Vector Boson Scattering @ the LHC

Terascale meeting, Marseille, October 2023

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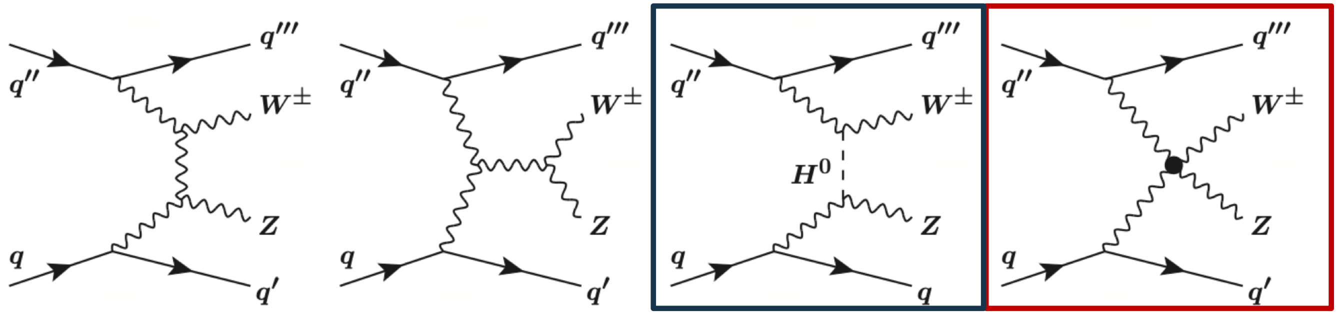
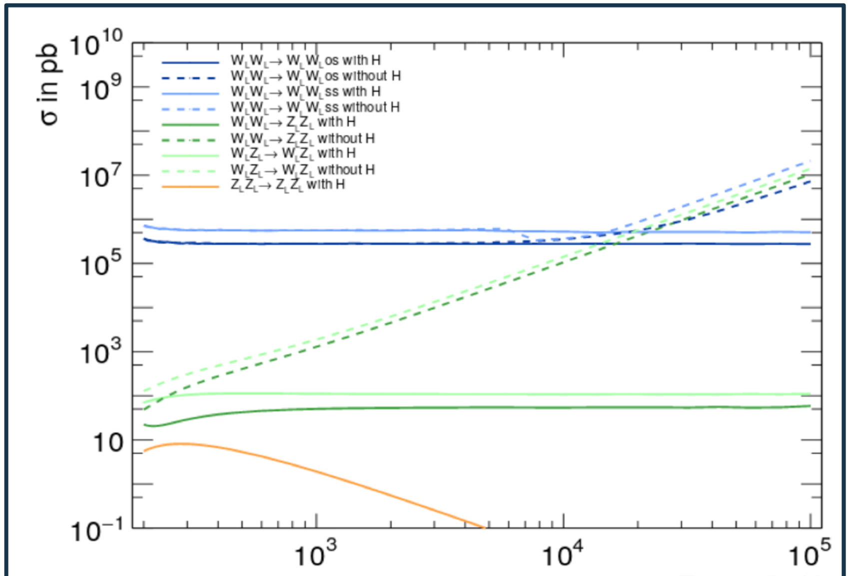
- What is (and what isn’t) vector boson scattering?
- Why is it interesting?
- How can we study VBS?
- First observations from both ATLAS and CMS
- Interpretation of the results

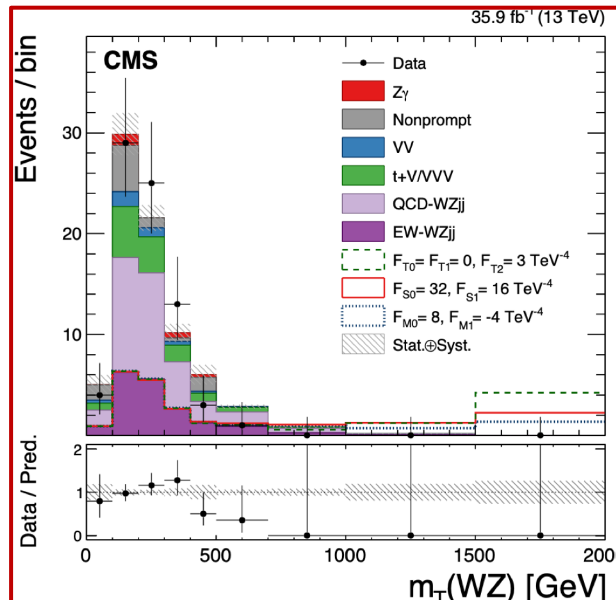
Note: this is an incomplete list of VBS-relates activities that leaves space for future discussions at Terascale meetings

Electroweak VVjj production via Vector Boson Scattering:

