Vector boson scattering results in CMS

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on behalf of the CMS Collaboration

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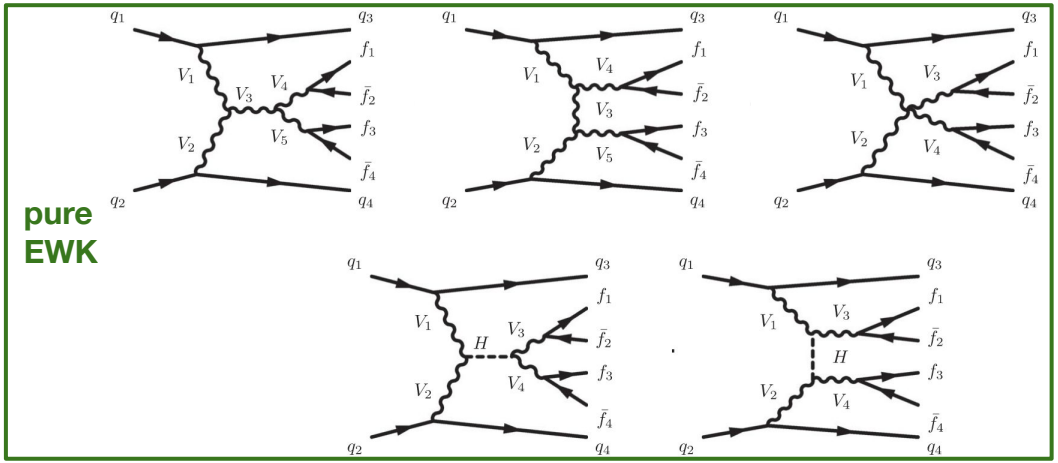
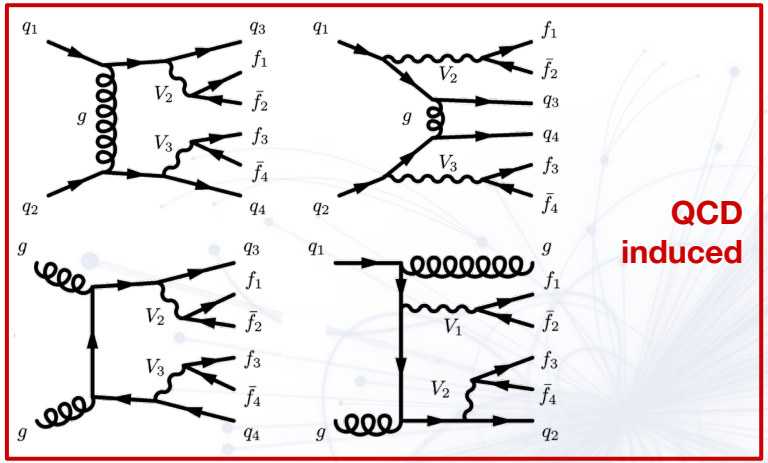
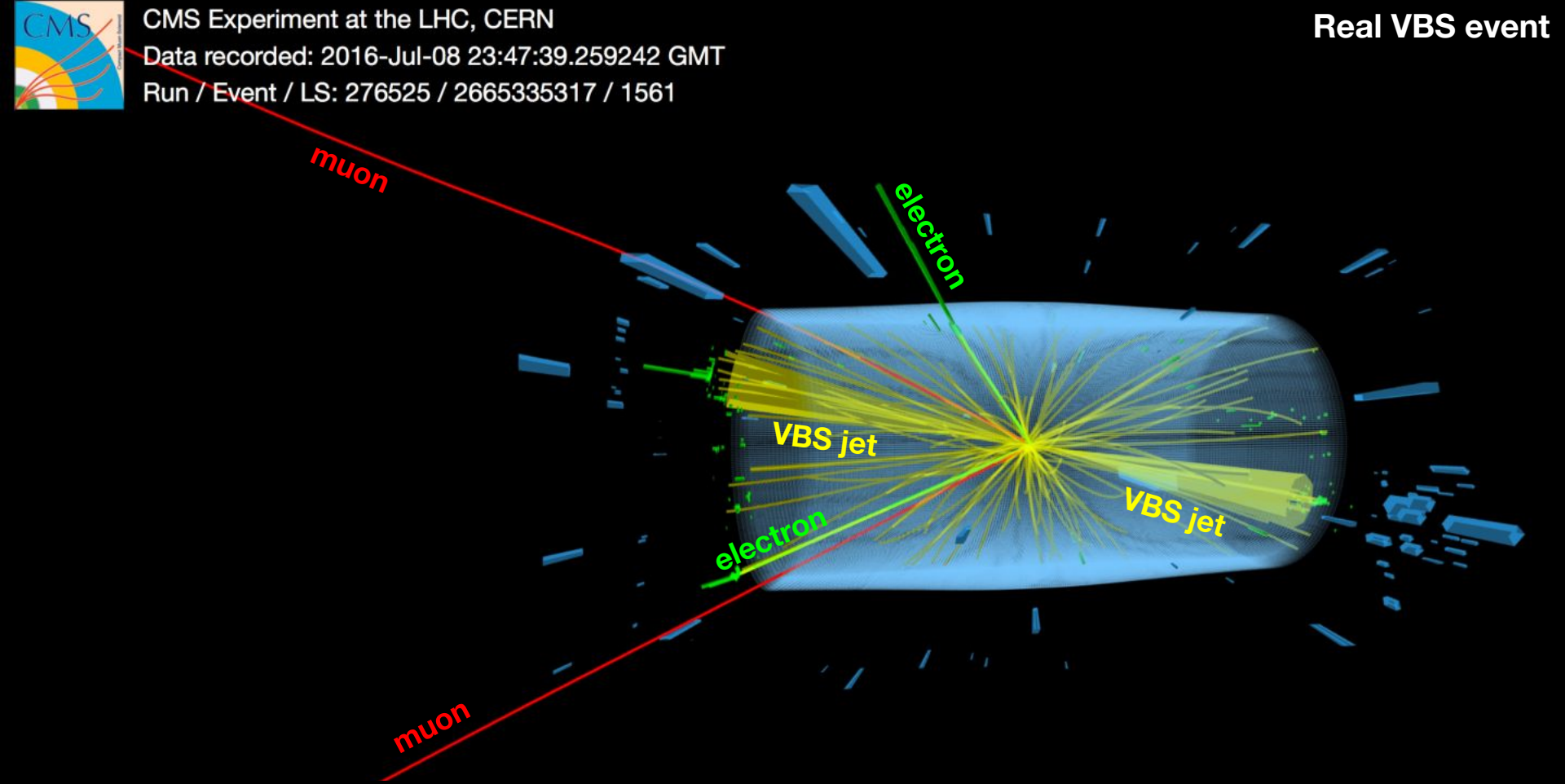
What is VBS?

