VBS measurements - CMS

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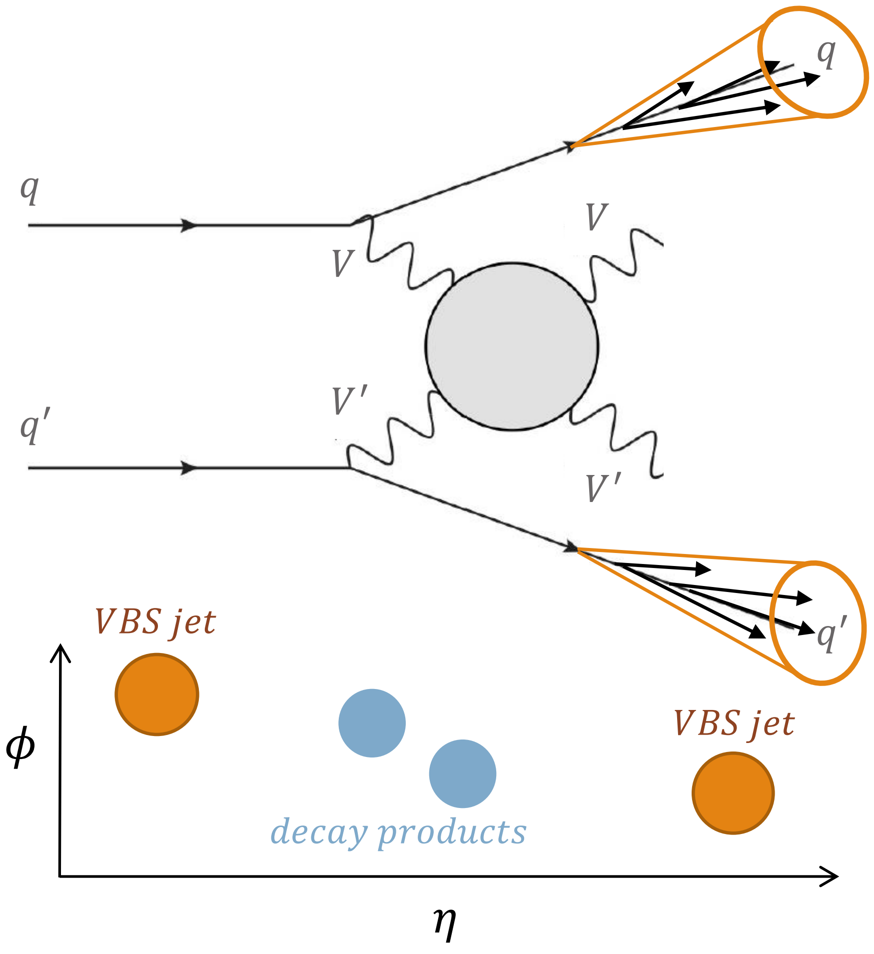
ON BEHALF OF THE CMS COLLABORATION

Introduction

- **Vector Boson Scattering (VBS)**, i.e. $VV \rightarrow VV$ scattering, with V being any vector boson, is a purely electroweak (EW) process which allows to probe the spontaneous symmetry breaking mechanism of the Standard Model (SM)



MAIN FEATURES:

- Rare processes (cross sections of the order of few fb)
- Indirect portal to the Higgs sector of the SM
- High sensitivity to beyond SM effects and anoumalus gauge couplings (aTGC/aQGC)

EXPERIMENTAL SIGNATURE:

- 2 VBS jets with large pseudorapidity gap $\left(\Delta\eta_{jj}\right)$ and invariant mass $\left(m_{jj}\right)$
- Little QCD activity between VBS jets
- Decay products centrally emitted with respect to VBS jets

Overview

- Since the Higgs boson discovery, **the CMS collaboration has dedicated a huge effort in EW precision physics**, in particular to the measurement of several VBS modes

- I will be focusing on the **most recent VBS results** by the CMS collaboration

	VBS mode	σ (fb) @ 13 TeV	Final state	$\mathcal{L}$ (fb^{-1})
	$WV(\to \ell\nu qq')$	$1.90^{+0.53}_{-0.46} \times 10^3$	Semi-leptonic	138
●	$W\gamma$	$23.5^{+4.9}_{-4.7}$	Lepton + photon	138
	$Z\gamma$	5.21 ± 0.76	Leptons + photon	137
●	$W^\pm W^\pm(\to \tau_h\nu_\tau\ell\nu)$	$1.44^{+0.63}_{-0.56} \times \sigma_{SM}$	Hadronic tau + lepton	138
●	$W^+W^-(\to 2\ell2\nu)$	10.2 ± 2.0	Leptons	138
	$W^\pm W^\pm(\to 2\ell2\nu)$	3.83 ± 0.74	Leptons	35.9
	$W^\pm W^\pm(\to 2\ell2\nu)$	3.93 ± 0.57	Leptons	137
	$W_L^\pm W_L^\pm(\to 2\ell2\nu)$	$0.32^{+0.42}_{-0.40}$	Leptons	137
	$WZ(\to 3\ell\nu)$	1.81 ± 0.41	Leptons	137
	$ZZ(\to 4\ell)$	$0.33^{+0.12}_{-0.10}$	Leptons	137

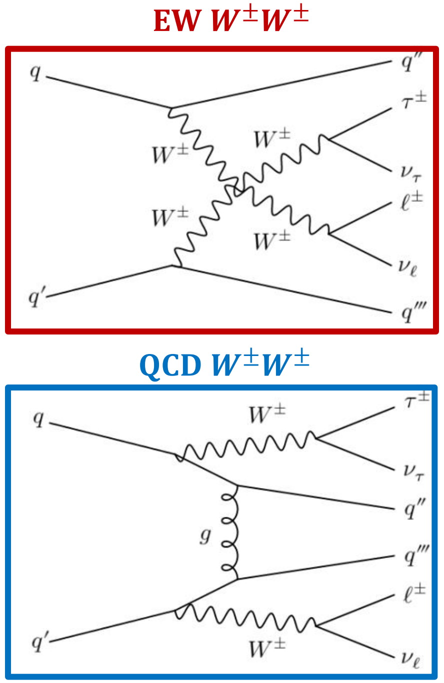
VBS $W^{\pm}W^{\pm} \rightarrow \tau_h \nu_\tau \ell \nu$

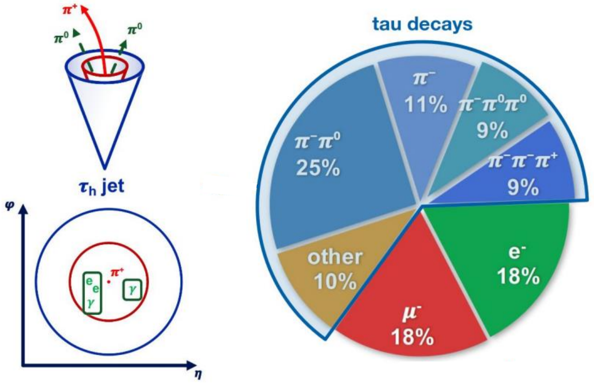
CMS-PAS-SMP-22-008

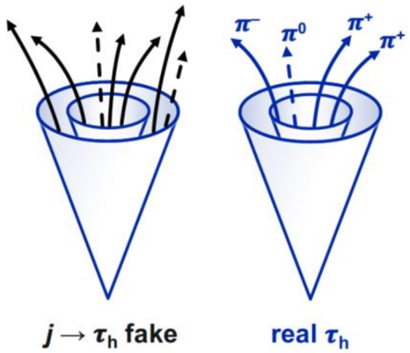
VBS with a τ_h lepton

- **First VBS measurement with an hadronically decaying tau (τ_h) in the final state**
- The signal reconstruction is based on the presence of:
  - **2 VBS jets**
  - **2 same-charged leptons (one being a τ_h lepton)**
  - **Imbalance on the total transverse momentum $\left(p_T^{miss}\right)$**

