VBS/VBF measurements (with γ) at ATLAS and CMS

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on behalf of the CMS and ATLAS collaborations

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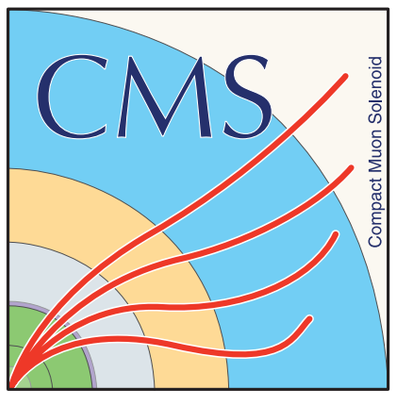
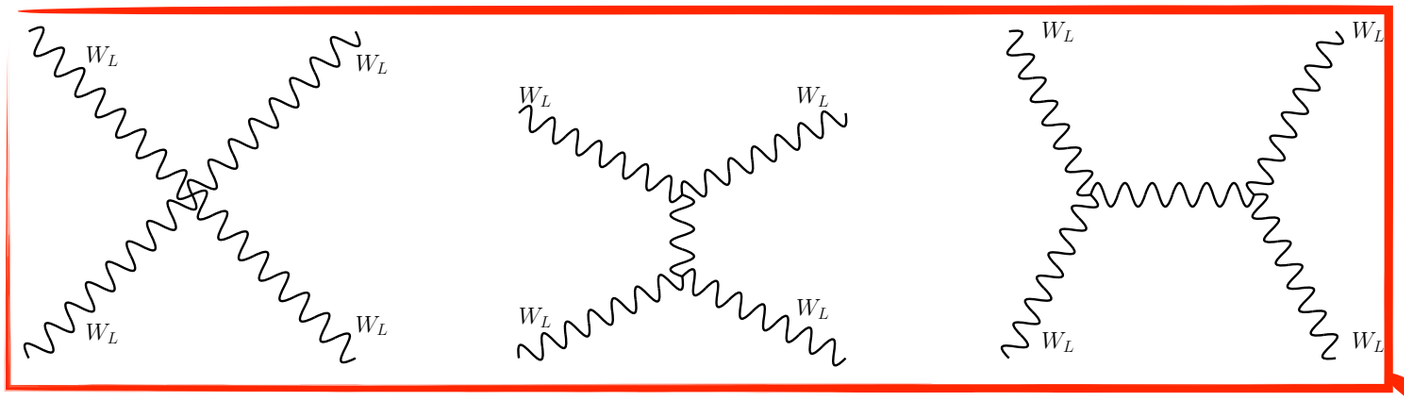


Outline

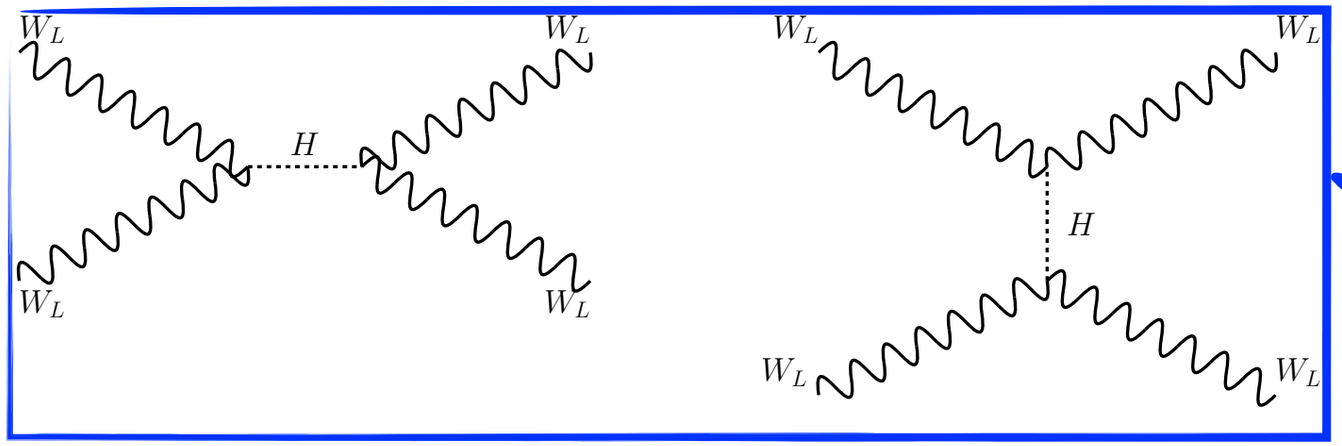
- Physics motivation
- Analyses
  - VBS Zγ where Z → ee/μμ
  - VBS Zγ where Z → νν aiming at low/high p_{T}^{γ} energy
  - VBS W($\ell\nu$)γ
- Prospect & Summary

VBS/VBF with γ	Final states	CMS	ATLAS
Zγjj	$\ell\ell\gamma$jj	PRD 104 (2021) 072001	ATLAS-CONF-2021-038 (m_{jj} > 150 GeV)
			STDM-2018-36 (m_{jj} > 500 GeV) **New!**
Zγjj	$\nu\nu\gamma$jj	—	EPJC 82 (2022) 105
			JHEP accepted, arXiv:2208.12741
Wγjj	$\ell\nu\gamma$jj	PRD accepted, arXiv:2212.12592	—

Physics motivation



$$iM_{\text{gauge}} \approx -i\frac{g^2}{4m_W^2[s+t]}$$



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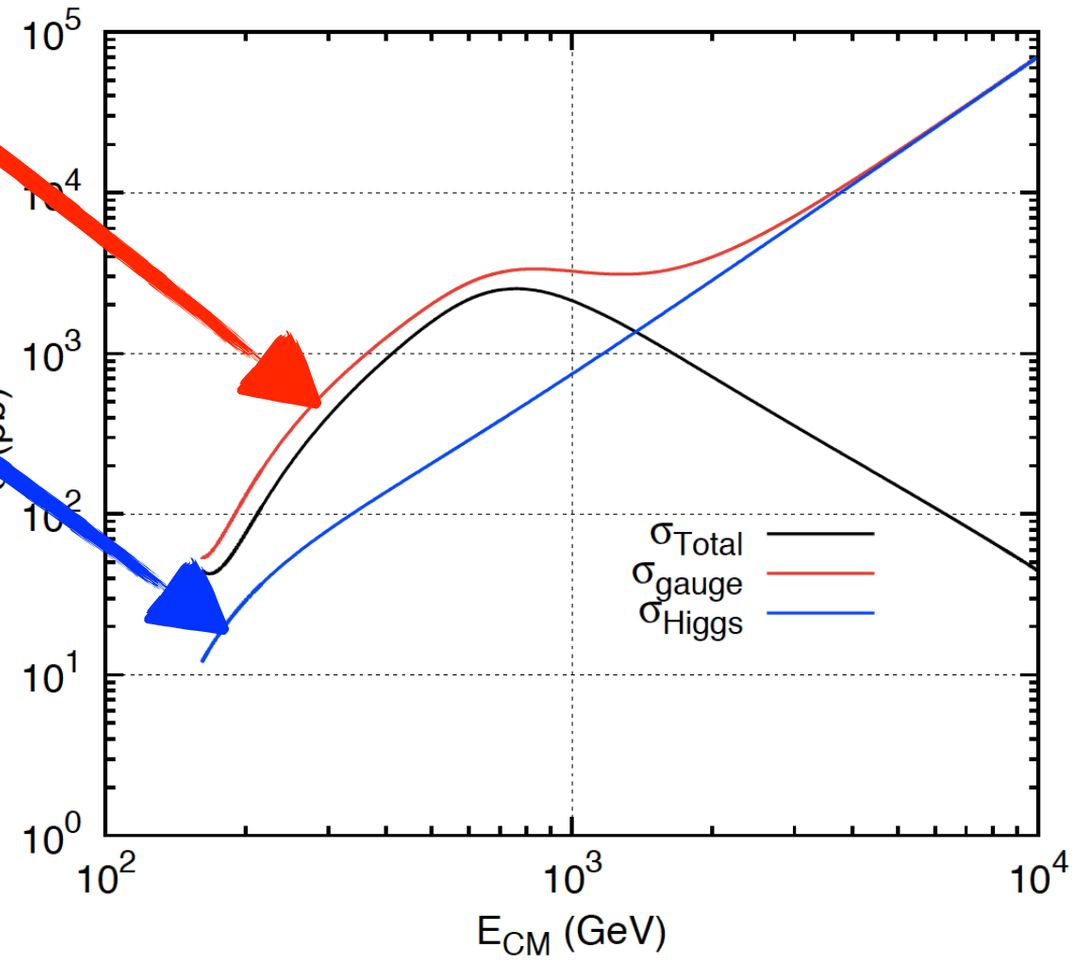
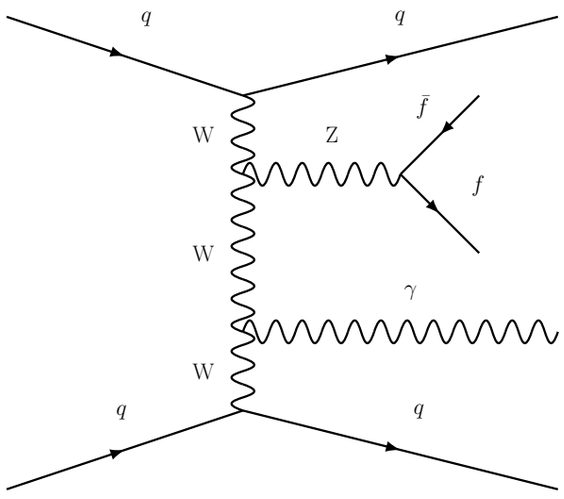
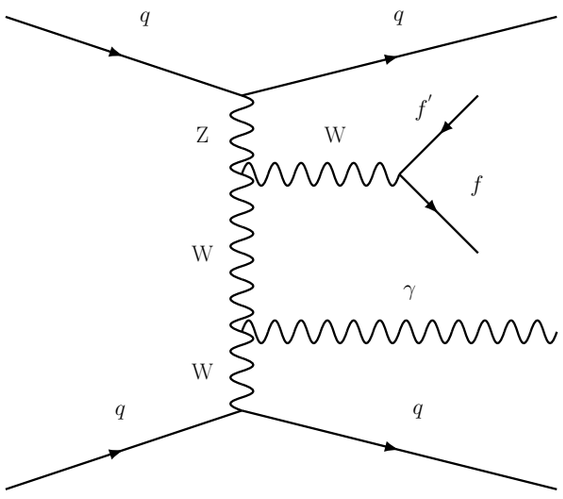


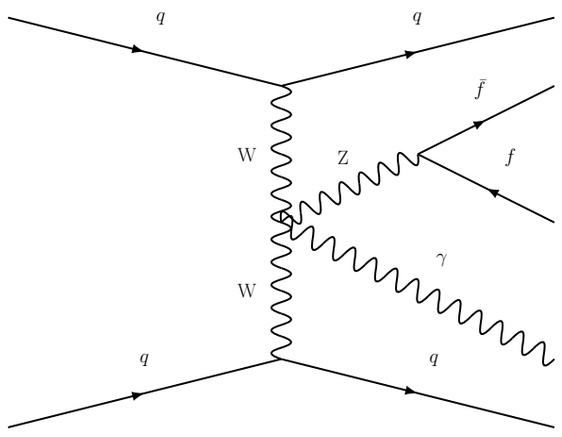
The Higgs boson contribution cancels exactly the E^2 dependance of the cross section at high energy in ***massive VBS only***

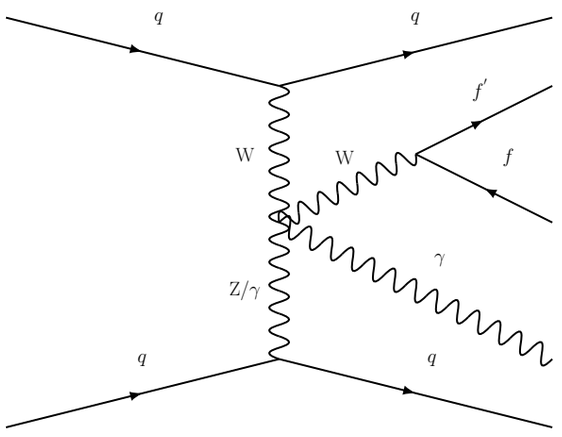
- Unitarises the scattering amplitudes
- Key process linked with Electro-Weak Symmetry Breaking (EWSB)

