VBF and VBS measurements

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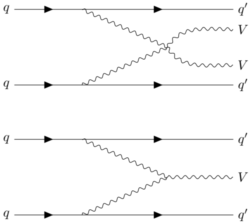
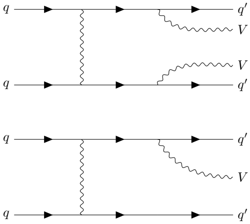
LHCP online, 28 May 2020

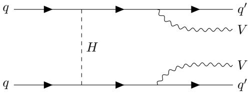
VBF and VBS: measurable, but not measurable

weak boson scattering/fusion



weak boson bremsstrahlung



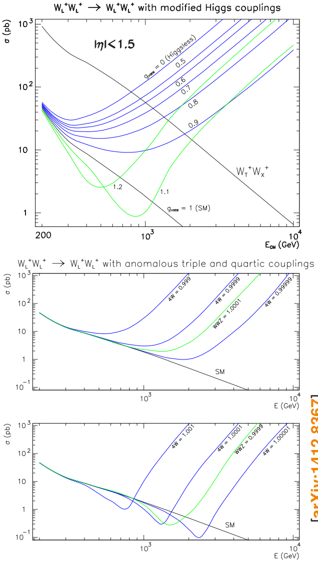


$$V = W, Z, \gamma$$

- ➔ gauge invariant set of electroweak $V(V)jj$ diagrams at tree level, i.e. $\mathcal{O}(\alpha_{\text{w}}^{3(4)})$
- ➔ strong **negative interference between all diagrams** involving the exchange of a colour-singlet in the t-channel
- ➔ part of the NLO electroweak correction to QCD $V(V) + 2$ jet production, i.e. $\mathcal{O}(\alpha_{\text{s}}^2 \alpha_{\text{w}}^{1(2)})$
  - ➔ mixed QCD–EW contribution, i.e. $\mathcal{O}(\alpha_{\text{s}} \alpha_{\text{w}}^{2(3)})$, significant at large jet p_{T} (10–50 % at 1–4 TeV)

Probing the foundations of electroweak symmetry breaking

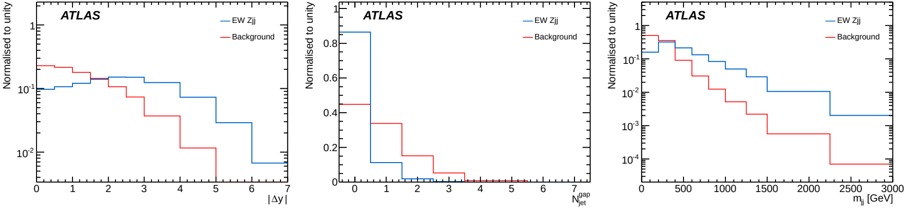
- ➜ high-energy behaviour of weak boson scattering subject to delicate cancellation between different terms
  - ➜ the cross-section for the longitudinal component $W_L W_L \rightarrow W_L W_L$ grows with centre-of-mass energy in the absence of the Higgs
- ➜ very sensitive to slight shifts in the trilinear or quartic gauge coupling strenghts
- ➜ $V(V)jj$ measurements are a fundamental test of the $SU(2)_L \times U(1)_Y$ gauge symmetry



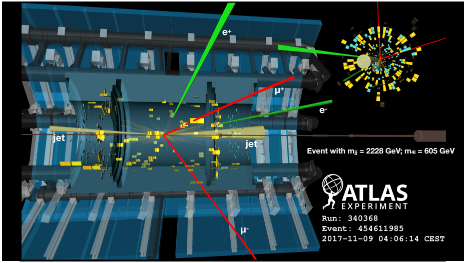
[arXiv:1412.8367]

Characteristics of electroweak $V(V)jj$ production

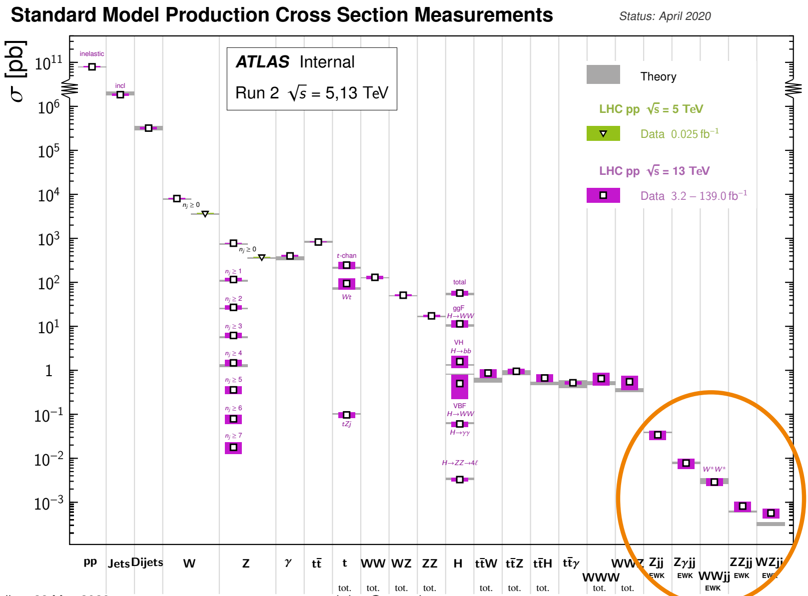
[JHEP 04 (2014) 031]



