Multi-boson measurements in ATLAS

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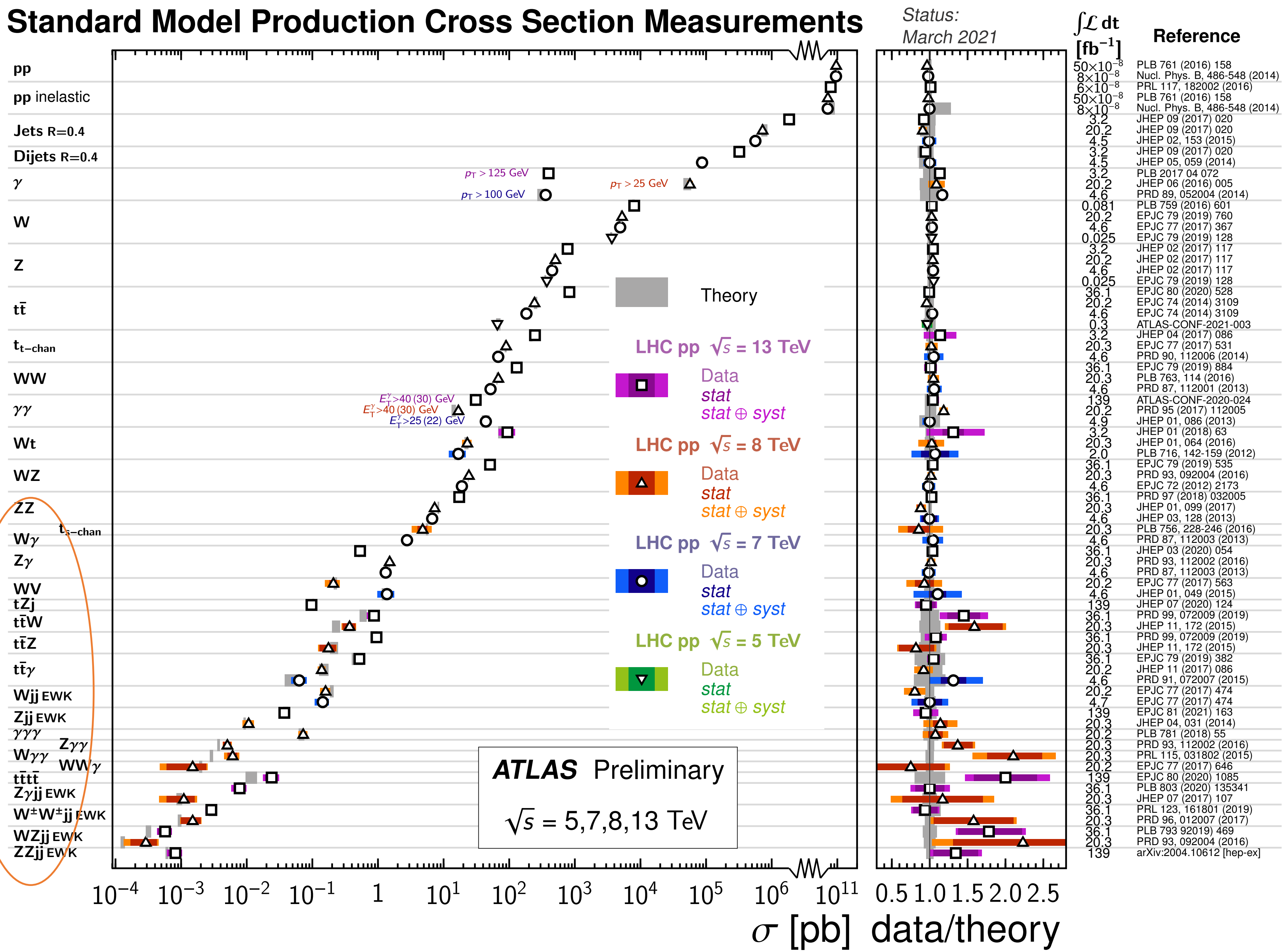
Outline

- Motivation
  - searches for electroweak di-boson production
  - measurements of triple and quatric gauge boson couplings
  - searches for BSM physics in the framework of Standard Model Electroweak Field Theory (SMEFT)
- Vector Boson Scattering
  - two same-sign W bosons accompanied by two jets
  - Z boson pair and two jets
  - photon-induced production of W boson pairs
  - vector boson fusion Higgs production using decays to two W bosons
- Measurement of the four-lepton invariant mass spectrum
- Production of two W bosons and at least one jet

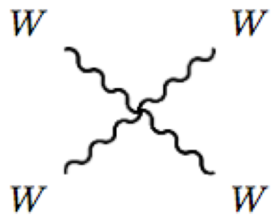


Higgs boson cross sections

in this talk

Higgs – gauge bosons interactions in the SM

- the Higgs mechanism introduces masses of gauge bosons and their longitudinal polarisations
- $W_L W_L$ scattering amplitude (quatric coupling) diverges with $O(s^2)$



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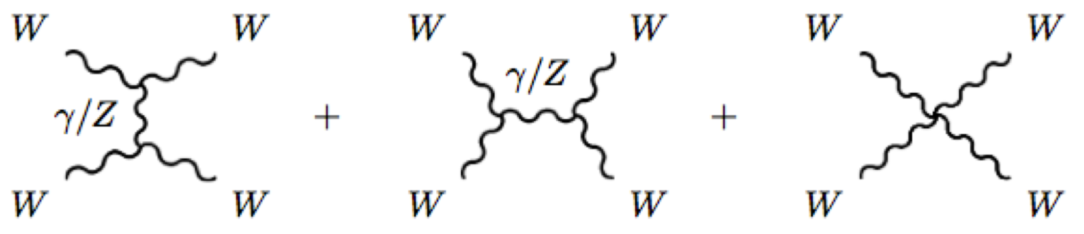
- Gauge bosons interactions partly regularise, leaving O(s) divergence



Higgs – gauge bosons interactions in the SM

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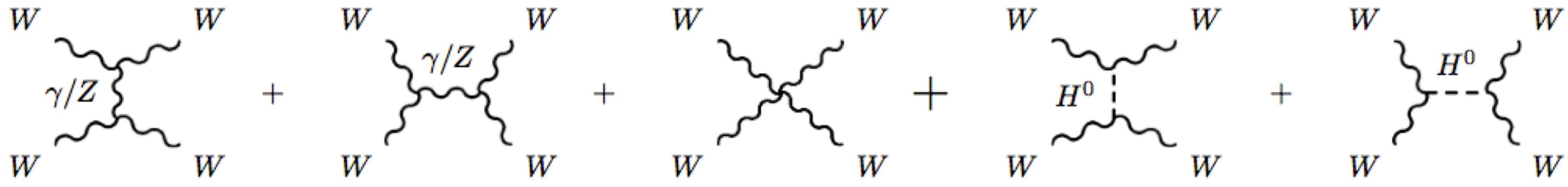
- $W_L W_L$ scattering amplitude (quatric coupling) diverges with $O(s^2)$
- Gauge bosons interactions partly regularise, leaving O(s) divergence
- Higgs boson interactions subtract O(s) divergence

