Vector Boson Scattering in CMS

Duje Giljanović

2022 LHC Days in Split

Outline

1. What is VBS?
2. Why study VBS?
3. BSM physics in the EFT approach

introduction

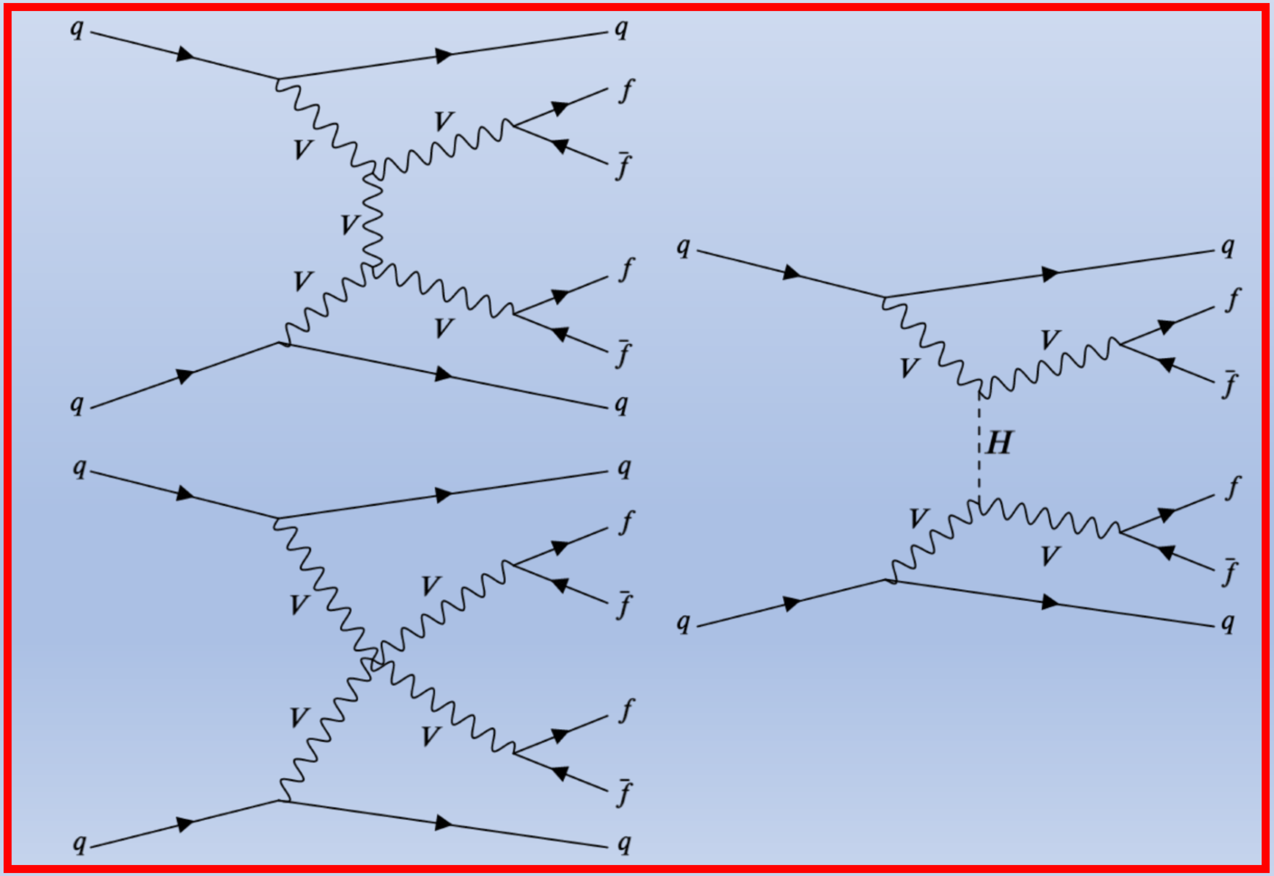
4. Summary of recent VBS measurements at CMS
5. Zγjj channel
6. OS $WWjj$ channel
7. Fully leptonic $ZZjj$ channel
8. Same-sign $W_L W_L jj$ production
9. Prospective studies for the $Z_L Z_L jj$ production

most recent CMS analyses

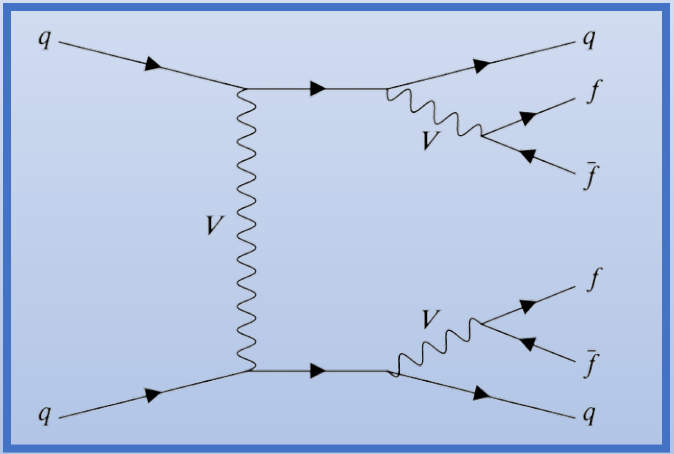
10. Conclusion

What is VBS?

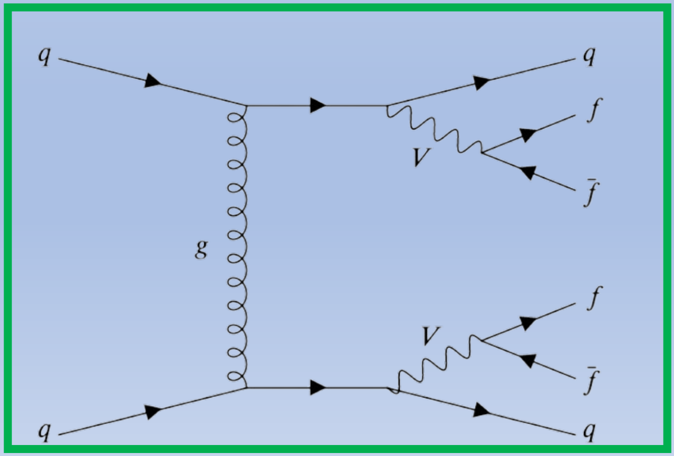
- subset of EW processes in which VV pair is radiated from two initial quark lines



VBS production of the 4l2j final state



non-VBS production of the 4l2j final state



QCD-induced product. of the 4l2j final state

Why study VBS?

