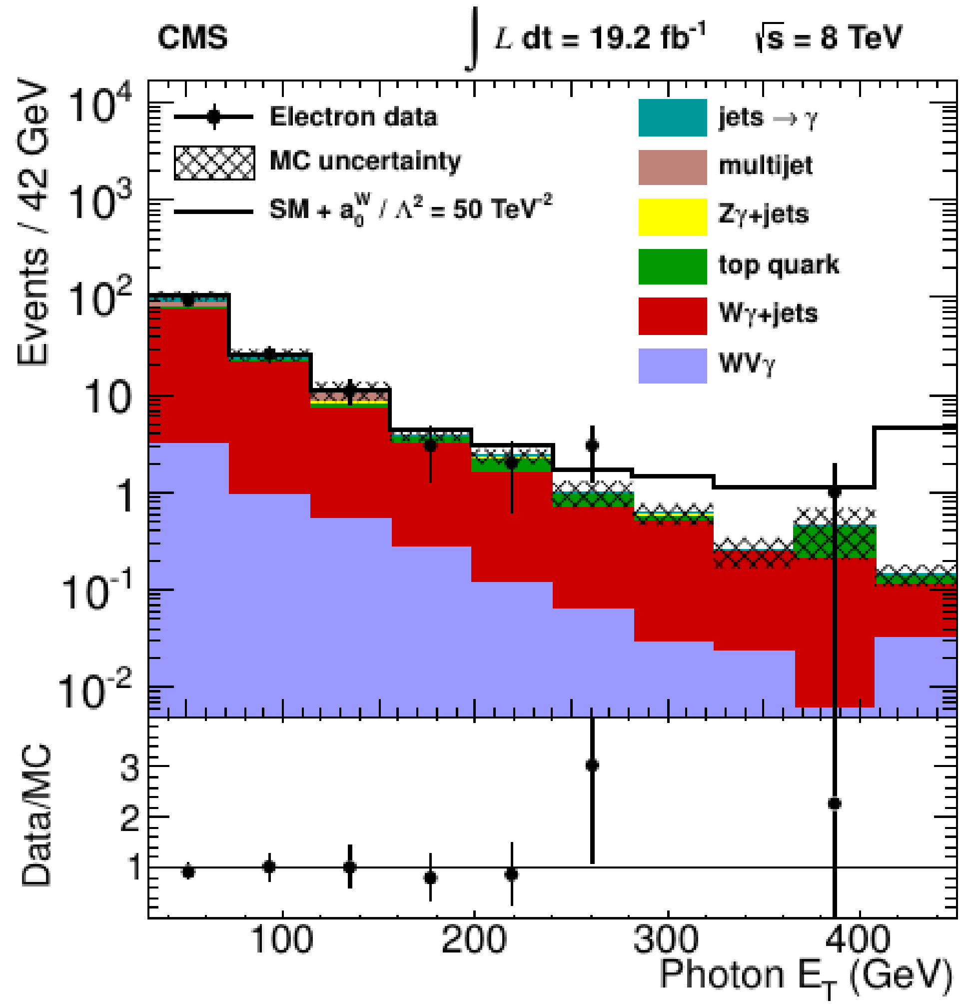


Thank you!

WWγ & WZγ production

Phys. Rev. D 90, 032008 - Published 25 August 2014





WWγ & WZγ production

Phys. Rev. D 90, 032008 - Published 25 August 2014

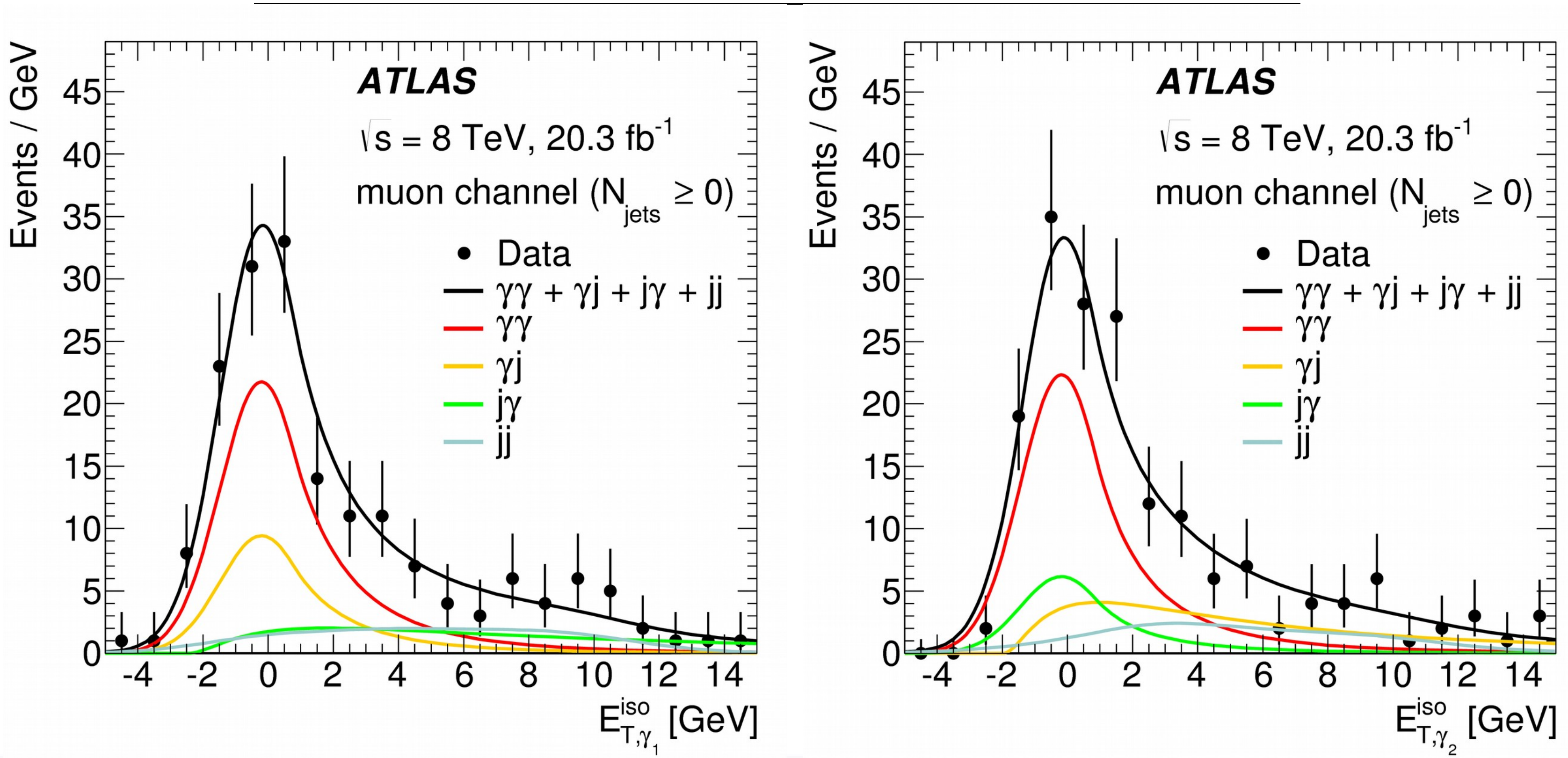
Process	Muon channel number of events	Electron channel number of events
SM WWγ	6.6 ± 1.5	5.0 ± 1.1
SM WZγ	0.6 ± 0.1	0.5 ± 0.1
Wγ + jets	136.9 ± 10.5	101.6 ± 8.5
WV + jet, jet $\to \gamma$	33.1 ± 4.8	21.3 ± 3.3
MC t$\bar{\text{t}}\gamma$	12.5 ± 3.0	9.1 ± 2.2
MC single top quark	2.8 ± 0.8	1.7 ± 0.6
MC Zγ + jets	1.7 ± 0.1	1.5 ± 0.1
Multijets	—	7.2 ± 5.1
Total prediction	194.2 ± 11.5	147.9 ± 10.7
Data	183	139

Observed limits (TeV^{-4})	Expected limits (TeV^{-4})
$-77 < f_{M,0}/\Lambda^4 < 81$	$-89 < f_{M,0}/\Lambda^4 < 93$
$-131 < f_{M,1}/\Lambda^4 < 123$	$-143 < f_{M,1}/\Lambda^4 < 131$
$-39 < f_{M,2}/\Lambda^4 < 40$	$-44 < f_{M,2}/\Lambda^4 < 46$
$-66 < f_{M,3}/\Lambda^4 < 62$	$-71 < f_{M,3}/\Lambda^4 < 66$

