Vector Boson Scattering results from CMS

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(on behalf of the CMS Collaboration)

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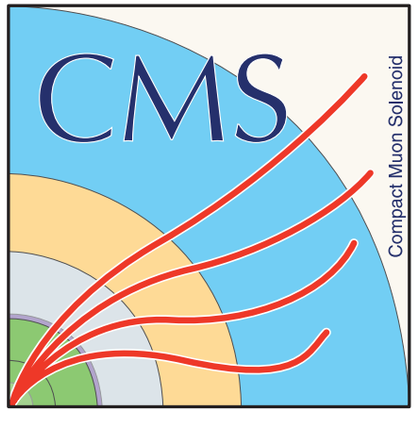
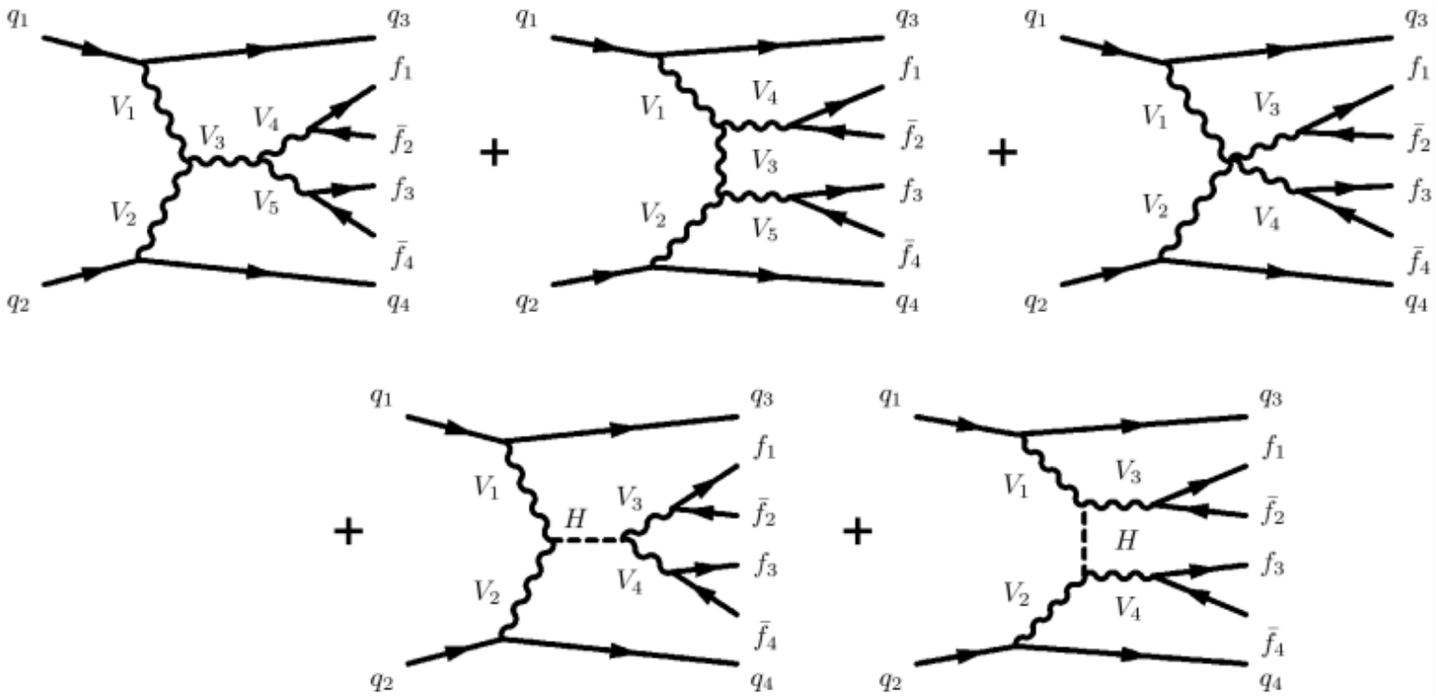
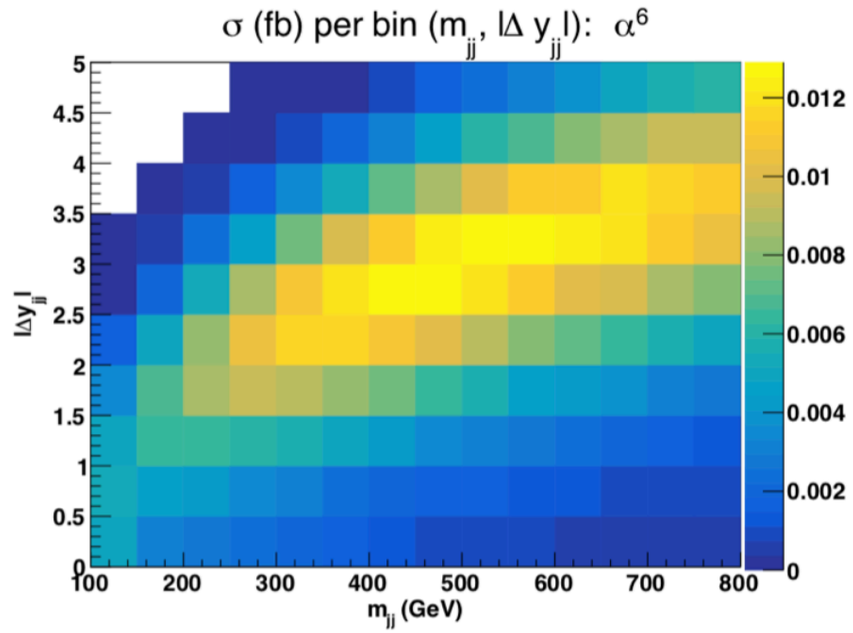
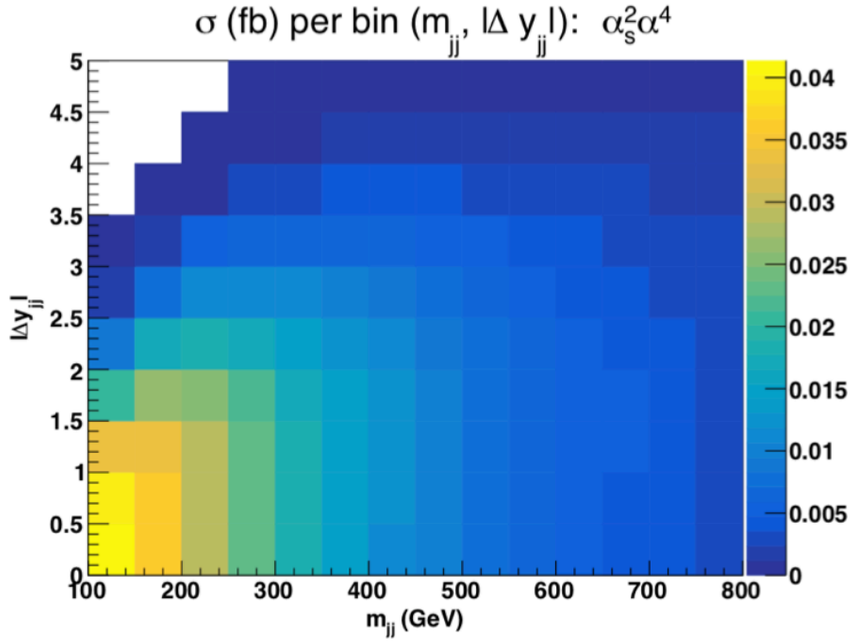


Introduction & Motivation







- **Signal:** six fermions final state at leading order $\mathcal{O}(\alpha^6)$
- **Irreducible background:** QCD-induced $\mathcal{O}(\alpha^4\alpha_s^2)$
- Interference: between EW and QCD $\mathcal{O}(\alpha^5\alpha_s)$
- **Reducible** background due to mis-ID of final state particles
- Significant systematic uncertainties from jet energy reconstruction and background modeling

Introduction & Motivation

Important process to investigate electroweak symmetry breaking(EWSB)

- ☑ Probe the nature of EW symmetry breaking
- ☑ Unitarity preservation visible only in VV scattering