- massless gauge fields in the EW sector gain longitudinal degrees of freedom due to EWSB
- longitudinal VVs exhibit interesting high-energy behaviour
  - at high energies scattering amplitude becomes constant
  - the cross-section decreases linearly - scattering of longitudinal VVs = scattering of Goldstone bosons of the EWSB
- if there is no Higgs boson or even if its coupling to the VV differ from SM values --> cross-section diverges
- VBS enables
  - precise study of Higgs couplings
  - studying the non-Abelian structure of EW sector by probing the quartic vertices (WWZZ, WWZγ, WW γ γ and WWWW)

BSM physics in the EFT approach

- some BSM phenomena can be described in the EFT approach
- EFT Lagrangian $\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{d>4} \sum_{i} \frac{f_i \mathcal{O}_i^d}{\Lambda^{d-4}}$
- dim-8 operators lead to anomalous quartic gauge couplings (aQGCs)
  - VBS is sensitive to aQGCs!
- effect of aQGC is to enhance production xs for large boson scattering energies

Class	Definition
Scalar *involve only the scalar field*	$\mathcal{O}_{S,0} = [(D_\mu\Phi)^\dagger D_\nu\Phi] \times [(D^\mu\Phi)^\dagger D^\nu\Phi]$
	$\mathcal{O}_{S,1} = [(D_\mu\Phi)^\dagger D_\mu\Phi] \times [(D_\nu\Phi)^\dagger D^\nu\Phi]$
	$\mathcal{O}_{S,2} = [(D_\mu\Phi)^\dagger D_\nu\Phi] \times [(D^\nu\Phi)^\dagger D^\mu\Phi]$
Tensor *involve only the field strength tensor*	$\mathcal{O}_{T,0} = \mathrm{Tr}[\widehat{W}_{\mu\nu}, \widehat{W}^{\mu\nu}] \times \mathrm{Tr}[\widehat{W}_{\alpha\beta}, \widehat{W}^{\alpha\beta}]$
	$\mathcal{O}_{T,1} = \mathrm{Tr}[\widehat{W}_{\alpha\nu}, \widehat{W}^{\mu\beta}] \times \mathrm{Tr}[\widehat{W}_{\mu\beta}, \widehat{W}^{\alpha\nu}]$
	$\mathcal{O}_{T,2} = \mathrm{Tr}[\widehat{W}_{\alpha\mu}, \widehat{W}^{\mu\beta}] \times \mathrm{Tr}[\widehat{W}_{\beta\nu}, \widehat{W}^{\nu\alpha}]$
	$\mathcal{O}_{T,5} = \mathrm{Tr}[\widehat{W}_{\mu\nu}, \widehat{W}^{\mu\nu}] \times \widehat{B}_{\alpha\beta}\widehat{B}^{\alpha\beta}$
	$\mathcal{O}_{T,6} = \mathrm{Tr}[\widehat{W}_{\alpha\nu}, \widehat{W}^{\mu\beta}] \times \widehat{B}_{\mu\beta}\widehat{B}^{\alpha\nu}$
	$\mathcal{O}_{T,7} = \mathrm{Tr}[\widehat{W}_{\alpha\mu}, \widehat{W}^{\mu\beta}] \times \widehat{B}_{\beta\nu}\widehat{B}^{\nu\alpha}$
	$\mathcal{O}_{T,8} = \widehat{B}_{\mu\nu}\widehat{B}^{\mu\nu} \times \widehat{B}_{\alpha\beta}\widehat{B}^{\alpha\beta}$
	$\mathcal{O}_{T,9} = \widehat{B}_{\alpha\mu}\widehat{B}^{\mu\beta} \times \widehat{B}_{\beta\nu}\widehat{B}^{\nu\alpha}$
Mixed *involve the field strength tensor and the scalar field*	$\mathcal{O}_{M,0} = \mathrm{Tr}[\widehat{W}_{\mu\nu}, \widehat{W}^{\mu\nu}] \times [(D_\beta\Phi)^\dagger D^\beta\Phi]$
	$\mathcal{O}_{M,1} = \mathrm{Tr}[\widehat{W}_{\mu\nu}, \widehat{W}^{\nu\beta}] \times [(D_\beta\Phi)^\dagger D^\mu\Phi]$
	$\mathcal{O}_{M,2} = \widehat{B}_{\mu\nu}\widehat{B}^{\mu\nu} \times [(D_\beta\Phi)^\dagger D^\beta\Phi]$
	$\mathcal{O}_{M,3} = \widehat{B}_{\mu\nu}\widehat{B}^{\nu\beta} \times [(D_\beta\Phi)^\dagger D^\mu\Phi]$
	$\mathcal{O}_{M,4} = (D_\mu\Phi)^\dagger \widehat{W}_{\beta\nu} D^\mu\Phi \times \widehat{B}^{\beta\nu}$
	$\mathcal{O}_{M,5} = (D_\mu\Phi)^\dagger \widehat{W}_{\beta\nu} D^\nu\Phi \times \widehat{B}^{\beta\mu}$
	$\mathcal{O}_{M,7} = (D_\mu\Phi)^\dagger \widehat{W}_{\beta\nu} \widehat{W}^{\beta\mu} D^\nu\Phi$

	$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$, $\mathcal{O}_{S,2}$	$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$, $\mathcal{O}_{M,7}$	$\mathcal{O}_{M,2}$, $\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$, $\mathcal{O}_{M,5}$	$\mathcal{O}_{T,0}$, $\mathcal{O}_{T,1}$, $\mathcal{O}_{T,2}$	$\mathcal{O}_{T,5}$, $\mathcal{O}_{T,6}$, $\mathcal{O}_{T,7}$	$\mathcal{O}_{T,8}$, $\mathcal{O}_{T,9}$
$WWWW$	X	X		X		
$WWZZ$	X	X	X	X	X	
$ZZZZ$	X	X	X	X	X	X
$WWZ\gamma$		X	X	X	X	
$WW\gamma\gamma$		X	X	X	X	
$ZZZ\gamma$		X	X	X	X	X
$ZZ\gamma\gamma$		X	X	X	X	X
$Z\gamma\gamma\gamma$				X	X	X
$\gamma\gamma\gamma\gamma$				X	X	X

vertices modified by aQGC operator

Summary of recent VBS measurements at CMS

YEAR	CHANNEL	$\sqrt{s}\ [TeV]$	$L\ [fb^{-1}]$	COMMENT	PAPER
2017	same-sign WWjj	13	35.9	1st observation (5.5σ observed; 5.7σ expected)	10.1103/PhysRevLett.120.081801
2017	fully leptonic ZZjj	13	35.9	observed significance 2.7σ (1.6σ expected)	10.1016/j.physletb.2017.10.020
2018	$Z_L Z_L jj$	14/27	3000/15000	projections for HL-LHC and HE-LHC conditions	CMS-PAS-FTR-18-014
2019	WWjj and WZjj	13	137	1st observation (6.8σ observed; 5.3σ expected) of EW WZ production with 2 jets	10.1016/j.physletb.2020.135710
2020	Wγjj	13	138	1st measurements with the full Run2 data	10.1103/PhysRevD.105.052003
2020	fully leptonic $ZZjj$	13	137	1st evidence (4σ observed; 3.5σ expected)	10.1016/j.physletb.2020.135992
2020	same-sign $W_L W_L jj$	13	137	first measurement of the polarized WW production	10.1016/j.physletb.2020.136018
2021	$Z\gamma jj$	13	137	1st observation (9.4σ observed; 8.5σ expected)	cds.cern.ch/record/2759297
2021	opposite-sign WW	13	138	1st observation (5.6σ observed; 5.2σ expected)	arXiv:2205.05711