Physics motivation





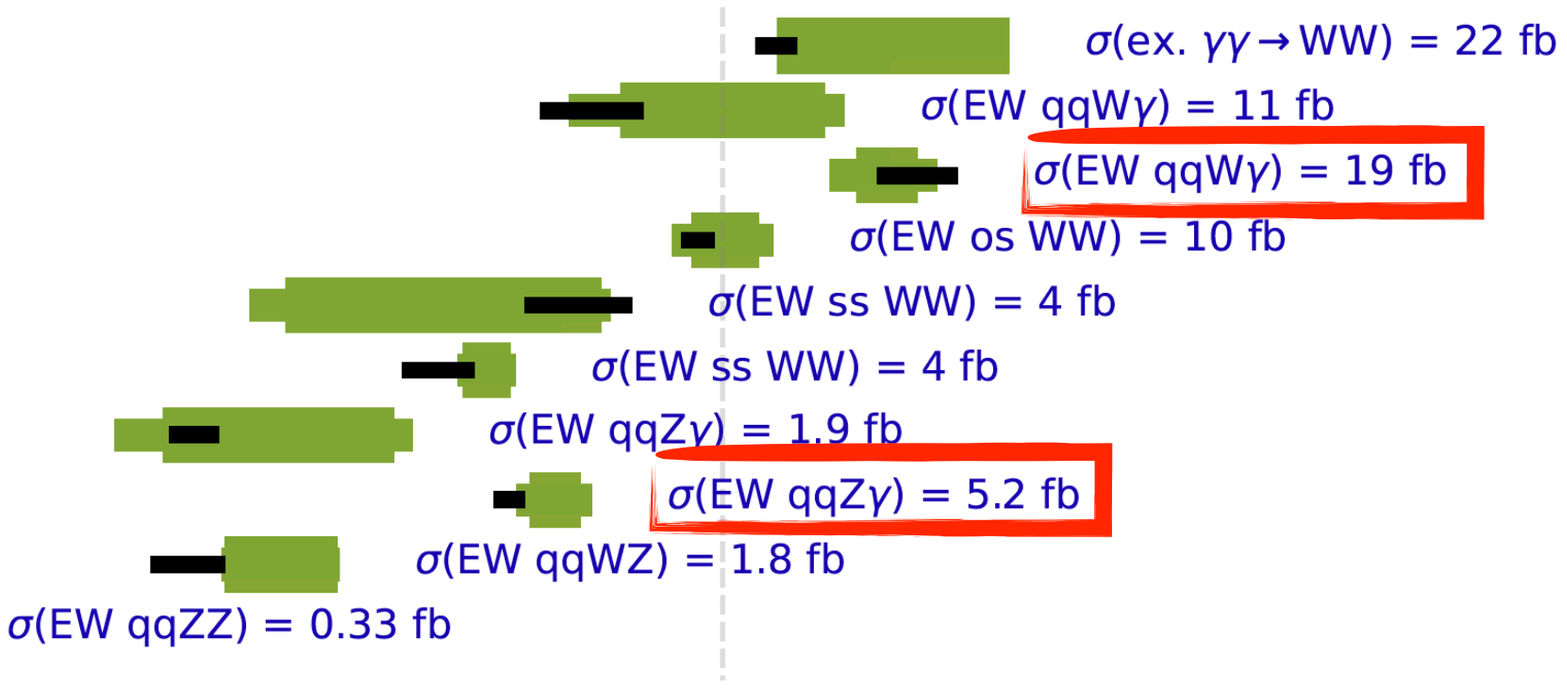




Larger cross sections:

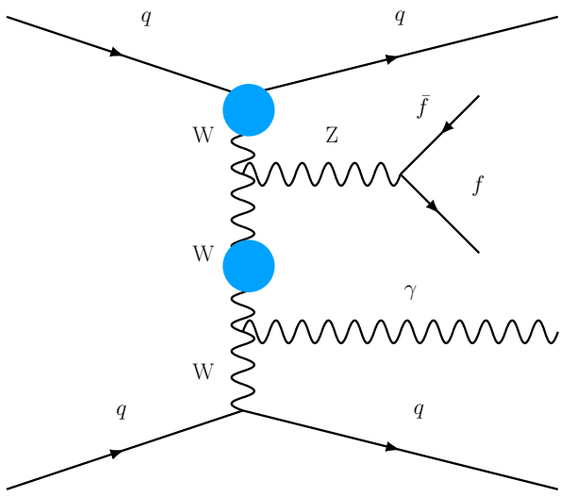
- More precise measurement for SM test
- Possibly accurate differential cross section

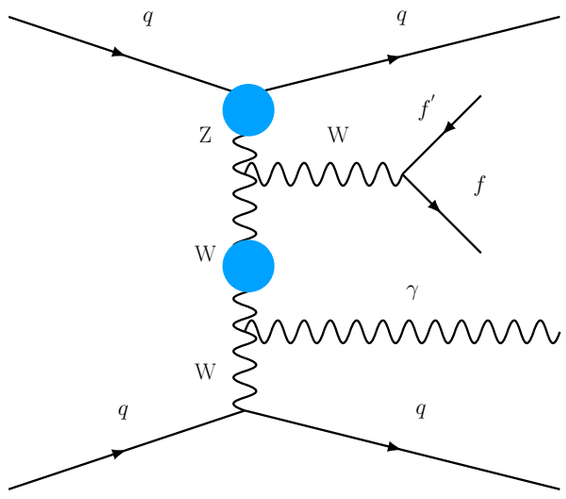
Very rare process (~ fb)



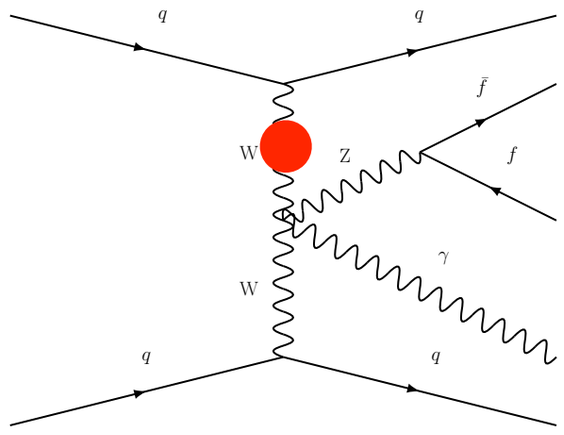
Physics motivation

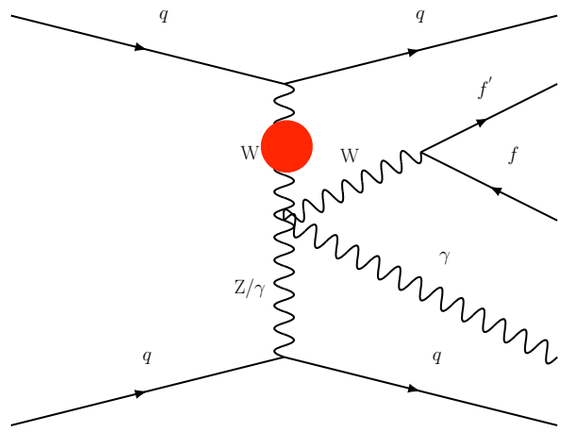
TGC: Triple gauge couplings





QGC: Quartic gauge couplings





Larger cross sections:

- More precise measurement for SM test
- Possibly accurate differential cross section

Multiboson couplings:

- T(Q)GC: WWZ, WWγ, WWZγ, WWγγ
- BSM TGC: ZZγ, Zγγ
- BSM QGC : ZZγγ, ZZZγ,Zγγγ

BSM Higgs decay by Z $\rightarrow \nu\nu$

Probe new physics through deviations from SM couplings

Unique EFT interpretations for the pure neutral gauge couplings

EW Z(ℓℓ)γ+jj

STDM-2018-36

PRD 104 (2021) 072001

- Measurements use full Run 2 data, from both experiments, in the Z→ ee/μμ channels
- Signal generated with MadGraph [1] at LO

CMS

Common selection	$p_{\mathrm{T}}^{\ell 1,\ell 2} > 25\,\mathrm{GeV}$, $\lvert\eta^{\ell 1,\ell 2}\rvert < 2.5$ for electron channel $p_{\mathrm{T}}^{\ell 1,\ell 2} > 20\,\mathrm{GeV}$, $\lvert\eta^{\ell 1,\ell 2}\rvert < 2.4$ for muon channel $p_{\mathrm{T}}^{\gamma} > 20\,\mathrm{GeV}$, $\lvert\eta^{\gamma}\rvert < 1.442$ or $1.566 < \lvert\eta^{\gamma}\rvert < 2.500$ $p_{\mathrm{T}}^{\mathrm{j1,j2}} > 30\,\mathrm{GeV}$, $\lvert\eta^{\mathrm{j1,j2}}\rvert < 4.7$ $70 < m_{\ell\ell} < 110\,\mathrm{GeV}$, $m_{\mathrm{Z}\gamma} > 100\,\mathrm{GeV}$ $\Delta R_{\mathrm{jj}}, \Delta R_{\mathrm{j}\gamma}, \Delta R_{\mathrm{j}\ell} > 0.5$, $\Delta R_{\ell\gamma} > 0.7$
Fiducial volume	Common selection, $m_{\mathrm{jj}} > 500\,\mathrm{GeV}$, $\lvert\Delta\eta_{\mathrm{jj}}\rvert > 2.5$
Control region	Common selection, $150 < m_{\mathrm{jj}} < 500\,\mathrm{GeV}$
EW signal region	Common selection, $m_{\mathrm{jj}} > 500\,\mathrm{GeV}$, $\lvert\Delta\eta_{\mathrm{jj}}\rvert > 2.5$, $\eta^{*} < 2.4$, $\Delta\phi_{\mathrm{Z}\gamma,\mathrm{jj}} > 1.9$
aQGC search region	Common selection, $m_{\mathrm{jj}} > 500\,\mathrm{GeV}$, $\lvert\Delta\eta_{\mathrm{jj}}\rvert > 2.5$, $p_{\mathrm{T}}^{\gamma} > 120\,\mathrm{GeV}$

Lepton	$p_{\mathrm{T}}^{\ell} > 20, 30(\mathrm{leading})\ \mathrm{GeV}, \quad \lvert\eta_{\ell}\rvert < 2.5$ $N_{\ell} \geq 2$
Photon	$E_{\mathrm{T}}^{\gamma} > 25\ \mathrm{GeV}, \quad \lvert\eta_{\gamma}\rvert < 2.37$ $E_{\mathrm{T}}^{\mathrm{cone20}} < 0.07 E_{\mathrm{T}}^{\gamma}$ $\Delta R(\ell,\gamma) > 0.4$
Jet	$p_{\mathrm{T}}^{j} > 50\ \mathrm{GeV}, \quad \lvert y_j\rvert < 4.4$ $\lvert\Delta y\rvert > 1.0$ $m_{jj} > 150\ \mathrm{GeV}$ or $m_{jj} > 500\ \mathrm{GeV}$ Remove jets if $\Delta R(\gamma, j) < 0.4$ or if $\Delta R(\ell, j) < 0.3$
Event	$m_{\ell\ell} > 40\ \mathrm{GeV}$ $m_{\ell\ell} + m_{\ell\ell\gamma} > 182\ \mathrm{GeV}$ $\zeta(Z\gamma) < 0.4$ $N_{\mathrm{jets}}^{\mathrm{gap}} = 0$

- ★ VBS signal is selected by the VBS signature
- ● Final state radiation (FSR) contribution is largely reduced by cutting on Zγ invariant mass

[1] http://madgraph.phys.ucl.ac.be/index.html

EW Z(ℓℓ)γ+jj: Background

- Largest background comes from QCD Zγjj production
  - Modelled using simulation, but constraint with data
- Other major background comes from Z+jets events, with a jet misidentified as a photon, estimated with data-driven method

CMS

Process	$\mu\mu\gamma_{\text{barrel}}$	$\mu\mu\gamma_{\text{endcap}}$	$ee\gamma_{\text{barrel}}$	$ee\gamma_{\text{endcap}}$
ST	0.7 ± 0.4	0.2 ± 0.2	0.6 ± 0.3	0.2 ± 0.2
TTγ	8.8 ± 1.3	2.1 ± 0.5	3.4 ± 0.6	0.2 ± 0.2
VV	6.0 ± 1.9	3.2 ± 1.2	4.1 ± 1.3	0.8 ± 0.3
Nonprompt photon	189 ± 9.2	143 ± 6.9	93.6 ± 6.5	74.3 ± 5.0
QCD Zγ	274 ± 10	108 ± 5.6	162 ± 7.4	62.4 ± 3.9
EW Zγ	133 ± 4.7	46.5 ± 1.7	84.5 ± 3.1	28.2 ± 1.1
Predicted yields	612 ± 13	303 ± 8	349 ± 9	166 ± 6
Data	584	320	375	174

$$N_{\text{tot}}^{\text{obs}} = 1453$$

ATLAS

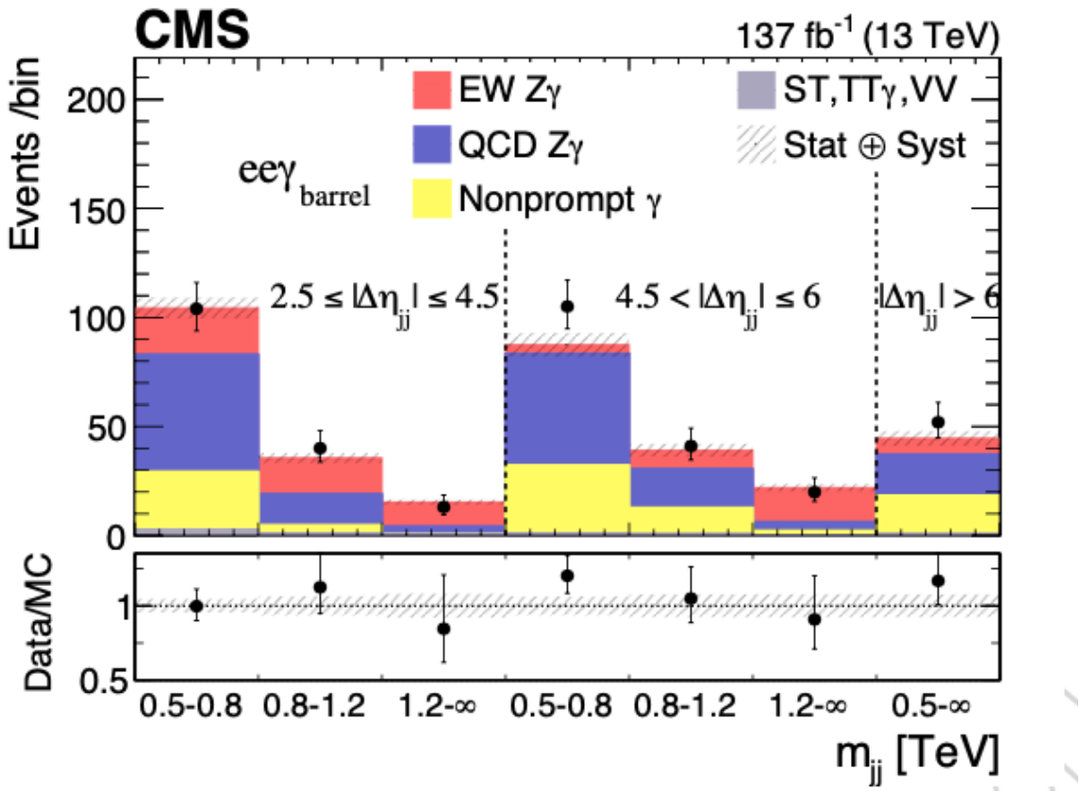
Sample	SR, $m_{jj} > 150$ GeV	SR, $m_{jj} > 500$ GeV
$N_{\text{EW}-\text{Z}\gamma\text{jj}}$		269 ± 27
$N_{\text{QCD}-\text{Z}\gamma\text{jj}}$		245 ± 21
$N_{\text{Z}\gamma\text{jj}}$	1292 ± 50	
$N_{Z+\text{jets}}$	78 ± 30	21 ± 8
$N_{t\bar{t}\gamma}$	73 ± 11	16 ± 2
N_{WZ}	17 ± 3	9 ± 2
Total	1461 ± 38	560 ± 23
N_{obs}	1461	562

