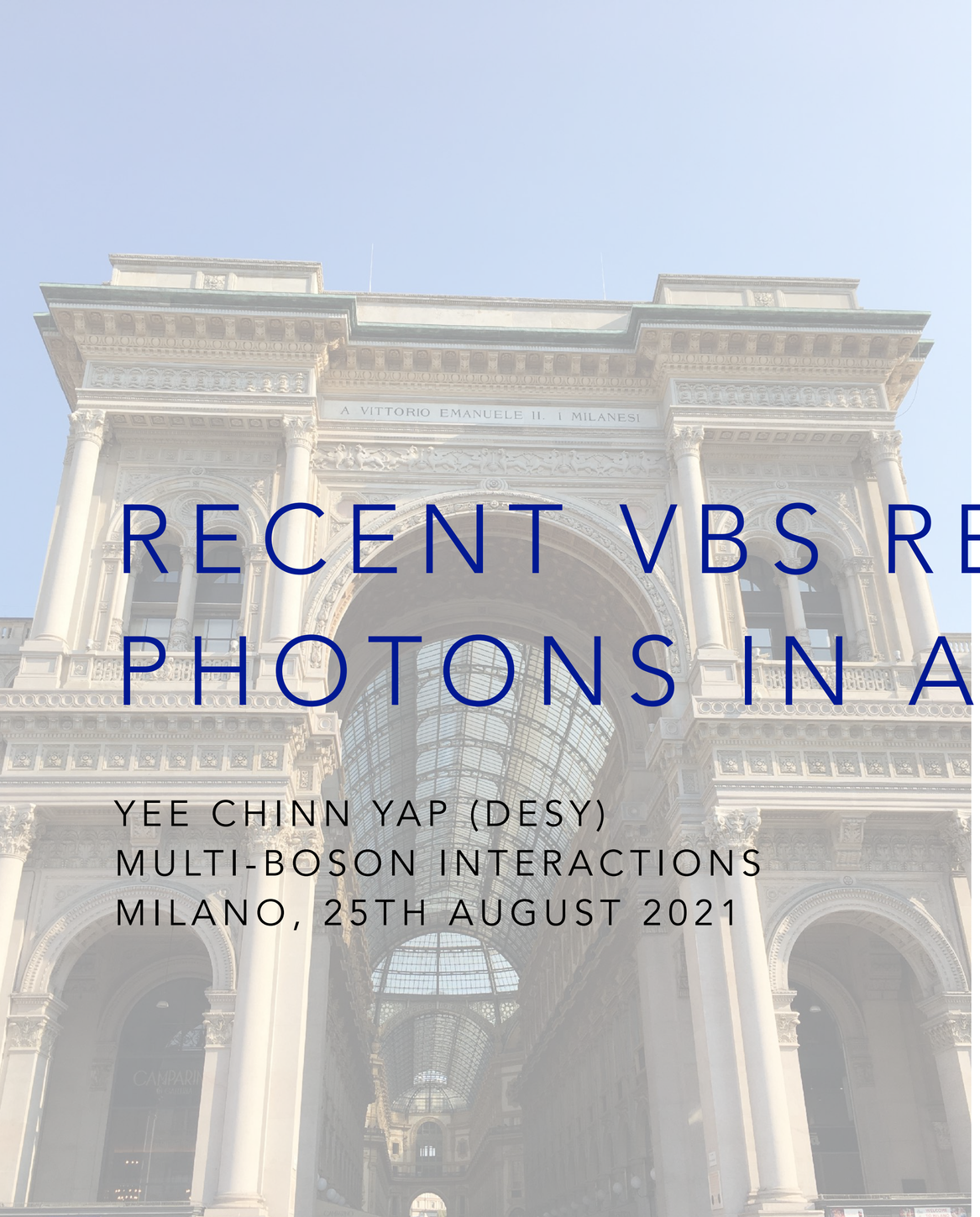


RECENT VBS RESULTS WITH PHOTONS IN ATLAS AND CMS

YEE CHINN YAP (DESY)

MULTI-BOSON INTERACTIONS

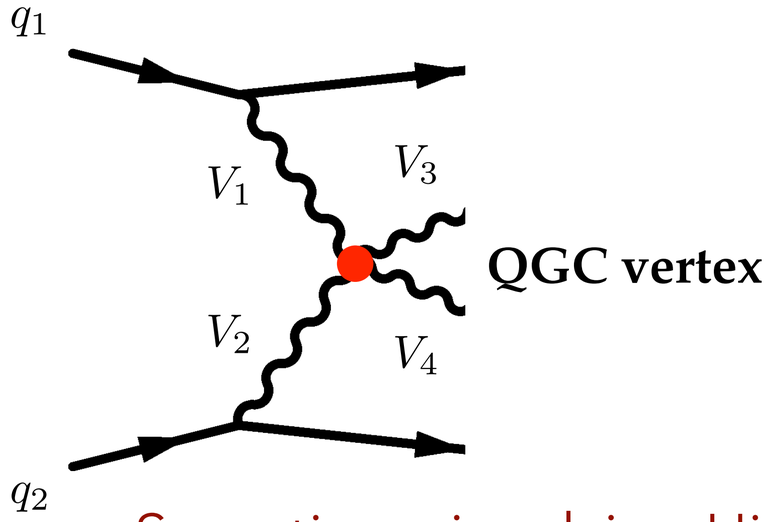
MILANO, 25TH AUGUST 2021

HELMHOLTZ

RESEARCH FOR GRAND CHALLENGES

INTRODUCTION

- VBS can involve quartic gauge coupling.
  - With photon: WWZγ, WWγγ
- Interesting in the context of EWSB due to Higgs boson's role in restoring unitarity in VV scattering cross-section.

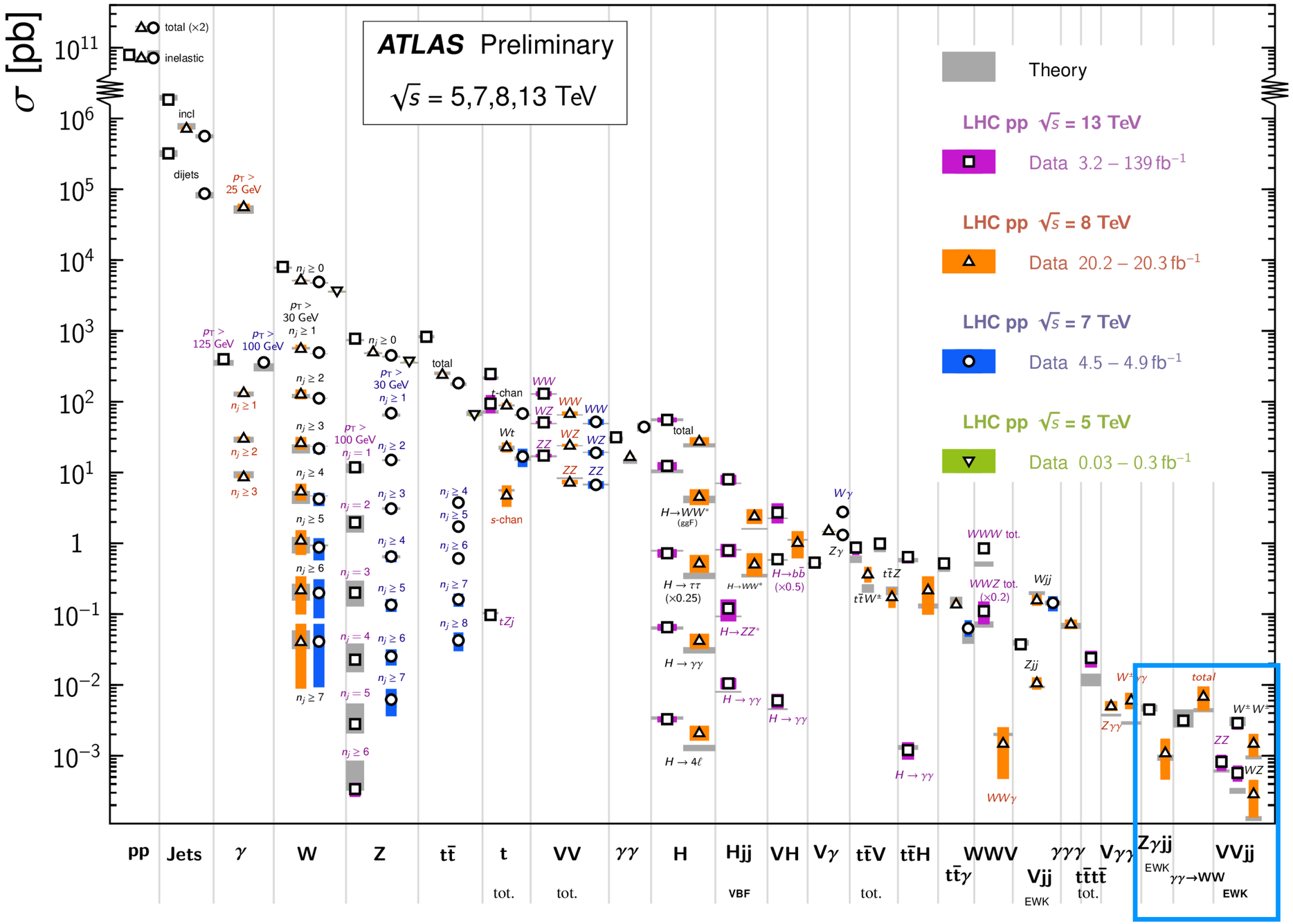


Sometimes involving Higgs exchange

- Also sensitive to triple gauge couplings, but well constrained in diboson production.
- Rare process and large background, only became accessible in recent years at the LHC.
- Can be used to search for aQGCs.

Standard Model Production Cross Section Measurements

Status: July 2021

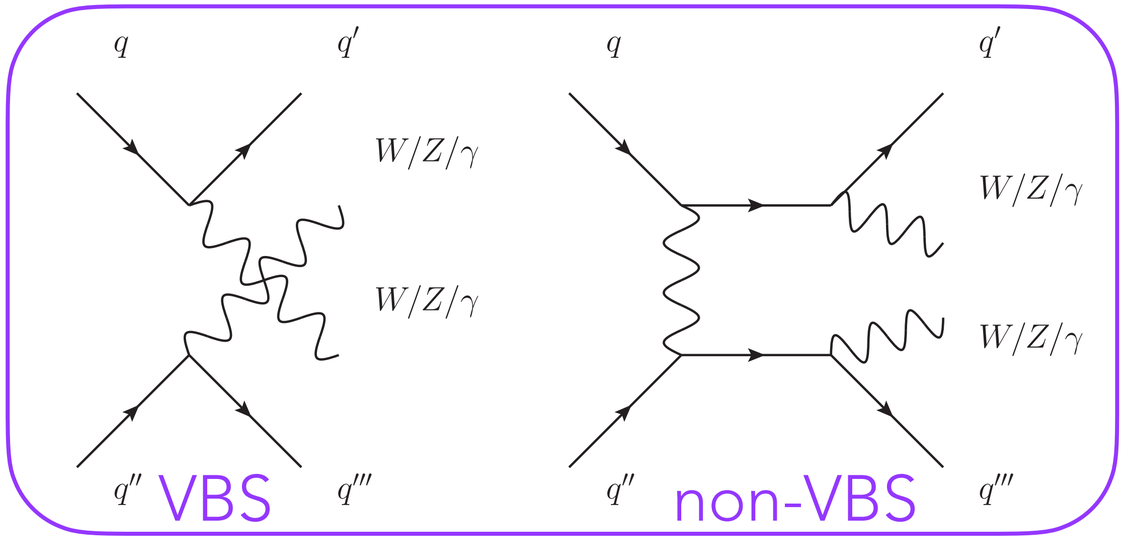


Some of the lowest measured SM cross-sections

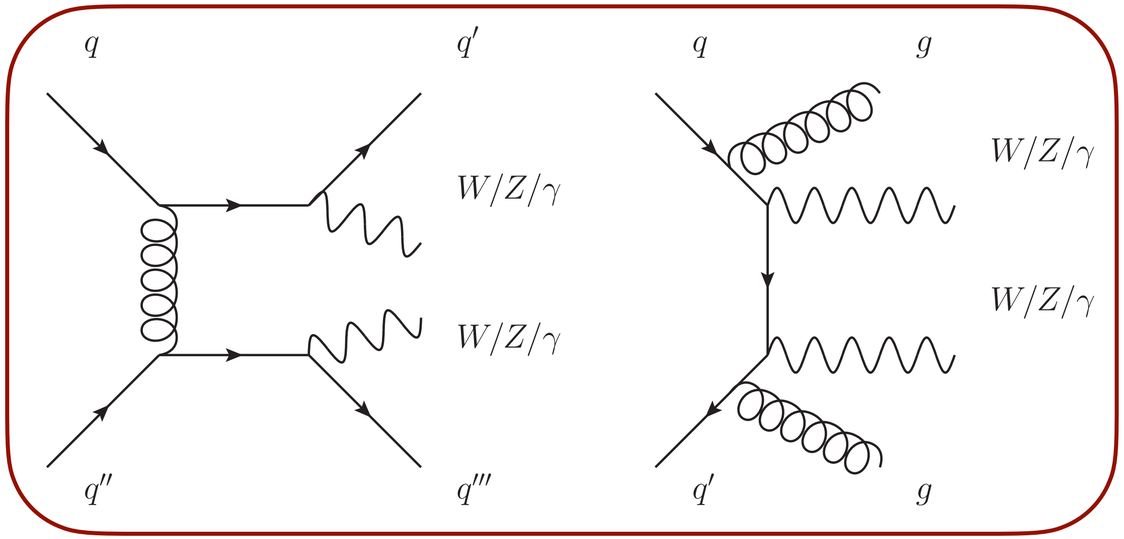
EW AND VBS

- Not counting decays of the boson, at LO:

EW $O(\alpha_{EW}^4)$



QCD $O(\alpha_S^2\alpha_{EW}^2)$

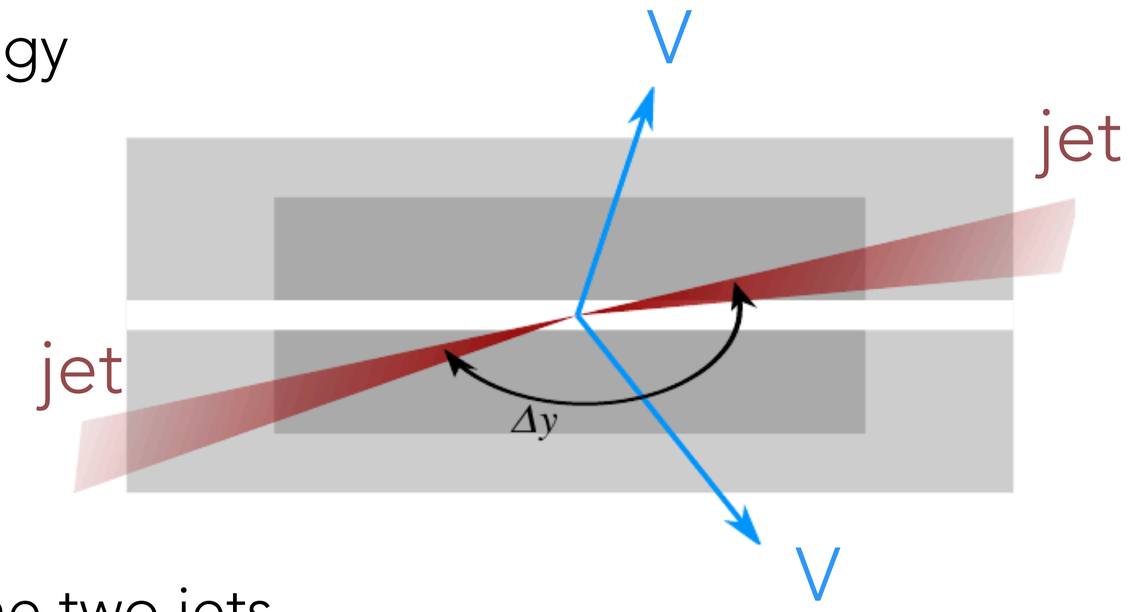


- All purely EW-induced processes treated as **signal**, QCD-induced (at least one strong interaction vertex) as **background**. EW and QCD-induced processes **interfere** ($O(\alpha_S\alpha_{EW}^3)$), effect typically few % of EW.

In the extraction of EW signal, QCD is treated as background, but can be part of signal when measuring EW+QCD cross-section

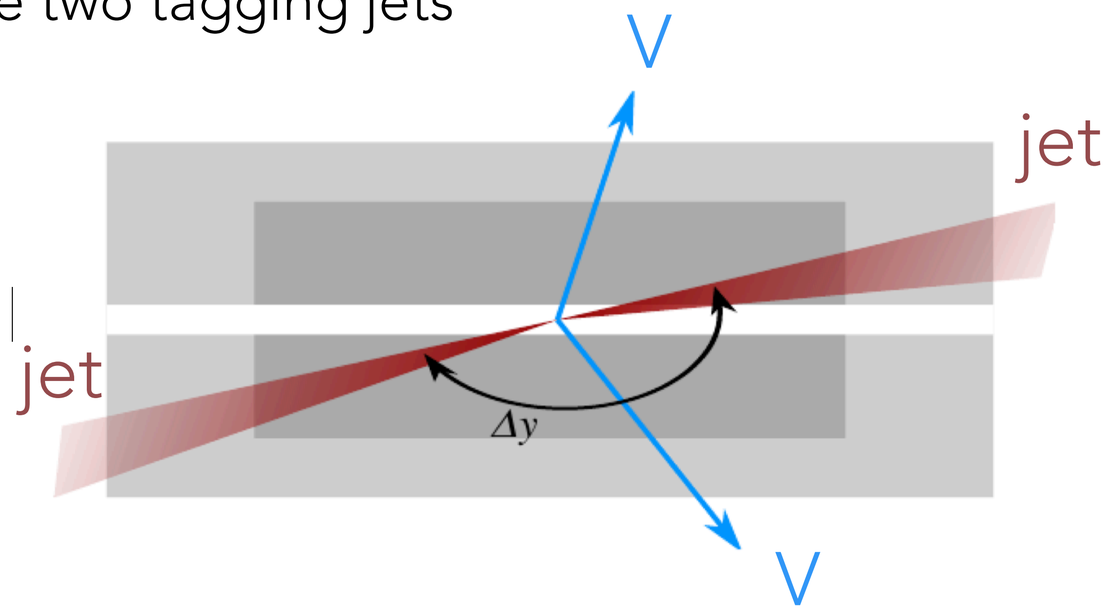
SIGNATURE

- At $O(\alpha_{EW}^4)$, EW process cross-sections are typically much smaller than QCD ones.
- Selection making use of typical VBS topology helps to minimise non-EW processes.
- Typical topology:
  - 2 high energy jets with wide rapidity separation and large invariant mass.
  - Hadronic activity suppressed between the two jets.
  - Boson pair more central than in non-EW processes.