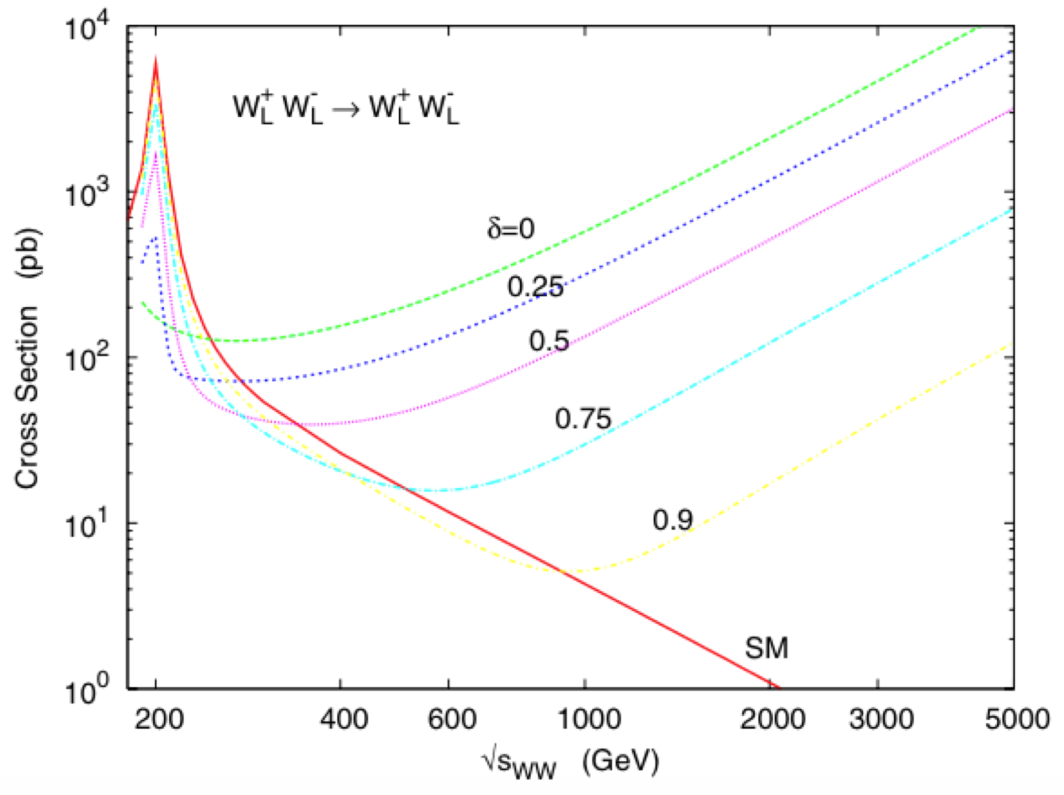


Higgs – gauge bosons interactions in the SM

- Measurements of (Higgs –) gauge bosons interactions is crucial for confirming the mechanism of electroweak symmetry breaking…

- Observing deviations from the SM couplings means finding new physics
  - anomalous gauge couplings
  - effective field theory (EFT)

[Cheung, Chiang, Yuan, 2008]



Standard Model Effective Field Theory

- BSM fields above Λ=1TeV give rise to higher-dimensions operators that form SMEFT Lagrangian

$$L_{\mathrm{EFT}} = L_{\mathrm{SM}} + \sum_i \frac{\bar{C}_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{\bar{C}_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \ldots \quad (*)$$

- The canonical dimension of SM operators is 4, dim-6 operators suppressed by Λ^{-2} wrt. the SM, dim-8 operators suppressed by Λ^{-4} , …
- $C_i^{(d)}$ specify the strength of the BSM interactions and are known as Wilson coefficients, $c_i^{(6)} = C_i^{(6)} / \Lambda^{-2}$
- The set of operators of each dimension is renormalizable
- The complete basis of dim-6 operators is known JHEP10(2010) 085

(*) neglecting all lepton- and baryon-number violating terms, which include dim-5 operators

EFT cross-section measurements

- EFT dimension 6 operators implemented in the SMEFTSim package at the leading order
- Predicted cross-sections can be decomposed into:

$$\vec{\sigma}^{\text{pred}} = \vec{\sigma}^{\text{SM}} \times \left(1 + c_i \cdot \vec{\sigma}^{\text{INT}} / \vec{\sigma}^{\text{LO SM}} + c_i^2 \cdot \vec{\sigma}^{\text{BSM}} / \vec{\sigma}^{\text{LO SM}}\right)$$

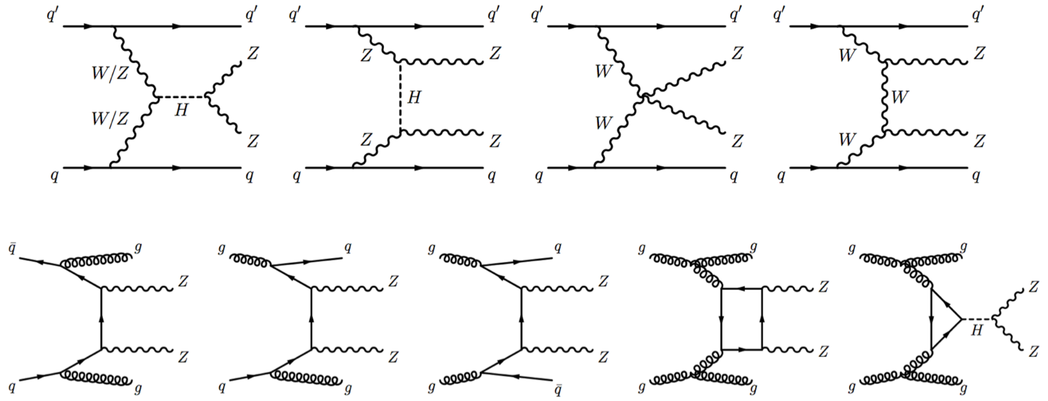
- The linear (interference) and non-linear (quadratic) EFT contributions
- Quadratic term is of the same dimension as higher-order linear term thus some fit variants do not include it

Vector boson scattering at the LHC

Vector boson scattering at the LHC

- Experimental signature consists of two jets and decay products of 2 gauge bosons (light leptons)
- Contributions from both electro-weak (EW) and chromodynamically (QCD) induced interactions
- Extracting the EW component provides access to gauge bosons self-interactions

- Characteristic kinematical features of EW processes:
  - two forward jets separated with a “rapidity gap”
  - leptons have small rapidities



Feymnam diagrams for pp→ZZjj process at leading order

Next To Leading Order cross-sections calculations

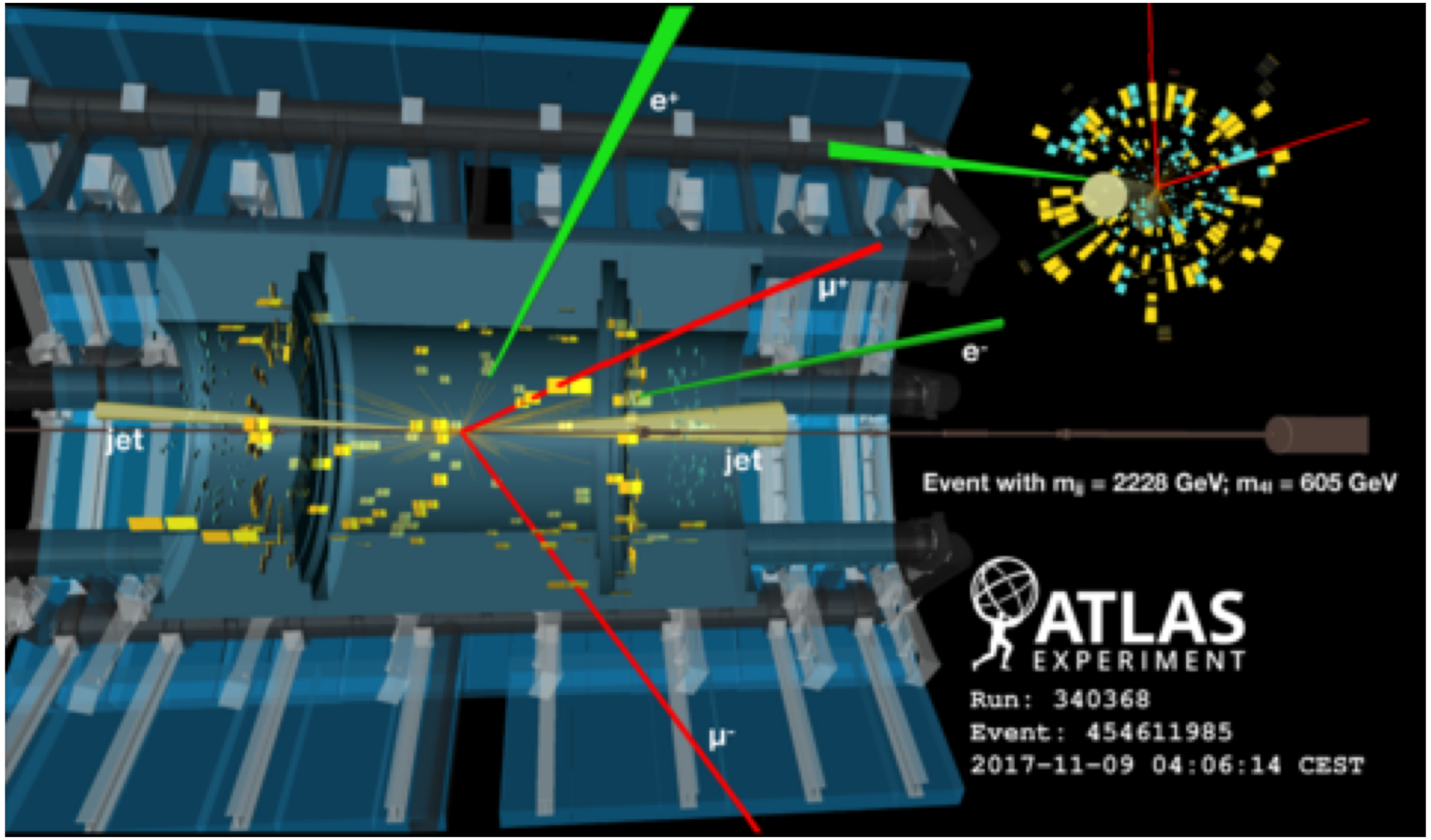
- LO contributions:
  - $\mathcal{O}(\alpha^6)$ EW
  - $\mathcal{O}(\alpha_s \alpha^5)$ interference
  - $\mathcal{O}(\alpha_s^2 \alpha^4)$ QCD
- NLO contributions
  - $\mathcal{O}(\alpha^7)$ EW corrections
  - $\mathcal{O}(\alpha_s \alpha^6)$ QCD+EW
  - $\mathcal{O}(\alpha_s^2 \alpha^5)$ QCD+EW
  - $\mathcal{O}(\alpha_s^3 \alpha^4)$ QCD corrections

