Recent CMS Results on Vector Boson Scattering

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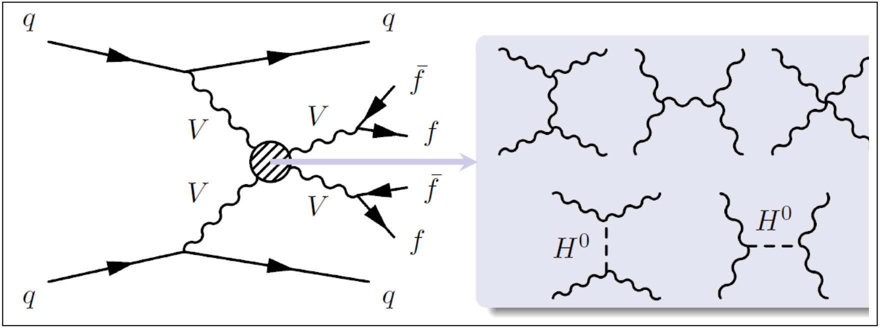
CERN LPCC EP-LHC Seminar, 10 Nov. 2020

Characterized by VVjj ($\mathrm{V} = \mathrm{W/Z}$) final state:

triple and quartic gauge couplings (QGCs)



Higgs boson exchange and Higgs boson production via VBS

- Sensitivity to QGC $\rightarrow$ setting exclusion limits on aQGCs
- Contributions to the final state (at leading order):
  - Electroweak (EW) = $O(\alpha_{EW}^6)$
  - QCD = $O(\alpha_{EW}^4 \alpha_S^2)$
  - Interference: $O(\alpha_{EW}^5 \alpha_S)$

Important Measurements

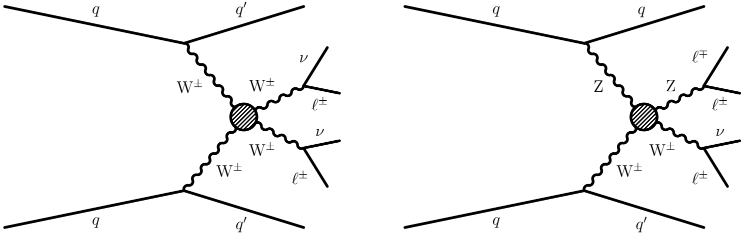
- Electroweak di(tri)boson measurements:
  - test of the EW sector of the Standard Model (SM) at the TeV scale
  - sensitive to Anomalous Triple (Quartic) Gauge Couplings (aTGC/aQGC)
  - background to other analyses
  - VV scattering $\rightarrow$ (massive, weak) VBS:
    - measurable key process linked with Electro-Weak Symmetry Breaking (EWSB)
    - general final state: diboson plus at least two jets
- VBS at the LHC is the key process to experimentally probe the SM nature of EWSB:
  - complementary to direct Higgs boson measurements

VV Scattering Event Topology

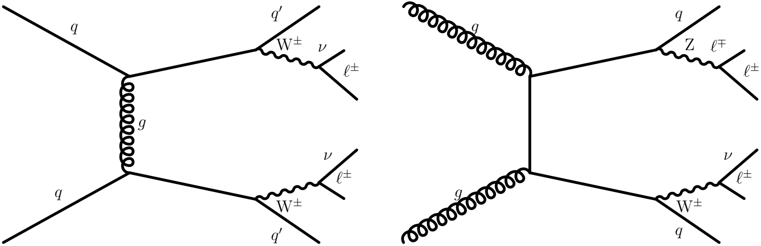
- Diboson final states:
  - fully leptonic:
    - $\mathrm{W^{\pm}W^{\pm}} \to \ell^{\pm}\nu\ell^{\pm}\nu$: best σ_{EW}/σ_{QCD} ratio
    - $\mathrm{W^{\pm}W^{\mp}} \to \ell^{\pm}\nu\ell^{\mp}\nu$: relatively large top-quark background
    - $\mathrm{W^{\pm}Z} \to 3\ell\nu$: clean channel with three leptons
    - $\mathrm{ZZ} \to 4\ell$: very clean, limited number of events
    - $\mathrm{ZZ} \to 2\ell 2\nu$: more difficult analysis to perform, but relatively large branching ratio
  - semi-leptonic/hadronic: $\mathrm{ZW/ZZ} \to \ell\ell\mathrm{jj}$, $\mathrm{WW/WZ} \to \ell\nu jj$, $\mathrm{ZZ/WW} \to \mathrm{jjjj}$, $\mathrm{ZZ/WZ} \to \mathrm{jj}\nu\nu$
    - more difficult due to larger backgrounds, powerful for aQGC searches
    - high m_{VV} generates boosted jets which can be merged
  - photonic:
    - $\mathrm{Z}\gamma \to \ell^{\pm}\ell^{\mp}\gamma$: relatively clean, except QCD-induced background
    - $\mathrm{W}\gamma \to \ell\nu\gamma$: larger signal, but larger nonprompt background
- VBS topology:
  - two very energetic forward-backward tagging jets
  - large m_{jj} and $\Delta\eta_{jj}$
  - little hadronic activity between the two tagging jets in fully leptonic/photonic final states

Representative Feynman Diagrams

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

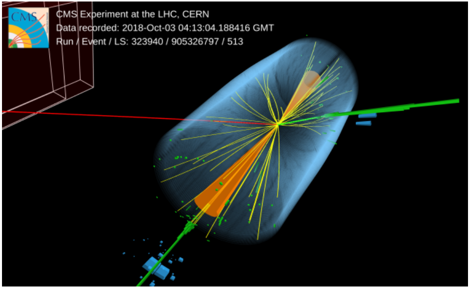


QCD-induced $W^{\pm}W^{\pm}jj$ and $WZjj$ production

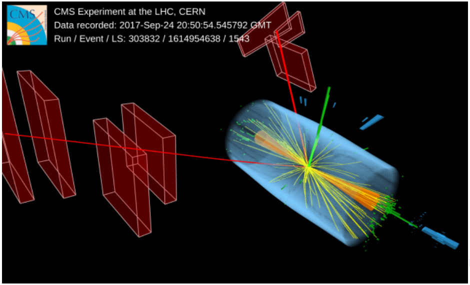


$W^{\pm}W^{\pm}jj$ and WZjj Data Candidates

$W^{+}W^{+}jj \to e^{+}\nu\mu^{+}\nu jj$ event



$W^{+}Zjj \to e^{+}\nu\mu^{+}\mu^{-}jj$ event



VBS Measurements in a Glance

- Select VVjj events with VBS-like jets
  - take into account specific final state
- Estimate non-VV backgrounds
  - combination of methods based in data and simulation
- Measure inclusive VVjj cross sections
  - EW+QCD production
  - EW production by discriminating against the QCD-induced production
  - cut-based (simpler) vs. multivariate (complex)
- Measure differential cross sections
  - need larger (and cleaner) data sets
- Search for new physics modifying VVV & VVVV interactions
  - generic effective field theory (EFT): e.g. aQGCs
  - explicit models: e.g. VBF $\mathrm{H}^{\pm\pm}$ and $\mathrm{H}^{\pm}$

$W^{\pm}W^{\pm}jj$ & WZjj Measurements

SMP-19-012

Arxiv:2005.01173

PLB 809 (2020) 135710

Overview

- First simultaneous $\mathrm{W^{\pm}W^{\pm}jj}$ & WZjj analysis using fully leptonic final states
- Select events in several signal regions (SRs) and control regions (CRs)
  - simultaneously measure $\mathrm{W^{\pm}W^{\pm}jj}$ & WZjj production
  - measure normalization of main background processes in situ
- Focus on:
  - measurements of $\mathrm{W^{\pm}W^{\pm}jj}$ (EW and EW+QCD) and WZjj (EW, EW+QCD, and QCD) inclusive fiducial cross sections
  - differential cross sections for EW+QCD production
  - anomalous couplings searches

$W^{\pm}W^{\pm}jj$ & WZjj Event Selection

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

$$z_\ell^* = \left| \eta^\ell - \frac{\eta^{j_1} + \eta^{j_2}}{2} \right| / \lvert \Delta\eta_{jj} \rvert$$