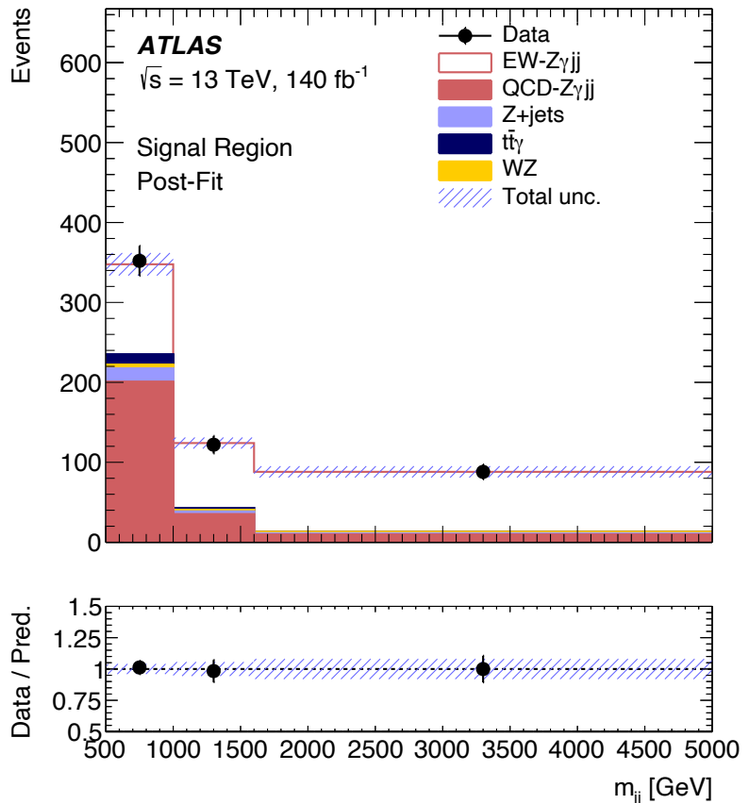
EW Z(ℓℓ)γ+jj: Results

- Simultaneous binned maximum likelihood fit in CR and SR is used for extracting signal significance and cross sections
  - CMS: m_{jj} and $\Delta\eta_{jj}$ in SR, m_{jj} in CR
  - ATLAS: m_{jj} in both SR and CR

Significance well above 5σ

- Both EW and EW+QCD cross sections are measured





$\sigma_{\mathrm{EW}}^{\mathrm{SM\,pred.}} = 4.34 \pm 0.26\,(\mathrm{scale}) \pm 0.06\,(\mathrm{PDF})$ fb

$\sigma_{\mathrm{EW}} = 5.21 \pm 0.52\,(\mathrm{stat}) \pm 0.56\,(\mathrm{syst})$ fb

$\sigma_{EW+QCD}^{pred.} = 13.3 \pm 1.72\,(\mathrm{scale}) \pm 0.10\,(\mathrm{PDF})$ fb

$\sigma_{EW+QCD} = 14.7 \pm 0.80\,(\mathrm{stat}) \pm 1.26\,(\mathrm{syst})$ fb

$\sigma_{\mathrm{EW}}^{\mathrm{SM\,pred.}} = 3.5 \pm 0.2$ fb

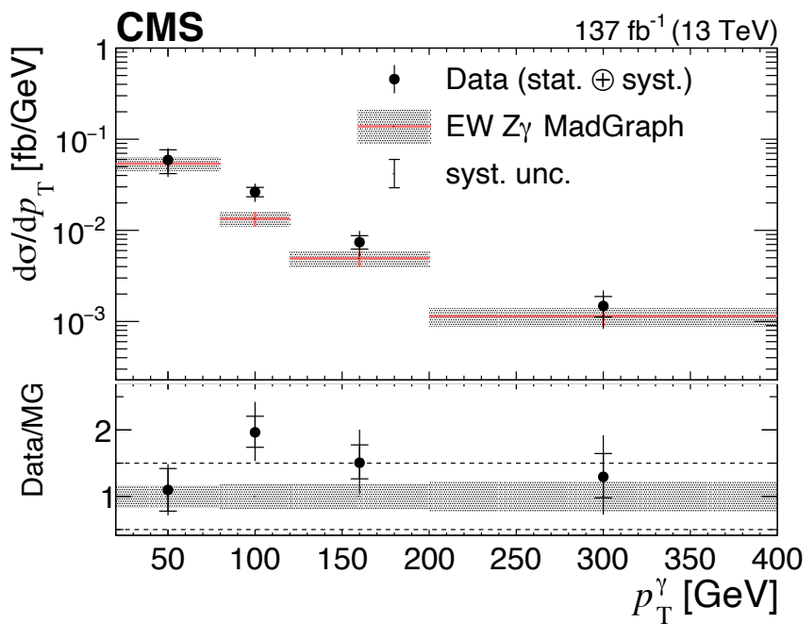
$\sigma_{\mathrm{EW}} = 3.6 \pm 0.5$ fb

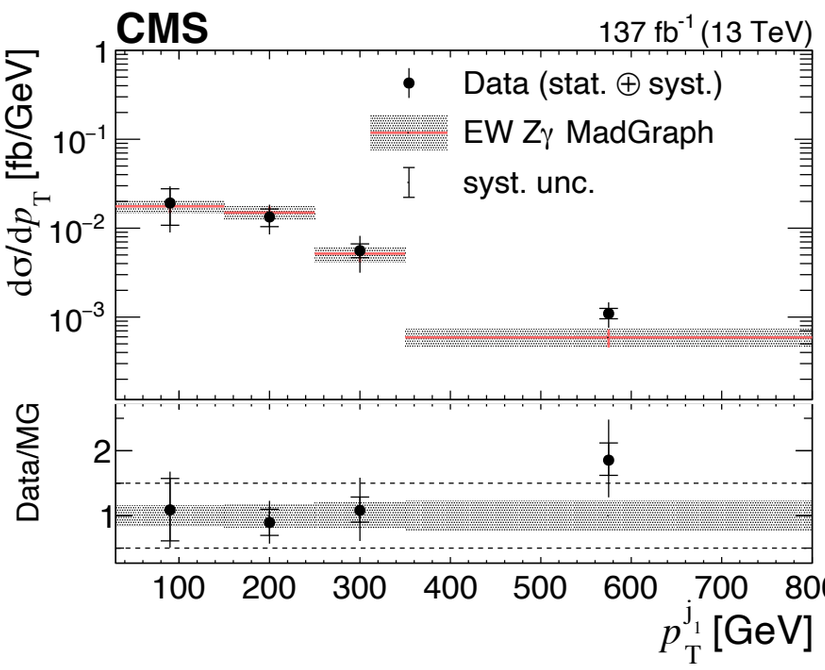
$\sigma_{EW+QCD}^{pred.} = 15.7^{+5.0}_{-2.6}$ fb

$\sigma_{EW+QCD} = 16.8^{+2.0}_{-1.8}$ fb

EW Z(ℓℓ)γ+jj: Results

- CMS has measured differential (1D and 2D) cross sections for EW, and EW + QCD Zγjj





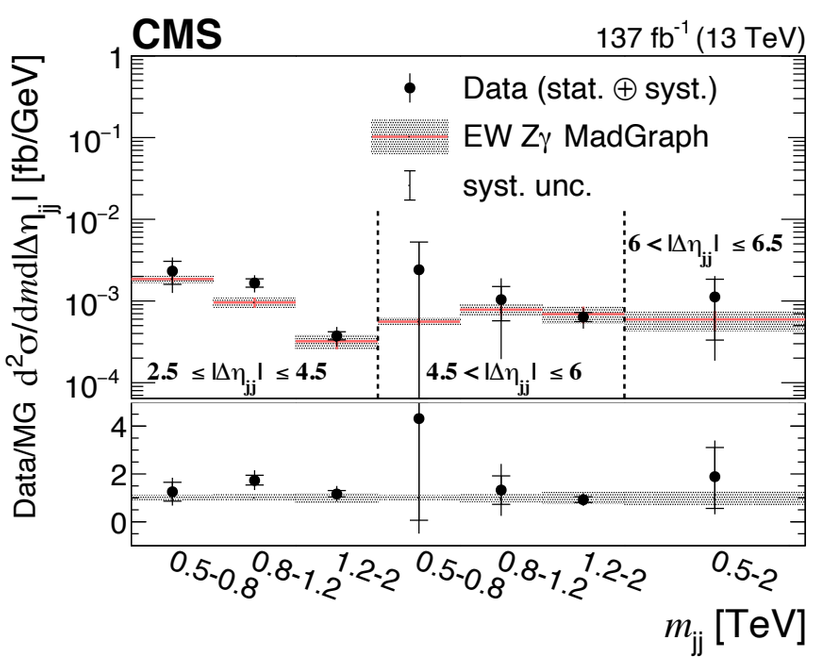


Table 5: The signal strengths and differential cross sections from SM expectation and fit calculated as part of the unfolding of 2D m_{jj}-$|\Delta\eta_{jj}|$ observables for EW Zγjj. The last bin includes overflow events.

$\|\Delta\eta_{jj}\|$ bin	m_{jj} bin [GeV]	$\mu \pm \Delta\mu$	Predicted $d^2\sigma/dm\, d\|\Delta\eta_{jj}\|$ [fb/GeV]	Observed $d^2\sigma/dm\, d\|\Delta\eta_{jj}\|$ [fb/GeV]
[2.5, 4.5)	[500, 800)	$1.25^{+0.59}_{-0.58}$	0.00185 ± 0.00017	0.0023 ± 0.0011
[2.5, 4.5)	[800, 1200)	$1.73^{+0.43}_{-0.40}$	0.00096 ± 0.00014	0.00166 ± 0.00040
[2.5, 4.5)	[1200, 2000]	$1.16^{+0.34}_{-0.30}$	0.000322 ± 0.000065	0.00037 ± 0.00011
[4.5, 6.0)	[500, 800)	$4.3^{+5.1}_{-4.8}$	0.000559 ± 0.000057	0.0024 ± 0.0028
[4.5, 6.0)	[800, 1200)	$1.3^{+1.1}_{-1.1}$	0.00078 ± 0.00012	0.00104 ± 0.00086
[4.5, 6.0)	[1200, 2000]	$0.92^{+0.28}_{-0.26}$	0.00069 ± 0.00016	0.00064 ± 0.00019
[6.0, 6.5]	[500, 2000]	$1.9^{+1.5}_{-1.6}$	0.00060 ± 0.00016	0.00112 ± 0.00092

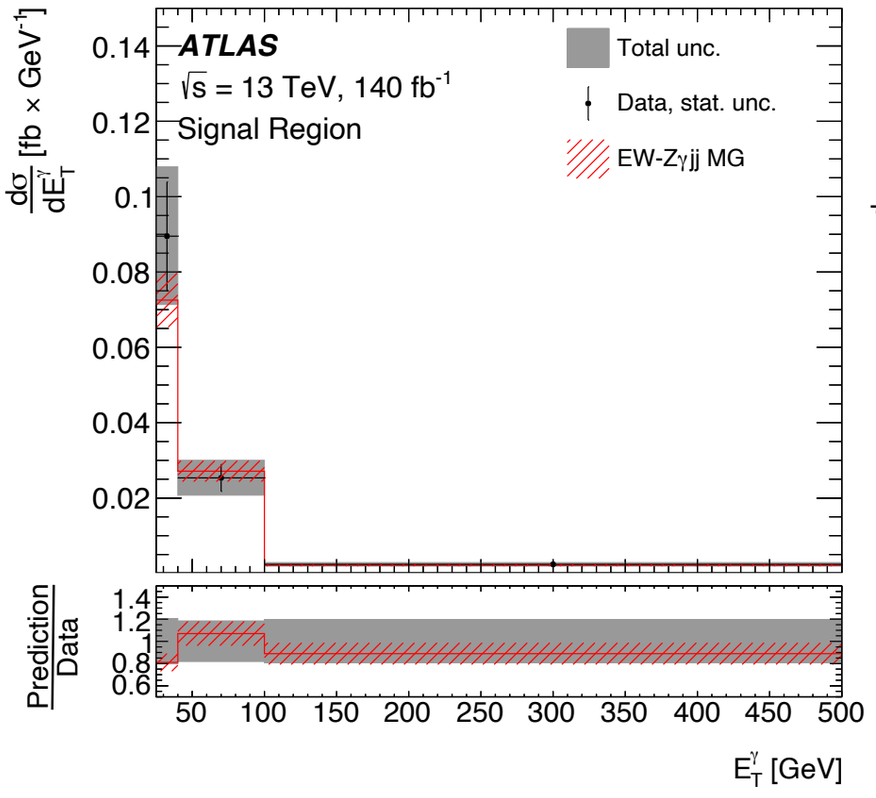
Within uncertainties, generally good agreement with predictions