Beyond the leading order the distinction between EW and QCD contributions is meaningless

State of the art of theory predictions:

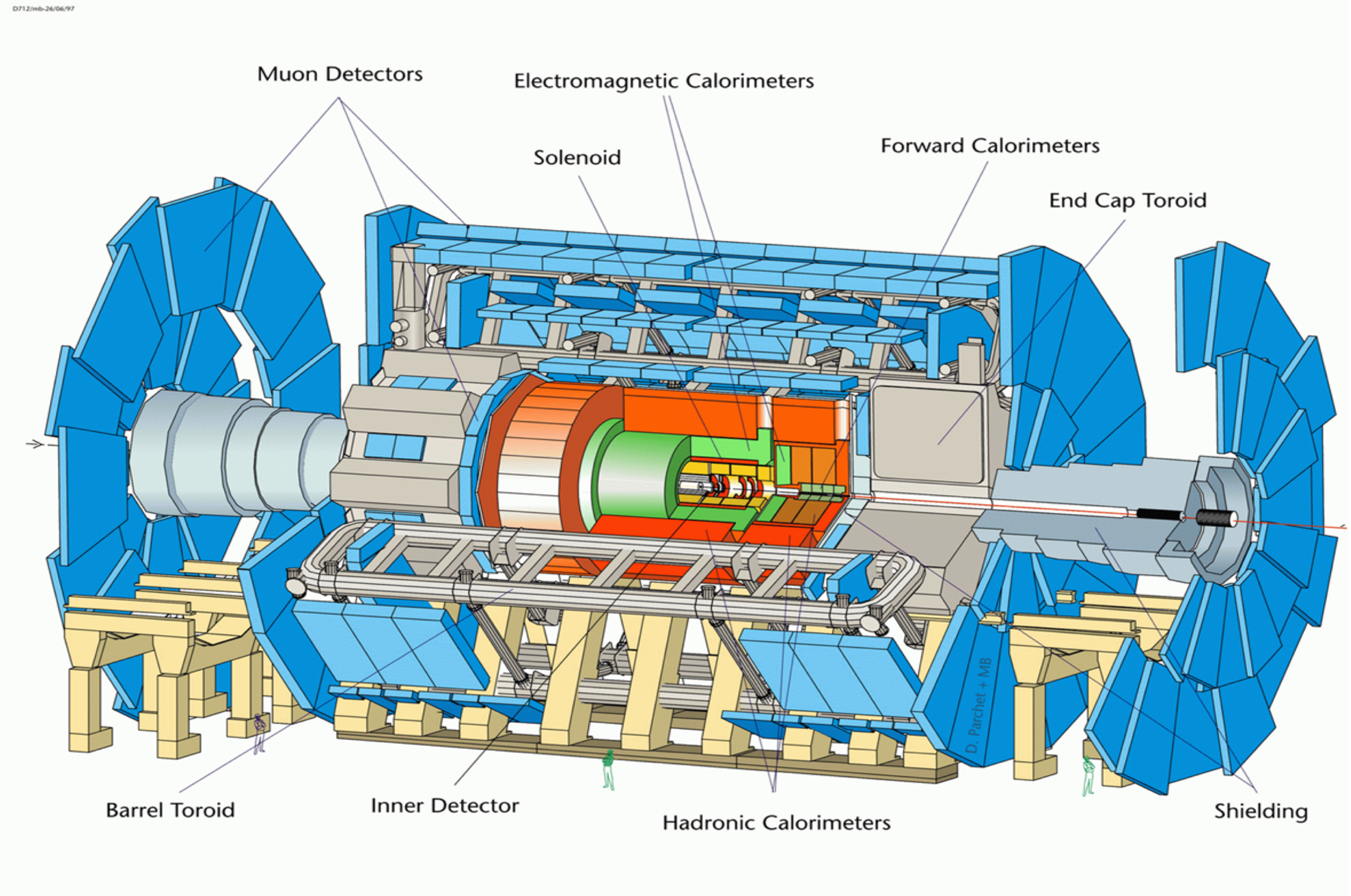
- pure NLO QCD predictions computed for:
  - $W^\pm W^\pm$j j (*)
  - $W^\pm$Z jj (**)
  - ZZjj (***) and W^+W^- jj (****)
- pure NLO EW corrections computed for:
  - $W^\pm W^\pm$j j (*)
  - $W^\pm$Zjj (**)
- QCD+EW corrections:
  - $W^\pm W^\pm$j j (*)
  - only $\mathcal{O}(\alpha_s \alpha^6)$ in $W^\pm$Zjj (***), ZZjj (+) and W^+W^- jj (+ +)

(*) Biedermann, Denner, Pellen; 1611.02951, 1708.00268
(**) Denner, Dittmaier, Maierhoefer, Pellen, Schwan; 1904.00882
(***) Campanario et al.; 1305.1623
(****) Jaeger, Zanderighi; 1301.1695
(+) Jaeger, Karlberg, Zanderighi; 1312.3252
(+ +) Greiner et al.; 1202.6004



Measurements at ATLAS

The ATLAS detector

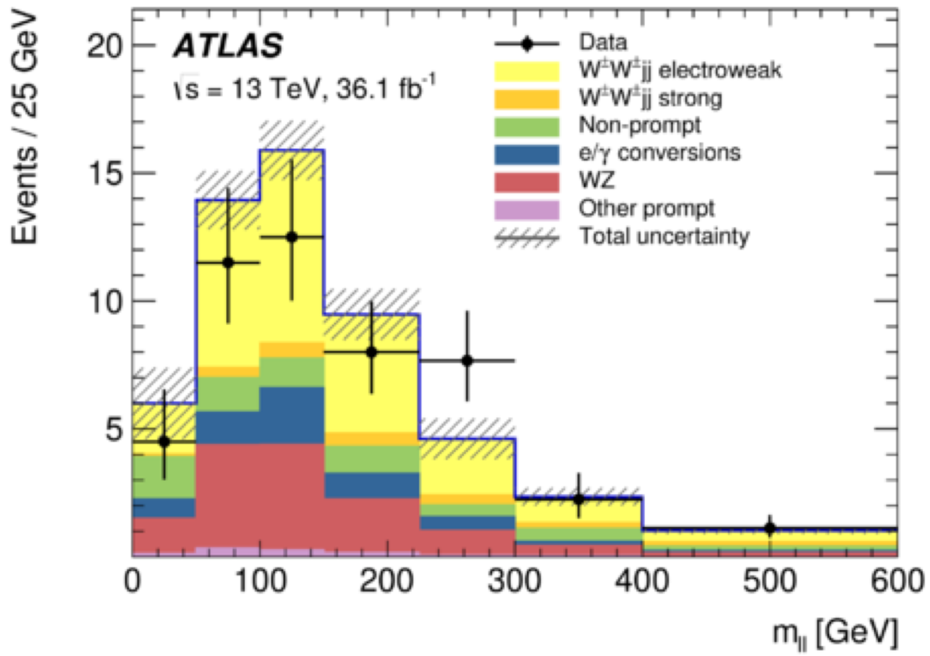


Observation of electroweak same-sign W boson pairs accompanied by two jets

1906.03203

- The $W^{\pm}W^{\pm}jj$ final state has the largest ratio of electroweak to strong production cross sections compared to other VBS diboson processes
- integrated luminosity 36.1 fb^{-1}
- NLO QCD corrections included in EW and QCD $W^{\pm}W^{\pm}jj$
- The measured fiducial signal cross section is