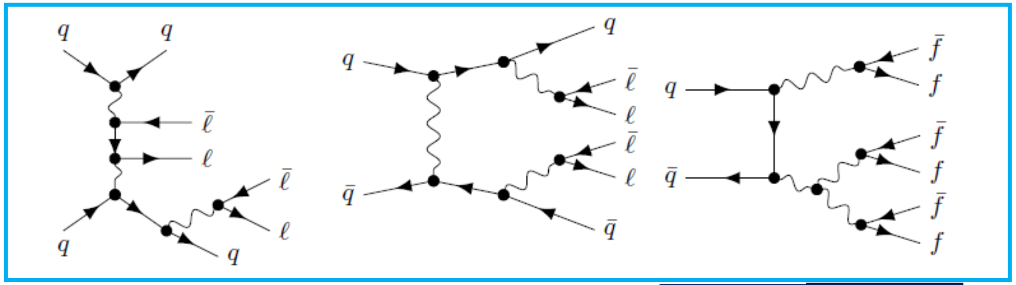


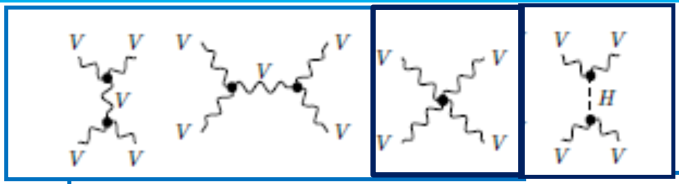


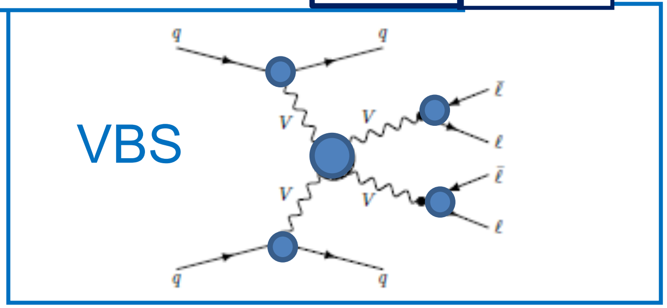
C. Bittrich, CERN-THESIS-2015-039



EW VVjj







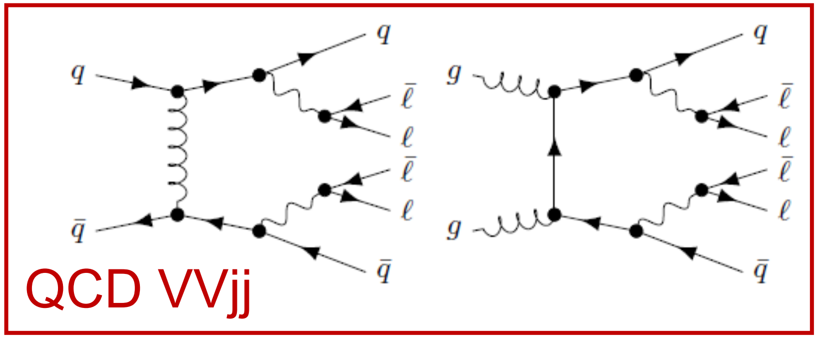
Electroweak VVjj production:
(including vector boson scattering)

- Characteristic kinematic signature
- Challenging S/B

Interference between the two processes

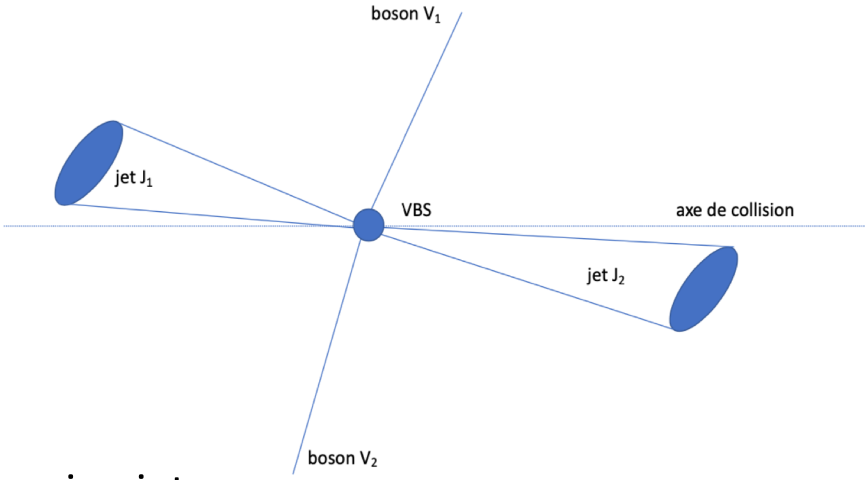
Main background:

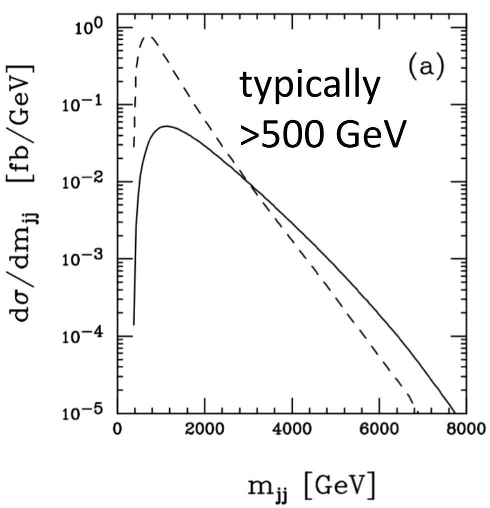
- QCD VVjj production
- Different kinematic signature
- Important criterion for all VBS analysis strategies

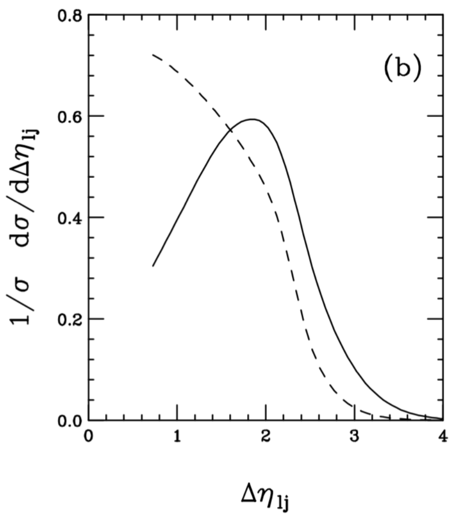


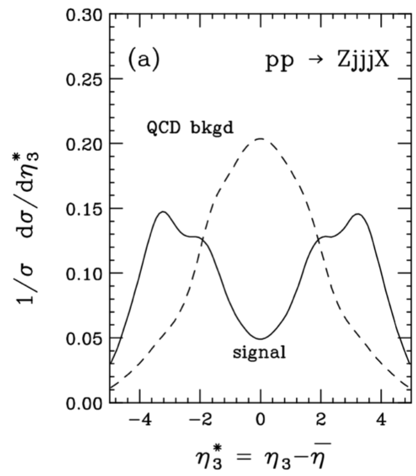
Characteristics of a typical VBS event:

- Two high energy forward jets (tagging jets)
- Generally central diboson products
- Suppressed hadronic activity in between the tagging jets