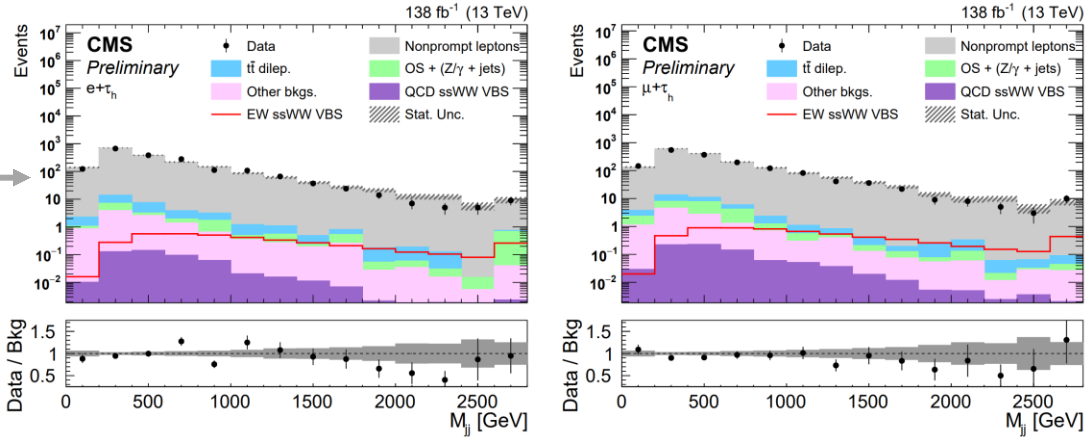
About 95% of background events in the signal region comes from jets mis-identified as leptons







This contribution is estimated from data and validated in a dedicated control region



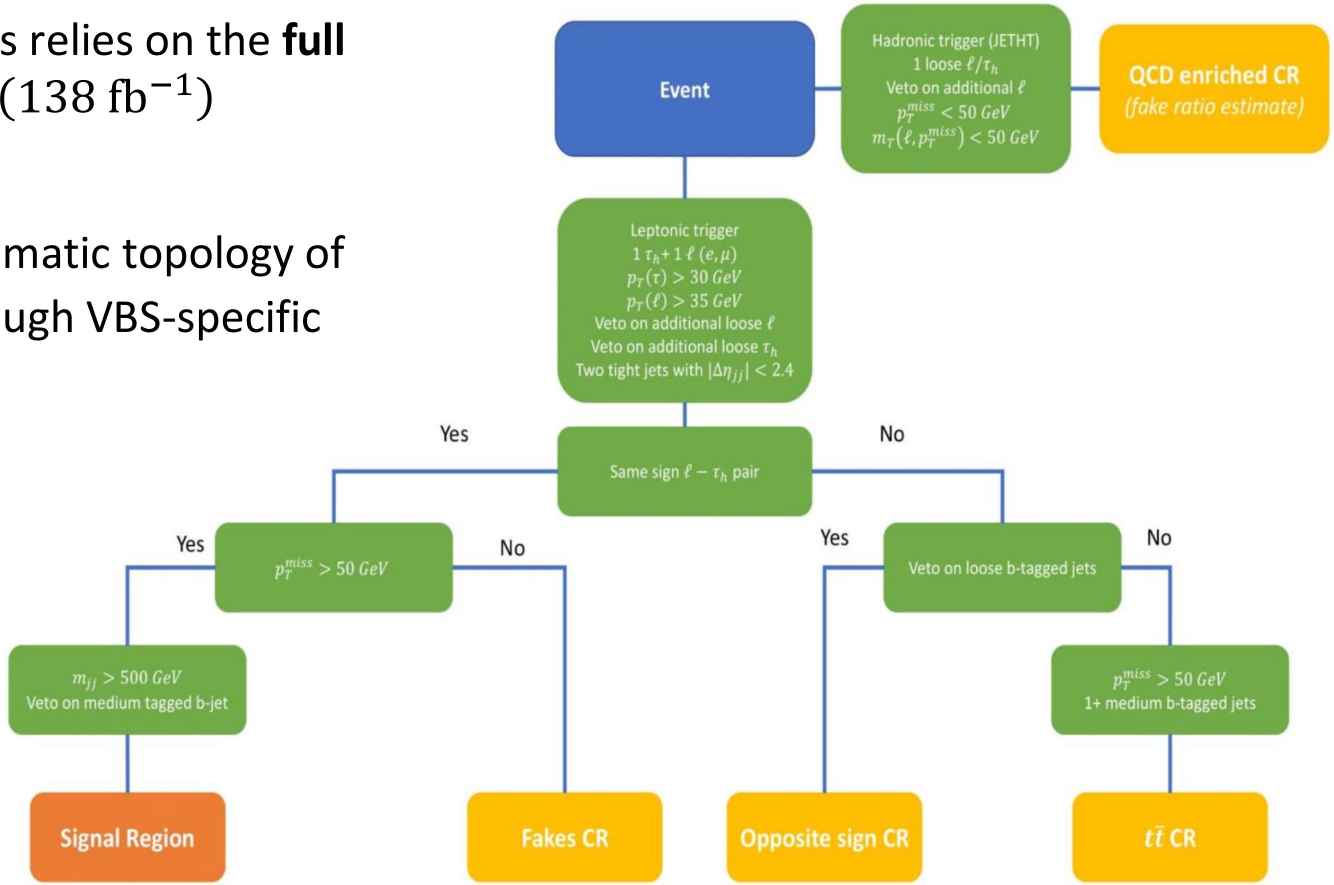
Analysis strategy

- The search for the VBS $W^{\pm}W^{\pm} \rightarrow \tau_h \nu_\tau \ell \nu$ process relies on the **full Run 2 data set** collected by the CMS experiment $(138\ \mathrm{fb}^{-1})$

- Signal candidates are selected exploiting the kinematic topology of the final state $\left(\boldsymbol{\tau_h^{\pm} \ell^{\pm} + p_T^{miss} + 2\ \mathbf{jets}}\right)$ and through VBS-specific requirements $\left(\boldsymbol{m_{jj} > 500\ \mathbf{GeV}}\right)$

- Control regions (CRs) are added to the signal extraction procedure in order to constrain the normalization of **fake leptons, $t\bar{t}$ pair production and opposite-charged leptons**

- The [DeepTau algorithm] is employed to efficiently reconstruct prompt τ leptons against non-prompt τs, jets, electrons and muons

