CMS Vector Boson Scattering SM combination and EFT at dimension-6 in the $WV \to l\nu qq$ decay channel

Based on Ph.D. thesis now available CERN-THESIS-2024-005

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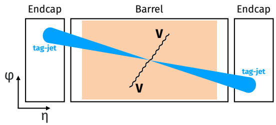
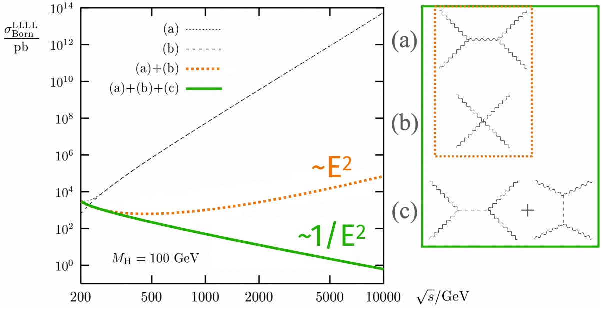
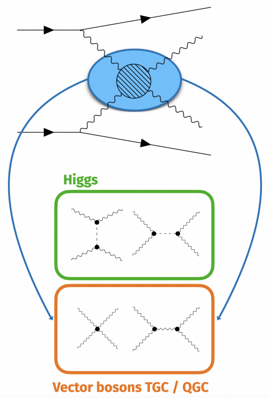
Vector boson scattering (**VBS**) happens at the LHC when the **two incoming partons radiate electroweak vector bosons that interact** with each other

- **One of the rarest processes** allowed by the SM
- **Peculiar kinematic properties** (m_{jj}^{VBS}, $\Delta\eta_{jj}^{\mathrm{VBS}}$, ...)
- Deep connection with **EWSB** mechanism
- **Rich phenomenology**: TGC, QGC, *s*- and *t*-channel *h* exchange

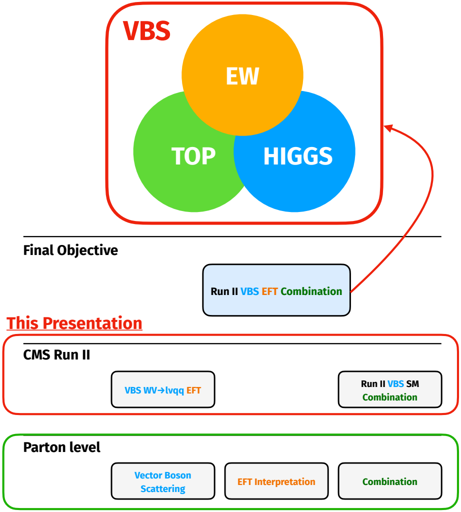






VBS and the EFT global picture

(*) View and opinion of authors, do not necessarily reflect the ones of CMS



Giorgio Pizzati presentation

No new resonance observed: new physics decoupled at $\sim$ TeV scale. Low-energy manifestation via effective parametrization: **SMEFT**

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} O_i^{(6)} + \mathcal{O}(\Lambda^{-4})$$

- c_i Wilson coefficients
- Λ unknown NP energy scale

Leading B/L conserving SMEFT contributions from **dim-6** terms. VBS usually used for dim-8 but presents a rich SMEFT phenomenology at dim-6 being a $2 \rightarrow 6$ process.

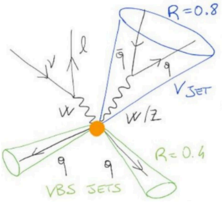
VBS can play as a link between EW, Higgs and top inputs in a global SMEFT interpretation of LHC data

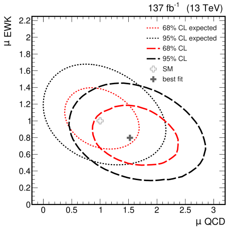
Dimension-6 SMEFT interpretation of the semileptonic VBS $WV \to l\nu qq$ with CMS Run-II data

Evidence for the VBS $WV \to l\nu qq$ EW production $\sigma_{obs} = 4.4$ physletb.2022.137438

Final state with **4 jets, one charged lepton + E_T^{miss}**. Search for VBS where $W^{\pm} \to l\nu$ and $V(W/Z) \to q\bar{q}$.

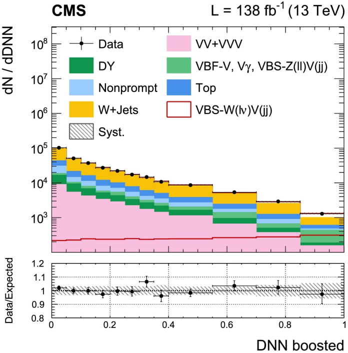
- **Resolved regime**: Four $R = 0.4$ jets with $\Delta R_{jj} > 0.4$
- **Boosted regime**: Two $R = 0.4$ jets with $\Delta R_{jj} > 0.4$ and one $R = 0.8$ jet (boosted $V \to q\bar{q}$)





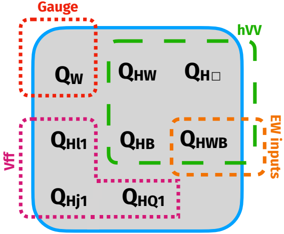
Background sources

- W+jets → dominant background. Data-driven corrections needed to MC simulations at LO
- QCD-induced VBS and triboson production
- Drell-Yan + jets
- Semileptonic $t\bar{t}$ and single top
- Nonprompt lepton background → mainly from QCD-multijet. Data-driven estimate



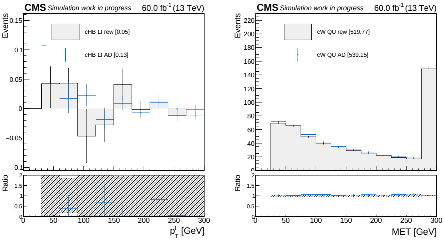
VBS $WV \to l\nu qq$ SMEFT

Opted to treat VBS as a $2 \to 6$ process for SMEFT dim-6 analysis. Include all EW-induced diagrams for EFT, **theoretically more precise.**



- Large number of diagrams involved: high **memory pressure + prohibitive computational time**
- **Choice of original point in EFT space** ensuring optimal coverage → start with **eight operators** turned on ($c_i = 1/\Lambda^2$)

Q_{HB} linear (left), **Q_W** quadratic (right)

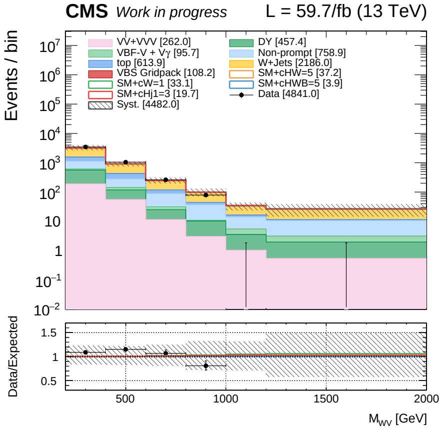


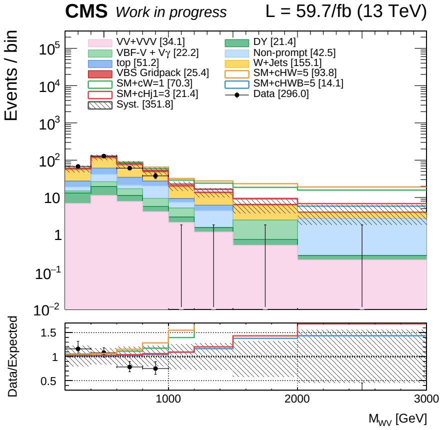
- The apriori value $c_i = 1/\Lambda^2$ can bias the phase space. **Subtle cancellations in linear components.**
- **Closure of SM component** between $2 \to 4$ and $2 \to 6$ heavily dependent on μ_F, μ_R scale choice.