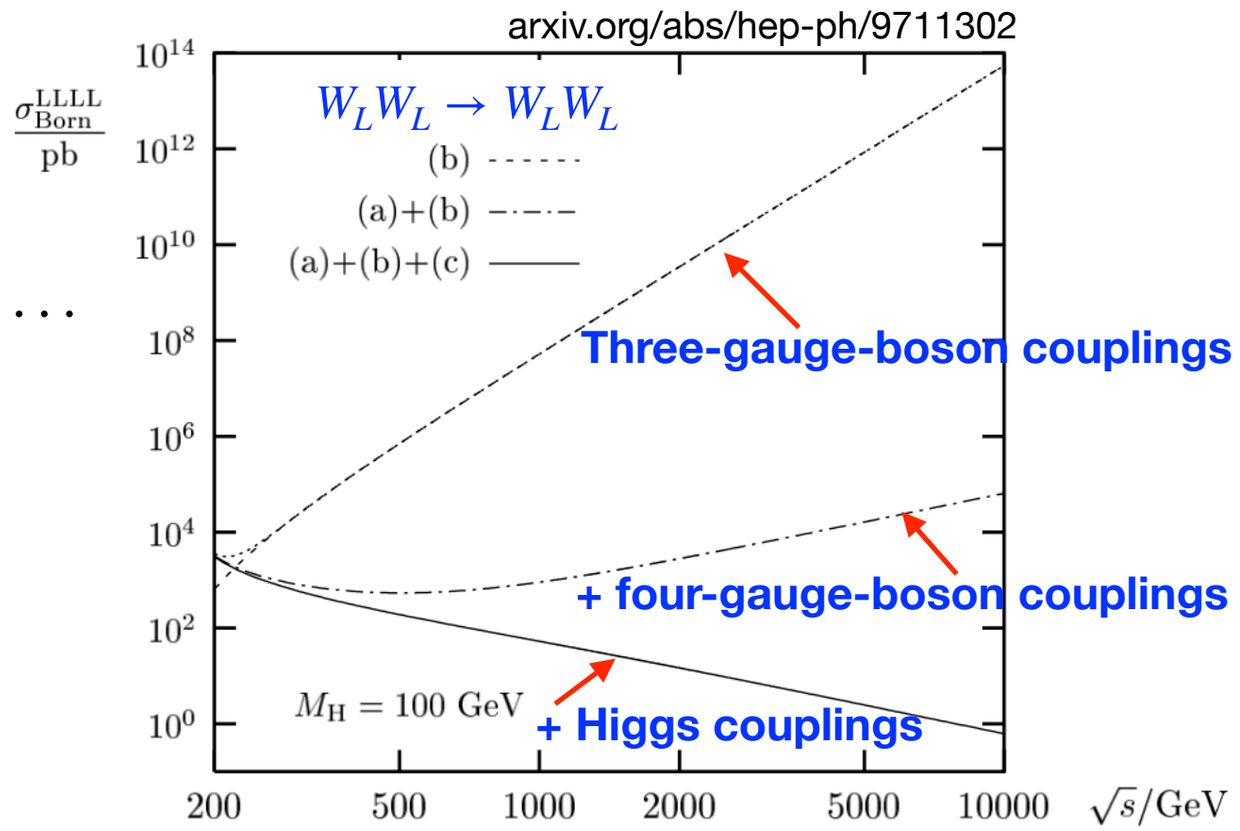
Complimentary to direct Higgs Boson measurement

- ☑ The perturbative cross section of longitudinal VBS ($V_L V_L \rightarrow V_L V_L$) diverges, if there was no Higgs boson or a similar mechanics

Sensitive to anomalous coupling

- ☑ Triple and quartic gauge coupling

$$\mathscr{L}_{EFT} = \mathscr{L}_{SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}^{(6)} + \frac{c_i^{(8)}}{\Lambda^2}\mathcal{O}^{(8)} + \ldots.$$

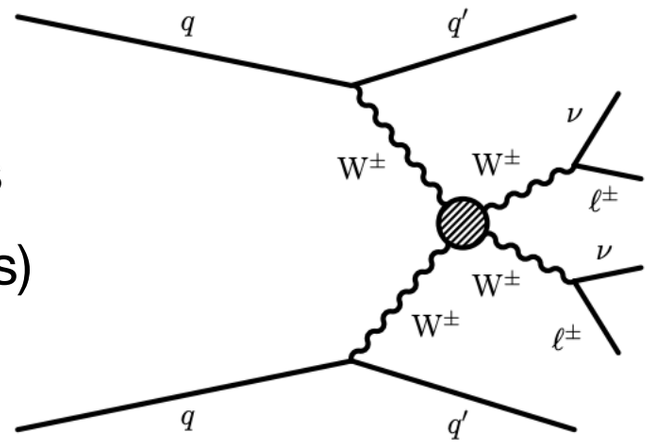


Recent VBS measurements from CMS

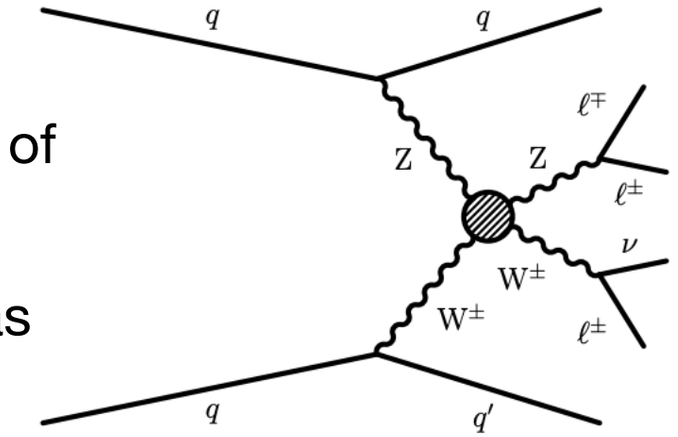
CADI	Analysis	Journal
SMP-20-016	**Zγjj**	**CDS preliminary result**
SMP-20-006	**Polarized W±W±jj**	**PLB 812 (2020) 136018**
SMP-20-001	**ZZjj**	**PLB 812 (2020) 135992**
SMP-19-008	**Wγjj (2016 data)**	**PLB 811 (2020) 135988**
SMP-19-012	**W±W±jj and WZjj**	**PLB 809 (2020) 135710**
SMP-18-007	Zγjj (2016 data)	JHEP 06 (2020) 076
SMP-18-006	VVjj (2016 data)	PLB 798 (2019)134985
SMP-18-001	WZjj (2016 data)	PLB 795 (2019) 281
SMP-17-004	W±W±jj (2016 data)	PRL 120 081801 (2018)
SMP-17-006	ZZjj (2016 data)	PLB 774 (2017) 682
SMP-16-018	Zjj (2016 data)	EPJC 78 (2018) 589

EW same-sign W±W±jj and WZjj production

CMS-**SMP-19-012** (Phys. Lett. B 809 (2020) 135710)

