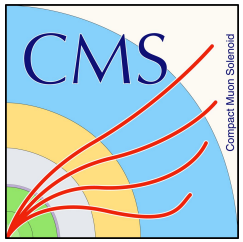


Recent results in VBS and VBF @ LHC

SM@LHC 2021

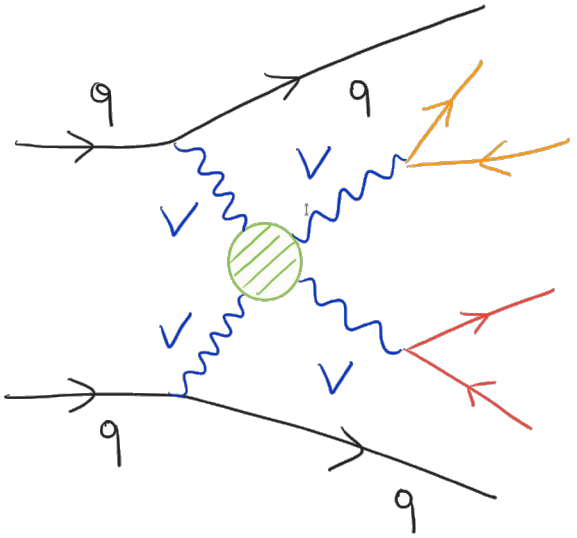
Davide Valsecchi
on behalf of the CMS and ATLAS collaborations

INFN & Università degli Studi di Milano-Bicocca
CERN

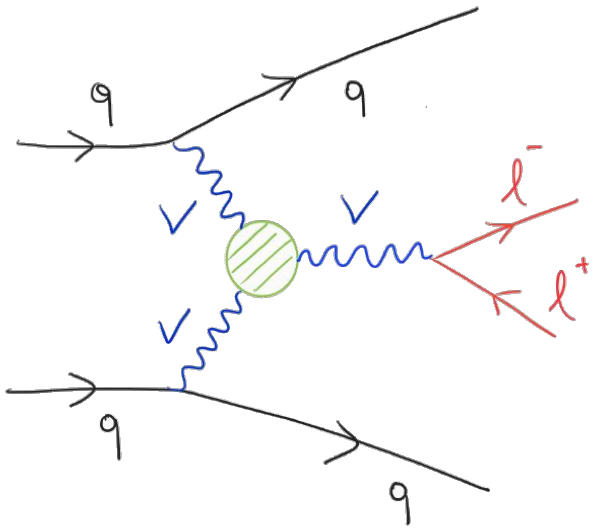
Introduction and experimental motivation

- LHC can be used as a **Vector Bosons collider**

- **VV production** via Vector Boson Scattering:
  - can proceed by pure EWK interactions **at tree level**
  - directly linked to EW symmetry breaking mechanism → deviations == New Physics ?
  - Many channels accessible at LHC

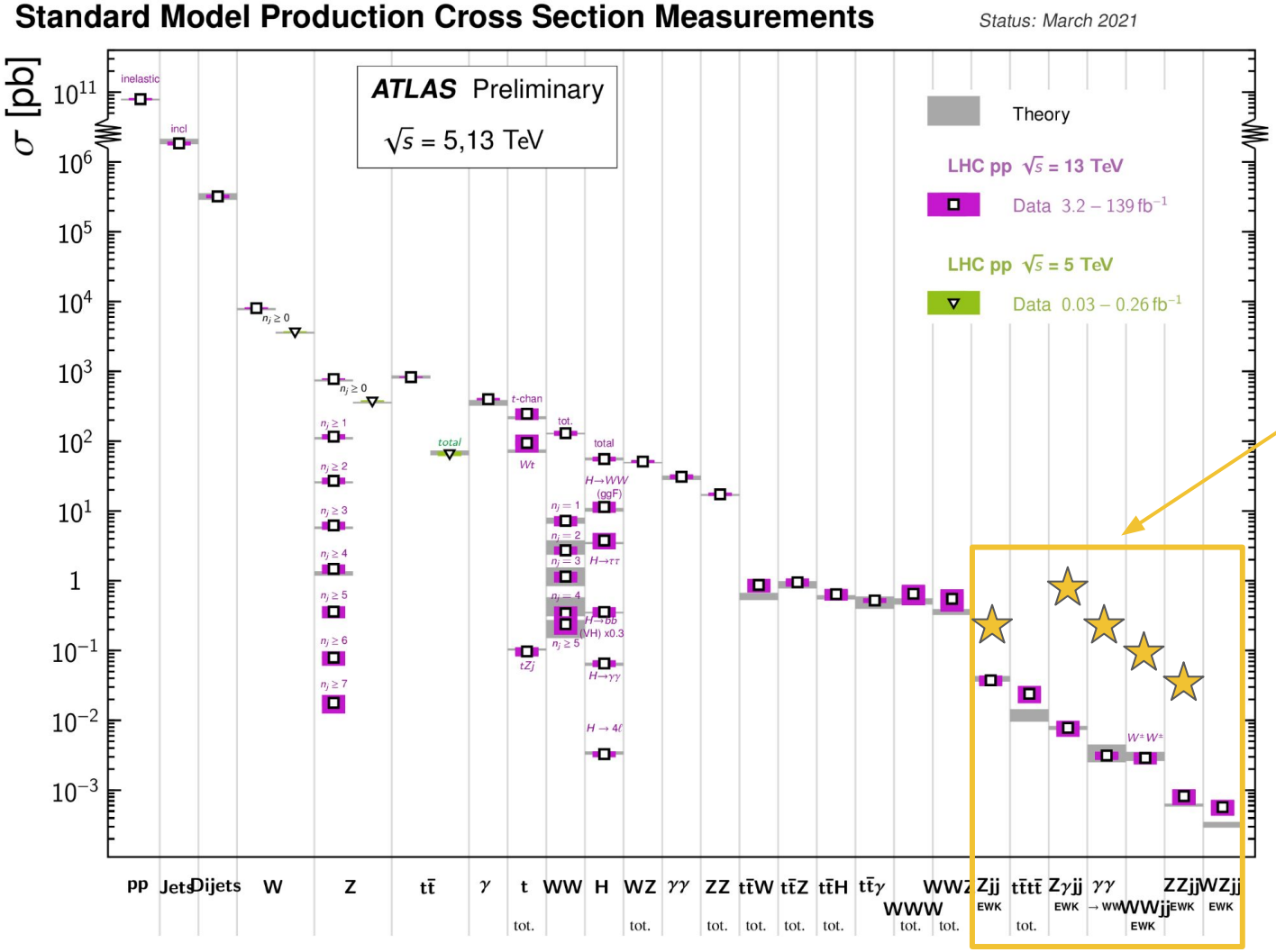


- **Precise EW V production** measurements crucial for SM and BSM analyses
  - differential cross-section measurements
  - stringent limits on dim-6 operators



VBS and VBF processes

- With Full Run2 data going **from search to precise measurements**
  - challenging experimental final states: forward jets and PU contamination
  - Sophisticated signal extraction and data-driven bkg estimations



We are looking down at the **smallest EW cross-sections** we are able to measure

★ in today's talk

Published results

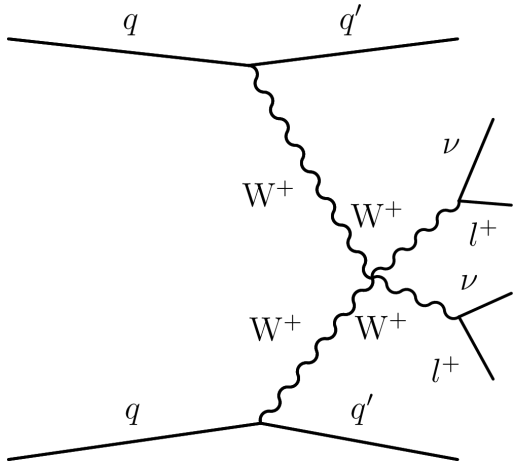
Recent review arXiv:2102.10991

		Energy, dataset	Results	Reference
VBF	W±jj	13 TeV, 36/fb	Inclusive XS + aTGC limits	Eur. Phys. J. C 80 (2020) 43
	Zjj	13 TeV, 36/fb	Inclusive XS + aTGC limits	Eur. Phys. J. C 78 (2018) 589
VBS	W±W± jj	13 TeV, 137/fb	Recent $W_L W_L$ measurement	Phys. Lett B 812 (2020) 136018 NEW
	WZ jj + W±W± jj	13 TeV, 137/fb	6.8 (5.3) σ. Differential XS.	Phys. Lett. B 809(2020) 135710
	W±γ jj	13 TeV, 36/fb	5.3 (4.8) σ	Phys. Lett. B 811 (2020) 135988
	Zγ jj	13 TeV, 137/fb	>5 σ, Differential XS + **EFT** limits	CMS-PAS-SMP-20-016 NEW
	ZZ jj	13 TeV, 137/fb	4.0 (3.5) σ + **EFT** limits	Phys. Lett. B 812 (2021) 135992 NEW
	γγWW excl. prod.	7,8 TeV, 5,20/fb	-	
	VV jj semilep	13 TeV, 36/fb	BSM + strong aQGC limit	Phys. Lett. B 798 (2019) 134985
VBF	W±jj	7,8 TeV. 5,20/fb	> 5 σ, Differential XS	Eur. Phys. J C 77 (2017) 474
	Zjj	13 TeV, 139/fb	Differential XS + **EFT** limits	Eur. Phys. J. C 81 (2021) 163 NEW
VBS	W±W± jj	13 TeV, 36/fb	6.5 (4.4) σ	Phys. Lett. B 123 (2019) 161801
	WZ jj	13 TeV, 36/fb	5.3 (3.2) σ, Differential XS	Phys. Lett. B 123 (2019) 469
	W±γ jj	-	-	
	Zγ jj	13 TeV, 36/fb	4.1 (4.1) σ	Phys. Lett. B 803 (2020) 135341
	ZZ jj	13 TeV, 139/fb	5.5 (4.3) σ	arXiv:2004:10612 NEW
	γγWW excl. prod.	13 TeV, 139/fb	>> 5 σ	Phys. Lett. B 816 (2021) 136190 NEW
	VV jj semilep	13 TeV, 36/fb	2.7 (2.5) σ	Phys. Rev. D 100 (2019) 032007

