VBS/VBF measurements (without photons) at CMS

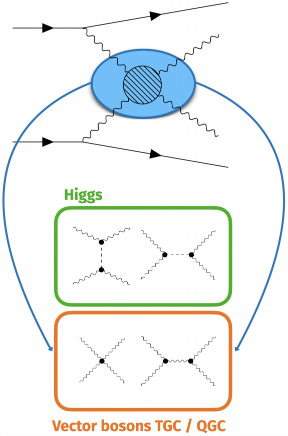
Giacomo Boldrini [1,2]

[1] University and INFN of Milano - Bicocca
[2] On the behalf of the CMS collaboration

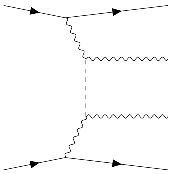
Vector Boson Scattering

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

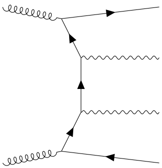
- **Without photons, VBS presents a 6-fermions final state**: 2 jets coming from the initial state partons, 4 coming from the scattered bosons
- **Peculiar kinematical properties:** 2 jets in the forward region with high $\Delta\eta_{jj}$ and m_{jj}, no additional hadronic activity in the **rapidity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



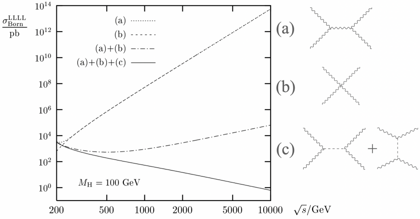
$\alpha_S^2\alpha^4$

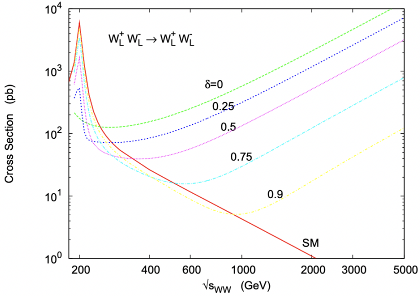
VBS is a fundamental probe to understand the electroweak symmetry breaking mechanism (EWSB)

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

- **A delicate equilibrium**: if the 2012 observed scalar does not behave precisely as the SM Higgs boson (δ), deviations can be detected in the energy-growth of VBS observables $\rightarrow$ **New physics**

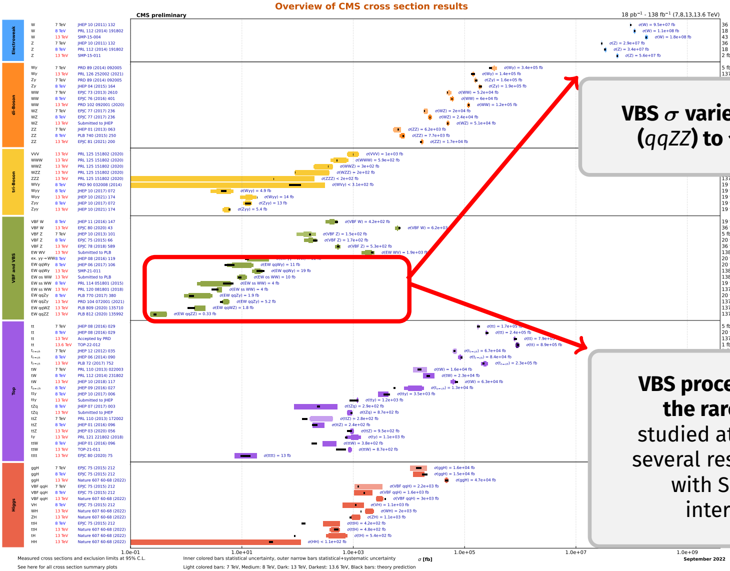
- **This behaviour is independent of the underlying BSM physics** $\rightarrow$ A model-agnostic physics probe





Upper: A. Denner et. al., lower: K. Cheung et. al.

Vector Boson Scattering at CMS



VBS σ varies from 0.33 fb ($qqZZ$) to 19 fb ($qqW\gamma$)