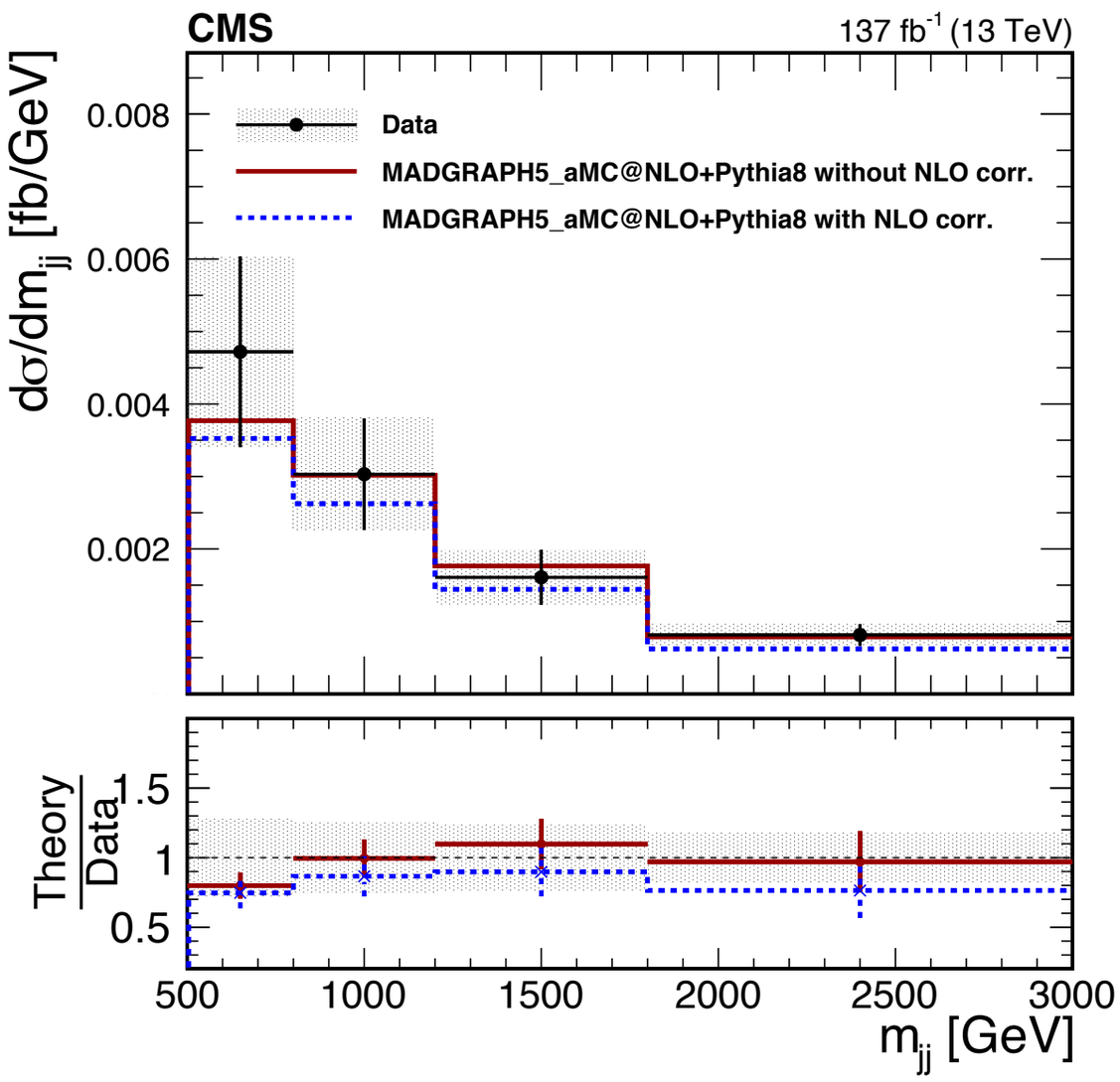


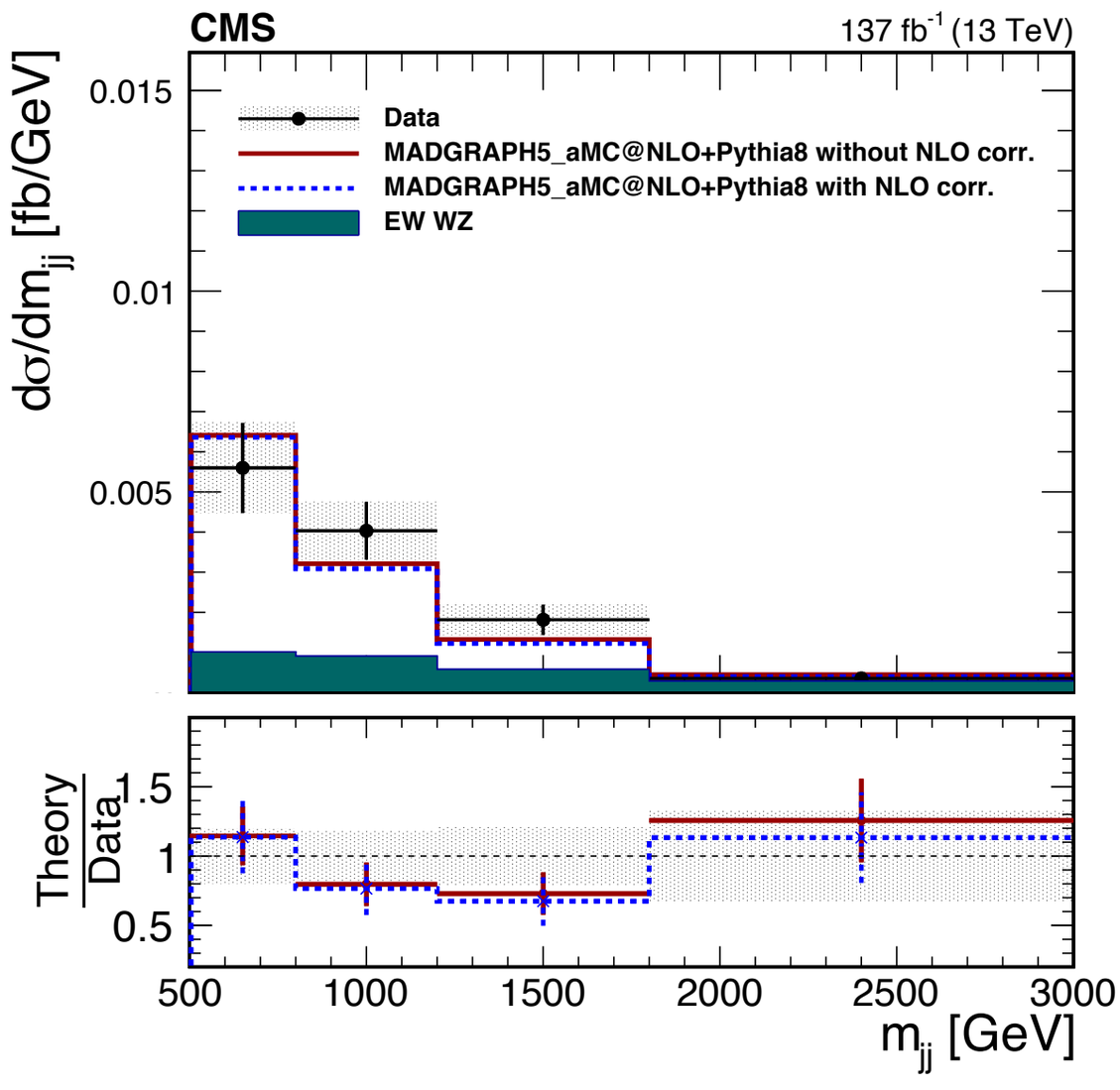
- Measurement of VBS W±W± and VBS WZ with fully leptonic final states
- Simultaneous fit in several signal regions (SRs) and control regions(CRs)
  - ☑ W±W± SR: $m_{jj} - m_{ll}$ 2D distributions
  - ☑ WZ SR: BDT discriminant variable
  - ☑ CRs to estimate the normalization of non-prompt leptons, tZq, and ZZ background processes
- Signal significance and cross section
  - ☑ W±W±: $\gg 5\sigma$; inclusive and differential cross section as functions of m_{jj}, m_{ll} and p_T^{max} in fiducial region
  - ☑ WZ: 6.8σ obs. (5.3σ exp.); inclusive and differential cross section as function of m_{jj} in fiducial region



Variable	W±W±	WZ
Leptons	2 leptons, $p_T > 25/20$ GeV	3 leptons, $p_T > 25/10/20$ GeV
p_T^j	>50 GeV	>50 GeV
$\lvert m_{\ell\ell} - m_Z \rvert$	>15 GeV (ee)	<15 GeV
$m_{\ell\ell}$	>20 GeV	—
$m_{\ell\ell\ell}$	—	>100 GeV
p_T^{miss}	>30 GeV	>30 GeV
b quark veto	Required	Required
$\max(z_\ell^*)$	<0.75	<1.0
m_{jj}	>500 GeV	>500 GeV
$\lvert \Delta\eta_{jj} \rvert$	>2.5	>2.5

