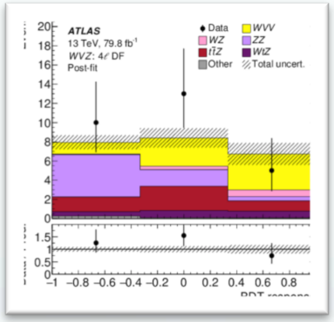
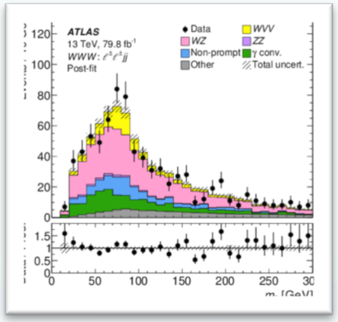
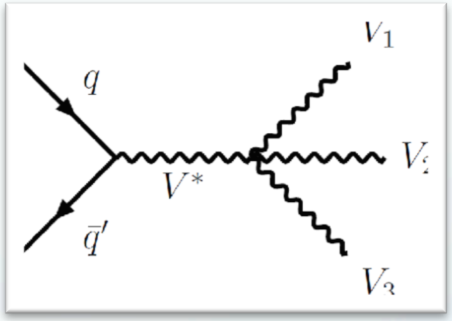
Evidence for the production of three massive vector bosons with ATLAS

Ulla Blumenschein, Queen Mary University of London







- Introduction
- Past measurements of 4-boson couplings
- Evidence for production of 3 heavy gauge bosons

Introduction:
Theory and motivation

Electroweak gauge fields

→ Lagrangian of free gauge fields:

$$\mathcal{L}^{EW}_{gauge} = -\frac{1}{4}F^a_{\mu\nu}F^{\mu\nu}_a - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}$$

with:

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$$

$$F^a_{\mu\nu} = \partial_\mu W^a_\nu - \partial_\nu W^a_\mu - g_w \epsilon_{abc} W^b_\mu W^c_\nu$$

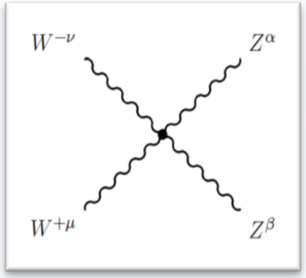
W/Z bosons carry
EM and/or weak charges

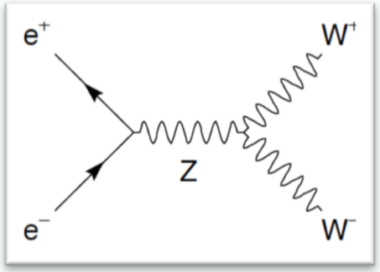
$$\left[\frac{\sigma_a}{2}, \frac{\sigma_b}{2}\right] = i\epsilon_{abc}\frac{\sigma_c}{2}$$

Electroweak gauge fields

→ Lagrangian of free gauge fields:

$$\mathcal{L}^{EW}_{gauge} = -\frac{1}{4} F^a_{\mu\nu} F^{\mu\nu}_a - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}$$





with:

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$$

$$F^a_{\mu\nu} = \partial_\mu W^a_\nu - \partial_\nu W^a_\mu - g_w \epsilon_{abc} W^b_\mu W^c_\nu$$

Leads to triple and quartic gauge boson couplings:

$$\begin{aligned}
\mathcal{L}^{EW}_{gauge} = \; & -\tfrac{1}{4}\left[(W^-_{\mu\nu})^\dagger W^{-\mu\nu} + (W^+_{\mu\nu})^\dagger W^{+\mu\nu} + Z_{\mu\nu}Z^{\mu\nu} + A_{\mu\nu}A^{\mu\nu}\right] \\
& -i g_w \left[(\cos\theta_w Z^\mu + \sin\theta_w A^\mu)(W^-_{\mu\nu} W^{+\nu} - W^+_{\mu\nu} W^{-\nu}) \right. \\
& \qquad \left. + (\cos\theta_w Z_{\mu\nu} + \sin\theta_w A_{\mu\nu}) W^{+\mu} W^{-\nu}\right] \\
& -\tfrac{g_w^2}{2}\left[2\cos^2\theta_w (W^+_\mu W^{-\mu} Z_\nu Z^\nu - W^+_\mu W^{-\nu} Z_\nu Z^\mu) \right. \\
& \qquad + 2\sin^2\theta_w (W^+_\mu W^{-\mu} A_\nu A^\nu - W^+_\mu W^{-\nu} A_\nu A^\mu) \\
& \qquad + 2\cos\theta_w \sin\theta_w (2 W^+_\mu W^{-\mu} Z_\nu A^\nu - W^+_\mu W^{-\nu} Z_\nu A^\mu - W^+_\mu W^{-\nu} A_\nu Z^\mu) \\
& \qquad \left. - W^+_\mu W^{+\mu} W^-_\nu W^{-\nu} + W^+_\mu W^{-\mu} W^-_\nu W^{+\nu}\right]
\end{aligned}$$

