EW V and multi-V production from ATLAS and CMS

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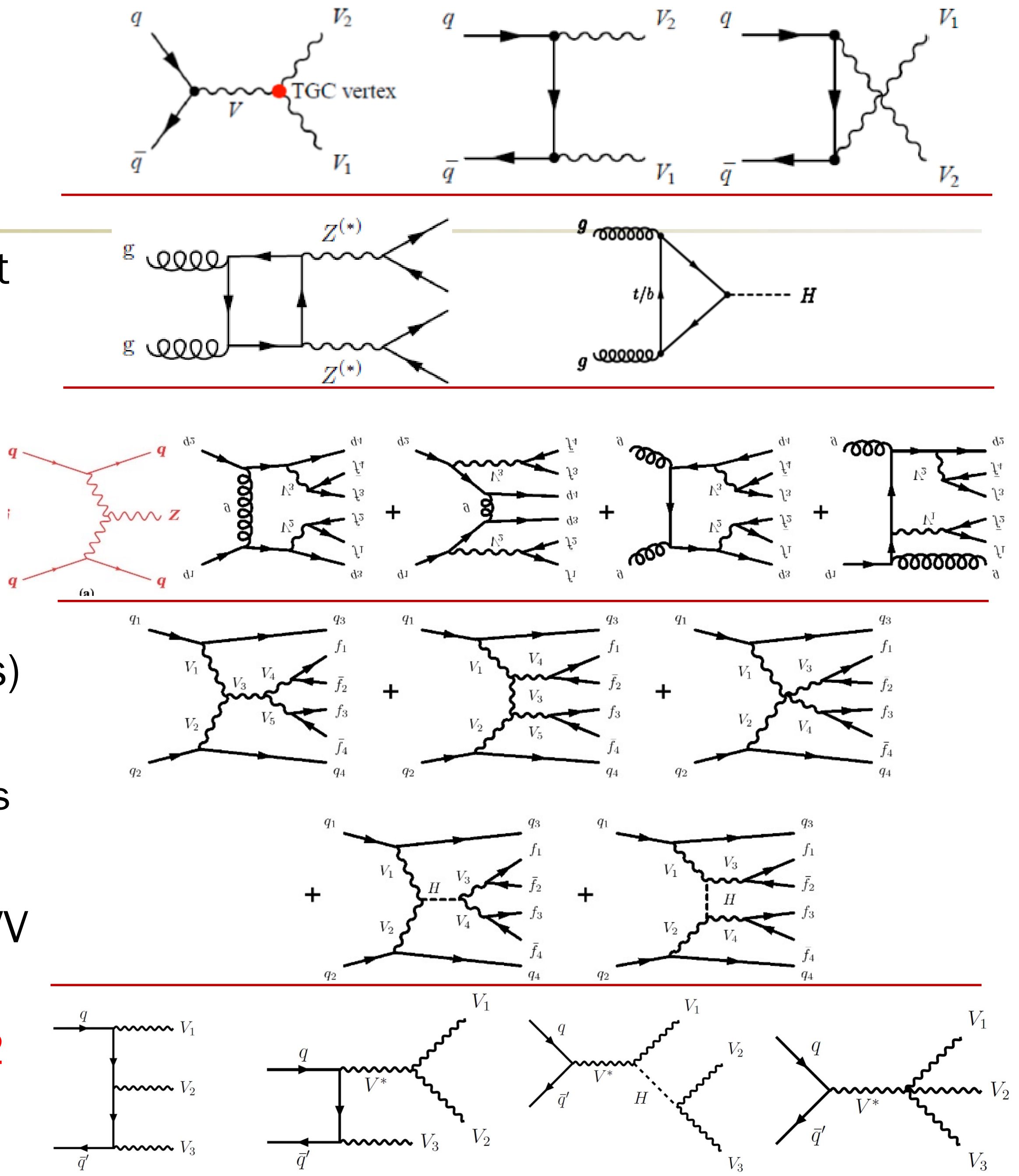
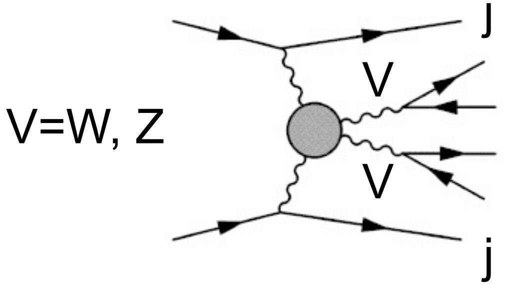
Single and multi-boson production @LHC

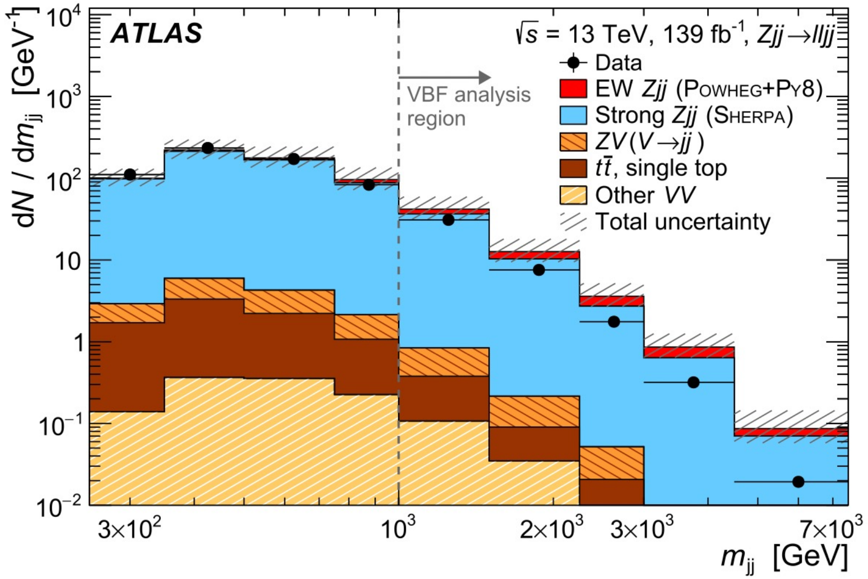
- Measurement of single and multi-boson productions at LHC is important to test the validity of the Standard Model (SM) at TeV scale
  - Many precision differential measurements
  - VBF/S processes with relative lower cross-section, being key process to probe the mechanism of electroweak symmetry breaking (EWSB)
- Involve with Triple or Quartic Gauge Couplings (T/QGCs)
  - To look for vector boson self-couplings
  - Probe new physics through deviations from SM couplings
- EFT interpretation $\mathcal{L}_{\text{SMEFT}} \approx \mathcal{L}_{\text{SM}}^{(4)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + \sum_j \frac{c_j^{(8)}}{\Lambda^4} O_j^{(8)}$
- A way to search for high mass resonance decaying to VV final state
- This presentation focuses on the VBF/S with full Run 2 data



The EW productions

- LHC provides unique opportunity to **discover the VBS/F processes** ever observed before. To pave the way for new observations we have systematically performed detailed EW measurements to understand the (multi-)boson production at the LHC
- General signature of two jets in forward and background regions, with large invariant mass and rapidity separation
- **From (multi-)V to (multi-)V + jj**
  - **Theoretically** more complicated mostly due to the jet modelling
    - Usually use dedicated data control regions to constrain
  - **Experimentally** also challenging
    - Pileup effect in the forward jet-tagging region
    - Lack of detector coverage in the very forward region makes it more difficult
    - Will be even more challenging at HL-LHC when luminosity further increased





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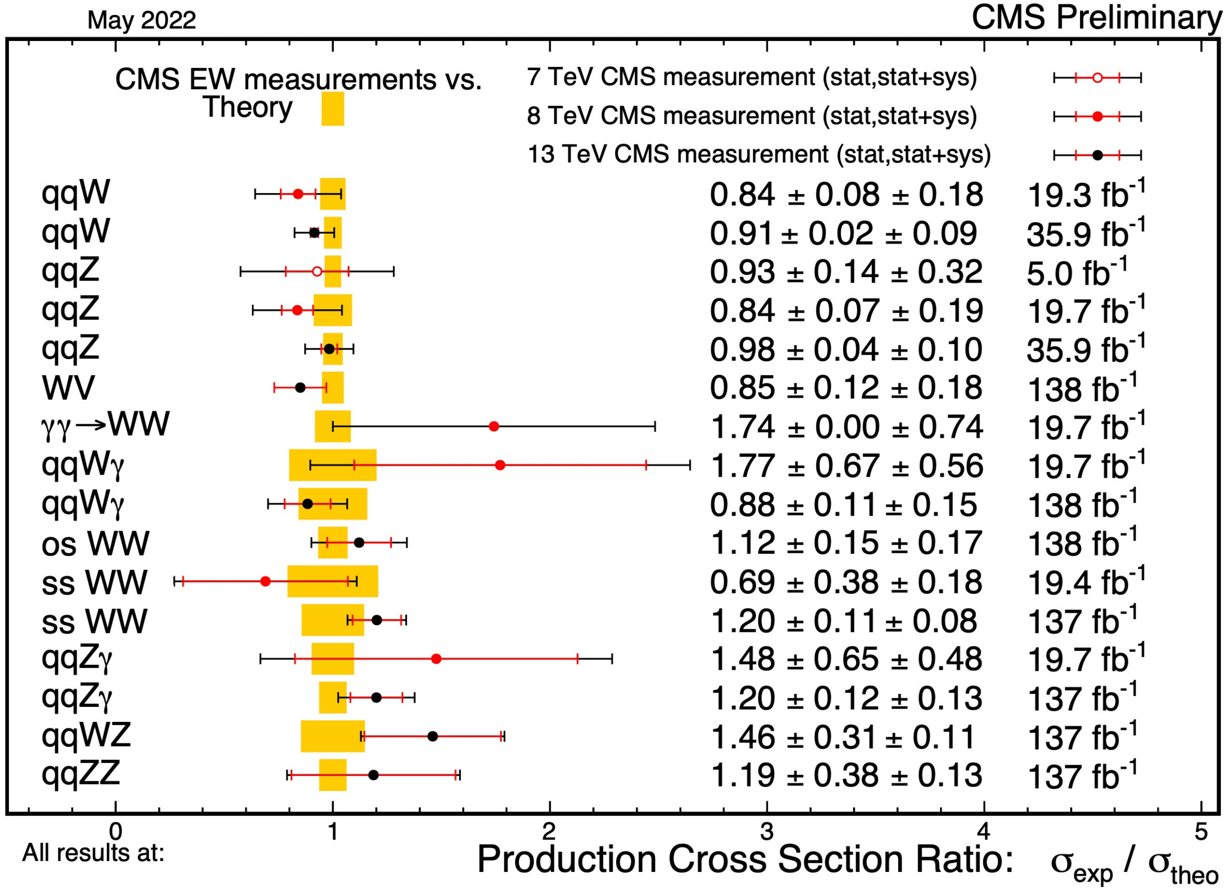
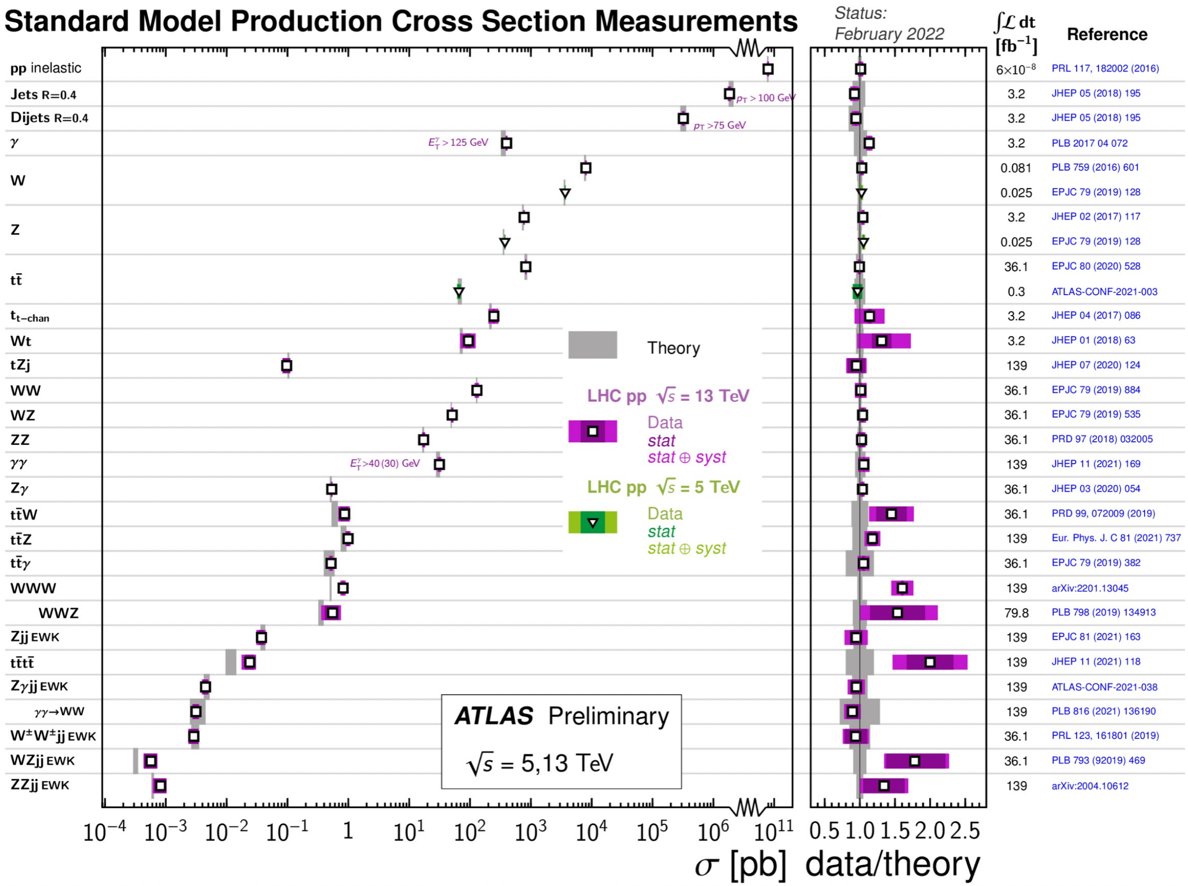
The Experimental Status

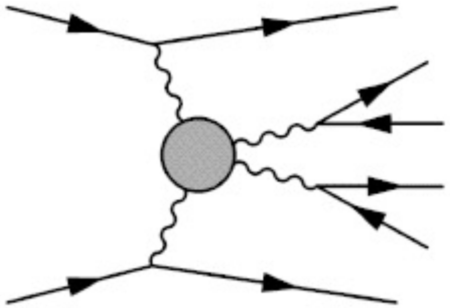


CMS summary



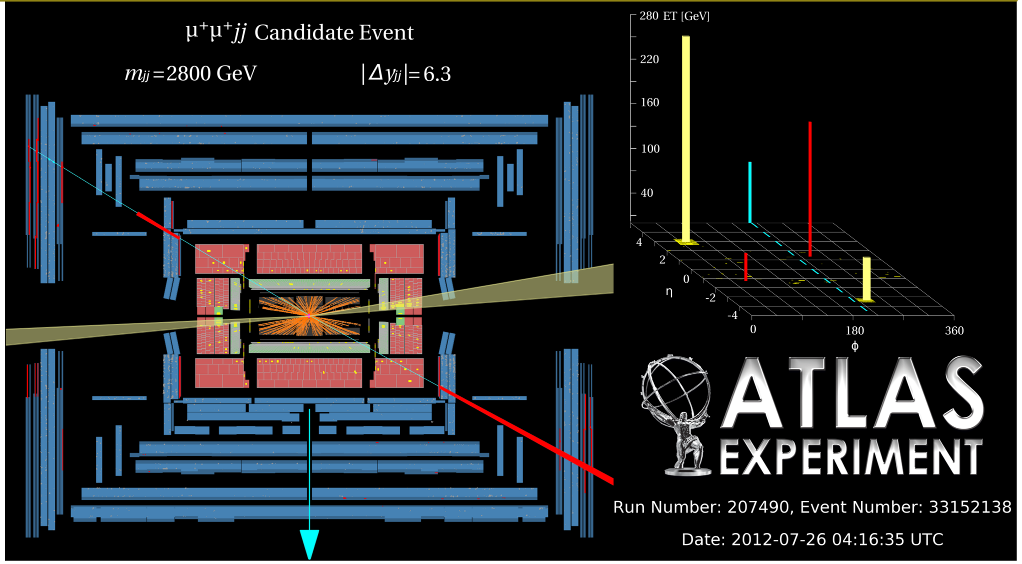
ATLAS summary

General Signatures



- Two intermediate vector bosons radiated from two incoming quarks
- Final state with decay products from vector bosons plus two forward/backward outgoing jets
- Two outgoing jets from quarks - large rapidity separation and large invariant mass
- Cross-sections of the EW VBS/F are small, suffer from irreducible QCD events
- Due to gauge invariance, VBS/F diagrams can not be separated from other V(V) + jj diagrams
  - Experimentally usually study the EW V(VV)+jj together, with dedicated kinematic selections to enhance the VBS/F contribution
  - Interference between EW and QCD diagrams are usually not large (% level), and treated either as systematic, or part of signal

The first evidence of VBS process at the LHC in the same-sign WW channel from Run 1
Since then, many more studies have been performed



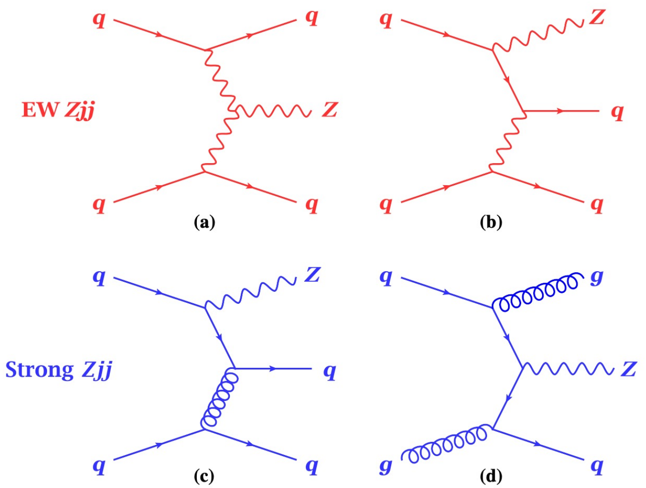
Candidate VBS event from ssWW
Phys. Rev. Lett. **113**, 141803

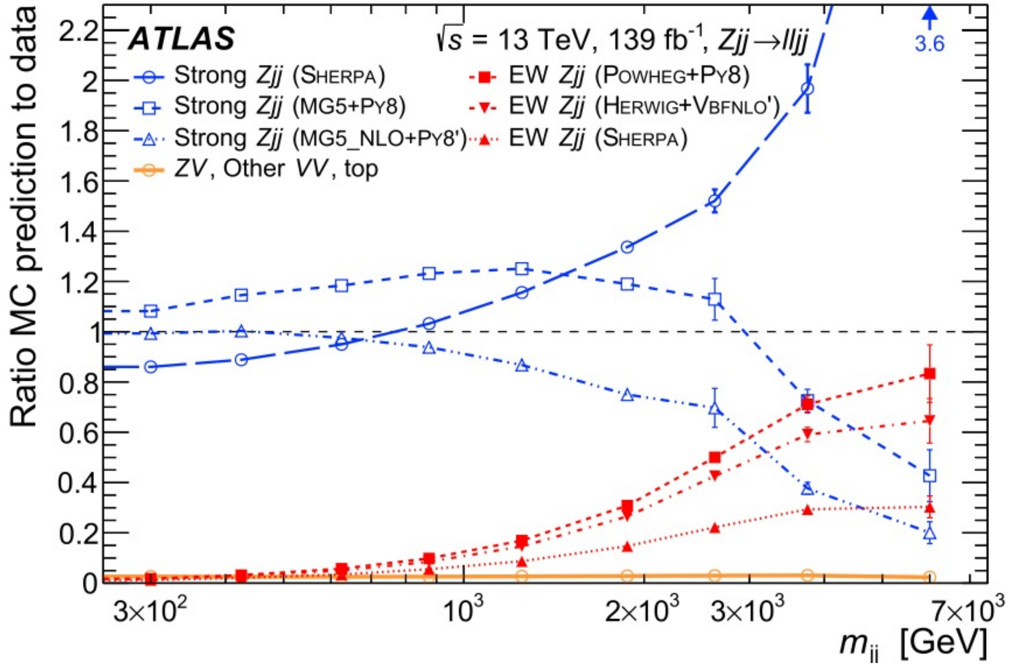
THE EW V PRODUCTION

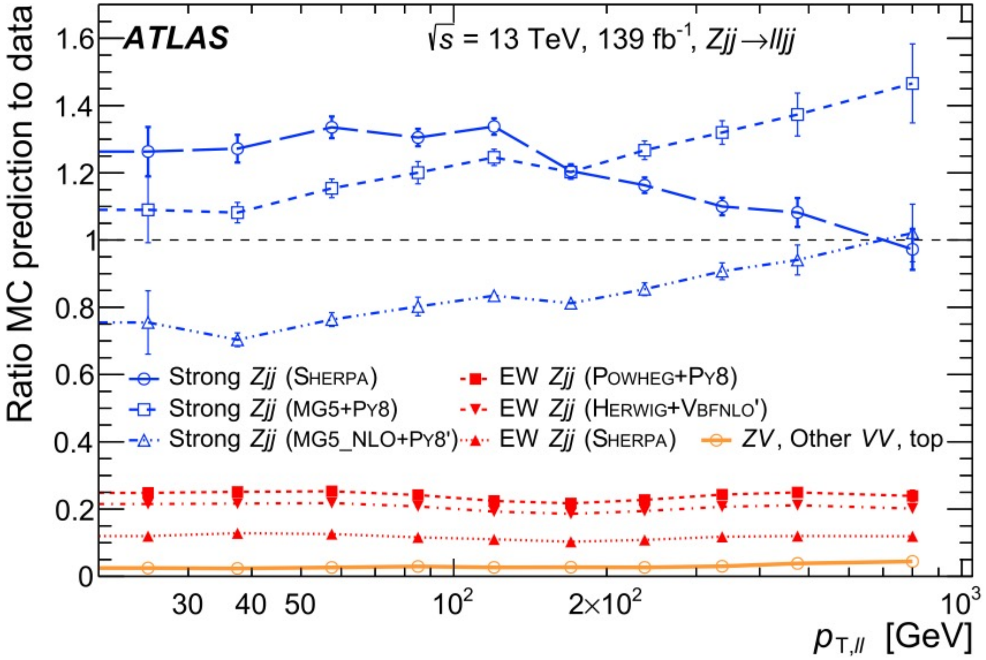
[Eur. Phys. J. C (2021) 81:163]

EW Z + jj

- Full Run 2 data used
- Signal
  - EW production of Z(->ee/μμ) + 2 jets in back and forward regions
  - No central jets between the two tag jets
- Major background
  - Strong production of Zjj
  - Poor theoretical modeling especially in the high m_{jj} region
  - Different MC generators used for comparison