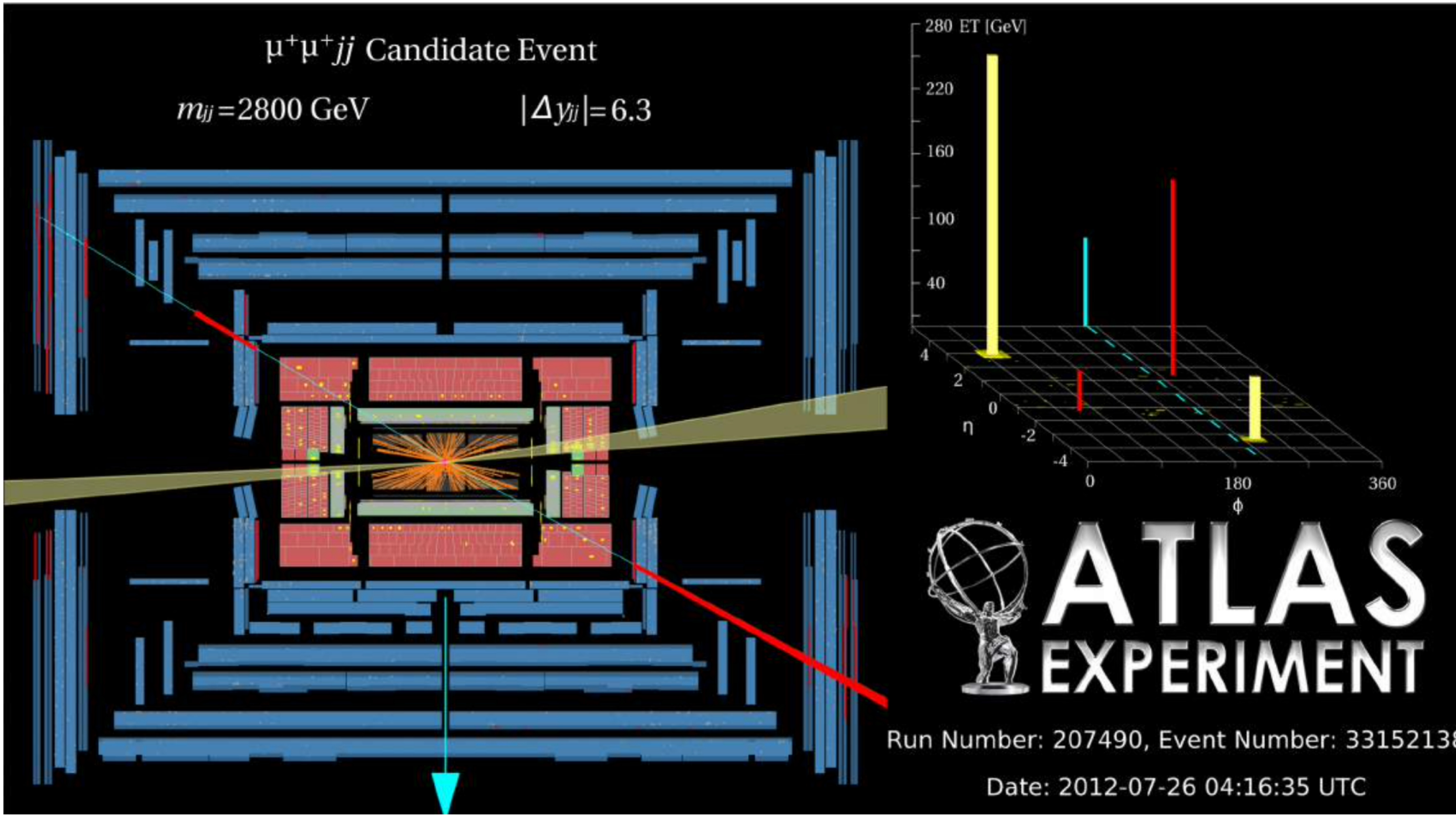




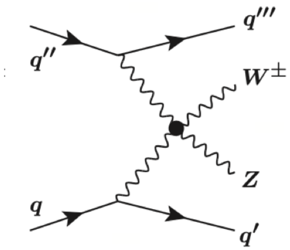


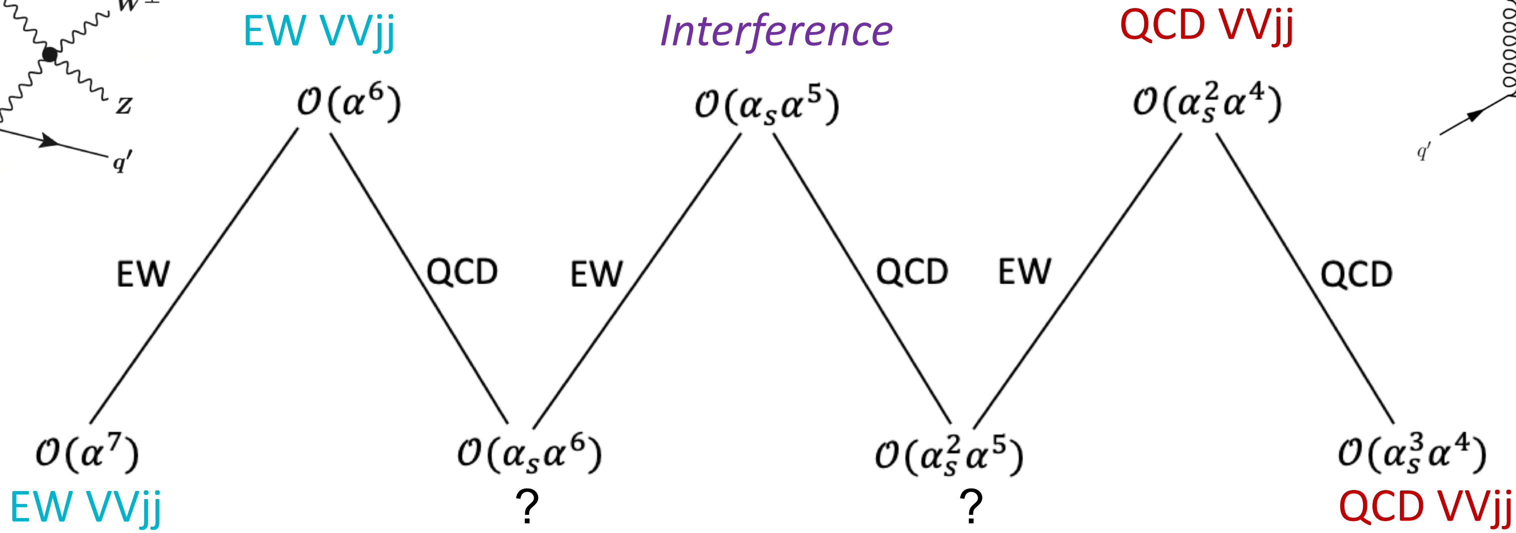


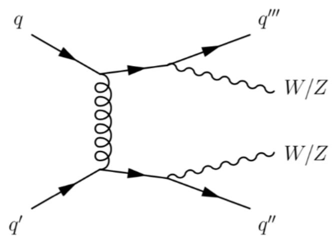
https://arxiv.org/abs/hep-ph/9605444


μ⁺μ⁺jj Candidate Event
m_{jj}=2800 GeV
|Δy_{jj}|=6.3
280 ET [GeV]
220
160
100
40
4
2
0
η
-2
-4
0
180
360
ϕ
ATLAS EXPERIMENT
Run Number: 207490, Event Number: 33152138
Date: 2012-07-26 04:16:35 UTC

VBS @ NLO (and beyond)







Adding higher order corrections makes VVjj-EW and VVjj-QCD obsolete

- Currently: include interference into the signal (or background) and assign an uncertainty on it
- Solution: make inclusive measurement creating ah high VVjj-EW purity phase space?

Non exhaustive list of VBS channels:

canal	état final	σ_{VVjj}^{EW}	σ_{VVjj}^{QCD}
$W^{\pm}W^{\pm}jj$	$l\nu l\nu jj$	4.28±0.01	1.69±0.02
$Z\gamma jj$	$ll\gamma jj$	9.24±0.02	71.28±0.33
$W^{\pm}Zjj$	$lll\nu jj$	2.36±0.01	7.19±0.01
$ZZjj$	$lllljj$	0.12±0.01	0.21±0.01

- $W^{\pm}W^{\pm}$: lead to the first observation in 2018 → suffers from high fake background
- WZ: first observation in 2018 → suffers from high QCD background