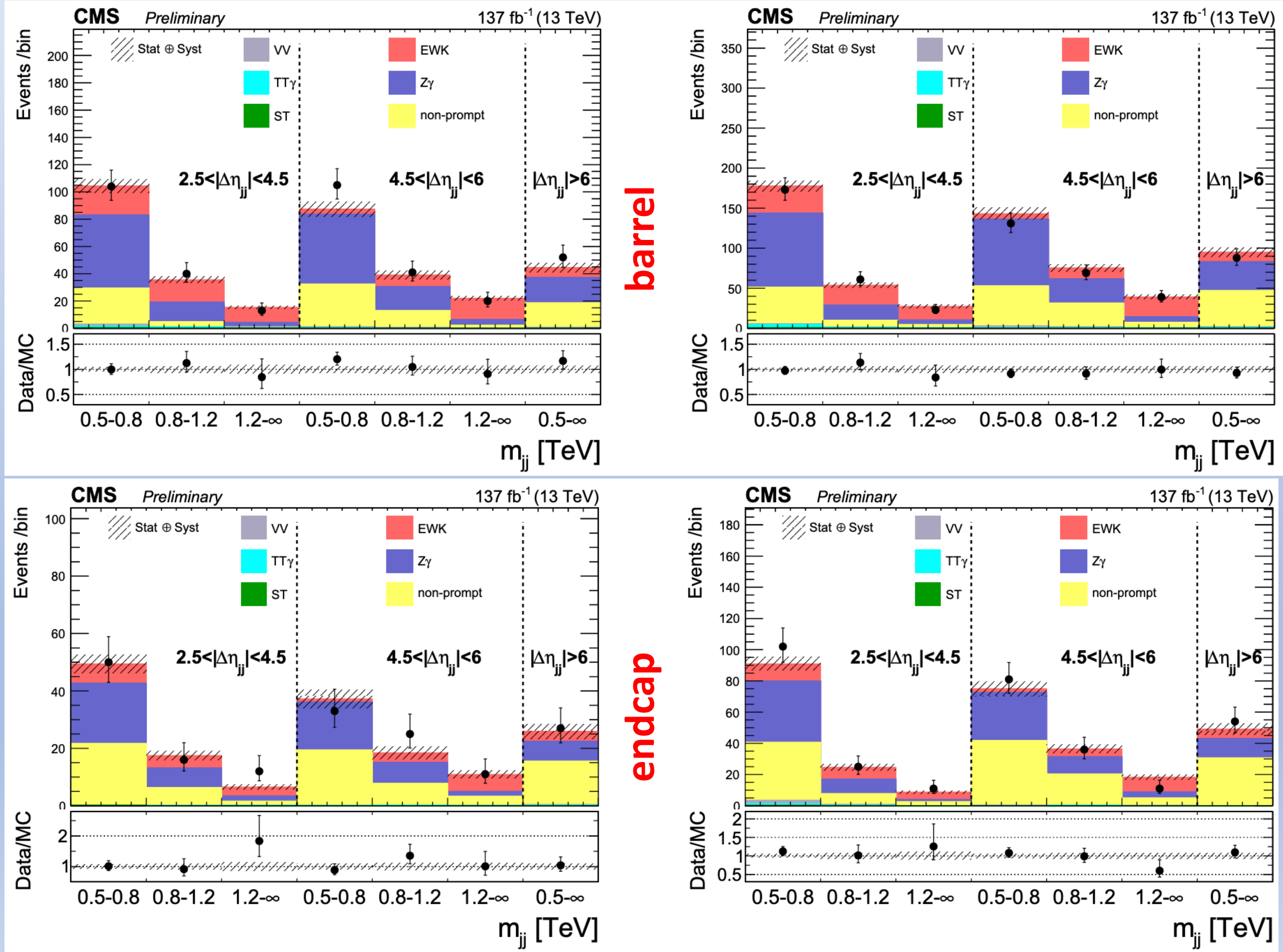
$Z\gamma jj$ channel

- signal: EW production of $Z\gamma jj$
- backgrounds: QCD-induced production of $Z\gamma$, $W\gamma$ and $\bar{t}t\gamma$, diboson processes (WW/WZ/ZZ) and single t quark production
- signal significance and fiducial cross-section calculated using the ML fit on the 2D $(m_{jj}, \Delta\eta_{jj})$ distribution
- unfolded differential cross-section also measured

Common selection	$p_T^{\ell 1,\ell 2} > 25\,\text{GeV}$, $\lvert\eta^{\ell 1,\ell 2}\rvert < 2.5$ for electron channel $p_T^{\ell 1,\ell 2} > 20\,\text{GeV}$, $\lvert\eta^{\ell 1,\ell 2}\rvert < 2.4$ for muon channel $p_T^{\gamma} > 20\,\text{GeV}$, $\lvert\eta^{\gamma}\rvert < 1.444$ or $1.566 < \lvert\eta^{\gamma}\rvert < 2.500$ $p_T^{j1,j2} > 30\,\text{GeV}$, $\lvert\eta^{j1,j2}\rvert < 4.7$ $70 < m_{\ell\ell} < 110\,\text{GeV}$, $m_{Z\gamma} > 100\,\text{GeV}$ ΔR_{jj}, $\Delta R_{j\gamma}$, $\Delta R_{j\ell} > 0.5$, $\Delta R_{\ell\gamma} > 0.7$
Control region	Common selection, $150 < m_{jj} < 500\,\text{GeV}$
EW signal region	Common selection, $m_{jj} > 500\,\text{GeV}$, $\lvert\Delta\eta_{jj}\rvert > 2.5$, $\eta^* < 2.4$, $\Delta\phi_{Z\gamma,jj} > 1.9$
Fiducial volume	Common selection, $m_{jj} > 500\,\text{GeV}$, $\lvert\Delta\eta_{jj}\rvert > 2.5$
aQGC search region	Common selection, $m_{jj} > 500\,\text{GeV}$, $\lvert\Delta\eta_{jj}\rvert > 2.5$, $p_T^{\gamma} > 120\,\text{GeV}$

$Z\gamma jj$ channel (cont'd)

- observed significance 9.4σ reported (8.5σ expected)
- $\sigma_{EW}^{fid} = 5.21 \pm 0.76\ fb$
- $\sigma_{EW+QCD}^{fid} = 14.7 \pm 1.53\ fb$
- signal strength and unfolded xs measured in bins of leading photon, lepton and jet p_T and in bins of two variables $m_{jj} - \Delta\eta_{jj}$