Next step for $W^{\pm}W^{\pm}$ VBS

PLB 812 (2020) 136018

- **Same-sign WW VBS :** Golden VBS channel
  - EWK production **>** QCD one
  - First observation with 2016 data → with full Run 2 data going towards precise measurements
  - Two same sign, same flavour, tight leptons. Two tag jets with VBS selections ($M_{jj} > 500$ GeV, $|\Delta\eta_{jj}| > 2.5$)

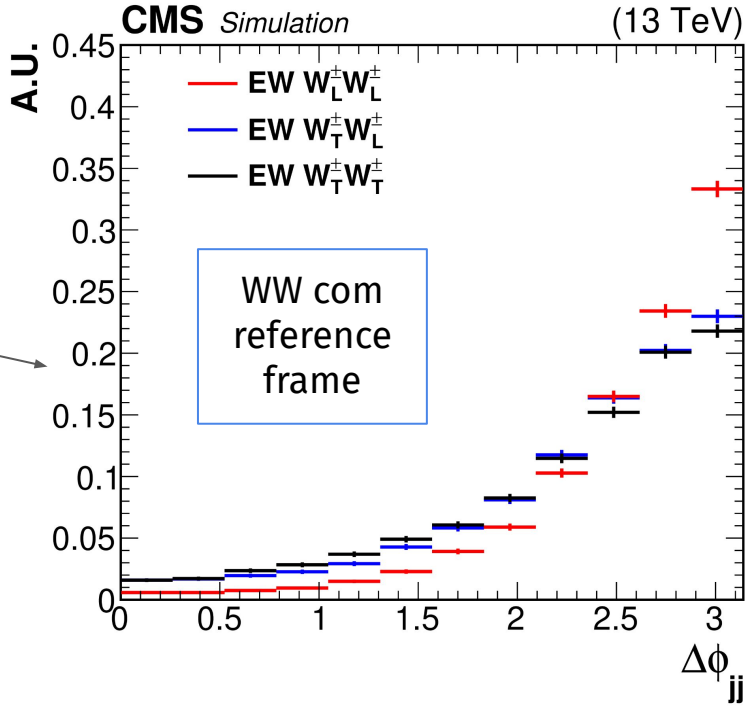


NEW **First** measurement of the **polarization components** W_LW_L , W_TW_T **and** W_LW_T

- **Angular variables** powerful for polarization components extraction

- **Backgrounds**:
  - control regions to measure WZ, ZZ, tZq bkgs
  - Non-prompt data-driven and mis-charge ID

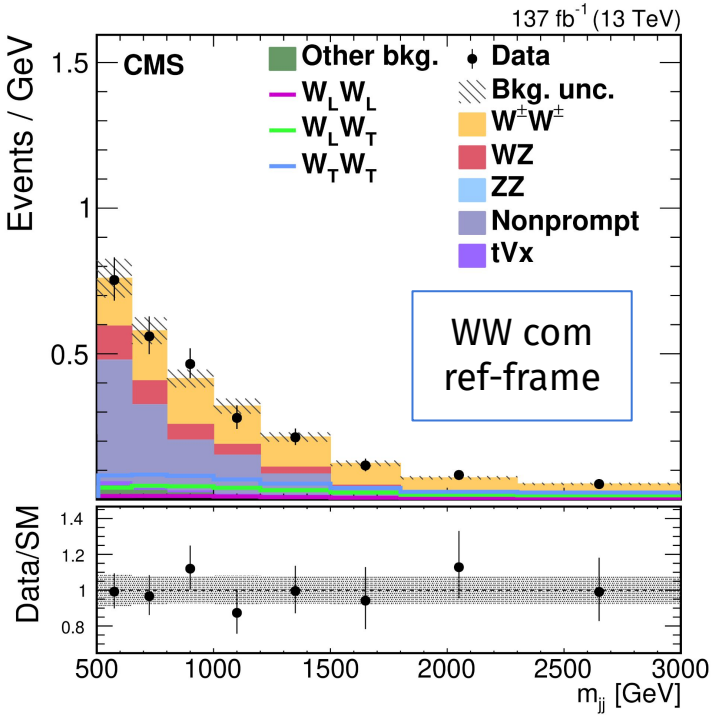
- Results are **reference-frame-dependent**:
  - presented both in parton-parton and WW com reference frames

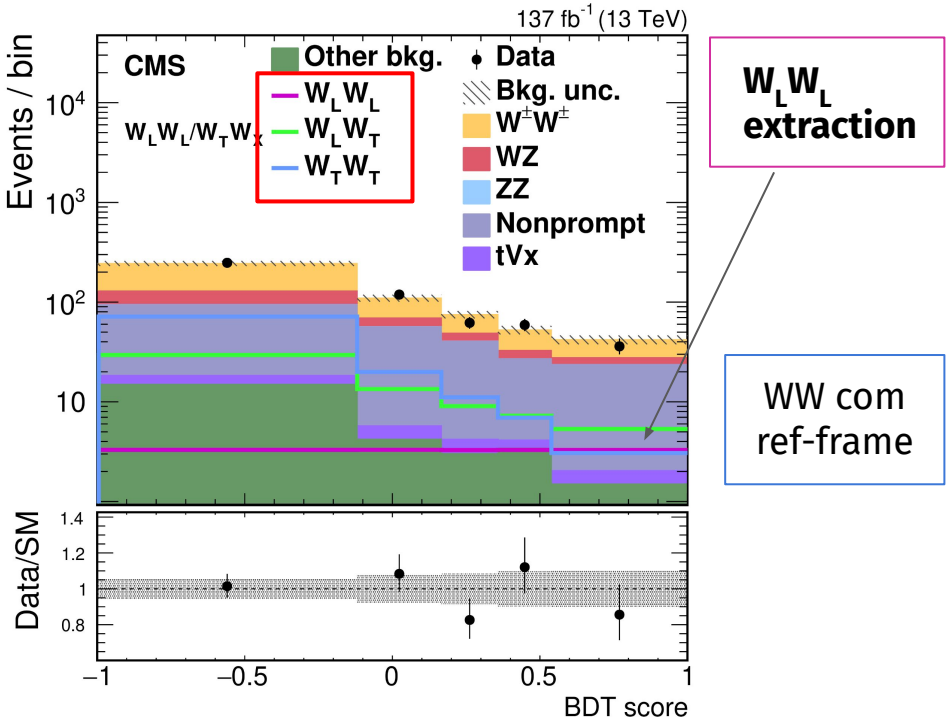


Polarized $W^{\pm}_{L}W^{\pm}_{L}$ extraction

PLB 812 (2020) 136018

- **Two steps** strategy:
  - inclusive BDT to extract WW same-sign signal
  - specific signal BDT for (W_LW_L vs W_XW_T) and (W_TW_T vs W_XW_L)
- and separate likelihood **fits** (repeated and re-optimized for different reference frames)
  - **W_LW_L** and **W_TW_X** components
  - **W_TW_T** and **W_LW_X** components
- Fit M_{jj} in the control regions with 4 bins
- **2D fit** in signal region → inclusive BDT (5 bins), specific signal BDT (5 bins)

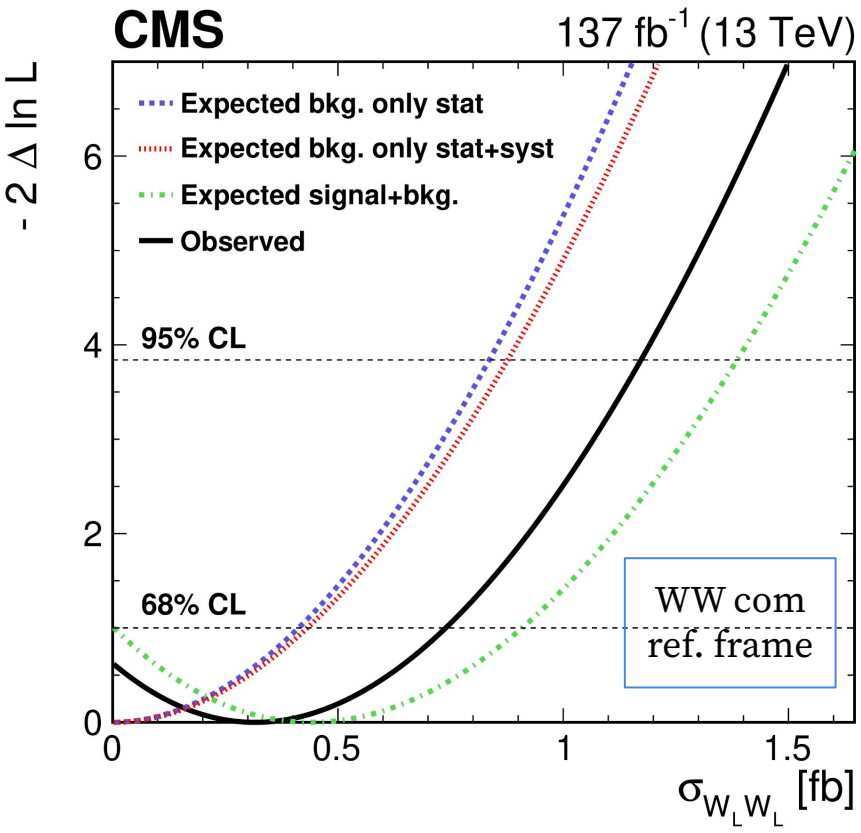




Polarized $W^{\pm}W^{\pm}$ results

PLB 812 (2020) 136018

- The significance of the measured $W_L W_X$ yield is 3.1 σ expected, **2.3** σ observed
- Exclude **> ~2 x SM** $W_L W_L$ production at 95% confidence-level
- Fiducial cross-sections extracted for all the polarizations → **agrees with SM** within uncertainties



WW com reference frame

Process	$\sigma\,\mathcal{B}$ (fb)	Theoretical prediction (fb)
$W_L^{\pm}W_L^{\pm}$	$0.32^{+0.42}_{-0.40}$	0.44 ± 0.05
$W_X^{\pm}W_T^{\pm}$	$3.06^{+0.51}_{-0.48}$	3.13 ± 0.35
$W_L^{\pm}W_X^{\pm}$	$1.20^{+0.56}_{-0.53}$	1.63 ± 0.18
$W_T^{\pm}W_T^{\pm}$	$2.11^{+0.49}_{-0.47}$	1.94 ± 0.21

parton-parton reference frame

Process	$\sigma\,\mathcal{B}$ (fb)	Theoretical prediction (fb)
$W_L^{\pm}W_L^{\pm}$	$0.24^{+0.40}_{-0.37}$	0.28 ± 0.03
$W_X^{\pm}W_T^{\pm}$	$3.25^{+0.50}_{-0.48}$	3.32 ± 0.37
$W_L^{\pm}W_X^{\pm}$	$1.40^{+0.60}_{-0.57}$	1.71 ± 0.19
$W_T^{\pm}W_T^{\pm}$	$2.03^{+0.51}_{-0.50}$	1.89 ± 0.21