- two forward “tagging” jets
- additional radiation between tagging jets heavily suppressed due to colour singlet exchange
- dijet invariant mass significantly harder than for QCD $V(V) + 2$ jet production



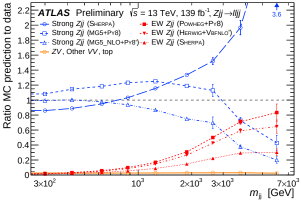
[arXiv:2004.10612]


Standard Model Production Cross Section Measurements
Status: April 2020
ATLAS Internal
Run 2 √s = 5,13 TeV
Theory
LHC pp √s = 5 TeV
Data 0.025 fb⁻¹
LHC pp √s = 13 TeV
Data 3.2 – 139.0 fb⁻¹
σ [pb]
pp
Jets
Dijets
W
Z
γ
tt̄
t
WW
WZ
ZZ
H
tt̄W
tt̄Z
tt̄H
tt̄γ
WWW
WWZ
Zjj EWK
Zγjj EWK
WWjj EWK
ZZjj EWK
WZjj EWK

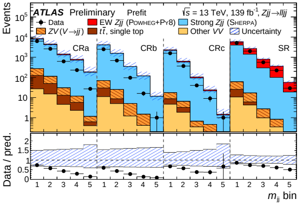
weak boson fusion

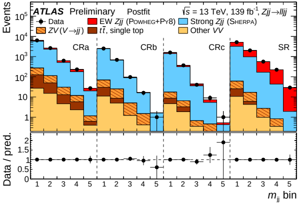
Background modelling in *Zjj*

- m_{jj} in general poorly modelled by event generators across the board
- modelling of the QCD $V + 2$ jet contribution constrained using data in dedicated control regions
  - more details in **Heather Russell**'s talk tomorrow
- data-driven constraint transferred into signal region using the Monte Carlo
- impact of interference component assigned as a systematic on the electroweak signal
- crucial to **measure inclusive $V(V) + 2$ jet** production in addition to extracting the $V(V)jj$ component



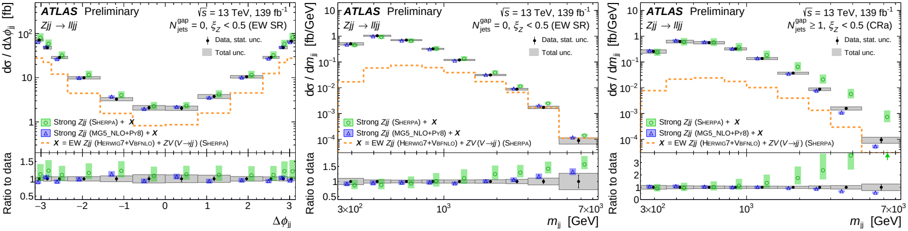
[CERN-EP-2020-045]





Inclusive $Z + 2$ jet cross-sections

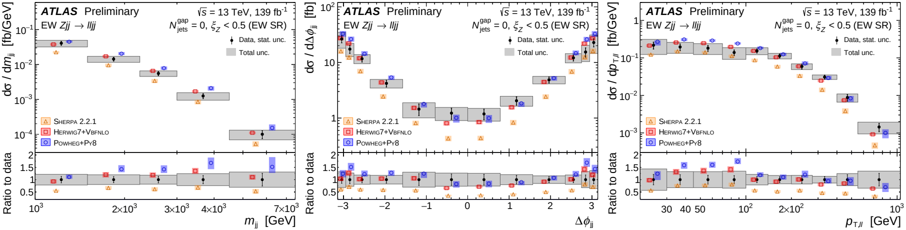
[CERN-EP-2020-045]



- fiducial differential cross-section measurements in m_{jj}, $|\Delta y_{jj}|$, $p_{\mathrm{T},\ell\ell}$, $\Delta\phi_{jj}$ in signal as well as control regions
- data compared to multi-leg predictions for QCD $Z + 0, 1, 2j$@NLO$+3, 4j$@LO
  - using MEPS@NLO from Sherpa 2.2.1
  - using FxFx from MadGraph5_aMC@NLO+Pythia8
- both supplemented with electroweak *Zjj*@NLO QCD from Herwig7+VBFNLO
- small contribution of semi-leptonic diboson production taken from Sherpa 2.2.1

Electroweak *Zjj* cross-sections

[CERN-EP-2020-045]



- fiducial differential cross-section measurements in m_{jj}, $|\Delta y_{jj}|$, $p_{T,\ell\ell}$, $\Delta\phi_{jj}$
- data compared to electroweak *Zjj* predictions (in the VBF approximation)
  - at NLO from Herwig7 + VBFNLO
  - at NLO from Powheg v1 + Pythia8
  - with up to two additional parton emissions at LO from Sherpa 2.2.1
- Sherpa 2.2 series known to have non-optimal colour flow for VBF/VBS processes, resulting in too much radiation between tagging jets
- integrated cross-section **37.4 ± 3.5(stat) ± 5.5(syst) fb** in excellent agreement with SM prediction 39.5 ± 3.4(scale) ± 1.2(pdf) fb from Herwig7+VBFNLO