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

CMS cross section summary

VBS Landscape at 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
8 TeV	$19.7\ fb^{-1}$	EW $Zjj(l^+l^-jj)$	Eur.Phys.J.C75(2015)66	2016: **»5**σ
	$19.7\ fb^{-1}$	EW $W^{\pm}jj(l^{\pm}\nu jj)$	JHEP11(2016)147	2016: **4**σ , Run II: Ongoing
	$19.4\ fb^{-1}$	EW $W^{\pm}W^{\pm}jj(2l2\nu jj)$	PhysRevLett.114.051801	CMS finds 2σ
	$19.7\ fb^{-1}$	EW $Z\gamma jj(\nu\nu/ll\gamma jj)$	PhysLettB770(2017)380-402	CMS finds 3σ
	$19.7\ fb^{-1}$	EW $W^{\pm}\gamma jj(lv\gamma jj)$	JHEP06(2017)106	CMS finds 2.7σ
	$19.4\ fb^{-1}$	EW $W^{\pm}Zjj(3l\nu jj)$	PhysRevLett.114.051801	CMS finds 2σ
13 TeV	$35.9\ fb^{-1}$	EW $Zjj(l^+l^-jj)$	Eur.Phys.J.C78(2018)589	2016: **»5**σ , Run II: Ongoing
	$35.9\ fb^{-1}$	EW $W^{\pm}jj(l^{\pm}\nu jj)$	Eur.Phys.J.C80(2020)43	2016: **»5**σ , Run II: Ongoing
	$137\ fb^{-1}$	EW $W^{\pm}W^{\pm}jj(2l2\nu jj)$	PhysLettB809(2020)	2016: **5.5**σ , Run II: **» 5**σ
	$137\ fb^{-1}$	EW $W^{\pm}Zjj(3l\nu jj)$	PhysLettB809(2020)135710	Run II: **6.8**σ
	$137\ fb^{-1}$	EW $ZZjj(4ljj)$	PhysLettB812(2021)135992	2016: 2.7σ , Run II: **4**σ
	$137\ fb^{-1}$	EW $Z\gamma jj(ll\gamma jj)$	PhysRevD.104.072001	2016: **4.7**σ , Run II: **»5**σ
	$35.9\ fb^{-1}$	EW $W^{\pm}\gamma jj(l\nu\gamma jj)$	PhysLettB811(2020)135988	2016: **5.3**σ , Run II: Ongoing
	$138\ fb^{-1}$	EW $W^{\pm}Vjj(l\nu jjjj)$	PhysLettB834(2022)137438	Run II: **4.4**σ
	$138\ fb^{-1}$	EW $W^{\pm}W^{\mp}jj(2l2\nu jj)$	PhysLettB841(2023)137495	Run II: **5.6**σ
	$138\ fb^{-1}$	EW $VVjj(4j/2j2\nu jj)$	...	Run II: Ongoing
	$138\ fb^{-1}$	EW $VVpp(4jpp)$	...	Run II: Ongoing
	$138\ fb^{-1}$	EW $W^{\pm}W^{\pm}jj(2\tau 2\nu jj)$	...	Run II: Ongoing
	$138\ fb^{-1}$	EW $ZVjj(2ljjjj)$	...	Run II: Ongoing
	$138\ fb^{-1}$	EW $ZZjj(2l2\nu jj)$	...	Run II: Ongoing

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

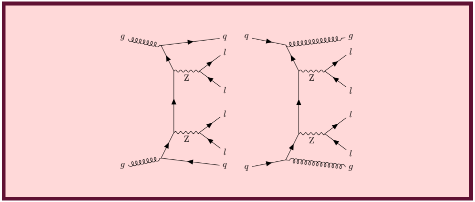
- EW significance, total fiducial cross sections and search for aQGCs in ZZ**-inclusive region** $m_{jj} > 100$ GeV
- fiducial cross section measurements done in **two VBS-enriched** regions with $\Delta\eta > 2.4$ and $m_{jj} > 400$ GeV or $m_{jj} > 1$ TeV
- **One background control region** with events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

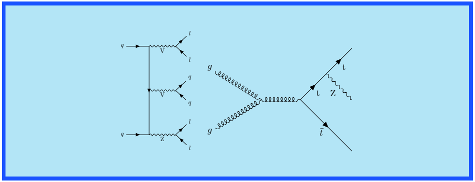
Backgrounds

- 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%

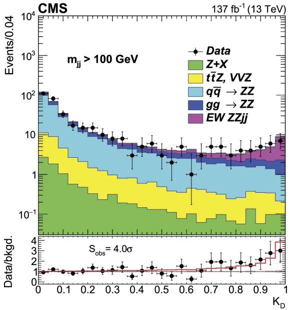




Signal extracted with Matrix Element Discriminant (K_D). Check that MVAs bring no significant gain

