Studies of $Z\gamma$ electroweak production in association with a high-mass di-jet system

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on behalf of the ATLAS collaboration

3rd CLHCP conference , Nanjing, China, 2017.12. 22-2017.12. 24

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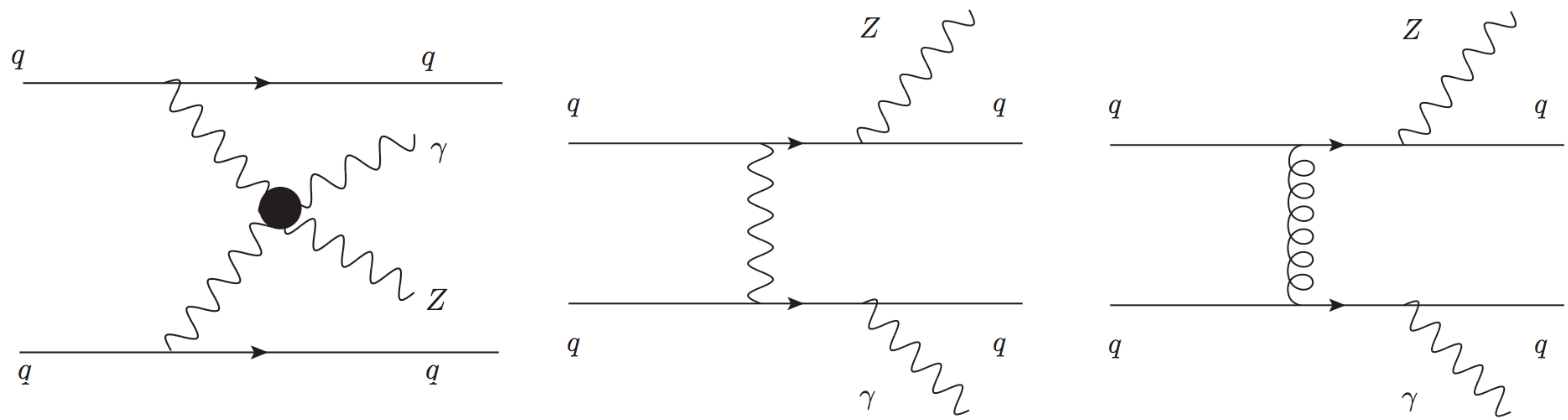
ATLAS EXPERIMENT

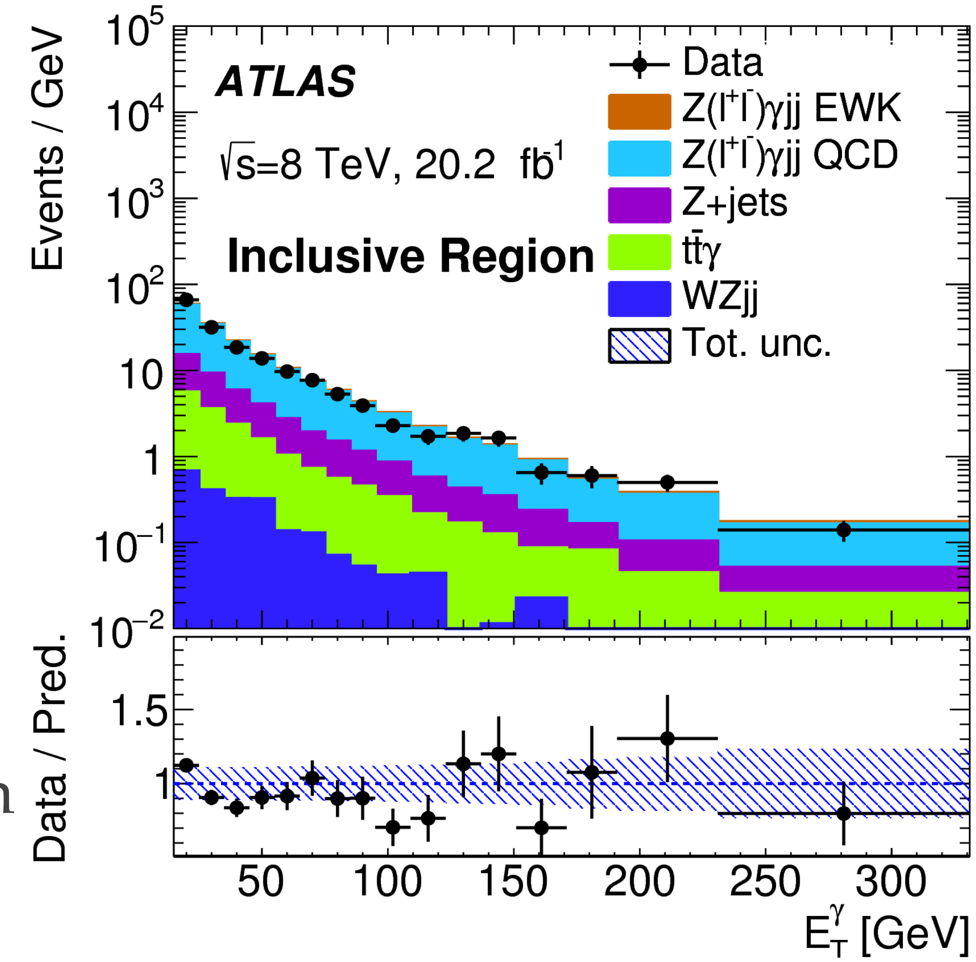
Introduction

- Two boson scattering is the key process to probe electroweak theory and measure the vector boson self-coupling.
- Important for independently testing the quartic gauge-boson coupling (QGCs).
- QGCs can be studied either by 3 bosons final state or electroweak vector boson production (VBS process)
  - With photon is more promised due to its relative larger rate than leptonic W/Z processes.
- Study on VBS process helps to explore the anomalous QGC (aQGC), especially in high photon energy region.



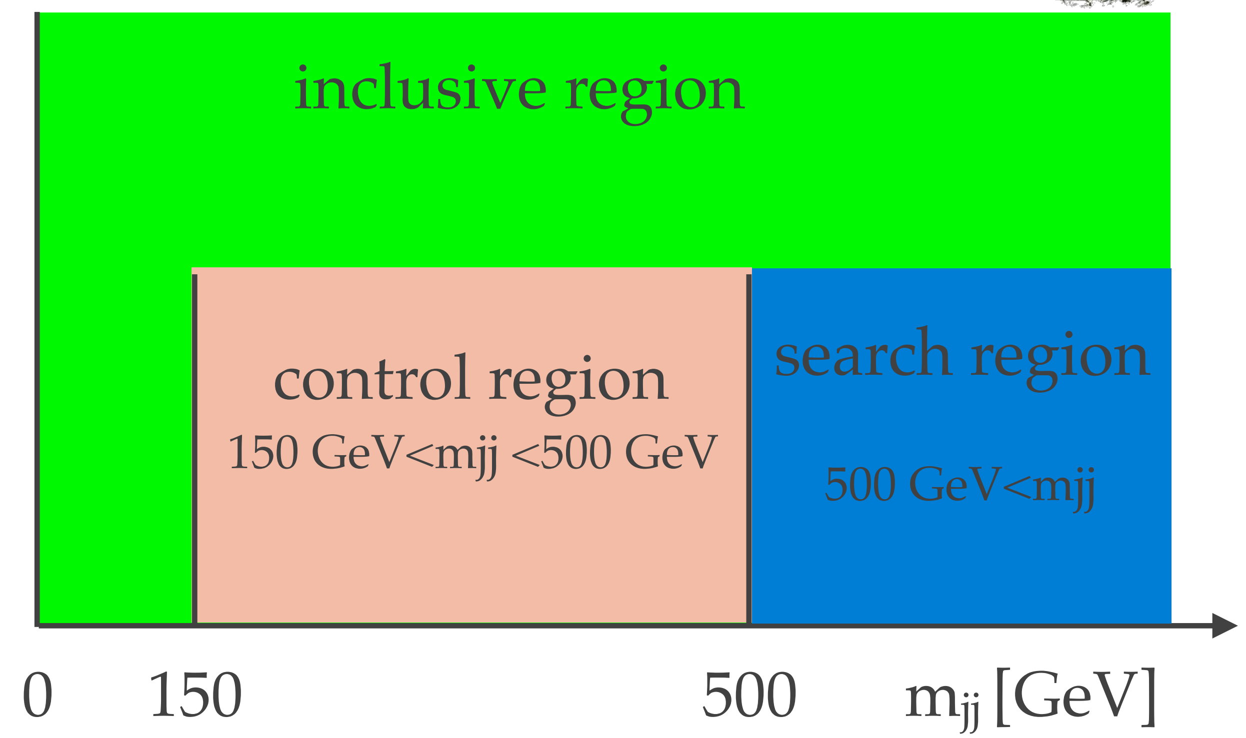
Object definition

- Electron
  - E_T>25 GeV with $|\eta|$<2.47
  - loose identification
  - E_T^{cone30}/E_T<0.1
  - ID track with $|z0\sin(\theta)|$<0.5 mm
  - ID track with $d0/\sigma(d0)$<6
- Muon
  - p_T>25 GeV with $|\eta|$<2.47
  - Good associated ID track
  - same impact parameters requirement as electron
  - p_T^{cone30}/p_T<0.1
- Photon
  - $|\eta|$<2.47 (without 1.37<$|\eta|$<1.52)
  - E_T^{cone40}<6 GeV
  - Remove photon when $\Delta R(\gamma, \ell)$<0.4
- Jet
  - Anti-k_T R=0.4 jet
  - p_T>30 GeV with $|\eta|$<4.5
  - JVF >0.5 (associate tracks to jet with ΔR<0.4) for jet with p_T<50 GeV and $|\eta|$<2.4
  - Remove jet when $\Delta R(j, \ell)$<0.3 or $\Delta R(j, \gamma)$<0.3



Event Selection

- $\ell\ell\gamma jj$ selections
  - One photon with E_T> 15 GeV,
  - Opposite-sign and same flavour leptons
  - At lease two well reconstructed jets
  - $m_{\ell\ell}$>40 GeV, $m_{\ell\ell}+m_{\ell\ell\gamma}$>182 GeV
  - Categorise event according to m_{jj} value
  - Phase space region is optimised for aQGC with photon E_T> 250 GeV.



