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Recent Results on Vector Boson Scattering from CMS

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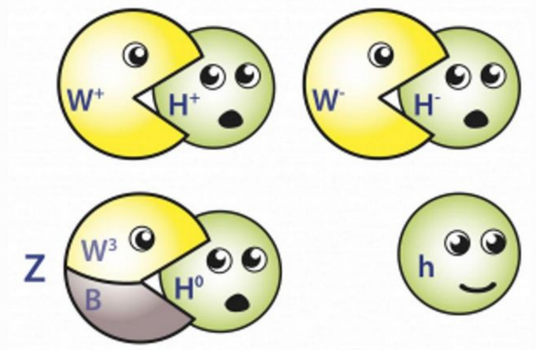
$W^{\pm}W^{\pm}$ WZ ZZ — Full Run II

$W\gamma$ — 2012+2016

Introduction & Motivation

- Observation of Higgs Boson
  - Consistent with the SM , within current uncertainties!
  - W and Z gauge bosons acquire longitudinal polarization via the Brout-Englert-Higgs mechanism : three goldstone bosons $H^{\pm}$ and H^0 "eaten up" by W and Z

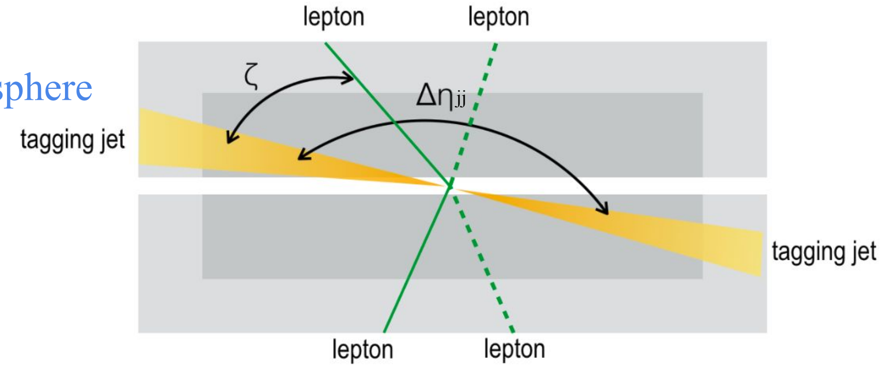


***Q*. Higgs Boson lone player responsible for Electroweak Symmetry Breaking ?**

- Measurements of **vector boson scattering (VBS) processes** → Key process to experimentally probe nature of EWSB
  - complementary to direct Higgs boson measurements
- The LHC makes it possible to measure many rare processes predicted by the SM

Overview of VBS Measurement

- **VBS topology**
  - two energetic forward jets in opposite hemisphere
  - large dijet mass and $\Delta\eta_{jj}$
- **Experimental Analysis**
  - Select VV events with VBS-like jets
  - Estimate non-VV backgrounds
    - Non prompt/fake (reducible)
      - Selected due to mis-ID ⟹from data
    - Prompt (irreducible)
      - Selected without mis-ID ⟹ from MC
  - Measurements
    - Inclusive and Differential Cross section Measurements
    - Search for anomalous Quartic Gauge Couplings



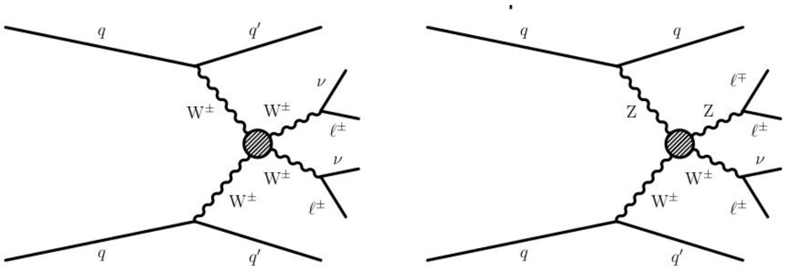
$W^{\pm}W^{\pm}$ & WZ VBS Full Run II : Overview

Submitted to Phys. Lett. B

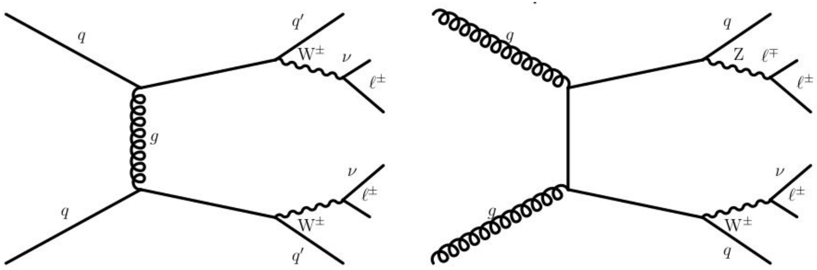
arXiv:2005.01173

- First simultaneous $W^{\pm}W^{\pm}jj$ & WZjj analyses using fully leptonic final states

- **Why $W^{\pm}W^{\pm}jj$?**
  - EW production dominant over QCD-induced
  - Distinct same-sign (SS) lepton state with low background
- **Why WZjj ?**
  - Sensitive to charged resonances or couplings
  - Clean signature but higher background compared to $W^{\pm}W^{\pm}$



EWK production



QCD production

$W^{\pm}W^{\pm}$ & WZ VBS: Event Selection & Background Estimation

EVENT SELECTION IN SIGNAL REGIONS

Variable	SSWW	WZ
leptons	2 SS, $P_T > 25/20$ GeV	1 OS pair + 1, $P_T >$ 25/10/20 GeV
$\|m_{\ell\ell} - m_Z\|$	> 15 GeV for ee	< 15 GeV
$m_{\ell\ell}$	> 20 GeV	-
$m_{\ell\ell\ell}$	-	>100GeV
p_T^j	> 50GeV	> 50GeV
p_T^{miss}	> 30 GeV	> 30 GeV
Anti b-tagging	applied	applied
tau veto	applied	applied
$\max(z^*_\ell)$	<0.75	<1.0
m_{jj}	> 500GeV	> 500GeV
$\|\Delta\eta_{jj}\|$	> 2.5	> 2.5

$z^*_\ell = |\eta_\ell - (\eta_{j1} + \eta_{j2})/2| / |\Delta\eta_{jj}|$

- WZ SR is dominated by QCD WZ events after the kinematic selection
- **MultiVariate Analysis for WZ** → enhance WZ EWK production w.r.t large WZ QCD production
- Overall good separation between EWK signal and background