KEY OBSERVABLES

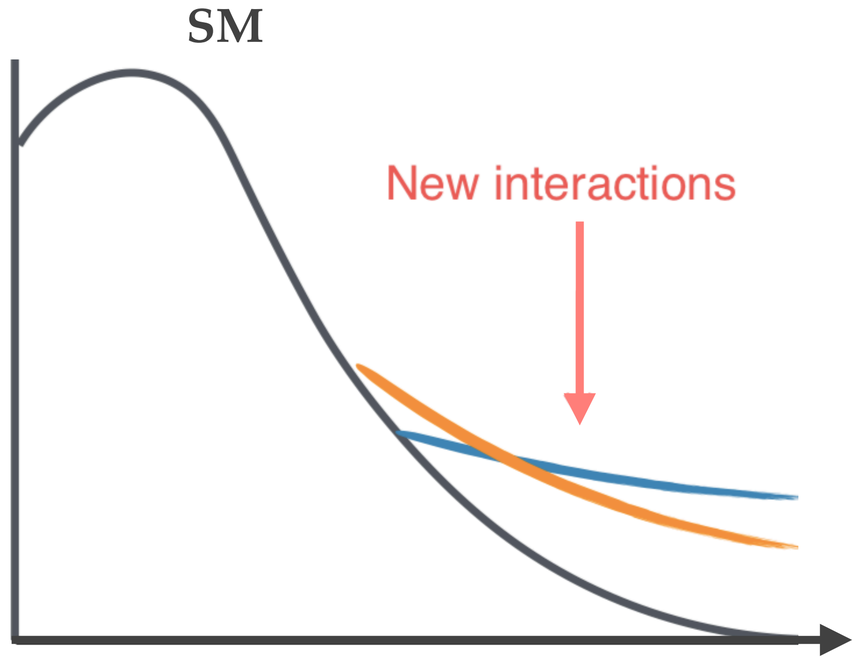
- ζ: centrality of the diboson system relative to the two tagging jets
  - $\zeta = \left| \dfrac{y_{VV} - (y_{j1} + y_{j2})/2}{y_{j1} - y_{j2}} \right|$
  - Zeppenfeld variable $\eta^* = |y_{VV} - (y_{j1} + y_{j2})/2|$
- m_{jj}: dijet invariant mass
- $|\Delta y_{jj}|$ or $|\Delta \eta_{jj}|$: (pseudo-)rapidity difference
- N^{gap}_{jets}: number of jets within the rapidity gap between the two tagging jets
- $|\Delta\phi(VV, jj)|$: azimuthal angle difference between diboson and dijet



ANOMALOUS GAUGE BOSON COUPLING

- Extend SM with dimension-6 and dimension-8 operators in Effective Field Theory (EFT) framework:

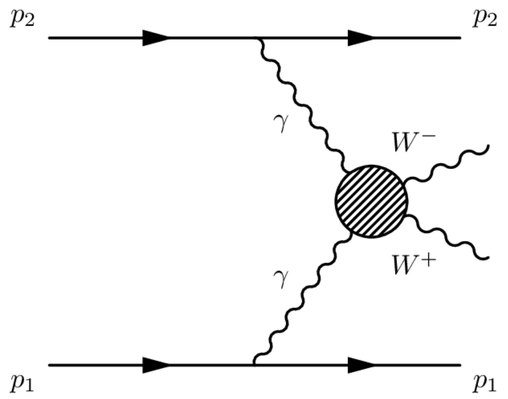
$$\mathscr{L} = \mathscr{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_j \frac{c_j}{\Lambda^4}\mathcal{O}_j^{(8)}$$



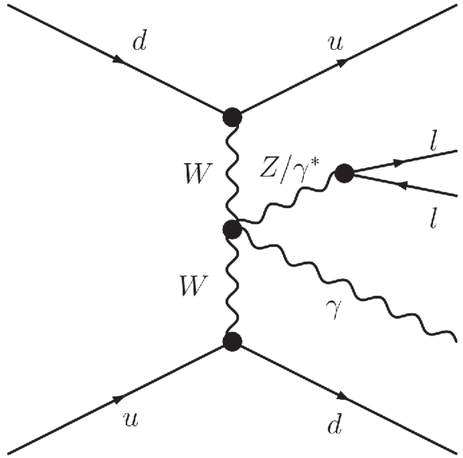
- Dimension-6 and 8 operators give rise to aTGC and/or aQGC, allowing new types of interactions between weak bosons with non-SM tensor structure.
- Anomalous gauge interactions would manifest themselves as enhancement in cross-sections at e.g. high m_{VV} or p_T^V.
- Lowest dimension operators that modify QGC but not TGC is dimension-8.

PROCESSES INVOLVING PHOTONS

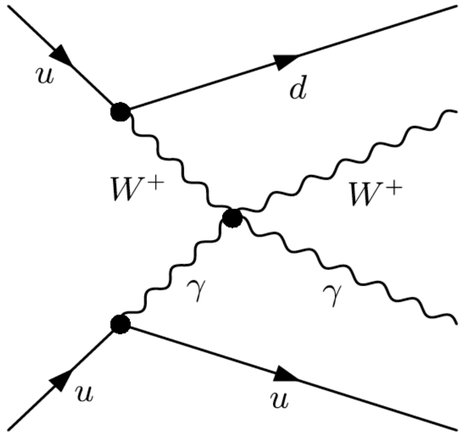
- γγ→WW: ATLAS (Phys. Lett. B 816 (2021) 136190, see Savannah Clawson's talk), CMS (JHEP 08 (2016) 119, 8 TeV)



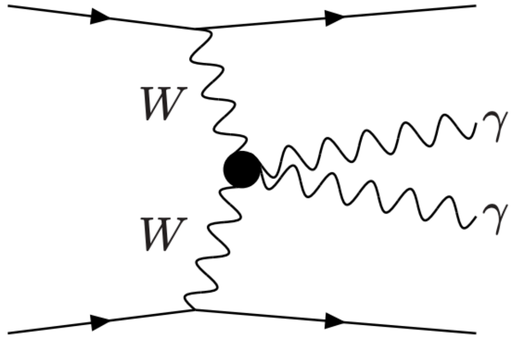
- Z(→ll)γ: ATLAS (ATLAS-CONF-2021-038), CMS (arXiv:2106.11082)



- Z(→νν)γ: ATLAS (CERN-EP-2021-137)

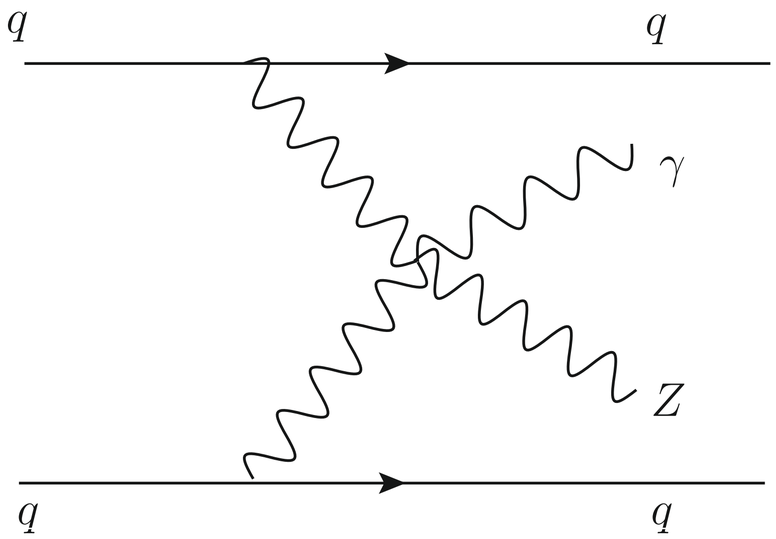


- W(→lν)γ: CMS (Phys. Lett. B 811 (2020) 135988)

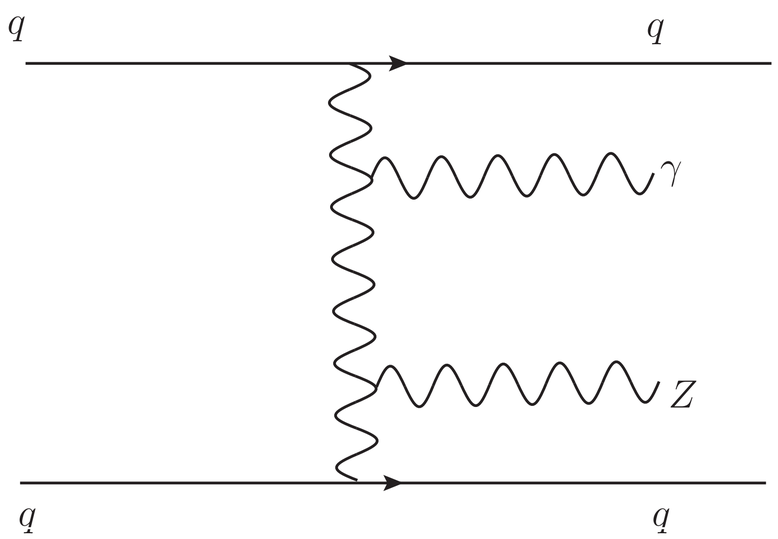


- γγ

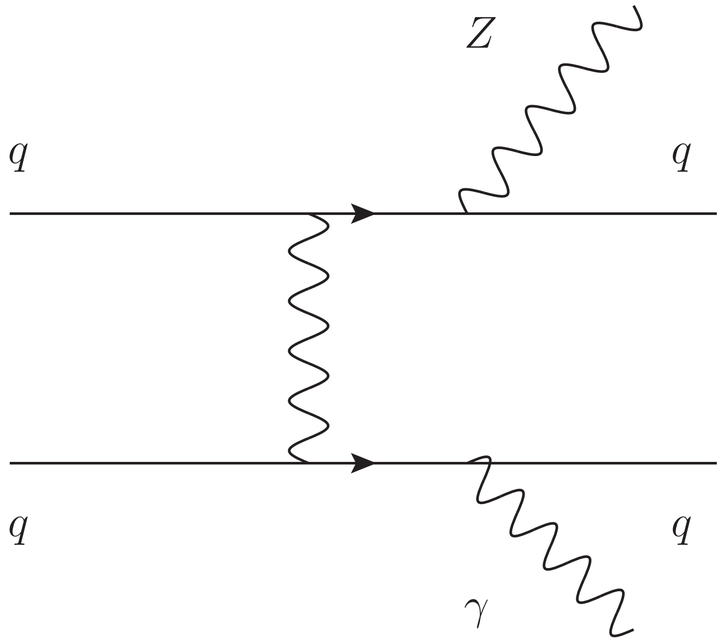
EW Zγjj



VBS via QGC



VBS via TGCs



non-VBS

ATLAS-CONF-2021-038

ATLAS Z(→ll)γ

- eeγjj and μμγjj channels combined.
- Found 4.1 σ evidence with 36 fb^{-1}.
- Data: 139 fb^{-1} full run 2 data recorded with single and di-lepton triggers.
- MC:
  - EW signal: Madgraph LO +Pythia with dipole recoil on.
  - QCD Zγ: Madgraph NLO(≤1j) with FxFx merging.
  - Interference: Madgraph O($\alpha_S \alpha_{EW}^3$). Treated as a systematic on EW.
  - Others: ttγ with Madgraph LO, Sherpa NLO for WZ QCD and Madgraph LO for WZ EW.

ATLAS Z(→ll)γ: Selection

- VBS-enriched selection: m_{jj}>150 GeV, $|\Delta y_{jj}|$>1, N^{gap}_{jets}=0.
- SR defined as ζ<0.4 and QCD-enriched CR as ζ>0.4.

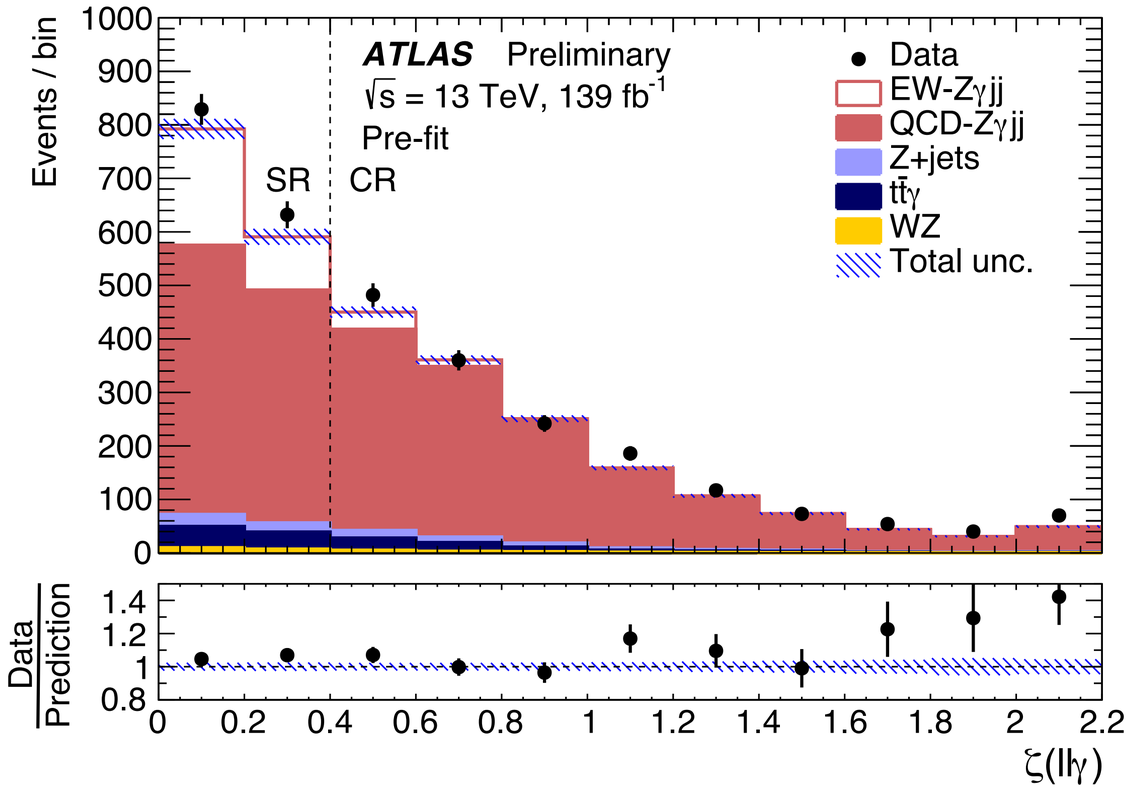
Lepton	$p_{\mathrm{T}}^{\ell} > 20, 30(\text{leading})\ \text{GeV}, \quad \lvert\eta_{\ell}\rvert < 2.47$ $N_{\ell} \geq 2$
Photon	$E_{\mathrm{T}}^{\gamma} > 25\ \text{GeV}, \quad \lvert\eta_{\gamma}\rvert < 2.37$ $E_{\mathrm{T}}^{cone20} < 0.07 E_{\mathrm{T}}^{\gamma}$ $\Delta R(\ell, \gamma) > 0.4$
Jet	$p_{\mathrm{T}}^{jet} > 50\ \text{GeV}, \quad \lvert y_{jet}\rvert < 4.4$ $\lvert\Delta y\rvert > 1.0$ $m_{jj} > 150\ \text{GeV}$ remove jets if $\Delta R(\gamma, j) < 0.4$ or if $\Delta R(\ell, j) < 0.3$
Event	$m_{\ell\ell} > 40\ \text{GeV}$ $m_{\ell\ell} + m_{\ell\ell\gamma} > 182\ \text{GeV}$ $\zeta(\ell\ell\gamma) < 0.4$ $N_{jets}^{gap} = 0$

to remove FSR

Particle-level fiducial selection, similar to SR

ATLAS Z(→ll)γ: Backgrounds

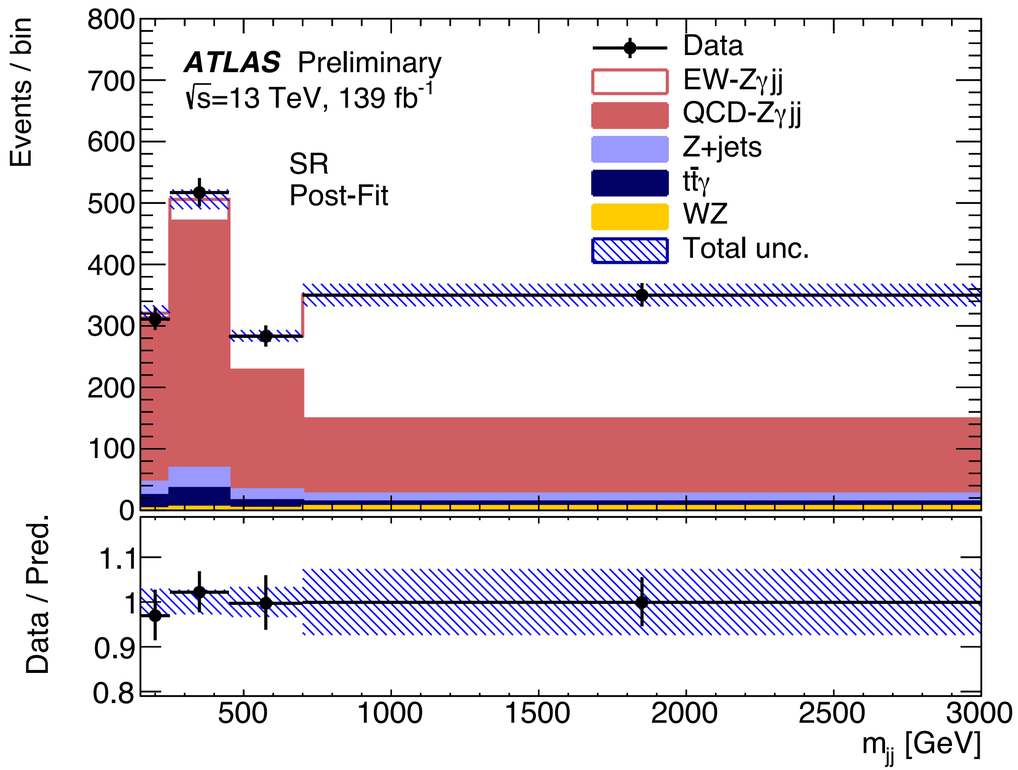
- QCD Zγ dominant.
  - CR designed to validate the MC modelling of this largest background.
- Z+jets (6% in SR): obtained from data-driven 2D sideband method utilising photon isolation and identification.

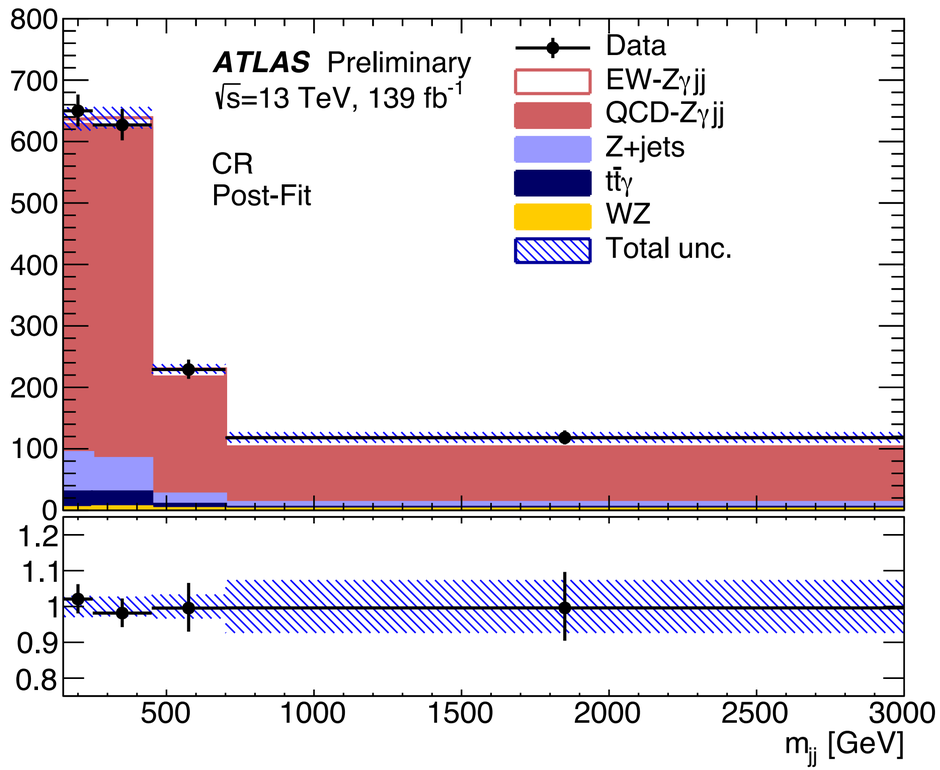


- tty (5% in SR): from MC, using NLO k-factor and validated in a data eμγ CR.
- WZ (EW+QCD, 1% in SR): from MC.

ATLAS Z(→ll)γ: EW Signal Extraction

- m_{jj} distributions fitted simultaneously in SR and CR.
- Good description of QCD Zγ by Madgraph MC is found in both regions.





ATLAS Z(→ll)γ: Results

- ~10 σ (11 σ) observed (expected).
- Fiducial cross-section measured by scaling predicted cross-section by signal strength.

$$\mu_{EW} = 0.95^{+0.14}_{-0.13}$$
$$= 0.95 \pm 0.08\ (\text{stat}) \pm 0.11\ (\text{syst})$$
$$\sigma_{EW} = 4.49 \pm 0.40\ (\text{stat.}) \pm 0.42\ (\text{syst.})\ \text{fb}$$

- For EW+QCD fiducial cross-section, only SR is fitted.

$$\sigma_{EW+QCD} = 20.6 \pm 0.6\ (\text{stat.})^{+1.2}_{-1.0}\ (\text{syst.})\ \text{fb}$$

Uncertainty on σ_{EW}

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	$^{+13.4}_{-12.6}$

CMS Z(→ll)γ

arXiv:2106.11082

- Found 4.2 σ evidence with 36 fb^{-1}.
- Data: 137 fb^{-1} full run 2 data recorded with dilepton triggers.
- MC:
  - Similar MC as ATLAS for the EW, QCD Zγ and interference.
  - ttγ with Madgraph NLO, Pythia LO or Powheg NLO for VV and single top.
  - aQGCs with Madgraph LO.
- Backgrounds:
  - QCD Zγ from simulation but constrained by fit to data. Interference treated as part of QCD.
  - Z+jets: data-driven.
  - Other: tW and WW to NNLO, WZ, ZZ, QCD Wγjj and ttγ to NLO.