- **Scattering of two Electroweak (EWK) Vector Boson (W, Z)**
  - Triple and Quartic Gauge Couplings (TGC/QGC)
- "Fermionic" final state at LO
  - Two jets coming from initial state quark after Vs emission
  - Four fermions coming from the scattered Vs
- Three possible contributions
  - pure EWK $O(\alpha_{EW}^{6})$ - **signal**
  - QCD-induced $O(\alpha_{EW}^{4}\,\alpha_{S}^{2})$ - **irreducible contribution**
  - EWK-QCD interference $O(\alpha_{EW}^{5}\,\alpha_{S})$

- Peculiar experimental signature
  - Two very energetic forward-backward jets → **VBS jets**
    - Large m_{jj} and $\Delta\eta_{jj}$
  - Hadronic activity suppressed between the two jets → **rapidity gap**
- Main reducible background due to nonprompt leptons
  - QCD-induced jets misreconstructed as charged leptons
  - Usually estimated with data-driven methods
- Machine-Learning discriminator to enhance signal sensitivity

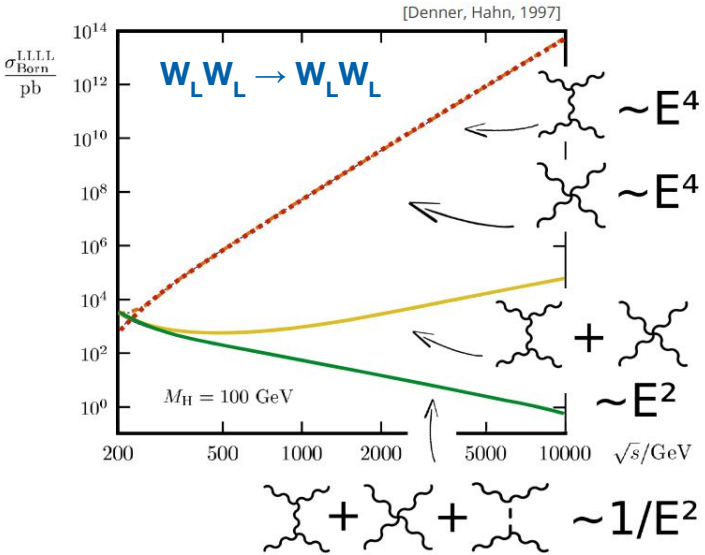




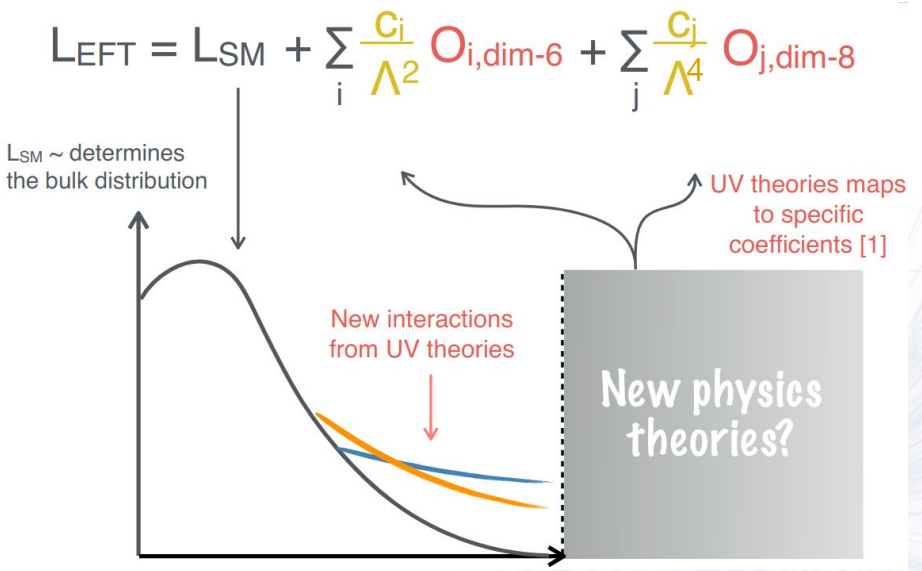

CMS Experiment at the LHC, CERN
Data recorded: 2016-Jul-08 23:47:39.259242 GMT
Run / Event / LS: 276525 / 2665335317 / 1561
Real VBS event
muon
electron
VBS jet
VBS jet
electron
muon

Why study VBS?

- **Key process to probe EW Symmetry Breaking (EWSB)**
  - Higgs-like field necessary to preserve unitarity
    Only investigable in VV scattering
  - Complimentary to Higgs-sector studies
- General test of the EW sector in SM
- Background wrt other signals with similar final state

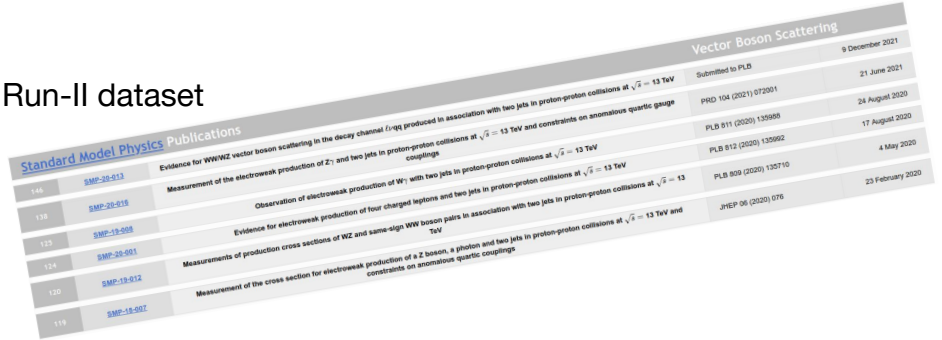


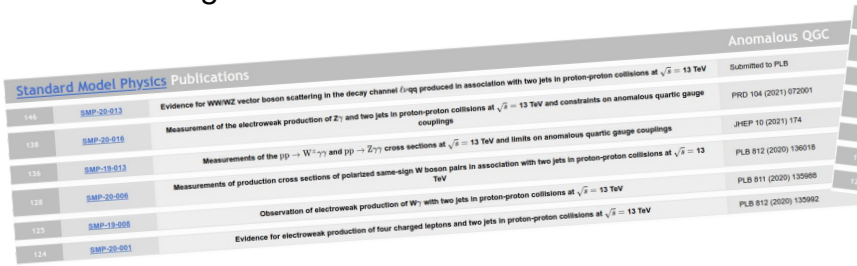
- Higgs affecting VBS processes → **New Physics!**
  - Suitable to investigate indirect NP effects
    - anomalous Triple/Quartic Gauge Coupling **(aTGC/aQGC)**
    - **EFT** approach (dim6 and dim8) - model independent
  - Direct search for new resonances
    - new Higgs states, e.g. $H^{\pm}$ and $H^{\pm\pm}$

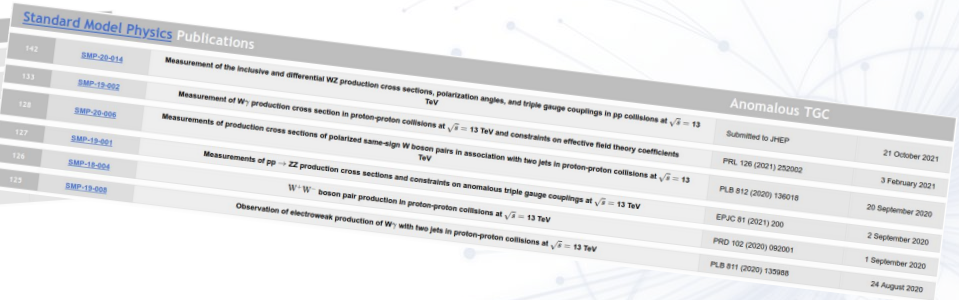


VBS measurements in CMS

- **Big experimental effort** to investigate VBS processes with full Run-II dataset
  - Inclusive cross-section measurements
  - Differential cross-section wrt different variables
  - Indirect search for New Physics within the EFT framework
- Several final state analyzed
  - **Fully-leptonic** → very clean final state
  - **Semileptonic**/fully-hadronic → more suitable for aQGC searches
  - Photonic → clean, but with larger background
- Outstanding results with the full Run-II dataset
  - **Observation of leptonic WZ diboson and VBS - SMP-20-014, SMP-19-012**
  - **Observation of leptonic W^+W^- scattering - SMP-21-001**
  - **Observation of semileptonic WV scattering - SMP-21-013**
  - Observation of polarized scattering $W^\pm W^\pm$ - SMP-20-006
  - Observation of Zγ scattering - SMP-20-016
  - …and the tightest limits on EFT coefficients!