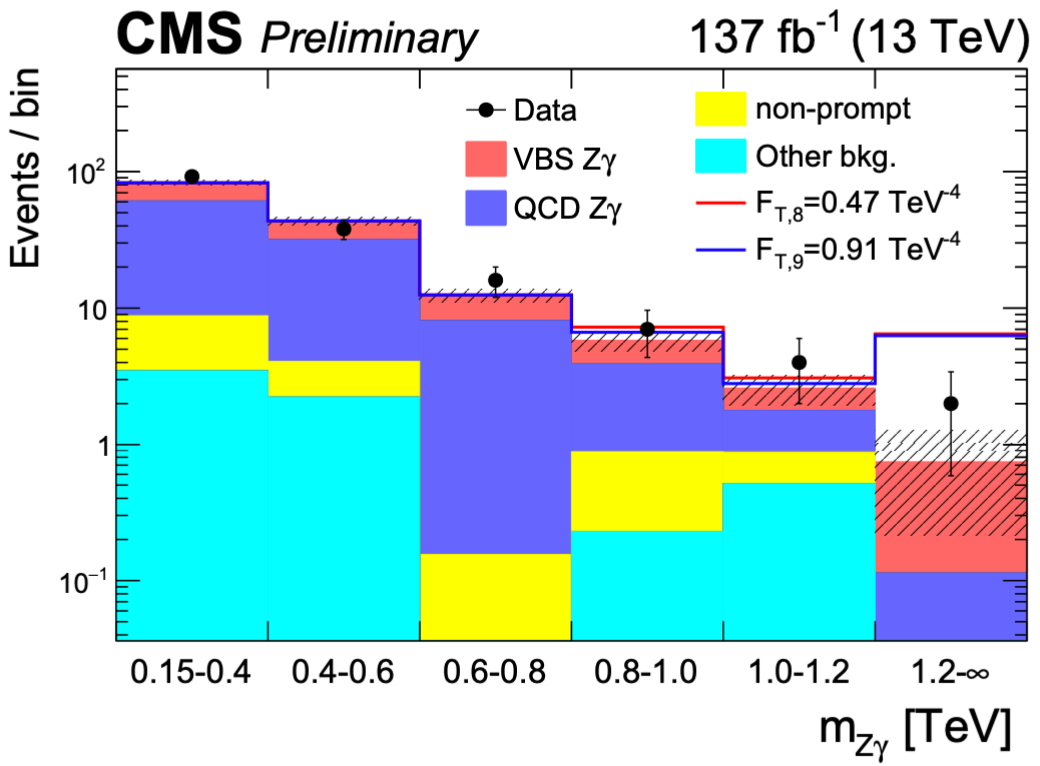


$Z\gamma jj$ channel (cont'd)

- limits imposed on aQGCs in the EFT approach
- most stringent limits on the neutral-current operator T9

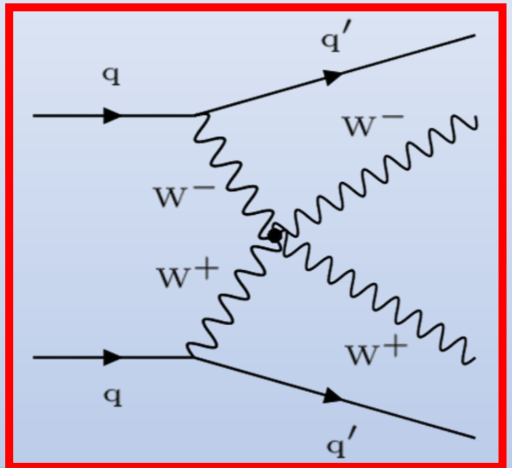
95% CL exclusion limits for $F_{M_{0-7}}$ and $F_{T_{0-2,5-9}}$ parameters

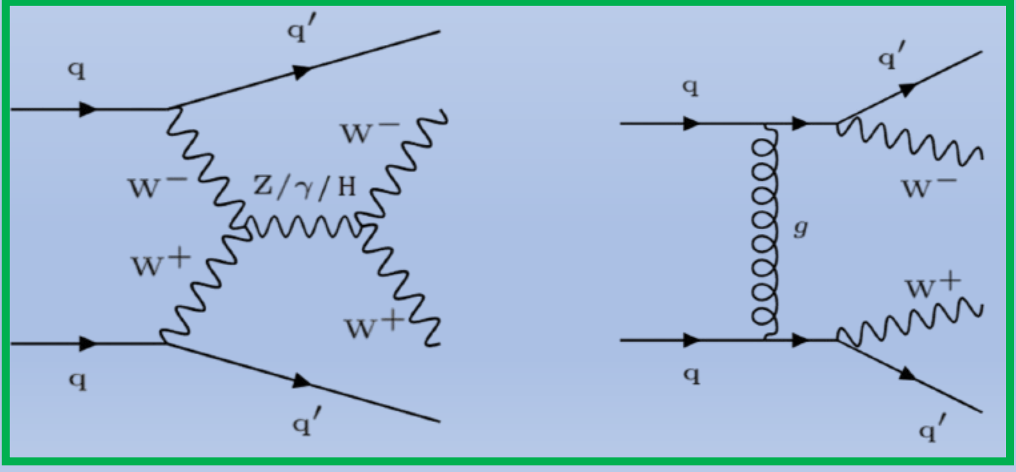
Operator coefficients	Expected [TeV^{-4}]	Observed [TeV^{-4}]	Freeze all syst. [TeV^{-4}]	Unitarity bound [TeV]
F_{M0}/Λ^4	-12.5 , 12.8	-15.8 , 16.0	-15.2 , 15.4	1.1
F_{M1}/Λ^4	-28.1 , 27.0	-35.0 , 34.7	-33.8 , 33.3	1.2
F_{M2}/Λ^4	-5.21 , 5.12	-6.55 , 6.49	-6.32 , 6.23	1.4
F_{M3}/Λ^4	-10.2 , 10.3	-13.0 , 13.0	-12.4 , 12.5	1.6
F_{M4}/Λ^4	-10.2 , 10.2	-13.0 , 12.7	-12.5 , 12.3	1.4
F_{M5}/Λ^4	-17.6 , 16.8	-22.2 , 21.3	-21.4 , 20.4	1.8
F_{M6}/Λ^4	-25.0 , 25.6	-31.7 , 32.0	-30.4 , 30.8	1.1
F_{M7}/Λ^4	-44.7 , 45.0	-56.6 , 55.9	-54.3 , 53.8	1.3
F_{T0}/Λ^4	-0.52 , 0.44	-0.64 , 0.57	-0.62 , 0.55	1.4
F_{T1}/Λ^4	-0.65 , 0.63	-0.81 , 0.90	-0.78 , 0.77	1.5
F_{T2}/Λ^4	-1.36 , 1.21	-1.68 , 1.54	-1.63 , 1.48	1.4
F_{T5}/Λ^4	-0.45 , 0.52	-0.58 , 0.64	-0.55 , 0.62	1.8
F_{T6}/Λ^4	-1.02 , 1.07	-1.30 , 1.33	-1.25 , 1.29	1.7
F_{T7}/Λ^4	-1.67 , 1.97	-2.15 , 2.43	-2.06 , 2.36	1.8
F_{T8}/Λ^4	-0.36 , 0.36	-0.47 , 0.47	-0.46 , 0.46	1.5
F_{T9}/Λ^4	-0.72 , 0.72	-0.91 , 0.91	-0.88 , 0.88	1.6