Observable for EFT limit setting

The **reconstructed WV invariant mass is found to be the most sensitive observable in all channels** for all operators

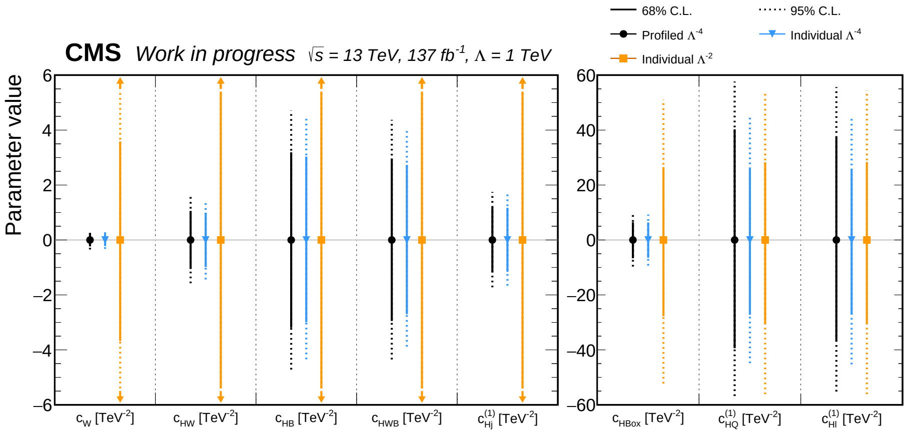
EFT signal extracted via m_{WV}: 8 bins in boosted SR [200-3000 GeV], 6 bins in resolved SR [200-2000 GeV]. **Boosted regions lead the EFT sensitivity**





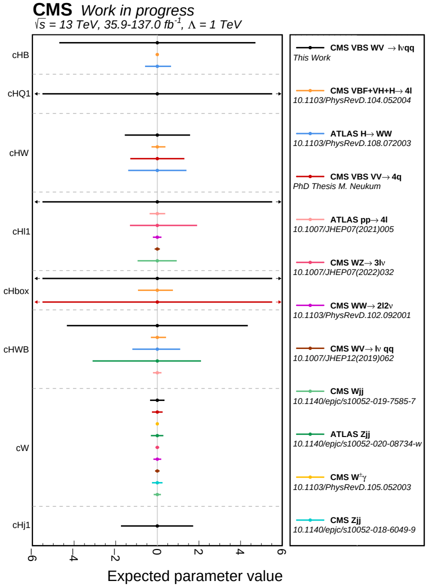
VBS $WV \to l\nu qq$ SMEFT: Results

- **Profiled** Λ^{-4}: all eight Wilson coefficients freely floating, profiling W.C. not of interest with nuisance parameters. Procedure only well defined including quadratics (Λ^{-4})
- **Individual** Λ^{-2}: Only one W.C. (c) allowed to float $N \propto \mathrm{SM} + c\mathrm{Lin}$
- **Individual** Λ^{-4}: Only one W.C. (c) allowed to float $N \propto \mathrm{SM} + c\mathrm{Lin} + c^2\mathrm{Quad}$



Results have been compared to both VBS and non-VBS public results from ATLAS and CMS

- **Agrees with previous results in VBS**
- **Boosted channels favoured**
- **Competitive limits on Q_W** but dominated by diboson $W^{\pm}\gamma$. Higgs operators (Q_{HW}, Q_{HWB}, Q_{HB} and $Q_{H\Box}$) better constrained by Higgs-dedicated analyses
- $Q^{(1)}_{HQ}$ **and** $Q^{(1)}_{Hj}$ **never studied before**
- **No flat direction observed** in the 8 parameters studied: optimal feature for a candidate link in a global combination



CMS Run II combination of VBS measurements

VBS SM Combination

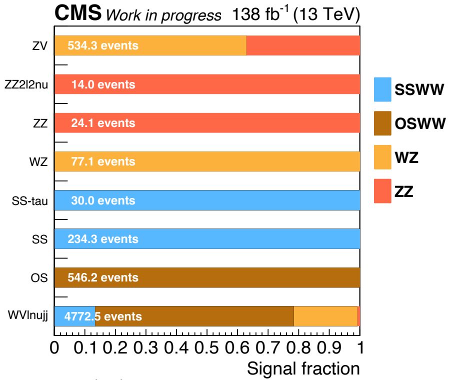
A general picture of VBS is useful to spot deviations from the SM in a global view + **a first step towards a global EFT interpretation of VBS processes**

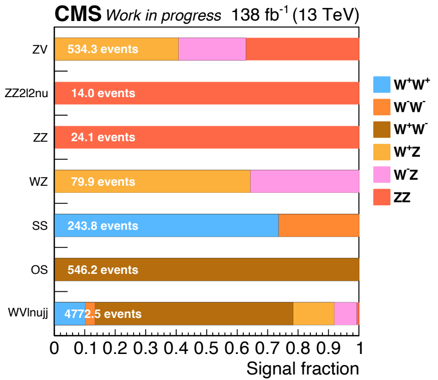
6 parameters

$W^\pm W^\mp, W^+W^+, W^-W^-, W^+Z, W^-Z, ZZ$

4 parameters

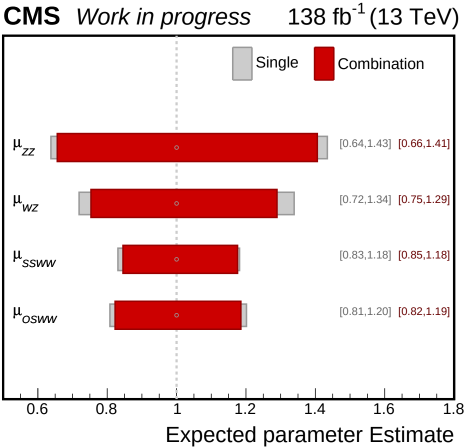
$W^\pm W^\pm, W^\pm W^\mp, W^\pm Z, ZZ$





Results

Nuisance correlations between channels studied in details

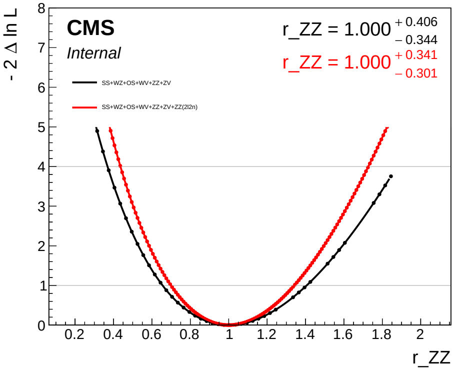


- **Single: leading channel for the measurements**
- **SS+WZ+OS+WV+ZV+ZZ(4l) Full nuisances**
- Improved by **15%** in significance on **OSWW**, 13% on **WZ** and 16% on **ZZ** (w ZZ2l2ν)

Expected to get evidence for all 6 parameters

	OSWW	SSWW		WZ		ZZ
σ	6.2	$\gg 5$		5.5		3.7
	W^+W^-	W^+W^+	W^-W^-	W^+Z	W^-Z	ZZ
σ	6.2	$\gg 5$	4.6	4.9	3.4	3.7

Inclusion of SSWW+τ_h and $ZZ(2l2\nu)$



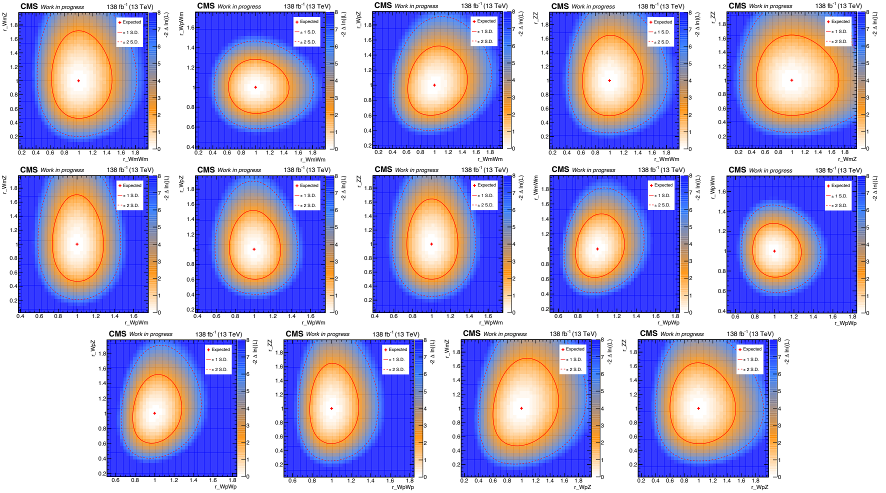
Two new analyses can be included: $ZZ(2l2\nu)$ and SSWW+τ_h (preliminary)

- **Not straightforward**: OSWW DY CR is overlapping with both the $ZZ(2l2\nu)$ signal region and DY CR.
- Need a **dedicated nuisance treatment** for the combination.