- ZZ: first observation in 2021 → very low cross section
- Zγ: first observation in 2021 → suffers from high QCD background

Notes:

- not all leptonic channels will be discussed in details, see some references (last slide)
- **semi leptonic VBS is of high theoretical interest → to be followed (not discussed today)**

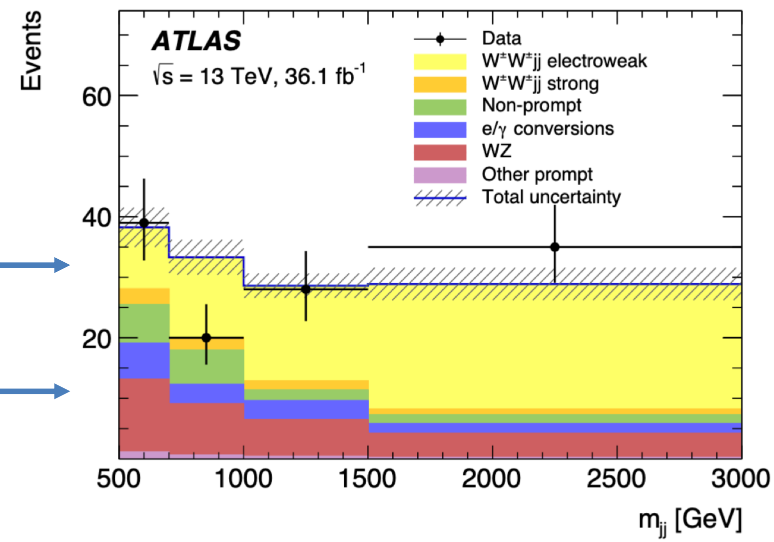
The $W^{\pm}W^{\pm}$ jj channel: ATLAS

Signal region: m_{jj}>500 GeV

41 signal events

32 WZ events
from dedicated CR (m_{jj}<500 GeV)

+ 23 events from reducible background



Main systematic uncertainties:

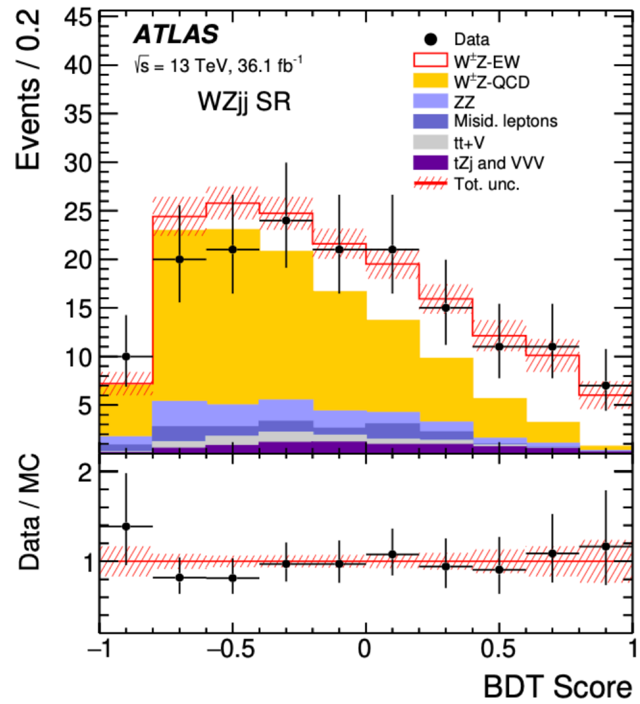
Source	Impact [%]
Experimental	
Electron energy scale and resolution, and efficiency	0.6
Muon momentum scale and resolution, and efficiency	1.3
Jet energy and E_T^{miss} scale and resolution	3.2
b-tagging inefficiency	2.1
Pileup modeling	1.6
Theory modeling	
$W^{\pm}W^{\pm}jj$ electroweak-strong interference	1.0
$W^{\pm}W^{\pm}jj$ electroweak, EW corrections	1.4
$W^{\pm}W^{\pm}jj$ electroweak, shower, scale, PDF & α_s	2.8
$W^{\pm}W^{\pm}jj$ strong	2.9
WZ	3.3