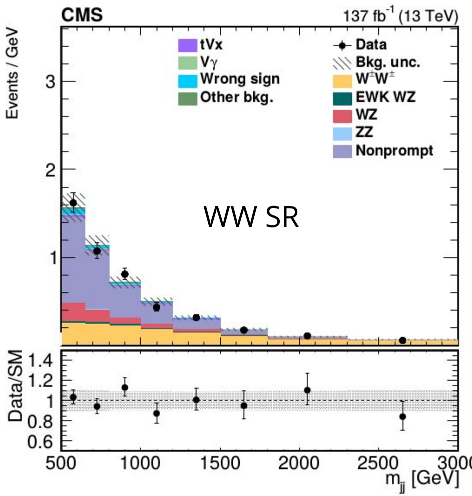
BACKGROUND ESTIMATION :

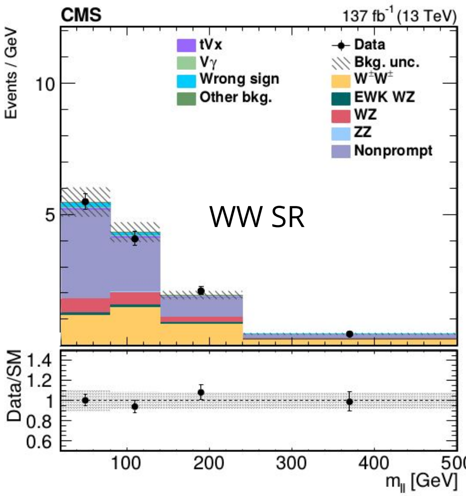
➔ Backgrounds estimated from simulation marked with [*] have **normalization assessed from data,** others are normalized to the best theoretical cross section prediction

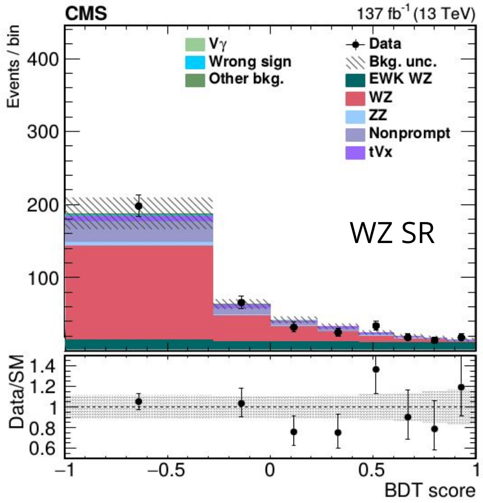
Category	Estimation
Non Prompt	From Data-Driven technique
Wrong sign	From charge mis-ID scale factors and simulated opposite sign events
QCD WZ[*], ZZ[*], tZq[*], WW QCD, WW DPS, VVV	From simulation

W$^{\pm}$W$^{\pm}$ & WZ VBS: Analysis Strategy

➔ Statistical analysis by simultaneously fitting signal yields in WW & WZ signal regions as well as background yields in control Regions (Non prompt, WZb(tZq) and ZZ) , to assess normalization from data







Process	W$^{\pm}$W$^{\pm}$ SR		WZ SR	
	Pre-fit	Post-fit	Pre-fit	Post-fit
Total SM	535 ± 60	522 ± 49	216 ± 12	229 ± 23
Data	524		229	

Source of uncertainty	W$^{\pm}$W$^{\pm}$ (%)	WZ (%)
Total systematic uncertainty	5.7	7.9
Statistical uncertainty	8.9	22
Total uncertainty	11	23

$W^{\pm}W^{\pm}$ & WZ VBS Full Run II : Results

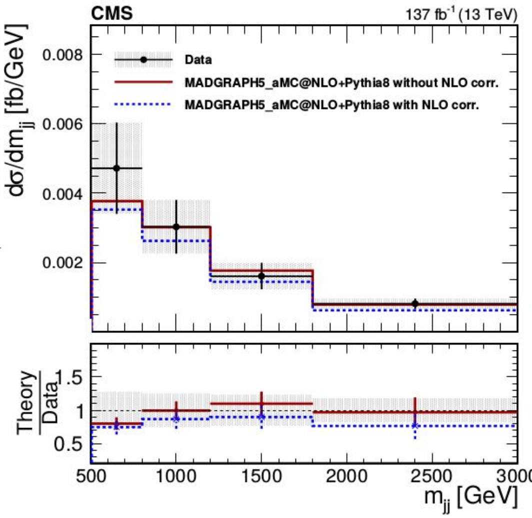
Inclusive Fiducial Cross section Measurements

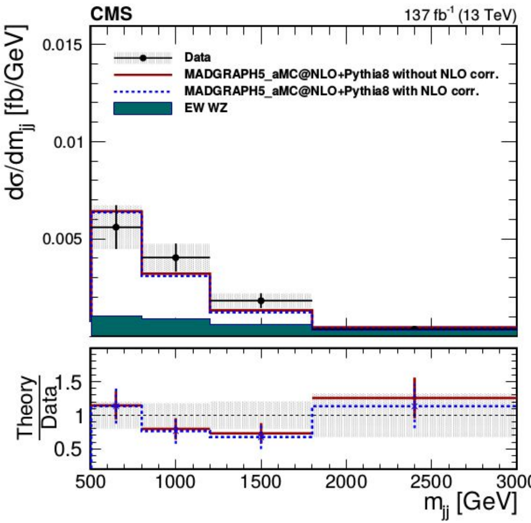
Process	$\sigma\mathcal{B}$ (fb)	Theoretical prediction without NLO corrections (fb)	Theoretical prediction with NLO corrections (fb)
EW $W^{\pm}W^{\pm}$	3.98 ± 0.45 $0.37\,(\text{stat}) \pm 0.25\,(\text{syst})$	3.93 ± 0.57	3.31 ± 0.47
EW+QCD $W^{\pm}W^{\pm}$	4.42 ± 0.47 $0.39\,(\text{stat}) \pm 0.25\,(\text{syst})$	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

Significance Observed(Expected)

EWK WZ : 6.8 (5.3) σ
EWK WW : far above 5 σ

Absolute and normalized - WW (EWK+QCD) differential cross section measurements on m_{jj} (left plot), m_{ll} & p_T^{max} and WZ (EWK+QCD) differential cross section measurements on m_{jj} (right plot)