The $ZZ(2l2\nu)$ + $ZZ(4l)$ CMS combination targets the 5σ on ZZ parameter (already achieved by ATLAS)

POI	σ_{exp}	σ_{exp} (w $ZZ(2l2\nu)$)	σ_{exp} (w SSWW-τ_h)	σ_{exp} single channel
SSWW	10.8	10.8	10.8	10.4
OSWW	6.2	6.2	6.2	5.5
WZ	5.5	5.5	5.5	4.7
ZZ	3.7	4.2	3.7	3.6

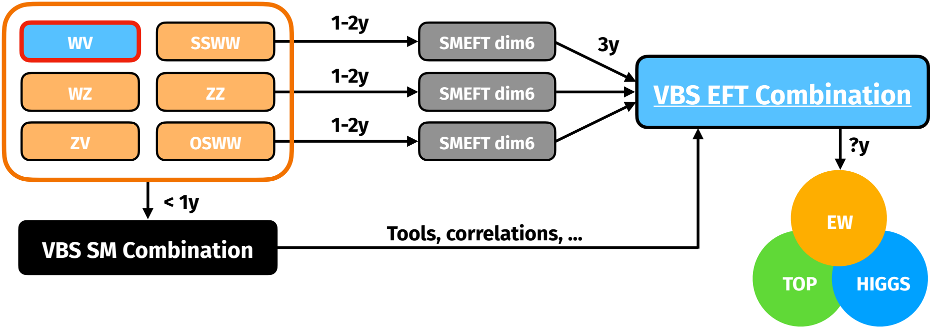
Charged + and − components positively **correlated. Mild correlation** among **SSWW and WZ** parameters as WZ EW contaminates SSWW SR



Conclusions

This work lays the foundation for a global dim-6 interpretation of VBS processes in CMS

- The **first dim-6** interpretations of a VBS process with **semileptonic final state**
- The VBS SM combination: **starting point for a global EFT interpretation of VBS**



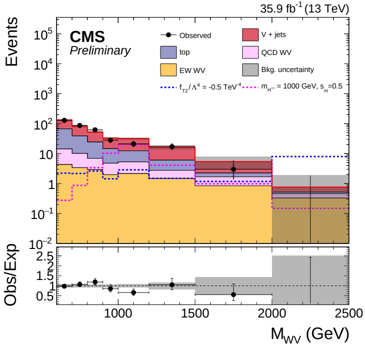
BACKUP

Dimension-6 SMEFT interpretation of the semileptonic VBS $WV \to l\nu qq$ with CMS Run-II data

VBS $WV \to l\nu qq$ dimension 6

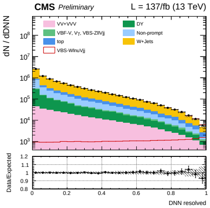
First **strong evidence** of VBS with a semileptonic final state from **CMS**: $\boldsymbol{WV \to l\nu qq}$ (j.physletb.2022.137438)

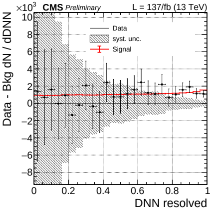
- Exploits **higher statistical power** due to BR of $V \to q\bar{q} \sim 70\%$
- Challenging V+jets background modelling and reduction
- Features **boosted hadronic decays** of vector bosons → can probe **TeV energy regimes**
- Semileptonic VBS channels **lead sensitivity to dimension-8** operators **PLB**
- Run II dimension-8 VBS WV+ZV ongoing



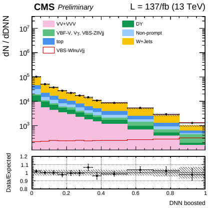
Provide the **first SMEFT dimension-6 interpretation of VBS with a semileptonic channel** ($WV \to l\nu qq$) with CMS Run II data

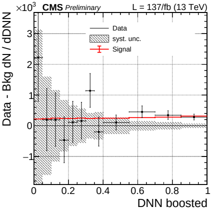
Resolved



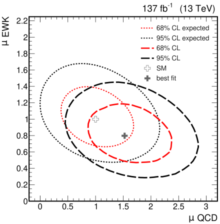


Boosted





Results are 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**



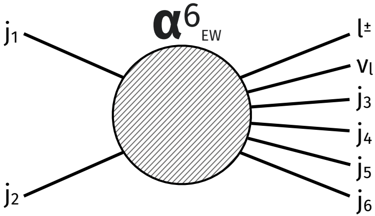
Evidence for the VBS EW production ($WV \to l\nu qq$) $\sigma_{obs} = 4.4$.

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

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

SMEFT sample generation

Opted to treat VBS as a $2 \to 6$ process for SMEFT dim-6 analysis. Include all EW-induced diagrams for EFT, **theoretically more precise.** than inserting EFT in $2 \to 4$

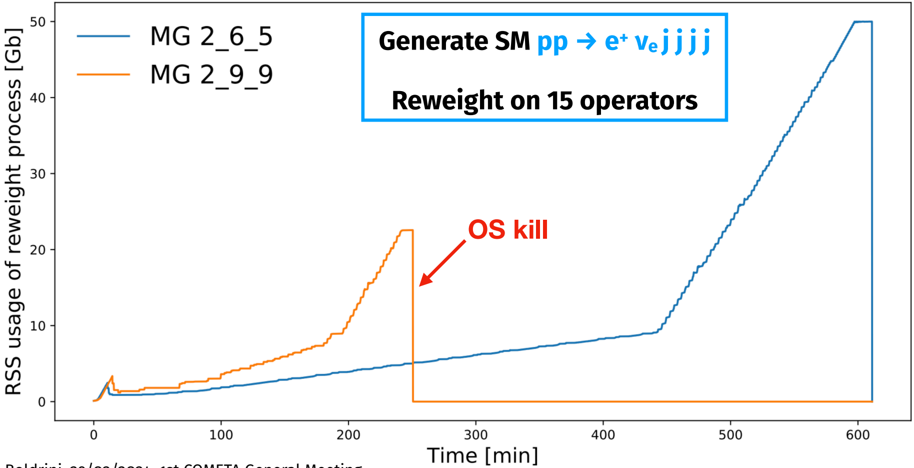


- Use **SMEFTsimv3** + **MadGraph** reweighting to generate signal
- Follow **LHC EFT WG prescriptions**, use Warsaw basis $(\boldsymbol{m_W}, \boldsymbol{m_Z}, \boldsymbol{G_F})$ input scheme
- **topU3l** flavour symmetry: $\overbrace{U(2)_q \times U(2)_u \times U(2)_d}^{(t,b)\neq[(u,d),(c,s)]} \times \underbrace{U(3)_l \times U(3)_e}_{e=\mu=\tau}$

Faced problematics studied in details: Madgraph memory pressure, choice of initial EFT point, choice of μ_F and μ_R computation.

Reweight memory pressure

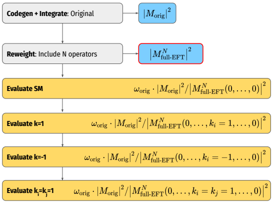
MadGraph reweight computes a new event weight $\omega_{\text{new}} = \omega_{\text{orig}} \cdot |M_{\text{new}}|^2 / |M_{\text{orig}}|^2$ where "orig" refers to the baseline hypothesis.
Problem: when computing $|M_{\text{new}}|^2$ for EFT, all diagrams are included even if Wilson coefficients are set to 0 (independently on the chosen baseline hypothesis) $\rightarrow$ **memory pressure induces OS kill**.



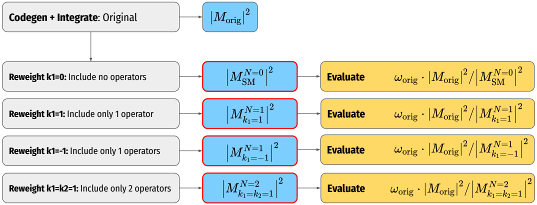
$$N \propto \overbrace{|\mathcal{A}_{SM}|^2}^{\text{SM:0 W.C}} + \sum_{\alpha} \frac{c_\alpha}{\Lambda^2} \cdot \underbrace{2\,\mathrm{Re}(\mathcal{A}_{SM}\mathcal{A}^\dagger_{Q_\alpha})}_{\text{Lin:1 W.C}} + \frac{c_\alpha^2}{\Lambda^4} \cdot \overbrace{|\mathcal{A}_{Q_\alpha}|^2}^{\text{Quad:1 W.C}} + \sum_{\alpha,\beta} \frac{c_\alpha c_\beta}{\Lambda^4} \cdot \underbrace{\mathrm{Re}(\mathcal{A}_{Q_\alpha}\mathcal{A}^\dagger_{Q_\beta})}_{\text{Mix:2 W.C}}$$

Solution: EFT parametrization can be computed evaluating $|M_{new}|^2$ including **at most 2 operators**. **Parallelize** the computation of $n(n+3)/2$ (for n operators) matrix elements $|M_{new}|^2$ that include 0 (SM), 1 (Lin, Quad) and 2 (Mix) operators. **Drastically reduce computational time and memory consumption**

Baseline Madgraph reweight



Parallel Madgraph reweight



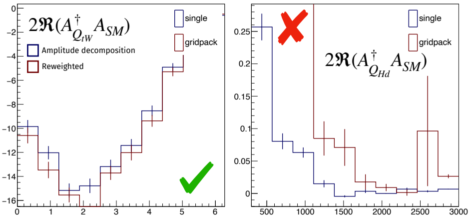
Choice of original point critical for optimal phase space coverage at reweighting$\rightarrow$ **include eight operators**

Start from SM $\rightarrow$ reweight on EFT

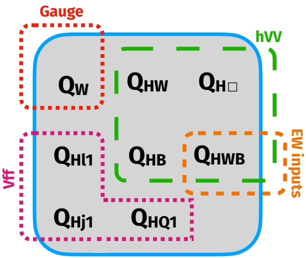
- Computationally efficient 👍
- Can sample full Warsaw basis 👍
- **Phase space coverage not optimal for some operators** 👎

