Vector Boson Scattering in ATLAS and CMS

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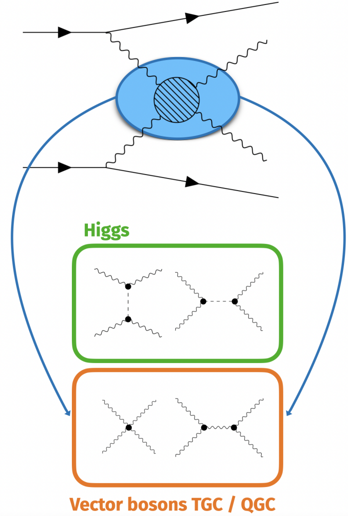
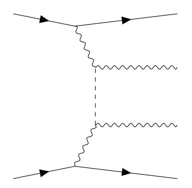
Vector Boson Scattering

Vector boson scattering (**VBS**) happens at the LHC when the **two incoming partons radiate electroweak vector bosons that interact** with each other

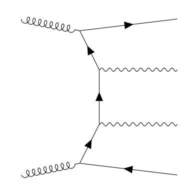
- **Without photons, VBS presents a 6-fermions final state**: 2 jets coming from the initial state partons, 4 coming from the scattered bosons
- **Peculiar kinematical properties:** 2 jets in the forward region with high $\Delta\eta_{jj}$ and m_{jj}, no additional hadronic activity in the **rapidity gap**



At LO VBS contributions come from **purely-EW processes** α^6, **QCD-induced** $\alpha_S^2\alpha^4$ and the interference $\alpha_S\alpha^5$



α^6

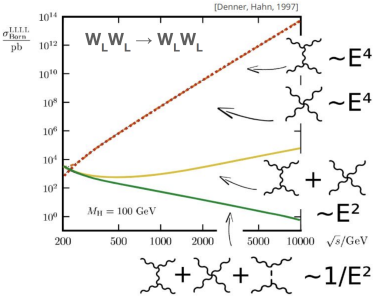


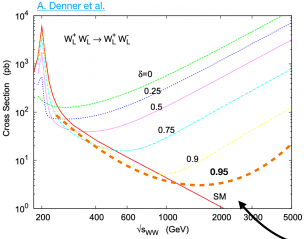
$\alpha_S^2\alpha^4$

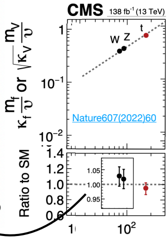
Vector Boson Scattering

VBS is a fundamental probe to understand the electroweak symmetry breaking mechanism

The presence of the Higgs field regularizes the VBS cross-section by canceling exactly the E^2 behaviour of bosonic-only processes.



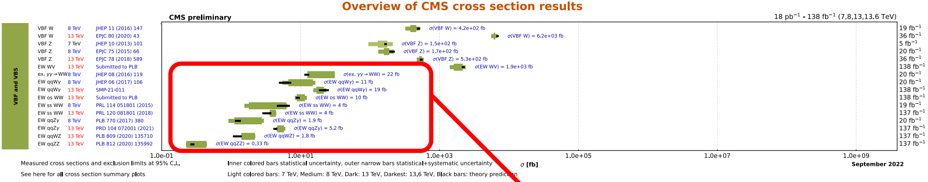


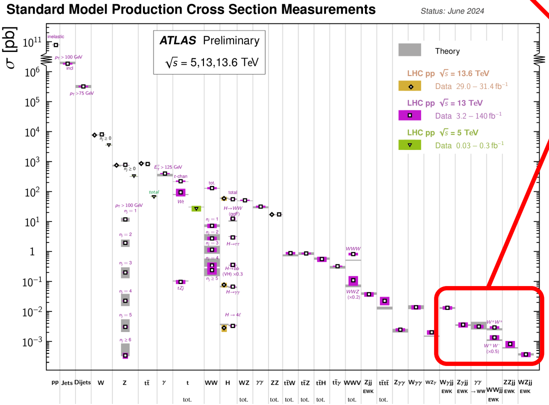


~5% Uncertainty on hVV couplings

A delicate equilibrium: if Higgs boson not SM one (δ), energy-growth of $V_L V_L \to V_L V_L$ cross section $\to$ **New physics**

VBS Landscape at ATLAS and CMS





VBS σ varies from 0.33 *fb* (*qqZZ*) to 19 *fb* (*qqWγ*)

VBS processes amongst the rarest we have studied at the LHC. Now several results are public with SM and BSM interpretation

CMS summary plot

ATLAS summary plot

VBS Landscape at ATLAS and CMS

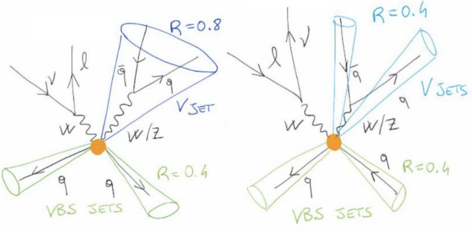
Thanks to the integrated Run II Luminosity, **VBS measurements are quickly populating the experimental landscape** of Standard Model (SM) measurements. This talk

$\sqrt{s}$	$\mathcal{L}$	Process	Article	Comments
13 TeV	137 fb^{-1}	EW $W^{\pm}W^{\pm}jj(2l2\nu jj)$	PhysLettB809(2020)	Run II: » 5σ
	137 fb^{-1}	EW $W^{\pm}Zjj(3l\nu jj)$	PhysLettB809(2020)135710	Run II: 6.8σ
	137 fb^{-1}	EW $ZZjj(4ljj)$	PhysLettB812(2021)135992	Run II: 4σ
	137 fb^{-1}	EW $Z\gamma jj(ll\gamma jj)$	PhysRevD.104.072001	Run II: »5σ
	138 fb^{-1}	EW $W^{\pm}\gamma jj(l\nu\gamma jj)$	PhysRevD108(2023)032017	Run II: 6.0σ
	138 fb^{-1}	EW $W^{\pm}Vjj(l\nu jjjj)$	PhysLettB834(2022)137438	Run II: 4.4σ
	138 fb^{-1}	EW $W^{\pm}W^{\mp}jj(2l2\nu jj)$	PhysLettB841(2023)137495	Run II: 5.6σ
	138 fb^{-1}	EW $W^{\pm}W^{\pm}jj(\tau l2\nu jj)$	CMS-PAS-SMP-22-008	Run II: 2.7σ

$\sqrt{s}$	$\mathcal{L}$	Process	Article	Comments
13 TeV	140 fb^{-1}	EW $Z(\nu\nu\gamma jj)$	JHEP06(2023)082	Run II: 3.2σ
	140 fb^{-1}	EW $Z(ll\gamma jj)$	PhysLettB846(2023)138222	Run II: »5σ
	139 fb^{-1}	EW $ZZjj(4l+2l2\nu jj)$	NaturePhysics19(2023)237	Run II: 5.7σ
	139 fb^{-1}	EW $ZZjj(4ljj)$	JHEP01(2024)004	-
	139 fb^{-1}	EW $W^{\pm}W^{\pm}jj(2l2\nu jj)$	JHEP04(2024)026	Run II: »5σ
	140 fb^{-1}	EW $W^{+}W^{-}jj(e\mu\nu\nu jj)$	JHEP07(2024)254	Run II: 7.1σ
	140 fb^{-1}	EW $W^{\pm}\gamma jj(l\nu\gamma jj)$	CERN-EP-2024-048	Run II: »5σ
	140 fb^{-1}	EW $W^{\pm}Zjj(3l\nu jj)$	JHEP06(2024)192	Run II: »5σ

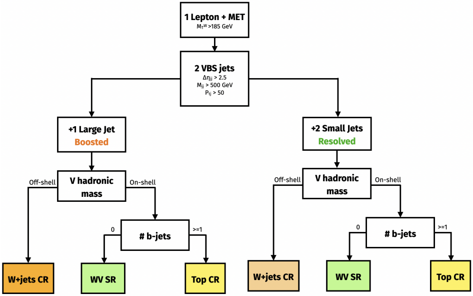
First LHC evidence of a semileptonic VBS process. Final state with 4 jets, one charged lepton + MET. Search for *WV* VBS where the $W^{\pm} \rightarrow l^{\pm}\nu_l$ and $V(W^{\pm}/Z) \rightarrow q\bar{q}$