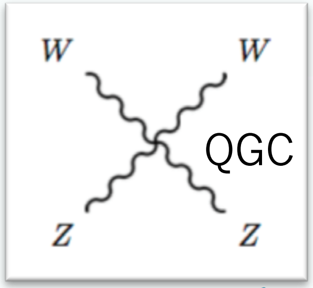
TGC

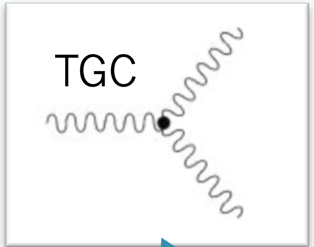
QGC

SM Lagrangian

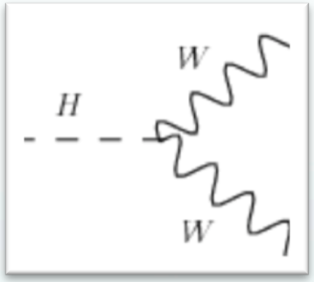
$$\mathcal{L}_{SM} = i\Psi_i\gamma^\mu \mathbf{D}_\mu \Psi_i - \frac{1}{4} V^j_{\mu\nu} V^{\mu\nu}_j + [\mathbf{D}_\mu \Phi]^2 - V(\Phi^*\Phi) - \mathcal{L}_{Yukawa}$$

