Vector-Boson Scattering
- current status and future prospects

RTG 2994 Inauguration Workshop Würzburg

TECHNISCHE UNIVERSITÄT DRESDEN

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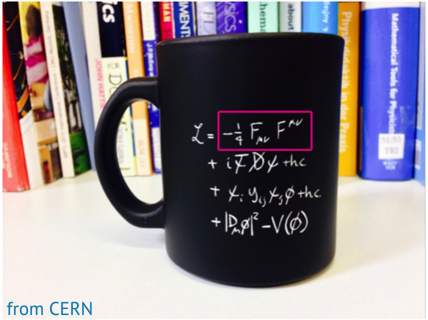
The Standard Model

- The Standard Model (SM) describes the fundamental constituents of matter and their interactions
  - strong and electroweak (EW) interaction
- Rich variety of interactions from a rather simple set of symmetries
- Self-interactions of electroweak gauge bosons
  - Quantum corrections at EW mass scale
    (probed in W/Z precision measurements)
  - Large effects at highest energies
- At the LHC we can test the electroweak theory at highest energies



from CERN

$SU(3)_C$	$\times$ $SU(2)_L$	$\times$ $U(1)_Y$
colour red, green, blue	weak isospin $I_3 = 0, \pm\frac{1}{2}$	weak hypercharge Y
8 gluons	W^1, W^2, W^3	B

$\rightarrow W^+, W^-, Z, \gamma$

Electroweak Theory

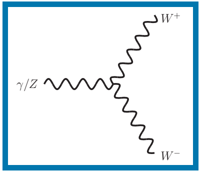
- Gauge couplings arise from the SU(2) potential term $\mathcal{L} = -\frac{1}{4} W^a_{\mu\nu} W^{\mu\nu}_a$, with field strength tensor $W^a_{\mu\nu} = \partial_\mu W^a_\nu - \partial_\nu W^a_\mu - g f_{abc} W^b_\mu W^c_\nu$
- It generates cubic and quartic couplings

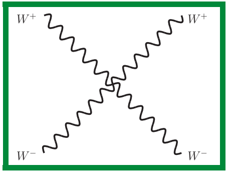
$$\mathcal{L}_3 = ie_{V=\gamma,Z}\left[W^+_{\mu\nu} W^{-\mu} V^\nu - W^-_{\mu\nu} W^{+\mu} V^\nu + W^+_\mu W^-_\nu V^{\mu\nu}\right]$$

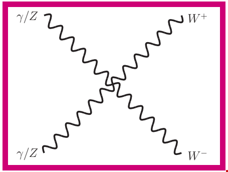
$$\mathcal{L}_4 = e^2_W \left[W^-_\mu W^{+\mu} W^-_\nu W^{+\nu} - W^-_\mu W^{-\mu} W^+_\nu W^{+\nu}\right]$$

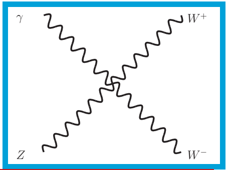
$$+ e^2_{V=\gamma,Z}\left[W^-_\mu W^{+\mu} V_\nu V^\nu - W^-_\mu V^\mu W^+_\nu Z^\nu\right]$$

$$+ e_\gamma e_Z \left[2 W^-_\mu W^{+\mu} Z_\nu A^\nu - W^-_\mu Z^\mu W^+_\nu A^\nu - W^-_\mu A^\mu W^+_\nu Z^\nu\right]$$







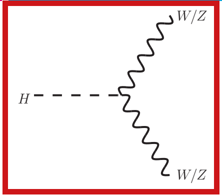


- With precise predictions of the coupling strength:

$$e_\gamma = g \sin\theta_W,\; e_W = \frac{e_\gamma}{2\sqrt{2}\sin\theta_W} \text{ and } e_Z = e_\gamma \cot\theta_W$$

- They *always* involve a pair of W bosons (there are no neutral vertices)
- Gauge interactions to Higgs boson

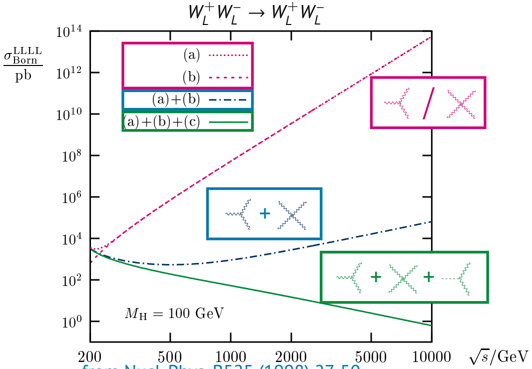
$$\mathcal{L}_{\text{Higgs}} = \frac{m_W^2}{v^2} W^+_\mu W^{-\mu} h^2 + \frac{m_Z^2}{v^2} Z_\mu Z^\mu h^2$$



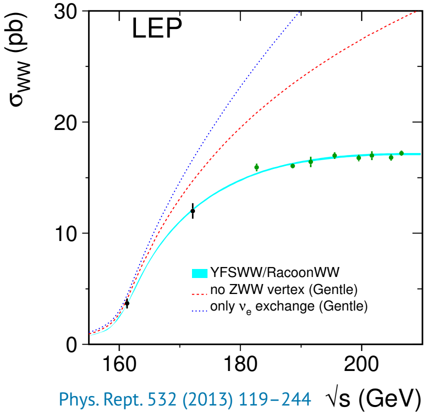
Electroweak Gauge Structure

- Gauge-boson self interactions play a crucial role for the renormalisability of the electroweak theory
- Large cancellations of divergences arising in individual diagrams are exact if couplings take the values of the SM

⇒ Diboson measurements are a sensitive probe of the inner structure of the electroweak symmetry



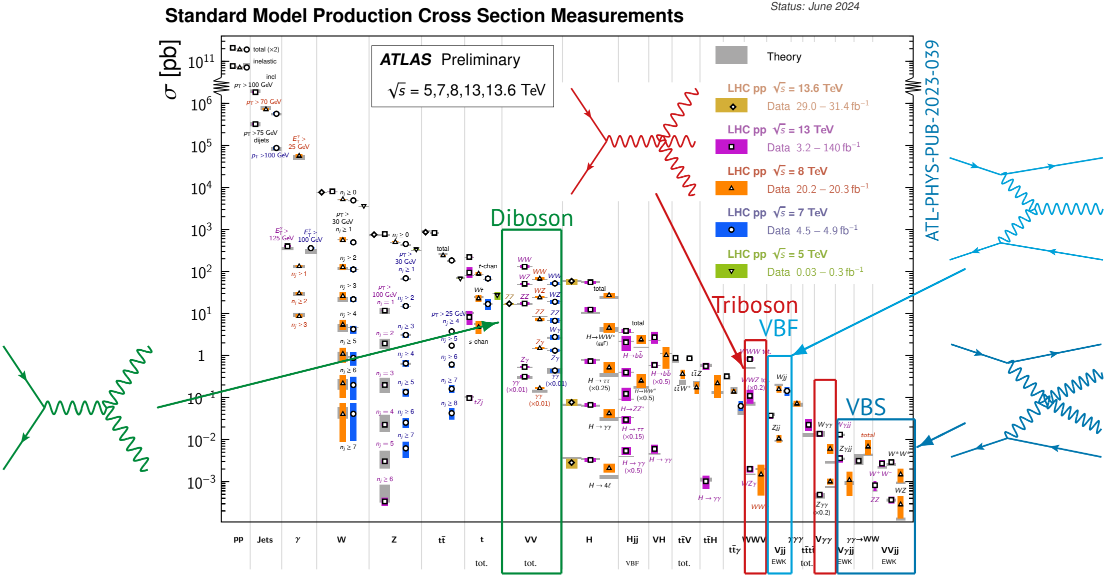
from Nucl. Phys. B525 (1998) 27-50



Phys. Rept. 532 (2013) 119–244

- In processes involving quartic couplings, the Higgs boson is governing the high-energy behaviour
  (if only massive gauge bosons participate in the scattering)
- Such processes became experimentally accessible for the first time in the LHC run-2