- **Resolved regime**: Four $R = 0.4$ jets resolved in ΔR
- **Boosted regime**: Two $R = 0.4$ and one $R = 0.8$ jets for boosted decays of the *V*-boson



Harsh multijet background

- **Dominant W+jets** production → data driven based corrections in $p_T^{W,\ell}$ and $p_{T,j2}^{VBS}$ in CR.
- **semileptonic $t\bar{t}$ and single top**: constrained from data in *b*-enriched CR.
- **Non-prompt** mainly from QCD-multijet, data driven estimate

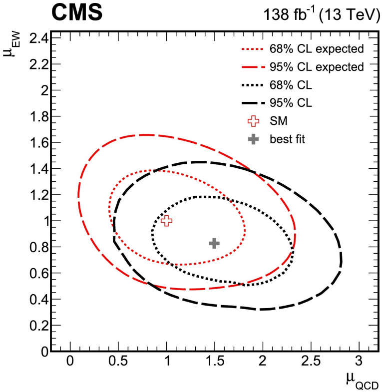


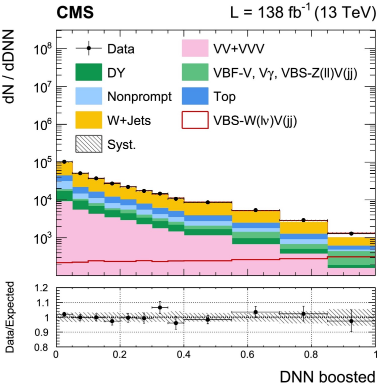
Semi-leptonic VBS $W^{\pm}V \to l\nu jj$

DNN is used for signal extraction (boost/res) which improves the significance of a factor 3 with respect to m_{jj} Results reported for **pure EW VBS** production, for the joint fit with the **QCD-induced background** and in **2 dimensions** for μ_{EW}, μ_{QCD}. **Measurement agrees with SM expectations**

Evidence for the VBS EW production of $W^{\pm}V \to l\nu jj$ with a significance of 4.4σ

$$\mu_{EW} = 0.85 \pm 0.12(\text{stat})^{+0.19}_{-0.17}(\text{syst}) = 0.85^{+0.23}_{-0.21}$$
$$\mu_{EW+QCD} = 0.97 \pm 0.06(\text{stat})^{+0.19}_{-0.21}(\text{syst}) = 0.97^{+0.20}_{-0.22}$$

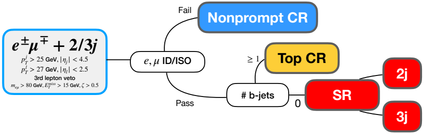


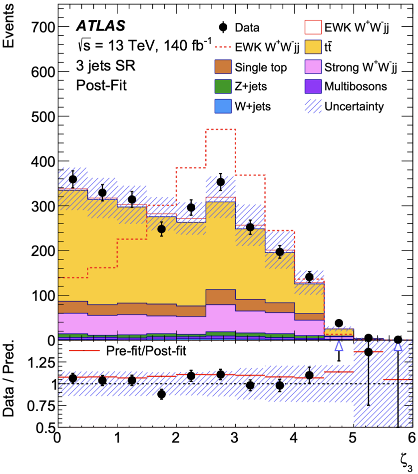


Leptonic $W^+W^- \to e\mu 2\nu$ ATLAS

Final state with **2/3 jets, two isolated leptons with opposite charge, different flavour and MET**.

- $e\mu$ Drell-Yan reduced (low contamination from $\tau\tau \to e\mu$)
- $m_{e\mu} < 80$ **GeV** suppresses VBF-h
- $E_T^{miss} > 15$ **GeV** further suppresses Drell-Yan
- **No m_{jj} cut** but SR split by jet multiplicity (2/3) $\to$ **1σ increase**



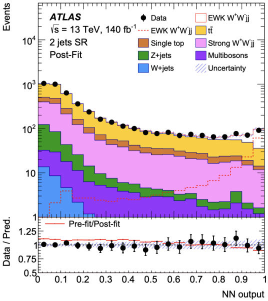


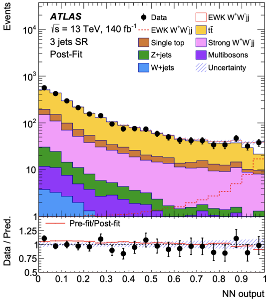
Backgrounds

- **Dominant leptonic $t\bar{t}$** and **single-t**. Dedicated CR for normalization
- **QCD-induced VBS**. No CR but normalization freely floating

Region	EW-VBS	QCD-VBS	Top
SR2j	3.4%	26.3%	62.6%
SR3j	2.1%	20.2%	72.7%

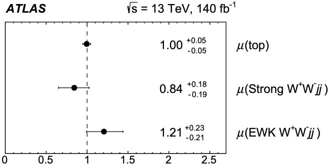
Leptonic $W^+W^- \to e\mu 2\nu$ ATLAS





- Two DNNs trained in 2j and 3j SR to distinguish **EW VBS WW** from **$t\bar{t}$** + **single-t** + **QCD-induced VBS**.
- Profiled likelihood fit on DNN spectra in SR(2j,3j) and Top CR
- Floating signal strength, top and QCD-induced VBS normalization

Observation of EW $W^+W^-jj \to e\mu 2\nu jj$ with a significance of 7.1σ (6.2 expected)



Source	Impact %
Total	**18.5**
Data stat.	12.3
Tot. syst.	13.8
MC stat.	7.7
Top theory	6.3
Sig. theory	5.8
JES	4.9
Top norm.	4.9
...	...

σ^{VBS}_{EW} measured in a fiducial region close to the SR with **additional $m_{jj} > 500$ GeV** ($\sim$ DNN > 0.6): suppress triboson

$$\sigma^{fid}_{obs} = 2.65^{+0.49}_{-0.46}\,\text{fb}; \quad \sigma^{fid}_{exp} = 2.20^{+0.14}_{-0.13}\,\text{fb}$$

Leptonic $W^+W^- \to 2l2\nu$ CMS

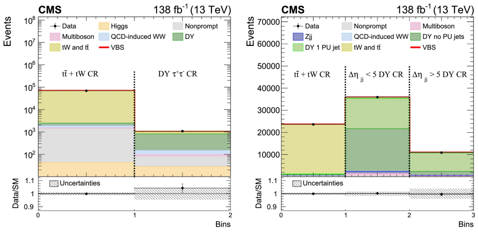
ATLAS: $e\mu 2\nu$, **CMS: $2l2\nu$** $\to$ different background composition with flavour

- ee, $\mu\mu$ additional DY contribution
- $e\mu$ DY reduced (low contamination from $\tau\tau \to e\mu$) $\to$ **Driving the sensitivity**

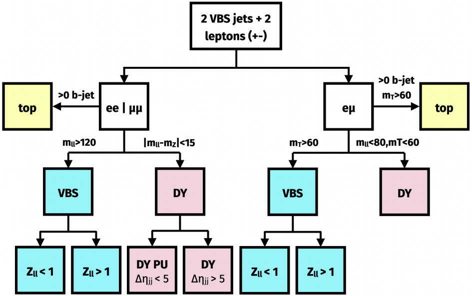
Fine regions definition based on Z_{ll} and $\Delta\eta_{jj}$.