Wγγ production

Phys. Rev. Lett. 115, 031802 - Published 16 July 2015

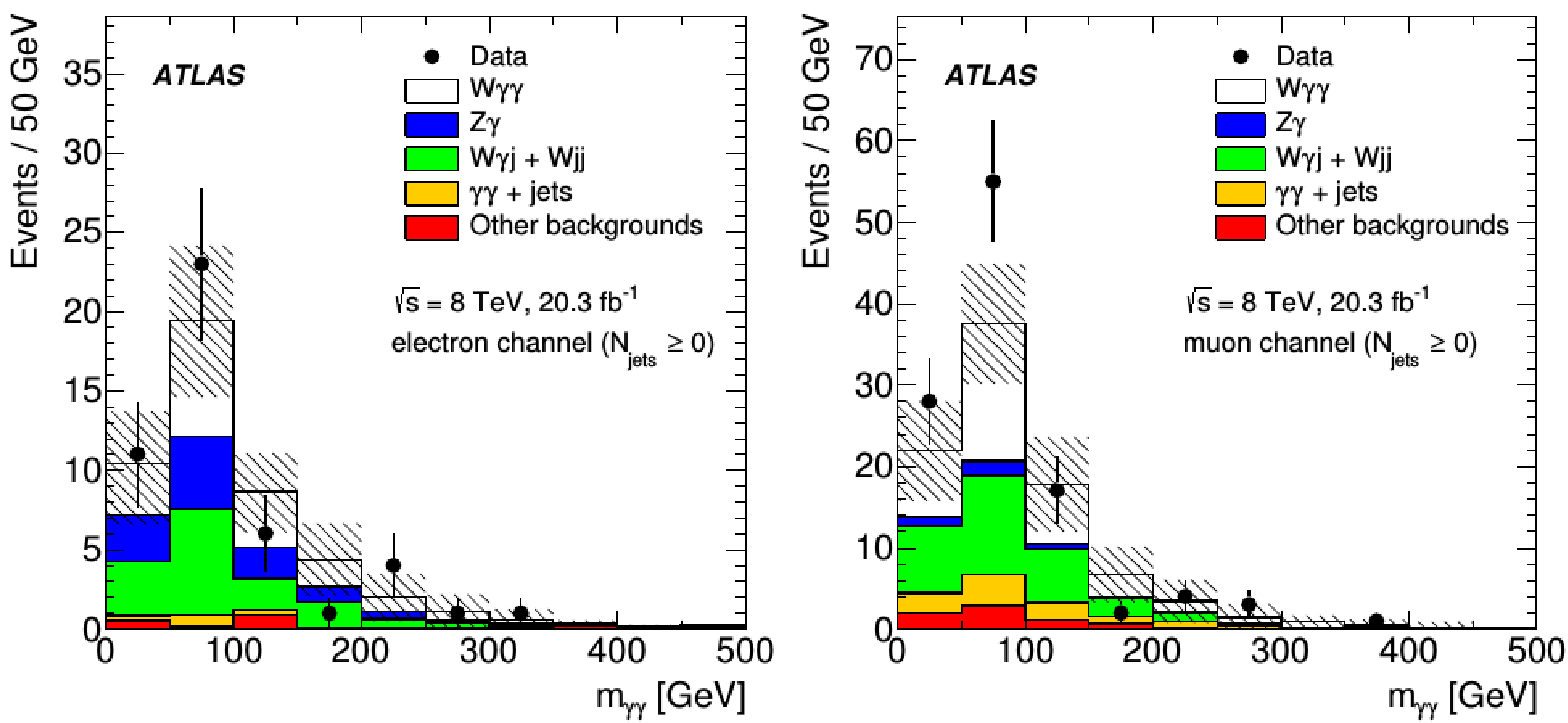
Definition of the fiducial region
$p_T^\ell > 20$ GeV, $p_T^\gamma > 25$ GeV, $\lvert\eta_\ell\rvert < 2.5$
$m_T > 40$ GeV
$E_T^\gamma > 20$ GeV, $\lvert\eta^\gamma\rvert < 2.37$, iso. fraction $\epsilon_h^p < 0.5$
$\Delta R(\ell,\gamma) > 0.7$, $\Delta R(\gamma,\gamma) > 0.4$, $\Delta R(\ell/\gamma,\text{jet})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



Wγγ production

Phys. Rev. Lett. 115, 031802 - Published 16 July 2015

	Electron channel	Muon channel	Electron channel	Muon channel
	$N_{\text{jet}} \geq 0$		$N_{\text{jet}} = 0$	
$W\gamma j + Wjj$	15.3 ± 4.8 (stat.) ± 5.3 (syst.)	30.5 ± 7.7 (stat.) ± 6.8 (syst.)	5.8 ± 2.1 (stat.) ± 2.0 (syst.)	14.4 ± 4.9 (stat.) ± 4.9 (syst.)
$\gamma\gamma$ + jets	1.5 ± 0.6 (stat.) ± 1.0 (syst.)	11.0 ± 4.0 (stat.) ± 4.9 (syst.)	0.2 ± 0.2 (stat.) ± 0.2 (syst.)	6.1 ± 3.5 (stat.) ± 3.1 (syst.)
$Z\gamma$	11.2 ± 1.1 (stat.)	3.9 ± 0.2 (stat.)	2.4 ± 0.5 (stat.)	2.8 ± 0.2 (stat.)
Other backgrounds	2.2 ± 0.6 (stat.)	6.7 ± 2.0 (stat.)	0.3 ± 0.1 (stat.)	1.1 ± 0.3 (stat.)
Total background	30.2 ± 5.0 (stat.) ± 5.4 (syst.)	52.1 ± 8.9 (stat.) ± 8.4 (syst.)	8.7 ± 2.2 (stat.) ± 2.0 (syst.)	24.4 ± 6.0 (stat.) ± 5.8 (syst.)
Data	47	110	15	53



$W\gamma\gamma$ production

Phys. Rev. Lett. 115, 031802 - Published 16 July 2015

	σ^{fid} [fb]	σ^{MCFM} [fb]
Inclusive ($N_{\text{jet}} \geq 0$)		
$\mu\nu\gamma\gamma$	$7.1\ ^{+1.3}_{-1.2}$ (stat.) ± 1.5 (syst.) ± 0.2 (lumi.)	2.90 ± 0.16
$e\nu\gamma\gamma$	$4.3\ ^{+1.8}_{-1.6}$ (stat.) $^{+1.9}_{-1.8}$ (syst.) ± 0.2 (lumi.)	
$\ell\nu\gamma\gamma$	$6.1\ ^{+1.1}_{-1.0}$ (stat.) ± 1.2 (syst.) ± 0.2 (lumi.)	
Exclusive ($N_{\text{jet}} = 0$)		
$\mu\nu\gamma\gamma$	3.5 ± 0.9 (stat.) $^{+1.1}_{-1.0}$ (syst.) ± 0.1 (lumi.)	1.88 ± 0.20
$e\nu\gamma\gamma$	$1.9\ ^{+1.4}_{-1.1}$ (stat.) $^{+1.1}_{-1.2}$ (syst.) ± 0.1 (lumi.)	
$\ell\nu\gamma\gamma$	$2.9\ ^{+0.8}_{-0.7}$ (stat.) $^{+1.0}_{-0.9}$ (syst.) ± 0.1 (lumi.)	

Limits with form factor exponent n

		Observed [TeV^{-4}]	Expected [TeV^{-4}]
$n = 0$	f_{T0}/Λ^4	$[-0.9, 0.9] \times 10^2$	$[-1.2, 1.2] \times 10^2$
	f_{M2}/Λ^4	$[-0.8, 0.8] \times 10^4$	$[-1.1, 1.1] \times 10^4$
	f_{M3}/Λ^4	$[-1.5, 1.4] \times 10^4$	$[-1.9, 1.8] \times 10^4$
$n = 1$	f_{T0}/Λ^4	$[-7.6, 7.3] \times 10^2$	$[-9.6, 9.5] \times 10^2$
	f_{M2}/Λ^4	$[-4.4, 4.6] \times 10^4$	$[-5.7, 5.9] \times 10^4$
	f_{M3}/Λ^4	$[-8.9, 8.0] \times 10^4$	$[-11.0, 10.0] \times 10^4$
$n = 2$	f_{T0}/Λ^4	$[-2.7, 2.6] \times 10^3$	$[-3.5, 3.4] \times 10^3$
	f_{M2}/Λ^4	$[-1.3, 1.3] \times 10^5$	$[-1.6, 1.7] \times 10^5$
	f_{M3}/Λ^4	$[-2.9, 2.5] \times 10^5$	$[-3.7, 3.3] \times 10^5$