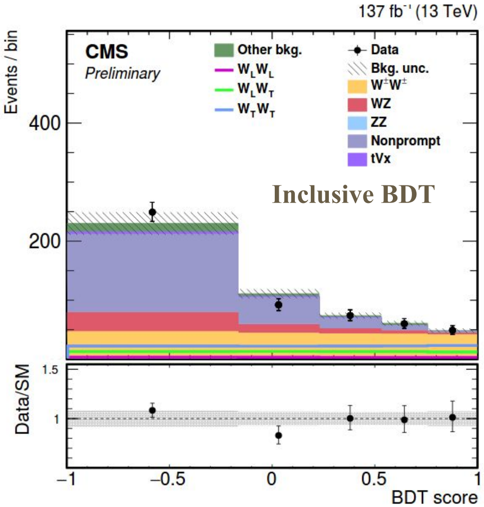
Polarized $W^{\pm}W^{\pm}$ VBS Full Run II : Overview

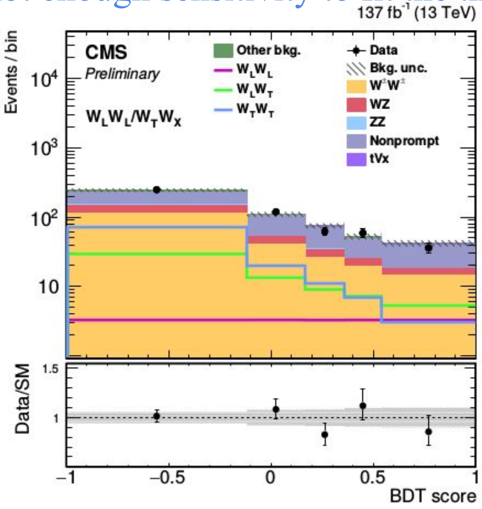
CMS-PAS-SMP-20-006

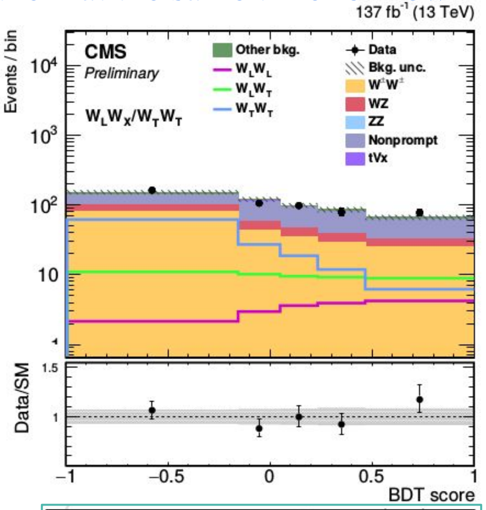
- **First measurements of EW production cross sections of polarized $W^{\pm}W^{\pm}$**
  - **First analysis of its kind with real Data**
  - **One of the high profile analyses for HL-LHC**
- **Signal** : SM EW $W_L^{\pm}W_L^{\pm}$, $W_L^{\pm}W_T^{\pm}$, $W_T^{\pm}W_T^{\pm}$ ⟵ MadGraph5_aMC@NLO 2.7.2
- **Event Selection & Background Estimation**
  - same as unpolarized WW VBS analysis
- 2 sets of results based on frame of defining helicity eigenstates
  - $W^{\pm}W^{\pm}$ COM Frame
  - Initial state parton parton frame
- **Multivariate Analysis**
  - Two Signal BDTs
    - to measure W_LW_L and W_XW_T component
    - to measure W_LW_X and W_TW_T component
  - Inclusive BDT
    - to separate EW $W^{\pm}W^{\pm}$ from SM bkg
- **Analysis Strategy** : simultaneous fit
  - WW SR(2D distribution)
    - 5 bins(inclusive BDT) x 5 bins (signal BDT)
  - Remaining CRs
    - same as unpolarized WW VBS analysis

Polarized $W^{\pm}W^{\pm}$ VBS Full Run II : Distributions

Two different fits because there is not enough sensitivity to fit the three of them at the same time for now







Expected Yields in Longitudinal Component Analysis ► ►

Process	Yields in $W^{\pm}W^{\pm}$ SR
$W^{\pm}_L W^{\pm}_L$	16.0 ± 18.3
$W^{\pm}_L W^{\pm}_T$	63.1 ± 10.7
$W^{\pm}_T W^{\pm}_T$	110.1 ± 18.1
QCD WW	13.8 ± 1.6
Interference WW	8.4 ± 0.6
WZ	63.3 ± 7.8
ZZ	0.7 ± 0.2
Nonprompt	213.7 ± 52.3
tVX	7.1 ± 2.2
Other background	26.9 ± 9.9
Total SM	522.9 ± 60.7
Data	524

Uncertainties on Cross section Measurements

Source of uncertainty	$W^{\pm}_L W^{\pm}_L$ (%)	$W^{\pm}_X W^{\pm}_T$ (%)	$W^{\pm}_L W^{\pm}_X$ (%)	$W^{\pm}_T W^{\pm}_T$ (%)
Total systematic uncertainty	44	6.6	18	7.0
Statistical uncertainty	123	15	42	22
Total uncertainty	130	16	46	23

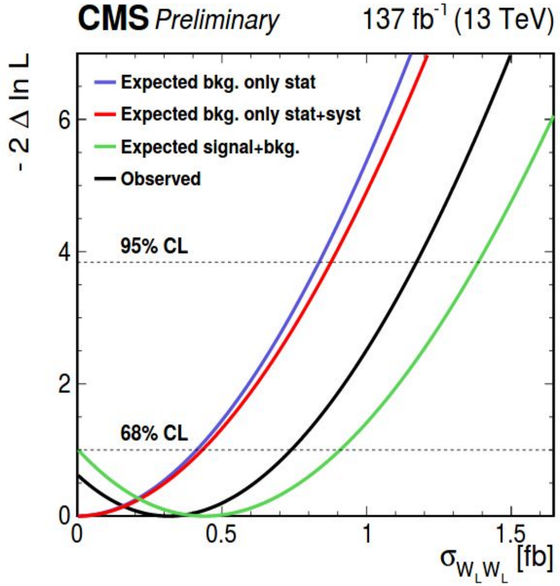
Polarized $W^{\pm}W^{\pm}$ VBS Full Run II : Results

➔ **Fiducial cross sections Measurement**

- **$W^{\pm}W^{\pm}$ COM 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

- **Observed (expected) upper limit: 1.17 (0.88)fb**
- **Observed (expected) significance ($W_L^{\pm}W_X^{\pm}$) : 2.3 (3.1) σ**