Tight lepton selection to reduce nonprompt lepton background

Only electrons and muons are considered

BDT to Discriminate EW & QCD WZjj Production

- Enhance WZjj EW production w.r.t larger WZjj QCD production
  - $\sigma_{EW}/\sigma_{QCD} \sim 1/2$
- 13 input variables retained out of a larger set tested
  - jet kinematics, vector boson kinematics, and vector boson - jet mix
- Improved sensitivity w.r.t. using m_{jj}–$|\Delta\eta_{jj}|$ by ~20%

Variable	Definition
m_{jj}	Mass of the leading and trailing jets system
$\lvert\Delta\eta_{jj}\rvert$	Absolute difference in rapidity of the leading and trailing jets
$\Delta\phi_{jj}$	Absolute difference in azimuthal angles of the leading and trailing jets
p_T^{j1}	p_T of the leading jet
p_T^{j2}	p_T of the trailing jet
η^{j1}	Pseudorapidity of the leading jet
$\lvert\eta^W - \eta^Z\rvert$	Absolute difference between η^W and η^Z
$z^*_{\ell_i}(i = 1-3)$	Zeppenfeld variable of the three selected leptons
$z^*_{3\ell}$	Zeppenfeld variable of the vector sum of the three leptons
$\Delta R_{j1,Z}$	ΔR between the leading jet and the Z boson
$\lvert\vec{p_T}^{tot}\rvert / \sum_i p_T^i$	Vector sum p_T normalized to their scalar p_T sum

Background Estimation & Analysis Strategy

- Combination of data-driven methods and detailed simulation studies to estimate backgrounds
  - nonprompt lepton background estimated from data, in addition to a CR
  - charge misidentification electron rate estimated using $\mathrm{Z} \rightarrow \mathrm{ee}$
  - ZZ and $t\mathrm{Z}q$ backgrounds normalized with CRs
  - other small background processes from simulation
- Analysis strategy: single fit with the following regions
  - $\mathrm{W}^{\pm}\mathrm{W}^{\pm}\mathrm{jj}$ SR: 2D $m_{jj} - m_{\ell\ell}$
  - WZjj SR: BDT
  - nonprompt lepton background CR (inverting b-tagging): m_{jj}
  - $t\mathrm{Z}q$ CR (inverting b-tagging): m_{jj}
  - ZZ CR (4 leptons): m_{jj}

Yields & Significance

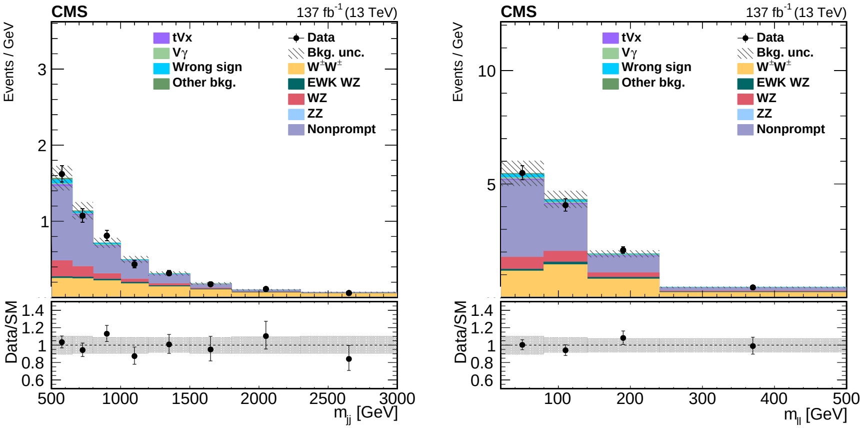
Expected yields from SM processes and observed data events in $W^{\pm}W^{\pm}jj$ and WZjj SRs. Expected yields are shown before the fit to the data (pre-fit) and with their best fit normalizations from the simultaneous fit (post-fit)

Process	$W^{\pm}W^{\pm}jj$ SR		WZjj SR	
	Pre-fit	Post-fit	Pre-fit	Post-fit
EW $W^{\pm}W^{\pm}jj$	209 ± 22	210 ± 26	–	–
QCD $W^{\pm}W^{\pm}jj$	13.6 ± 2.3	13.7 ± 2.2	–	–
Interference $W^{\pm}W^{\pm}jj$	8.4 ± 2.3	8.7 ± 2.3	–	–
EW WZjj	14.1 ± 1.7	17.8 ± 3.9	54.3 ± 5.7	69 ± 15
QCD WZjj	42.9 ± 4.7	42.7 ± 7.4	117.9 ± 6.8	117 ± 17
Interference WZjj	0.3 ± 0.1	0.3 ± 0.2	2.2 ± 0.6	2.7 ± 1.0
ZZ	0.7 ± 0.1	0.7 ± 0.2	6.1 ± 0.4	6.0 ± 1.8
Nonprompt	211 ± 55	193 ± 40	14.6 ± 7.6	14.4 ± 6.7
tVx	9.0 ± 3.1	7.4 ± 2.2	15.1 ± 1.9	14.3 ± 2.8
$W\gamma$	7.8 ± 2.0	9.1 ± 2.9	1.1 ± 0.5	1.1 ± 0.4
Wrong-sign	13.5 ± 7.1	13.9 ± 6.5	1.6 ± 0.7	1.7 ± 0.7
Other background	5.0 ± 2.4	5.2 ± 2.1	3.3 ± 0.7	3.3 ± 0.7
Total SM	535 ± 60	522 ± 49	216 ± 12	229 ± 23
Data	524		229	

EW WZjj observed (expected) statistical significance: 6.8 (5.3) s.d.

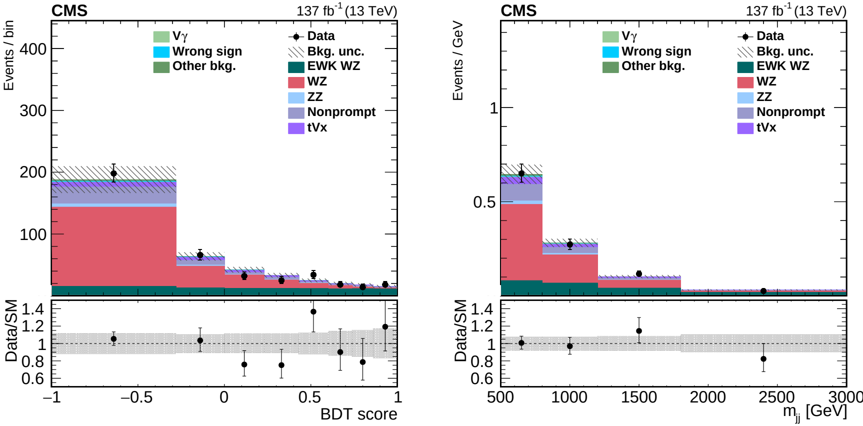
EW $W^{\pm}W^{\pm}jj$ statistical significance: $\gg$ 5 s.d.

Distributions in $W^\pm W^\pm jj$ SR



- m_{jj} (left) & $m_{\ell\ell}$ (right) distributions used in the main fit
- Several other distributions shown in back-up

Distributions in WZjj SR



- Flat distribution of EW WZjj production by construction
- Comparison of BDT (left) vs. m_{jj} (right)

Systematic Uncertainties in Inclusive Cross Sections

Source of uncertainty	$W^{\pm}W^{\pm}jj$ (%)	WZjj (%)
Integrated luminosity	1.5	1.6
Lepton measurement	1.8	2.9
Jet energy scale and resolution	1.5	4.3
Pileup	0.1	0.4
b tagging	1.0	1.0
Nonprompt rate	3.5	1.4
Trigger	1.1	1.1
Limited sample size	2.6	3.7
Theory	1.9	3.8
Total systematic uncertainty	5.7	7.9
Statistical uncertainty	8.9	22
Total uncertainty	11	23