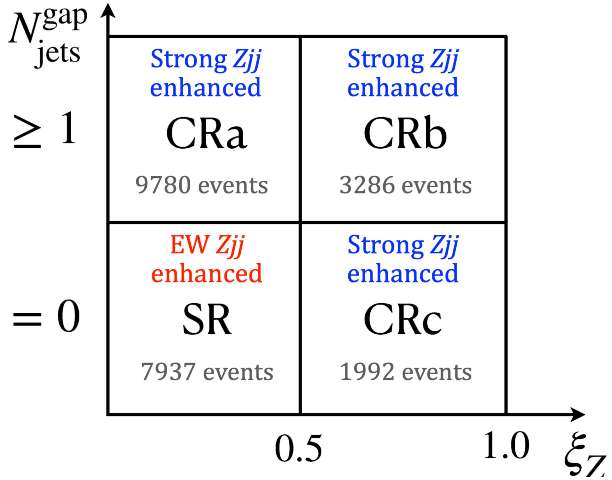






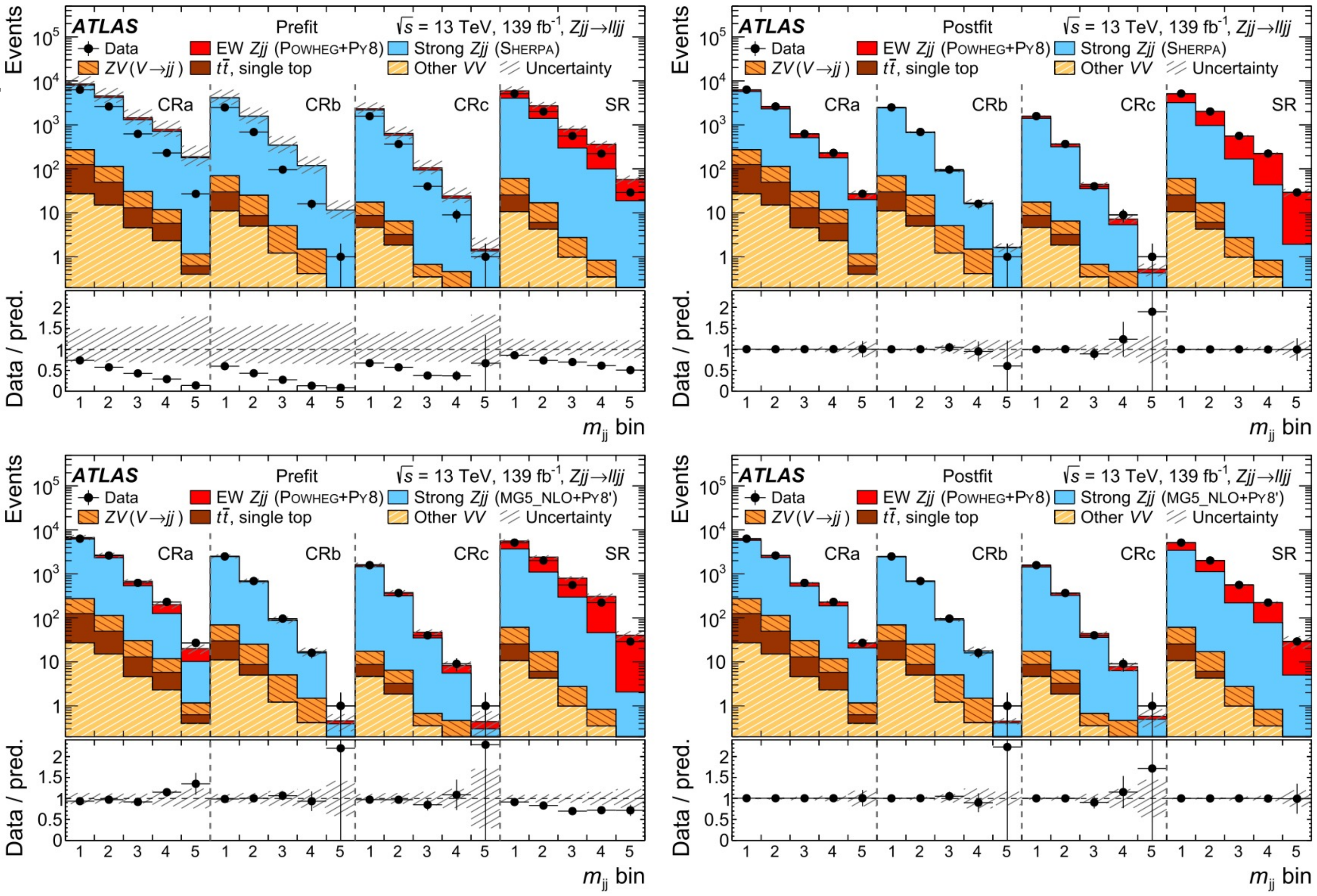
QCD Background constrain in control regions

- Dedicated control regions used to constrain the QCD Zjj modeling, for both normalization and shape
- SR and CRs defined using number of gap jets, and centrality of the Z boson
- SR and 3 CRs fitted simultaneously when extracting the EW component



$$\xi_Z = |y_{\ell\ell} - 0.5(y_{j1} + y_{j2})| \,/\, |\Delta y_{jj}|$$

Prefit　　Postfit

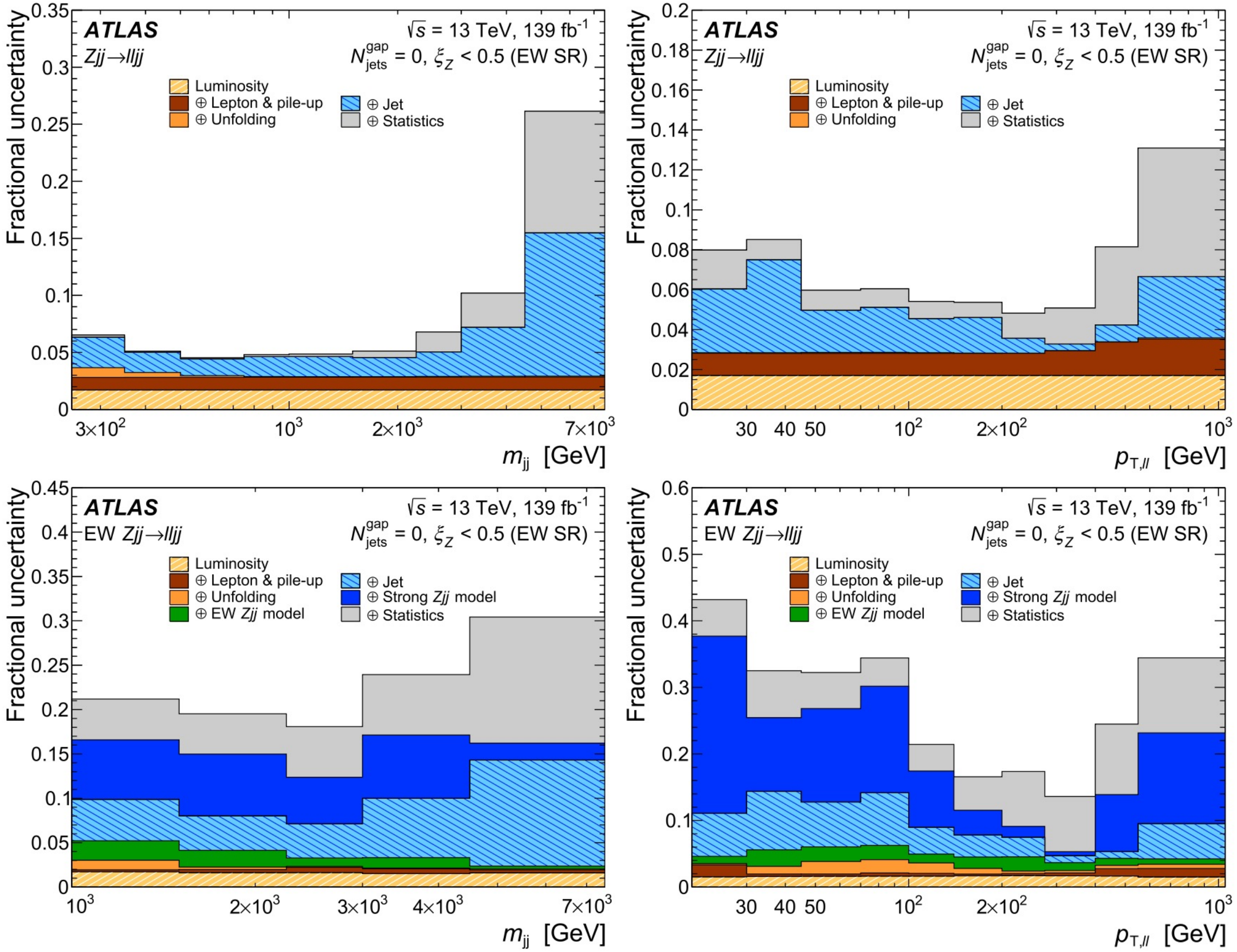


Clear improvement after fit in CRs

Systematics breakdown

Inclusive

EW

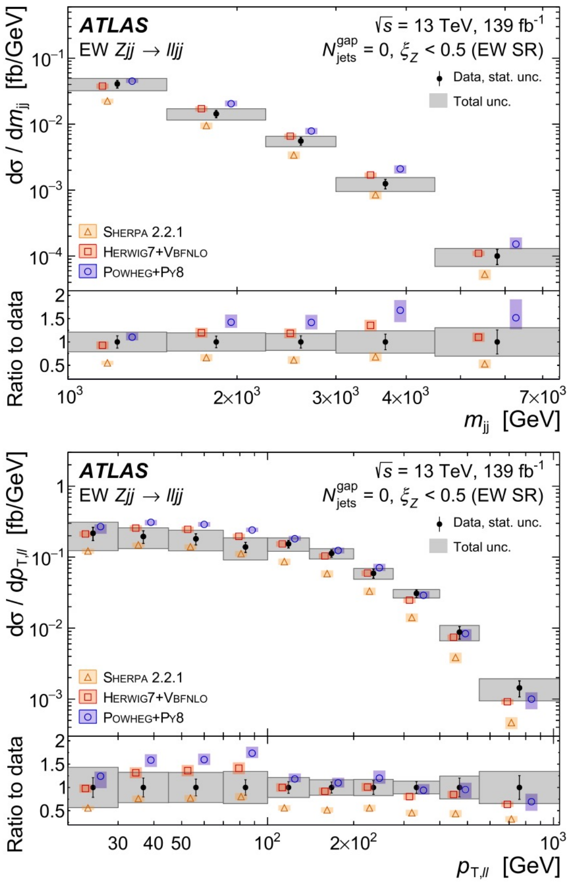


Large systematic from QCD modelling, especially in the high mass, pT region – usually the sensitive region for EW measurement and BSM search

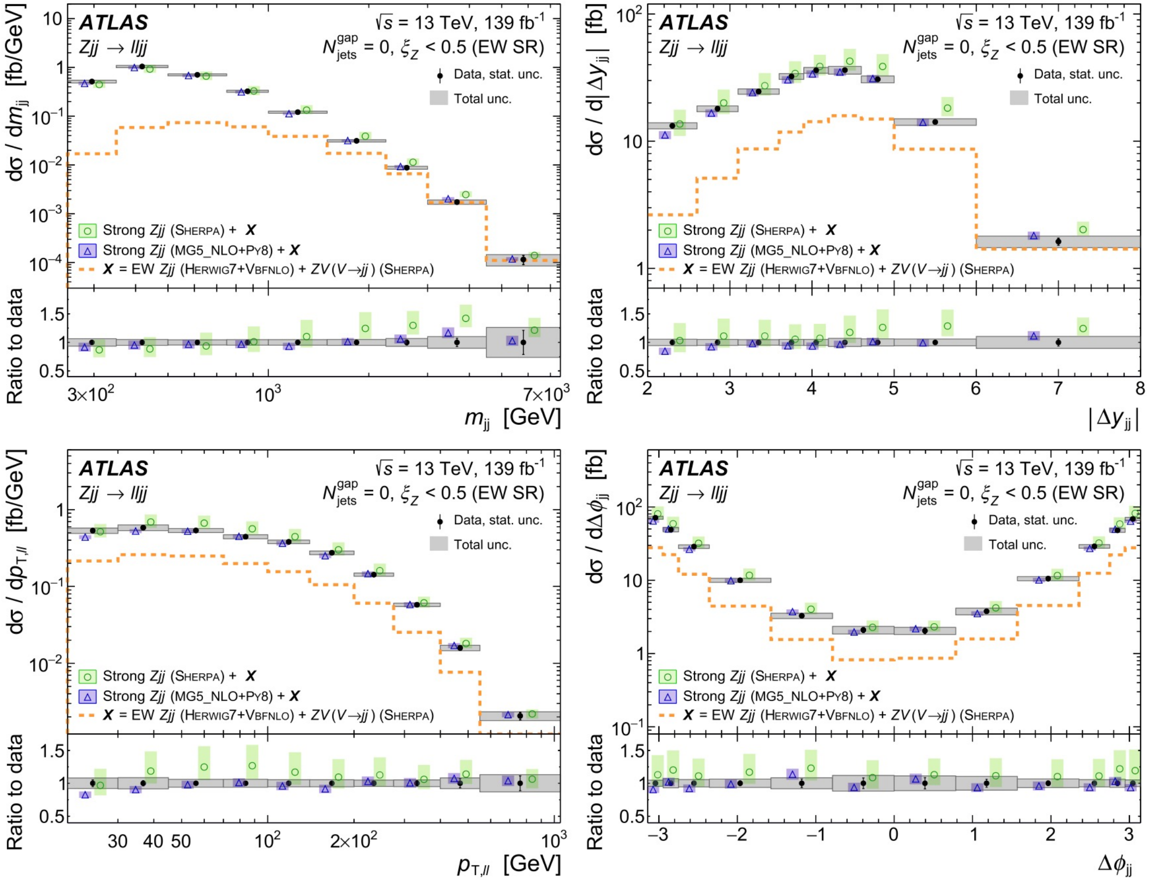
Differential Cross-section Measurements

EW Zjj $\sigma_{\text{EW}} = 37.4 \pm 3.5\,(\text{stat}) \pm 5.5\,(\text{syst})$ fb.

Herwig7+VBFNLO agrees best with data

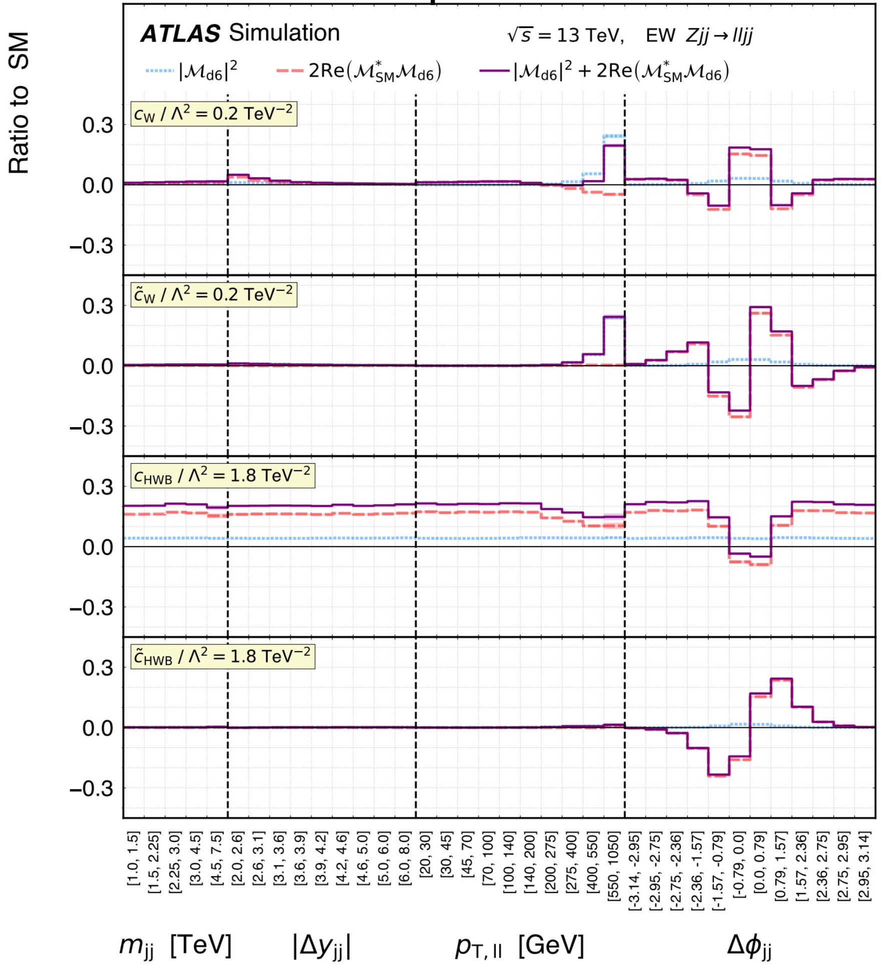


Inclusive Zjj



EFT Interpretations

Impact on the EW Zjj differential XS from different operators



$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2} O_i, \quad O_i \text{ are dimension-six operators}$$

Two CP-even and two CP-odd operators tested.

Wilson coefficient	Includes $|\mathcal{M}_{d6}|^2$	95% confidence interval [TeV^{-2}] Expected	Observed	p-value (SM)
c_W/Λ^2	no	[−0.30, 0.30]	[−0.19, 0.41]	45.9%
	yes	[−0.31, 0.29]	[−0.19, 0.41]	43.2%
$\tilde{c}_W/\Lambda^2$	no	[−0.12, 0.12]	[−0.11, 0.14]	82.0%
	yes	[−0.12, 0.12]	[−0.11, 0.14]	81.8%
c_{HWB}/Λ^2	no	[−2.45, 2.45]	[−3.78, 1.13]	29.0%
	yes	[−3.11, 2.10]	[−6.31, 1.01]	25.0%
$\tilde{c}_{HWB}/\Lambda^2$	no	[−1.06, 1.06]	[0.23, 2.34]	1.7%
	yes	[−1.06, 1.06]	[0.23, 2.35]	1.6%

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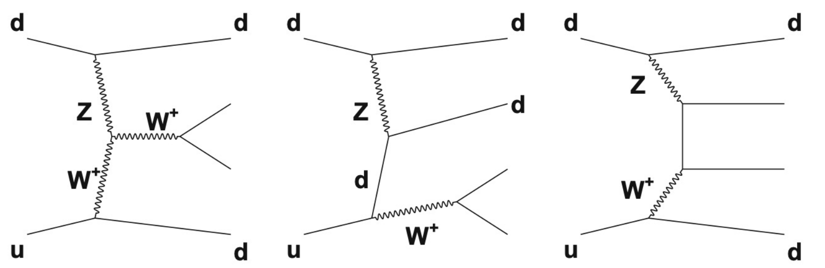
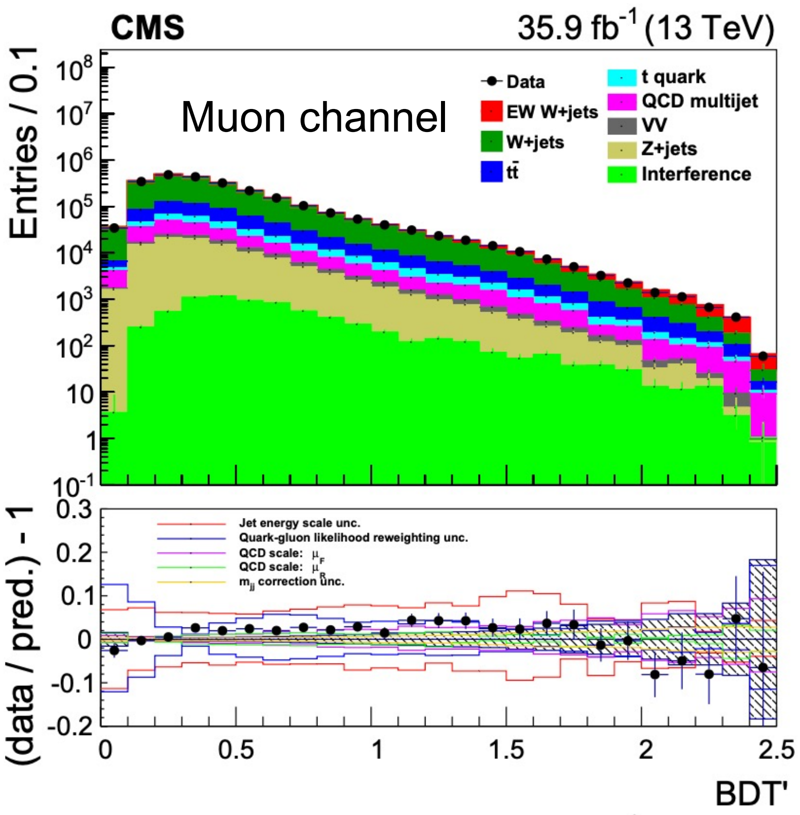
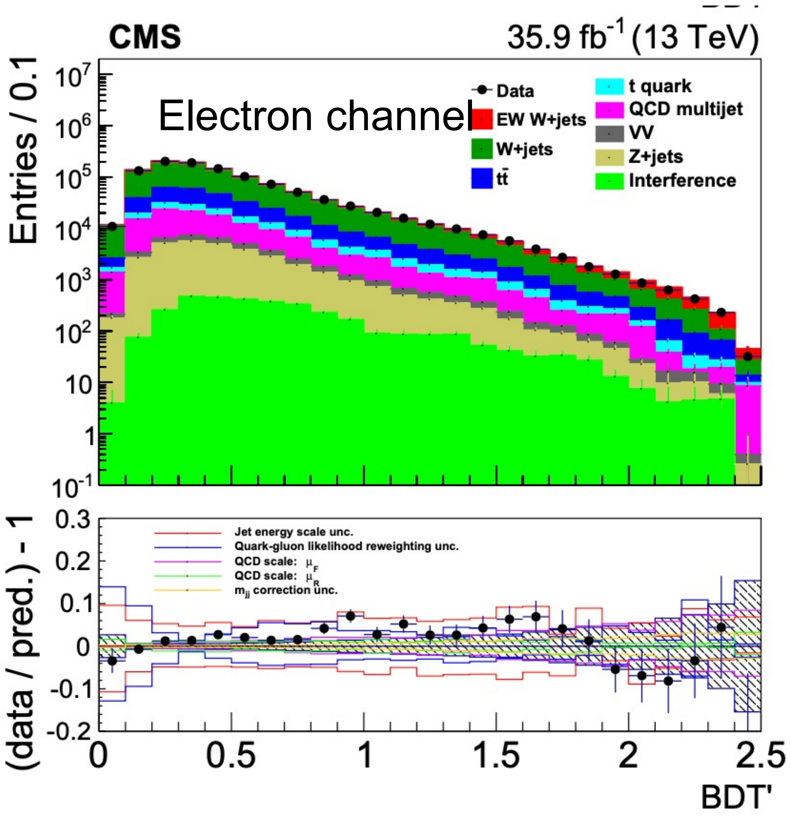
EW W + jj



- Partial Run 2 data used, 35.9 fb^{-1}
- BDT used to separate EW and QCD Wjj





BDT': BDT transformed with tanh^{-1}

From the combined fit of the two channels, the signal strength is measured to be

$$\mu = 0.91 \pm 0.02\,(\text{stat}) \pm 0.10\,(\text{syst}) = 0.91 \pm 0.10\,(\text{total}),$$

corresponding to a measured signal cross section

$$\sigma\,(\text{EW } \ell\nu\text{jj}) = 6.23 \pm 0.12\,(\text{stat}) \pm 0.61\,(\text{syst})\,\text{pb}$$
$$= 6.23 \pm 0.62\,(\text{total})\,\text{pb},$$

Sample	BDT > 0.95	
	μ	e
VV	11.0 ± 2.5	9.6 ± 2.8
DY Zjj	9.4 ± 5.9	7.7 ± 3.0
$t\bar{t}$	146 ± 17	102 ± 12
Single top quark	35.5 ± 5.6	25.7 ± 4.2
QCD multijet	98 ± 39	17.0 ± 5.6
DY Wjj	356 ± 65	240 ± 41
Interference	18.2 ± 8.1	9.8 ± 5.5
Total backgrounds	674 ± 78	412 ± 44
EW Wjj signal	503 ± 54	308 ± 34
EW Zjj signal	11.2 ± 1.3	6.6 ± 0.9
Total prediction	1186 ± 95	726 ± 56
Data	1138	686

THE EW VV PRODUCTION

ATLAS-CONF-2021-038
Phys. Rev. D 104 (2021) 072001

EW Z(ll)γ + jj

- Measurements use full Run 2 data, from both experiments, in the Z->ee/mm channel
- Signal generated with MadGraph5_aMC@NLO at LO

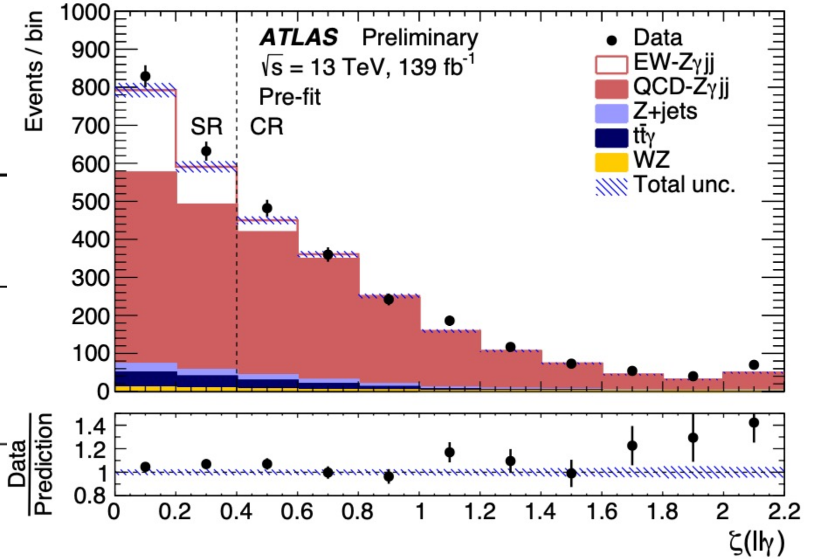
CMS

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

ATLAS

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

Table 1: Summary of selection criteria applied at particle level.