- **Initial state parton parton 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

- **Observed(expected) upper limit : 1.06 (0.85) fb**
- **Observed (expected) significance ($W_L^{\pm}W_X^{\pm}$) : 2.6 (2.9) σ**

ZZ VBS Full Run II : Overview

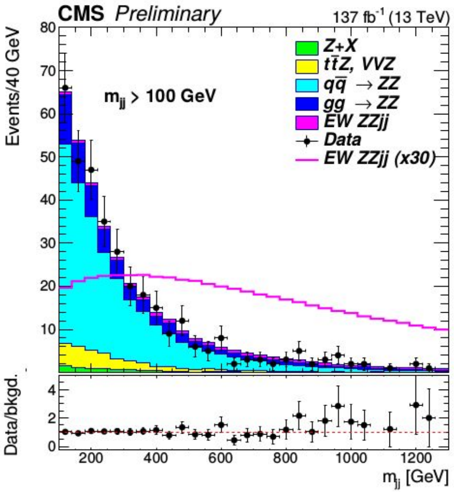
CMS-PAS-SMP-20-001

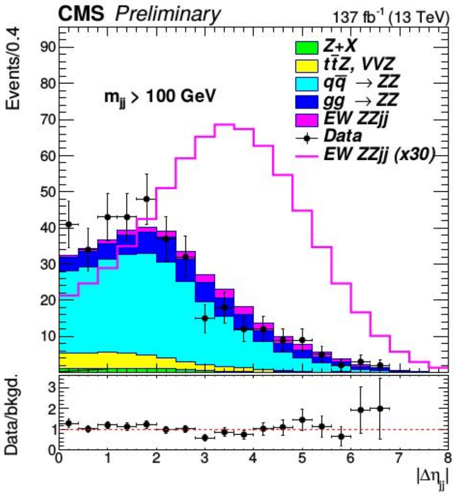
- Measurement of EW ZZjj production using 4ℓ events
  - Really clean , fully reconstructable final state
  - Small instrumental background
- Challenges
  - Small cross-section
  - Large QCD induced background
- Background Estimation
  - Irreducible Backgrounds
    - QCD ZZ , ttZ , VVZ ⟵From MC
  - Reducible Backgrounds (Z+X)
    - Z+jets , tt+jets , WZ+jets ⟵Data Driven
- Making use of a matrix-element discriminant (K_D) to enhance EW production
  - BDT was also studied - gave consistent results
- Define three regions to measure EW production
  - ZZjj inclusive
  - VBS-enriched loose
  - VBS-enriched tight

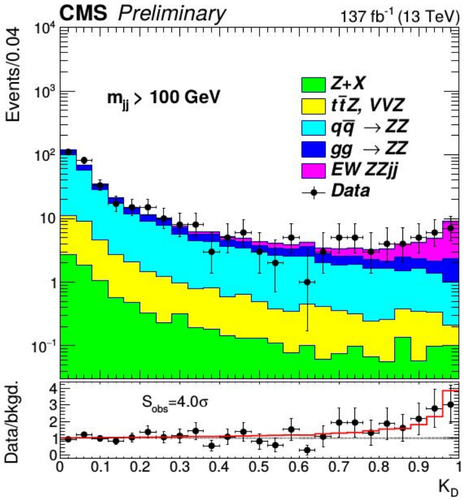
Object	Selection
	ZZjj inclusive
Leptons	$p_T(\ell_1) > 20$ GeV
	$p_T(\ell_2) > 10$ GeV
	$p_T(\ell) > 5$ GeV
	$\lvert\eta(\ell)\rvert < 2.5$
	(γ with $\Delta R(\ell,\gamma) < 0.1$ added to ℓ 4-vector)
Z and ZZ	$60 < m(\ell\ell) < 120$ GeV
	$m(4\ell) > 180$ GeV
Jets	at least 2
	$p_T(j) > 30$ GeV
	$\lvert\eta(j)\rvert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

ZZ VBS Full Run II : Results

Distributions in inclusive ZZjj region







Cross-section Measurements→

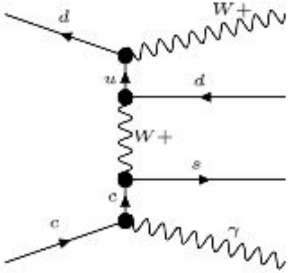
	SM σ (fb)	Measured σ (fb)
ZZjj inclusive		
EW	0.275 ± 0.021 (theo)	$0.33\ ^{+0.11}_{-0.10}$ (stat) $^{+0.04}_{-0.03}$ (syst)
EW+QCD	5.35 ± 0.51 (theo)	$5.29\ ^{+0.31}_{-0.30}$ (stat) ± 0.46 (syst)
VBS-enriched (loose)		
EW	0.186 ± 0.015 (theo)	$0.200\ ^{+0.078}_{-0.067}$ (stat) $^{+0.023}_{-0.013}$ (syst)
EW+QCD	1.21 ± 0.09 (theo)	$1.00\ ^{+0.12}_{-0.11}$ (stat) $^{+0.06}_{-0.05}$ (syst)
VBS-enriched (tight)		
EW	0.050 ± 0.005 (theo)	$0.06\ ^{+0.05}_{-0.04}$ (stat) ± 0.01 (syst)
EW+QCD	0.171 ± 0.012 (theo)	0.17 ± 0.04 (stat) ± 0.01 (syst)

Significance Observed (expected)
EWK ZZ : 4.0 (3.5) σ

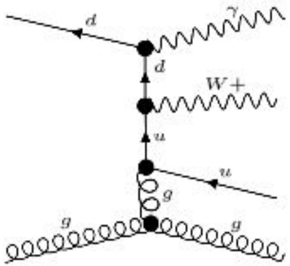
Wγ VBS 2016 dataset : Overview

CMS-PAS-SMP-19-008

- Wγ VBS : Larger cross-section
- Backgrounds
  - QCD Wγjj
    - From Simulation
  - Fake Photon , Fake Lepton, Double Fake
    - Data-driven
  - Diboson, ttγ, SingleTop, QCD Zγ, e⟶γ
    - From Simulation