$W\gamma\gamma$ & $Z\gamma\gamma$ production

CMS-PAS-SMP-15-008 - February 2016

Definition of $W^{\pm}\gamma\gamma$ Fiducial Region
$p_T^{\gamma} > 25\,\mathrm{GeV}$, $\lvert\eta^{\gamma}\rvert < 2.5$
$p_T^{\ell} > 25\,\mathrm{GeV}$, $\lvert\eta^{\ell}\rvert < 2.5$
Exactly one candidate muon and two candidate photons
$m_T(\ell, \nu(s)) > 40\,\mathrm{GeV}$
$\Delta R(\gamma,\gamma) > 0.4$ and $\Delta R(\gamma,\ell) > 0.4$

Signal region expectations $W\gamma\gamma$

Region	jet misID	$Z\gamma\gamma$ + Irreducible	Total Background	Data	Expected signal
Muon Channel					
Barrel-Barrel	25 ± 6	9.6 ± 1.3	34 ± 6	62	16.5 ± 1.8
Barrel-Endcap	17 ± 3	1.9 ± 0.4	19 ± 3	26	4.1 ± 0.5
Endcap-Barrel	21 ± 4	2.5 ± 0.5	24 ± 4	20	4.1 ± 0.5
Sum	63 ± 11	14 ± 2	77 ± 12	108	25 ± 3

$W\gamma\gamma$ & $Z\gamma\gamma$ production

CMS-PAS-SMP-15-008 - February 2016

Table 5: Systematic and statistical uncertainties affecting the $W^{\pm}\gamma\gamma$ fiducial cross section for events with a leading photon having $p_T > 25\,GeV$.

Systematic Uncertainties	$W\gamma\gamma \to \mu\gamma\gamma$
Signal Simulation Systematics	$\delta(\sigma_{W^{\pm}\gamma\gamma})$
Simulation Statistics	2.40%
Trigger	0.26%
Photon Identification	2.04%
Muon Identification and Isolation	0.27%
Photon Pixel Seed Electron Veto	
Photon Energy Scale	2.10%
Muon Energy Scale	0.19%
E_T^{miss} Scale	1.39%
PDF	1.45%
Renormalization and Factorization	0.77%
Pile-up	0.17%
Total Signal Simulation Systematics	4.38%
Background Systematics	$\delta(\sigma_{W^{\pm}\gamma\gamma})$
Misidentified Jet	37.19%
$Z\gamma\gamma$	5.73%
Other Multiboson Backgrounds	1.02%
Total Background	37.64%
Statistical Uncertainties	$\delta(\sigma_{W^{\pm}\gamma\gamma})$
Signal Region	29.30%
Sidebands	4.39%
Total Statistical	29.60%
Total Systematic	37.89%
Total Luminosity	2.72%

$W\gamma\gamma$ & $Z\gamma\gamma$ production

CMS-PAS-SMP-15-008 - February 2016

Definition of $Z\gamma\gamma$ Fiducial Region
$p_T^\gamma > 15\,\text{GeV}, \lvert\eta^\gamma\rvert < 2.5$
$p_T^\ell > 10\,\text{GeV}, \lvert\eta^\ell\rvert < 2.5$
Exactly two candidate leptons and two candidate photons
lead $p_T^\gamma > 20\,\text{GeV}$
$M_{\ell\ell} > 40\,\text{GeV}$
$\Delta R(\gamma,\gamma) > 0.4$, $\Delta R(\gamma,\ell) > 0.4$, and $\Delta R(\ell,\ell) > 0.4$

Signal region expectations $Z\gamma\gamma$

Region	jet misID	Irreducible	Total Background	Data	Expected Signal
Muon Channel					
Barrel-Barrel	28 ± 5	0.4 ± 0.1	29 ± 5	72	47 ± 8
Barrel-Endcap	21 ± 3	0.1 ± 0.1	21 ± 3	29	13 ± 2
Endcap-Barrel	19 ± 3	0.1 ± 0.1	19 ± 3	40	14 ± 3
Sum	68 ± 9	0.6 ± 0.2	68 ± 9	141	73 ± 10
Electron Channel					
Barrel-Barrel	21 ± 4	0.2 ± 0.1	21 ± 4	65	37 ± 6
Barrel-Endcap	21 ± 3	0.1 ± 0.1	21 ± 3	28	9 ± 2
Endcap-Barrel	20 ± 3	0.01 ± 0.01	20 ± 3	24	11 ± 2
Sum	62 ± 8	0.3 ± 0.1	62 ± 8	117	56 ± 8

$W\gamma\gamma$ & $Z\gamma\gamma$ production

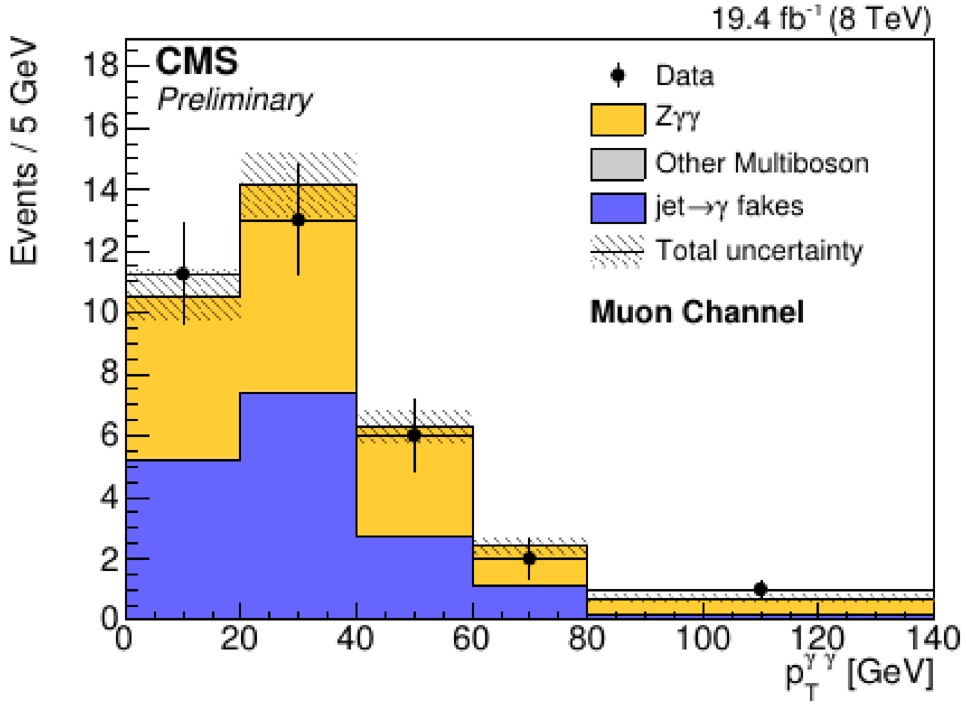
CMS-PAS-SMP-15-008 - February 2016

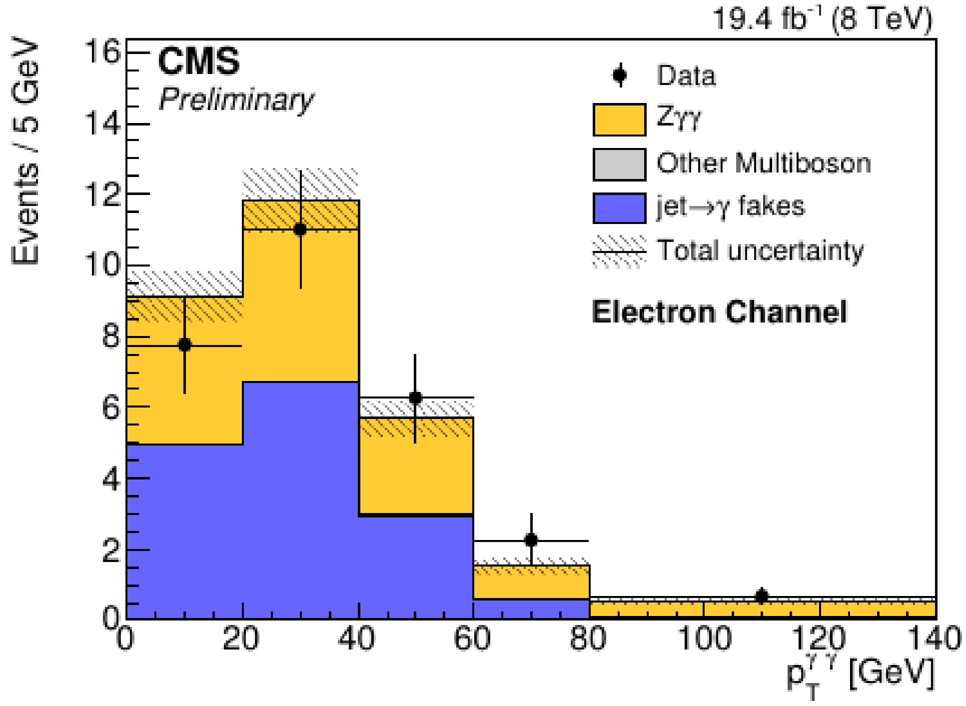
Table 6: Systematic and statistical uncertainties affecting the $Z\gamma\gamma$ fiducial cross section for events with a leading photon having $p_T > 15\,\text{GeV}$.