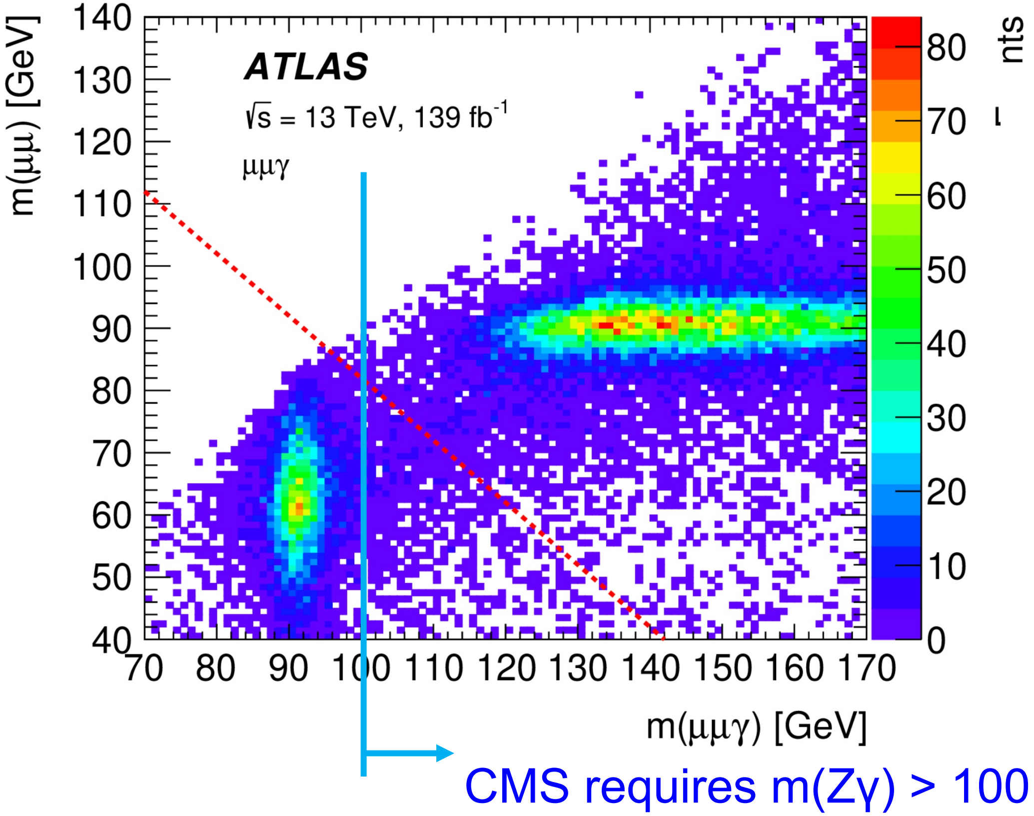
Centrality

JHEP 03 (2020) 054

Suppress the FSR contribution

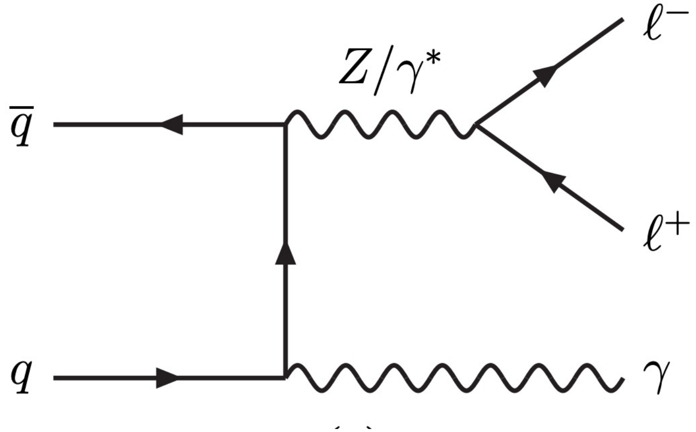
- Final state radiation (FSR) contribution is largely reduced by cutting on Zγ inv. mass

m(ℓℓ)+m(ℓℓγ) > 182 GeV to suppress FSR events

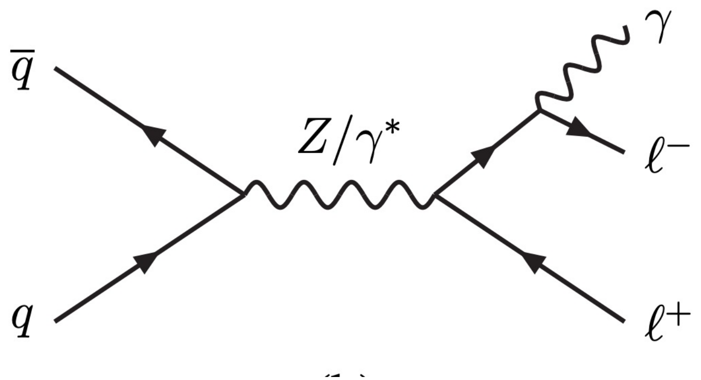


CMS requires m(Zγ) > 100 GeV

Process with photon radiated from initial-state quarks



Final state radiation (FSR) photon from leptons



Just for illustration of the FSR and ISR processes. Not VBS.

Background Estimation

- 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

TABLE III. Post-fit yields of predicted signal and background with total uncertainties, and observed event counts after the selection in the EW signal region. The γ_{barrel} and γ_{endcap} columns represent events with photons in the ECAL barrel and endcaps, respectively.

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 $Z\gamma$	274 ± 10	108 ± 5.6	162 ± 7.4	62.4 ± 3.9
EW $Z\gamma$	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

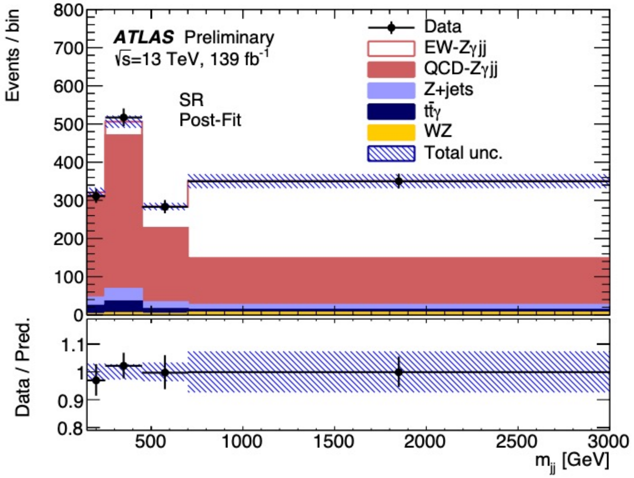
CMS. Events further split into barrel and endcap region depends on the selected photon

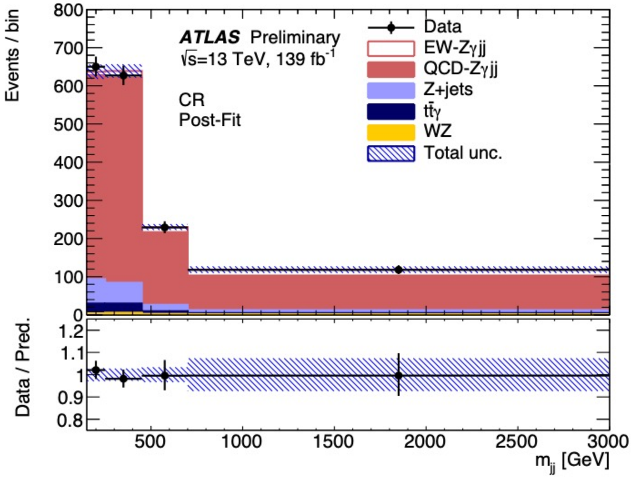
Sample	SR	CR
$N_{EW-Z\gamma jj}$	300 ± 36	55 ± 7
$N_{QCD-Z\gamma jj}$	987 ± 55	1352 ± 60
$N_{t\bar{t}\gamma}$	72 ± 11	59 ± 9
N_{WZ}	17 ± 3	14 ± 3
N_{Z+jets}	85 ± 30	143 ± 43
Total	1461 ± 38	1624 ± 40
N_{obs}	1461	1624

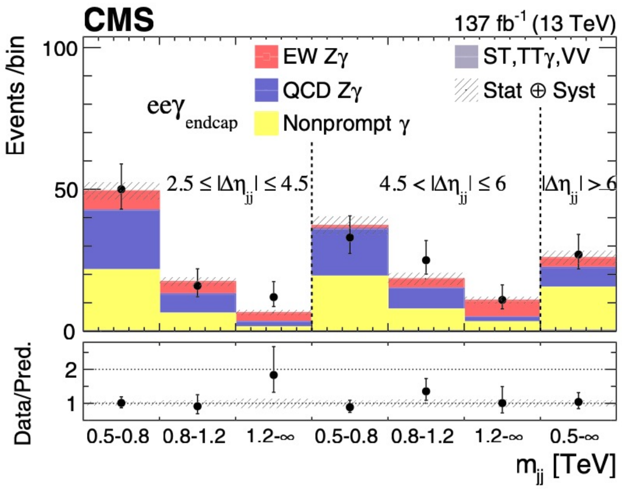
ATLAS

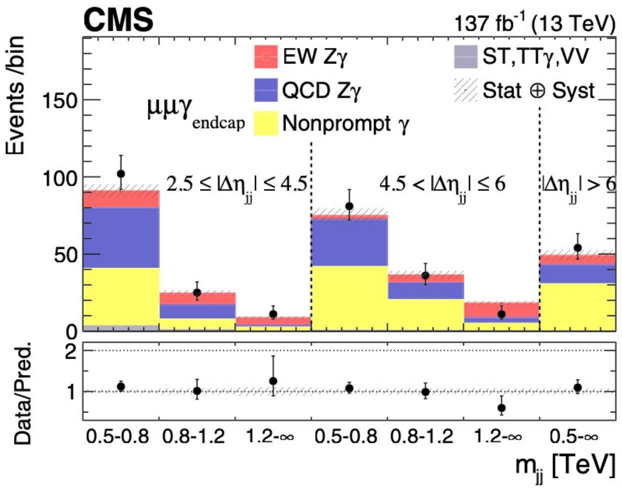
Observation of the EW Z(ll)γ + jj

- Fit done using the m_{jj} distributions. CMS has further split to different dy_{jj} regions









Significance well above 5σ

Measured cross sections. Both agree well with SM predictions.

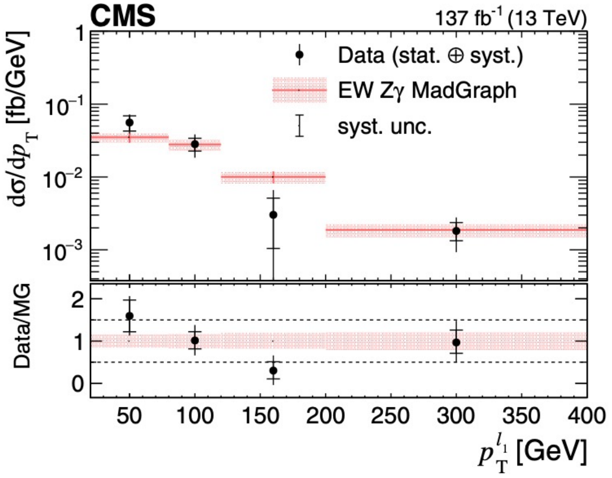
ATLAS

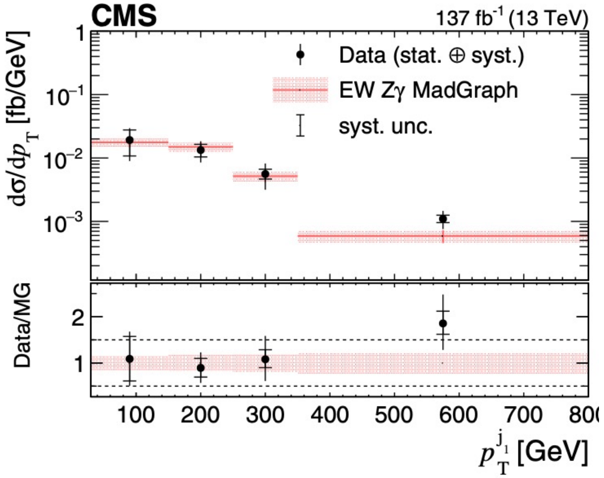
$$\sigma_{EW} = 4.49 \pm 0.40\,(\text{stat.}) \pm 0.42\,(\text{syst.})\ \text{fb}$$

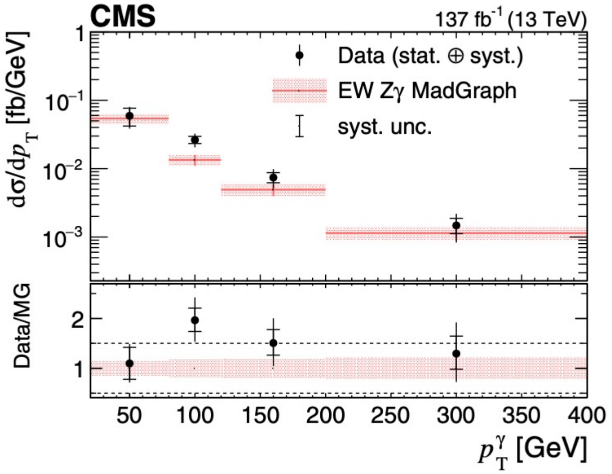
CMS

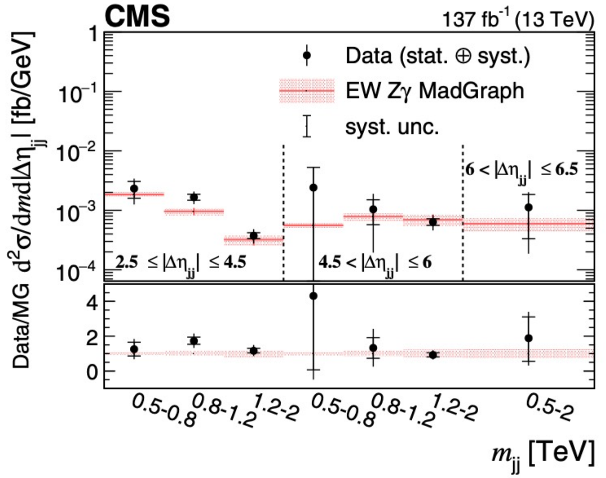
$$\sigma^{\text{fid}}_{\text{EW}} = 5.21 \pm 0.52(\text{stat}) \pm 0.56(\text{syst})\ \text{fb}$$
$$= 5.21 \pm 0.76\ \text{fb}.$$

Differential cross section









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

Generally good agreement with predictions

TABLE VII. 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 + QCD $Z\gamma$jj. 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)	$0.96^{+0.23}_{-0.21}$	0.0319 ± 0.0023	0.0306 ± 0.0070
[2.5, 4.5)	[800, 1200)	$1.34^{+0.23}_{-0.21}$	0.0140 ± 0.0011	0.0189 ± 0.0031
[2.5, 4.5)	[1200, 2000]	$1.09^{+0.26}_{-0.23}$	0.00445 ± 0.00038	0.0049 ± 0.0010
[4.5, 6.0)	[500, 800)	$0.52^{+1.3}_{-1.3}$	0.0123 ± 0.0012	0.006 ± 0.016
[4.5, 6.0)	[800, 1200)	$1.14^{+0.46}_{-0.42}$	0.0121 ± 0.0010	0.0138 ± 0.0053
[4.5, 6.0)	[1200, 2000]	$0.86^{+0.22}_{-0.20}$	0.00942 ± 0.00076	0.0081 ± 0.0020
[6.0, 6.5]	[500, 2000]	$0.3^{+1.6}_{-1.6}$	0.00864 ± 0.00049	0.0024 ± 0.0014

All close to 1 with uncertainties

Limit on aQGC

- CMS also set limit on aQGC, with events in dedicated search region with high pT photon. Fit on invariant mass of the Zγ system, $m_{Z\gamma}$

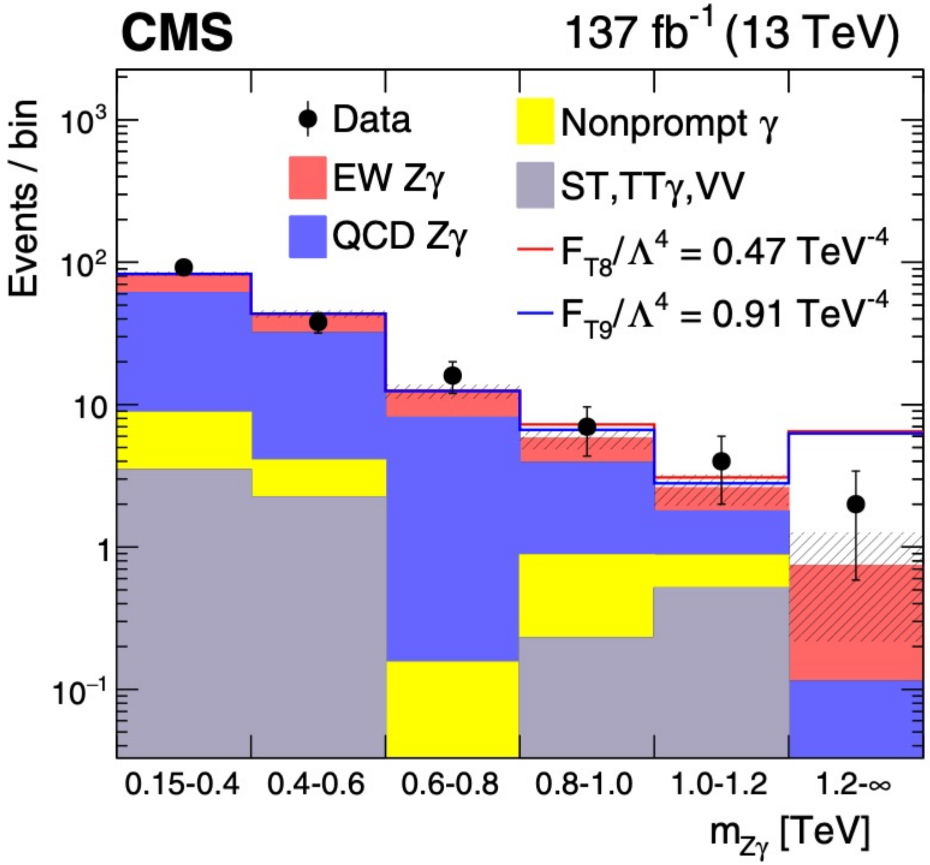


TABLE VIII. The expected and observed limits on the aQGC parameters at 95% confidence level. The last column presents the scattering energy values for which the amplitude would violate unitarity for the observed value of the aQGC parameter. All coupling parameter limits are set in TeV^{-4}, whereas the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

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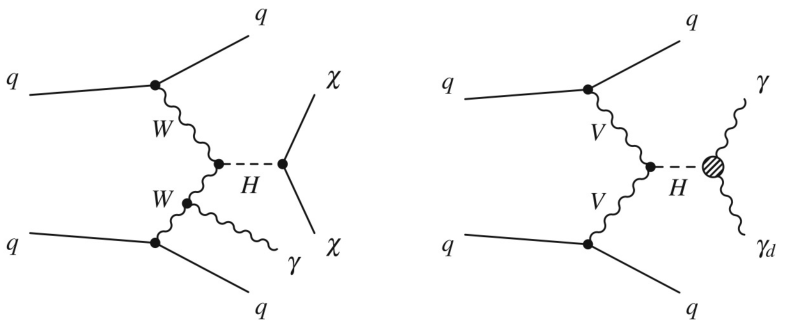
EW Z(νν)γ + jj

- Observation also done in the Z->νν channel by ATLAS, with full Run 2 data
- Signal generated with MG5
- Mostly focus on low energy region
- Also searches for BSM due to invisible Higgs decay or dark photon
- Several CRs defined to constrain backgrounds from different sources

Table 3 Summary of the requirements defining the baseline SR and various CRs considered in this analysis. Where present, the values in square brackets refer to the regions defined in the search for a $H \to \gamma\gamma_d$ signal. The leading and subleading jets must satisfy the fJVT requirements mentioned in Sect. 5. In the SR, $Z^{\gamma}_{\mathrm{Rev.Cen.}}$ CR, and Low-$E_{\mathrm{T}}^{\mathrm{miss}}$ VR definitions $E_{\mathrm{T}}^{\mathrm{miss,lep\text{-}rm}} \equiv E_{\mathrm{T}}^{\mathrm{miss}}$ since no lepton is present. The m_{T} variable is defined in Sect. 6.4. When the same requirement is applied to multiple regions, this is reported once in the corresponding row of the table, centred across columns, and is considered to be valid in all the columns to the left or right until a different requirement is explicitly reported