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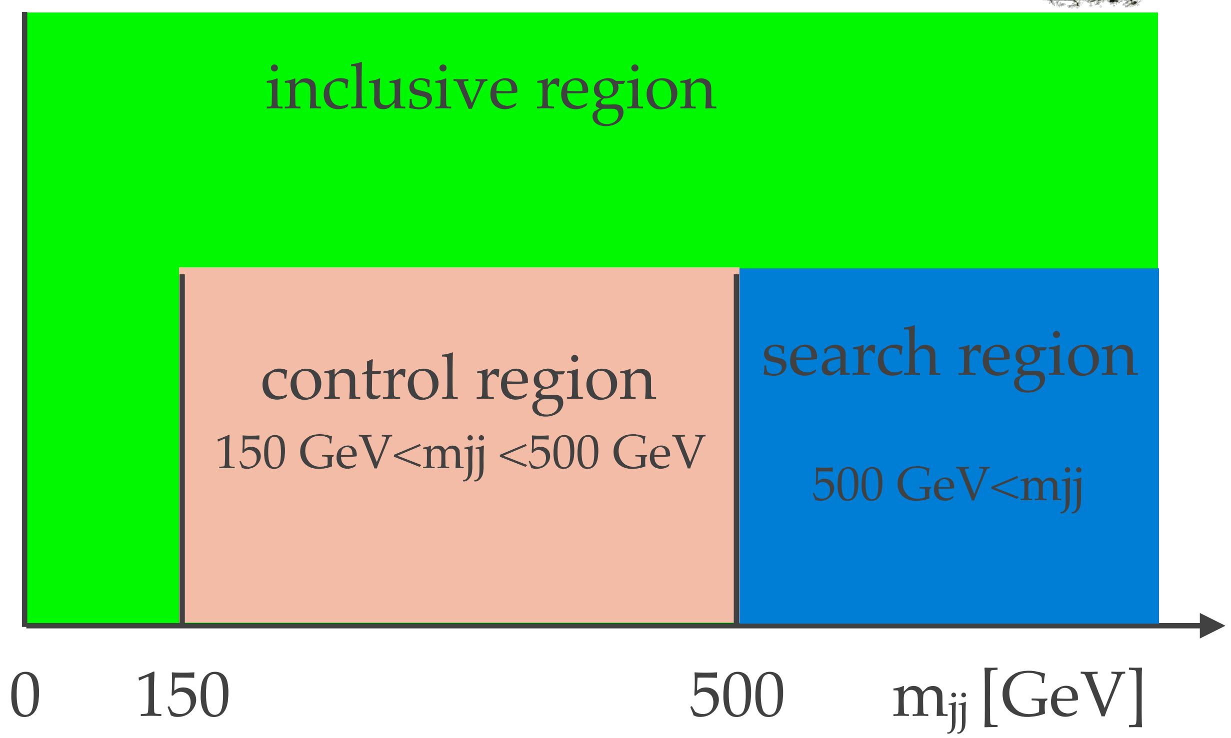
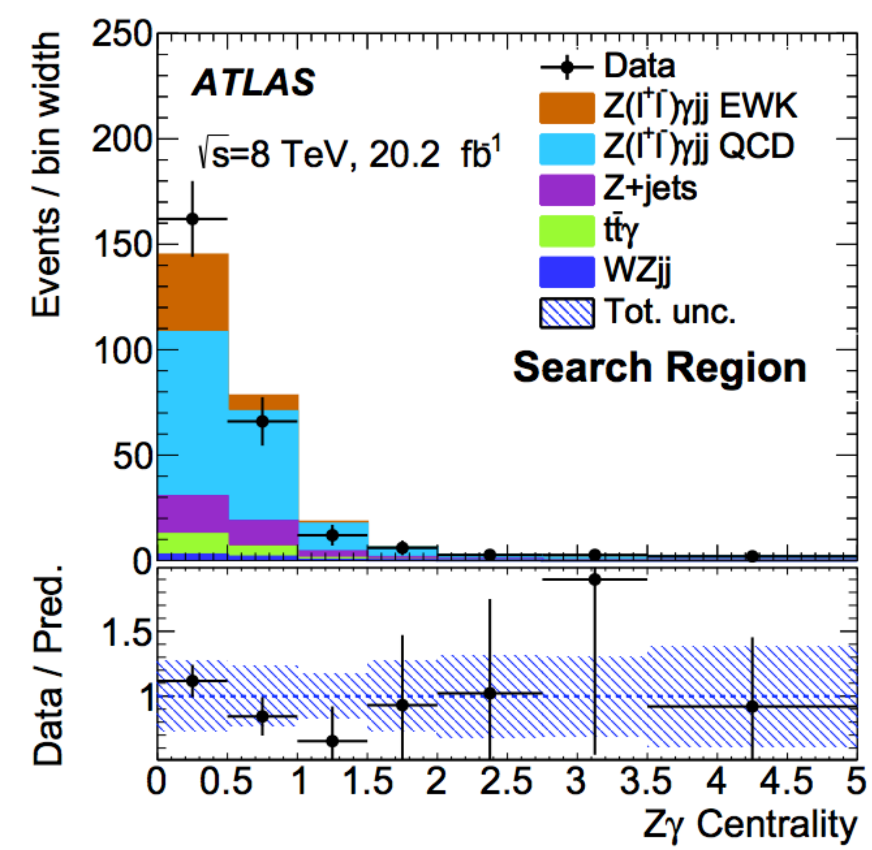
- Centrality observable (ζ) is used to discriminate Zγjj EWK and QCD production and is used to extract cross section



$$\zeta_{Z\gamma} = \left| \frac{\eta_{Z\gamma} - \bar{\eta}_{jj}}{\Delta\eta_{jj}} \right|, \bar{\eta}_{jj} = \frac{\eta_{j_1} + \eta_{j_2}}{2}, \Delta\eta_{jj} = \eta_{j_1} - \eta_{j_2}$$



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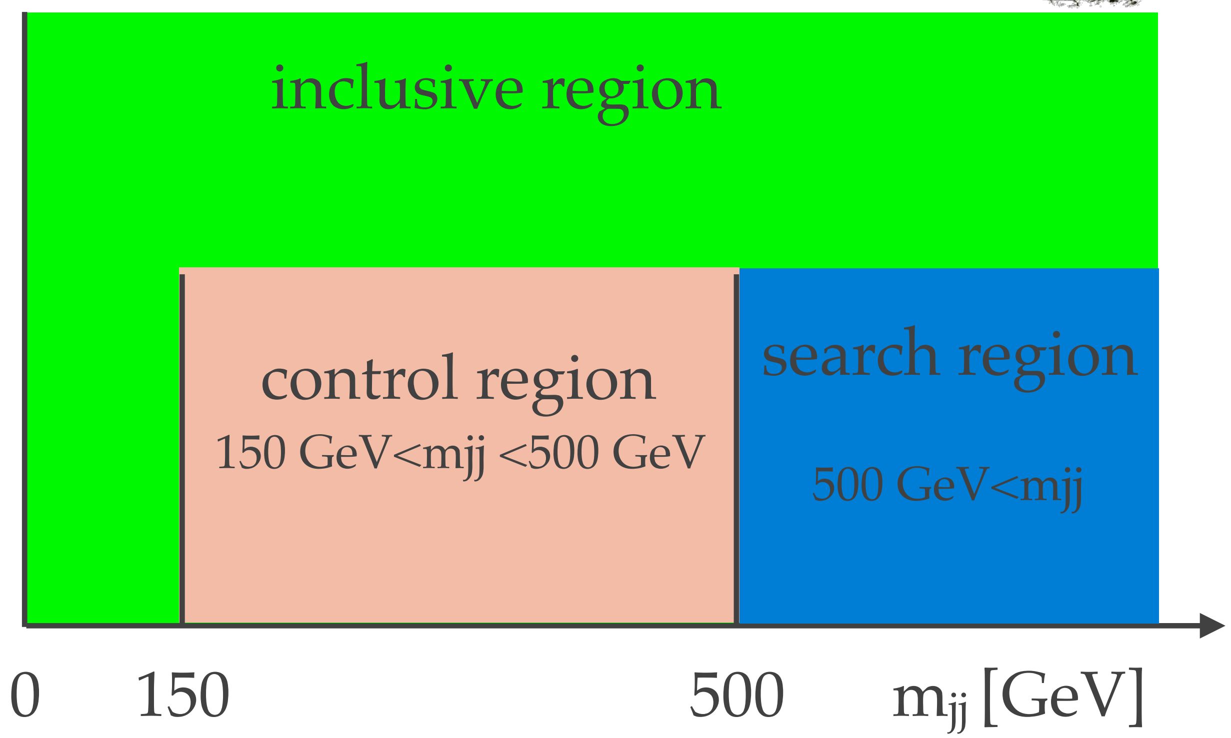