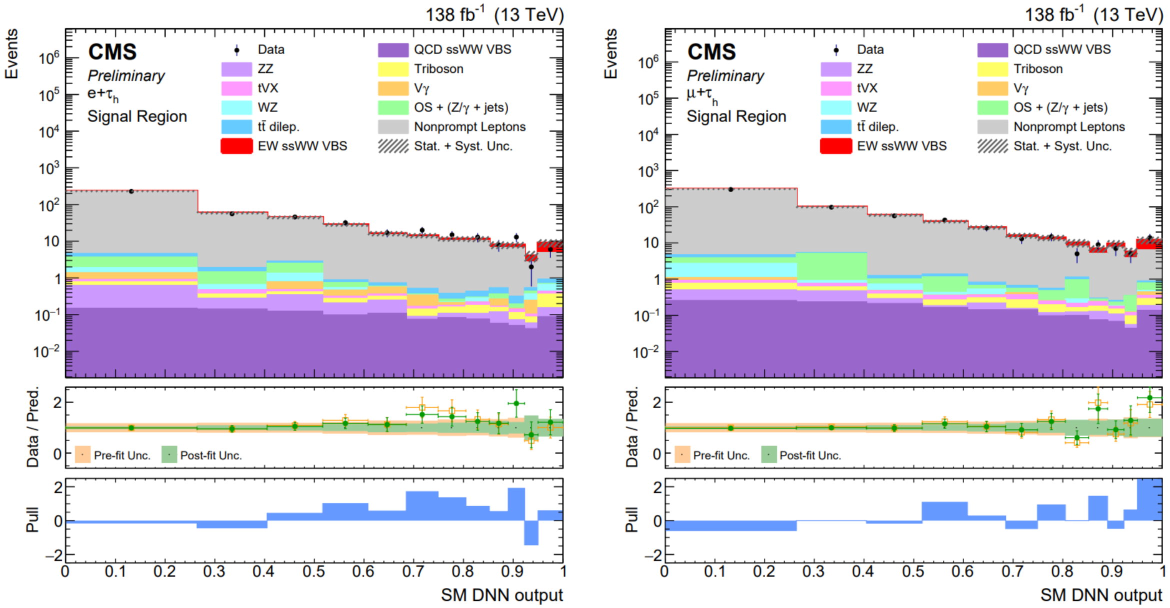


Results

- A **Deep Neural Network** (DNN) is trained to obtain an observable which is capable of discriminating the VBS signal against other backgrounds, and therefore it is **used as fitting variable to extract the signal**

- The DNN output template from SR and CRs is simultaneously fit to data to extract the signal strength parameter defined as $\boldsymbol{\mu} = \boldsymbol{\sigma_{obs}}/\boldsymbol{\sigma_{SM}}$

- **Signal strength parameters are extracted in two cases**, one where just the EW $W^{\pm}W^{\pm}$ contribution is measured, and the other one where EW + QCD $\mathrm{W}^{\pm}\mathrm{W}^{\pm}$ are scaled together in the fit procedure



	Significance [#σ] (expected)	μ (expected)
EW	**2.7** (1.9)	$\mathbf{1.44^{+0.63}_{-0.56}}(1.00^{+0.60}_{-0.53})$
EW + QCD	**2.9** (2.0)	$\mathbf{1.43^{+0.60}_{-0.54}}(1.00^{+0.57}_{-0.51})$

- Results are largely dominated by the statistical uncertainty of collected data and **this measurement will benefit from the ongoing LHC Run 3**

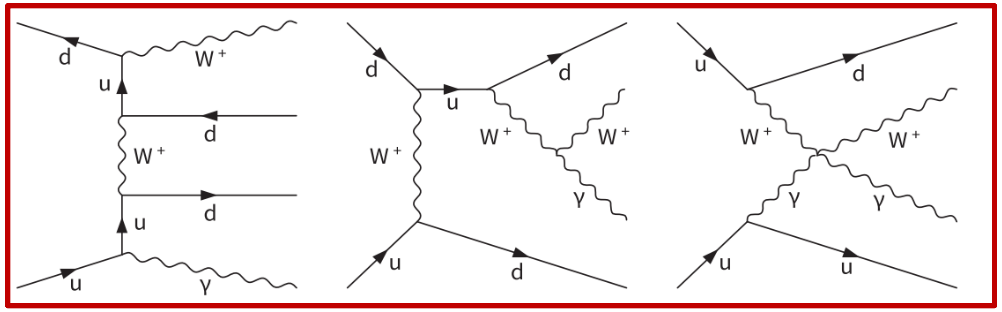
- This analysis will be complemented by the **addition of EFT interpretation** (before journal submission)

VBS $W\gamma \to \ell\nu\gamma$

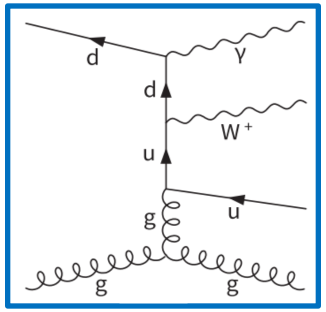
Phys. Rev. D 108 (2023) 032017

VBS $W\gamma$

EW $W\gamma$



QCD $W\gamma$



- The signal reconstruction is based on the presence of:
  - **2 VBS jets**
  - **1 high-p_T and well-isolated lepton (either e or μ) + 1 high-p_T and well-isolated photon (γ)**
  - **Imbalance on the total transverse momentum $\left(p_T^{miss}\right)$**

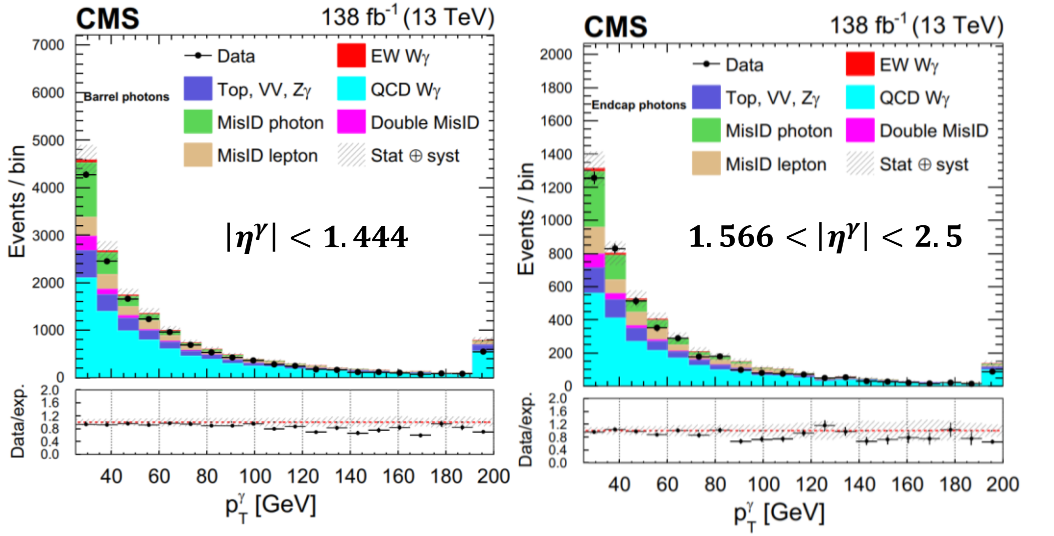
Jets mis-identified as either photons or leptons constitute another source of background **(W + jets and top quark processes)**

The fraction of fake objects entering the signal region is estimated with a data-driven technique

- VBS $W\gamma jj$ **fiducial + differential cross section** measurements and **aQGCs interpetetration** using CMS Run 2 data

- **QCD $W\gamma jj$ production is the dominant background** of the analysis (interference with EWK $W\gamma jj$ taken into account)

