Experimental Analyses on Electroweak (Massive) Diboson Production

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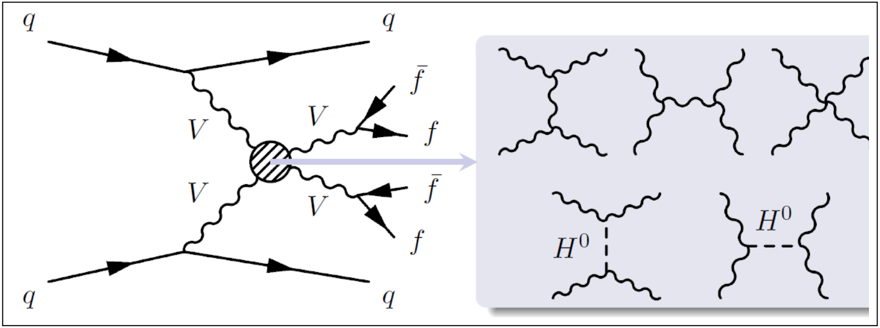
Preface

- Will give some emphasis on vector boson scattering polarization studies, although this talk will cover more
- Talk biased towards CMS experiment:
  - focused on recent analyses
- Physics outcome should be anyway consistent between CMS and ATLAS
- Skeleton:
  - introduction
  - electroweak (EW) diboson Standard Model (SM) measurements
  - searches
  - polarization measurements
- A lot of numbers and details, go back to the documentation to undertand them, or ask later on!

Vector Boson Scattering (VBS) at the LHC

Characterized by VVjj (V = W/Z) final state:

triple and quartic gauge couplings (QGCs)



Higgs boson exchange and Higgs boson production via VBS

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

Important Measurements

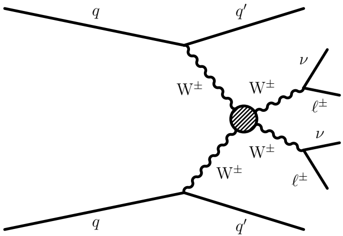
- Electroweak di(tri)boson measurements:
  - test of the EW sector of the SM at the TeV scale
  - sensitive to Anomalous Triple (Quartic) Gauge Couplings (aTGC/aQGC)
  - sensitive to searches for new physics, e.g., $\mathrm{H}^{\pm}/\mathrm{H}^{\pm\pm}$
  - background to other analyses
  - VV scattering $\rightarrow$ (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

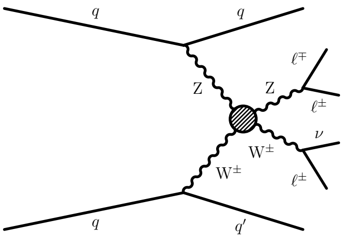
VV Scattering Event Topology

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

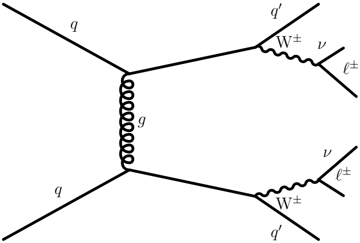
Representative Feynman Diagrams

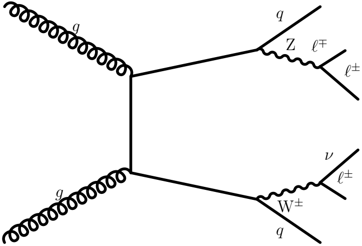
EW-induced $W^{\pm}W^{\pm}jj$ and WZjj production





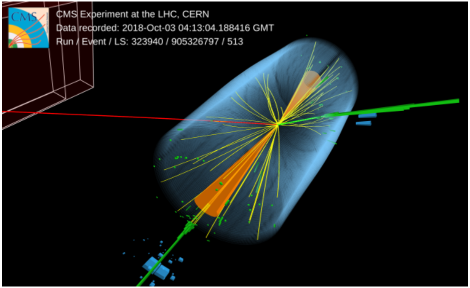
QCD-induced $W^{\pm}W^{\pm}jj$ and WZjj production



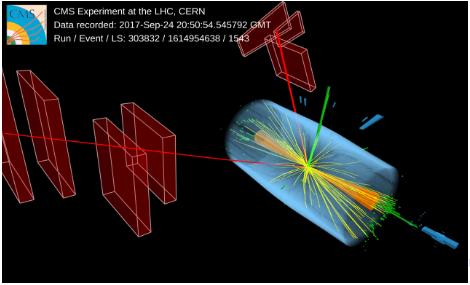


$W^{\pm}W^{\pm}jj$ and WZjj Data Candidates

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



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



VBS Measurements in a Glance

- Select VVjj events with VBS-like jets
  - take into account specific final state
- Estimate non-VVjj 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
  - explicit models: e.g. VBF $\mathrm{H}^{\pm\pm}$ and $\mathrm{H}^{\pm}$
  - generic effective field theory (EFT): e.g. aQGCs

Inclusive & Differential Fiducial Cross Sections

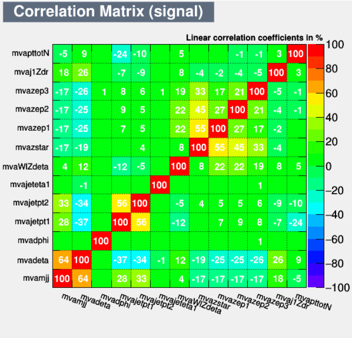
- Cross section: $\sigma_{observed} = \frac{N_{data} - N_{bkg.}}{\mathcal{L}\epsilon}$
- Signal strength: $\mu = \sigma_{observed} / \sigma_{expected}$
  - very useful way to report it since values are $\sim$1, instead of arbitrary quantities
- Inclusive cross sections, i.e., with no requirements at generator level are hard to quote, even meaningless
  - in particular for these VBS processes, a requirement on the dijet mass is always present
- Fiducial cross sections, defined with a set of generator-level requirements
  - usually defined as close as possible to the reconstructed-level selection to avoid theoretical dependence
  - should not be "too close" either to avoid too many signal events selected at reconstructed-level, but not part of the fiducial region
- Differential (fiducial) cross sections: measure an observable split in several generator-level bins
  - need to take care the reconstructed-level migrations among different generator-level bins (2-D reco-gen matrix)

Multivariate Techniques (I)

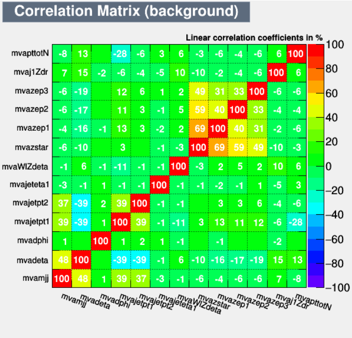
- Multivariate (MVA) techniques are commonly used to separate signal and backgrounds
  - Boosted Decision Trees (BDTs), Deep Neural Nets (DNNs), Artifitial Neural Nets (ANNs)...
  - full MVA variable is usually used as final discriminant variable
- Variables in VBS analyses
  - related to dijet system (m_{jj}, $|\Delta\eta_{\mathrm{jj}}|$, $\Delta\phi_{\mathrm{jj}}$, $p_{\mathrm{T}}^{\mathrm{j1}}$, $p_{\mathrm{T}}^{\mathrm{j2}}$...)
  - related to diboson system (p_{T}^{ℓ}, m_{VV}, $p_{\mathrm{T}}^{\mathrm{miss}}$...)
  - related to jet-boson system ($\Delta R_{\mathrm{j1,Z}}$, $\left|\eta^{\ell} - \frac{\eta^{\mathrm{j}_1}+\eta^{\mathrm{j}_2}}{2}\right|/|\Delta\eta_{\mathrm{jj}}|$...)
- Correlations among variables taken into account by the multivariate algorithm

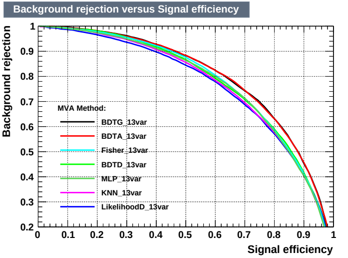
Multivariate Techniques (II)

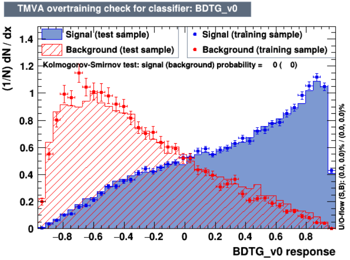
Signal



Background





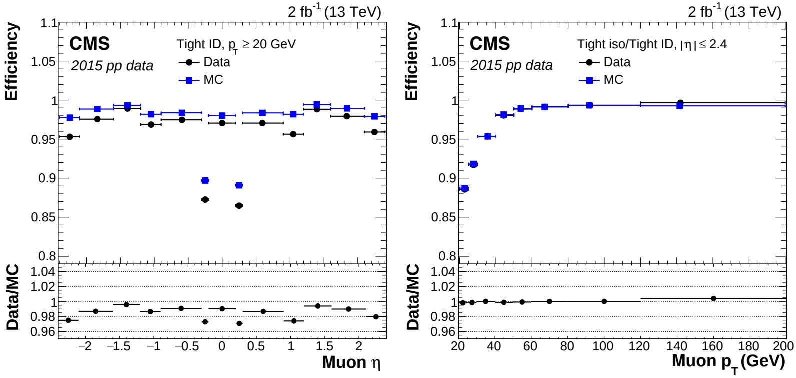


Select Basic Objects

Object Definition (Generic)

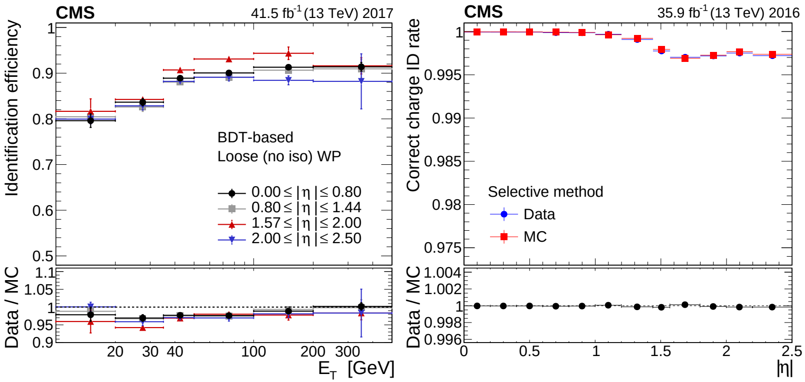
- Trigger paths:
  - single and double lepton triggers in leptonic final states
  - $p_{\mathrm{T}}^{\mathrm{miss}}$ or multijet triggers if no leptons in the final state
- Muons and electrons: select or veto
  - tight object: tight Id & isolation working points (WPs)
  - loose object: loose Id WP$\leftarrow$ used to reject events with additional charged leptons
  - fakeable object: used to estimate nonprompt lepton background
- Photon: select
  - tight WPs
- Tau: select or veto
  - tight (loose) WP, used to select (reject) events with τ leptons
- $p_{\mathrm{T}}^{\mathrm{miss}}$:
  - $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}} = -\sum_i \vec{p}_{\mathrm{T}}^{\,\mathrm{i}}$, i == all reconstructed particles in the event
  - used to emulate neutrinos in the final state
- Jets:
  - $p_{\mathrm{T}}^{\mathrm{j}} > 30 - 50$ GeV, $|\eta^j| < 4.7 - 5.0$
- B-tagging:
  - loose/medium WPs, to reject top-quark production
  - medium/tight WPs, to select $\mathrm{Z} \rightarrow bb$ decays