- Statistically limited measurements

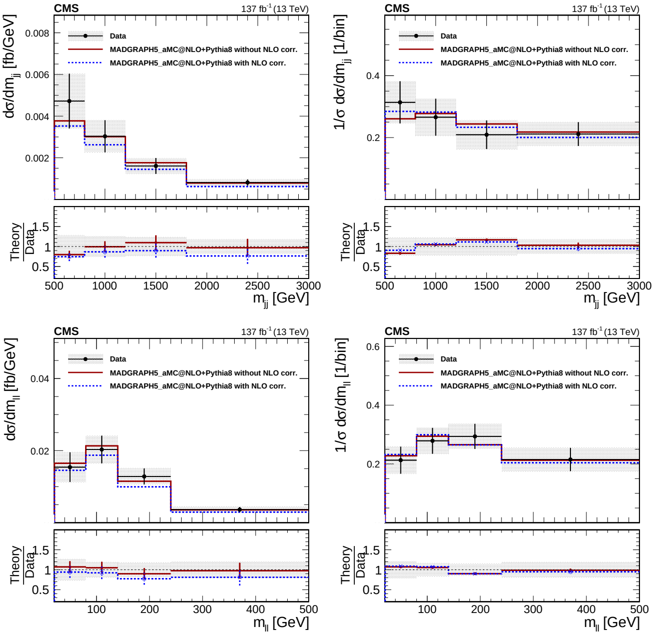
Inclusive Fiducial Cross Sections

- $W^{\pm}W^{\pm}jj$ fiducial region:
  - two same-sign leptons with $p_T > 20\text{GeV}$, $|\eta| < 2.5$, and $m_{\ell\ell} > 20\text{GeV}$
  - two jets with $m_{jj} > 500\text{GeV}$ and $|\Delta\eta_{jj}| > 2.5$
- WZjj fiducial region:
  - three leptons with $p_T > 20\text{GeV}$, $|\eta| < 2.5$, and an opposite charge same-flavor lepton pair with $|m_{\ell\ell} - m_Z| < 15\text{GeV}$
  - two jets with $m_{jj} > 500\text{GeV}$ and $|\Delta\eta_{jj}| > 2.5$

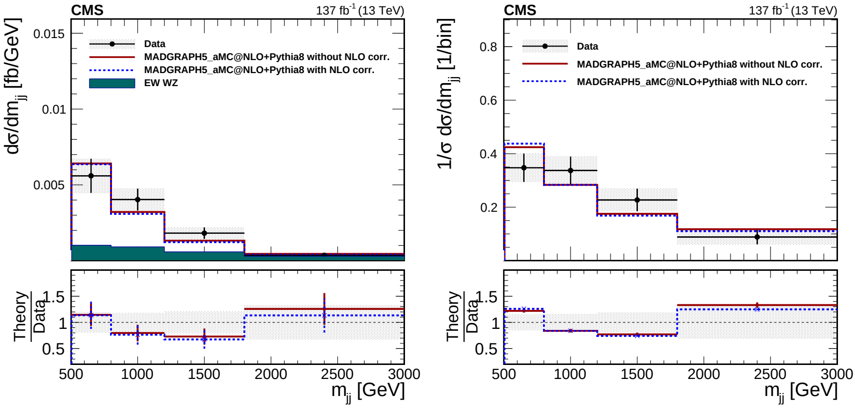
Process	$\sigma\mathcal{B}$ (fb)	Theoretical prediction without NLO corrections (fb)	Theoretical prediction with NLO corrections (fb)
EW $W^{\pm}W^{\pm}$	3.98 ± 0.45 $0.37\,(\text{stat}) \pm 0.25\,(\text{syst})$	3.93 ± 0.57	3.31 ± 0.47
EW+QCD $W^{\pm}W^{\pm}$	4.42 ± 0.47 $0.39\,(\text{stat}) \pm 0.25\,(\text{syst})$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

- Measurement compatible with predictions within uncertainties

m_{jj} & $m_{\ell\ell}$ $W^{\pm}W^{\pm}jj$ Fiducial Cross Section Measurements



m_{jj} WZjj Fiducial Cross Section Measurements

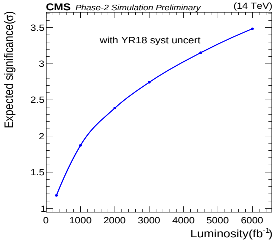


- Good agreement between data and prediction
- Performed by replacing BDT to m_{jj} in the fit

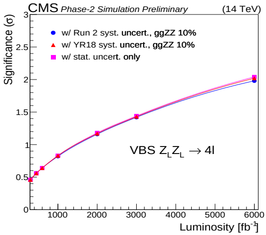
Polarized $W^{\pm}W^{\pm}$ Scattering

- Heavy vector V bosons acquire their mass through the Brout-Englert-Higgs mechanism
- Three polarization modes of V bosons: one longitudinal and two transverse
- The unitarity of the longitudinally polarized VBS at high energies is restored in the SM by a Higgs boson
    - Higgs boson contribution cancels cross section increase
    - provide complementary information to direct Higgs boson measurements

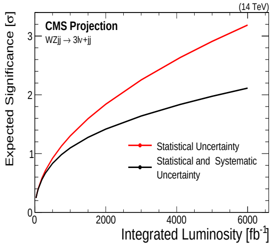
$W^{\pm}W^{\pm}jj$



$ZZjj$



$WZjj$



Polarized $W^{\pm}W^{\pm}jj$ Cross Sections

SMP-20-006

Arxiv:2009.09429

Overview

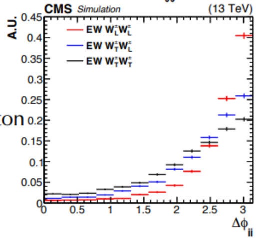
- First measurement of the EW production cross sections of the polarized VBS!
  - longitudinal scattering contributes to about $\sim$10% of the overall EW production
  - run 2 integrated luminosity opens up first possibilities to study polarization modes
- Analysis solely based on the previous discussed CMS-SMP-19-012 analysis
  - WZjj treated as another background in a simultaneous fit
  - Polarization configurations: EW $\mathrm{W^\pm_L W^\pm_L}$ (LL), EW $\mathrm{W^\pm_L W^\pm_T}$ (LT), and EW $\mathrm{W^\pm_T W^\pm_T}$ (TT)
- Measurements:
  - ideally, measure all three contributions separately
    - unreliable currently due to limited data sample size
  - provide two maximum-likelihood fits
    - LL and XT (X = L or T) / LX and TT (X = L or T)
  - two sets reported with the helicity eigenstates defined
    - in the $\mathrm{W^\pm W^\pm}$ center-of-mass (c.m.) frame
    - in the initial-state parton-parton c.m frame

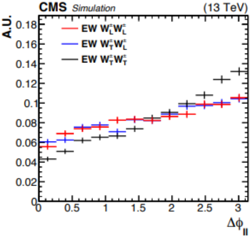
Signal Distributions

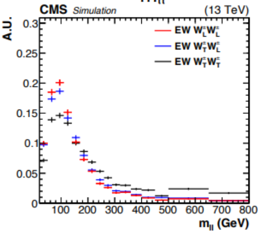
- Distributions of three variables with great separation power are shown
- Different between LL and XT, between LX and TT (X=L or T)

$\Delta\Phi_{jj}$ | $\Delta\Phi_{ll}$ | m_{ll}

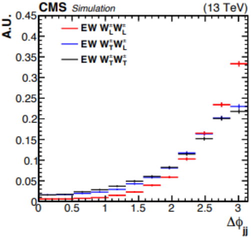
parton-parton frame

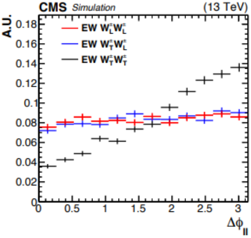


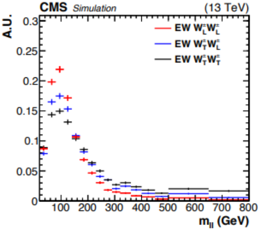




WW frame



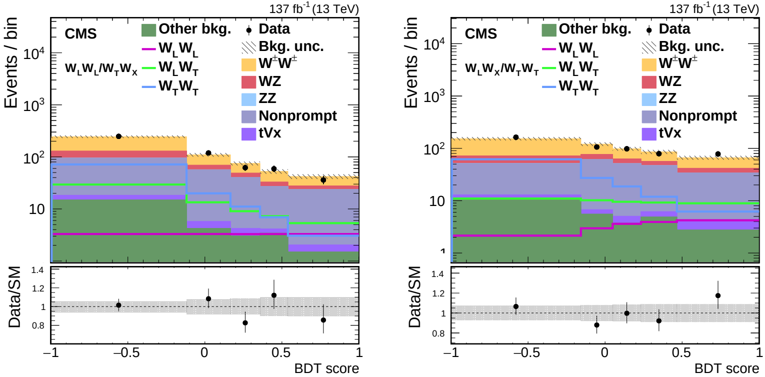




Signal Extraction

- Multivariate techniques are used to enhance the separation between different processes
- Two sets of BDTs are trained
  - LL against (LT+TT)
  - (LL+LT) against TT
- Different polarization states lead to different kinematic distributions
- Different trainings for WW and parton-parton c.m. frames
- Inclusive BDT to isolate EW $\mathrm{W^{\pm}W^{\pm}jj}$ signal from nonVBS backgrounds
  - dominated by nonprompt $\mathrm{t\bar{t}}$ background
- Three categories of discriminating variables:
  - jet kinematics, vector boson kinematics, and vector boson - jet mix
- $\mathrm{W^{\pm}W^{\pm}jj}$ SR: 2D BDT scores, signal-BDT vs. inclusive BDT