$\sigma_{fid.} = 2.89^{+0.51}_{-0.48}$ (stat.) $^{+0.29}_{-0.28}$(syst.) fb.



	e^+e^+	e^-e^-	$e^+\mu^+$	$e^-\mu^-$	$\mu^+\mu^+$	$\mu^-\mu^-$	Combined
WZ	1.48 ± 0.32	1.09 ± 0.27	11.6 ± 1.9	7.9 ± 1.4	5.0 ± 0.7	3.4 ± 0.6	30 ± 4
Non-prompt	2.2 ± 1.1	1.2 ± 0.6	5.9 ± 2.5	4.7 ± 1.6	0.56 ± 0.05	0.68 ± 0.13	15 ± 5
e/γ conversions	1.6 ± 0.4	1.6 ± 0.4	6.3 ± 1.6	4.3 ± 1.1	—	—	13.9 ± 2.9
Other prompt	0.16 ± 0.04	0.14 ± 0.04	0.90 ± 0.20	0.63 ± 0.14	0.39 ± 0.09	0.22 ± 0.05	2.4 ± 0.5
$W^{\pm}W^{\pm}jj$ strong	0.35 ± 0.13	0.15 ± 0.05	2.9 ± 1.0	1.2 ± 0.4	1.8 ± 0.6	0.76 ± 0.25	7.2 ± 2.3
Expected background	5.8 ± 1.4	4.1 ± 1.1	28 ± 4	18.8 ± 2.6	7.7 ± 0.9	5.1 ± 0.6	69 ± 7
$W^{\pm}W^{\pm}jj$ electroweak	5.6 ± 1.0	2.2 ± 0.4	24 ± 5	9.4 ± 1.8	13.4 ± 2.5	5.1 ± 1.0	60 ± 11
Data	10	4	44	28	25	11	122

Observation of electroweak production of two jets and a *Z*-boson pair

arXiv:2004.10612

- 2 final states: 4l jj and 2l2νjj
- integrated luminosity 139 fb^{-1}
- a fully reconstructed final state when both of the Z bosons decay into charged leptons
- VBS ZZ production is sensitive to the possible anomalous interaction between four Z bosons (forbidden at tree-level in the SM)

- small signal rate predicted by the SM, low background
- EW ZZjj signal generated at the LO, QCD-induced ZZjj production includes NLO QCD corrections
- Dominating sources of uncertainties are: data statics, experimental uncertainties related to jet measurements and the background estimate

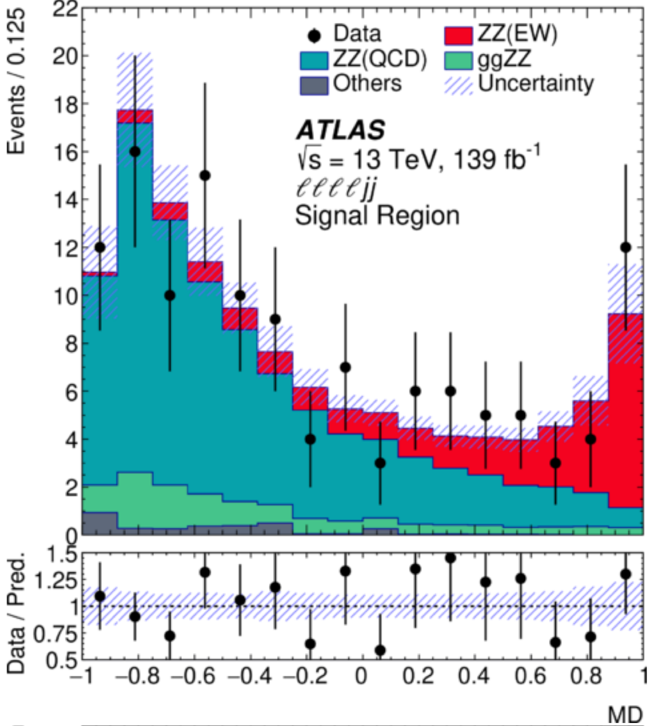
Electroweak production of ZZjj

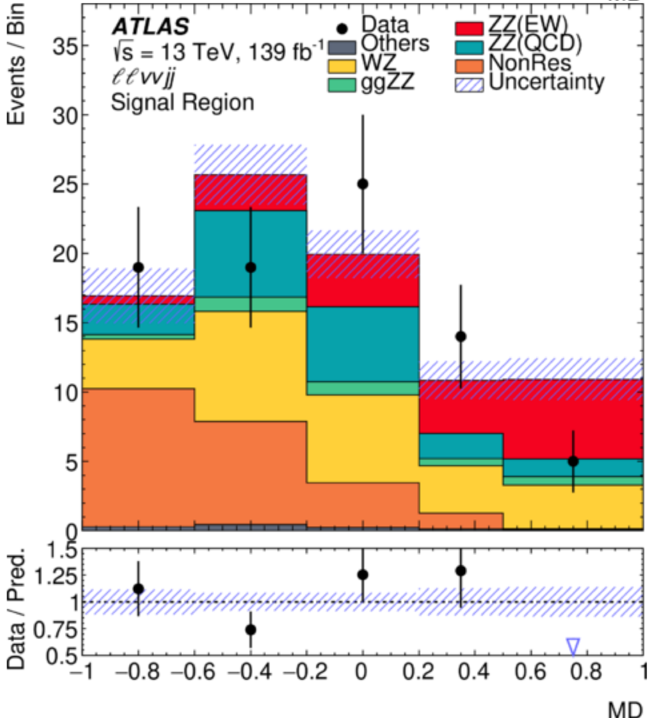
The hypothesis of no electroweak production is rejected with a statistical significance of 5.5σ, and the measured cross-section for electroweak production is consistent with the SM prediction.

signal strengths for QCD and EW production

	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	$5.5\ (3.9)\ \sigma$
$\ell\ell\nu\nu jj$	0.7 ± 0.7	–	$1.2\ (1.8)\ \sigma$
Combined	1.35 ± 0.34	0.96 ± 0.22	$5.5\ (4.3)\ \sigma$

	Measured fiducial σ [fb]	Predicted fiducial σ [fb]
$\ell\ell\ell\ell jj$	$1.27 \pm 0.12(\mathrm{stat}) \pm 0.02(\mathrm{theo}) \pm 0.07(\mathrm{exp}) \pm 0.01(\mathrm{bkg}) \pm 0.03(\mathrm{lumi})$	$1.14 \pm 0.04(\mathrm{stat}) \pm 0.20(\mathrm{theo})$
$\ell\ell\nu\nu jj$	$1.22 \pm 0.30(\mathrm{stat}) \pm 0.04(\mathrm{theo}) \pm 0.06(\mathrm{exp}) \pm 0.16(\mathrm{bkg}) \pm 0.03(\mathrm{lumi})$	$1.07 \pm 0.01(\mathrm{stat}) \pm 0.12(\mathrm{theo})$