Opposite-sign WWjj channel

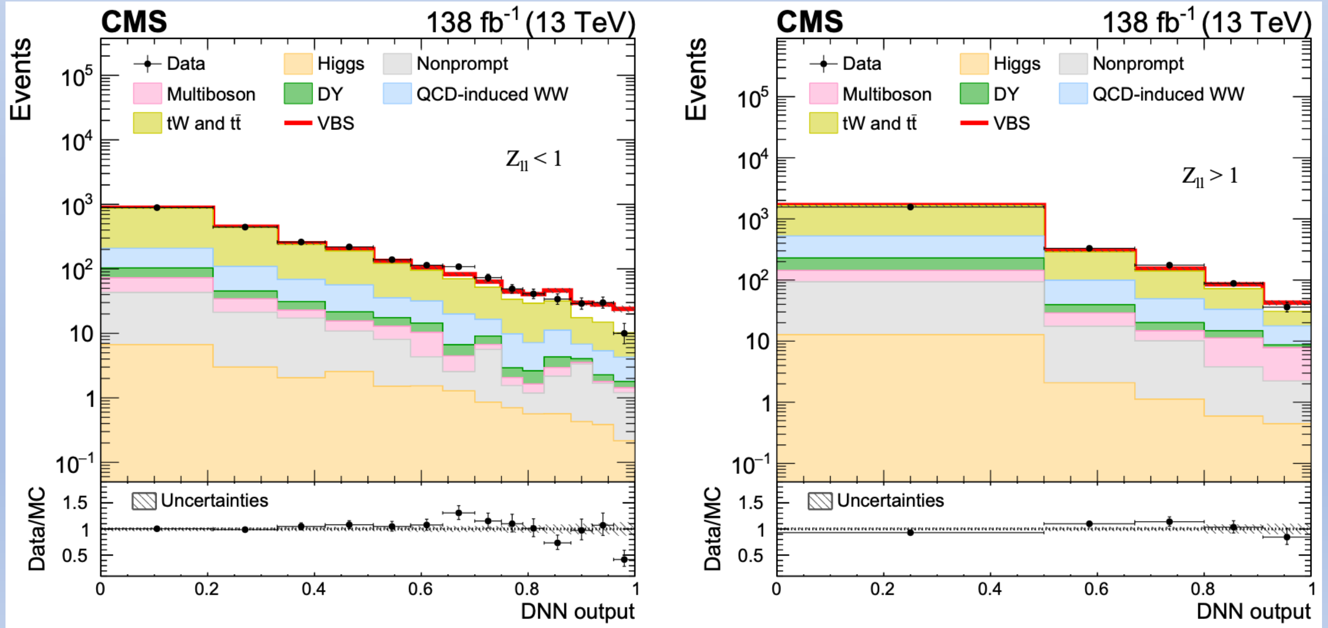
- signal: EW production of 2 OS, leptonically decaying Ws
- background: QCD-induced production of the W^+W^-jj, reducible bkg. from t$\bar{t}$ production, DY+j and W+j production
- more challenging than $W^{\pm}W^{\pm}$ because of OS bkg from t$\bar{t}$ prod.
- only recently first NLO calculation fpr the EW production of W^+W^- become available
- selection: 2 OS leptons with $m_{ll} > 50\ GeV$, $p_T^{ll} > 30\ GeV$, $p_T^{l_1(l_2)} > 25(13) GeV$, $p_T^{miss} > 20\ GeV$, at least 2j with $p_T > 30\ GeV$ $m_{jj} > 300\ GeV$ and $\Delta\eta_{jj} > 2.5$





Opposite-sign WWjj channel (cont'd)

- deep neural network (DNN) used to separate VBS signal from QCD-induced and t$\bar{t}$ backgrounds
  - for optimization, 2 models built: for the region with low ($Z_{ll} < 1$) and high ($Z_{ll} > 1$)values of the Zeppenfeld variable
- observed (expected) signal significance 5.6σ (5.2σ)
- fid. xs $10.2 \pm 2.0\ fb$ in agreement with the SM prediction $9.1 \pm 0.6\ fb$



Fully leptonic $ZZjj$ channel

- signal extraction based on the MELA discriminant (K_D)
- performance checked against the BDT
- ZZ selection used to measure signal significance, total fid. xs and aQGC search
- **1st evidence for the EW production of the fully leptonic ZZ channel**
- measured EW signal significance 4σ (3.5σ expected)
- measured EW and EW+QCD sig. strength agree with SM expectation

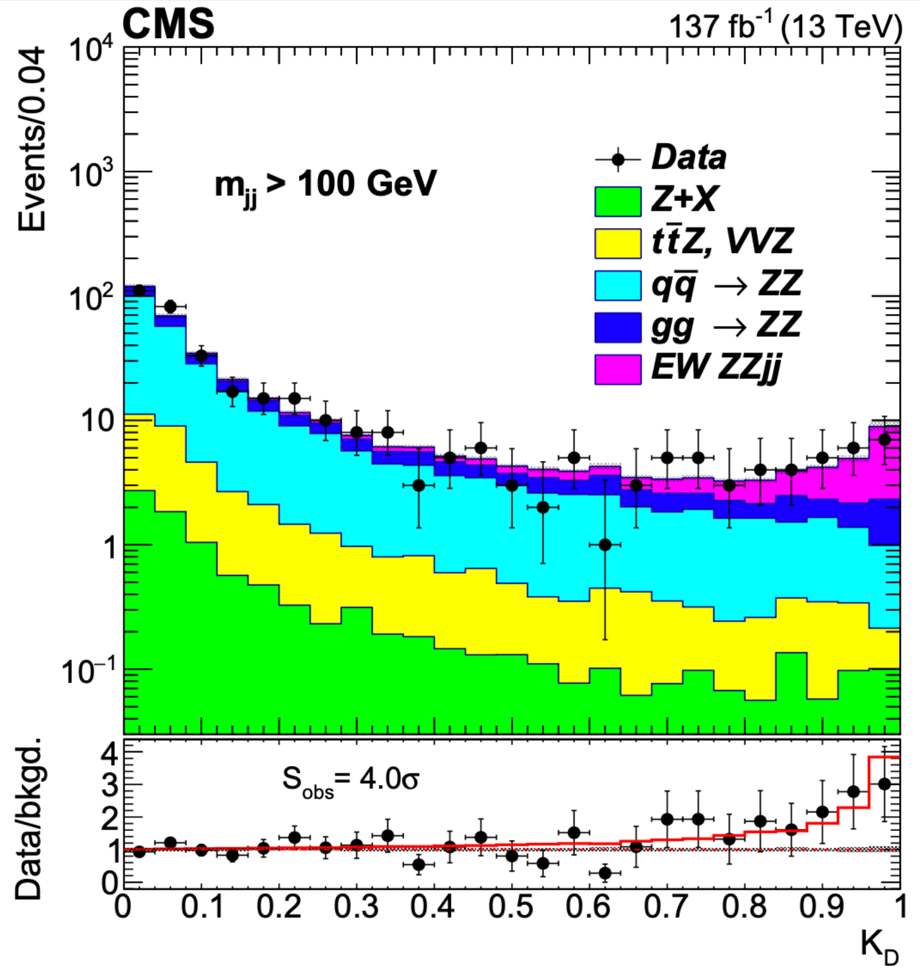
lepton candidates	$p_T^e > 7GeV$ $p_T^\mu > 5GeV$ $\lvert\eta\rvert^e < 2.5$ $\lvert\eta\rvert^\mu < 2.4$ $\lvert d_{xy}\rvert < 0.5\ cm$ $\lvert d_z\rvert < 1\ cm$ $\lvert SIP_{3D}\rvert < 4$ ID passed iso. in ID $R^\mu_{iso} < 0.35$
jet candidates	$p_T > 30\ GeV$ $\lvert\eta\rvert < 4.7$ $\Delta R(j, l/\gamma) > 0.4$ ID passed L1 prefiring correction
Z candidate	tight lepton pair (e^+e^- or $\mu^+\mu^-$) $60\ GeV < m_{ll} < 120\ GeV$
ZZ selection	require pair of non-overlapping Z bosons $\Delta R(\eta,\phi) > 0.02$ between each of the four leptons $p_T(l_1) > 20\ GeV$ $p_T(l_2) > 10\ GeV$ $m_{Z1} > 60\ GeV$ $m_{Z2} > 60\ GeV$ $m_{4l} > 180\ GeV$ QCD suppression cut "smart" cut
Inclusive ZZjj selection	ZZ selection + $m_{jj} > 100GeV$
loose VBS selection	ZZ selection + $m_{jj} > 400GeV + \lvert\Delta\eta_{jj}\rvert > 2.4$
tight VBS selection	ZZ selection + $m_{jj} > 1\ TeV + \lvert\Delta\eta_{jj}\rvert > 2.4$