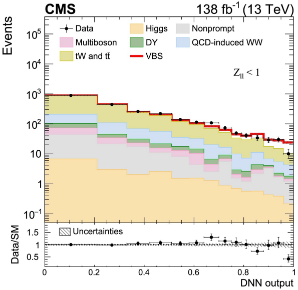
Backgrounds

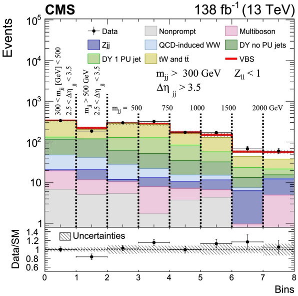
- **Dominant leptonic $t\bar{t}$** and tW
- **DY** only in SF categories $\to$ divided into PU and no-PU
- **QCD-induced VBS**. No CR for this background but normalization freely floating
- **Nonprompt** mainly from W+jets, data driven estimate



CR post-fit yeld. Right: $e\mu$, Left ee + $\mu\mu$







Lepton-flavour dependent signal extraction

Different flavour $e\mu$

- DNN trained against $t\bar{t}$, tW and QCD-VBS
- Different models for $Z_{ll} < 1$ and $Z_{ll} > 1$

Same flavour ee/$\mu\mu$

- 5 m_{jj} bins for $m_{jj} \geq 500$ GeV and $\Delta\eta \geq 3.5$
- 3 bins in $\Delta\eta$ and m_{jj} with lower sensitivity

The VBS EW production of $W^{\pm}W^{\mp}$ is observed with a significance 5.6σ (5.2 expected)

Two fiducial volumes (inclusive and exclusive) used to measure the process cross-section. **Good agreement with SM predictions at LO**

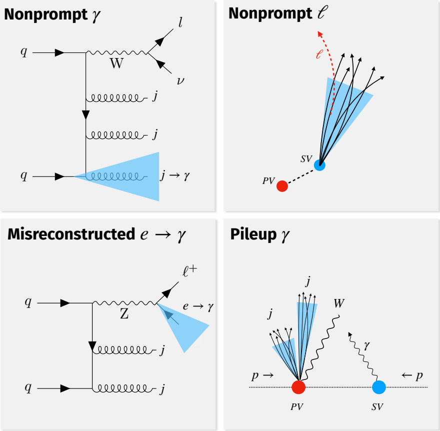
Fiducial region	σ measured	σ SM@LO
Inclusive	99 ± 20 fb	89 ± 5 fb
Exclusive	10.2 ± 2.0 fb	9.1 ± 0.6

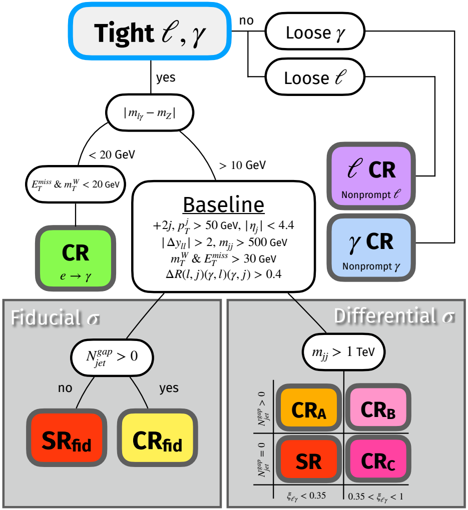
Leptonic $W^{\pm}\gamma \to l\nu\gamma$ ATLAS

Final state with **2 VBS-jets, high-p_T e/μ and γ and MET**. High cross-section (α_{EW}^5) but difficult nonprompt ℓ,γ estimation

Backgrounds

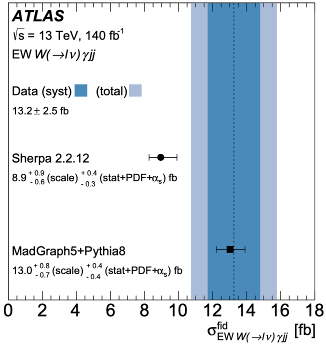
- **Prompt ℓ,γ**: QCD-VBS, $Z\gamma jj$, $tX+\gamma$





Region	EW-VBS	QCD-VBS	Nonprompt
SR_{fid}	17.3%	51.7%	23.1%
CR_{fid}	3.8%	62.7%	22.2%

Leptonic $W^{\pm}\gamma \to l\nu\gamma$ ATLAS

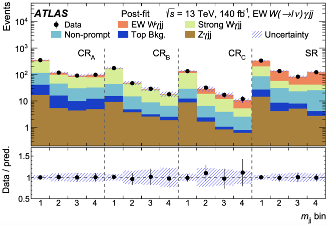


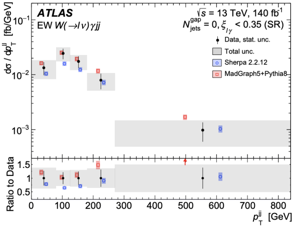
Profile likelihood fit of **DNN spectra** (EW-VBS vs QCD-VBS + $Z\gamma jj$ + top) in SR_{fid}, CR_{fid} **to measure μ_{EW}** and σ_{EW} in fiducial phase space $\to$ large uncertainty in generator choice (`Sherpa`, `MG5`)

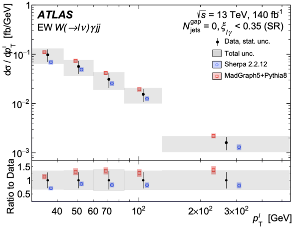
Observation of EW Wγjj with a significance $> 6.0\ \sigma$

$$\sigma^{fid}_{EW} = 12.3 \pm 2.5 \text{ fb}; \quad \mu_{EW} = 1.5 \pm 0.5$$

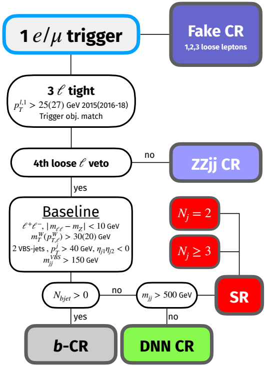
Differential cross section in m_{jj}, p_T^{jj}, $\Delta\phi_{jj}$, $m_{\ell\gamma}$, p_T^{ℓ}, $\Delta\phi_{\ell\gamma}$ (iterative $n = 2$ Bayesian unfolding). **EFT dimension-8 interpretation** from p_T^{jj} (f_T, i), p_T^{ℓ} (f_M, i): **in agreement with SM** within unitary bounds on $m_{W\gamma}$





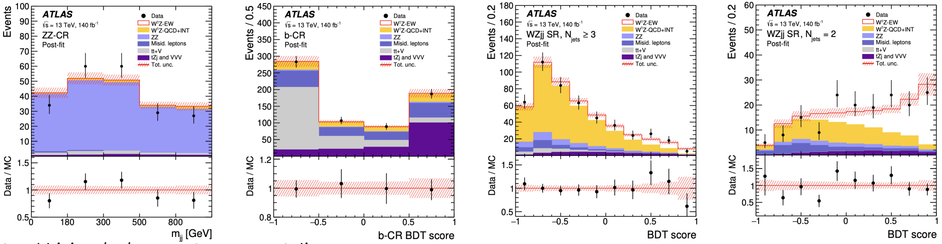


Leptonic $W^{\pm}Z \to 3l\nu$ ATLAS



Final state with **2 VBS-jets, 3 leptons** (e, μ) compatible with WZ and **MET**

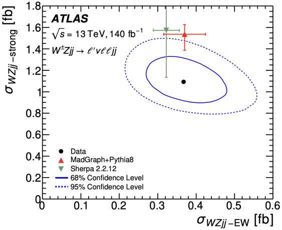
- Good S/B, **dominant background strong-WZjj** production ($\alpha_{EW}^4 \alpha_S^2$) $\to$ BDT to separate from EW signal
- **Nonprompt** ($Z + j$, $Z\gamma$, $t\bar{t}$, tW, WW) data-driven matrix method
- BDT to separate $t\bar{t} + V$ and **tZj** in b-CR, constrain normalization in data
- **ZZjj** CR to constrain normalization in data
- **Signal BDT validated** in low m_{jj}^{VBS} region and with an **Adversarial-NN unbiased** in m_{jj}^{VBS}



