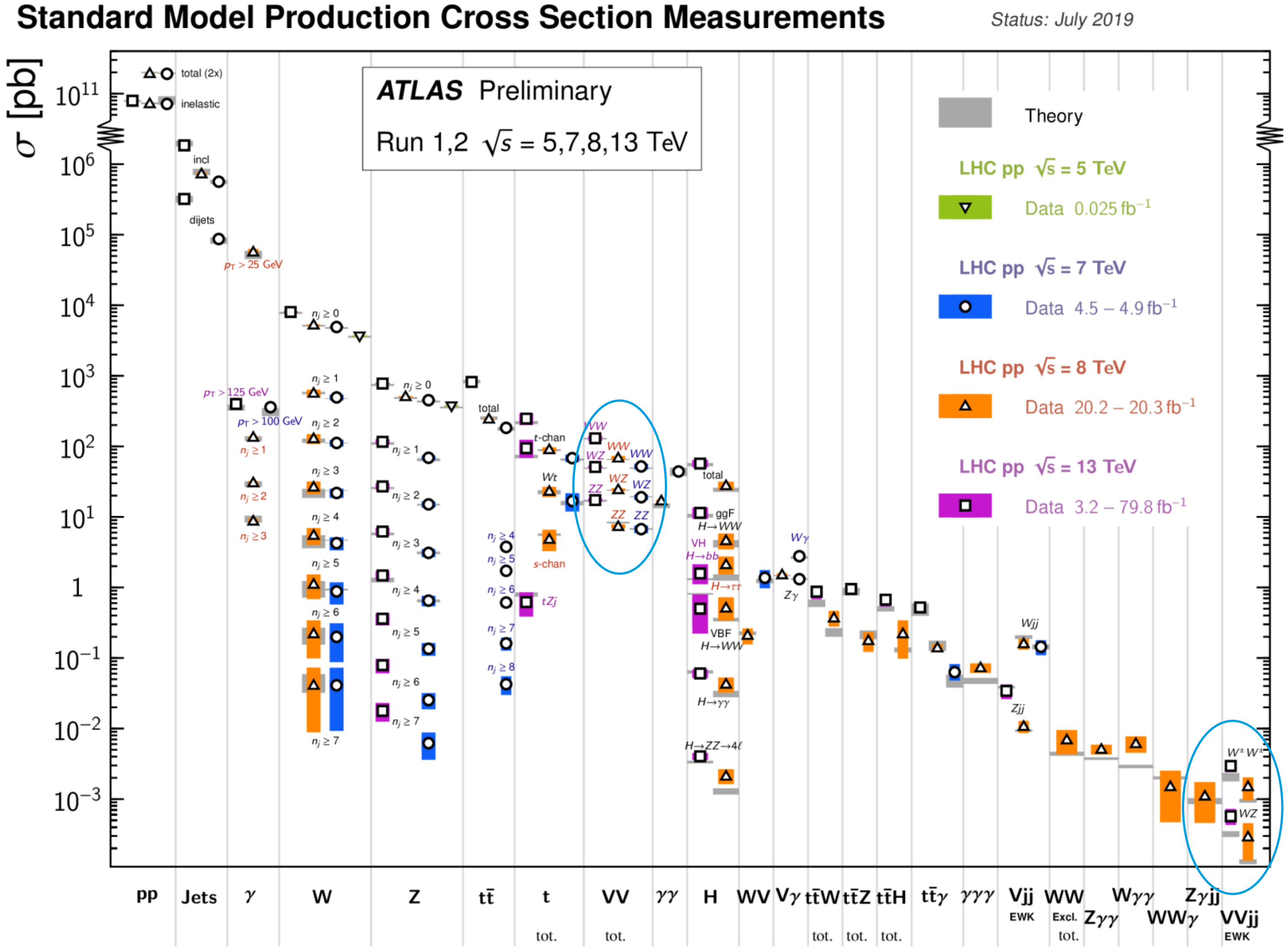
Precision measurements of diboson differential and total cross sections from ATLAS

Valerie Lang
On behalf of the ATLAS Collaboration
Multi-Boson Interactions Workshop, Thessaloniki, Greece
26 August 2019

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

What do we know?

The Standard Model of particle physics



- Diboson processes
  - Beautiful probes of the electroweak gauge structure in the SM
  - Stringent test for physics beyond the SM
- Two fronteers
  - Precision
  - Cross section

→ Explore both → Push towards smaller values

Dibosons in ATLAS

An inventory

- Inclusive diboson production and vector boson scattering (VBS)
  - Listing the most recent measurements in each channel at 13 TeV

Precision fronteer	Cross section fronteer
WW 13 TeV, 36.1 fb^{-1}	WWjj 13 TeV, 36.1 fb^{-1}
WZ 13 TeV, 36.1 fb^{-1}	WZjj 13 TeV, 36.1 fb^{-1}
ZZ (4l) 13 TeV, 36.1 fb^{-1} (2l2v) 13 TeV, 36.1 fb^{-1}	**ZZjj (4l/2l2v) 13 TeV, 139 fb^{-1}**
	VVjj 13 TeV, 36.1 fb^{-1}
Zγ **(llγ) 13 TeV, 139 fb^{-1}** (vvγ) 13 TeV, 36.1fb-1	Zγjj 13 TeV, 36.1 fb^{-1}

More details on
- EWK diboson production with aQGC by A. Levin on Tuesday
- Semileptonic decay modes of diboson production by R. Aggleton on Tuesday
- Diboson production involving photons by N. Lorenzo Martinez on Wednesday

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	VVjj 13 TeV, 36.1 fb^{-1}
Zγ (llγ) 13 TeV, 139 fb^{-1} (vvγ) 13 TeV, 36.1fb-1	Zγjj 13 TeV, 36.1 fb^{-1}

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→ Focus on new WW and ZZ measurements, both inclusive and VBS

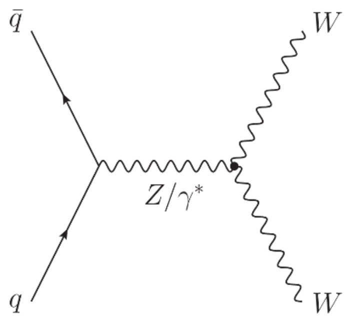
Inclusive diboson production

Measurement of WW production

arXiv:1905.04242

Triple gauge coupling in the SM

- WW production includes WWZ/γ* coupling



- Measure in the $WW \rightarrow e\nu\mu\nu$ decay channel
  - Opposite sign leptons!
  - Fiducial definition excludes presence of jets

Fiducial selection requirements		
p_{T}^{ℓ}	>	27 GeV
$\|\eta^{\ell}\|$	<	2.5
$m_{e\mu}$	>	55 GeV
$p_{\mathrm{T}}^{e\mu}$	>	30 GeV
$E_{\mathrm{T}}^{\mathrm{miss}}$	>	20 GeV
No jets with p_{T}	>	35 GeV, $\|\eta\| < 4.5$

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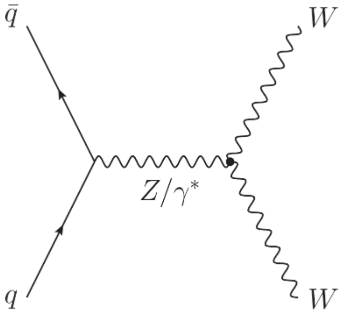

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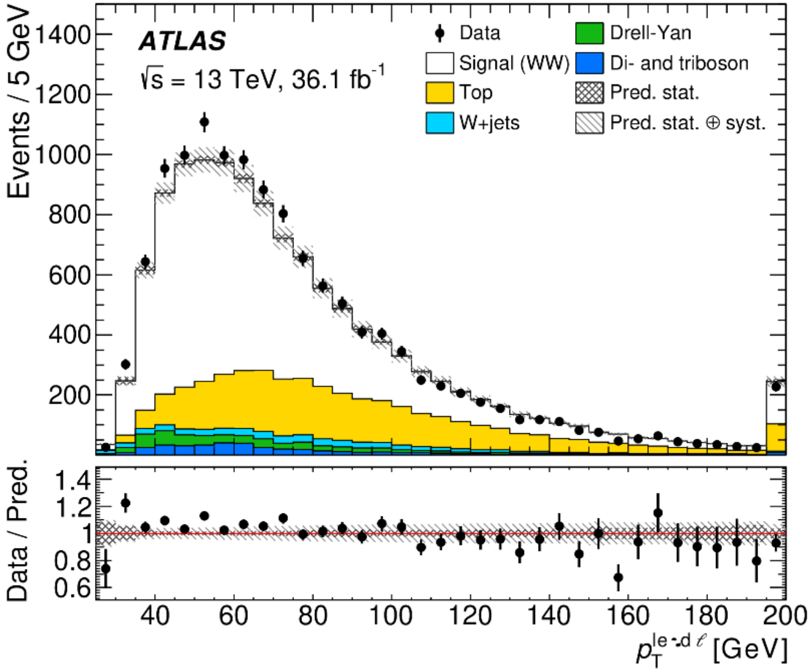
- Jet veto needed for background suppression
  - Top-quark production includes real W bosons → in general, more jets than direct WW production



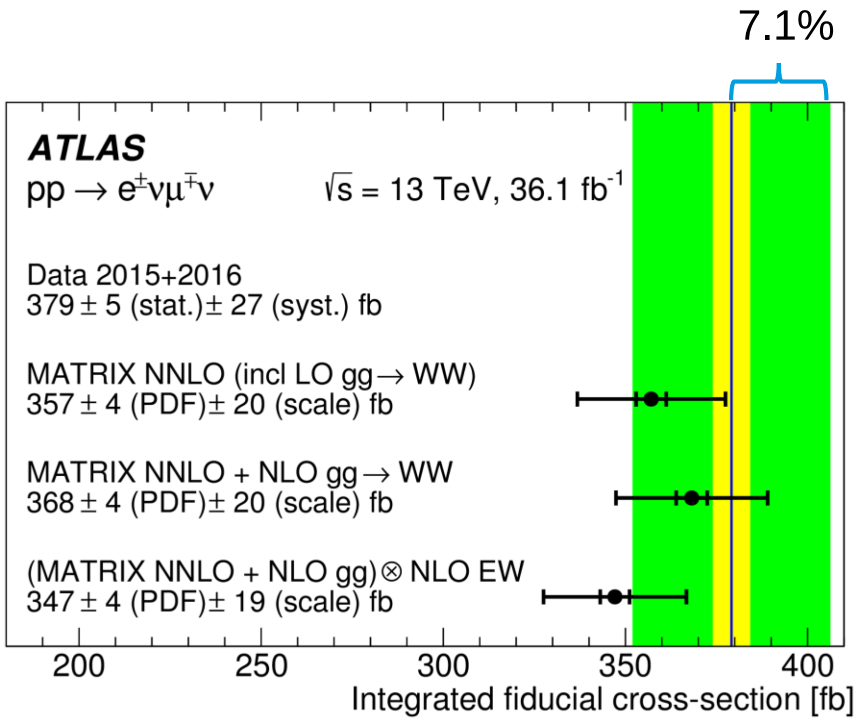
  - After jet-veto and b-jet veto: top-quark production still largest contribution: ~26% → Partially data-driven estimate for reduced uncertainties

Fiducial and differential cross sections

arXiv:1905.04242

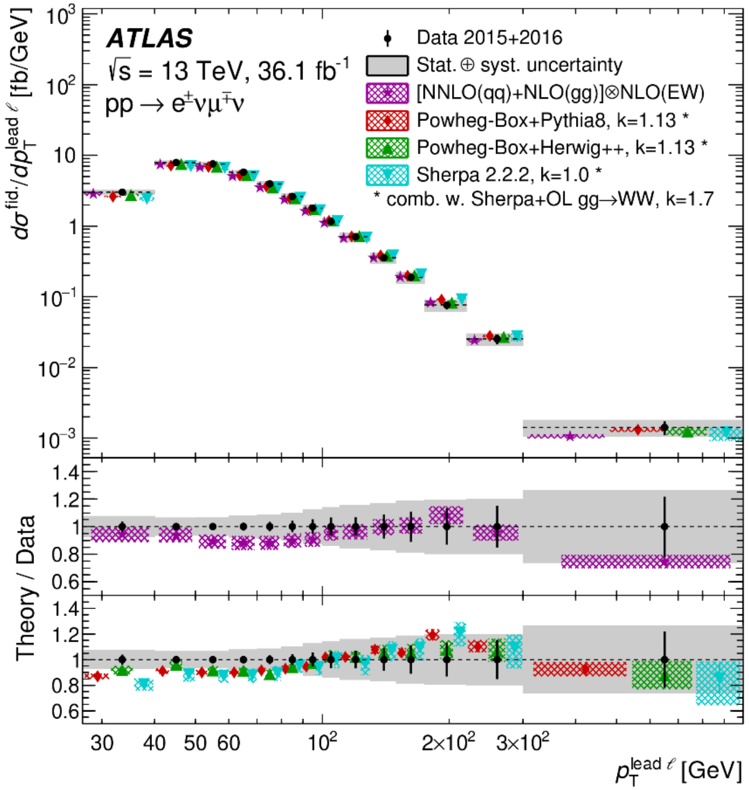
WW in action

- Integrated cross section vs. NNLO prediction
  - Most precise WW measurement at the LHC so far



  - In agreement, but at lower uncertainty boundary

- Six kinematic distributions measured



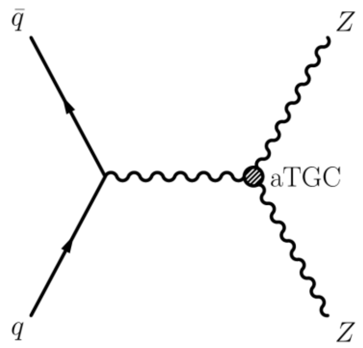
  - No strong deviation from SM observed
  - Leading lepton p_T used to set limits on anomalous triple gauge couplings (aTGC)