Muon Performance



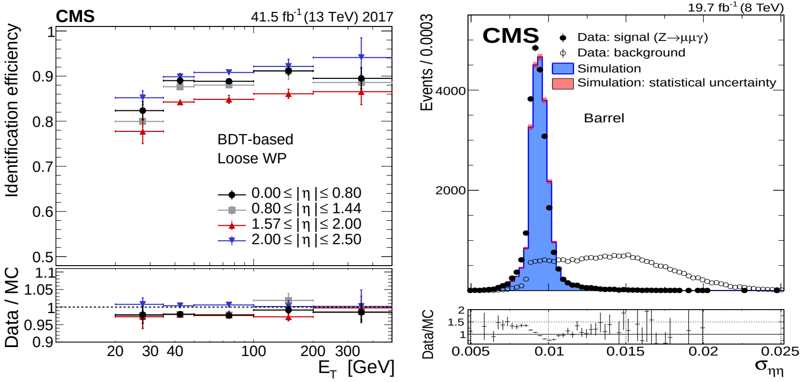
- Muon selection efficiency measured in data and simulation
- Scale factors applied to correct the simulation as a function of p_{T} and η

Electron Performance



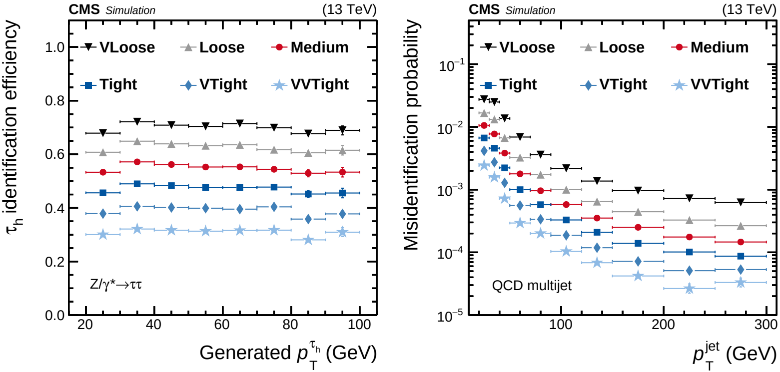
- BDT selections usually overperformed over cut-based approaches
- Electron wrong-charge probability crucial aspect in same-sign $\mathrm{W}^{\pm}\mathrm{W}^{\pm}$ analysis to reduce opposite-sign dilepton background

Photon Performance



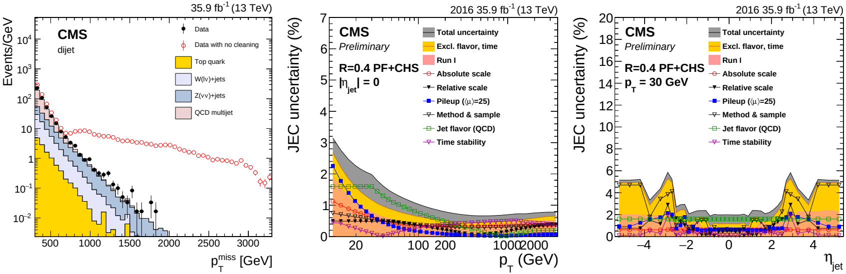
- Scale factors applied to correct the simulation as a function of p_{T} and η
- Sidebands used to estimate nonprompt photon background

Tau Performance



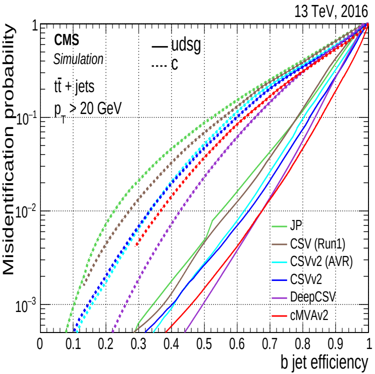
- Loose or very loose selections applied to veto as many hadronic τ decays as possible

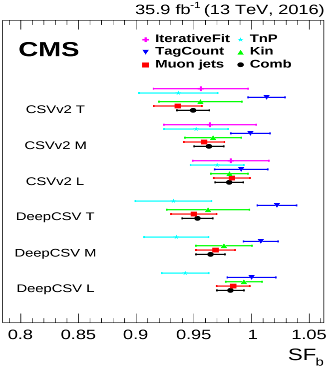
Jets & $p_{\mathrm{T}}^{\mathrm{miss}}$ Performance



- Objects cleaning crucial to improve $p_{\mathrm{T}}^{\mathrm{miss}}$ measurement
- Clear η and p_{T} dependence on the jet energy scale uncertainty

B-tagging Performance





- Several algorithms used to select/reject b/c/light-jets
- Three WPs are usually defined (tight/medium/loose)
- Data to simulation scale factors estimated from several methods

EW $W^{\pm}W^{\pm}$ & WZ

CMS-SMP-19-012

Arxiv:2005.01173

PLB 809 (2020) 135710

Overview

- First simultaneous $W^\pm W^\pm jj$ & $WZjj$ analysis using fully leptonic final states
- Select events in several signal regions (SRs) and control regions (CRs)
  - simultaneously measure $W^\pm W^\pm jj$ & $WZjj$ production
  - measure normalization of main background processes in situ
- Focus on:
  - measurements of $W^\pm W^\pm jj$ (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}–$|\Delta\eta_{\mathrm{jj}}|$ by ~20%

Variable	Definition
m_{jj}	Mass of the leading and trailing jets system
$\lvert\Delta\eta_{\mathrm{jj}}\rvert$	Absolute difference in rapidity of the leading and trailing jets
$\Delta\phi_{\mathrm{jj}}$	Absolute difference in azimuthal angles of the leading and trailing jets
$p_{\mathrm{T}}^{\mathrm{j1}}$	p_{T} of the leading jet
$p_{\mathrm{T}}^{\mathrm{j2}}$	p_{T} of the trailing jet
η^{j1}	Pseudorapidity of the leading jet
$\lvert\eta^{\mathrm{W}} - \eta^{\mathrm{Z}}\rvert$	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
$\Delta R_{\mathrm{j1,Z}}$	ΔR between the leading jet and the Z boson
$\lvert\vec{p_{\mathrm{T}}}^{\mathrm{tot}}\rvert/\sum_i p_{\mathrm{T}}^i$	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 $\mathrm{Z} \to \mathrm{ee}$
  - 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

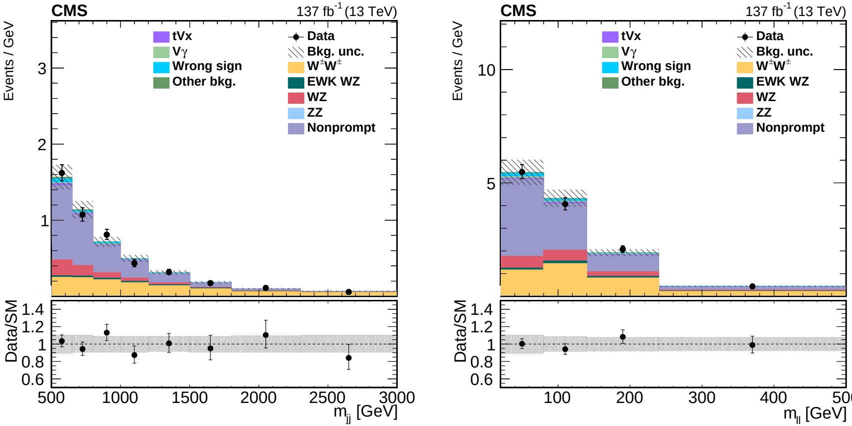
Expected yields from SM processes and observed data events in $\mathrm{W}^{\pm}\mathrm{W}^{\pm}\mathrm{jj}$ and WZjj SRs. Expected yields are shown before the fit to the data (pre-fit) and with their best fit normalizations from the simultaneous fit (post-fit)

Process	$\mathrm{W}^{\pm}\mathrm{W}^{\pm}\mathrm{jj}$ SR		WZjj SR	
	Pre-fit	Post-fit	Pre-fit	Post-fit
EW $\mathrm{W}^{\pm}\mathrm{W}^{\pm}\mathrm{jj}$	209 ± 22	210 ± 26	–	–
QCD $\mathrm{W}^{\pm}\mathrm{W}^{\pm}\mathrm{jj}$	13.6 ± 2.3	13.7 ± 2.2	–	–
Interference $\mathrm{W}^{\pm}\mathrm{W}^{\pm}\mathrm{jj}$	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
$t\mathrm{Vx}$	9.0 ± 3.1	7.4 ± 2.2	15.1 ± 1.9	14.3 ± 2.8
$\mathrm{W}\gamma$	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.

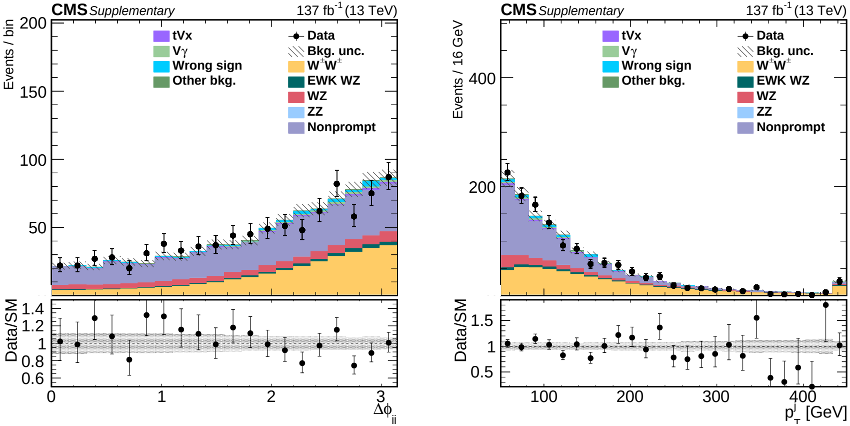
EW $\mathrm{W}^{\pm}\mathrm{W}^{\pm}\mathrm{jj}$ statistical significance: $\gg$ 5 s.d.

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



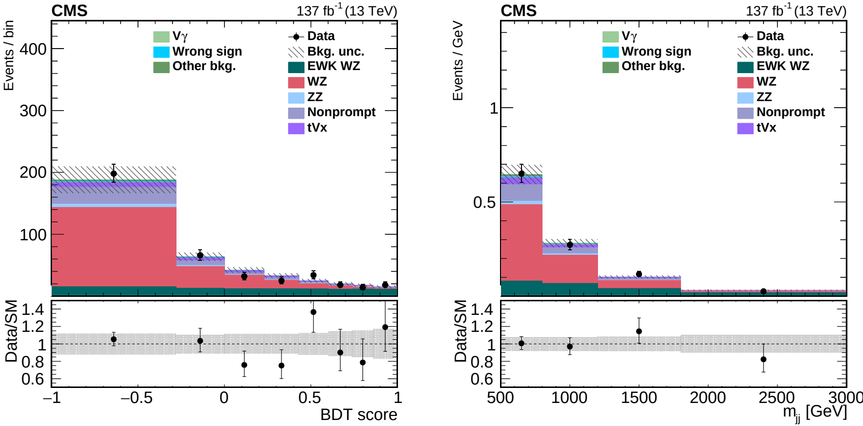
- m_{jj} (left) & $m_{\ell\ell}$ (right) distributions used in the main fit

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



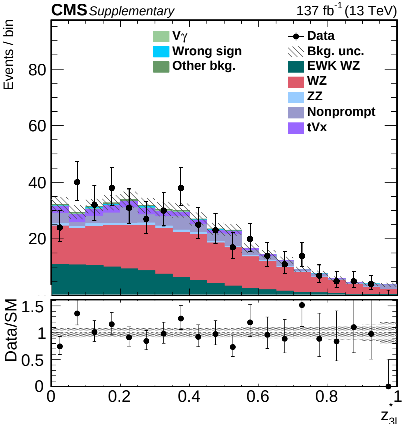
- Example of distributions not directly used in the main fit