Fully leptonic $ZZjj$ channel (cont'd)

- cross-section measured in 3 fiducial regions

	SM σ $[fb]$	Measured σ $[fb]$	μ_{exp}	μ_{obs}
ZZjj inclusive				
EWK	LO: $0.275 \pm 0.021_{th.}$ NLO QCD: $0.278 \pm 0.017_{th.}$ NLO EWK: $0.242^{+0.015_{th.}}_{-0.013_{th.}}$	$0.33^{+0.11\ (+0.04)}_{-0.10\ (-0.03)}$	$1.00^{+0.43\ (+0.39)}_{-0.36\ (-0.34)}$	$1.21^{+0.47}_{-0.40}$
EWK+QCD	$5.35 \pm 0.51_{th.}$	$5.29^{+0.31\ (+0.46)}_{-0.30\ (-0.46)}$	$1.00^{+0.13\ (+0.06)}_{-0.12\ (-0.06)}$	$0.99^{+0.13}_{-0.12}$
VBS signal-enriched (loose)				
EWK	LO: $0.186 \pm 0.015_{th.}$ NLO QCD: $0.197 \pm 0.013_{th.}$	$0.200^{+0.078\ (+0.023)}_{-0.067\ (-0.013)}$	$1.00^{+0.45\ (+0.40)}_{-0.38\ (-0.35)}$	$1.08^{+0.47}_{-0.38}$
EWK+QCD	$1.21 \pm 0.09_{th.}$	$1.00^{+0.12\ (+0.06)}_{-0.11\ (-0.05)}$	$1.00^{+0.16\ (+0.13)}_{-0.15\ (-0.12)}$	$0.83^{+0.15}_{-0.13}$
VBS signal-enriched (tight)				
EWK	LO: $0.104 \pm 0.008_{th.}$ NLO QCD: $0.108 \pm 0.007_{th.}$	$0.09^{+0.04\ (+0.02)}_{-0.03\ (-0.02)}$	$1.00^{+0.52\ (+0.50)}_{-0.44\ (-0.41)}$	$0.87^{+0.48}_{-0.39}$
EWK+QCD	$0.221 \pm 0.014_{th.}$	$0.20^{+0.05\ (+0.02)}_{-0.04\ (-0.02)}$	$1.00^{+0.42\ (+0.40)}_{-0.34\ (-0.32)}$	$0.92^{+0.39}_{-0.32}$

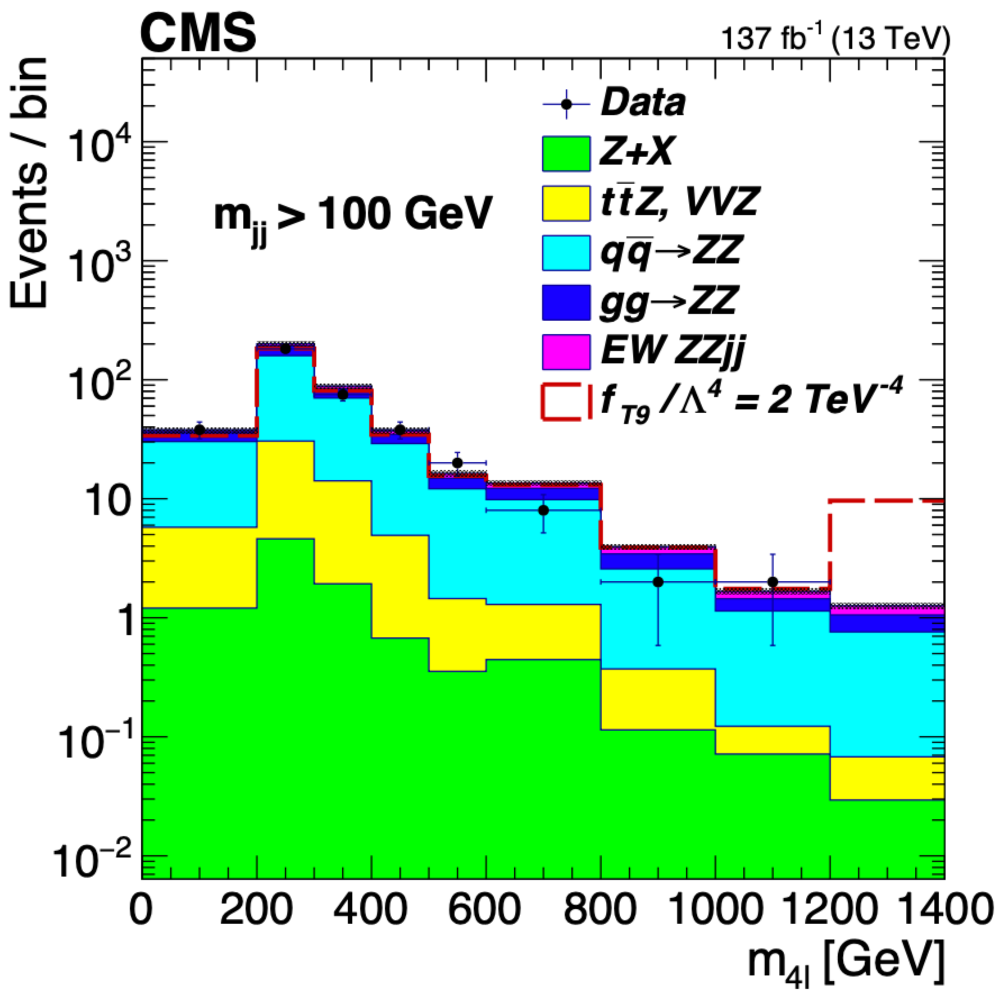
- SM predictions extracted from generated events in MC samples
- for EWK, theory predictions at NLO included