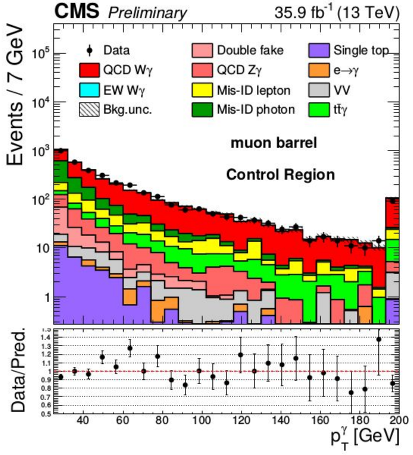


EWK production



QCD production

Low m_{jj} control Region →

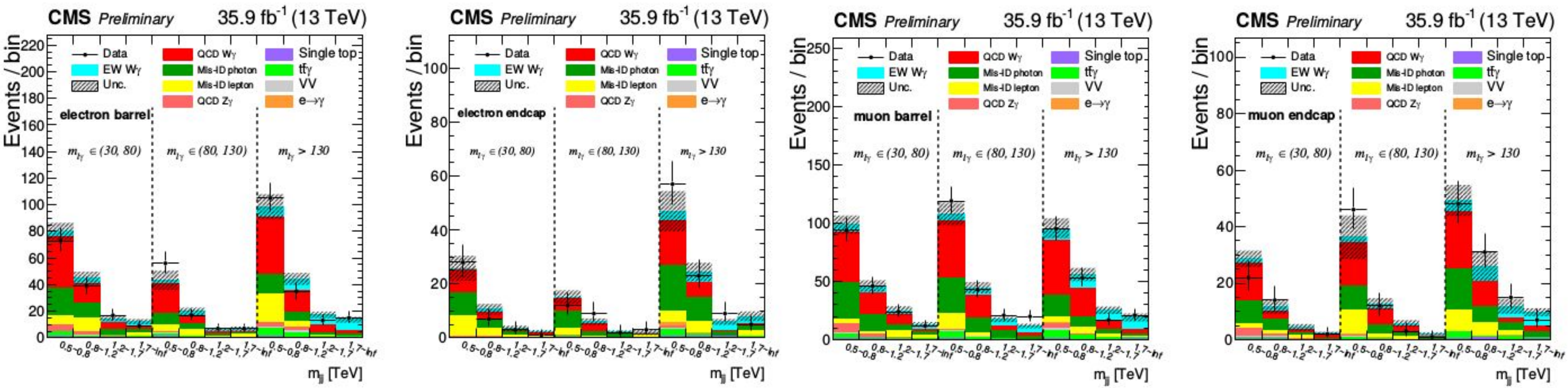


Yields in EW Signal Region

	electron barrel	electron endcap	muon barrel	muon endcap
Total background	348.3 ± 18.4	129.1 ± 9.9	463.4 ± 21.2	163.8 ± 10.4
EW Wγjj	48.8 ± 2.2	16.1 ± 1.0	74.5 ± 2.8	24.4 ± 1.3
Data	393	159	565	201

Wγ VBS 2016 dataset : Results

Post-fit 2D distributions



Combining 13 TeV + 8TeV results

Significance	Observed (Expected)
EW Wγ	5.3 (4.8)

Fiducial Cross-section Measurements

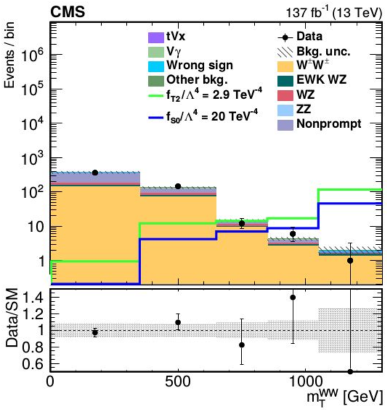
$$\sigma^{\text{fid}}_{\text{EW}} = 20.4 \pm 0.4\,(\text{lumi}) \pm 2.8\,(\text{stat}) \pm 3.5\,(\text{syst})\,\text{fb} = 20.4 \pm 4.5\,\text{fb}.$$

Searches for Anomalous Couplings

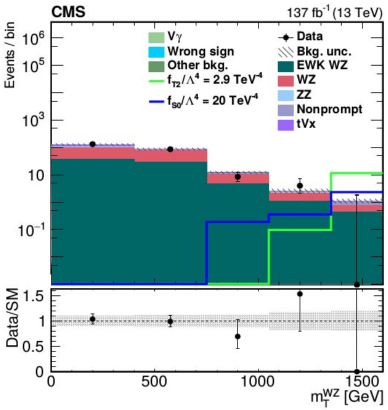
aQGCs : Overview

- Traces of heavy states from Beyond Standard Model Physics can be parameterized in terms of the Effective Field Theory (EFT) approach.
- In this analysis, limits on **aQGCs** are set via EFT approach. Dimension-8 operators that can modify VVjj production through aQGCs are considered; one at a time

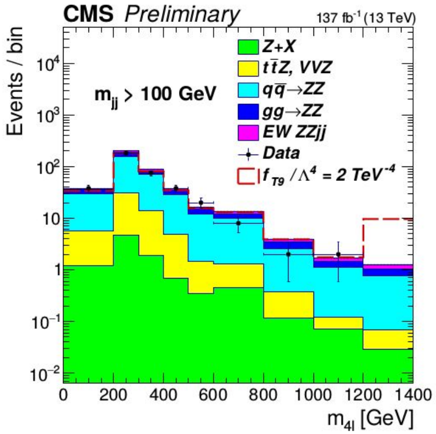
W±W±



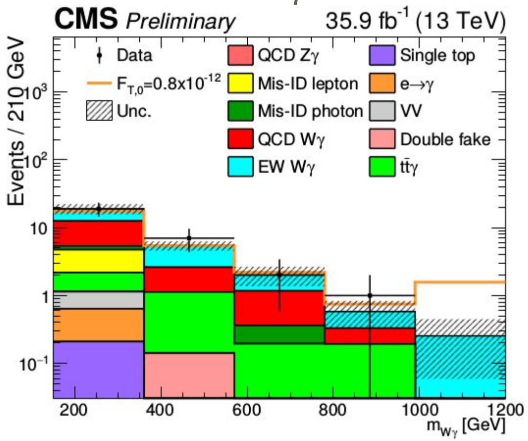
WZ



ZZ



Wγ



aQGCs: Unitarity Issue

- It is well known that 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 EFT-controlled part of the signal is given by:

$$D_i^{model} = \underbrace{\int_{2M_W}^{\Lambda} \frac{d\sigma}{dM}|_{model} dM}_{\text{EFT in its range of validity}} + \underbrace{\int_{\Lambda}^{M_{max}} \frac{d\sigma}{dM}|_{SM} dM}_{\text{Only SM contribution}}$$