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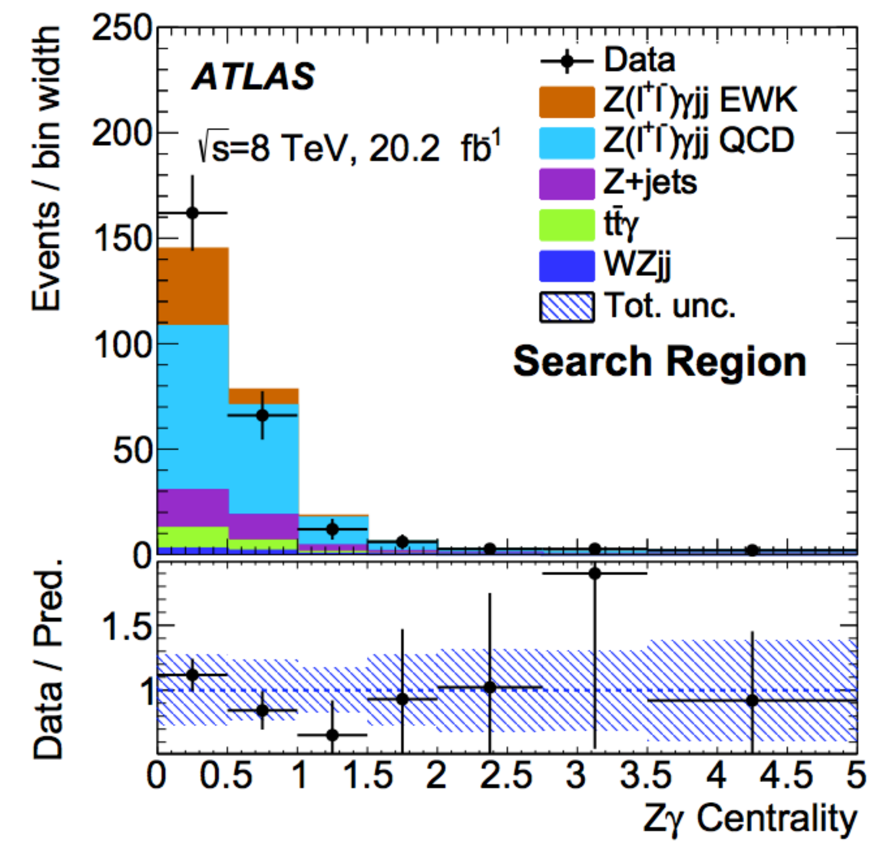
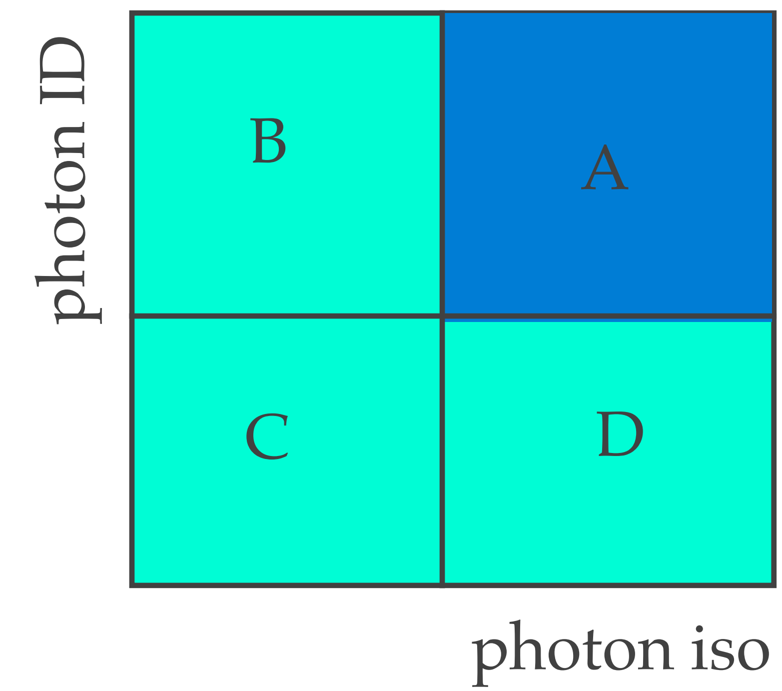
- $\nu\nu\gamma jj$ selections
  - E_T^{miss}>100 GeV
  - One photon with E_T> 150 GeV,
  - At lease two well reconstructed jets
  - Veto leptons
  - $\Delta\phi(p_T^{miss}, \gamma jj)>3\pi/4$, $\Delta\phi(p_T^{miss}, \gamma)>\pi/2$, $\Delta\phi(p_T^{miss}, j)>1$
  - $|\Delta y_{jj}|>2.5$ with photon centrality $\zeta_\gamma<0.3$
  - $p_T^{balance}<0.1$

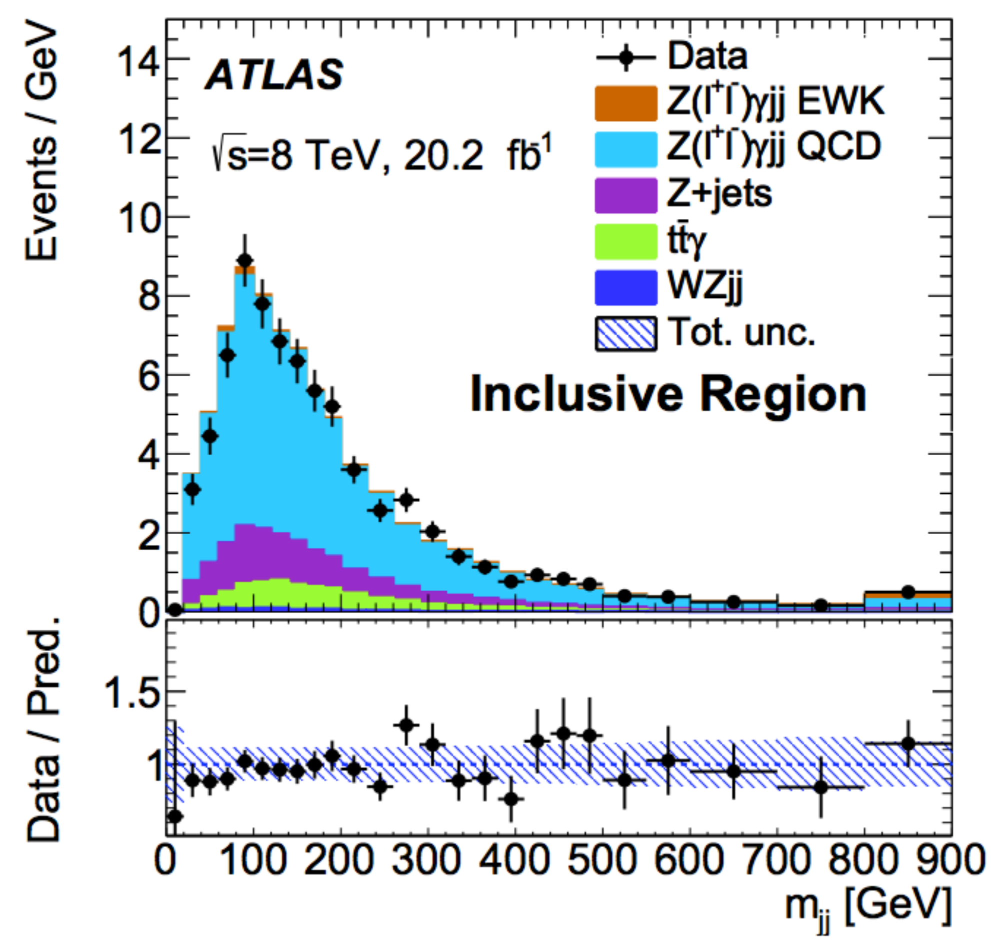
$$p_T^{\text{balance}} \equiv \frac{|\vec{p}_T^{\,\text{miss}} + \vec{p}_T^{\,\gamma} + \vec{p}_T^{\,j_1} + \vec{p}_T^{\,j_2}|}{E_T^{\text{miss}} + |\vec{p}_T^{\,\gamma}| + |\vec{p}_T^{\,j_1}| + |\vec{p}_T^{\,j_2}|},$$



Background estimation ($\ell\ell\gamma jj$)

- $\ell\ell\gamma$**jj** channel main backgrounds come from Zjet with jet faking photon,
  - Its contribution is estimated by using 2D sidebands
  - An enlarged region (m_{jj}>100 GeV) is used for estimation
  - Contribute to SR with (23±6)% of $Z\gamma$ events
    - Main source of systematics uncertainty due to the correlation between two variables
    - Checked with MC for different generators
    - Systematics related to other sources (CR definition, signal contamination and mjj difference between Zjet and $Z\gamma$) are found to be negligible





- Other background contribution like WZ+jet, $t\bar{t}\gamma$ are estimated from MC prediction

Background estimation ($\nu\nu\gamma jj$)

- $\nu\nu\gamma$**jj** channel, the dominate background contribution is W($\ell\nu$)γ+jets (59%).
  - This background is estimated from a CR by requiring one charged lepton instead of vetoing with purity of 80%.
  - The correction factor (**1.06**) is derived from CR and applied to SR . The dominant systematic uncertainty is estimated by comparing different generators and found to be **41**%.
- Followed backgrounds is Z($\nu\nu$)+jets,
  - Estimated by using 2D sidebands method
  - Estimation is dominant by statistical uncertainty (50 %) compare to systematic uncertainty (20%)
- γ+jets with fake MET
  - 2D sideband method with E_T^{miss} and $\Delta\phi(p_T^{miss}, \gamma)$
  - A looser photon energy requirement (45 GeV)
  - Difference between Sherpa and Alpgen results for extrapolating to SR is the dominant uncertainty
- W+jets:
  - Estimated by applying fake factor (e→γ) to W+jets CR with high momentum electron instead of photon
  - Statistis in CR contribute 43% uncertainty

Summary of systematic uncertainties

- Systematic uncertainties in charged channel for ee(mm) SR

Source of uncertainty	EWK yield [%]		QCD yield [%]		Bkg. yield [%]	
	CR	SR	CR	SR	CR	SR
Trigger			0.2 (0.4)			
Pile-up			0.6			
Lepton selection			3.8 (2.3)			
Photon selection			1.6			
Jet reconstruction	1.1	2.5	5.0	12	4.9	12
Bkg. 2D sideband	-	-	-	-	26	26
Total experimental	4.3 (3.1)	4.9 (3.8)	6.5 (5.8)	13 (12)	27 (27)	29 (29)
Theory	5.2	8.7	5.6	3.8	5.6	3.8

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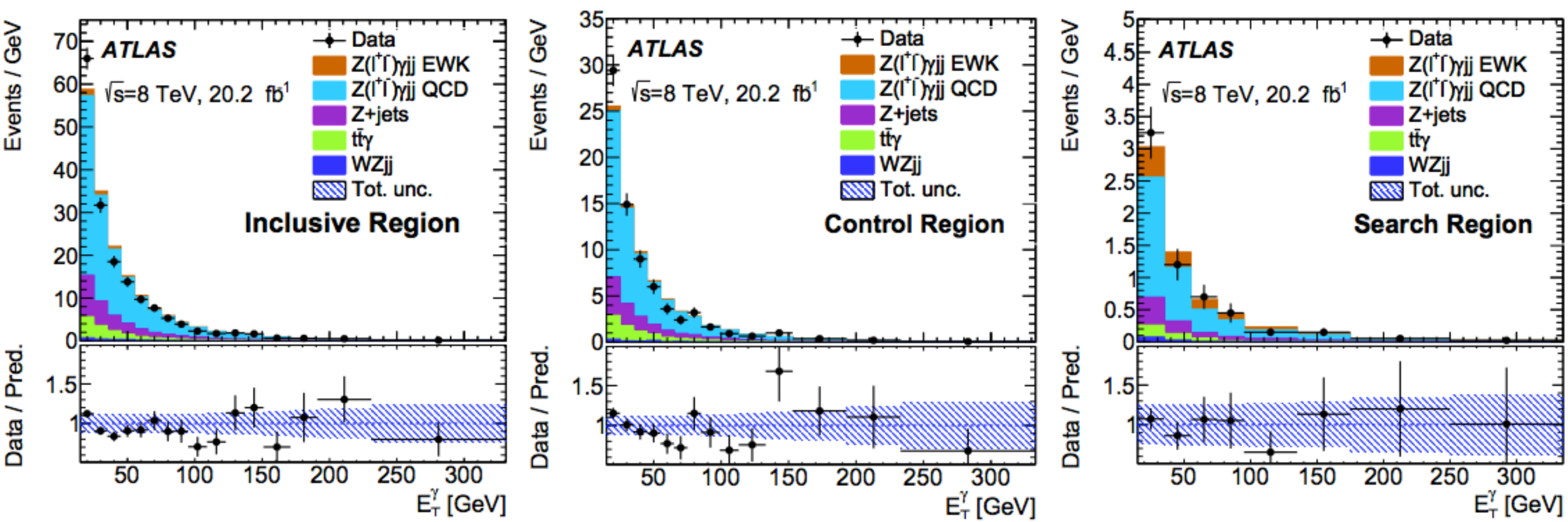
- Systematic uncertainties in aQGC region