$$\sigma^{\text{fid.}}_{W^{\pm}W^{\pm}jj-EW} = 2.89\ ^{+0.51}_{-0.48}\,(\text{stat})\ ^{+0.24}_{-0.22}\,(\text{exp syst})\ ^{+0.14}_{-0.16}\,(\text{mod syst})\ ^{+0.08}_{-0.06}\,(\text{lumi})\ \text{fb}$$

Signal region: m_{jj}>500 GeV

44 signal events

90 QCD events
from dedicated CR (m_{jj}<500 GeV)



- EW/QCD VVjj separation using dedicated BDT

Main systematic uncertainties:

Source	Uncertainty [%]
$WZjj$–EW theory modelling	4.8
$WZjj$–QCD theory modelling	5.2
$WZjj$–EW and $WZjj$–QCD interference	1.9
Jets	6.6
Pile-up	2.2

$$\sigma^{\text{fid.}}_{W^\pm Zjj\,-\,EW} = 0.57\,^{+0.14}_{-0.13}\,(\text{stat.})\,^{+0.05}_{-0.04}\,(\text{exp. syst.})\,^{+0.05}_{-0.04}\,(\text{mod. syst.})\,^{+0.01}_{-0.01}\,(\text{lumi.})\text{ fb}$$
$$= 0.57\,^{+0.16}_{-0.14}\text{ fb},$$

using 137 fb^{-1}

EW $W^{\pm}W^{\pm}$	210 ± 26
QCD$W^{\pm}W^{\pm}$	13.7 ± 2.2
Interference $W^{\pm}W^{\pm}$	8.7 ± 2.3
EW WZ	17.8 ± 3.9
QCD WZ	42.7 ± 7.4

2D fit using: m_{ll}, m_{jj}

EW WZ	69 ± 15
QCD WZ	117 ± 17

2D fit using: BDT, m_{jj}

Variable	$W^{\pm}W^{\pm}$	WZ
Leptons	2 leptons, $p_T > 25/20$GeV	3 leptons,
$p_T > 25/10/20$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

Simultaneous measurement:

EW $W^{\pm}W^{\pm}$	3.98 ± 0.45 0.37 (stat) ± 0.25 (syst)
EW WZ	1.81 ± 0.41 0.39 (stat) ± 0.14 (syst)

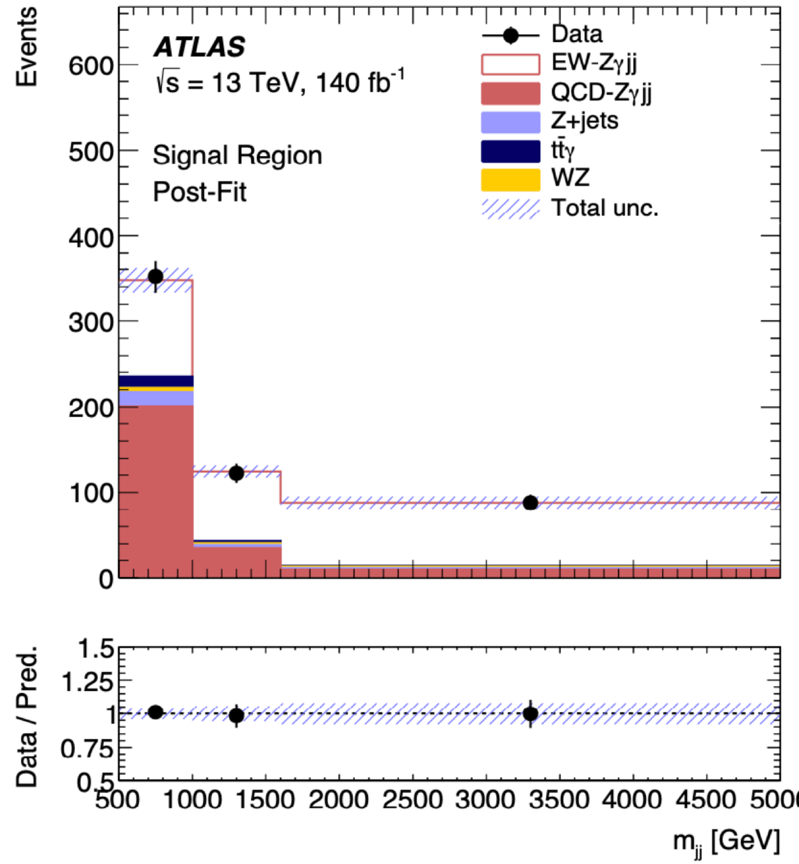
Signal region: m_{jj}>500 GeV, centrality<0.4

Sample	SR, $m_{jj} > 500$ GeV
$N_{EW-Z\gamma jj}$	269 ± 27
$N_{QCD-Z\gamma jj}$	245 ± 21

QCD CR (centrality<0.4)