Measurement of ZZ production

arXiv:1905.07163

No triple gauge coupling in the SM

- ZZ production through TGC forbidden at tree level
  - Through correction with fermion loop: $O(10^{-4})$



- Measure in $ZZ \rightarrow ll\nu\nu$ channel
  - Need better signal-to-background suppression than $ZZ \rightarrow llll$ → Move to high p_T, boosted configuration
  - Selected requirements on the ZZ system

Boosted Z boson back-to-back with E_T^{miss}
$E_T^{miss} > 90$ GeV
$V_T/S_T > 0.65$

V_T: magnitude of vector sum
S_T: scalar sum
} of selected leptons and jets

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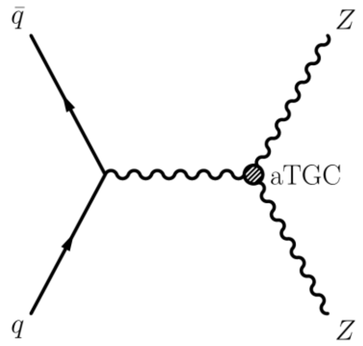

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Boosted Z boson back-to-back with E_T^{miss}
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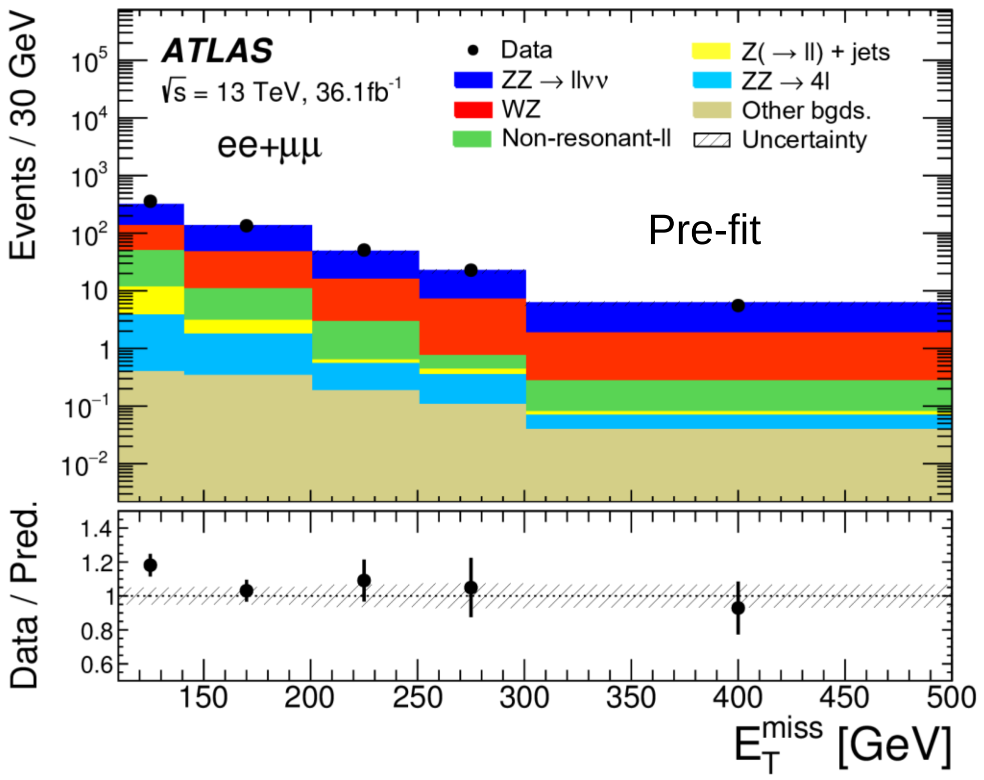
- Extract total & fiducial cross sections
  - Binned maximum likelihood fit of E_T^{miss} distribution



  - In fit, ee and μμ channel treated separately

Total, fiducial and differential cross sections

arXiv:1905.07163

ZZ in action

- Integrated cross sections
  - Uncertainty in the combined fiducial cross section

Total	Data stat.	Total syst.
7.0%	5.5%	4.3%

  - Measurement precision: 7.0%!
  - Big contribution from data statistics
    → Gain with full run 2!
- Compared to NNLO QCD+NLO EW predictions

		Measured	Predicted
$\sigma^{\text{fid}}_{ZZ\to\ell\ell\nu\nu}$ [fb]	ee	12.2 ± 1.0 (stat) ± 0.5 (syst) ± 0.3 (lumi)	11.2 ± 0.6
	$\mu\mu$	13.3 ± 1.0 (stat) ± 0.5 (syst) ± 0.3 (lumi)	11.2 ± 0.6
	$ee+\mu\mu$	25.4 ± 1.4 (stat) ± 0.9 (syst) ± 0.5 (lumi)	22.4 ± 1.3
σ^{tot}_{ZZ} [pb]	Total	17.8 ± 1.0 (stat) ± 0.7 (syst) ± 0.4 (lumi)	15.7 ± 0.7

  - In agreement, but again prediction slightly lower

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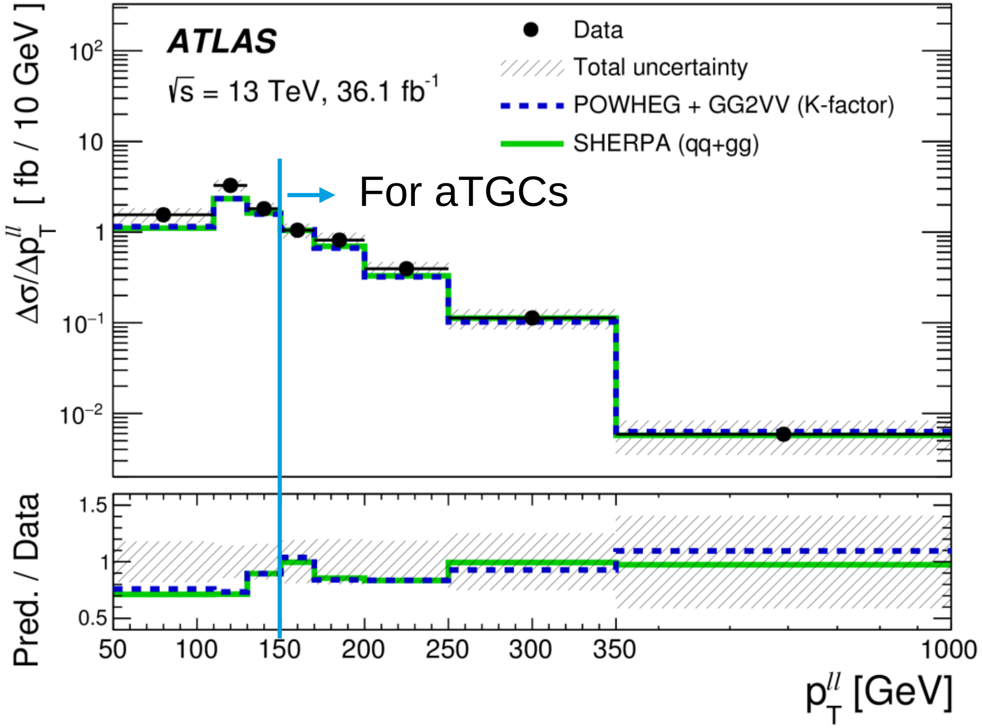
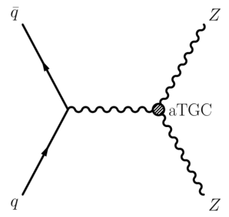
- Eight differential cross sections measured
  - Obtained from iterative Bayesian unfolding procedure
    → Similar to what is used in WW



  - No strong deviation from SM observed
  - Dilepton system p_T^{ll} used to set limits on aTCGs

Limits on aTGCs

Effective field theory and effective vertex function approach



- WW → Limits on Wilson coefficients of operators
  - c_B/Λ^2, c_{WWW}/Λ^2, c_W/Λ^2 (CP-even)
  - $c_{\widetilde{W}WW}/\Lambda^2$, $c_{\widetilde{W}}/\Lambda^2$ (CP-odd)
- ZZ → Limits on coupling parameters
  - f_4^γ, f_4^Z (CP-violating)
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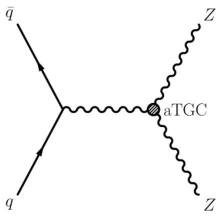

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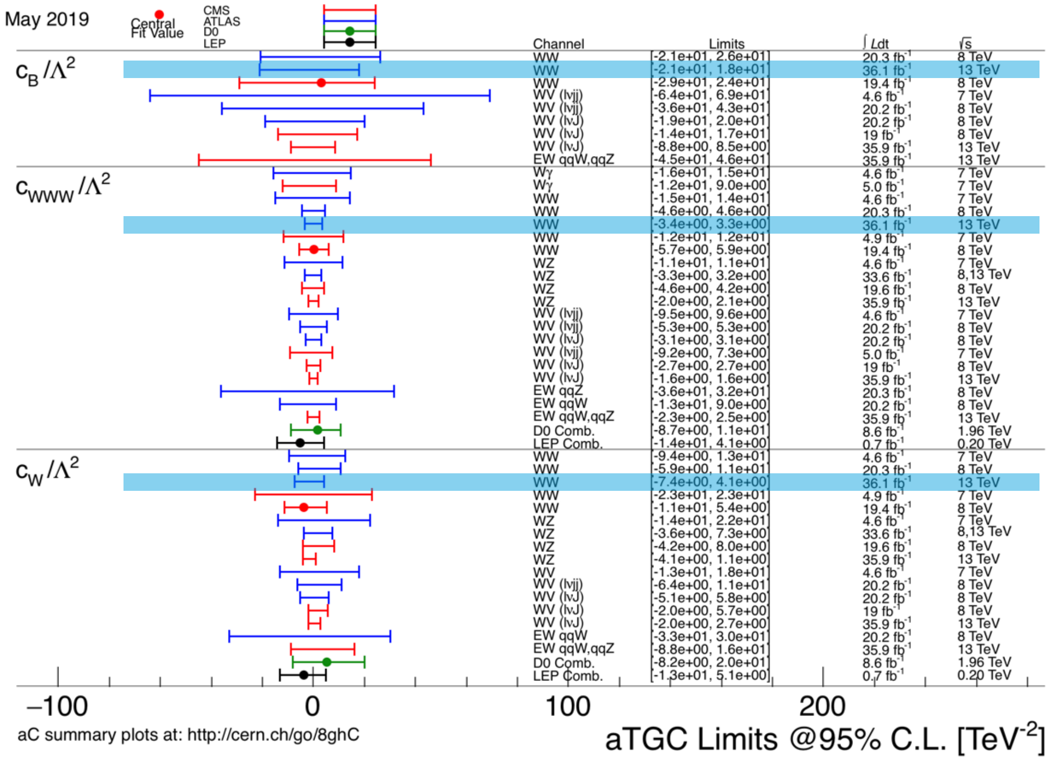

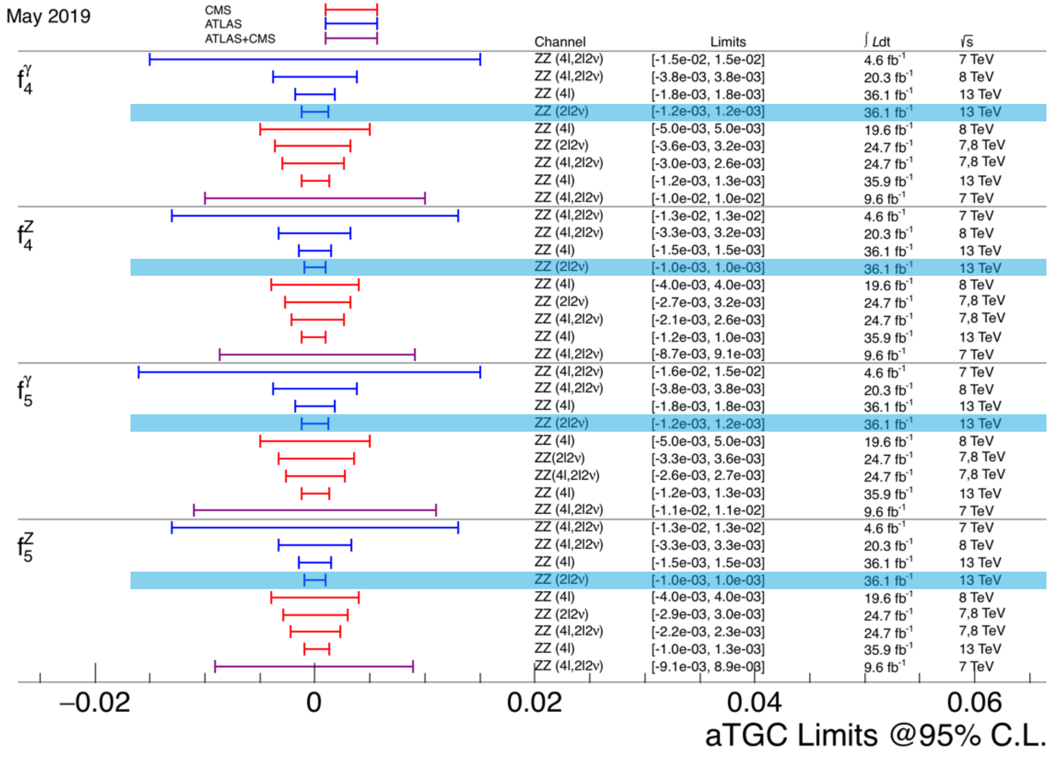

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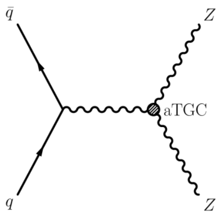