Systematic Uncertainties	$Z\gamma\gamma \to ee\gamma\gamma$	$Z\gamma\gamma \to \mu\mu\gamma\gamma$
Signal Simulation Systematics	$\delta(\sigma_{Z\gamma\gamma})$	
Simulation Statistics	3.25%	2.89%
Dilepton Trigger	1.33%	1.20%
Photon Identification	2.78%	2.82%
Muon Identification and Isolation		0.46%
Electron loose Identification	3.71%	
Photon Conversion Safe Electron Veto	0.76%	0.76%
Photon and Electron Energy Scale	2.52%	2.62%
Muon Energy Scale	–	1.60%
PDF	1.05%	1.11%
Renormalization and Factorization	0.55%	0.68%
Pile-up	1.31%	0.43%
Total Signal Simulation	6.60%	5.46%
Background Systematics	$\delta(\sigma_{Z\gamma\gamma})$	
Misidentified Jet	15.08%	12.51%
Other Multiboson Backgrounds	0.21%	0.26%
Total Background	15.08%	12.51%
Statistical Uncertainties	$\delta(\sigma_{Z\gamma\gamma})$	
Signal Region	16.54%	13.64%
Sidebands	1.39%	1.20%
Total Statistical	16.60%	13.70%
Total Systematic	16.46%	13.64%
Total Luminosity	2.60%	2.60%

Wγγ & Zγγ production

CMS-PAS-SMP-15-008 - February 2016



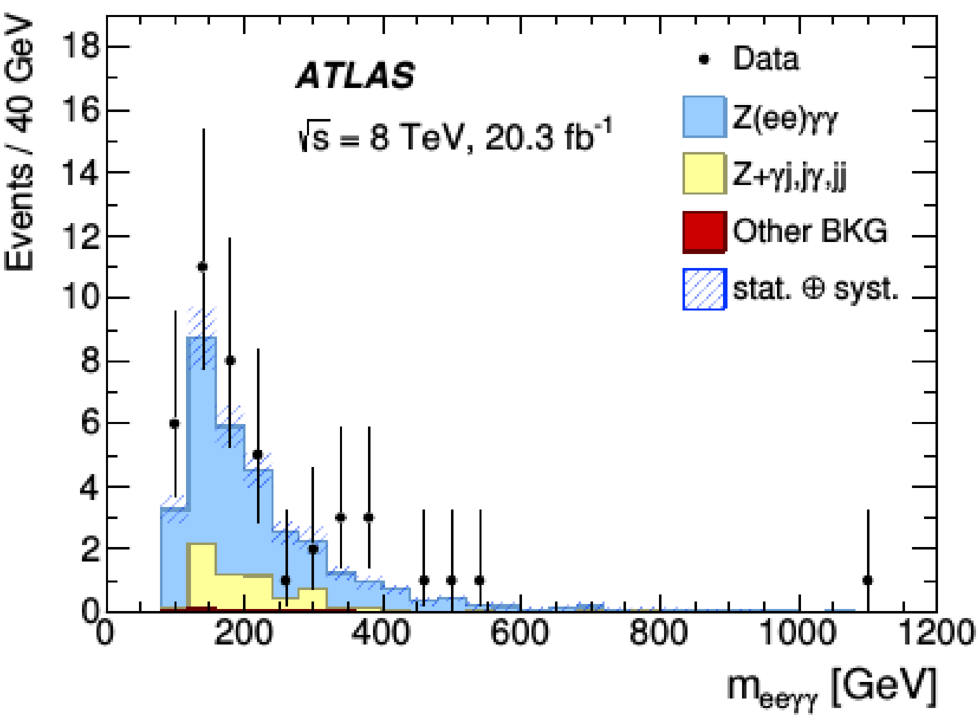


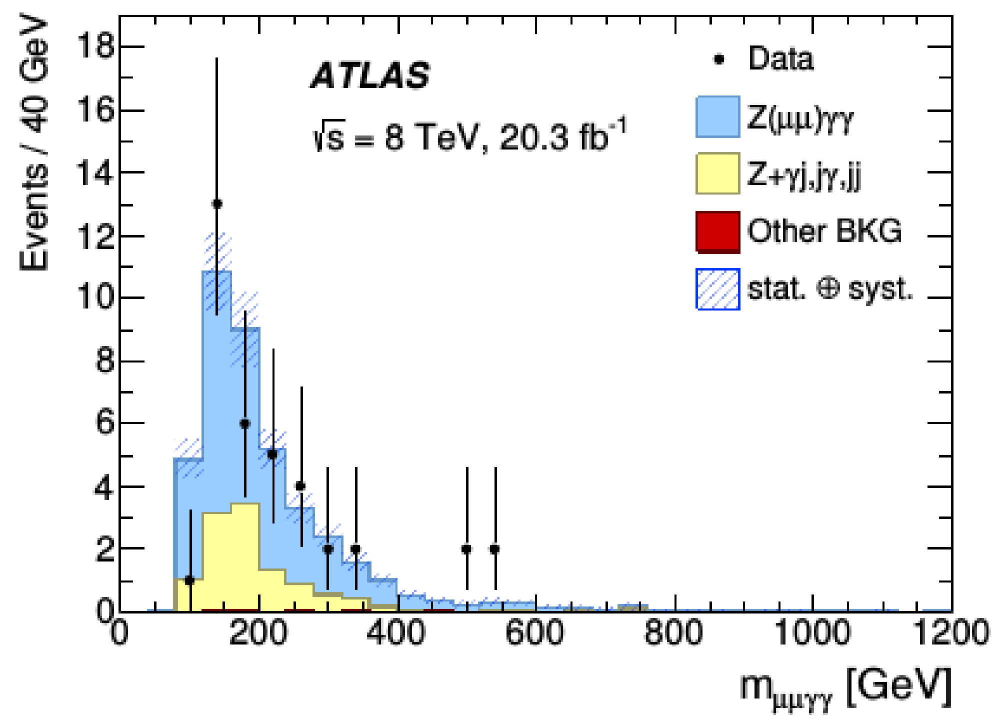
Expected Limits (TeV^{-4})	Observed Limits (TeV^{-4})
$-30.5 < \frac{f_{T0}}{\Lambda^4} < 31.1$	$-37.5 < \frac{f_{T0}}{\Lambda^4} < 38.1$
$-36.9 < \frac{f_{T1}}{\Lambda^4} < 37.5$	$-46.1 < \frac{f_{T1}}{\Lambda^4} < 46.9$
$-83.2 < \frac{f_{T2}}{\Lambda^4} < 83.2$	$-103 < \frac{f_{T2}}{\Lambda^4} < 103$
$-623 < \frac{f_{M2}}{\Lambda^4} < 603$	$-751 < \frac{f_{M2}}{\Lambda^4} < 729$
$-1080 < \frac{f_{M3}}{\Lambda^4} < 1110$	$-1290 < \frac{f_{M3}}{\Lambda^4} < 1340$

$Z\gamma\gamma$ production

Phys. Rev. D 93, 112002 - Published 2 June 2016

	$e^+e^-\gamma\gamma$	$\mu^+\mu^-\gamma\gamma$	$e^+e^-\gamma\gamma$	$\mu^+\mu^-\gamma\gamma$
	$N_{\text{jets}} \geq 0$		$N_{\text{jets}} = 0$	
$N^{\text{obs}}_{Z\gamma\gamma}$	43	37	29	22
$N^{j\to\gamma}_{Z\gamma\gamma}$	$5.8 \pm 1.0 \pm 1.4$	$10.9 \pm 1.1 \pm 2.8$	$3.08 \pm 0.73 \pm 0.75$	$6.4 \pm 0.9 \pm 1.8$
$N^{\text{Other BKG}}_{Z\gamma\gamma}$	$0.42 \pm 0.08 \pm 0.18$	$0.194 \pm 0.047 \pm 0.097$	$0.24 \pm 0.05 \pm 0.11$	$0.105 \pm 0.028 \pm 0.055$
$N^{\text{sig}}_{Z\gamma\gamma}$ (SHERPA)	$25.7 \pm 0.5 \pm 1.6$	$29.5 \pm 0.6 \pm 1.7$	$18.9 \pm 0.5 \pm 1.5$	$21.8 \pm 0.5 \pm 1.7$