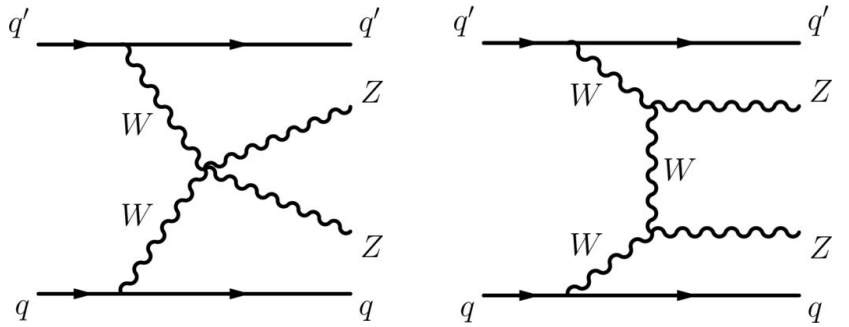
ZZ + 2 jets ATLAS

arXiv:2004.10612

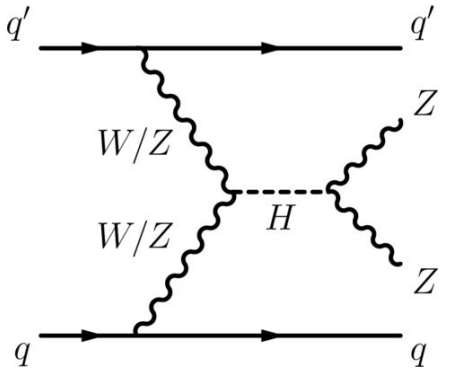
- One of the **rarest SM processes** observed to date
  - Clean fully leptonic channel with small experimental background
  - Full polarization available → important for future studies with more data
  - Progress in theory precision: **NLO corrections** available NEW

- **2 fully-leptonic channels:**
  - 4l+jj channel: 2 pairs of opposite sign, same flavour charged leptons
  - 2l2v+jj channel: 1 l^+l^- pair only + MET with high significance.
- **Multivariate discriminator** for signal extraction using 12 variables:
  - M_{jj}, Δy_{jj}, jet p_T and η, etc.
- Main background **QCD ZZ** production
  - controlled in dedicated region defined inverting Z boson centrality requirement, M_{jj} and Δy_{jj} cuts

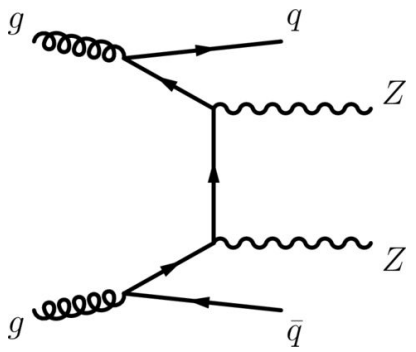
EWK production



Higgs s-channel



QCD production



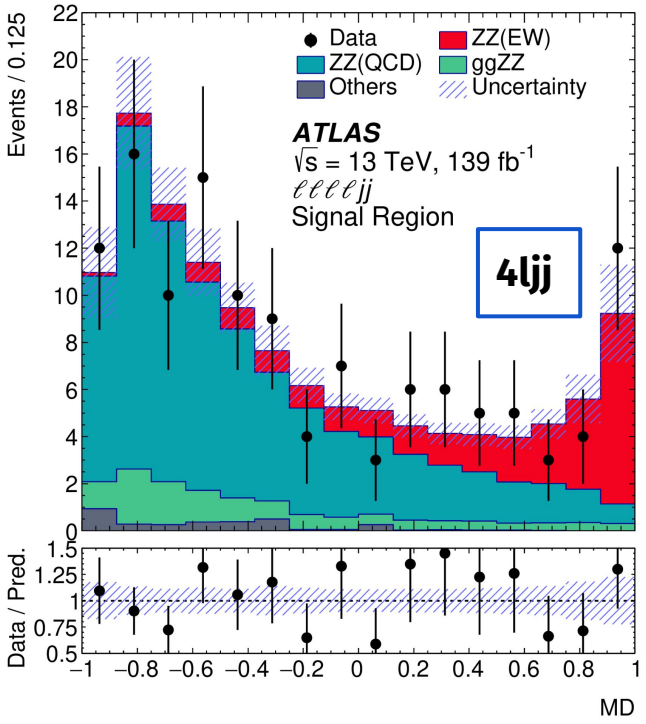
ZZ + 2 jets ATLAS - Results

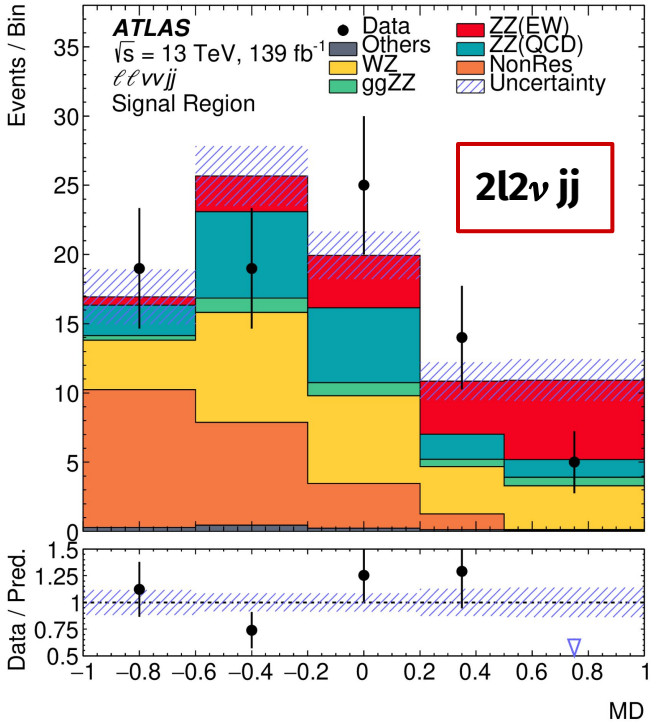
arXiv:2004.10612

- Combined fit in 4ljj and 2l2νjj channels → **observation**!
- BDT variables used in the fit
- Fiducial XS in agreement with SM expectation

	μ_{EW}	$\mu_{\mathrm{QCD}}^{\ell\ell\ell\ell jj}$	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

	Measured fiducial σ [fb]	Predicted fiducial σ [fb]
$\ell\ell\ell\ell jj$	$1.27 \pm 0.12(\mathrm{stat}) \pm 0.02(\mathrm{theo}) \pm 0.07(\mathrm{exp}) \pm 0.01(\mathrm{bkg}) \pm 0.03(\mathrm{lumi})$	$1.14 \pm 0.04(\mathrm{stat}) \pm 0.20(\mathrm{theo})$
$\ell\ell\nu\nu jj$	$1.22 \pm 0.30(\mathrm{stat}) \pm 0.04(\mathrm{theo}) \pm 0.06(\mathrm{exp}) \pm 0.16(\mathrm{bkg}) \pm 0.03(\mathrm{lumi})$	$1.07 \pm 0.01(\mathrm{stat}) \pm 0.12(\mathrm{theo})$

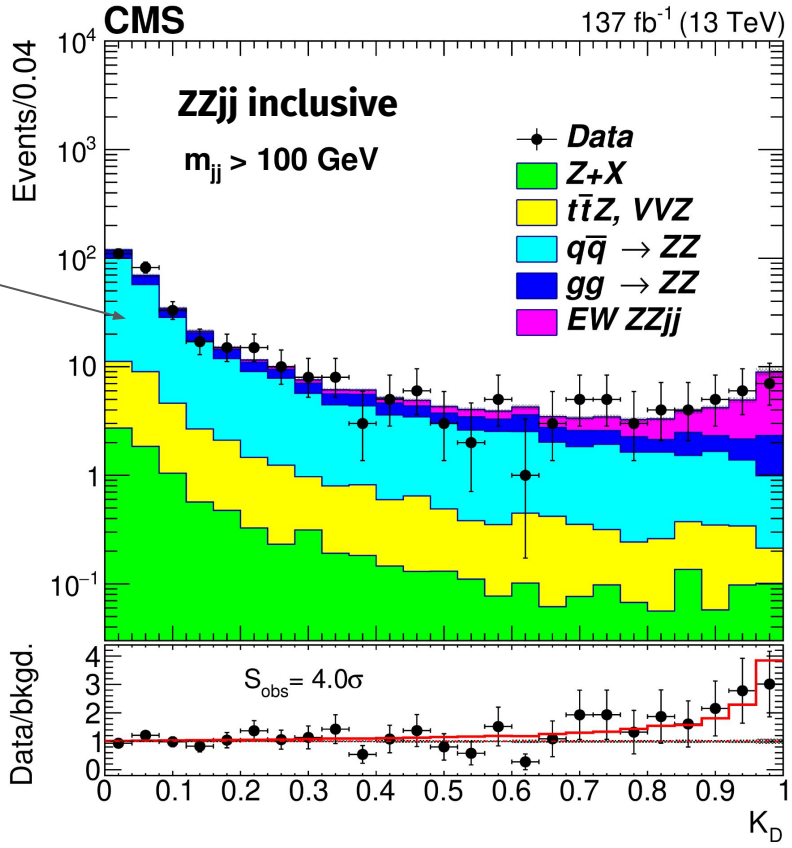




ZZ + 2 jets CMS

PLB 812 (2021) 135992

- 4l jj final state only, 137/fb dataset
- Evidence of EW ZZjj production at **4σ** using **matrix element discriminant** K_D
- 3 regions for fiducial cross-sections: inclusive, loose VBS and tight VBS
  - EW and EW+QCD measurements
  - In **agreement** with SM prediction
- Main background:
  - QCD ZZjj production constrained in the bkg dominated region of the discriminator