EW same-sign $W^{\pm}W^{\pm}jj$ and $WZjj$ production



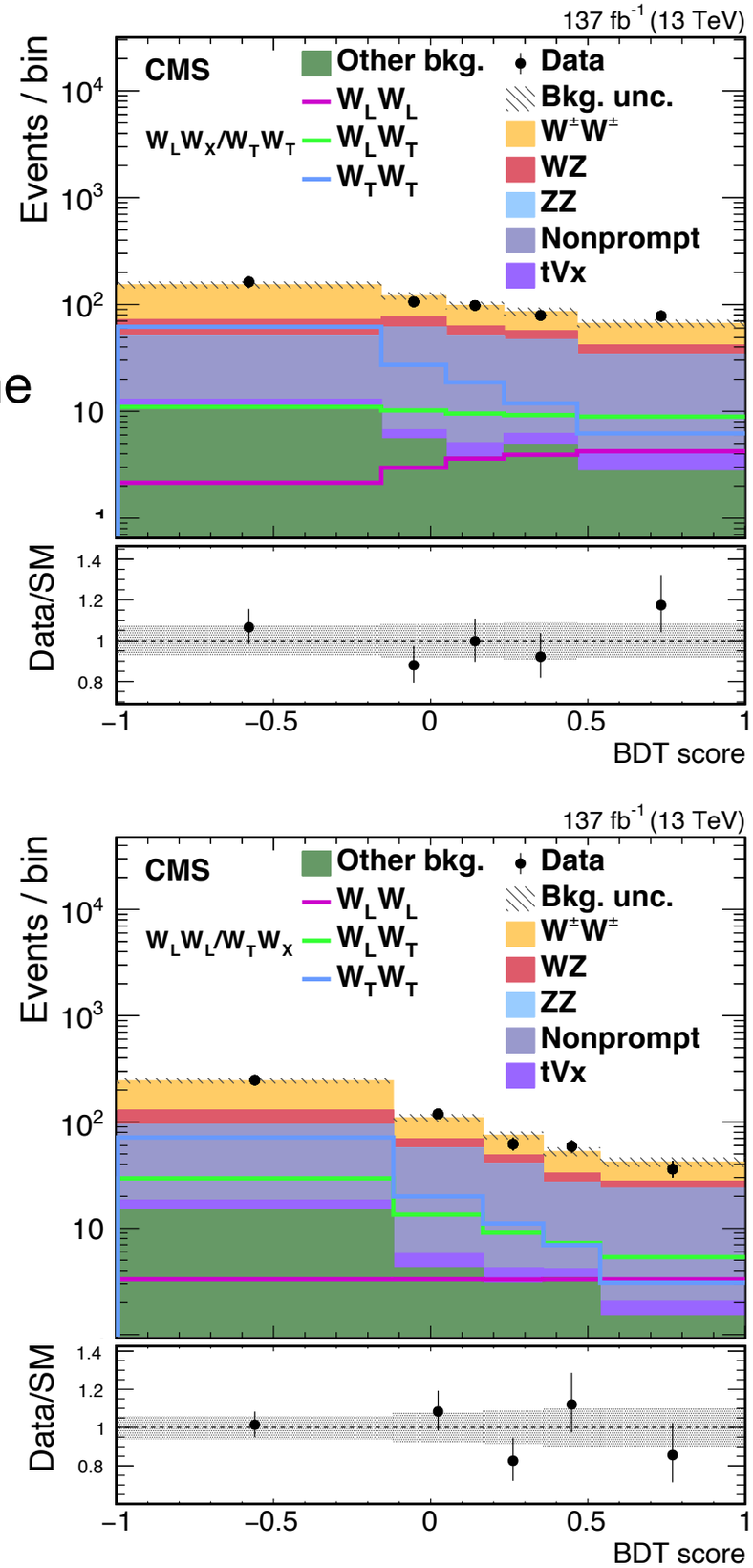


Process	$\sigma\,\mathcal{B}$ (fb)	Theoretical prediction without NLO corrections (fb)	Theoretical prediction with NLO corrections (fb)
EW $W^{\pm}W^{\pm}$	3.98 ± 0.45 (0.37 (stat) $\pm$ 0.25 (syst))	3.93 ± 0.57	3.31 ± 0.47
EW+QCD $W^{\pm}W^{\pm}$	4.42 ± 0.47 (0.39 (stat) $\pm$ 0.25 (syst))	4.34 ± 0.69	3.72 ± 0.59
EW WZ	1.81 ± 0.41 (0.39 (stat) $\pm$ 0.14 (syst))	1.41 ± 0.21	1.24 ± 0.18
EW+QCD WZ	4.97 ± 0.46 (0.40 (stat) $\pm$ 0.23 (syst))	4.54 ± 0.90	4.36 ± 0.88
QCD WZ	3.15 ± 0.49 (0.45 (stat) $\pm$ 0.18 (syst))	3.12 ± 0.70	3.12 ± 0.70

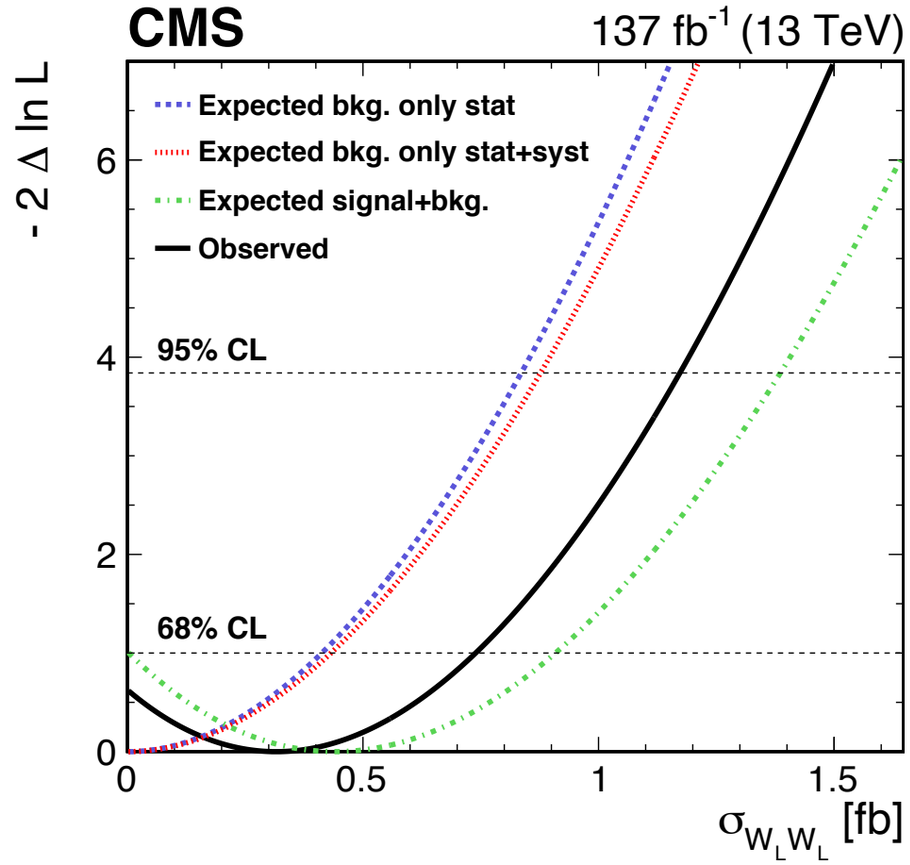
Polarized EW same-sign W±W±jj production