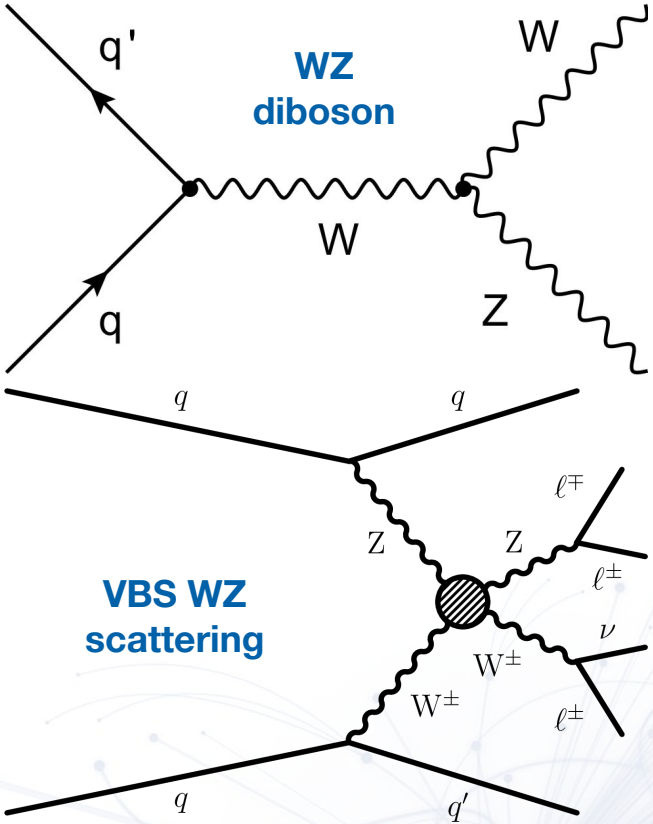




Leptonic WZ: overview

SMP-20-014 - Submitted to *JHEP* (diboson)
SMP-19-012 - *Phys. Lett. B 809 (2020)* (VBS)

- Push (very) forward the **knowledge of WZ** in leptonic channel
  - Very important for several SM-related studies
  - High statistical power, very clean final state
- Several investigation performed (with the full Run-II dataset)
  - Inclusive cross-section measurement (**diboson and VBS**)
  - Charge asymmetry (**diboson**)
  - W/Z boson polarization fraction (**diboson**)
  - Search for anomalous couplings within the EFT framework
    dim8 with VBS, dim6 with diboson (in backup)
  - Differential cross-sections for the most interesting observables (in backup)
- Event categorization to optimize signal vs. backgrounds discrimination
  - Lepton selected with a dedicated prompt-vs-nonprompt BDT
- Control Regions to separately to take care of the main backgrounds
  - Nonprompt background estimated with the data-driven *fakeable method*
  - ZZ, Zγ and tVX estimated with dedicated Monte-Carlo (MC) simulations



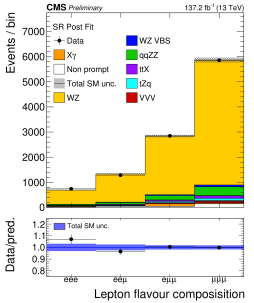
Region	N_ℓ	$p_T\{\ell_{Z1}, \ell_{Z2}, \ell_W, \ell_4\}$	N_{OSSF}	$\lvert M(\ell_{Z1}, \ell_{Z2}) - m_Z \rvert$	p_T^{miss}	N_{btag}	$\min(M(\ell\ell'))$	$M(\ell_{Z1}, \ell_{Z2}, \ell_W)$
SR	=3	>{25, 10, 25} GeV	≥1	<15 GeV	>30 GeV	=0	>4 GeV	>100 GeV
CR-$t\bar{t}Z$	=3	>{25, 10, 25} GeV	≥1	<15 GeV	>30 GeV	>0	>4 GeV	>100 GeV
CR-ZZ	=4	>{25, 10, 25, 10} GeV	≥1	<15 GeV	-	=0	>4 GeV	>100 GeV
CR-conv	=3	>{25, 10, 25} GeV	≥1	-	≤30 GeV	=0	>4 GeV	<100 GeV

Leptonic WZ: diboson measurements

Total cross-section

- Fit to lepton flavour distribution performed in CRs + SR
  - Main backgrounds let free to float
- Signal strength estimated both for each final state and inclusively
- Cross-section measurement extrapolated from SR to a Fiducial (detector-independent) Region
- Inclusive measurement (in FR)

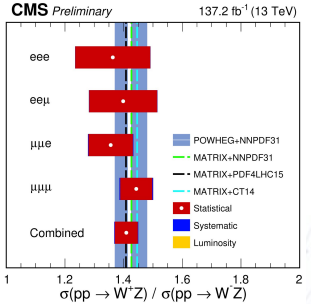
  298.9 ± 4.8 (stat.) ± 7.7 (syst.) ± 5.4 (lumi.) ± 2.7 (theo.) fb



Charge asymmetry

- Similar fit strategy applied for total cross-section measurement
  - Distributions divided upon final state total charge (**W^+Z** and **W^-Z**)
- Consistency with PDF uncertainties verified with Bayesian reweighting techniques
  - p-value = 0.747
- Charge asymmetry estimated in FR

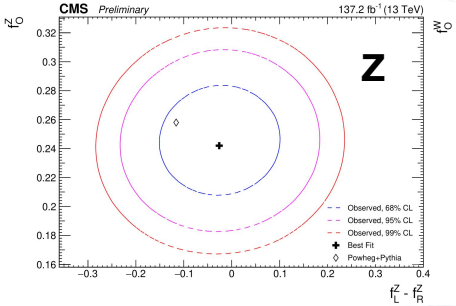
  1.41 ± 0.04 (stat.) ± 0.01 (syst.) ± 0.01 (lumi.)

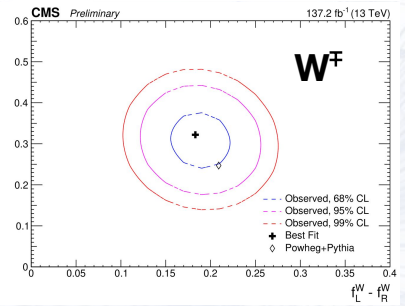


Boson polarization

- W/Z polarization measured in the **helicity frame** (first time)
  - Polarization components estimated at generator-level
  - Simultaneous fit with every polarization
- Observation of longitudinally polarized W and Z

  Observed L-polarized W (Z) significance: 5.6σ (>9.0σ)





Leptonic WZ: VBS measurement

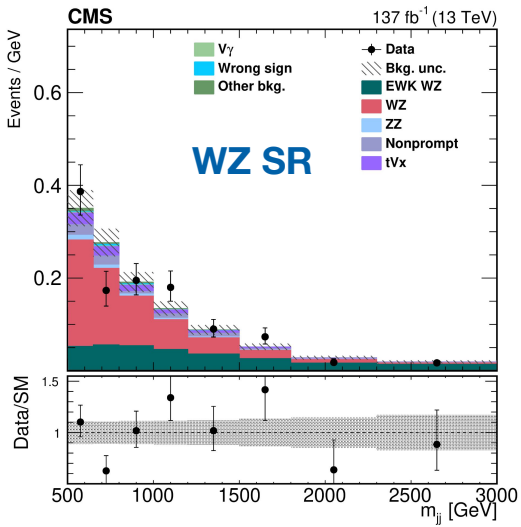
- Event categorization as diboson
  - Zeppenfeld variable used to enhance VBS sensitivity