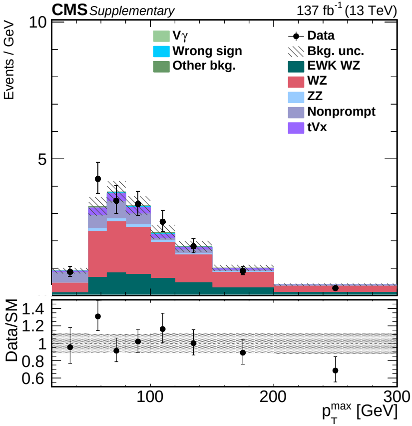
Distributions in WZjj SR (I)



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

Distributions in WZjj SR (II)





- Good agreement between data and prediction

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

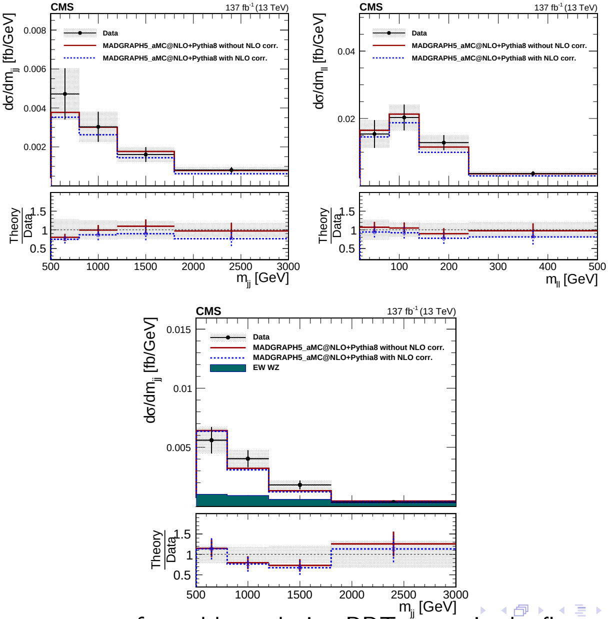
- Statistically limited measurements

- $W^\pm W^\pm jj$ 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

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



WZjj measurement performed by replacing BDT to m_{jj} in the fit

EW $ZZ \to 4\ell$

CMS-SMP-20-001

Arxiv:2008.07013

PLB 812 (2020) 135992

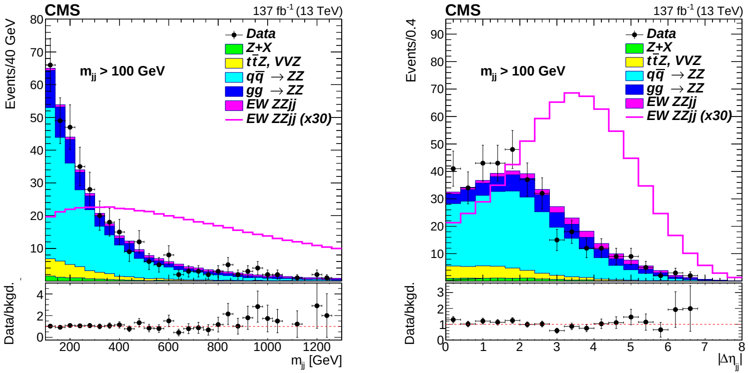
Overview

- Measure EW ZZjj production using 4ℓ events
  - ZZ selection similar to that used in the CMS $\mathrm{H} \to \mathrm{ZZ} \to 4\ell$ measurement, see Arxiv:1706.09936
- Very clean sample with rather small non-ZZ background
  - low signal yields $\to$ 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

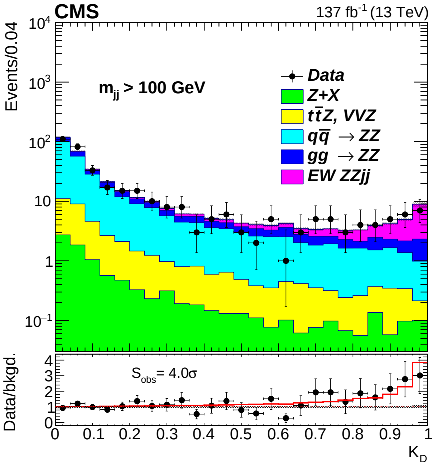
Particle type	Selection
	ZZjj inclusive
Leptons	$p_T(\ell_1) > 20\,\text{GeV}$
	$p_T(\ell_2) > 10\,\text{GeV}$
	$p_T(\ell) > 5\,\text{GeV}$
	$\|\eta(\ell)\| < 2.5$
	(γ with $\Delta R(\ell, \gamma) < 0.1$ added to ℓ 4-vector)
Z and ZZ	$60 < m(\ell\ell) < 120\,\text{GeV}$
	$m(4\ell) > 180\,\text{GeV}$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

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



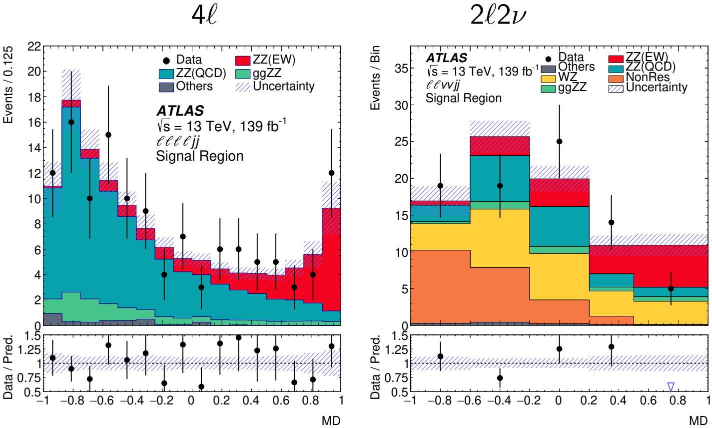
- Visible excess of data events by excluding EW ZZjj contribution in prediction
- Observed (expected) statistical significance 4.0 (3.5) s.d.

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	$0.33^{+0.11}_{-0.10}\,(\text{stat})^{+0.04}_{-0.03}\,(\text{syst})$
	NLO QCD	0.278 ± 0.017	
EW+QCD		5.35 ± 0.51	$5.29^{+0.31}_{-0.30}\,(\text{stat}) \pm 0.46\,(\text{syst})$
		VBS-enriched (loose)	
EW	LO	0.186 ± 0.015	$0.200^{+0.078}_{-0.067}\,(\text{stat})^{+0.023}_{-0.013}\,(\text{syst})$
	NLO QCD	0.197 ± 0.013	
EW+QCD		1.21 ± 0.09	$1.00^{+0.12}_{-0.11}\,(\text{stat})^{+0.06}_{-0.05}\,(\text{syst})$
		VBS-enriched (tight)	
EW	LO	0.104 ± 0.008	$0.09^{+0.04}_{-0.03}\,(\text{stat}) \pm 0.02\,(\text{syst})$
	NLO QCD	0.108 ± 0.007	
EW+QCD		0.221 ± 0.014	$0.20^{+0.05}_{-0.04}\,(\text{stat}) \pm 0.02\,(\text{syst})$

EW ZZ $\rightarrow 4\ell/2\ell2\nu$
ATLAS-STDM-2017-19
Arxiv:2004.10612

Final Distributions in ZZjj



	μ_{EW}	$\mu_{\mathrm{QCD}}^{\ell\ell\ell\ell jj}$	Significance Obs. (Exp.)
$\ell\ell\ell\ell jj$	1.5 ± 0.4	0.95 ± 0.22	5.5 (3.9) σ
$\ell\ell\nu\nu jj$	0.7 ± 0.7	–	1.2 (1.8) σ
Combined	1.35 ± 0.34	0.96 ± 0.22	5.5 (4.3) σ

- To compare with observed (expected) statistical significance 4.0 (3.5) s.d. from CMS, using 4ℓ events only

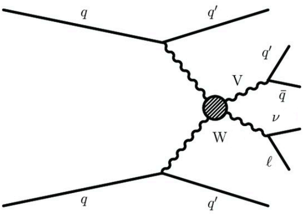
EW WV $\to \ell\nu$qq

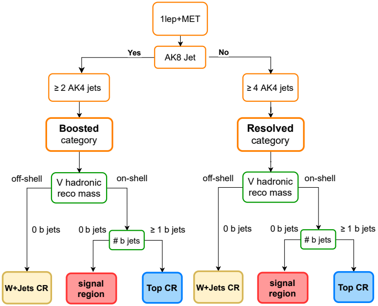
CMS-SMP-20-013

CDS:2776799

$WW/WZ \to \ell\nu jj$ Analysis

- Two vector bosons (WV)





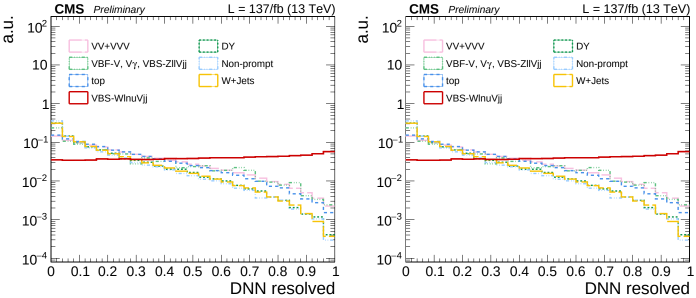
- $\mathrm{W} \to \mathrm{e}/\mu\nu$
- $\mathrm{V}(\equiv \mathrm{W}/\mathrm{Z}) \to \mathrm{qq}$
  - two jets: detector able to resolve them as separated objects
  - One large-radius jet: boosted V boson reconstructed as one large-radius jet

- W+Jets CR: off-shell V boson mass
- Top-quark CR: at least one tagged b-jet

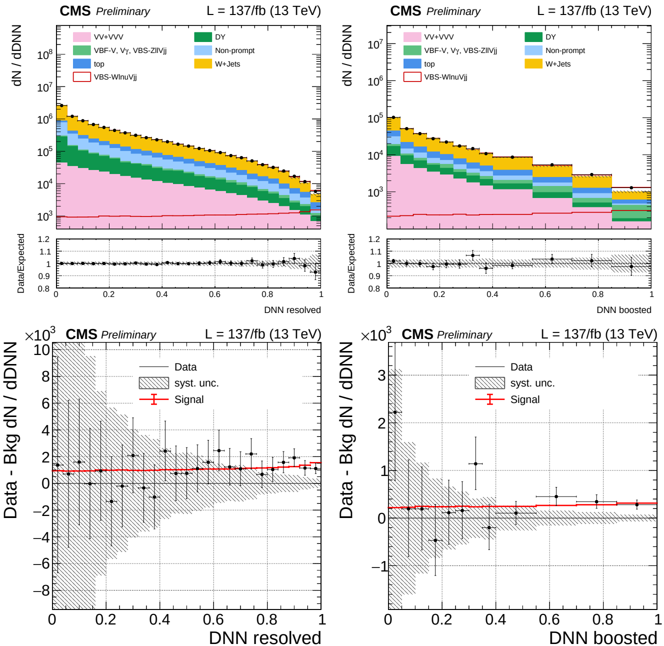
DNN Final Discriminant

Variable	Resolved	Boosted
Lepton pseudorapidity	✓	✓
Lepton transverse momentum	✓	✓
Zeppenfeld variable for the lepton	✓	✓
Number of jets with $p_T > 30$ GeV	✓	✓
VBS leading tag-jet p_T	-	✓
VBS trailing tag-jet p_T	✓	✓
Pseudorapidity interval between VBS tag-jets	✓	✓
Quark Gluon discriminator of the highest p_T jet of the VBS tag-jets	✓	✓
Azimuthal angle distance between VBS tag-jets	✓	✓
Invariant mass of the VBS tag-jets pair	✓	✓
p_T of jets from V_{had}	✓	-
Pseudorapidity difference between V_{had} jets	✓	-
Quark Gluon discriminator of the V_{had} jets	✓	-
V_{had} p_T	-	✓
Invariant mass of the V_{had}	✓	✓
Zeppenfeld variable for the V_{had}	-	✓
V_{had} centrality	-	✓