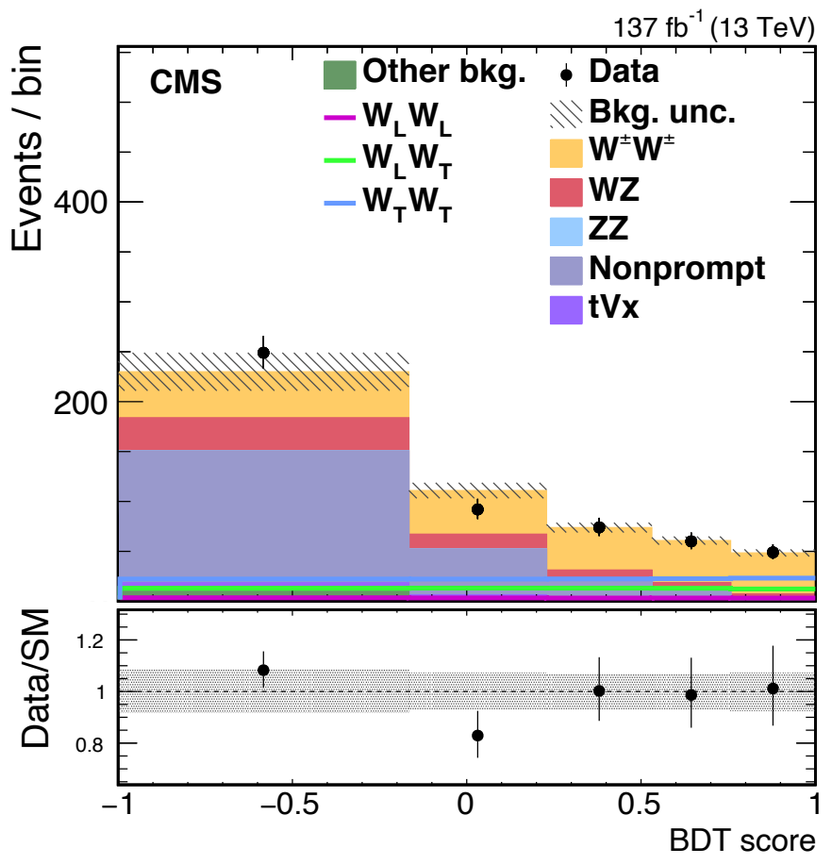
CMS-**SMP-20-006** **(**Phys. Lett. B 812 (2020) 136018)

- First measurement of the EW production cross sections for polarized same-sign W±W± boson pairs (based on SMP-19-012)
- Signal sample $W_L^{\pm}W_L^{\pm}$ simulated in WW/pp center-of-mass frame
- Simultaneous fit in bins of two BDT discriminant variables
  - ☑ $W_L^{\pm}\,W_L^{\pm}$: signal BDT ($W_L^{\pm}\,W_L^{\pm}$ vs $W_T^{\pm}W_X^{\pm}$) and inclusive BDT (VBS vs Bkg.)
  - ☑ $W_L^{\pm}\,W_X^{\pm}$: signal BDT ($W_L^{\pm}\,W_X^{\pm}$ vs $W_T^{\pm}W_T^{\pm}$) and inclusive BDT (VBS vs Bkg.)
  - ☑ Selection and CRs are same as EW W±W± production (SMP-19-012)
- Signal significance and cross section
  - ☑ WW frame
  - ☑ pp frame



Polarized EW same-sign $W^{\pm}W^{\pm}jj$ production





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

☑ WW frame

Observed (expected) limit of 1.17 (0.88) fb for $W_L^{\pm}\ W_L^{\pm}$;

Observed (expected) significance 2.3σ (3.1σ) for $W_L^{\pm}\ W_X^{\pm}$

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

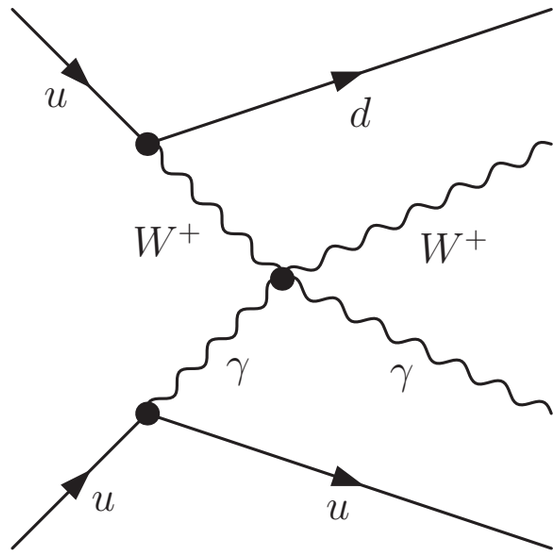
☑ pp frame

Observed (expected) limit of 1.06 (0.85) fb for $W_L^{\pm}\ W_L^{\pm}$;

Observed (expected) significance 2.6σ (2.9σ) for $W_L^{\pm}\ W_X^{\pm}$

EW Wγjj production

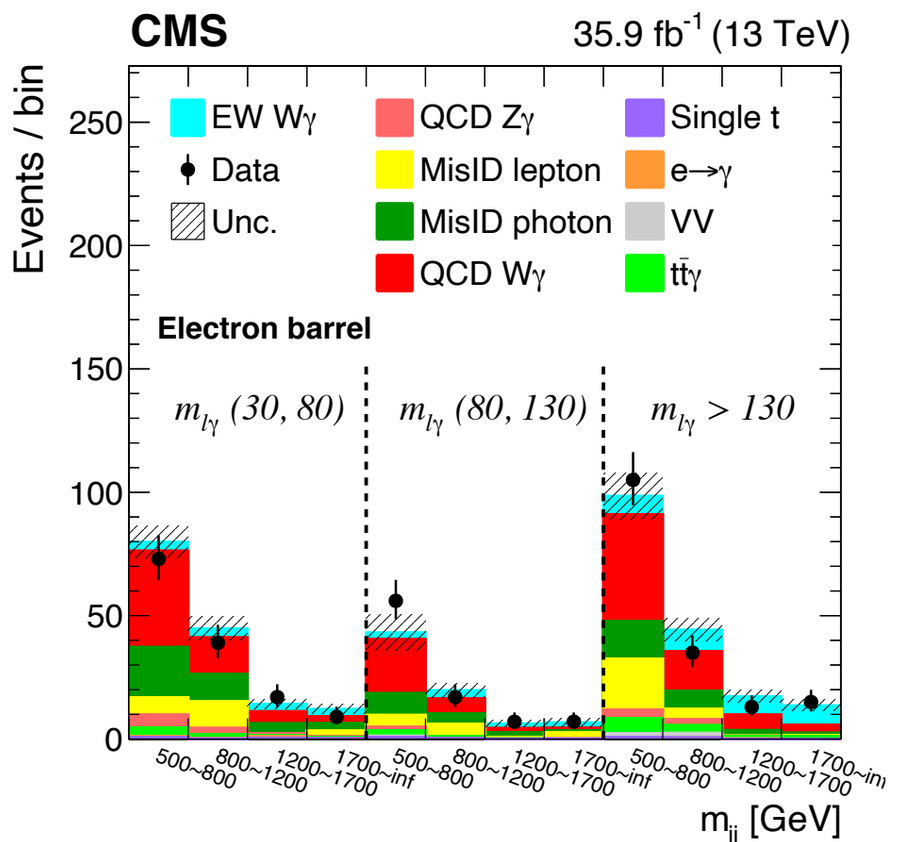
CMS-**SMP-19-008** (Phys. Lett. B 811 (2020) 135988)



- First observation of the VBS Wγ production with leptonic final states
- Signal events are extracted from 2D m_{jj}-$m_{l\gamma}$ distribution
  - ☑ Simultaneous fit in the CR and SR
- Signal significance and cross section
  - ☑ Observed (expected) significance 5.3σ (4.8σ) (13 TeV+8TeV)
  - ☑ Fiducial cross section are measured as:

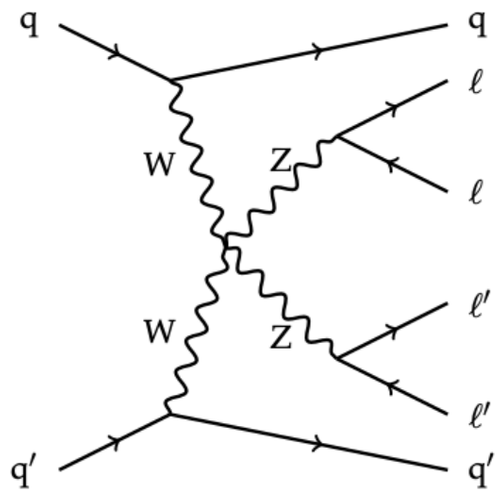
$$\sigma_{EW} = 20.4 \pm 4.5\,\text{fb} \qquad \sigma_{EW}^{theory} = 17.0 \pm 4.1\,\text{fb}$$

$$\sigma_{EW+QCD} = 108 \pm 16\,\text{fb} \qquad \sigma_{EW+QCD}^{theory} = 89.7 \pm 13.9\,\text{fb}$$