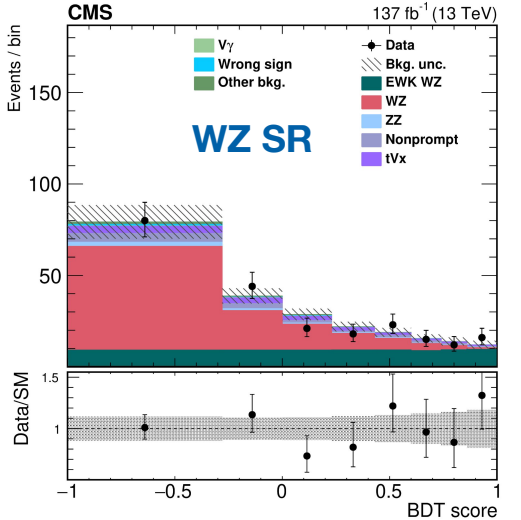
$$z_\ell^* = \left| \eta^\ell - \frac{\eta^{j_1} + \eta^{j_2}}{2} \right| / |\Delta\eta_{jj}| \qquad \text{maximum } < 1.0$$

- BDT model to discriminate pure EWK against QCD-induced process
- Fit to m_{jj} in CRs and BDT output in SR
- **Observation of pure EWK WZ scattering!**
  - Observed significance = **6.8σ**
  - Observed fiducial cross-section

    σ_{EWK} = 1.81 ± 0.39 (stat) ± 0.14 (syst) fb
  - LO (NLO) theoretical prediction

    σ_{th} = 1.41 ± 0.21 (1.24 ± 0.18) fb





Leptonic WZ VBS: anomalous Quartic Gauge Coupling

- Search for **New Physics** in WZ scattering with **EFT approach**
  - Process suitable to study **EFT dim8** operator (→ **aQGC** effect)
  - Set of operators $O_{X,Y}$ from Eboli's basis
- **CL limits on $f_{X,Y}$** coefficients extracted via likelihood scan
  - EFT effect separately simulated for each operator
  - 2D fit to m_{jj} and m_T (WZ) with one $O_{X,Y}$ operator at time
  - **Most stringent limits** in this channel up to date
- **Unitarity bound Λ_U** estimated for each operator
  - $\Lambda_{EFT} > \Lambda_U$ → unitarity-violating scattering amplitude!
  - Applied to EFT effects on physical distribution with **clipping technique**
  - Make limits less stringent

Only Higgs doublet

$$\mathcal{O}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right]$$
$$\mathcal{O}_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]$$

Only EWK field strengths

$$\mathcal{O}_{T,0} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\widehat{W}_{\alpha\beta}\widehat{W}^{\alpha\beta}\right]$$
$$\mathcal{O}_{T,1} = \mathrm{Tr}\left[\widehat{W}_{\alpha\nu}\widehat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\widehat{W}_{\mu\beta}\widehat{W}^{\alpha\nu}\right]$$
$$\mathcal{O}_{T,2} = \mathrm{Tr}\left[\widehat{W}_{\alpha\mu}\widehat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\widehat{W}_{\beta\nu}\widehat{W}^{\nu\alpha}\right]$$

Higgs doublet and EWK field strengths

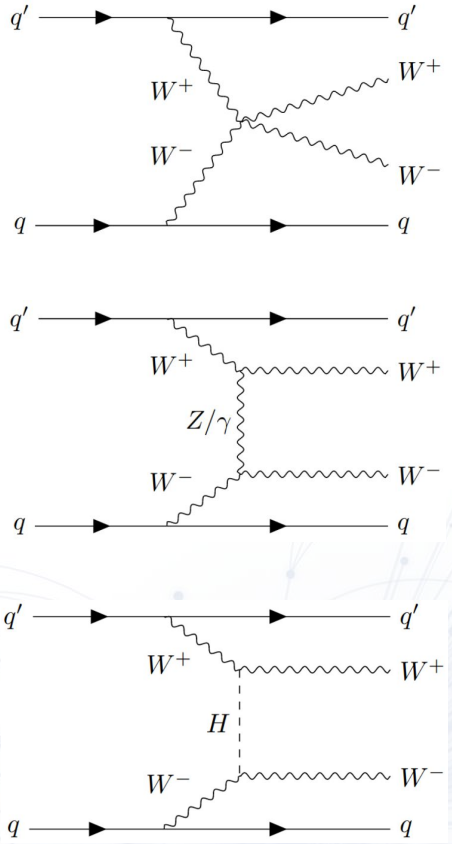
$$\mathcal{O}_{M,0} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$
$$\mathcal{O}_{M,1} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$
$$\mathcal{O}_{M,6} = \left[\left(D_\mu\Phi\right)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\nu}D^\mu\Phi\right]$$
$$\mathcal{O}_{M,7} = \left[(D_\mu\Phi)^\dagger \widehat{W}_{\beta\nu}\widehat{W}^{\beta\mu}D^\nu\Phi\right]$$

	Observed (WZ) (TeV^{-4})	Observed (WZ) (TeV^{-4})
f_{T0}/Λ^4	[-0.62, 0.65]	[-1.6, 1.9]
f_{T1}/Λ^4	[-0.37, 0.41]	[-1.3, 1.5]
f_{T2}/Λ^4	[-1.0 , 1.3]	[-2.7, 3.4]
f_{M0}/Λ^4	[-5.8, 5.8]	[-16, 16]
f_{M1}/Λ^4	[-8.2, 8.3]	[-19, 20]

	Observed (WZ) (TeV^{-4})	Observed (WZ) (TeV^{-4})
f_{M6}/Λ^4	[-12, 12]	[-34, 33]
f_{M7}/Λ^4	[-10, 10]	[-22, 22]
f_{S0}/Λ^4	[-19, 19]	[-83, 85]
f_{S1}/Λ^4	[-30, 30]	[-110, 110]

Leptonic W^+W^- scattering: overview
SMP-21-001 - Approved

- **First cross-section measurement in this channel for the pure EW process!**
  - **Rare SM process** - irreducible background from QCD-mediated process
  - Measurement performed with the full Run-II dataset
- Event categorization based upon the lepton pair flavour
  - Different flavour (DF) - eμ pair
  - Same flavour (SF) - ee/μμ pair
- Deep Neural Network developed to discriminate signal vs backgrounds
  - Exploited in the DF final state
- Control Regions to separately estimate main backgrounds in the fit
  - top-antitop pair and associated tW productions estimated with simulations
  - Drell-Yan → ττ → leptons data-driven, Drell-Yan → ee/μμ simulation-based
  - Nonprompt leptons estimated with data-driven *fakeable method*



VBS	$e\mu/\mu e$	$Z_{\ell\ell} < 1$	$m^T > 60$ GeV $m^{\ell\ell} > 50$ GeV no bjet with $p_T > 20$ GeV
		$Z_{\ell\ell} \geq 1$	
	ee	$Z_{\ell\ell} < 1$	$m^{\ell\ell} > 120$ GeV $E_T^{miss} > 60$ GeV no bjet with $p_T > 20$ GeV
		$Z_{\ell\ell} \geq 1$	
	$\mu\mu$	$Z_{\ell\ell} < 1$	
		$Z_{\ell\ell} \geq 1$	

top	$e\mu/\mu e$	$m^{\ell\ell} > 50$ GeV no bjet with $p_T > 20$ GeV
	ee	$m^{\ell\ell} > 120$ GeV $E_T^{miss} > 60$ GeV at least one bjet with $p_T > 20$ GeV
	$\mu\mu$	