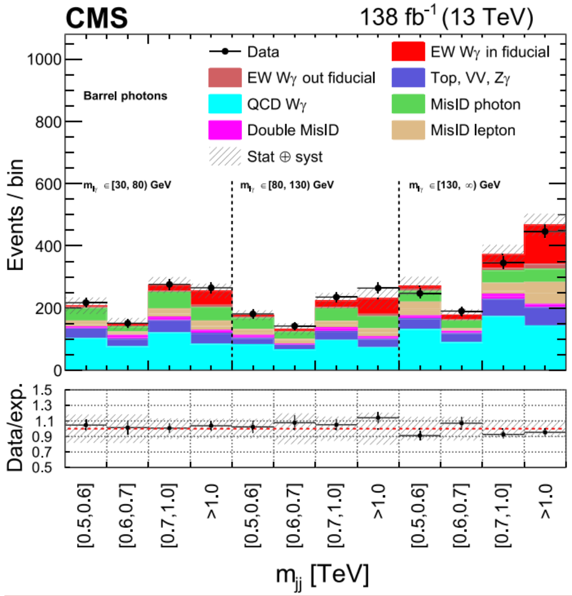
p_T^γ in $QCD\ W\gamma jj$ CR

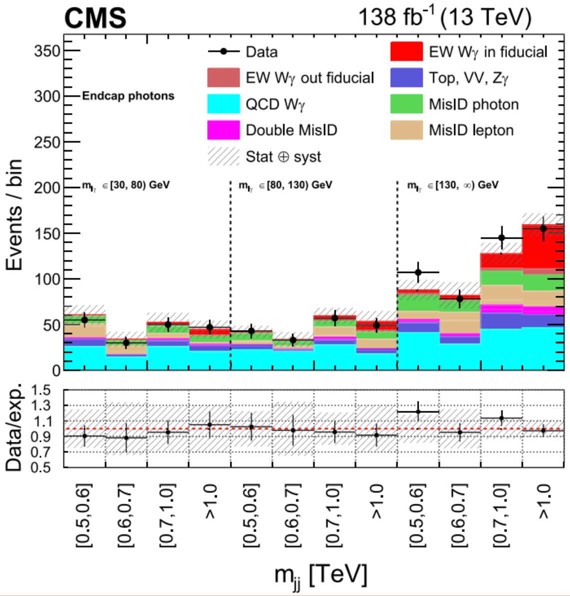


Cross section measurements

FIDUCIAL CROSS SECTIONS

- m_{jj} vs $m_{\ell\gamma}$ distribution is fit to data in both the SR and CR
- Observed 6.0 σ for the EW $W\gamma jj$ process (6.8 σ expected)



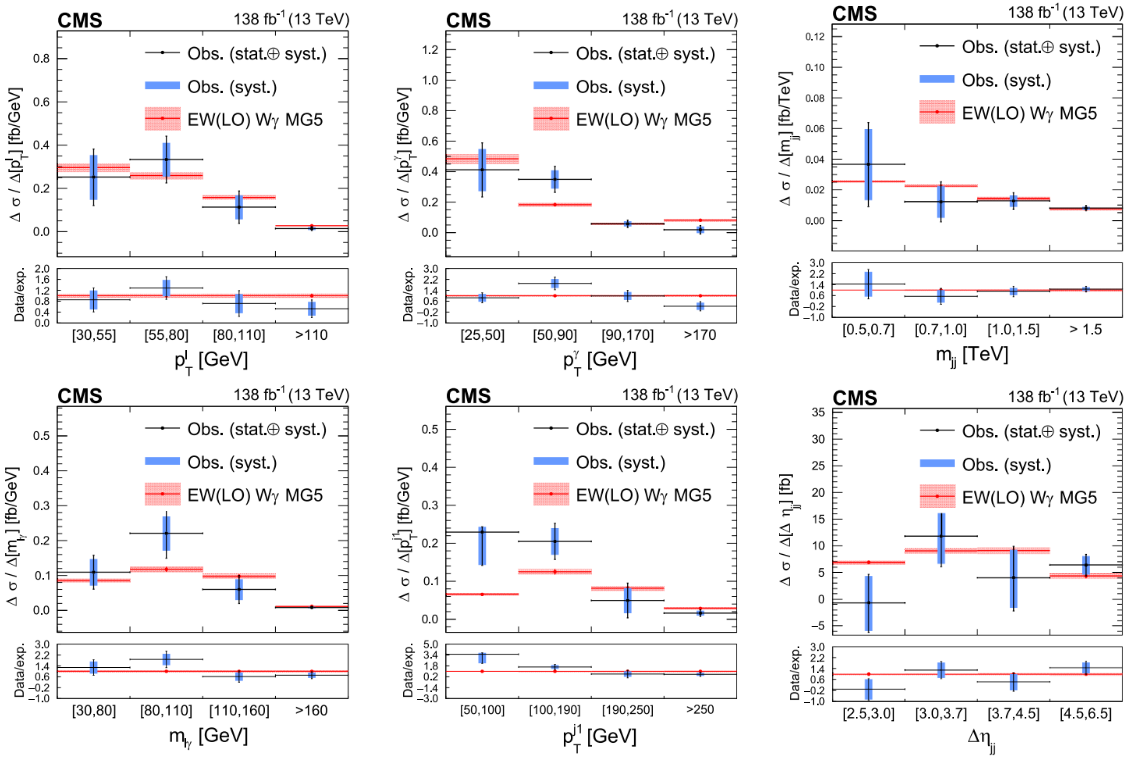


$$\sigma^{\text{fid}}_{\text{EW}} = 23.5 \pm 2.8\,(\text{stat})^{+1.9}_{-1.7}\,(\text{theo})^{+3.5}_{-3.4}\,(\text{syst})\text{ fb}$$

$$\sigma^{\text{fid}}_{\text{EW+QCD}} = 113 \pm 2.0\,(\text{stat})^{+2.5}_{-2.3}\,(\text{theo})^{+13}_{-13}\,(\text{syst})\text{ fb}$$

FIDUCIAL & DIFFERENTIAL CROSS SECTIONS

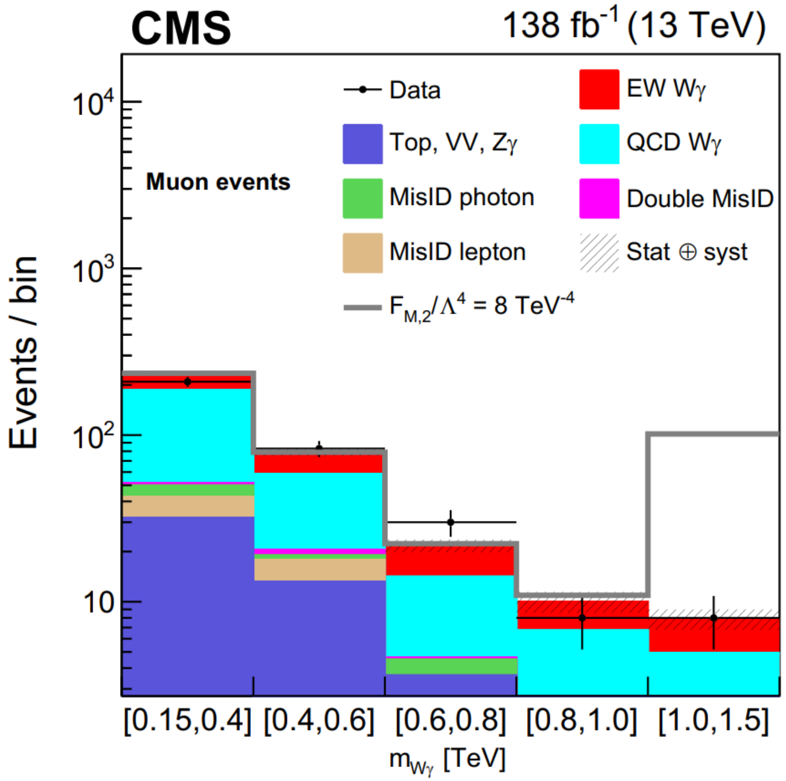
- Several variables unfolded at the generator-level
- Out-of-fiducial signal events are treated as background