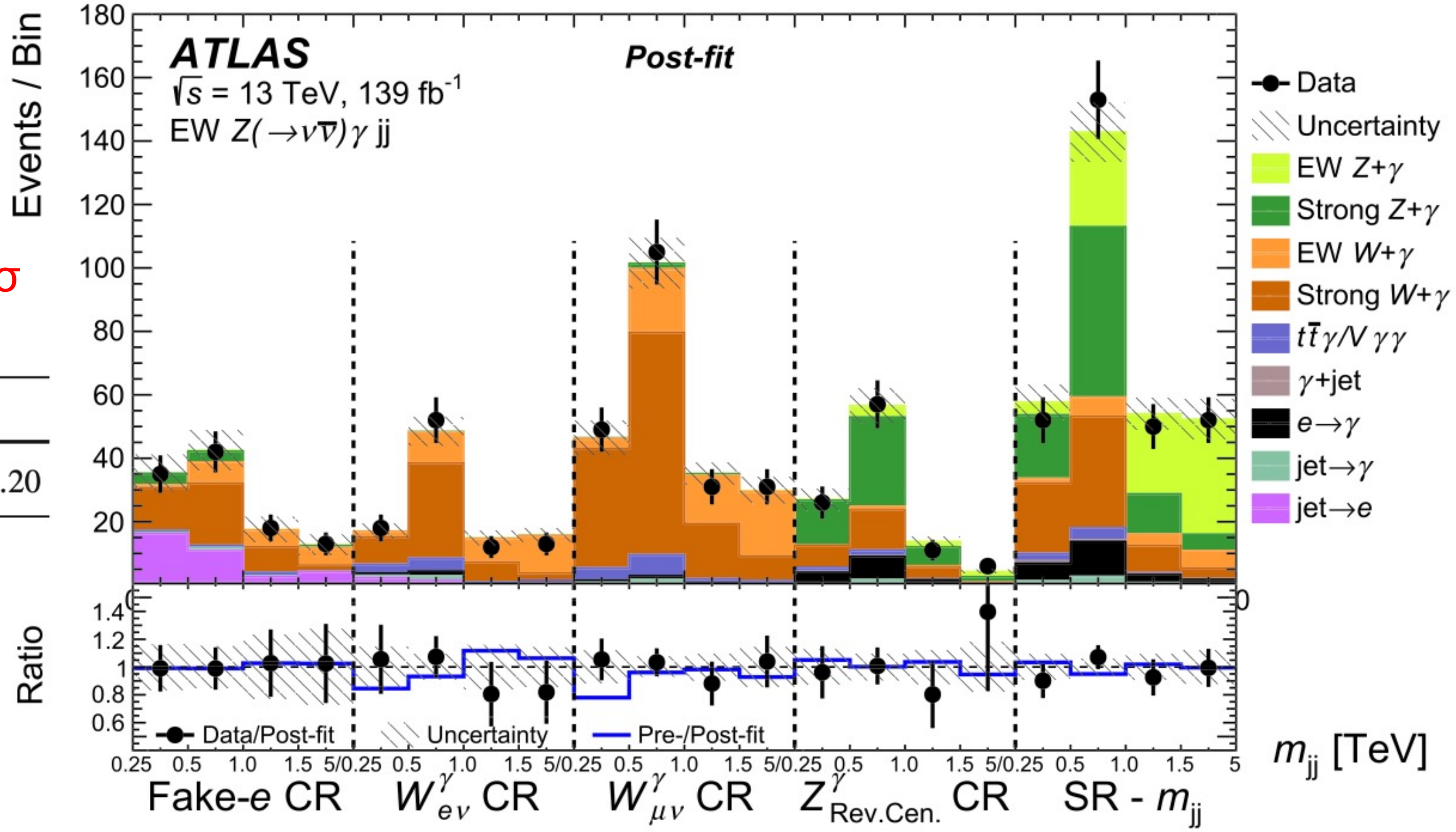
Variable	SR	$W^{\gamma}_{\mu\nu}$ CR	$W^{\gamma}_{e\nu}$ CR	$Z^{\gamma}_{\mathrm{Rev.Cen.}}$ CR	Fake-e CR	Low-$E_{\mathrm{T}}^{\mathrm{miss}}$ VR
$p_{\mathrm{T}}(j_1)$ [GeV]	> 60					
$p_{\mathrm{T}}(j_2)$ [GeV]	> 50					
$p_{\mathrm{T}}(j_{>2})$ [GeV]	> 25					
N_{jet}	2,3					
$N_{b\text{-jet}}$	<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



(a) Invisible Higgs boson signal **(b)** Dark-photon signal

Observation of the SM EW Z(νν)γ + jj

- Observation is achieved by fitting on the m_{jj}, in SR and CRs simultaneously



Observed (expected) significance: 5.2 (5.1)σ

Wγ and QCD Zγ is floating in the fit

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

Signal strength for EW Z(νν)γ + jj:

$$1.03 \pm 0.16(\text{stat}) \pm 0.19(\text{syst}) \pm 0.02(\text{lumi}).$$

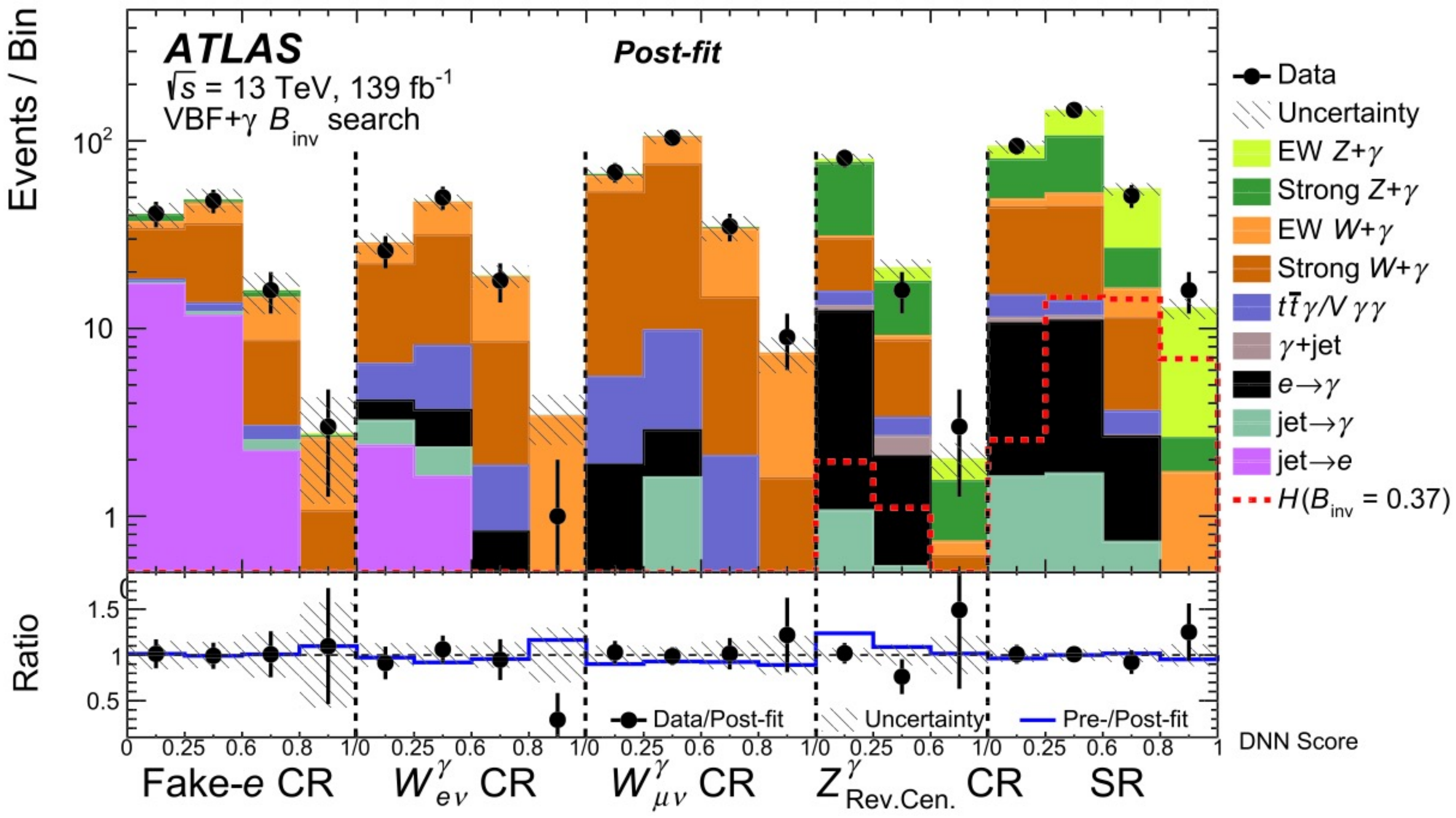
Measure fiducial cross section:

$$1.31 \pm 0.20(\text{stat}) \pm 0.20(\text{syst})\ \text{fb}$$

Search for H invisible decay

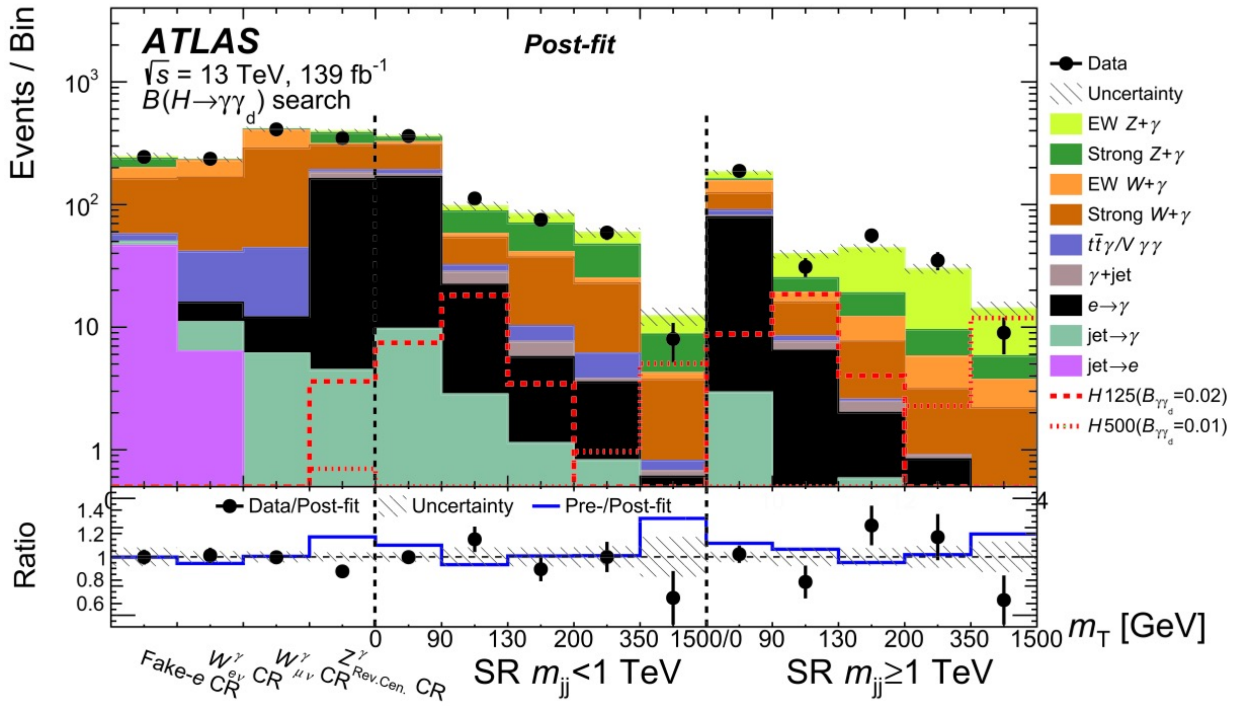
- DNN is trained and used to enhance sensitivity
- Looser event selections applied to increase statistic for DNN training

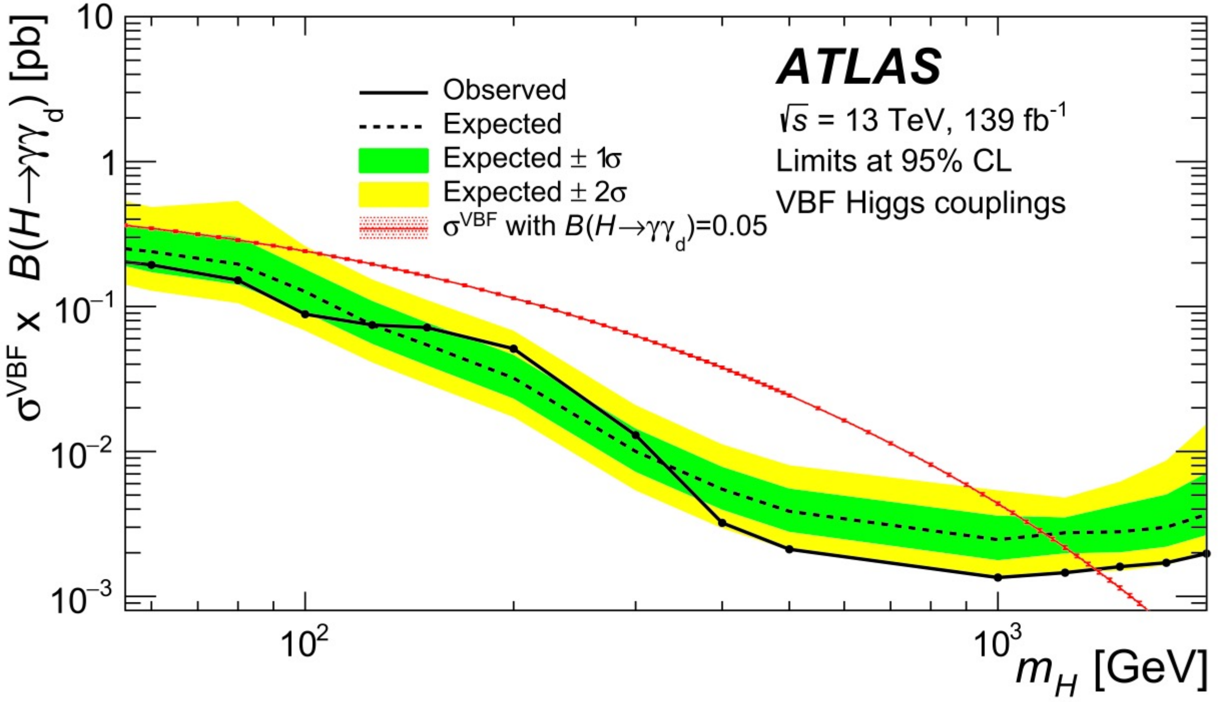
No evidence of new physics.
Observed (expected) 95% CL
upper limit on Higgs invisible decay
is set as 0.37 (0.34)



Search for Higgs decays to dark photon

- Transverse mass of the photon and MET systema is used for fitting

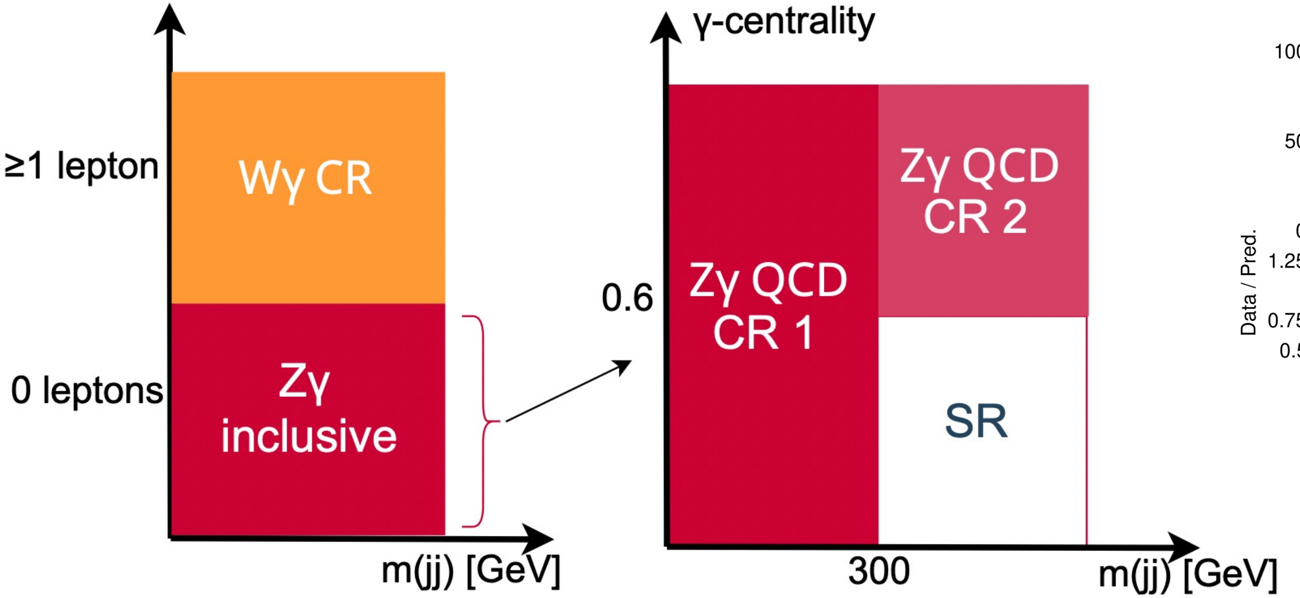


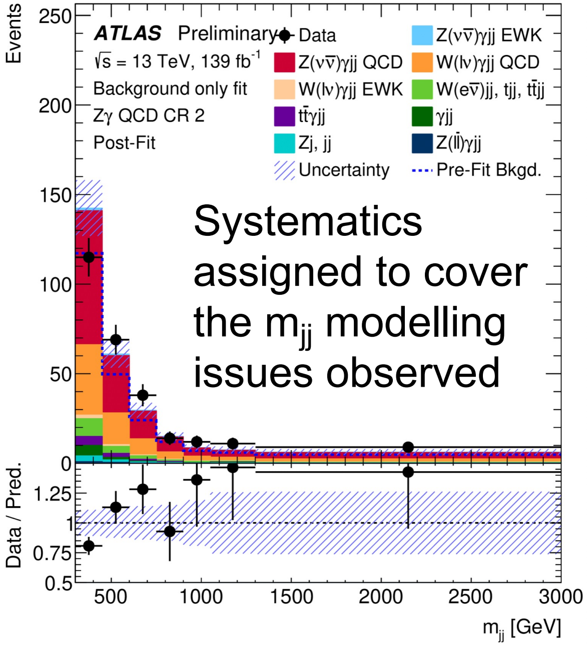


STDM-2018-59

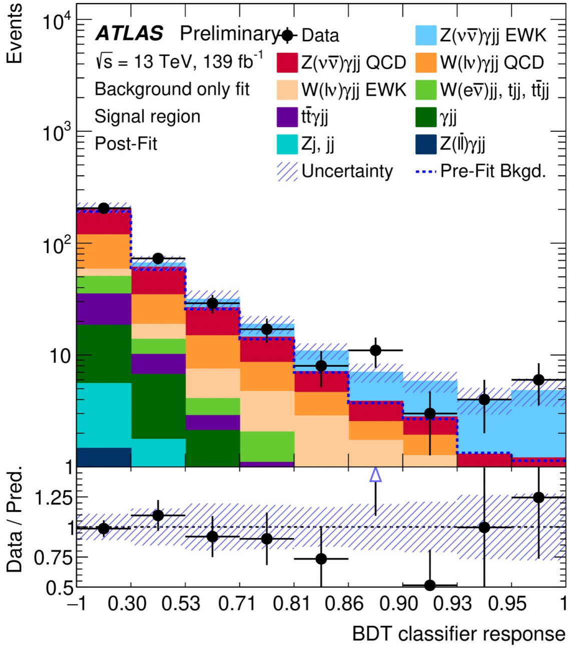
EW Z(vv)γ + jj in high energy region

- Anomalous couplings have larger contributions in high energy region, thus ATLAS has a dedicated analysis in those region, by requiring pT(γ) > 150 GeV
- Zγ QCD CR1: used to estimate QCD yield
- Zγ QCD CR2: used to check the m_{jj} modelling
- BDT used to extrapolate EW signal





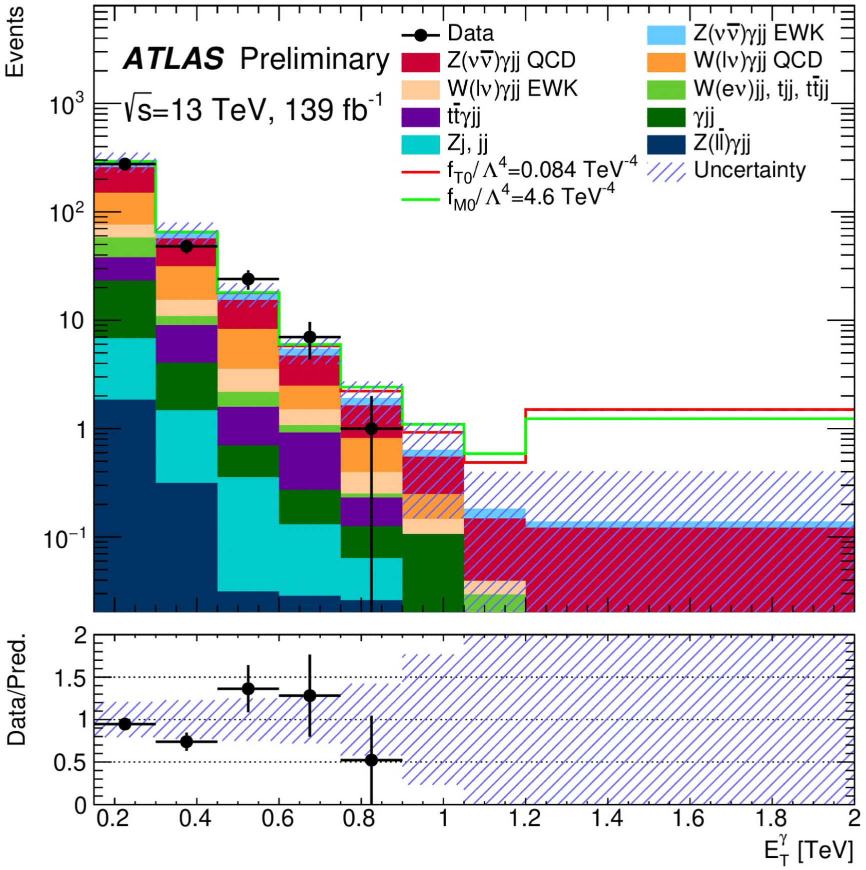
Systematics assigned to cover the m_{jj} modelling issues observed



Comparison with previous

POI	Value: Current analysis	Ref. [7]	Combination
$\mu_{Z\gamma\mathrm{EWK}}$	0.78 ± 0.33	1.04 ± 0.23	0.96 ± 0.18
$\mu_{Z\gamma\mathrm{QCD}}$	1.21 ± 0.37	1.02 ± 0.41	1.17 ± 0.27
$\mu_{W\gamma}$	1.02 ± 0.22	1.01 ± 0.20	1.01 ± 0.13

Limit on aQGC

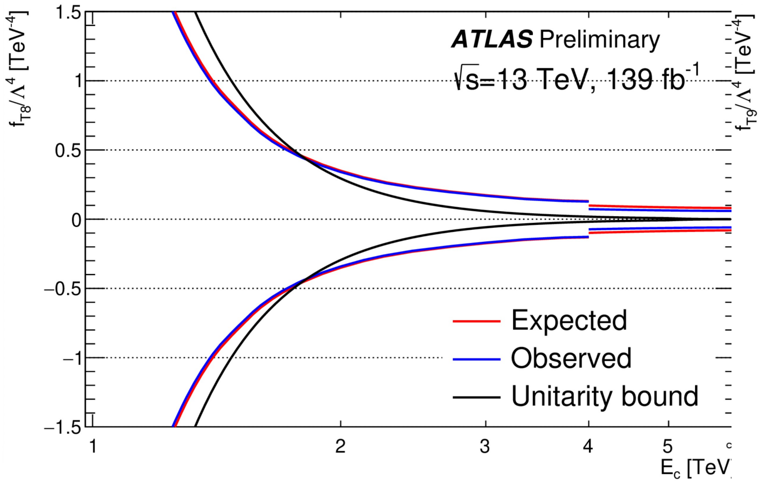


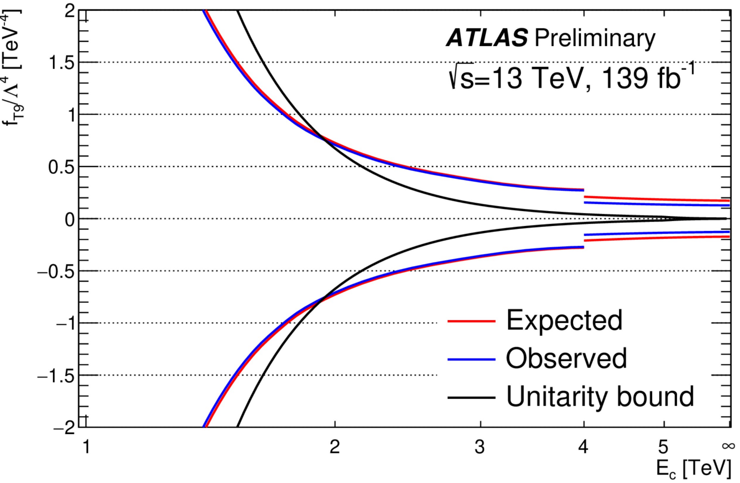
Photon E_T is used

Without cutoff

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	$[-1.9, 1.9]$	$[-2.6, 2.6]$

Limits vs. cutoff





SMP-21-011

EW Wγ + jj

- Measurements using full Run 2 data by CMS, with W decays leptonically
- EW and QCD Wγ + jj both generated with MG5
- Transverse mass of W, $m_T(W) > 30$ GeV
- Events selected requiring one good electron/muon, and one photon
  - In the electron channel, events with $|m_{e\gamma} - m_Z| < 10$ GeV are removed to suppress the background from Z->ee, where one electron mis-identified as a photon
  - Depending on photon pseudorapidity, events are further split into barrel and end-cap regions
- $m_{W\gamma} > 100$ GeV, $dy_{jj} > 2.5$ and additional angular cuts (between Wγ and jet system) to enhance the EW contributions
- SR: $m_{jj} > 500$ GeV. CR: $200 < m_{jj} < 500$ GeV.