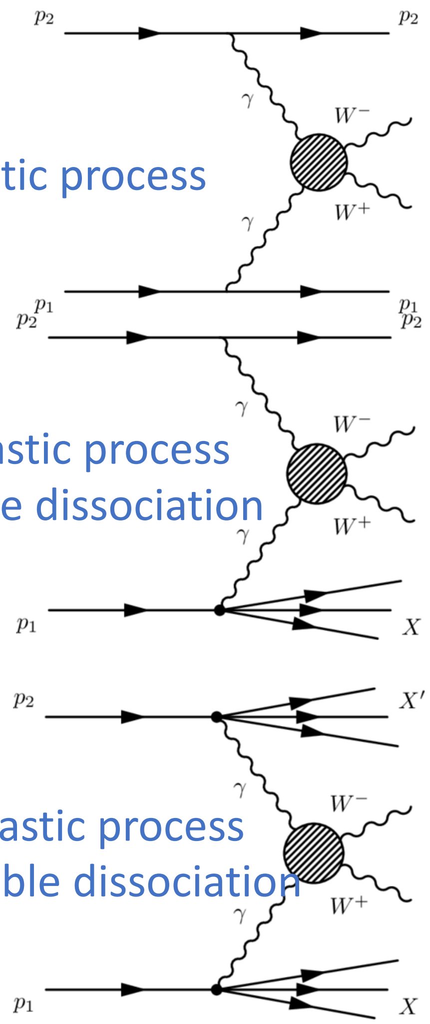
Arxiv:2010.04019

Observation of photon-induced production of W boson pairs

Elastic process

Inelastic process single dissociation

Inelastic process double dissociation

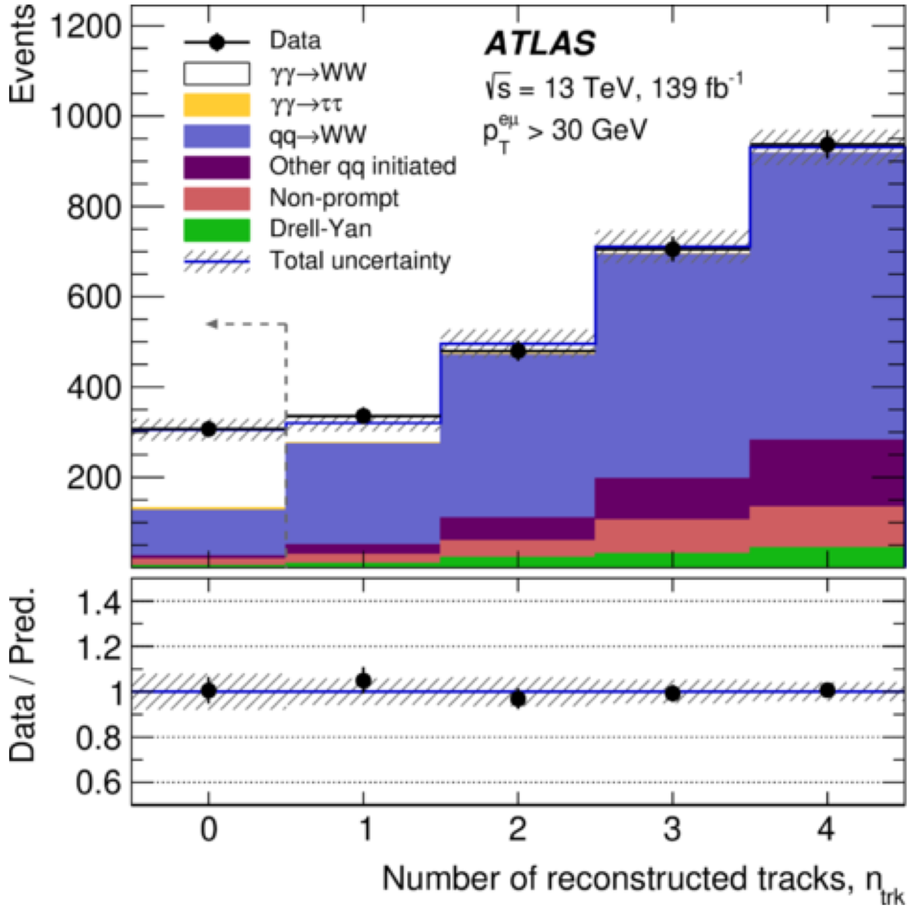


The signal is sensitive to triple and quartic gauge boson couplings

In the signal events the number of charged particles tracks is expected to be 0

- Modeling of hadronic activity is constrained using Drell-Yan events in data
- Observed significance of 6.7 standard deviations
- • Measured cross section:

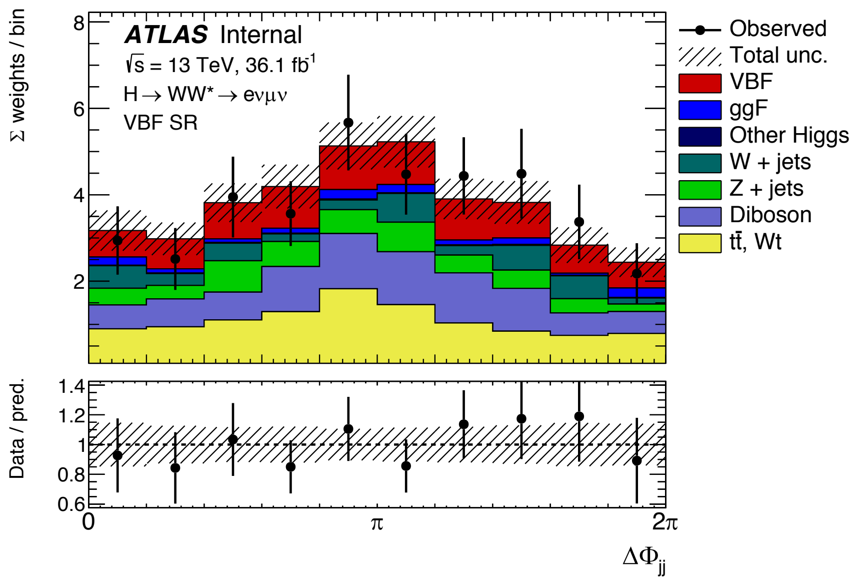
$$3.13 \pm 0.31(\text{stat.}) \pm 0.28(\text{syst.})\ \text{fb}$$



Constraining the Higgs boson couplings to longitudinally and transversally polarised W and Z bosons

- Vector boson fusion Higgs production and WW final state
- Integrated luminosity of 36 fb^{-1}
- $a_L = g_{HVLVL}/g_{HVV}$ and $a_T = g_{HVTVT}/g_{HVV}$,
  - in the SM $a_L = a_T = 1$
  - defined in the Higgs rest frame so that only HV_LV_L and HV_TV_T coupling combinations are present (see 1404.5951)

- Anomalous couplings extracted from:
- $\sigma \cdot Br(H \rightarrow WW^*)$
- the distribution of the signed azimuthal angle between two tagging jets $\Delta\Phi_{jj}$



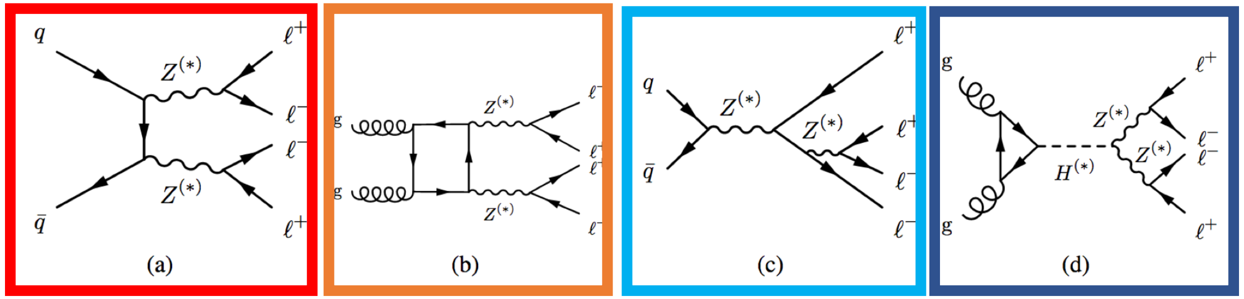
Type	exp.	obs.
a_L shape-only fit ($a_T = 1$)	–	–
a_T shape-only fit ($a_L = 1$)	$1.00 \pm 0.5(\text{stat.})^{+0.35}_{-0.39}(\text{syst.})$	$1.27^{+0.8}_{-0.4}(\text{stat.})^{+0.35}_{-0.27}(\text{syst.})$
a_L shape + rate fit ($a_T = 1$)	$1.00^{+0.08}_{-0.10}(\text{stat.})^{+0.08}_{-0.13}(\text{syst.})$	$0.90^{+0.10}_{-0.13}(\text{stat.})^{+0.09}_{-0.19}(\text{syst.})$
a_T shape + rate fit ($a_L = 1$)	$1.00^{+0.36}_{-0.49}(\text{stat.})^{+0.22}_{-0.32}(\text{syst.})$	$1.18^{+0.26}_{-0.31}(\text{stat.})^{+0.14}_{-0.16}(\text{syst.})$
a_L shape + rate fit (a_T profiled)	$1.00^{+0.08}_{-0.10}(\text{stat.})^{+0.08}_{-0.13}(\text{syst.})$	$0.91^{+0.10}_{-0.18}(\text{stat.})^{+0.09}_{-0.18}(\text{syst.})$
a_T shape + rate fit (a_L profiled)	$1.00^{+0.38}_{-0.5}(\text{stat.})^{+0.22}_{-0.43}(\text{syst.})$	$1.16 \pm 0.4(\text{stat.})^{+0.4}_{-0.3}(\text{syst.})$