EFT interpretation

- VBS processes are particularly sensitive to aQCGs, therefore the EW $W\gamma jj$ signal is suitable to constrain EFT dimension-8 operators (SM-BSM interference term included in the signal definition)

- Because BSM physics is expected to enhance the VBS production in the high-energy regime, **the invariant mass of the $W\gamma$ system $(m_{W\gamma})$ is used to extract limits on EFT operators**



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

Unitarity bound limit derived for each operator (following the formulation discussed here)

Most stringent limits to date on aQGCs parameters

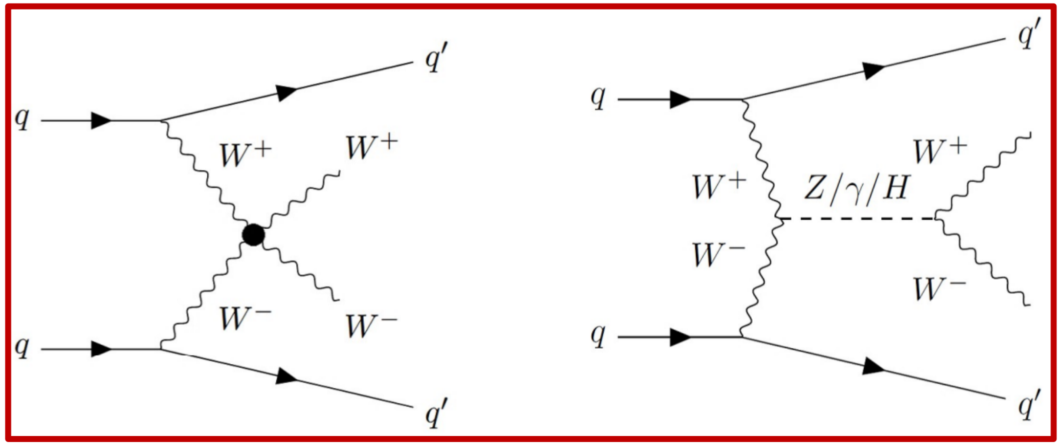
VBS $W^+W^- \rightarrow 2\ell 2\nu$

[Phys.Lett.B 841 (2023) 137495]

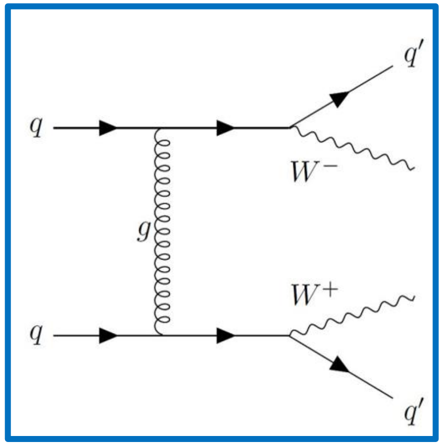
VBS W^+W^-

- The EW W^+W^-jj production plays a special role among VBS processes, as the Higgs boson prevents unitarity violation of $W_L W_L \rightarrow W_L W_L$ scattering
- Nevertheless, this process poses several experimental challenges, mainly because of the **large $t\bar{t}$ background contamination that enters the signal selection**
- **The CMS collaboration has recently published the first observation of this process** in the fully leptonic final state (Run 2 data), and this was confirmed by the ATLAS collaboration as well, although two different strategies have been pursued (see Todd's talk)

EW W^+W^-



QCD W^+W^-

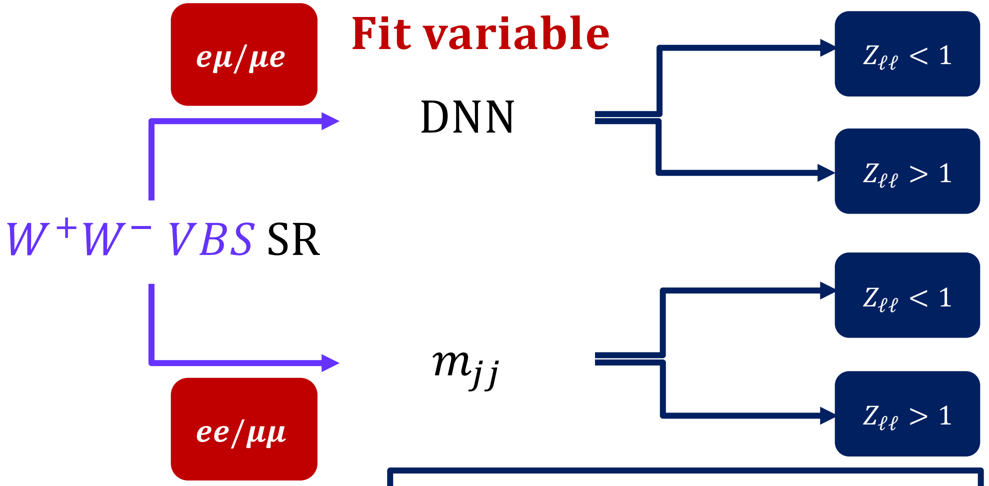


- The signal reconstruction is based on the presence of:
  - **2 VBS jets**
  - **2 opposite-charged leptons (either e or μ)**
  - **Imbalance on the total transverse momentum $\left(p_T^{miss}\right)$**