CMS Z(→ll)γ: Selection

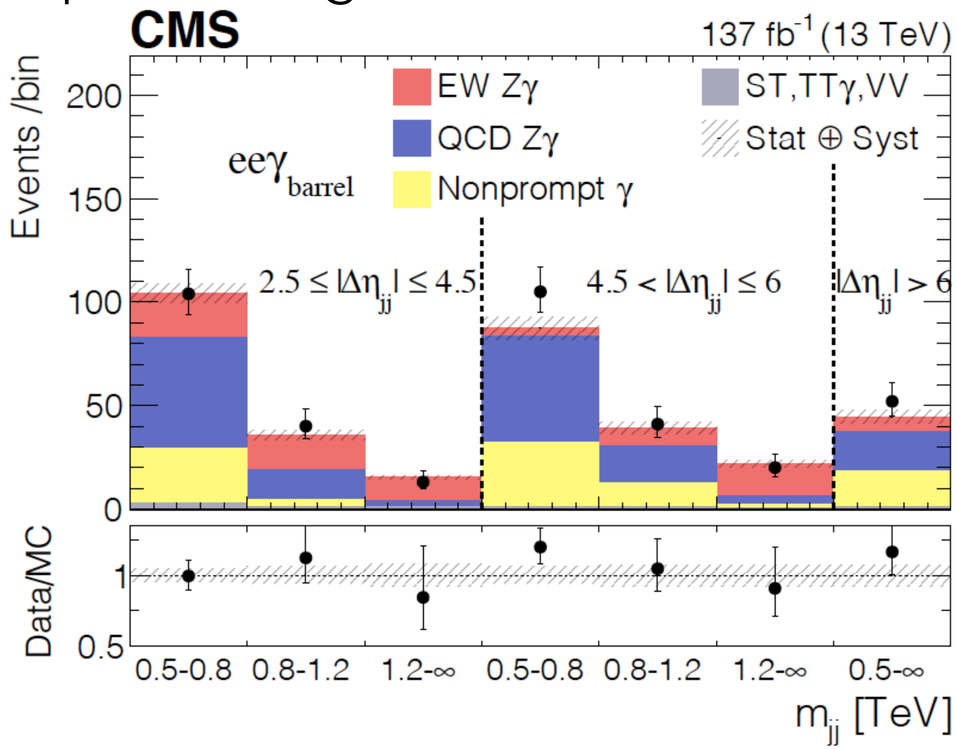
Common selection	$p_{\mathrm{T}}^{\ell 1,\ell 2} > 25\,\mathrm{GeV}$, $\lvert\eta^{\ell 1,\ell 2}\rvert < 2.5$ for electron channel $p_{\mathrm{T}}^{\ell 1,\ell 2} > 20\,\mathrm{GeV}$, $\lvert\eta^{\ell 1,\ell 2}\rvert < 2.4$ for muon channel $p_{\mathrm{T}}^{\gamma} > 20\,\mathrm{GeV}$, $\lvert\eta^{\gamma}\rvert < 1.442$ or $1.566 < \lvert\eta^{\gamma}\rvert < 2.500$ $p_{\mathrm{T}}^{\mathrm{j1,j2}} > 30\,\mathrm{GeV}$, $\lvert\eta^{\mathrm{j1,j2}}\rvert < 4.7$ $70 < m_{\ell\ell} < 110\,\mathrm{GeV}$, $m_{\mathrm{Z}\gamma} > 100\,\mathrm{GeV}$ ← to remove FSR $\Delta R_{\mathrm{jj}}, \Delta R_{\mathrm{j}\gamma}, \Delta R_{\mathrm{j}\ell} > 0.5$, $\Delta R_{\ell\gamma} > 0.7$
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, $m_{\mathrm{jj}} > 500\,\mathrm{GeV}$, $\lvert\Delta\eta_{\mathrm{jj}}\rvert > 2.5$, $p_{\mathrm{T}}^{\gamma} > 120\,\mathrm{GeV}$ ← Higher p_T^{γ} in aQGC search

Zeppenfeld variable $\eta^{*}=\lvert\eta_{Z\gamma}-(\eta_{j1}+\eta_{j2})/2\rvert$

CMS Z(→ll)γ: EW Signal Extraction

- SR and CR divided into lepton flavour and whether photon in ECAL barrel/endcap. SR divided further into 7 bins in m_{jj} and $|\Delta\eta_{jj}|$, CR into 3 bins in m_{jj}.

- Observed (expected) significance: 9.4 σ (8.5 σ).



Systematic uncertainty on μ_{EW}

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

CMS Z(→ll)γ: Cross-sections

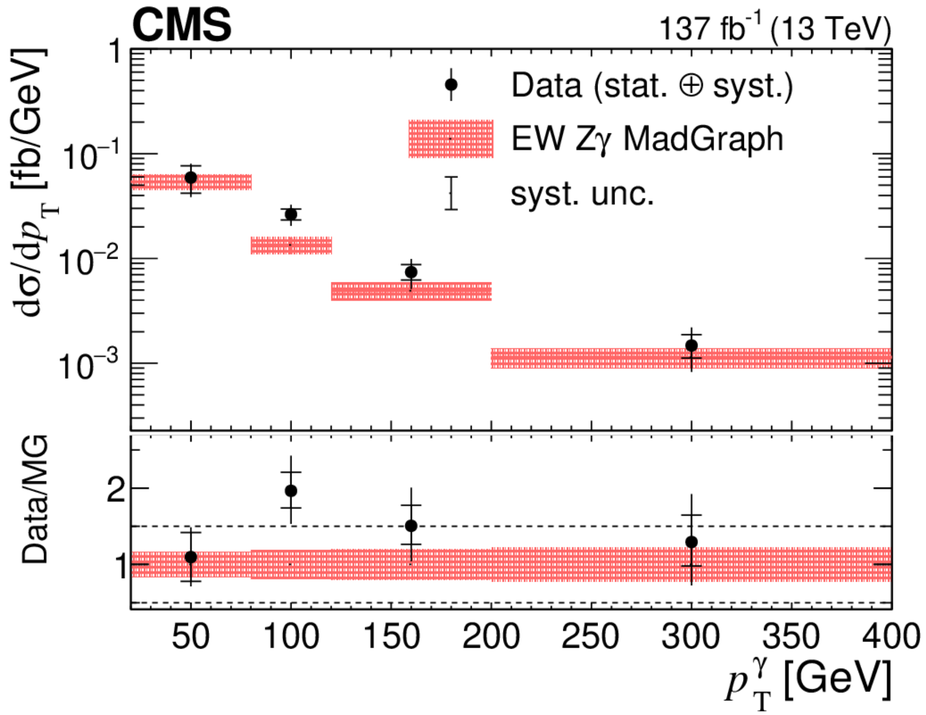
- $\mu_{\mathrm{EW}} = 1.20^{+0.12}_{-0.12}\,(\mathrm{stat})\,^{+0.14}_{-0.12}\,(\mathrm{syst})$ $\quad \sigma^{\mathrm{fid}}_{\mathrm{EW}} = 5.21 \pm 0.52\,(\mathrm{stat}) \pm 0.56\,(\mathrm{syst})\,\mathrm{fb}$

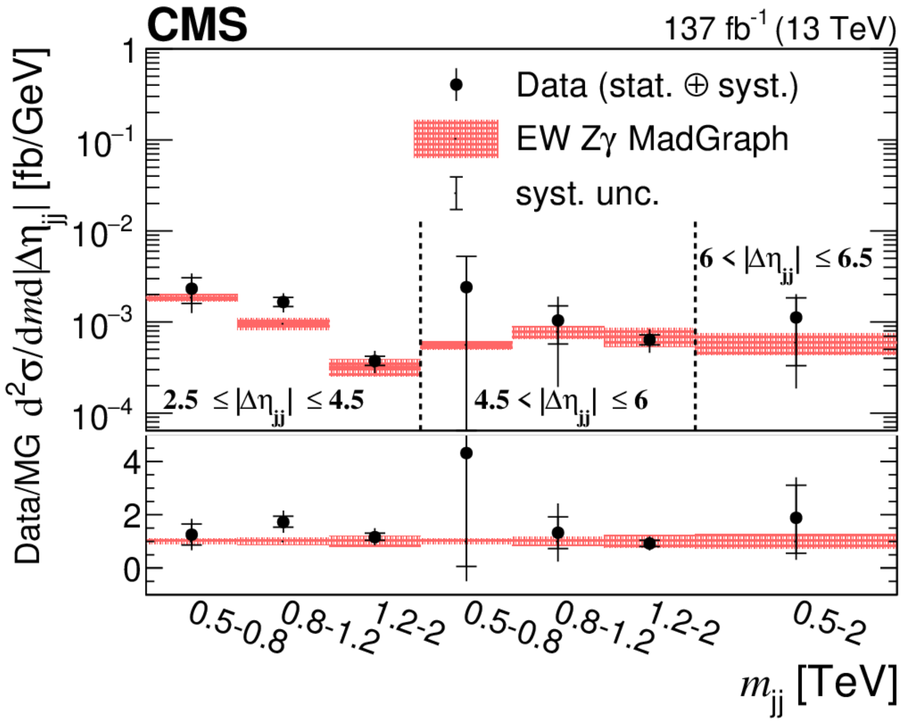
  $\mu_{\mathrm{EW+QCD}} = 1.11^{+0.06}_{-0.06}\,(\mathrm{stat})\,^{+0.10}_{-0.09}\,(\mathrm{syst})$ $\quad \sigma^{\mathrm{fid}}_{\mathrm{EW+QCD}} = 14.7 \pm 0.80\,(\mathrm{stat}) \pm 1.26\,(\mathrm{syst})\,\mathrm{fb}$

- Differential cross-sections in p_T^{γ}, p_T^{l1}, p_T^{j1}. Unfold via ML fit in bins of observables.

- Double differential m_{jj} vs $|\Delta\eta_{jj}|$.

- Both for EW and EW+QCD



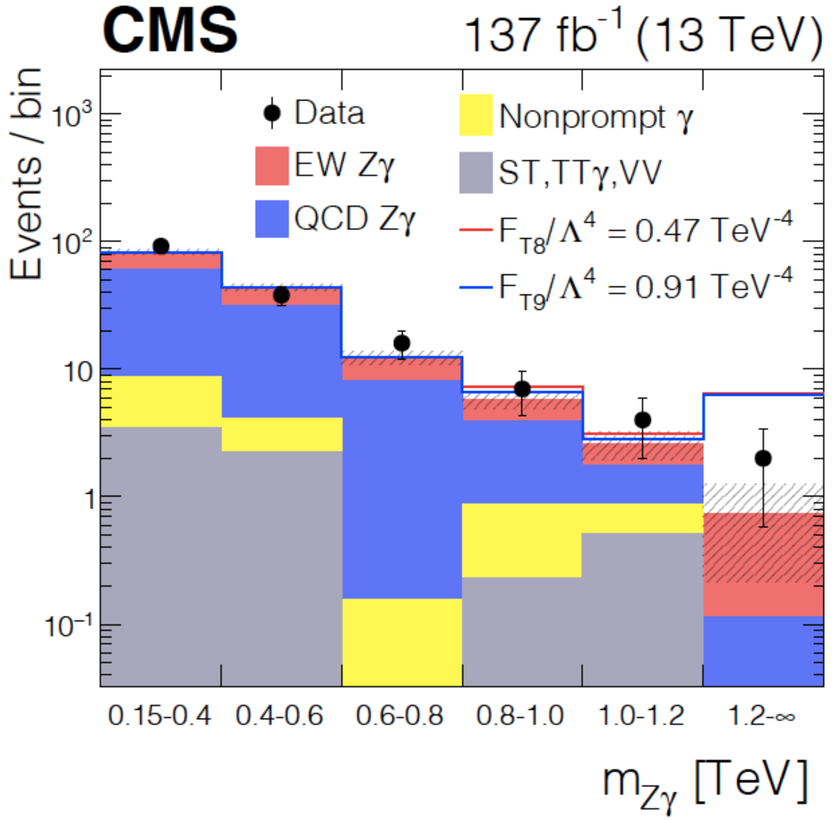


CMS Z(→ll)γ: Limits on aQGCs

- $m_{Z\gamma}$ used to extract limits.

Table 8: The expected and observed limits on the aQGC parameters at 95% confidence level. The last column presents the scattering energy values for which the amplitude would violate unitarity for the observed value of the aQGC parameter. All coupling parameter limits are set in TeV^{-4}, whereas the unitarity bounds are in TeV.

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

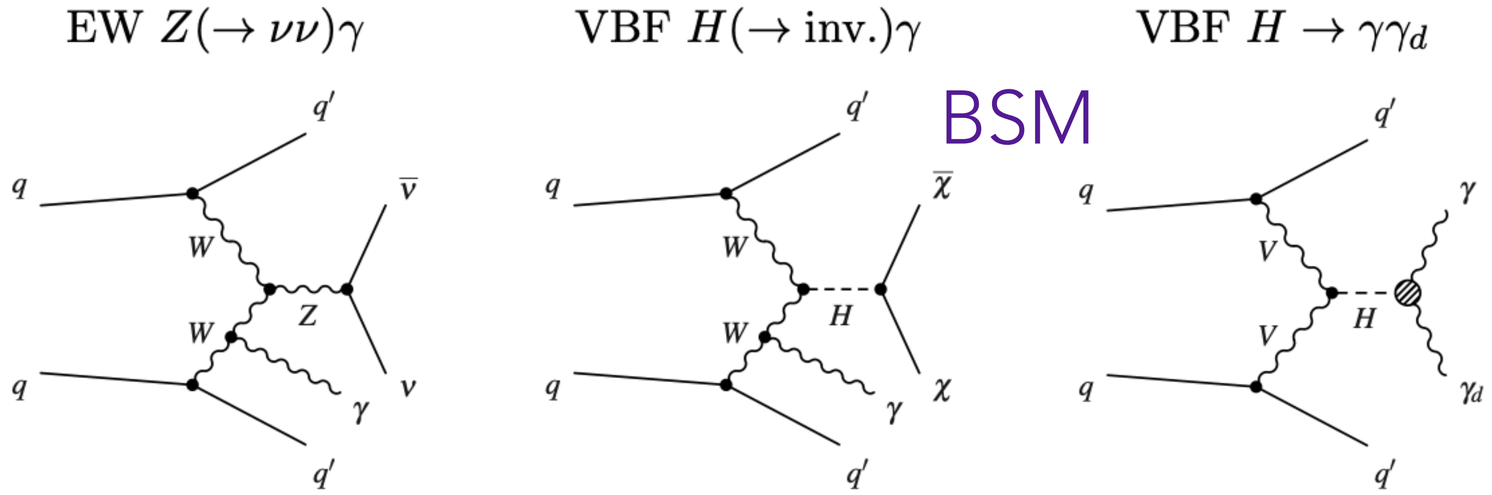


- 95% CL limits on EFT dimension-8 operators M_0 to M_5 , M_7, T_0 to T_2, T_5 to T_9.

- Most stringent limit to date on T_9.

Z(→νν)γ

- Part of an analysis looking for 3 signal processes using a final state of missing E_T, a photon and two jets with VBF/VBS topology:



- Dominant background from Vγ+jets (QCD Zγ and EW+QCD Wγ). Other backgrounds from jet faking photon, electron faking photon, jet faking electron, fake MET and ttγ/Vγγ.

Z(→νν)γ: Samples

- Data: 139 fb^{-1} full Run 2 data, collected with missing E_T triggers.
- MC:
  - EW signal: Madgraph LO+Pythia with dipole recoil on.
    - Normalised to NLO (QCD) predictions from VBFNLO via m_{jj}-dependent correction.
  - QCD Zγ: Sherpa 2.2.8 NLO (≤1j), with NLO EW correction.
    - Alternative sample with Madgraph NLO (≤1j) using FxFx scheme. Difference taken as an uncertainty.
  - Interference: Madgraph $O(\alpha_S \alpha_{EW}^3)$. Treated as a systematic on EW.
  - Other backgrounds: Wγ samples similar to Zγ, Vγγ with Sherpa NLO, tty.

Z(→νν)γ: SR and CRs

- **SR** for EW Z(→νν)γ:
  - p_T^j>60 (50) GeV, $\eta_{j1}x\eta_{j2}$<0.
  - m_{jj}>250 GeV, $|\Delta\eta_{jj}|$>3, $|\Delta\phi_{jj}|$<2.5 to reduce multi-jet.
  - 15<p_T^γ<110 GeV (upper bound to reduce γ+jets).
  - E_T^{miss}>150 GeV, lepton veto.
  - $$C_\gamma = \exp[-\frac{4}{(\eta_{j1}-\eta_{j2})^2}(\eta_\gamma - \frac{\eta_{j1}+\eta_{j2}}{2})^2] > 0.4$$
    - C_γ=1 when photon in the middle between the two tagging jets, =1/e when aligned with one of the jets, and →0 when farther forward in η than the jets.
  - A third jet with p_T>25 GeV can be present, if C_3 (similar to C_γ but replacing η_γ with third leading jet η)<0.7.

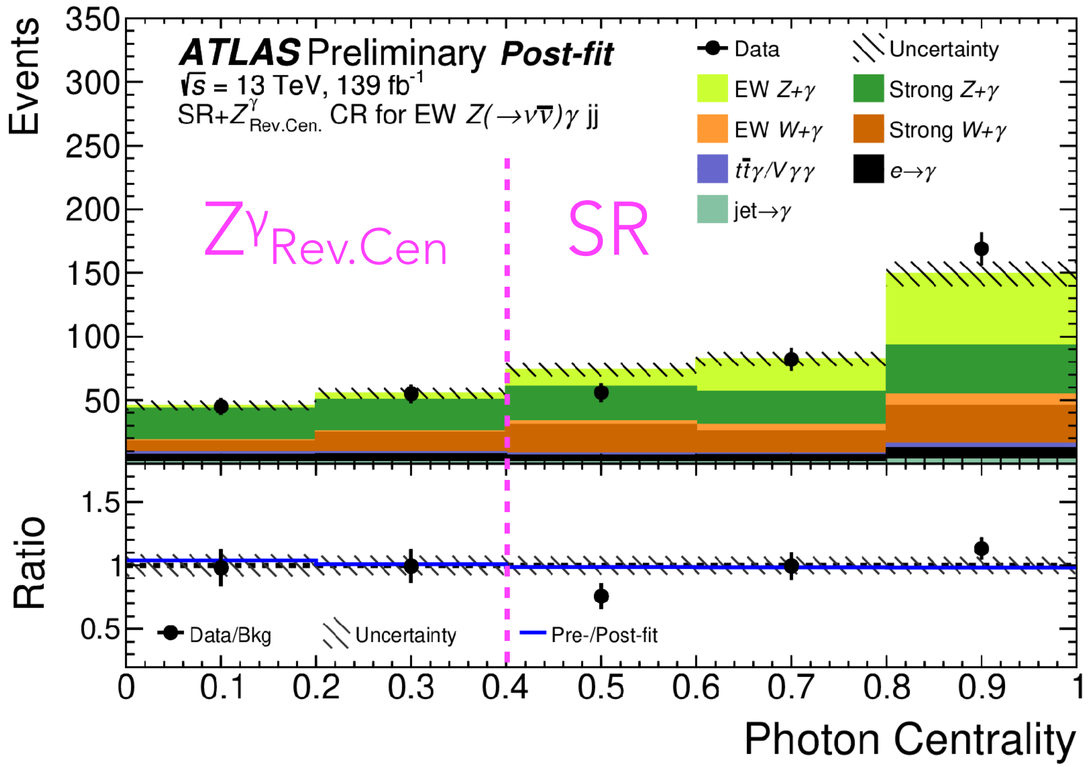
- **Four CRs** to constrain backgrounds:
  - $W\gamma_{e\nu}$ and $W\gamma_{\mu\nu}$ CRs: require an additional e/μ with p_T>30 GeV to constrain Wγ.
  - $Z\gamma_{Rev.Cen.}$ CR: reverse centrality cut to constrain QCD Zγ.
  - Fake-e CR: like $W\gamma_{e\nu}$ but reverse E_T^{miss} cut.

Z(→νν)γ: Backgrounds and Extraction of EW Signal

- Normalisation of EW+QCD Wγ and QCD Zγ background determined from fit through use of CRs.