- **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**

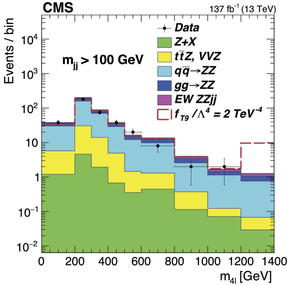
Region	σ (EW) fb
Inclusive	$0.33^{+0.11}_{-0.10}(\text{stat})^{+0.04}_{-0.03}(\text{syst})$
Loose	$0.180^{+0.070}_{-0.060}(\text{stat})^{+0.021}_{-0.012}(\text{syst})$
Tight	$0.09^{+0.04}_{-0.03}(\text{stat}) \pm 0.02(\text{syst})$



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)

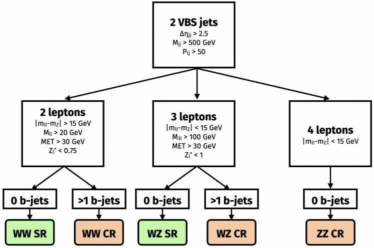
- **Unitarization** of the scattering amplitude $|\mathcal{A}_{SM} + \frac{f_i}{\Lambda^4}\mathcal{A}_{\mathcal{O}_8}|$ taken into account
- **No significant deviations from SM observed**

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



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**

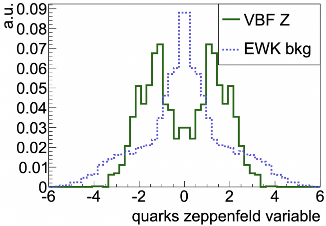
Golden channel: the presence of two same-signed leptons reduces drastically the QCD-induced background



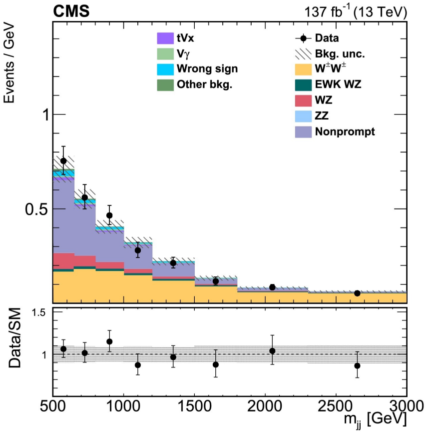
Backgrounds

- **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 $W^{\pm}Z \rightarrow 3l\nu$

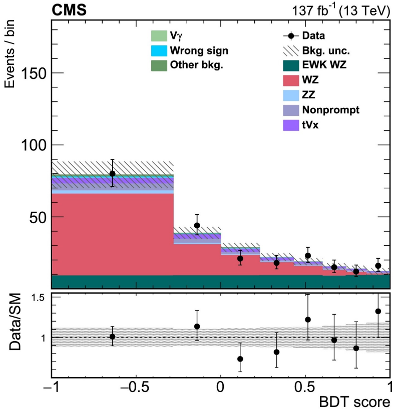
The VBS production of WZ is treated as a background to the $W^{\pm}W^{\pm}$ analysis but **is an interesting process by itself**. Measured together with $W^{\pm}W^{\pm}$.

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

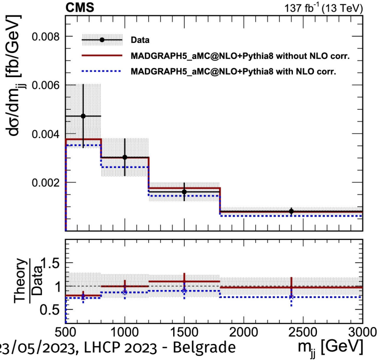
Variable	Definition
m_{jj}	Mass of the leading and trailing jets system
$\Delta\eta_{\mathrm{jj}}$	Absolute difference in rapidity of the leading and trailing jets
$\Delta\phi_{\mathrm{jj}}$	Difference in azimuth angles of the leading and trailing jets
$p_{\mathrm{T}}^{\mathrm{j1}}$	p_{T} of the leading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

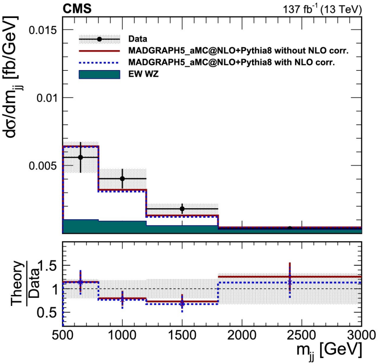


The VBS EW production of $W^{\pm}Z$ is observed with a significance of 6.8σ (5.3 expected)