$Z\gamma\gamma$ production

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Cuts	$\ell^+\ell^-\gamma\gamma$	$\nu\bar{\nu}\gamma\gamma$
Lepton	$p_T^\ell > 25$ GeV	-
	$\|\eta^\ell\| < 2.47$	-
Boson	$m_{\ell^+\ell^-} > 40$ GeV	$p_T^{\nu\bar{\nu}} > 110$ GeV
Photon	$E_T^\gamma > 15$ GeV	$E_T^\gamma > 22$ GeV
	$\|\eta^\gamma\| < 2.37$	
	$\Delta R(\ell,\gamma) > 0.4$	-
	$\Delta R(\gamma,\gamma) > 0.4$	$\Delta R(\gamma,\gamma) > 0.4$
	$\epsilon_h^p < 0.5$	
Jet	$p_T^{\text{jet}} > 30$ GeV, $\|\eta^{\text{jet}}\| < 4.5$	
	$\Delta R(\text{jet}, \ell/\gamma) > 0.3$	$\Delta R(\text{jet}, \gamma) > 0.3$
	Inclusive : $N_{\text{jet}} \geq 0$, Exclusive : $N_{\text{jet}} = 0$	

	$N_{\text{jets}} \geq 0$	$N_{\text{jets}} = 0$
$N_{Z\gamma\gamma}^{\text{obs}}$	46	19
$N_{Z\gamma\gamma}^{\text{jets}+\gamma(\gamma)}$	$12.2 \pm 6.7 \pm 1.8$	$2.9 \pm 4.0 \pm 0.4$
$N_{Z\gamma\gamma}^{W(\ell\nu)\gamma\gamma}$	$3.6 \pm 0.1 \pm 3.6$	$1.0 \pm 0.1 \pm 1.0$
$N_{Z\gamma\gamma}^{W(e\nu)\gamma}$	$10.4 \pm 0.5 \pm 2.1$	$3.47 \pm 0.28 \pm 0.69$
$N_{Z\gamma\gamma}^{Z(\nu\bar{\nu})\gamma+\text{jets}}$	$0.71 \pm 0.71 \pm 0.90$	$0.71 \pm 0.71 \pm 0.75$
$N_{Z\gamma\gamma}^{Z(\tau^+\tau^-)\gamma\gamma}$	$0.381 \pm 0.055 \pm 0.027$	$0.141 \pm 0.036 \pm 0.010$
$N_{Z\gamma\gamma}^{\text{bkg}}$	$27.2 \pm 6.8 \pm 4.6$	$8.3 \pm 4.1 \pm 1.5$
$N_{Z\gamma\gamma}^{\text{sig}}$ (SHERPA)	$7.54 \pm 0.07 \pm 0.34$	$4.80 \pm 0.06 \pm 0.29$

$Z\gamma\gamma$ production

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Channel	Measurement [fb]	MCFM Prediction [fb]
	$N_{\text{jets}} \geq 0$	
$e^+e^-\gamma\gamma$	$6.2\ ^{+1.2}_{-1.1}(\text{stat.}) \pm 0.4(\text{syst.}) \pm 0.1(\text{lumi.})$	$3.70^{+0.21}_{-0.11}$
$\mu^+\mu^-\gamma\gamma$	$3.83\ ^{+0.95}_{-0.85}(\text{stat.})^{+0.48}_{-0.47}(\text{syst.}) \pm 0.07(\text{lumi.})$	
$\ell^+\ell^-\gamma\gamma$	$5.07\ ^{+0.73}_{-0.68}(\text{stat.})^{+0.41}_{-0.38}(\text{syst.}) \pm 0.10(\text{lumi.})$	
$\nu\bar{\nu}\gamma\gamma$	$2.5\ ^{+1.0}_{-0.9}(\text{stat.}) \pm 1.1(\text{syst.}) \pm 0.1(\text{lumi.})$	$0.737^{+0.039}_{-0.032}$
	$N_{\text{jets}} = 0$	
$e^+e^-\gamma\gamma$	$4.6\ ^{+1.0}_{-0.9}(\text{stat.})^{+0.4}_{-0.3}(\text{syst.}) \pm 0.1(\text{lumi.})$	$2.91^{+0.23}_{-0.12}$
$\mu^+\mu^-\gamma\gamma$	$2.38\ ^{+0.77}_{-0.67}(\text{stat.})^{+0.33}_{-0.32}(\text{syst.})^{+0.05}_{-0.04}(\text{lumi.})$	
$\ell^+\ell^-\gamma\gamma$	$3.48\ ^{+0.61}_{-0.56}(\text{stat.})^{+0.29}_{-0.25}(\text{syst.}) \pm 0.07(\text{lumi.})$	
$\nu\bar{\nu}\gamma\gamma$	$1.18\ ^{+0.52}_{-0.44}(\text{stat.})^{+0.48}_{-0.49}(\text{syst.}) \pm 0.02(\text{lumi.})$	$0.395^{+0.049}_{-0.037}$

$Z\gamma\gamma$ production

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Channel	Measurement [fb]	Prediction [fb]
$\ell^+\ell^-\gamma\gamma$ ($m_{\gamma\gamma} > 200$ GeV)	$0.12^{+0.11}_{-0.07}$(stat.)$^{+0.03}_{-0.01}$(syst.)	0.0674 ± 0.0013(stat.) $\pm$ 0.0053(syst.)
$\nu\bar{\nu}\gamma\gamma$ ($m_{\gamma\gamma} > 300$ GeV)	$0.16^{+0.17}_{-0.11}$(stat.)$^{+0.04}_{-0.01}$(syst.)	0.0499 ± 0.0008(stat.) $\pm$ 0.0062(syst.)

Table 12: Theoretical VBFNLO SM and observed cross sections in chosen aQGC regions (with the exclusive selection) for the channels studied. The $m_{\gamma\gamma}$ threshold is 200 GeV for the electron and muon channels and is 300 GeV for the neutrino channel. The first uncertainty is statistical, the second is systematic.

n	Λ_{FF} [TeV]	Limits 95% C.L.	Observed [TeV^{-4}]	Expected [TeV^{-4}]
0	∞	f_{M2}/Λ^4	$[-1.6, 1.6] \times 10^4$	$[-1.2, 1.2] \times 10^4$
		f_{M3}/Λ^4	$[-2.9, 2.7] \times 10^4$	$[-2.2, 2.2] \times 10^4$
		f_{T0}/Λ^4	$[-0.86, 1.03] \times 10^2$	$[-0.65, 0.82] \times 10^2$
		f_{T5}/Λ^4	$[-0.69, 0.68] \times 10^3$	$[-0.52, 0.52] \times 10^3$
		f_{T9}/Λ^4	$[-0.74, 0.74] \times 10^4$	$[-0.58, 0.59] \times 10^4$
2	5.5	f_{M2}/Λ^4	$[-1.8, 1.9] \times 10^4$	$[-1.4, 1.5] \times 10^4$
	5.0	f_{M3}/Λ^4	$[-3.4, 3.3] \times 10^4$	$[-2.6, 2.6] \times 10^4$
	0.7	f_{T0}/Λ^4	$[-2.3, 2.1] \times 10^3$	$[-1.9, 1.6] \times 10^3$
	0.6	f_{T5}/Λ^4	$[-2.3, 2.2] \times 10^4$	$[-1.8, 1.8] \times 10^4$
	0.4	f_{T9}/Λ^4	$[-0.89, 0.86] \times 10^6$	$[-0.71, 0.68] \times 10^6$