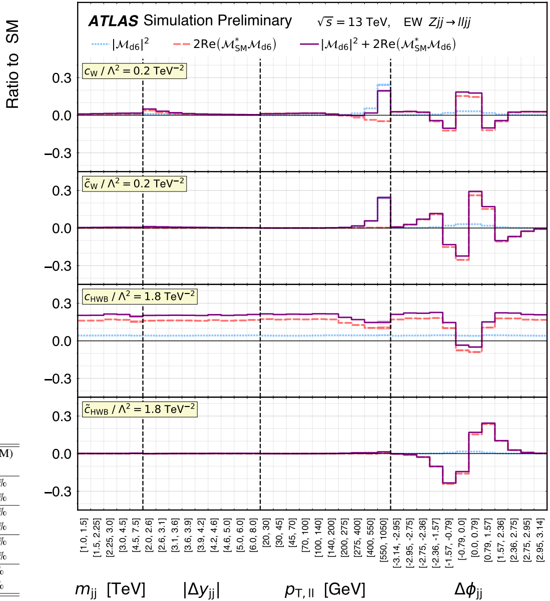
EFT constraints

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

- constraints placed on dim-6 operators in Warsaw basis
  - $\mathcal{CP}$-even: $\mathcal{O}_W$, $\mathcal{O}_{HWB}$
  - $\mathcal{CP}$-odd: $\tilde{\mathcal{O}}_W$, $\tilde{\mathcal{O}}_{HWB}$
- SM predictions modified as:
  $$|\mathcal{M}|^2 = |\mathcal{M}_{\text{SM}}|^2 + |\mathcal{M}_{\text{d6}}|^2 + 2\text{Re}(\mathcal{M}^*_{\text{SM}}\mathcal{M}_{\text{d6}})$$
  with pure SM-term taken from Herwig7+VBFNLO and using SMEFTsim and MadGraph5+Pythia8 for remaining terms

[CERN-EP-2020-045]

Wilson coefficient	Includes $\lvert\mathcal{M}_{\text{d6}}\rvert^2$	95% confidence interval [TeV^{-2}] Expected	Observed	CL (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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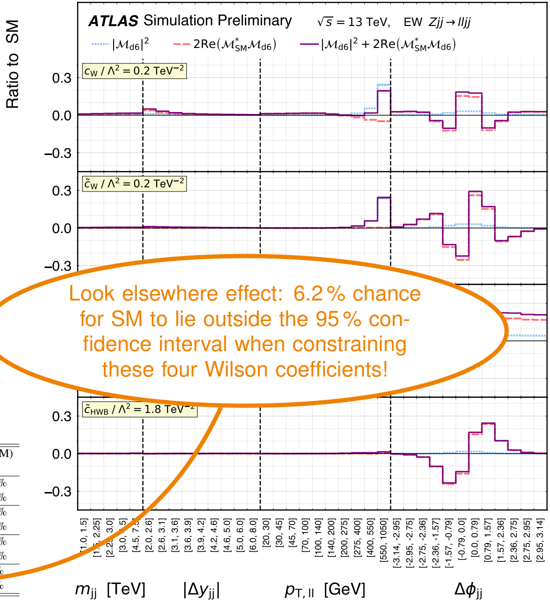


Look elsewhere effect: 6.2 % chance for SM to lie outside the 95 % confidence interval when constraining these four Wilson coefficients!

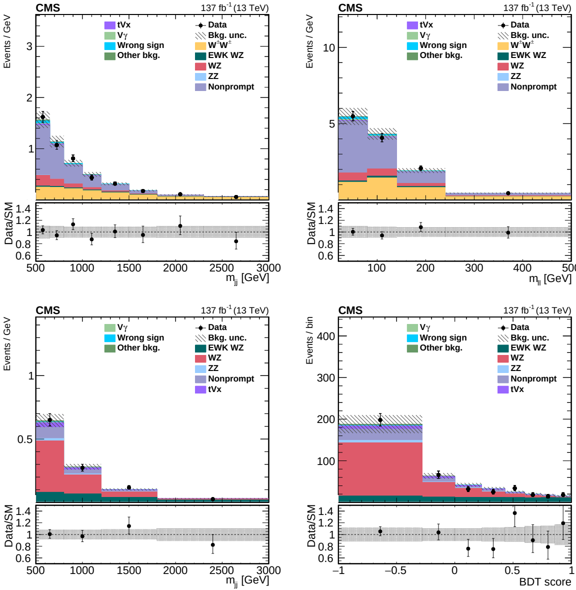
weak boson scattering

$W^{\pm}W^{\pm}jj$ and $WZjj$

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

➜ QCD and electroweak *WW* / *WZ* processes calculated at LO using MadGraph5+Pythia8