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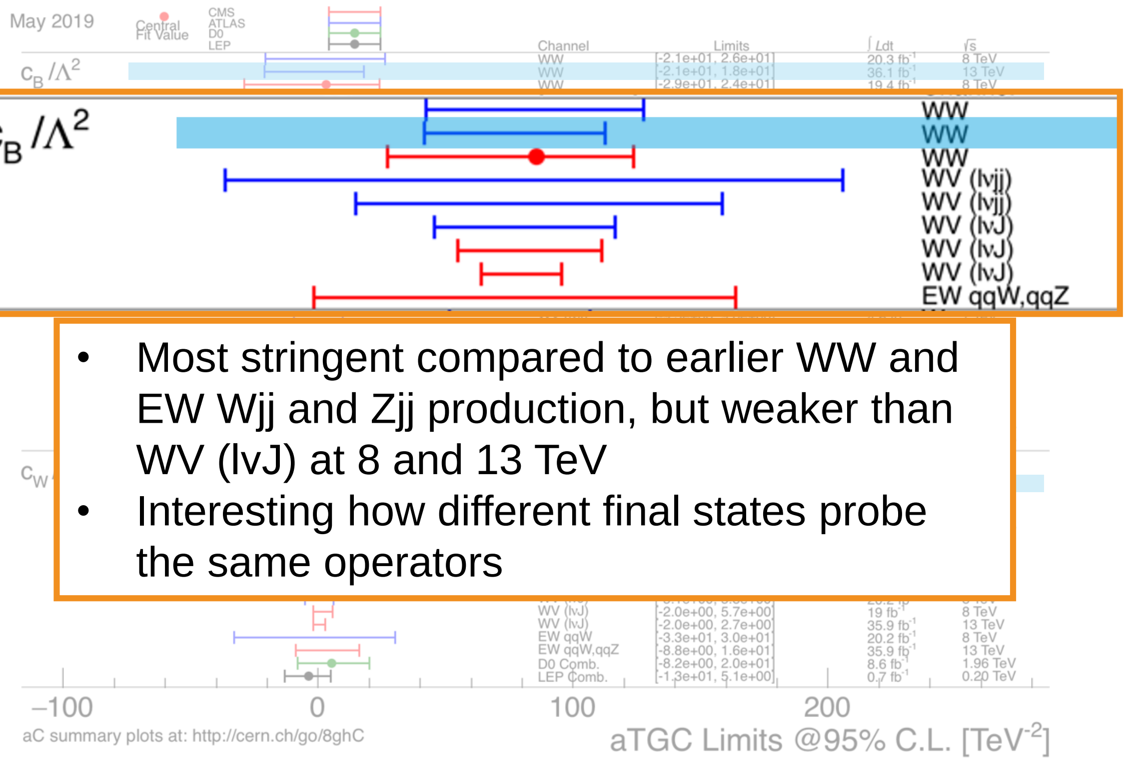
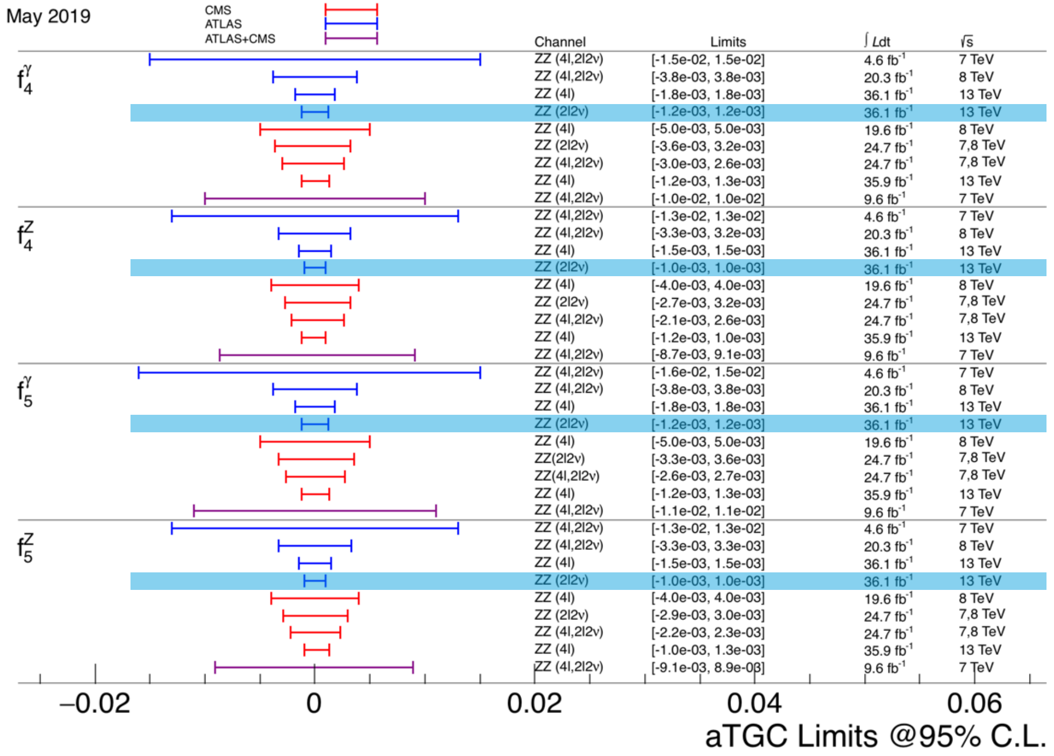


- Most stringent compared to earlier WW and EW Wjj and Zjj production, but weaker than WV (lvJ) at 8 and 13 TeV
- Interesting how different final states probe the same operators



Channel	Limits	∫Ldt	√s
ZZ (4l,2l2ν)	[-1.5e-02, 1.5e-02]	4.6 fb^{-1}	7 TeV
ZZ (4l,2l2ν)	[-3.8e-03, 3.8e-03]	20.3 fb^{-1}	8 TeV
ZZ (4l)	[-1.8e-03, 1.8e-03]	36.1 fb^{-1}	13 TeV
ZZ (2l2ν)	[-1.2e-03, 1.2e-03]	36.1 fb^{-1}	13 TeV
ZZ (4l)	[-5.0e-03, 5.0e-03]	19.6 fb^{-1}	8 TeV
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ZZ (4l)	[-1.2e-03, 1.3e-03]	35.9 fb^{-1}	13 TeV
ZZ (4l,2l2ν)	[-1.0e-02, 1.0e-02]	9.6 fb^{-1}	7 TeV
ZZ (4l,2l2ν)	[-1.3e-02, 1.3e-02]	4.6 fb^{-1}	7 TeV
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ZZ (4l)	[-1.2e-03, 1.0e-03]	35.9 fb^{-1}	13 TeV
ZZ (4l,2l2ν)	[-8.7e-03, 9.1e-03]	9.6 fb^{-1}	7 TeV
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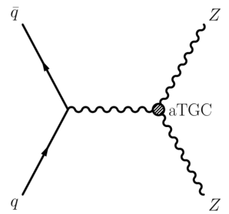

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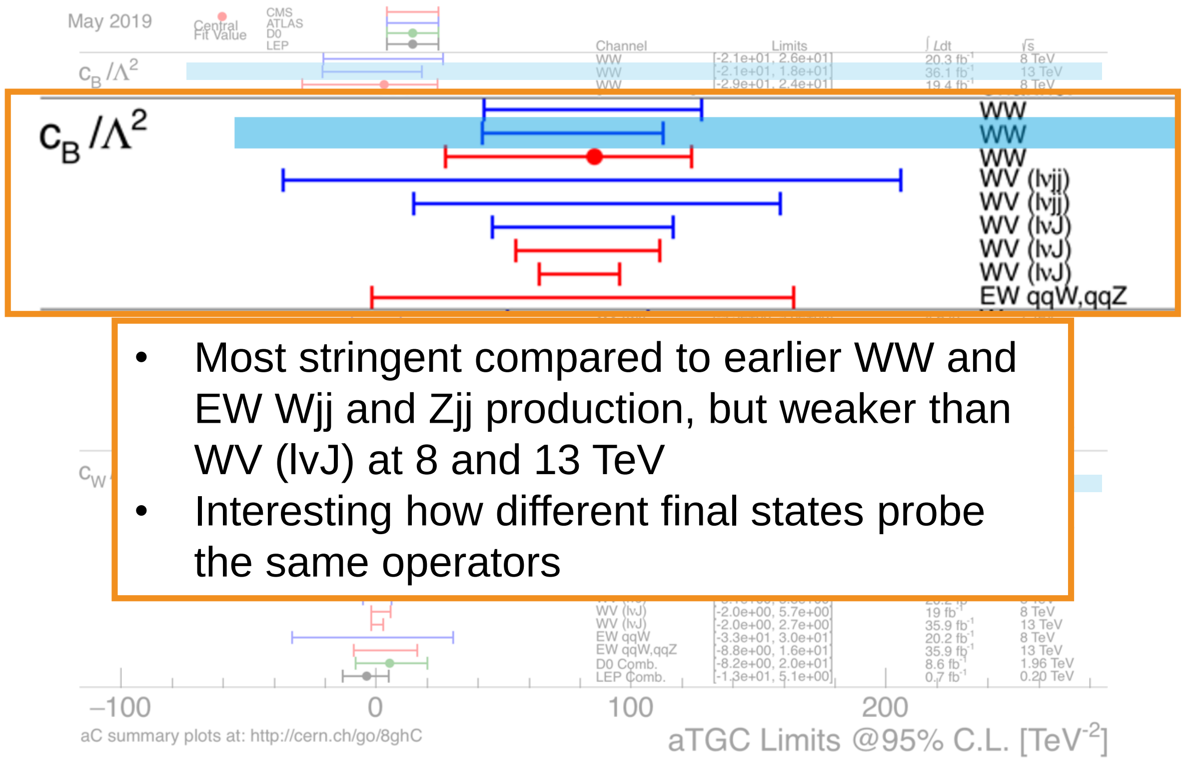

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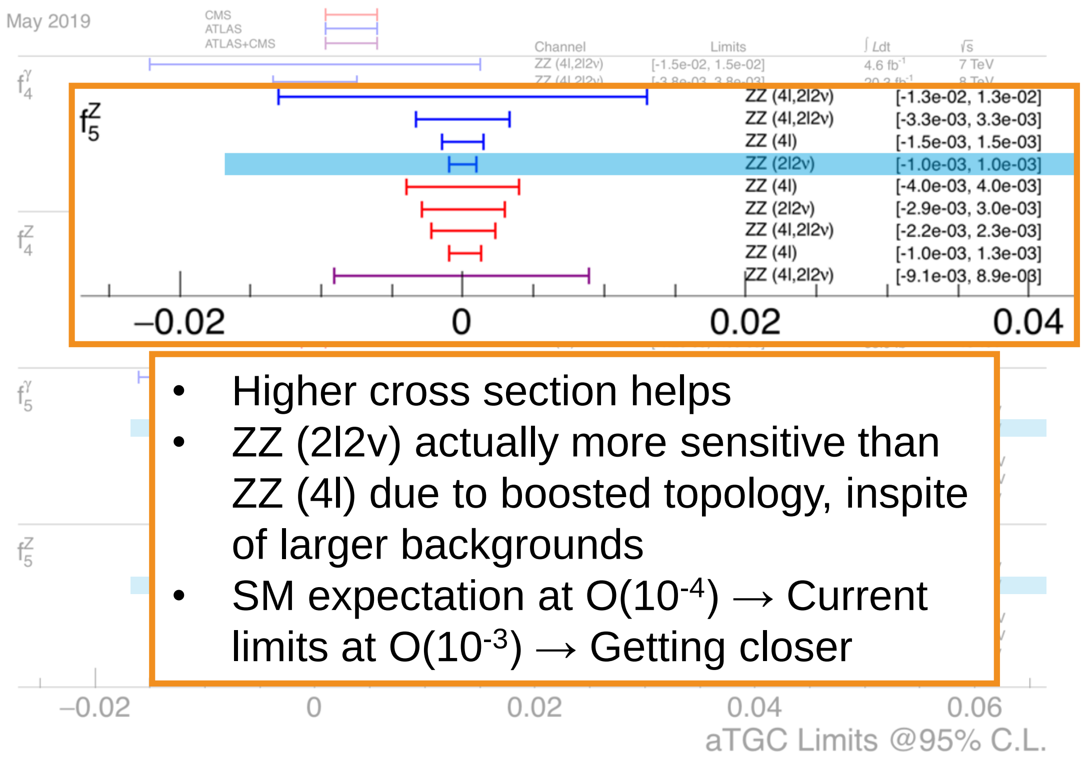


- Higher cross section helps
- ZZ (2l2v) actually more sensitive than ZZ (4l) due to boosted topology, inspite of larger backgrounds
- SM expectation at O(10^{-4}) → Current limits at O(10^{-3}) → Getting closer

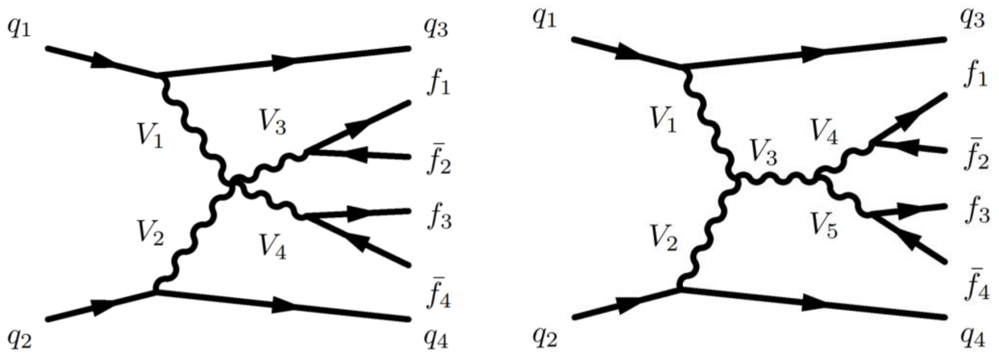
Vector boson scattering

Measurement of WWjj production

arXiv:1906.03203

Vector boson scattering (VBS) of same-sign W bosons

- VBS with quartic gauge coupling (QGC)
  - Electroweak production $O(\alpha_{QED}^6)$ about 5 times larger than strong production $O(\alpha_{QED}^4\ \alpha_S^2)$! → Best ratio