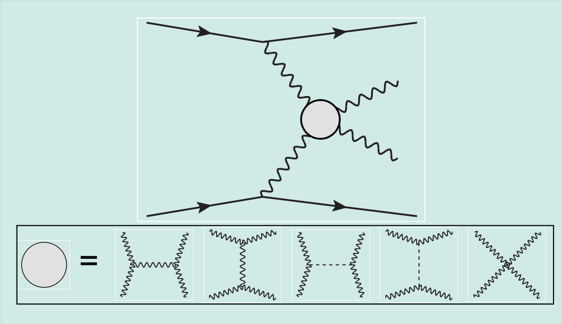
Experimental Probes



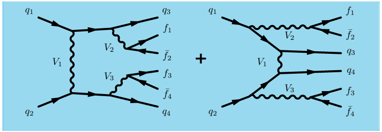
Experimental access to quartic electroweak interactions in triboson production and vector-boson scattering (VBS)

Vector-boson Fusion and Vector-boson Scattering

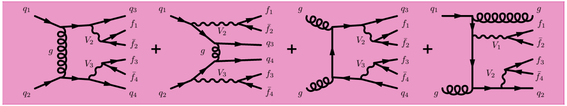
- Quartic *electroweak* (EW) coupling experimentally accessible in EW production of *VVjj*



Purely electroweak interactions involving only cubic and quartic self interactions ●



Purely electroweak interactions without self interactions ●



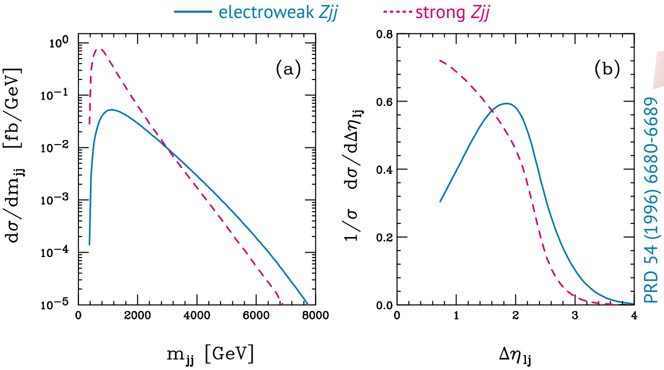
Processes involving both strong and electroweak interactions ●

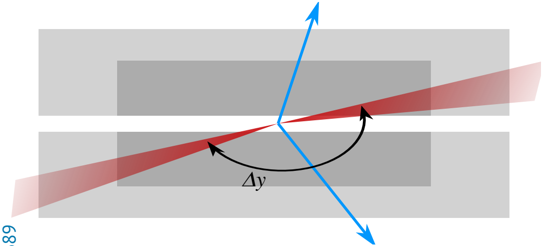
●+● not gauge-invariantly separable → measure EW production

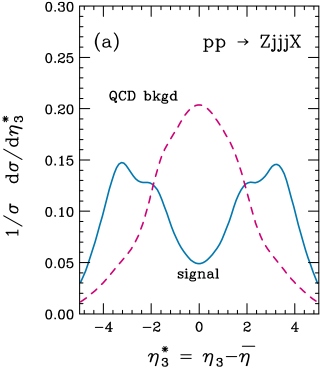
●+●+● interference & not separable at all orders → provide measurement of sum

Experimental Signature

- No colour connection between scattering quarks leads to characteristic signature



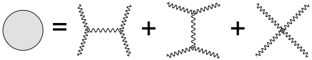




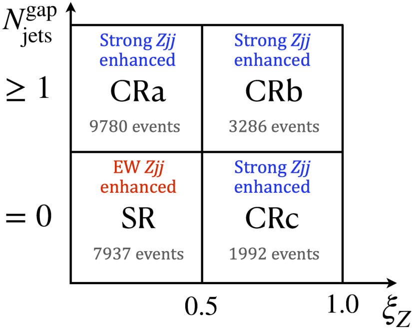
- Additional activity measured relative to centre of "tagging jets", e.g.:

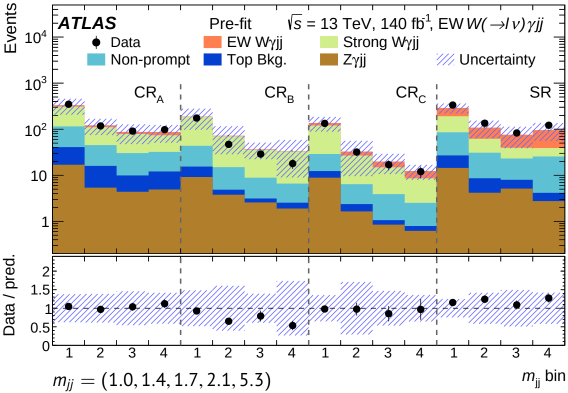
$$\zeta_X = \left|\frac{y_X - \left(y_{j1} + y_{j2}\right)/2}{y_{j1} - y_{j2}}\right|, \qquad C_X = \exp\left[-4\left(\frac{\eta_X - \left(\eta_{j1} + \eta_{j2}\right)/2}{\eta_{j1} - \eta_{j2}}\right)^2\right]$$

Electroweak $W\gamma jj$ Production



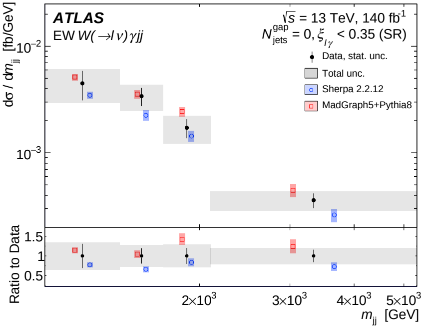
- Critical for a good measurements of $W\gamma jj$-electroweak is a precise understanding of $W\gamma jj$-strong background

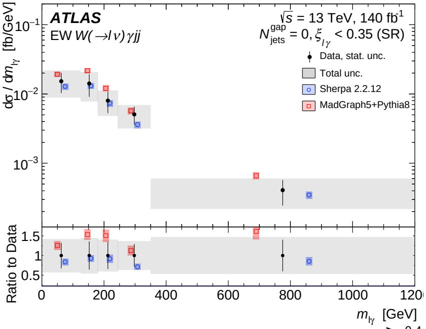




- Estimation of strong $W\gamma jj$ production relies on $\ell\gamma$ centrality and central jet activity