Fully leptonic $ZZjj$ channel (cont'd)

95% CL limits on couplings of operators $T_{0,1,2,8,9}$ imposed in the EFT framework

Coupling	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unit. limit (VBFNLO)	Unit. limit (Eboli)
f_{T_0}/Λ^4	-0.37	0.35	-0.24	0.22	2.9	2.4
f_{T_1}/Λ^4	-0.49	0.49	-0.31	0.31	2.7	2.6
f_{T_2}/Λ^4	-0.98	0.95	-0.63	0.59	2.8	2.5
f_{T_8}/Λ^4	-0.68	0.68	-0.43	0.43	1.8	1.8
f_{T_9}/Λ^4	-1.46	1.46	-0.92	0.92	1.8	1.8



Same-sign $W_L W_L jj$ channel

- signal: EW production of $W_L^{\pm}W_L^{\pm}$, $W_L^{\pm}W_T^{\pm}$ and $W_T^{\pm}W_T^{\pm}$ (+ 2j)
- background: EW production of WZ, QCD-induced production of WZ, $t\bar{t}$, tW (and other VV), $t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}\gamma$, VVV and tZq processes
- signal extracted using BDT
- 2 BDTs trained to separate either
  - $W_L^{\pm}W_L^{\pm}$ and $W_X^{\pm}W_T^{\pm}$ processes
  - $W_L^{\pm}W_X^{\pm}$ and $W_T^{\pm}W_T^{\pm}$ processes
- 2 ML fits performed to calculate signal significance

Variable	Requirement
Leptons	Exactly 2 same-sign leptons, $p_T > 25/20$ GeV
p_T^j	>50 GeV
$\lvert m_{\ell\ell} - m_Z \rvert$	>15 GeV (ee)
$m_{\ell\ell}$	>20 GeV
p_T^{miss}	>30 GeV
b quark veto	Required
$Max(z_\ell^*)$	<0.75
m_{jj}	>500 GeV
$\lvert \Delta\eta_{jj} \rvert$	>2.5

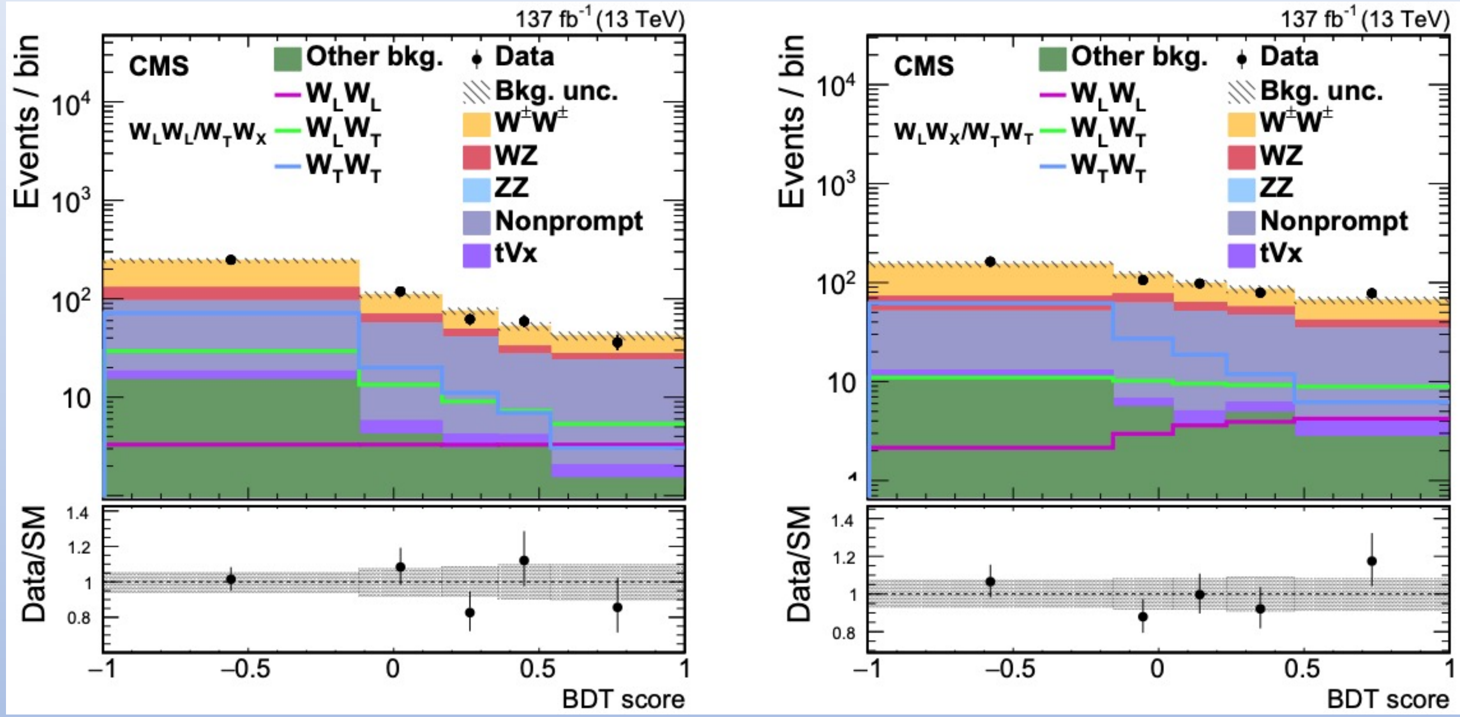
requirements defining $W^{\pm}W^{\pm}$ SR

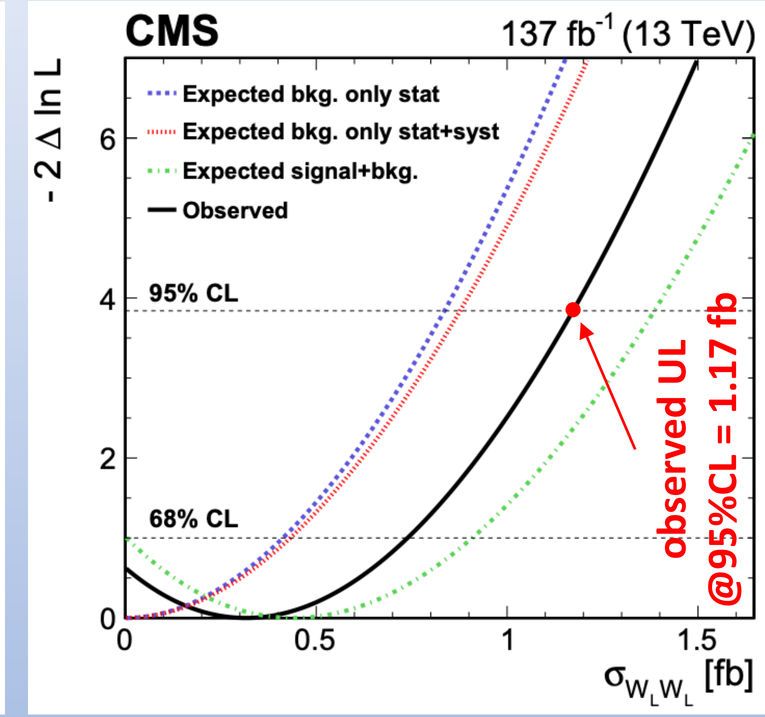
Same-sign $W_L W_L jj$ channel (cont'd)