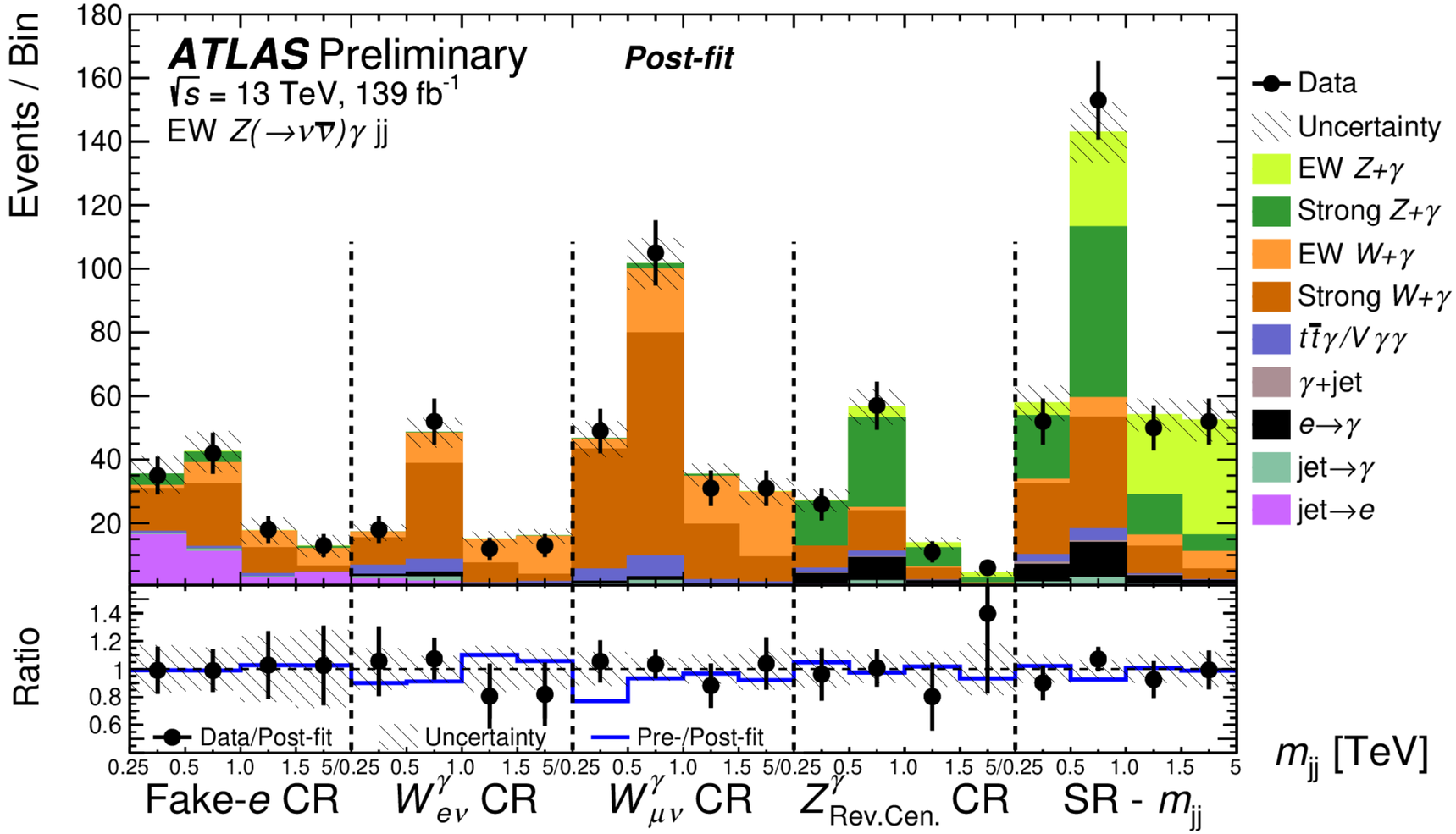
$\mu_{Z\gamma_{\mathrm{EW}}}$	$\beta_{Z\gamma_{\mathrm{QCD}}}$	$\beta_{W\gamma}$
1.03 ± 0.25	1.02 ± 0.41	1.01 ± 0.20

- Jet faking photon: data-driven with 2D sideband method to determine fake rate.
- Electron faking photon: using fake rate from Z→ee data
- Jet faking electron (affecting $W\gamma_{ev}$ CR): from Fake-e CR using anti-eID information.
- Fake MET: MC using data-driven jet smearing.
- ttγ/Vγγ.



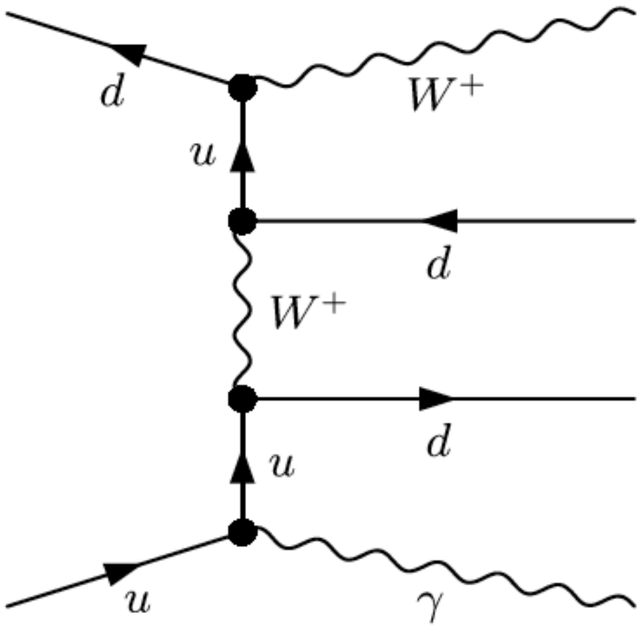
Z(→νν)γ: Results

- EW Z(→νν)γjj observed with 5.2 σ (5.1 σ expected).

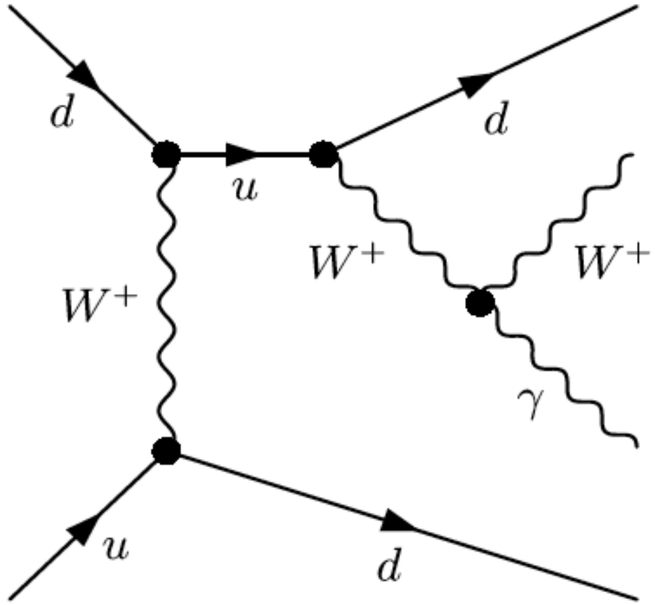


$$\sigma^{fid} = 1.31 \pm 0.20(\text{stat}) \pm 0.20(\text{syst}) \text{ fb}$$

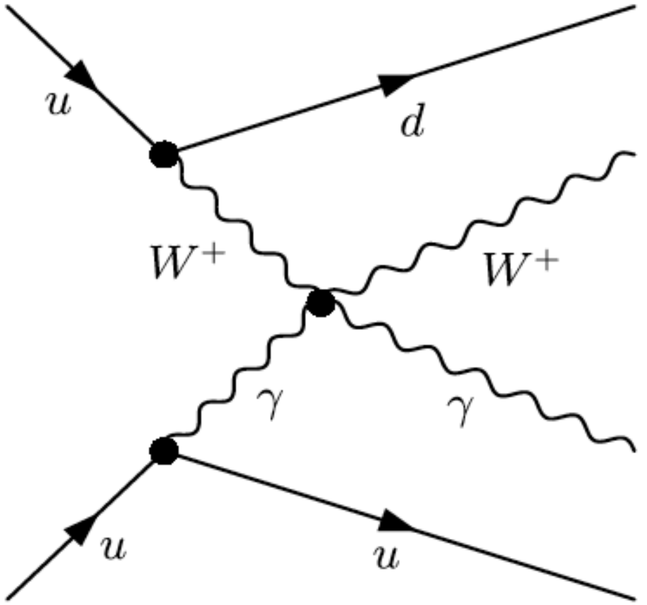
EW Wγjj



non-VBS



TGC



VBS via QGC

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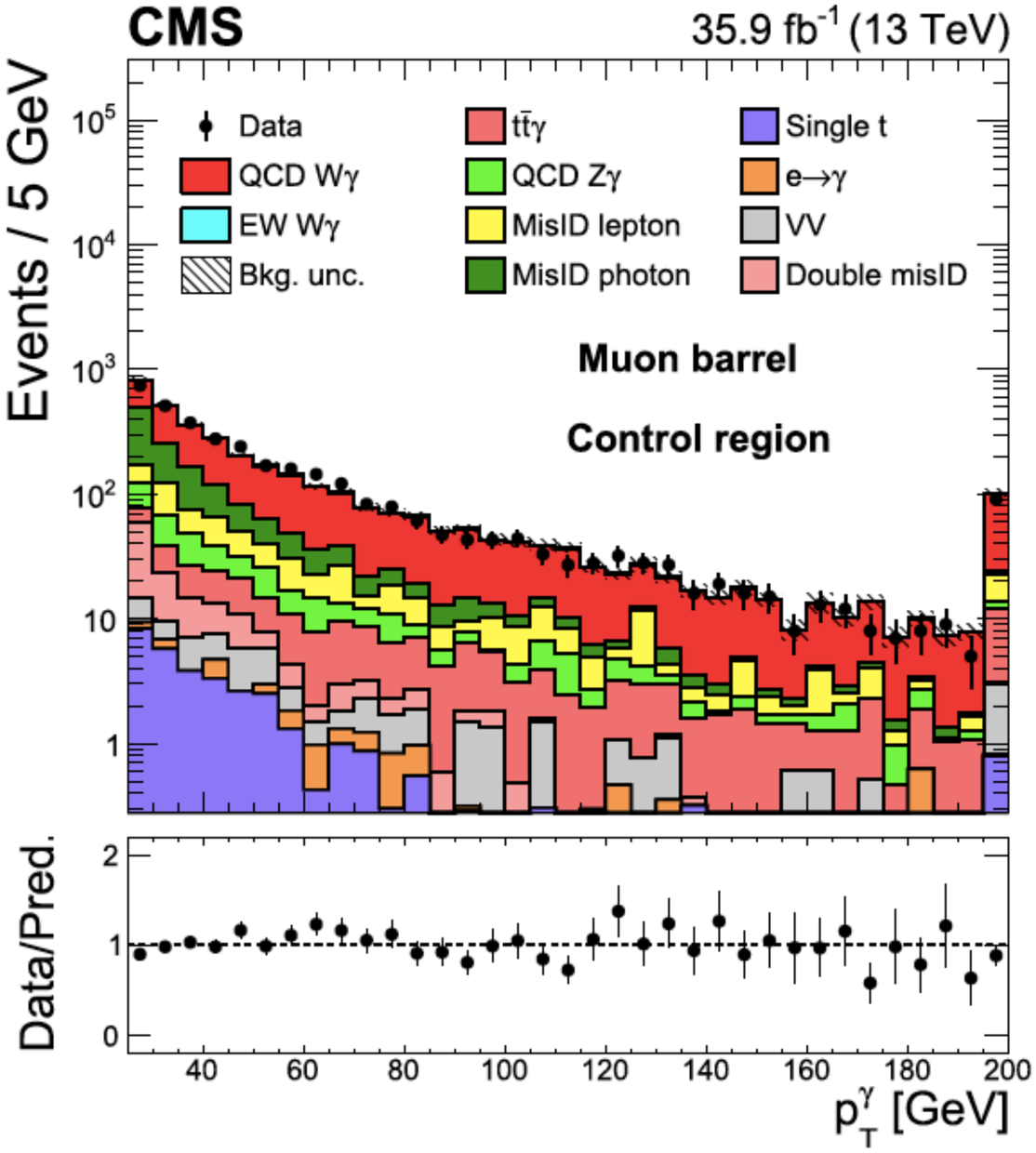
W(→lν)γ

- Partial Run 2 data analysis with 35.9 fb^{-1}.
- MC:
  - EW signal: Madgraph LO
  - QCD Wγ: Madgraph NLO (≤1j) with FxFx merging
  - Interference (Madgraph LO) treated as uncertainty on the signal.
  - Others: VV Pythia LO, single top Powheg, ttγ Madgraph NLO. All normalised to NLO cross-sections.

Common	p_T^l>30 GeV, p_T^γ>25 GeV, p_T^j>40 (30) GeV, m_T^W>30 GeV, p_T^{miss}>30 GeV, ΔR>0.5 between selected objects, $\lvert m_{e\gamma}-91\rvert$>10 GeV
CR	200<m_{jj}<400 GeV
SR	mjj>500 GeV, $\lvert\Delta\eta_{jj}\rvert$>2.5, $m_{W\gamma}$>100 GeV, η*<1.2, $\lvert\Delta\phi(W\gamma, jj)\rvert$>2

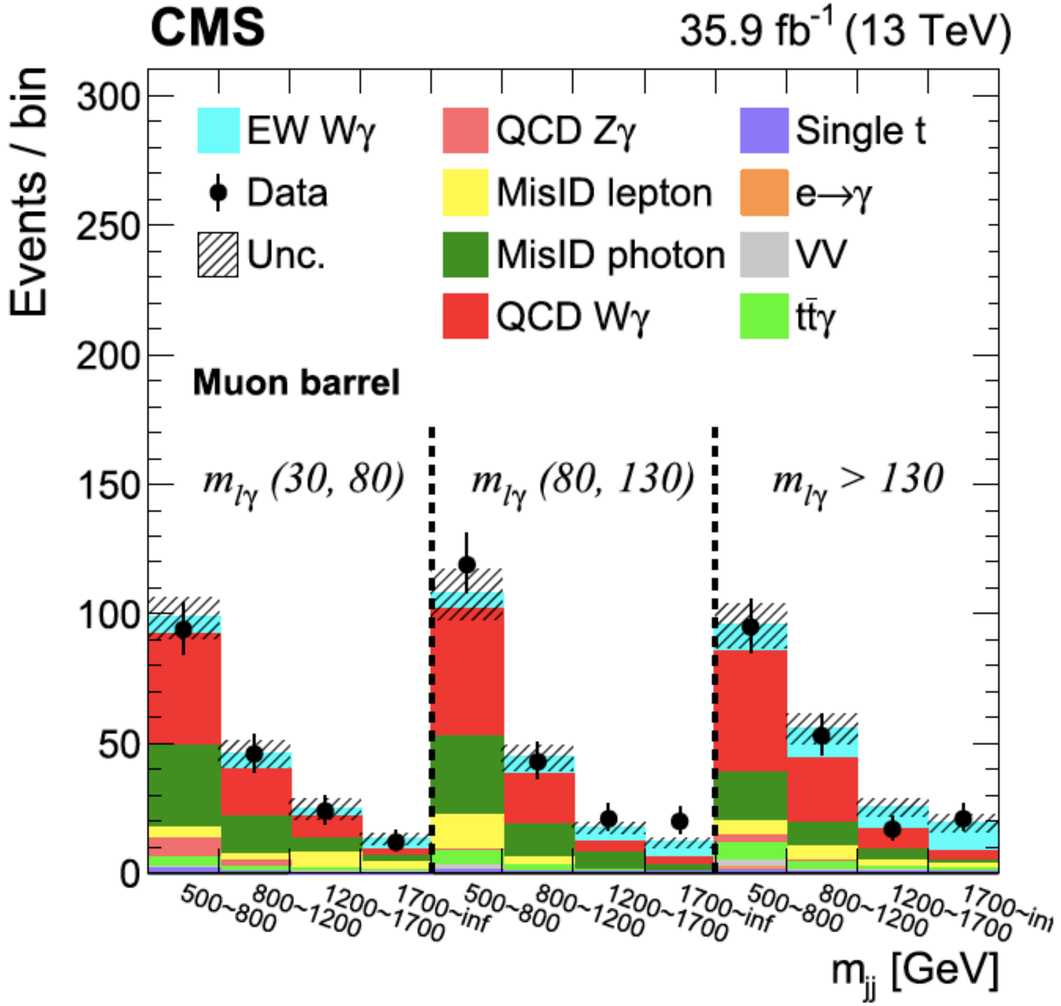
W(→lν)γ: Backgrounds

- QCD Wγ: simultaneous fit to SR and CR. $\mu_{QCD} = 1.28^{+0.18}_{-0.16}$
- Misidentified photon or lepton or both: data-driven.
- e→**γ**: from MC.
- Others: from MC, normalised to NLO.



W(→lν)γ: EW Signal Extraction

- 2D fit in 4 m_{jj} bins and 3$m_{l\gamma}$ bins simultaneously in SR and in CR.
- $\sigma_{EW} = 1.20^{+0.26}_{-0.24}$, 4.9 (4.6) σ
- Combined with 8 TeV : 5.3 (4.8) σ.
- $\sigma^{fid}_{EW-W\gamma jj} = 20.4 \pm 2.8(\text{stat}) \pm 3.5(\text{syst})$ fb
- For EW+QCD fiducial cross-section, only SR is fitted.
- $\sigma^{fid}_{EW+QCD-W\gamma jj} = 108 \pm 5(\text{stat}) \pm 15(\text{syst})$ fb

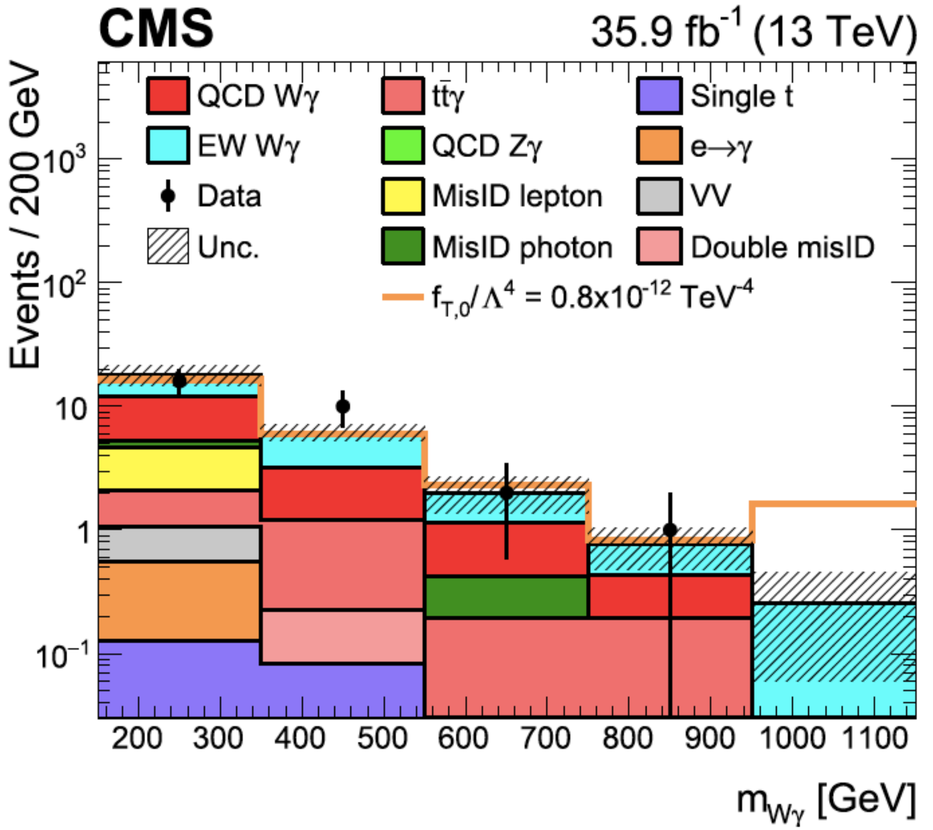


W(→lν)γ: Limits on aQGCs

- $m_{W\gamma}$ used to extract limits.

The exclusion limits at 95% CL on each aQGC coefficient, parameterized using the distribution in $m_{W\gamma}$, and listed along with the unitarity bound. All coupling parameter limits are in TeV^{-4}, while the U_{bound} values are in TeV.