Zγγ production

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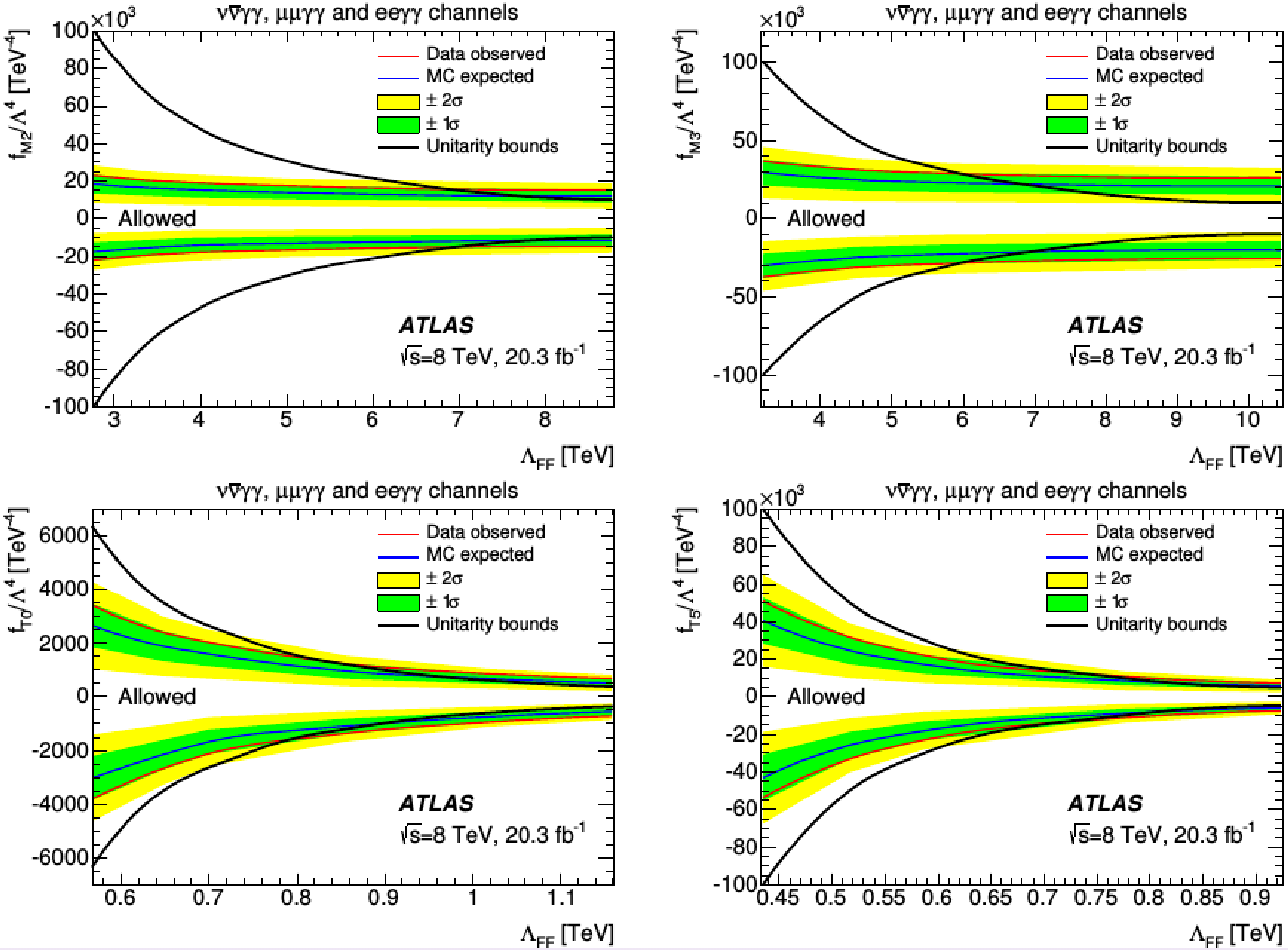
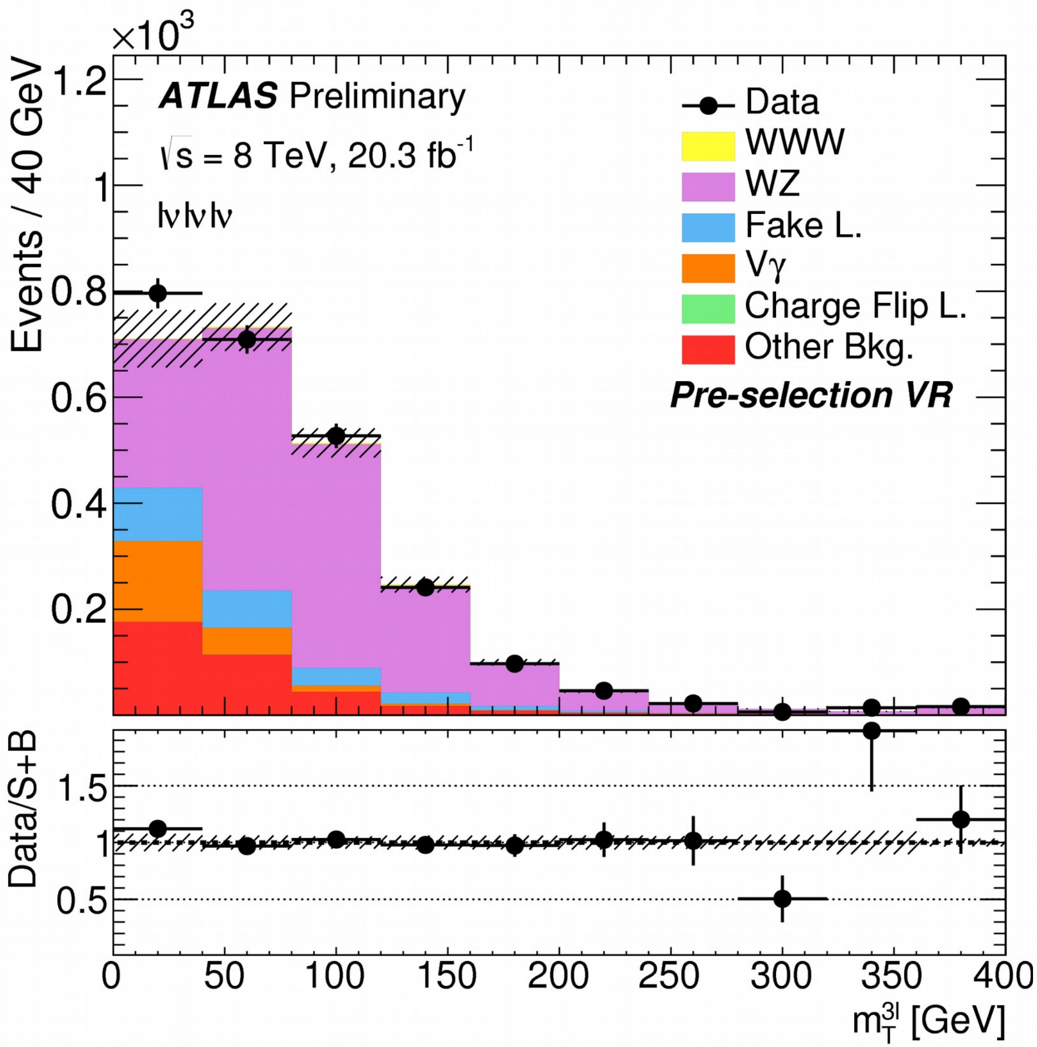
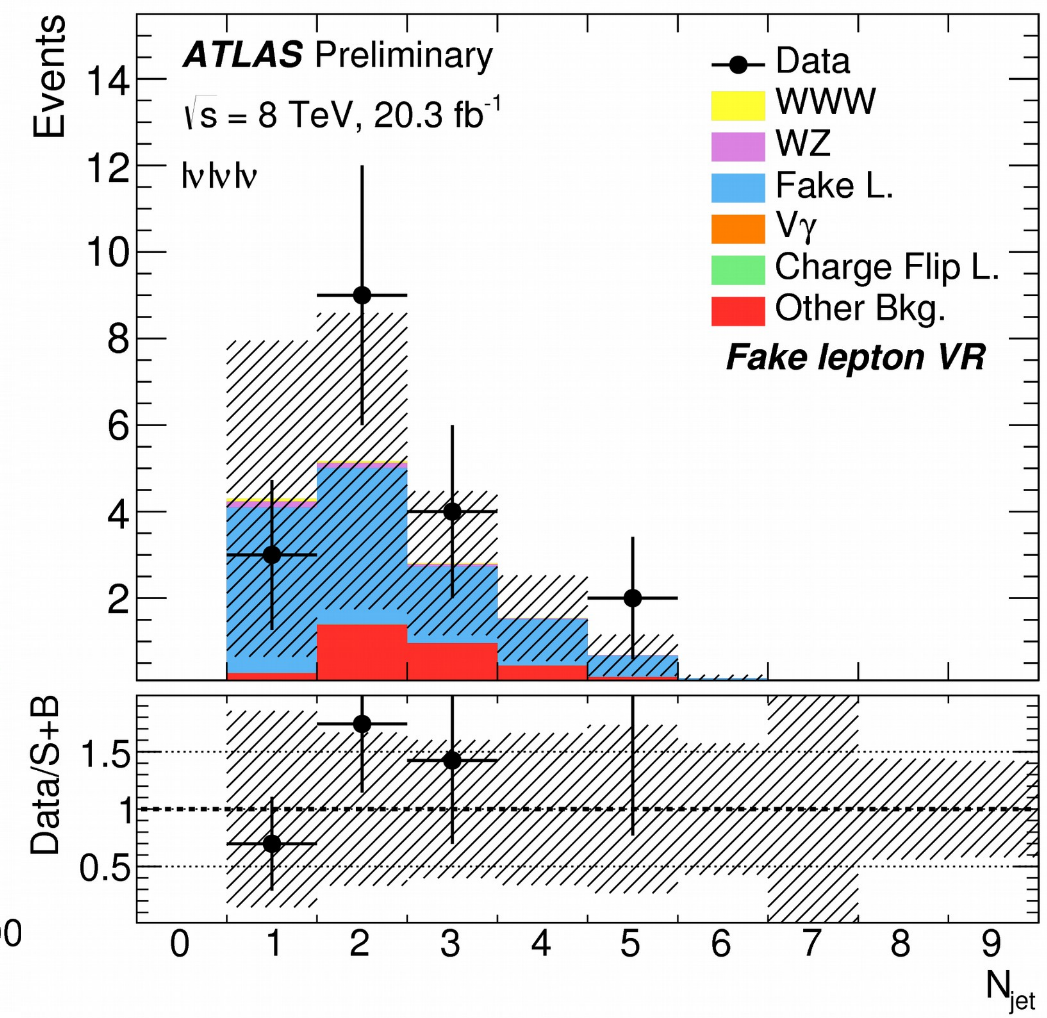