Differential Electroweak $W\gamma jj$ Production

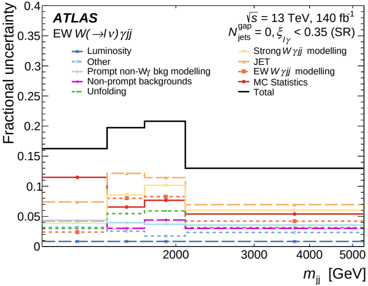




Theoretical predictions:

- Sherpa, LO@0,1j
- Madgraph+Pythia, LO

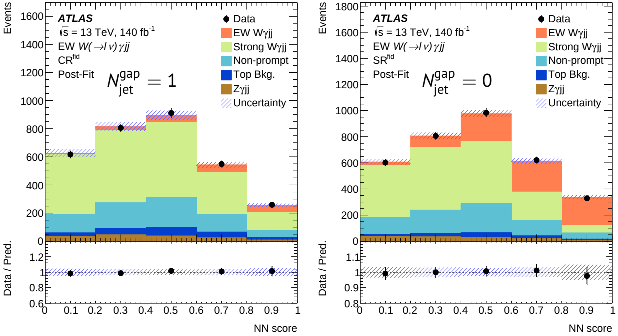
- Differential measurement of electroweak $W\gamma jj$ production in a variety of variables characterising the VBS signature or the diboson system (m_{jj}, p_T^{jj}, $\Delta\phi_{jj}$, p_T^{ℓ}, $m_{\ell\gamma}$ and $\Delta\phi_{\ell\gamma}$)
- Leading uncertainty in jet reconstruction and strong $W\gamma jj$ modelling



Electroweak $W\gamma jj$ Production

- Technique to estimate strong $W\gamma jj$ background introduces large statistical uncertainties
- To maximise sensitivity, measurements use:
  - fits exploring characteristic VBS variables
  - e.g. in combination with neural-networks

→ introducing modelling assumptions



- Control of strong production remains critical
- Electroweak $W\gamma jj$ production observed with $\gg 5\sigma$, measured to be:

$$\sigma_{\text{EW, meas.}} = 13.2 \pm 2.5 \text{ fb}$$

with large uncertainties in strong *and* electroweak theoretical modelling

Uncertainty Source	Fractional Uncertainty [%]
Statistics	11
Jets	8
Lepton, photon, pile-up	8
EW $W\gamma jj$ modelling	7
Strong $W\gamma jj$ modelling	6
Non-prompt background	2
Luminosity	2
Other Background modelling	2
E_T^{miss}	1

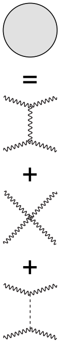
- Compared to theoretical predictions:

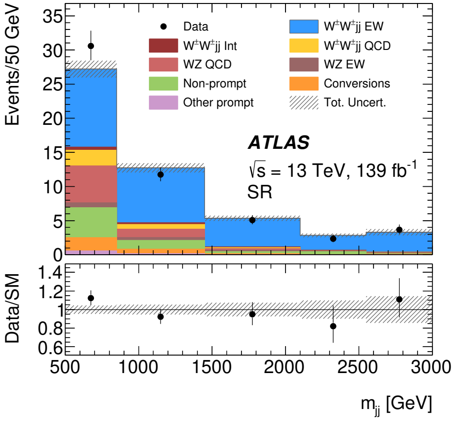
$$\sigma_{\text{EW, theo.}} = 8.9^{+1.0}_{-0.7} \text{ fb (Sherpa 2.2.12, LO@0,1j)}$$

$$\sigma_{\text{EW, theo.}} = 13.0^{+0.9}_{-0.8} \text{ fb (Madgraph+Pythia8, LO)}$$

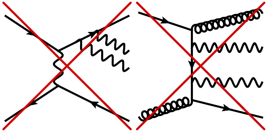
- Full set of results in **EPJC 84 (2024) 1064**

Electroweak $W^\pm W^\pm jj$ Production

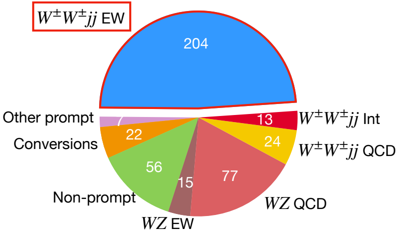




- In the $W^\pm W^\pm jj$ final state, strong and electroweak diagrams without self-interactions are suppressed



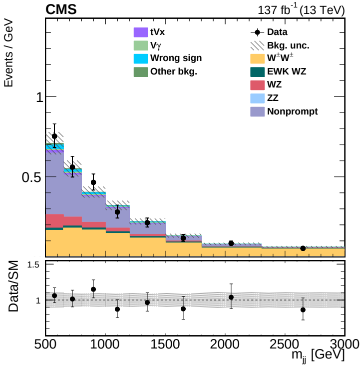
- (almost) all background contributions are instrumental

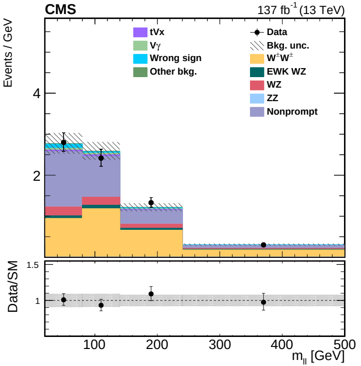


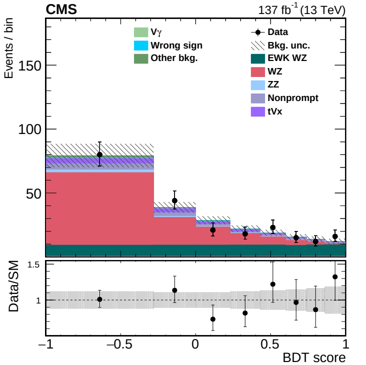
- Theoretically understood well, at NLO EW⊗QCD (JHEP 1710 (2017) 124, PRL 118, 261801 (2017))

⇒ the $W^\pm W^\pm jj$ final state is often referred to as the *golden channel*

Electroweak $W^{\pm}W^{\pm}jj$ and $WZjj$ Production







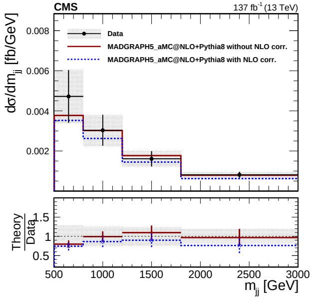
Source of uncertainty	$W^{\pm}W^{\pm}$ (%)	WZ (%)
Integrated luminosity	1.5	1.6
Lepton measurement	1.8	2.9
Jet energy scale and resolution	1.5	4.3
Pileup	0.1	0.4
btagging	1.0	1.0
Nonprompt rate	3.5	1.4
Trigger	1.1	1.1
Limited sample size	2.6	3.7
Theory	1.9	3.8
Total systematic uncertainty	5.7	7.9
Statistical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