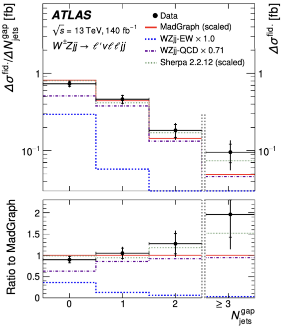
Leptonic $W^{\pm}Z \rightarrow 3l\nu$ ATLAS

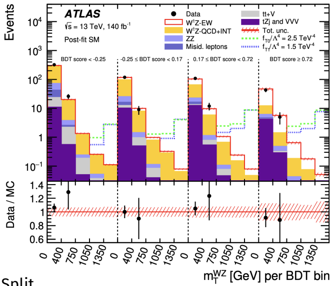
WZjj-EW and QCD **inclusive and differential measurements**. EW prediction in agreement, QCD shows tension in $N_j = 2$ SR and for $0.5 < m_{jj}^{VBS} < 1.3$ TeV

$$\sigma_{WZjj}^{EW} = 0.37 \pm 0.07 \text{ fb}; \quad \sigma_{WZjj}^{QCD} = 1.09 \pm 0.14 \text{ fb}$$



Differential cross section for the **WZjj(EW+QCD)** production in $\sum p_T^{\ell}$, $\Delta\phi_{WZ}$, m_T^{WZ}, N_j, δy_{jj}, $m_j j$, N_j^{gap}, $\Delta\phi_{jj}$, z_{j3} and BDT (iterative $n = 3$ Bayesian unfolding). **Direct EFT interpretation at dimension-8** from m_T^{WZ} preserving unitarity. **No deviation from SM observed**, agreement with CMS.





	Expected [TeV $^{-4}$]	Observed [TeV $^{-4}$]
f_{T0}/Λ^4	[-0.80, 0.80]	[-0.57, 0.56]
f_{T1}/Λ^4	[-0.52, 0.49]	[-0.39, 0.35]
f_{T2}/Λ^4	[-1.6, 1.4]	[-1.2, 1.0]
f_{M0}/Λ^4	[-8.3, 8.3]	[-5.8, 5.6]
f_{M1}/Λ^4	[-12.3, 12.2]	[-8.6, 8.5]
f_{M7}/Λ^4	[-16.2, 16.2]	[-11.3, 11.3]
f_{S02}/Λ^4	[-14.2, 14.2]	[-10.4, 10.4]
f_{S1}/Λ^4	[-42, 41]	[-30, 30]

Leptonic $W^{\pm}W^{\pm} \to \tau_h \ell 2\nu$ CMS

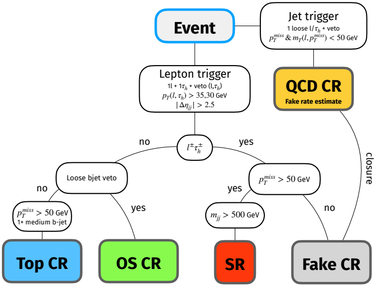
$\boldsymbol{W^{\pm}W^{\pm}}$ VBS: minimum QCD-induced background. Exploit τ_h **channel for the first time in VBS**. Final state with 2 VBS-jets, high-pT e/μ τ_h and MET.

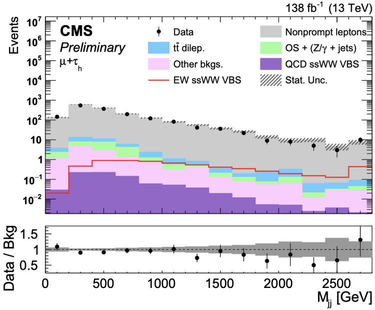
τ Decay	e	μ	π^-	$\pi^-\pi^0$	3π	Other
BR (%)	18	18	11	25	18	10

Backgrounds

- **Dominant Nonprompt** ($W + jets$, QCD) jets misidentified as leptons or τ_h, dedicated CR
- **Leptonic $t\bar{t}$**, normalization constrained in CR
- **Opposite sign** (VBS, Z/γ+jets), normalization constrained in CR

Region	EW-VBS	Fake	$t\bar{t}$	OS+Z/γ	QCD-VBS
SR $e\tau_h$	3.0%	92.2%	0.9%	2.0%	0.3%
SR $\mu\tau_h$	3.1%	93.3%	0.5%	1.7%	0.3%
$t\bar{t}$ CR	-	37.1%	61.6%	8.2%	-
OS CR	-	56.4%	7.9%	35.1%	-





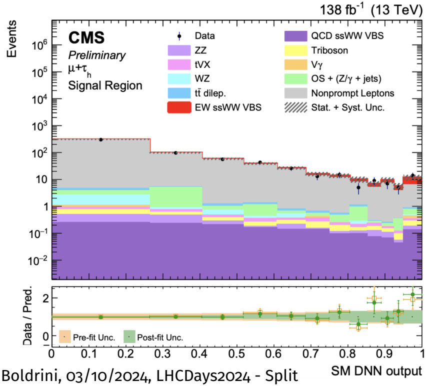
Leptonic $W^{\pm}W^{\pm} \to \tau_h \ell 2\nu$ CMS

Profiled likelihood fit to DNN spectra in SR and OS, Top CR $\to$ enhance discrimination of EW VBS from backgrounds:

- **SR + loose ℓ** (nonprompt proxy): W+jets, had/semilep $t\bar{t}$, Z/γ + jets
- **SR + tight ℓ**: ZZ, OS, leptonic $t\bar{t}$

EW $W^{\pm}W^{\pm}jj \to \ell\tau_h 2\nu jj$ significance of 2.7σ (2.9σ EW+QCD).

$\mu_{EW} = 1.44^{+0.63}_{-0.53}$; $\mu_{EW+QCD} = 1.43^{+0.60}_{-0.54}$

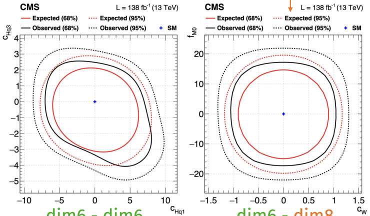


BSM search in the context of SMEFT up to dimension-8: no deviations from SM

Wilson coefficient		95% CL interval Observed	95% CL interval Expected
dim-6	c_W	$[-0.842, 0.818]$	$[-0.987, 0.974]$
	c_{HW}	$[-8.68, 7.60]$	$[-9.99, 9.05]$
dim-8	f_{T0}	$[-1.32, 1.38]$	$[-1.52, 1.58]$
	f_{M0}	$[-13.1, 12.8]$	$[-14.6, 14.5]$
	f_{S0}	$[-15.9, 16.1]$	$[-17.4, 17.9]$

$$|\mathcal{A}|^2 = |\mathcal{A}_{SM}|^2 + \sum_{\alpha} \frac{c_\alpha}{\Lambda^2} \cdot 2\,\mathrm{Re}(\mathcal{A}_{SM}\mathcal{A}^{\dagger}_{Q_\alpha}) + \sum_{\alpha,\beta} \frac{c_\alpha c_\beta}{\Lambda^4} \cdot (\mathcal{A}_{Q_\alpha}\mathcal{A}^{\dagger}_{Q_\beta}) + \sum_i \left[\frac{f_i}{\Lambda^4} \cdot 2\,\mathrm{Re}(\mathcal{A}_{SM}\mathcal{A}^{\dagger}_{\mathcal{O}_i}) + \frac{f_i^2}{\Lambda^8} \cdot |\mathcal{A}_{\mathcal{O}_i}|^2\right]$$

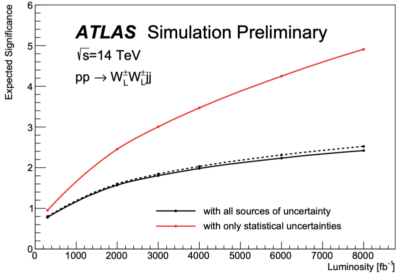
First time in VBS!

