

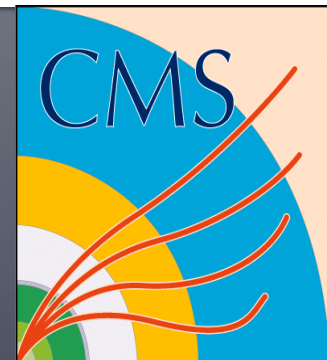


Measurements of Standard Model VBS/VBF productions with ATLAS+CMS detectors



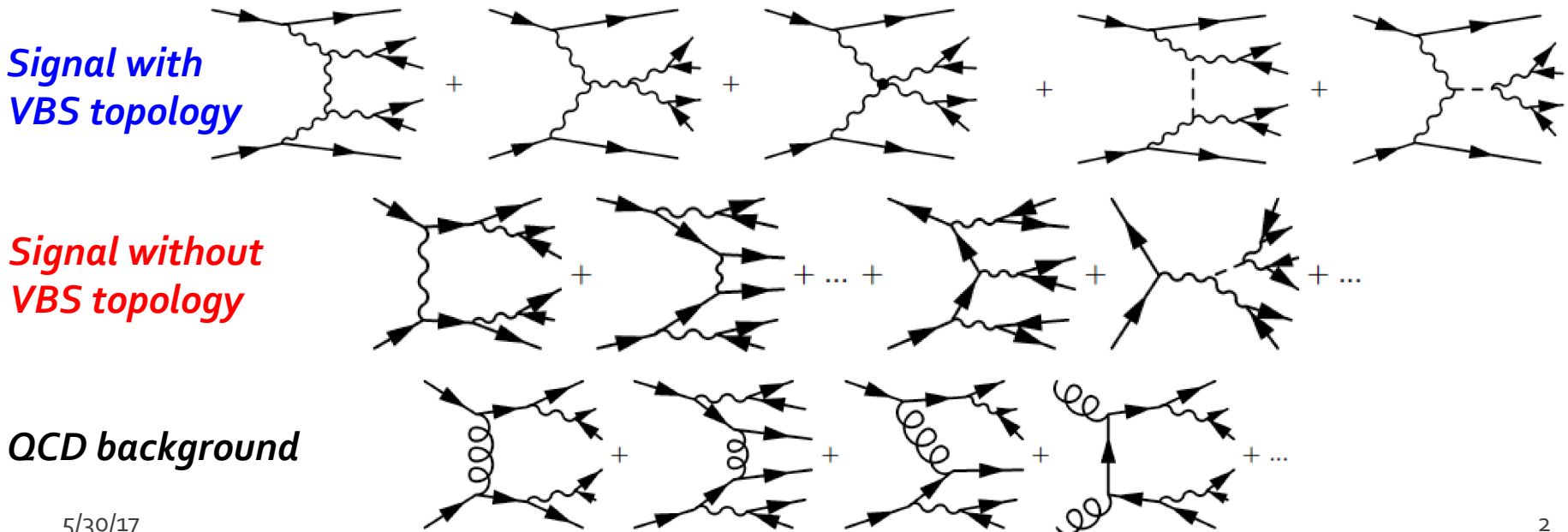
Shu Li
Duke University

On behalf of the ATLAS+CMS collaborations



Motivation: the SM diboson measurements

- Stringent test of EWSB mechanism and EW sector of SM predictions. Probe of Higgs Mechanism for scattering w/ longitudinal polarization
- Sensitive to beyond SM physics via anomalous gauge couplings and narrow resonances. Neutral coupling is forbidden at tree-level in SM.
- Irreducible backgrounds of many new physics searches in vector boson fusion mode.
- **Signature: associated di-jet production with high inv. mass and large gap.**



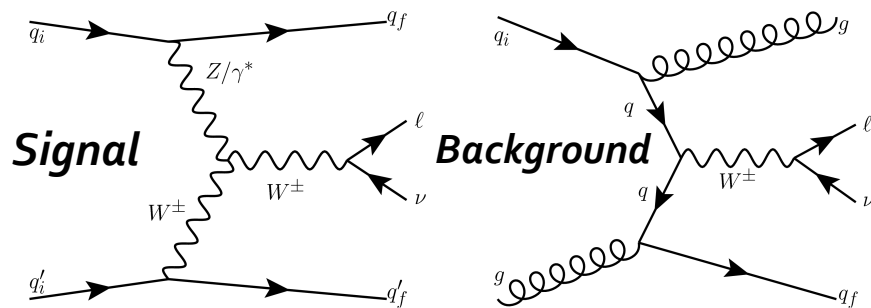
Overview of recent ATLAS/CMS VBF/VBS results

- *VBF Vjj productions + Anomalous Triple Gauge Couplings (αTGC)*
 - *ATLAS: VBF Wjj (7/8TeV), VBF Zjj (13TeV)*
 - *CMS: VBF Zjj (13TeV)*
- *VBS $VVjj$ productions + Anomalous Quartic Gauge Couplings (αQGC)*
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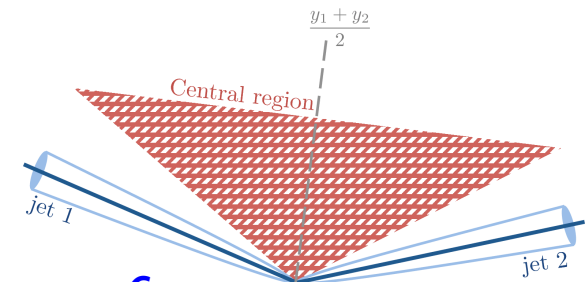
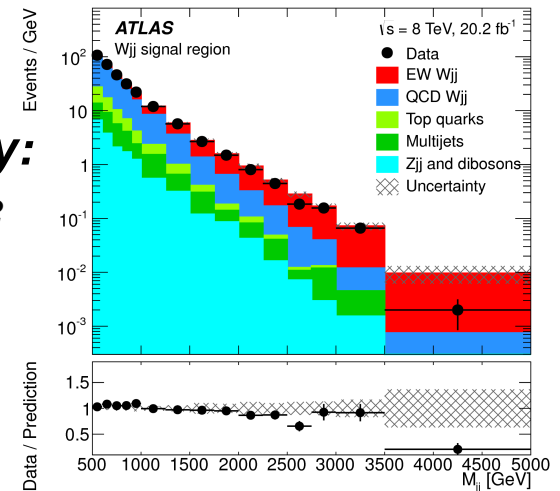
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Measurement of electroweak $W(\rightarrow l\nu)jj$ production cross section at 7/8 TeV by ATLAS



VBF topology:
Di-jet w/ large rapidity gap and high inv. mass



[arXiv:1703.04362](https://arxiv.org/abs/1703.04362)

Fiducial definition:

Fiducial and differential measurements

Signal region	$N_{\text{lepton}}^{\text{cen}} = 1, N_{\text{jets}}^{\text{cen}} = 0$
Forward-lepton control region	$N_{\text{lepton}}^{\text{cen}} = 0, N_{\text{jets}}^{\text{cen}} = 0$
Central-jet validation region	$N_{\text{lepton}}^{\text{cen}} = 1, N_{\text{jets}}^{\text{cen}} \geq 1$

Differential measurements only

Inclusive regions	$M_{jj} > 0.5 \text{ TeV}, 1 \text{ TeV}, 1.5 \text{ TeV}, \text{ or } 2 \text{ TeV}$
Forward-lepton/central-jet region	$N_{\text{lepton}}^{\text{cen}} = 0, N_{\text{jets}}^{\text{cen}} \geq 1$
High-mass signal region	$M_{jj} > 1 \text{ TeV}, N_{\text{lepton}}^{\text{cen}} = 1, N_{\text{jets}}^{\text{cen}} = 0$