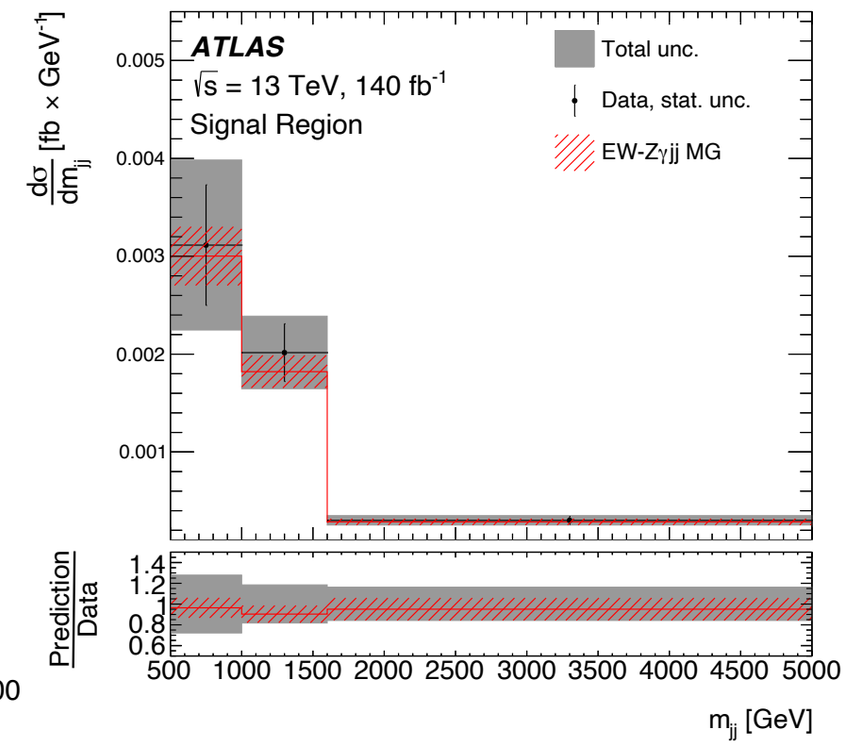
EW Z(ℓℓ)γ+jj: Results

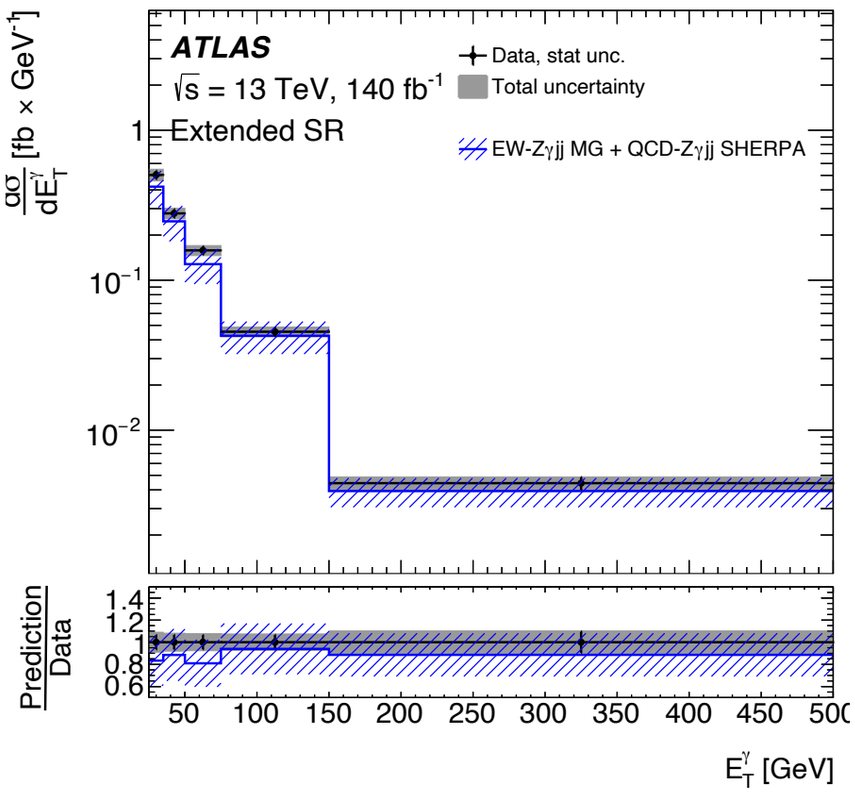
New!

STDM-2018-36

- New results for the VBS Z(ℓℓ)γ process from ATLAS
- Several differential cross sections are provided for EW, and EW + QCD
  - As functions of p_{T}^{γ} , $p_{\mathrm{T}}^{\mathrm{j}}$, p_{T}^{ℓ} , $p_{\mathrm{T}}^{Z\gamma}$, m_{jj} , $|\Delta y|$, $|\Delta\phi(Z\gamma, \mathrm{jj})|$





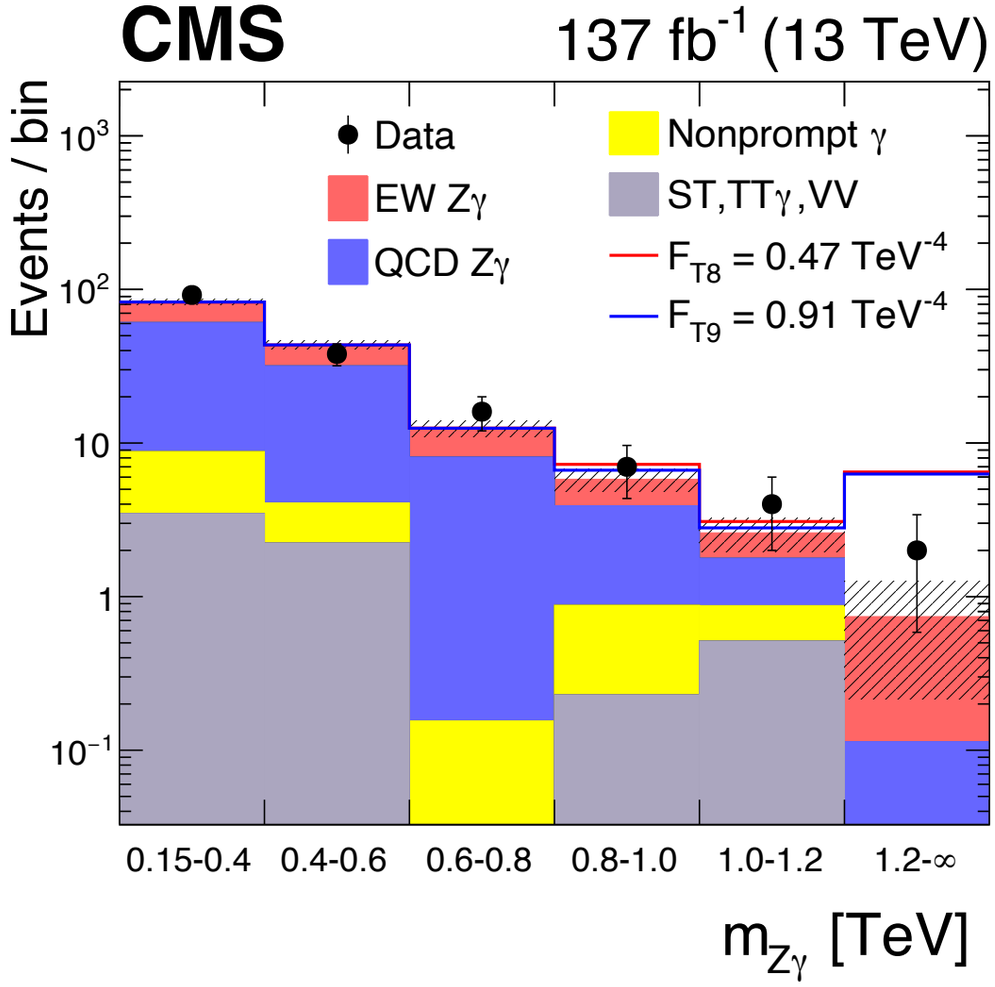


Within uncertainties, generally good agreement with predictions

EW Z(ℓℓ)γ+jj: Results

- CMS also set limit on aQGC by EFT, with events in dedicated search region with high p_T photon ($p_T^\gamma > 120$ GeV).
- Fit on invariant mass of the Zγ system ($m_{Z\gamma}$)

$$\mathscr{L}_{EFT} = \mathscr{L}_{SM} + \sum \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}^{(6)} + \frac{c_i^{(8)}}{\Lambda^4}\mathcal{O}^{(8)} + \ldots.$$



Coupling	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unitarity bound
F_{M0}/Λ^4	−12.5	12.8	−15.8	16.0	1.3
F_{M1}/Λ^4	−28.1	27.0	−35.0	34.7	1.5
F_{M2}/Λ^4	−5.21	5.12	−6.55	6.49	1.5
F_{M3}/Λ^4	−10.2	10.3	−13.0	13.0	1.8
F_{M4}/Λ^4	−10.2	10.2	−13.0	12.7	1.7
F_{M5}/Λ^4	−17.6	16.8	−22.2	21.3	1.7
F_{M7}/Λ^4	−44.7	45.0	−56.6	55.9	1.6
F_{T0}/Λ^4	−0.52	0.44	−0.64	0.57	1.9
F_{T1}/Λ^4	−0.65	0.63	−0.81	0.90	2.0
F_{T2}/Λ^4	−1.36	1.21	−1.68	1.54	1.9
F_{T5}/Λ^4	−0.45	0.52	−0.58	0.64	2.2
F_{T6}/Λ^4	−1.02	1.07	−1.30	1.33	2.0
F_{T7}/Λ^4	−1.67	1.97	−2.15	2.43	2.2
F_{T8}/Λ^4	−0.36	0.36	−0.47	0.47	1.8
F_{T9}/Λ^4	−0.72	0.72	−0.91	0.91	1.9

EW Z(νν)γ+jj

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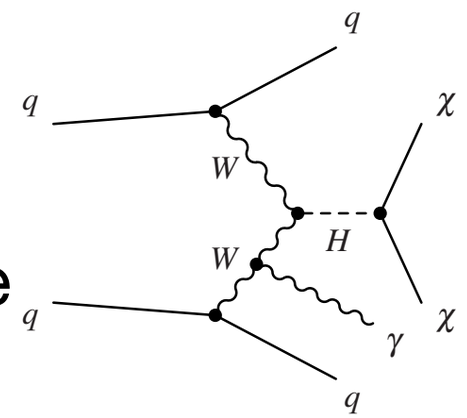
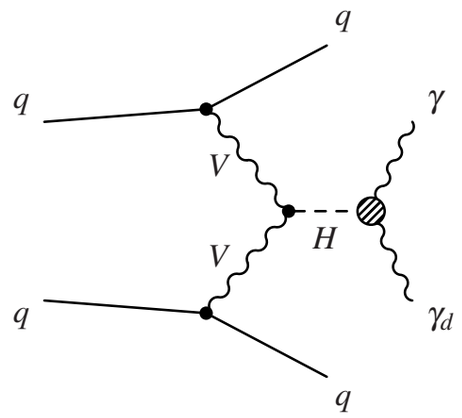
- First measurement and observation in full run2 data
  - Search for H(→inv)γ with VBF+MET+Photon signature
  - Search for H decays to dark photon
- Mostly focus on low energy region $p_{\mathrm{T}}^{\gamma} \in [\mathbf{15}, \mathbf{110}]$ GeV