Resolved | boosted



DNN in SRs


CMS Preliminary
L = 137/fb (13 TeV)
dN / dDNN
VV+VVV
VBF-V, Vγ, VBS-ZllVjj
top
VBS-WlnuVjj
DY
Non-prompt
W+Jets
Data/Expected
DNN resolved
DNN boosted
Data - Bkg dN / dDNN
Data
syst. unc.
Signal

$WW/WZ \to \ell\nu jj$ Results

- EW WV measurements:
  - observed (expected) significance is 4.4 (5.1) s.d.
  - $\mu_{EW} = \sigma^{obs}/\sigma^{SM} = 0.85^{+0.24}_{-0.20} =^{+0.21}_{-0.17}$ (syst.) $^{+0.12}_{-0.12}$(stat.)
  - observed (expected) fiducial cross section: 1.9 ± 0.5 ($2.23^{+0.08}_{-0.11}$(scale) $^{+0.05}_{-0.05}$(pdf)) pb
- QCD+EW WV measurements:
  - $\mu_{EW+QCD} = \sigma^{obs}/\sigma^{SM} = 0.98^{+0.20}_{-0.17} =^{+0.19}_{-0.16}$ (syst.) $^{+0.07}_{-0.07}$(stat.)
  - observed (expected) fiducial cross section: $16.6^{+3.4}_{-2.9}$ ($16.9^{+2.9}_{-2.1}$(scale) $^{+0.5}_{-0.5}$(pdf)) pb

Uncertainty source	$\Delta\mu_{EW}$
Statistical	0.12
Limited sample size	0.10
Normalization of backgrounds	0.08
Experimental	0.06
b-tagging	0.05
Jet energy scale and resolution	0.04
Luminosity	0.01
Leptons identification	0.01
Boosted V boson identification	0.01
Theory	0.12
Signal modeling	0.09
Background modeling	0.08
Total	0.22

Search for VBF $\mathrm{H}^{\pm\pm}$ & $\mathrm{H}^{\pm}$ Production

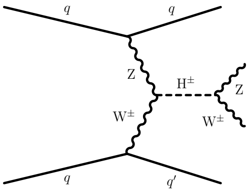
CMS-HIG-20-017

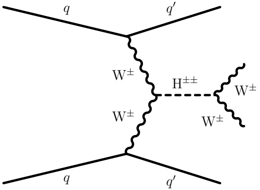
Arxiv:2104.04762

Eur. Phys. J. C 81 (2021) 723

VBF $H^{\pm\pm}$ & $H^{\pm}$ Production

- Search for VBF $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$ and $H^{\pm} \rightarrow WZ$ in fully leptonic, electrons or muons, decays
- Same object selection and background estimation as CMS-SMP-19-012
- Main features:
  - signal and control regions fits to simultaneously search for $H^{\pm\pm}$ and $H^{\pm}$ decays
  - making use of full m_T variable, instead of simpler options

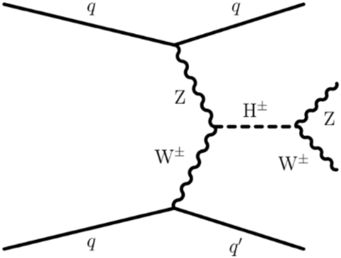


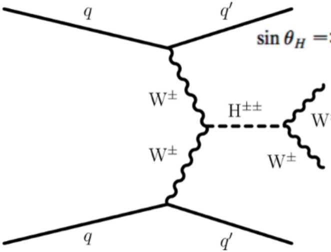


Georgi–Machacek (GM) model

- Two-Higgs-double model (2HDM) - Minimal extension of SM
  - Five physical scalar states: h, H, A, H^+, H^-
- Higgs triplet extensions
  - Georgi-Machacek: One real and one complex triplet
  - Tree level H^+WZ coupling
  - Presence of doubly charged higgs: H^{++}

$$\Phi = \begin{pmatrix} \phi_2^* & \phi_1 \\ -\phi_1^* & \phi_2 \end{pmatrix}, \qquad \Xi = \begin{pmatrix} \chi_3^* & \xi_1 & \chi_1 \\ -\chi_2^* & \xi_2 & \chi_2 \\ \chi_1^* & -\xi_1^* & \chi_3 \end{pmatrix}.$$

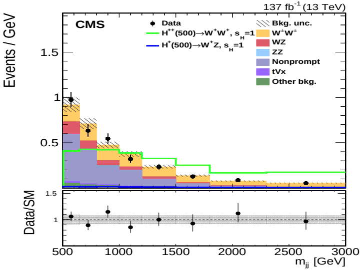




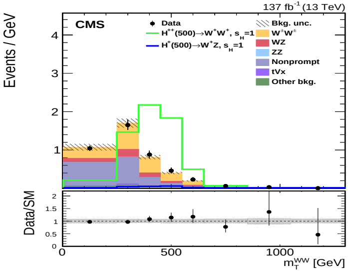
$$\sin\theta_H =: s_H = \frac{2\sqrt{2}v_\Xi}{v_{SM}}$$

Distributions in the SRs

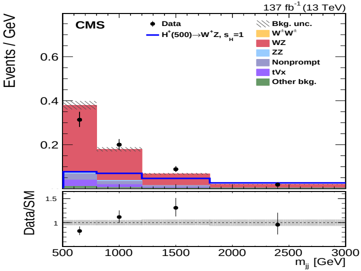
$W^{\pm}W^{\pm}$ SR: m_{jj}



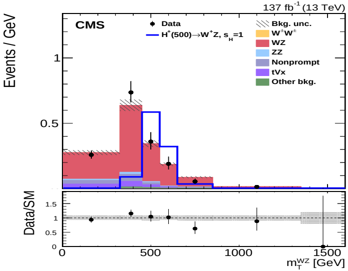
$W^{\pm}W^{\pm}$ SR: m_T



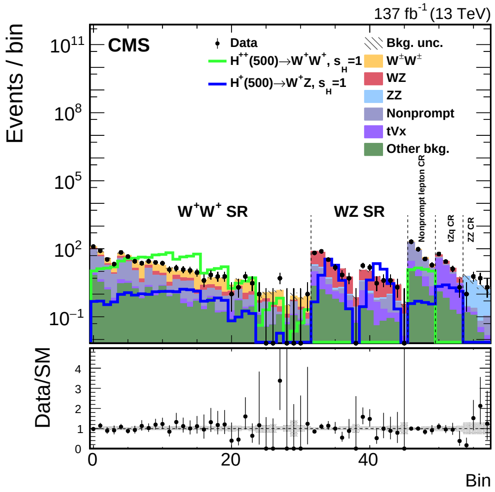
WZ SR: m_{jj}



WZ SR: m_T



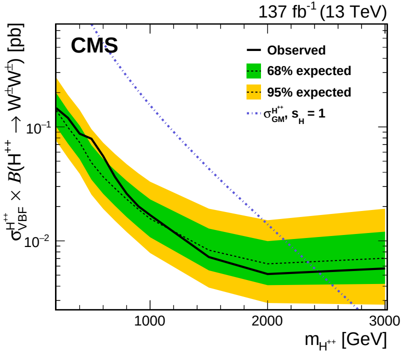
Multidimensional Fit with SRs & CRs



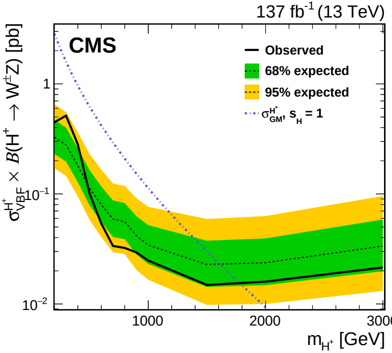
Distributions for signal, backgrounds, and data for the bins used in the simultaneous fit. The bins 1–32 (4×8) show the events in the WW SR ($m_{jj} \times m_T$), the bins 33–46 (2×7) show the events in the WZ SR ($m_{jj} \times m_T$), the 4 bins 47–50 show the events in the nonprompt lepton CR (m_{jj}), the 4 bins 51–54 show the events in the tZq CR (m_{jj}), and the 4 bins 55–58 show the events in the ZZ CR (m_{jj})

Model Indepependent Limits

$H^{\pm\pm}$



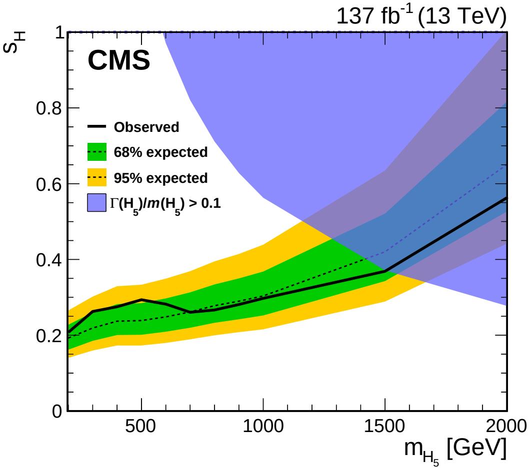
$H^{\pm}$



- Model-independent cross section limits for VBF $H^{\pm\pm} \to W^{\pm}W^{\pm}$ and $H^{\pm} \to WZ$ decays
- Extended search up to $3\mathrm{TeV}$

s_{H} Limits in GM Model

- In GM model, charged Higgs bosons $\mathrm{H}^{\pm\pm}$ and $\mathrm{H}^{\pm}$ degenerate in mass (m_{H_5})
- Coupling depends on m_{H_5} and the parameter s_{H}, where s_{H}^2 characterizes the fraction of the W boson mass squared generated by the vacuum expectation value of the triplet field



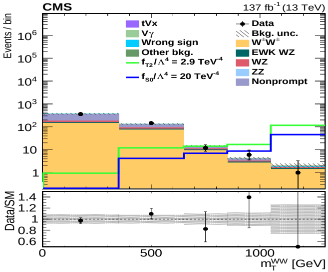
Anomalous Couplings

aQGCs

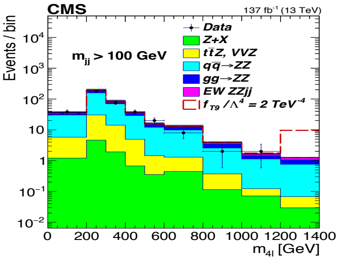
- Extensions of the SM induce coupling modifications that can be parameterized in terms of an EFT approach
- In these analyses, limits on aQGCs are set via EFT approach. Dimension-8 operators that can modify the VVjj production through aQGCs are considered
- Simplified version of SM analyses are pursued
  - simpler one-dimensional discriminant, instead of using several variables or MVA techniques
- Variables sensitive to diboson system