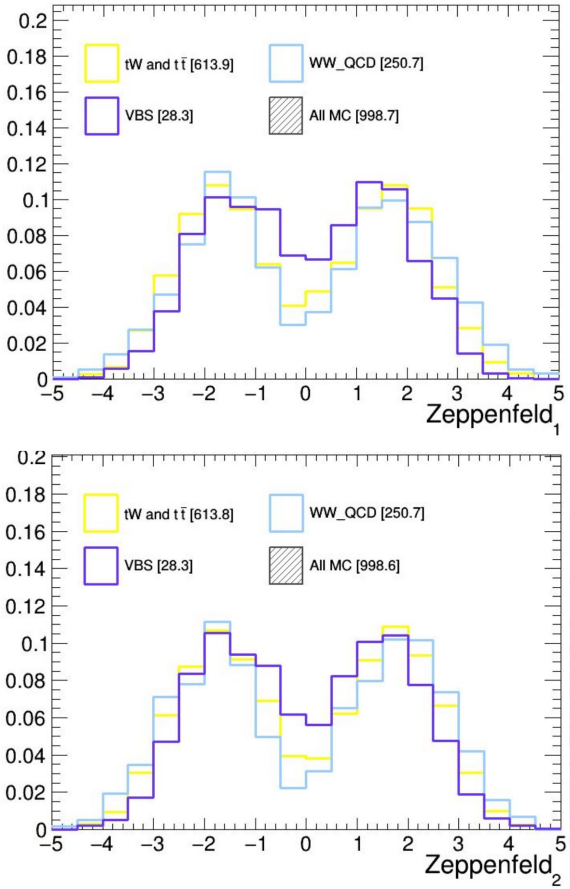
DY	$e\mu/\mu e$	$m^T < 60$ GeV 50 GeV$< m^{\ell\ell} <$ 80 GeV no bjet with $p_T > 20$ GeV	
	ee	$\Delta\eta_{jj} < 5$	$\lvert m^{\ell\ell} - m_Z \rvert < 15$ GeV $E_T^{miss} > 60$ GeV no bjet with $p_T > 20$ GeV
		$\Delta\eta_{jj} \geq 5$	
	$\mu\mu$	$\Delta\eta_{jj} < 5$	
		$\Delta\eta_{jj} \geq 5$	

Leptonic W^+W^- scattering: statistical analysis strategy

- Fit to the most discriminating variabile in **SR**
  - Splitted in two sub-regions upon the **Zeppenfeld variable**

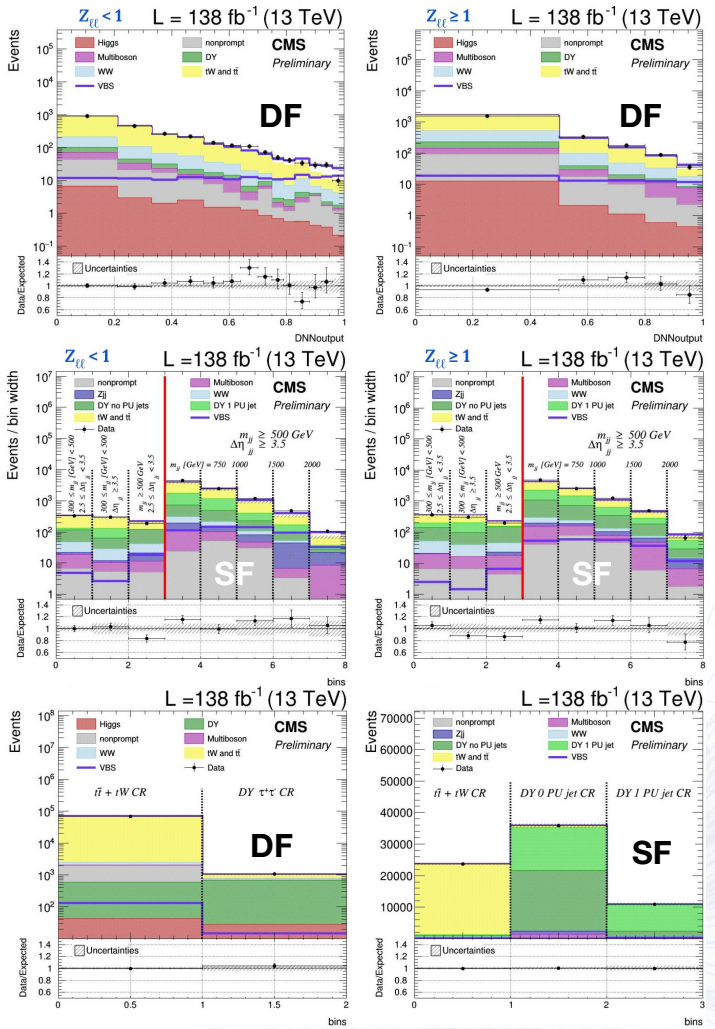
$$Z_{\ell\ell} = \frac{1}{2}|Z_{\ell_1} + Z_{\ell_2}|, \quad \text{where } Z_{\ell_i} = \eta_{\ell_i} - \frac{1}{2}(\eta_{j_1} + \eta_{j_2})$$ **separation at $|Z_{ll}| = 1$**

  - DF → DNN output
    - One model for each Zeppenfeld sub-region
  - SF → divided in four m_{jj} - $\Delta\eta_{jj}$ bins
    - $2.5 < \Delta\eta_{jj} < 3.5$ and $300\ \text{GeV} < m_{jj} < 500\ \text{GeV}$ → **number of events**
    - $2.5 < \Delta\eta_{jj} < 3.5$ and $m_{jj} > 500\ \text{GeV}$ → **number of events**
    - $\Delta\eta_{jj} > 3.5$ and $300\ \text{GeV} < m_{jj} < 500\ \text{GeV}$ → **number of events**
    - $\Delta\eta_{jj} > 3.5$ and $m_{jj} > 500\ \text{GeV}$ → **m_{jj} distribution**
- Simultaneous fit in **CRs** to **number of events**
  - Constrain normalization of main backgrounds
  - Three Drell-Yan subsamples to take under control the corresponding peculiarities
    - Drell-Yan → ττ → leptons
    - Drell-Yan without Pileup-induced jets
    - Drell-Yan with 1 Pileup-induced jet



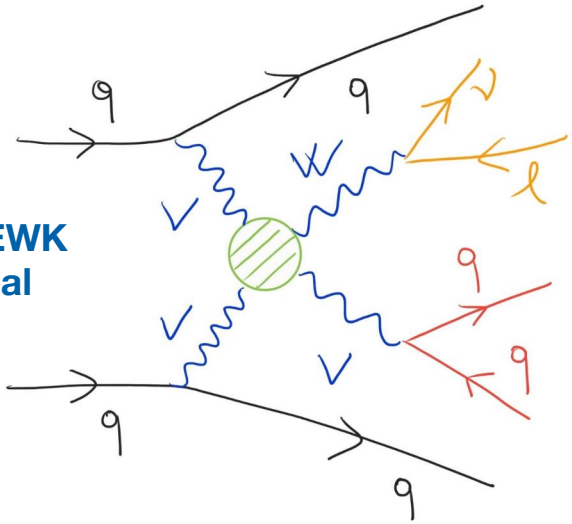
Leptonic W^+W^- scattering: results

- Observed signal significance
  5.6σ → First observation ever!
- Inclusive signal strength
  1.12 ± 0.17 (stat) ± 0.14 (syst) ± 0.07 (theo)
- Measured cross-section extrapolated to Fiducial Region
  - σ_{EWK} = **10.2 ± 2.0 fb** (LO prediction: 9.1 ± 0.6 fb)