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



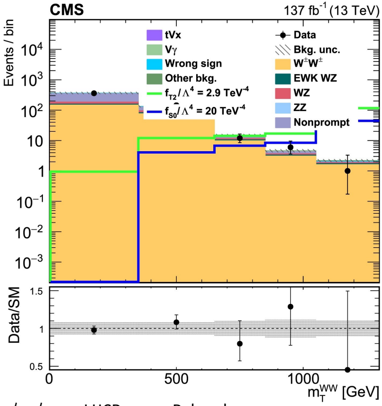


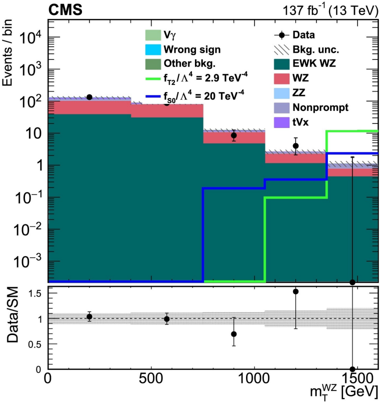
$W^\pm W^\pm$ and $W^\pm Z$ Effective Field Theory

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}**

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

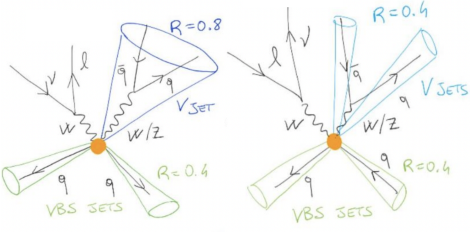
- **9 operators** investigated
- No unitarization procedure is applied → **Clipping EFT predictions at limit**
- **No excess of events with respect to the SM is observed**





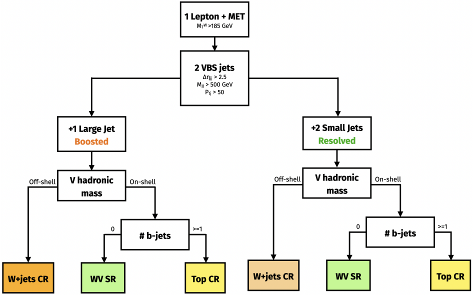
First LHC evidence of a semileptonic VBS process. Final state with 4 jets, one charged lepton + MET. Search for *WV* VBS where the $W^{\pm} \rightarrow l^{\pm}\nu_l$ and $V(W^{\pm}/Z) \rightarrow q\bar{q}$

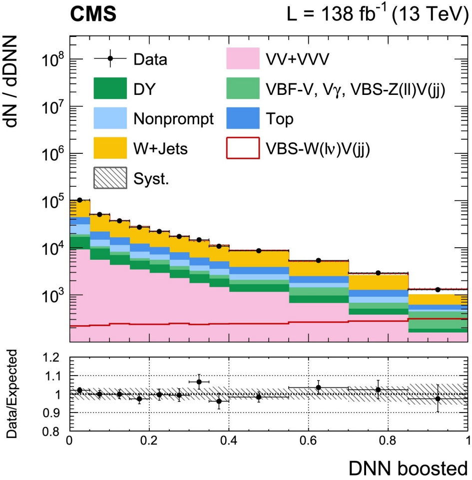
- **Resolved regime**: Four $R = 0.4$ jets resolved in ΔR
- **Boosted regime**: Two $R = 0.4$ and one $R = 0.8$ jets for boosted decays of the V-boson



Backgrounds

- **Dominant W+jets** production → data driven based corrections needed to simulations
- **QCD induced** VBS production
- **Drell Yan + jets**
- **semileptonic $t\bar{t}$ and single top**
- **Non-prompt** mainly from QCD-multijet, data driven estimate





Poor description of dominant background in VBS jets p_T and $p_T^{W,l}$. **Differential data-driven correction** to MC

- Split W+jets MC in bins of $p_T^{W,l}$ and $p_T^{VBS,2}$, leave normalization freely floating in fit
- **Closure check** in W+jets CR outside the V resonance

Non-trivial jet tagging $\to$ efficiency $\sim 70\%$

- Tag as VBS the dijet pair with highest m_{jj}
- In resolved region, from the remaining jets, selected the one with mass closest to $(m_W + m_Z)/2$ = 85 GeV

A DNN is used for signal extraction which improves the significance of a factor 3 with respect to m_{jj}

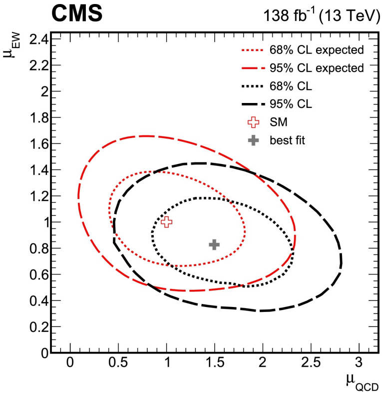
Semi-leptonic VBS $W^{\pm}V \rightarrow l\nu jj$