Final Distributions for aQGCs

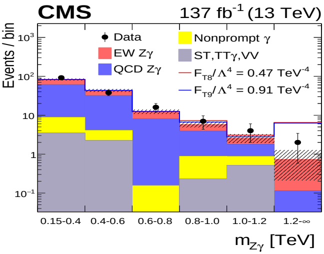
$W^{\pm}W^{\pm}jj$



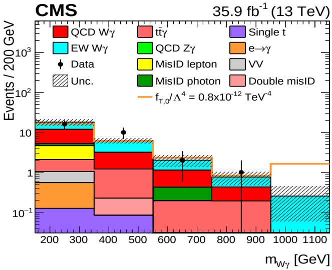
$ZZjj$



$Z\gamma jj$



$W\gamma jj$

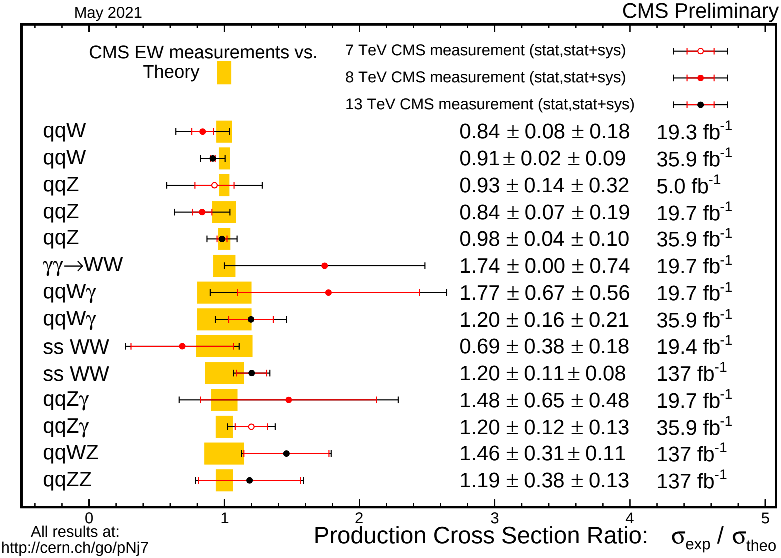


aQGCs Limits From Shown Final States

	Observed	Expected	Observed	Expected	Observed	Expected	Observed	Expected
	$W^{\pm}W^{\pm} + WZ$ (TeV^{-4})		ZZ (TeV^{-4})		$W\gamma$ (TeV^{-4})		$Z\gamma$ (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]	[-0.52,0.44]	[-0.64,0.57]
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]	[-0.65,0.63]	[-0.81,0.90]
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]	[-1.36,1.21]	[-1.68,1.54]
f_{T5}/Λ^4	—	—	—	—	[-0.5, 0.5]	[-0.4, 0.4]	[-0.45,0.52]	[-0.58,0.64]
f_{T6}/Λ^4	—	—	—	—	[-0.4, 0.4]	[-0.3, 0.4]	[-1.02,1.07]	[-1.30,1.33]
f_{T7}/Λ^4	—	—	—	—	[-0.9, 0.9]	[-0.8, 0.9]	[-1.67,1.97]	[-2.15,2.43]
f_{T8}/Λ^4	—	—	[-0.43, 0.43]	[-0.68, 0.68]	—	—	[-0.36,0.36]	[-0.47,0.47]
f_{T9}/Λ^4	—	—	[-0.92, 0.92]	[-1.50, 1.50]	—	—	[-0.72,0.72]	[-0.91,0.91]
f_{M0}/Λ^4	[-2.7, 2.9]	[-3.6, 3.7]	—	—	[-8.1, 8.0]	[-7.7, 7.6]	[-12.5,12.8]	[-15.8,16.0]
f_{M1}/Λ^4	[-4.1, 4.2]	[-5.2, 5.5]	—	—	[-12, 12]	[-11, 11]	[-28.1,27.0]	[-35.0,34.7]
f_{M2}/Λ^4	—	—	—	—	[-2.8, 2.8]	[-2.7, 2.7]	[-5.21,5.12]	[-6.55,6.49]
f_{M3}/Λ^4	—	—	—	—	[-4.4, 4.4]	[-4.0, 4.1]	[-10.2,10.3]	[-13.0,13.0]
f_{M4}/Λ^4	—	—	—	—	[-5.0, 5.0]	[-4.7, 4.7]	[-10.2,10.2]	[-13.0,12.7]
f_{M5}/Λ^4	—	—	—	—	[-8.3, 8.3]	[-7.9, 7.7]	[-17.6,16.8]	[-22.2,21.3]
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]	[-44.7,45.0]	[-56.6,55.9]
f_{S0}/Λ^4	[-5.7, 6.1]	[-5.9, 6.2]	—	—	—	—	—	—
f_{S1}/Λ^4	[-16, 17]	[-18, 18]	—	—	—	—	—	—

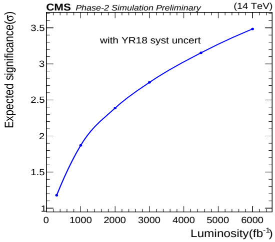
- Competitive sensitivity among different final states
- Results obtained without using any unitarization procedure, results taking into account unitarization limit in back-up
- Best stringent limits to date using semileptonic final states (SMP-18-006)

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

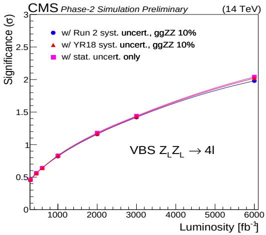


- Heavy vector V bosons acquire their mass through the Brout-Englert-Higgs mechanism
- Three polarization modes of V bosons: one longitudinal and two transverse
- The unitarity of the longitudinally polarized VBS at high energies is restored in the SM by a Higgs boson
  - Higgs boson contribution cancels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

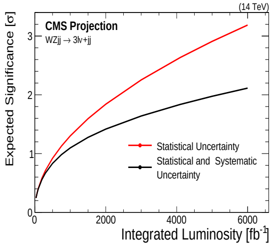
$W^{\pm}W^{\pm}jj$



ZZjj

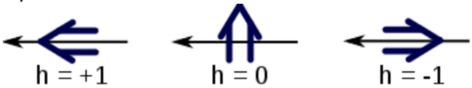


WZjj



$W^{\pm}W^{\pm}$ Polarization Components

Helicity: $h = \vec{p} \cdot \vec{\epsilon}$



Definition according to the **final state** of the scattering:

$$w^{\pm}w^{\pm} \rightarrow w^{\pm}_{L}w^{\pm}_{T}$$
$$w^{\pm}w^{\pm} \rightarrow w^{\pm}_{T}w^{\pm}_{L}$$
$$w^{\pm}w^{\pm} \rightarrow w^{\pm}_{T}w^{\pm}_{T}$$
$$w^{\pm}w^{\pm} \rightarrow w^{\pm}_{L}w^{\pm}_{L} \qquad = \text{SIGNAL}$$

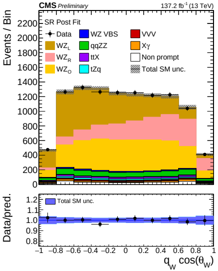
Summary of the fractions of the $\mathrm{W}^{\pm}_{\mathrm{L}}\mathrm{W}^{\pm}_{\mathrm{L}}$, $\mathrm{W}^{\pm}_{\mathrm{L}}\mathrm{W}^{\pm}_{\mathrm{T}}$, and $\mathrm{W}^{\pm}_{\mathrm{T}}\mathrm{W}^{\pm}_{\mathrm{T}}$ processes

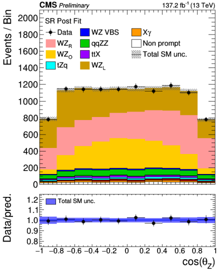
Cross sections with $m_{jj} > 200\mathrm{GeV}$ and $p^{\mathrm{j}}_{\mathrm{T}} > 10\mathrm{GeV}$		
Mode	WW rest-frame fraction (%)	Parton-parton rest-frame fraction (%)
$\mathrm{W}^{\pm}_{\mathrm{L}}\mathrm{W}^{\pm}_{\mathrm{L}}$	10.9	7.3
$\mathrm{W}^{\pm}_{\mathrm{L}}\mathrm{W}^{\pm}_{\mathrm{T}}$	31.9	37.4
$\mathrm{W}^{\pm}_{\mathrm{T}}\mathrm{W}^{\pm}_{\mathrm{T}}$	57.2	55.3

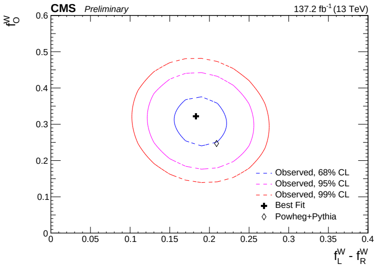
Each rest-frame produces different fractions, and hence different distributions

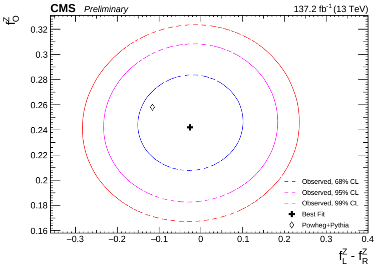
Polarization Measurements in Inclusive WZ Production

V polarization angle θ^{V} $\equiv$ angular distance between the momenta of the V boson and the negatively charged lepton from its decay chain









First observation of longitudinally polarized W bosons in WZ production!