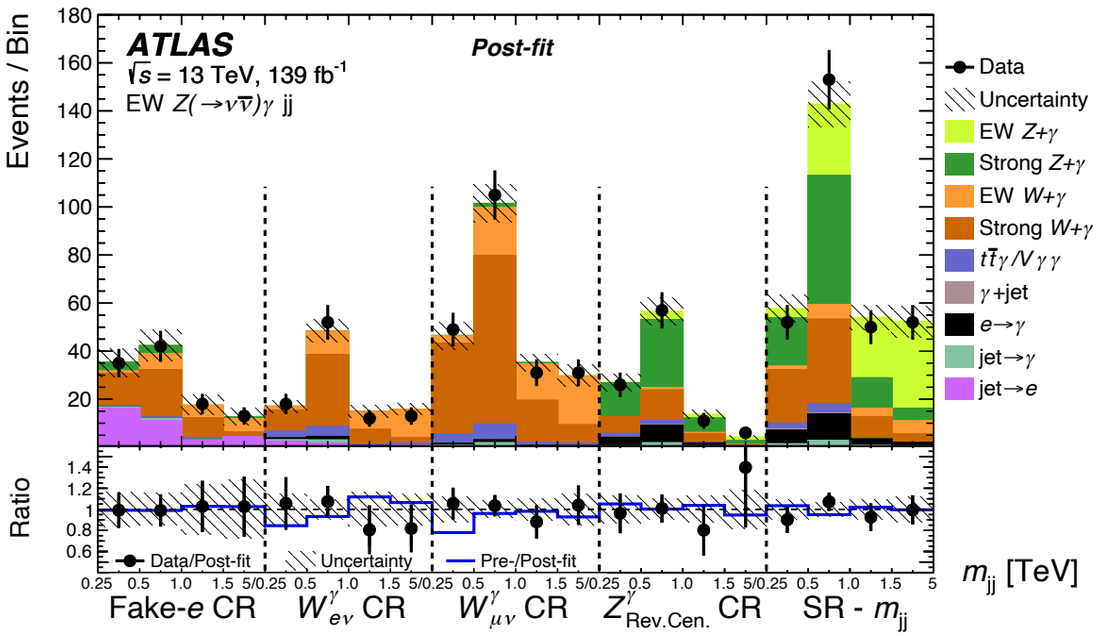


Variable	SR	$W_{\mu\nu}^{\gamma}$ CR	$W_{e\nu}^{\gamma}$ CR	$Z_{\mathrm{Rev.Cen.}}^{\gamma}$ CR	Fake-e CR	Low-$E_{\mathrm{T}}^{\mathrm{miss}}$ VR
$p_{\mathrm{T}}(j_1)$ [GeV]				> 60		
$p_{\mathrm{T}}(j_2)$ [GeV]				> 50		
$p_{\mathrm{T}}(j_{>2})$ [GeV]				> 25		
N_{jet}				2,3		
$N_{b\text{-jet}}$				< 2		
$\Delta\phi_{\mathrm{jj}}$				< 2.5 [2.0]		
$\lvert\Delta\eta_{\mathrm{jj}}\rvert$				> 3.0		
$\eta(j_1) \times \eta(j_2)$				< 0		
C_3				< 0.7		
m_{jj} [TeV]			> 0.25			0.25–1.0
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 150	–	> 80	> 150	< 80	110–150
$E_{\mathrm{T}}^{\mathrm{miss,lep\text{-}rm}}$ [GeV]	–	> 150	> 150	–	> 150	110–150
$E_{\mathrm{T}}^{\mathrm{jets,no\text{-}jvt}}$ [GeV]			> 130			> 100
$\Delta\phi(j_i, \vec{E}_{\mathrm{T}}^{\mathrm{miss,lep\text{-}rm}})$				> 1.0		
N_{γ}				1		
$p_{\mathrm{T}}(\gamma)$ [GeV]			$> 15, < 110$ [$> 15, < \max(110, 0.733 \times m_{\mathrm{T}})$]			
C_{γ}	> 0.4	> 0.4	> 0.4	< 0.4	> 0.4	> 0.4
$\Delta\phi(\gamma, \vec{E}_{\mathrm{T}}^{\mathrm{miss,lep\text{-}rm}})$				> 1.8 [–]		
N_{ℓ}	0	1 μ	1 e	0	1 e	0
$p_{\mathrm{T}}(\ell)$ [GeV]	–	> 30	> 30	–	> 30	–

- EW signal sample by MadGraph at LO
- Higgs related sample at least at NLO
- Dominant background from QCD Zγ+jets and W(ℓν)γ+jets and controlled with CRs
  - $W\gamma(\mu\nu)$, $W\gamma(e\nu)$ and Fake-e region: allowing one lepton (or jet fake electron)
  - $Z_{Rev.Cen.}(\gamma)$ CR: QCD-Zγjj enriched

EW Z(νν)γ+jj

- Signal extracted from simultaneous fitting across all the regions
  - QCD Wγ and Zγ normalisations are floating in the fit



$\mu_{Z\gamma_{\mathrm{EW}}}$	$\beta_{Z\gamma_{\mathrm{strong}}}$	$\beta_{W\gamma}$
1.03 ± 0.25	1.02 ± 0.41	1.01 ± 0.20

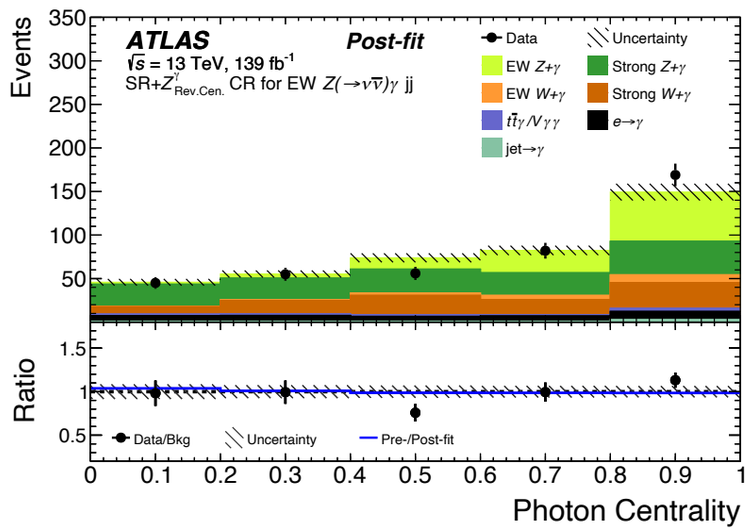
$$\sigma_{\mathrm{EW}} = 1.31 \pm 0.20\,(\mathrm{stat}) \pm 0.20\,(\mathrm{syst})\ \mathrm{fb}$$

Observed (expected) significance: 5.2 (5.1) σ

Centrality cut:

$$C_\gamma = \exp\left[-\frac{4}{(\eta_1 - \eta_2)^2}\left(\eta_\gamma - \frac{\eta_1 + \eta_2}{2}\right)^2\right],$$

Observable	Requirements
N_{jet} with $p_{\mathrm{T}} > 25$ GeV	≥ 2
$\lvert\eta(j_{1,2})\rvert$	< 4.5
$p_{\mathrm{T}}(j_1)$ [GeV]	> 60
$p_{\mathrm{T}}(j_2)$ [GeV]	> 50
$\Delta R(j, \ell)$	> 0.4
$\lvert\Delta\eta_{\mathrm{jj}}\rvert$	> 3.0
C_3	< 0.7
m_{jj} [TeV]	> 0.5
truth-$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 150
$\Delta\phi$(truth-$\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, j_i$)	> 1.0
$p_{\mathrm{T}}(\gamma)$ [GeV]	$> 15, < 110$
$\lvert\eta(\gamma)\rvert$	< 2.37
$E_{\mathrm{T}}^{\mathrm{cone20}}/E_{\mathrm{T}}^{\gamma}$	< 0.07
$\Delta R(\gamma$, jet-or-$\ell)$	> 0.4
C_γ	> 0.4
$\Delta\phi$(truth-$\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \gamma$)	> 1.8
N_ℓ with $p_{\mathrm{T}} > 4$ GeV and $\lvert\eta\rvert < 2.47$	0



EW Z(νν)γ+jj: BSM search

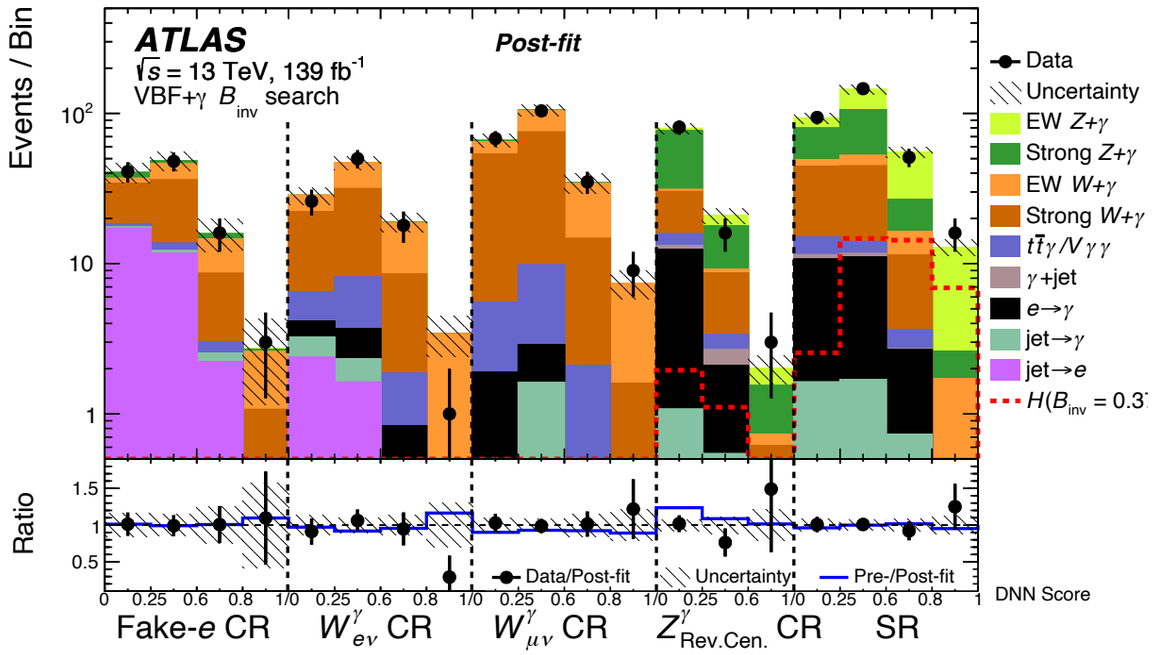
Same VBF signature used to search for $H \to \boldsymbol{inv}$. and $H \to \gamma\gamma_d$

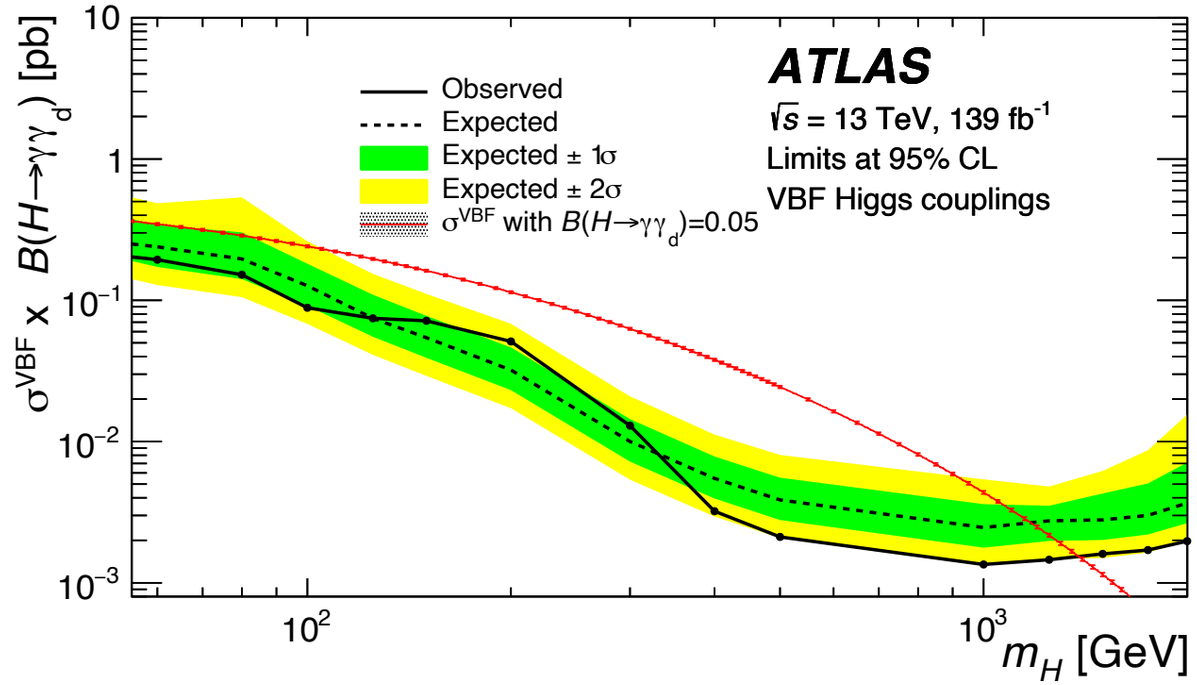
1. $H \to \boldsymbol{inv}$.