Observed Results



- $W^{\pm}W^{\pm}$ c.m. frame
  - Observed (expected) limit of 1.17 (0.88) fb for $W_L^{\pm}W_L^{\pm}$
  - Observed (expected) significance of 2.3 (3.1) s.d. for $W_L^{\pm}W_X^{\pm}$
- Parton-parton c.m. frame
  - Observed (expected) limit of 1.06 (0.85) fb for $W_L^{\pm}W_L^{\pm}$
  - Observed (expected) significance of 2.6 (2.9) s.d. for $W_L^{\pm}W_X^{\pm}$

$W^\pm W^\pm$ Polarization Cross Sections

- Same fiducial region as SMP-19-012
- Consistent theory predictions between MADGRAPH and PHANTOM generators
- Reported cross sections $W^\pm_L W^\pm_L / W^\pm_X W^\pm_T$ or $W^\pm_L W^\pm_X / W^\pm_T W^\pm_T$

$W^\pm W^\pm$ c.m. frame

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

parton-parton c.m. frame

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

- Good agreement among results and theoretical predictions

$ZZ \rightarrow 4\ell$

CMS-SMP-20-001

Arxiv:2008.07013

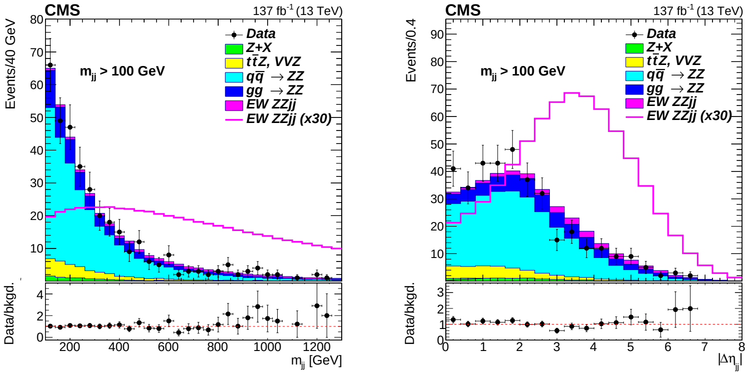
Overview

- Measure EW ZZjj production using 4ℓ events
  - ZZ selection similar to that used in the CMS $\mathrm{H} \rightarrow \mathrm{ZZ} \rightarrow 4\ell$ measurement, see Arxiv:1706.09936
- Very clean sample with rather small non-ZZ background
  - low signal yields $\rightarrow$ lepton selection as efficient as possible
- Large, relatively speaking, QCD-induced production
- Simple variable approach not enough:
  - making use of a matrix-element discriminant (K_D) to enhance EW production
  - details can be found in Arxiv:1309.4819
- Define three regions to measure EW production
  - ZZjj inclusive
  - VBS-enriched loose
  - VBS-enriched tight

Detailed ZZjj Selection

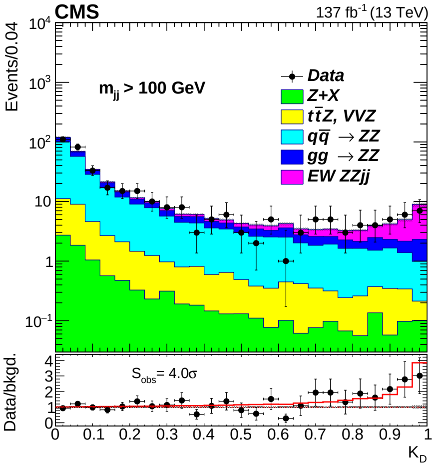
Particle type	Selection
	ZZjj inclusive
Leptons	$p_{\mathrm{T}}(\ell_1) > 20\,\mathrm{GeV}$
	$p_{\mathrm{T}}(\ell_2) > 10\,\mathrm{GeV}$
	$p_{\mathrm{T}}(\ell) > 5\,\mathrm{GeV}$
	$\lvert\eta(\ell)\rvert < 2.5$
	(γ with $\Delta R(\ell,\gamma) < 0.1$ added to ℓ 4-vector)
Z and ZZ	$60 < m(\ell\ell) < 120\,\mathrm{GeV}$
	$m(4\ell) > 180\,\mathrm{GeV}$
Jets	at least 2
	$p_{\mathrm{T}}(\mathrm{j}) > 30\,\mathrm{GeV}$
	$\lvert\eta(\mathrm{j})\rvert < 4.7$
	$m_{\mathrm{jj}} > 100\,\mathrm{GeV}$
	$\Delta R(\ell,\mathrm{j}) > 0.4$ for each ℓ,j
	VBS-enriched (loose)
	ZZjj inclusive +
Jets	$\lvert\Delta\eta_{\mathrm{jj}}\rvert > 2.4$
	$m_{\mathrm{jj}} > 400\,\mathrm{GeV}$
	VBS-enriched (tight)
	ZZjj inclusive +
Jets	$\lvert\Delta\eta_{\mathrm{jj}}\rvert > 2.4$
	$m_{\mathrm{jj}} > 1\,\mathrm{TeV}$

Distributions in $ZZjj$ Inclusion Region



- Rather small non-ZZ contribution in data
- EW $ZZjj$ contribution scaled by a factor of 30 for visibility
- Different shapes of EW signal and backgrounds, but a single kinematic distribution not good enough to observe it

Final K_D Distribution in ZZjj Inclusion Region



- Visible excess of data events by excluding EW ZZjj contribution in prediction
- Observed (expected) statistical significance 4.0 (3.5) s.d.

Yields & Cross Section Measurements

Year	Signal (EW ZZjj)	Z+X	$q\bar{q} \to$ ZZjj	gg $\to$ ZZjj	$t\bar{t}$Z+VVZ	Total predicted	Data
			ZZjj inclusive				
2016	6.3 ± 0.7	2.8 ± 1.1	65.6 ± 9.5	13.5 ± 2.0	8.4 ± 2.2	96 ± 13	95
2017	7.4 ± 0.8	2.4 ± 0.9	77.7 ± 11.2	20.3 ± 3.0	9.6 ± 2.5	117 ± 15	111
2018	10.4 ± 1.1	4.1 ± 1.6	98.1 ± 14.2	29.1 ± 4.3	14.2 ± 3.8	156 ± 20	159
All	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)				
2016	4.2 ± 0.4	0.4 ± 0.2	9.7 ± 1.4	3.2 ± 0.5	1.1 ± 0.3	18.7 ± 2.3	21
2017	4.9 ± 0.5	0.5 ± 0.2	13.5 ± 1.9	5.5 ± 0.8	1.2 ± 0.3	25.5 ± 3.1	17
2018	6.9 ± 0.7	0.8 ± 0.3	14.9 ± 2.2	8.3 ± 1.2	1.7 ± 0.5	32.6 ± 3.9	30
All	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)				
2016	2.4 ± 0.3	0.10 ± 0.04	1.3 ± 0.2	0.7 ± 0.1	0.24 ± 0.06	4.8 ± 0.5	4
2017	2.7 ± 0.3	0.05 ± 0.02	1.9 ± 0.3	1.2 ± 0.2	0.14 ± 0.04	6.0 ± 0.7	3
2018	3.9 ± 0.4	0.17 ± 0.06	2.0 ± 0.3	1.5 ± 0.2	0.30 ± 0.08	7.8 ± 0.9	10
All	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