Source of uncertainty	EWK yield [%] $\ell^+\ell^-$ channel	EWK yield [%] $\nu\bar{\nu}$ channel	QCD yield [%] $\ell^+\ell^-$ channel	QCD yield [%] $\nu\bar{\nu}$ channel
Trigger	0.2 (0.4)	2	0.2 (0.4)	2
Pile-up	0.6			
Lepton selection	3.8 (2.3)	-	3.8 (2.3)	-
$E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction	-	0.4	-	0.4
Photon selection	6.5	3.3	6.5	3.3
Jet reconstruction	2.5	3.2	12	3.2
Total experimental	8.0 (7.4)	5.1	13	5.1
Theory	8.7	4.1	3.8	4.1

Distributions after final selections

	Inclusive region $Z(\ell^+\ell^-)\gamma + \geq 2$ jets		Control region $150 < m_{jj} < 500$ GeV		Search region $m_{jj} > 500$ GeV	
	$e^+e^-\gamma jj$	$\mu^+\mu^-\gamma jj$	$e^+e^-\gamma jj$	$\mu^+\mu^-\gamma jj$	$e^+e^-\gamma jj$	$\mu^+\mu^-\gamma jj$
Data	781	949	362	421	58	72
Z+jets bkg.	134 ± 36	154 ± 42	57 ± 16	67 ± 18	8.5 ± 2.5	9.4 ± 2.7
Other bkg. ($t\bar{t}\gamma$, WZ)	88 ± 17	91 ± 18	47 ± 9	46 ± 9	5.8 ± 1.1	5.0 ± 1.0
$N_{\text{data}} - N_{\text{bkg}}$	559 ± 46	704 ± 53	258 ± 24	308 ± 27	44 ± 7	58 ± 8
$N_{Z\gamma\ \text{QCD}}$ (Sherpa MC)	583 ± 41	671 ± 47	249 ± 24	290 ± 26	37 ± 5	41 ± 5
$N_{Z\gamma\ \text{EWK}}$ (Sherpa MC)	25.4 ± 1.5	27.3 ± 1.7	8.6 ± 0.6	9.3 ± 0.6	11.2 ± 0.8	11.6 ± 0.7
$N_{Z\gamma}$ (Sherpa MC)	608 ± 42	698 ± 49	258 ± 25	299 ± 27	48 ± 6	53 ± 6



Fiducial cross sections (charged channel)

- The fiducial EWK cross section from data is derived in charged lepton channel from signal strength times the fiducial cross section predicted by Sherpa MC

$$\mu = \frac{N^{\text{signal}}_{\text{data}}}{N^{\text{signal}}_{\text{MC}}} = \frac{\sigma_{\text{data}}}{\sigma_{\text{MC}}},$$

From data

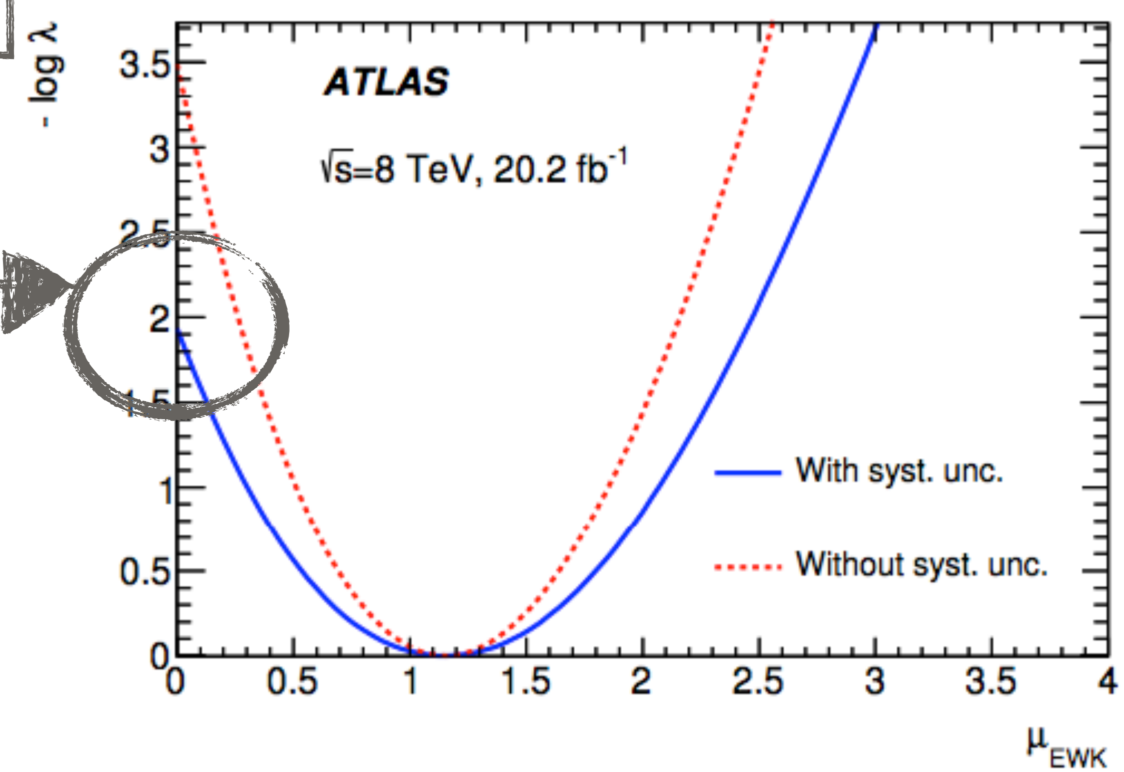
$$\sigma^{\text{EWK}}_{Z\gamma jj} = 1.1 \pm 0.5\ (\text{stat}) \pm 0.4\ (\text{syst})\ \text{fb} = 1.1 \pm 0.6\ \text{fb}.$$

$$\sigma^{\text{VBFNLO,EWK}}_{Z\gamma jj} = 0.94 \pm 0.09\ \text{fb}.$$

NLO prediction

Objects	Particle- (Parton-) level selection
Leptons	$p_{\mathrm{T}}^{\ell} > 25$ GeV and $\lvert\eta^{\ell}\rvert < 2.5$ Dressed leptons, OS charge
Photon (kinematics)	$E_{\mathrm{T}}^{\gamma} > 15$ GeV, $\lvert\eta^{\gamma}\rvert < 2.37$ $\Delta R(\ell,\gamma) > 0.4$
Photon (isolation)	$E_{\mathrm{T}}^{\text{iso}} < 0.5 \cdot E_{\mathrm{T}}^{\gamma}$ (no isolation)
FSR cut	$m_{\ell\ell} + m_{\ell\ell\gamma} > 182$ GeV $m_{\ell\ell} > 40$ GeV
Particle jets (Outgoing partons) (j = jets) (p = outgoing quarks or gluons)	At least two jets (outgoing partons) $E_{\mathrm{T}}^{j(p)} > 30$ GeV, $\lvert\eta^{j(p)}\rvert < 4.5$ $\Delta R(\ell, j(p)) > 0.3$ $\Delta R(\gamma, j(p)) > 0.4$
Control region (CR)	$150 < m_{jj(pp)} < 500$ GeV
Search region (SR)	$m_{jj(pp)} > 500$ GeV
aQGC region	$m_{jj(pp)} > 500$ GeV $E_{\mathrm{T}}^{\gamma} > 250$ GeV

significance: **2.0** **(1.8 exp)** σ



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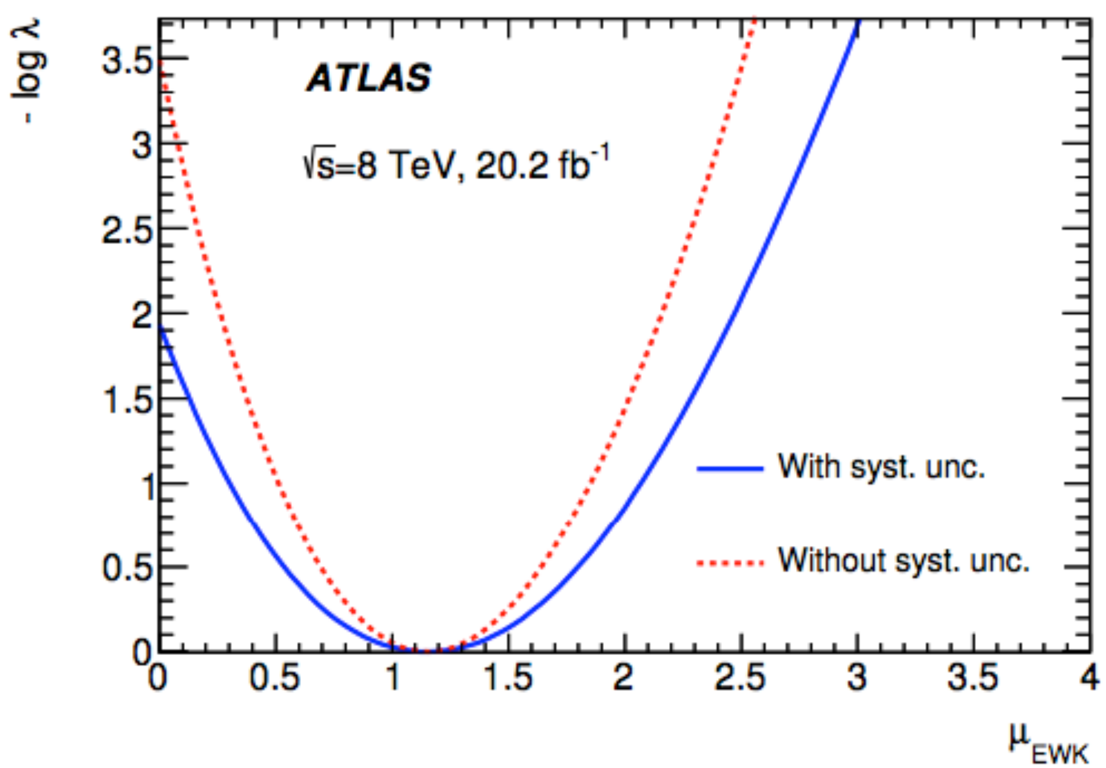
- Total (EWK+QCD) cross sections are also derived with SR and CR separated