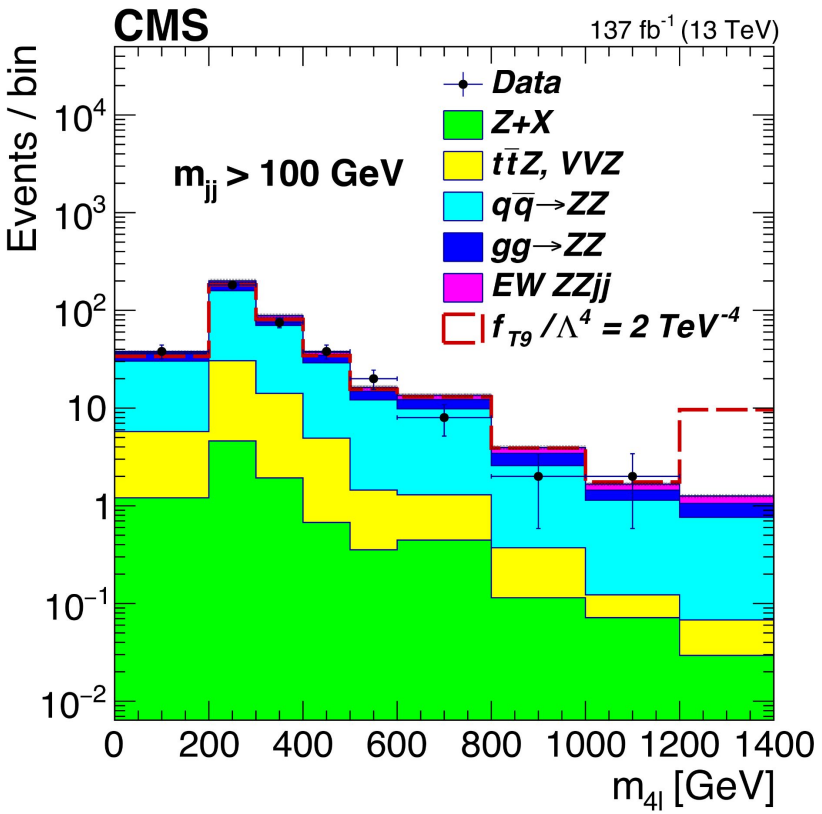


	Perturbative order	SM σ (fb)	Measured σ (fb)
		ZZjj inclusive	
EW	LO	0.275 ± 0.021	$0.33^{+0.11}_{-0.10}\,(\text{stat})^{+0.04}_{-0.03}\,(\text{syst})$
	NLO QCD	0.278 ± 0.017	
EW+QCD		5.35 ± 0.51	$5.29^{+0.31}_{-0.30}\,(\text{stat}) \pm 0.46\,(\text{syst})$
		VBS-enriched (loose)	
EW	LO	0.186 ± 0.015	$0.200^{+0.078}_{-0.067}\,(\text{stat})^{+0.023}_{-0.013}\,(\text{syst})$
	NLO QCD	0.197 ± 0.013	
EW+QCD		1.21 ± 0.09	$1.00^{+0.12}_{-0.11}\,(\text{stat})^{+0.06}_{-0.05}\,(\text{syst})$
		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	$0.20^{+0.05}_{-0.04}\,(\text{stat}) \pm 0.02\,(\text{syst})$

ZZ + 2 jets CMS - aQGC

PLB 812 (2021) 135992

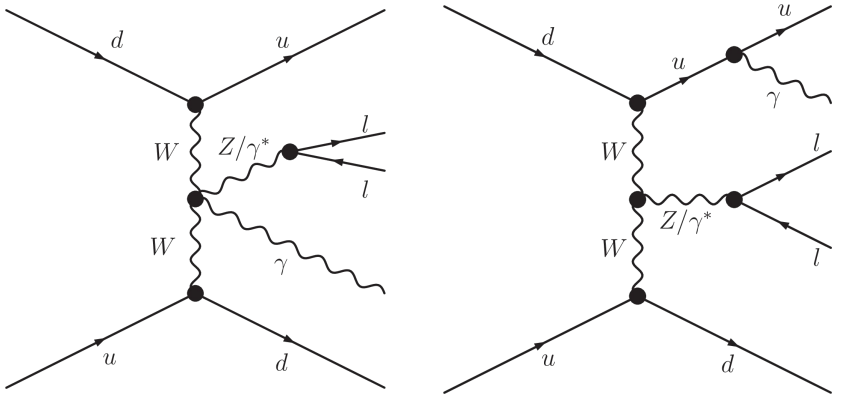
- Limits on **dim-8 EFT** operators at 95% CL
  - charged-current operators: T0, T1, and T2
  - neutral current operators: T8 and T9
- **M_{4l}** observable used for the fit
- The **most stringent** limit to date on neutral current operator **T8** NEW
  - The recent CMS Zγjj analysis **improves** the T9 operator limit to ± 0.91

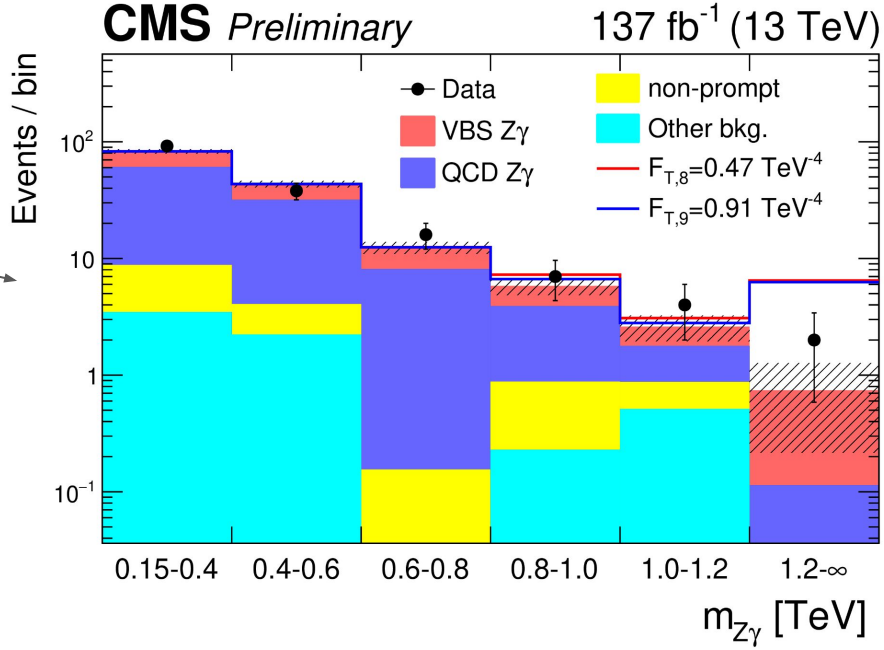


Coupling	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unitarity bound
f_{T0}/Λ^4	−0.37	0.35	−0.24	0.22	2.4
f_{T1}/Λ^4	−0.49	0.49	−0.31	0.31	2.6
f_{T2}/Λ^4	−0.98	0.95	−0.63	0.59	2.5
f_{T8}/Λ^4	−0.68	0.68	−0.43	0.43	1.8
f_{T9}/Λ^4	−1.5	1.5	−0.92	0.92	1.8

units in TeV^{-4}

- **Observation** of the process
  - **Differential** XS measurement
  - **EFT dim-8** operators limits NEW
- Measured fiducial inclusive EWK and EWK+QCD cross-section → **agreement with SM**
- Differential unfolded XS in lepton and photon p_T, leading jet p_T, Mjj and $\Delta\eta_{jj}$ bins
- **The most stringent limits** to date on the dim-8 operator T9:
  - $-0.91 < F_{T9}/\Lambda^4 < 0.91$



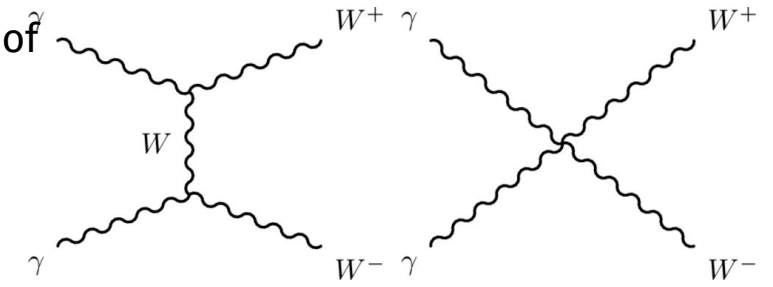


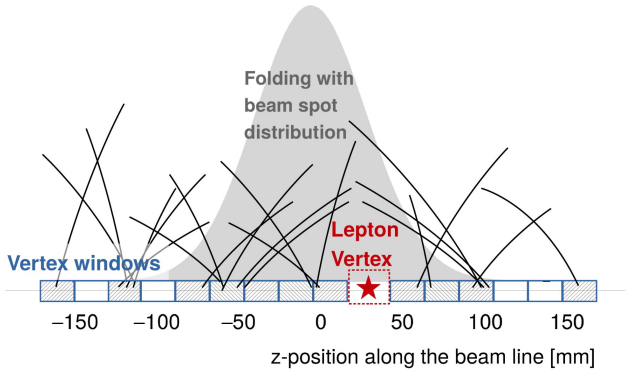
More info in the dedicated talk from Ying An (Peking Univ.)