EW ZZjj production

CMS-**SMP-20-001** (Phys. Lett. B 812 (2020) 135992)



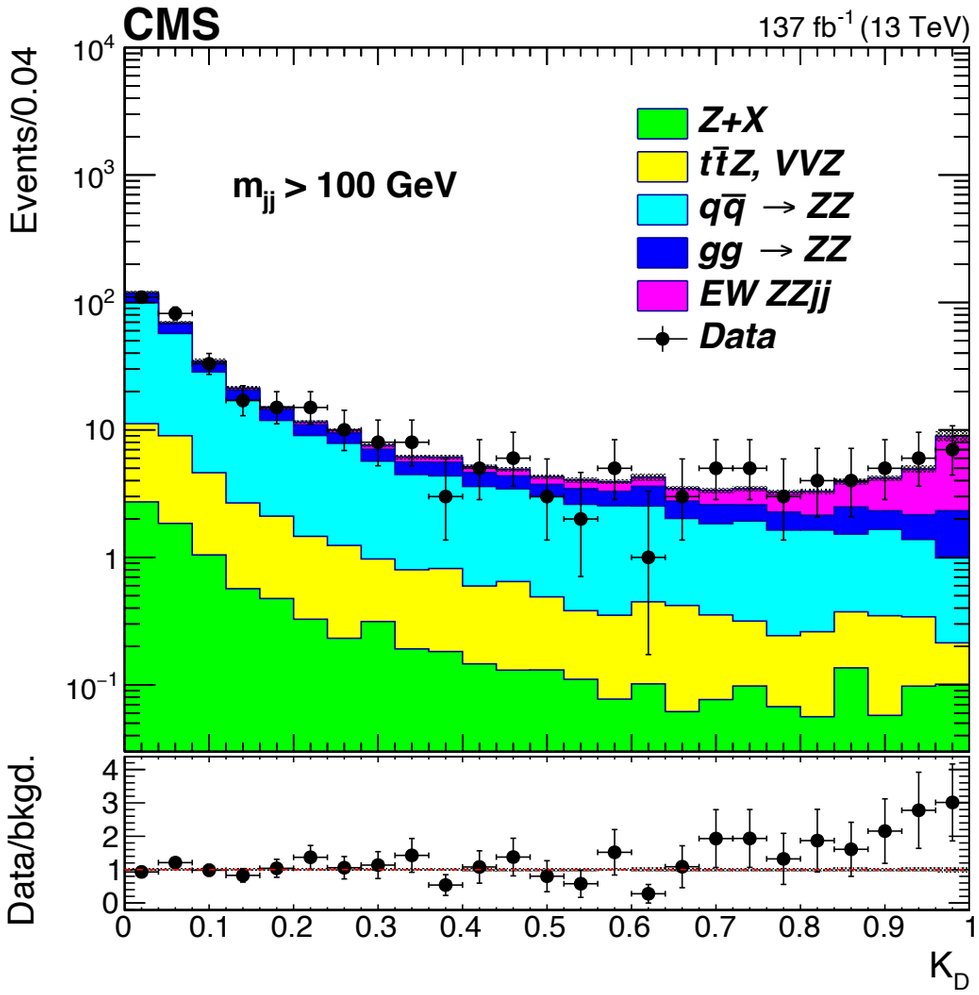
- Evidence of VBS ZZ production with fully leptonic final states
- Irreducible background $q\bar{q}\rightarrow$ZZjj simulated in NLO, loop-induced production gg → ZZjj simulated at LO
  - ☑ K-factor from higher order applied
- Signal events are extracted from the K_D discriminant distribution.
  - ☑ A matrix-element discriminant K_D is used to separate the signal and QCD background. (Similar sensitivity with BDT).

$$[1 + c(m_{4l})\frac{P_{QCD}(\vec{\Omega}^{4l+jj} \,|\, m_{4l})}{P(VBS)(\vec{\Omega}^{4l+jj} \,|\, m_{4l})}]^{-1}$$

- Fiducial cross section is measured in the three phase-spaces
  - ☑ ZZjj inclusive
  - ☑ Loose VBS-enriched
  - ☑ Tight VBS-enriched

Particle type	Selection
ZZjj inclusive	
Leptons	$p_T(\ell_1) > 20\,GeV$ $p_T(\ell_2) > 10\,GeV$ $p_T(\ell) > 5\,GeV$ $\lvert\eta(\ell)\rvert < 2.5$
Z and ZZ	$60 < m(\ell\ell) < 120\,GeV$ $m(4\ell) > 180\,GeV$
Jets	at least 2 $p_T(j) > 30\,GeV$ $\lvert\eta(j)\rvert < 4.7$ $m_{jj} > 100\,GeV$ $\Delta R(\ell, j) > 0.4$ for each ℓ,j
VBS-enriched (loose)	
Jets	ZZjj inclusive + $\lvert\Delta\eta_{jj}\rvert > 2.4$ $m_{jj} > 400\,GeV$
VBS-enriched (tight)	
Jets	ZZjj inclusive + $\lvert\Delta\eta_{jj}\rvert > 2.4$ $m_{jj} > 1\,TeV$

EW ZZjj production



	Perturbative order	SM σ (fb)	Measured σ (fb)
		ZZjj inclusive	
EW	LO	0.275 ± 0.021	
	NLO QCD	0.278 ± 0.017	$0.33^{+0.11}_{-0.10}\,(\text{stat})^{+0.04}_{-0.03}\,(\text{syst})$
	NLO EW	$0.242^{+0.015}_{-0.013}$	
EW+QCD		5.35 ± 0.51	$5.29^{+0.31}_{-0.30}\,(\text{stat}) \pm 0.47\,(\text{syst})$
		VBS-enriched (loose)	
EW	LO	0.186 ± 0.015	
	NLO QCD	0.197 ± 0.013	$0.180^{+0.070}_{-0.060}\,(\text{stat})^{+0.021}_{-0.012}\,(\text{syst})$
EW+QCD		1.21 ± 0.09	$1.00^{+0.12}_{-0.11}\,(\text{stat}) \pm 0.07\,(\text{syst})$
		VBS-enriched (tight)	
EW	LO	0.104 ± 0.008	
	NLO QCD	0.108 ± 0.007	$0.09^{+0.04}_{-0.03}\,(\text{stat}) \pm 0.02\,(\text{syst})$
EW+QCD		0.221 ± 0.014	$0.20^{+0.05}_{-0.04}\,(\text{stat}) \pm 0.02\,(\text{syst})$

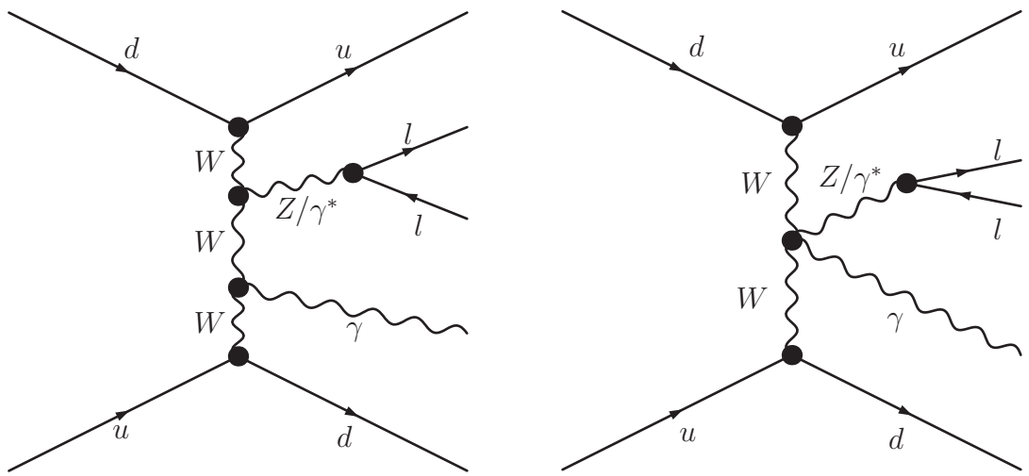
Year	Signal (EW ZZjj)	Z+X	$q\bar{q} \rightarrow$ZZjj	gg$\rightarrow$ZZjj	$t\bar{t}$Z+VVZ	Total predicted	Data
			ZZjj inclusive				
All (137)	24.1 ± 2.5	9.4 ± 3.6	241.5 ± 34.9	62.9 ± 9.3	32.2 ± 8.5	370 ± 48	365
			VBS signal-enriched (loose)				
All (137)	16.0 ± 1.7	1.6 ± 0.6	38.1 ± 5.5	17.0 ± 2.5	4.1 ± 1.1	76.8 ± 9.3	68
			VBS signal-enriched (tight)				
All (137)	9.0 ± 1.0	0.32 ± 0.12	5.3 ± 0.8	3.3 ± 0.5	0.68 ± 0.18	18.6 ± 2.1	17