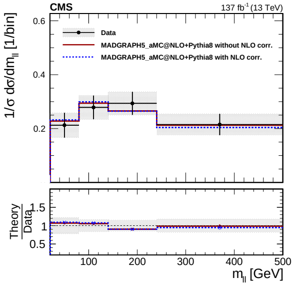
Variable	WZ
Leptons	3 leptons, $p_T > 25/10/20\,GeV$
p_T^j	$> 50\,GeV$
$\lvert m_{\ell\ell} - m_Z \rvert$	$< 15\,GeV$
$m_{\ell\ell}$	-
$m_{\ell\ell\ell}$	$> 100\,GeV$
p_T^{miss}	$> 30\,GeV$
b quark veto	Required
$\max(z_\ell^*)$	< 1.0
m_{jj}	$> 500\,GeV$
$\Delta\eta_{jj}$	> 2.5

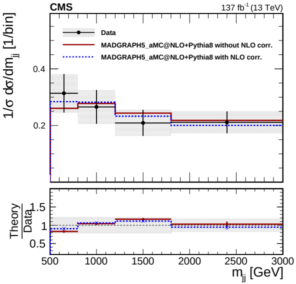


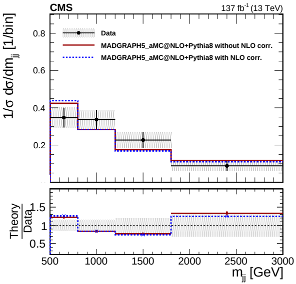
[arXiv:2005.01173]

$W^{\pm}W^{\pm}jj$ and $WZjj$

- electroweak component extracted using binned maximum-likelihood fit
- interference component counted towards signal
- leading systematics: non-prompt rate (3.5 %) for $W^{\pm}W^{\pm}$, JES/JER (4.3 %) and theory (3.8 %) for WZ







[arXiv:2005.01173]

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

ZZjj (ATLAS)

[arXiv:2004.10612]

	$\ell\ell\ell\ell jj$	$\ell\ell\nu\nu jj$
Electrons	$p_{\mathrm{T}} > 7$ GeV, $\lvert\eta\rvert < 2.47$	$p_{\mathrm{T}} > 7$ GeV, $\lvert\eta\rvert < 2.5$
Muons	$p_{\mathrm{T}} > 7$ GeV, $\lvert\eta\rvert < 2.7$	$p_{\mathrm{T}} > 7$ GeV, $\lvert\eta\rvert < 2.5$
Jets	$p_{\mathrm{T}} > 30$ (40) GeV for $\lvert\eta\rvert < 2.4$ ($2.4 < \lvert\eta\rvert < 4.5$)	$p_{\mathrm{T}} > 60$ (40) GeV for the leading (sub-leading) jet
ZZ selection	$p_{\mathrm{T}} > 20, 20, 10$ GeV for the leading, sub-leading and third leptons Two OSSF lepton pairs with smallest $\lvert m_{\ell^+\ell^-} - m_Z\rvert + \lvert m_{\ell'^+\ell'^-} - m_Z\rvert$ $m_{\ell^+\ell^-} > 10$ GeV for lepton pairs $\Delta R(\ell, \ell') > 0.2$ $60 < m_{\ell^+\ell^-} < 120$ GeV	$p_{\mathrm{T}} > 30$ (20) GeV for the leading (sub-leading) lepton One OSSF lepton pair and no third leptons $80 < m_{\ell^+\ell^-} < 100$ GeV $E_{\mathrm{T}}^{\mathrm{miss}} > 130$ GeV
Dijet selection	Two most energetic jets with $y_{j_1} \times y_{j_2} < 0$ $m_{jj} > 300$ GeV and $\Delta y(jj) > 2$	$m_{jj} > 400$ GeV and $\Delta y(jj) > 2$

- electroweak *ZZjj* component simulated at LO using MadGraph5+Pythia8
- QCD $ZZ + 0, 1j$@NLO$+2, 3, 4j$@LO simulated using Sherpa 2.2.2
  - control regions used to constrain the modelling of the strong $ZZ + 2$ jets component
- multivariate discriminant (MD) based on gradient BDT used to extract electroweak *ZZjj* component
- impact of interference component assigned as a systematic on the electroweak signal
- systematics: largest impact from theoretical uncertainties (up to 30 % for $ZZ + 2$ jets)

ZZjj (ATLAS)

➜ extraction of *ZZjj* component:

	μ_{EW}	$\mu_{\text{QCD}}^{\ell\ell\ell\ell jj}$	Significance Obs. (Exp.)
$\ell\ell\ell\ell jj$	1.5 ± 0.4	0.95 ± 0.22	5.5 (3.9) σ
$\ell\ell\nu\nu jj$	0.7 ± 0.7	–	1.2 (1.8) σ
Combined	1.35 ± 0.34	0.96 ± 0.22	5.5 (4.3) σ

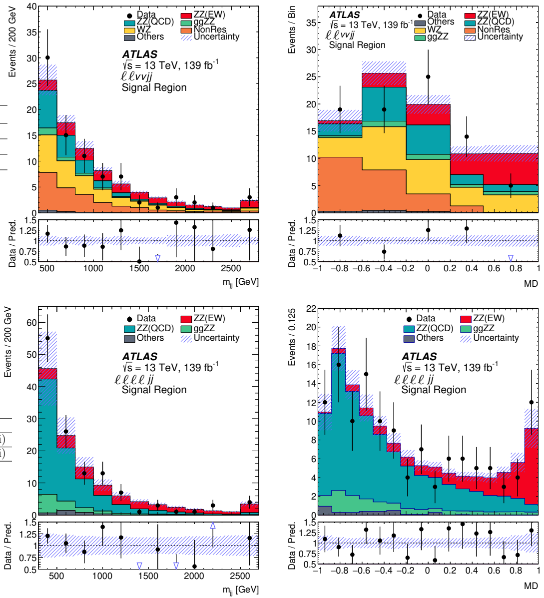
First observation of this rare and important process!