- The technique is known as "Clipping", and essentially means using EFT only in the region it is valid!
- **Implementation** of "Clipping" in CMS Results
- For aqgc simulation, events violating unitarity (vary with operator values) are rejected ~ max 80%(WW) & max 50%(WZ). Data & SM processes are not affected.
- Limits on WW or/and WZ aQGC are reported in this way also for the first time

[*] Eur. Phys. J. C (2018) 78: 403 Eur. Phys. J. C 80, 181 (2020)

aQGCs : Results

$W^{\pm}W^{\pm}$ & WZ without considering unitarity bounds

	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]

$W^{\pm}W^{\pm}$ & WZ with considering unitarity bounds

	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]

ZZ

Coupling	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unitarity bound
f_{T0}/Λ^4	-0.37	0.35	-0.24	0.22	2.9
f_{T1}/Λ^4	-0.49	0.49	-0.31	0.31	2.7
f_{T2}/Λ^4	-0.98	0.95	-0.63	0.59	2.8
f_{T8}/Λ^4	-0.68	0.68	-0.43	0.43	3.3
f_{T9}/Λ^4	-1.46	1.46	-0.92	0.92	3.3

Wγ

Observed limits [TeV^{-4}]	Expected limits [TeV^{-4}]	Unitarity bound [TeV]
$-8.07 < F_{M,0}/\Lambda^4 < 7.99$	$-7.67 < F_{M,0}/\Lambda^4 < 7.55$	1.0
$-11.8 < F_{M,1}/\Lambda^4 < 12.1$	$-10.8 < F_{M,1}/\Lambda^4 < 11.3$	1.2
$-2.81 < F_{M,2}/\Lambda^4 < 2.81$	$-2.68 < F_{M,2}/\Lambda^4 < 2.68$	1.3
$-4.41 < F_{M,3}/\Lambda^4 < 4.49$	$-4.04 < F_{M,3}/\Lambda^4 < 4.10$	1.5
$-4.99 < F_{M,4}/\Lambda^4 < 4.95$	$-4.70 < F_{M,4}/\Lambda^4 < 4.67$	1.5
$-8.27 < F_{M,5}/\Lambda^4 < 8.31$	$-7.85 < F_{M,5}/\Lambda^4 < 7.73$	1.8
$-16.2 < F_{M,6}/\Lambda^4 < 16.0$	$-15.4 < F_{M,6}/\Lambda^4 < 15.1$	1.0
$-20.8 < F_{M,7}/\Lambda^4 < 20.2$	$-19.4 < F_{M,7}/\Lambda^4 < 18.7$	1.3
$-0.62 < F_{T,0}/\Lambda^4 < 0.64$	$-0.60 < F_{T,0}/\Lambda^4 < 0.62$	1.4
$-0.35 < F_{T,1}/\Lambda^4 < 0.39$	$-0.34 < F_{T,1}/\Lambda^4 < 0.38$	1.5
$-0.99 < F_{T,2}/\Lambda^4 < 1.18$	$-0.98 < F_{T,2}/\Lambda^4 < 1.16$	1.5
$-0.45 < F_{T,5}/\Lambda^4 < 0.46$	$-0.43 < F_{T,5}/\Lambda^4 < 0.44$	1.8
$-0.36 < F_{T,6}/\Lambda^4 < 0.38$	$-0.34 < F_{T,6}/\Lambda^4 < 0.36$	1.7
$-0.87 < F_{T,7}/\Lambda^4 < 0.93$	$-0.83 < F_{T,7}/\Lambda^4 < 0.89$	1.8

Summary

- Latest CMS results on EW scattering of WW, WZ, ZZ and Wγ presented
- Inclusive cross sections Measurements
- First Measurement of polarized WW EW cross sections
- First Differential cross sections measurements of $W^{\pm}W^{\pm}$ jj & WZjj processes on several distributions
- Limits on dim-8 Wilson coefficients are set for anomalous quartic gauge couplings within the EFT validity for the first time

BACK UP

MVA for WZ

- **Multivariate analysis** → enhance WZ EWK production w.r.t large WZ QCD production
- 13 Input variables retained ; BDT Gradient chosen from ROC curve

	Variable	Definition
jj variables	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
VV variable	$\lvert\eta^W - \eta^Z\rvert$	Absolute difference between the rapidities of the Z boson and the charged lepton from the decay of the W boson
V-j mix variables	$z^*_{\ell_i} (i = 1 - 3)$	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
	$\lvert\vec{p}_T^{\,tot}\rvert / \sum_i p_T^i$	Transverse component of the vector sum of the bosons and tagging jets momenta, normalized to their scalar p_T sum

- **Overall good separation between EWK WZ and QCD WZ**

Note: Larger set of discriminating observables studied but variables improving sensitivity & showing some S/B separation retained.

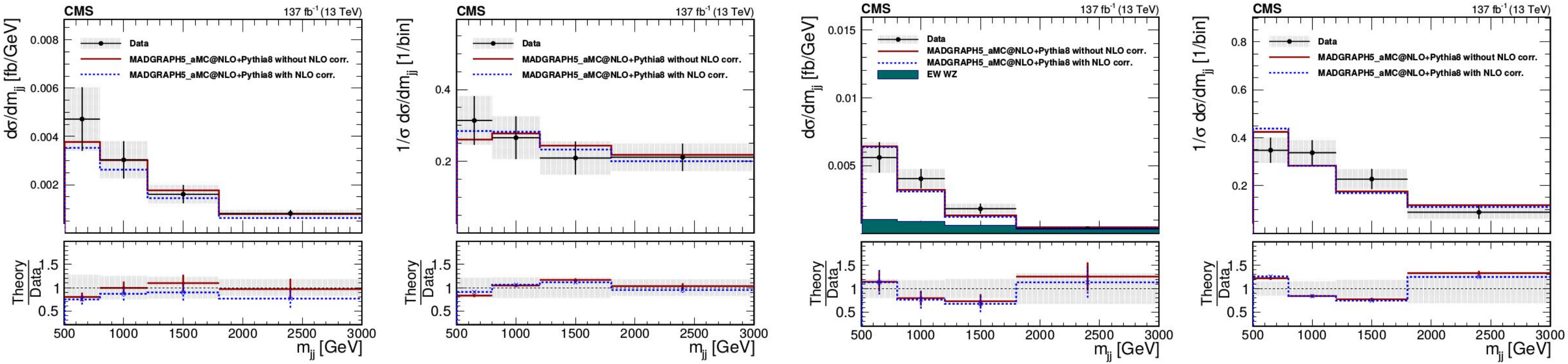
$W^\pm W^\pm$ & WZ VBS: Analysis Strategy & Yields