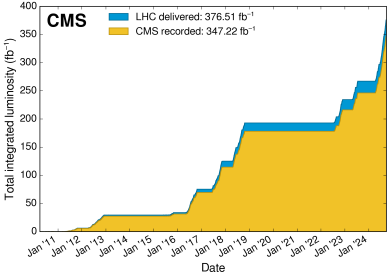


dim6 - dim6   dim6 - dim8

Conclusions

- VBS **among the rarest processes** to be measured at ATLAS and CMS
- Significant advancements from both collaborations: evidences and observations in various final states. **Good agreement with SM so far**
- Systematic indirect searches for new physics call for a coordinated and collective effort.
- **Run-3 data under analysis**: statistically limited channels will largely benefit from additional data





BACKUP

Leptonic VBS ZZ $\to 4l$

Final state with **2 VBS-jets and two pairs of oppositely charged isolated leptons** with same flavour compatible with decay products of a Z boson.

Regions

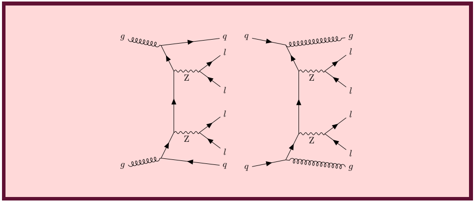
- EW significance, total fiducial cross sections and search for aQGCs in *ZZ*-**inclusive region** $m_{jj} > 100$ GeV
- fiducial cross section measurements done in **two VBS-enriched** regions with $\Delta\eta > 2.4$ and $m_{jj} > 400$ GeV or $m_{jj} > 1$ TeV
- **One background control region** with events from inclusive region not entering the loose VBS-enriched region

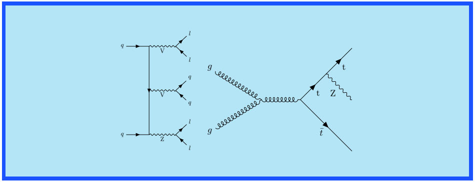
Backgrounds

- Dominant QCD-induced *ZZ* production ($q\bar{q} \to ZZ$, $gg \to ZZ$)
- $t\bar{t}Z$+jets, VVZ+jets irreducible
- Fake and non-prompt leptons mainly from Z+jets but also $t\bar{t}$+jets, WZ+jets

PhysLettB812(2021)135992

Region	EW-VBS	QCD-ZZ	Irr.	Z+jets
Inclusive	6.5%	82.3%	8.7%	2.5%
Loose	21.0%	71.7%	5.3%	2.1%
Tight	48.4%	46.2%	3.7%	1.7%



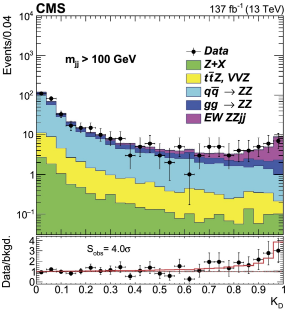


Leptonic VBS ZZ $\to 4l$

Signal extracted with Matrix Element Discriminant (K_D). Check that MVAs bring no significant gain

- **Evidence for EW VBS production** 4.0 σ (3.5 expected)
- Cross section (EW and EW+QCD) measured in three fiducial volumes with VBS-EW simulation at LO and NLO **Good agreement with SM**

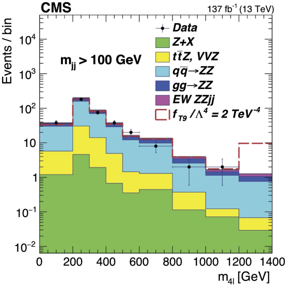
Region	σ (EW) fb
Inclusive	$0.33^{+0.11}_{-0.10}$(stat)$^{+0.04}_{-0.03}$(syst)
Loose	$0.180^{+0.070}_{-0.060}$(stat)$^{+0.021}_{-0.012}$(syst)
Tight	$0.09^{+0.04}_{-0.03}$(stat) $\pm$ 0.02(syst)



Limits on Wilson coefficients (W.c.) of transverse (T) dimension-8 operators extracted from m_{4l} distribution. The VBS-ZZ is extremely sensitive to charged (T_0, T_1, T_2) and neutral operators (T_8, T_9)

- **Unitarization** of the scattering amplitude $|\mathcal{A}_{SM} + \frac{f_i}{\Lambda^4}\mathcal{A}_{\mathcal{O}_8}|$ taken into account
- **No significant deviations from SM observed**

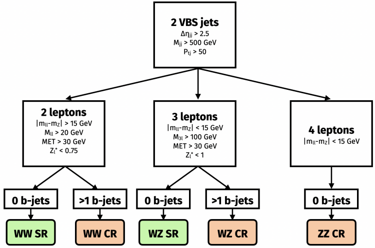
Coupling	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unitarity bound
f_{T0}/Λ^4	−0.37	0.35	−0.24 (−0.26)	0.22 (0.24)	2.4
f_{T1}/Λ^4	−0.49	0.49	−0.31 (−0.34)	0.31 (0.34)	2.6
f_{T2}/Λ^4	−0.98	0.95	−0.63 (−0.69)	0.59 (0.65)	2.5
f_{T8}/Λ^4	−0.68	0.68	−0.43 (−0.47)	0.43 (0.48)	1.8
f_{T9}/Λ^4	−1.5	1.5	−0.92 (−1.02)	0.92 (1.02)	1.8



Leptonic VBS $W^{\pm}W^{\pm} \to 2l^{\pm}2\nu$

Final state with **2 VBS-jets, two isolated leptons with same charge and MET**. A Significant background comes from VBS-WZ $\to$ **measure** $W^{\pm}W^{\pm}$ **and** WZ **together**

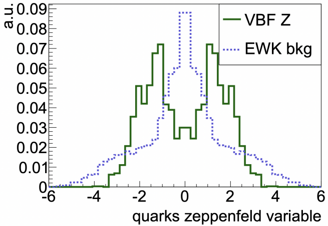
Golden channel: the presence of two same-signed leptons reduces drastically the QCD-induced background



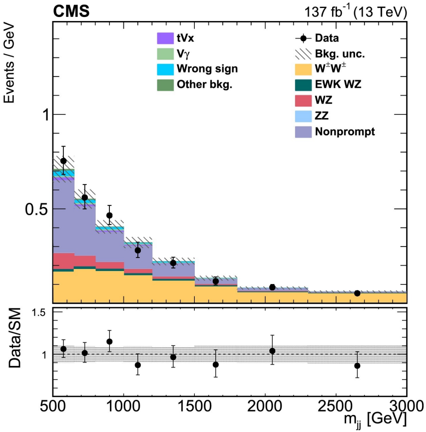
Backgrounds

- **Dominant non-prompt**, estimated from data
- **Wrong-sign** from mischarge identification mainly from Z+jets
- **EW VBS** $W^{\pm}Z$ where one Z-lepton is lost
- **QCD-induced** $W^{\pm}W^{\pm}$ + 2jets and $W^{\pm}Z$ + 2jets
- QCD and EW induced **ZZ + 2jets**

The Zeppenfeld variable Z_l used to reduce QCD-induced background $Z_X = |\eta_X - \bar{\eta}_j|/|\Delta\eta_{jj}|$. Plot from P. Govoni, C. Mariotti



Maximum Likelihood (ML) fit to 5 regions simultaneously. **Including NLO EW+QCD corrections** ($\mathcal{O}$(10%)) at order α^7, $\alpha_S\alpha^6$ to VBS $W^{\pm}W^{\pm}$ and WZ



Observables

- $W^{\pm}W^{\pm}$ signal extracted with **2D variable**: $\mathbf{m_{ll}}$ and $\mathbf{m_{jj}}$
- **Boosted Decision Tree** trained for EW VBS WZ
- $\mathbf{m_{jj}}$ to measure WZ-QCD and ZZ normalization from data

The VBS EW production of $W^{\pm}W^{\pm}$ is observed with a significance » 5σ

Leptonic VBS $W^{\pm}Z \to 3l\nu$

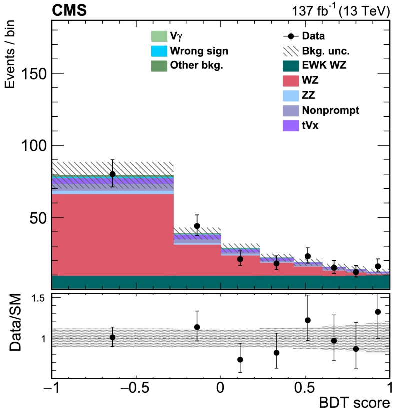
The VBS production of WZ is treated as a background to the $W^{\pm}W^{\pm}$ analysis but **is an interesting process by itself**. Measured together with $W^{\pm}W^{\pm}$.