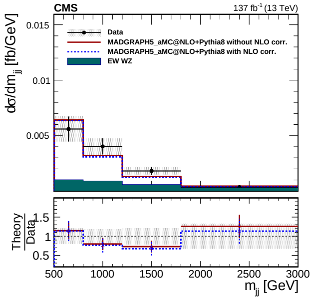
- Simultaneous measurement of $W^{\pm}W^{\pm}jj$ and $WZjj$ production (in CMS)
- Fit of m_{jj} and $m_{\ell\ell}$ distributions ($W^{\pm}W^{\pm}jj$) and BDT discriminant ($WZjj$)
- $W^{\pm}W^{\pm}jj$ with smaller uncertainties in almost all individual sources
  (background from misid. leptons smaller in ATLAS)

Electroweak $W^{\pm}W^{\pm}jj$ and $WZjj$ Results

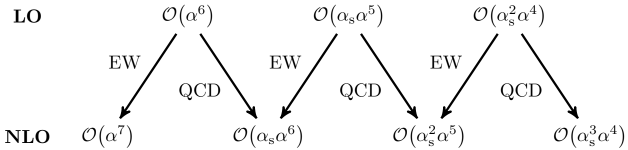
Process	$\sigma\,\mathcal{B}$ (fb)	Theoretical prediction without NLO corrections (fb)	Theoretical prediction with NLO corrections (fb)
EW $W^{\pm}W^{\pm}$	3.98 ± 0.45 $0.37\,(\text{stat}) \pm 0.25\,(\text{syst})$	3.93 ± 0.57	3.31 ± 0.47
EW+QCD $W^{\pm}W^{\pm}$	4.42 ± 0.47 $0.39\,(\text{stat}) \pm 0.25\,(\text{syst})$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

(JHEP 06 (2019) 067)





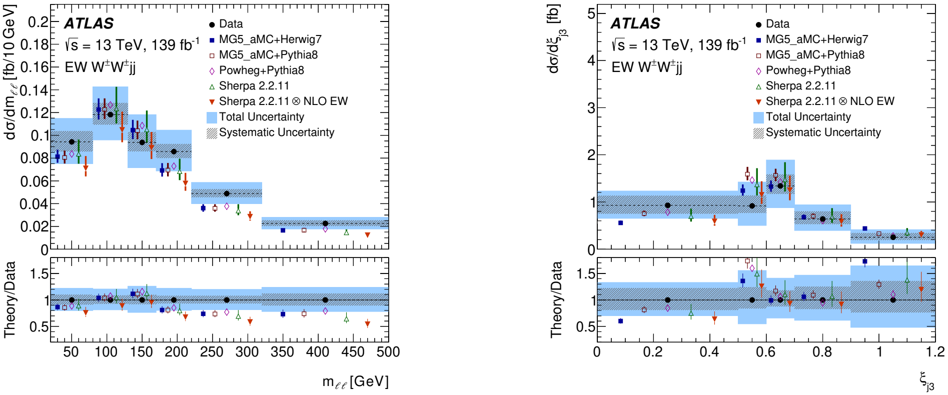
- Inclusive cross sections measured for electroweak and ew+strong production



from JHEP 1710 (2017) 124

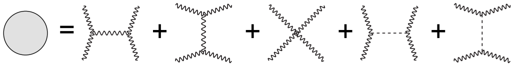
- Results in agreement with theoretical predictions at LO and NLO

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



- Both experiments provide differential $W^{\pm}W^{\pm}jj$ measurements in a wide range of variables
- Full details in **JHEP 04 (2024) 026** (ATLAS) and **PLB 809 (2020) 135710** (CMS)

Semi-leptonic Vector-boson Scattering



- Semi-leptonic $VV \rightarrow \ell\nu jj$ or $\ell\nu J$ benefit from high $V \rightarrow qq$ branching ratio
- Much larger levels of background, mainly from W+jets production

→ categorisation into resolved and boosted categories

- Lower precision than measurements in leptonic decays:

$$\mu_{\mathrm{EW}} = 0.85^{+0.23}_{0.21}$$

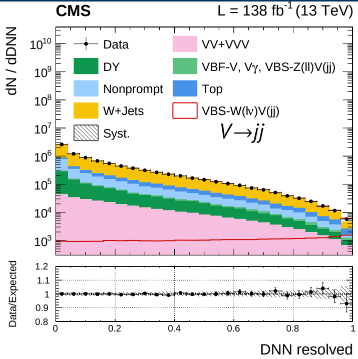
- However, semi-leptonic decays provide leading constraints on non-SM quartic gauge couplings
- Full measurement in **PLB 834 (2022) 137438**

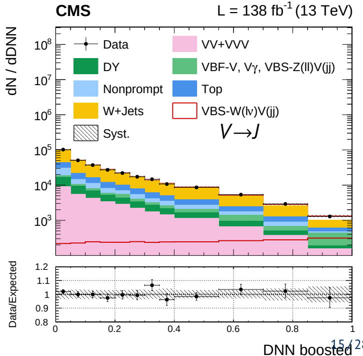
- Previous results on 2015+2016 data:

ATLAS PRD 100 (2019) 032007 (0ℓ, 1ℓ and 2ℓ final states)

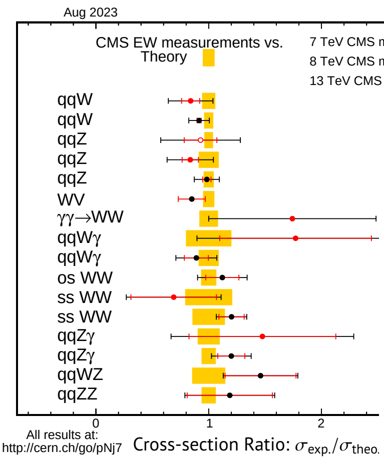
CMS PLB 798 (2019) 134985 (1ℓ and 2ℓ final states, **w/ EFT limits**)