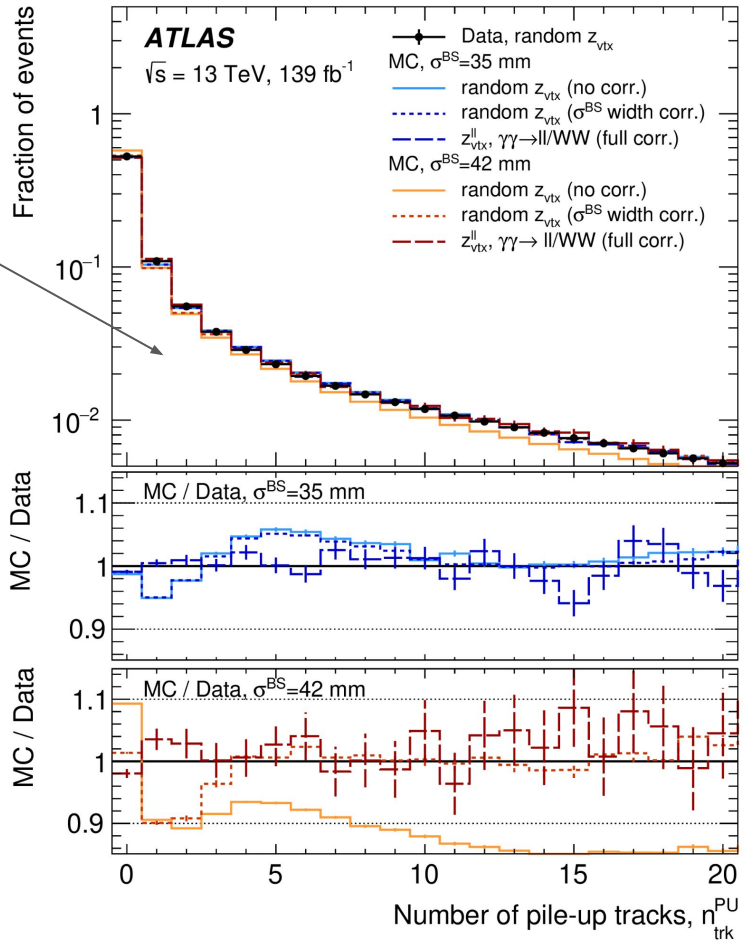
γγ → WW exclusive production

PLB 816 (2021) 136190

- Observation of photon-induced exclusive production of W boson pairs with the ATLAS detector and full Run 2 dataset 137/fb NEW
- Direct test of SU(2)XU(1) structure of SM and sensitive to anomalous gauge-bosons interactions
- Signal extraction: **0 additional charged particle tracks**
- Background modelling quite complex
  - **pileup tracks** contribution corrected from data
  - Modeling of hadronic activity is constrained using Drell-Yan events in data
  - Unfold $N_{charged}$ to N_{tot} tracks after background subtraction and PU corrections





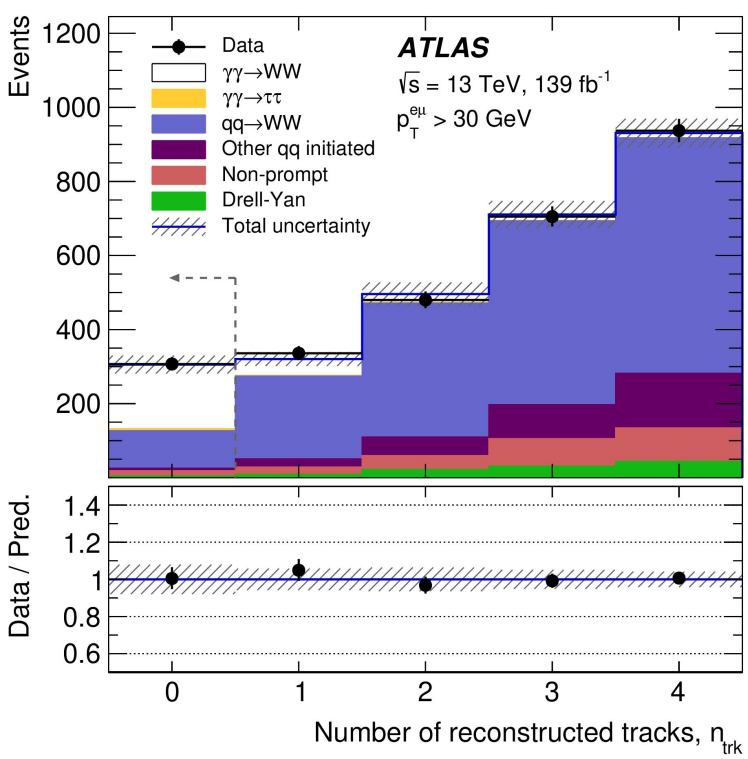


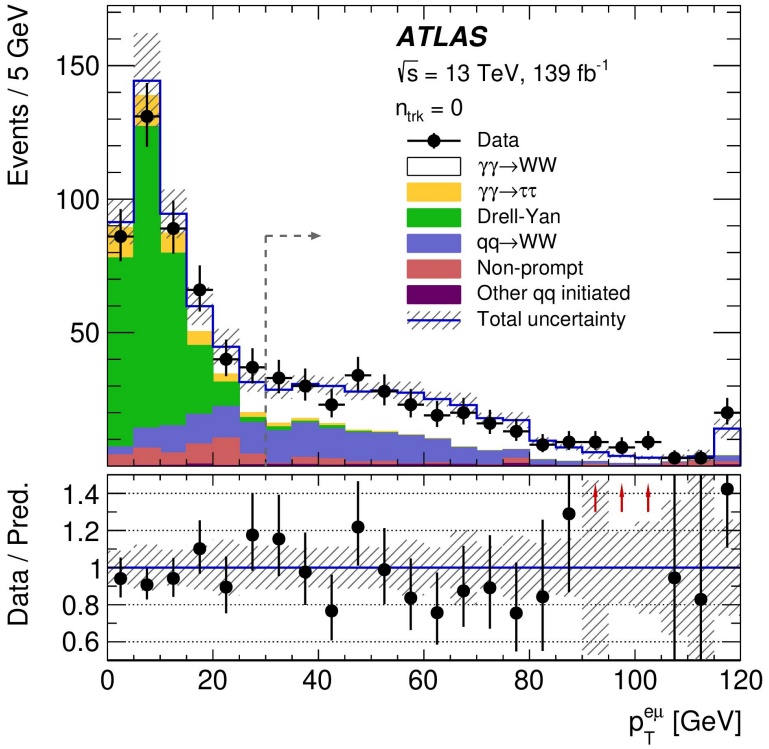
γγ → WW: results

PLB 816 (2021) 136190

- Data driven DY background correction in M_{ll} CR with $N_{track} = 5$
- Fit event yields in the **4 categories** :
  - 1 signal region with $N_{track} = 0$ and $p_T^{l} > 30$ GeV and
  - 3 orthogonal control regions
- Bkg-only hypothesis rejected at **8.4 σ** (>5 exp.)
- Fiducial XS measured and in **agreement with SM** calculation

σ_{fid} = 3.13 ± 0.31 (stat.) ± 0.28 (syst.) fb
σ_{theo} = 2.34 ± 0.27 fb

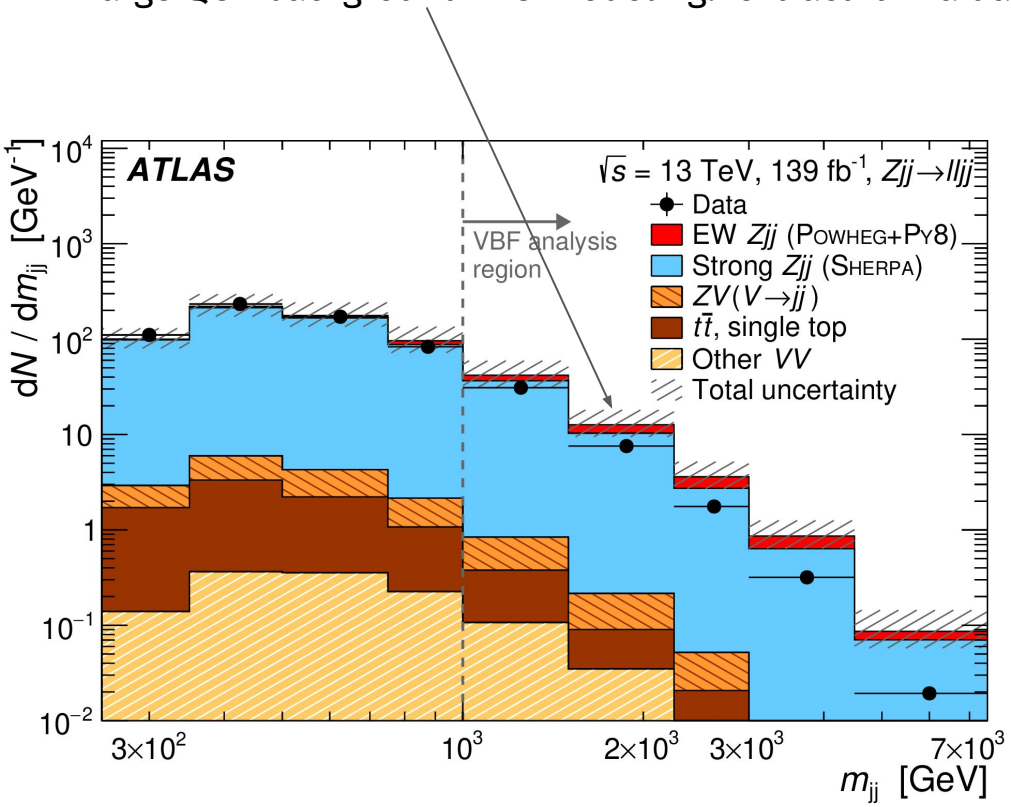




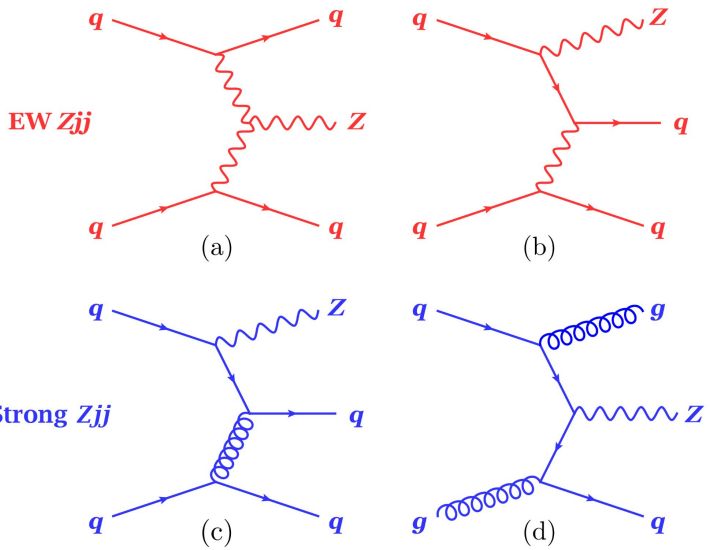
EWK Z + 2 jets

Eur. Phys. J. C 81 (2021) 163

- **Differential XS** measurement for EW production of Z + 2 jets with 139/fb NEW
- Compare different **MC generators** looking at kinematic variables of interest for VBF and VBS processes
- 3 MC samples for EW Zjj and 3 for QCD Zjj (main background)
- Limits on **dimension 6** EFT operators: CP-even and CP-odd
- Large QCD background mis-modeling: extract it in a data-driven way from 3 control regions