Sample	CR, $m_{jj} > 500$ GeV
$N_{EW-Z\gamma jj}$	25 ± 6
$N_{QCD-Z\gamma jj}$	224 ± 18

$$\sigma_{EW} = 3.6 \pm 0.5 \text{ fb}$$

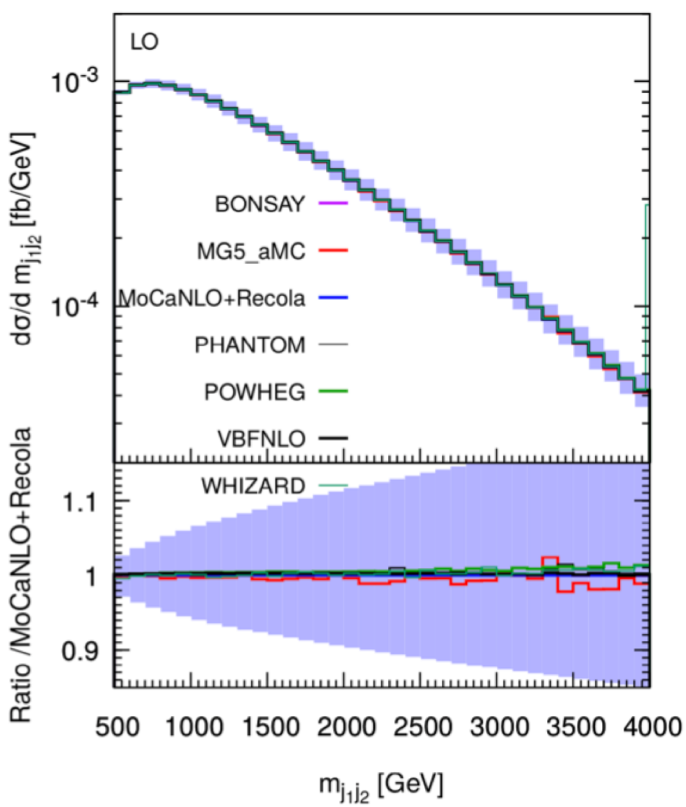


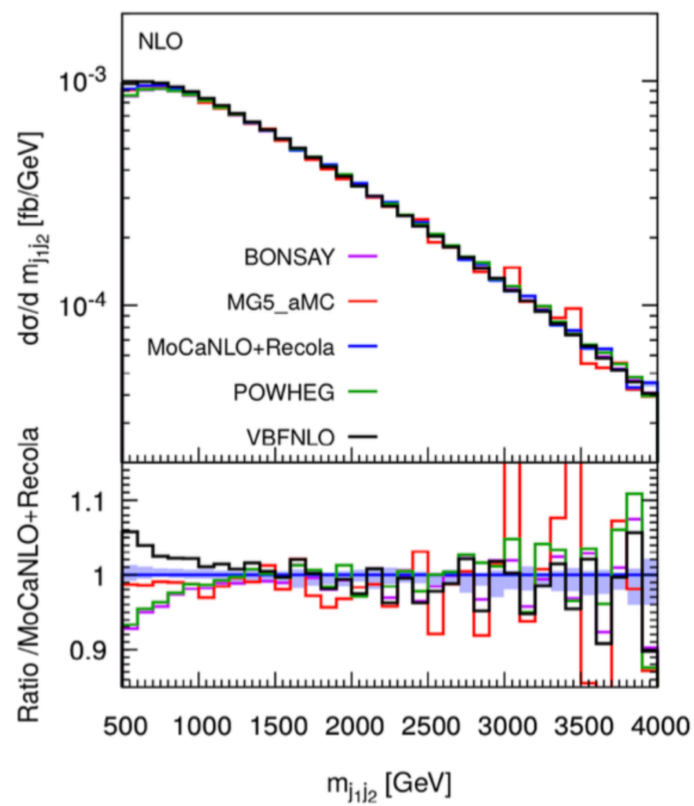
	Data stat.	MC stat.	Background	Reco	EW mod.	QCD mod.	Total
$\Delta\sigma_{EW}/\sigma_{EW}$ [%]	±9	±1	±1	±4	$^{+8}_{-6}$	±2	±13
$\Delta\sigma_{Z\gamma}/\sigma_{Z\gamma}$ [%]	±3	±1	±2	$^{+4}_{-3}$	$^{+7}_{-6}$	±9	$^{+12}_{-11}$

Status of theoretical calculations

Note: all previous results use LO samples for the signal

QCD NLO corrections using different generators ($W^{\pm}W^{\pm}$ channel):