WWW production

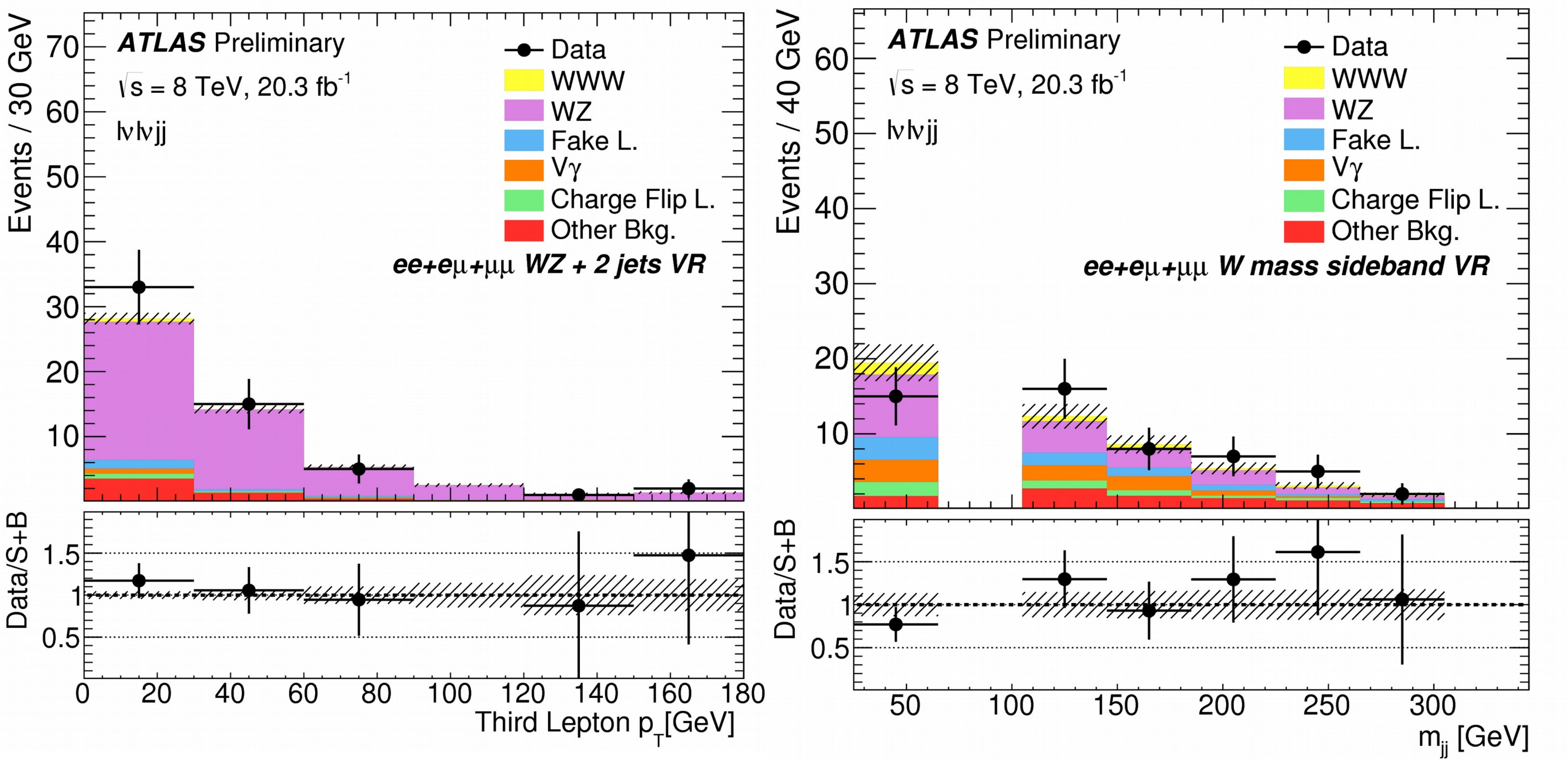
To be published





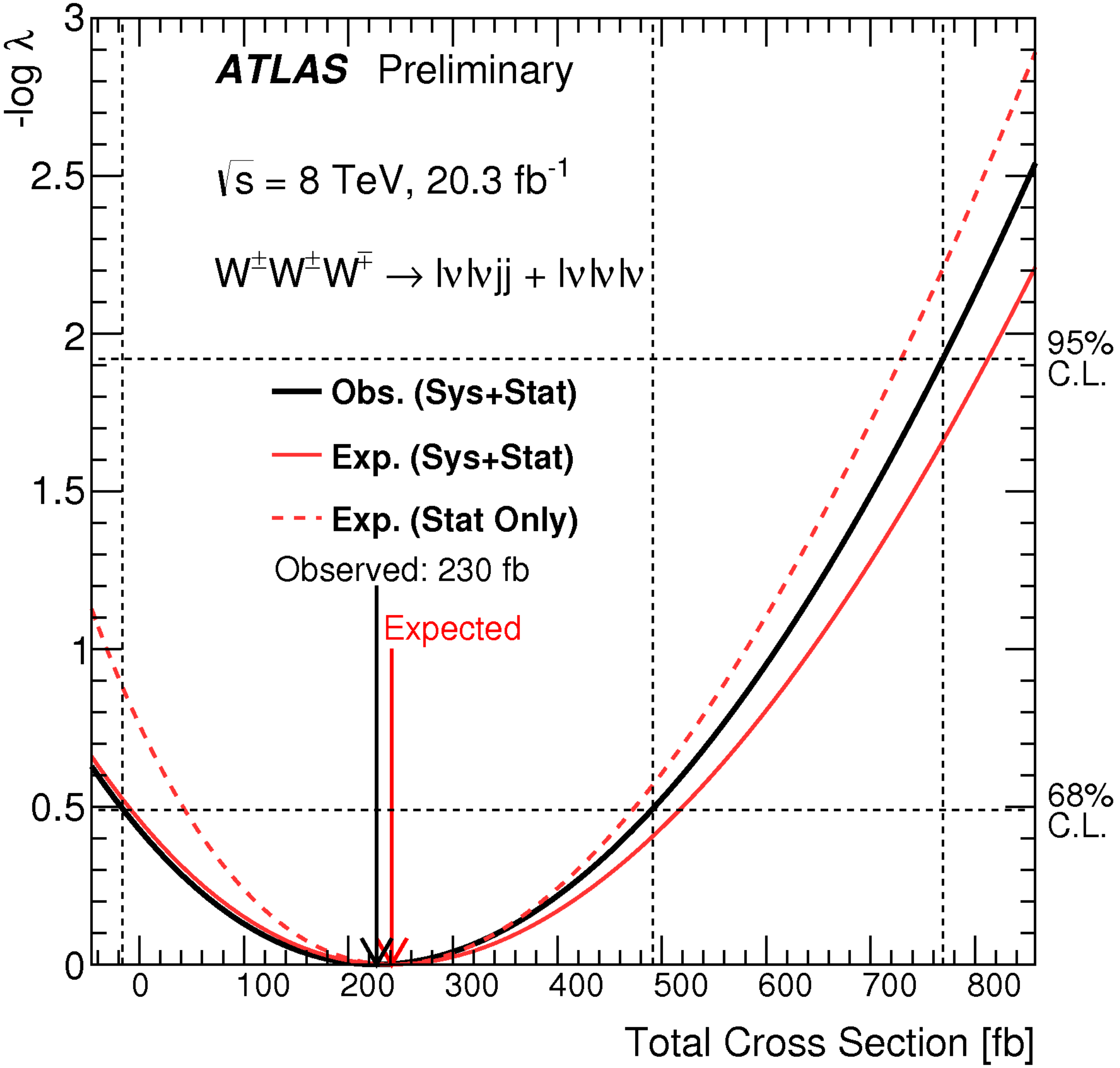
WWW production

To be published



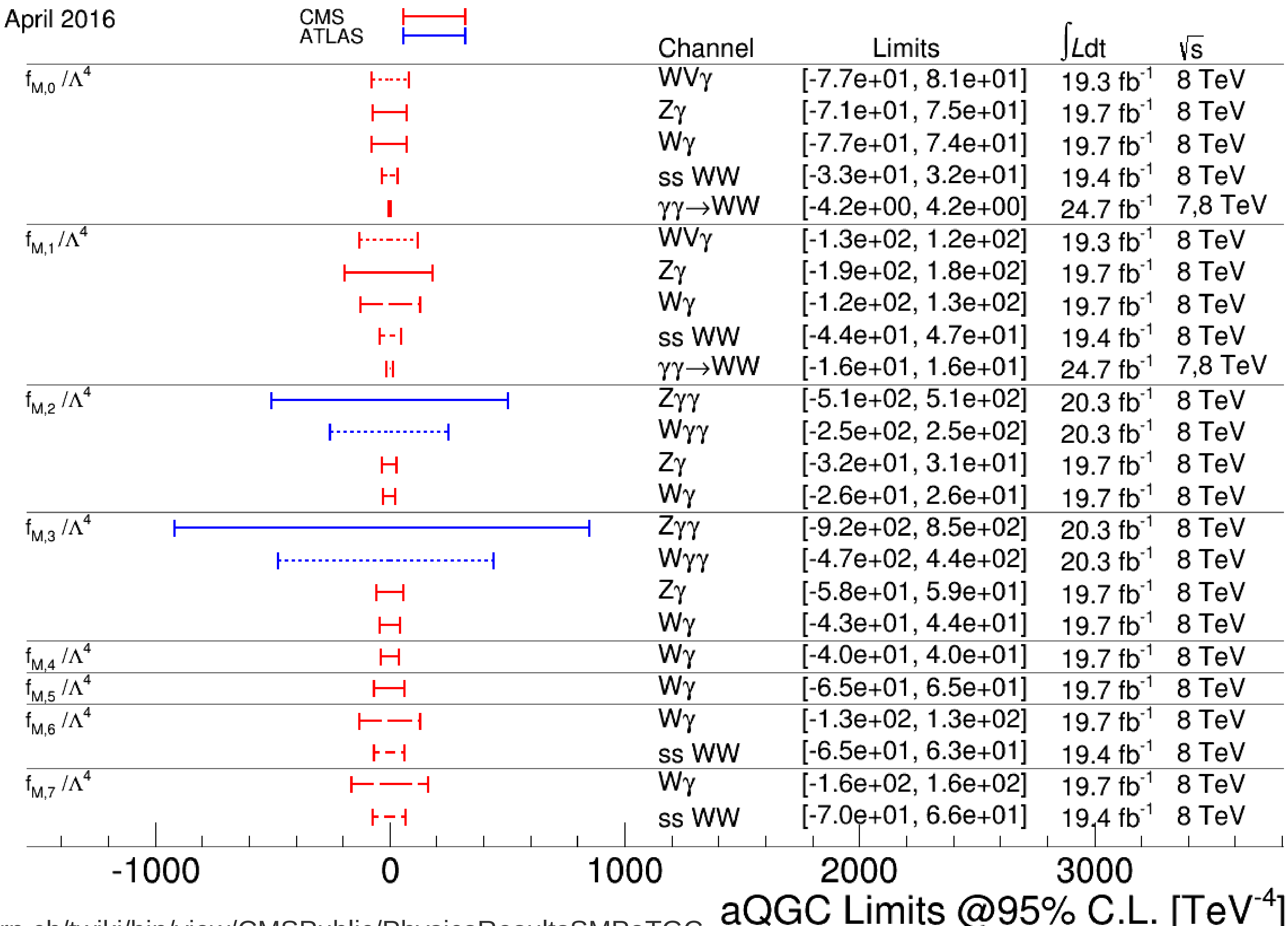
WWW production

To be published



Eboli parametrisation used