Start from SM+EFT $\rightarrow$ reweight to EFT

- Computationally expensive 👎
- Allows fewer operators 👎
- **Better phase space coverage** 👍



Final configuration: include up to 8 operators to fit within computing time limitations



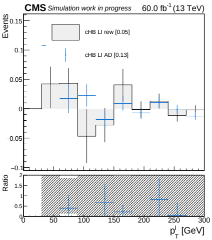
EFT generation starting point

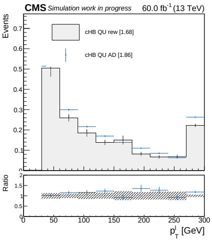
The **starting phase space** is chosen with all **eight operators** turned on, with **Wilson coefficient value of 1**

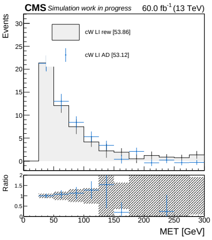
- **Optimal** phase space coverage at reweighting: all operators considered
- For $k = 1$ it might be that $|\mathcal{A}_k|^2 \gg 2\mathrm{Re}(\mathcal{A}_k^\dagger \mathcal{A}_{SM}) \rightarrow \mathrm{SM} + k\mathrm{Lin} + k^2\mathrm{Quad} \sim \mathrm{SM} + k^2\mathrm{Quad}$.
  Quadratic component of Q_W dominates phase space
- **Linear templates might suffer from statistical precision** because
  $\omega_{\mathrm{Lin}} = 0.5 \times [\omega(k=1) - \omega(k=-1)] \sim [\omega(\mathrm{SM} + k^2\mathrm{Quad}) - \omega(\mathrm{SM} + k^2\mathrm{Quad})] = 0$
- Statistical precision reduced in signal regions due to **loose gen-level cuts** on $2 \rightarrow 6$ process: **generate $\sim$ 40M events $\times$ year**

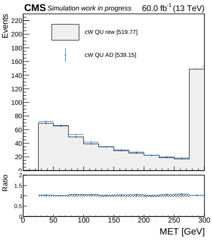
Q_{HB} linear (left) and quadratic (right)

Q_W linear (left) and quadratic (right)









EW VBS SM samples comparison

Need to reproduce the published WVjj analysis with the new signal sample (in the SM analysis a 2 $\rightarrow$ 4 was employed). When **comparing the two samples** in the analyses regions

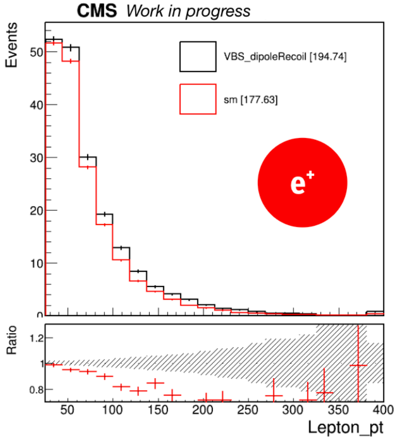
- **Shape + normalization difference** in resolved and boosted regimes (larger in SR, modest in W+jest CR, absent in top-CR)
- For observables entering in the fit, only 15% normalization $\rightarrow$ **Size compatible with QCD scale uncertainties at LO i.e. precision used in the signal generation**

The SM analysis measured a MC excess of exactly 15%

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

2→6 VBS EW sample (EFT study)

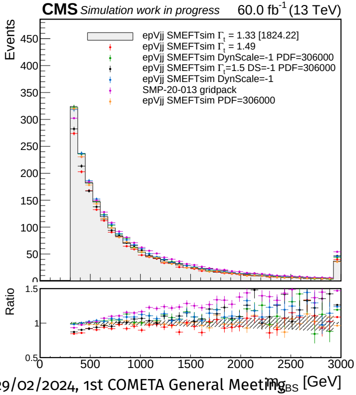
2→4 VBS EW sample (SM analysis)

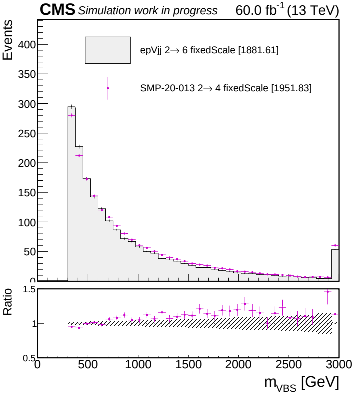


μ_F, μ_R scales

Origin of the **shape difference** between $2 \to 4$ and $2 \to 6$ investigated in detail **changing important generation parameters**: PDF set, Γ_t, analytical form of μ_F, μ_R dynamical computation.

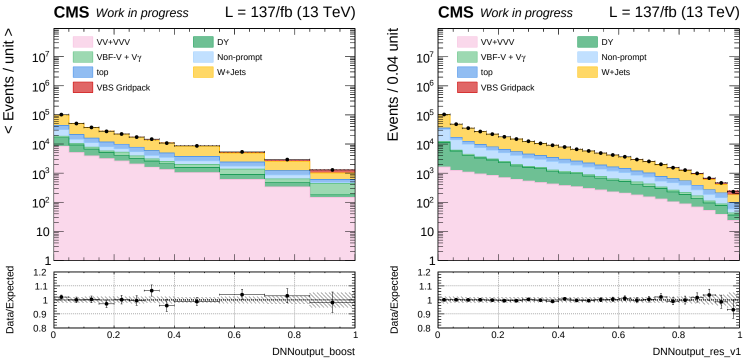
Origin of the shape difference traced back to the dynamical computation of $\mu_{F,R}$ in $2 \to 4$ and $2 \to 6$. Cross checked with indipendent generations **fixing both scales** to $\mu_{F,R} = m_Z \sim 91$ GeV $\to$ **UV divergence is removed, 15% normalization deficit in SR remains.** Will use $2 \to 6$ with dynamical scale $H_T/2$





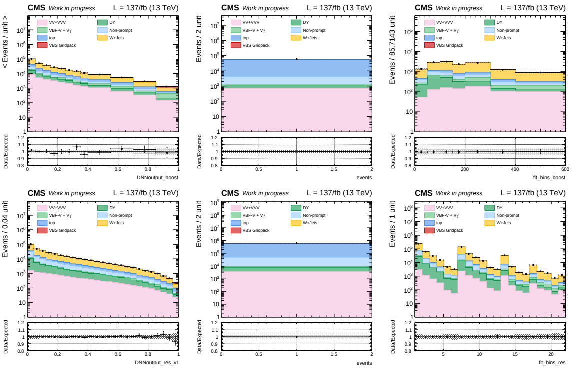
Good closure with the CMS analysis

- Post-fit shapes keeping $\mu_{\mathrm{QCD}} = 1$ show **good agreement with data**
- Observed and expected **significance** for all years and regions **agree**



		CMS Analysis				New configuration			
σ	**Category**	**2016**	**2017**	**2018**	**Combined**	**2016**	**2017**	**2018**	**Combined**
Observed	Boosted	1.4	1.5	3.8	3.8	1.2	1.6	3.8	3.7
	Resolved	2.4	0.0	3.7	3.6	1.7	0.0	3.7	3.6
	Combined	2.2	0.7	4.9	4.4	2.0	0.7	5.0	4.6

VBS $WV \to l\nu qq$ SMEFT: closure on SM

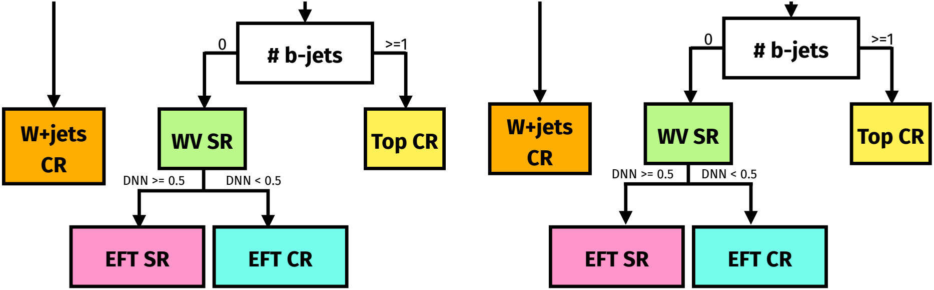


Good closure on the SM analysis

- Post-fit shapes keeping $\mu_{\mathrm{QCD}} = 1$ show good agreement with data
- Observed and expected significance for year and regions agree for $2 \to 4$ and $2 \to 6$.