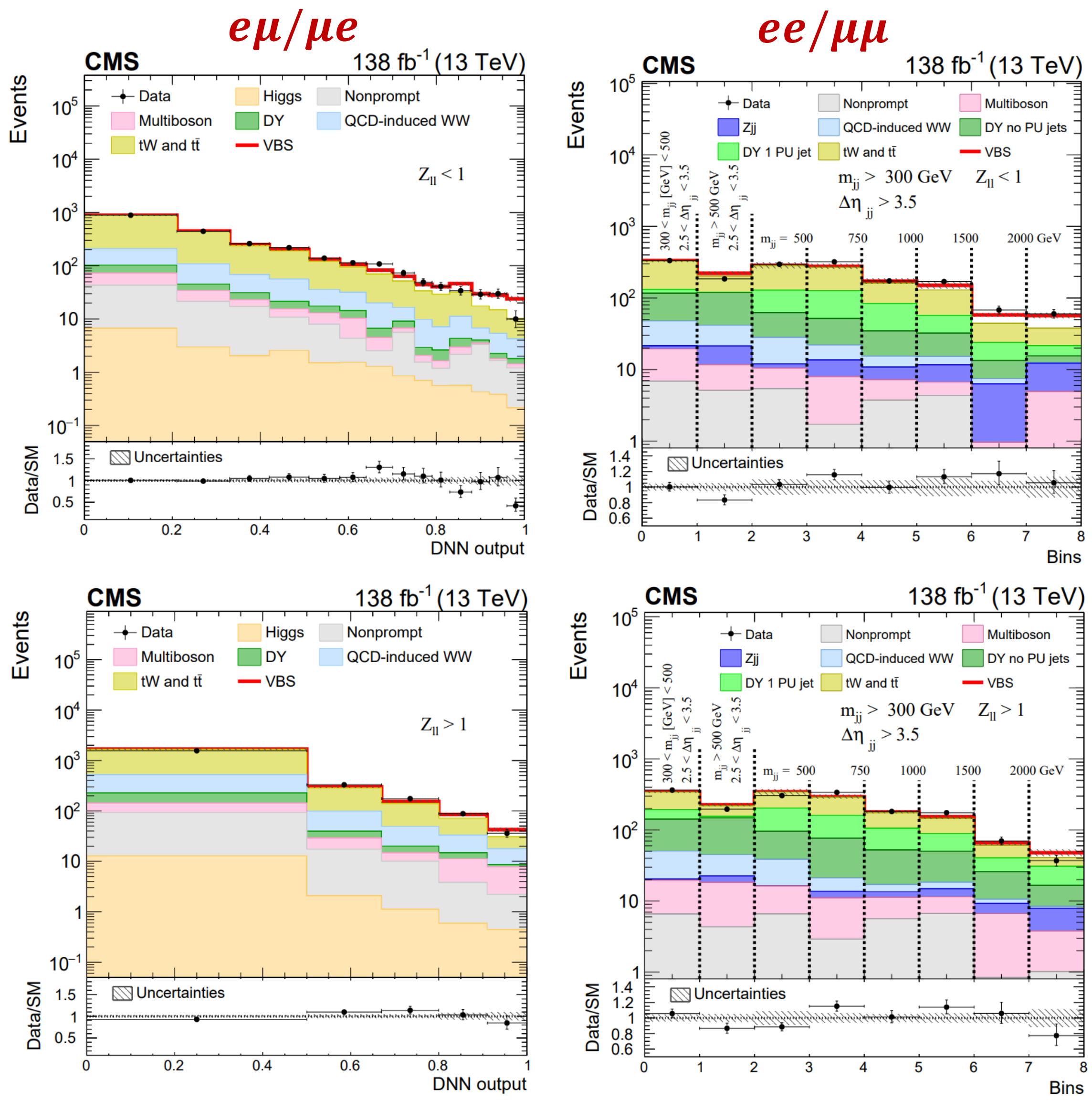
Analysis strategy

- Signal candidates are selected in two SRs:
  - ➢ ***eμ* final state** (dominated by $t\bar{t}$ pair production)
  - ➢ ***ee/μμ* final state** (DY + jets events discarded by imposing $m_{\ell\ell} > 120$ GeV)

- Main background processes ($t\bar{t}$, DY $\rightarrow \tau^+\tau^-/\ell^+\ell^-$) are constrained through dedicated CRs, **QCD W^+W^-jj normalization is measured from SRs**



$$Z_{\ell\ell} \equiv \frac{1}{2}\left|(\eta_{\ell_1} + \eta_{\ell_2}) - (\eta_{j_1} + \eta_{j_2})\right|$$



Results

- **The EW W^+W^- production cross section is measured in two fiducial volumes**, one more inclusive and one closer to the region defined by kinematic requirements applied in the preselection

- In the inclusive phase space, a minimal parton level selection is applied: the two outgoing partons are required to have $p_T > 10$ GeV and an invariant mass $m_{qq'} > 100$ GeV

$$\boldsymbol{\sigma_{incl} = 99 \pm 20\ \mathrm{fb}}$$

$$\boldsymbol{\sigma_{incl}^{theo} = 89 \pm 5\ \mathrm{fb}\ @\mathrm{LO}}$$

- The selection applied in the "exclusive" phase space is shown in the table and mimics the SR

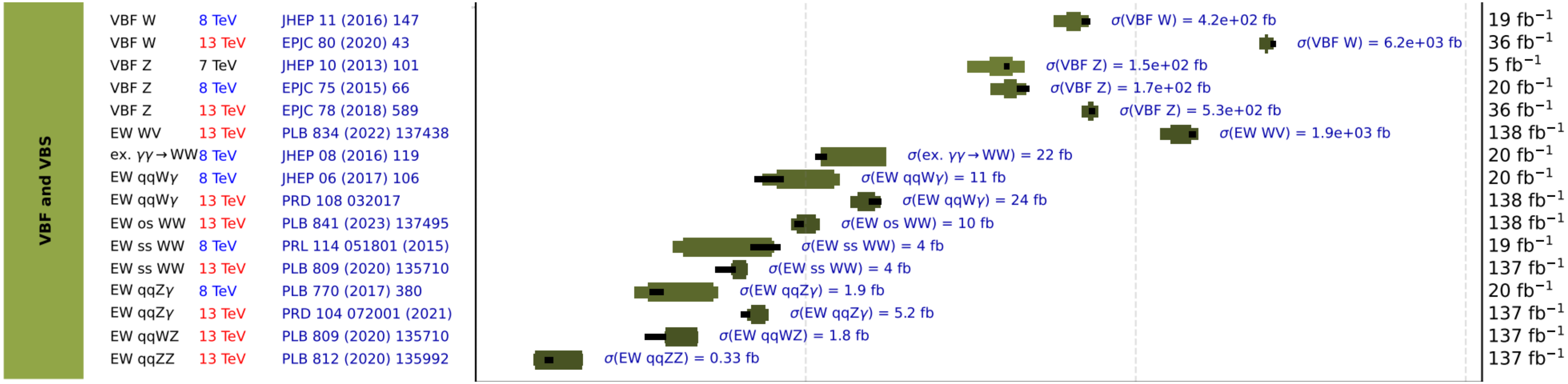
$$\boldsymbol{\sigma_{fid} = 10.2 \pm 2.0\ \mathrm{fb}}$$

$$\boldsymbol{\sigma_{fid}^{theo} = 9.1 \pm 0.6\ \mathrm{fb}\ @\mathrm{LO}}$$

- **The statistical significance with respect to the background-only hypothesis is $\boldsymbol{5.6\ \sigma}$** (5.0 σ expected)

Objects	Requirements
Leptons	eμ, ee, $\mu\mu$ (not from τ decay), opposite charge
	$p_T^{\mathrm{dressed}\,\ell} = p_T^{\ell} + \sum_i p_T^{\gamma_i}$ if $\Delta R(\ell, \gamma_i) < 0.1$
	$p_T^{\ell_1} > 25$ GeV, $p_T^{\ell_2} > 13$ GeV, $p_T^{\ell_3} < 10$ GeV
	$\lvert\eta\rvert < 2.5$
	$p_T^{\ell\ell} > 30$ GeV, $m_{\ell\ell} > 50$ GeV
Jets	$p_T^{j} > 30$ GeV
	$\Delta R(j, \ell) > 0.4$
	At least 2 jets, no b jets
	$\lvert\eta\rvert < 4.7$
	$m_{jj} > 300$ GeV, $\lvert\Delta\eta_{jj}\rvert > 2.5$
p_T^{miss}	$p_T^{miss} > 20$ GeV

Conclusions



- The CMS collaboration has been very prolific in the context of EW precision physics throughout the years, and the **VBS mechanism is an exceptional tool to push the SM to its far range of validity**
- Most of **VBS analyses** are still statistically limited, therefore they **will greatly benefit from the new data that are being collected by the LHC**, opening the path to differential measurements and combinations among different channels
- A lot of work is still in progress, so stay tuned for upcoming results!