Parameters	Obs. limit	Exp. limit	U_{bound}
$f_{M,0}/\Lambda^4$	$[-8.1, 8.0]$	$[-7.7, 7.6]$	1.0
$f_{M,1}/\Lambda^4$	$[-12, 12]$	$[-11, 11]$	1.2
$f_{M,2}/\Lambda^4$	$[-2.8, 2.8]$	$[-2.7, 2.7]$	1.3
$f_{M,3}/\Lambda^4$	$[-4.4, 4.4]$	$[-4.0, 4.1]$	1.5
$f_{M,4}/\Lambda^4$	$[-5.0, 5.0]$	$[-4.7, 4.7]$	1.5
$f_{M,5}/\Lambda^4$	$[-8.3, 8.3]$	$[-7.9, 7.7]$	1.8
$f_{M,6}/\Lambda^4$	$[-16, 16]$	$[-15, 15]$	1.0
$f_{M,7}/\Lambda^4$	$[-21, 20]$	$[-19, 19]$	1.3
$f_{T,0}/\Lambda^4$	$[-0.6, 0.6]$	$[-0.6, 0.6]$	1.4
$f_{T,1}/\Lambda^4$	$[-0.4, 0.4]$	$[-0.3, 0.4]$	1.5
$f_{T,2}/\Lambda^4$	$[-1.0, 1.2]$	$[-1.0, 1.2]$	1.5
$f_{T,5}/\Lambda^4$	$[-0.5, 0.5]$	$[-0.4, 0.4]$	1.8
$f_{T,6}/\Lambda^4$	$[-0.4, 0.4]$	$[-0.3, 0.4]$	1.7
$f_{T,7}/\Lambda^4$	$[-0.9, 0.9]$	$[-0.8, 0.9]$	1.8



- Selection for aQGCs search: Common selection + m_{jj}>800 GeV, $|\Delta\eta_{jj}|$>2.5, $m_{W\gamma}$>150 GeV, p_T^{γ}>100 GeV.

- Limits on operators M0 to M7, T0 to T2, T5 to T7. Very stringent.

SUMMARY

- Observations of EW production of Zγjj and Wγjj at 13TeV from ATLAS and CMS.

Experiment	Process	L [fb^{-1}]	Reference
ATLAS	Z(→ll)γ	139	ATLAS-CONF-2021-038
CMS	Z(→ll)γ	137	arXiv:2106.11082
ATLAS	Z(→νν)γ	139	CERN-EP-2021-137
CMS	W(→lν)γ	35.9	Phys. Lett. B 811 (2020) 135988)

- Measured EW cross sections agree generally well with predictions (LO in most cases, NLO QCD in Z(→νν)γ).

- Main challenge in constraining the dominant QCD-induced production of Vγjj ☞ design dedicated CRs.

- Process involving photon has larger cross-sections, and sensitive to anomalous quartic gauge couplings.

BACK-UP SLIDES

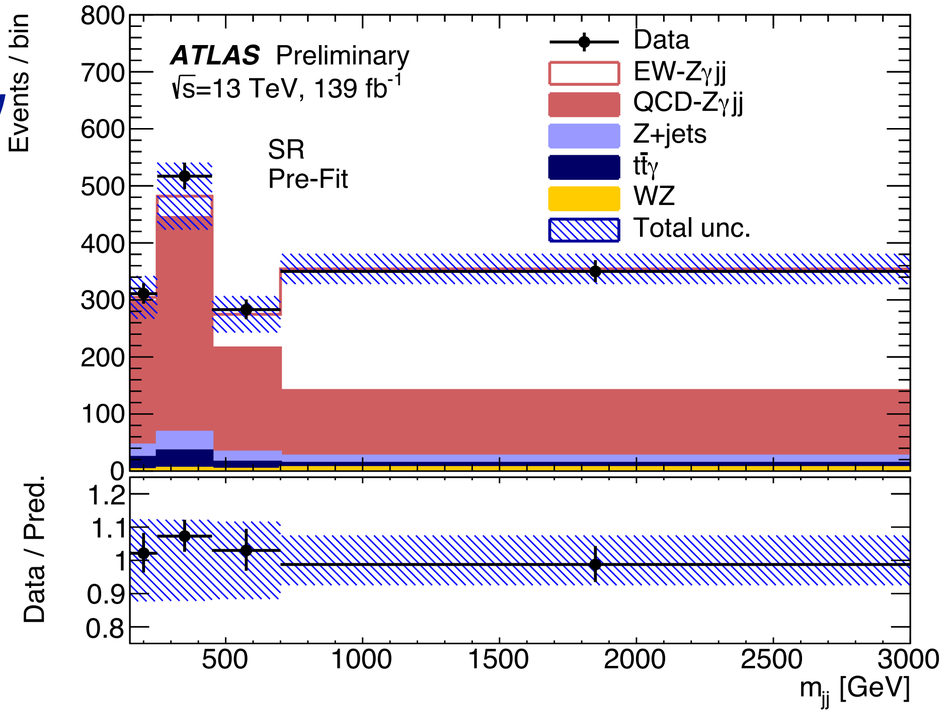
DIMENSION-8 OPERATORS

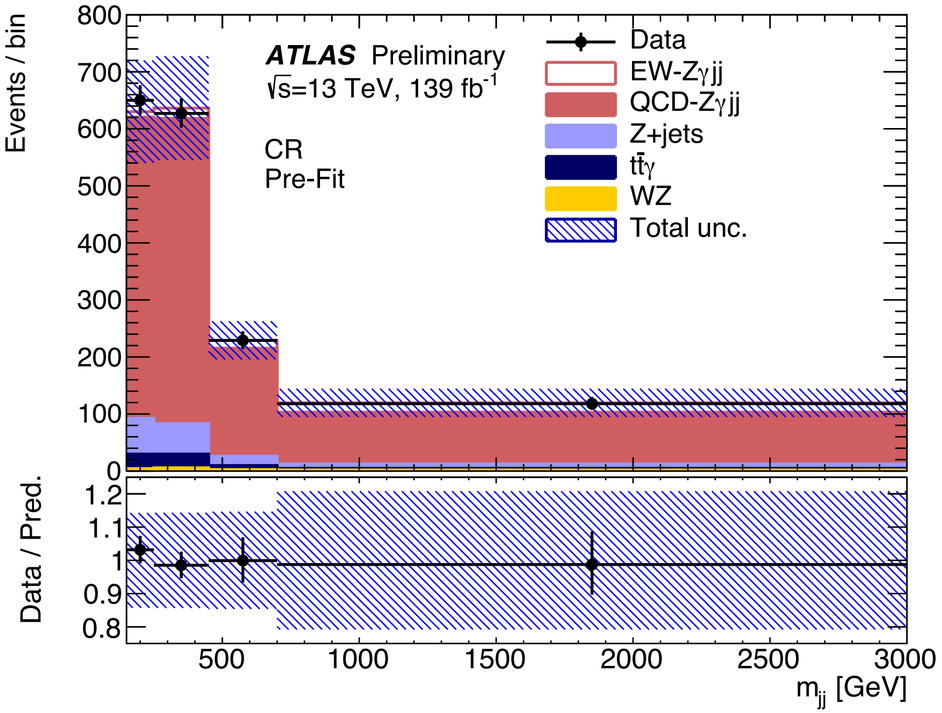
S: Pure Higgs field, pure longitudinal
M: Mixed Higgs-field-strength, mixed long-transverse
T: Pure field-strength tensor, pure transverse

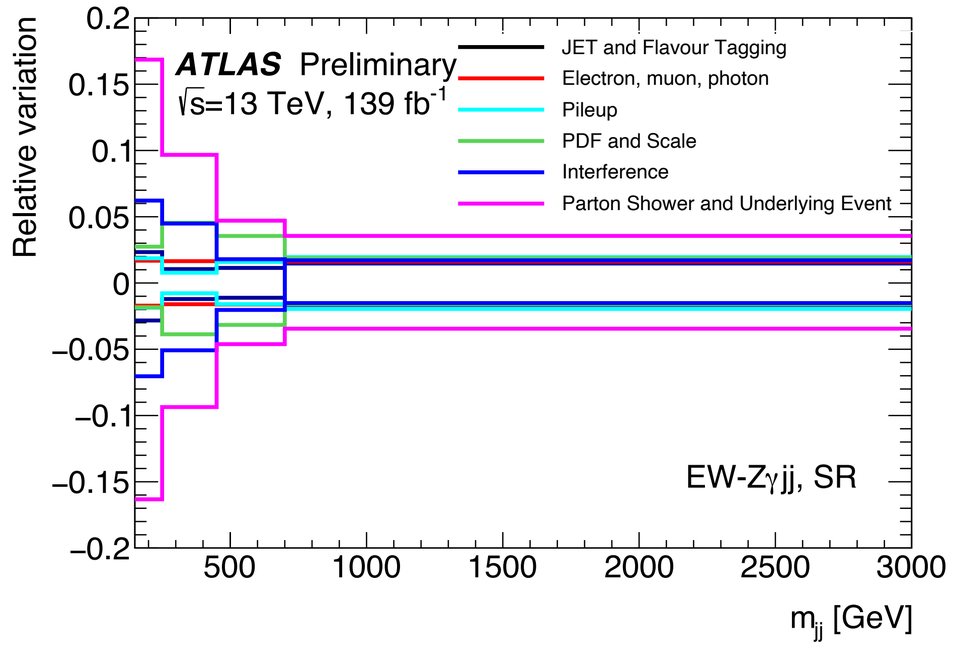
	$WWWW$	$WWZZ$	$WW\gamma Z$	$WW\gamma\gamma$	$ZZZZ$	$ZZZ\gamma$	$ZZ\gamma\gamma$	$Z\gamma\gamma\gamma$	$\gamma\gamma\gamma\gamma$
$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$	✓	✓			✓				
$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$,$\mathcal{O}_{M,6}$,$\mathcal{O}_{M,7}$	✓	✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{M,2}$,$\mathcal{O}_{M,3}$,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

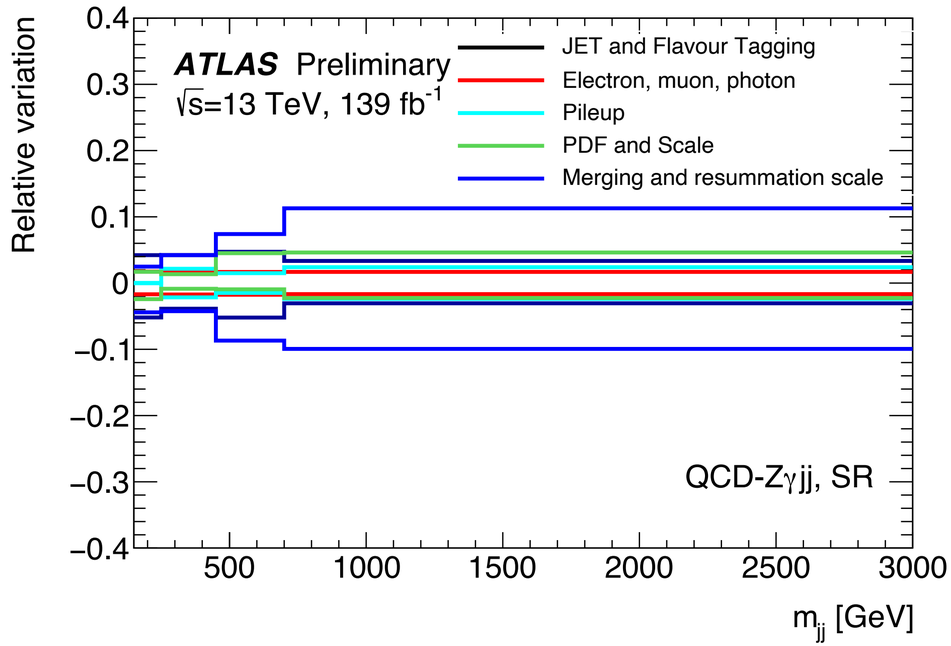
Allowed by SM

ATLAS Z(→ll)γ

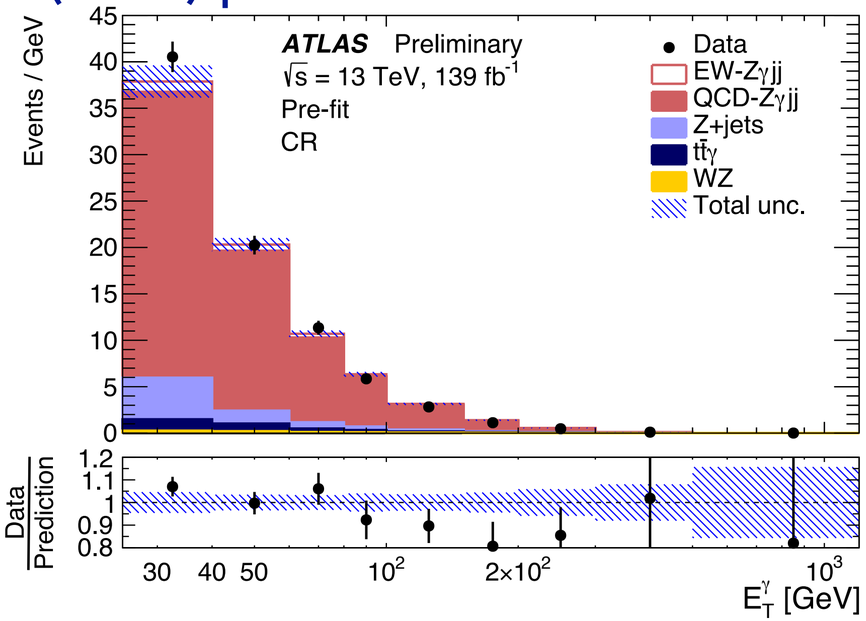

ATLAS Preliminary
√s=13 TeV, 139 fb-1
SR
Pre-Fit
Data
EW-Zγjj
QCD-Zγjj
Z+jets
tt̄γ
WZ
Total unc.
Events / bin
Data / Pred.
mjj [GeV]

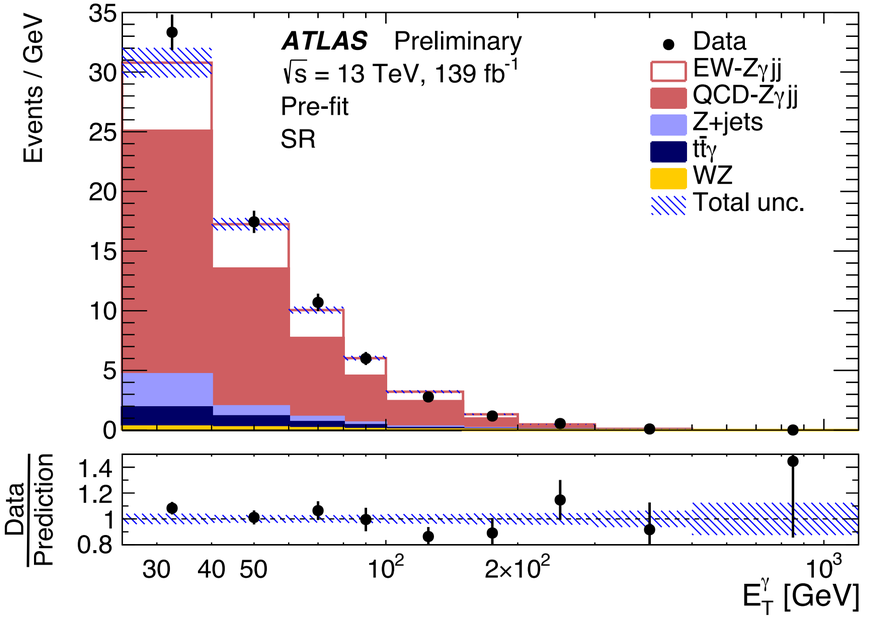

ATLAS Preliminary
√s=13 TeV, 139 fb-1
CR
Pre-Fit
Data
EW-Zγjj
QCD-Zγjj
Z+jets
tt̄γ
WZ
Total unc.
Events / bin
Data / Pred.
mjj [GeV]

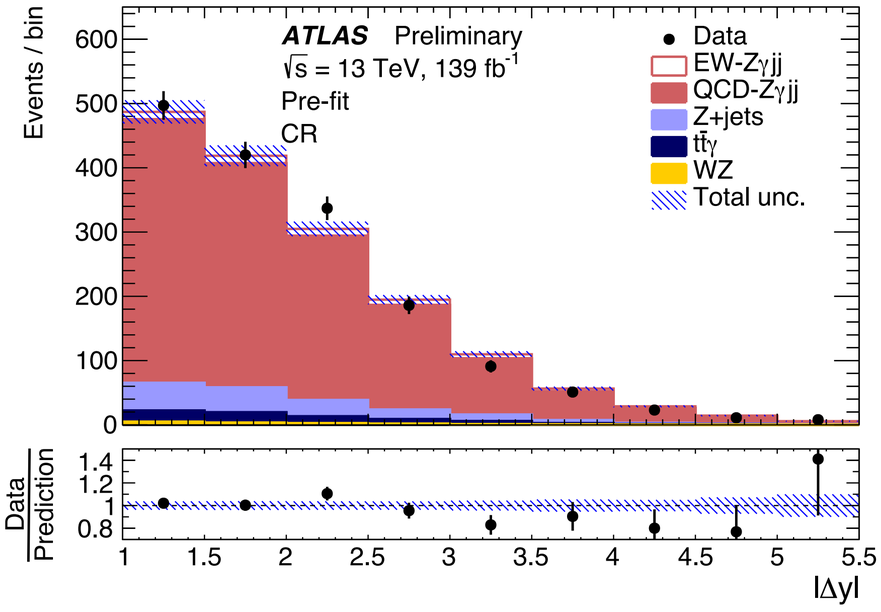

ATLAS Preliminary
√s=13 TeV, 139 fb-1
JET and Flavour Tagging
Electron, muon, photon
Pileup
PDF and Scale
Interference
Parton Shower and Underlying Event
EW-Zγjj, SR
Relative variation
mjj [GeV]

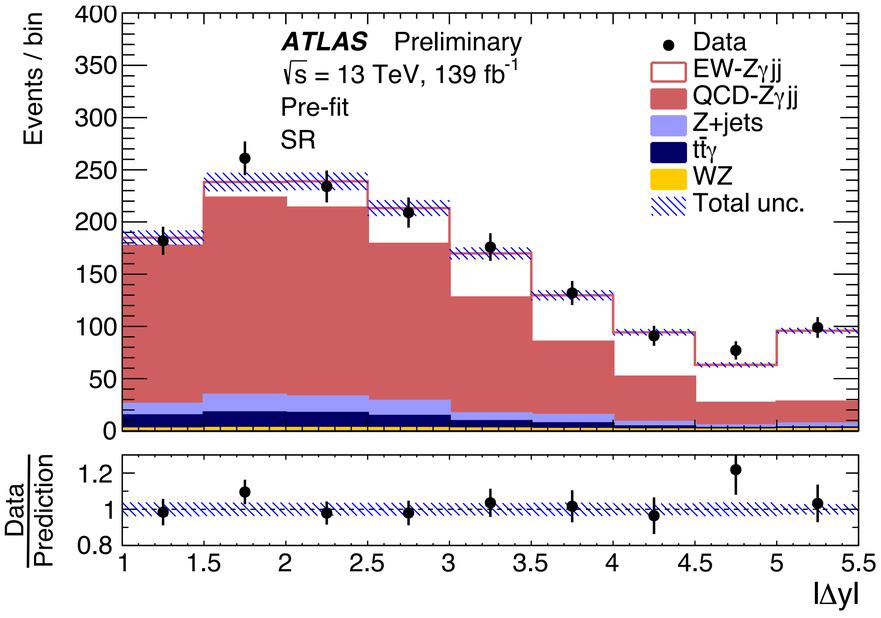

ATLAS Preliminary
√s=13 TeV, 139 fb-1
JET and Flavour Tagging
Electron, muon, photon
Pileup
PDF and Scale
Merging and resummation scale
QCD-Zγjj, SR
Relative variation
mjj [GeV]

ATLAS Z(→ll)γ


ATLAS Preliminary
√s = 13 TeV, 139 fb-1
Pre-fit
CR
Data
EW-Zγjj
QCD-Zγjj
Z+jets
tt̄γ
WZ
Total unc.
Events / GeV
Data / Prediction
E_T^γ [GeV]


ATLAS Preliminary
√s = 13 TeV, 139 fb-1
Pre-fit
SR
Data
EW-Zγjj
QCD-Zγjj
Z+jets
tt̄γ
WZ
Total unc.
Events / GeV
Data / Prediction
E_T^γ [GeV]


ATLAS Preliminary
√s = 13 TeV, 139 fb-1
Pre-fit
CR
Data
EW-Zγjj
QCD-Zγjj
Z+jets
tt̄γ
WZ
Total unc.
Events / bin
Data / Prediction
|Δy|


ATLAS Preliminary
√s = 13 TeV, 139 fb-1
Pre-fit
SR
Data
EW-Zγjj
QCD-Zγjj
Z+jets
tt̄γ
WZ
Total unc.
Events / bin
Data / Prediction
|Δy|