		SM Analysis				EFT Analysis			
σ	**Category**	**2016**	**2017**	**2018**	**Combined**	**2016**	**2017**	**2018**	**Combined**
Expected	Boosted	2.3	2.0	2.7	3.7	2.0	1.7	2.1	3.1
	Resolved	2.4	1.8	3.2	3.6	2.1	1.4	2.9	3.8
	Combined	3.1	2.6	4.1	5.3	2.5	1.9	3.5	4.7
Observed	Boosted	1.4	1.5	3.8	3.8	1.2	1.6	3.8	3.7
	Resolved	2.4	0.0	3.7	3.6	1.7	0.0	3.7	3.6
	Combined	2.2	0.7	4.9	4.4	2.0	0.7	5.0	4.6

SMEFT analysis strategy



- **The signal region is split** with the SM EW VBS signal extractor (DNN). High DNN region (≥ 0.5) present reduced background, used to extract EFT signal
- **Low DNN region retained** for residual EFT sensitivity
- While the observable entering the fit for W+jets CR and Top CR is fixed, we have freedom to **optimize the sensitivity in the EFT signal regions**

A combine-based model has been developed for EFT limits setting in CMS: AnalyticAnomalousCoupling

- Supports an **arbitrary number of Wilson Coefficients**
- **Linear and quadratic** EFT parametrizations
- Linear and quadratic terms as templates $\rightarrow$ **can include systematic unc. on EFT**
- Solves the negative interference problem by rewriting the EFT formula in terms of **positive-definite quantities** ($|\mathcal{A}|^2$)
- Cross-checked with other EFT limit-setting tools (aTGCRooStat, InterferenceModel)

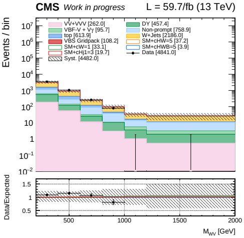
$$
\begin{aligned}
N = & \ \mathrm{SM} \cdot \Big(1 - \sum_i k_i + \sum_{i,i<j} \sum_j k_i \cdot k_j\Big) \\
& + \Big[\sum_i k_i - \sum_{i \neq j} k_i \cdot k_j\Big] \cdot (\mathrm{SM} + \mathrm{Lin}_i + \mathrm{Quad}_i) \\
& + \sum_i \left(k_i^2 - k_i\right) \cdot \mathrm{Quad}_i \\
& + \sum_{i,i<j} \sum_j k_i \cdot k_j \cdot \left[\mathrm{SM} + \mathrm{Lin}_i + \mathrm{Lin}_j + \mathrm{Quad}_i + \mathrm{Quad}_j + 2 \cdot \mathrm{Mix}_{ij}\right]
\end{aligned}
$$

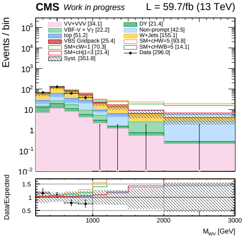
The following nominal templates are provided at datacard level via **reweighting of the VBS EW** $2 \rightarrow 6$ **sample**:

- **SM** $\rightarrow \omega(0)$
- **Quad** $\rightarrow 0.5[\omega(1) + \omega(-1) - 2\omega(0)]$
- **SM+Lin+Quad** $\rightarrow \omega(1)$
- **SM+Lin+Quad+Mix** $\rightarrow \omega(1, 1)$

Summary of SMEFT interpretation of VBS WV semileptonic

- 8 operators: Q_W, Q_{HWB}, $Q_{H\Box}$, Q_{HW}, $Q_{Hl}^{(1)}$, Q_{HB}, $Q_{HQ}^{(1)}$, $Q_{Hj}^{(1)}$
- EFT from $2 \to 6$ EW VBS included in all analysis regions
- EFT signal extracted via m_{WV}: 8 bins in boosted SR (200-3000 GeV), 6 bins in resolved SR (200-2000 GeV)



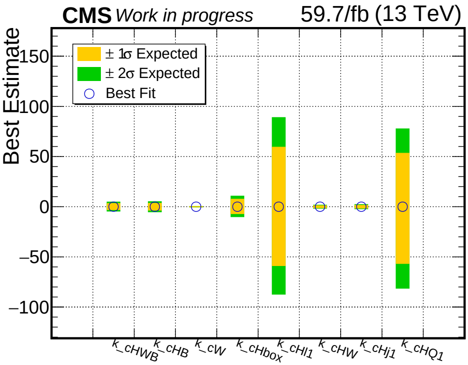


Regions, observables and bins entering in the fit for each year

	Region	Obs.	Bins
Signal regions	Boost e DNN$\geq$0.5	m_{WV}	8
	Boost e DNN<0.5	m_{WV}	8
	Boost μ DNN$\geq$0.5	m_{WV}	8
	Boost μ DNN<0.5	m_{WV}	8
	Res e DNN$\geq$0.5	m_{WV}	6
	Res e DNN<0.5	m_{WV}	6
	Res μ DNN$\geq$0.5	m_{WV}	6
	Res μ DNN<0.5	m_{WV}	6
W+jets CR	Boost e W+jet	$p_T^{W\to l\nu}$	7
	Boost μ W+jet	$p_T^{W\to l\nu}$	7
	Res e W+jet	$p_T^{W\to l\nu}$: $p_T^{\text{VBS},2}$	21
	Res μ W+jet	$p_T^{W\to l\nu}$: $p_T^{\text{VBS},2}$	21
Top CR	Boost e Top	Events	1
	Boost μ Top	Events	1
	Res e Top	Events	1
	Res μ Top	Events	1
	Total	16	116

VBS $WV \to l\nu qq$ SMEFT: optimal observable

Expected 1-2σ intervals from the optimal observable found for each operator.



Ranking methodology

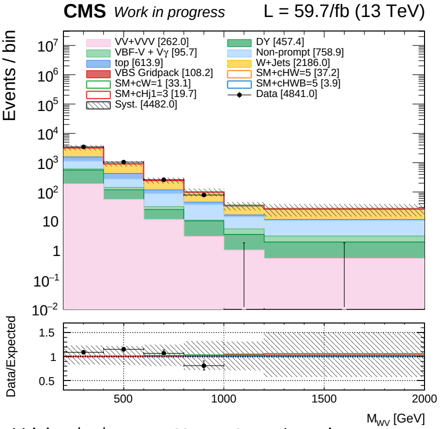
- Conservative binning and ranges
- All observables have the same number of bins (10)
- Systematic uncertainties not included
- All W+jets and Top rate parameters free to float and fit to data in CR
- Using boosted signal region (DNN>0.5) only $\to$ drives sensitivity
- Use 2018 data only
- All other operators free to float in the fit

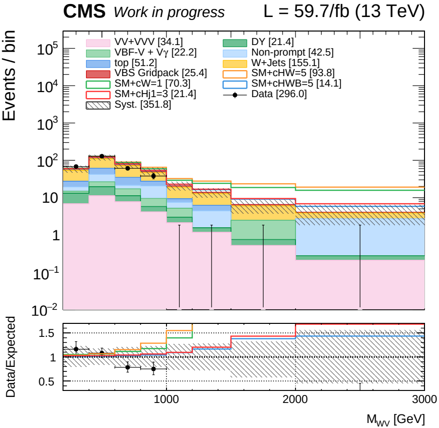
The **reconstructed WV invariant mass is always found to be the most sensitive observable** for all operators (even more than DNN spectra)

Observable for EFT limit setting

The **reconstructed WV invariant mass is found to be the most sensitive observable in all channels** for all operators

EFT signal extracted via m_{WV}: 8 bins in boosted SR [200-3000 GeV], 6 bins in resolved SR [200-2000 GeV]. **Boosted regions lead the EFT sensitivity**



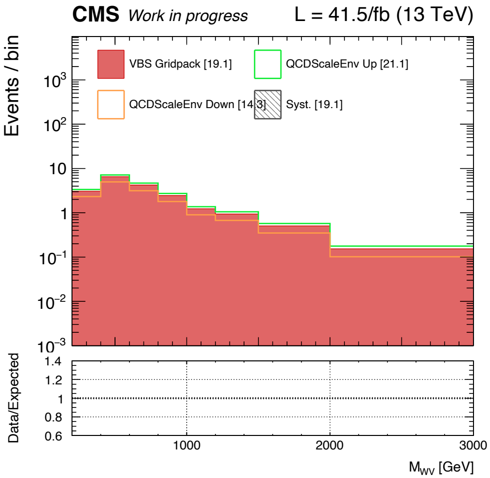


Account for different QCD scales in $2 \to 4$ and $2 \to 6$ generations

$$\hat{\mu} = \begin{cases} m_X, & \forall \text{ decay } X \to x_i \\ \text{dynamical} & \forall \text{ scattering} \end{cases}$$

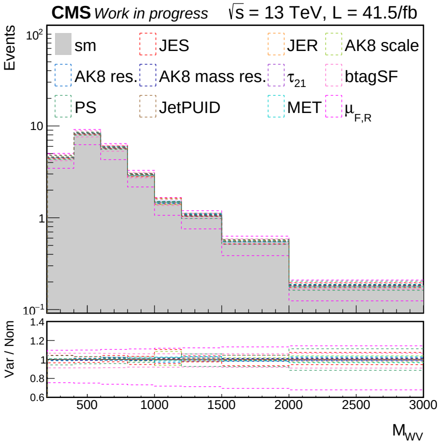
Take envelope of $\mu_{R,F} \in$[0.5, 1, 2], **all analytical forms for dynamical scales** (45 variations):