Process	$W^\pm W^\pm$ SR		WZ SR	
	Pre-fit	Post-fit	Pre-fit	Post-fit
EW $W^\pm W^\pm$	209 ± 22	210 ± 26	—	—
QCD $W^\pm W^\pm$	13.6 ± 2.3	13.7 ± 2.2	—	—
Interference $W^\pm W^\pm$	8.4 ± 2.3	8.7 ± 2.3	—	—
EW WZ	14.1 ± 1.7	17.8 ± 3.9	54.3 ± 5.7	69 ± 15
QCD WZ	42.9 ± 4.7	42.7 ± 7.4	117.9 ± 6.8	117 ± 17
Interference WZ	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	

Source of uncertainty	$W^\pm W^\pm$ (%)	WZ (%)
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 MC 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

$W^{\pm}W^{\pm}$ & WZ VBS Full Run II : Results

- Absolute and normalized - WW (EWK+QCD) differential cross section measurements on m_{jj} (shown below), m_{ll} & p_T^{max} and WZ (EWK+QCD) differential cross section measurements on m_{jj} (shown below)



Polarized $W^{\pm}W^{\pm}$ VBS Full Run II : Overview

➔ **Multivariate Analysis**

- Two Signal BDTs : same set of variables for both
  - to measure W_LW_L and W_XW_T component
  - to measure W_LW_X and W_TW_T component

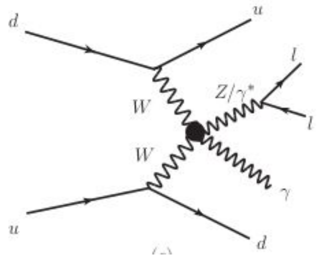
Variables	Definitions
$\Delta\phi_{jj}$	Difference in azimuth angles between the leading and trailing jets
p_T^{j1}	p_T of the leading jet
p_T^{j2}	p_T of the trailing jet
$p_T^{\ell_1}$	Leading lepton p_T
$p_T^{\ell_2}$	Trailing lepton p_T
$\Delta\phi_{\ell\ell}$	Azimuthal angle between the two leptons
$m_{\ell\ell}$	Dilepton mass
p_T^{miss}	Missing transverse momentum
$p_T^{\ell\ell}$	Dilepton p_T
m_T^{WW}	Transverse WW diboson mass
$z^*_{\ell_1}$	Zeppenfeld variable of the leading lepton
$z^*_{\ell_2}$	Zeppenfeld variable of the trailing lepton
$\Delta R_{j1,\ell\ell}$	ΔR between the leading jet and the dilepton system
$\Delta R_{j2,\ell\ell}$	ΔR between the trailing jet and the dilepton system
$(p_T^{\ell_1} p_T^{\ell_2})/(p_T^{j1} p_T^{j2})$	Ratio of scalar p_T products between leptons and jets

- Inclusive BDT
  - to separate EW $W^{\pm}W^{\pm}$ from SM bkg
  - Variables : m_{jj}, $|\Delta\eta_{jj}|$, $\Delta\Phi_{jj}$, p_T^{j1}, p_T^{j2}, p_T^{j1}, $p_T^{\ell 1}$, p_T^{miss}, $p_T^{\ell\ell}$, $z^*_{\ell 1}$ and $z^*_{\ell 2}$

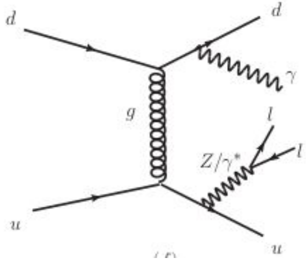
Zγ VBS 2016 dataset : Overview

JHEP06(2020)076

- Zγ VBS : Larger cross-section & sensitive to pure neutral aQGCs
- Backgrounds
  - QCD Zγjj <- From Simulation
  - Fake Photon <- From template fit method, data-driven
  - Diboson, ttγ, SingleTop, QCD Wγ <- From Simulation
- Theoretical uncertainties ⟵ Largest impact on the measurement



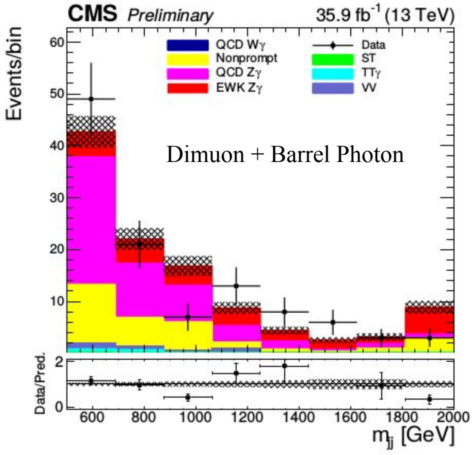
EWK production

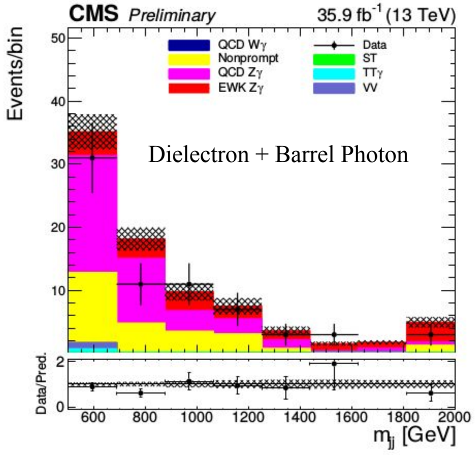


QCD production

Yields in EW Signal Region

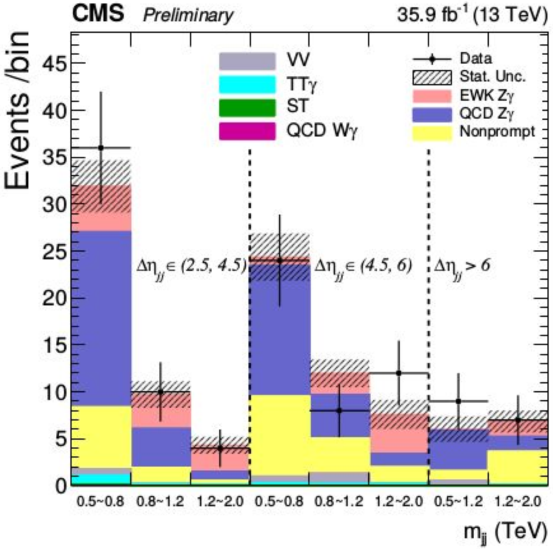
	muon channel	electron channel
Total background	117.9 ± 5.6	91.6 ± 4.8
Data	172 ± 13	113 ± 11