BACKUP

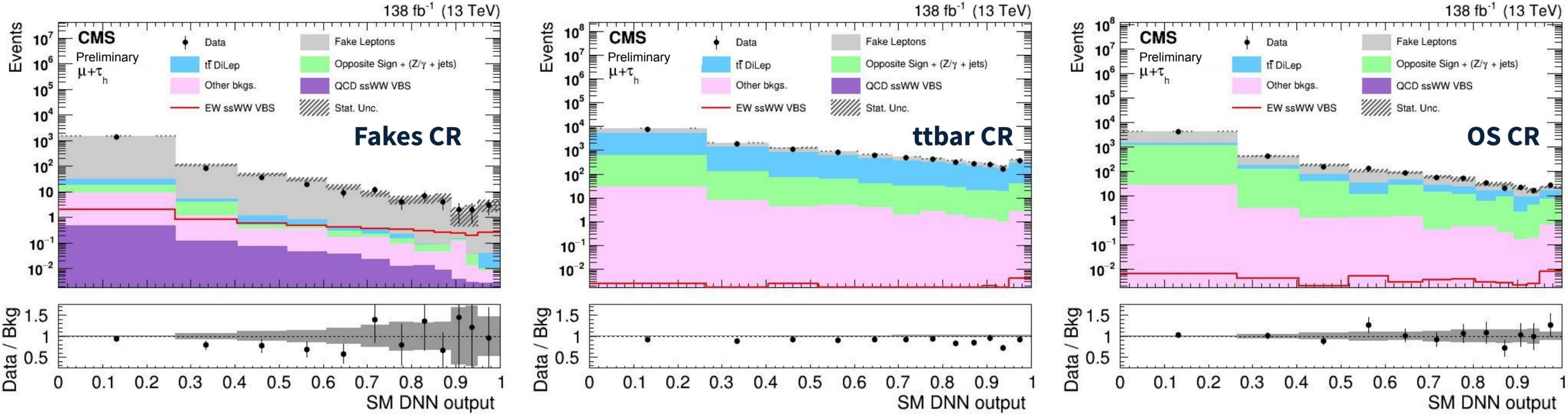
VBS $W^{\pm}W^{\pm} \rightarrow \tau_h \nu_\tau \ell \nu$

DNN input variables

- M_{jj} — **VBS jet pair invariant mass**
- $M_T\left(\ell, \vec{p}_T^{miss}\right)$ — **Transverse mass between ℓ and p_T^{miss}**
- $M_{1T}^2 \equiv \left(\sqrt{M_{\tau_h\ell}^2 + p_{T,\tau_h\ell}^2} + p_T^{miss}\right)^2 - \left|\vec{p}_{T,\tau_h\ell} + \vec{p}_T^{miss}\right|^2$ — **Transverse mass between the $\tau_h + \ell$ system and p_T^{miss}**
- $M_{\circ T}^2 \equiv \left(p_{T,\tau_h} + p_{T,\ell} + p_T^{miss}\right)^2 - \left|\vec{p}_{T,\tau_h} + \vec{p}_{T,\ell} + \vec{p}_T^{miss}\right|^2$ — **Transverse mass of the three objects, obtained after projecting them in a reference frame where the $\tau_h + \ell$ momenta has a null invariant mass**
- $p_{T,j_1},\ p_{T,j_2},\ p_{T,\tau_h},\ p_{T,\ell}$ — **p_T of leading and sub-leading VBS jet, τ_h and ℓ**
- $\dfrac{p_{T,\tau_h}(\text{track})}{p_{T,\tau_h}}$ — **Ratio between the leading track p_T associated to the τ_h and p_{T,τ_h}**