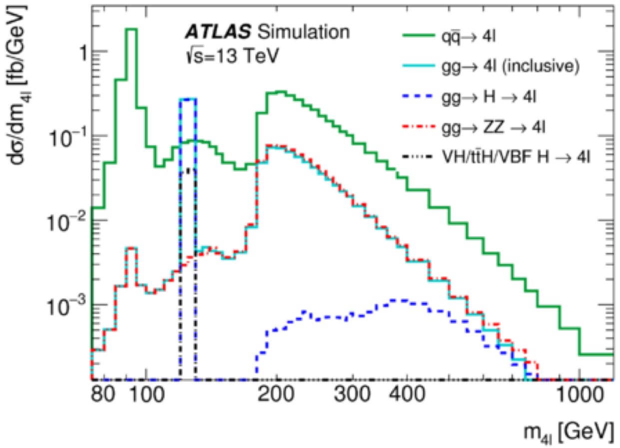
di-boson measurements

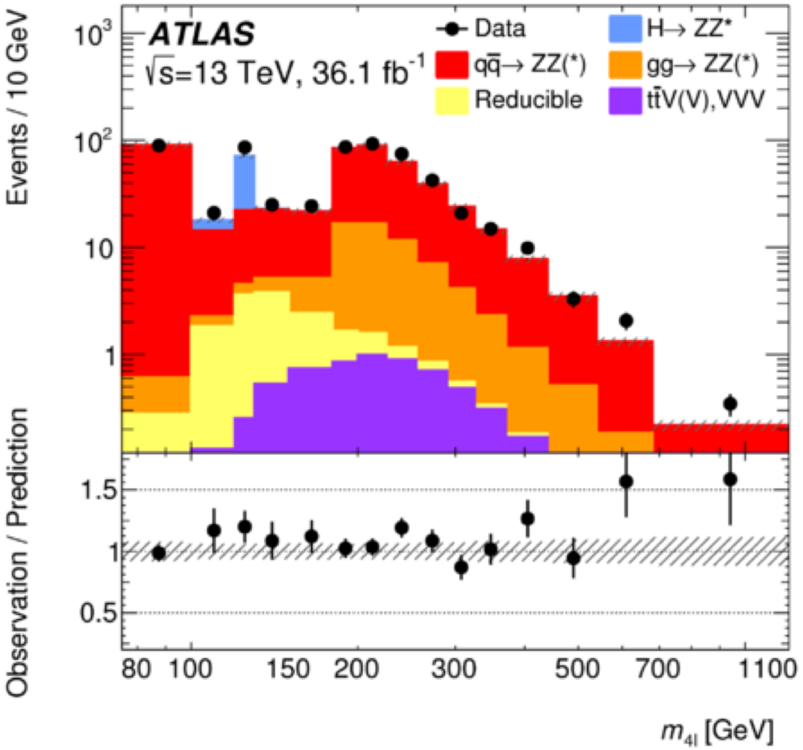
Measurement of the four-lepton invariant mass spectrum

- The integrated luminosity of 139 fb^{-1}
- Selected events contain two same-flavour opposite-sign lepton pairs.
- Measurements of differential cross-section in the invariant four-lepton mass m_{4l},
- Measurements of double-differential cross-sections with respect to both m_{4l} and the following kinematic variables:
  - the transverse momentum of the four-lepton system p_{4l},
  - the rapidity of the four-lepton system y_{4l},
  - and a matrix-element discriminant DME

Measurement of the four-lepton invariant mass spectrum







The final state has contributions from a number of processes that dominate in different four-lepton invariant mass regions.

measurement of Z→4l branching fraction

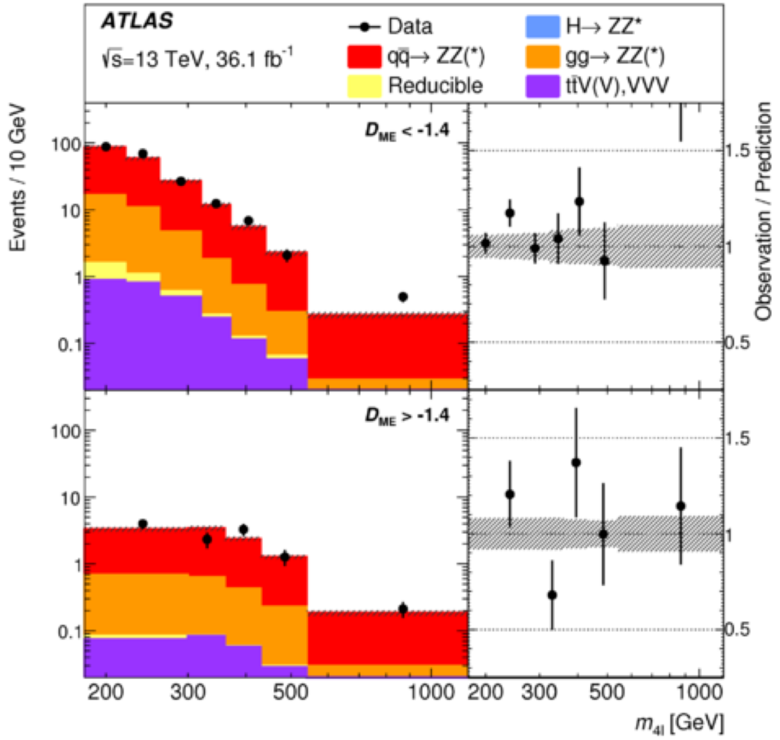
Extracted from the measured fiducial cross-section in the mass bin corresponding to m_Z

Measurement	$\mathcal{B}_{Z\to 4\ell}/10^{-6}$
ATLAS, $\sqrt{s}=7$ TeV and 8 TeV [8]	4.31±0.34(stat)±0.17(syst)
CMS, $\sqrt{s}=13$ TeV [6]	4.83 $^{+0.23}_{-0.22}$(stat) $^{+0.32}_{-0.29}$(syst)±0.08(theo)±0.12(lumi)
ATLAS, $\sqrt{s}=13$ TeV	**4.70 ± 0.32(stat) ± 0.21(syst) ± 0.14(lumi)**

Higgs boson measurements using 4 lepton invariant mass

- Constraint on off-shell Higgs boson signal strength

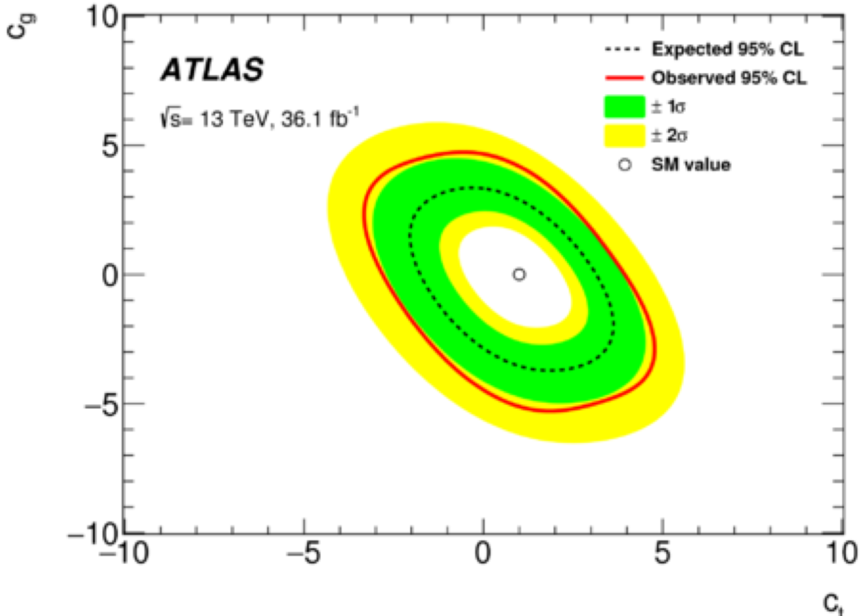
-> from double-differential cross-section measured as a function of m_{4l} and the matrix element discriminant D_{ME},



- Constraints to tree level Higgs couplings to top quarks (c_t) and to gluons (c_g)

-> from the measured differential cross-section as a function of m_{4l}.