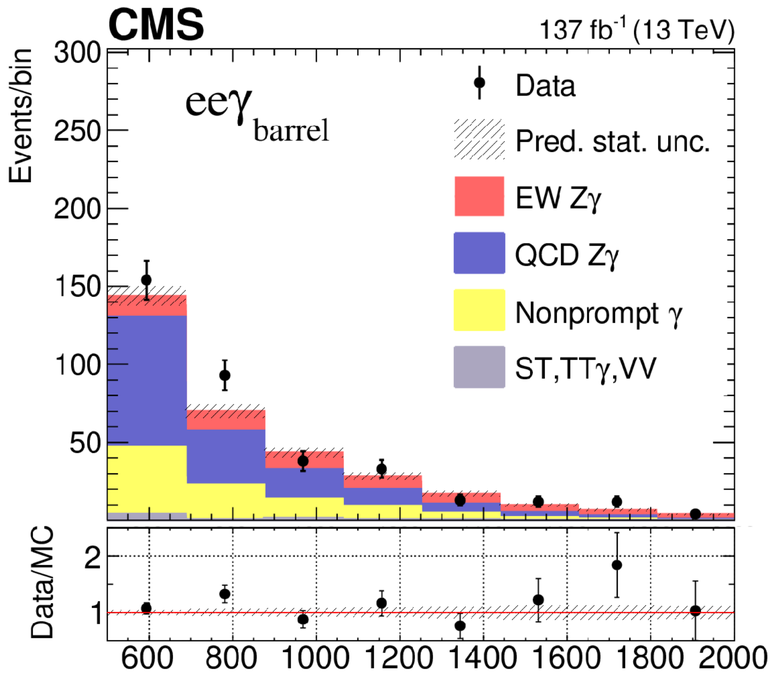
ATLAS Z(→ll)γ

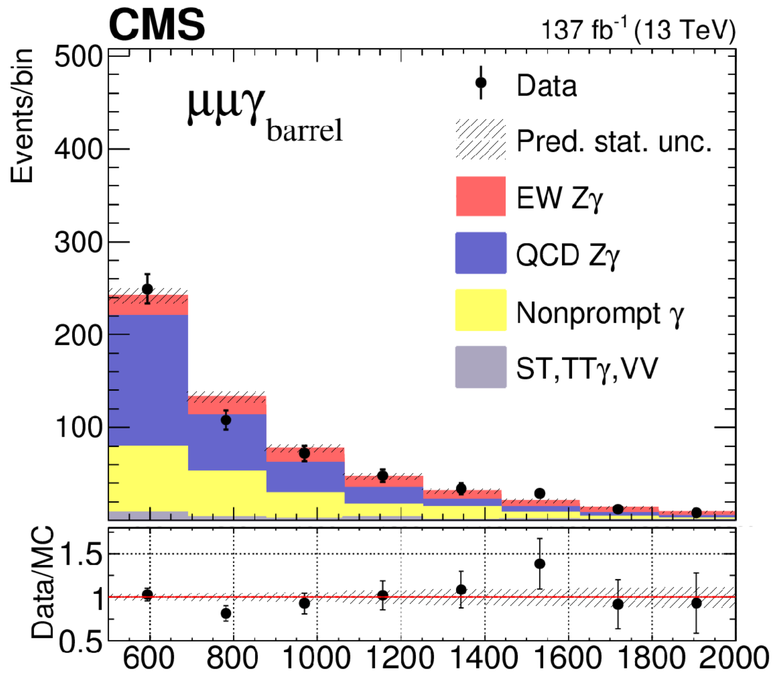
Sample	SR	CR
$N_{EW-Z\gamma jj}$	300 ± 36	55 ± 7
$N_{QCD-Z\gamma jj}$	987 ± 55	1352 ± 60
$N_{t\bar{t}\gamma}$	72 ± 11	59 ± 9
N_{WZ}	17 ± 3	14 ± 3
N_{Z+jets}	85 ± 30	143 ± 43
Total	1461 ± 38	1624 ± 40
N_{obs}	1461	1624

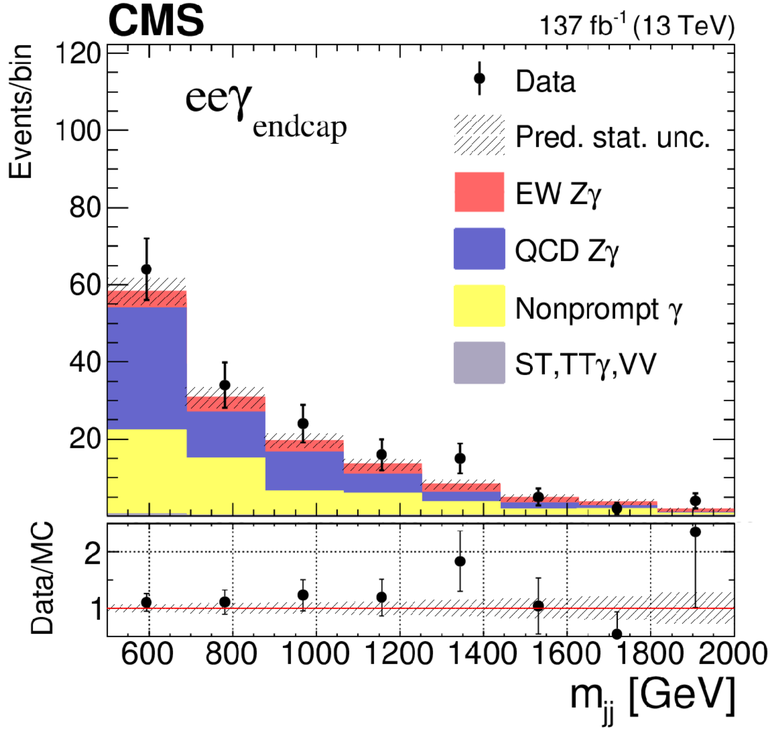
	Data stat.	MC stat.	Background	Reco	EW mod.	QCD mod.	Total
$\Delta\sigma_{EW}/\sigma_{EW}$ [%]	± 9	± 1	± 1	± 5	$^{+6}_{-5}$	$^{+5}_{-4}$	± 13