State of the Art in aQGC



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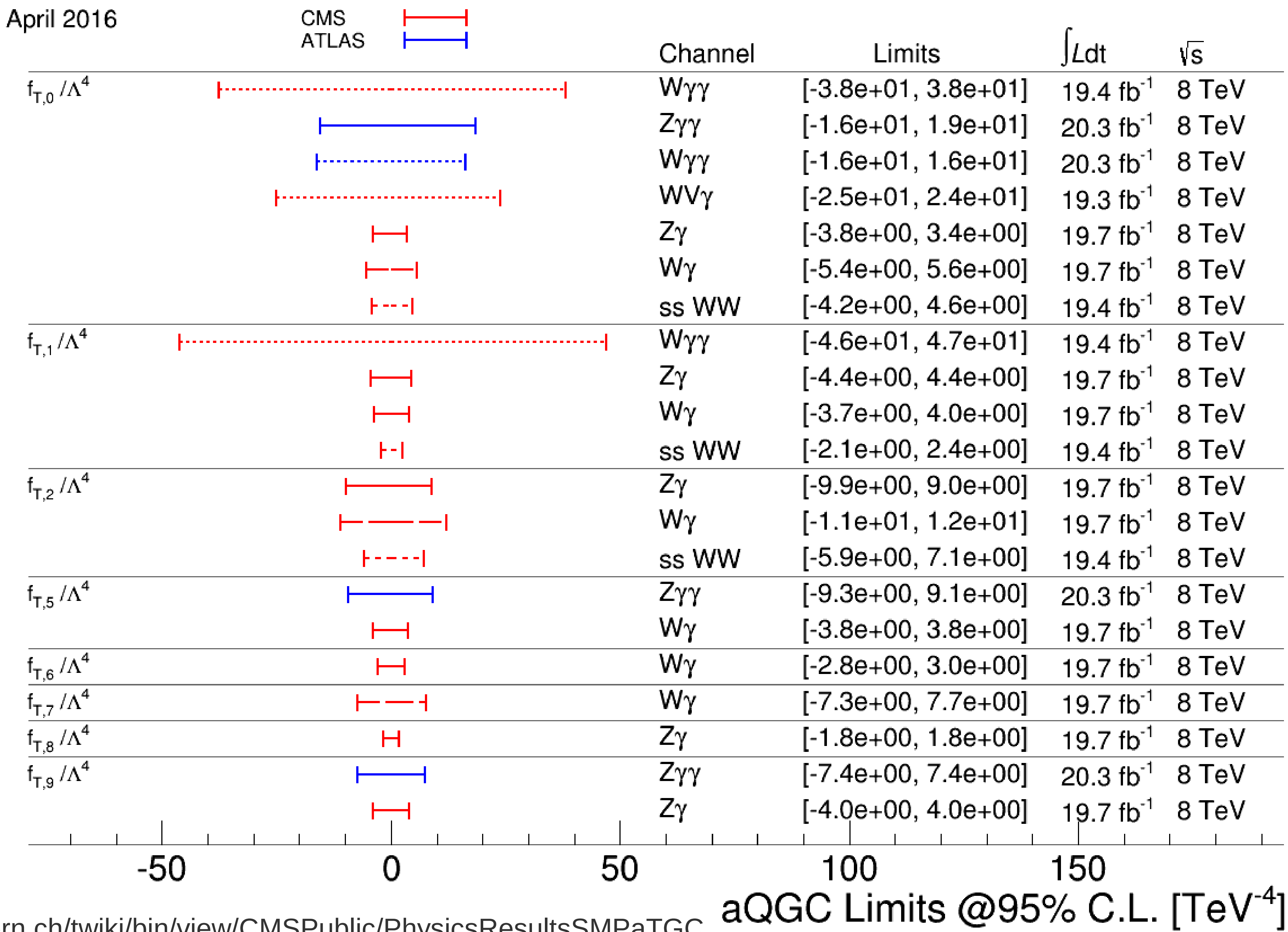
Eboli parametrisation used

State of the Art in aQGC



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