Anomalous coupling measurements only

High- q^2 region	$M_{jj} > 1 \text{ TeV}, N_{\text{lepton}}^{\text{cen}} = 1, N_{\text{jets}}^{\text{cen}} = 0, p_T^{j1} > 600 \text{ GeV}$
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\sqrt{s}	$\sigma_{\text{meas}}^{\text{fid}}$ [fb]	$\sigma_{\text{SM}}^{\text{fid}}$ [fb]	Acceptance \mathcal{A}	$\sigma_{\text{meas}}^{\text{inc}}$ [fb]
7 TeV	$144 \pm 23 \text{ (stat)} \pm 23 \text{ (exp)} \pm 13 \text{ (th)}$	144 ± 11	0.053 ± 0.004	2760 ± 670
8 TeV	$159 \pm 10 \text{ (stat)} \pm 17 \text{ (exp)} \pm 20 \text{ (th)}$	198 ± 12	0.058 ± 0.003	2890 ± 510

Measurement of electroweak $W(\rightarrow lv)jj$ production cross section at 7/8 TeV by ATLAS

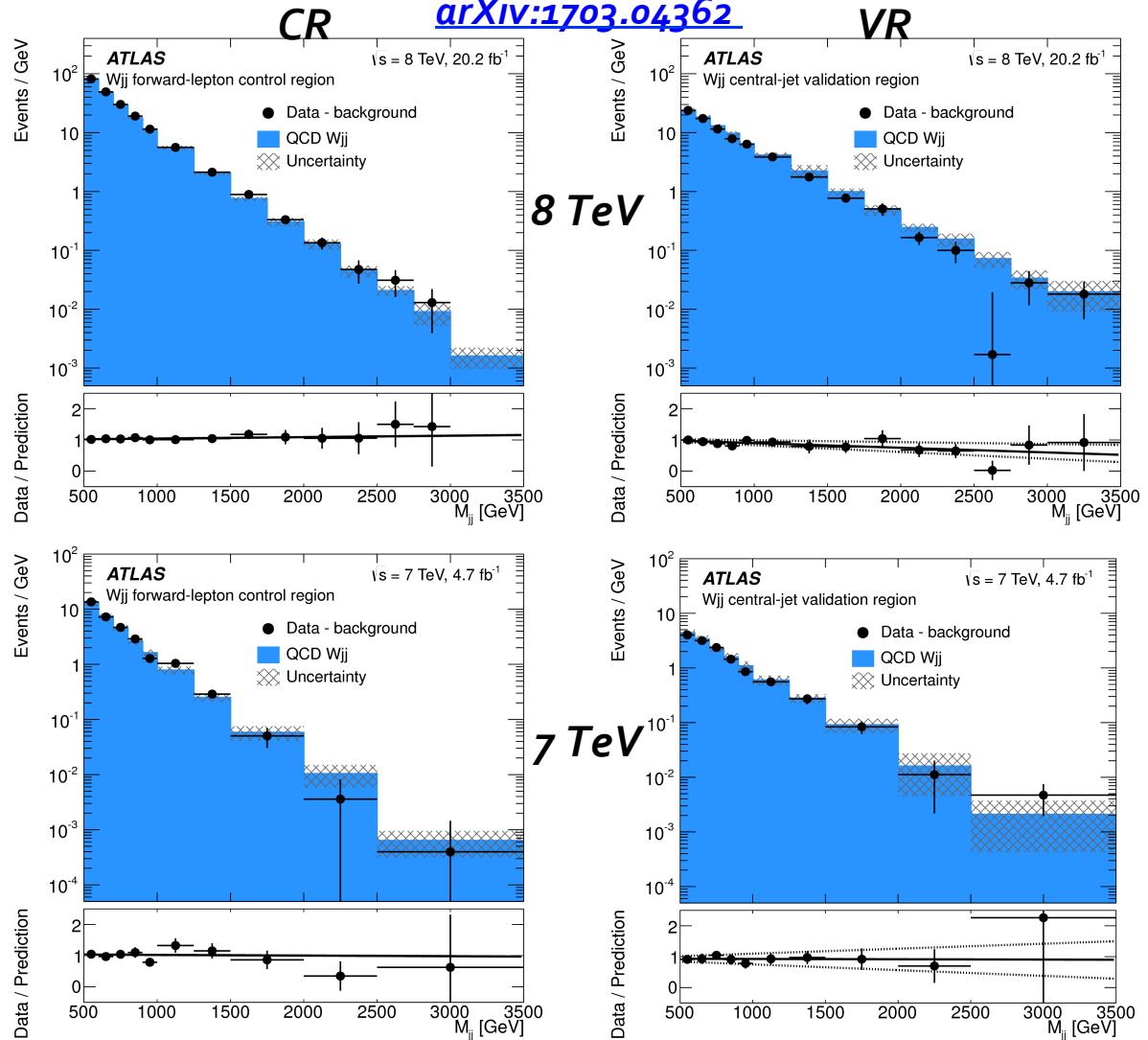
QCD Wjj distribution from forward lepton control region w/ linear fit correction to M_{jj}

Validation in central-jet validation region w/ other bgd subtracted

*CR: with forward lepton
VR: with central jet*

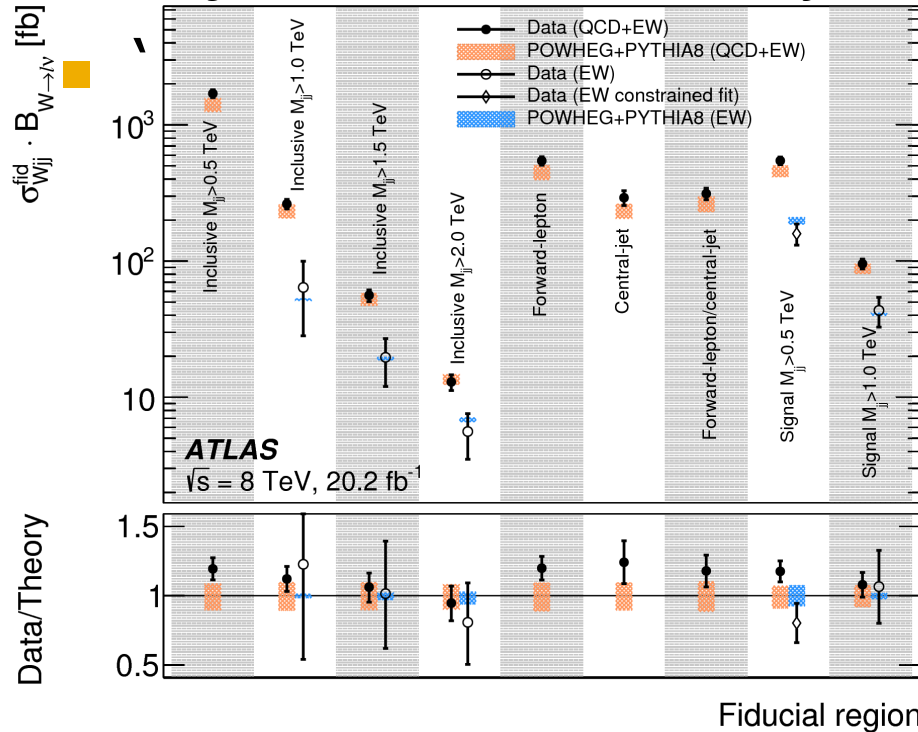
*Signal extraction:
binned likelihood fit of M_{jj} in signal and control regions*

[arXiv:1703.04362](https://arxiv.org/abs/1703.04362)