- transverse mass of $2 \to 2$ system resulting of a k_T clustering
- $\sum_{i=1}^{N} \sqrt{m_i^2 + p_{T,i}^2}$
- $0.5 \times \sum_{i=1}^{N} \sqrt{m_i^2 + p_{T,i}^2}$
- $\sum_{i=1}^{N} E_i \cdot p_{T,i} / |\vec{p_i}|$
- $\sqrt{\hat{s}}$



μ_F, μ_R **uncertainties** amount to $\sim$ **15 — 20%** on the SM EW VBS process

The treatment of **systematic uncertainties follows from the CMS SM analysis.** Experimental and theory uncertainties computed also for EFT predictions



Experimental / background modeling

- **Lumi** (lnN): all MC + EFT/top & W+jets
- **PU** (lnN): all MC + EFT
- **Lepton eff + scale** (shape): all MC + EFT
- **JES + JER (AK4)** (lnN): all MC + EFT
- **JES + JER (AK8)** (lnN): all MC + EFT
- **AK8 mass scale + res** (lnN): all MC + EFT
- τ_{21} (shape): all MC + EFT
- **MET** (lnN): all MC + EFT
- **QGL morphing** (shape): all MC + EFT
- **JetPUID SF** (shape): all MC + EFT
- **btag SF** (shape): all MC + EFT

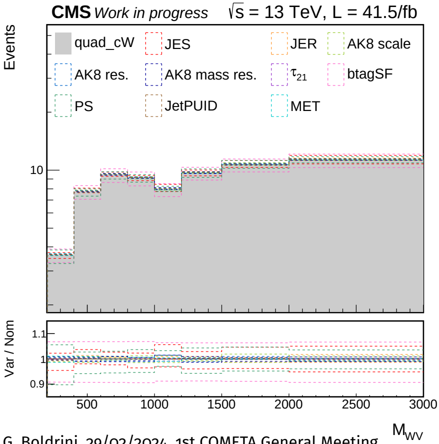
Theory

- **PS+UE** (shape): all MC + EFT
- **PDF** (shape): all MC/top & W+jets
- μ_F, μ_R (shape): all MC/top & W+jets

VBS $WV \to l\nu qq$ SMEFT: Uncertainties

The treatment of **systematic uncertainties on the background follows from the SM analysis**. Special attention SM EW VBS and to EFT.

Account for different QCD scales in $2 \to 4$ and $2 \to 6$: envelope of $\mu_{R,F} \in$[0.5, 1, 2], all analytical forms (44 variations).



Experimental / background modeling

- **Lumi** (lnN): all MC + EFT/top & W+jets
- **PU** (lnN): all MC + EFT
- **Lepton eff + scale** (shape): all MC + EFT
- **JES + JER (AK4)** (lnN): all MC + EFT
- **JES + JER (AK8)** (lnN): all MC + EFT
- **AK8 mass scale + res** (lnN): all MC + EFT
- $\boldsymbol{\tau_{21}}$ (shape): all MC + EFT
- **MET** (lnN): all MC + EFT
- **QGL morphing** (shape): all MC + EFT
- **JetPUID SF** (shape): all MC + EFT
- **btag SF** (shape): all MC + EFT

Theory

- **PS** (shape): all MC + EFT
- **UE+PDF** (shape): all MC + EFT/top & W+jets
- $\boldsymbol{\mu_F, \mu_R}$ (shape): all MC/top & W+jets

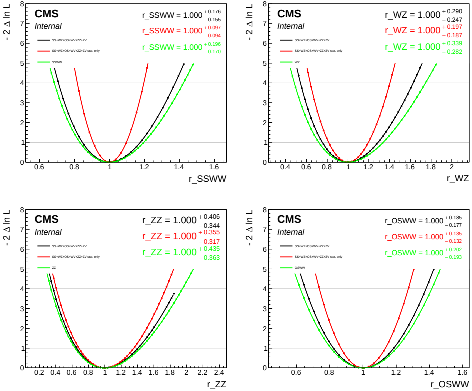
CMS Run II combination of VBS measurements

The Analyses Involved

More than 1 parameter (green) | Only 1 parameter (yellow)

	OSWW	SSWW		WZ		ZZ
Analysis	W^+W^-	W^-W^-	W^+W^+	W^-Z	W^+Z	ZZ
$WVjj \rightarrow l\nu jjjj$	✓	✓	✓	✓	✓	-
$ZVjj \rightarrow 2ljjjj$	-	-	-	✓	✓	✓
$W^+W^-jj \rightarrow 2l2\nu jj$	✓	-	-	-	-	-
$W^\pm W^\pm jj \rightarrow 2l2\nu jj$	-	✓	✓	-	-	-
$W^\pm Zjj \rightarrow 2l2\nu jj$	-	-	-	✓	✓	-
$ZZjj \rightarrow 4ljj$	-	-	-	-	-	✓
$W^\pm W^\pm jj \rightarrow l\tau_h 2\nu jj$	-	✓	✓	-	-	-
$ZZjj \rightarrow 2l2\nu jj$	-	-	-	-	-	✓
$VVjj \rightarrow 6j$	✓	✓	✓	✓	✓	✓

Nuisance correlations between channels studied in details

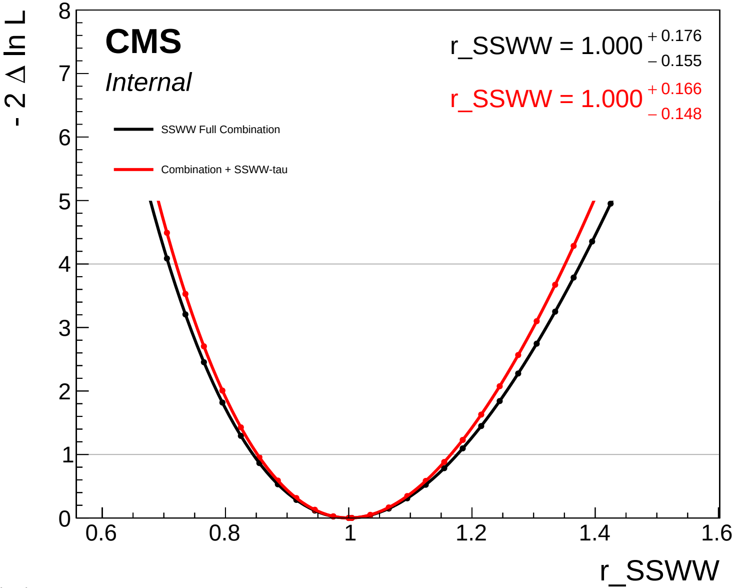


- **Leading channel**
- **SS+WZ+OS+WV+ZV+ZZ(4l) stat. only**
- **SS+WZ+OS+WV+ZV+ZZ(4l) Full nuisances**
- Improved by **15%** in significance on **OSWW**, 13% on **WZ** and 16% on **ZZ** (w ZZ2l2ν)

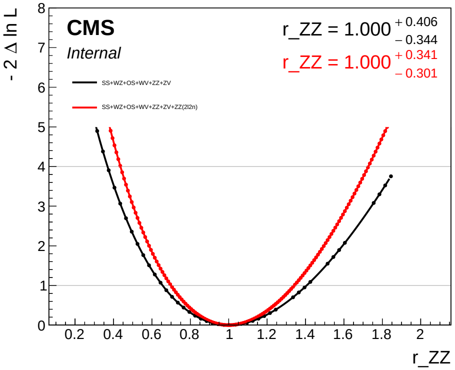
Expected to get evidence for all 6 parameters

		OSWW	SSWW		WZ		ZZ
4-POI	μ	$1.000^{+0.181}_{-0.172}$	$1.000^{+0.174}_{-0.155}$		$1.000^{+0.291}_{-0.248}$		$1.000^{+0.403}_{-0.344}$
	σ	6.2	10.8		5.5		3.7
		WpWm	WpWp	WmWm	WpZ	WmZ	ZZ
6-POI	μ	$1.000^{+0.184}_{-0.176}$	$1.000^{+0.178}_{-0.156}$	$1.000^{+0.300}_{-0.261}$	$1.000^{+0.328}_{-0.277}$	$1.000^{+0.451}_{-0.374}$	$1.000^{+0.412}_{-0.349}$
	σ	6.2	11.7	4.6	4.9	3.4	3.7

Inclusion of SSWW+τ_h



Inclusion of SSWW+τ_h and $ZZ(2l2\nu)$



- **Including $ZZ(2l2\nu)$ not straightforward**: OSWW DY CR is overlapping with both the $ZZ(2l2\nu)$ signal region and DY CR.
- SSWW+τ_h and $ZZ(2l2\nu)$ event processing is different $\rightarrow$ might need a **dedicated nuisance treatment**.
- Little gain from SSWW+τ_h while **$ZZ(2l2\nu)$ gives significant contributions.**