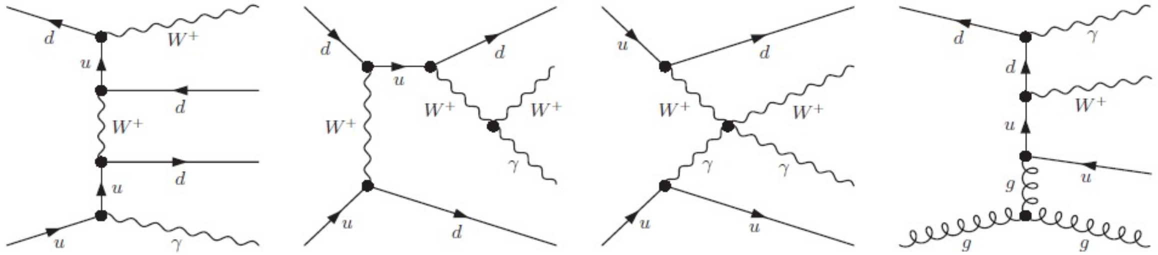
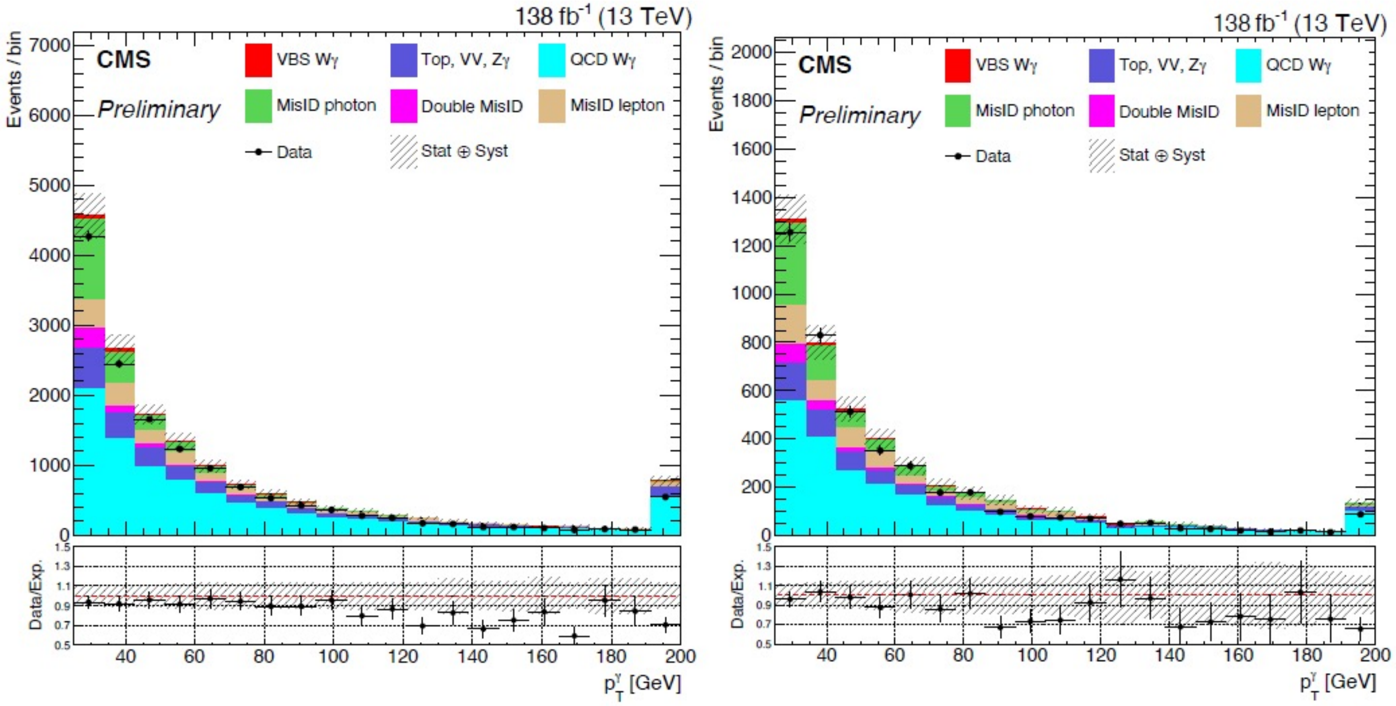


Figure 1: Representative Feynman diagrams for the Wγjj production at the LHC: EW (left), EW through triple (middle left) and quartic (middle right) gauge boson couplings, and QCD-induced (right).

Background estimation

- Background with mis-identified leptons or photons from jets are estimated with data
  - Mostly from W + jets and top processes
- Other background estimated from MC
- Validated in the CR

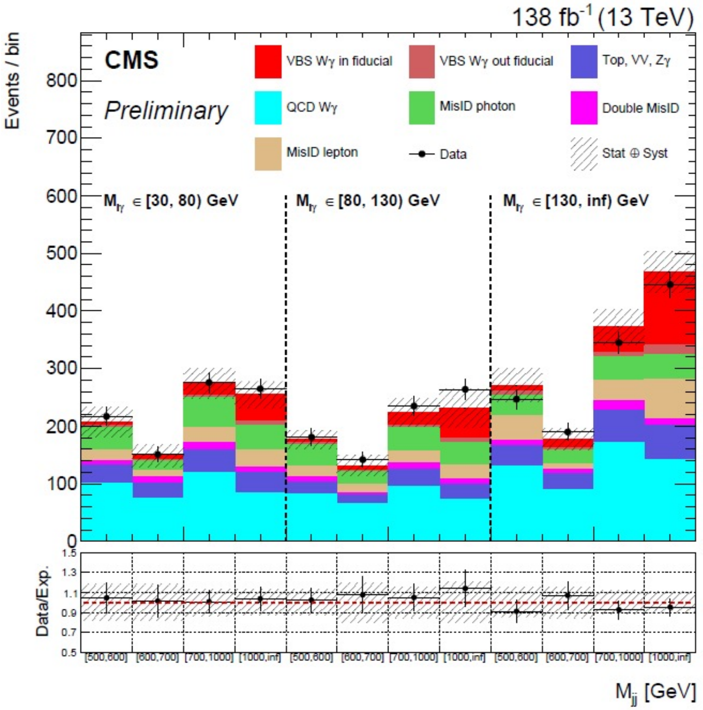


(a) Barrel (b) Endcap

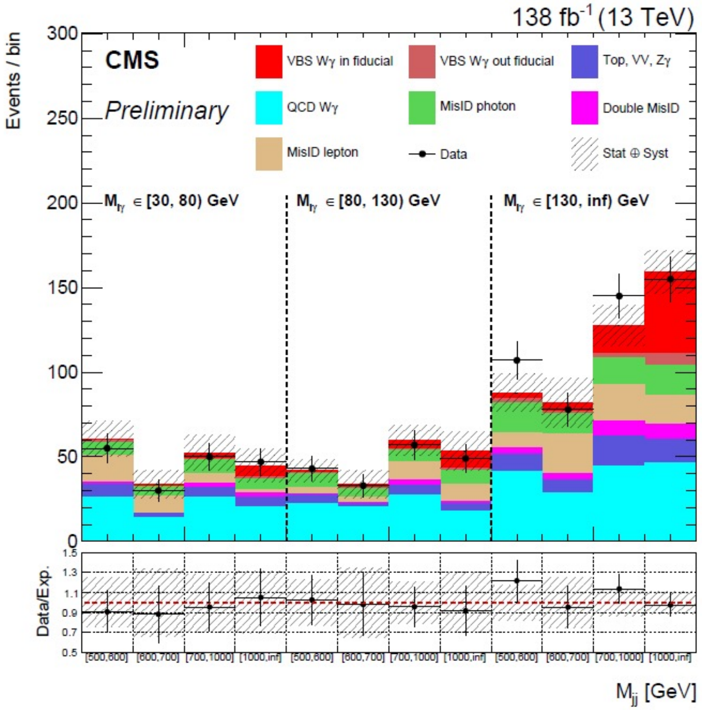
Observation of the EW processes

- Two dimensional distributions in m_{jj} and $m_{l\gamma}$ are used to extract the EW processes

	Barrel	Endcap
EW Wγ in fiducial	316 ± 16	90.2 ± 5.5
EW Wγ out fiducial	64.7 ± 2.0	20.4 ± 1.0
QCD Wγ	1301 ± 28	362 ± 13
$t\bar{t}\gamma$,VV,Zγ	402 ± 14	93.3 ± 7.2
Nonprompt photon	434 ± 13	120.2 ± 5.7
Nonprompt muon	134 ± 27	45 ± 11
Nonprompt electron	189 ± 20	86 ± 13
Nonprompt photon, nonprompt muon	43.0 ± 7.0	14.6 ± 3.4
Nonprompt photon, nonprompt electron	75.5 ± 5.5	25.0 ± 2.0
Total prediction	2960 ± 43	856 ± 21
Data	2959 ± 57	849 ± 32



(a) Barrel



(b) Endcap

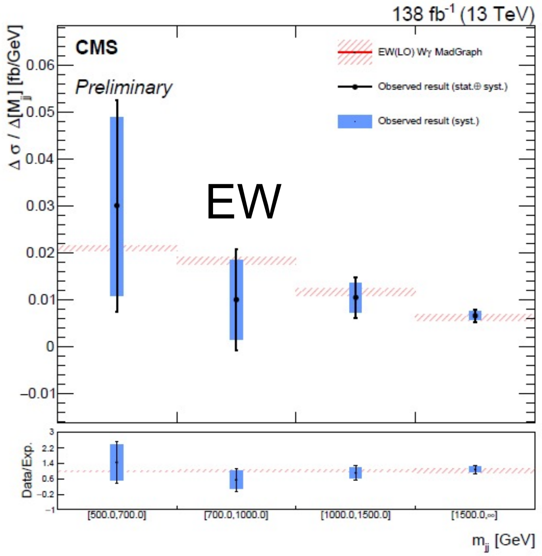
Observed (expected) significance: 6.03 (6.79)σ

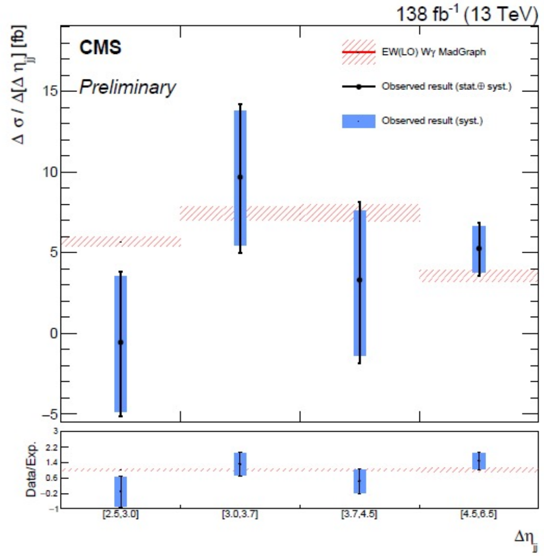
Measured fiducial cross sections

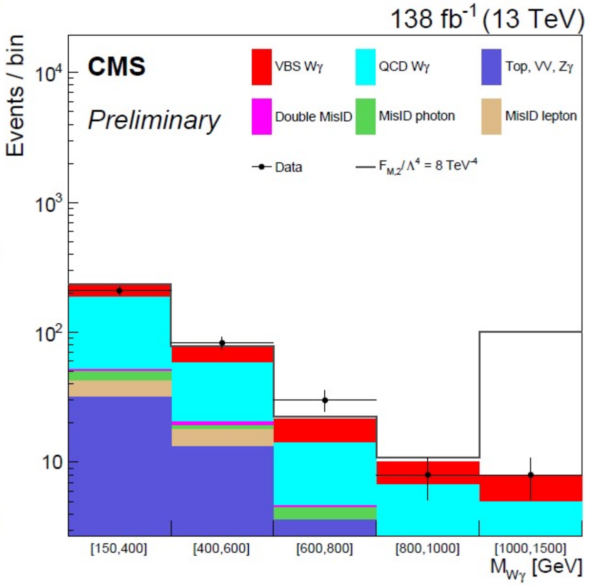
EW Wγjj (mu = 0.88 +0.19 -0.18): $\sigma^{\text{fid}}_{\text{EW}} = 19.2^{+2.3}_{-2.3}\,(\text{stat})^{+1.6}_{-1.4}\,(\text{theo})^{+2.9}_{-2.8}\,(\text{syst})\,\text{fb} = 19.2^{+4.0}_{-3.9}\,\text{fb}$

Inclusive Wγjj (mu = 0.98 +0.12 -0.11): $\sigma^{\text{fid}}_{\text{EW+QCD}} = 90^{+1.6}_{-1.6}\,(\text{stat})^{+2.0}_{-1.8}\,(\text{theo})^{+10}_{-10}\,(\text{syst})\,\text{fb} = 90^{+11}_{-10}\,\text{fb}$

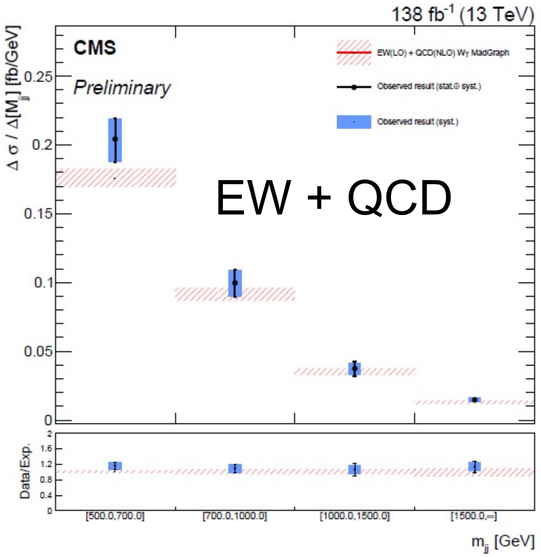
Differential cross section measurements and aQGC limit

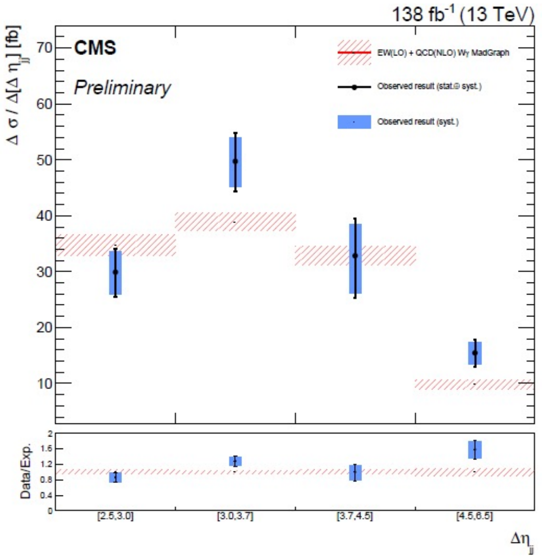






Expected. limit	Observed. limit	U_{bound}
$-5.1 < f_{M0}/\Lambda^4 < 5.1$	$-5.6 < f_{M0}/\Lambda^4 < 5.5$	1.7
$-7.1 < f_{M1}/\Lambda^4 < 7.4$	$-7.8 < f_{M1}/\Lambda^4 < 8.1$	2.1
$-1.8 < f_{M2}/\Lambda^4 < 1.8$	$-1.9 < f_{M2}/\Lambda^4 < 1.9$	2.0
$-2.5 < f_{M3}/\Lambda^4 < 2.5$	$-2.7 < f_{M3}/\Lambda^4 < 2.7$	2.7
$-3.3 < f_{M4}/\Lambda^4 < 3.3$	$-3.7 < f_{M4}/\Lambda^4 < 3.6$	2.3
$-3.4 < f_{M5}/\Lambda^4 < 3.6$	$-3.9 < f_{M5}/\Lambda^4 < 3.9$	2.7
$-13 < f_{M7}/\Lambda^4 < 13$	$-14 < f_{M7}/\Lambda^4 < 14$	2.2
$-0.43 < f_{T0}/\Lambda^4 < 0.51$	$-0.47 < f_{T0}/\Lambda^4 < 0.51$	1.9
$-0.27 < f_{T1}/\Lambda^4 < 0.31$	$-0.31 < f_{T1}/\Lambda^4 < 0.34$	2.5
$-0.72 < f_{T2}/\Lambda^4 < 0.92$	$-0.85 < f_{T2}/\Lambda^4 < 1.0$	2.3
$-0.29 < f_{T5}/\Lambda^4 < 0.31$	$-0.31 < f_{T5}/\Lambda^4 < 0.33$	2.6
$-0.23 < f_{T6}/\Lambda^4 < 0.25$	$-0.25 < f_{T6}/\Lambda^4 < 0.27$	2.9
$-0.60 < f_{T7}/\Lambda^4 < 0.68$	$-0.67 < f_{T7}/\Lambda^4 < 0.73$	3.1





Mass of the Wγ is used to set limit on aQGC, in an optimized region with higher mass/pT requirement

$$m_{jj} > 800\,\text{GeV},\ |\Delta\eta_{jj}| > 2.5,\ m_{W\gamma} > 150\,\text{GeV, and } p_T^{\gamma} > 100\,\text{GeV}$$

2004.10612, accepted by Nature Physics
Phys. Lett. B 812, 135992 (2020)

EW ZZjj

- Both experiments have studied this using full Run 2 data
  - Clear experimental signatures, particular in the ZZ->4l channel
  - Even lower statistic, compared to other channels
- ATLAS used both lllljj and llvvjj channel. CMS focused on lllljj
- EW signal modelled with both Powheg V2 and MG (for nominal and check) for ATLAS and CMS. Interference between EW and QCD diagrams estimated with MG
- Major background comes from the QCD production, and suffers from relatively poor modelling
  - Both analyses used data to constrain these processes
- MVA methods are used to increase sensitivity

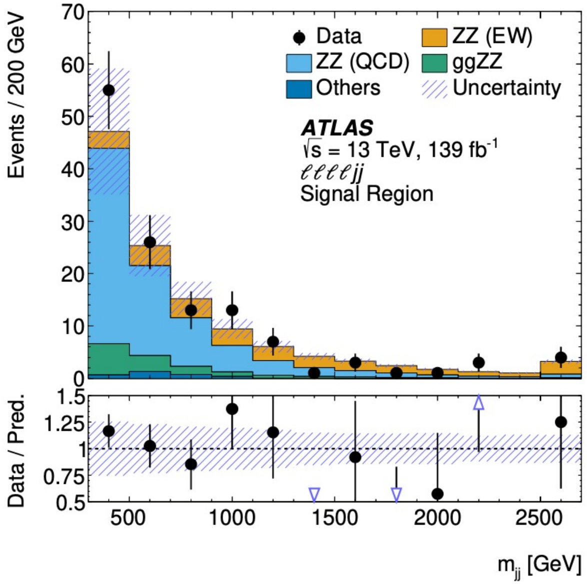
Selections to observe the EW ZZjj

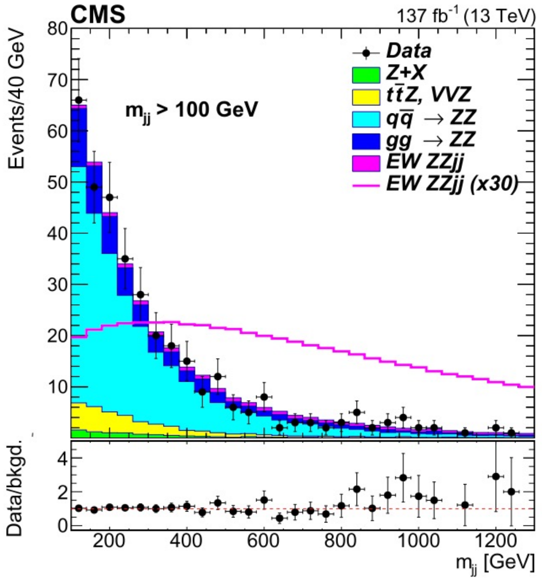
- Basic lepton selections to pick up two (one) on-shell Z boson in the llll (llvv) channel
- ATLAS trained BDTs in VBS-enriched regions, by requiring m_{jj} > 300 (400) GeV for llll (llvv) channel, and dy_{jj} > 2
- CMS used matrix element discriminant (K_D), with events in a much larger phase space: m_{jj} > 100 GeV

Year CMS	Signal (EW ZZjj)	Z+X	$q\bar{q} \to$ ZZjj	$gg \to$ ZZjj	$t\bar{t}Z + VVZ$	Total predicted	Data
			ZZjj inclusive				
2016 ($36\,fb^{-1}$)	6.3 ± 0.7	2.8 ± 1.1	65.6 ± 9.5	13.5 ± 2.0	8.4 ± 2.2	96 ± 13	95
2017 ($41\,fb^{-1}$)	7.4 ± 0.8	2.4 ± 0.9	77.7 ± 11.2	20.3 ± 3.0	9.6 ± 2.5	117 ± 15	111
2018 ($60\,fb^{-1}$)	10.4 ± 1.1	4.1 ± 1.6	98.1 ± 14.2	29.1 ± 4.3	14.2 ± 3.8	156 ± 20	159
All ($137\,fb^{-1}$)	24.1 ± 2.5	9.4 ± 3.6	241.5 ± 34.9	62.9 ± 9.3	32.2 ± 8.5	370 ± 48	365

ATLAS

Process	$\ell\ell\ell\ell jj$	$\ell\ell\nu\nu jj$
EW $ZZjj$	22.4 ± 2.5	13.6 ± 0.7
QCD $ZZjj$	77 ± 25	17.2 ± 3.5
QCD $ggZZjj$	13.1 ± 4.4	3.5 ± 1.1
Non-resonant-$\ell\ell$	–	21.4 ± 4.8
WZ	–	24.6 ± 1.1
Others	3.2 ± 2.1	1.2 ± 0.9
Total	115 ± 26	81.5 ± 6.4
Data	127	82