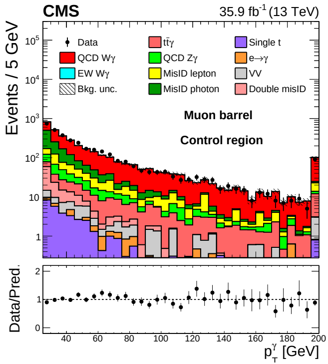
	Perturbative order	SM σ (fb)	Measured σ (fb)
		ZZjj inclusive	
EW	LO	0.275 ± 0.021	$0.33^{+0.11}_{-0.10}$ (stat) $^{+0.04}_{-0.03}$ (syst)
	NLO QCD	0.278 ± 0.017	
EW+QCD		5.35 ± 0.51	$5.29^{+0.31}_{-0.30}$ (stat) ± 0.46 (syst)
		VBS-enriched (loose)	
EW	LO	0.186 ± 0.015	$0.200^{+0.078}_{-0.067}$ (stat) $^{+0.023}_{-0.013}$ (syst)
	NLO QCD	0.197 ± 0.013	
EW+QCD		1.21 ± 0.09	$1.00^{+0.12}_{-0.11}$ (stat) $^{+0.06}_{-0.05}$ (syst)
		VBS-enriched (tight)	
EW	LO	0.104 ± 0.008	$0.09^{+0.04}_{-0.03}$ (stat) ± 0.02 (syst)
	NLO QCD	0.108 ± 0.007	
EW+QCD		0.221 ± 0.014	$0.20^{+0.05}_{-0.04}$ (stat) ± 0.02 (syst)

Observation of EW $W\gamma$ Production

SMP-19-008

Arxiv:2008.10521

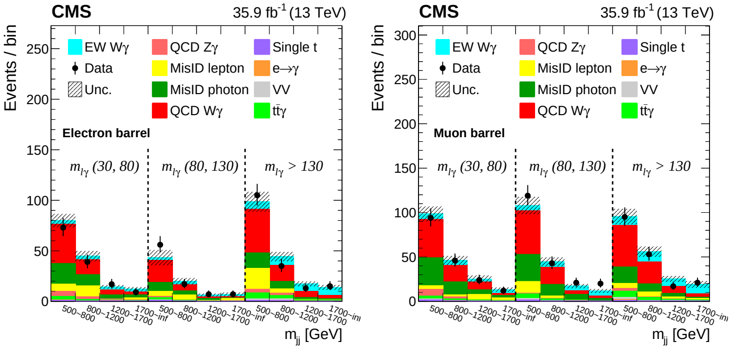
- 2016 data analysis
- Event selection:
  - one high-p_{T} electron or muon, and one high-p_{T} photon
  - moderate $p_{\mathrm{T}}^{\mathrm{miss}}$ and m_T^{W} to reject nonprompt lepton/photon background
  - $m_{jj} > 500\mathrm{GeV}$ and $|\Delta\eta_{\mathrm{jj}}| > 2.5$ to select VBS-like topology
- Background estimation:
  - QCD-induced $\mathrm{W}\gamma$ estimated in-situ
  - nonprompt lepton/photon extrapolated from data
  - $e \to \gamma$ background estimated using $\mathrm{Z} \to ee$ events
  - other processes from simulation



	Electron barrel	Electron endcap	Muon barrel	Muon endcap
MisID photon	81.0 ± 5.2	48.1 ± 4.9	134.8 ± 8.2	52.1 ± 4.8
MisID lepton	63.7 ± 12.3	27.8 ± 7.2	46.8 ± 10.6	23.1 ± 6.5
QCD $\mathrm{W}\gamma\mathrm{jj}$	154.2 ± 12.0	41.1 ± 4.4	221.2 ± 15.8	72.1 ± 6.2
$\mathrm{t\bar{t}}\gamma$	20.6 ± 1.6	5.1 ± 0.6	28.3 ± 1.8	6.9 ± 0.8
QCD $\mathrm{Z}\gamma$	18.0 ± 3.1	1.9 ± 0.9	16.2 ± 3.0	4.9 ± 1.3
Single t	4.9 ± 0.8	2.5 ± 0.5	6.8 ± 0.9	2.4 ± 0.5
VV	4.2 ± 1.6	0.6 ± 0.6	7.5 ± 2.1	1.4 ± 0.7
$\mathrm{e} \to \gamma$	1.5 ± 0.6	2.1 ± 0.8	1.7 ± 0.7	1.1 ± 0.6
Total background	348.3 ± 18.4	129.1 ± 9.9	463.4 ± 21.2	163.8 ± 10.4
EW $\mathrm{W}\gamma\mathrm{jj}$	48.8 ± 2.2	16.1 ± 1.0	74.5 ± 2.8	24.4 ± 1.3
Total predicted	397.1 ± 18.5	145.2 ± 10.0	537.9 ± 21.4	188.2 ± 10.5
Data	393	159	565	201

EW Wγjj Measurement

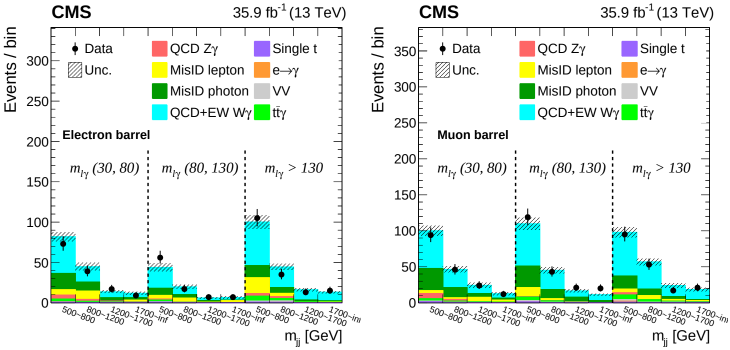
2D (m_{jj}-$m_{\ell\gamma}$) distributions to the fit for the signal strength of EW Wγjj



- This result: observed (expected) significance is 4.9 (4.6) s.d.
- 8+13 TeV combination: observed (expected) significance is 5.3 (4.8) s.d.
- $\sigma^{fid}_{EW}(13\mathrm{TeV}) = 20.4 \pm 0.4(lumi) \pm 2.8(stat) \pm 3.5(syst)$ fb $= 20.4 \pm 4.5$ fb

Fiducial QCD+EW $W\gamma jj$ Cross Section

2D (m_{jj}-$m_{\ell\gamma}$) distributions to fit for the signal strength of EW+QCD $W\gamma jj$



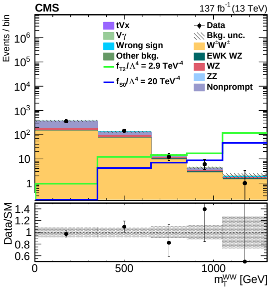
- $\sigma^{fid}_{EW+QCD}(13\text{TeV}) = 108 \pm 2(lumi) \pm 5(stat) \pm 15(syst)$ fb $= 108 \pm 16$ fb

Anomalous Couplings

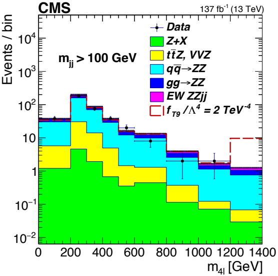
aQGCs

- Extensions of the SM induce coupling modifications that can be parameterized in terms of an EFT approach
- In these analyses, limits on aQGCs are set via EFT approach. Dimension-8 operators that can modify the VVjj production through aQGCs are considered
- Simplified versions analyses are pursued
- Variables sensitive to diboson system (mass/transverse mass)