$$\sigma^{\text{SR}}_{Z\gamma jj} = 3.4 \pm 0.3\ (\text{stat}) \pm 0.4\ (\text{syst})\ \text{fb} = 3.4 \pm 0.5\ \text{fb},$$
$$\sigma^{\text{CR}}_{Z\gamma jj} = 21.9 \pm 0.9\ (\text{stat}) \pm 1.8\ (\text{syst})\ \text{fb} = 21.9 \pm 2.0\ \text{fb}.$$

$$\sigma^{\text{VBFNLO,SR}}_{Z\gamma jj} = 4.0 \pm 0.4\ \text{fb},$$
$$\sigma^{\text{VBFNLO,CR}}_{Z\gamma jj} = 22.9 \pm 1.9\ \text{fb}.$$



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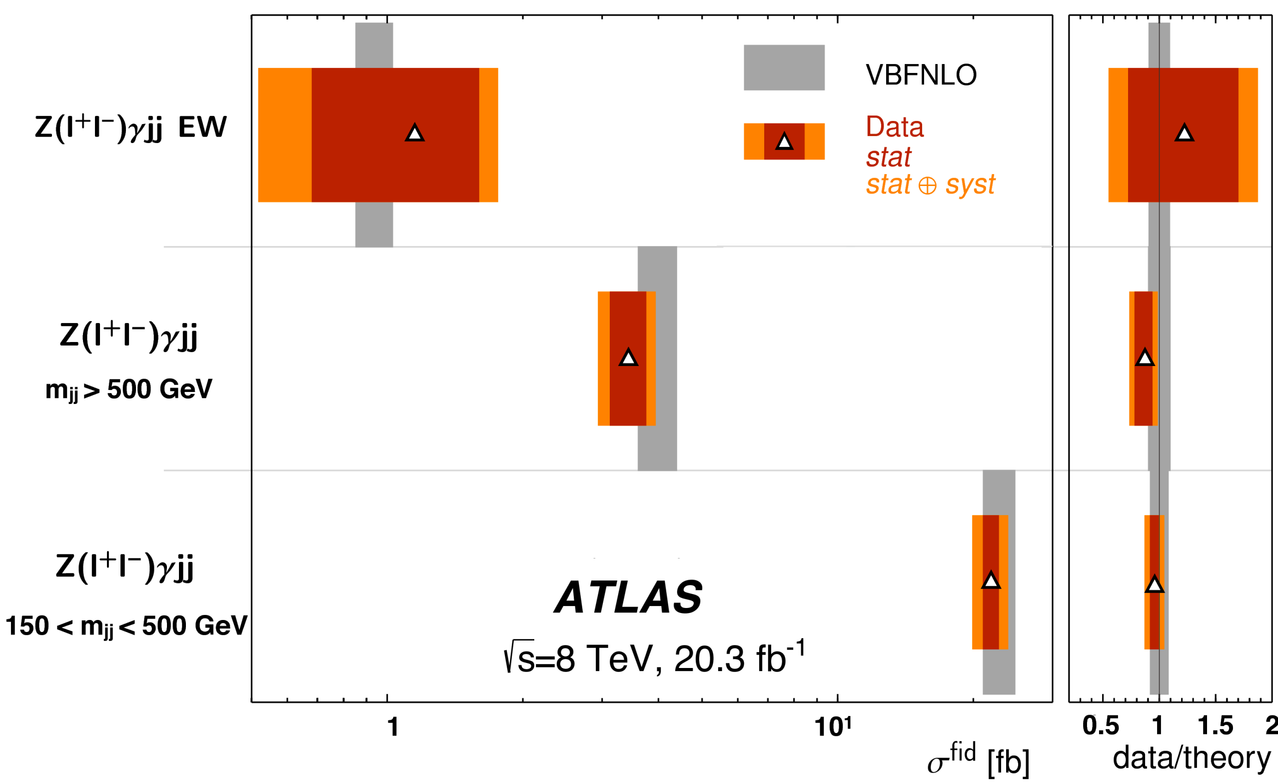
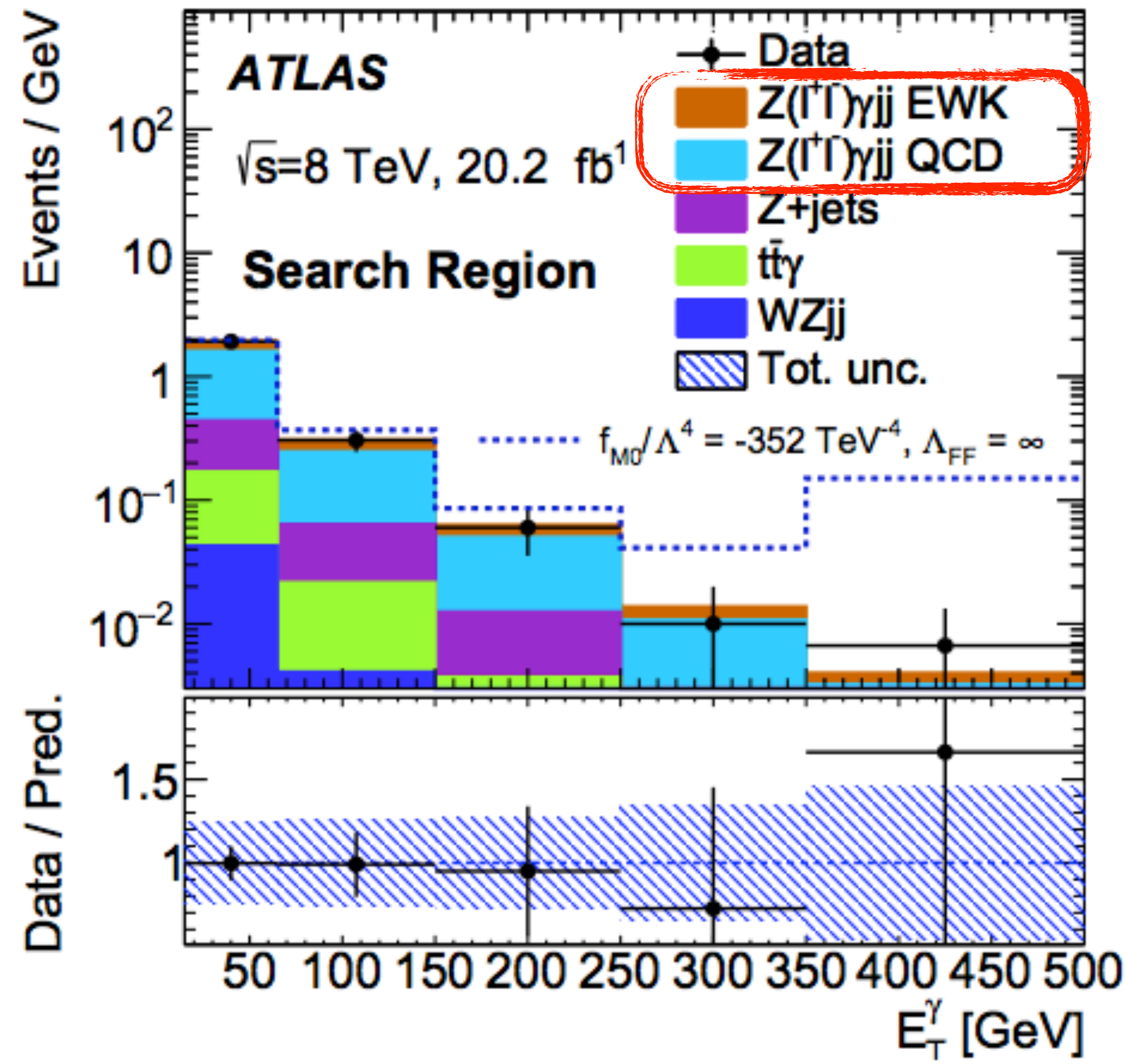