On-shell rates for Higgs production via gluon–gluon fusion are only sensitive to $|ct+cg|^2$, but measurements at higher mass (>180GeV) can be used to probe these parameters independently



Constraints on EFT Wilson coefficients

operators affecting:

Higgs-gauge bosons couplings

gauge bosons couplings

Z→ll vertex

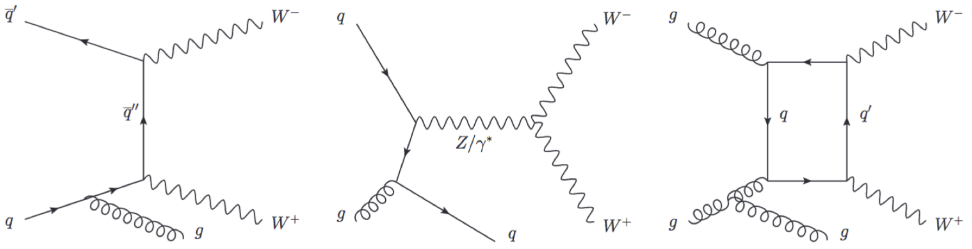
four-fermion contact terms

Only linear term included in the fit (non-linear variant included in the paper as well)

Coefficient	Observable	95% CL Expected [TeV^{-2}]	95% CL Observed [TeV^{-2}]
c_{HG}	m_{34} vs $m_{4\ell}$	$[-0.011, 0.013]$	$[-0.0090, 0.014]$
$\tilde{c}_{HG}$	m_{34} vs $m_{4\ell}$	–	–
c_{HD}	m_{34} vs $m_{4\ell}$	$[-0.46, 0.44]$	$[-0.63, 0.28]$
c_{HWB}	m_{34} vs $m_{4\ell}$	$[-0.21, 0.20]$	$[-0.29, 0.13]$
c_{Hd}	$p_{T,12}$ vs $m_{4\ell}$	$[-10, 10]$	$[-3.0, 18]$
c_{Hu}	$\lvert\Delta\phi_{\ell\ell}\rvert$ vs $m_{4\ell}$	$[-3.5, 3.7]$	$[-1.6, 6.2]$
c_{He}	$\lvert\Delta\phi_{\text{pairs}}\rvert$ vs $m_{4\ell}$	$[-0.48, 0.46]$	$[-0.76, 0.21]$
$c_{Hl}^{(1)}$	$\lvert\Delta\phi_{\text{pairs}}\rvert$ vs $m_{4\ell}$	$[-0.37, 0.38]$	$[-0.19, 0.57]$
$c_{Hl}^{(3)}$	$\lvert\Delta\phi_{\ell\ell}\rvert$ vs $m_{4\ell}$	$[-0.29, 0.28]$	$[-0.51, 0.12]$
$c_{Hq}^{(1)}$	m_{34} vs $m_{4\ell}$	$[-0.81, 0.78]$	$[-1.1, 0.46]$
$c_{Hq}^{(3)}$	$\lvert\Delta\phi_{\text{pairs}}\rvert$ vs $m_{4\ell}$	$[-0.34, 0.33]$	$[-0.15, 0.54]$
c_{ed}	m_{34} vs $m_{4\ell}$	$[-1.3, 1.8]$	$[-0.98, 2.3]$
c_{ee}	m_{34} vs $m_{4\ell}$	$[-58, 64]$	$[-27, 100]$
c_{eu}	$m_{4\ell}$	$[-0.61, 0.45]$	$[-0.36, 0.64]$
c_{ld}	m_{34} vs $m_{4\ell}$	$[-1.8, 2.5]$	$[-1.4, 3.0]$
c_{le}	m_{34} vs $m_{4\ell}$	$[-63, 68]$	$[-18, 130]$
c_{ll}	m_{34} vs $m_{4\ell}$	$[-39, 43]$	$[-17, 71]$
$c_{ll}^{(1)}$	$\lvert\Delta\phi_{\text{pairs}}\rvert$ vs $m_{4\ell}$	$[-0.33, 0.34]$	$[-0.17, 0.51]$
$c_{lq}^{(1)}$	$m_{4\ell}$	$[-0.77, 0.40]$	$[-4.1, 0.55]$
$c_{lq}^{(3)}$	m_{34} vs $m_{4\ell}$	$[-0.061, 0.083]$	$[-0.051, 0.098]$
c_{lu}	$m_{4\ell}$	$[-1.4, 0.98]$	$[-0.77, 1.4]$
c_{qe}	$m_{4\ell}$	$[-1.1, 0.84]$	$[-0.67, 1.2]$

Arxiv:2103.10319

WW+jets

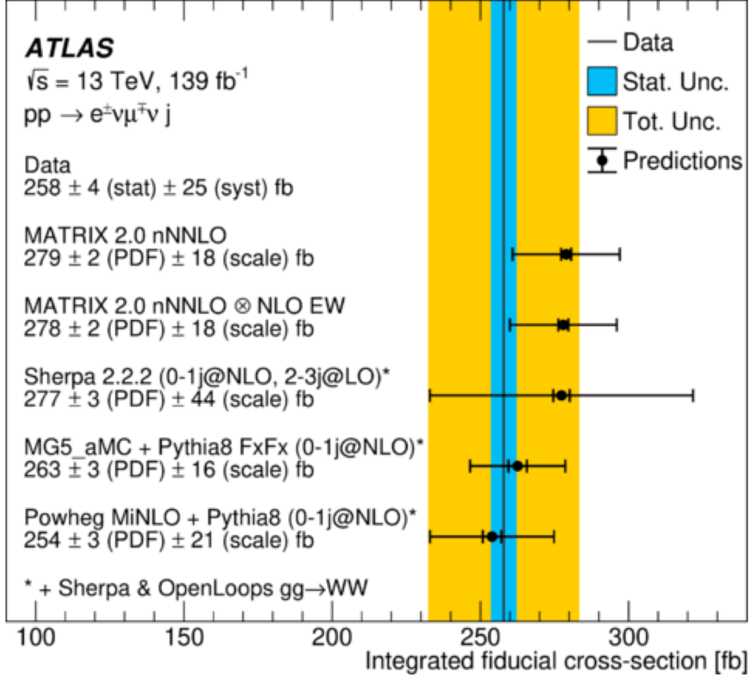


WW+j production

Fiducial selection requirements		
p_{T}^{ℓ}	>	27 GeV
$\|\eta^{\ell}\|$	<	2.5
$m_{e\mu}$	>	85 GeV
p_{T}^{j}	>	30 GeV
$\|y^{j}\|$	<	4.5

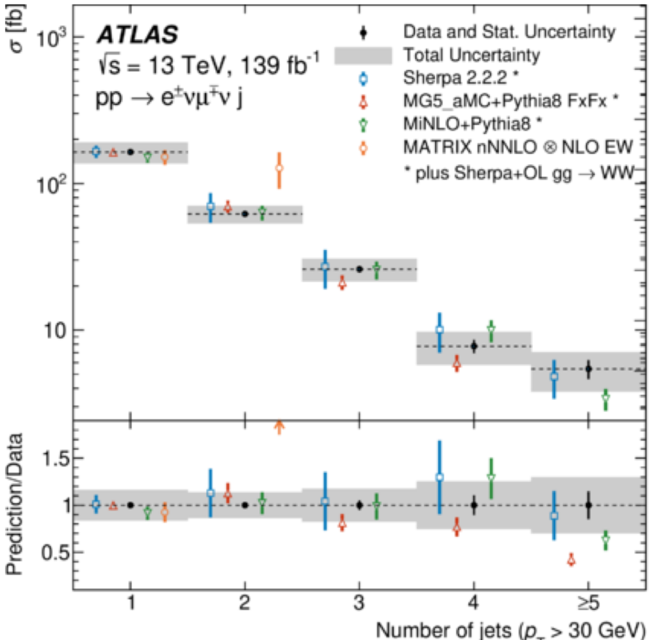
- The WW+jets cross-section is evaluated in the fiducial phase space of the WW→$e\nu\mu\nu$ decay channel
- at least one jet required in the event selection
- Background estimation:
  - Top quark: ttbar from CR, Wt from simulation
  - Drell-Yan from MC (validation region)
  - Fake-lepton backgrounds estimated using a data-driven technique
  - Backgrounds from WZ, ZZ, $W\gamma$ and $Z\gamma$ from simulation
  - triboson background neglected