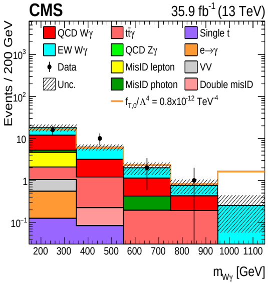
$W^{\pm}W^{\pm}jj$



ZZjj



$W\gamma jj$

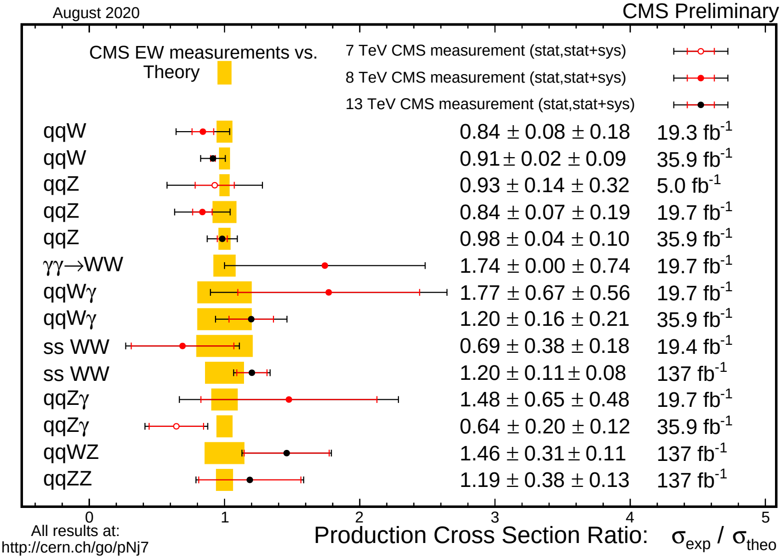


aQGCs Limits From Shown Final States

	Observed $W^{\pm}W^{\pm} + WZ$ (TeV^{-4})	Expected $W^{\pm}W^{\pm} + WZ$ (TeV^{-4})	Observed ZZ (TeV^{-4})	Expected ZZ (TeV^{-4})	Observed $W\gamma$ (TeV^{-4})	Expected $W\gamma)$ (TeV^{-4})
f_{T0}/Λ^4	[-0.25, 0.28]	[-0.35, 0.37]	[-0.24, 0.22]	[-0.37, 0.35]	[-0.6, 0.6]	[-0.6, 0.6]
f_{T1}/Λ^4	[-0.12, 0.14]	[-0.16, 0.19]	[-0.31, 0.31]	[-0.49, 0.49]	[-0.4, 0.4]	[-0.3, 0.4]
f_{T2}/Λ^4	[-0.35, 0.48]	[-0.49, 0.63]	[-0.63, 0.59]	[-0.98, 0.95]	[-1.0, 1.2]	[-1.0, 1.2]
f_{T5}/Λ^4	—	—	—	—	[-0.5, 0.5]	[-0.4, 0.4]
f_{T6}/Λ^4	—	—	—	—	[-0.4, 0.4]	[-0.3, 0.4]
f_{T7}/Λ^4	—	—	—	—	[-0.9, 0.9]	[-0.8, 0.9]
f_{T8}/Λ^4	—	—	[-0.43, 0.43]	[-0.68, 0.68]	—	—
f_{T9}/Λ^4	—	—	[-0.92, 0.92]	[-1.50, 1.50]	—	—
f_{M0}/Λ^4	[-2.7, 2.9]	[-3.6, 3.7]	—	—	[-8.1, 8.0]	[-7.7, 7.6]
f_{M1}/Λ^4	[-4.1, 4.2]	[-5.2, 5.5]	—	—	[-12, 12]	[-11, 11]
f_{M2}/Λ^4	—	—	—	—	[-2.8, 2.8]	[-2.7, 2.7]
f_{M3}/Λ^4	—	—	—	—	[-4.4, 4.4]	[-4.0, 4.1]
f_{M4}/Λ^4	—	—	—	—	[-5.0, 5.0]	[-4.7, 4.7]
f_{M5}/Λ^4	—	—	—	—	[-8.3, 8.3]	[-7.9, 7.7]
f_{M6}/Λ^4	[-5.4, 5.8]	[-7.2, 7.3]	—	—	[-16, 16]	[-15, 15]
f_{M7}/Λ^4	[-5.7, 6.0]	[-7.8, 7.6]	—	—	[-21, 20]	[-19, 19]
f_{S0}/Λ^4	[-5.7, 6.1]	[-5.9, 6.2]	—	—	—	—
f_{S1}/Λ^4	[-16, 17]	[-18, 18]	—	—	—	—

- Competitive sensitivity among different final states
- $W^{\pm}W^{\pm} + WZ$ & ZZ $(W\gamma)$ analyses: 2016-18 (2016)
- Results obtained without using any unitarization procedure, results taking into account unitarization limit in back-up
- Best stringent limits to date using semileptonic final states (SMP-18-006 / PLB 798 (2019)134985)

Summary of EW $\sigma_{exp}/\sigma_{theo}$ Measurements



Summary

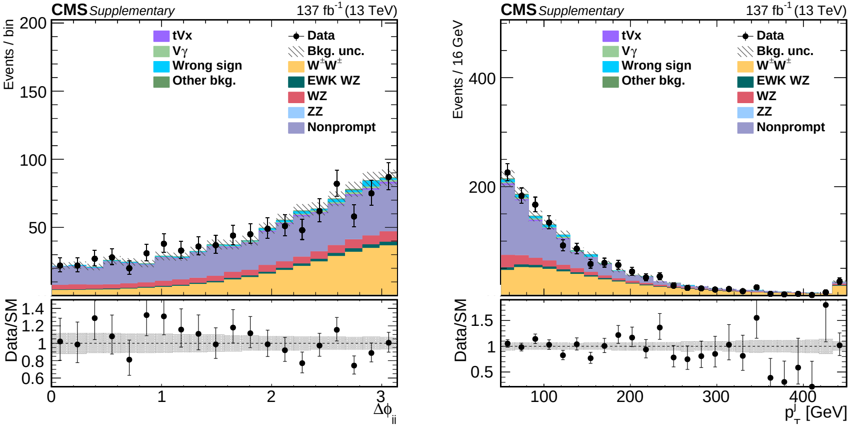
- Presented study of electroweak scattering of $W^{\pm}W^{\pm}jj$, $WZjj$, $ZZjj$, & $W\gamma jj$ bosons in leptonic final states
  - first $W^{\pm}W^{\pm}$ polarization cross section measurements
- Observation of EW $WZjj$ & $W\gamma$ production, evidence of EW $ZZjj$ production
- Measured inclusive cross sections of the $W^{\pm}W^{\pm}jj$, $WZjj$, $ZZjj$, & $W\gamma jj$ processes in fiducial regions dominated by EW production
- Measured differential cross sections of $W^{\pm}W^{\pm}jj$ & $WZjj$ processes on several distributions for first time
- Limits on dimension-8 Wilson coefficients are set for anomalous couplings
- This is just the starting point of a long physics program:
  - study additional final states
  - increase scope of polarization measurements
  - finer differential measurements
  - expand EFT analyses
  - expand searches using these final states

Documentation

- All results available on http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP/index.html
- $W^{\pm}W^{\pm}jj/WZjj$ in lepton final states: SMP-19-012 / PLB 809 (2020) 135710
  - polarized $W^{\pm}W^{\pm}jj$ measurements: SMP-20-006 / arXiv:2009.09429
- $ZZjj$: SMP-20-001 / arXiv:2008.07013
- $VVjj$ in semileptonic final states: SMP-18-006 / PLB 798 (2019)134985
- $Z\gamma jj$: SMP-18-007 / JHEP 06 (2020) 076
- $W\gamma jj$: SMP-19-008 / arXiv:2008.10521
- Zjj: SMP-16-018 / EPJC 78 (2018) 589
- Wjj: SMP-13-012 / JHEP 11 (2016) 147

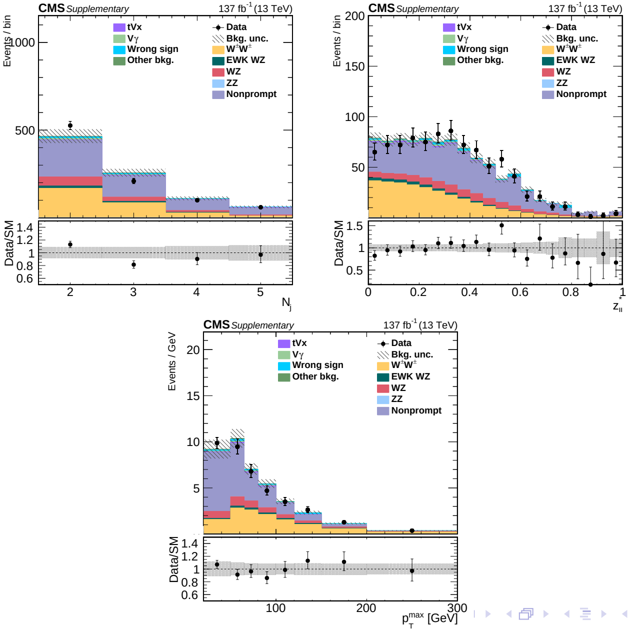
Back-Up

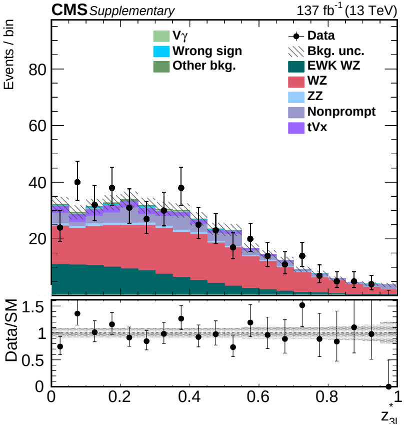
Other Distributions in $W^{\pm}W^{\pm}jj$ SR (I)