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

CMS-SMP-20-006

Arxiv:2009.09429

PLB 812 (2020) 136018

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

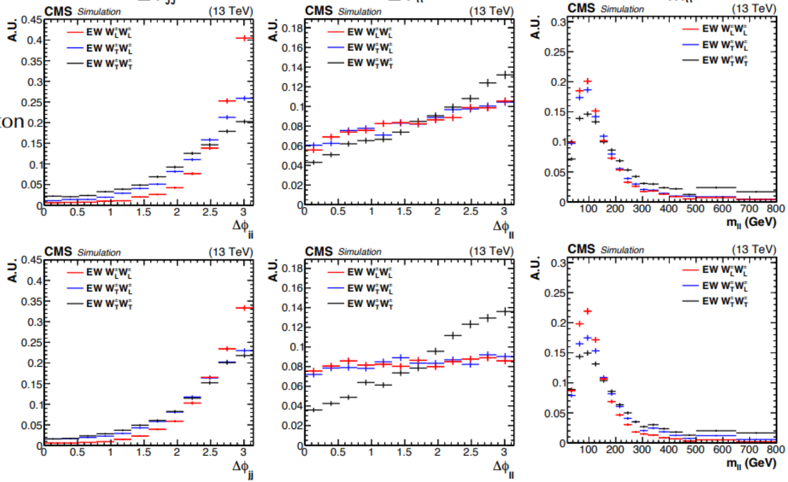
Signal Distributions

- 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

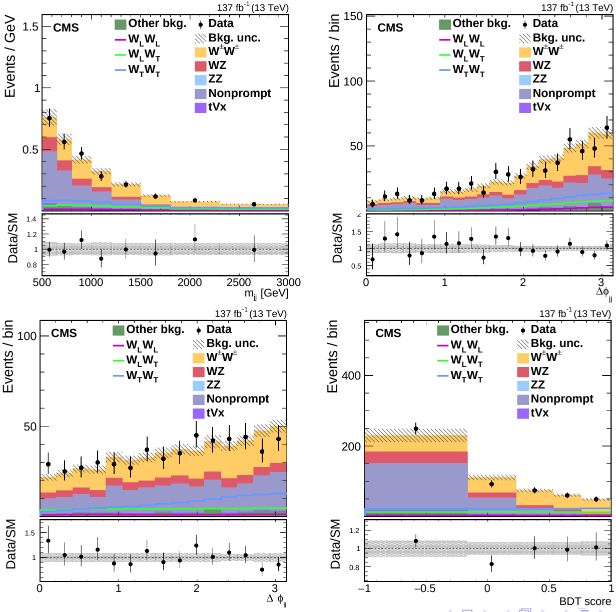
WW frame



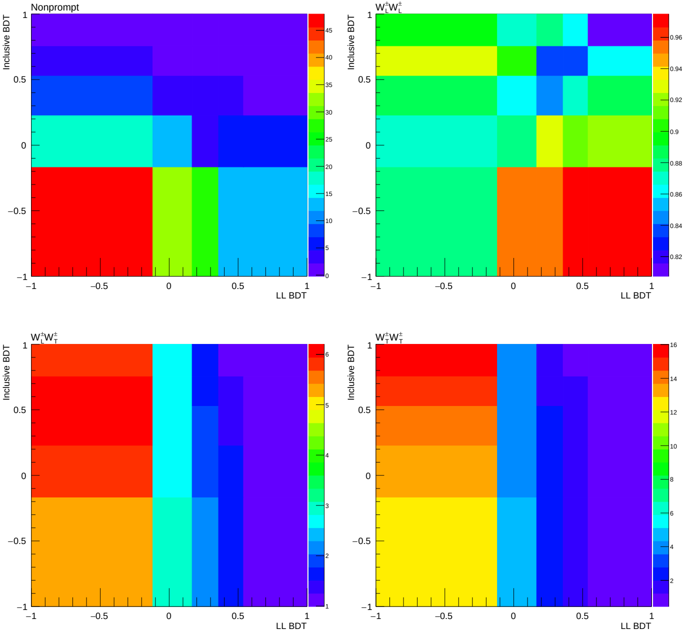
Signal Extraction

- 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

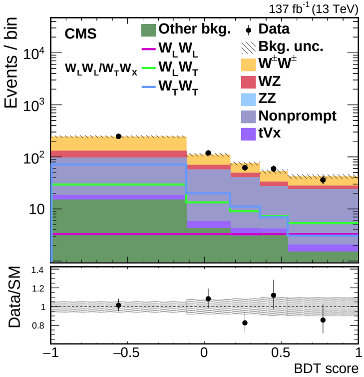
Input Variables / Inclusive BDT



Inclusive BDT vs. LL BDT Distributions in $W^{\pm}W^{\pm}jj$ SR



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 $W_L^{\pm}W_X^{\pm}$

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

Results shown in $W^{\pm}W^{\pm}$ c.m. frame

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

- Same fiducial region as CMS-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

Prospects for the measurement of VBS production in leptonic $W^{\pm}W^{\pm}$ and WZ diboson events at $\sqrt{s} = 14$ TeV at the High-Luminosity LHC

CMS-FTR-21-001

CDS:2776773

Introduction

- Prospects for the study of the VBS $\mathrm{W}^{\pm}\mathrm{W}^{\pm}$ and WZ production processes:
  - SM EW production measurements
  - polarized EW same-sign W boson pairs production measurements
- Analysis based on existing measurements at $\sqrt{s} = 13$ TeV:
  - CMS-SMP-19-012 (SM measurements)
  - CMS-SMP-20-006 ($\mathrm{W}^{\pm}\mathrm{W}^{\pm}$ polarization)
    - reporting results on $\mathrm{W}^{\pm}\mathrm{W}^{\pm}$ and parton-parton rest-frames
- Analysis based on existing measurements at $\sqrt{s} = 13\mathrm{TeV}$
  - extrapolated to the full integrated luminosity at the High-Luminosity LHC at $\sqrt{s} = 14\mathrm{TeV}$
- No attempt is made to assess the possible improvements due to upgraded detectors, or the possible degradation due to the harder data taking conditions

Fitting Strategy

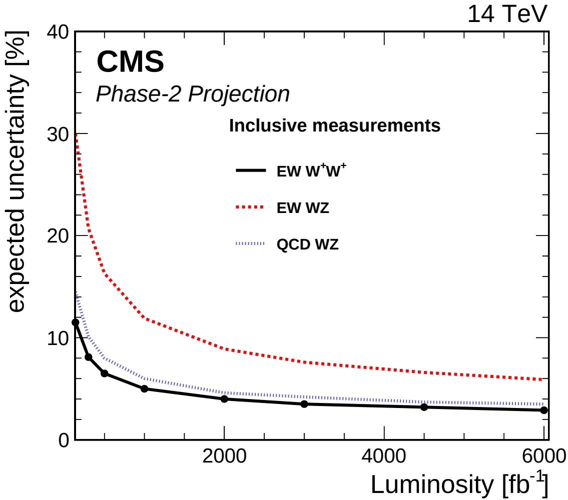
- Binned maximum-likelihood fits to discriminate signals and backgrounds
  - SM EW production measurements: $\mathrm{W^\pm W^\pm}$ and WZ SRs, and nonprompt lepton, tZq, and ZZ CRs
  - polarized EW same-sign W boson pairs production measurements: $\mathrm{W^\pm W^\pm}$ (BDTs) SR and WZ, nonprompt lepton, tZq, and ZZ CRs
  - 3D fit in the $\mathrm{W^\pm W^\pm}$ SR to discriminate all three $\mathrm{W^\pm W^\pm}$ polarization modes:
    - making use of the inclusive BDT (EW $\mathrm{W^\pm W^\pm}$ vs. the non-VBS processes) and the two signal BDTs ($\mathrm{W^\pm_L W^\pm_L}$ vs. $\mathrm{W^\pm_{\mathit{X}} W^\pm_T}$ and $\mathrm{W^\pm_L W^\pm_{\mathit{X}}}$ vs. $\mathrm{W^\pm_T W^\pm_T}$)

Projection Strategy

- Procedure:
  - applied QCD+EW corrections for EW $W^{\pm}W^{\pm}$ and WZ (-10% yields)
  - selection efficiency of the signal and background processes is assumed to be unchanged
  - $(\sigma^{14\text{TeV}}/\sigma^{13\text{TeV}})^{\text{VV}} = 1.1$, $(\sigma^{14\text{TeV}}/\sigma^{13\text{TeV}})^{\text{t}} = 1.2$
- Systematic uncertainties:
  - most uncertainties based on the estimations performed with the run II data set
    - 1% integrated luminosity, 0.5/2.5% lepton efficiency
  - limited sample size taken to scale with the data set

Aspect	Comment
Signal and background efficiency	Unchanged
QCD+EW corrections for EW $W^{\pm}W^{\pm}$ and WZ processes	Applied
Theoretical uncertainties	1/2
Luminosity uncertainty	1%
Lepton efficiency uncertainty for $p_T^{\ell} > 20\text{GeV}$	0.5%
Lepton efficiency uncertainty for $p_T^{\ell} \leq 20\text{GeV}$	2.5%
Jet energy scale and resolution	1/2
$(\sigma^{14\text{TeV}}/\sigma^{13\text{TeV}})^{\text{VV}}$	1.1
$(\sigma^{14\text{TeV}}/\sigma^{13\text{TeV}})^{\text{t}}$	1.2

Uncertainty in the VBS cross section measurements (I)



Projected estimated uncertainty in the EW $\mathrm{W}^{\pm}\mathrm{W}^{\pm}$, EW WZ, and QCD WZ cross section measurements as a function of the integrated luminosity

Uncertainty in the VBS cross section measurements (II)

Projected systematic uncertainties (in %) of the EW $W^{\pm}W^{\pm}$, EW WZ, and QCD WZ cross section measurements with an integrated luminosity of $3000 fb^{-1}$

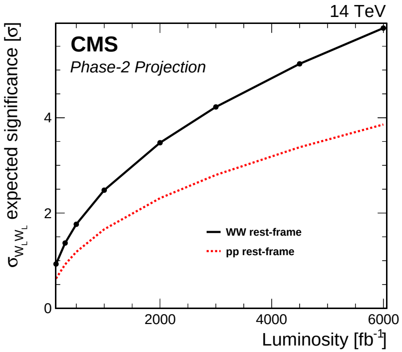
Source of uncertainty	EW $W^{\pm}W^{\pm}$	EW WZ	QCD WZ
Integrated luminosity	1.1	1.0	1.0
Lepton measurement	1.1	1.5	1.5
Jet energy scale and resolution	0.3	2.0	0.4
Pileup	0.1	0.5	0.3
btagging	1.2	1.2	1.2
Limited sample size	0.8	1.0	0.5
Nonprompt lepton rate	1.2	1.7	1.3
Theory	1.7	2.6	1.4
Total systematic uncertainty	3.0	4.4	3.0
Statistical uncertainty	1.8	6.1	2.8
Total uncertainty	3.5	7.6	4.2

Old projection uncertainties:

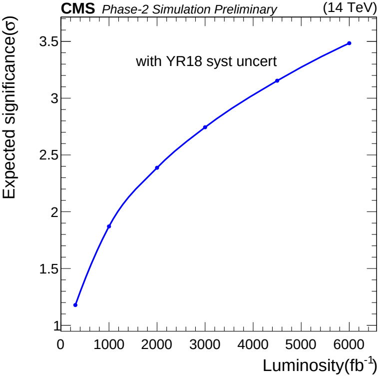
- $W^{\pm}W^{\pm}$: $\sim$4.5% (slightly larger theory uncertainty)
- WZ: $\sim$5.5% (slightly lower theory uncertainty)

Measurement of EW W_L-boson pairs (I)

New projections

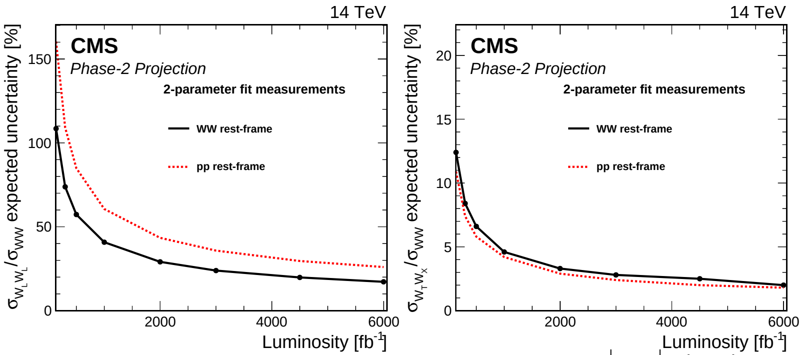


Old projections (parton-parton center-of-mass frame only)



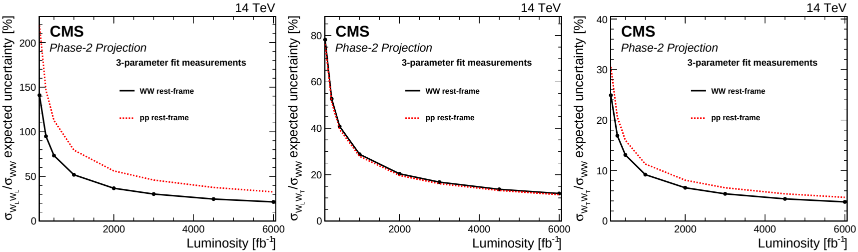
Projected estimated significance for the EW $W_L^{\pm}W_L^{\pm}$ process as a function of the integrated luminosity for the $W^{\pm}W^{\pm}$ and parton-parton center-of-mass frames

Measurement of EW W_L-boson pairs (II)



Projected estimated uncertainties for the EW $W^{\pm}_{L}W^{\pm}_{L}$ (left) and EW $W^{\pm}_{X}W^{\pm}_{T}$ (right) production cross section ratio measurements as a function of the integrated luminosity for the $W^{\pm}W^{\pm}$ and parton-parton center-of-mass frames

Measurements of $W^\pm_L W^\pm_L$, $W^\pm_L W^\pm_T$, & $W^\pm_T W^\pm_T$ Modes



Projected estimated uncertainties for the EW $W^\pm_L W^\pm_L$ (left), EW $W^\pm_L W^\pm_T$ (center), and EW $W^\pm_T W^\pm_T$ (right) production cross section ratio measurements as a function of the integrated luminosity for the $W^\pm W^\pm$ and parton-parton center-of-mass frames