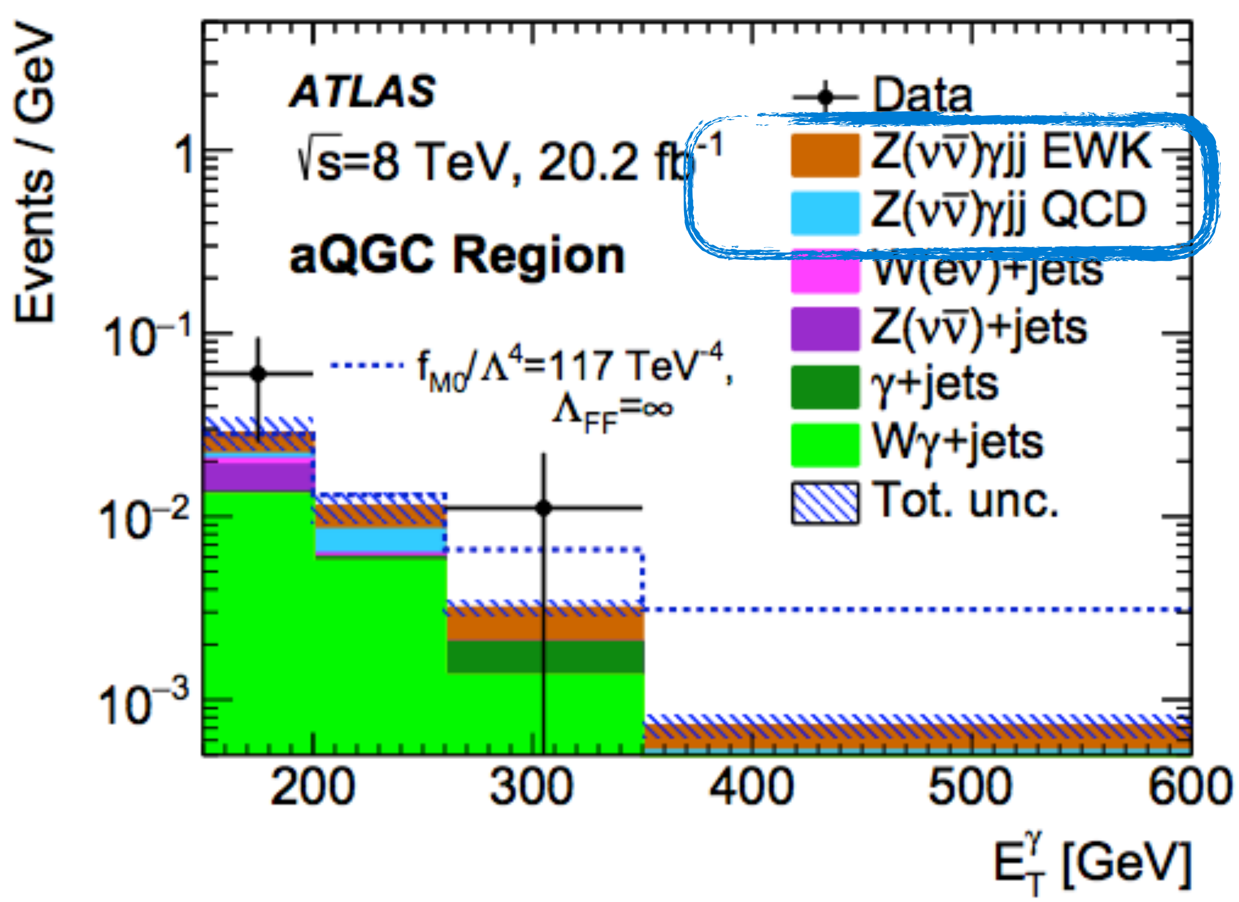
Breakdown of uncertainties

Source of uncertainty	EWK [%]	Total (EWK+QCD) [%] SR	CR
Statistical	40	9	4
Jet energy scale	36	9	4
Theory	10	5	4
All other	8	5	6
Total systematic	38	11	8

Distributions for aQGC region

	aQGC region	
	$m_{jj} > 500$ GeV	$m_{jj} > 600$ GeV
	$E_T^{\gamma} > 250$ GeV	$E_T^{\gamma} > 150$ GeV
	$\ell^+\ell^-\gamma jj$	$\nu\bar{\nu}\gamma jj$
Data	2	4
Z+jets background	0.28 ± 0.08	0.3 ± 0.2
$W(\ell\nu)\gamma$+jets background	-	1.1 ± 0.5
γ+jets background	-	0.13 ± 0.08
$W(e\nu)$+jets background	-	0.09 ± 0.04
$t\bar{t}\gamma$, WZ background	0.02 ± 0.01	-
$N_{\text{data}} - N_{\text{bkg}}$	1.7 ± 1.4	2.4 ± 2.0
$N_{Z\gamma\ \text{QCD}}$ (Sherpa MC)	1.2 ± 0.4	0.29 ± 0.07
$N_{Z\gamma\ \text{EWK}}$ (Sherpa MC)	0.41 ± 0.04	0.65 ± 0.05
$N_{Z\gamma}$ (Sherpa MC)	1.6 ± 0.4	0.9 ± 0.1





95 % CL upper limit on fiducial XS in high photon pt region:

σ_{charged}=1.06 fb (exp. 0.99 fb)

σ_{neutral}=1.03 fb (exp. 1.01 fb)

aQGC

- An effective field theory with higher dimensional operators is used to model the anomalous couplings

Dimension-8

$$\mathcal{L} = \mathcal{L}^{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \sum_j \frac{f_j}{\Lambda^4}\mathcal{O}_j$$

Dimension-6

- Dimension-8 operators is the lowest dimension to induce only QGC without TGC (triple gauge coupling)

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- Coefficient f_j induced γ vertices can be sub-categorized as $f_{T,x}$, (contain field tensor) $f_{M,x}$ (contains both Higgs SU(2) double derivatives and filed tensor)
- Charged aQGC (WWZγ) can only be induced by the $f_{M,x}$ (x=0…7) and $f_{T,x}$ (x=0…7), the neutral aQGC ZZZ$\gamma$and ZZ$\gamma\gamma$ can be induced by $f_{M,x}$ (x=0…7) and $f_{T,x}$ (x=0…9) operators and Z$\gamma\gamma\gamma$ can only be modified by $f_{T,x}$ (x=0…9) operators

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- Following coefficients are probed in this analysis:

$$f_{\mathrm{T},0}/\Lambda^4,\ f_{\mathrm{T},8}/\Lambda^4,\ f_{\mathrm{T},9}/\Lambda^4$$

$$f_{\mathrm{M},0}/\Lambda^4,\ f_{\mathrm{M},1}/\Lambda^4,\ f_{\mathrm{M},2}/\Lambda^4,\ f_{\mathrm{M},3}/\Lambda^4$$

- Sample are generated with aQGC for each coefficient to study efficiency
- The aQGC cross sections are parametrised as the function of each coefficient as 2-order polynomial

aQGC limit

- Feldman-Cousins method is used to derive limit on aQGC.
- Only one dimensional limits are derived and presented.

	Limits 95% CL	Measured [TeV^{-4}]	Expected [TeV^{-4}]
ATLAS $Z(\to \ell\bar{\ell}/\nu\bar{\nu})\gamma$-EWK	f_{T9}/Λ^4	$[-3.9, 3.9]$	$[-2.7, 2.8]$
	f_{T8}/Λ^4	$[-1.8, 1.8]$	$[-1.3, 1.3]$
	f_{T0}/Λ^4	$[-3.4, 2.9]$	$[-3.0, 2.3]$
	f_{M0}/Λ^4	$[-76, 69]$	$[-66, 58]$
	f_{M1}/Λ^4	$[-147, 150]$	$[-123, 126]$
	f_{M2}/Λ^4	$[-27, 27]$	$[-23, 23]$
	f_{M3}/Λ^4	$[-52, 52]$	$[-43, 43]$
CMS $Z(\to \ell\bar{\ell})\gamma$-EWK **Phys. Lett. B 770 (2017) 380**	f_{T9}/Λ^4	$[-4.0, 4.0]$	$[-6.0, 6.0]$
	f_{T8}/Λ^4	$[-1.8, 1.8]$	$[-2.7, 2.7]$
	f_{T0}/Λ^4	$[-3.8, 3.4]$	$[-5.1, 5.1]$
	f_{M0}/Λ^4	$[-71, 75]$	$[-109, 111]$
	f_{M1}/Λ^4	$[-190, 182]$	$[-281, 280]$
	f_{M2}/Λ^4	$[-32, 31]$	$[-47, 47]$
	f_{M3}/Λ^4	$[-58, 59]$	$[-87, 87]$
CMS $W(\to \ell\nu)\gamma$-EWK **JHEP 06 (2017) 106**	f_{T0}/Λ^4	$[-5.4, 5.6]$	$[-3.2, 3.4]$
	f_{M0}/Λ^4	$[-77, 74]$	$[-47, 44]$
	f_{M1}/Λ^4	$[-125, 129]$	$[-72, 79]$
	f_{M2}/Λ^4	$[-26, 26]$	$[-16, 15]$
	f_{M3}/Λ^4	$[-43, 44]$	$[-25, 27]$

Summary

- The study of $Z\gamma$ with high mass 2j system with ATLAS 8 TeV dataset is presented
- Charged lepton and neutral lepton channels are considered
  - Charged lepton channel is used for both fiducial cross section measurement and test the aQGC
  - Neutral channel is only used to test aQGC and been firstly considered in LHC
- Both EWK production and inclusive production of $Z\gamma$+2j in fiducial region are measured (with probe of EWK production of 2.0 σ (1.8 σ exp.)) and found to be consistent with NLO theoretical predictions.
- aQGC is test with EFT framework
  - No significant excess is found.
  - 95% limits on EFT dimension-8 operators coefficients are derived.
  - By combining charged and neutral channels, gives most stringent limits on aQGC in LHC.
- Results is published in JHEP (JHEP07(2017)107)
- Will have more exciting results in Run-II

Backup

	$WWWW$	$WWZZ$	$ZZZZ$	$WW\gamma Z$	$WW\gamma\gamma$	$ZZZ\gamma$	$ZZ\gamma\gamma$	$Z\gamma\gamma\gamma$	$\gamma\gamma\gamma\gamma$
$\mathcal{L}_{S,0}$, $\mathcal{L}_{S,1}$	X	X	X	O	O	O	O	O	O
$\mathcal{L}_{M,0}$, $\mathcal{L}_{M,1}$, $\mathcal{L}_{M,6}$, $\mathcal{L}_{M,7}$	X	X	X	X	X	X	X	O	O
$\mathcal{L}_{M,2}$, $\mathcal{L}_{M,3}$, $\mathcal{L}_{M,4}$, $\mathcal{L}_{M,5}$	O	X	X	X	X	X	X	O	O
$\mathcal{L}_{T,0}$, $\mathcal{L}_{T,1}$, $\mathcal{L}_{T,2}$	X	X	X	X	X	X	X	X	X
$\mathcal{L}_{T,5}$, $\mathcal{L}_{T,6}$, $\mathcal{L}_{T,7}$	O	X	X	X	X	X	X	X	X
$\mathcal{L}_{T,8}$, $\mathcal{L}_{T,9}$	O	O	X	O	O	X	X	X	X