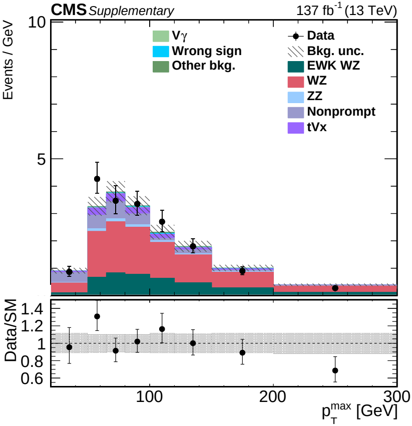


- Example of distributions not directly used in the main fit

Other Distributions in $W^{\pm}W^{\pm}jj$ SR (II)

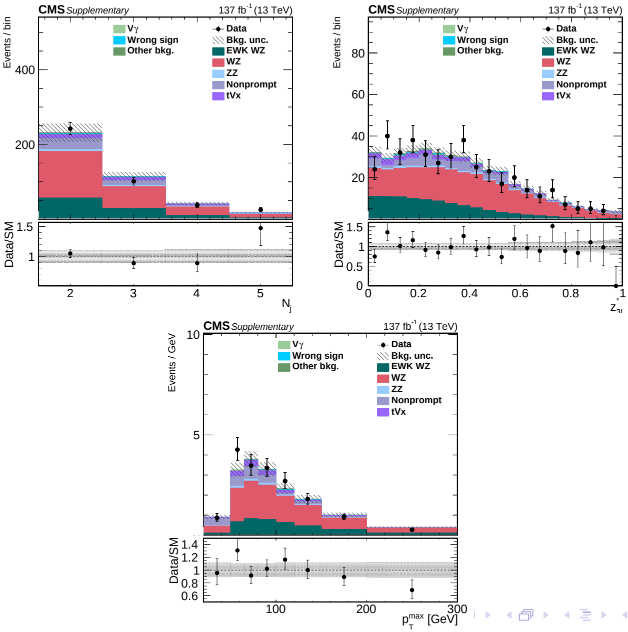




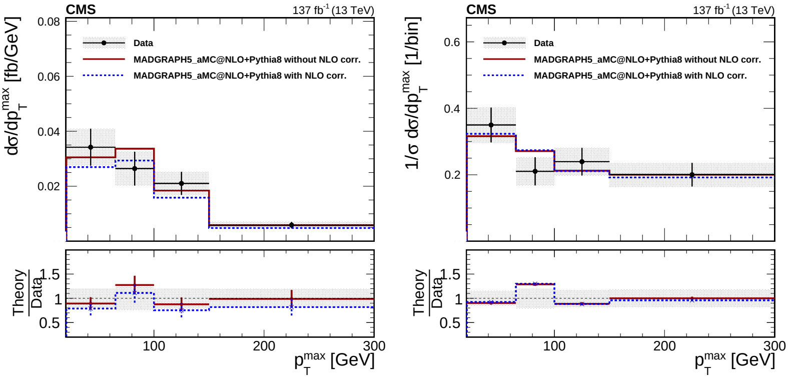


- Good agreement between data and prediction

Other Distributions in WZjj SR (II)

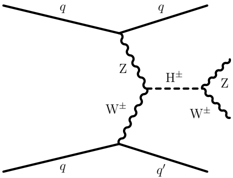


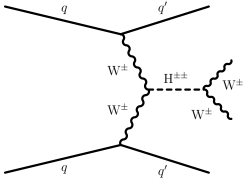
$p_T^{\ell\ max}$ $W^\pm W^\pm jj$ Fiducial Cross Section Measurements



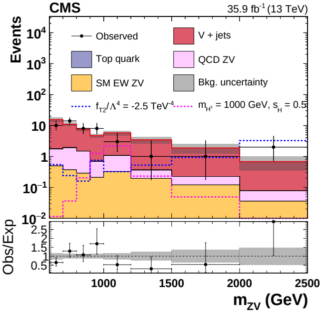
- Performed by replacing $m_{\ell\ell}$ to $p_T^{\ell\ max}$ in the fit

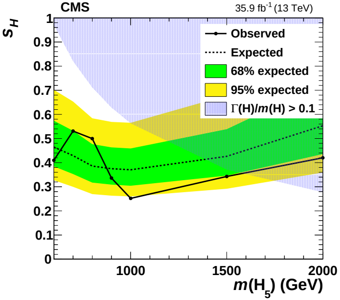
VBF $H^{\pm\pm}$ and $H^{\pm}$ Searches (Georgi-Machacek Model)





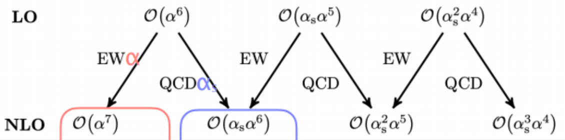
- Same VBS topology in resonant production
- Searching for enhancements in diboson mass-related observables
- Limits as a function of m_{H} and s_{H} (theory parameter relating the W boson and the vacuum expectation value of the triplet fields)





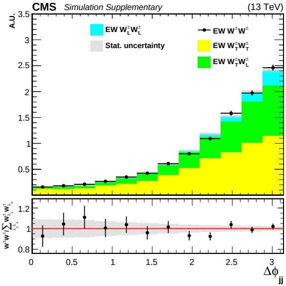
NLO Corrections

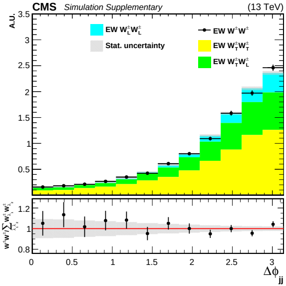
- The full NLO QCD and EW corrections for the leptonic unpolarized $W^\pm W^\pm$ scattering have been computed *B.Biedermann, A.Denner, and M.Pellen arXiv:1611.02951 arXiv:1708.00268*
- Reduce the LO cross section for the EW $W^\pm W^\pm$ process by approximately 10–15%
- Unknown for LL, LT, TT processes
  - α_s corrections expected to be the **same for all the 3** polarization modes
  - α corrections expected to be **small for the L** mode
  - Take the NLO corrections for the unpolarized EW $W^\pm W^\pm$ and apply
    - $\mathcal{O}(\alpha_s\alpha^6)$ and $\mathcal{O}(\alpha^7)$ to **TT**
    - Only $\mathcal{O}(\alpha_s\alpha^6)$ to **LL** and **LT**
    - $\mathcal{O}(\alpha^7)$ on the shapes of **LL** and **LT** considered as a systematic uncertainty

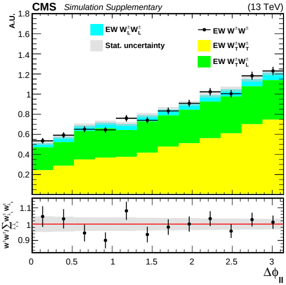


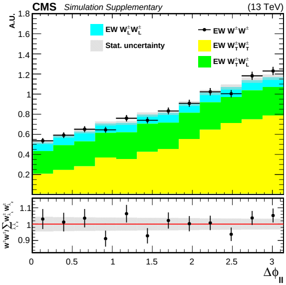
Order	$\mathcal{O}(\alpha^7)$	$\mathcal{O}(\alpha_s\alpha^6)$	$\mathcal{O}(\alpha_s^2\alpha^5)$	$\mathcal{O}(\alpha_s^3\alpha^4)$	Sum
$\delta\sigma_{\text{NLO}}$ [fb]	−0.2169(3)	−0.0568(5)	−0.00032(13)	−0.0063(4)	−0.2804(7)
$\delta\sigma_{\text{NLO}}/\sigma_{\text{LO}}$ [%]	−13.2	−3.5	0.0	−0.4	−17.1