- And you should watch this link during this week





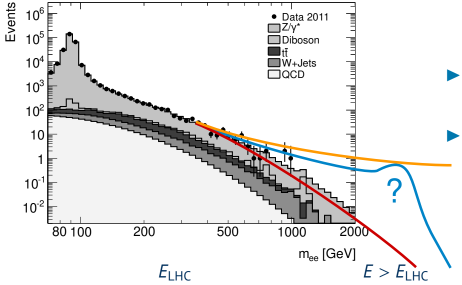
Experimental Status



	ATLAS			CMS		
VBF Z	139 fb^{-1},	$\gg 5\sigma$	EPJC 81 (2021) 163	36 fb^{-1},	$\gg 5\sigma$	EPJC 78 (2018) 589
VBF W		–		36 fb^{-1},	$\gg 5\sigma$	EPJC 80 (2020) 43
VBS $W^{\pm}W^{\pm}$	140 fb^{-1},	$\gg 5\sigma$	JHEP 04 (2024) 026	137 fb^{-1},	$\gg 5\sigma$	PLB 809 (2020) 135710
VBS $W^{\pm}Z$	140 fb^{-1},	$\gg 5\sigma$	JHEP 06 (2024) 192	137 fb^{-1},	6.8σ	PLB 809 (2020) 135710
VBS ZZ	139 fb^{-1},	5.5σ	NPHYS 19 (2023) 237	137 fb^{-1},	4.0σ	PLB 812 (2020) 135992
VBS $W\gamma$	140 fb^{-1},	$\gg 5\sigma$	EPJC 84 (2024) 1064	(137+20) fb^{-1},	5.3σ	PLB 811 (2020) 135988
VBS $Z\gamma$	140 fb^{-1},	$\gg 5\sigma$ $(Z\to\ell\ell)$	PLB 846 (2023) 138222	137 fb^{-1},	9.4σ	PRD 104 (2021) 072001
	140 fb^{-1},	6.3σ $(Z\to\nu\nu)$	JHEP 06 (2023) 082	,		
VBS $W^{+}W^{-}$	140 fb^{-1},	7.1σ	JHEP 07 (2024) 254	137 fb^{-1},	5.6σ	PLB 841 (2023) 137495
$\gamma\gamma\to W^{+}W^{-}$	139 fb^{-1},	8.4σ	PLB 816 (2021) 136190	100 fb^{-1},	–	JHEP 07 (2023) 229
VBS VV	36 fb^{-1},	2.7σ	PRD 100 (2019) 032007	137 fb^{-1},	4.4σ	PLB 834 (2022) 137438

- Electroweak *VVjj* production has been observed in all major channels in the LHC run-2
- They are amongst the rarest processes experimentally accessible at the LHC

Interpretation of Measurements



- Deviations from the SM couplings are quantified in an Effective Field Theory approach
- Expansion of SM Lagrangian with higher-dimensional operators

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4} O_i^{(8)} + \ldots$$

four $\partial_\mu \Phi$ → $\mathcal{L}_{S,0}, \mathcal{L}_{S,1}$

two $\partial_\mu \Phi$, two $F_{\mu\nu}$ → $\mathcal{L}_{M,0}, \ldots, \mathcal{L}_{M,7}$

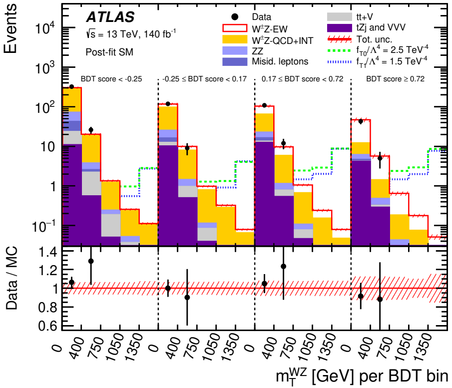
four $F_{\mu\nu}$ → $\mathcal{L}_{T,0}, \ldots$

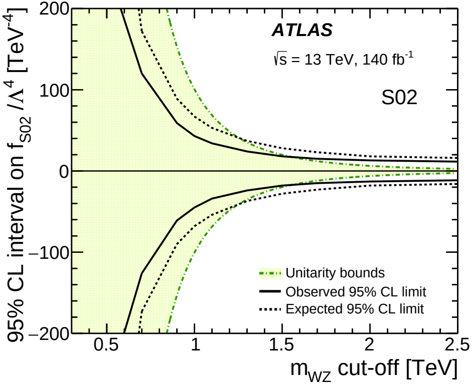
	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{L}_{S,0}, \mathcal{L}_{S,1}$	X	X	X	O	O	O	O	O	O
$\mathcal{L}_{M,0}, \mathcal{L}_{M,1}, \mathcal{L}_{M,6}, \mathcal{L}_{M,7}$	X	X	X	X	X	X	X	O	O
$\mathcal{L}_{M,2}, \mathcal{L}_{M,3}, \mathcal{L}_{M,4}, \mathcal{L}_{M,5}$	O	X	X	X	X	X	X	O	O
$\mathcal{L}_{T,0},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

from PRD 93 093013 (2016)

- There are no dim-6 operators that affect only the quartic electroweak couplings
- In VBS and triboson processes we study dim-8 operators only affecting quartic EW couplings
  (assuming the dim-6 coefficients are 0, and other dim-8 operators are constrained elsewhere)
- For interplay with HEFT, see this talk

Limits on aQGCs from VBS

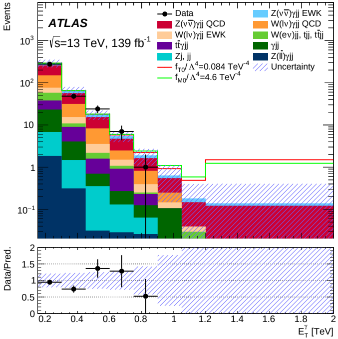


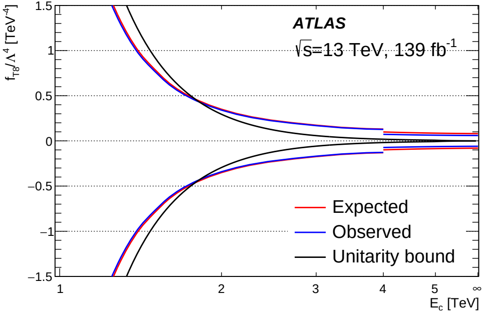


- Sensitivity to EFT effects in high-energy tails, but growth of amplitude with $\sqrt{s}$ can violate unitarity
- Partial-wave unitarity for $VV \to VV$ scattering calculated in PRD 101, 113003
- Experimentally, provide limits with EFT contribution restricted as a function of $m_{VV} < E_c$
- First unitarised limits on S-family operators from $WZjj$ production, **JHEP 06 (2024) 192**

Summary of aQGC Limits

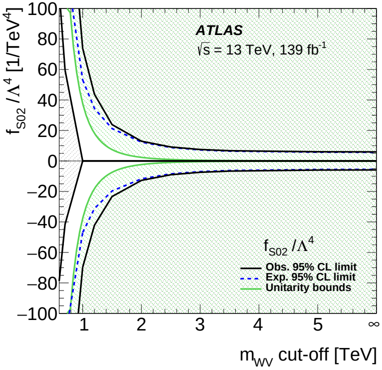
- To constrain the full set of non-SM quartic gauge couplings, important to explore a variety of VBS channels

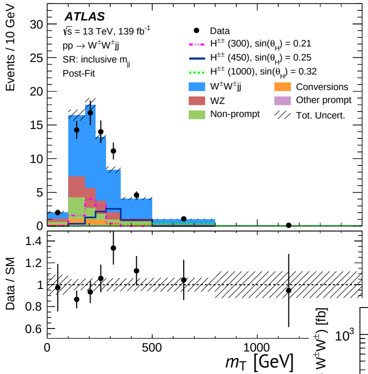


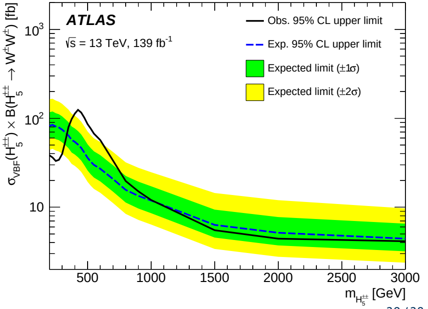


- e.g. leading experimental constraints on T_8, T_9 (and a few others) from $Z(\to \nu\nu)\gamma jj$ production
- Limits on M-family dominated by $W\gamma jj$ production
- Sensitivity to S-family operators from $WWjj$, $WZjj$, $ZZjj$ channels