Separated channels

Neutral

	Limits 95% CL	Measured $[\text{TeV}^{-4}]$	Expected $[\text{TeV}^{-4}]$	Λ_{FF} [TeV]
$n=0$	f_{T9}/Λ^4	$[-4.6, 4.6] \times 10^3$	$[-3.9, 3.9] \times 10^3$	
	f_{T8}/Λ^4	$[-2.2, 2.2] \times 10^3$	$[-1.8, 1.9] \times 10^3$	
	f_{T0}/Λ^4	$[-2.2, 2.1] \times 10^1$	$[-1.9, 1.8] \times 10^1$	
	f_{M0}/Λ^4	$[-2.0, 2.0] \times 10^2$	$[-1.7, 1.7] \times 10^2$	
	f_{M1}/Λ^4	$[-4.4, 4.5] \times 10^2$	$[-3.7, 3.7] \times 10^2$	
	f_{M2}/Λ^4	$[-1.1, 1.1] \times 10^3$	$[-9.5, 9.5] \times 10^2$	
	f_{M3}/Λ^4	$[-2.1, 2.1] \times 10^3$	$[-1.8, 1.8] \times 10^3$	
$n=2$	f_{T9}/Λ^4	$[-7.6, 7.6] \times 10^4$	$[-6.3, 6.2] \times 10^4$	0.7
	f_{T8}/Λ^4	$[-3.6, 3.6] \times 10^4$	$[-3.0, 3.0] \times 10^4$	0.7
	f_{T0}/Λ^4	$[-8.6, 7.8] \times 10^1$	$[-7.3, 6.5] \times 10^1$	1.7
	f_{M0}/Λ^4	$[-1.2, 1.1] \times 10^3$	$[-9.7, 9.4] \times 10^2$	1.0
	f_{M1}/Λ^4	$[-2.0, 2.0] \times 10^3$	$[-1.6, 1.7] \times 10^3$	1.2
	f_{M2}/Λ^4	$[-1.3, 1.3] \times 10^4$	$[-1.1, 1.1] \times 10^4$	0.7
	f_{M3}/Λ^4	$[-2.0, 1.9] \times 10^4$	$[-1.6, 1.6] \times 10^4$	0.8

Charged

	Limits 95% CL	Measured $[\text{TeV}^{-4}]$	Expected $[\text{TeV}^{-4}]$	Λ_{FF} [TeV]
$n=0$	f_{T9}/Λ^4	$[-5.8, 6.0] \times 10^3$	$[-3.5, 3.7] \times 10^3$	
	f_{T8}/Λ^4	$[-2.6, 2.6] \times 10^3$	$[-1.6, 1.7] \times 10^3$	
	f_{T0}/Λ^4	$[-2.2, 1.6] \times 10^1$	$[-2.1, 1.5] \times 10^1$	
	f_{M0}/Λ^4	$[-1.7, 2.1] \times 10^2$	$[-1.7, 2.1] \times 10^2$	
	f_{M1}/Λ^4	$[-4.0, 3.9] \times 10^2$	$[-3.8, 3.8] \times 10^2$	
	f_{M2}/Λ^4	$[-1.0, 1.0] \times 10^3$	$[-1.0, 1.0] \times 10^3$	
	f_{M3}/Λ^4	$[-2.3, 2.4] \times 10^3$	$[-1.8, 1.8] \times 10^3$	
$n=2$	f_{T9}/Λ^4	$[-1.2, 1.2] \times 10^5$	$[-7.7, 7.2] \times 10^4$	0.7
	f_{T8}/Λ^4	$[-5.8, 5.5] \times 10^4$	$[-3.7, 3.5] \times 10^4$	0.7
	f_{T0}/Λ^4	$[-8.8, 7.3] \times 10^1$	$[-7.7, 6.2] \times 10^1$	1.7
	f_{M0}/Λ^4	$[-1.2, 1.2] \times 10^3$	$[-1.2, 1.3] \times 10^3$	1.0
	f_{M1}/Λ^4	$[-2.0, 2.0] \times 10^3$	$[-1.9, 1.9] \times 10^3$	1.2
	f_{M2}/Λ^4	$[-1.3, 1.4] \times 10^4$	$[-1.3, 1.4] \times 10^4$	0.7
	f_{M3}/Λ^4	$[-2.6, 2.5] \times 10^4$	$[-2.0, 1.9] \times 10^4$	0.8

With VBFNLO implemented formulae

aQGC limit

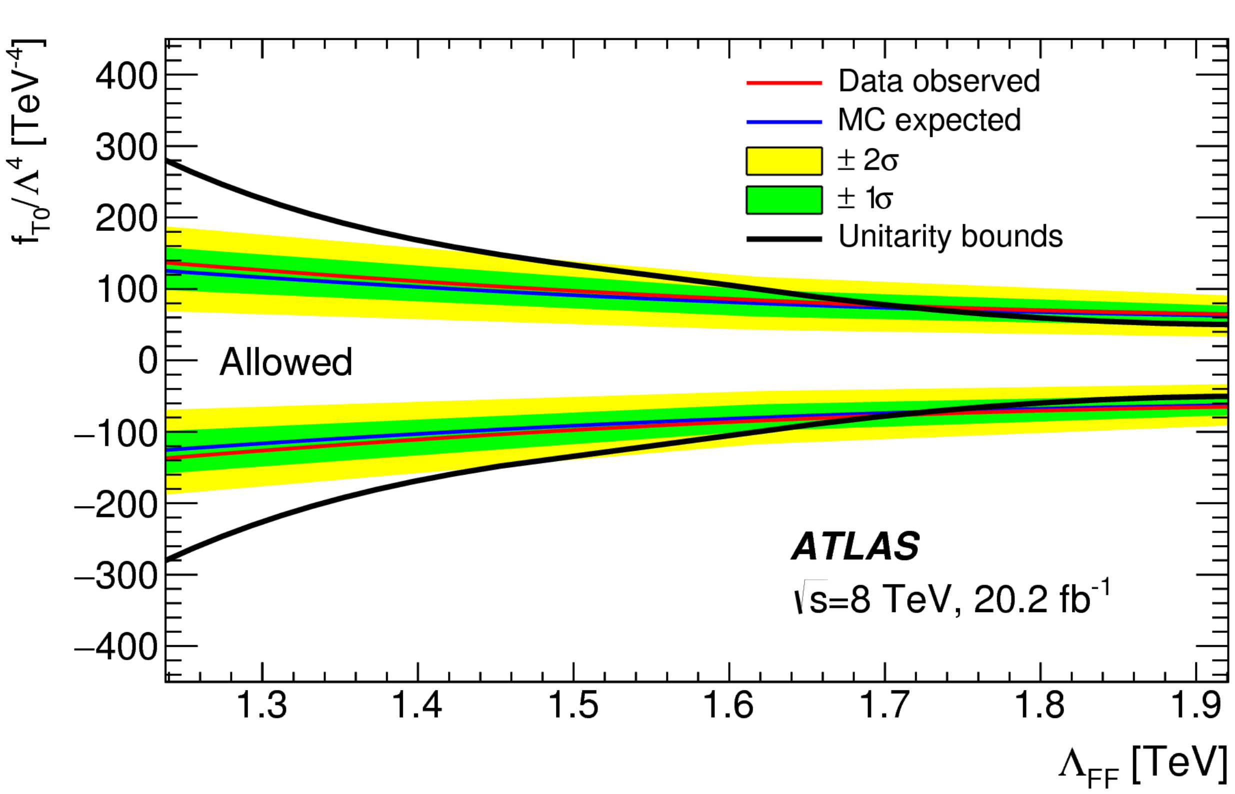
- Feldman-Cousin method is used to derive limit on aQGC.
- Only one dimensional limits are derived and presented.

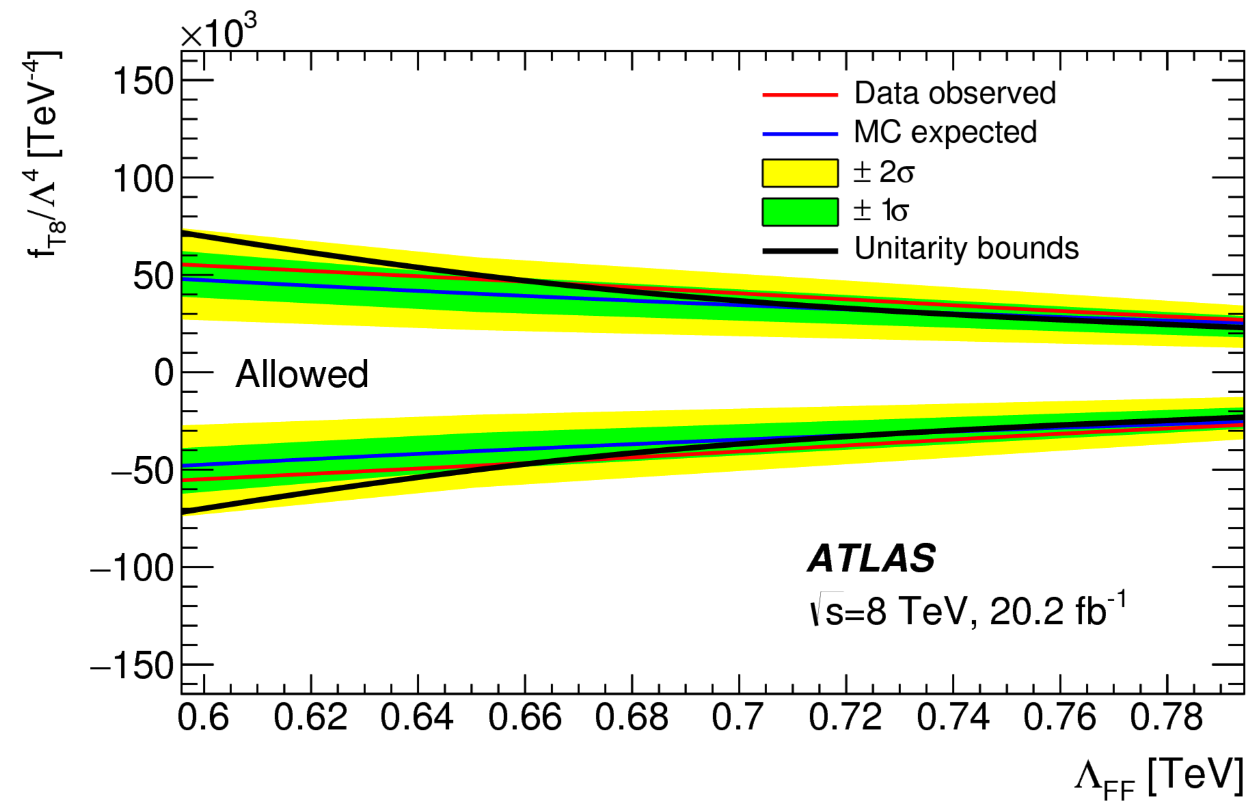
	95% CL intervals	Measured [TeV^{-4}]	Expected [TeV^{-4}]	Λ_{FF} [TeV]
$n = 0$	f_{T9}/Λ^4	$[-4.1, 4.2] \times 10^3$	$[-2.9, 3.0] \times 10^3$	
	f_{T8}/Λ^4	$[-1.9, 2.1] \times 10^3$	$[-1.2, 1.7] \times 10^3$	
	f_{T0}/Λ^4	$[-1.9, 1.6] \times 10^1$	$[-1.6, 1.3] \times 10^1$	
	f_{M0}/Λ^4	$[-1.6, 1.8] \times 10^2$	$[-1.4, 1.5] \times 10^2$	
	f_{M1}/Λ^4	$[-3.5, 3.4] \times 10^2$	$[-3.0, 2.9] \times 10^2$	
	f_{M2}/Λ^4	$[-8.9, 8.9] \times 10^2$	$[-7.5, 7.5] \times 10^2$	
	f_{M3}/Λ^4	$[-1.7, 1.7] \times 10^3$	$[-1.4, 1.4] \times 10^3$	
$n = 2$	f_{T9}/Λ^4	$[-6.9, 6.9] \times 10^4$	$[-5.4, 5.3] \times 10^4$	0.7
	f_{T8}/Λ^4	$[-3.4, 3.3] \times 10^4$	$[-2.6, 2.5] \times 10^4$	0.7
	f_{T0}/Λ^4	$[-7.2, 6.1] \times 10^1$	$[-6.1, 5.0] \times 10^1$	1.7
	f_{M0}/Λ^4	$[-1.0, 1.0] \times 10^3$	$[-8.8, 8.8] \times 10^2$	1.0
	f_{M1}/Λ^4	$[-1.6, 1.7] \times 10^3$	$[-1.4, 1.4] \times 10^3$	1.2
	f_{M2}/Λ^4	$[-1.1, 1.1] \times 10^4$	$[-9.2, 9.6] \times 10^3$	0.7
	f_{M3}/Λ^4	$[-1.6, 1.6] \times 10^4$	$[-1.4, 1.3] \times 10^4$	0.8