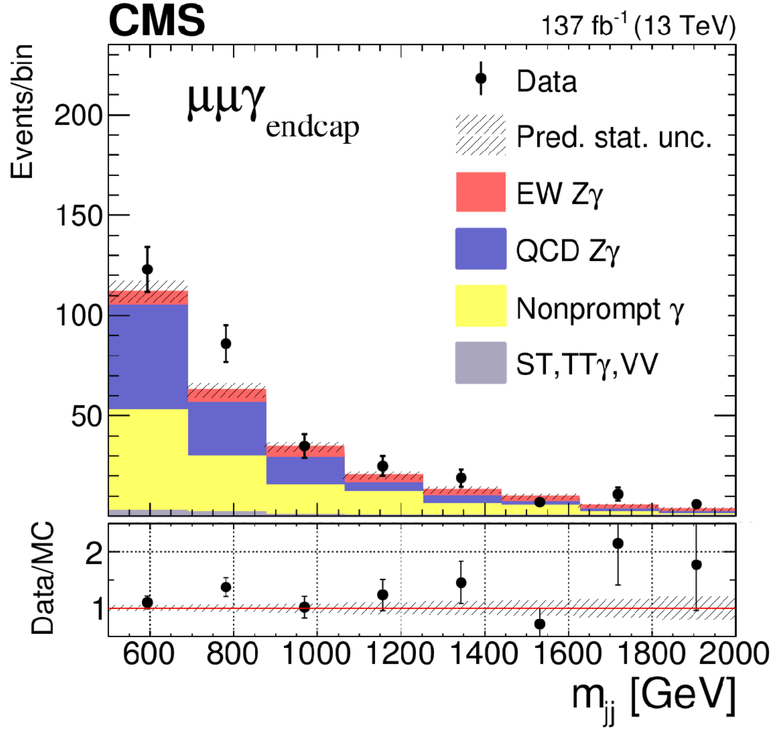
CMS Z(→ll)γ

- SR, pre-fit



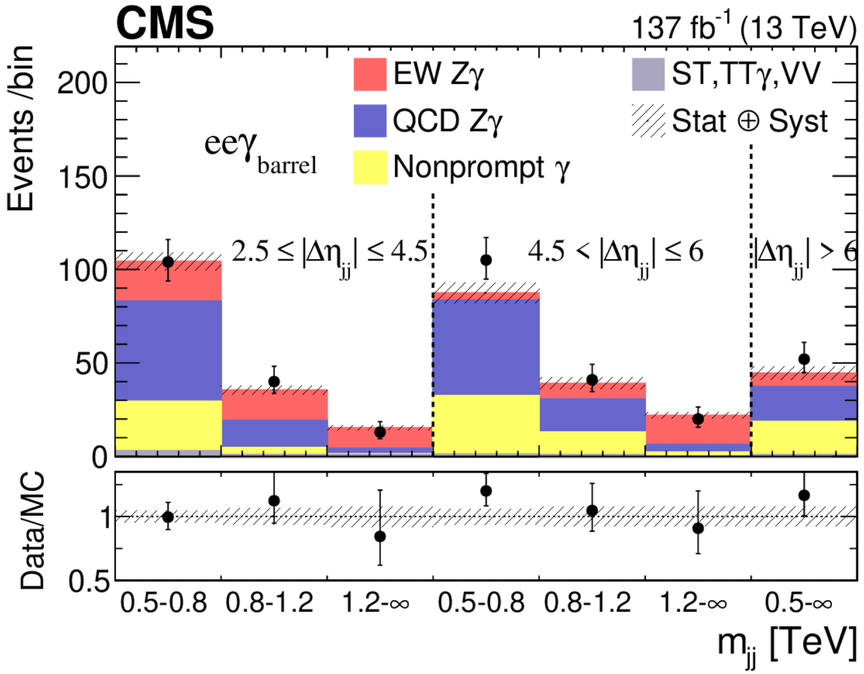


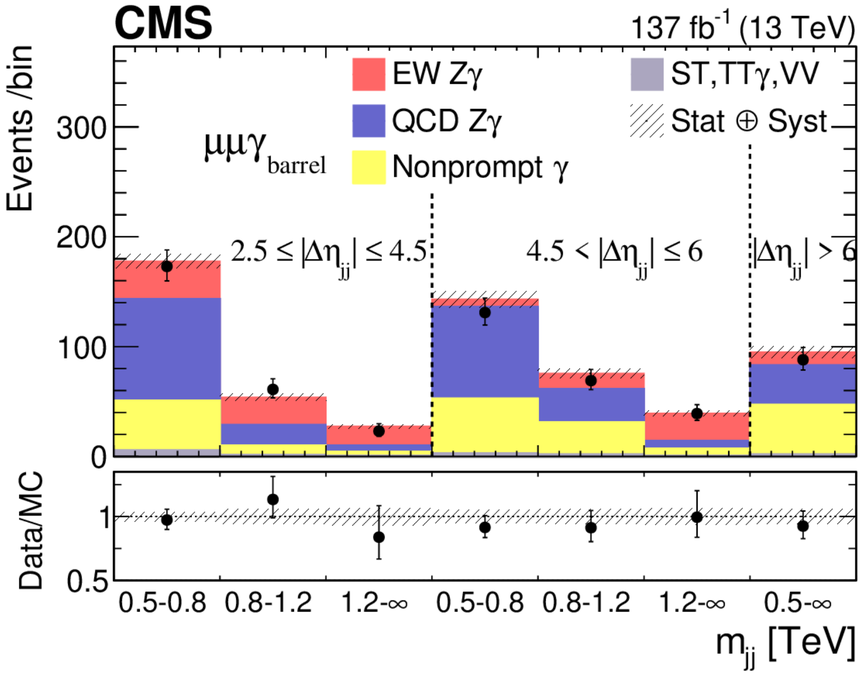


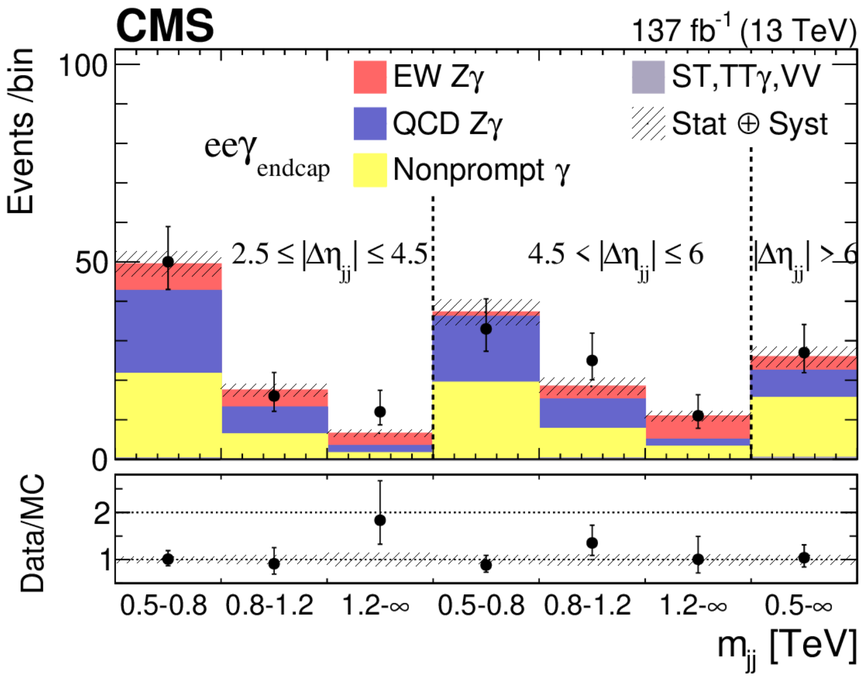


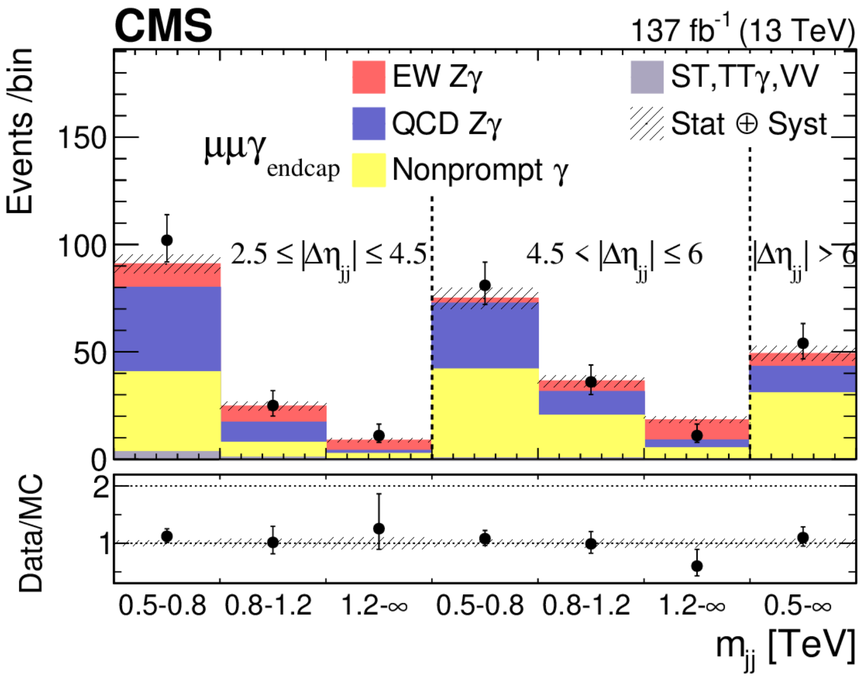
CMS Z(→ll)γ

- SR, post-fit



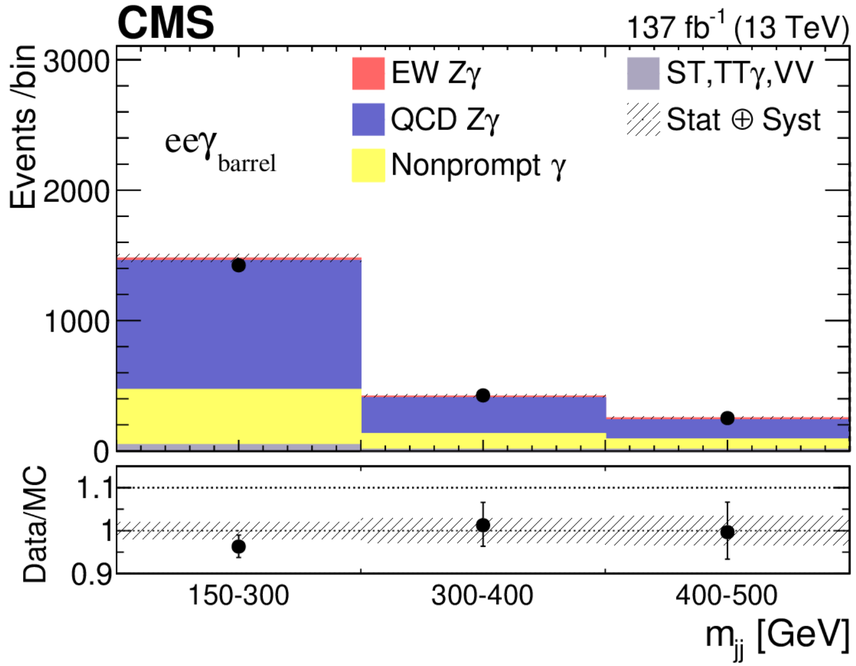


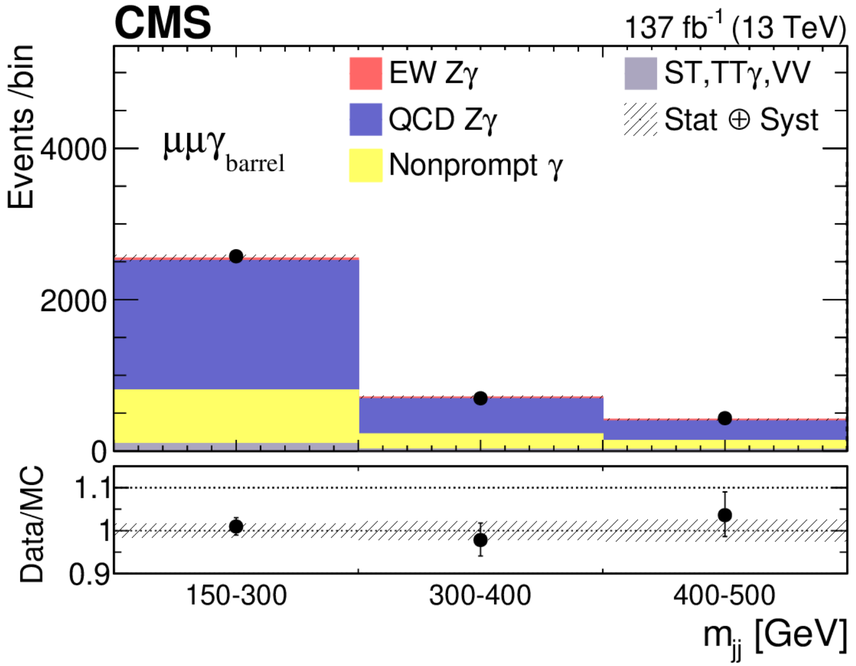


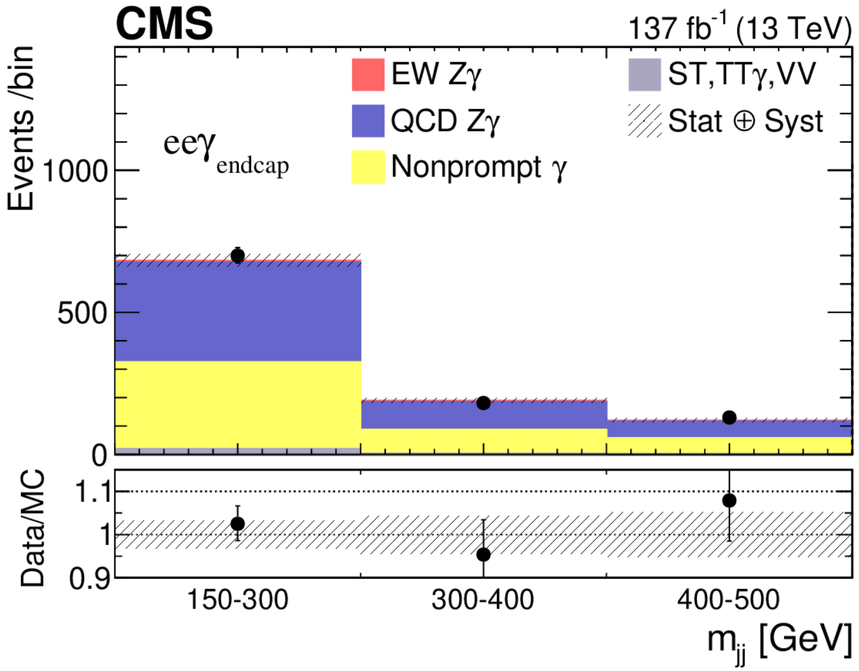


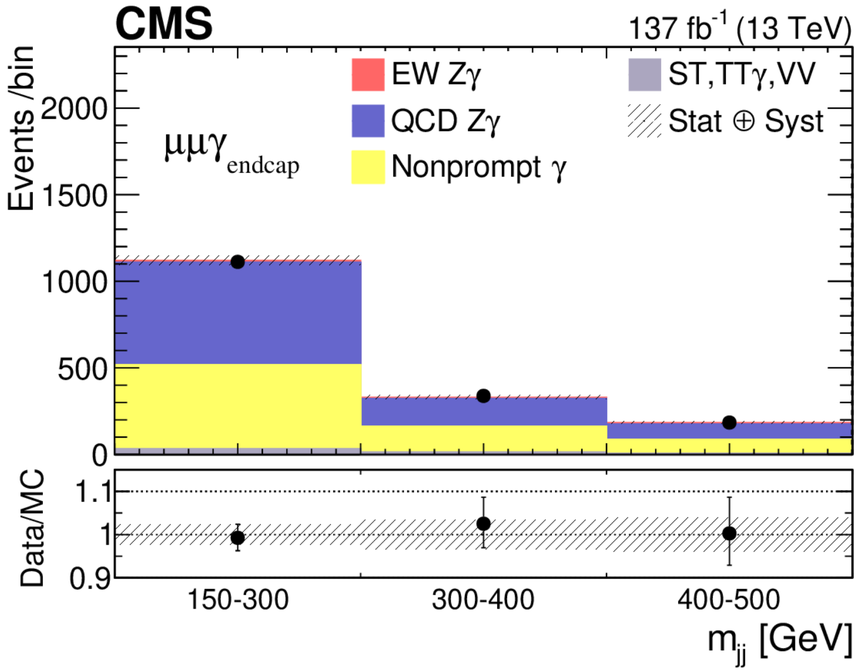
CMS Z(→ll)γ

- CR, post-fit



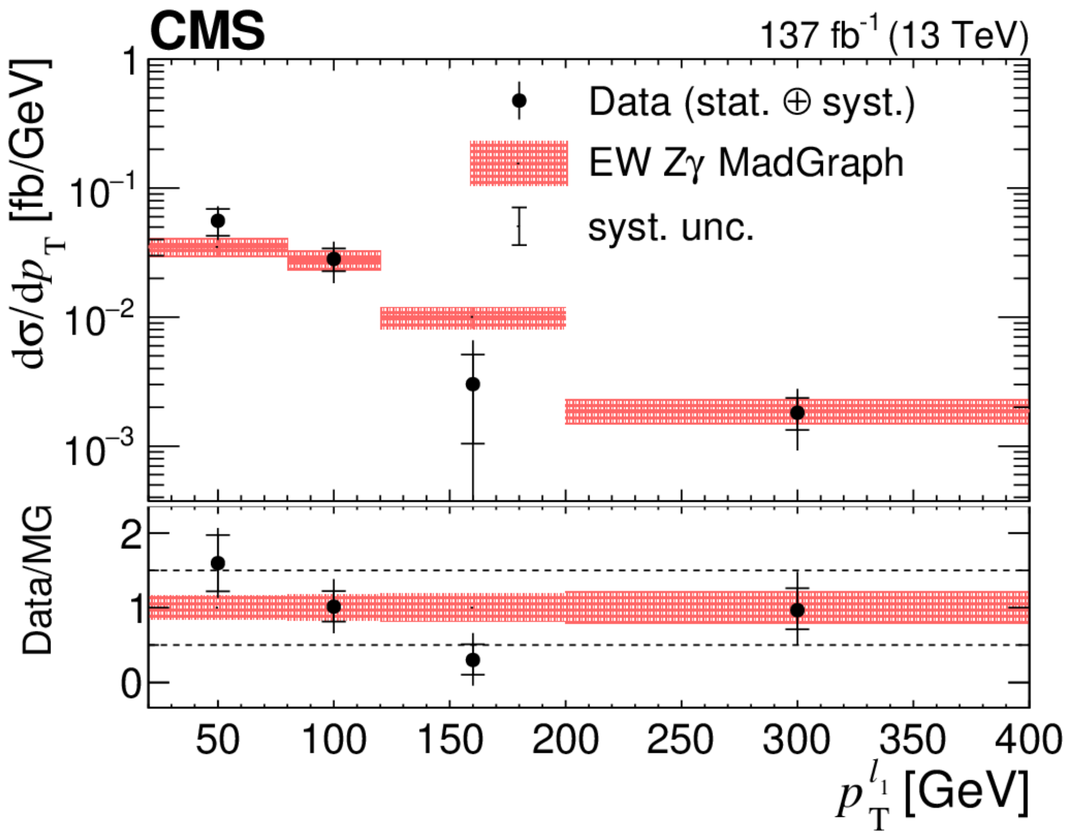


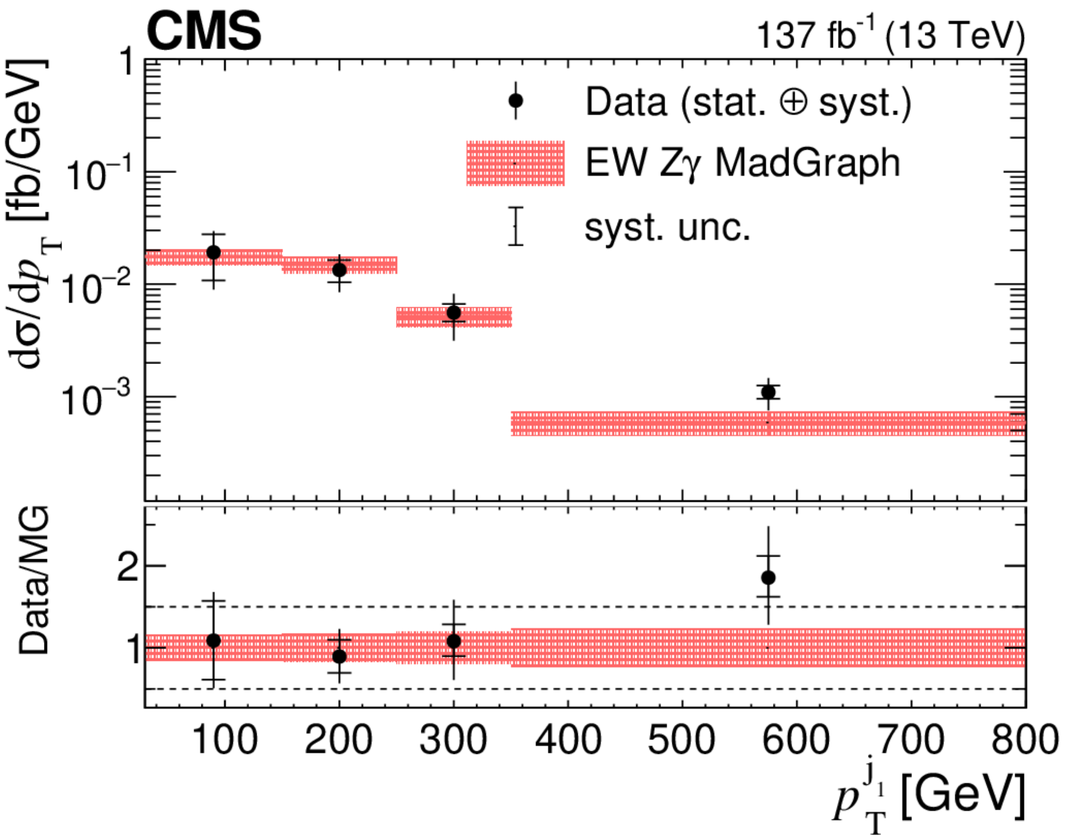




CMS Z(→ll)γ

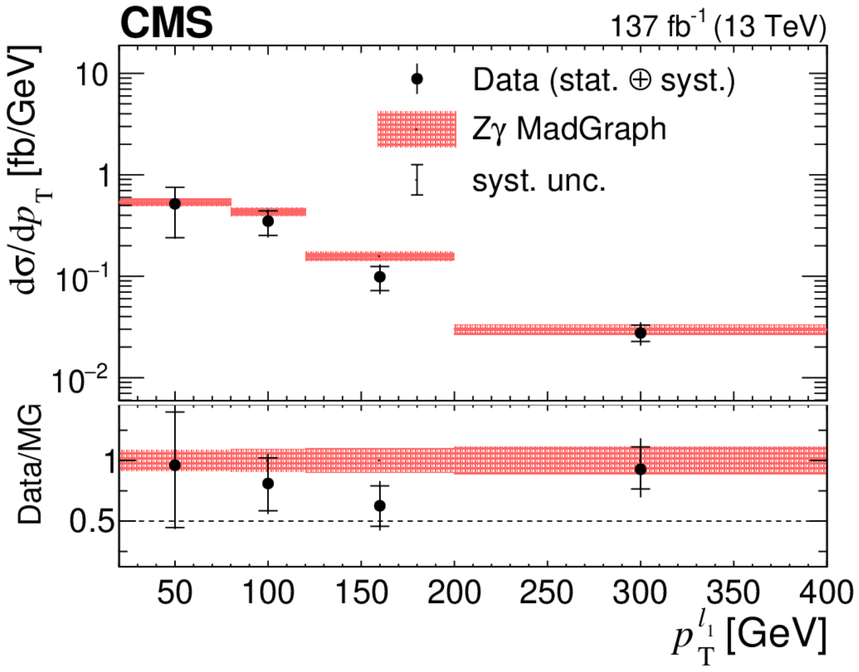
- EW differential cross-sections

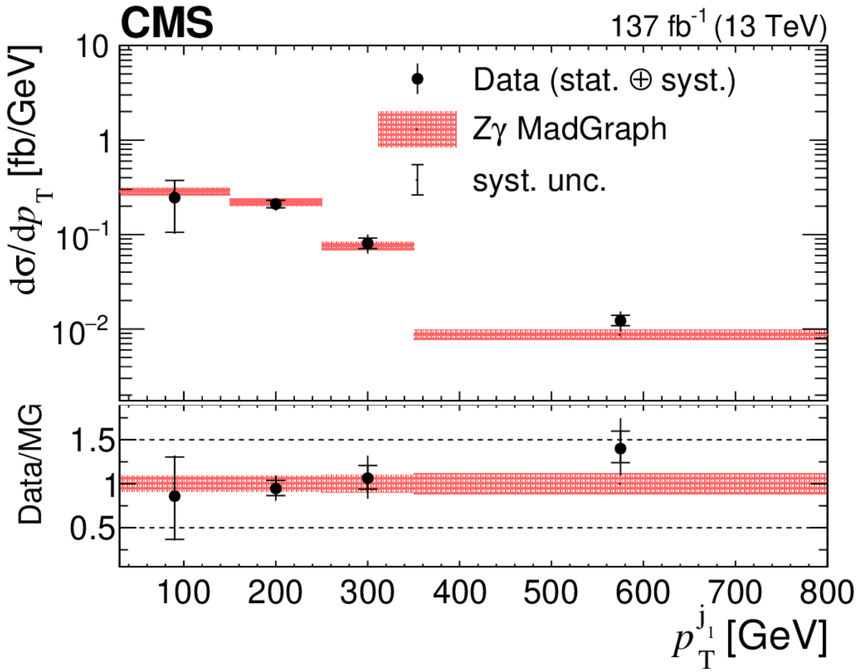


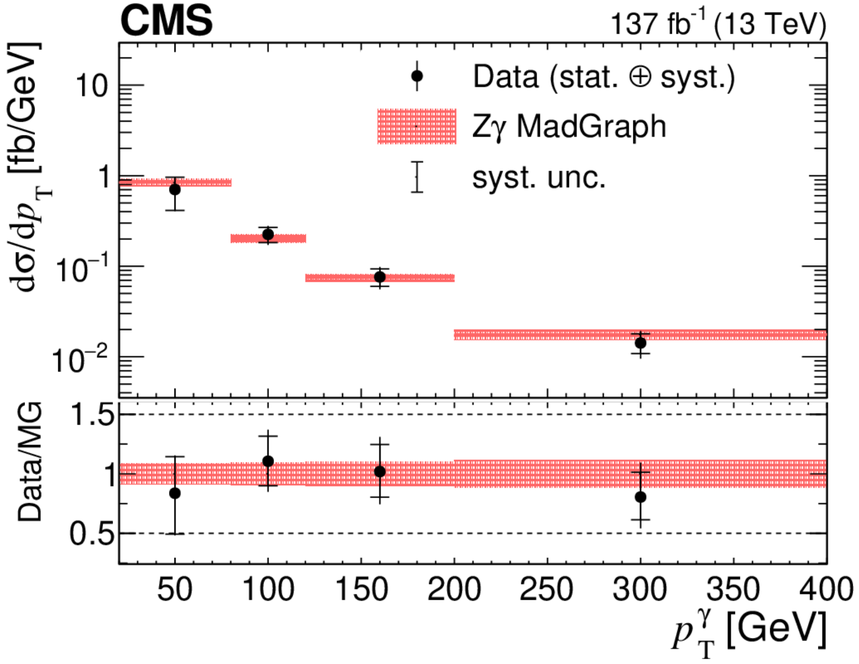


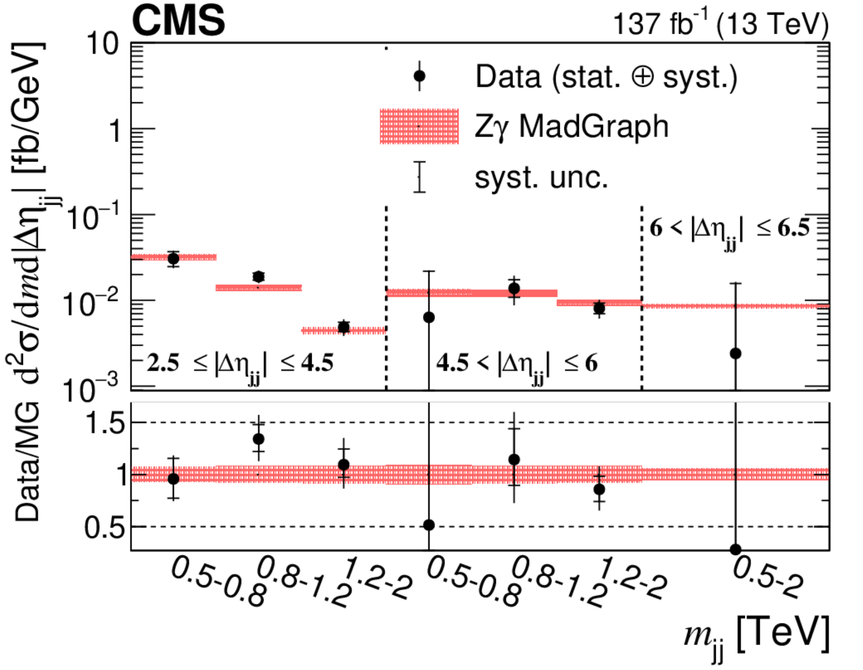
CMS Z(→ll)γ

- EW+QCD differential cross-sections







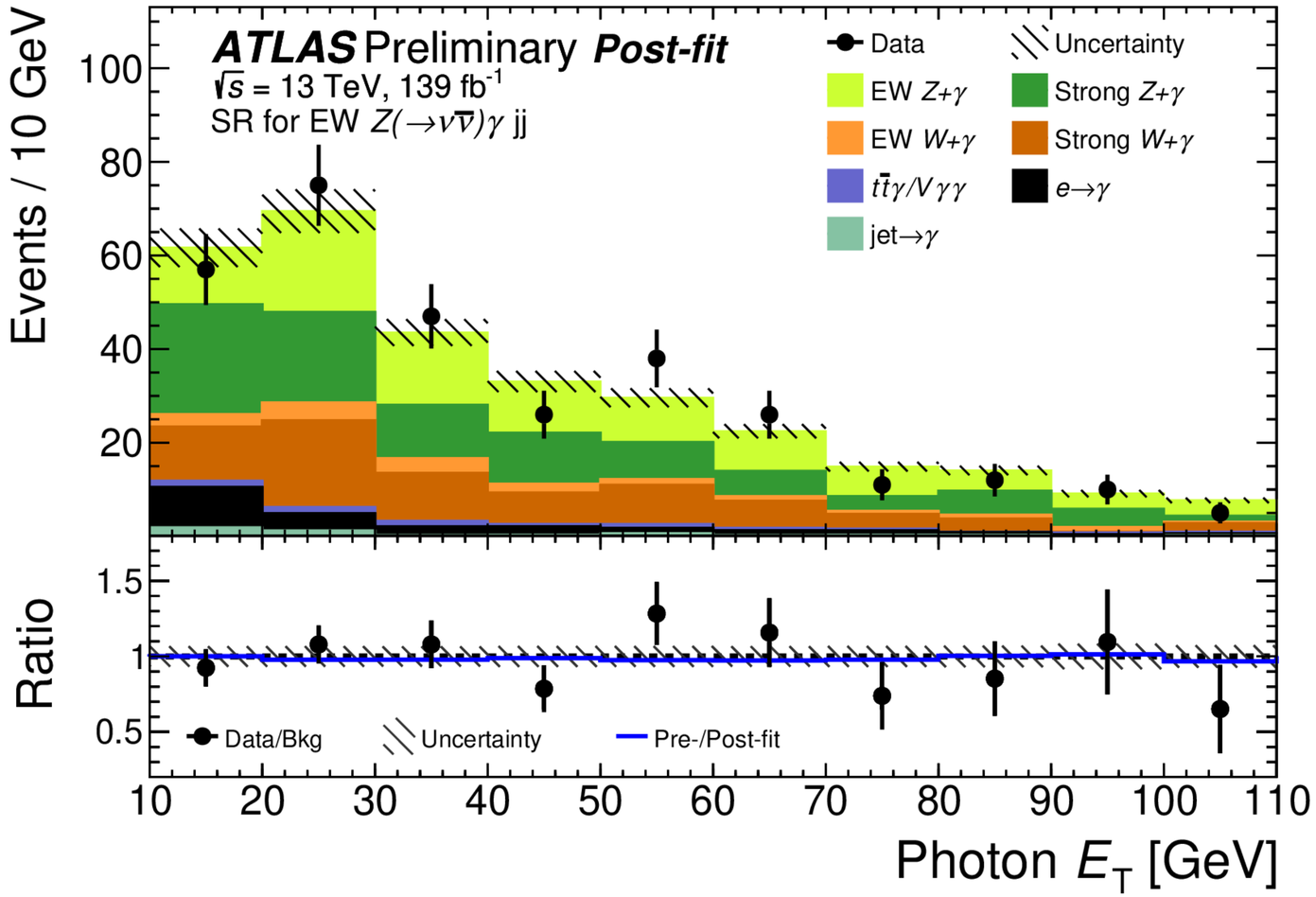


CMS Z(→ll)γ

Post-fit yields

Process	$\mu\mu\gamma_{\text{barrel}}$	$\mu\mu\gamma_{\text{endcap}}$	$\text{ee}\gamma_{\text{barrel}}$	$\text{ee}\gamma_{\text{endcap}}$
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