EFT Approach vs. Direct Searches





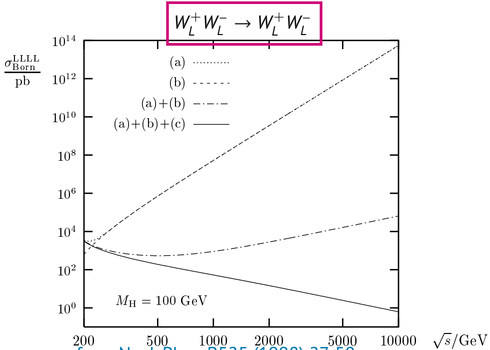


- Example: 2.5σ excess in m_T distribution of VBS $W^\pm W^\pm$
- Limits on S-family operators ($m_{\ell\ell}$ based) in agreement with expectation (although for low clipping values, exclusion of the Standard Model at 95%)

⇒ EFT limits complement but do not replace direct searches

- Further reading: PLB 860 (2025) 139137, EPJC 81 (2021) 723

Polarisation Measurements



from Nucl. Phys. B525 (1998) 27-50

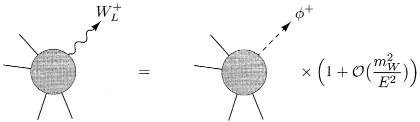


Figure 21.3. The Goldstone boson equivalence theorem. At high energy, the amplitude for emission or absorption of a longitudinally polarized massive gauge boson becomes equal to the amplitude for emission or absorption of the Goldstone boson that was eaten by the gauge boson.

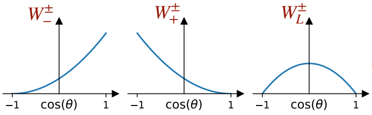
Peskin, Schroeder; An Introduction to QFT

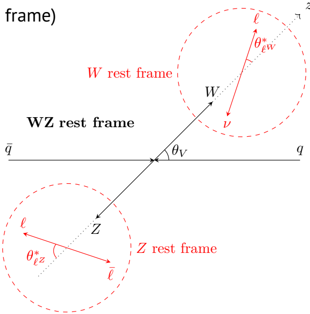
- Divergencies in individual VBS diagrams are associated with longitudinally polarised $W^\pm$ and Z bosons
- Longitudinal polarisation states arise from electroweak symmetry breaking via the BEH mechanism

⇒ Polarisation measurements are a direct probe of electroweak symmetry breaking

Experimental Method

- Polarisation is *not* invariant under Lorentz transformation (→ depends on chosen reference frame)
- Measured on a statistical basis from decay angles
- Theoretical decomposition in individual components (00, T0, 0T, TT)
- Main challenge in measurements: incorporate higher-order QCD effects (PLB **814** (2021) 136107, JHEP **10** (2021) 097, JHEP 04 (2019) 065)

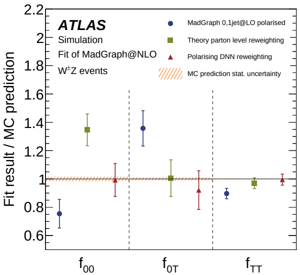




PLB 843 (2023) 137895

Incorporating higher-order corrections:

- ● Decomposition in event-generators at 0,1j@LO
- ■ + reweighting to fixed-order calculations
- ▲ Truth-level DNN (similar to pol. tagging)
- ❏ NLO+PS becoming available



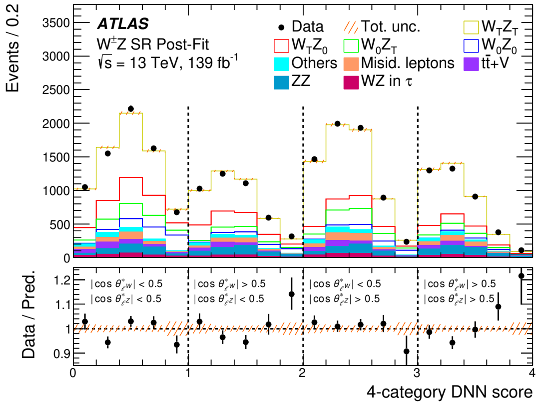
Gauge-Boson Polarisation in $pp \to W^{\pm}Z$

- Polarisation fractions measured in fit to DNN exploiting kinematic and angular variables
- In four categories:

$$\left|\cos\theta^*_{\ell W}\right| \lessgtr 0.5$$

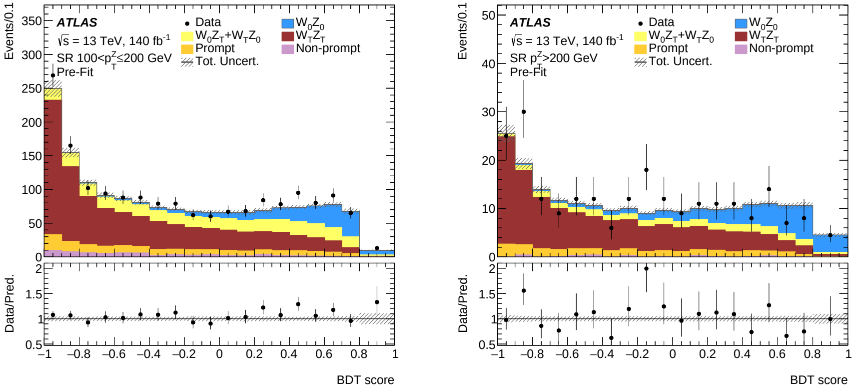
$$\left|\cos\theta^*_{\ell Z}\right| \lessgtr 0.5$$

	f_{00}	$f_{0\mathrm{T}}$	$f_{\mathrm{T}0}$	f_{TT}
Relative uncertainty [%]				
e energy scale and id. efficiency	0.34	0.6	0.8	0.31
μ energy scale and id. efficiency	0.8	0.23	0.23	0.13
$E_{\mathrm{T}}^{\mathrm{miss}}$ and jets	3.3	1.3	1.2	0.4
Pile-up	0.6	0.17	0.4	0.15
Misidentified lepton background	2.3	1.6	0.8	0.26
ZZ background	0.9	0.17	0.32	0.07
Other backgrounds	3.0	1.6	1.3	0.4
Parton Distribution Function	0.5	1.8	0.09	0.5
QCD scale	0.19	8	0.9	2.0
Modelling	9	4	2.9	1.2
Total systematic uncertainty	14	15	8	4
Luminosity	0.35	0.24	0.15	0.05
Statistical uncertainty	13	10	12	3.0
Total	19	18	14	5



- Largest source of uncertainty in f_{00}: polarisation modelling and $E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction
- $pp \to W_0^{\pm}Z_0$ production observed with 7.1σ
- Reported in **PLB 843 (2023) 137895**