Backgrounds

- **Dominant QCD induced**
- **Non-prompt** estimated from data
- **Wrong-sign** from mischarge identification mainly from Z+jets
- QCD and EW induced **ZZ + 2jets**

In order to reduce the overwhelming QCD background **a BDT is employed to extract the signal** trained with reported variables

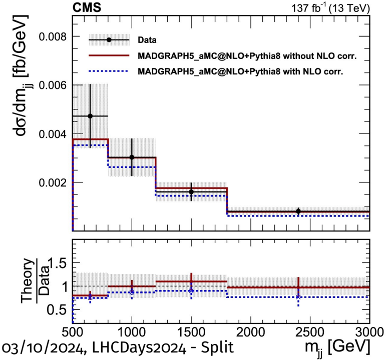
Variable	Definition
m_{jj}	Mass of the leading and trailing jets system
$\Delta\eta_{jj}$	Absolute difference in rapidity of the leading and trailing jets
$\Delta\phi_{jj}$	Difference in azimuth angles of the leading and trailing jets
p_T^{j1}	p_T of the leading jet
p_T^{j2}	p_T of the trailing jet
η^{j1}	Pseudorapidity of the leading jet
$\lvert\eta^W - \eta^Z\rvert$	Absolute difference between the rapidities of the Z boson and the lepton from the decay of the W boson
$z^*_{\ell_i}(i=1,2,3)$	Zeppenfeld variable of the three selected leptons: $z^*_\ell = \lvert\eta_{\ell_i} - (\eta_{j1}+\eta_{j2})/2.\rvert/\Delta\eta_{jj}$
$z^*_{3\ell}$	Zeppenfeld variable of the triple-lepton system
$\Delta R_{j1,Z}$	The ΔR between the leading jet and the Z boson
$\lvert p_T^{\vec{tot}}\rvert/\sum_i p_T^i$	Transverse component of the vector sum of the bosons and tagging jets momenta, normalised to their scalar p_T sum

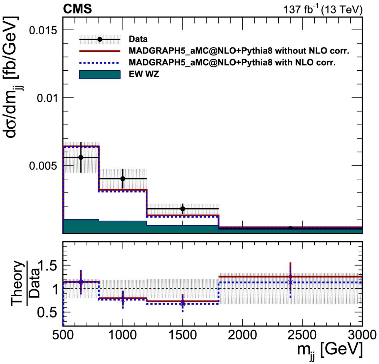


The VBS EW production of $W^{\pm}Z$ is observed with a significance of 6.8σ (5.3 expected)

Inclusive and differential cross-sections measurements are reported in fiducial phase spaces for $W^{\pm}W^{\pm}$ and $W^{\pm}Z$ with selections targeting VBS-signature. **Good agreement with SM**

Process	$\sigma\mathcal{B}$ (fb)	Theory prediction (fb)	Theory 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 ± 0.4 $(0.45\,(\text{stat}) \pm 0.18\,(\text{syst}))$	3.12 ± 0.70	3.12 ± 0.70

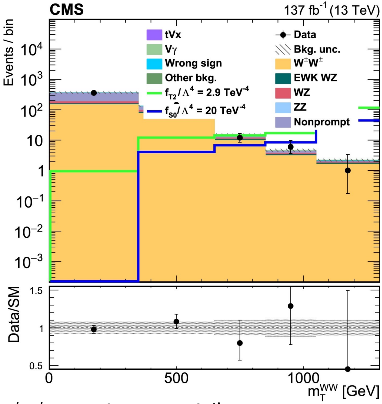


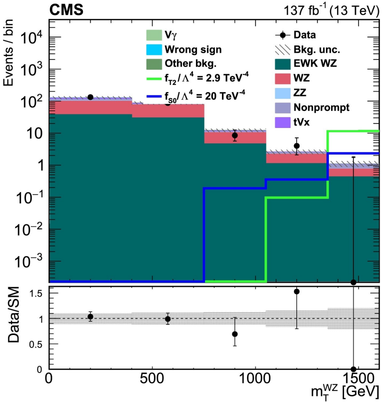


Anomalous quartic gauge coupling search carried under **EFT** framework constraining dimension-8 operators.
Cannot define m_{VV}, 2D variable with **transverse mass m_T and m_{jj}**

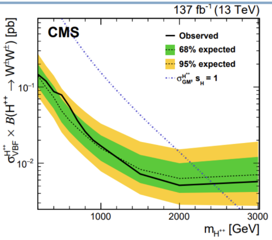
$$m_T(VV) = \sqrt{(\sum_i E_i)^2 - \sum_i p_{z,i})^2}$$

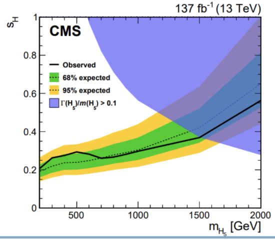
- **9 operators** investigated
- No unitarization procedure is applied → **Clipping EFT predictions at limit**
- **No excess of events with respect to the SM is observed**

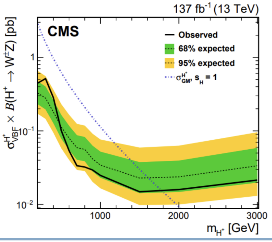




Leptonic $W^{\pm}W^{\pm} \to 2\ell 2\nu$ CMS

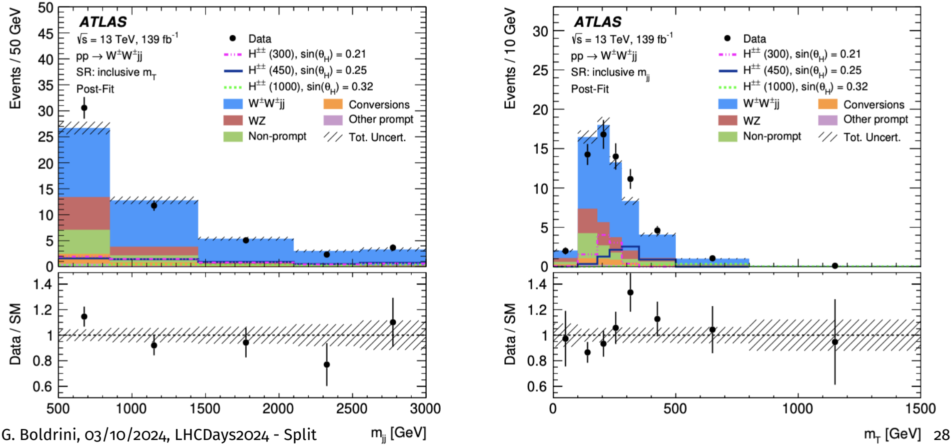






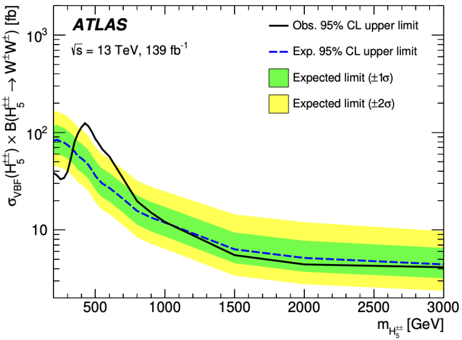
JHEP04(2024)026

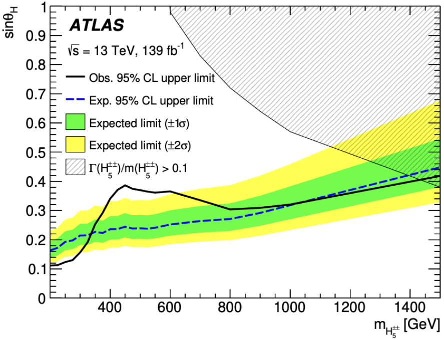
Doubly-charged Higgs boson interpretation (GM model doi.10.1016). $H_5^{\pm\pm}$ BR to SSWW pairs in VBF topology is 100%. VBF $H_5^{\pm\pm}$ production depends on two parameters $m_{H_5^{\pm\pm}}$ and $sin\theta_H$. $m_{T,WW}$ used to extract limits.