➜ inclusive cross-sections:

	Measured fiducial σ [fb]
$\ell\ell\ell\ell jj$	$1.27 \pm 0.12(\text{stat}) \pm 0.02(\text{theo}) \pm 0.07(\text{exp}) \pm 0.01(\text{bkg}) \pm 0.03(\text{lumi})$
$\ell\ell\nu\nu jj$	$1.22 \pm 0.30(\text{stat}) \pm 0.04(\text{theo}) \pm 0.06(\text{exp}) \pm 0.16(\text{bkg}) \pm 0.03(\text{lumi})$

	Predicted fiducial σ [fb]
$\ell\ell\ell\ell jj$	$1.14 \pm 0.04(\text{stat}) \pm 0.20(\text{theo})$
$\ell\ell\nu\nu jj$	$1.07 \pm 0.01(\text{stat}) \pm 0.12(\text{theo})$

[arXiv:2004.10612]



ZZjj (CMS)

- full electroweak *ZZjj* component including triboson component simulated at LO using MadGraph5+Pythia8
- QCD $ZZ + 0, 1j$@NLO using FxFx from MadGraph5_aMC@NLO+Pythia8
  - differential NNLO QCD K factor applied as a function of m_{ZZ}
  - EW corrections for $m_{ZZ} > 2m_Z$ applied
  - control regions used to constrain the the strong $ZZ + 2$ jets modelling
- matrix-element discriminant (K_D) used to extract electroweak *ZZjj* component
- systematics: largest impact from jet energy scale (5-11 %) and QCD scales (2-11 %)

Object	Selection
	ZZjj inclusive
Leptons	$p_T(\ell_1) > 20$ GeV $p_T(\ell_2) > 10$ GeV $p_T(\ell) > 5$ GeV $\lvert\eta(\ell)\rvert < 2.5$ (γ with $\Delta R(\ell,\gamma) < 0.1$ added to ℓ 4-vector)
Z and ZZ	$60 < m(\ell\ell) < 120$ GeV $m(4\ell) > 180$ GeV
Jets	at least 2 $p_T(j) > 30$ GeV $\lvert\eta(j)\rvert < 4.7$ $m_{jj} > 100$ GeV $\Delta R(\ell, j) > 0.4$ for each ℓ, j
	VBS-enriched (loose)
Jets	ZZjj inclusive + $\lvert\Delta\eta(jj)\rvert > 2.4$ $m_{jj} > 400$ GeV
	VBS-enriched (tight)
Jets	ZZjj inclusive + $\lvert\Delta\eta(jj)\rvert > 5$ $m_{jj} > 400$ GeV

[CMS-PAS-SMP-20-001]

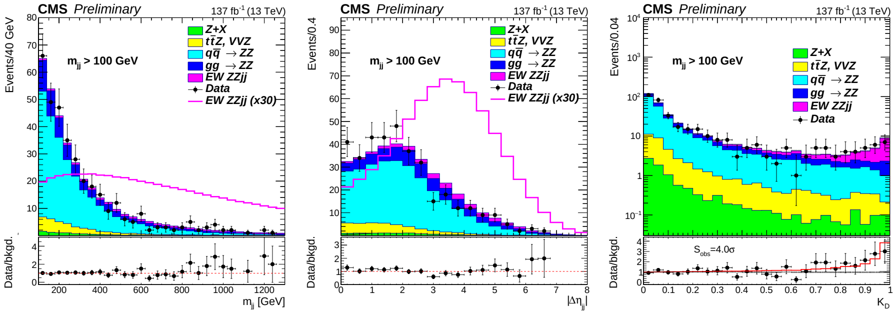
ZZjj (CMS)

	SM σ (fb)	Measured σ (fb)
ZZjj inclusive		
EW	0.275 ± 0.021 (theo)	$0.33\,^{+0.11}_{-0.10}$ (stat) $^{+0.04}_{-0.03}$ (syst)
EW+QCD	5.35 ± 0.51 (theo)	$5.29\,^{+0.31}_{-0.30}$ (stat) $\pm\,0.46$ (syst)
VBS-enriched (loose)		
EW	0.186 ± 0.015 (theo)	$0.200\,^{+0.078}_{-0.067}$ (stat) $^{+0.023}_{-0.013}$ (syst)
EW+QCD	1.21 ± 0.09 (theo)	$1.00\,^{+0.12}_{-0.11}$ (stat) $^{+0.06}_{-0.05}$ (syst)
VBS-enriched (tight)		
EW	0.050 ± 0.005 (theo)	$0.06\,^{+0.05}_{-0.04}$ (stat) $\pm\,0.01$ (syst)
EW+QCD	0.171 ± 0.012 (theo)	0.17 ± 0.04 (stat) $\pm\,0.01$ (syst)