Future Directions

- Increase scope of polarization measurements:
  - add production modes: WZ, ZZ, $\mathrm{W}^{\pm}\mathrm{W}^{\mp}$
  - add other final states: semileptonic and fully-hadronic modes
  - finer analysis treatment, e.g., splitting in $\mathrm{W}^{+}\mathrm{W}^{+}$ and $\mathrm{W}^{-}\mathrm{W}^{-}$
- Finer differential measurements:
  - extended reach in variables
  - add other variables, studied correlations between variables
- Expand EFT analyses
- Expand searches using these final states

Summary

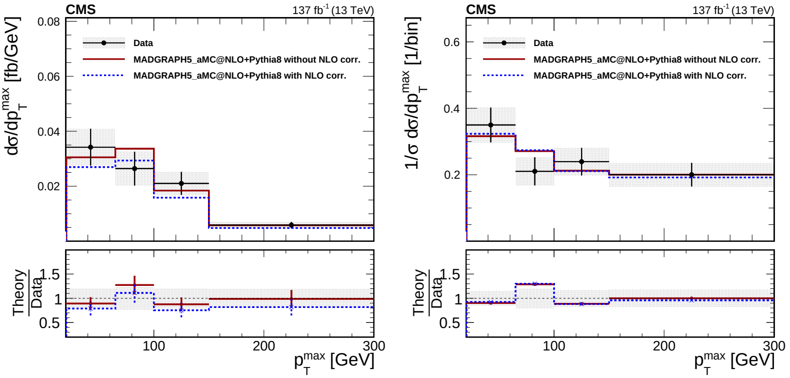
- Presented study of electroweak scattering of VVjj bosons in leptonic final states
  - first $\mathrm{W^\pm W^\pm}$ polarization cross section measurements
- Observation/strong evidence of EW VVjj production in several modes
- Measured inclusive cross sections of the VVjj processes in fiducial regions dominated by EW production
- Measured differential cross sections of VVjj processes on several distributions for first time
- This is just the starting point of a long physics program

Documentation

- All CMS results available on
  http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP/index.html
  http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/FTR/index.html
- All ATLAS results available on
  https://twiki.cern.ch/twiki/bin/view/AtlasPublic

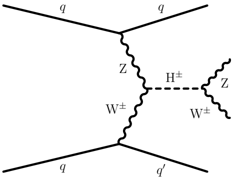
Back-Up

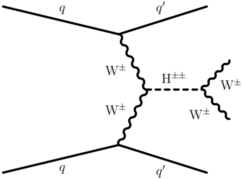
$p_T^{\ell\ max}$ $W^{\pm}W^{\pm}jj$ Fiducial Cross Section Measurements



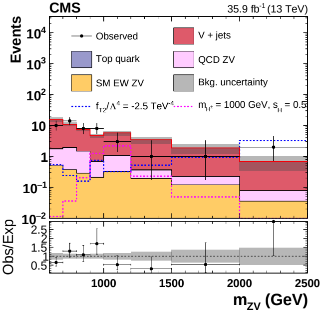
- Performed by replacing $m_{\ell\ell}$ to $p_T^{\ell\ max}$ in the fit

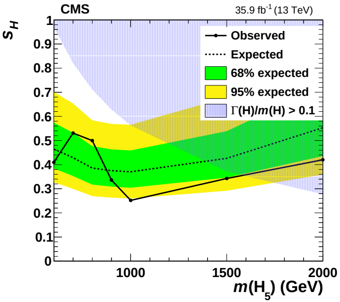
VBF $H^{\pm\pm}$ and $H^{\pm}$ Searches (GM Model)





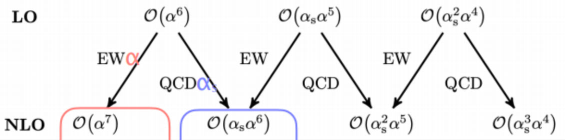
- Same VBS topology in resonant production
- Searching for enhancements in diboson mass-related observables
- Limits as a function of m_{H} and s_{H} (theory parameter relating the W boson and the vacuum expectation value of the triplet fields)





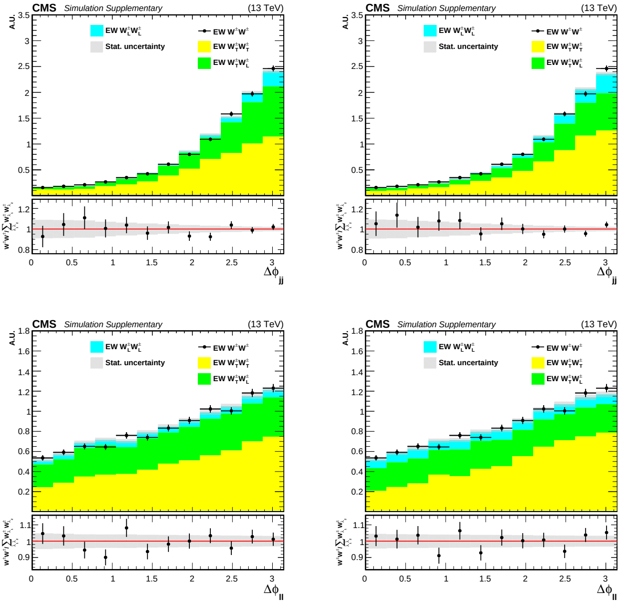
NLO Corrections

- 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

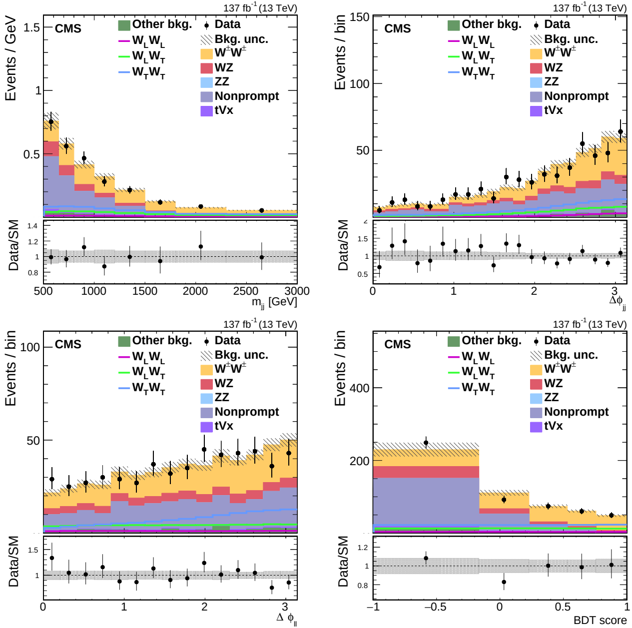


Order	$\mathcal{O}(\alpha^7)$	$\mathcal{O}(\alpha_s\alpha^6)$	$\mathcal{O}(\alpha_s^2\alpha^5)$	$\mathcal{O}(\alpha_s^3\alpha^4)$	Sum
$\delta\sigma_{NLO}$ [fb]	−0.2169(3)	−0.0568(5)	−0.00032(13)	−0.0063(4)	−0.2804(7)
$\delta\sigma_{NLO}/\sigma_{LO}$ [%]	−13.2	−3.5	0.0	−0.4	−17.1

Closure of Signal Samples

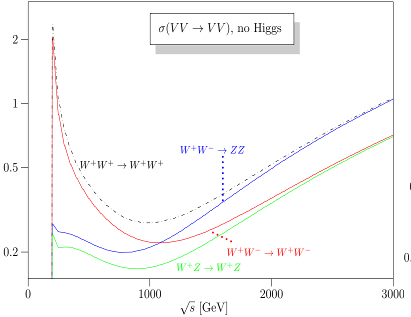


$W^{\pm}W^{\pm}$ Polarization Distributions

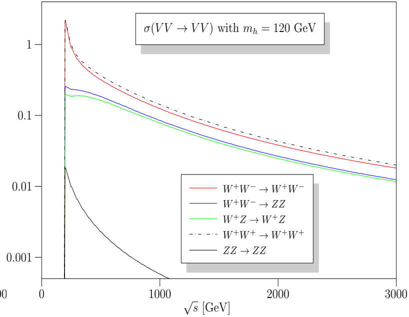


Unitarity Violation

SM without a Higgs boson



SM with a 120 GeV Higgs boson



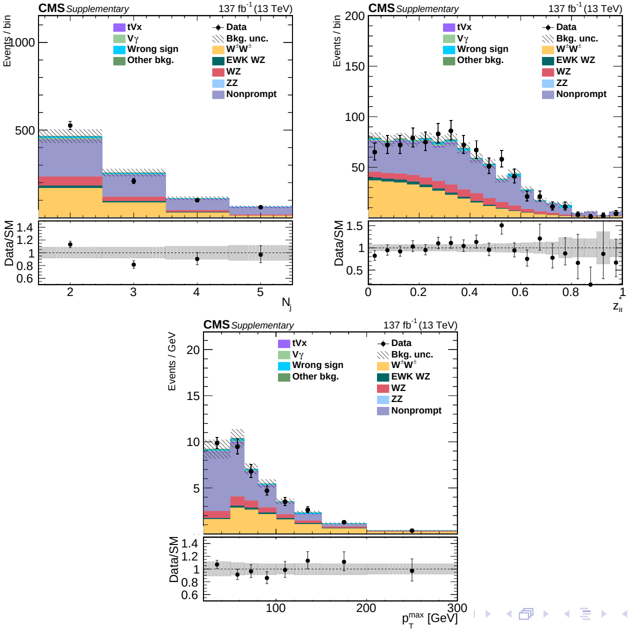
from ArXiv:0806.4145

- 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

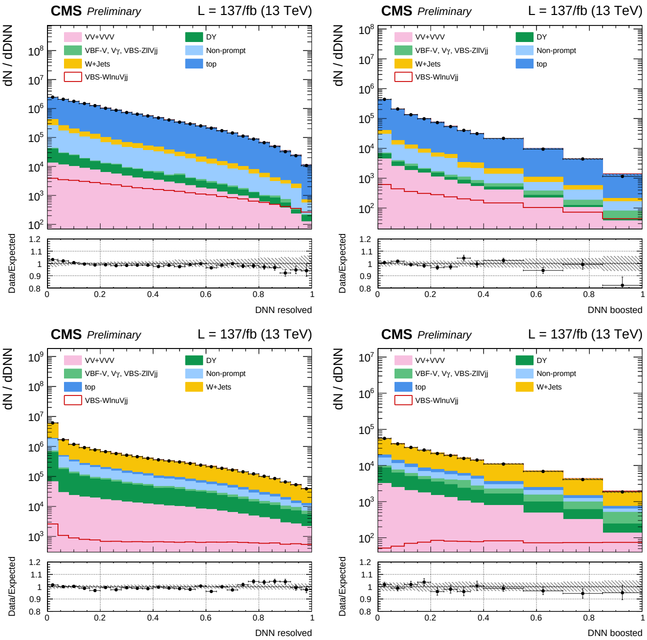
aQGCs: Unitarity Issue

- 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

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



DNN in CRs CMS-SMP-20-013



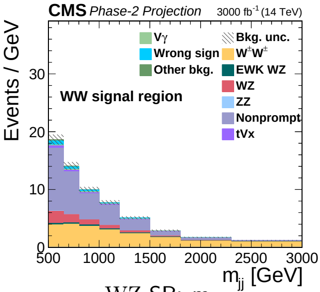
Systematic Uncertainties in the VBF Search