- Measure in 6 decay channels $e^{\pm}e^{\pm}$, $e^{\pm}\mu^{\pm}$, $\mu^{\pm}\mu^{\pm}$
  - Selected requirements for the fiducial region

2-jet system
p_T > 65 (35) GeV for leading (subleading) jet
m_{jj} > 500 GeV
$\lvert\Delta y_{jj}\rvert$ > 2

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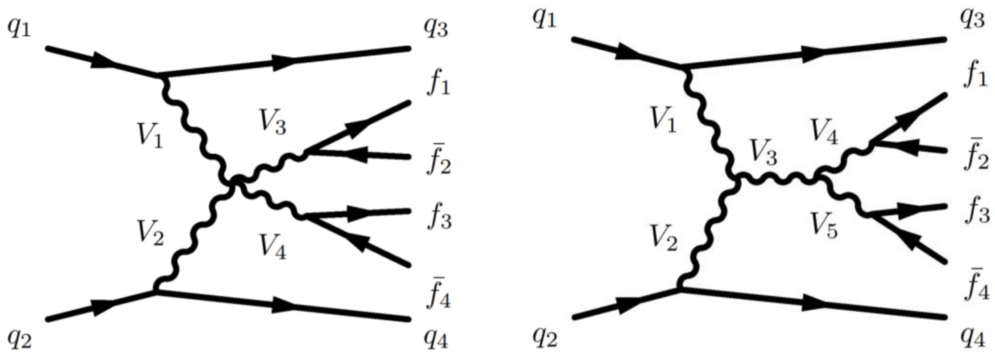

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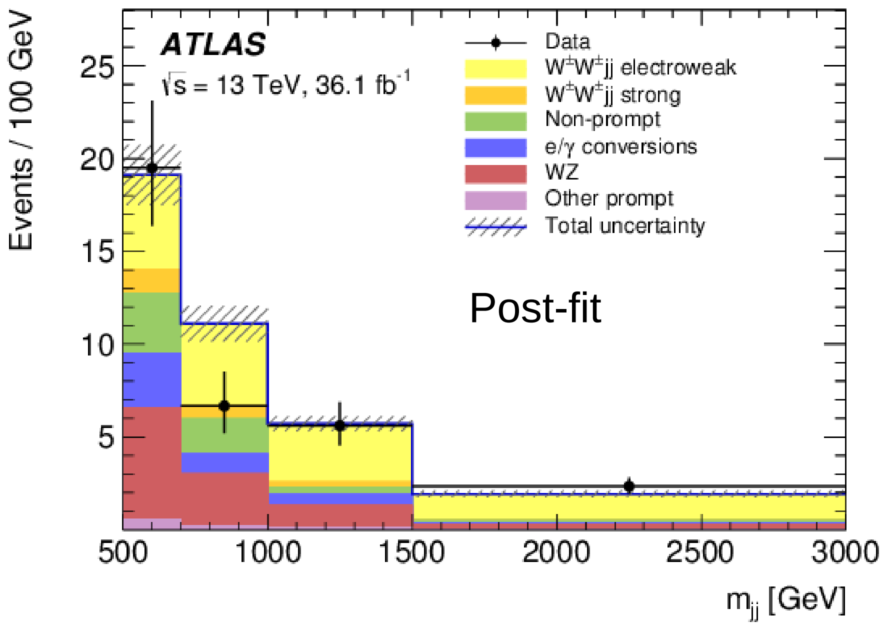
p_T > 65 (35) GeV for leading (subleading) jet
m_{jj} > 500 GeV
$\lvert\Delta y_{jj}\rvert$ > 2

- Determine signal strength $\mu_{EW\ ssWW}$
  - Fit to m_{jj} distribution → 6 signal region (SR) channels + 1 low m_{jj} control region (CR) per channel + 1 WZ CR



  - Main background: WZ → Normalization simultaneously constrained in the fit
  - $\mu_{EW\ ssWW} = 1.44^{+0.26}_{-0.24}\ (\text{stat.})\ ^{+0.28}_{-0.22}\ (\text{syst.})$ w.r.t. Sherpa

Observation of WWjj production

arXiv:1906.03203

It is there!

- Event yields in the signal region
  - For the 6 channels combined

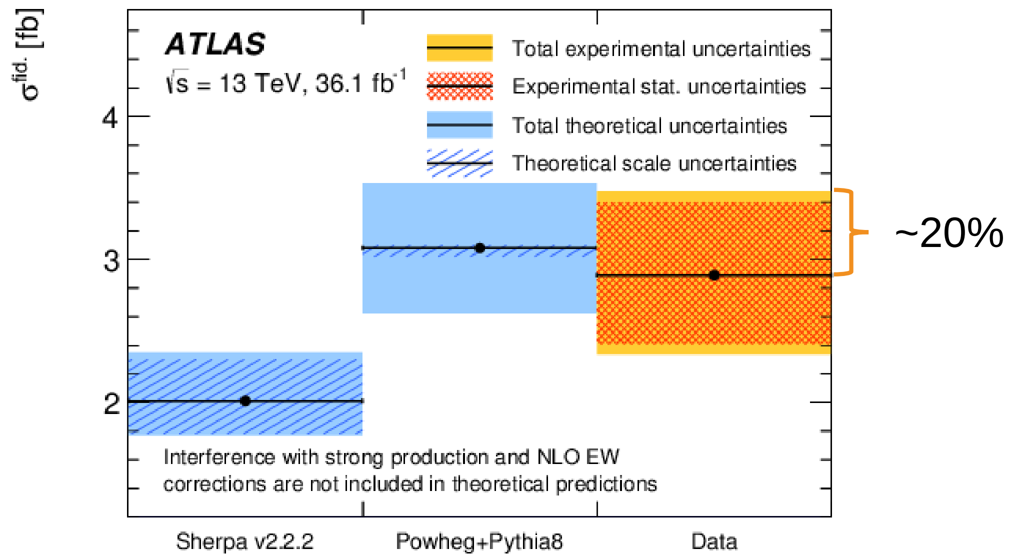
Post-fit

	Combined
WZ	30 ± 4
Non-prompt	15 ± 5
e/γ conversions	13.9 ± 2.9
Other prompt	2.4 ± 0.5
$W^{\pm}W^{\pm}jj$ strong	7.2 ± 2.3
Expected background	69 ± 7
$W^{\pm}W^{\pm}jj$ electroweak	60 ± 11
Data	122

  - EWK WW production observed with 6.5σ significance!
    → Expected 4.4σ/6.5σ for Sherpa/Powheg-Box

- Fiducial cross section $\sigma^{fid.} = \mu_{EW\ ssWW} \cdot \sigma^{fid.}_{pred}$
  - Includes the interference with WWjj strong production

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



  - Data agrees well with Powheg+Pythia8 (NLO QCD), less well with Sherpa (LO-multileg QCD)[1]
  - Interference not included in predictions

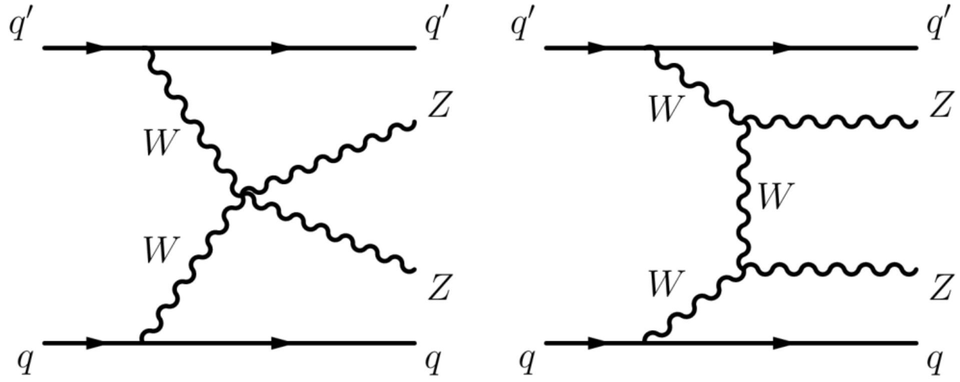
1) An issue in the Sherpa 2.2.2 color flow handling reduced the cross section artificially. This is fixed in Sherpa 3.0.0, leading to an increase of ~20% in the cross section. [1]

Measurement of ZZjj production

ATLAS-CONF-2019-033

With a little help from a boosted decision tree (BDT)

- VBS with other outcome: ZZ
  - Very rare! → O(0.1) fb with full leptonic final state



- Measurement in final states with ZZ→4l/2l2v
  - Defining characteristics

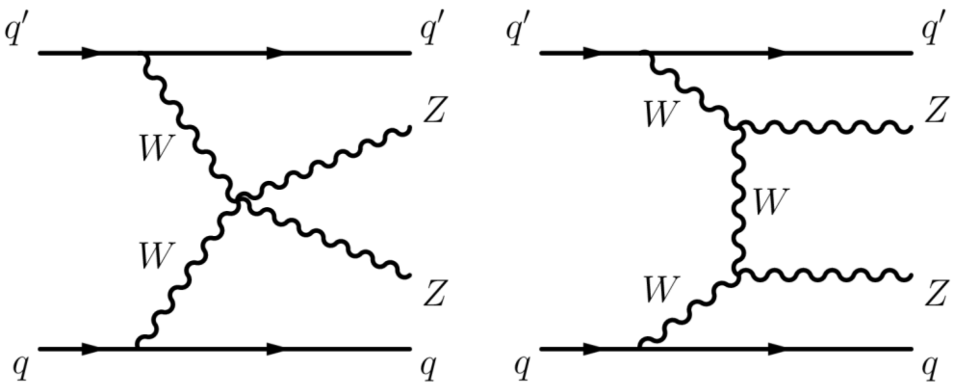
Leptons pairs and the 2-jet system
Opposite sign, same flavor (OSSF) lepton pairs consistent with Z boson(s)
2 most energetic jets in opposite rapidity regions
m_{jj} > 300 (400) GeV for llllјj (llvvjj) & $\|\Delta y_{jj}\|$ > 2

Measurement of ZZjj production

ATLAS-CONF-2019-033

With a little help from a boosted decision tree (BDT)

- VBS with other outcome: ZZ
  - Very rare! → O(0.1) fb with full leptonic final state



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2 most energetic jets in opposite rapidity regions
m_{jj} > 300 (400) GeV for llllјј (llvvjj) & $\lvert\Delta y_{jj}\rvert$ > 2

- Selected events in data

~97% purity (ℓℓℓℓjj) ~42% purity (ℓℓνν jj)

Process	$\ell\ell\ell\ell jj$	$\ell\ell\nu\nu jj$
EW $ZZjj$	20.6 ± 2.5	12.3 ± 0.7
QCD $ZZjj$	77.4 ± 25.0	17.2 ± 3.5
QCD $ggZZjj$	13.1 ± 4.4	3.5 ± 1.1
Non-resonant-$\ell\ell$	-	21.4 ± 4.8
WZ	-	22.8 ± 1.1
Others	3.2 ± 2.1	1.2 ± 0.9
Total	114.3 ± 25.6	78.4 ± 6.2
Data	127	82

- Fiducial cross section for inclusive ZZjj production
  - Very small fiducial cross section!