Coupling	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unitarity bound
f_{T0}/Λ^4	-0.37	0.35	-0.24	0.22	2.9
f_{T1}/Λ^4	-0.49	0.49	-0.31	0.31	2.7
f_{T2}/Λ^4	-0.98	0.95	-0.63	0.59	2.8
f_{T8}/Λ^4	-0.68	0.68	-0.43	0.43	3.3
f_{T9}/Λ^4	-1.46	1.46	-0.92	0.92	3.3

➜ 4.0(3.5)σ observed (expected) significance

[CMS-PAS-SMP-20-001]



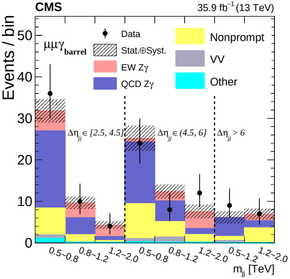
$Z\gamma jj$ (CMS)

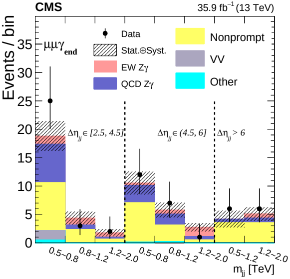
[CMS, arXiv:2002.09902]

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, $\lvert\eta^{\gamma}\rvert < 1.444$ 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 $\Delta R_{jj}, \Delta R_{j\gamma}, \Delta R_{j\ell} > 0.5$, $\Delta R_{\ell\gamma} > 0.7$
Control region	$150 < m_{jj} < 400$ GeV, Common selection
EW signal region	$m_{jj} > 500$ GeV, $\Delta\eta_{jj} > 2.5$, $\eta^* < 2.4$, $\Delta\phi_{Z\gamma,jj} > 1.9$, Common selection
Fiducial region	$m_{jj} > 500$ GeV, $\Delta\eta_{jj} > 2.5$, Common selection, without requirement on $m_{Z\gamma}$
aQGC search region	$m_{jj} > 500$ GeV, $\Delta\eta_{jj} > 2.5$, $p_T^{\gamma} > 100$ GeV, Common selection, without requirement on $m_{Z\gamma}$

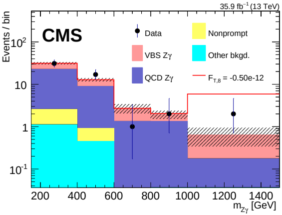
- electroweak $Z\gamma jj$ component simulated at LO using MadGraph5+Pythia8
- QCD $Z\gamma + 0, 1j$@NLO using FxFx from MadGraph5_aMC@NLO+Pythia8
- impact of interference component assigned as a systematic on the electroweak signal
- systematics: largest impact from theoretical uncertainties (QCD scales up to 25 %)

$Z\gamma jj$ (CMS)





[arXiv:2002.09902]

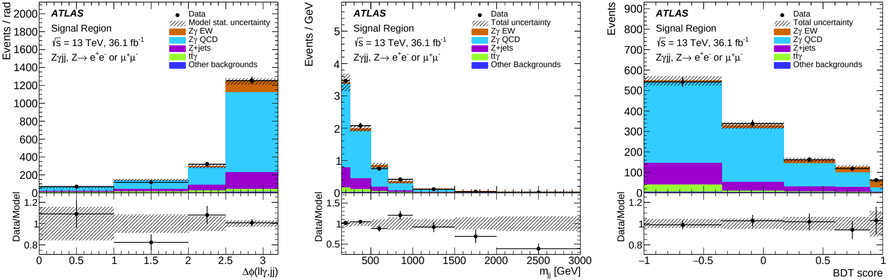


- fiducial cross-section for inclusive $Z\gamma jj$ production
  14.3 ± 0.4(lumi) $\pm$ 1.1(stat) $\pm$ 2.7(syst) fb in good agreement
  with SM prediction 15.7 ± 1.7(scale) $\pm$ 0.2(pdf) fb from MadGraph5_aMC@NLO+Pythia8

- fiducial cross-section for electroweak $Z\gamma jj$ production
  3.2 ± 0.2(lumi) $\pm$ 1.1(stat) $\pm$ 0.6(syst) fb agrees within 2σ with
  with SM prediction 4.97 ± 0.25(scale) $\pm$ 0.14(pdf) fb from MadGraph5+Pythia8

$Z\gamma jj$ (ATLAS)

[Phys. Lett. B 803, 135341 (2020)]



➜ Fiducial electroweak $Z\gamma jj$ cross-section:

$$\sigma^{\text{fid.}}_{Z\gamma jj-\text{EW}} = 7.8 \pm 1.5\,(\text{stat.}) \pm 1.0\,(\text{syst.})\,^{+1.0}_{-0.8}\,(\text{mod.})\text{ fb}$$

$$\sigma^{\text{fid., MadGraph}}_{Z\gamma jj-\text{EW}} = 7.75 \pm 0.03\,(\text{stat.}) \pm 0.20\,(\text{PDF} + \alpha_S) \pm 0.40\,(\text{scale})\text{ fb}$$

$$\sigma^{\text{fid., Sherpa}}_{Z\gamma jj-\text{EW}} = 8.94 \pm 0.08\,(\text{stat.}) \pm 0.20\,(\text{PDF} + \alpha_S) \pm 0.50\,(\text{scale})\text{ fb}$$