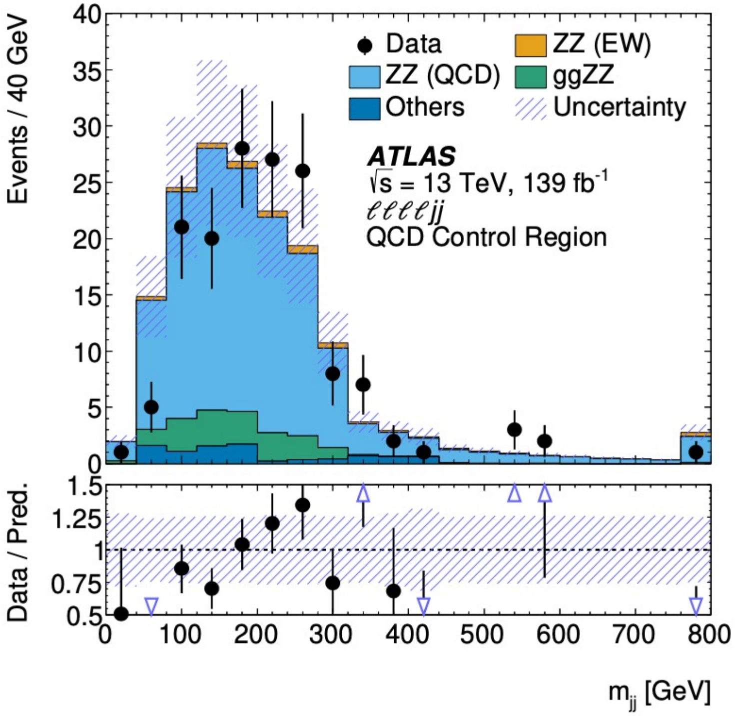


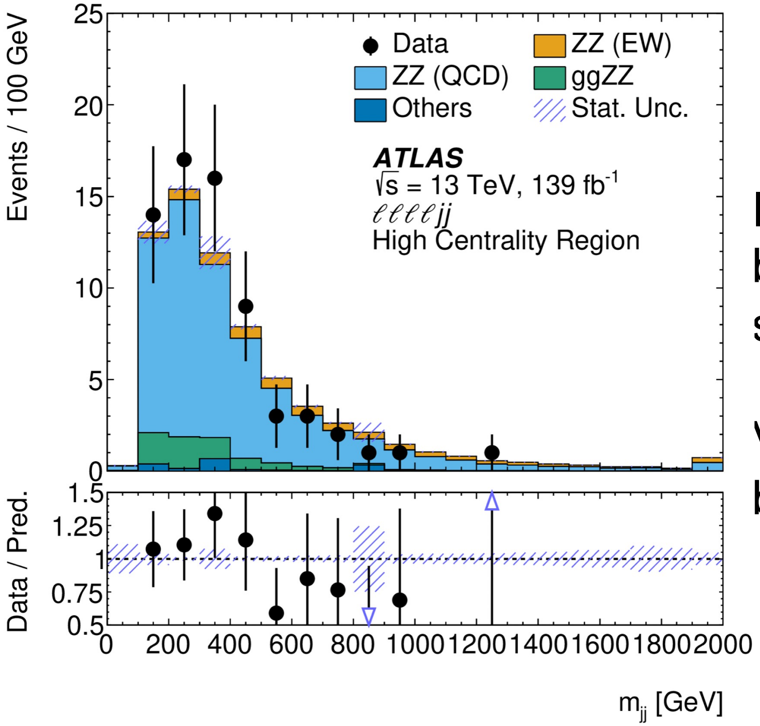


Starting from 300 GeV, event yields are quite comparable

Constrain the QCD ZZjj

- ATLAS used a dedicated QCD-enriched region by reverting either the m_{jj} or the dy_{jj} cut, to constrain the QCD ZZjj production
- In the final fit, different correlation schemes of the theoretical uncertainties in the SR and QCD CR are tested
- The m_{jj} modelling has been further checked in another high centrality validation region



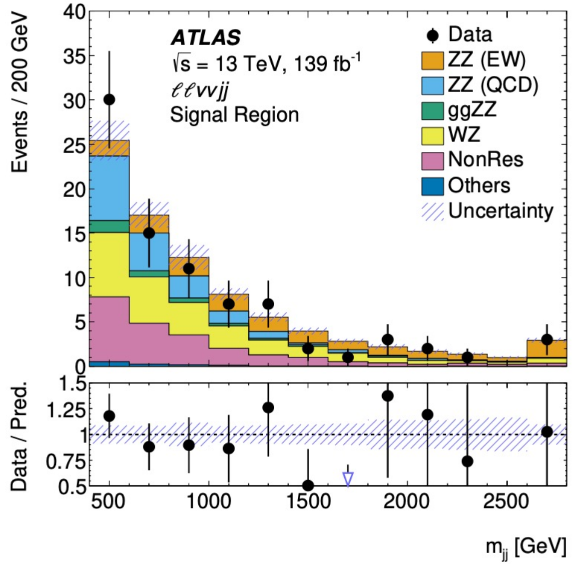


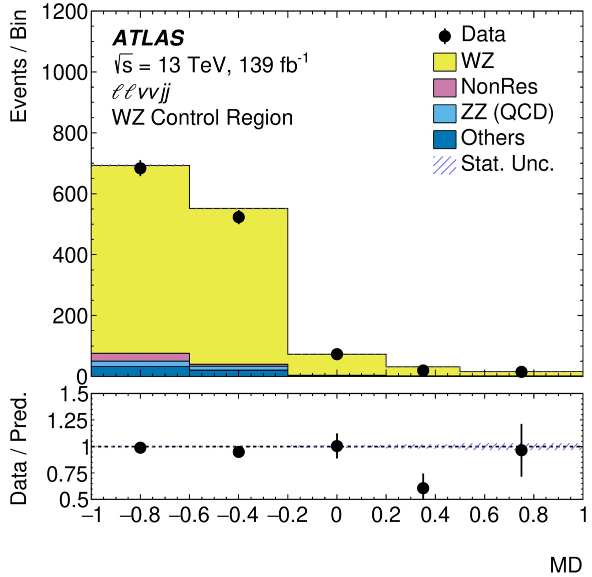
In general, no clear mismodelling has been observed, with the limited statistics in the ZZjj channel

Very conservative systematics have been assigned

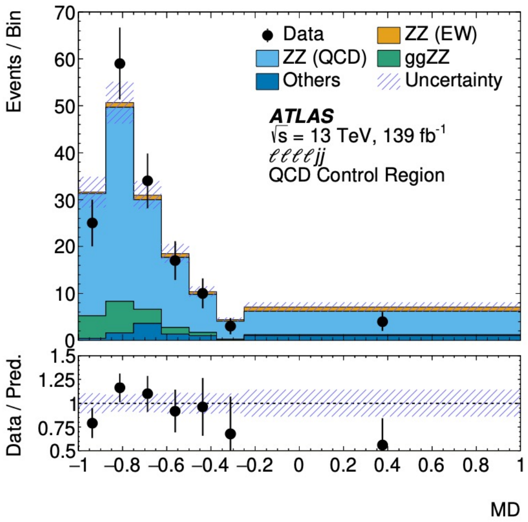
Background estimate in the llvv channel

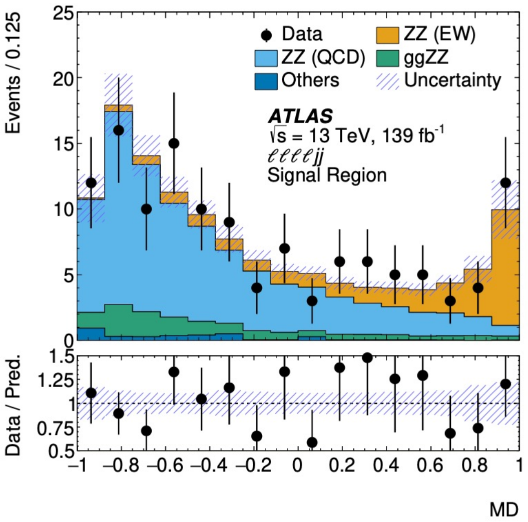
- ATLAS also explored the llvvjj channel
  - Larger and more complex background expected
  - Tighter cuts applied compared to llllljj channel
    - Higher jet kinematic requirements (pT, invariant mass)
    - MET-significance requirement to largely reduce Z+jet
  - WZjj - scaled with normalization factor derived in dedicated 3lepton control region
    - The EW WZjj has been scaled by 1.77 following previous ATLAS results in the EW WZjj analysis
  - NonRes (WWjj and ttbar) – estimated with a control region with em pair

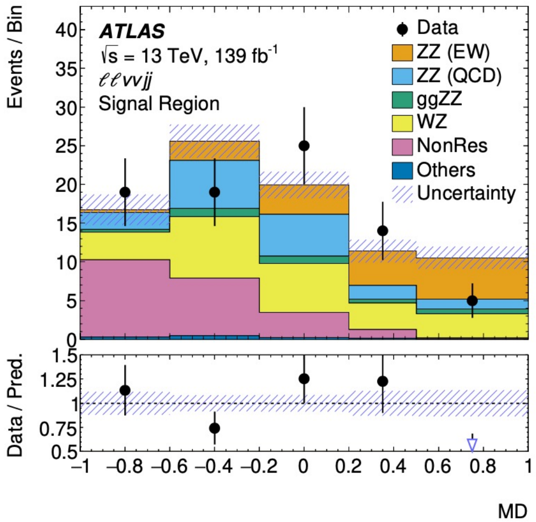


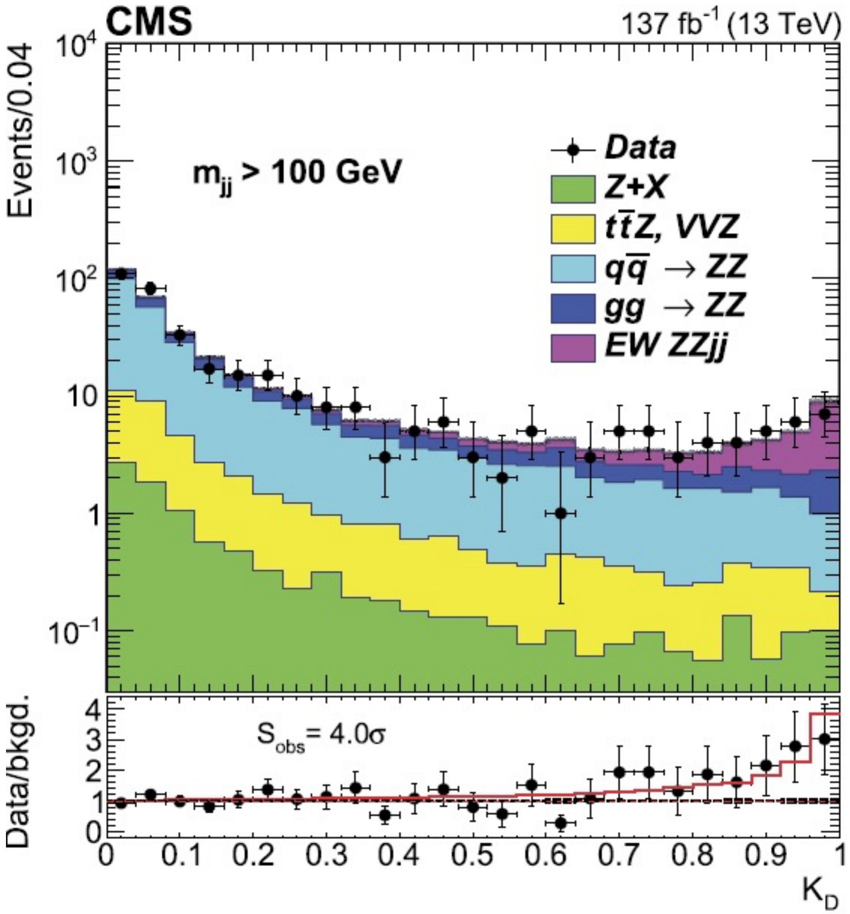


Multivariable analyses









BDT (ATLAS) and K_D (CMS) trained using sensitive variables

- ✓ Mostly jet related ones in llllјj
- ✓ Both jet and dilepton related ones are important in llvvjj

Simultaneous fit performed to get the final significance of EW ZZjj

ATLAS

	μ_{EW}	$\mu_{\text{QCD}}^{\ell\ell\ell\ell jj}$	Significance Obs. (Exp.)
$\ell\ell\ell\ell jj$	1.4 ± 0.4	0.98 ± 0.22	$5.5\ (4.4)\ \sigma$
$\ell\ell\nu\nu jj$	0.8 ± 0.6	–	$1.3\ (2.0)\ \sigma$
Combined	1.21 ± 0.31	0.99 ± 0.22	$5.7\ (4.8)\ \sigma$

Observation

CMS

Observed: 4.0σ

Expected: 3.5σ

$\mu_{\text{EW}} = 1.22^{+0.47}_{-0.40}$

Fiducial cross section measurements

ATLAS

EW ZZjj (combining llllјj and llvvjj): 0.82 +/- 0.21 fb

EW+QCD	Measured fiducial σ [fb]	Predicted fiducial σ [fb]
$\ell\ell\ell\ell jj$	$1.27 \pm 0.12(\text{stat}) \pm 0.02(\text{theo}) \pm 0.07(\text{exp}) \pm 0.01(\text{bkg}) \pm 0.02(\text{lumi})$	$1.16 \pm 0.04(\text{stat}) \pm 0.20(\text{theo})$
$\ell\ell\nu\nu jj$	$1.13 \pm 0.28(\text{stat}) \pm 0.04(\text{theo}) \pm 0.06(\text{exp}) \pm 0.15(\text{bkg}) \pm 0.02(\text{lumi})$	$1.07 \pm 0.01(\text{stat}) \pm 0.12(\text{theo})$

CMS

	Perturbative order	SM σ (fb)	Measured σ (fb)
		ZZjj inclusive	
	LO	0.275 ± 0.021	
EW	NLO QCD	0.278 ± 0.017	$0.33^{+0.11}_{-0.10}\,(\text{stat})^{+0.04}_{-0.03}\,(\text{syst})$
	NLO EW	$0.242^{+0.015}_{-0.013}$	
EW+QCD		5.35 ± 0.51	$5.29^{+0.31}_{-0.30}\,(\text{stat}) \pm 0.47\,(\text{syst})$
		VBS-enriched (loose)	
EW	LO	0.186 ± 0.015	$0.180^{+0.070}_{-0.060}\,(\text{stat})^{+0.021}_{-0.012}\,(\text{syst})$
	NLO QCD	0.197 ± 0.013	
EW+QCD		1.21 ± 0.09	$1.00^{+0.12}_{-0.11}\,(\text{stat}) \pm 0.07\,(\text{syst})$
		VBS-enriched (tight)	
EW	LO	0.104 ± 0.008	$0.09^{+0.04}_{-0.03}\,(\text{stat}) \pm 0.02\,(\text{syst})$
	NLO QCD	0.108 ± 0.007	
EW+QCD		0.221 ± 0.014	$0.20^{+0.05}_{-0.04}\,(\text{stat}) \pm 0.02\,(\text{syst})$

CMS has reported cross sections in several fiducial regions, the inclusive ,VBS-enriched (loose) and VBS-enriched (tight), defined with different m_{jj} and dy_{jj} cuts

Constraint on aQGC

- CMS also set limit on the sensitive aQGCs, using the m_{4l} distributions, and get the most stringent limits to date on the neutral current operators T8 and T9
- Very sensitive in the last bin, containing overflow events with m_{4l} > 1400 GeV

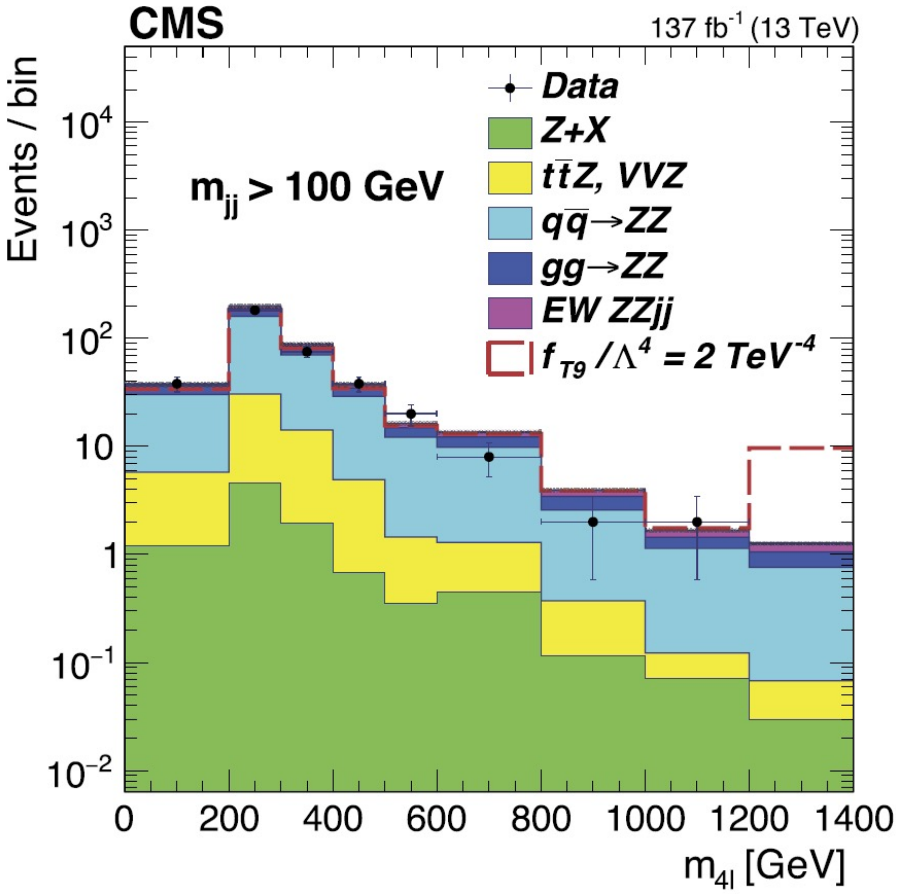
$$-0.24 < f_{T0}/\Lambda^4 < 0.22$$

$$-0.31 < f_{T1}/\Lambda^4 < 0.31$$

$$-0.63 < f_{T2}/\Lambda^4 < 0.59$$

$$-0.43 < f_{T8}/\Lambda^4 < 0.43$$

$$-0.92 < f_{T9}/\Lambda^4 < 0.92$$



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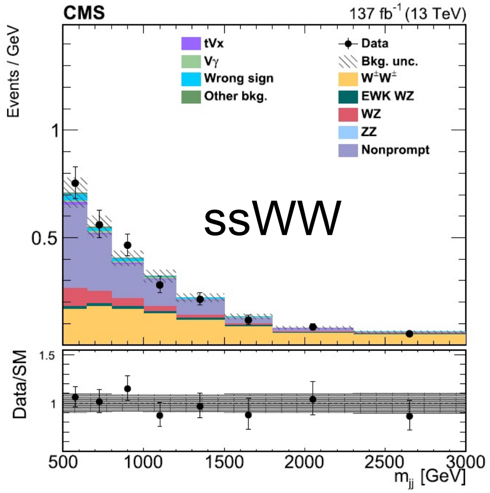
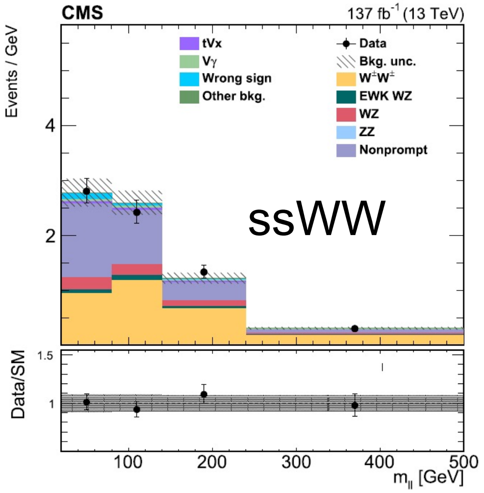
EW WZ and same-sign WW

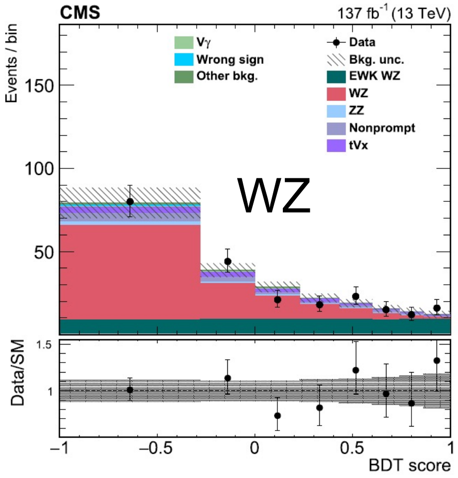
- Both collaborations have published results in those channels. CMS has used the full Run 2 data

Summary of the selection requirements defining the $W^{\pm}W^{\pm}$ and WZ SRs. The looser lepton p_T requirement on the WZ selection refers to the trailing lepton from the Z boson decays. The $|m_{\ell\ell} - m_Z|$ requirement is applied to the dielectron final state only in the $W^{\pm}W^{\pm}$ SR.