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

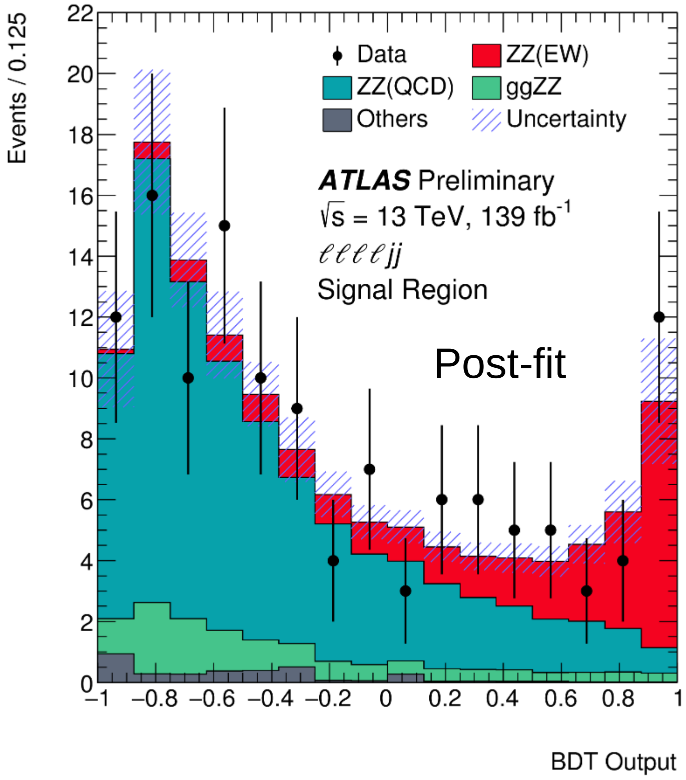
  - Now extract EW ZZjj only from that
    → Expect ~19 % (~37%) contribution for llllјј (llvvjj)
    → Use **BDT!**

Observing EW ZZjj production

ATLAS-CONF-2019-033

Trained BDT does the job

- One multivariate discriminant per channel
  - 12 input variables for llllјj → jet-related information
  - 13 input variables for llvvjj → jet- & dilepton-related information important



→ Fit multivariate discriminant distributions

	μ_{EW}
$\ell\ell\ell\ell jj$	1.54 ± 0.42
$\ell\ell\nu\nu jj$	0.73 ± 0.65
Combined	1.35 ± 0.34

Observing EW ZZjj production

ATLAS-CONF-2019-033

Trained BDT does the job

- One multivariate discriminant per channel
  - 12 input variables for llllјј → jet-related information
  - 13 input variables for llvvjj → jet- & dilepton-related information important

- It's an observation
  - Test statistics using the profile likelihood ratio method
  - Likelihood includes all fitted bins in the BDT output distribution

→ Fit multivariate discriminant distributions

Post-fit

	μ_{EW}
$\ell\ell\ell\ell jj$	1.54 ± 0.42
$\ell\ell\nu\nu jj$	0.73 ± 0.65
Combined	1.35 ± 0.34

- EW ZZjj cross section → from the combined μ_{EW}
  - $\sigma^{fid}_{EW\ ZZjj} =$

- It's an observation
  - Test statistics using the profile likelihood ratio method
  - Likelihood includes all fitted bins in the BDT output distribution

	Significance Obs. (Exp.)
$\ell\ell\ell\ell jj$	5.48 (3.90) σ
$\ell\ell\nu\nu jj$	1.15 (1.80) σ
Combined	5.52 (4.30) σ

Madgraph5 (LO QCD)

- EW ZZjj cross section → from the combined μ_{EW}
  - $\sigma^{fid}_{EW\ ZZjj} = 0.82 \pm 0.21$ fb

→ Among the smallest measured cross sections in ATLAS
→ Already ~26% measurement precision

Summary

Measurement of diboson production in ATLAS

- Inclusive diboson production and via vector boson scattering at 13 TeV well on their way
  - Window to electroweak symmetry breaking in the SM and search for anomalous triple and quartic couplings
  - Aim for highest precision and tiniest cross sections in the SM

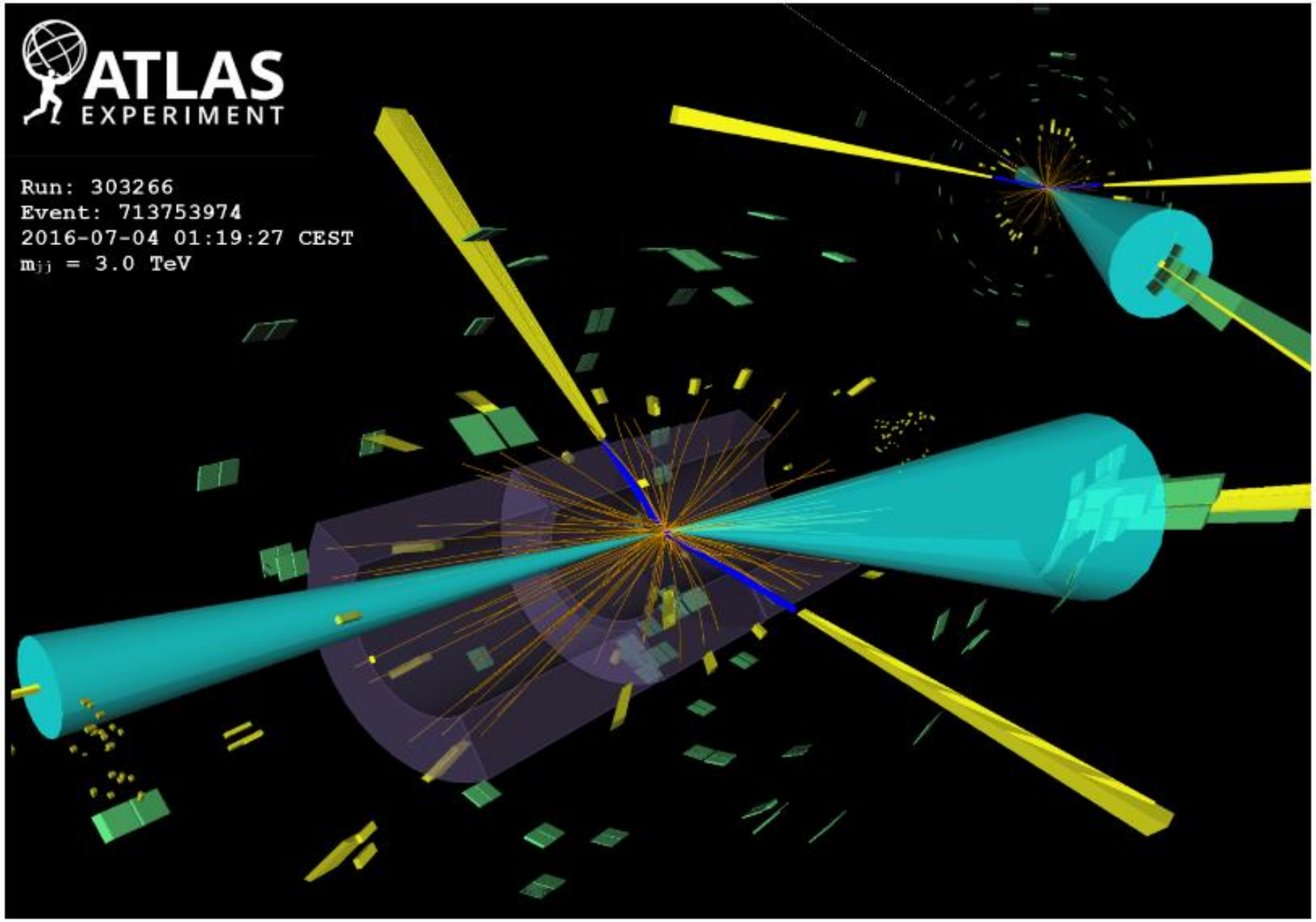
Precision fronteer	**Cross section fronteer**
WW 13 TeV, 36.1 fb^{-1}	WWjj 13 TeV, 36.1 fb^{-1}
WZ 13 TeV, 36.1 fb^{-1}	WZjj 13 TeV, 36.1 fb^{-1}
ZZ (4l) 13 TeV, 36.1 fb^{-1} (2l2v) 13 TeV, 36.1 fb^{-1}	**ZZjj (4l/2l2v) 13 TeV, 139 fb^{-1}**
	VVjj 13 TeV, 36.1 fb^{-1}
Zγ **(llγ) 13 TeV, 139 fb^{-1}** (vvγ) 13 TeV, 36.1fb-1	Zγjj 13 TeV, 36.1 fb^{-1}

→ 2 results already with the full run 2 dataset of 139 fb^{-1} → More to come. Stay tuned!

Summary

Measurement of diboson production in ATLAS

WWjj in ATLAS!



Thanks for your attention.

Extra information.

WW measurement

arXiv:1905.04242

Selection and backgrounds

Partially data-driven
MC with validation region
Otherwise MC

- Selection at detector level

Selection requirement	Selection value
p_T^ℓ	> 27 GeV
η^ℓ	$\lvert\eta^e\rvert < 2.47$ (excluding $1.37 < \lvert\eta^e\rvert < 1.52$), $\lvert\eta^\mu\rvert < 2.5$
Lepton identification	*TightLH* (electron), *Medium* (muon)
Lepton isolation	*Gradient* working point
Number of additional leptons ($p_T > 10$ GeV)	0
Number of jets ($p_T > 35$ GeV, $\lvert\eta\rvert < 4.5$)	0
Number of b-tagged jets ($p_T > 20$ GeV, $\lvert\eta\rvert < 2.5$)	0
$E_T^{\text{miss,track}}$	> 20 GeV
$p_T^{e\mu}$	> 30 GeV
$m_{e\mu}$	> 55 GeV

- Definition of |cosθ*|

$$|\cos\theta^*| = \left|\tanh\left(\frac{\Delta\eta_{e\mu}}{2}\right)\right|$$

- Events at detector level

	Number of events	Statistical uncertainty	Systematic uncertainty
Top-quark	3120	± 50	± 370
Drell–Yan	431	± 13	± 44
W+jets	310	± 60	± 280
WZ	290	± 11	± 33
ZZ	16	± 1	± 2
$V\gamma$	66	± 11	± 10
Triboson	8	± 1	± 3
Total background	4240	± 80	± 470
Signal (WW)	7690	± 30	± 220
Total signal+background	11 930	± 90	± 520
Data	12 659	-	-

- Uncertainties in fiducial cross section

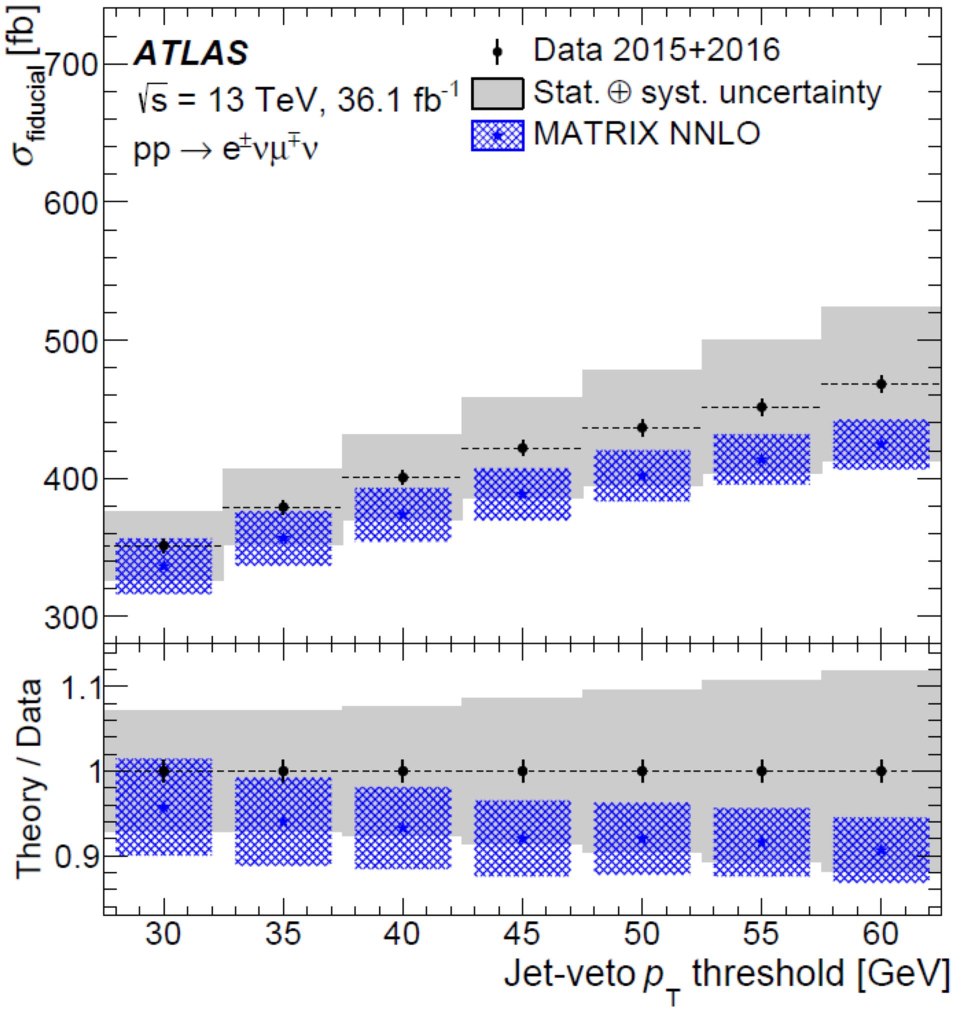
Uncertainty source	Uncertainty [%]
Electron	0.7
Muon	0.9
Jets	3.0
b-tagging	3.4
$E_T^{\text{miss,track}}$	0.4
Pile-up	1.6
W+jets background modelling	3.1
Top-quark background modelling	2.6
Other background modelling	1.3
Unfolding, incl. signal MC stat. uncertainty	1.4
PDF+scale	0.1
Systematic uncertainty	6.7
Statistical uncertainty	1.3
Luminosity uncertainty	2.1
Total uncertainty	7.1

WW measurement

arXiv:1905.04242

Cross section and limits

- Cross section as function of jet-veto p_T threshold



- Limits on additional dimension-6 operators
  - Can generate aTGCs

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} O_i$$

Parameter	Observed 95% CL [TeV^{-2}]	Expected 95% CL [TeV^{-2}]
c_{WWW}/Λ^2	[−3.4 , 3.3]	[−3.0 , 3.0]
c_W/Λ^2	[−7.4 , 4.1]	[−6.4 , 5.1]
c_B/Λ^2	[−21 , 18]	[−18 , 17]
$c_{\tilde{W}WW}/\Lambda^2$	[−1.6 , 1.6]	[−1.5 , 1.5]
$c_{\tilde{W}}/\Lambda^2$	[−76 , 76]	[−91 , 91]

ZZ measurement

arXiv:1905.07163

Selection and likelihood

- Selection at the detector level

Step	Selection criteria
Two leptons	Two opposite-sign leptons, leading (subleading) $p_T > 30$ (20) GeV
Jets	$p_T > 20$ GeV, $\|\eta\| < 4.5$, and $\Delta R > 0.4$ relative to the leptons
Third-lepton veto	No additional lepton with $p_T > 7$ GeV
$m_{\ell\ell}$	$76 < m_{\ell\ell} < 106$ GeV
Hard jets	$p_T > 25$ GeV for $\|\eta\| < 2.4$, $p_T > 40$ GeV for $2.4 < \|\eta\| < 4.5$
E_T^{miss} and V_T/S_T	$E_T^{miss} > 110$ GeV and $V_T/S_T > 0.65$
$\Delta R_{\ell\ell}$	$\Delta R_{\ell\ell} < 1.9$
$\Delta\phi(\vec{p}_T^{\ell\ell}, \vec{E}_T^{miss})$	$\Delta\phi(\vec{p}_T^{\ell\ell}, \vec{E}_T^{miss}) > 2.2$ radians
b-jet veto	$N(b\text{-jets}) = 0$ with b-jet $p_T > 20$ GeV and $\|\eta\| < 2.5$