➜ Fiducial inclusive $Z\gamma + 2$ jet cross-section:

$$\sigma^{\text{fid.}}_{Z\gamma jj} = 71 \pm 2\,(\text{stat.})\,^{+9}_{-7}\,(\text{syst.})\,^{+21}_{-17}\,(\text{mod.})\text{ fb}$$

$$\sigma^{\text{fid., MadGraph+Sherpa}}_{Z\gamma jj} = 88.4 \pm 2.4\,(\text{stat.}) \pm 2.3\,(\text{PDF} + \alpha_S)^{+29.4}_{-19.1}\,(\text{scale})\text{ fb.}$$

$W\gamma jj$

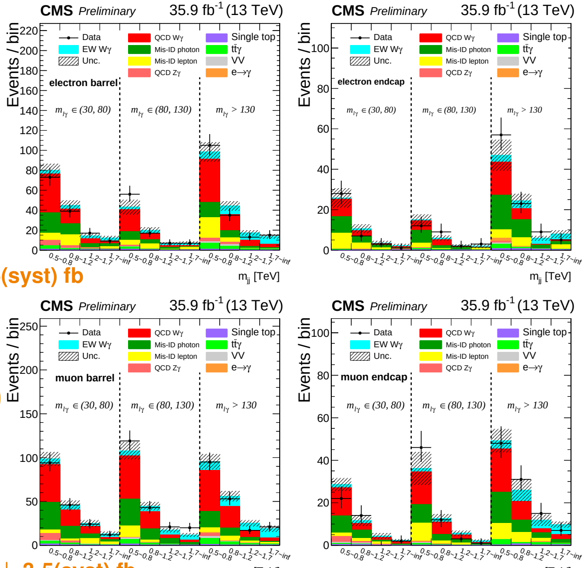
- interference impact assigned as a systematic on the electroweak signal
- fiducial cross-section for inclusive $W\gamma jj$ production

108 ± 2(lumi) ± 5(stat) ± 15(syst) fb

4.9(4.6)σ observed (expected) with 2016 data set, 5.3(4.8)σ observed (expected) when combined with 8 TeV result!

- fiducial cross-section for electroweak $W\gamma jj$ production

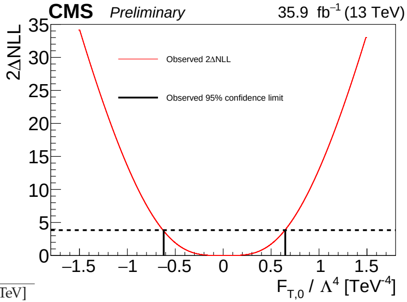
20.4 ± 0.4(lumi) ± 2.8(stat) ± 3.5(syst) fb



[CMS-PAS-SMP-19-008]

$W\gamma jj$

➜ unitarity bound given by scattering energy at which the aQGC coupling strength, when set equal to the observed limit, would result in a scattering amplitude that violates unitarity



[CMS-PAS-SMP-19-008]

Observed limits [TeV^{-4}]	Expected limits [TeV^{-4}]	Unitarity bound [TeV]
$-8.07 < F_{M,0}/\Lambda^4 < 7.99$	$-7.67 < F_{M,0}/\Lambda^4 < 7.55$	1.0
$-11.8 < F_{M,1}/\Lambda^4 < 12.1$	$-10.8 < F_{M,1}/\Lambda^4 < 11.3$	1.2
$-2.81 < F_{M,2}/\Lambda^4 < 2.81$	$-2.68 < F_{M,2}/\Lambda^4 < 2.68$	1.3
$-4.41 < F_{M,3}/\Lambda^4 < 4.49$	$-4.04 < F_{M,3}/\Lambda^4 < 4.10$	1.5
$-4.99 < F_{M,4}/\Lambda^4 < 4.95$	$-4.70 < F_{M,4}/\Lambda^4 < 4.67$	1.5
$-8.27 < F_{M,5}/\Lambda^4 < 8.31$	$-7.85 < F_{M,5}/\Lambda^4 < 7.73$	1.8
$-16.2 < F_{M,6}/\Lambda^4 < 16.0$	$-15.4 < F_{M,6}/\Lambda^4 < 15.1$	1.0
$-20.8 < F_{M,7}/\Lambda^4 < 20.2$	$-19.4 < F_{M,7}/\Lambda^4 < 18.7$	1.3
$-0.62 < F_{T,0}/\Lambda^4 < 0.64$	$-0.60 < F_{T,0}/\Lambda^4 < 0.62$	1.4
$-0.35 < F_{T,1}/\Lambda^4 < 0.39$	$-0.34 < F_{T,1}/\Lambda^4 < 0.38$	1.5
$-0.99 < F_{T,2}/\Lambda^4 < 1.18$	$-0.98 < F_{T,2}/\Lambda^4 < 1.16$	1.5
$-0.45 < F_{T,5}/\Lambda^4 < 0.46$	$-0.43 < F_{T,5}/\Lambda^4 < 0.44$	1.8
$-0.36 < F_{T,6}/\Lambda^4 < 0.38$	$-0.34 < F_{T,6}/\Lambda^4 < 0.36$	1.7
$-0.87 < F_{T,7}/\Lambda^4 < 0.93$	$-0.83 < F_{T,7}/\Lambda^4 < 0.89$	1.8