POI	σ_{exp}	σ_{exp} (w ZZ($2l2\nu$))	σ_{exp} (w SSWW-τ_h)	σ_{exp} single channel
SSWW	10.8	10.8	10.8	10.4
OSWW	6.2	6.2	6.2	5.5
WZ	5.5	5.5	5.5	4.7
ZZ	3.7	4.2	3.7	3.6

Nuisance correlation

Built framework for nuisance correlation on top of hh-inference tools.
Some changes affect the following categories:

- **Lumi**: Updated all analysis lumi uncertainties with LUM POG recommandations
- **QCDscales**: Correlated for signals and some backgrounds.
- **Lepton efficiency**: Correlated all analyses
- **Lepton scales**: Correlated OSWW,WV,ZV
- **UE**: Correlated. Only present in OSWW,WV,ZV
- **Trigger**: Correlated OSWW,WV,ZV as share same triggers
- **Fakes**: Correlated syst. OSWW,WV,ZV, identical fake computation while decorrelated 30% lnN due to different fake sources
- **JES+JER**: Correlated OSWW,WV,ZV (full split) for AK4. Correlated WV,ZV for AK8
- **MET**: Correlated OSWW,WV only present in these channels
- **Prefiring**: Correlated all analyses
- **PUID/PU**: Correlated OSWW,WV,ZV
- **Btag**: Correlated OSWW,WV,ZV

Full correlation tables in Slide 23 and Slide 24

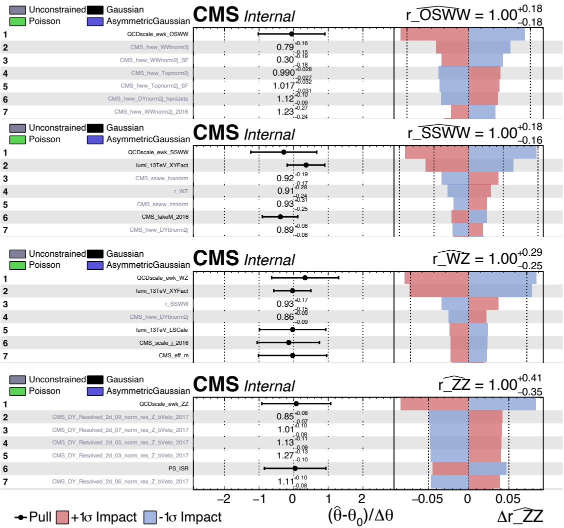
Most nuisances not correlated mainly due to different correlation scheme (Full / Minimal), due to **missing nuisances** (e.g. PU, PS) or due to **differences in the calculations** (e.g. trigger, fakes, ...)

Uncertainties Impacts

Impact of nuisance parameters: re-evaluating fit shifting the nuisance value.

- Constrained (unconstrained) Nuisances parameter prefit value $\theta_0 = 1(0)$
- Perform **best fit** of $\mu \rightarrow \hat{\mu}$ profiling nuisance parameters $\rightarrow \hat{\theta} \pm \sigma(\hat{\theta})$
- **Shift one nuisance** up $(+\sigma)$ and down $(-\sigma)$, fix other ones. Perform the fit for $\mu \rightarrow \mu_{\pm}$
- **Nuisance pull**: $(\hat{\theta} - \theta_0)/\sigma(\hat{\theta})$
- **Nuisance Impact**: $\Delta\mu = \mu_{\pm} - \hat{\mu}$

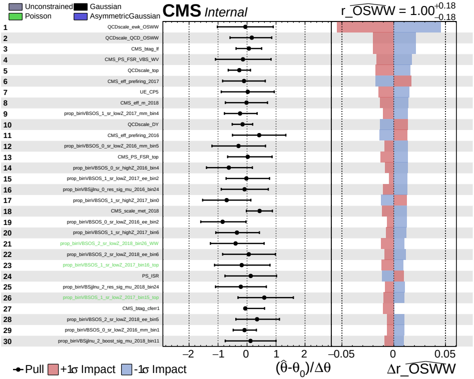
μ_F, μ_R uncertainties **on EW VBS signals and backgrounds** dominate sensitivity + data driven background x-sec measurements



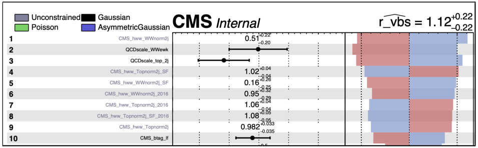
The combination is stable within each analysis stability

Impacts - OSWW

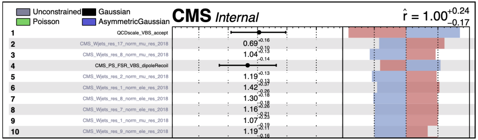
Data Asimov impacts Combination (no ZZ($2l2\nu$))



Observed impacts VBS-OSWW



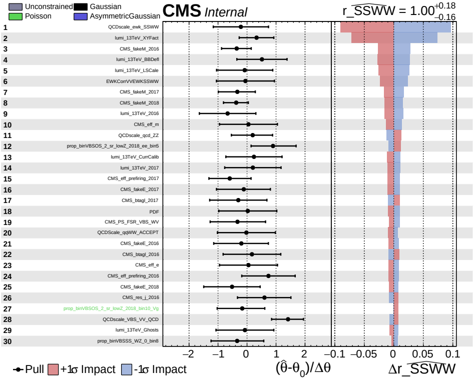
Observed impacts VBS-WV



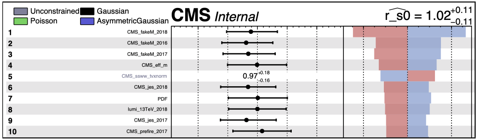
Only constrained nuisances shown for combination. For full tables check this link

Impacts - SSWW

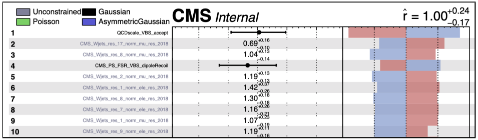
Data Asimov impacts Combination (no ZZ($2l2\nu$))



Observed impacts VBS-SSWW



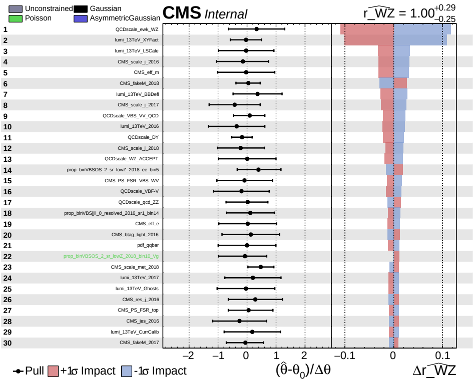
Observed impacts VBS-WV



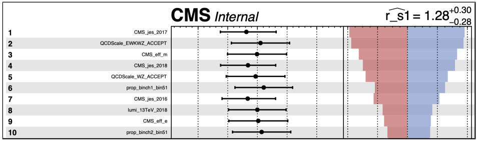
Only constrained nuisances shown for combination. For full tables check this link

Impacts - WZ

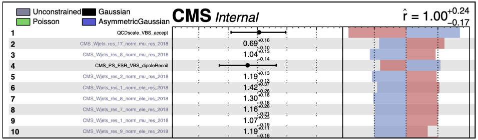
Data Asimov impacts Combination (no ZZ($2l2\nu$))



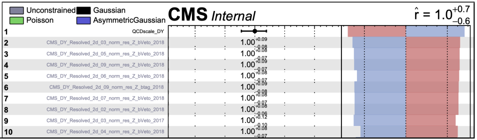
Observed impacts VBS-WZ



Observed impacts VBS-WV



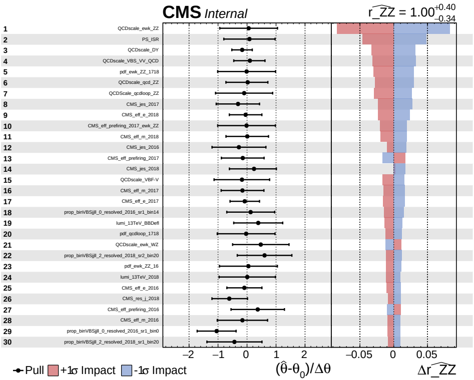
Expected MC impacts VBS-ZV



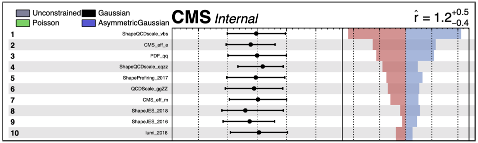
Only constrained nuisances shown for combination. For full tables check this link

Impacts - ZZ

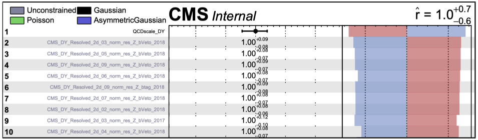
Data Asimov impacts Combination (no ZZ($2l2\nu$))