QCD production		EWK production	
Generator	ME accuracy	Generator	ME accuracy
Sherpa 2.2.1	NLO (0–2j), LO (3–4j)	POWHEG+PY8	NLO
MG5+PY8	LO (0–4j)	Herwig7+VBFNLO	NLO
MG5_NLO+PY8	NLO (0–2j), LO (3–4j)	Sherpa 2.2.1	LO (2–4j)

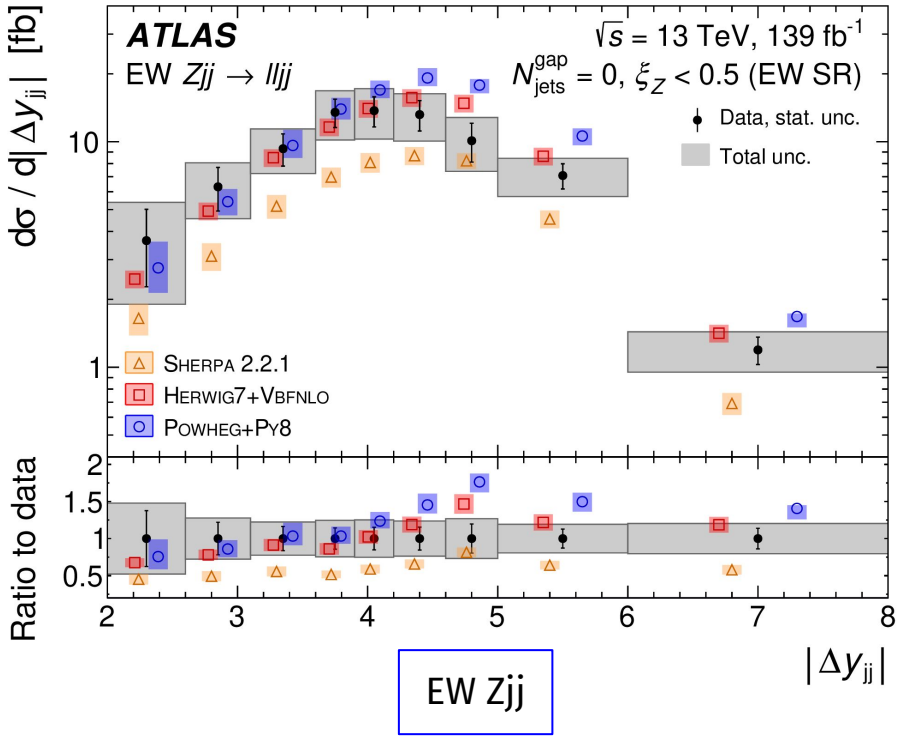


EWK Z + 2 jet: differential XS

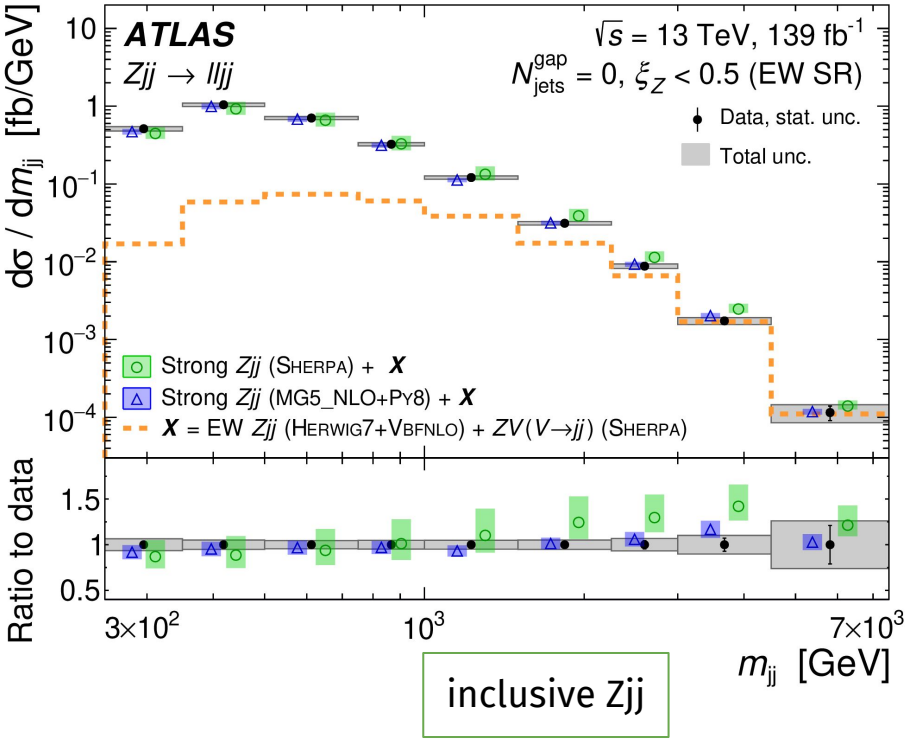
Eur. Phys. J. C 81 (2021) 163

- EW and EW+QCD Zjj differential cross-section **unfolded**: p_T^{ll}, M_{jj}, $|\Delta y_{jj}|$, $\Delta\phi_{jj}$
- Main systematic uncertainty from QCD Zjj modelling in the EW component extraction
- **Herwig7+VBFNLO** found to be the most compatible with data for EW production

$$\sigma_{EW}^{fid} = 37.4 \pm 3.5\ (stat.) \pm 5.5\ (syst.)\ fb$$
$$\sigma_{Herwig} = 39.5 \pm 3.4\ (scale) \pm 1.2\ (PDF)\ fb$$



EW Zjj



inclusive Zjj

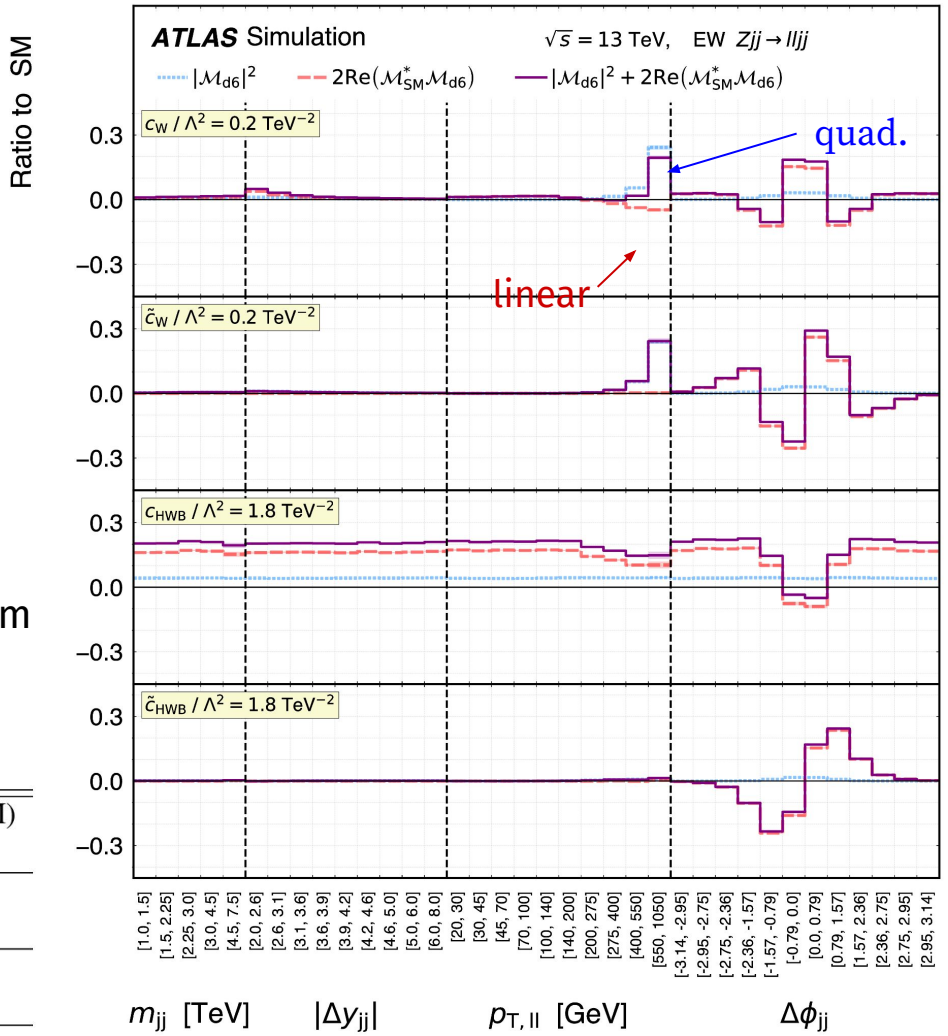
EWK Z + 2 jets: EFT limits

Eur. Phys. J. C 81 (2021) 163

- Limits on dim-6 EFT operators producing anomalous WWZ interactions
- Derived with/without pure dim-6 terms included in the theoretical prediction (SMEFT Madgraph)

$$|\mathcal{M}|^2 = |\mathcal{M}_{\mathrm{SM}}|^2 + 2\,\mathrm{Re}(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\mathrm{d6}}) + |\mathcal{M}_{\mathrm{d6}}|^2,$$

- $\Delta\phi_{jj}$ most sensitive observable → used for Wilson coefficient fit
  - parity odd observable → test of CP invariance
- Strongest limits **when pure dim-6 excluded** from theoretical prediction → interference term dominates