Variable	$W^{\pm}W^{\pm}$	WZ
Leptons	2 leptons, $p_T > 25/20$ GeV	3 leptons, $p_T > 25/10/20$ GeV
p_T^j	>50 GeV	>50 GeV
$\lvert m_{\ell\ell} - m_Z \rvert$	>15 GeV (ee)	<15 GeV
$m_{\ell\ell}$	>20 GeV	—
$m_{\ell\ell\ell}$	—	>100 GeV
p_T^{miss}	>30 GeV	>30 GeV
b quark veto	Required	Required
$\max(z_\ell^*)$	<0.75	<1.0
m_{jj}	>500 GeV	>500 GeV
$\lvert\Delta\eta_{jj}\rvert$	>2.5	>2.5





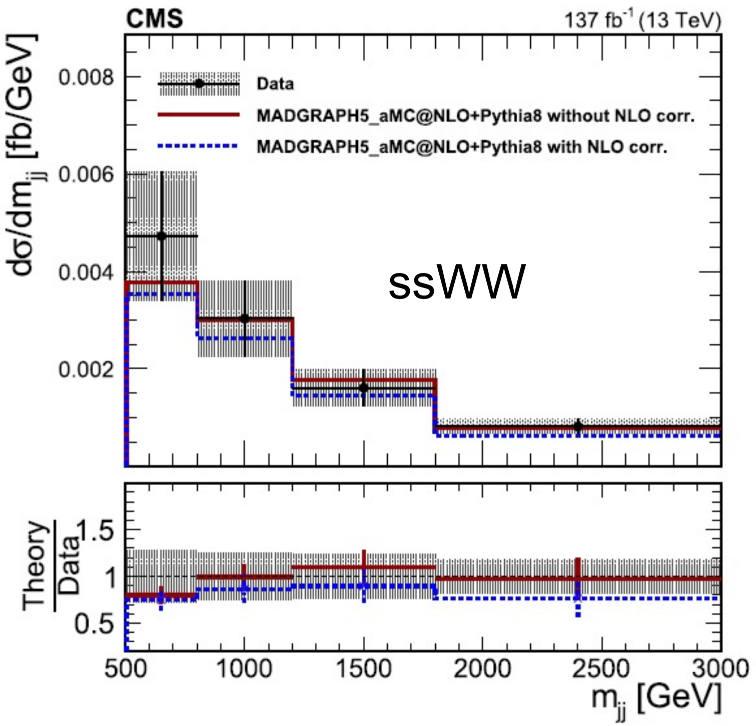


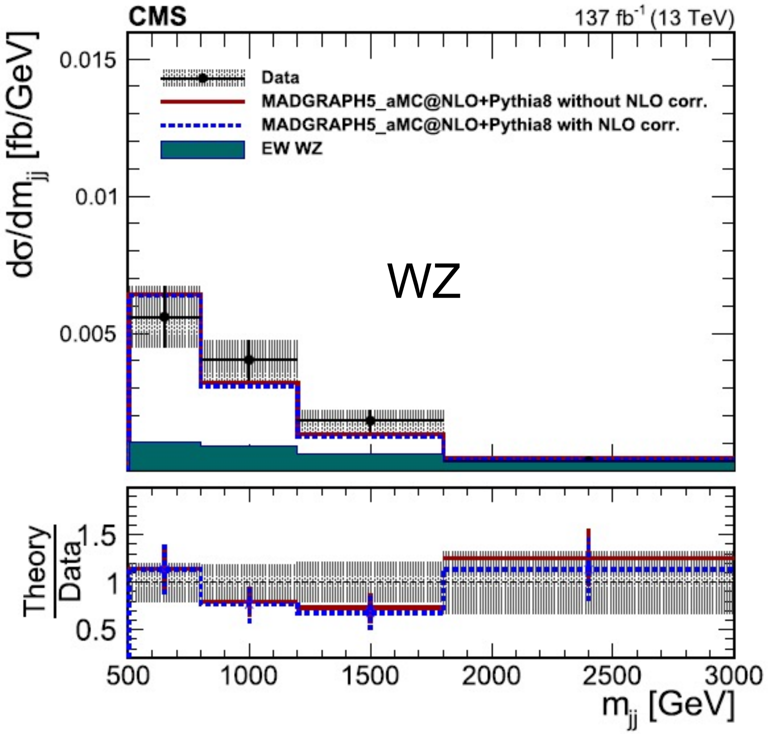
2D fit (m_{jj} vs m_{ll}) for ssWW
BDT for WZ

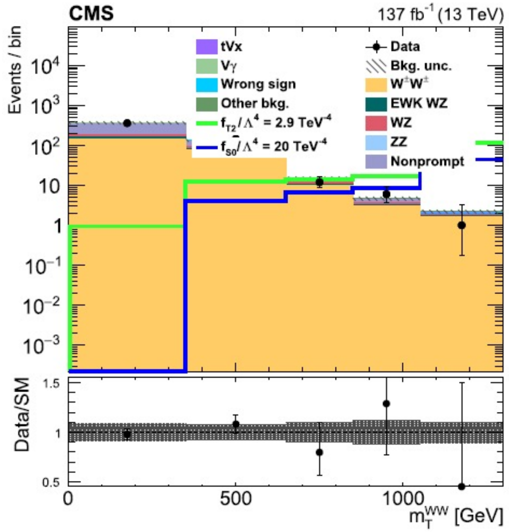
Significance

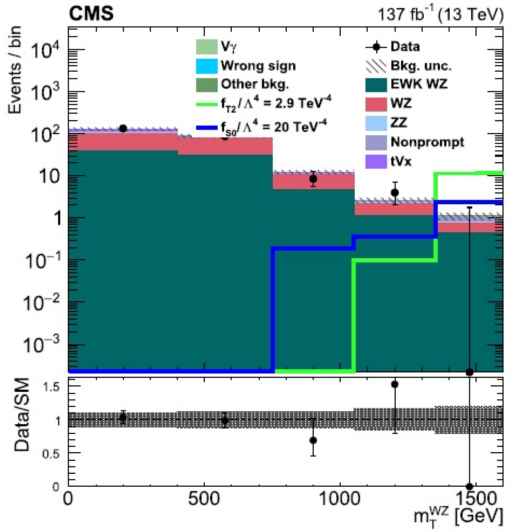
WZ: 6.8 (5.3) σ for observed (expected)
ssWW: already far above 5σ

Cross sections and aQGC









Process	$\sigma\mathcal{B}$ (fb)	Theoretical prediction without NLO corrections (fb)	Theoretical prediction with NLO corrections (fb)
EW $W^{\pm}W^{\pm}$	3.98 ± 0.45 $0.37\,(\text{stat}) \pm 0.25\,(\text{syst})$	3.93 ± 0.57	3.31 ± 0.47
EW+QCD $W^{\pm}W^{\pm}$	4.42 ± 0.47 $0.39\,(\text{stat}) \pm 0.25\,(\text{syst})$	4.34 ± 0.69	3.72 ± 0.59
EW WZ	1.81 ± 0.41 $0.39\,(\text{stat}) \pm 0.14\,(\text{syst})$	1.41 ± 0.21	1.24 ± 0.18
EW+QCD WZ	4.97 ± 0.46 $0.40\,(\text{stat}) \pm 0.23\,(\text{syst})$	4.54 ± 0.90	4.36 ± 0.88
QCD WZ	3.15 ± 0.49 $0.45\,(\text{stat}) \pm 0.18\,(\text{syst})$	3.12 ± 0.70	3.12 ± 0.70

SMP-21-001

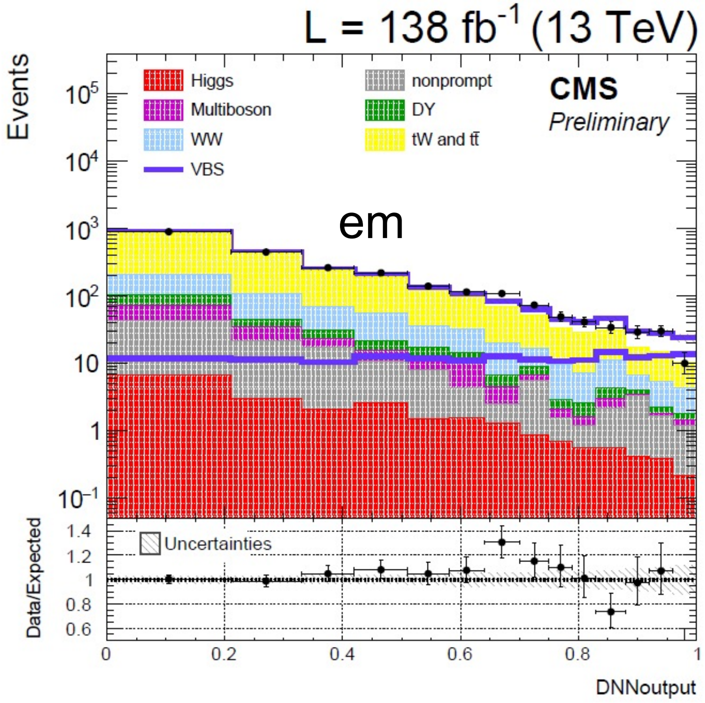
EW opposite-sign WWjj

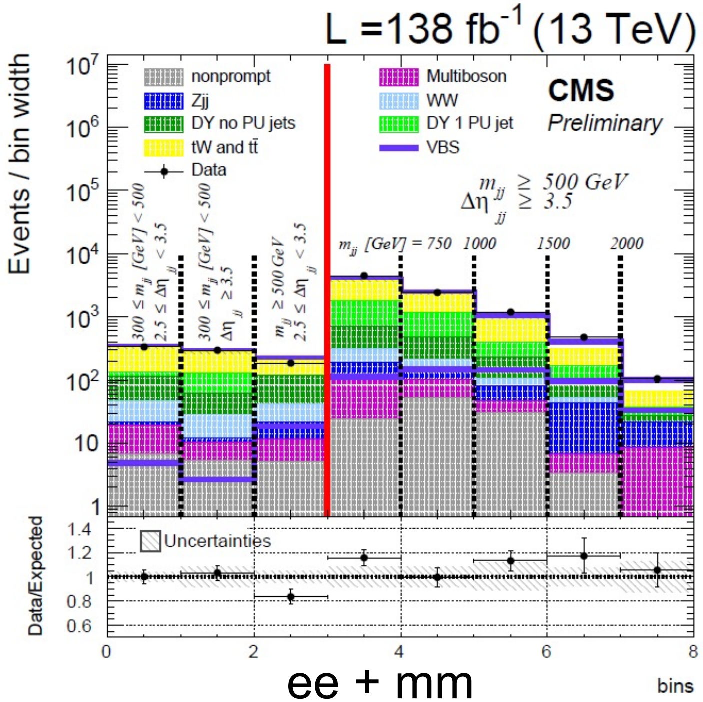
- CMS also released the results in WW channel with opposite sign, with full Run 2 data
- EW WWjj modeled with MG5. QCD WWjj with Powheg v2. Interference estimated at percent level
- Events categorized in different lepton flavor and centrality regions

Objects	Requirements
Leptons	$e\mu, ee, \mu\mu$ final state, opposite charge $p_T^\ell = p_T^{bare\,\ell} + \sum_i p_T^{\gamma_i}$ if $\Delta R(\ell,\gamma_i) < 0.1$ $p_T^{\ell_1} > 25\,\text{GeV}$, $p_T^{\ell_2} > 13\,\text{GeV}$, $p_T^{\ell_3} < 10\,\text{GeV}$ $\lvert\eta\rvert < 2.5$ $p_{T\ell\ell} > 30\,\text{GeV}$, $m_{\ell\ell} > 50\,\text{GeV}$
Jets	$p_T^j > 30\,\text{GeV}$ $\Delta R(j,\ell) > 0.4$ At least 2 jets, no b jets $\lvert\eta\rvert < 4.7$ $m_{jj} > 300\,\text{GeV}$, $\Delta\eta_{jj} > 2.5$
MET	$p_T^{miss} > 20\,\text{GeV}$

Observation of the EW processes

- Different discriminators are used for the fit
  - In em channel – DNN
  - In ee/mm channel with VBS enhance region (m_{jj} > 500 GeV and dy_{jj} > 3.5) – m_{jj}
  - Other regions – one bin event count





ee + mm

Observed significance: 5.6σ

Fiducial cross section

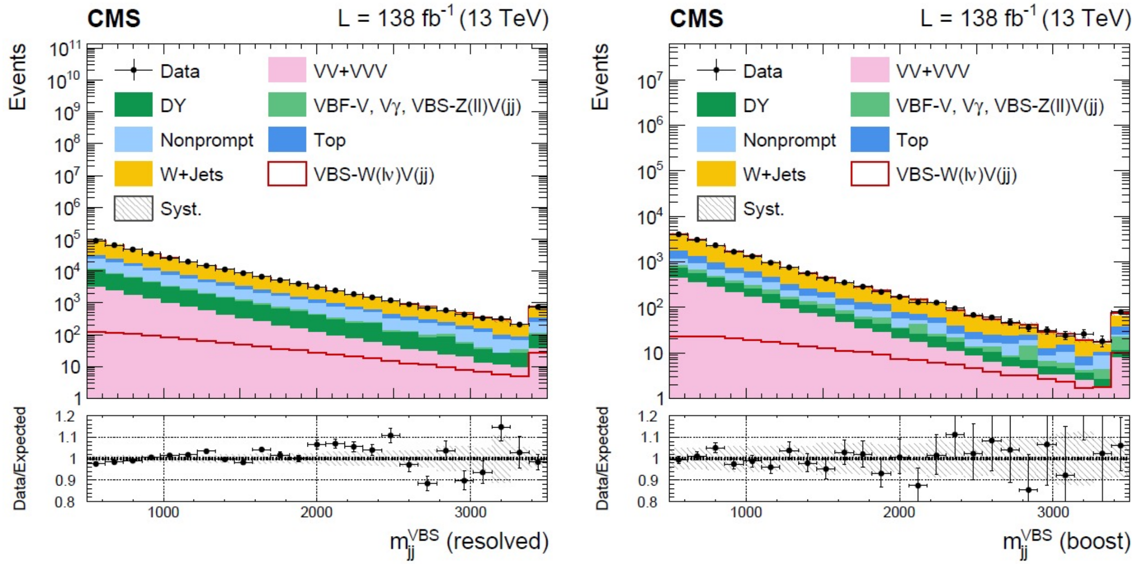
Measured: 10.2 +/- 2.0 fb

Predicted: 9.1 +/- 0.6 fb

SMP-20-013

EW WW/WZ + jj in semi-leptonic channel

- CMS has released results in the semi-leptonic channel (lvjj) of WW/WZ decay, with full Run 2 data
- EW WVjj from MG. The Z(ll)V(jj), with one lepton beyond the acceptance, is treated as background. Interference between EW and QCD is checked to be below 3% and is neglected
- Both large R (0.8) and small R (0.4) jets are used. Events are split into two categories based on the jets from V decay
  - Boosted category – events with one large R jet from V decay
  - Resolved category – events with two small R jets from V decay. In such case, the jet pair with m_{jj} closest to 85 GeV is chosen
  - Higher priority for boosted category
- For the two tag jets (VBS jets)
  - m_{jj} > 500 GeV and dy_{jj} > 2.5



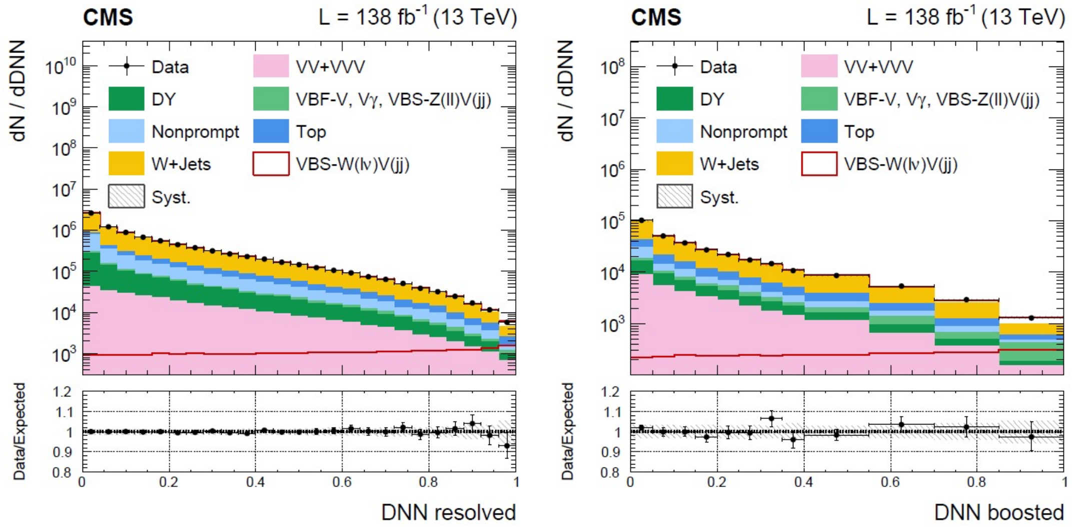
Evidence of the EW processes

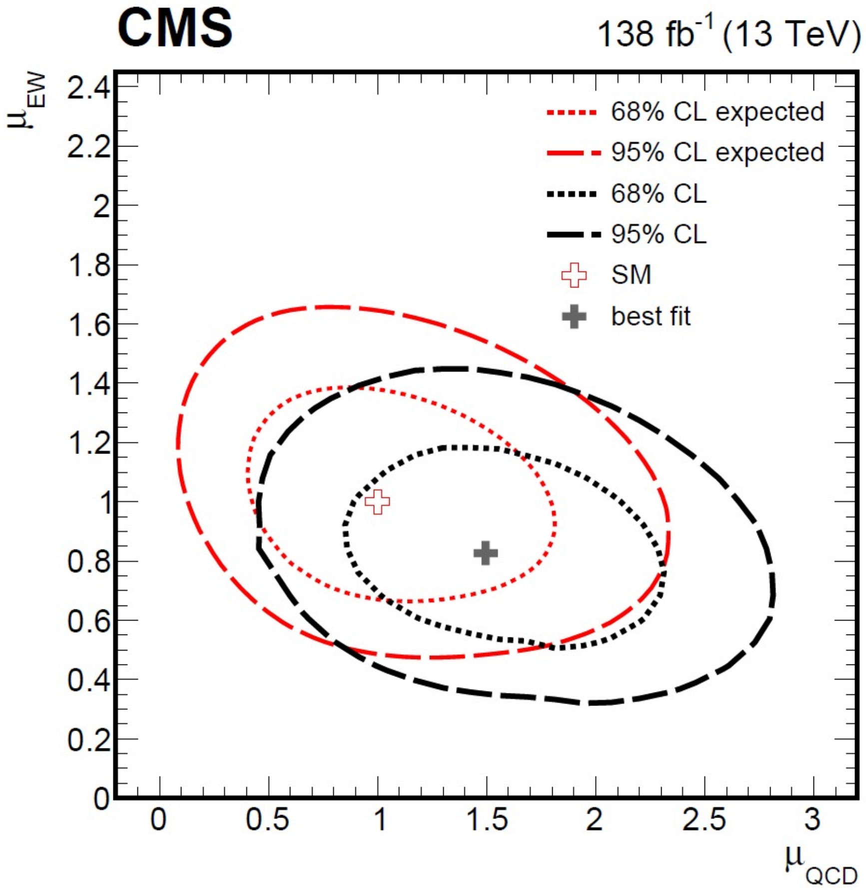
- Three scenarios considered
  - EW-signal-only fit – fix the QCD WV contributions as SM prediction, $\mu_{QCD} = 1$
  - Treat the EW and QCD together as signal – $\mu_{EW} = \mu_{QCD}$
  - Simultaneous fit the EW and QCD – μ_{EW}, μ_{QCD} both floating
- In the EW-signal-only case
  - Observed (expected) significance: 4.4 (5.1)σ

$$\mu_{EW} = \frac{\sigma^{obs}}{\sigma^{SM}} = 0.85 \pm 0.12\,(\text{stat})^{+0.19}_{-0.17}\,(\text{syst}) = 0.85^{+0.23}_{-0.21},$$

- In the second case $\mu_{EW+QCD} = 0.97 \pm 0.06\,(\text{stat})^{+0.19}_{-0.21}\,(\text{syst}) = 0.97^{+0.20}_{-0.22},$

DNN used



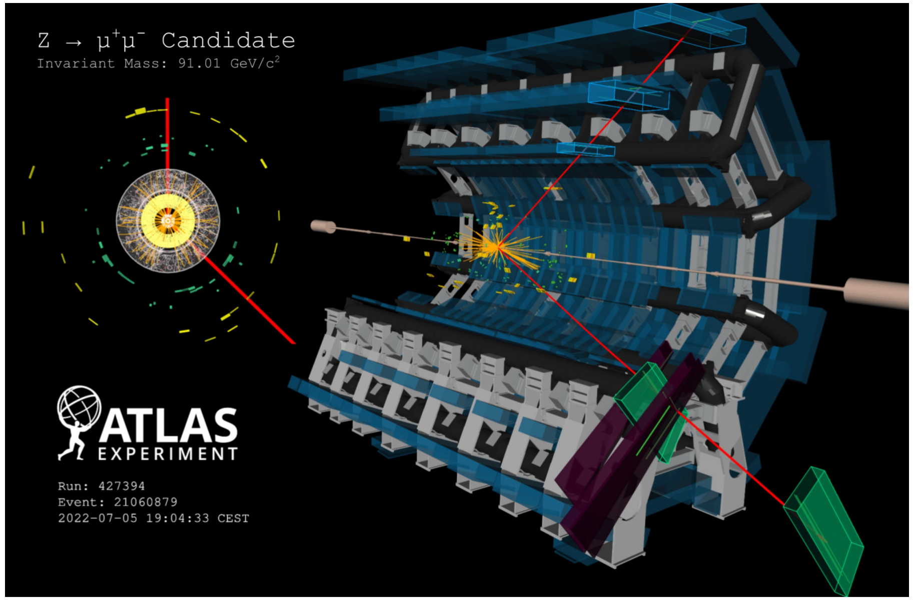


Summary

- Overview of the EW V + jj and VV + jj measurements at ATLAS and CMS, focus on the VBF and VBS processes
- With successful run and data-taking during Run 2, and comprehensive analysis studies, the VBF and VBS processes have been observed in all the boson channels
- Moving to new stage and start looking into detailed differential measurements

- Looking forward to the Run 3 data!

Candidate Z->mm event from 13.6 TeV collision!



This presentation focuses on full Run 2 results, unless only partial data results available
All public results are available at
ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/Publications
CMS: http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP/index.html

backup

EW W + jj

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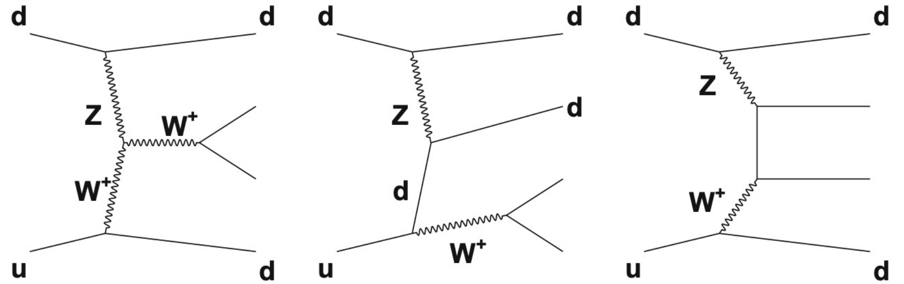
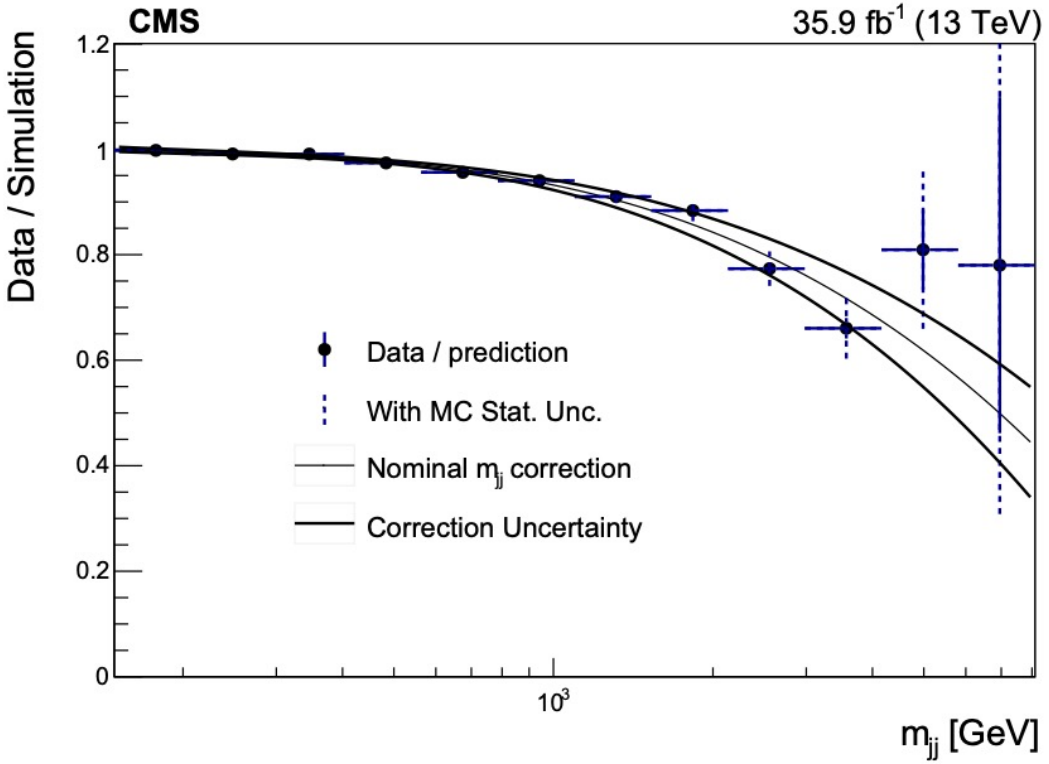


- Partial Run 2 data used, 35.9 fb^{-1}
- Signal at LO with MadGraph5_aMC@NLO. QCD W events generated with MadGraph5_aMC@NLO with up to 3 partons at NLO, and up to 4 partons at LO
- Interference calculated with MG5
- m_{jj} > 200 GeV. Event pT balance, R(pT) < 0.2

$$R(p_T) = \frac{|\vec{p}_{Tj_1} + \vec{p}_{Tj_2} + \vec{p}_{TW}|}{|\vec{p}_{Tj_1}| + |\vec{p}_{Tj_2}| + |\vec{p}_{TW}|}$$