Observed impacts VBS-ZZ



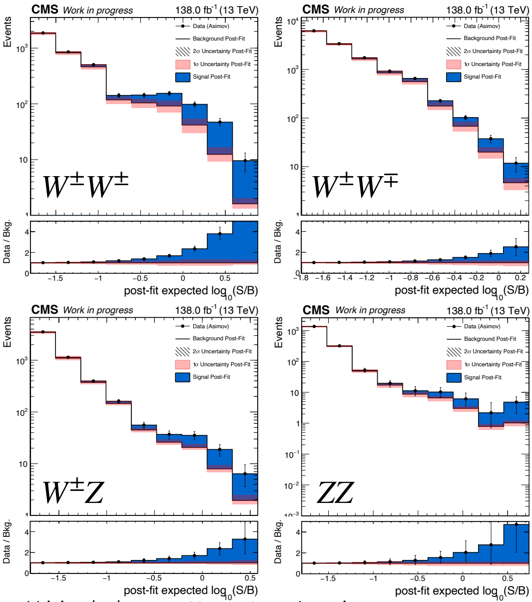
Expected MC impacts VBS-ZV



Only constrained nuisances shown for combination. For full tables check this link

One sided-behaviour for jet energy scales coming from VBS-ZZ4l. Templates are one-sided for all years. The behaviour disappears once correlating with VBS-SSWW / WZ Slide 37

S/B plots

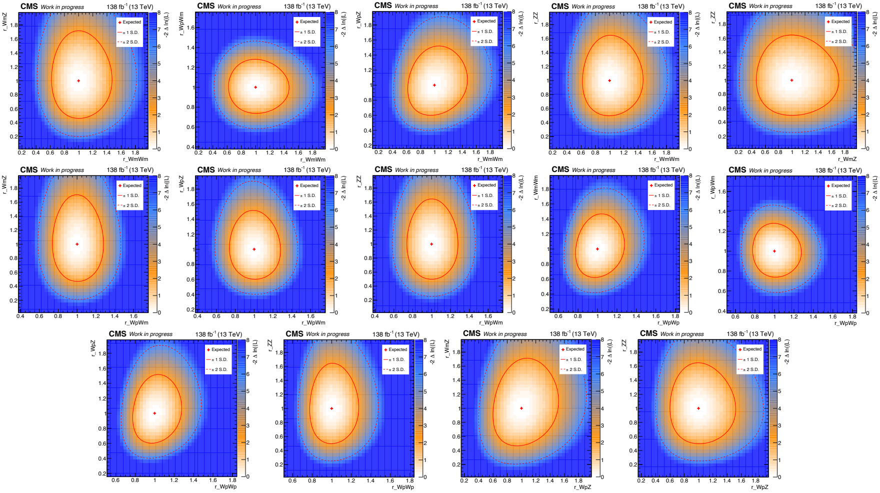


log(S/B) plots from postfit **profiling** nuisances and fitting background normalization to data but keeping $\mu = 1$. All regions considered.

The **post-fit background uncertainties** from each bin are computed with 500 toys

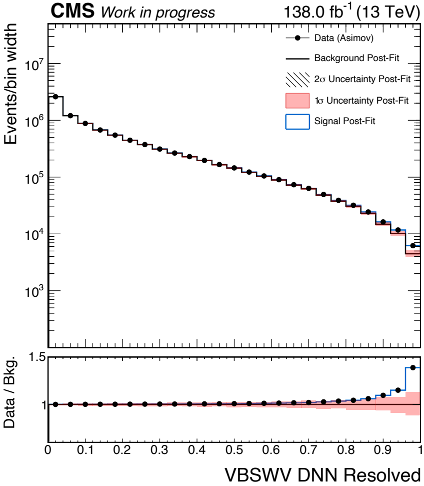
Bi-dimensional scans

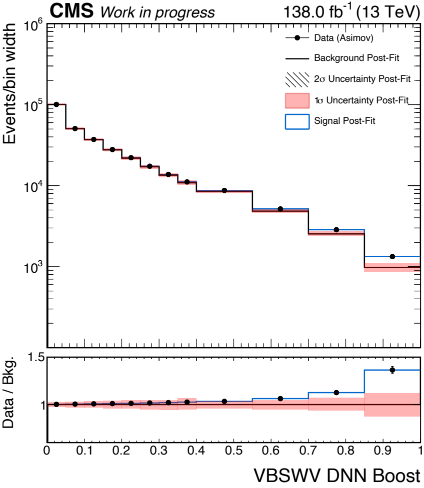
Charged + and − components positively **correlated. Mild correlation** among **SSWW and WZ** parameters as WZ EW contaminates SSWW SR



Post-fit WV

Throw 500 toys from best post-fit value for each of the 4 POI and fit them to evaluate **post-fit background uncertainty**. * Signal is prefit (r=1) and data is Asimov

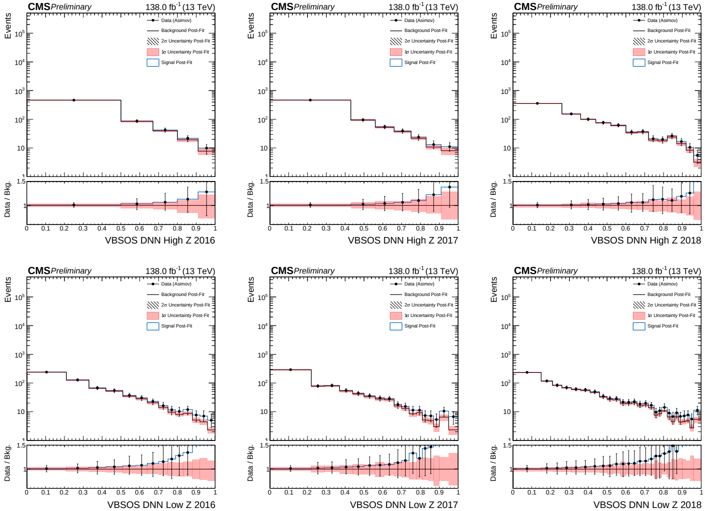




* Signal is prefit (r=1) and data is Asimov

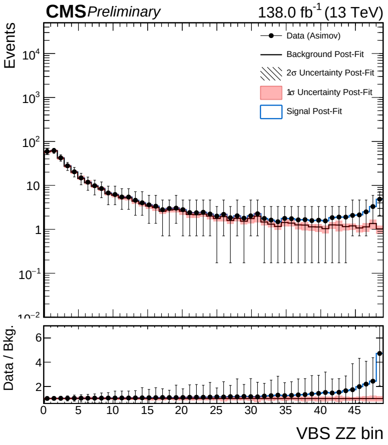
Post-fit OSWW

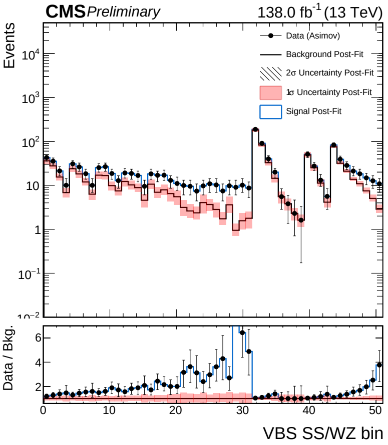
Throw 500 toys from best post-fit value for each of the 4 POI and fit them to evaluate **post-fit background uncertainty**. * Signal is prefit (r=1) and data is Asimov



Post-fit

Throw 500 toys from best post-fit value for each of the 4 POI and fit them to evaluate **post-fit background uncertainty**. * Signal is prefit (r=1) and data is Asimov





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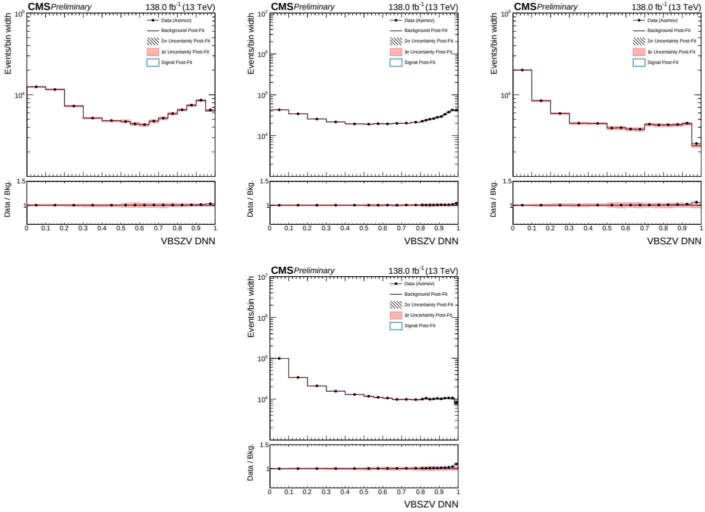

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