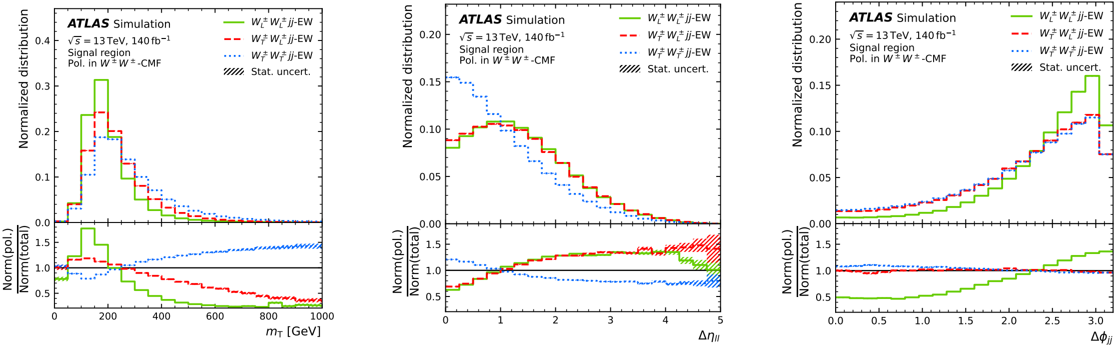
$W^{\pm}Z$ Polarisation at High-p_{T}



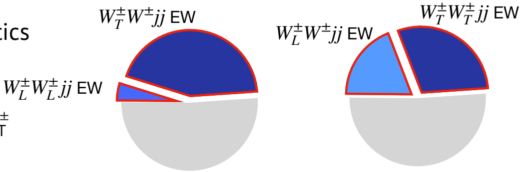
- First study of the energy dependence in two phase-space regions, 100 GeV $< p_{\mathrm{T}} <$ 200 GeV and $p_{\mathrm{T}} >$ 200 GeV
- Using individual BDTs of ang. and kin. variables
- Documented in **PRL 133 (2024) 101802**
- Similar technique used to obtain evidence for $Z_L Z_L$ production **JHEP 12 (2023) 107**

	Measurement		Prediction		
	$100 < p_T^Z \leq 200$ GeV	$p_T^Z > 200$ GeV		$100 < p_T^Z \leq 200$ GeV	$p_T^Z > 200$ GeV
f_{00}	$0.19 \pm^{0.03}_{0.03}$ (stat) $\pm^{0.02}_{0.02}$ (syst)	$0.13 \pm^{0.09}_{0.08}$ (stat) $\pm^{0.02}_{0.02}$ (syst)	f_{00}	0.152 ± 0.006	0.234 ± 0.007
f_{0T+T0}	$0.18 \pm^{0.07}_{0.08}$ (stat) $\pm^{0.05}_{0.06}$ (syst)	$0.23 \pm^{0.17}_{0.18}$ (stat) $\pm^{0.06}_{0.10}$ (syst)	f_{0T}	0.120 ± 0.002	0.062 ± 0.002
f_{TT}	$0.63 \pm^{0.05}_{0.05}$ (stat) $\pm^{0.04}_{0.04}$ (syst)	$0.64 \pm^{0.12}_{0.12}$ (stat) $\pm^{0.06}_{0.06}$ (syst)	f_{T0}	0.109 ± 0.001	0.058 ± 0.001
f_{00} obs (exp) sig.	5.2 (4.3) σ	1.6 (2.5) σ	f_{TT}	0.619 ± 0.007	0.646 ± 0.008

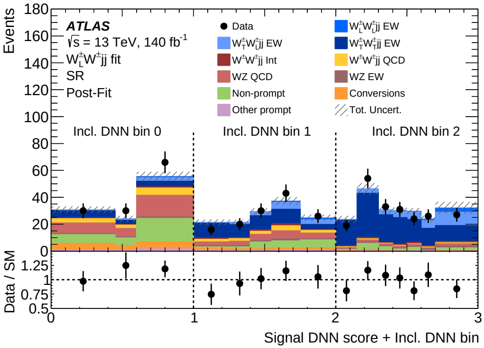
Polarisation in Vector-boson Scattering

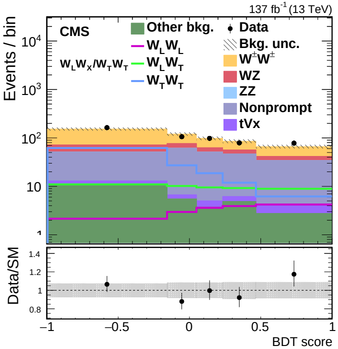


- In VBS, polarisation states differ in diboson *and* jet kinematics
- Maximise sensitivity through combination in DNN/BDT
  - Separating $W^\pm W^\pm jj$ from other bkg.
  - Discriminating either $W_0^\pm W_0^\pm$ and $W_T^\pm W^\pm$, or $W_0^\pm W^\pm$ and $W_T^\pm W_T^\pm$
- Separately for $W_0^\pm W^\pm$ and $W_0^\pm W_0^\pm$



Single W Polarisation in VBS



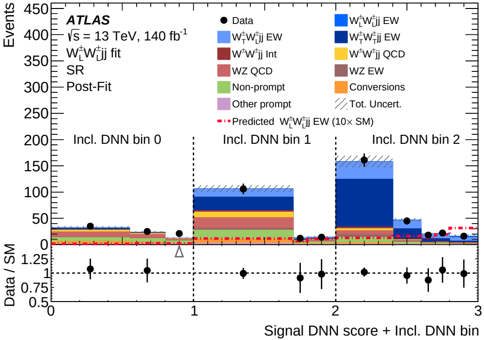


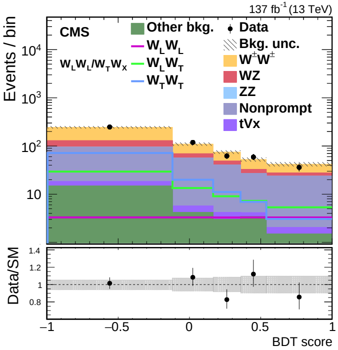
- Measurement from double differential DNN/BDT distribution
- Evidence for purely electroweak $W_0^{\pm}Wjj$ production:
  - ATLAS: 3.3σ obs. (4.0σ exp.)
  - CMS: 2.3σ obs. (3.1σ exp.)
- Cross sections in agreement with theoretical predictions

ATLAS	0.88 ± 0.28 (stat) ± 0.09 (syst) fb	1.18 ± 0.29 fb (Sherpa LO@0,1j + corrections)
CMS	$1.20^{+0.56}_{-0.53}$ fb	1.63 ± 0.21 fb (Madgraph LO + corrections)

(where fiducial phase space differs between both experiments)

Double W Polarisation in VBS





- Experiments barely sensitive to double-longitudinal polarisation, yet

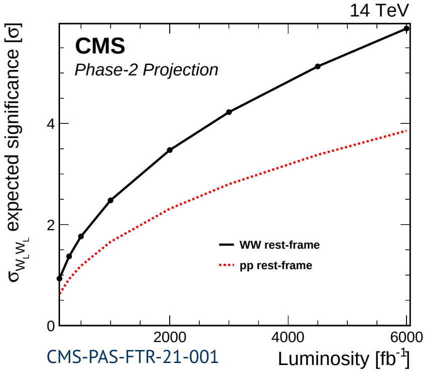
ATLAS	0.01 ± 0.20 (stat) ± 0.05 (syst) fb	0.29 ± 0.07 fb (Sherpa LO@0,1j + corrections)
CMS	$0.32^{+0.42}_{-0.40}$ fb	0.44 ± 0.05 fb (Madgraph LO + corrections)