- Dense Neural Network (DNN) used as fitting discriminant
  - Looser event to increase statistic
  - Highly suppress the QCD production Zγjj events
- Obs. (Exp.) branching ratio upper limit is 0.37 $(0.34^{+0.15}_{-0.14})$ at 95% CL

2. $H \to \gamma\gamma_d$

- Transverse mass of the photon and MET system is used for fitting
- Obs. (Exp.) $H \to \gamma\gamma_d$ branching ratio upper limit is 0.018 $(0.017^{+0.007}_{-0.005})$ at 95% CL when m_h= 125 GeV

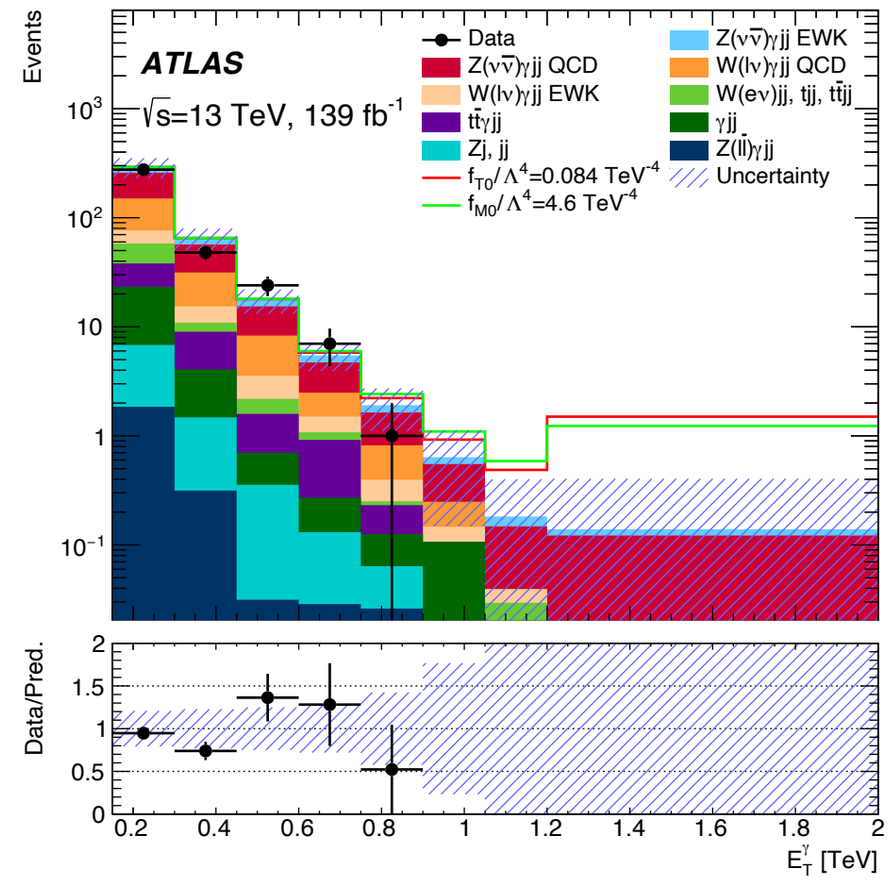


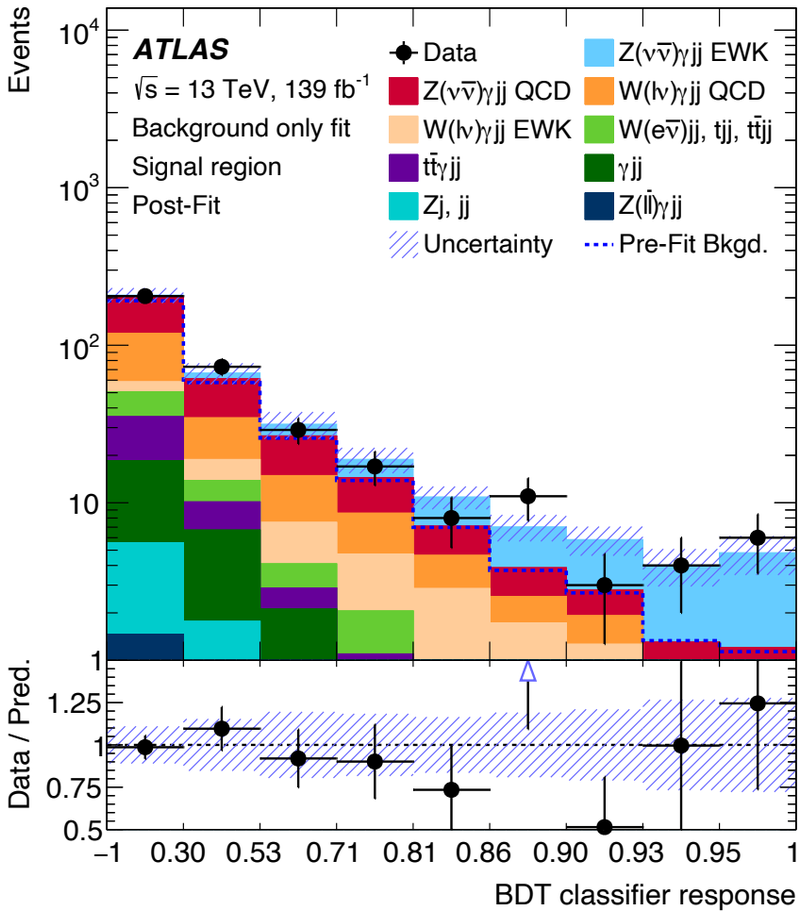


EW Z(νν)γ+jj: high energy region

JHEP accepted, arXiv:2208.12741

- New measurement with extra $p_{\mathrm{T}}^{\gamma} > 150$ GeV to enrich the QGC events:
- BDT to separate signal from backgrounds
- Observed (expected): 3.2σ (3.7σ)
- Photon E_T is used in aQGC search





In the region where unitarity is preserved

Coefficient	E_c [TeV]	Observed limit [TeV^{-4}]	Expected limit [TeV^{-4}]
f_{T0}/Λ^4	1.7	$[-8.7, 7.1] \times 10^{-1}$	$[-8.9, 7.3] \times 10^{-1}$
f_{T5}/Λ^4	2.4	$[-3.4, 4.2] \times 10^{-1}$	$[-3.5, 4.3] \times 10^{-1}$
f_{T8}/Λ^4	1.7	$[-5.2, 5.2] \times 10^{-1}$	$[-5.3, 5.3] \times 10^{-1}$
f_{T9}/Λ^4	1.9	$[-7.9, 7.9] \times 10^{-1}$	$[-8.1, 8.1] \times 10^{-1}$
f_{M0}/Λ^4	0.7	$[-1.6, 1.6] \times 10^{2}$	$[-1.5, 1.5] \times 10^{2}$
f_{M1}/Λ^4	1.0	$[-1.6, 1.5] \times 10^{2}$	$[-1.4, 1.4] \times 10^{2}$
f_{M2}/Λ^4	1.0	$[-3.3, 3.2] \times 10^{1}$	$[-3.0, 3.0] \times 10^{1}$

EW W(ℓν)γ+jj

PRD accepted, arXiv:2212.12592

- Measurements using full Run 2 data by CMS, with W leptonic decay
- Signal is generated with MadGraph at LO
- Main backgrounds from QCD Wγ and nonprompt γ/ℓ by data-driven method
- Results extracted from 2D variables of m_{jj} and $m_{\ell\gamma}$
  - Simultaneous fit in the CR and SR

Common selection

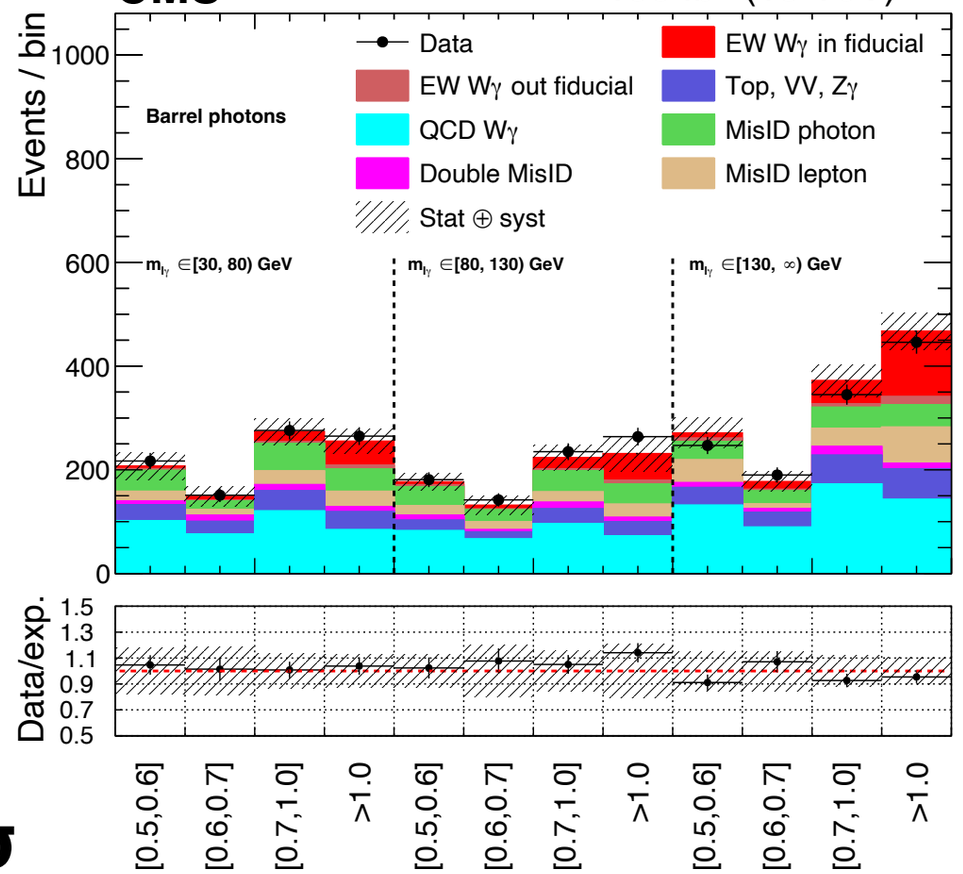
- $pT(\ell/\gamma) > 35\ (25)$ GeV
- Jets with $p_T > 50$ GeV
- $\Delta R(\ell,\gamma/j) > 0.5$
- $m_T(W) > 30$ GeV
- MET > 30 GeV
- $|m_{e\gamma} - m_Z| > 10$ GeV
- $m_{W\gamma} > 100$ GeV

Control region

- 200 GeV < m_{jj} < 400 GeV

Signal region

- $\Delta\phi(\phi_{Z\gamma},\phi_{jj}) > 2$
- $|\eta_{Z\gamma} - (\eta_{j1} + \eta_{j2})/2| < 1.2$
- $m_{jj} > 500$ GeV
- $\Delta\eta_{jj} > 2.5$



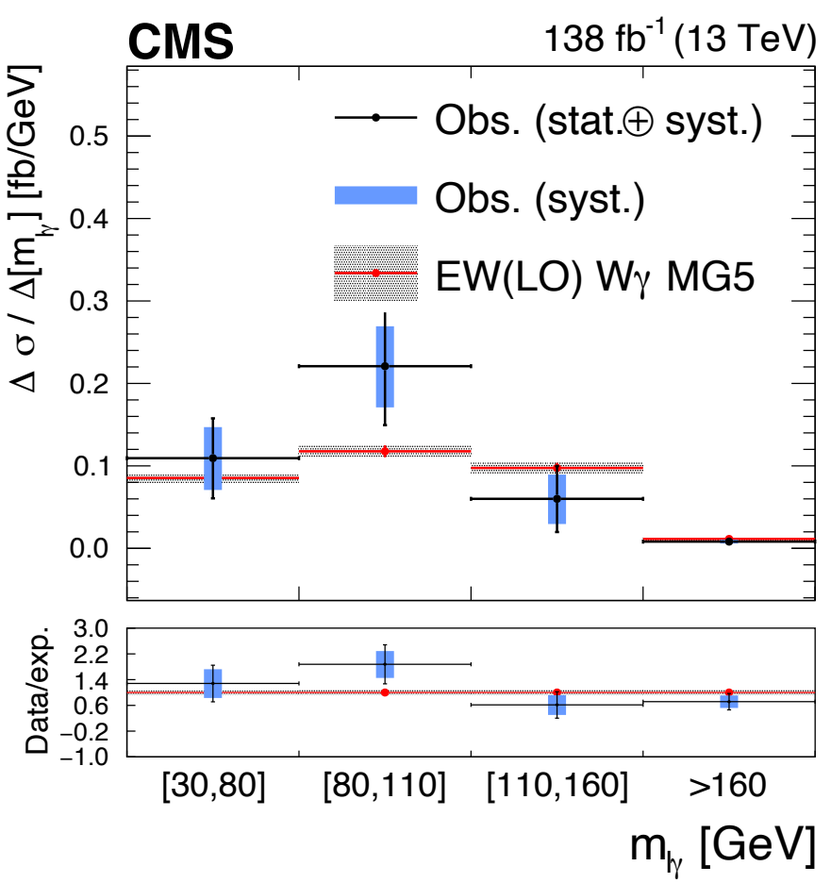
Observed (expected) significance: 6.03 (6.79)σ