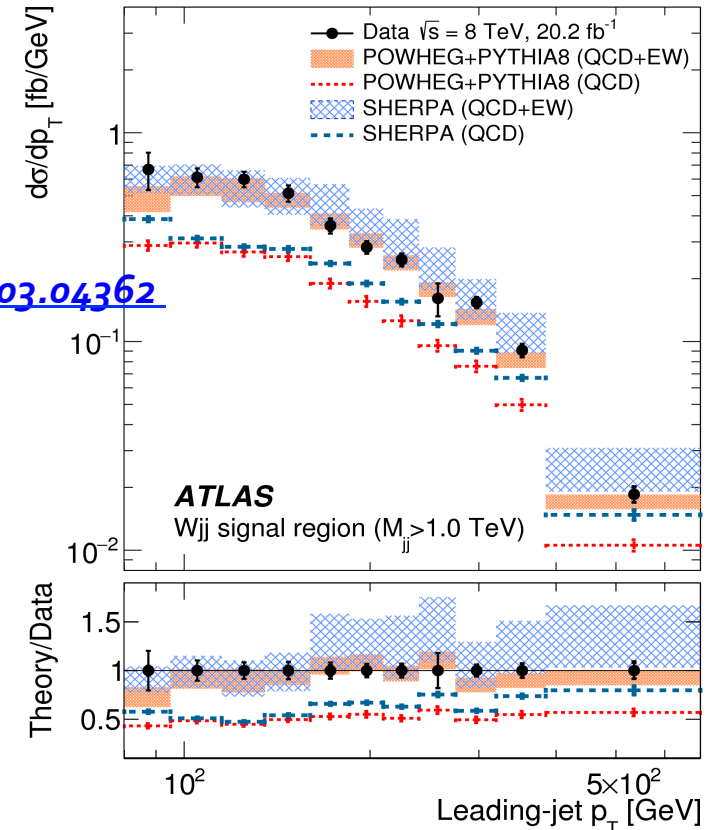


Measurement of electroweak $W(\rightarrow lv)jj$ production cross section at 7/8 TeV by ATLAS

Measured fiducial cross section summary



[arXiv:1703.04362](https://arxiv.org/abs/1703.04362)

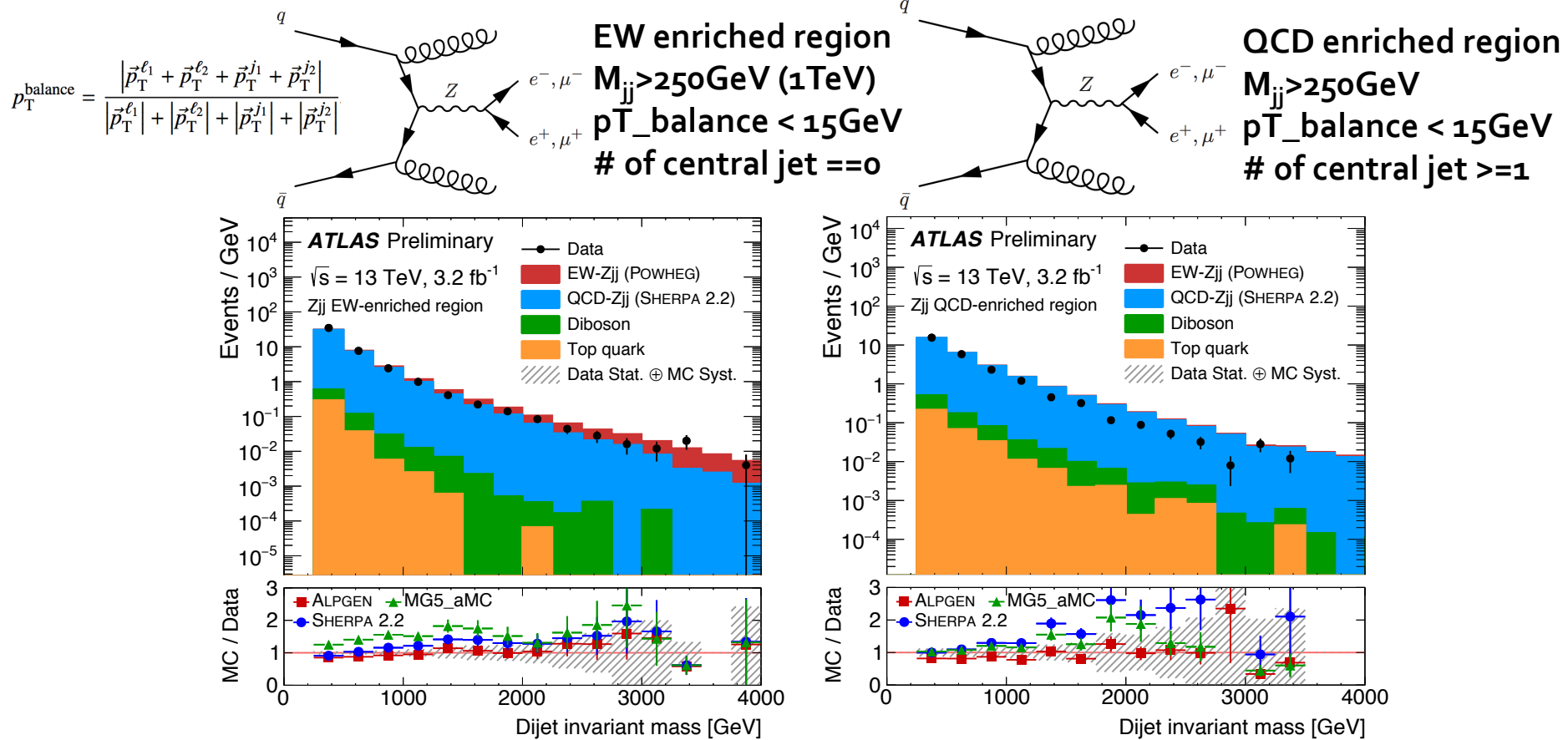


Differential cross section measured for both EW-Only and EW+QCD Wjj processes in various fiducial regions in agreement w/ prediction

High $M_{jj}(>1 \text{ TeV})$ region is used to constrain aTGCs w/ both EFT and Effective lagrangian approach

	$\Lambda = 4 \text{ TeV}$		$\Lambda = \infty$	
	Expected	Observed	Expected	Observed
Δg_1^Z	[-0.39, 0.35]	[-0.32, 0.28]	[-0.16, 0.15]	[-0.13, 0.12]
$\Delta \kappa_Z$	[-0.38, 0.51]	[-0.29, 0.42]	[-0.19, 0.19]	[-0.15, 0.16]
λ_V	[-0.16, 0.12]	[-0.13, 0.090]	[-0.064, 0.054]	[-0.053, 0.042]
$\tilde{\kappa}_Z$	[-1.7, 1.8]	[-1.4, 1.4]	[-0.70, 0.70]	[-0.56, 0.56]
$\tilde{\lambda}_V$	[-0.13, 0.15]	[-0.10, 0.12]	[-0.058, 0.057]	[-0.047, 0.046]