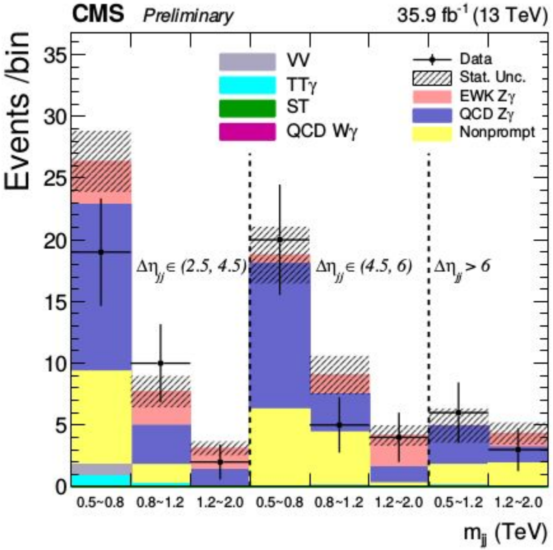


Zγ VBS 2016 dataset : Results

Post-fit 2D distributions



Dimuon + Barrel Photon



Dielectron + Barrel Photon

Combining 13 TeV + 8TeV results

Significance	Observed (Expected)
EW Zγ	4.7 (5.5)

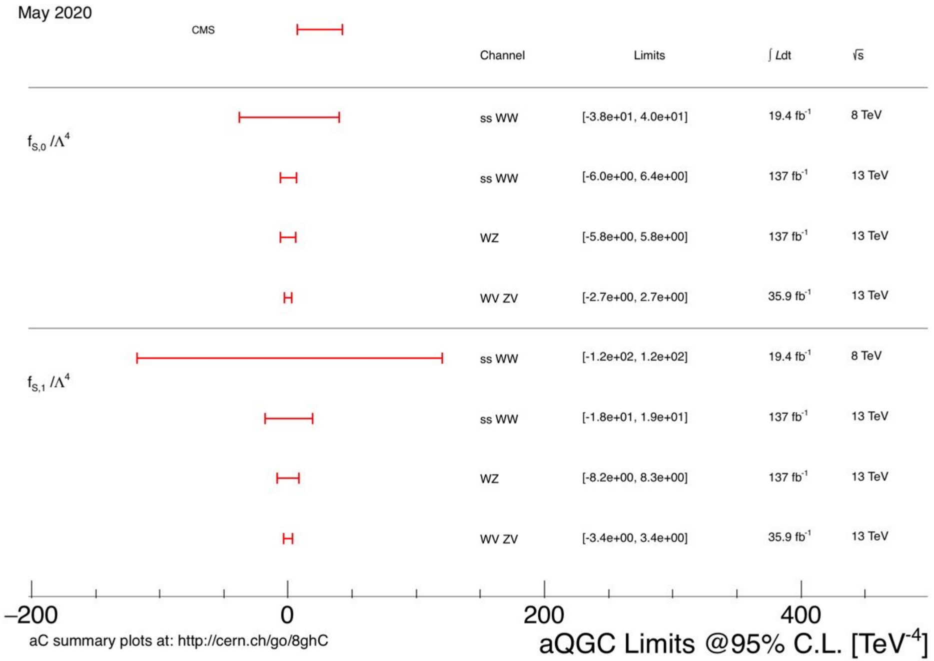
Fiducial Cross-section Measurements

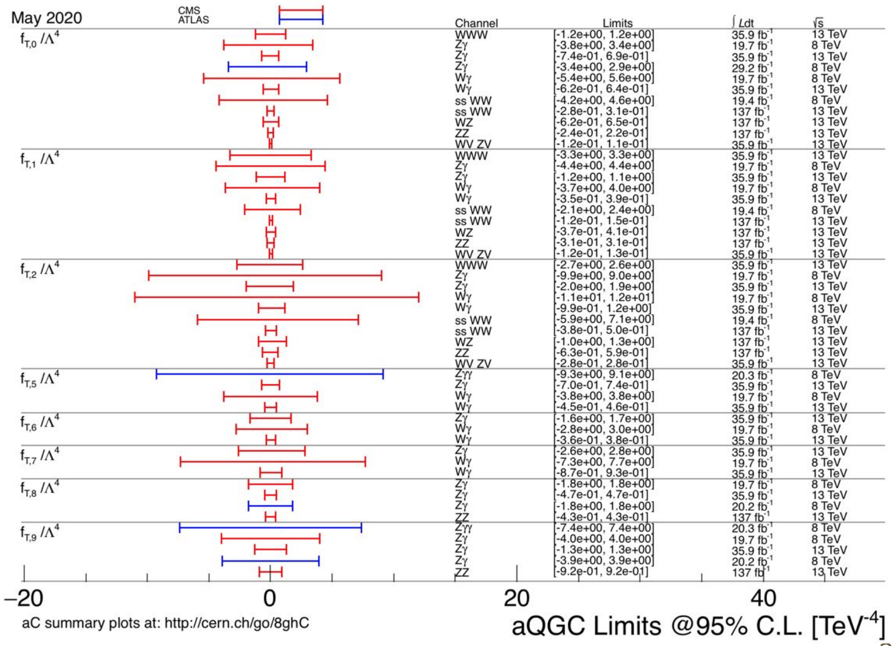
$$\sigma_{\mathrm{EW}}^{\mathrm{fid}} = 3.20 \pm 0.07\,(\mathrm{lumi}) \pm 1.00\,(\mathrm{stat}) \pm 0.57\,(\mathrm{syst})\ \mathrm{fb} = 3.20 \pm 1.15\ \mathrm{fb}.$$

Theoretically predicted: σ_{EW} = 4.97 ±0.25 (scale) ±0.14 (PDF) fb

aQGCs : Results

- Analyses improve constraints on wide range of operators
  - Limits without considering unitarization shown here
  - Limits on WW or/and WZ aQGC evaluated after "clipping" as well (backup)
  - Unitarity Bounds provided for ZZ and Zγ (backup)





Production Cross section Ratio