- Upper limit of 0.45 fb ⇒ important constraint on BSM models
- Incorporating polarised (JHEP **11** (2024) 115) or inclusive NLO EW corrections
- More details in **PLB 812 (2020) 136018** (CMS) and **arXiv:2503.11317** (ATLAS)

Summary

- The LHC tests the electroweak theory at highest energies in measurements of multiboson production
- Processes involving quartic electroweak couplings became experimentally accessible in the LHC run-2
- Observation of all major VBS channels
- First measurements of polarisation in diboson and VBS

$\Rightarrow$ These are important steps in the study of EW symmetry breaking with the Higgs mechanism

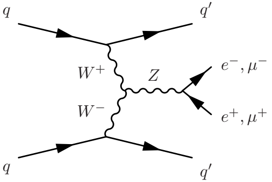


CMS-PAS-FTR-21-001

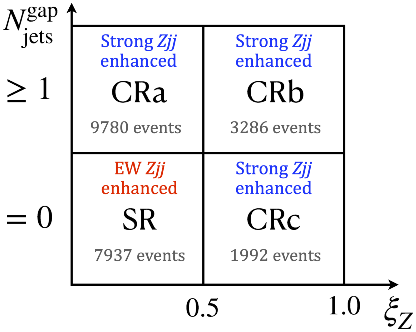
We're well prepared to systematically explore EW couplings in run-3 and beyond

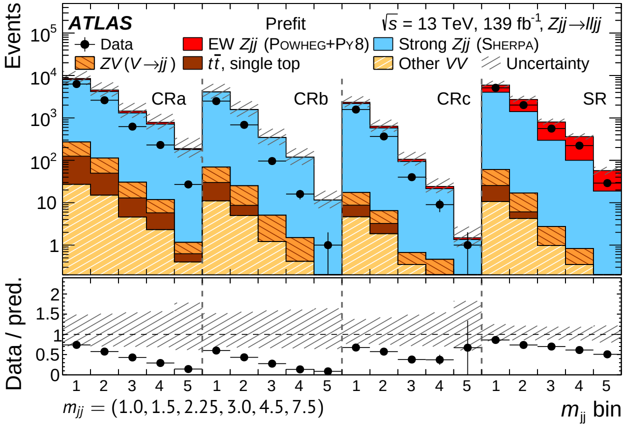
Backup

Electroweak *Zjj* Production



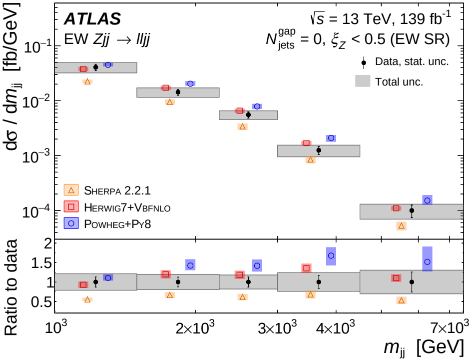
- Electroweak *Zjj* production is a model process for *VVjj* production
- Critical for precise measurements of *Zjj*-electroweak is a good understanding of *Zjj*-strong background





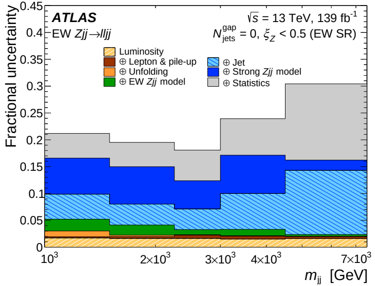
- Estimation of strong *Zjj* production relies on *Z* centrality and central jet activity

Electroweak *Zjj* Results



Status 2020:

- ▲ wrong colour flow in Sherpa
- ● Pythia8 ignorant of colour flow



- Inclusive EW *Zjj* cross sections measured to be:

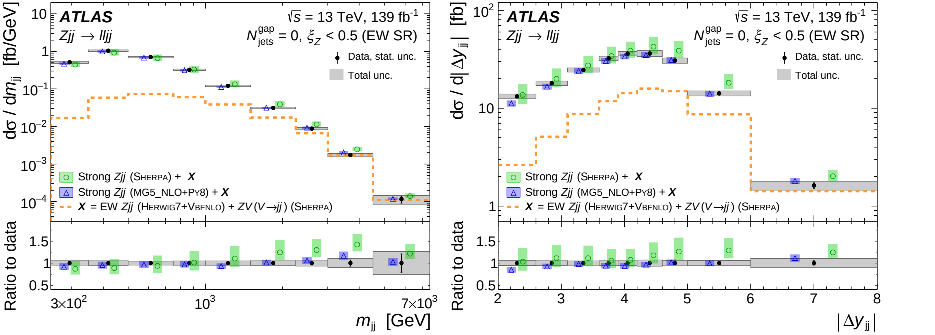
$$\sigma_{\text{EW}} = 37.4 \pm 3.5\ (\text{stat}) \pm 5.5\ (\text{syst})\ \text{fb}$$

- Leading uncertainty in strong *Zjj* modelling and jet reconstruction
- Only small reduction of stat. unc. compared to result from 3.2 fb^{-1}:

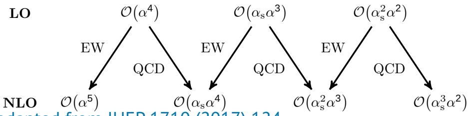
  $\sigma_{\text{EW}} = 34.2 \pm 5.8$ (stat) $\pm$ 5.5(syst) fb (relying much more on *Zjj* modelling)

- Reducing reliance on theory modelling of strong *Zjj* production introduces large stat. unc. in control regions

Strong and Electroweak *Zjj* Measurements



- In addition, combined measurement of the strong and electroweak *Zjj* production processes
  - At higher order, distinction is ambiguous
  - Insensitive to strong and electroweak interference



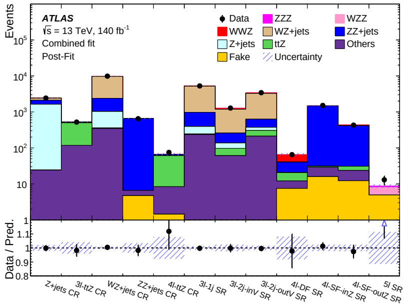
adapted from JHEP 1710 (2017) 124

- *Zjj* production is standard candle to benchmark theo. calculations relevant for vector-boson scattering
- More information in **EPJC 81 (2021) 163**

Bonus: Limits from Triboson Production

- Quartic couplings experimentally accessible in triboson production
- Experimentally and theoretically more difficult than VBS
- Recent measurement of *WVZ* production slightly higher than prediction at NLO (similar as in *WWW* before)
- *My personal impression:* EFT limits are valid to higher energies

→ triboson processes could be a valuable addition to EFT programme



- Observation of *WVZ* production reported in **arXiv:2412.15123**