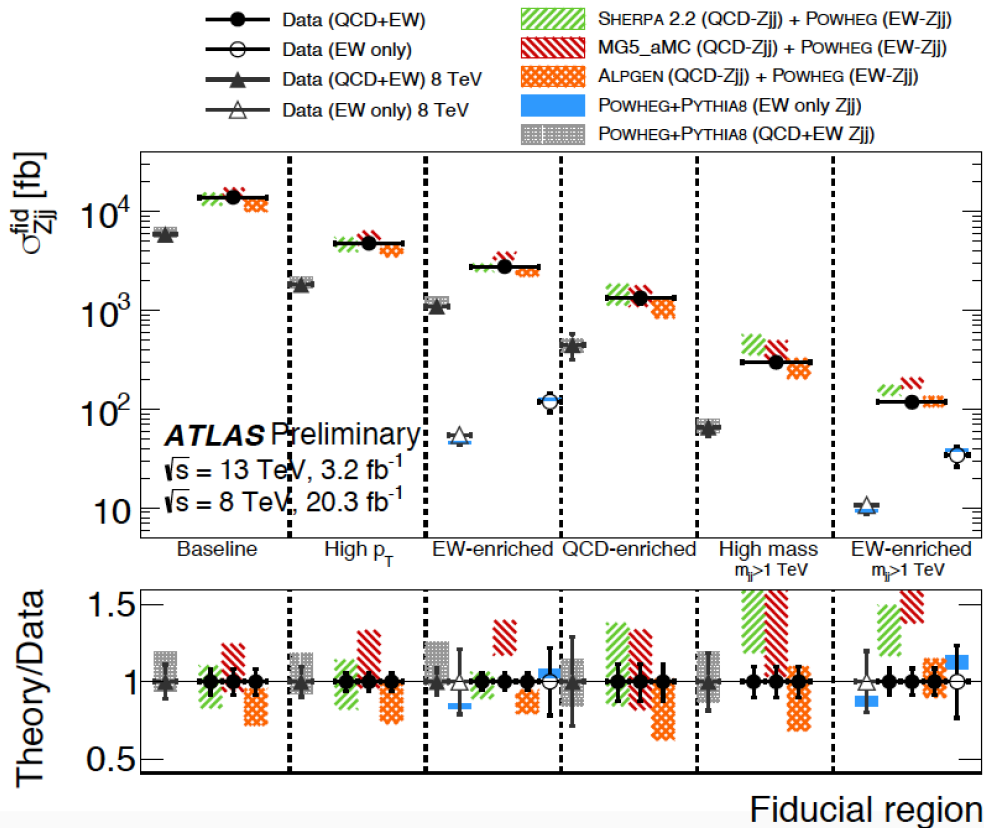
Measurement of electroweak Z(\rightarrow ll)jj production cross section at 13 TeV by ATLAS



[ATLAS-STDM-2016-09](#)

Signal extraction via binned likelihood fit of QCD&EWK m_{jj} templates in EWK-enriched region after reweighting the m_{jj} shape of the QCD Zjj MC based on a fit to the data in the QCD-enriched region

Measurement of electroweak $Z(\rightarrow ll)jj$ production cross section at 13 TeV by ATLAS



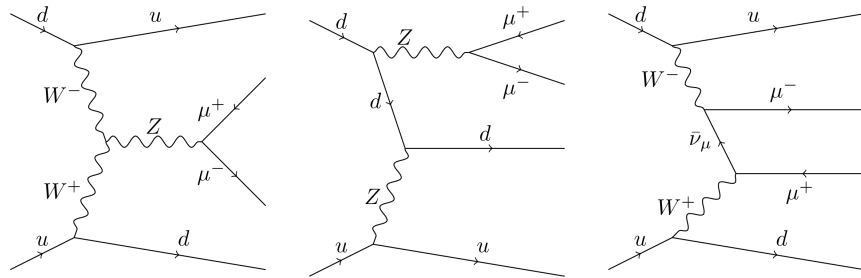
QCD+EWK cross section measured in six fiducial regions.

EWK-ONLY cross section measured in two fiducial regions with EWK component enriched.

Measurements in good agreement with theory.

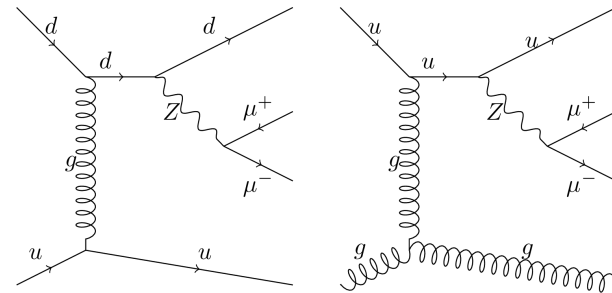
Measurement of electroweak $Z(\rightarrow ll)jj$ production cross section at 13 TeV by CMS

EW Zjj signal

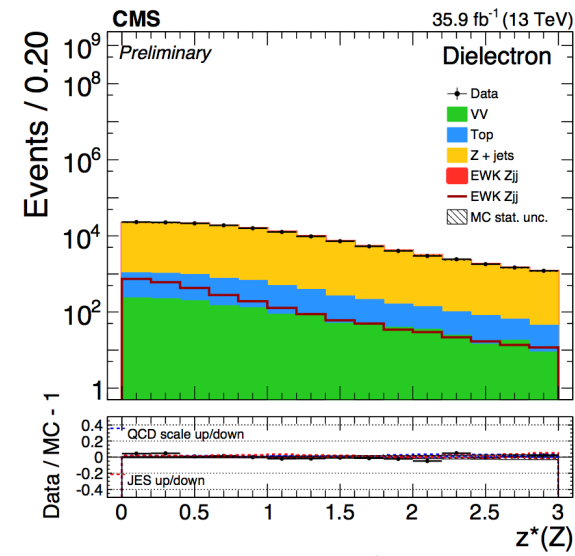
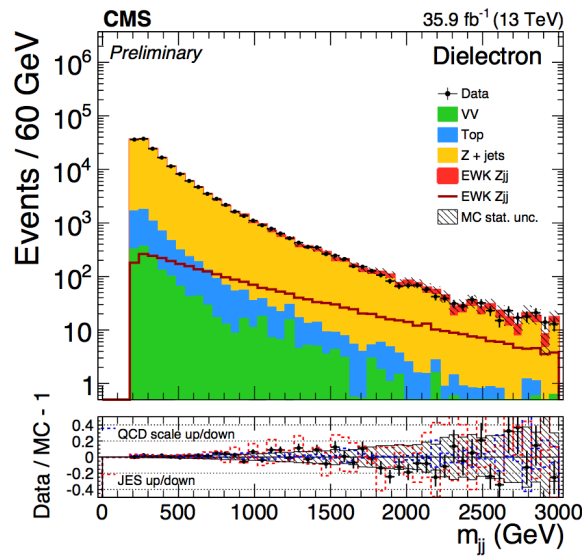
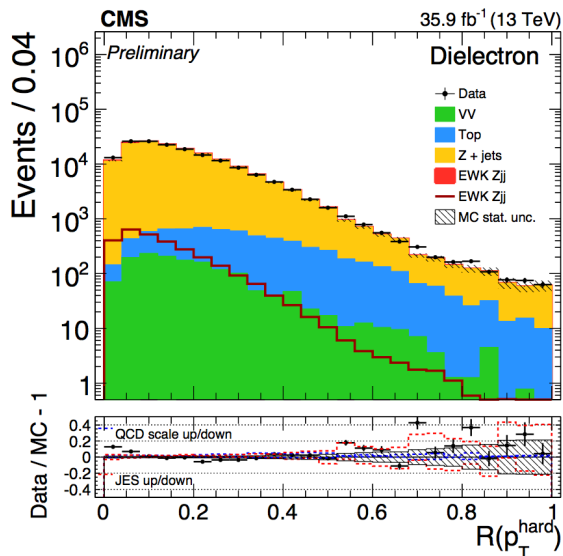


VBF bremsstrahlung multiperipheral

QCD Zjj background



[CMS-PAS-SMP-16-018](#)