- first, BDT trained to separate WW from SM backgrounds
  - variables in table + m_{jj} and $\Delta\eta_{jj}$
- next, BDT trained to separate different polarizations (many variables studied for BDT training, those in the table used)
- 2 set of results obtained:
  - for helicity states defined in the WW c.o.m. frame
  - for helicity states defined in the initial-state parton-parton frame

Variables	Definitions
$\Delta\phi_{\mathrm{jj}}$	Difference in azimuthal angle between the leading and subleading jets
$p_{\mathrm{T}}^{\mathrm{j1}}$	p_{T} of the leading jet
$p_{\mathrm{T}}^{\mathrm{j2}}$	p_{T} of the subleading jet
$p_{\mathrm{T}}^{\ell_1}$	Leading lepton p_{T}
$p_{\mathrm{T}}^{\ell_2}$	Subleading lepton p_{T}
$\Delta\phi_{\ell\ell}$	Difference in azimuthal angle between the two leptons
$m_{\ell\ell}$	Dilepton mass
$p_{\mathrm{T}}^{\ell\ell}$	Dilepton p_{T}
$m_{\mathrm{T}}^{\mathrm{WW}}$	Transverse WW diboson mass
$z^*_{\ell_1}$	Zeppenfeld variable of the leading lepton
$z^*_{\ell_2}$	Zeppenfeld variable of the subleading lepton
$\Delta R_{\mathrm{j1},\ell\ell}$	ΔR between the leading jet and the dilepton system
$\Delta R_{\mathrm{j2},\ell\ell}$	ΔR between the subleading jet and the dilepton system
$(p_{\mathrm{T}}^{\ell_1} p_{\mathrm{T}}^{\ell_2})/(p_{\mathrm{T}}^{\mathrm{j1}} p_{\mathrm{T}}^{\mathrm{j2}})$	Ratio of p_{T} products between leptons and jets
$p_{\mathrm{T}}^{\mathrm{miss}}$	Missing transverse momentum

Same-sign $W_L W_L jj$ channel (cont'd)





scans of the negative profile log-likelihood as a function of W_LW_L xs

fiduc. xs.

WW c.o.m.

Process	$\sigma\mathcal{B}$ (fb)	Theoretical prediction (fb)
$W^\pm_L W^\pm_L$	$0.32^{+0.42}_{-0.40}$	0.44 ± 0.05
$W^\pm_X W^\pm_T$	$3.06^{+0.51}_{-0.48}$	3.13 ± 0.35
$W^\pm_L W^\pm_X$	$1.20^{+0.56}_{-0.53}$	1.63 ± 0.18
$W^\pm_T W^\pm_T$	$2.11^{+0.49}_{-0.47}$	1.94 ± 0.21

part.-part. c.o.m.

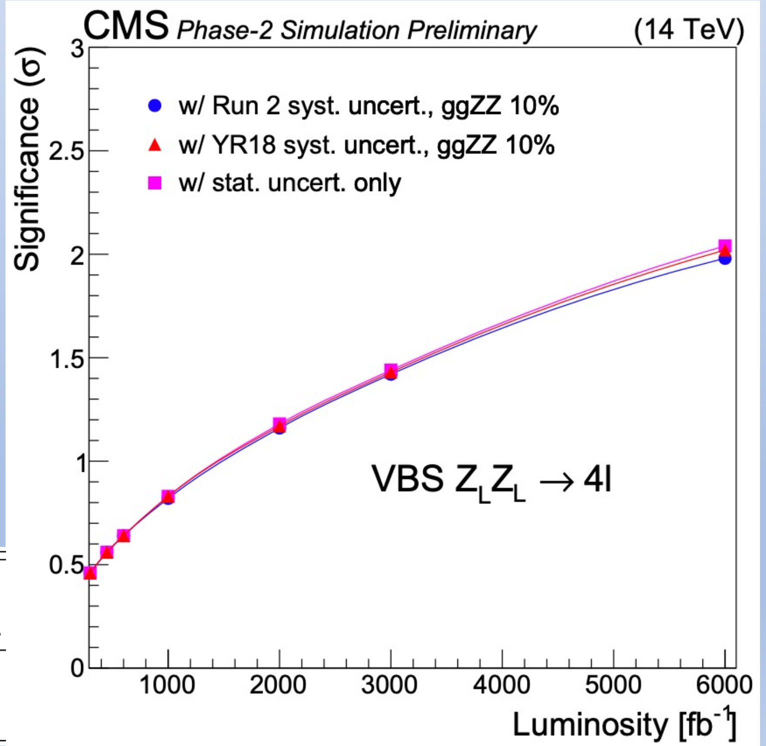
Process	$\sigma\mathcal{B}$ (fb)	Theoretical prediction (fb)
$W^\pm_L W^\pm_L$	$0.24^{+0.40}_{-0.37}$	0.28 ± 0.03
$W^\pm_X W^\pm_T$	$3.25^{+0.50}_{-0.48}$	3.32 ± 0.37
$W^\pm_L W^\pm_X$	$1.40^{+0.60}_{-0.57}$	1.71 ± 0.19
$W^\pm_T W^\pm_T$	$2.03^{+0.51}_{-0.50}$	1.89 ± 0.21

EW prod. of S-S WW with at least 1 W_L (in WW com frame) measured with 2.3σ (3.1σ expected)

Prospective studies for the $Z_L Z_L jj$ production

- starting point: 2016 analysis in the ZZjj channel using $36\ fb^{-1}$ of data
- projected sensitivity for the HL-LHC ($14\ \text{TeV c. o. m. energy},\ 3000\ fb^{-1}$) and HE-LHC conditions $27\ \text{TeV c. o. m. energy}, 15000\ fb^{-1}$)
  - luminosity scaling
  - energy scaling
  - increased acceptance
- Delphes simulation used to assess the sensitivity to $Z_L Z_L$ at 14 TeV
- at HE-LHC condition, first observation of the $Z_L Z_L$ scattering expected!

	significance	
	w/ syst. uncert.	w/o syst. uncert.
HL-LHC	1.4σ	1.4σ
HE-LHC	5.2σ	5.7σ



Conclusion

- Full CMS Run2 data analyses brought significant new results:
  - first observation of WZjj
  - first evidence of ZZjj
  - first observation of OS WWjj
  - first measurements of longitudinal scattering in the SS WWjj channel
  - important test of the EWSB mechanism
  - more stringent limits on the aQGC parameters
- ToDo: extraction of the polarisation components in the VVjj channels, further constraints on the aQGC
- at the HE-LHC conditions the first observation of the longitudinal scattering in the ZZjj channel expected ⟶ **significant benefit of further energy increase for further understanding EW sector of the SM**