- Full fiducial phase space

Total phase space	Born-level leptons (ee or $\mu\mu$) $66 < m_{\ell\ell}, m_{\nu\nu} < 116$ GeV
Fiducial phase space	Dressed leptons (e or μ): $p_T > 7$ GeV, $\|\eta\| < 2.5$ Jets: $p_T > 20$ GeV, $\|\eta\| < 4.5$ Reject leptons if overlapping with a jet within $\Delta R < 0.4$ Two leptons with leading (subleading) $p_T > 30$ (20) GeV $76 < m_{\ell\ell} < 106$ GeV $E_T^{miss} > 90$ GeV and $V_T/S_T > 0.65$ $\Delta\phi(\vec{p}_T^{\ell\ell}, \vec{E}_T^{miss}) > 2.2$ radians and $\Delta R_{\ell\ell} < 1.9$

- Extracting the cross section from likelihood fit

$$L(\sigma, \vec{\theta}) = \prod_i \prod_j \text{Pois}(N_{\text{obs}}^{ij} | N_{\text{exp}}^{ij}(\sigma, \vec{\theta})) \times \prod_k \text{Gaus}(\theta_k),$$

- With $N_{\text{exp}}^{ij} = \sigma_{ZZ\to\ell\ell\nu\nu}^{\text{fid}} \times \mathcal{L} \times C_{ZZ}^{i} \times f_{ZZ}^{ij} + N_{\text{bkg}}^{ij}$
- (i = ee, μμ channels, j = bin in fitted E_T^{miss} distribution)

Pre-fit

	ee	$\mu\mu$
Data	371	416
Signal		
$qqZZ$	194 ± 3 ± 12	202 ± 3 ± 12
$ggZZ$	25.1 ± 0.3 ± 7.7	26.4 ± 0.3 ± 8.1
Backgrounds		
WZ	92.9 ± 3.0 ± 4.8	100.7 ± 3.2 ± 5.2
Non-resonant-$\ell\ell$	25.5 ± 3.4 ± 1.8	31.5 ± 4.2 ± 2.2
Z + jets	4.7 ± 0.2 ± 2.3	5.9 ± 0.3 ± 2.8
$ZZ \to 4\ell$	3.8 ± 0.2 ± 0.3	4.2 ± 0.2 ± 0.3
Others	0.87 ± 0.03 ± 0.17	0.87 ± 0.03 ± 0.17
Background expected	128 ± 5 ± 6	143 ± 5 ± 6
Total expected	347 ± 5 ± 15	372 ± 6 ± 16

ZZ measurement

arXiv:1905.07163

Uncertainties and limits

- Uncertainties in the measured combined fiducial cross section

Total	Data stat.	Total syst.	Lumi.	Electron	Muon	Jet
7.0%	5.5%	4.3%	2.2%	1.2%	1.1%	2.1%
			WZ	Non-resonant-$\ell\ell$	Z + jets	Sim. stat.
			1.6%	1.6%	0.4%	0.7%

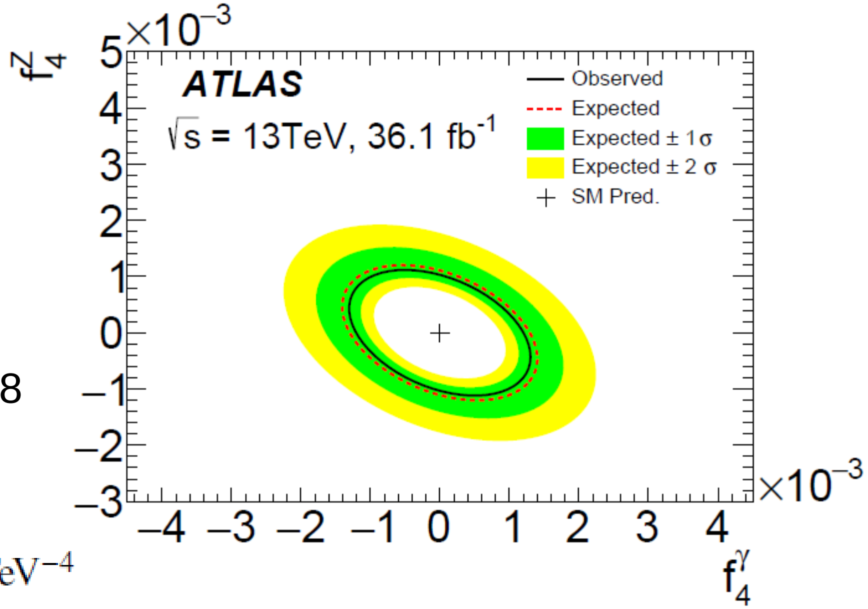
- Differentially → p_T^{ll}

$p_T^{\ell\ell}$ range [GeV]	50–110	110–130	130–150	150–170	170–200	200–250	250–350	350–1000
Measured σ (fb)	9.3	6.6	3.6	2.1	2.5	2.0	1.1	0.4
Total unc.	17.7 %	13.6 %	15.2 %	18.6 %	18.6 %	17.6 %	24.9 %	40.5 %
Stat. unc.	14.7 %	11.1 %	14.0 %	17.7 %	16.0 %	16.9 %	23.4 %	39.4 %
Syst. unc.	7.0 %	4.5 %	5.0 %	4.3 %	3.9 %	4.6 %	4.6 %	5.5 %
Bkg. unc.	6.9 %	6.4 %	3.2 %	3.7 %	8.6 %	2.1 %	7.1 %	7.6 %
Sim. stat.	1.2 %	0.7 %	0.7 %	0.8 %	0.9 %	0.9 %	1.1 %	2.0 %
Electron	0.7 %	0.8 %	0.9 %	1.7 %	1.3 %	1.6 %	2.1 %	3.2 %
Muon	1.0 %	1.3 %	1.0 %	1.1 %	1.2 %	1.4 %	2.0 %	1.7 %
Jet	5.4 %	2.9 %	3.8 %	3.0 %	2.3 %	2.1 %	2.7 %	2.5 %
Soft	3.6 %	2.2 %	2.0 %	0.8 %	1.3 %	2.7 %	0.3 %	1.7 %
Luminosity	2.1 %	2.1 %	2.1 %	2.1 %	2.1 %	2.1 %	2.1 %	2.1 %

- One-dimensional 95% confidence intervals (CIs)

	f_4^γ	f_4^Z	f_5^γ	f_5^Z
Expected [$\times 10^{-3}$]	[−1.3, 1.3]	[−1.1, 1.1]	[−1.3, 1.3]	[−1.1, 1.1]
Observed [$\times 10^{-3}$]	[−1.2, 1.2]	[−1.0, 1.0]	[−1.2, 1.2]	[−1.0, 1.0]

- Two-dimensional CIs



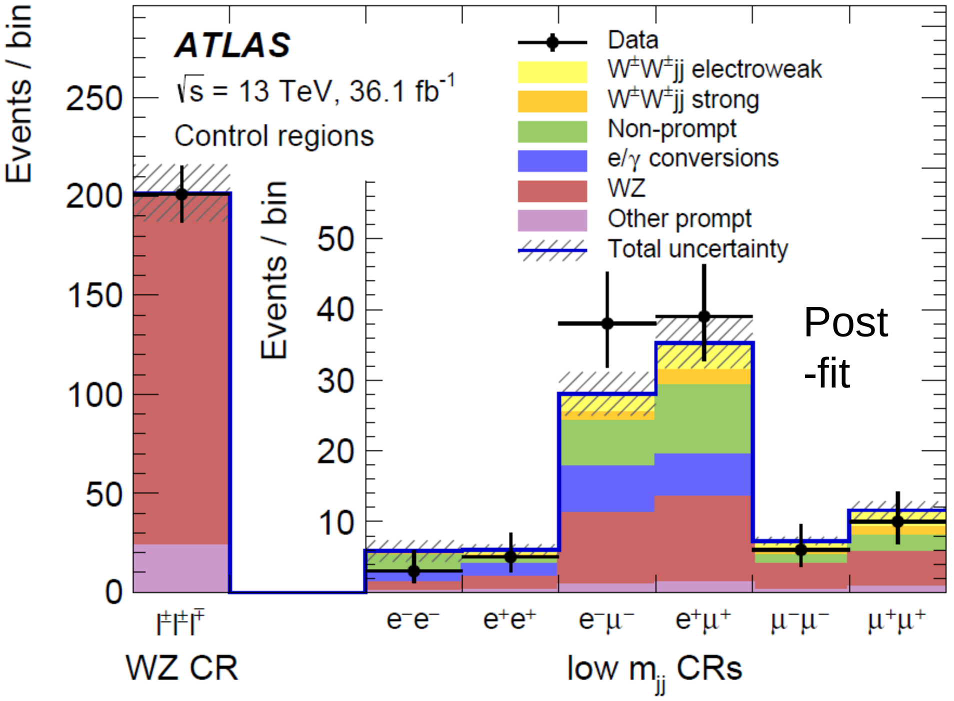
- Conversion to effective field theory
  - CP-even dim-8 operator
  - Observed:

$C_{\tilde{B}W}/\Lambda^4$ [−4.0, 4.0] TeV^{-4}

WWjj measurement

Fit and event yields

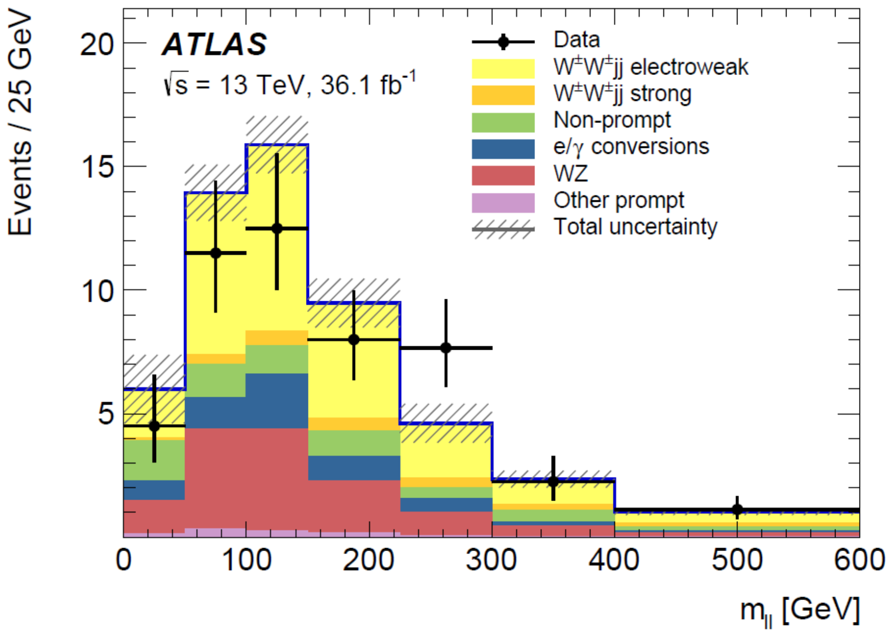
- Fit input



- Together with mjj distribution (see main part of talk)

- Event yields after the fit

	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



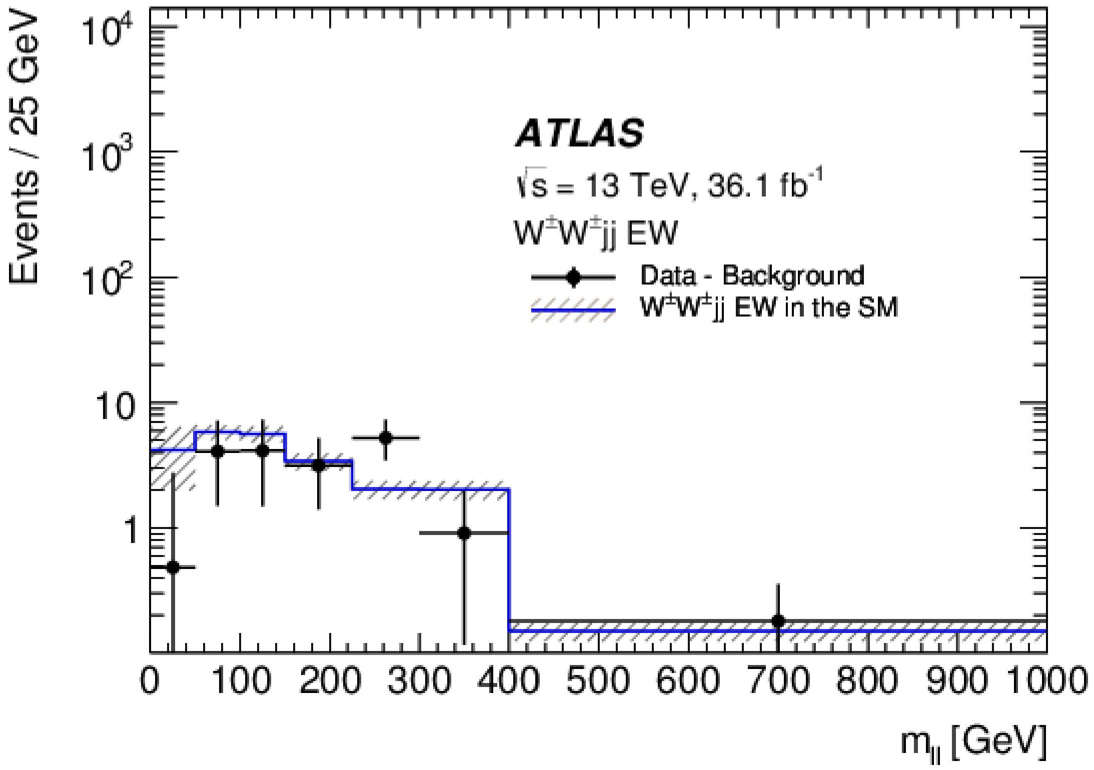
WWjj measurement

Uncertainties

- Uncertainties in the measured fiducial cross section
  - Estimated by repeating the fit with corresponding uncertainty nuissance parameter fixed to ±1σ