$Z(\rightarrow \nu\nu)\gamma$



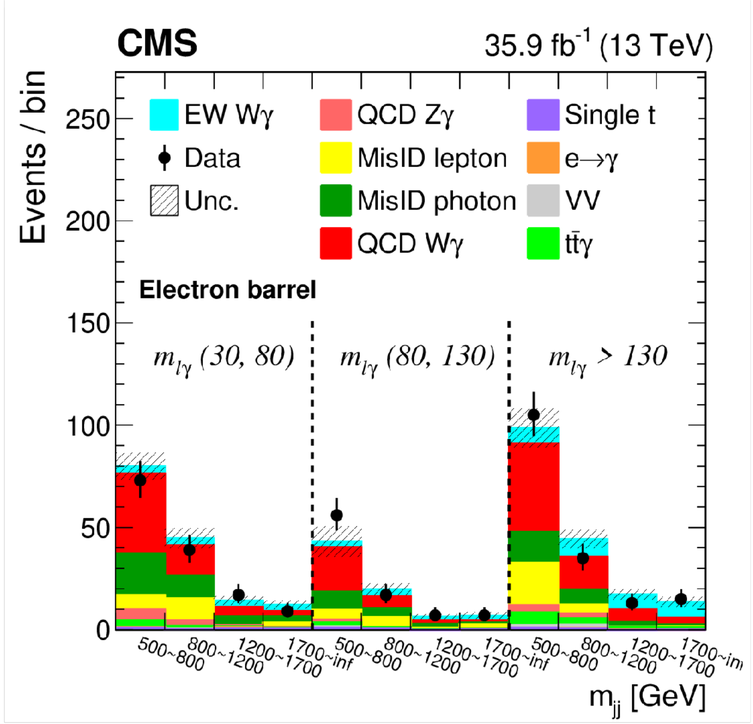
Z(→νν)γ

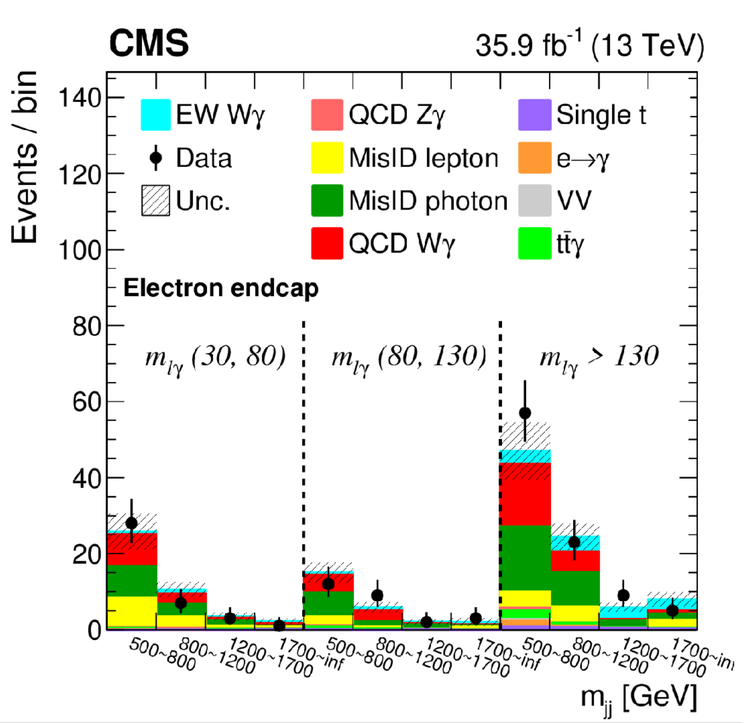
Post-fit yields

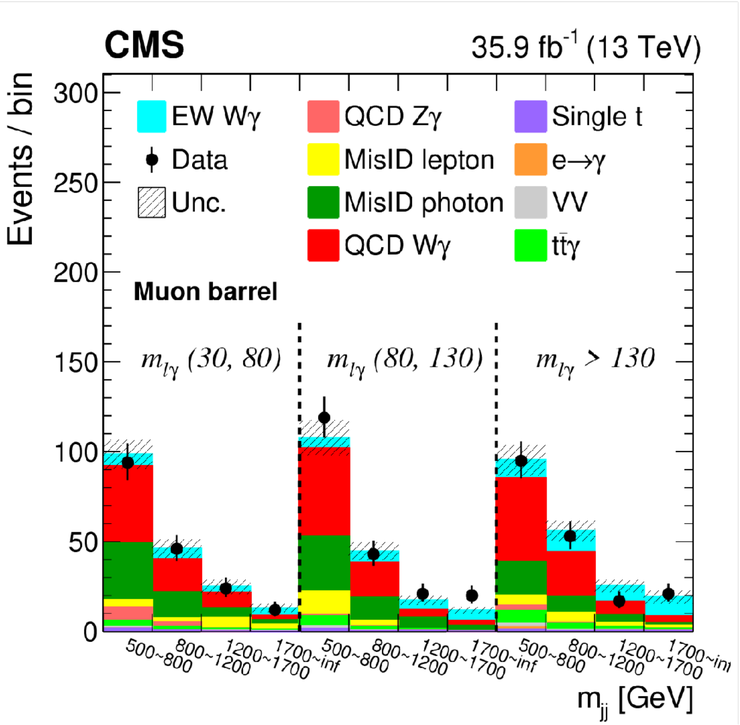
Process	Fake-e CR	$W^{\gamma}_{e\nu}$ CR	$W^{\gamma}_{\mu\nu}$ CR	$Z^{\gamma}_{\text{Rev.Cen.}}$ CR	SR - m_{jj} [TeV] 0.25-0.5	0.5-1.0	1.0-1.5	≥ 1.5
Strong $Z\gamma+\text{jets}$	8 ± 8	0 ± 1	3 ± 2	50 ± 12	20 ± 6	54 ± 12	13 ± 5	5 ± 2
EW $Z\gamma+\text{jets}$	0.6 ± 0.2	0.3 ± 0.2	0.4 ± 0.2	7 ± 2	4 ± 1	30 ± 7	25 ± 5	36 ± 7
Strong $W\gamma+\text{jets}$	43 ± 9	47 ± 9	133 ± 21	24 ± 6	22 ± 6	35 ± 10	9 ± 3	3 ± 1
EW $W\gamma+\text{jets}$	19 ± 6	31 ± 7	59 ± 13	1.4 ± 0.5	2 ± 1	6 ± 1	4 ± 1	5 ± 1
jet$\to\gamma$	1 ± 1	2 ± 2	3 ± 2	2 ± 2	1 ± 1	2 ± 2	1 ± 1	0.4 ± 0.3
jet$\to e$	34 ± 17	5 ± 3	–	–	–	–	–	–
$e \to \gamma$	–	2.7 ± 0.4	2.9 ± 0.4	13 ± 1	6 ± 1	11 ± 1	2.6 ± 0.4	1.4 ± 0.3
$\gamma+\text{jet}$	–	–	–	0.7 ± 0.5	0.7 ± 0.5	0.4 ± 0.3	0.1 ± 0.1	0.1 ± 0.1
$t\bar{t}\gamma/V\gamma\gamma$	3 ± 1	9 ± 2	13 ± 2	3 ± 1	2 ± 1	4 ± 1	0.4 ± 0.2	0.1 ± 0.1
Fitted Yields	108 ± 10	96 ± 8	213 ± 14	102 ± 9	58 ± 6	143 ± 12	54 ± 5	52 ± 6
Data	108	95	216	100	52	153	50	52
Data/Fit	1.00 ± 0.14	0.99 ± 0.12	1.01 ± 0.09	0.98 ± 0.13	0.90 ± 0.15	1.07 ± 0.11	0.93 ± 0.16	0.99 ± 0.1

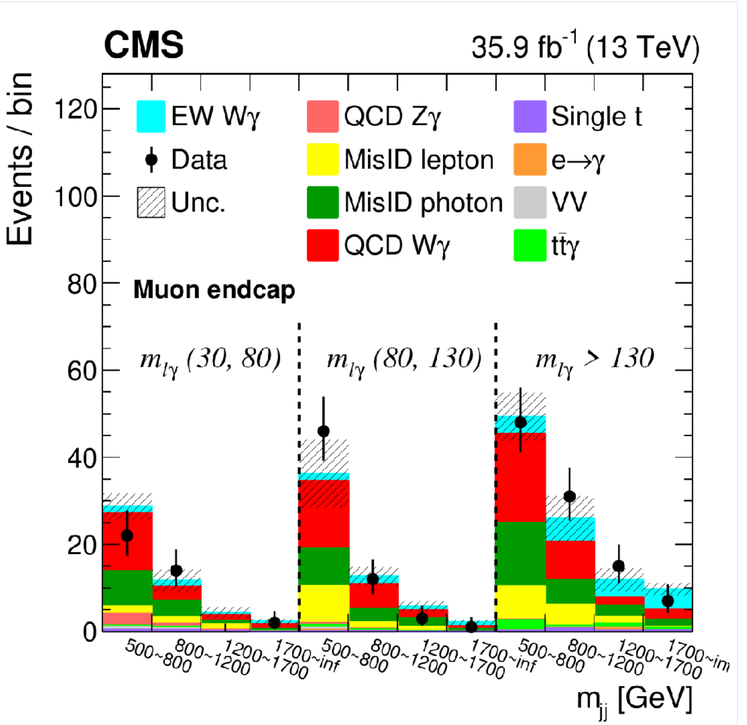
W(→lν)γ

- SR, EW extraction



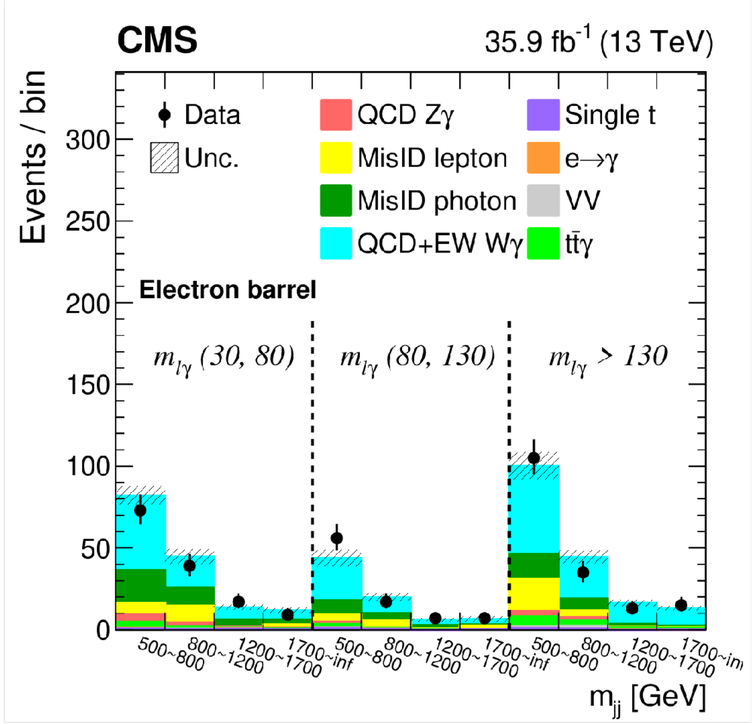


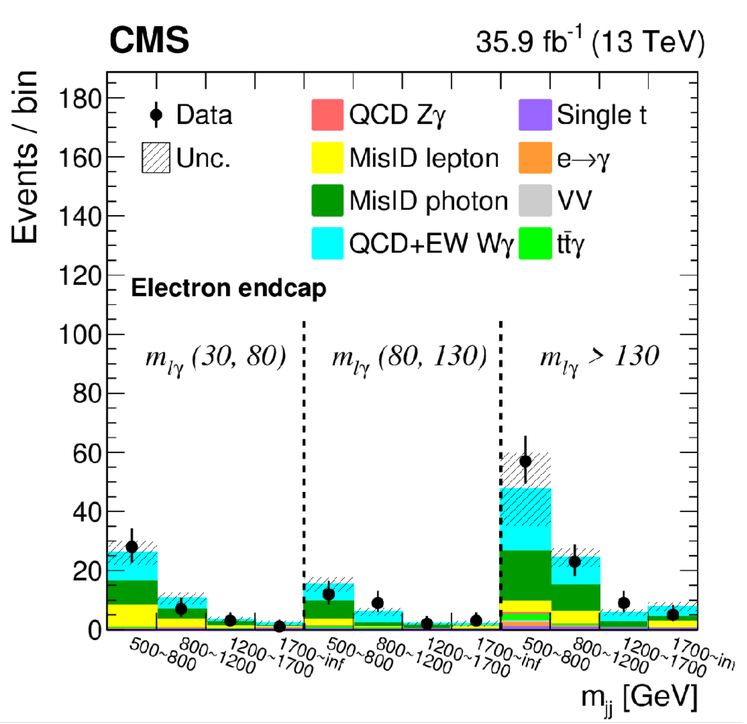


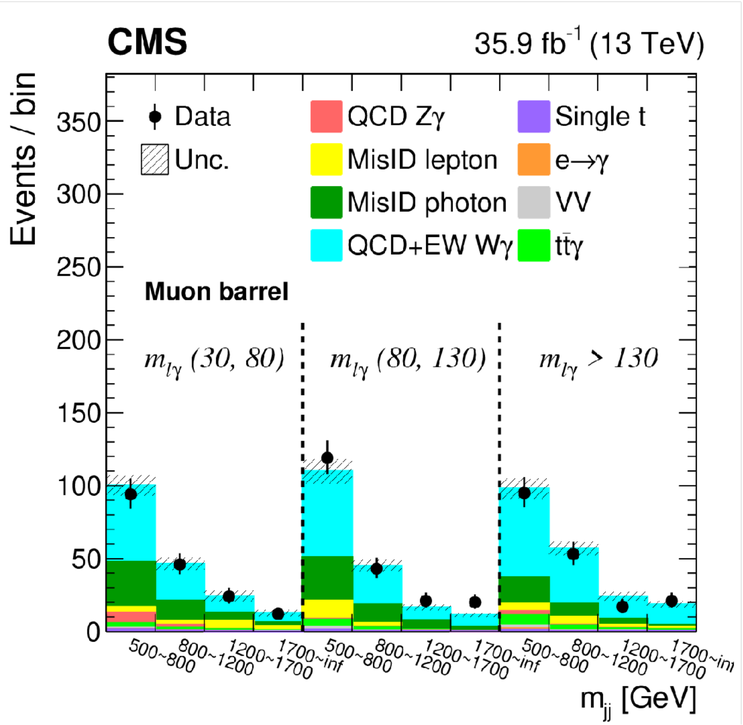


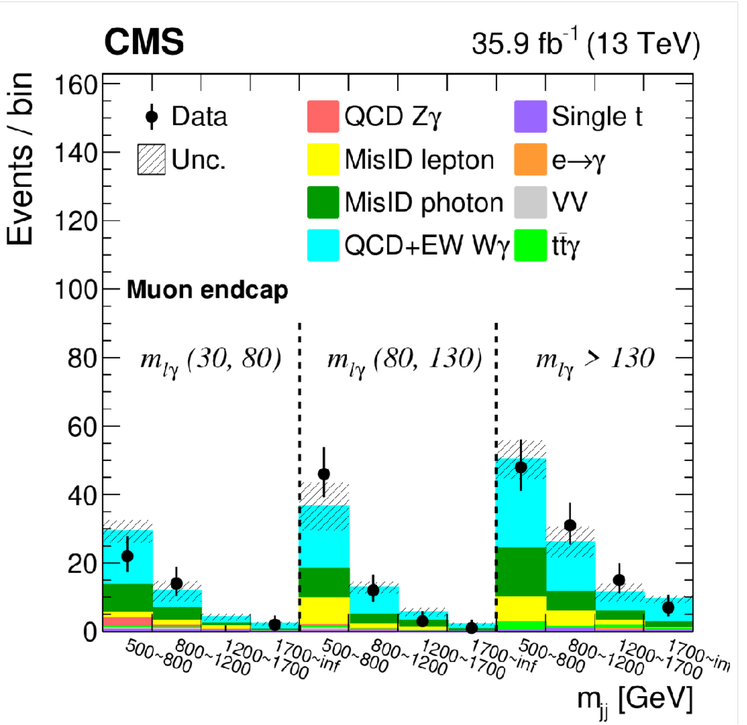
W(→lν)γ

- SR, EW+QCD extraction





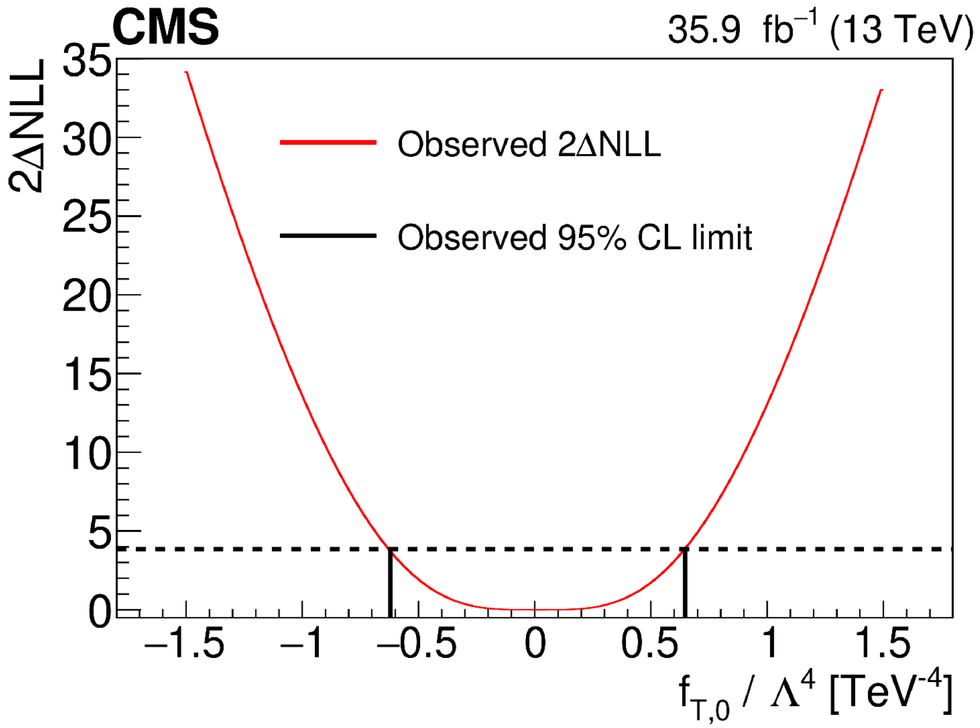




W(→lν)γ

Source	EW Wγjj	QCD Wγjj	VV	t$\bar{\text{t}}\gamma$	QCD Zγ	Single t	MisID photon	MisID lepton	Double misID	e $\rightarrow \gamma$
JES	0.9–6.9	11–28	6.4–38	3.7–16	12–78	3.3–18	—	—	—	11–28
JER	0.7–2.2	0.7–4.1	6.9–21	1.3–4.9	6.5–15	2.9–7.1	—	—	—	0.7–4.1
Integrated luminosity	2.5	2.5	2.5	2.5	2.5	2.5	—	—	—	2.5
MisID photon	—	—	—	—	—	—	12–22	—	12–22	—
MisID lepton	—	—	—	—	—	—	—	30	30	—
$\mu_{\text{R}}/\mu_{\text{F}}$ scales	1.5–11	6.1–20	—	—	—	—	—	—	—	—
PDF	3.2–5.6	1–2	—	—	—	—	—	—	—	—
Interference	1.8–2.8	—	—	—	—	—	—	—	—	—
Cross section for t$\bar{\text{t}}\gamma$	—	—	—	10	—	—	—	—	—	—
Cross section for VV	—	—	10	—	—	—	—	—	—	—
Modeling of pileup	0–0.6	0.3–1.4	4.8–13	2.6–3.9	6.2–19	1.0–3.9	—	—	—	0.3–1.4
Statistical uncertainty	7–11	6–36	45–100	13–56	16–100	17–55	7–36	43–72	30–100	54–100
L1 mistiming	1.7–2.4	0.8–1.6	0.5–1.6	1.4–2.5	0.6–3.6	1.0–2.1	—	—	—	1.1–2.8
Muon ID/Iso	0.3	0.3	0.3	0.3	0.3	0.3	—	—	—	0.3
Muon trigger	0.3	0.2	0.2	0.2	0.1	0.1	—	—	—	0.2
Electron reconstruction	0.5	0.6	0.5	0.6	0.6	0.5	—	—	—	0.5
Electron ID/Iso	1.3	1.3	1.3	1.3	1.3	1.3	—	—	—	1.3
Electron trigger	2.5	2.5	2.5	2.5	2.5	2.5	—	—	—	2.5
Photon ID	1.2	1.2	1.1	1.2	1.3	1.2	—	—	—	1.2

W(→lν)γ



Pre-fit yields

	Electron barrel	Electron endcap	Muon barrel	Muon endcap
MisID photon	81.0 ± 5.2	48.1 ± 4.9	134.8 ± 8.2	52.1 ± 4.8
MisID lepton	63.7 ± 12.3	27.8 ± 7.2	46.8 ± 10.6	23.1 ± 6.5
QCD Wγjj	154.2 ± 12.0	41.1 ± 4.4	221.2 ± 15.8	72.1 ± 6.2
t$\bar{\text{t}}\gamma$	20.6 ± 1.6	5.1 ± 0.6	28.3 ± 1.8	6.9 ± 0.8
QCD Zγ	18.0 ± 3.1	1.9 ± 0.9	16.2 ± 3.0	4.9 ± 1.3
Single t	4.9 ± 0.8	2.5 ± 0.5	6.8 ± 0.9	2.4 ± 0.5
VV	4.2 ± 1.6	0.6 ± 0.6	7.5 ± 2.1	1.4 ± 0.7
e $\rightarrow \gamma$	1.5 ± 0.6	2.1 ± 0.8	1.7 ± 0.7	1.1 ± 0.6
Total background	348.3 ± 18.4	129.1 ± 9.9	463.4 ± 21.2	163.8 ± 10.4
EW Wγjj	48.8 ± 2.2	16.1 ± 1.0	74.5 ± 2.8	24.4 ± 1.3
Total predicted	397.1 ± 18.5	145.2 ± 10.0	537.9 ± 21.4	188.2 ± 10.5
Data	393	159	565	201