Leptonic $W^{\pm}W^{\pm} \to 2\ell 2\nu$ ATLAS

Local excess of 3.2 σ 450 GeV, 2.5 *ma* global.





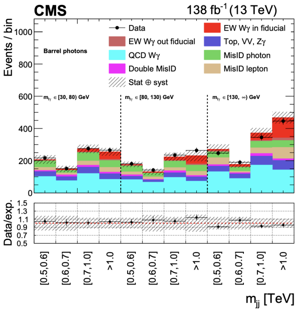
Final state with **2 VBS-jets, high-p_T e/μ and γ and MET**. Purely EW at α^5 order

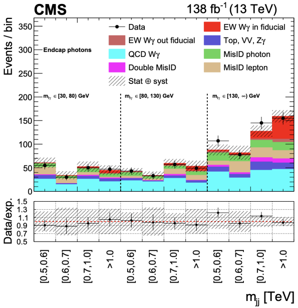
- **SR**: m_{jj} ($>$ 500 GeV), extract signal with $\boldsymbol{m_{jj} - m_{l\gamma}}$
- **CR**: 200 $< m_{jj} <$ 500 GeV, constrain QCD-induced $W\gamma jj$

Backgrounds

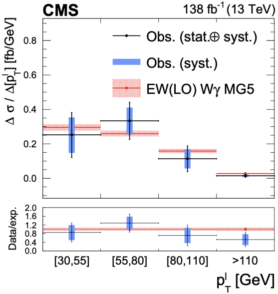
- **Dominant QCD-induced VBS**. constrained from data
- **One misID lepton**: from $W + jets$. data-driven $\sigma_{\eta\eta}$ template fit $\rightarrow$ loose-to-tight factors ($p_{T,\gamma} - \eta_\gamma$)
- **One misID photon**: from $W + jets$. data-driven loose-to-tight factor $f_l/(1 - f_l)$, f_l being lepton misID rate.
- **One misID photon and lepton**: loose-to-tight factor product l, γ. Weight subtraction to avoid double counting in single misID data-driven estimates.

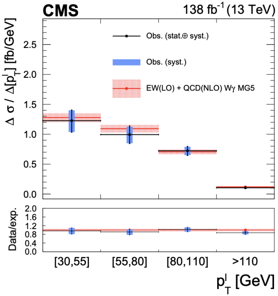
Region	EW-VBS	QCD-VBS	misID γ	misID l	misID l, γ
Barrel	12.9%	44.0%	14.7%	10.9%	4.0%
Endcap	12.9%	42.3%	14.0%	15.2%	4.6%





Leptonic $W^{\pm}\gamma \to l\nu\gamma$ CMS





Observation of EW $W^{+}\gamma jj \to l\nu\gamma jj$ with a significance of 6.0σ (6.8 expected). **Fiducial cross-section measurement** in agreement with SM (MG@LO) for EW and EW+QCD

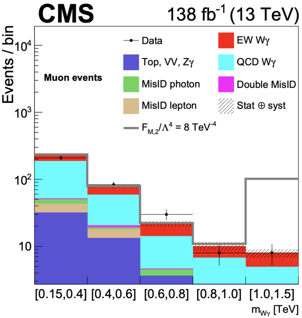
$$\sigma_{fid}^{EW} = 23.5^{+4.9}_{-4.7}\ \text{fb};\quad \sigma_{fid}^{EW+QCD} = 113.0^{+13.0}_{-13.0}\ \text{fb}$$

BSM search with aQGC (EFT dimension-8) using reconstructed $m_{W\gamma}$. VBS enhanced phase space $m_{jj} > 800\text{GeV}$, $|\Delta\eta_{jj}| > 2.5$, $m_{W\gamma} > 150$ GeV, $p_T^{\gamma} > 100$ GeV

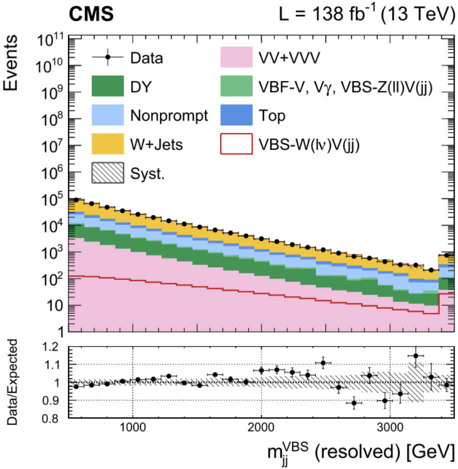
$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + c_i^{(8)}/\Lambda^4 \mathcal{O}_i^{(8)}$$

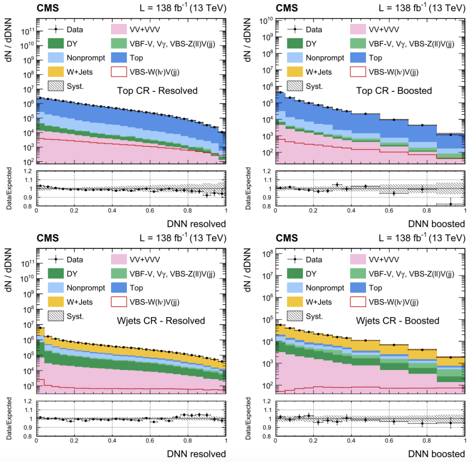
Expected limit	Observed limit	U_{bound}
$-5.1 < f_{M,0}/\Lambda^4 < 5.1$	$-5.6 < f_{M,0}/\Lambda^4 < 5.5$	1.7
$-7.1 < f_{M,1}/\Lambda^4 < 7.4$	$-7.8 < f_{M,1}/\Lambda^4 < 8.1$	2.1
$-1.8 < f_{M,2}/\Lambda^4 < 1.8$	$-1.9 < f_{M,2}/\Lambda^4 < 1.9$	2.0
$-2.5 < f_{M,3}/\Lambda^4 < 2.5$	$-2.7 < f_{M,3}/\Lambda^4 < 2.7$	2.7
$-3.3 < f_{M,4}/\Lambda^4 < 3.3$	$-3.7 < f_{M,4}/\Lambda^4 < 3.6$	2.3
$-3.4 < f_{M,5}/\Lambda^4 < 3.6$	$-3.9 < f_{M,5}/\Lambda^4 < 3.9$	2.7
$-13 < f_{M,7}/\Lambda^4 < 13$	$-14 < f_{M7}/\Lambda^4 < 14$	2.2
$-0.43 < f_{T,0}/\Lambda^4 < 0.51$	$-0.47 < f_{T,0}/\Lambda^4 < 0.51$	1.9
$-0.27 < f_{T,1}/\Lambda^4 < 0.31$	$-0.31 < f_{T,1}/\Lambda^4 < 0.34$	2.5
$-0.72 < f_{T,2}/\Lambda^4 < 0.92$	$-0.85 < f_{T,2}/\Lambda^4 < 1.0$	2.3
$-0.29 < f_{T,5}/\Lambda^4 < 0.31$	$-0.31 < f_{T,5}/\Lambda^4 < 0.33$	2.6
$-0.23 < f_{T,6}/\Lambda^4 < 0.25$	$-0.25 < f_{T,6}/\Lambda^4 < 0.27$	2.9
$-0.60 < f_{T,7}/\Lambda^4 < 0.68$	$-0.67 < f_{T,7}/\Lambda^4 < 0.73$	3.1

Most stringent constraints



Semi-leptonic VBS $W^{\pm}V \to l\nu jj$

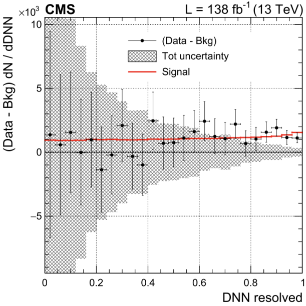


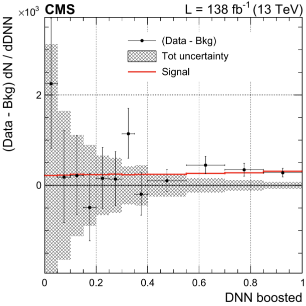


Semi-leptonic VBS $W^{\pm}V \to l\nu jj$

Table 2
Breakdown of the uncertainties in the EW WV VBS signal strength measurement.