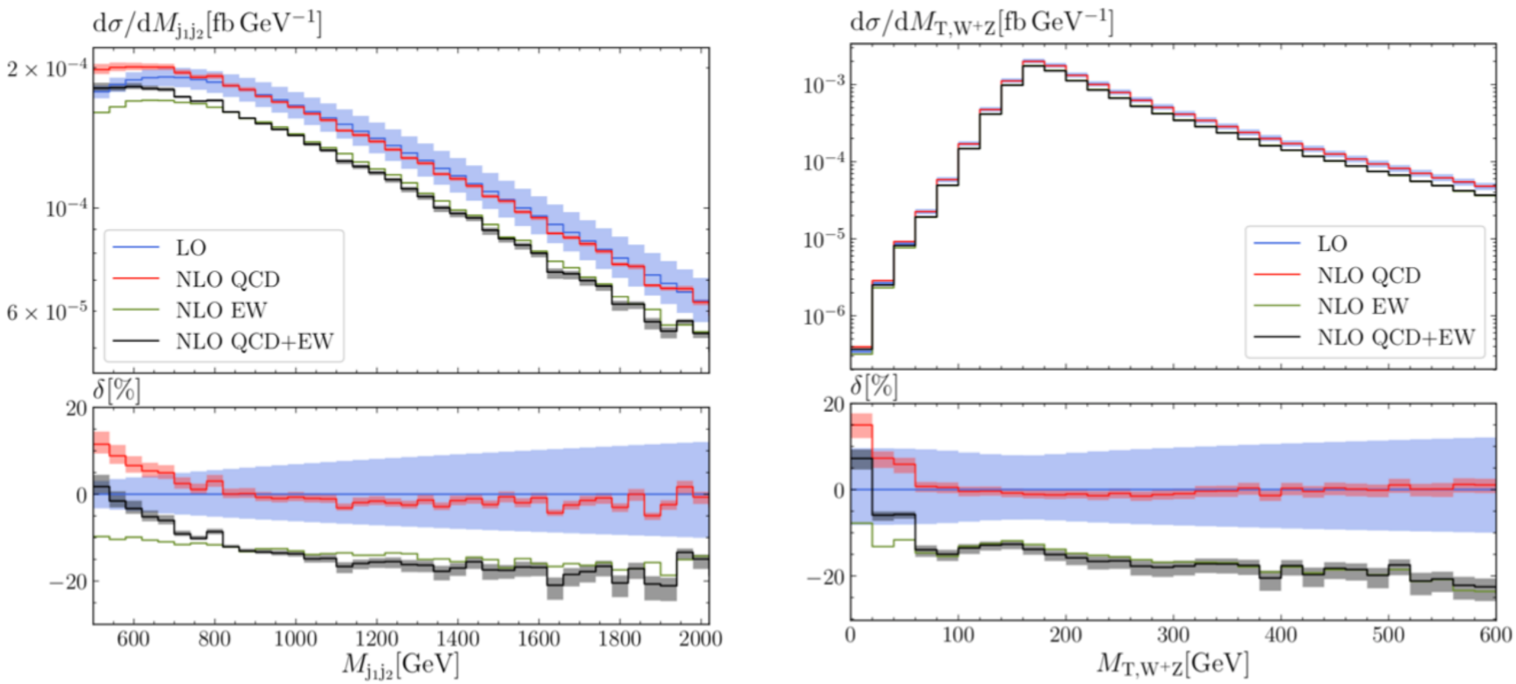


- Non negligible effect when using approximations

https://arxiv.org/abs/1803.07943

> *Note: all previous results use LO samples for the signal*

QCD and EW corrections ($W^{\pm}Z$ channel):



- Important shape effects on m_{jj} distribution

J. High Energ. Phys. **2019**, 67 (2019)

Anomalous triple and quartic gauge boson couplings on a EFT frame

$$\mathcal{L} = \boxed{\mathcal{L}_{SM}} + \boxed{\sum_i \frac{c_i^{(6)}}{\mathcal{L}^2}\mathcal{O}_i^{(6)}} + \boxed{\sum_j \frac{f_j^{(8)}}{\mathcal{L}^4}\mathcal{O}_j^{(8)}}$$

SM effective Lagrangian

Gauge boson interactions as described by the SM

dim-6 operators

Describing aTGCs and aQGCs
VBS not really competitive for their constraint

dim-8 operators

Lowest order operators describing only aQGCs

Can only be constrained by VBS (and tribosons)

Three different types of parameters:

$$\mathcal{L}_{T,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}\right]$$
$$\mathcal{L}_{T,1} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right]$$
$$\mathcal{L}_{T,2} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}\right]$$
$$\mathcal{L}_{T,5} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta}$$
$$\mathcal{L}_{T,6} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu}$$
$$\mathcal{L}_{T,7} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha}$$
$$\mathcal{L}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta}$$
$$\mathcal{L}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}$$

pure field-strength tensor (f_T)
pure transverse: only neutral couplings can be induced

$$\mathcal{L}_{M,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$
$$\mathcal{L}_{M,1} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$
$$\mathcal{L}_{M,2} = \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$
$$\mathcal{L}_{M,3} = \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$
$$\mathcal{L}_{M,4} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}D^\mu\Phi\right] \times B^{\beta\nu}$$
$$\mathcal{L}_{M,5} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}D^\nu\Phi\right] \times B^{\beta\mu}$$
$$\mathcal{L}_{M,6} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\nu}D^\mu\Phi\right]$$
$$\mathcal{L}_{M,7} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu}D^\nu\Phi\right]$$

mixted Higgs-field-strength (f_M)
mixted longitudinal-transverse

$$\mathcal{L}_{S,0} = \frac{c_{S,0}}{\Lambda^4}\left[(D_\mu\Phi)^\dagger(D_v\Phi)\right] \times \left[(D^\mu\Phi)^\dagger(D^v\Phi)\right]$$
$$\mathcal{L}_{S,1} = \frac{c_{S,1}}{\Lambda^4}\left[(D_\mu\Phi)^\dagger(D^\mu\Phi)\right] \times \left[(D_v\Phi)^\dagger(D^v\Phi)\right]$$

pure Higgs-field (f_S) pure longitudinal: cannot induce couplings with photons

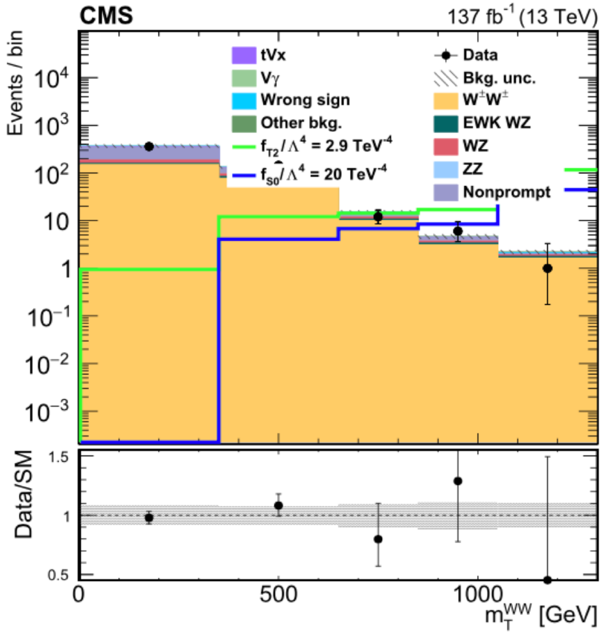
	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{L}_{S,0}, \mathcal{L}_{S,1}$	X	X	X	O	O	O	O	O	O
$\mathcal{L}_{M,0}, \mathcal{L}_{M,1}, \mathcal{L}_{M,6}, \mathcal{L}_{M,7}$	X	X	X	X	X	X	X	O	O
$\mathcal{L}_{M,2}, \mathcal{L}_{M,3}, \mathcal{L}_{M,4}, \mathcal{L}_{M,5}$	O	X	X	X	X	X	X	O	O
$\mathcal{L}_{T,0}, \mathcal{L}_{T,1}, \mathcal{L}_{T,2}$	X	X	X	X	X	X	X	X	X
$\mathcal{L}_{T,5}, \mathcal{L}_{T,6}, \mathcal{L}_{T,7}$	O	X	X	X	X	X	X	X	X
$\mathcal{L}_{T,9}, \mathcal{L}_{T,9}$	O	O	X	O	O	X	X	X	X