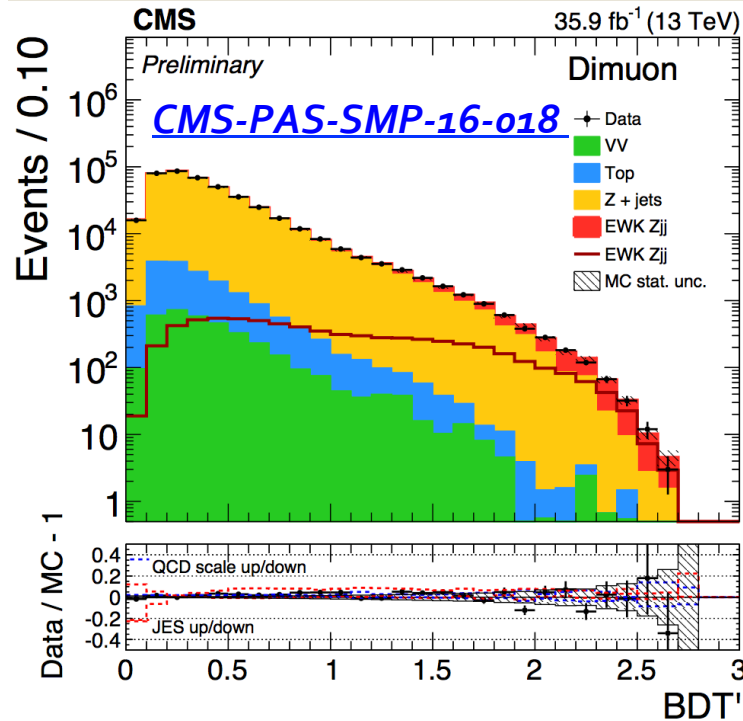
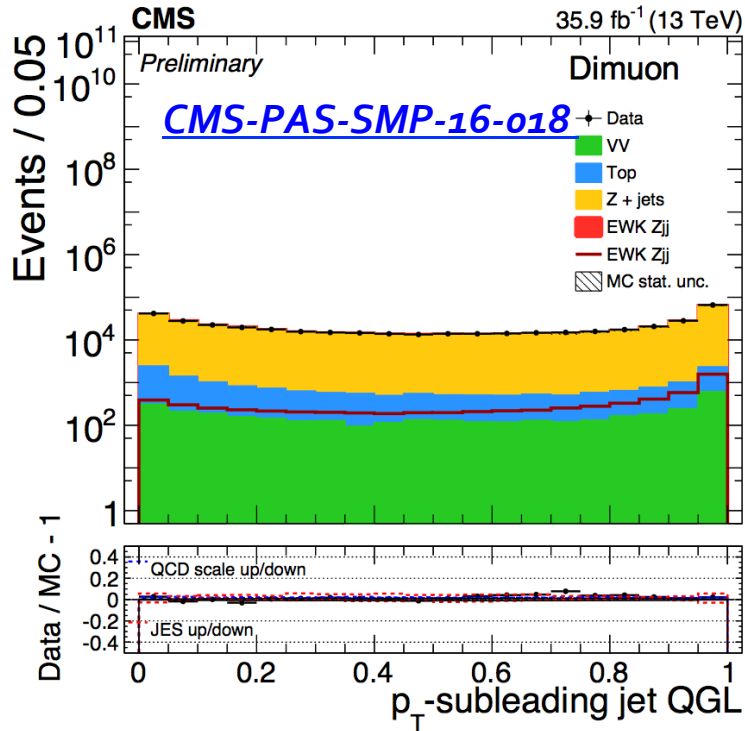


$$R(p_T^{\text{hard}}) = \frac{|\vec{p}_{Tj_1} + \vec{p}_{Tj_2} + \vec{p}_{TZ}|}{|\vec{p}_{Tj_1}| + |\vec{p}_{Tj_2}| + |\vec{p}_{TZ}|} = \frac{|\vec{p}_T^{\text{hard}}|}{|\vec{p}_{Tj_1}| + |\vec{p}_{Tj_2}| + |\vec{p}_{TZ}|}$$

$$y^* = y_Z - \frac{1}{2}(y_{j_1} + y_{j_2})$$

$$z^* = \frac{y^*}{\Delta y_{jj}}$$

Measurement of electroweak $Z(\rightarrow ll)jj$ production cross section at 13 TeV by CMS



Signal Extraction:

Binned maximum likelihood fit with strength modifiers for all MC components w/ BDT

Signal enriched with BDT > 0.92

S/B ~ 1

MVA inputs w/ m_{jj} ; $\Delta\eta_{jj}$; p_{Tjj} ; QGL; $R(p_T^{hard})$ and z^*

$$\sigma(\text{EW } lljj) = 552 \pm 19 (\text{stat}) \pm 55 (\text{syst}) \text{ fb} = 552 \pm 58 (\text{total}) \text{ fb}$$

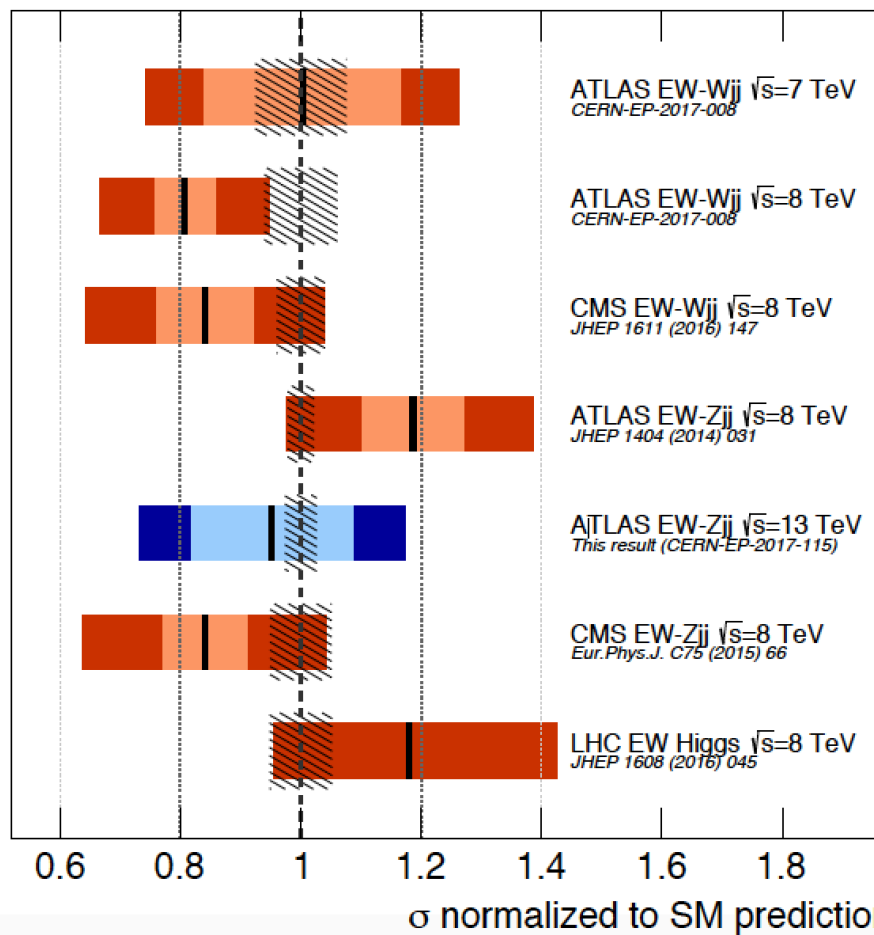
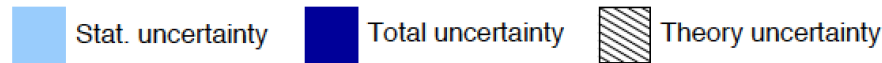
In agreement with LO pred. $\sigma_{\text{LO}}(\text{EW } lljj) = 543 \pm 24 \text{ fb}$

To separate EW from QCD, Jet-QGL (quark-gluon likelihood) is built from:

- (i) particle multiplicity,**
- (ii) η - ϕ minor RMS,**
- (iii) $p_T^D \sqrt{(\Sigma p_T^2)/(\Sigma p_T)}$**