Source	Impact [%]
Experimental	
Electrons	0.6
Muons	1.3
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$	3.2
b-tagging	2.1
Pileup	1.6
Background, statistical	3.2
Background, misid. leptons	3.3
Background, charge misrec.	0.3
Background, other	1.8
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
Luminosity	2.4

- Data vs. prediction



ZZjj measurement

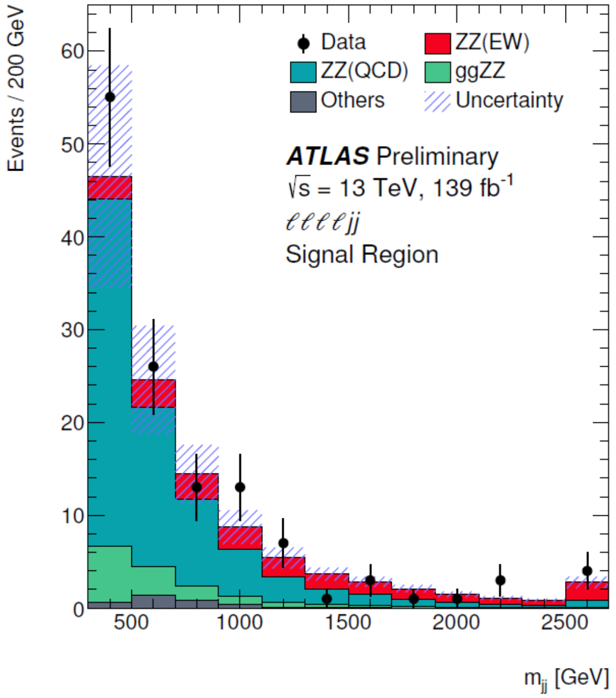
ATLAS-CONF-2019-033

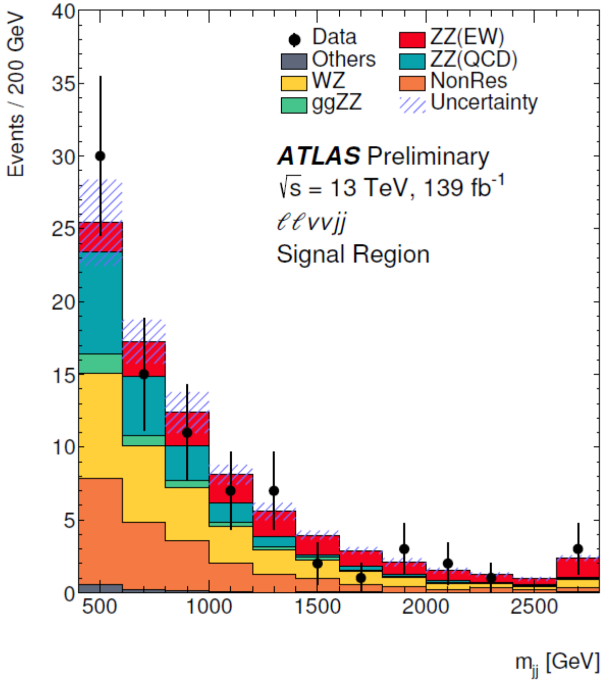
Selection

- Selection at the detector level
  - Select both EW and QCD ZZjj production together

	$\ell\ell\ell\ell jj$	$\ell\ell\nu\nu jj$
Electrons	$p_T > 7$ GeV, $\|\eta\| < 2.47$ $\|d_0/\sigma_{d_0}\| < 5$ and $\|z_0 \times \sin\theta\| < 0.5$ mm	
Muons	$p_T > 7$ GeV, $\|\eta\| < 2.7$ $\|d_0/\sigma_{d_0}\| < 3$ and $\|z_0 \times \sin\theta\| < 0.5$ mm	$p_T > 7$ GeV, $\|\eta\| < 2.5$
Jets	$p_T > 30$ (40) GeV for $\|\eta\| < 2.4$ ($2.4 < \|\eta\| < 4.5$)	$p_T > 60$ (40) GeV for the leading (sub-leading) jet
ZZ selection	$p_T > 20, 20, 10$ GeV for the leading, sub-leading and third leptons Two OSSF lepton pairs with smallest $\|m_{\ell^+\ell^-} - m_Z\| + \|m_{\ell'^+\ell'^-} - m_Z\|$ $m_{\ell^+\ell^-} > 10$ GeV for lepton pairs $\Delta R(\ell, \ell') > 0.2$ $66 < m_{\ell^+\ell^-} < 116$ GeV	$p_T > 30$ (20) GeV for the leading (sub-leading) lepton One OSSF lepton pair and no third leptons $80 < m_{\ell^+\ell^-} < 100$ GeV No b-tagged jets E_T^{miss} significance > 12
Dijet selection	Two most energetic jets with $y_{j_1} \times y_{j_2} < 0$ $m_{jj} > 300$ GeV and $\Delta y(jj) > 2$	$m_{jj} > 400$ GeV and $\Delta y(jj) > 2$

- Distributions in the signal region





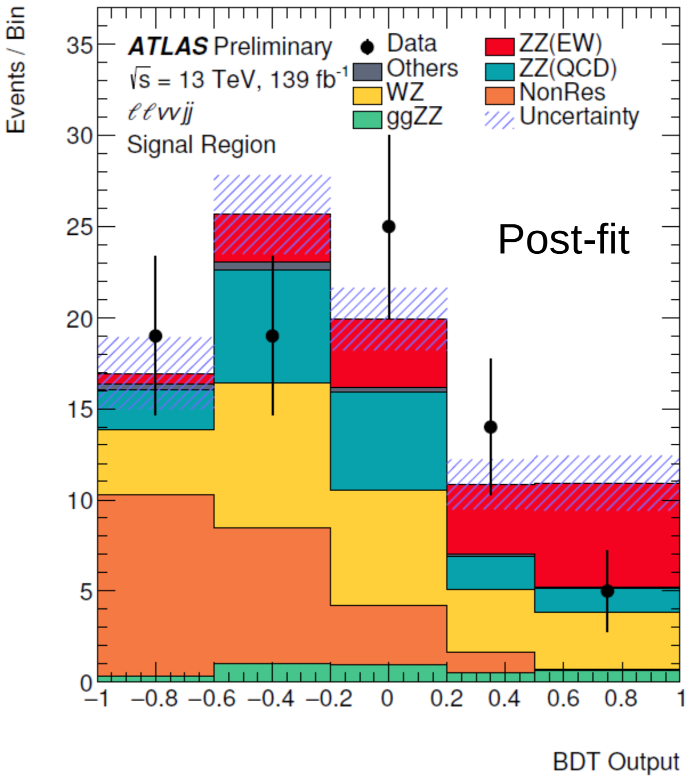
- EW and QCD contributions scaled according to fit normalizations from combined fit

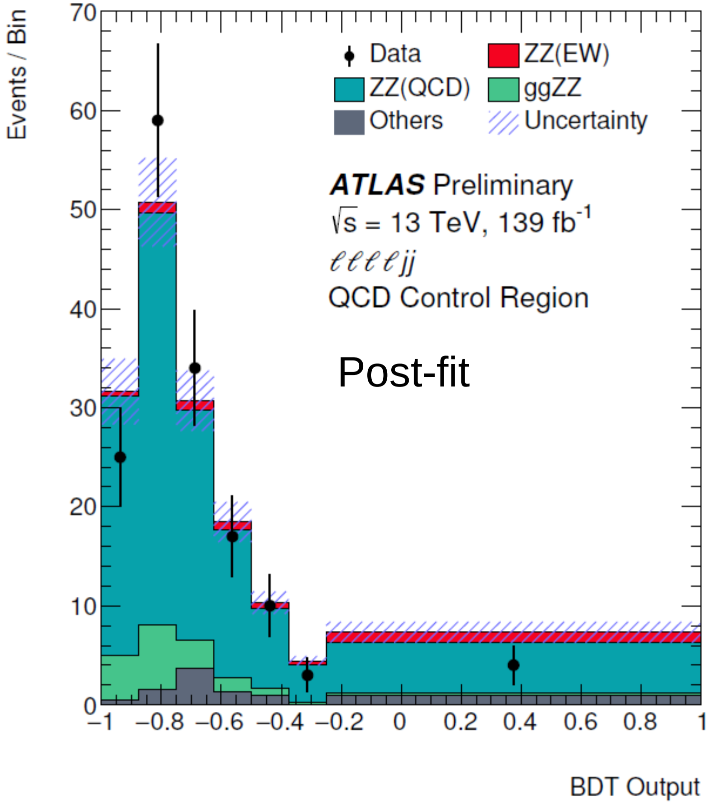
ZZjj measurement

ATLAS-CONF-2019-033

Selection and distributions in the signal region

- Further BDT distributions





- Fitted signal significance

	μ_{EW}	$\mu_{QCD}^{\ell\ell\ell\ell jj}$	Significance Obs. (Exp.)
$\ell\ell\ell\ell jj$	1.54 ± 0.42	0.95 ± 0.22	5.48 (3.90) σ
$\ell\ell\nu\nu jj$	0.73 ± 0.65	-	1.15 (1.80) σ
Combined	1.35 ± 0.34	0.96 ± 0.22	5.52 (4.30) σ

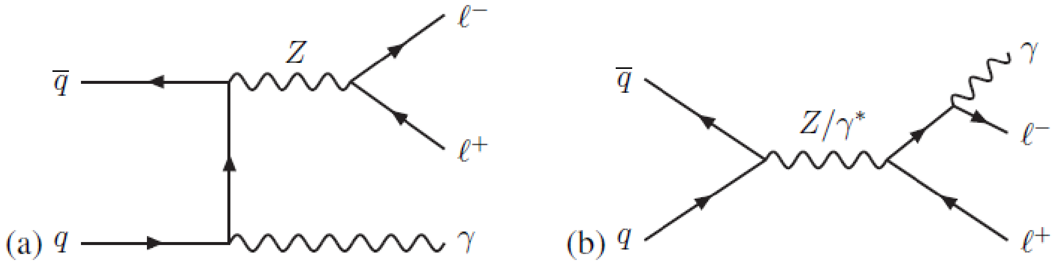
Additional analyses.

Measurement of Zγ production

ATLAS-CONF-2019-034

Selecting initial state radiation in Zγ events

- Initial and final state radiation



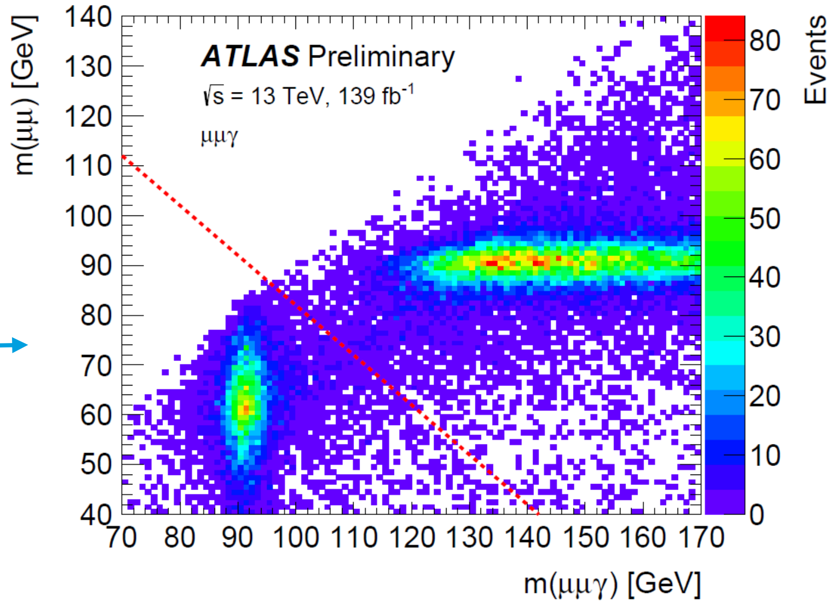
- Selecting the final state llγ

	Photons	Electrons	Muons
Kinematics:	$E_T > 30$ GeV	$p_T > 30, 25$ GeV	$p_T > 30, 25$ GeV
	$\|\eta\| < 2.37$	$\|\eta\| < 2.47$	$\|\eta\| < 2.5$
	excl. $1.37 < \|\eta\| < 1.52$	excl. $1.37 < \|\eta\| < 1.52$	
Identification:	Tight [53]	Medium [54]	Medium [52]
Isolation:	FixedCutLoose [53]	FCLoose [54]	FCLoose_FixedRad [52]
	$\Delta R(\ell, \gamma) > 0.4$	$\Delta R(\mu, e) > 0.2$	
Event selection:	$m(\ell\ell) > 40$ GeV, $m(\ell\ell) + m(\ell\ell\gamma) > 182$ GeV		

- Suppress final state radiation

- Events at the detector level

	$e^+e^-\gamma$	$\mu^+\mu^-\gamma$
N_{obs}	41343	54413
N_{Z+jets}	4130 ± 440	5470 ± 580
N_{PU}	870 ± 870	1140 ± 1140
$N_{t\bar{t}\gamma}$	1650 ± 250	1980 ± 300
N_{WZ}	254 ± 76	199 ± 60
N_{ZZ}	64 ± 19	102 ± 31
$N_{WW\gamma}$	92 ± 28	112 ± 34
$N_{\tau\tau\gamma}$	46 ± 15	39 ± 12
$N_{obs} - N_{bkg}$	34240 ± 1000	45370 ± 1300