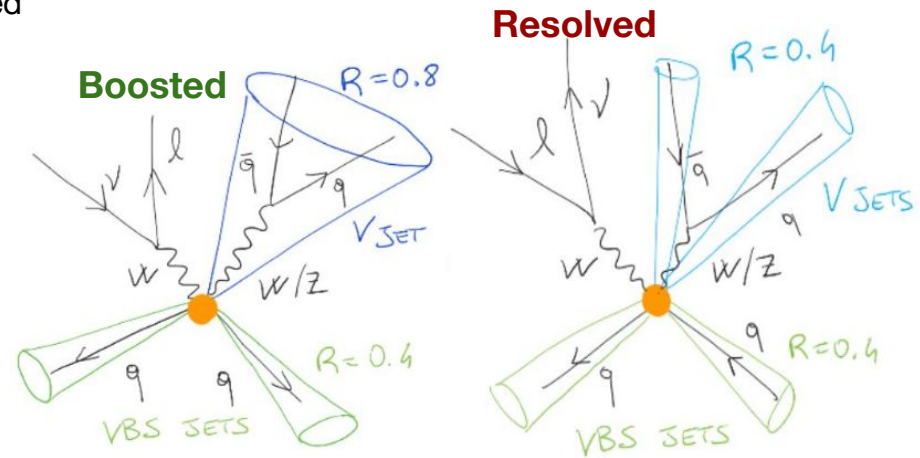


Semileptonic WV scattering: overview

SMP-20-013 - Approved arXiv:2112.05259



- **First evidence of the SM process at LHC!**
  - Performed with the full Run-II dataset - Submitted to PLB
- **WV scattering** in semileptonic channel
  - one V boson decays leptonically and the other hadronically
  - irreducible contribution from QCD-induced process
- **Resolved** and **boosted** hadronic boson decay regimes considered
  - Events separately categorized
- Big efforts to properly estimate backgrounds (more in backup)
  - DNN signal-vs-background discriminator in both categories
  - Dedicated Control Regions to costrain main sources



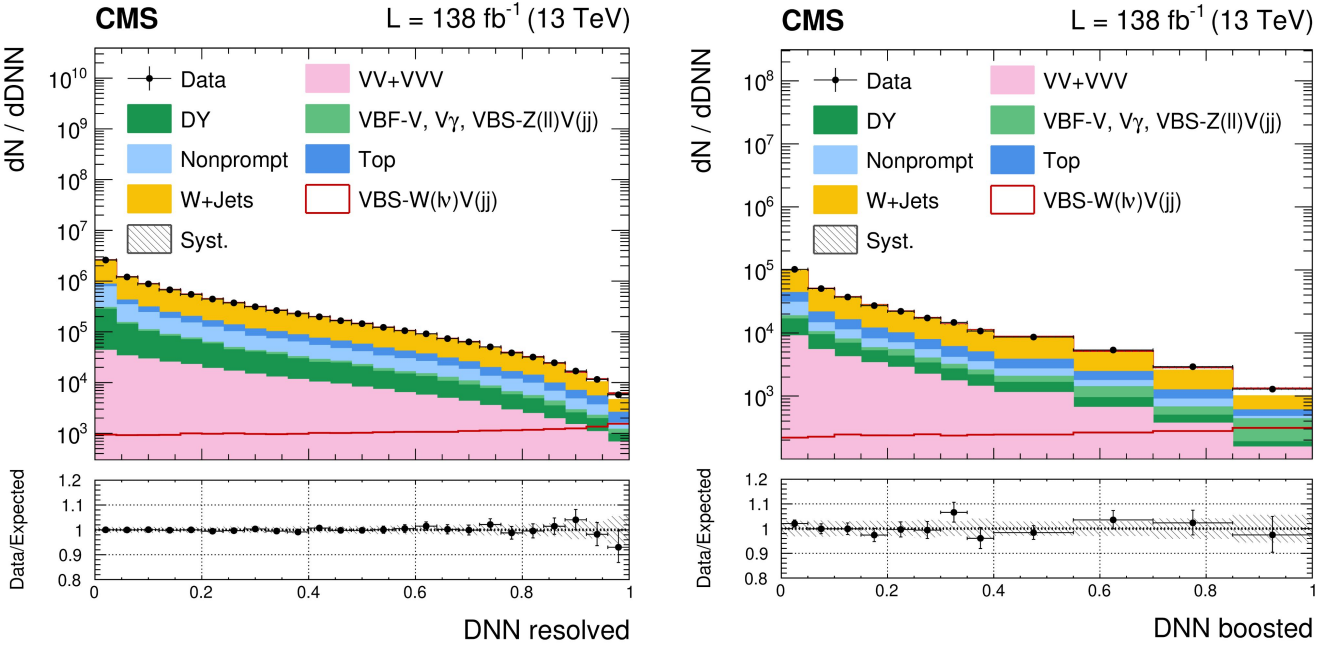
Semileptonic WV scattering: statistical analysis

Simultaneous fits in all the regions

- Performed both for **pure EWK** and **EWK+QCD** signals
- **2D fit** of **EWK and QCD** signal strengths

- **Signal Regions**
  - Fit to DNN shape (depending on the category)
- **Control Regions**
  - **W+jets:** fit to normalization per each correction bin in its CRs
  - **ttbar:** fit to overall normalization in corresponding CRs

Post-fit distributions in SRs (pure EWK signal)