VBS $W^{\pm}W^{\pm} \rightarrow \tau_h \nu_\tau \ell \nu$

CONTROL REGIONS

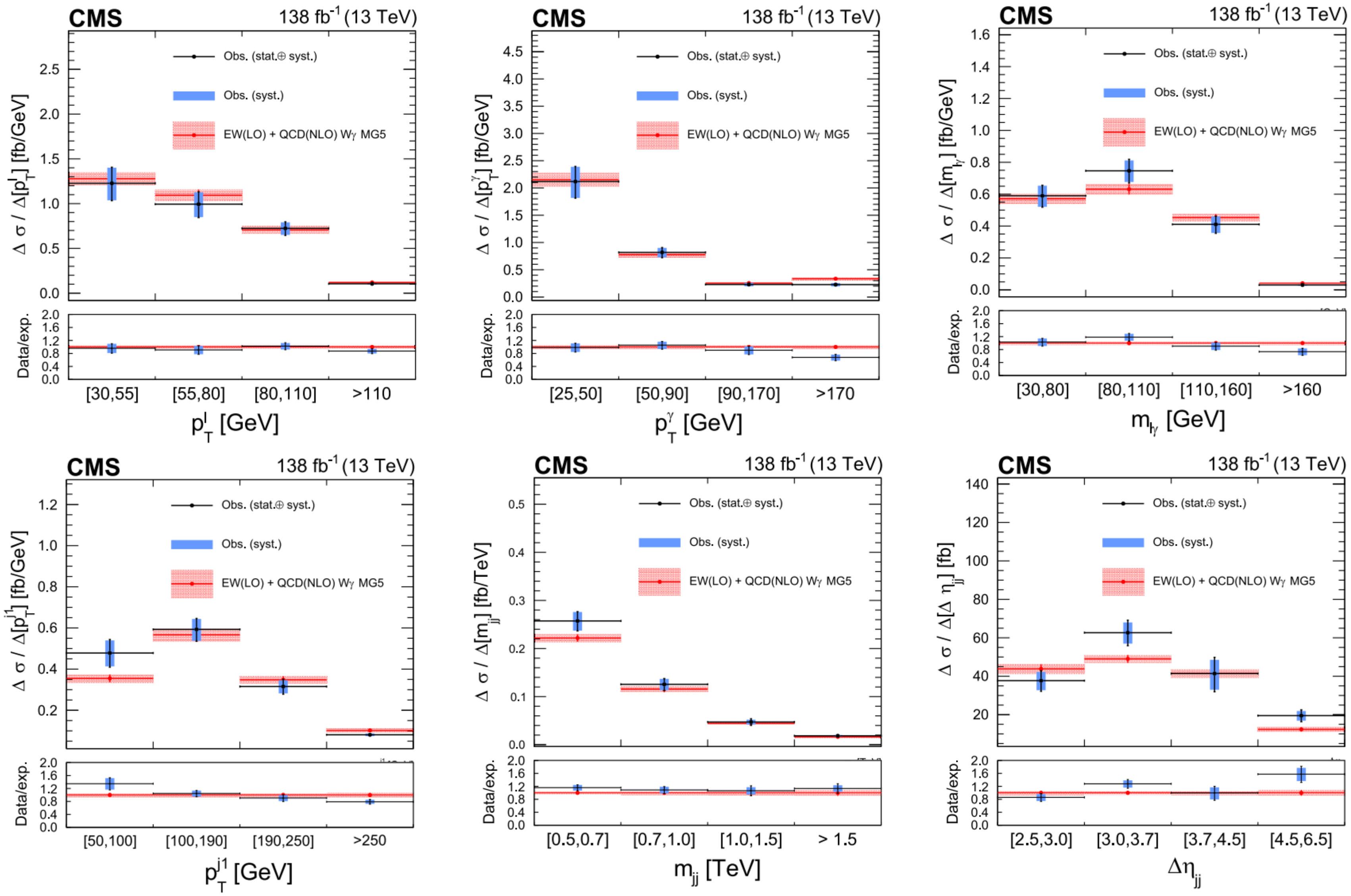


VBS $W^{\pm}W^{\pm} \rightarrow \tau_h \nu_\tau \ell \nu$

UNCERTAINTIES

Uncertainty source	$+\Delta\mu$	$-\Delta\mu$
Theory (PDF, QCD-scale, ISR, and FSR)	+0.157	−0.099
Non-prompt estimation	+0.136	−0.125
$t\bar{t}$ normalization	+0.051	−0.023
Prefiring	+0.105	−0.059
Luminosity	+0.079	−0.092
b-tagging and mistagging	+0.007	−0.004
Jet energy scale and resolution, Pile-up jet ID	+0.079	−0.097
Pileup	+0.152	−0.162
LO-to-NLO VBS corrections	+0.043	−0.025
Unclustered energy	+0.003	−0.010
Hadronic tau energy scale and DEEPTAU	+0.154	−0.152
Charge misidentification	+0.005	−0.010
Lepton reconstruction, identification, and isolation	+0.005	−0.024
MC statistical	+0.324	−0.322
Total systematic uncertainty	+0.344	−0.302
Data statistical uncertainty	+0.522	−0.477
Total uncertainty	+0.625	−0.564

VBS $W\gamma \rightarrow \ell\nu\gamma$

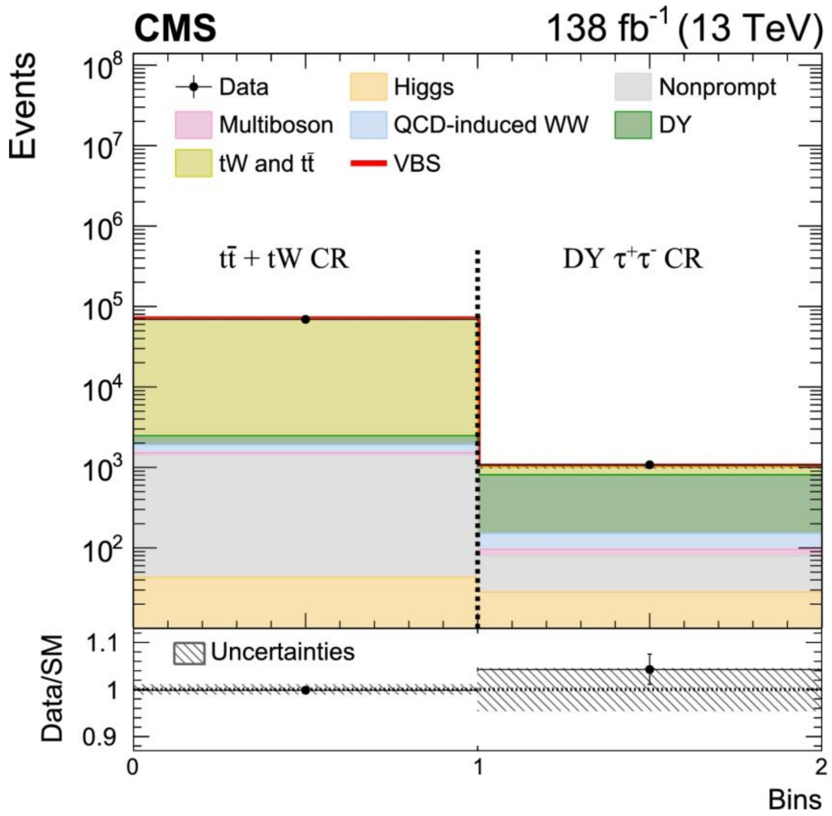


- **Differential cross section measurements unfolded at generator level**
- **EW and QCD contributions are scaled together during the fit procedure**

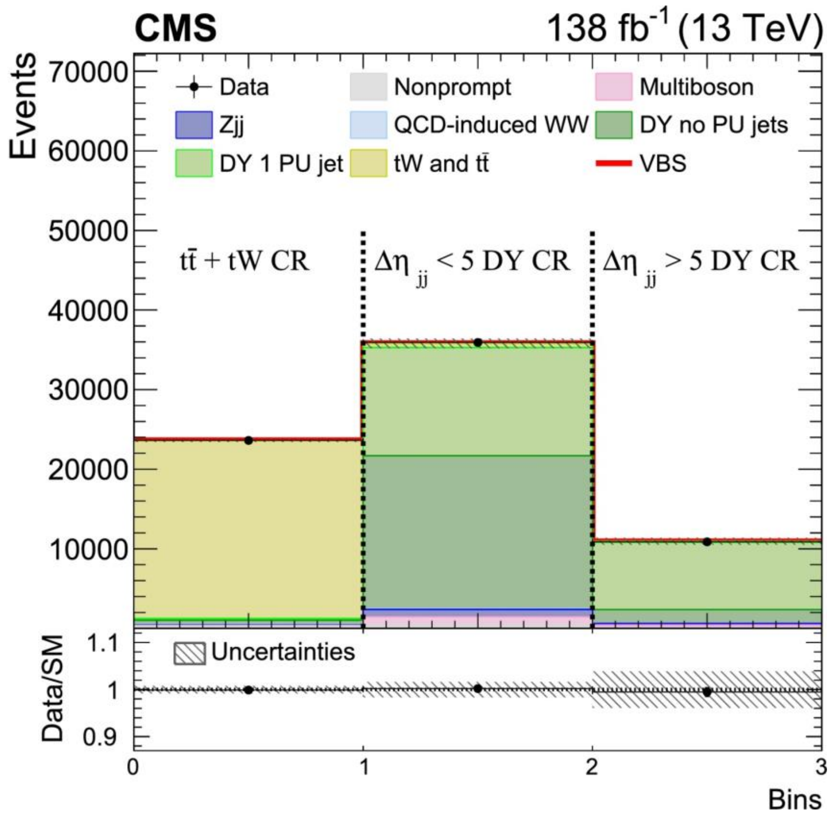
VBS $W^+W^- \to 2\ell2\nu$

CONTROL REGIONS

$e\mu/\mu e$



$ee/\mu\mu$



VBS $W^+W^- \to 2\ell 2\nu$

UNCERTAINTIES

Uncertainty source	Value
QCD-induced W^+W^- normalization	5.3%
$t\bar{t}$ scale variation	5.1%
VBS signal scale variation	5.0%
$t\bar{t}$ normalization	4.9%
b tagging	3.5%
Trigger corrections	3.3%
DY normalization	2.9%
Jet energy scale + resolution	2.6%
Unclustered p_T^{miss}	2.4%
QCD-induced W^+W^- scale variation	2.1%
Integrated luminosity	2.0%
Muon efficiency	2.0%
Pileup	1.8%
Electron efficiency	1.5%
Underlying event	1.3%
Parton shower	1.0%
Other	<1%
Total systematic uncertainty	13.1%
Total statistical uncertainty	14.9%
Total uncertainty	19.8%

OTHER PLOTS

$e\mu/\mu e$ *VBS SR*