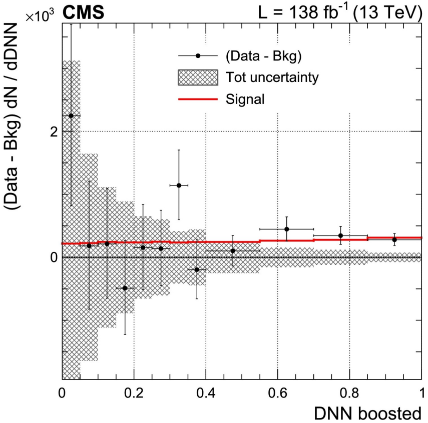
Results reported for **pure EW VBS** production, for the joint fit with the **QCD-induced background** and in **2 dimensions** for μ_{EW}, μ_{QCD}. **Measurement agrees with SM expectations**

Evidence for the VBS EW production of $W^{\pm}V \rightarrow l\nu jj$ with a significance of 4.4σ
(5.1 expected)

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

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





Leptonic $W^{\pm}W^{\mp} \to 2l2\nu$

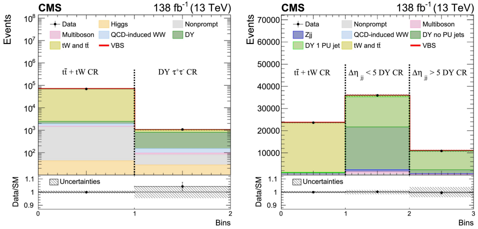
Final state with **2 VBS-jets, two isolated leptons with opposite charge and MET**.
Background composition with lepton flavour significantly changes

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

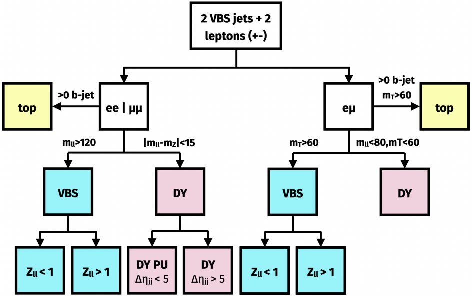
Fine regions definition based on Z_{ll} and $\Delta\eta_{jj}$.

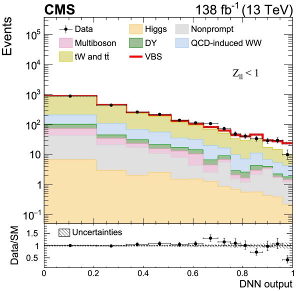
Backgrounds

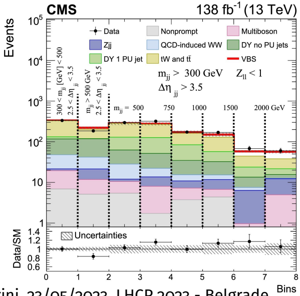
- Dominant leptonic $t\bar{t}$ and tW
- **DY** only in SF categories $\to$ divided into PU and no-PU
- **QCD-induced VBS**. No CR for this background but normalization freely floating
- **Nonprompt** mainly from W+jets, data driven estimate



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/$\mu\mu$

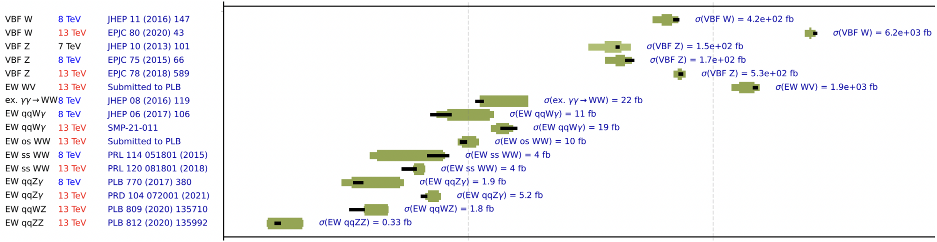
- 5 m_{jj} bins for $m_{jj} \geq 500$ GeV and $\Delta\eta \geq 3.5$
- 3 orthogonal bins in $\Delta\eta$ and m_{jj} with lower sensitivity

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

Conclusions



- VBS **among the rarest processes** to be measured at CMS
- final state with multiple leptons and high jets multiplicity: advanced techniques in order to isolate signal
- **An excess (not significant) is observed** in VBS measurements: need for further investigation and precise theory predictions for QCD-induced backgrounds
- **Good agreement with SM so far**