Source of uncertainty	$\Delta\mu$ background-only	$\Delta\mu$ $s_{\mathrm{H}} = 1.0$ and $m_{\mathrm{H}_5} = 500\,\mathrm{GeV}$
Integrated luminosity	0.002	0.019
Pileup	0.001	0.001
Lepton measurement	0.003	0.033
Trigger	0.001	0.007
JES and JER	0.003	0.006
btagging	0.001	0.006
Nonprompt rate	0.002	0.002
$\mathrm{W}^{\pm}\mathrm{W}^{\pm}/\mathrm{WZ}$ rate	0.014	0.015
Other prompt background rate	0.002	0.015
Signal rate	—	0.064
Simulated sample size	0.005	0.005
Total systematic uncertainty	0.016	0.078
Statistical uncertainty	0.021	0.044
Total uncertainty	0.027	0.090

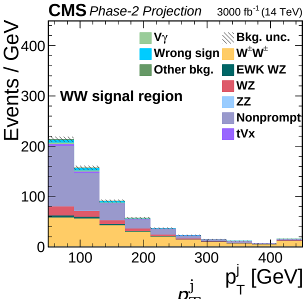
- Statistically dominated if no signal is seen

Signal & Background Distributions CMS-FTR-21-001

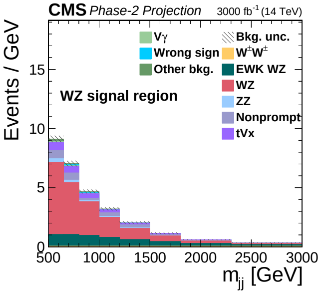
$W^{\pm}W^{\pm}$ SR: m_{jj}



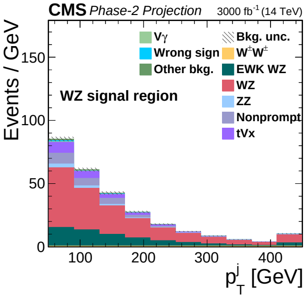
p_{T}^{j}



WZ SR: m_{jj}



p_{T}^{j}



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]

EW $Z\gamma$

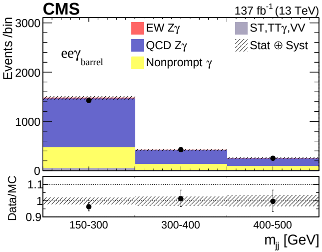
CMS-SMP-20-016

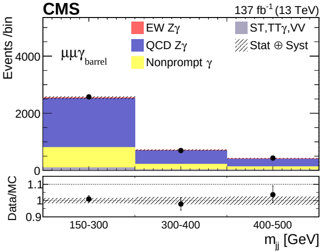
Arxiv:2106.11082

$Z\gamma$ Analysis

- 2016-8 data analysis

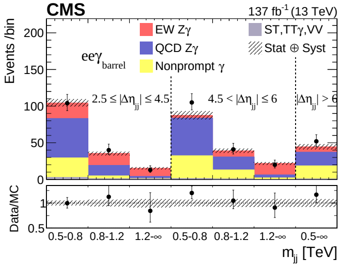
Common selection	$p_T^{\ell1,\ell2} > 25\,\text{GeV}$, $\lvert\eta^{\ell1,\ell2}\rvert < 2.5$ for electron chann $p_T^{\ell1,\ell2} > 20\,\text{GeV}$, $\lvert\eta^{\ell1,\ell2}\rvert < 2.4$ for muon channe $p_T^{\gamma} > 20\,\text{GeV}$, $\lvert\eta^{\gamma}\rvert < 1.444$ or $1.566 < \lvert\eta^{\gamma}\rvert < 2.5$ $p_T^{j1,j2} > 30\,\text{GeV}$, $\lvert\eta^{j1,j2}\rvert < 4.7$ $70 < m_{\ell\ell} < 110\,\text{GeV}$, $m_{Z\gamma} > 100\,\text{GeV}$ $\Delta R_{jj}, \Delta R_{j\gamma}, \Delta R_{j\ell} > 0.5$, $\Delta R_{\ell\gamma} > 0.7$
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, $m_{jj} > 500\,\text{GeV}$, $\lvert\Delta\eta_{jj}\rvert > 2.5$, $p_T^{\gamma} > 120\,\text{GeV}$





- Background estimation:
  - QCD-induced $W\gamma$ estimated in-situ
  - nonprompt lepton/photon extrapolated from data
  - other processes from simulation

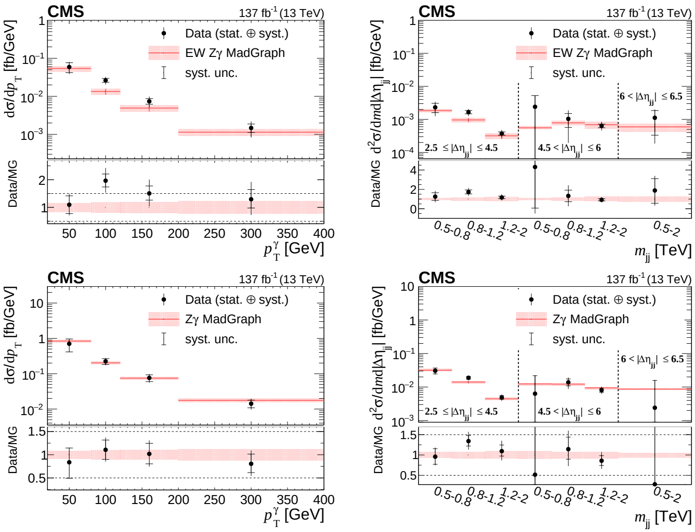
2D (m_{jj}-$|\Delta\eta_{jj}|$) distributions to the fit for the signal strength of EW $Z\gamma jj$



- Events further split in photons in the barrel and in the endcap
- Observed (expected) significance of EW process is 9.4 (8.5) s.d.

Measurement	Observed (fb)	Expected (fb)	Observed/Expected
σ^{fid}_{EW}	$5.21 \pm 0.52(stat) \pm 0.56(syst)$	$4.34 \pm 0.26(scale) \pm 0.06(PDF)$	1.20 ± 0.18
σ^{fid}_{QCD+EW}	$14.7 \pm 0.80(stat) \pm 1.26(syst)$	$13.3 \pm 1.72(scale) \pm 0.10(PDF)$	1.11 ± 0.11

Unfolded Differential Cross Sections



- p_T^γ differential cross section measurements performed by adding this variable in the simultaneous fit

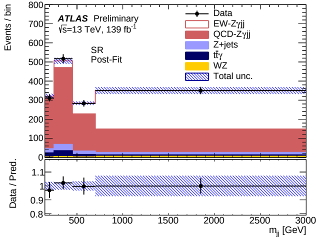
EW $Z\gamma$

ATLAS-CONF-2021-038

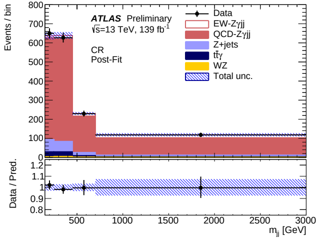
CDS:2777238

Final Distributions in $Z\gamma jj$

CR



SR



ATLAS

Source	Size [%]
Electron/photon calibration	$\pm$ 0.3
Photon	$\pm$ 0.3
Backgrounds	$\pm$ 1.0
Electron	$\pm$ 1.1
Flavour tagging	$\pm$ 1.1
Muon	$\pm$ 1.1
MC stat.	$\pm$ 1.4
Pileup	$\pm$ 2.6
Jets	$\pm$ 4.7
$QCD\text{-}Z\gamma jj$ modelling	$^{+4.8}_{-4.3}$
$EW\text{-}Z\gamma jj$ modelling	$^{+5.7}_{-4.6}$
Data stat.	$\pm$ 8.8
Total	$^{+13.4}_{-12.6}$

CMS

Systematic uncertainty	Impact [%]	
Jet energy correction	+7.9	−6.7
Theoretical uncertainties	+5.5	−4.7
MC statistical uncertainties	+4.7	−4.5
PU	+4.7	−4.1
Related to e, γ	+4.5	−3.6
PU jet ID	+3.7	−3.4
ECAL timing shift at L1	+3.5	−2.8
Nonprompt-γ bkg. estimate	+2.0	−1.6
Related to μ	+1.7	−1.4
Integrated luminosity	+0.8	−0.6
Total systematic uncertainty	+14	−12

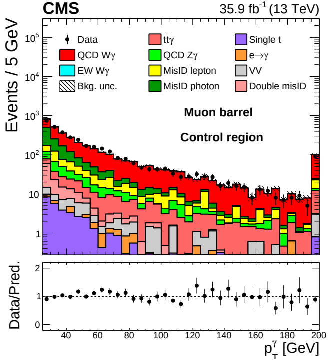
EW $W\gamma$

SMP-19-008

Arxiv:2008.10521

PLB 811 (2020) 135988

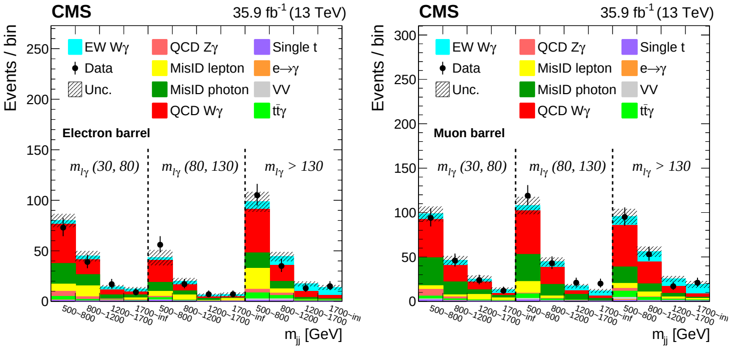
- 2016 data analysis
- Event selection:
  - one high-p_T electron or muon, and one high-p_T photon
  - moderate p_T^{miss} and m_T^W to reject nonprompt lepton/photon background
  - $m_{jj} > 500\mathrm{GeV}$ and $|\Delta\eta_{jj}| > 2.5$ to select VBS-like topology
- Background estimation:
  - QCD-induced $W\gamma$ estimated in-situ
  - nonprompt lepton/photon extrapolated from data
  - $e \to \gamma$ background estimated using $Z \to ee$ 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 $W\gamma jj$	154.2 ± 12.0	41.1 ± 4.4	221.2 ± 15.8	72.1 ± 6.2
$t\bar{t}\gamma$	20.6 ± 1.6	5.1 ± 0.6	28.3 ± 1.8	6.9 ± 0.8
QCD $Z\gamma$	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
$e \to \gamma$	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 $W\gamma jj$	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 $W\gamma jj$ Measurement

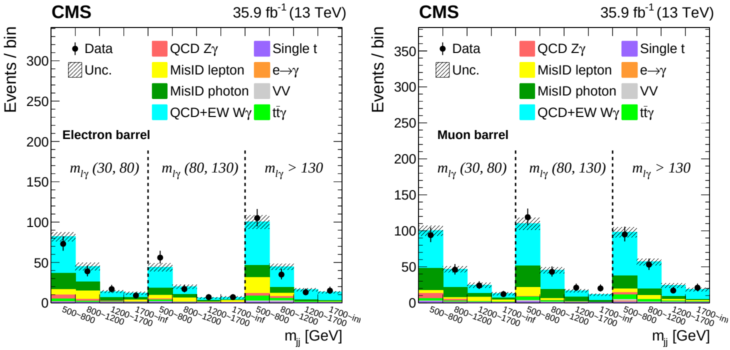
2D (m_{jj}-$m_{\ell\gamma}$) distributions to the fit for the signal strength of EW $W\gamma jj$



- 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.
- $\sigma_{EW}^{fid}(13\text{TeV}) = 20.4 \pm 0.4(lumi) \pm 2.8(stat) \pm 3.5(syst)$ 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