Summary of LHC electroweak Vjj production measurements

LHC electroweak Xjj production measurements **ATLAS Preliminary**



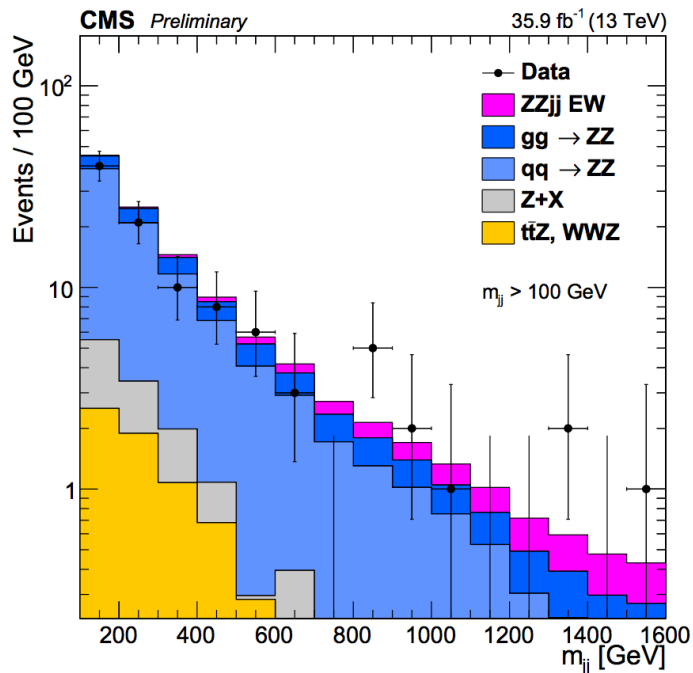
[ATLAS-STDM-2016-09](#)

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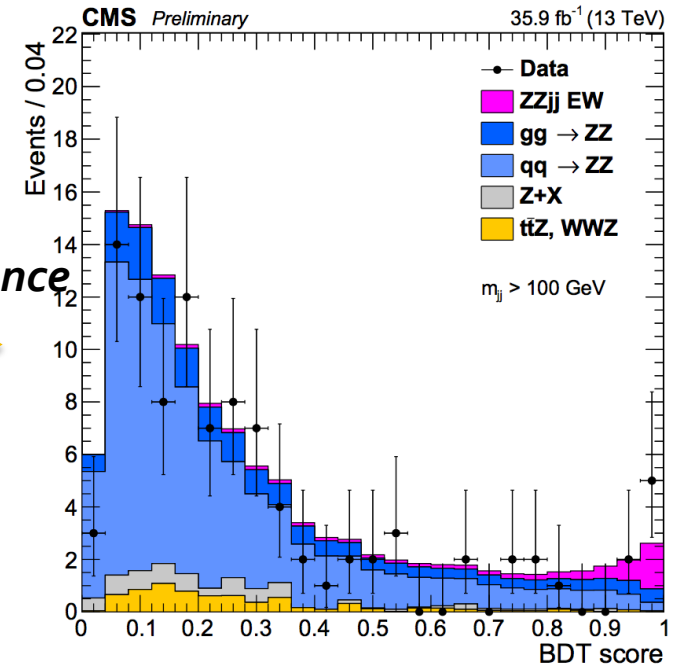
Measurement of electroweak $ZZ(\rightarrow 4l)jj$ production cross section at 13 TeV by CMS

[CMS-PAS-SMP-16-019](#)



+ $\Delta\eta_{jj} + m_{ZZ} +$
Centrality + P_T balance

→
BDT training



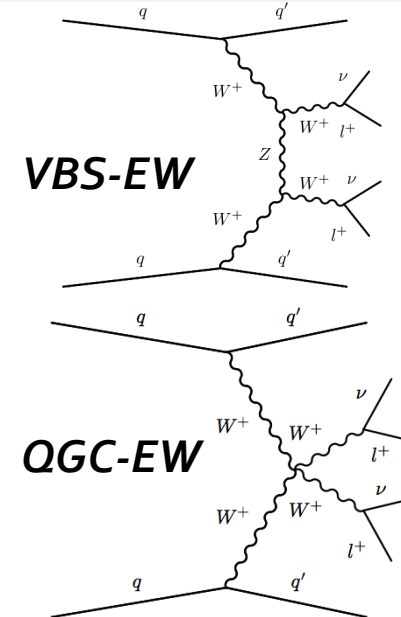
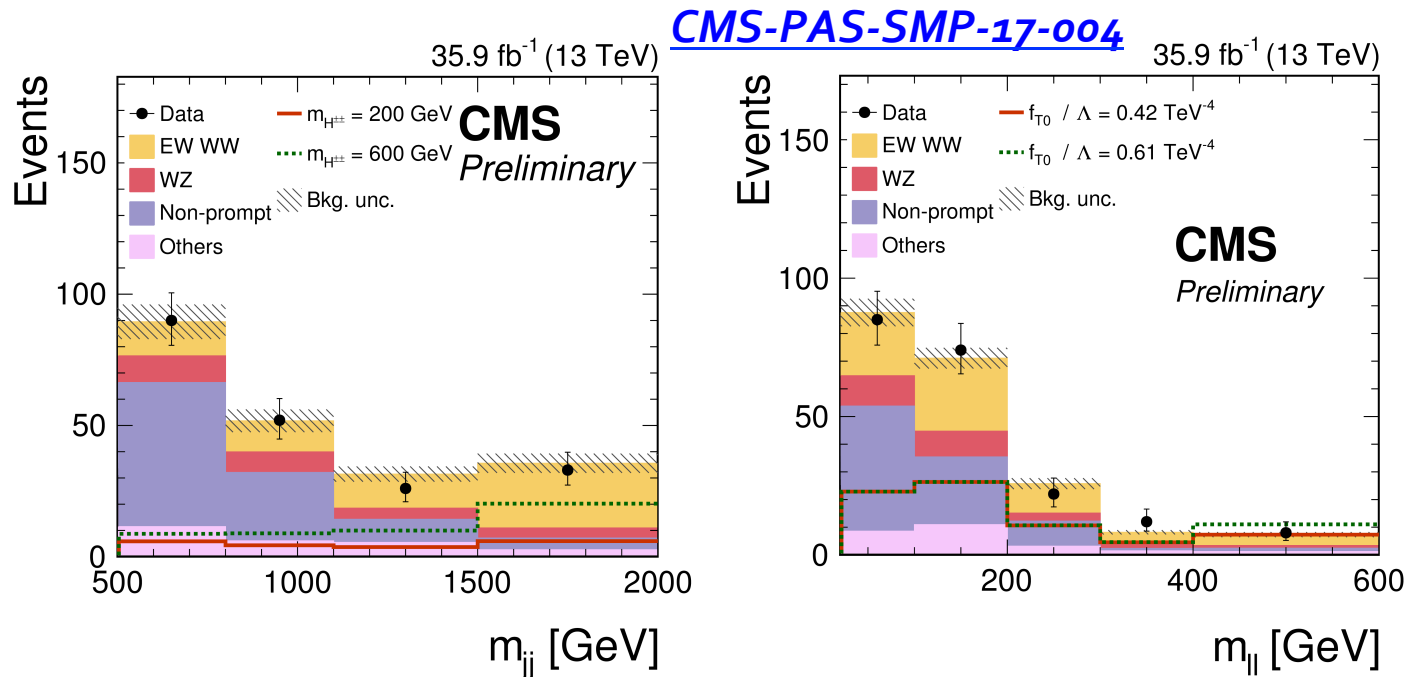
Limits on aQGCs w/ EFT dim-8 operators
and comparison with unitarity validity range

Coupling	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unitarity bound
f_{T_0}/Λ^4	-0.53	0.51	-0.46	0.44	0.6
f_{T_1}/Λ^4	-0.72	0.71	-0.61	0.61	0.6
f_{T_2}/Λ^4	-1.4	1.4	-1.2	1.2	0.6
f_{T_8}/Λ^4	-0.99	0.99	-0.84	0.84	2.8
f_{T_9}/Λ^4	-2.1	2.1	-1.8	1.8	2.9

Inclusive region: $m_{jj} > 100 \text{ GeV}$
VBS region: $|\Delta\eta_{jj}| > 2.4 + m_{jj} > 400 \text{ GeV}$
non-VBS region: $|\Delta\eta_{jj}| < 2.4$ or $m_{jj} < 400 \text{ GeV}$

EWK signal significance 2.7σ (exp 1.6σ)