➜ more details in **Mariarosaria D'Alfonso**'s talk tomorrow

Summary

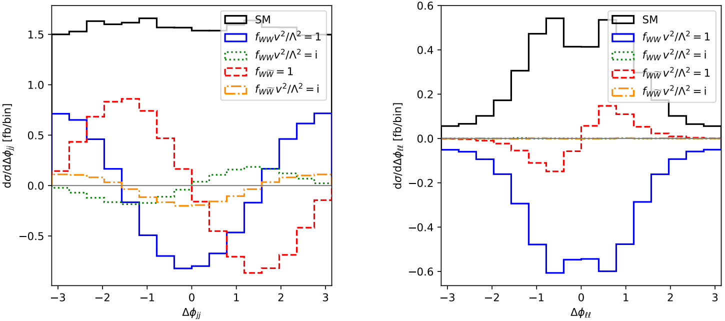
- measurements of *Vjj* and *VVjj* final states are a **vital probe of the electroweak sector**
  - unitarity bound achieved through delicate cancellation of terms
- measurements of inclusive $V + 2$ jet and $VV + 2$ jet production in VBF/VBS topologies provide a **stress test of perturbative QCD**
  - understanding the background modelling key to pinning down these important processes
  - crucial to **make data available on HEPData and provide a Rivet routine** to maximise impact
- go **see Heather Russell's and Mariarosaria D'Alfonso's talks** tomorrow!

Thank you!

Backup

Azimuthal decorrelation

[Phys. Rev. D 97, 095017 (2018)]



➜ crucial to precisely measure jet/lepton kinematics in VBF/VBS topologies

➜ azimuthal difference sensitive to different spin and $\mathcal{CP}$ states [JHEP 01 (2013) 148]

$W^{\pm}W^{\pm}jj$ and $WZjj$ systematics (CMS)

Source of uncertainty	$W^{\pm}W^{\pm}$ (%)	WZ (%)
Integrated luminosity	1.5	1.6
Lepton measurement	1.8	2.9
Jet energy scale and resolution	1.5	4.3
Pileup	0.1	0.4
btagging	1.0	1.0
Nonprompt rate	3.5	1.4
Trigger	1.1	1.1
Limited MC sample size	2.6	3.7
Theory	1.9	3.8
Total systematic uncertainty	5.7	7.9
Statistical uncertainty	8.9	22
Total uncertainty	11	23

$Z\gamma jj$ systematics (CMS)

Source of systematic uncertainty	Relative uncertainty [%]
Scales in QCD-induced $Z\gamma$ bkg	5–25
Scales in EW $Z\gamma$ signal	2–14
Interference	4–8
JES	1–49
JER	1–26
Nonprompt photon bkg	9–37
Integrated luminosity	2.5
L1 mistiming correction	1–4
Photon identification	3
Pileup modeling	1
Trigger and selection efficiency	2–3

$Z\gamma jj$ systematics (ATLAS)

Source	Uncertainty [%]
Statistical	$^{+19}_{-18}$
$Z\gamma jj$–EW theory modelling	$^{+10}_{-6}$
$Z\gamma jj$–QCD theory modelling	±6
$t\bar{t}+\gamma$ theory modelling	±2
$Z\gamma jj$–EW and $Z\gamma jj$–QCD interference	$^{+3}_{-2}$
Jets	±8
Pile-up	±5
Electrons	±1
Muons	$^{+3}_{-2}$
Photons	±1
Electrons/photons energy scale	±1
b-tagging	±2
MC statistical uncertainties	±8
Other backgrounds normalisation (including Z+jets)	$^{+9}_{-8}$
Luminosity	±2
Total uncertainty	±26

$W\gamma jj$ systematics (CMS)

Source	EW Wγjj	QCD Wγjj	VV	$t\bar{t}\gamma$	QCD Zγ	Single top	Mis-ID photon	Mis-ID lepton	Double fake	e $\to \gamma$
Jet energy scale	0.9-6.9	11-28	6.4-38	3.7-16	12-78	3.3-18	—	—	—	11-28
Jet energy resolution	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
Luminosity	2.5	2.5	2.5	2.5	2.5	2.5	—	—	—	2.5
Mis-ID photon	—	—	—	—	—	—	12-22	—	12.1-22	—
Mis-ID lepton	—	—	—	—	—	—	—	30	30	—
μ_R/μ_F scales	1.5-11	6.1-20	—	—	—	—	—	—	—	—
PDF	3.2-5.6	1-2	—	—	—	—	—	—	—	—
Interference	1.8-2.8	—	—	—	—	—	—	—	—	—
Cross section of $t\bar{t}\gamma$	—	—	—	10	—	—	—	—	—	—
Cross section of VV	—	—	10	—	—	—	—	—	—	—
Pileup modeling	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
Statistics	7-11	6-36	45-100	13-56	16-100	17-55	7-36	43-72	30-100	54-100
L1 prefiring correction	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
b-tagging veto	0.3	0.3	0.3	0.8	0.3	0.8	—	—	—	0.3
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