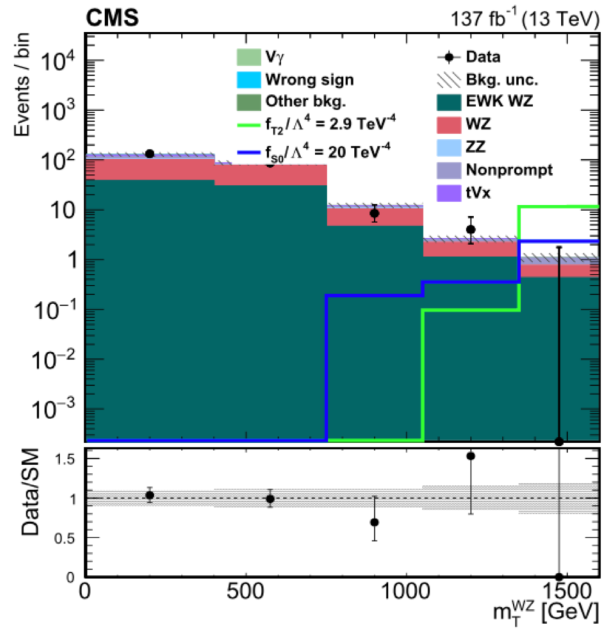
Discriminative variables:

- M_T^{VV} (BSM vs SM)

in combination with

- m_{jj} (EW vs QCD)





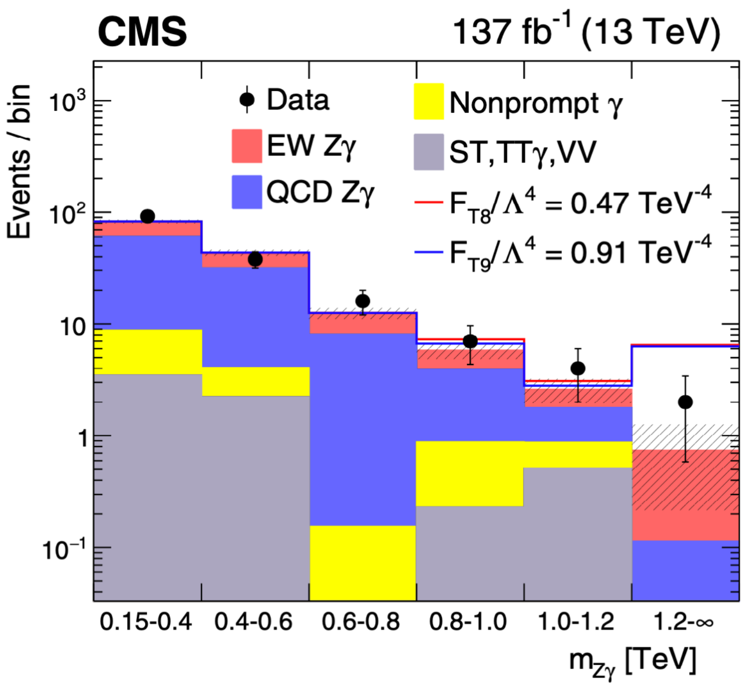
Considering that EFT model is valid at < 1.5 TeV:

	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]

The Zγjj EFT analysis: CMS

Discriminative variables:

- $m_{Z\gamma}$



Coupling	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unitarity bound
F_{M0}/Λ^4	−12.5	12.8	−15.8	16.0	1.3
F_{M1}/Λ^4	−28.1	27.0	−35.0	34.7	1.5
F_{M2}/Λ^4	−5.21	5.12	−6.55	6.49	1.5
F_{M3}/Λ^4	−10.2	10.3	−13.0	13.0	1.8
F_{M4}/Λ^4	−10.2	10.2	−13.0	12.7	1.7
F_{M5}/Λ^4	−17.6	16.8	−22.2	21.3	1.7
F_{M7}/Λ^4	−44.7	45.0	−56.6	55.9	1.6
F_{T0}/Λ^4	−0.52	0.44	−0.64	0.57	1.9
F_{T1}/Λ^4	−0.65	0.63	−0.81	0.90	2.0
F_{T2}/Λ^4	−1.36	1.21	−1.68	1.54	1.9
F_{T5}/Λ^4	−0.45	0.52	−0.58	0.64	2.2
F_{T6}/Λ^4	−1.02	1.07	−1.30	1.33	2.0
F_{T7}/Λ^4	−1.67	1.97	−2.15	2.43	2.2
F_{T8}/Λ^4	−0.36	0.36	−0.47	0.47	1.8
F_{T9}/Λ^4	−0.72	0.72	−0.91	0.91	1.9

Unitarity strategy:

Computing the energy scale for which the value of the limit violates unitarity (and thus EFT model isn't valid)

Conclusions and open items

- Vector boson scattering first observed during Run 2 of the LHC
- Several channels, each giving access to different quartic couplings
- Interpretation of the results using Effective Field Theory
- To do: global fit using several channels for simultaneous constraint of dim-8 operators
  - Status: preliminary studies, such as $W^{\pm}W^{\pm}jj/WZjj$
- To do: ultimate goal is the study of $V_L V_L \rightarrow V_L V_L$
  - Status: (simple cut-based) studies indicate a future observation at HL-LHC
  - Polarized inclusive VV production: see next talk

Observation of VVjj by ATLAS

WW: Phys. Rev. Lett. 123 (2019) 161801

WZ: Phys. Lett. B 793 (2019) 469

Zγ: JHEP 07 (2017) 107

ZZ: Nature Phys. 19 (2023) 237

Observation of VVjj by CMS

WW and WZ: PLB 809 (2020) 135710

Zγ: PRD 104 (2021) 072001

EFT interpretation of $W^{\pm}W^{\pm}jj$/WZjj by ATLAS:

ATL-PHYS-PUB-2023-002