- The high signal purity contribution is visible at large discriminant values
- Observed (expected) signal significance 4.0 (3.5) standard deviations.
- The fiducial cross section in three regions are measured

EW Zγjj production

CMS-**SMP-20-016** Preliminary result available

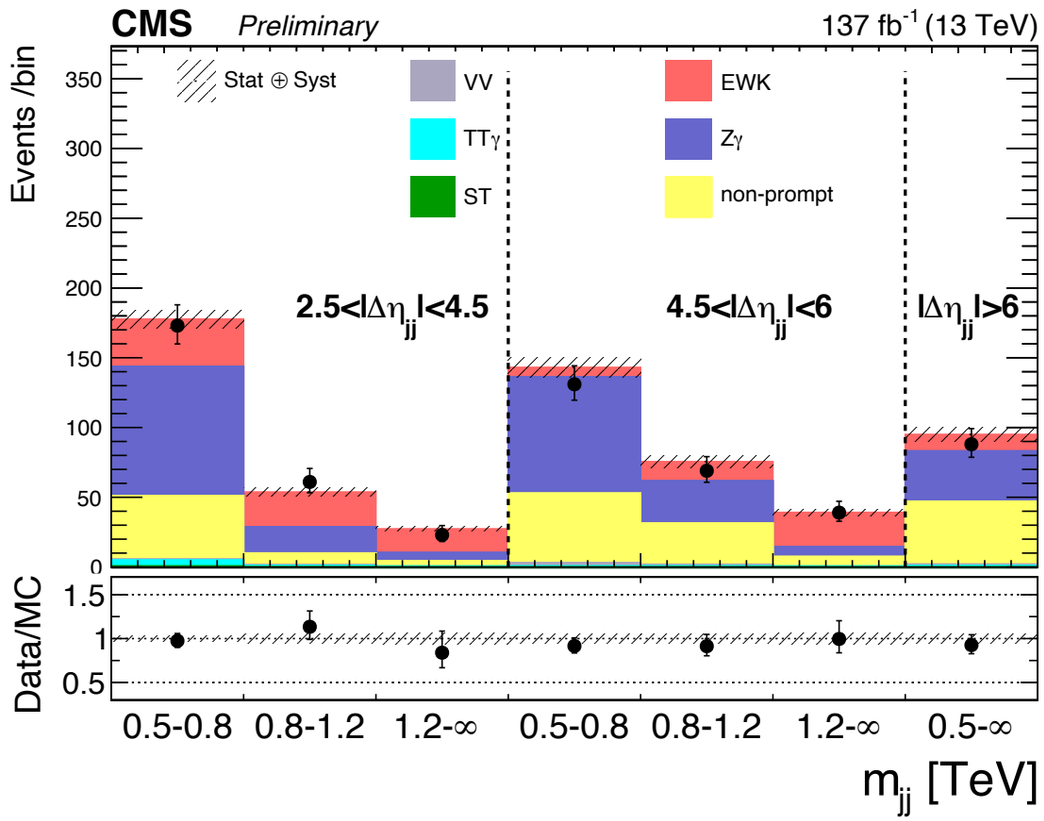
- First observation of the VBS Zγ production with leptonic final states
- Simultaneous fit in the control region(CR) and signal region(SR)
  - ☑ SR: 2D m_{jj}- $|\Delta\eta_{jj}|$ distribution
  - ☑ CR: 1D m_{jj} distribution

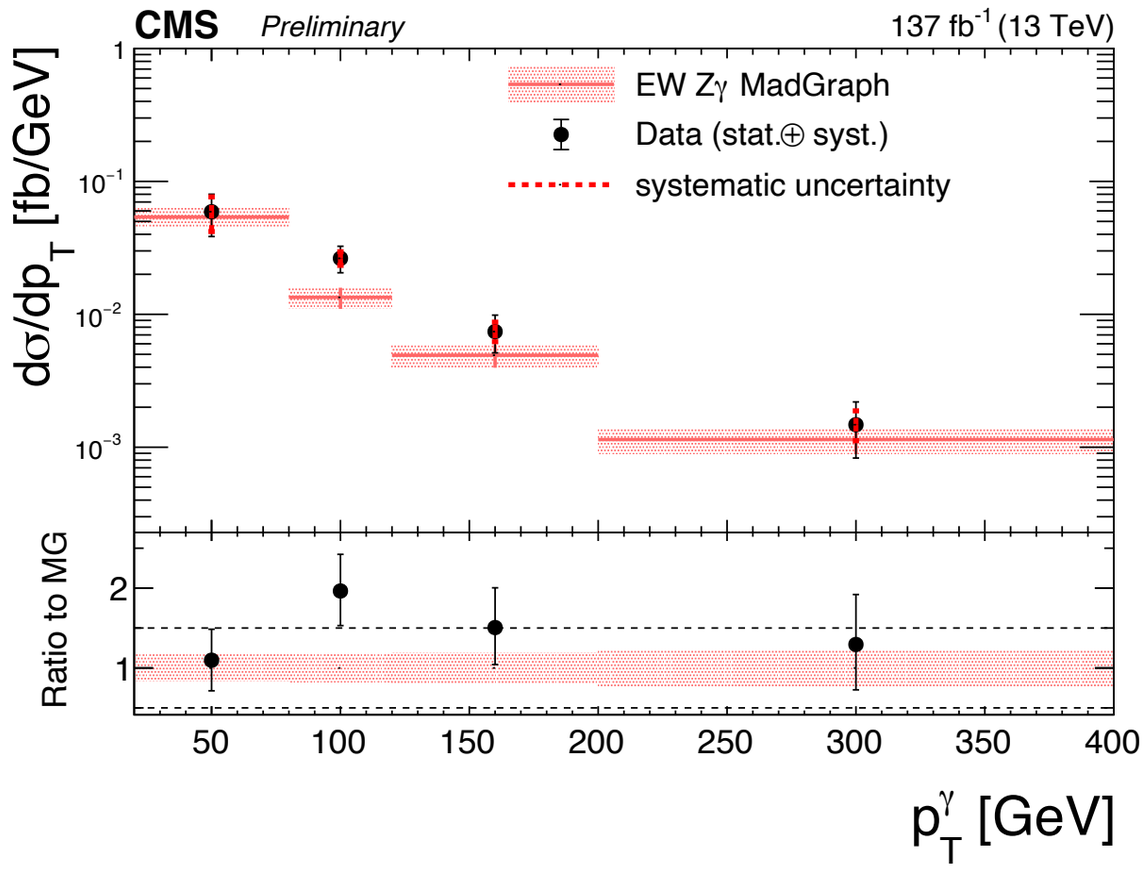


- Signal significance and cross section
  - ☑ Observed (expected) significance far than 5σ
  - ☑ Fiducial cross section for EW and EW+QCD
  - ☑ Differential cross section for EW/EW+QCD as functions of 1D variables $p_T^{l_1}$, $p_T^{j_1}$, p_T^{γ} and 2D variable m_{jj}- $|\Delta\eta_{jj}|$