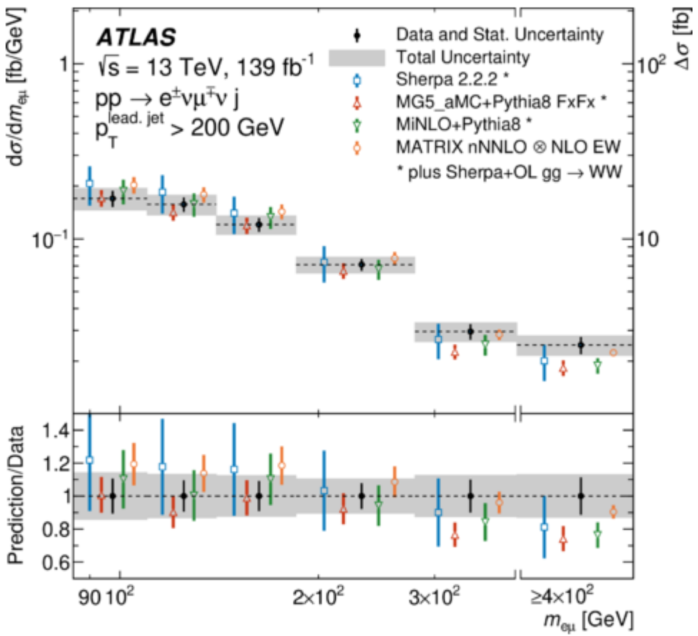
WW+jets



- The differential cross-sections are determined using an iterative Bayesian unfolding method and compared to numerous theory predictions

- Fiducial cross-section and differential cross-section with respect to several kinematical variables related to leptons and jets are measured





WW+ jets

- Limits set on anomalous triple gauge couplings

- Limits set on a single EFT parameter c_W

- Interference between the Standard Model amplitude and the anomalous amplitude enhanced by kinematical selection (p_T^j> 200 GeV)

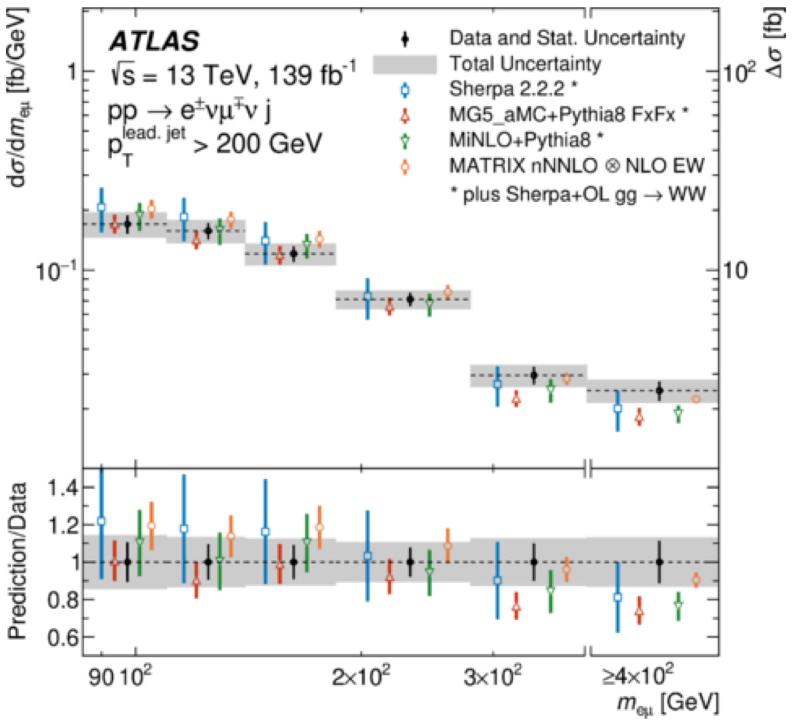


Table 8: Observed and expected confidence intervals (CI) for c_W for a linearized and a quadratic EFT fit of $m_{e\mu}$, when requiring either jet p_T > 30 GeV or jet p_T > 200 GeV. The new-physics scale Λ is set to 1 TeV.

Jet p_T	Linear only	68% CI obs.	95% CI obs.	68% CI exp.	95% CI exp.
> 30 GeV	yes	[–1.64, 2.86]	[–3.85, 4.97]	[–2.30, 2.27]	[–4.53, 4.41]
> 30 GeV	no	[–0.20, 0.20]	[–0.33, 0.33]	[–0.28, 0.27]	[–0.39, 0.38]
> 200 GeV	yes	[–0.29, 1.84]	[–1.37, 2.81]	[–1.12, 1.09]	[–2.24, 2.10]
> 200 GeV	no	[–0.43, 0.46]	[–0.60, 0.58]	[–0.38, 0.33]	[–0.53, 0.48]

Conclusions

- New di-boson measurements at the LHC crucial to fully explore the SM SU(2)xU(1) symmetry structure and EW symmetry breaking
- From first observations of rare EW processes to precision measurements
- Numerous constraints on New Physics using the SMEFT framework
- Interplay between SM and Higgs measurements are starting to be explored
- Most measurements statistically limited so improvements are expected at Run3
- Extensive work, challenges and opportunities ahead to collect quality data and produce quality physics

Backup

rapidity and pseudorapidity

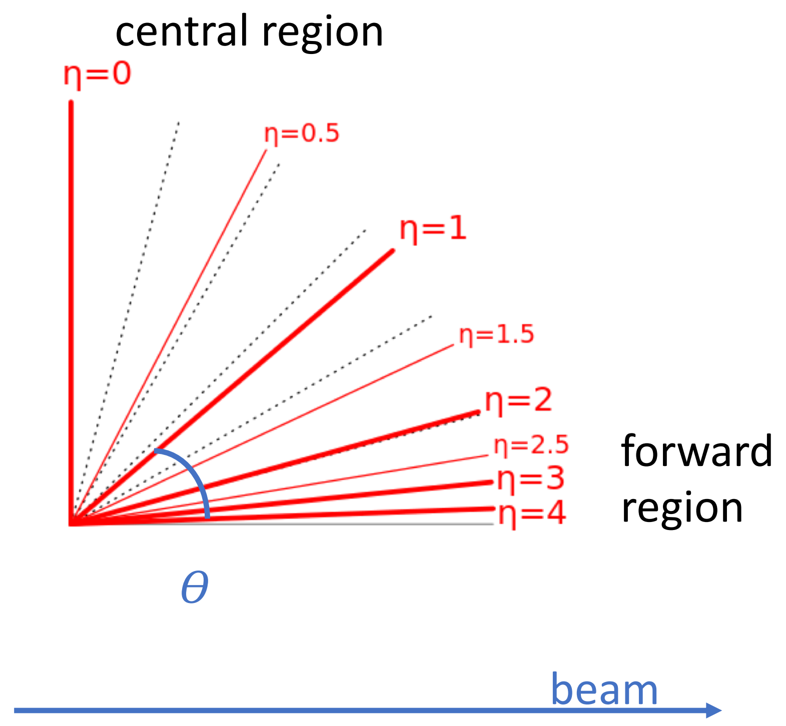
rapidity

$$y = \frac{1}{2} \ln \frac{E + p_z c}{E - p_z c},$$

pseudorapidity

$$\eta \equiv -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

$$\eta = \frac{1}{2} \ln\left(\frac{|\mathbf{p}| + p_\mathrm{L}}{|\mathbf{p}| - p_\mathrm{L}}\right)$$



In the limit m→ 0 η→ y