Measurement of electroweak $W^\pm W^\pm (\rightarrow 2l2\nu)jj$ production cross section at 13 TeV by CMS



Same-sign Highest EW/QCD ratio in all VVjj channels

Fid. Region: $M_{jj} > 500 \text{ GeV}$ and $\Delta\eta_{jj} > 2.5$

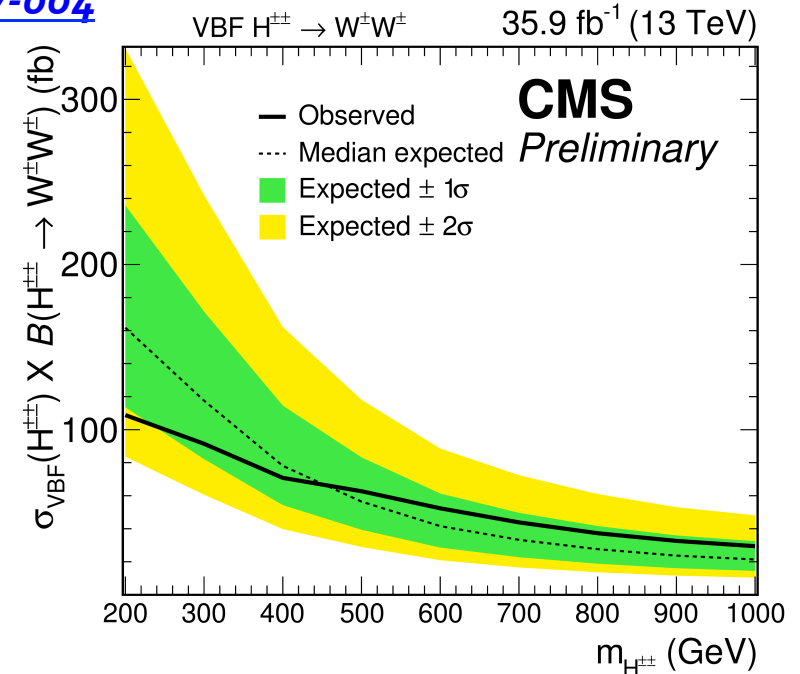
1st ever 5 σ observation of VVjj-EWK (w/ VBS signature)

Obs. $\sigma_{EW}(\ell\ell jj) = 3.83 \pm 0.66$ (stat) ± 0.35 (syst) fb, obs./exp. Signif. = 5.5/5.7 σ
In agreement with LO prediction $\sigma_{LO}(\ell\ell jj) = 4.25 \pm 0.21$ fb

Measurement of electroweak $W^\pm W^\pm (\rightarrow 2l2\nu)jj$ production cross section at 13 TeV by CMS

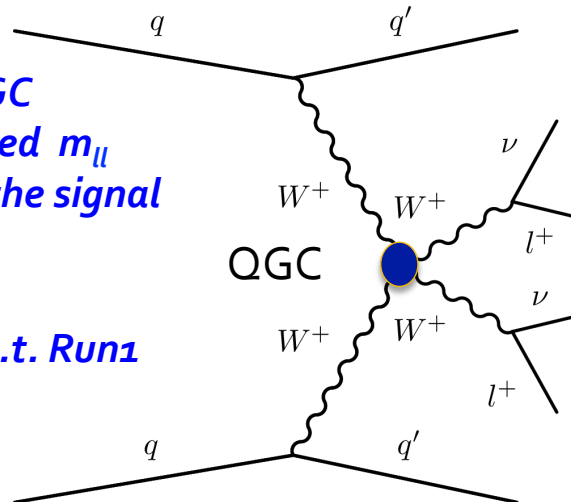
[CMS-PAS-SMP-17-004](#)

	Observed limits (TeV ⁻⁴)	Expected limits (TeV ⁻⁴)	Run-I limits (TeV ⁻⁴)
f_{S0}/Λ	[-7.7, 7.7]	[-7.0, 7.2]	[-38, 40] [11]
f_{S1}/Λ	[-21.6, 21.8]	[-19.9, 20.2]	[-118, 120] [11]
f_{M0}/Λ	[-6.0, 5.9]	[-5.6, 5.5]	[-4.6, 4.6] [29]
f_{M1}/Λ	[-8.7, 9.1]	[-7.9, 8.5]	[-17, 17] [29]
f_{M6}/Λ	[-11.9, 11.8]	[-11.1, 11.0]	[-65, 63] [11]
f_{M7}/Λ	[-13.3, 12.9]	[-12.4, 11.8]	[-70, 66] [11]
f_{T0}/Λ	[-0.62, 0.65]	[-0.58, 0.61]	[-3.8, 3.4] [30]
f_{T1}/Λ	[-0.28, 0.31]	[-0.26, 0.29]	[-1.9, 2.2] [11]
f_{T2}/Λ	[-0.89, 1.02]	[-0.80, 0.95]	[-5.2, 6.4] [11]



95% CL limits on aQGC
Using the the measured m_{ll}
distributions both in the signal
and WZ regions.

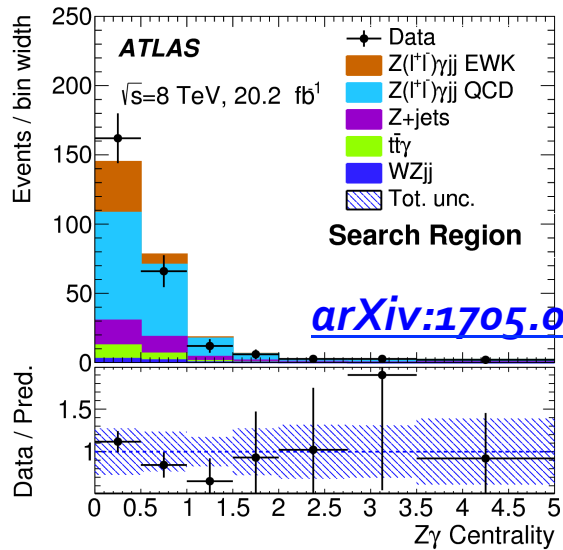
Greatly improved w.r.t. Run1



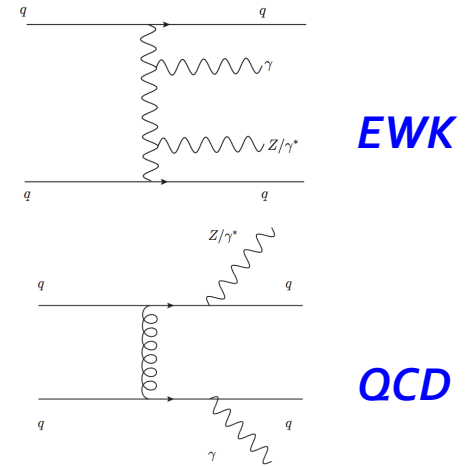
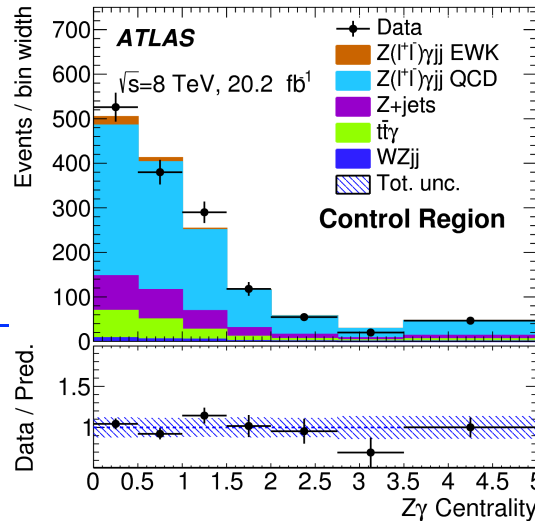
Doubly charged Higgs bosons are
predicted in models containing a
Higgs triplet field. (Georgi-
Machacek model)