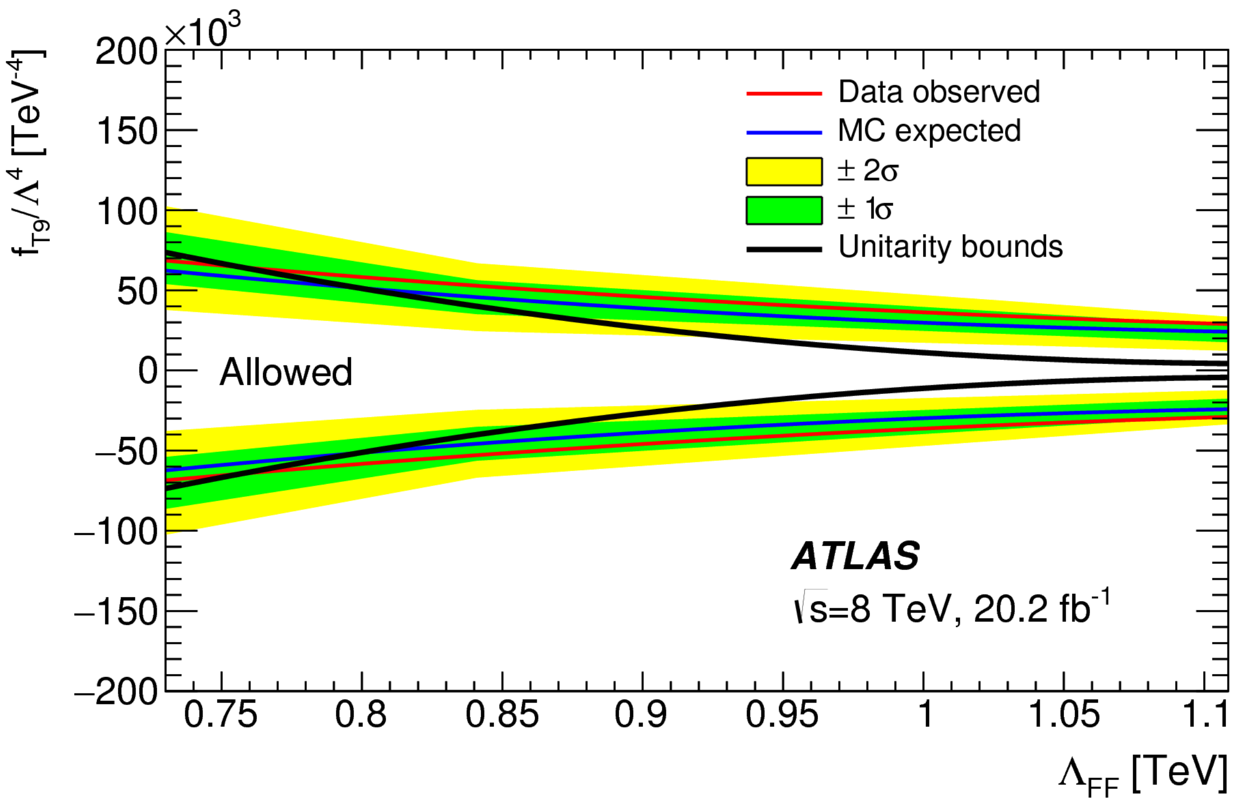
- Form factor is introduced to restore unitarity at very high parton center-of-mass energy. The value is chosen to prevent unitarity violation up to 8 TeV with FF exponent n=2

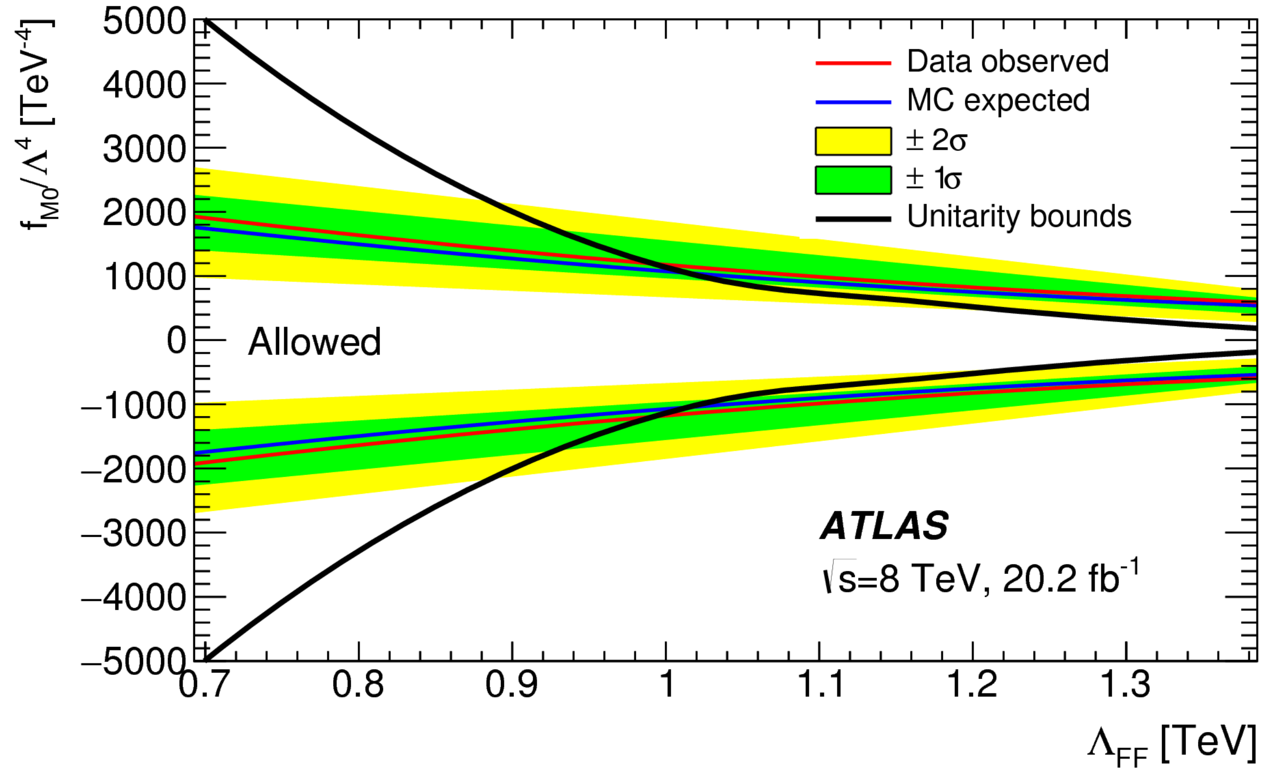
$$f_i(\hat{s}) = \frac{f_i}{(1 + \hat{s}/\Lambda_{\text{FF}}^2)^n}$$

Limits plots









Compare with different experiments

	Limits 95% CL	Measured [TeV^{-4}]	Expected [TeV^{-4}]
ATLAS $Z(\to \ell\bar{\ell}/\nu\bar{\nu})\gamma$-EWK	f_{T9}/Λ^4	$[-3.9, 3.9]$	$[-2.7, 2.8]$
	f_{T8}/Λ^4	$[-1.8, 1.8]$	$[-1.3, 1.3]$
	f_{T0}/Λ^4	$[-3.4, 2.9]$	$[-3.0, 2.3]$
	f_{M0}/Λ^4	$[-76, 69]$	$[-66, 58]$
	f_{M1}/Λ^4	$[-147, 150]$	$[-123, 126]$
	f_{M2}/Λ^4	$[-27, 27]$	$[-23, 23]$
	f_{M3}/Λ^4	$[-52, 52]$	$[-43, 43]$
CMS $Z(\to \ell\bar{\ell})\gamma$-EWK	f_{T9}/Λ^4	$[-4.0, 4.0]$	$[-6.0, 6.0]$
	f_{T8}/Λ^4	$[-1.8, 1.8]$	$[-2.7, 2.7]$
	f_{T0}/Λ^4	$[-3.8, 3.4]$	$[-5.1, 5.1]$
	f_{M0}/Λ^4	$[-71, 75]$	$[-109, 111]$
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	f_{M2}/Λ^4	$[-26, 26]$	$[-16, 15]$
	f_{M3}/Λ^4	$[-43, 44]$	$[-25, 27]$

With Madgraph implemented formulae