Closure of Signal Samples

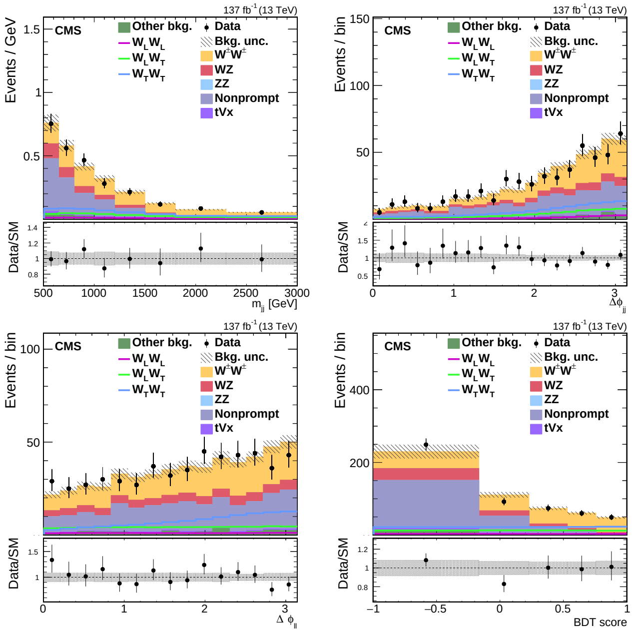






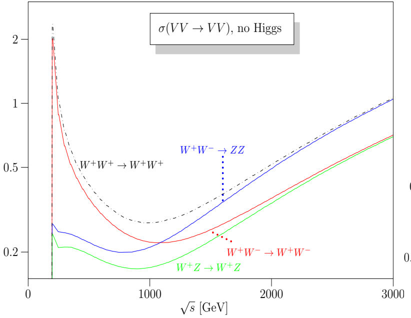


$W^\pm W^\pm$ Polarization Distributions

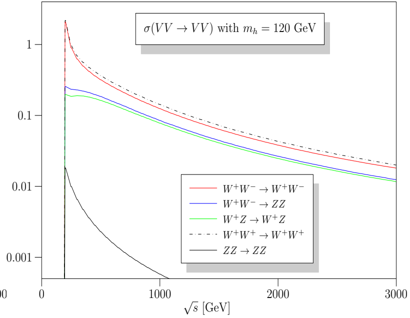


Unitarity Violation

SM without a Higgs boson



SM with a 120 GeV Higgs boson



from ArXiv:0806.4145

- Without a "light" SM Higgs boson ($m_{\mathrm{H}} \leq 1$ TeV) VBS would violate unitarity
- Higgs boson contribution cancels increase for large $\sqrt{s}$ for SM-HWW coupling

Systematic Uncertainties Polarization Analysis

Source of uncertainty	$W^{\pm}_{L}W^{\pm}_{L}$ (%)	$W^{\pm}_{X}W^{\pm}_{T}$ (%)	$W^{\pm}_{L}W^{\pm}_{X}$ (%)	$W^{\pm}_{T}W^{\pm}_{T}$ (%)
Integrated luminosity	3.2	1.8	1.9	1.8
Lepton measurement	3.6	1.9	2.5	1.8
Jet energy scale and resolution	11	2.9	2.5	1.1
Pileup	0.9	0.1	1.0	0.3
b tagging	1.1	1.2	1.4	1.1
Nonprompt lepton rate	17	2.7	9.3	1.6
Trigger	1.9	1.1	1.6	0.9
Limited sample size	38	3.9	14	5.7
Theory	6.8	2.3	4.0	2.3
Total systematic uncertainty	44	6.6	18	7.0
Statistical uncertainty	123	15	42	22
Total uncertainty	130	16	46	23

Statistically limited measurements

aQGCs: Unitarity Issue

- EFT amplitudes grow with m_{VV} and this growth is unphysical above a certain scale Λ; this sets the limit of validity of EFT approach
- This scale derived from partial wave unitarity condition (as function of Wilson coefficients)
- Above Λ, since the data is consistent with SM, we replace prediction of EFT amplitudes with SM in that region; this leads to conservative bounds on EFT Wilson coefficients
- The technique is known as "Clipping", and essentially means using EFT only in the region it is valid
  - first time limits are also reported in this way
- See details in Arxiv.1906.10769 and Arxiv.1802.02366

aQGCs 95% CL Limits: Without and With Unitarity Bounds

Results without using any unitarization procedure

	Observed ($W^{\pm}W^{\pm}$) (TeV^{-4})	Expected ($W^{\pm}W^{\pm}$) (TeV^{-4})	Observed (WZ) (TeV^{-4})	Expected (WZ) (TeV^{-4})	Observed (TeV^{-4})	Expected (TeV^{-4})
f_{T0}/Λ^4	[-0.28, 0.31]	[-0.36, 0.39]	[-0.62, 0.65]	[-0.82, 0.85]	[-0.25, 0.28]	[-0.35, 0.37]
f_{T1}/Λ^4	[-0.12, 0.15]	[-0.16, 0.19]	[-0.37, 0.41]	[-0.49, 0.55]	[-0.12, 0.14]	[-0.16, 0.19]
f_{T2}/Λ^4	[-0.38, 0.50]	[-0.50, 0.63]	[-1.0 , 1.3]	[-1.4, 1.7]	[-0.35, 0.48]	[-0.49, 0.63]
f_{M0}/Λ^4	[-3.0, 3.2]	[-3.7, 3.8]	[-5.8, 5.8]	[-7.6, 7.6]	[-2.7, 2.9]	[-3.6, 3.7]
f_{M1}/Λ^4	[-4.7, 4.7]	[-5.4, 5.8]	[-8.2, 8.3]	[-11, 11]	[-4.1, 4.2]	[-5.2, 5.5]
f_{M6}/Λ^4	[-6.0, 6.5]	[-7.5, 7.6]	[-12, 12]	[-15, 15]	[-5.4, 5.8]	[-7.2, 7.3]
f_{M7}/Λ^4	[-6.7, 7.0]	[-8.3, 8.1]	[-10, 10]	[-14, 14]	[-5.7, 6.0]	[-7.8, 7.6]
f_{S0}/Λ^4	[-6.0, 6.4]	[-6.0, 6.2]	[-19, 19]	[-24, 24]	[-5.7, 6.1]	[-5.9, 6.2]
f_{S1}/Λ^4	[-18, 19]	[-18, 19]	[-30, 30]	[-38, 39]	[-16, 17]	[-18, 18]

Results by cutting the EFT expansion at the unitarity limit

	Observed ($W^{\pm}W^{\pm}$) (TeV^{-4})	Expected ($W^{\pm}W^{\pm}$) (TeV^{-4})	Observed (WZ) (TeV^{-4})	Expected (WZ) (TeV^{-4})	Observed (TeV^{-4})	Expected (TeV^{-4})
f_{T0}/Λ^4	[-1.5, 2.3]	[-2.1, 2.7]	[-1.6, 1.9]	[-2.0, 2.2]	[-1.1, 1.6]	[-1.6, 2.0]
f_{T1}/Λ^4	[-0.81, 1.2]	[-0.98, 1.4]	[-1.3, 1.5]	[-1.6, 1.8]	[-0.69, 0.97]	[-0.94, 1.3]
f_{T2}/Λ^4	[-2.1, 4.4]	[-2.7, 5.3]	[-2.7, 3.4]	[-4.4, 5.5]	[-1.6, 3.1]	[-2.3, 3.8]
f_{M0}/Λ^4	[-13, 16]	[-19, 18]	[-16, 16]	[-19, 19]	[-11, 12]	[-15, 15]
f_{M1}/Λ^4	[-20, 19]	[-22, 25]	[-19, 20]	[-23, 24]	[-15, 14]	[-18, 20]
f_{M6}/Λ^4	[-27, 32]	[-37, 37]	[-34, 33]	[-39, 39]	[-22, 25]	[-31, 30]
f_{M7}/Λ^4	[-22, 24]	[-27, 25]	[-22, 22]	[-28, 28]	[-16, 18]	[-22, 21]
f_{S0}/Λ^4	[-35, 36]	[-31, 31]	[-83, 85]	[-88, 91]	[-34, 35]	[-31, 31]
f_{S1}/Λ^4	[-100, 120]	[-100, 110]	[-110, 110]	[-120, 130]	[-86, 99]	[-91, 97]