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 $p_T^{\gamma} > 20\text{GeV}$, $\lvert\eta^{\gamma}\rvert < 1.442$ or $1.566 < \lvert\eta^{\gamma}\rvert < 2.500$ $p_T^{\text{j1,j2}} > 30\text{GeV}$, $\lvert\eta^{\text{j1,j2}}\rvert < 4.7$ $70 < m_{\ell\ell} < 110\text{GeV}$, $m_{\text{Z}\gamma} > 100\text{GeV}$ ΔR_{jj}, $\Delta R_{\text{j}\gamma}$, $\Delta R_{\text{j}\ell} > 0.5$, $\Delta R_{\ell\gamma} > 0.7$
Control region	Common selection, $150 << 500\text{GeV}$
EW signal region	Common selection, $> 500\text{GeV}$, $\lvert\Delta\eta_{\text{jj}}\rvert > 2.5$, $\eta^{*} < 2.4$, $\Delta\phi_{\text{Z}\gamma,\text{jj}} > 1.9$
Fiducial volume	Common selection, $> 500\text{GeV}$, $\lvert\Delta\eta_{\text{jj}}\rvert > 2.5$
aQGC search region	Common selection, $> 500\text{GeV}$, $\lvert\Delta\eta_{\text{jj}}\rvert > 2.5$, $p_T^{\gamma} > 120\text{GeV}$

EW Zγjj production





$$\sigma_{\mathrm{EW}}^{\mathrm{theory}} = 4.34 \pm 0.26\,(\mathrm{scale}) \pm 0.06\,(\mathrm{PDF})\,\mathrm{fb}$$

$$\sigma_{\mathrm{EW}}^{\mathrm{fid}} = 5.21 \pm 0.52\,(\mathrm{stat}) \pm 0.56\,(\mathrm{syst})\,\mathrm{fb} = 5.21 \pm 0.76\,\mathrm{fb}$$

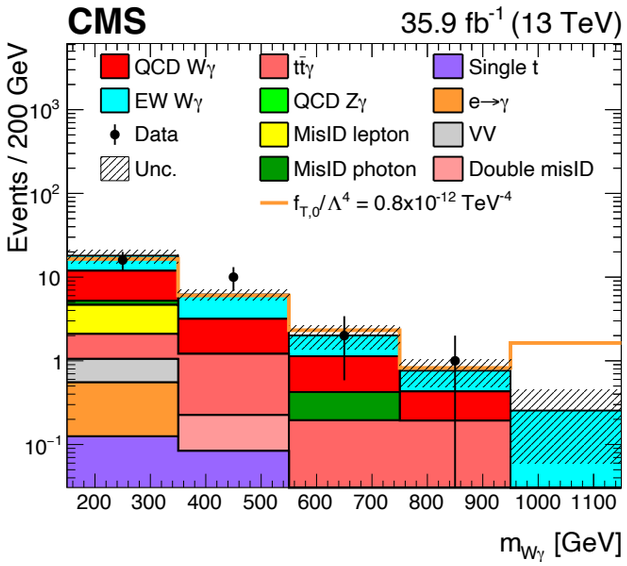
$$\sigma_{\mathrm{EW+QCD}}^{\mathrm{theory}} = 13.3 \pm 1.72\,(\mathrm{scale}) \pm 0.10\,(\mathrm{PDF})\,\mathrm{fb}$$

$$\sigma_{\mathrm{EW+QCD}}^{\mathrm{fid}} = 14.7 \pm 0.80\,(\mathrm{stat}) \pm 1.26\,(\mathrm{syst})\,\mathrm{fb} = 14.7 \pm 1.53\,\mathrm{fb}$$

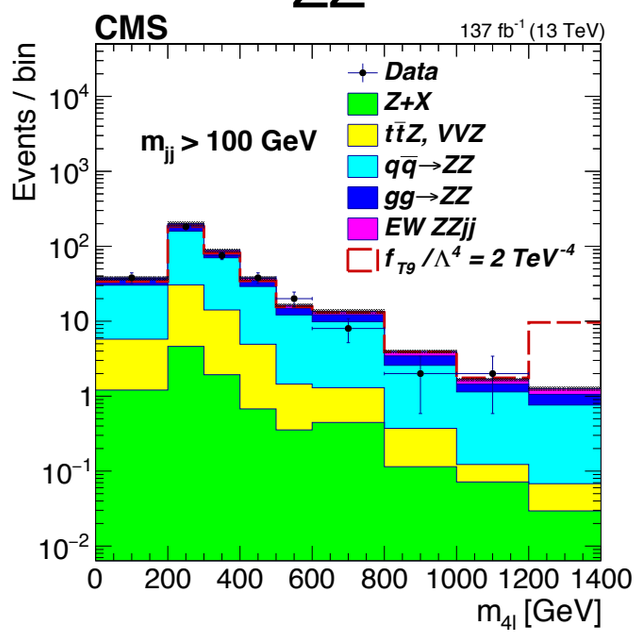
Anomalous coupling

- Limits on aQGCs are set by EFT approach.
- Dimension-8 operators that can modify the VVjj production through aQGCs are considered
- The di-boson system is sensitive to aQGCs
- The most stringent limits to date on the aQGC parameters:
  - ☑ $f_{M_{2-5}}$ and $f_{T_{5-7}}$ from Wγ
  - ☑ f_{T_8} from ZZ
  - ☑ f_{T_9} from Zγ
  - ☑ f_{T_2} from W±W± is competitive with WV ZV.

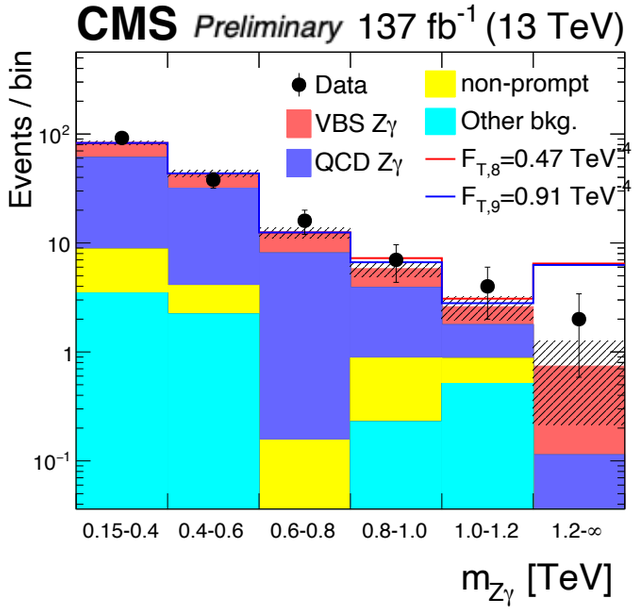
Wγ



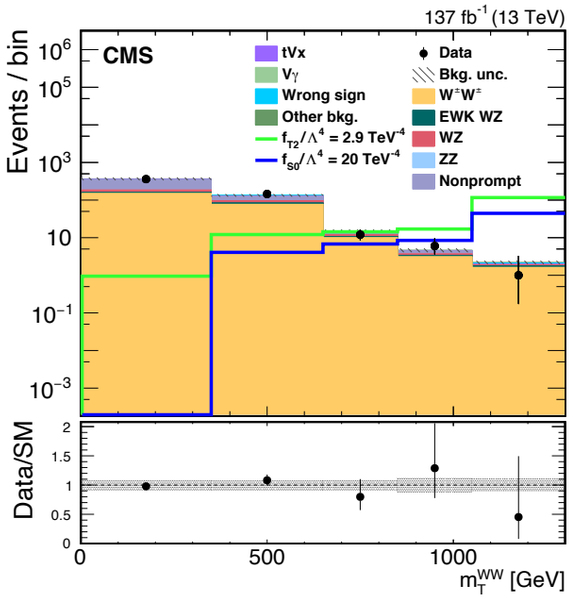
ZZ



Zγ



W±W±



Summary

- The first polarized same-sign $W^{\pm}W^{\pm}$ measurement
- The first observation of EW production of WZ (CMS), Zγ and Wγ
- Fiducial cross-sections are measured in all channels
- Differential cross sections as functions of interesting variables are measured in EW production of $W^{\pm}W^{\pm}$, WZ, and Zγ
- AQGC limits on dimension 8 operators are set
  - ☑ Several of the most stringent limits are provided by VBS