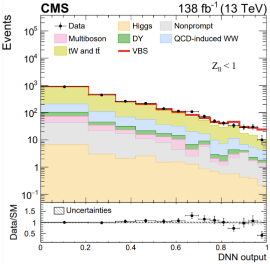
Uncertainty source	$\Delta\mu_{EW}$
Statistical	0.12
Limited sample size	0.10
Normalization of backgrounds	0.08
Experimental	
b-tagging	0.05
Jet energy scale and resolution	0.04
Integrated luminosity	0.01
Lepton identification	0.01
Boosted V boson identification	0.01
Total	0.06
Theory	
Signal modeling	0.09
Background modeling	0.08
Total	0.12
Total	0.22





CMS – input variables

- $m_{jj}, |\Delta\eta_{jj}|$
- $p^T_{j_1},\ p^T_{j_2}$
- Z_{ℓ_1}, Z_{ℓ_2}
- $p^T_{\ell\ell}, m^T_{\ell_1}, \Delta\phi_{\ell\ell}$



ATLAS – input variables

- $m_{jj}, |\Delta\eta_{jj}|$
- $m_{\ell\ell}, m_{\ell j}$
- $p^T_{j_1},\ p^T_{j_2}, \Delta\phi_{jj}$
- $E^T_{miss} = \frac{|\vec{p}^T_{miss}|^2}{\sigma_L^2 \times (1-\rho_{LT}^2)}$
- ζ, Z_{j_3}

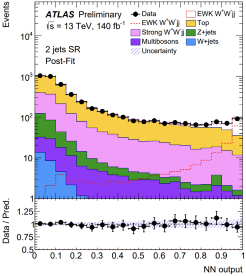


Figure: Slide from Mattia Lizzo

The most striking feature by ATLAS analysis is the $s/\sqrt{b}$ of the very last DNN bin, which ultimately is the key ingredient to reach the best possible sensitivity

- **CMS last bin**: $s \sim 14$, $b \sim 10 \to s/\sqrt{b} \sim 4.4$
- **ATLAS last bin**: $s \sim 60$, $b \sim 35 \to \mathbf{s/\sqrt{b} \sim 10.1}$

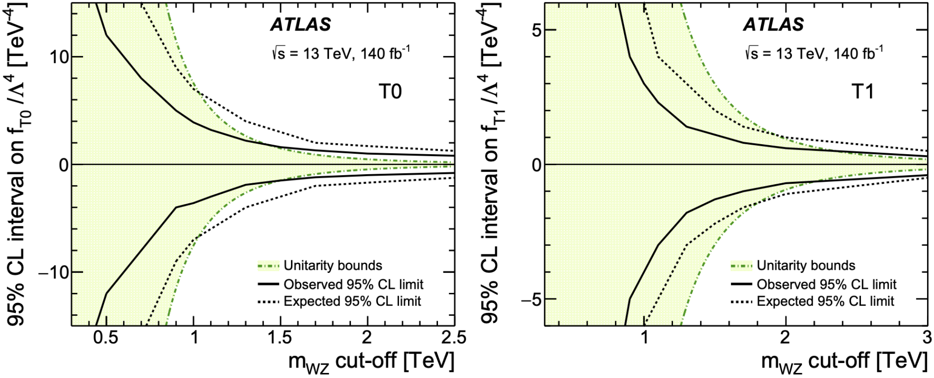
Very different phase space definition from ATLAS and CMS in the $e\mu$ final state

- Same amount of signal between ATLAS and CMS driving region but less background in CMS
- ATLAS larger significance driven by discrimination power if the NN model (last bin)
- Signal (background) fraction in last bin: CMS $\sim$ 9%(0.4%), ATLAS $\sim$ 38%(0.6%)

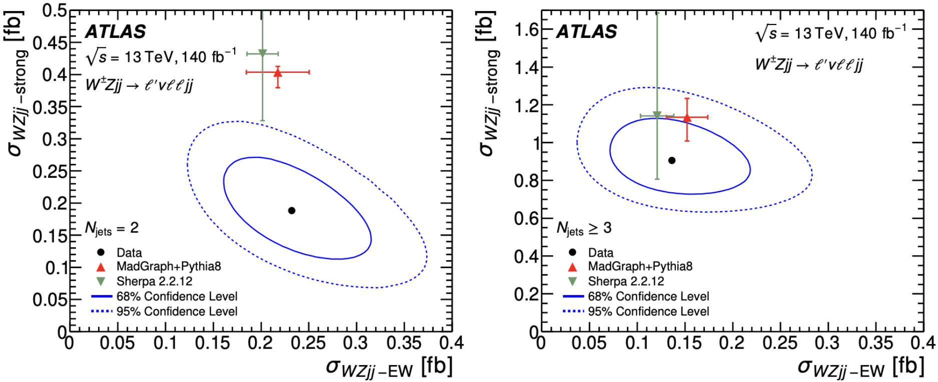
	CMS signal region $(e\mu)$		ATLAS signal region	
	$Z_{\ell\ell} < 1$	$Z_{\ell\ell} > 1$	$n_{jet} = 2$	$n_{jet} = 3$
EWK W^+W^-jj	169 ± 20	70 ± 8	158 ± 27	54 ± 13
$t\bar{t} + tW$	1629 ± 71	1453 ± 70	2885 ± 214	1851 ± 131
QCD W^+W^-	327 ± 62	409 ± 77	1214 ± 256	514 ± 121
W + jets (fake)	107 ± 18	110 ± 16	37 ± 97	19 ± 48
Z + jets	69 ± 5	102 ± 6	216 ± 62	65 ± 25
Multiboson	68 ± 7	76 ± 7	101 ± 5	42 ± 3
Higgs	27 ± 2	20 ± 1	–	–
MC prediction	2397 ± 99	2240 ± 106	4610 ± 77	2546 ± 48
DATA	2441	2192	4610	2533

Figure: Slide from Mattia Lizzo

Leptonic $W^\pm Z \to 3l\nu$ ATLAS



Leptonic $W^{\pm}Z \to 3l\nu$ ATLAS



Leptonic $W^{\pm}Z \to 3l\nu$ ATLAS

Source	$\frac{\Delta\sigma_{WZjj-\text{EW}}}{\sigma_{WZjj-\text{EW}}}$ [%]	$\frac{\Delta\sigma_{WZjj-\text{strong}}}{\sigma_{WZjj-\text{strong}}}$ [%]
$WZjj$–EW theory modelling	7	1.8
$WZjj$–QCD theory modelling	2.8	8
$WZjj$–EW and $WZjj$–QCD interference	0.35	0.6
PDFs	1.0	0.06
Jets	2.3	5
Pile-up	1.1	0.6
Electrons	0.8	0.8
Muons	0.9	0.9
b-tagging	0.10	0.11
MC statistics	1.9	1.2
Misid. lepton background	2.3	2.3
Other backgrounds	0.9	0.23
Luminosity	0.7	0.9
All systematics	16	12
Statistics	10	6
Total	19	13