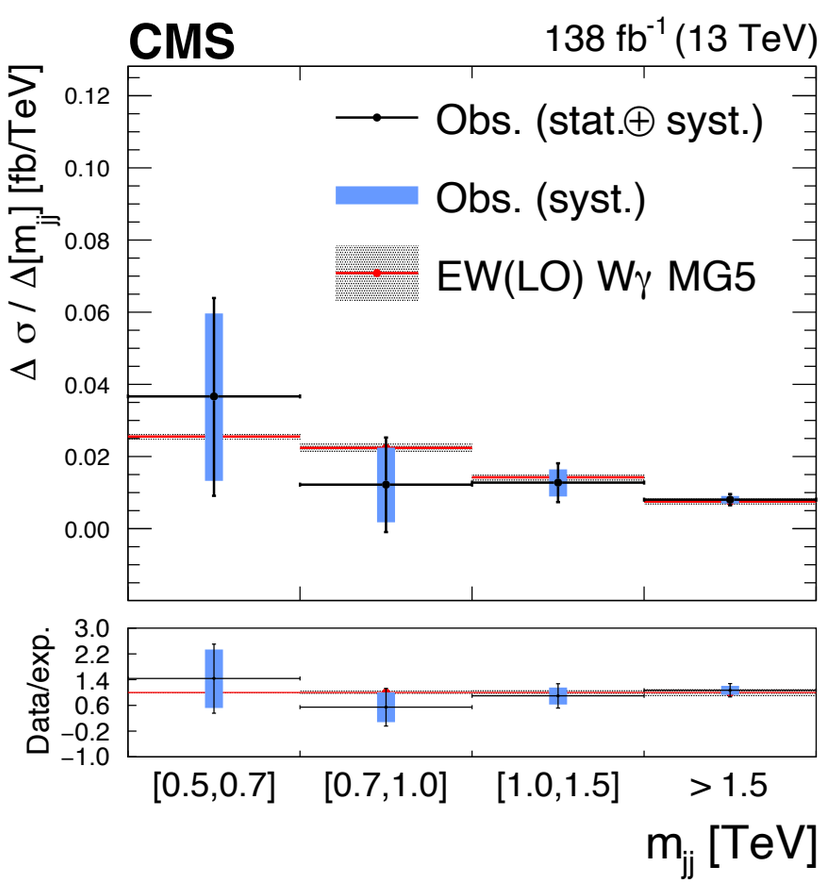
EW W(ℓν)γ+jj

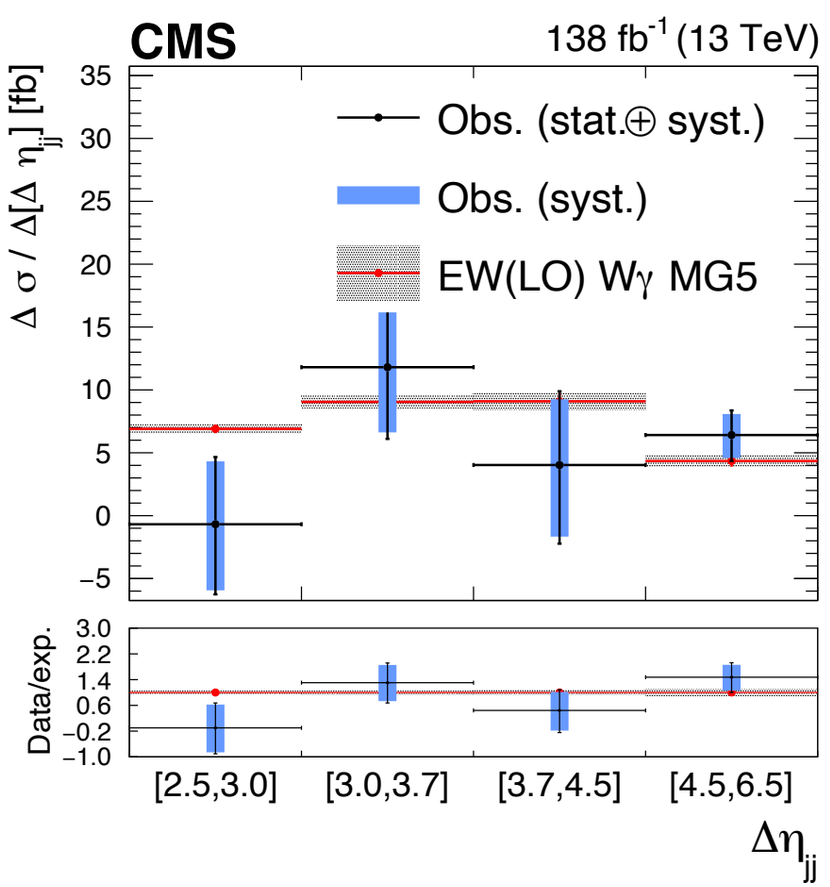
- Inclusive and differential cross sections are measured for both EW and EW+QCD productions

$$\mu_{\mathrm{EW}} = 0.88^{+0.19}_{-0.18} \qquad \sigma_{\mathrm{EW}} = 23.5 \pm 2.8\,(\mathrm{stat}) \pm^{+1.9}_{-1.7}\,(\mathrm{theo}) \pm^{+3.5}_{-3.4}\,(\mathrm{syst})\,\mathrm{fb}$$

$$\mu_{\mathrm{EW+QCD}} = 0.98^{+0.12}_{-0.11} \qquad \sigma_{\mathrm{EW+QCD}} = 113 \pm 2.0\,(\mathrm{stat}) \pm^{+2.5}_{-2.3}\,(\mathrm{theo}) \pm 13\,(\mathrm{syst})\,\mathrm{fb}$$



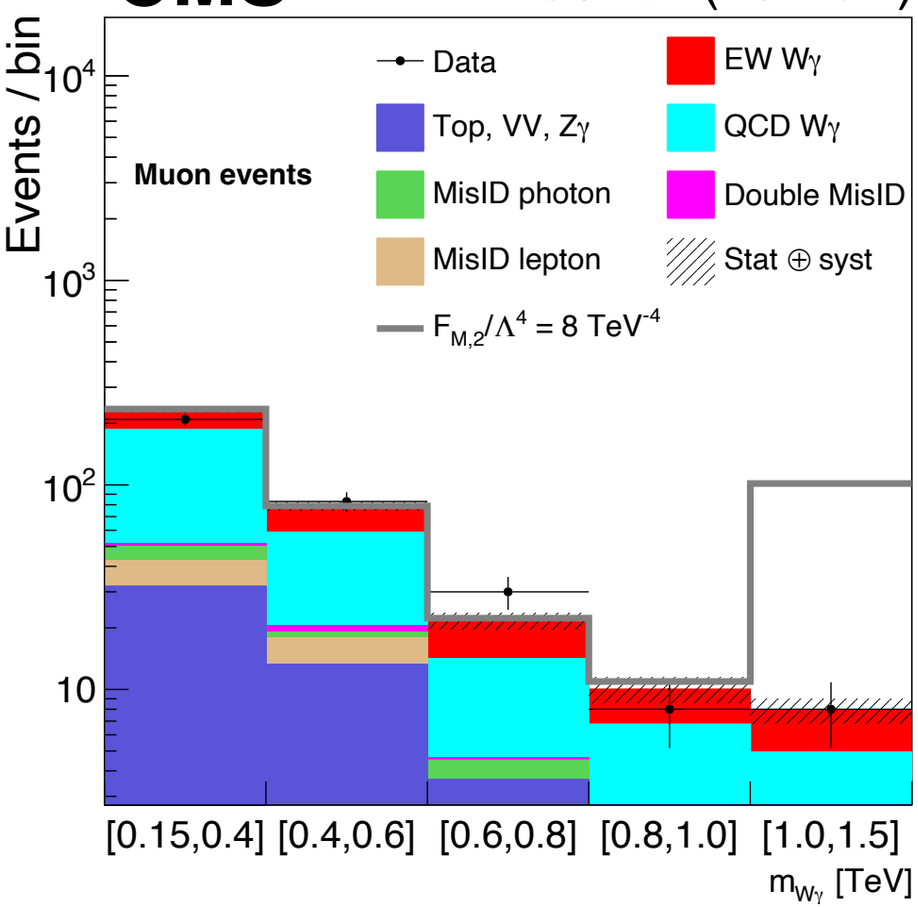




EW W(ℓν)γ+jj

- Set limit on aQGC by EFT, with events in dedicated search region.
- Fit on invariant mass of the Wγ system ($m_{W\gamma}$)

aQGC search region
- photon p_T > 100 GeV
- m_{jj} > 800 GeV
- $\Delta\eta_{jj}$ > 2.5



$$\mathscr{L}_{EFT} = \mathscr{L}_{SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}^{(6)} + \frac{c_i^{(8)}}{\Lambda^4}\mathcal{O}^{(8)} + \ldots.$$

Expected limit	Observed limit	U_{bound}
$-5.1 < f_{M,0}/\Lambda^4 < 5.1$	$-5.6 < f_{M,0}/\Lambda^4 < 5.5$	1.7
$-7.1 < f_{M,1}/\Lambda^4 < 7.4$	$-7.8 < f_{M,1}/\Lambda^4 < 8.1$	2.1
$-1.8 < f_{M,2}/\Lambda^4 < 1.8$	$-1.9 < f_{M,2}/\Lambda^4 < 1.9$	2.0
$-2.5 < f_{M,3}/\Lambda^4 < 2.5$	$-2.7 < f_{M,3}/\Lambda^4 < 2.7$	2.7
$-3.3 < f_{M,4}/\Lambda^4 < 3.3$	$-3.7 < f_{M,4}/\Lambda^4 < 3.6$	2.3
$-3.4 < f_{M,5}/\Lambda^4 < 3.6$	$-3.9 < f_{M,5}/\Lambda^4 < 3.9$	2.7
$-13 < f_{M,7}/\Lambda^4 < 13$	$-14 < f_{M7}/\Lambda^4 < 14$	2.2
$-0.43 < f_{T,0}/\Lambda^4 < 0.51$	$-0.47 < f_{T,0}/\Lambda^4 < 0.51$	1.9
$-0.27 < f_{T,1}/\Lambda^4 < 0.31$	$-0.31 < f_{T,1}/\Lambda^4 < 0.34$	2.5
$-0.72 < f_{T,2}/\Lambda^4 < 0.92$	$-0.85 < f_{T,2}/\Lambda^4 < 1.0$	2.3
$-0.29 < f_{T,5}/\Lambda^4 < 0.31$	$-0.31 < f_{T,5}/\Lambda^4 < 0.33$	2.6
$-0.23 < f_{T,6}/\Lambda^4 < 0.25$	$-0.25 < f_{T,6}/\Lambda^4 < 0.27$	2.9
$-0.60 < f_{T,7}/\Lambda^4 < 0.68$	$-0.67 < f_{T,7}/\Lambda^4 < 0.73$	3.1

most stringent to date

Summary

- Overview of VBS/F processes with a photon measurements in both ATLAS and CMS
  - VBS Zγ, Z $\rightarrow \ell\ell$
  - VBS Zγ, Z $\rightarrow \nu\nu$ in low and high photon p_T region
  - VBS Wγ, W $\rightarrow \ell\nu$
- Rich and comprehensive physics results
  - Differential cross sections
  - Search for aQGC
  - Search for Higgs invisible decay and to dark photon

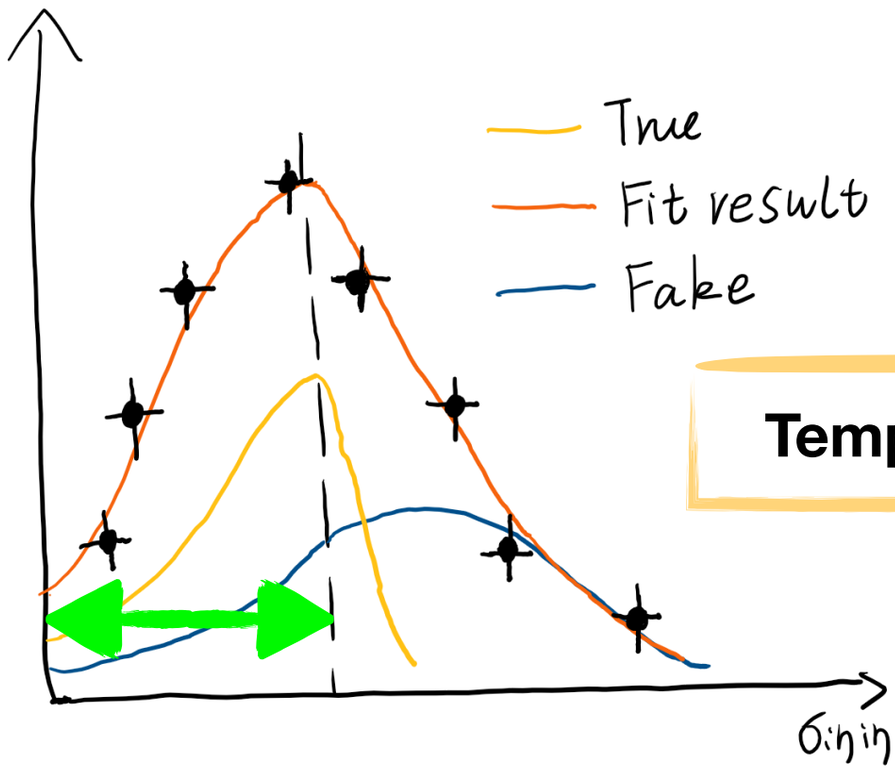
Backup

Backup

VBS/VBF with γ	Final states	CMS	ATLAS
Zγjj	$\ell\ell\gamma jj$	PRD 104 (2021) 072001	ATLAS-CONF-2021-038
			(m_{jj} > 500 GeV)
Zγjj	νγjj	—	EPJC 82 (2022) 105
			JHEP accepted, arXiv:2208.12741
Wγjj	$\ell\nu\gamma jj$	PRD accepted, arXiv:2212.12592	—

VBS/VBF with γ	Final states	CMS	ATLAS
Zγjj	$\ell\ell\gamma jj$	PRD 104 (2021) 072001	ATLAS-CONF-2021-038
Zγjj	νγjj	—	EPJC 82 (2022) 105
			JHEP accepted, arXiv:2208.12741
Wγjj	$\ell\nu\gamma jj$	PRD accepted, arXiv:2212.12592	—

Backup: EW Z(ℓℓ)γ+jj



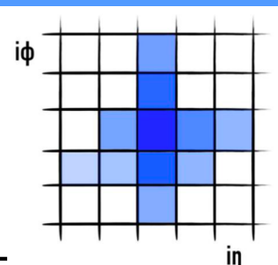
Template fit

Based on the Z+jets events, two good leptons from Z, $70 < m_{\ell\ell} < 110$ GeV	
Data	Remove $\sigma_{i\eta i\eta}$ cut
True Template	Remove $\sigma_{i\eta i\eta}$ cut $\Delta R(\gamma^{reco}, \gamma^{gen}) < 0.3$ Get shape from simulation
Fake template	Remove $\sigma_{i\eta i\eta}$ cut **Invert the charged isolation variable** Get shape from data

$$n^{predicted}_{fake-in-SR} = n_{tot} \times \epsilon_{\text{fake-fraction}} = N^{unweighted}_{fake-in-CR} \times weights$$