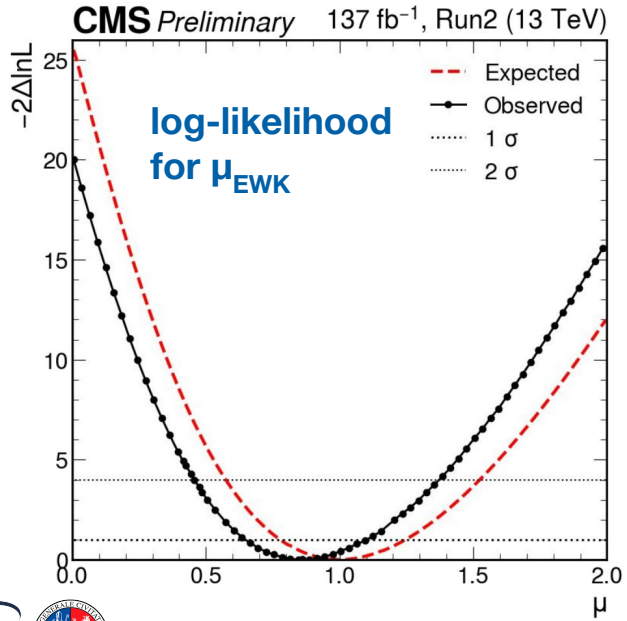
Semileptonic WV scattering: results

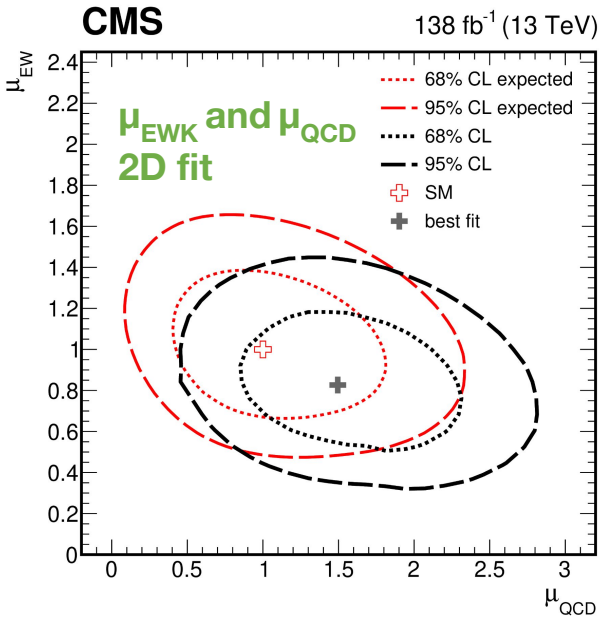
EWK

- Inclusive signal strength
  $\mu_{EWK} = 0.85 \pm 0.12(\text{stat})^{+0.19}_{-0.17}(\text{syst})$
  observed significance = 4.4σ
- Fiducial cross section measurement
  $\sigma_{EWK} = 1.90^{+0.53}_{-0.46}$ **pb**

EWK + QCD

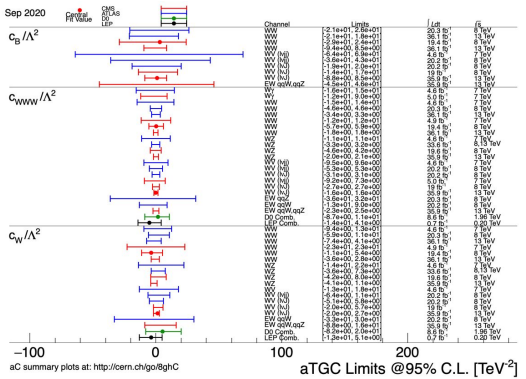
- Inclusive signal strength
  $\mu_{EWK+QCD} = 0.97 \pm 0.06(\text{stat})^{+0.19}_{-0.21}(\text{syst})$
- Fiducial cross section measurement
  $\sigma_{EWK+QCD} = 16.4^{+3.5}_{-2.8}$ pb

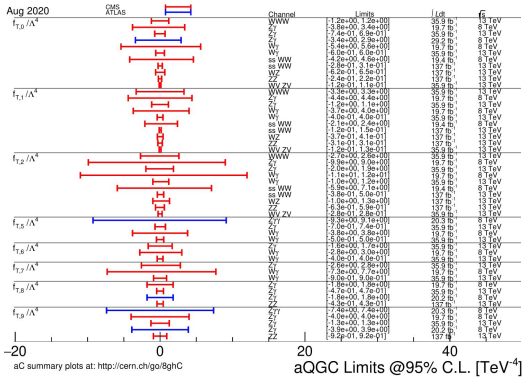


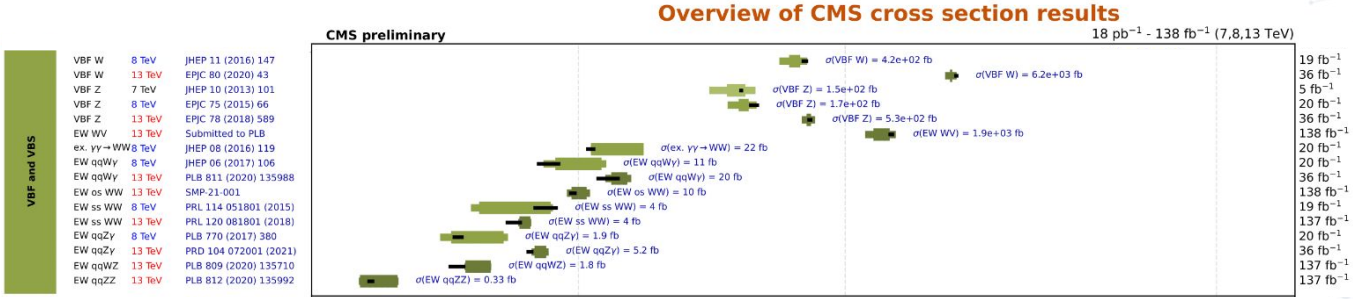


Conclusions

- **VBS processes as compelling physics scenario**
  - Both ideal to further investigate SM and New Physics effects induced in EWK sector
  - Challenging background that stimulates smart solutions
    - Cut-based and ML-based
- **CMS deeply involved in VBS analyses**
  - Several processes and final states investigated
  - Exploitation of the full Run-II available dataset
    - First observation of rare SM processes
    - Pushed forward BSM indirect studies with the EFT approach
  - Efforts to put together current and future studies
    - Combination of the experimental results
    - Get the theoretical basis uniform
    - Get the experimental frameworks uniform







New adventurers are welcome!

New data for our challenges are coming 😎

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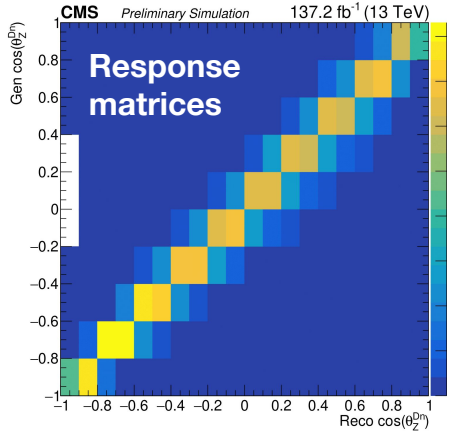
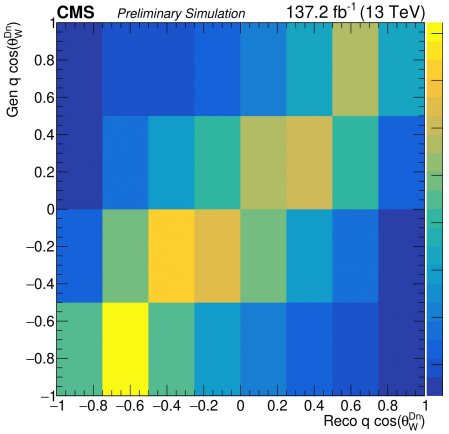
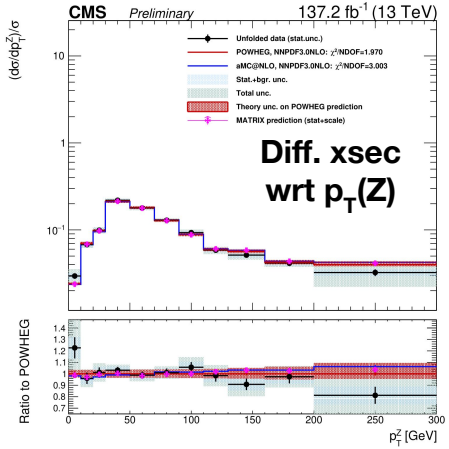
backup slides

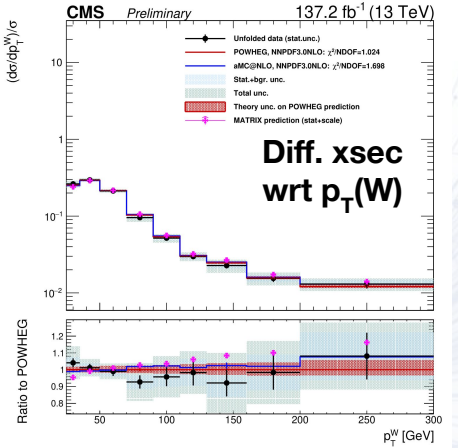
Leptonic WZ: diboson differential cross-sections