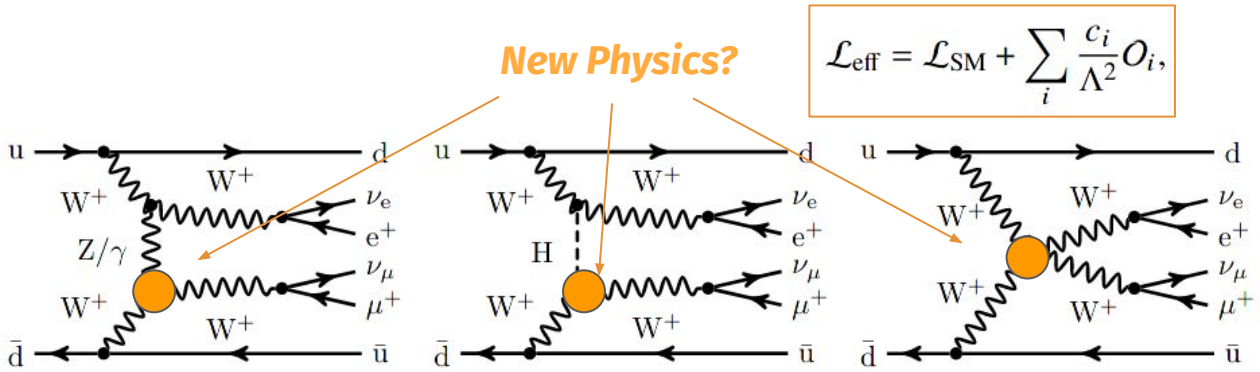


Wilson coefficient	Includes $\lvert\mathcal{M}_{\mathrm{d6}}\rvert^2$	95% confidence interval [TeV^{-2}] Expected	Observed	p-value (SM)
c_W/Λ^2	no	[−0.30, 0.30]	[−0.19, 0.41]	45.9%
	yes	[−0.31, 0.29]	[−0.19, 0.41]	43.2%
$\tilde{c}_W/\Lambda^2$	no	[−0.12, 0.12]	[−0.11, 0.14]	82.0%
	yes	[−0.12, 0.12]	[−0.11, 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%

poor compatibility with SM

Summary

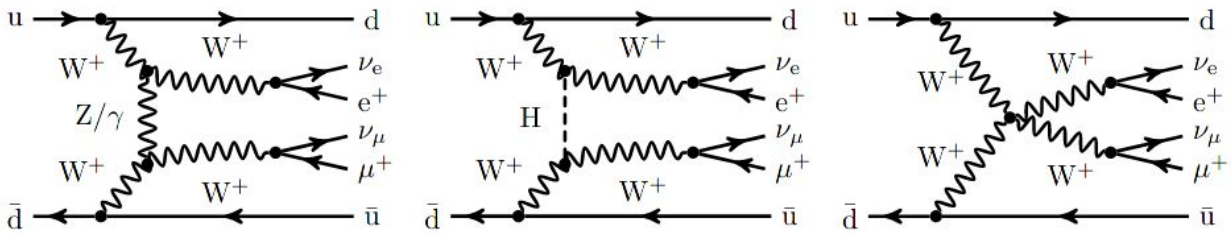
- **Inclusive and differential XS** measurements available for many important processes
  - Theory calculation compared to experiment with higher precision in more and more channels
- Many **VBS** new results (and more coming soon!) with **Full Run 2 ~140/fb dataset**:
  - **SM-like** properties demonstrated (*for the moment..*)
  - For precision measurements, better control of the backgrounds and sophisticated analyses techniques are being implemented
- VBS/VBF powerful enough to put **stringent limits to EFT operators** of dimension 6 and 8
  - Privileged handle on EW-higgs sectors interaction
  - Many new analyses under implementation keeping a **global EFT** fit in mind

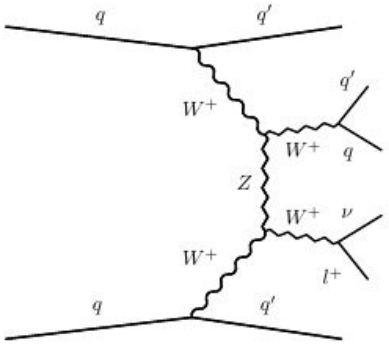


Thanks for your attention!

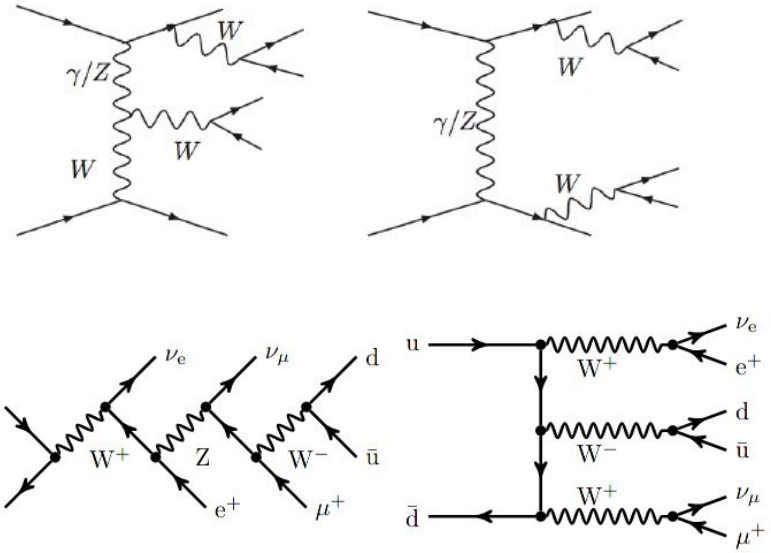
VBS EWK signal definition

Pure EWK scattering contributions

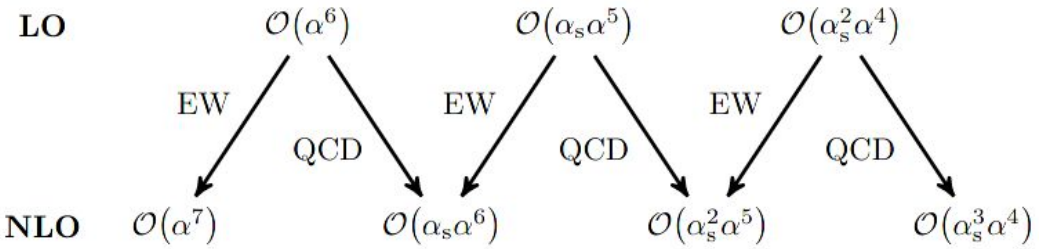




EW non-scattering contributions reduced by kinematic selections

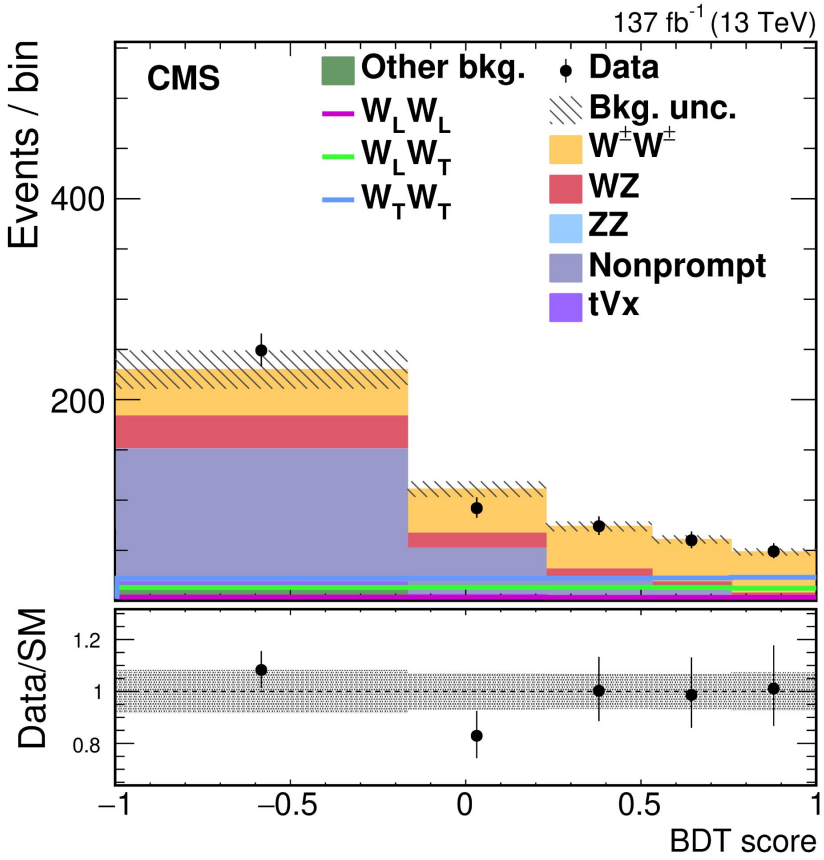


QCD component can be separated from EW one with a good approximation only for LO calculation

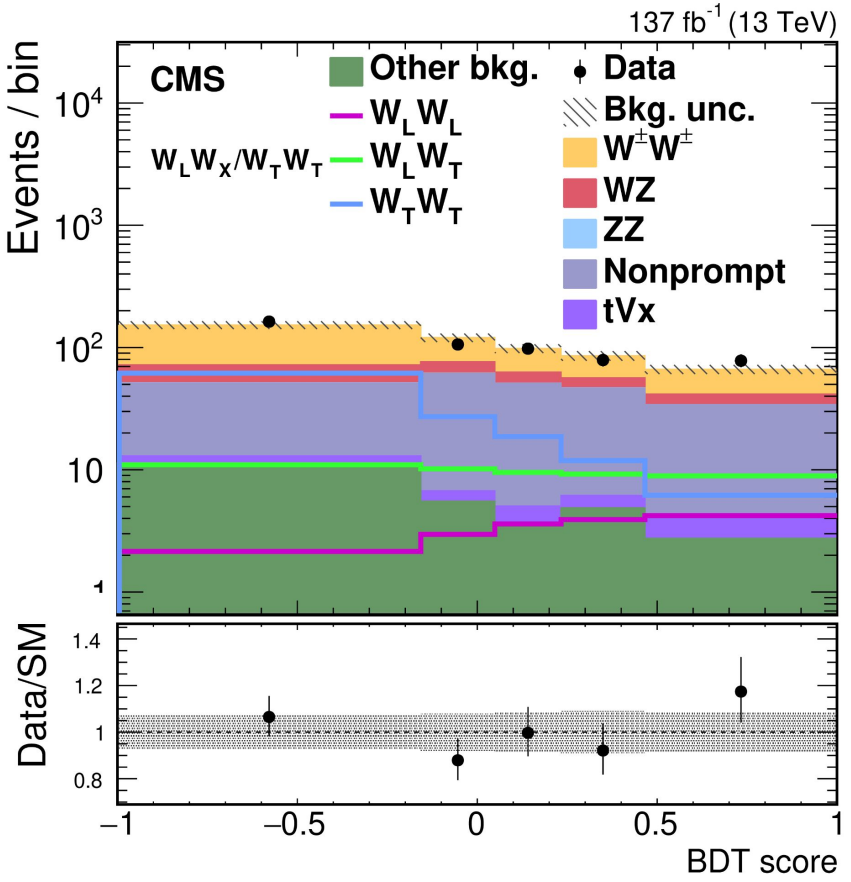


$W^{\pm}W^{\pm}$ inclusive and specific BDT

Distribution of the output score of the inclusive BDT in the $W^{\pm}W^{\pm}$ signal region