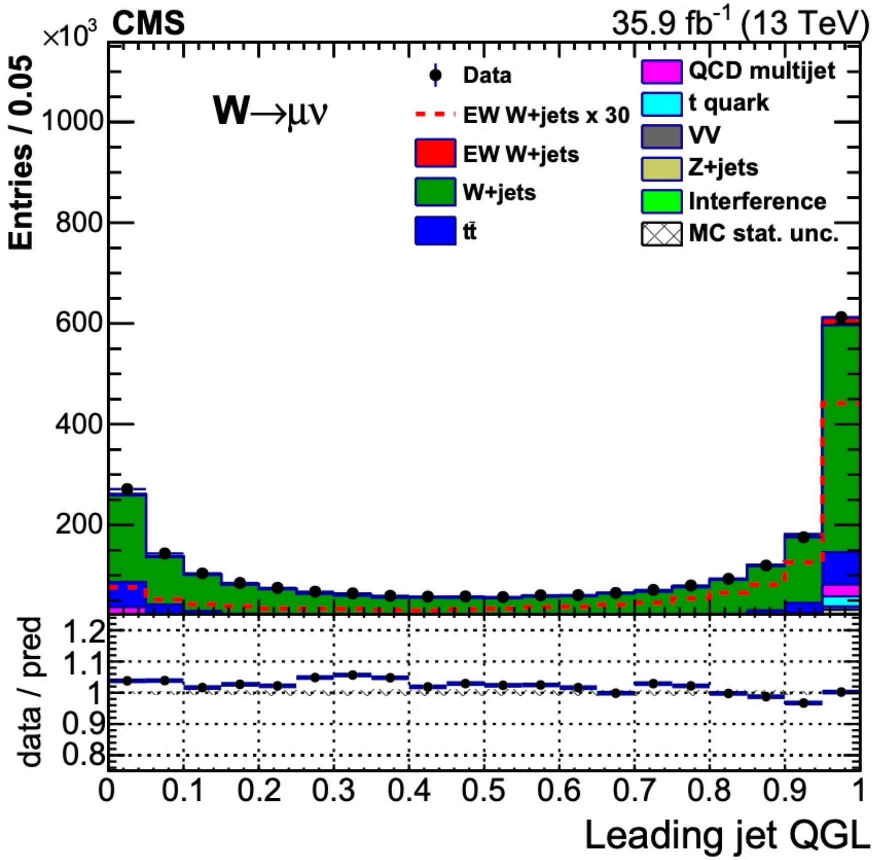
- BDT used to separate EW and QCD Wjj
- m_{jj} correction applied, since a systematic overestimation of the simulation yields is caused by a partial mistiming of the signals in the forward region of the ECAL endcaps

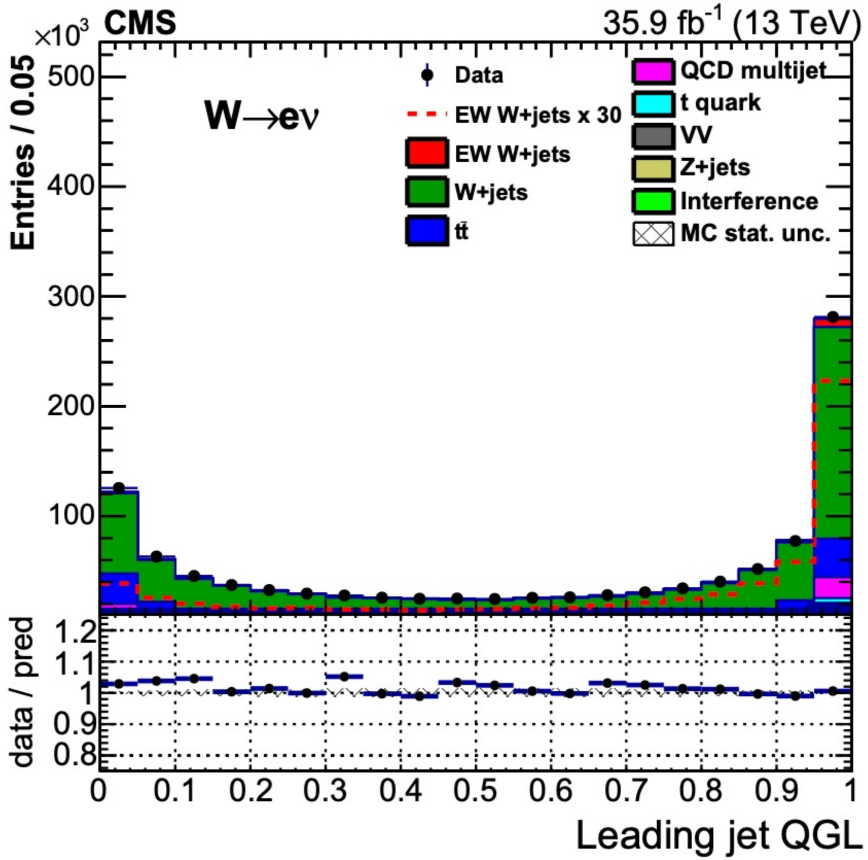


Derived in the region with R(pT) > 0.2

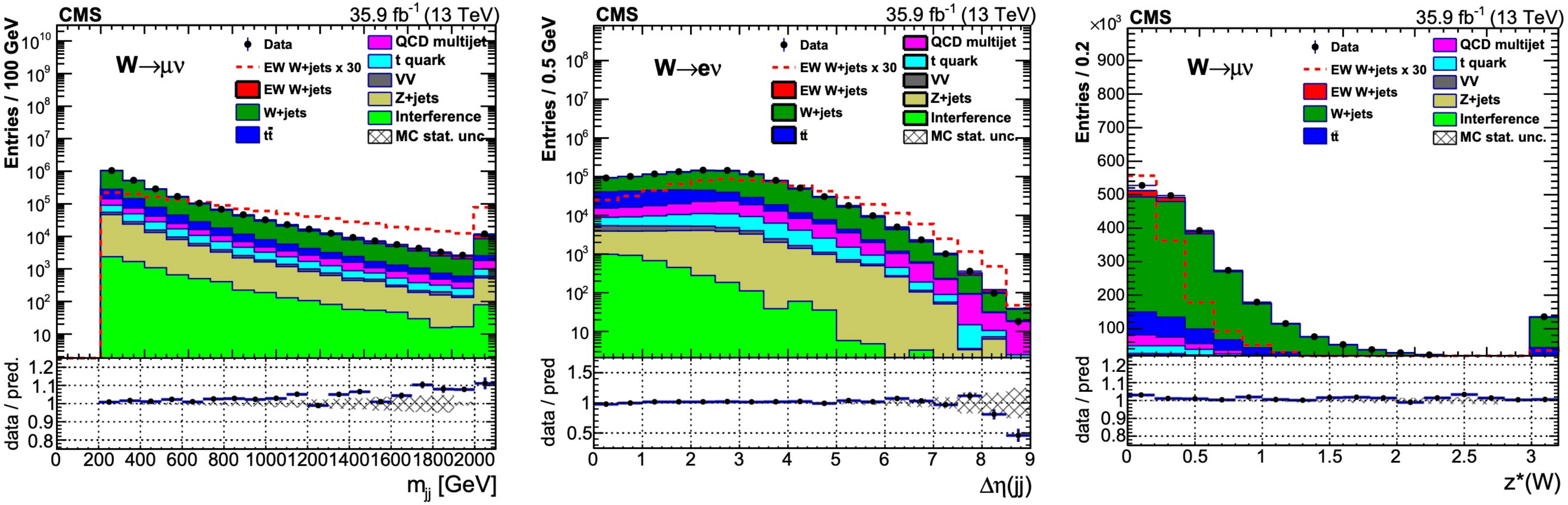
Jet from quarks/gluon

- A quark-gluon likelihood (QGL) discriminant is evaluated for the two tagging jests
  - Exploits differences in the showering and fragmentation of quarks and gluons



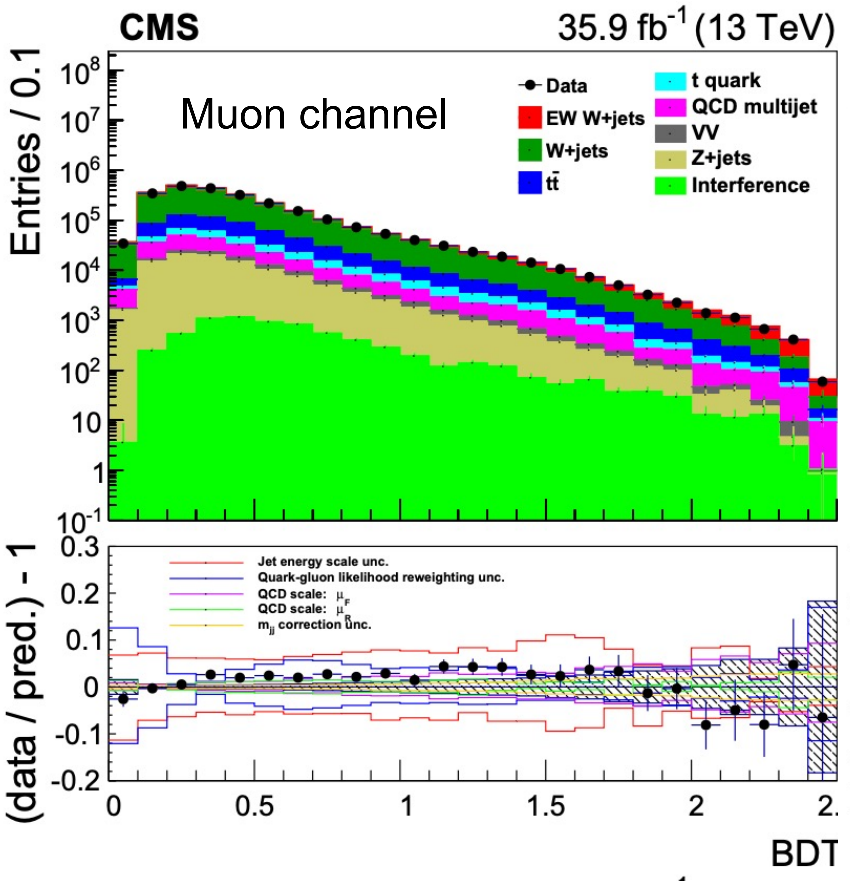


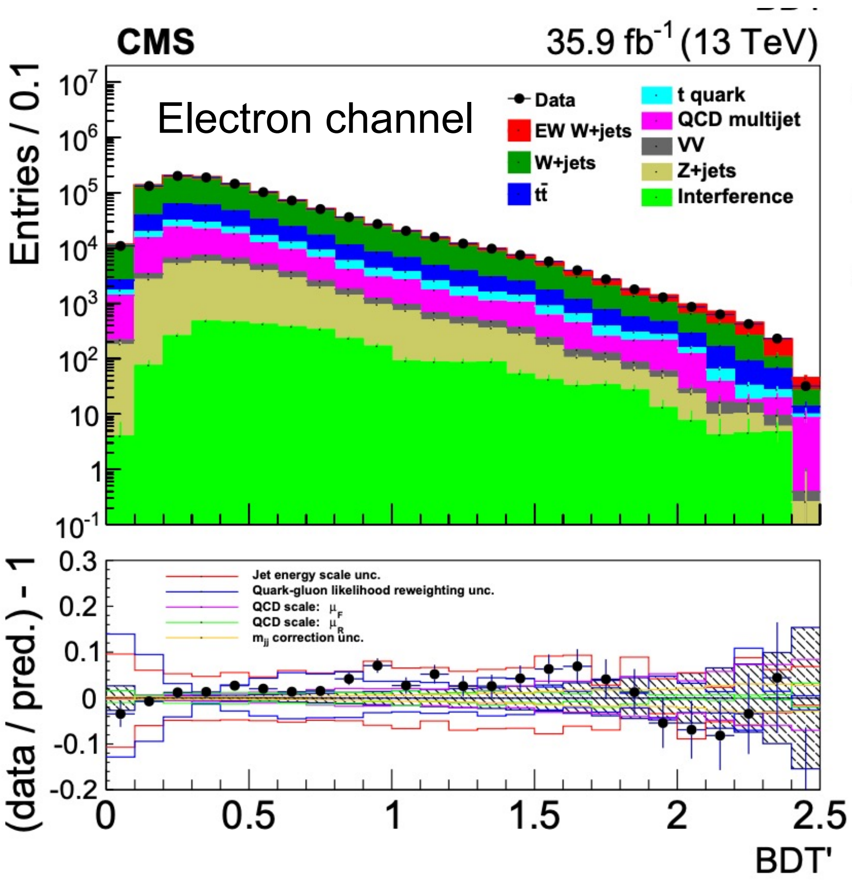
Sensitive variables



In general good agreement

BDT results





From the combined fit of the two channels, the signal strength is measured to be

$$\mu = 0.91 \pm 0.02\,(\text{stat}) \pm 0.10\,(\text{syst}) = 0.91 \pm 0.10\,(\text{total}),$$

corresponding to a measured signal cross section

$$\sigma(\text{EW } \ell\nu\text{jj}) = 6.23 \pm 0.12\,(\text{stat}) \pm 0.61\,(\text{syst})\,\text{pb}$$
$$= 6.23 \pm 0.62\,(\text{total})\,\text{pb},$$

Sample	BDT > 0.95	
	μ	e
VV	11.0 ± 2.5	9.6 ± 2.8
DY Zjj	9.4 ± 5.9	7.7 ± 3.0
$t\bar{t}$	146 ± 17	102 ± 12
Single top quark	35.5 ± 5.6	25.7 ± 4.2
QCD multijet	98 ± 39	17.0 ± 5.6
DY Wjj	356 ± 65	240 ± 41
Interference	18.2 ± 8.1	9.8 ± 5.5
Total backgrounds	674 ± 78	412 ± 44
EW Wjj signal	503 ± 54	308 ± 34
EW Zjj signal	11.2 ± 1.3	6.6 ± 0.9
Total prediction	1186 ± 95	726 ± 56
Data	1138	686

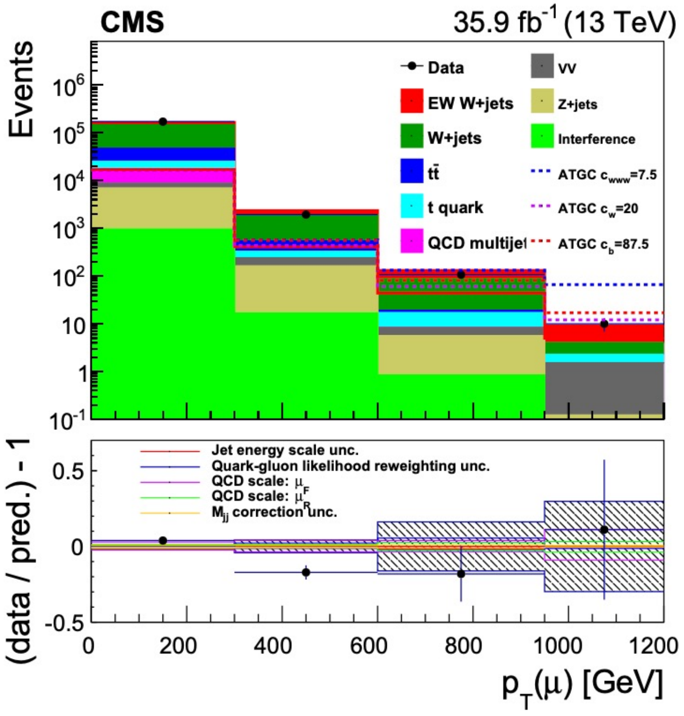
Overall large systematic from jet energy scale
In the high BDT region, QGL and QCD scale also large

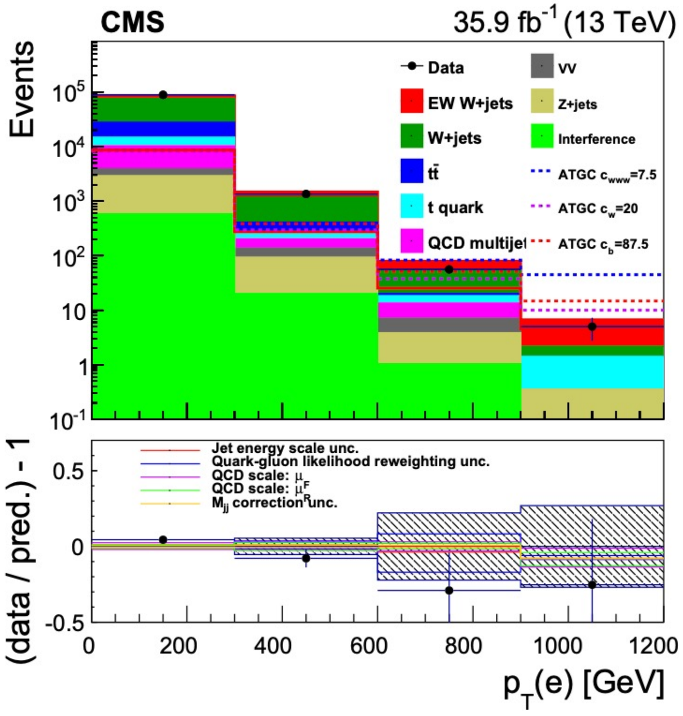
aTGC results

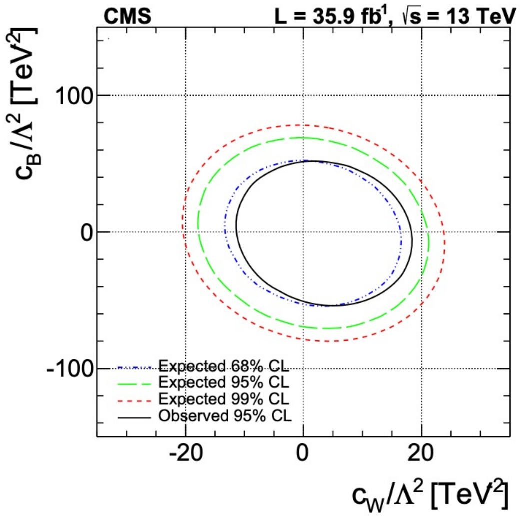
- A fit using pT of the lepton is developed to set limit on the aTGC
- BDT > 0.5 is required to enhance sensitivity

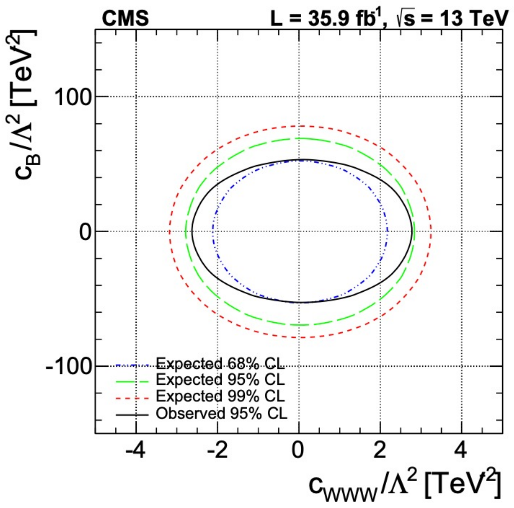
Table 3 One-dimensional limits on the ATGC EFT parameters at 95% CL

Coupling constant	Expected 95% CL interval (TeV^{-2})	Observed 95% CL interval (TeV^{-2})
c_{WWW}/Λ^2	[−2.5, 2.5]	[−2.3, 2.5]
c_W/Λ^2	[−16, 19]	[−8.8, 16]
c_B/Λ^2	[−62, 61]	[−45, 46]



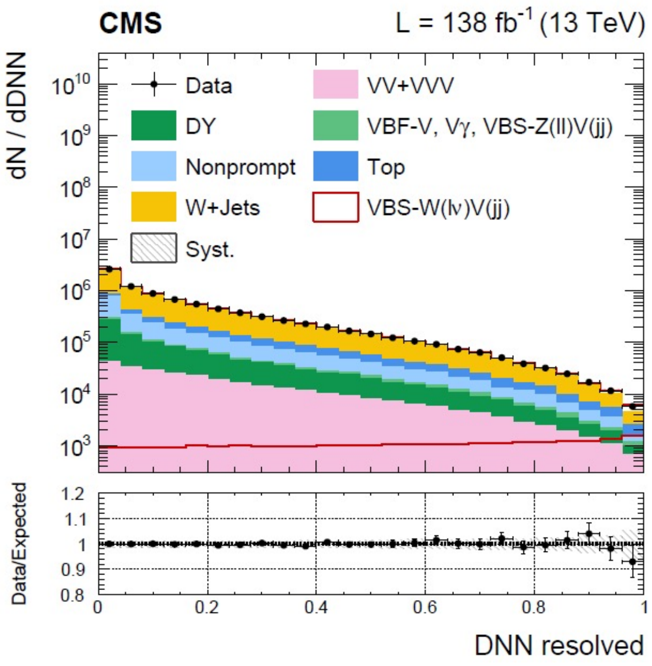


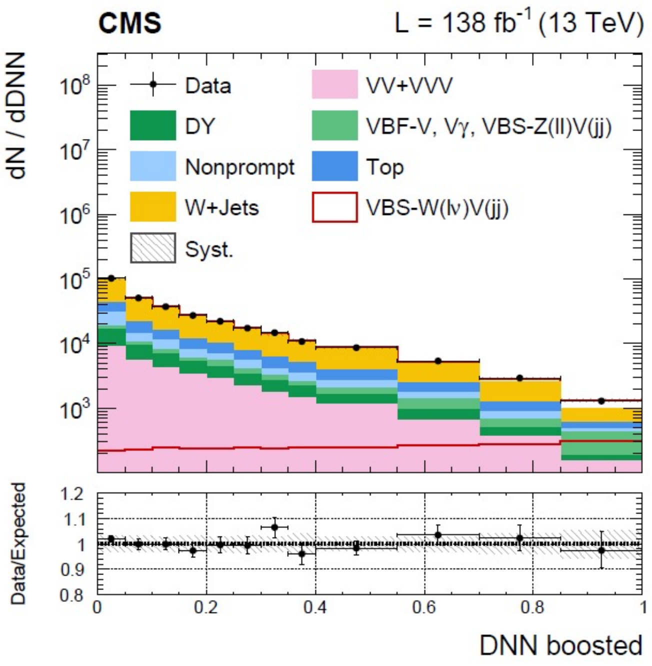




WW/WZ semileptonic - multivariable analysis

- DNNs are used to separate signal and background





Input variables

Variable	Resolved	Boosted	SHAP ranking	
			Resolved	Boosted
Lepton pseudorapidity	✓	✓	13	12
Lepton transverse momentum	✓	✓	16	10
Zeppenfeld variable for the lepton	✓	✓	2	2
Number of jets with $p_T > 30$ GeV	✓	✓	7	3
Leading VBS tag jet p_T	-	✓	-	11
Trailing VBS tag jet p_T	✓	✓	7	6
Pseudorapidity interval $\Delta\eta_{jj}^{VBS}$ between tag jets	✓	✓	4	4
Quark/gluon discriminator of leading VBS tag jet	✓	✓	9	7
Azimuthal angle distance between VBS tag jets	✓	-	10	-
Invariant mass of the VBS tag jets pair	✓	✓	1	1
p_T of the leading V_{had} jet	✓	-	14	-
p_T of the trailing V_{had} jet	✓	-	12	-
Pseudorapidity difference between V_{had} jets	✓	-	8	-
Quark/gluon discriminator of the leading V_{had} jet	✓	-	3	-
Quark/gluon discriminator of the trailing V_{had} jet	✓	-	5	-
p_T of the AK8 V_{had} jet candidate	-	✓	-	8
Invariant mass of V_{had}	✓	✓	11	5
Zeppenfeld variable for V_{had}	-	✓	-	9
Centrality	-	✓	15	13