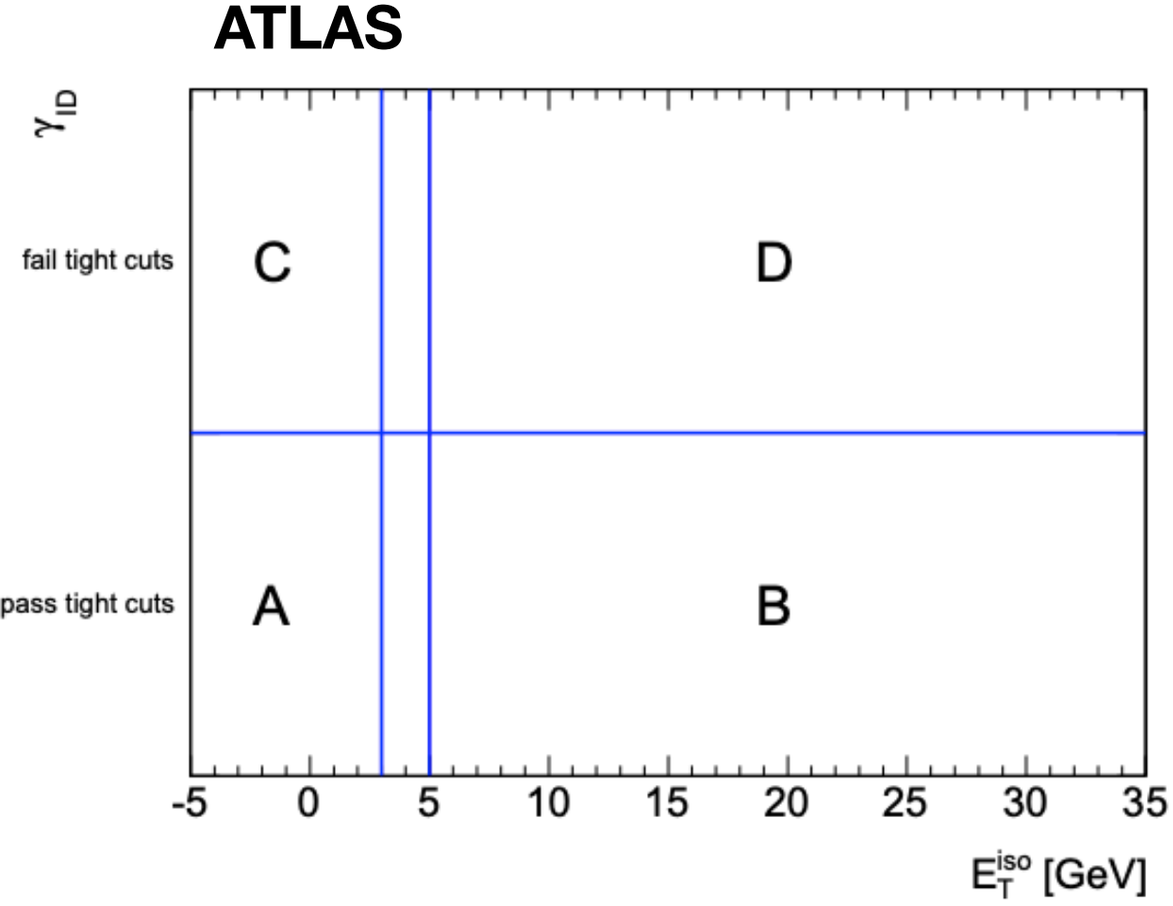
$$\sigma_{i\eta i\eta} = \sqrt{\frac{\sum_i^{5\times5} w_i(\eta_i - \bar{\eta}_{5\times5})^2}{\sum_i^{5\times5} w_i}}$$

$w_i \neq 0$, if $E_i > 0.9\%$ of E_{5x5}



Backup: EW Z(ℓℓ)γ+jj

- Refers to the analysis arXiv: 1012.4389 (Measurement of the inclusive isolated prompt photon cross section)



- The amount of nonprompt photons in A is N_B x N_C/N_D
- The shape of the *m*jj distribution for events with nonprompt photons is obtained from B,C, and D

Backup: EW Z(ℓℓ)γ+jj

ATLAS: mjj > 150 GeV

$$\sigma_{\mathrm{EW}}^{\mathrm{SM\,pred.}} = 4.73 \pm 0.22\,(\mathrm{scale}) \pm 0.15\,(\mathrm{PDF})\ \mathrm{fb}$$

$$\sigma_{\mathrm{EW}} = 4.49 \pm 0.40\,(\mathrm{stat}) \pm 0.42\,(\mathrm{syst})\ \mathrm{fb}$$

$$\sigma_{EW+QCD}^{pred.} = 20.4 \pm 0.2\,(\mathrm{PDF})^{-2.0}_{+2.6}\,(\mathrm{scale})\ \mathrm{fb}$$

$$\sigma_{EW+QCD} = 20.6 \pm 0.06\,(\mathrm{stat})\,^{-1.0}_{+1.2}\,(\mathrm{syst})\ \mathrm{fb}$$

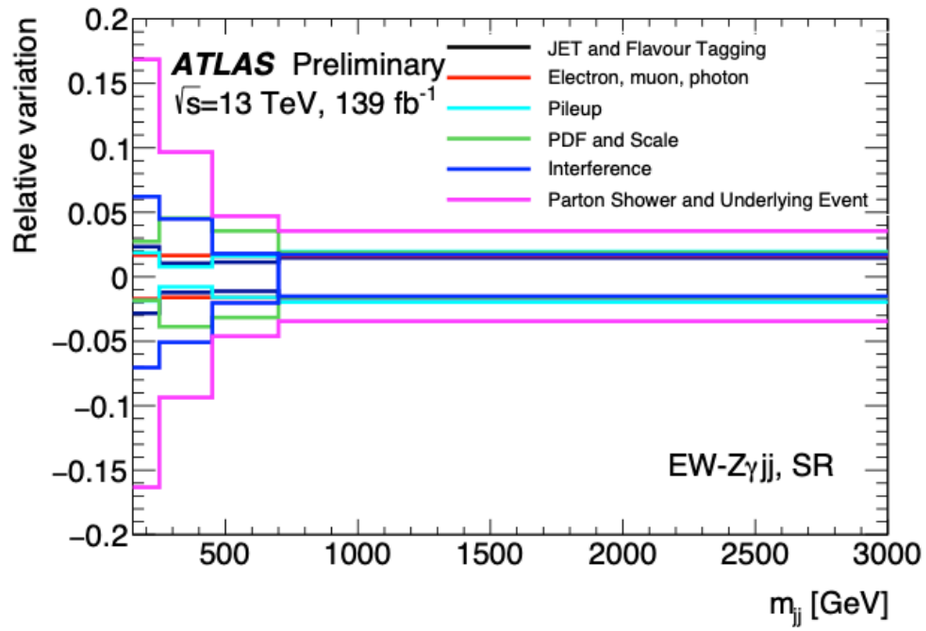
Backup: EW Z(ℓℓ)γ+jj

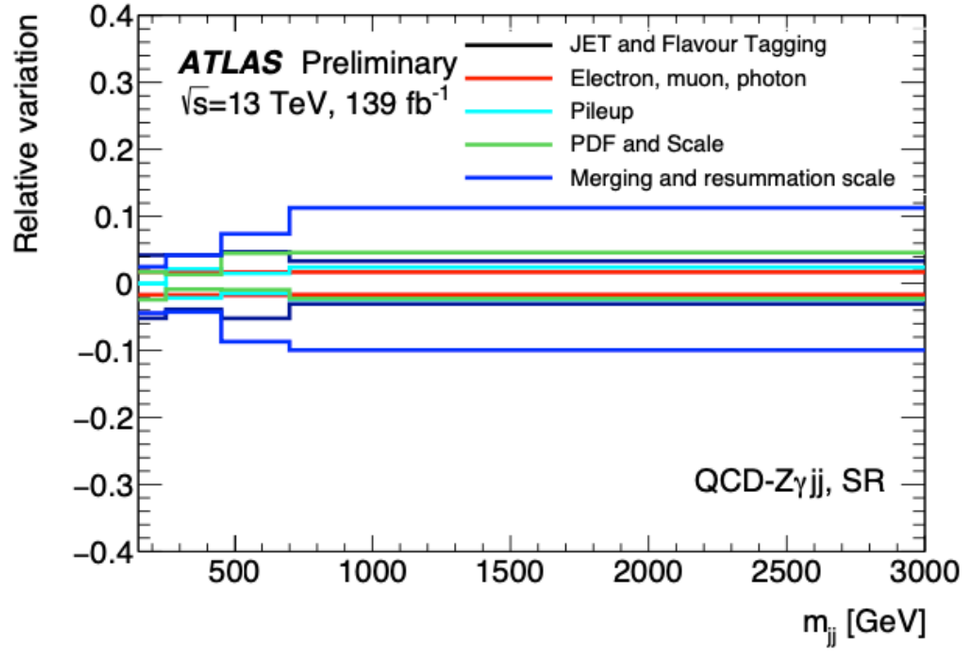
CMS

Systematic uncertainty	Impact [%]	
Jet energy correction	+7.9	−6.7
Theoretical uncertainties	+5.5	−4.7
MC statistical uncertainties	+4.7	−4.5
PU	+4.7	−4.1
Related to e, γ	+4.5	−3.6
PU jet ID	+3.7	−3.4
ECAL timing shift at L1	+3.5	−2.8
Nonprompt-γ bkg. estimate	+2.0	−1.6
Related to μ	+1.7	−1.4
Integrated luminosity	+0.8	−0.6
Total systematic uncertainty	+14	−12

Backup: EW Z(ℓℓ)γ+jj

Source	Size [%]
Electron/photon calibration	± 0.3
Photon	± 0.3
Backgrounds	± 1.0
Electron	± 1.1
Flavour tagging	± 1.1
Muon	± 1.1
MC stat.	± 1.4
Pileup	± 2.6
Jets	± 4.7
QCD-Zγjj modelling	$^{+4.8}_{-4.3}$
EW-Zγjj modelling	$^{+5.7}_{-4.6}$
Data stat.	± 8.8
Total	$^{+13.4}_{-12.6}$





	Data stat.	MC stat.	Background	Reco	EW mod.	QCD mod.	Total
$\Delta\sigma_{EW}/\sigma_{EW}$ [%]	±9	±1	±1	±5	$^{+6}_{-5}$	$^{+5}_{-4}$	±13

Table 3: Breakdown of the uncertainty on the *EW-Zγjj* cross-section.

Backup: EW Z(νν)γ+jj

- **Dominated by statistical unc. in all channels**
- **Large systematic variation from modelling:**
  - Scale var. 25%~56% (3%~11%) for QCD (EW)-Vγjj
  - Madgraph v.s. Sherpa up to 20% for QCD-Vγjj
  - Parton showering model: 4-15% for EW-Vγjj
  - Interference between EW- and QCD-Vγjj up to -22%
- **Post-fit impact of each systematics term →**
  - Largest exp. systematic impact from jet related

Source	1σ Uncertainty on $\mu_{Z\gamma_{\mathrm{EW}}}$
Jet scale and resolution	0.076
$V\gamma$ + jets theory	0.067
pile-up	0.040
Photon	0.035
$e \to \gamma$, jet$\to e, \gamma$ Bkg.	0.035
Lepton	0.027
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.023
Signal theory shape	0.020
Signal theory acceptance	0.12
Data stats.	0.16
$W\gamma$ + jets/$Z\gamma$ + jets Norm.	0.073
MC stats.	0.063
Total	0.25

Backup: EW Z(νν)γ+jj

Unitarity is preserved

Coefficient	E_c [TeV]	Observed limit [TeV^{-4}]	Expected limit [TeV^{-4}]
f_{T0}/Λ^4	1.7	$[-8.7, 7.1] \times 10^{-1}$	$[-8.9, 7.3] \times 10^{-1}$
f_{T5}/Λ^4	2.4	$[-3.4, 4.2] \times 10^{-1}$	$[-3.5, 4.3] \times 10^{-1}$
f_{T8}/Λ^4	1.7	$[-5.2, 5.2] \times 10^{-1}$	$[-5.3, 5.3] \times 10^{-1}$
f_{T9}/Λ^4	1.9	$[-7.9, 7.9] \times 10^{-1}$	$[-8.1, 8.1] \times 10^{-1}$
f_{M0}/Λ^4	0.7	$[-1.6, 1.6] \times 10^{2}$	$[-1.5, 1.5] \times 10^{2}$
f_{M1}/Λ^4	1.0	$[-1.6, 1.5] \times 10^{2}$	$[-1.4, 1.4] \times 10^{2}$
f_{M2}/Λ^4	1.0	$[-3.3, 3.2] \times 10^{1}$	$[-3.0, 3.0] \times 10^{1}$

Unitarity is not preserved

Coefficient	Observed limit [TeV^{-4}]	Expected limit [TeV^{-4}]
f_{T0}/Λ^4	$[-9.4, 8.4] \times 10^{-2}$	$[-1.3, 1.2] \times 10^{-1}$
f_{T5}/Λ^4	$[-8.8, 9.9] \times 10^{-2}$	$[-1.2, 1.3] \times 10^{-1}$
f_{T8}/Λ^4	$[-5.9, 5.9] \times 10^{-2}$	$[-8.1, 8.0] \times 10^{-2}$
f_{T9}/Λ^4	$[-1.3, 1.3] \times 10^{-1}$	$[-1.7, 1.7] \times 10^{-1}$
f_{M0}/Λ^4	$[-4.6, 4.6]$	$[-6.2, 6.2]$
f_{M1}/Λ^4	$[-7.7, 7.7]$	$[-1.0, 1.0] \times 10^{1}$
f_{M2}/Λ^4	$[-1.9, 1.9]$	$[-2.6, 2.6]$