1st limits placed on $H^{\pm\pm} \rightarrow W^\pm W^\pm$ cross
section using (m_{jj}, m_{ll}) two-
dimensional distributions

Measurement of electroweak $Z(\rightarrow ll/\nu\nu)\gamma jj$ production cross section at 8TeV by ATLAS



[arXiv:1705.01966](https://arxiv.org/abs/1705.01966)

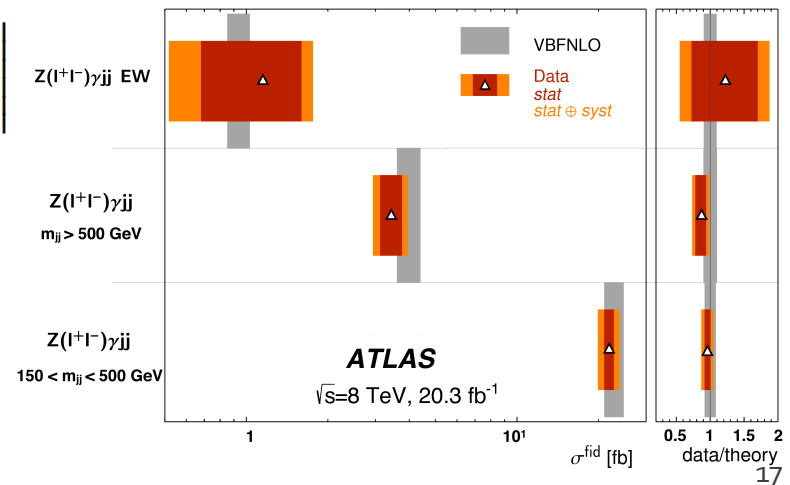


EWK obs. signif. 2.0(1.8)σ

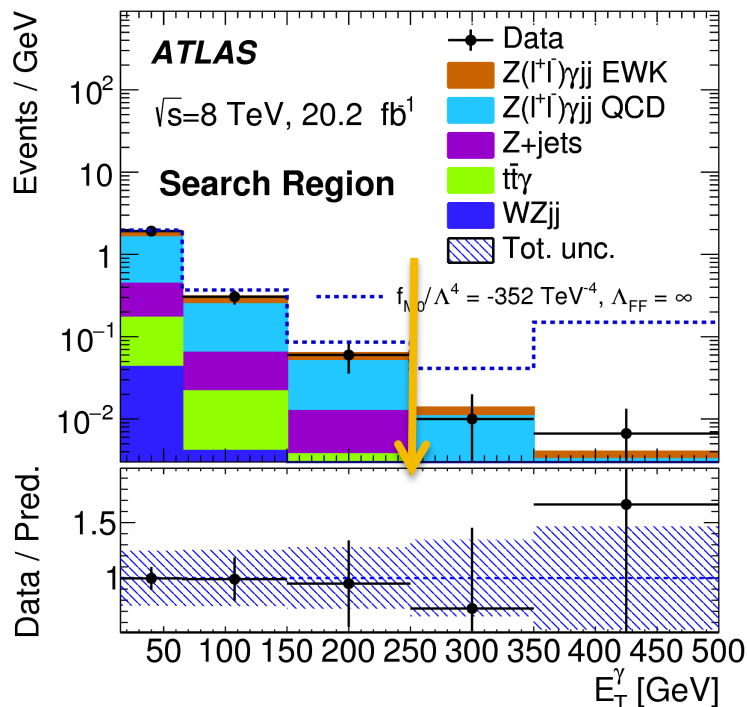
Control Region (CR)	$150 < m_{jj} < 500$ GeV
Search Region (SR)	$m_{jj} > 500$ GeV
aQGC Region	$m_{jj} > 500$ GeV $E_T^\gamma > 250$ GeV

$$\zeta \equiv \left| \frac{\eta - \bar{\eta}_{jj}}{\Delta\eta_{jj}} \right|$$

llyjj channel fid. cross section measured by applying a likelihood fit to the spectra of $Z\gamma$ -Centrality $\zeta_{Z\gamma}$ simultaneously to the CR and SR, constraining $Z\gamma$ -QCD bgd



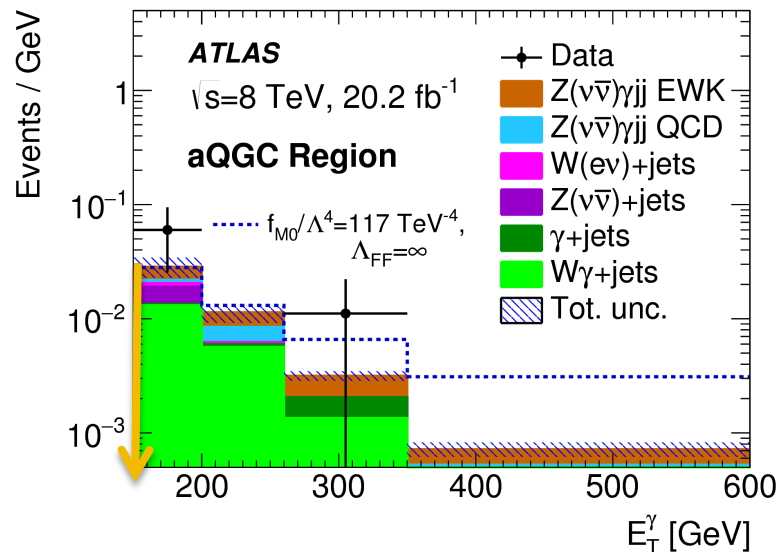
Measurement of electroweak $Z(\rightarrow \ell\bar{\ell}/\nu\bar{\nu})\gamma jj$ production cross section at 8 TeV by ATLAS



Dedicated high $E_T(\gamma)$ region defined for aQGC constraint. Limits are obtained via charged lepton and neutrino channel combination.

Best aQGC limits in $Z\gamma jj$ channel

5/30/17



[arXiv:1705.01966](https://arxiv.org/abs/1705.01966)

	Limits 95% CL	Measured [TeV^{-4}]	Expected [TeV^{-4}]
ATLAS $Z(\rightarrow \ell\bar{\ell}/\nu\bar{\nu})\gamma$ -EWK	f_{T9}/Λ^4	[-3.9, 3.9]	[-2.7, 2.8]
	f_{T8}/Λ^4	[-1.8, 1.8]	[-1.3, 1.3]
	f_{T0}/Λ^4	[-3.4, 2.9]	[-3.0, 2.3]
	f_{M0}/Λ^4	[-76, 69]	[-66, 58]
	f_{M1}/Λ^4	[-147, 150]	[-123, 126]
	f_{M2}/Λ^4	[-27, 27]	[-23, 23]
	f_{M3}/Λ^4	[-52, 52]	[-43, 43]
CMS $Z(\rightarrow \ell\bar{\ell})\gamma$ -EWK	f_{T9}/Λ^4	[-4.0, 4.0]	[-6.0, 6.0]
	f_{T8}/Λ^4	[-1.8, 1.8]	[-2.7, 2.7]
	f_{T0}/Λ^4	[-3.8, 3.4]	[-5.1, 5.1]
	f_{M0}/Λ^4	[-71, 75]	[-109, 111]
	f_{M1}/Λ^4	[-190, 182]	[-281, 280]
	f_{M2}/Λ^4	[-32, 31]	[-47, 47]
	f_{M3}/Λ^4	[-58, 59]	[-87, 87]

Summary

- Measurement of SM VBS/VBF processes are presented with both 7/8TeV Run-1 and 13TeV Run-2 data of both ATLAS and CMS, providing interesting probe of EWSB and Higgs unitarization mechanism
- Many interesting channels are investigated thoroughly despite limited production rate given the rare process cross-sections:
 - Same-sign WW VBS already reached 5sigma threshold of discovery, more are yet to explore
- With more data upcoming in the 2nd half of LHC Run-2, more excitement are absolutely anticipated 😊