- **Differential cross-sections** wrt different variables
  - Next-to-Leading-Order estimates
  - Cross-check of the predictions used for other measures
    $\cos(\theta_W)$, $\cos(\theta_Z)$, m_{WZ}
  - Characterization of lepton WZ scattering as SM process
    $p_T(Z)$, $p_T(W)$, $p_T(jet_1)$, N_{jets}
- **Unfolding procedure** to cancel out detector effect
  - Response matrices are almost diagonal
    Signature of well-established procedure
- Measurements performed for different channels
  - positive and negative boson charge (W)
  - charge-inclusive (W and Z)
- **Good agreement** with the NLO prediction from simulations



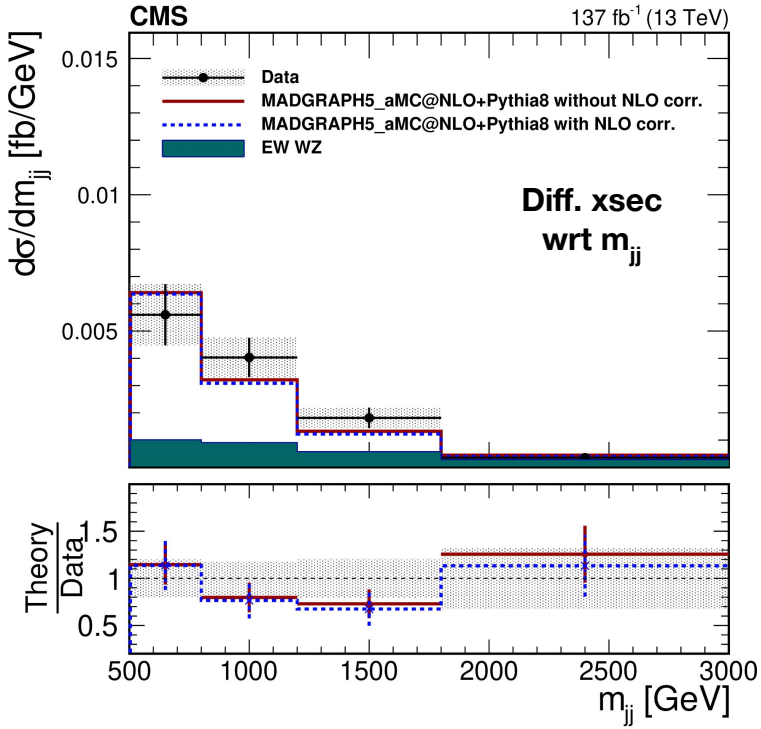






Leptonic WZ: VBS differential cross-section

- **Differential cross-section** wrt m_{jj}
  - Characterization of lepton WZ scattering as SM process
  - Fit to m_{jj} and $|\Delta\eta_{jj}|$
- **Same unfolding procedure** as diboson process
- **Good agreement** with the prediction from simulations
  - both LO and NLO



Leptonic WZ: anomalous Triple Gauge Coupling in diboson

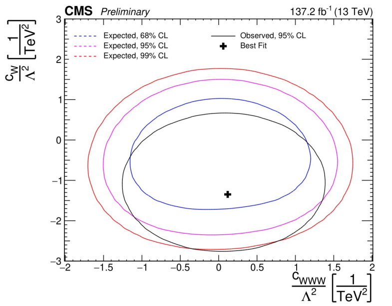
- Search for **New Physics** in WZ scattering with **EFT approach**
  - NP contribution parametrized with dim6 SM fields combination

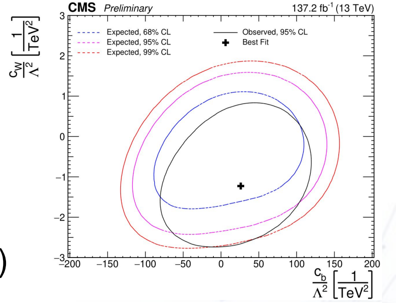
$$\delta\mathcal{L}_{AC} = \frac{c_{WWW}\mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W^{\mu}_{\rho}] + c_{W}\left(D_\mu H\right)^\dagger W^{\mu\nu}\left(D_\nu H\right) + c_{b}\left(D_\mu H\right)^\dagger B^{\mu\nu}\left(D_\nu H\right)}{\Lambda^2} + \frac{\tilde{c}_{WWW}\mathrm{Tr}[\tilde{W}_{\mu\nu}W^{\nu\rho}W^{\mu}_{\rho}] + \tilde{c}_{W}\left(D_\mu H\right)^\dagger \tilde{W}^{\mu\nu}\left(D_\nu H\right)}{\Lambda^2}$$

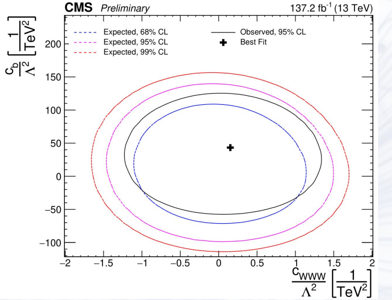
CP-even terms

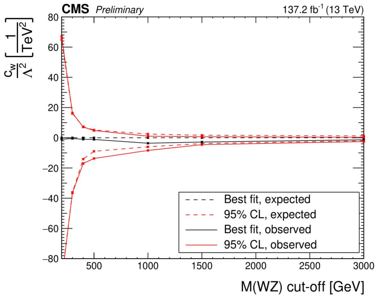
CP-even terms (1st time in WZ)

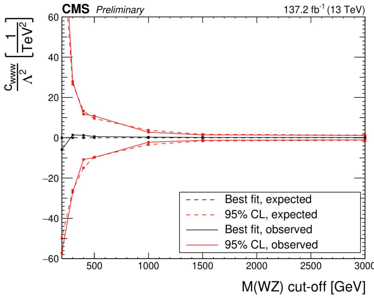
- Dependence of yields by each of CP-even (odd) terms estimated with a dedicated 3D (2D) fit
  - Possible contamination from dim8 operator evaluated in the parametrization
- Fit to m_{WZ} performed with a joint likelihood function
  - 1D and 2D CL limits extracted for dim6 EFT coefficients
  - Unitarity constraint impact provided varying the EFT cut-off scale Λ (M_{WZ} as proxy interaction energy)

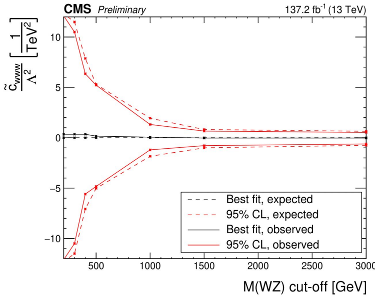


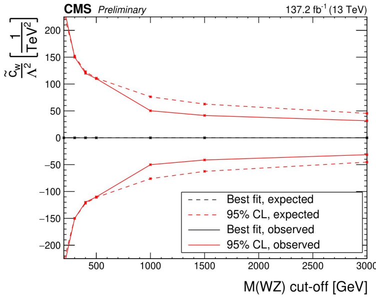












Semileptonic WV scattering: background estimation

- W + jets associated production
  - Differential data-driven corrections to predictions from simulation
    - Binned wrt to leptonic W p_T (**both** categories) and leading VBS jet p_T (only **resolved** category)
- ttbar pair production
  - Reduced with veto on b-tagged jets
- Nonprompt leptons
  - Estimated with the data-driven *fakeable* method
- Minor background estimated via simulations
- **DNN** in both categories as **signal vs bkg discriminator**