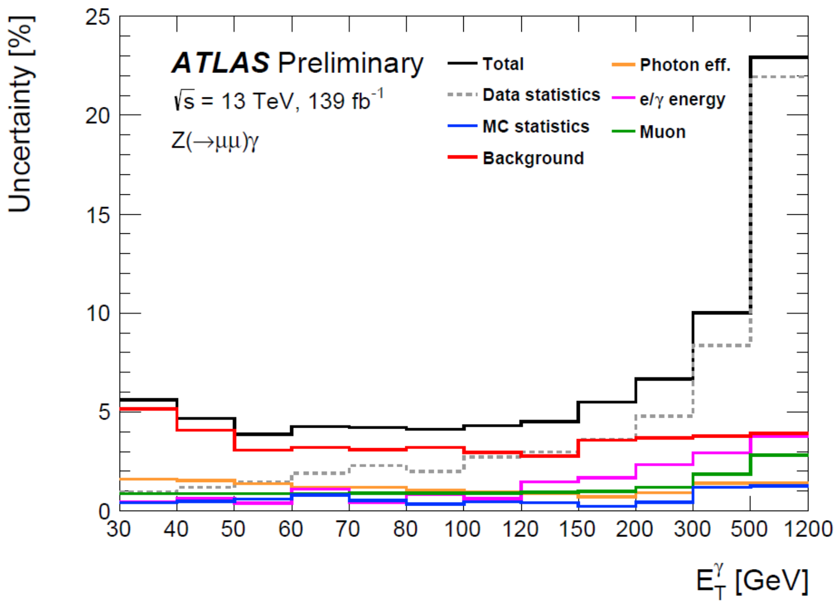
Extracting Zγ

ATLAS-CONF-2019-034

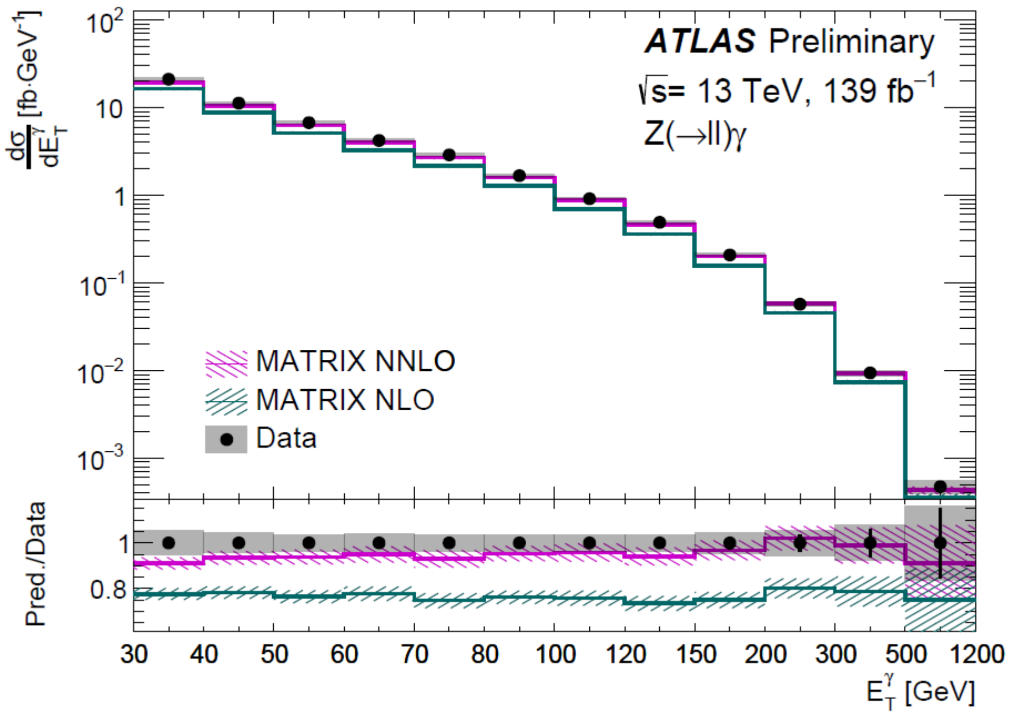
- Fiducial definition

Photons	Electrons/Muons
$E_T^\gamma > 30$ GeV	$p_T^\ell > 30, 25$ GeV
$\lvert\eta^\gamma\rvert < 2.37$	$\lvert\eta^\ell\rvert < 2.47$
$E_T^{\text{cone}0.2}/E_T^\gamma < 0.07$	dressed leptons
$\Delta R(\ell,\gamma) > 0.4$	
Event selection	
$m(\ell\ell) > 40$ GeV	
$m(\ell\ell) + m(\ell\ell\gamma) > 182$ GeV	

- Systematic uncertainties



- 4 differential distributions
  - Iterative Bayesian unfolding with 2 iterations

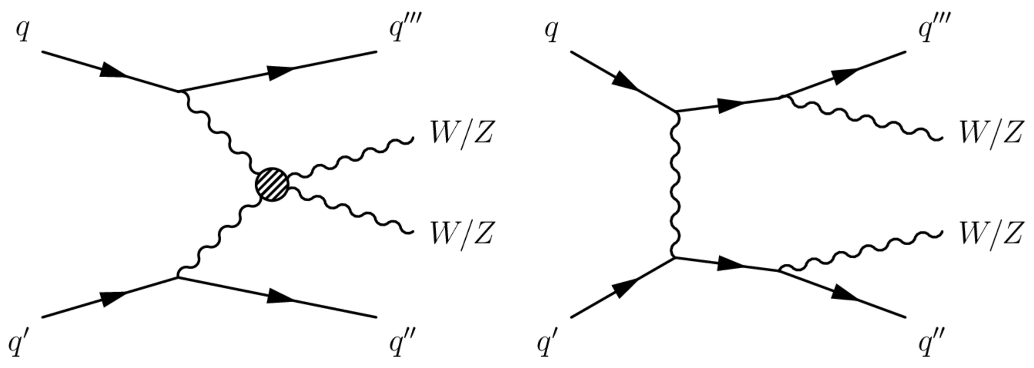


Measurement of VVjj production

arXiv:1905.07714

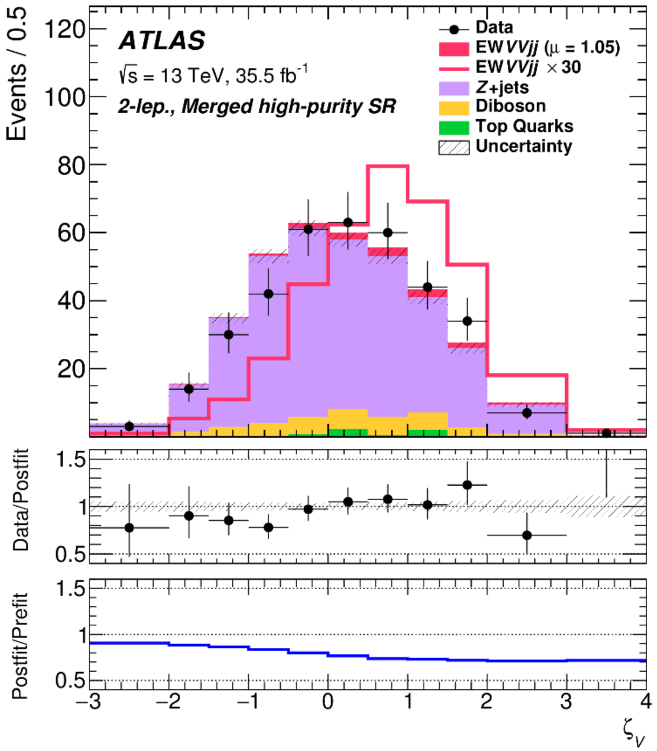
Checking the number of leptons

- EW production via VBS and non-VBS processes



- Measurement in semileptonic final states
  - One boson: $Z \to \nu\nu$ (0-lepton), $W \to l\nu$ (1-lepton), $Z \to ll$ (2-leptons)
  - Other boson: $Z \to qq$, $W \to qq'$ (2 small-radius jets or 1 large-radius jet with substructure) → resolved / merged
  - 2 small-radius tagging jets in opposite η-hemispheres and m_{jj} > 400GeV

- Training BDTs to separate EW- and QCD-induced VVjj production
  - One BDT per lepton channel and for merged & resolved regimes separately
  - Use various kinematic properties, such as "centrality of boson canditates" ζ_V

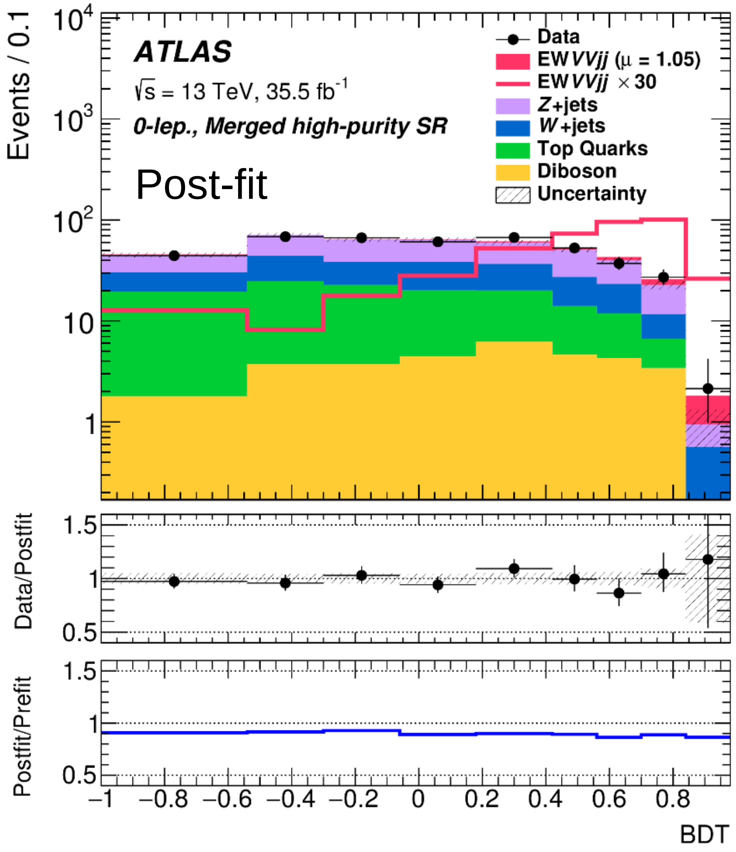


Extracting the signal

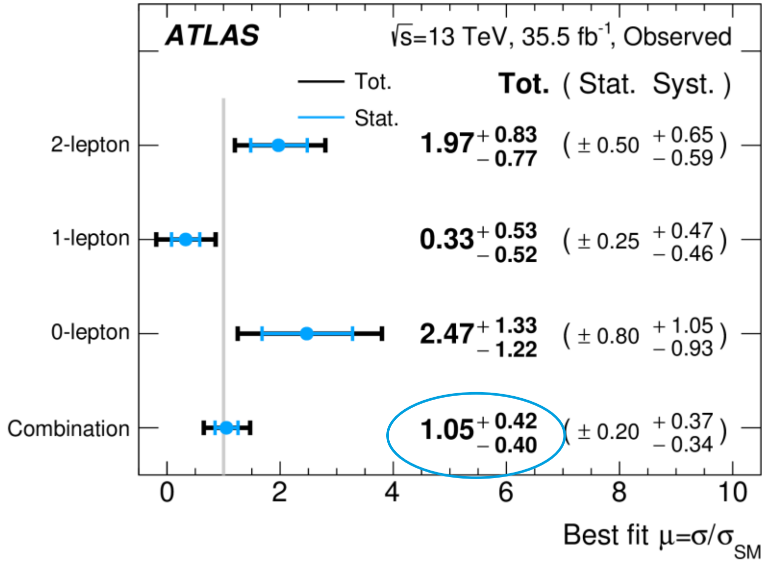
arXiv:1905.07714

Narrowing in on EW VVjj production

- Binned profile likelihood fit to extract EW VVjj
  - Fit BDT outputs in 9 SRs (split merged in low / high purity) + m_{jj}^{tag} or number of events in 12 CRs



- Extracted signal strength



→ Excluded background-only hypothesis with 2.7σ (2.5σ) significance observed (expected)

- Fiducial cross section $\sigma^{\mathrm{fid,obs}}_{\mathrm{EW}\,VVjj} = \mu^{\mathrm{obs}}_{\mathrm{EW}\,VVjj} \cdot \sigma^{\mathrm{fid,SM}}_{\mathrm{EW}\,VVjj}$

Fiducial phase space	Predicted $\sigma^{\mathrm{fid,SM}}_{\mathrm{EW}\,VVjj}$ [fb]	Measured $\sigma^{\mathrm{fid,obs}}_{\mathrm{EW}\,VVjj}$ [fb]
Merged	$11.4 \pm 0.7\,(\mathrm{theo.})$	$12.7 \pm 3.8\,(\mathrm{stat.})\,^{+4.8}_{-4.2}\,(\mathrm{syst.})$
Resolved	$31.6 \pm 1.8\,(\mathrm{theo.})$	$26.5 \pm 8.2\,(\mathrm{stat.})\,^{+17.4}_{-17.1}\,(\mathrm{syst.})$
Inclusive	$43.0 \pm 2.4\,(\mathrm{theo.})$	$45.1 \pm 8.6\,(\mathrm{stat.})\,^{+15.9}_{-14.6}\,(\mathrm{syst.})$