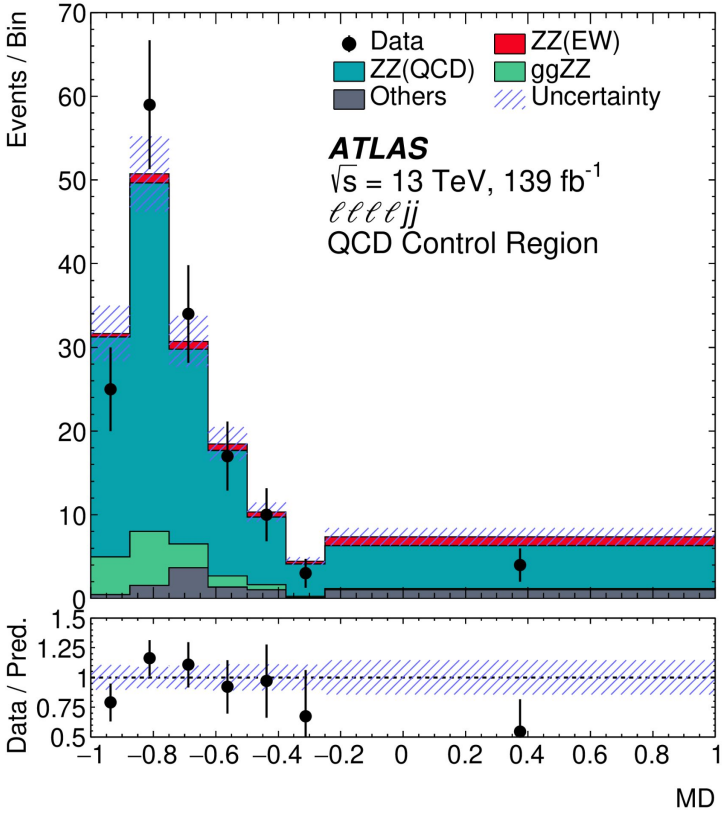


BDT used for $W^{\pm}_{L}W^{\pm}_{X}$ and $W^{\pm}_{T}W^{\pm}_{T}$ measurement

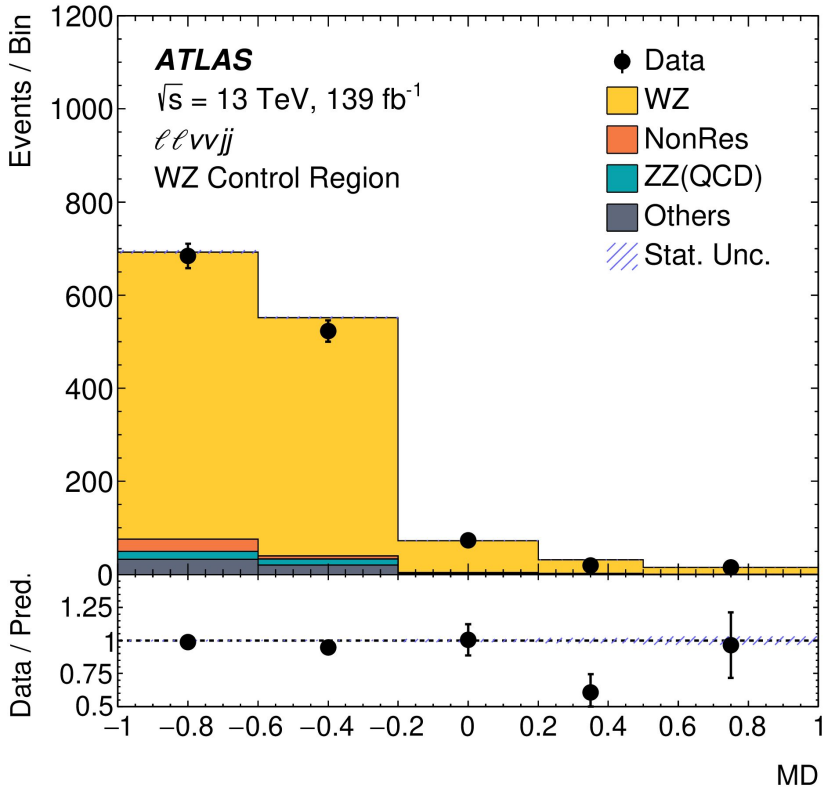


ZZ +2 jets ATLAS

Multivariate discriminant distributions after the fit in the QCD CR for 4ljj channel



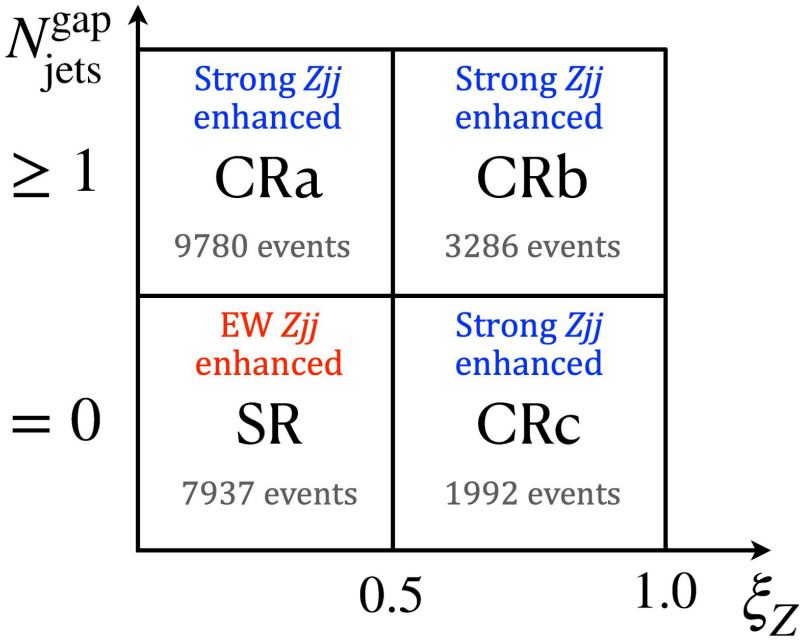
Multivariate discriminant distributions after the fit in the WZ CR for 2l2νjj channel

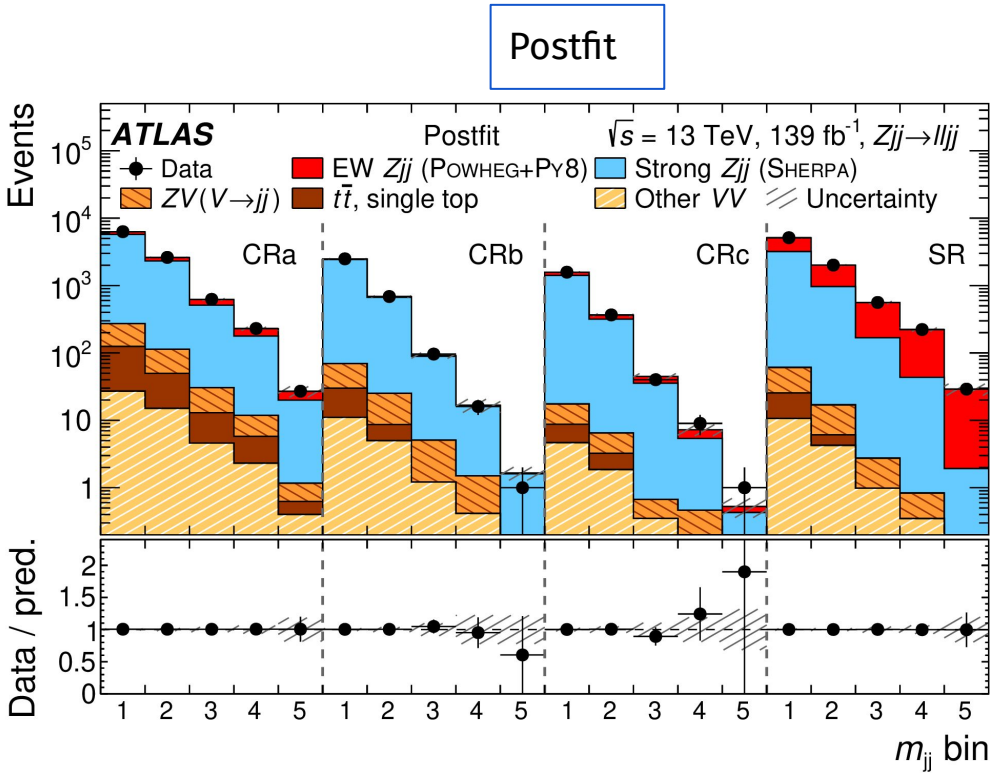


EWK Z + 2 jets (ATLAS)

arXiv:2006.15458

- Poor data-MC agreement: data-driven method constrain shape and normalisation of the strong Zjj bkg to extract EW Zjj event yield
- 4 regions defines using uncorrelated ξ_Z and multiplicity of jets in the rapidity interval between the leading and subleading jets
- 5 bins in M_{jj} variables used to extract correction factors in each region in a likelihood fit
- EW component in SR extracted using 3 different QCD Zjj models: get envelope + uncertainty





Zγ + 2 jets: results

- 2D fit in the signal region: M_{jj} and $\Delta\eta_{jj}$ bins
- Fit M_{jj} with 3 bins in the control region
- EWK signal significance well **over 5 σ**
- Fiducial **inclusive EWK** and **EWK+QCD cross-section** → **agreement with SM**
- Differential unfolded XS in lepton and photon p_T, leading jet p_T, Mjj and $\Delta\eta_{jj}$ bins

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

$$\sigma^{\text{fid}}_{\text{EW+QCD}} = 14.7 \pm 0.80\ (\text{stat}) \pm 1.26\ (\text{syst})\ \text{fb} = 14.7 \pm 1.53\ \text{fb}.$$

$\sigma^{\text{theo}}_{\text{EW}}$ = 4.34±0.26 (scale)±0.06(PDF)fb

$\sigma^{\text{theo}}_{\text{EW+QCD}}$ = 13.3 ± 1.72 (scale) ± 0.10(PDF) fb