Gauge boson kinematics and interaction:
Triple and Quartic Gauge Coupling



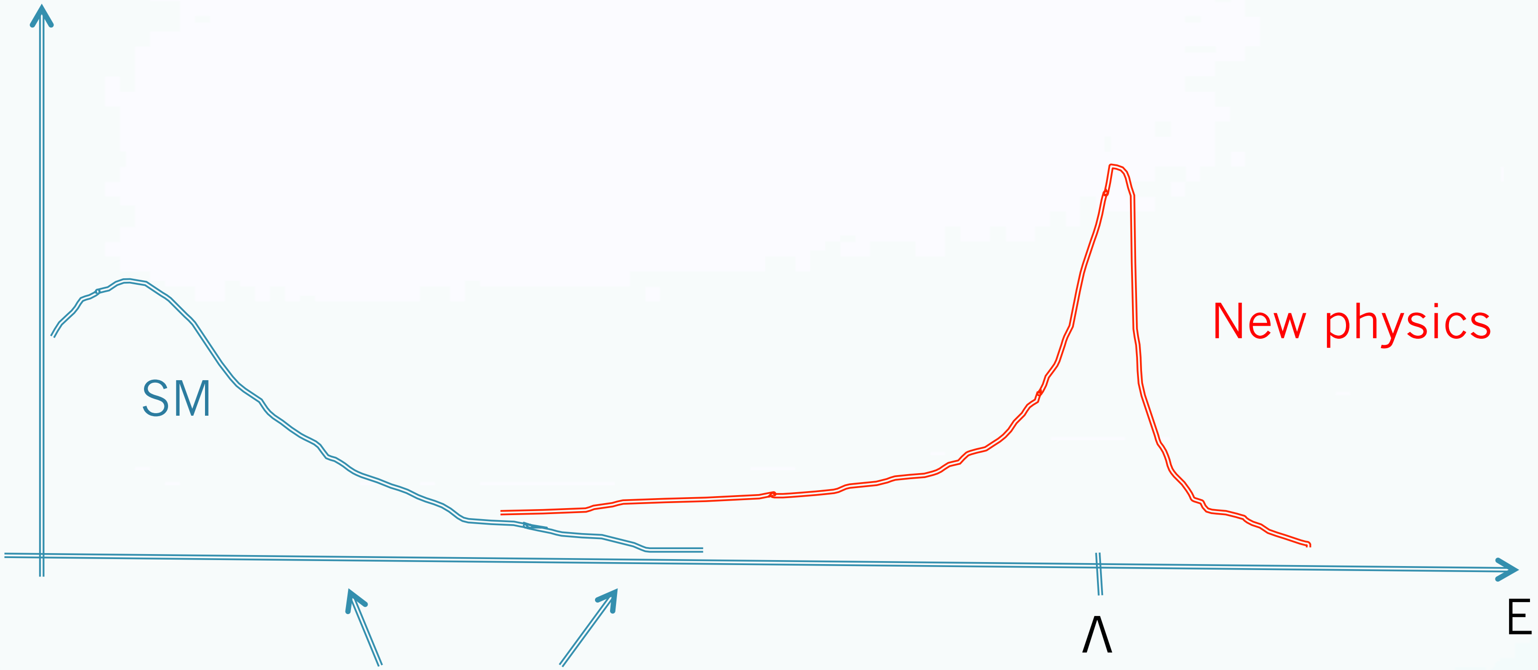


Higgs kinematics
and gauge boson coupling

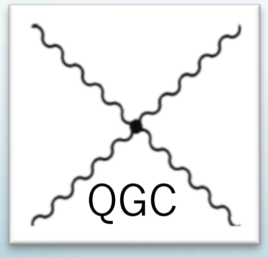


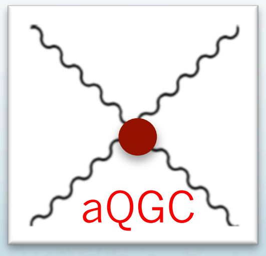
$$V^\alpha_{\mu\nu} = \partial_\mu V^\alpha_\nu - \partial_\nu V^\alpha_\mu + g f^{\alpha bc} V^b_\mu V^c_\nu$$

New physics at large energy scales



Measurement: E<<Λ

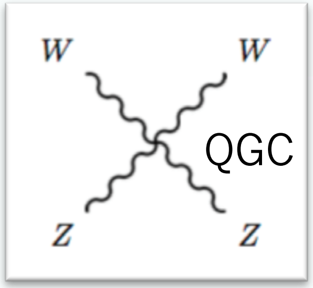


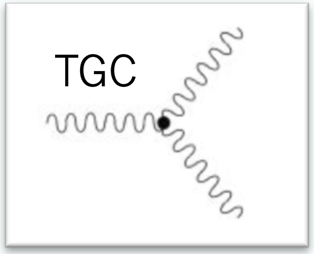


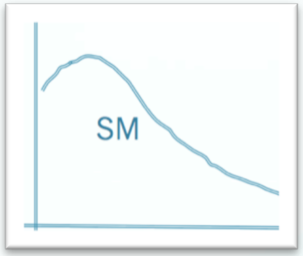
SM +EFT

$$\mathcal{L}_{SM} = i\Psi_i \gamma^\mu \mathbf{D}_\mu \Psi_i - \frac{1}{4} V^j_{\mu\nu} V^{\mu\nu}_j + [\mathbf{D}_\mu \Phi]^2 - V(\Phi^* \Phi) - \mathcal{L}_{Yukawa}$$

Gauge boson kinematics and interaction:
Triple and Quartic Gauge Coupling



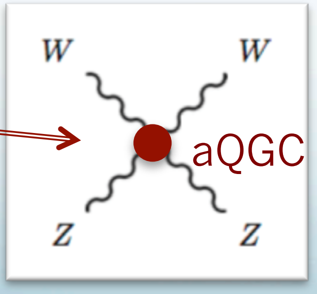


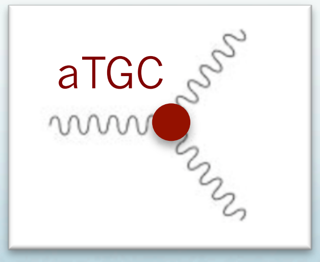


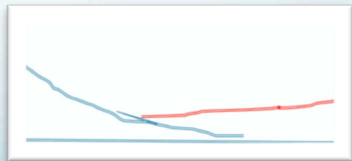
\+ +

New Physics:

→ anomalous TGC
→ anomalous QGC

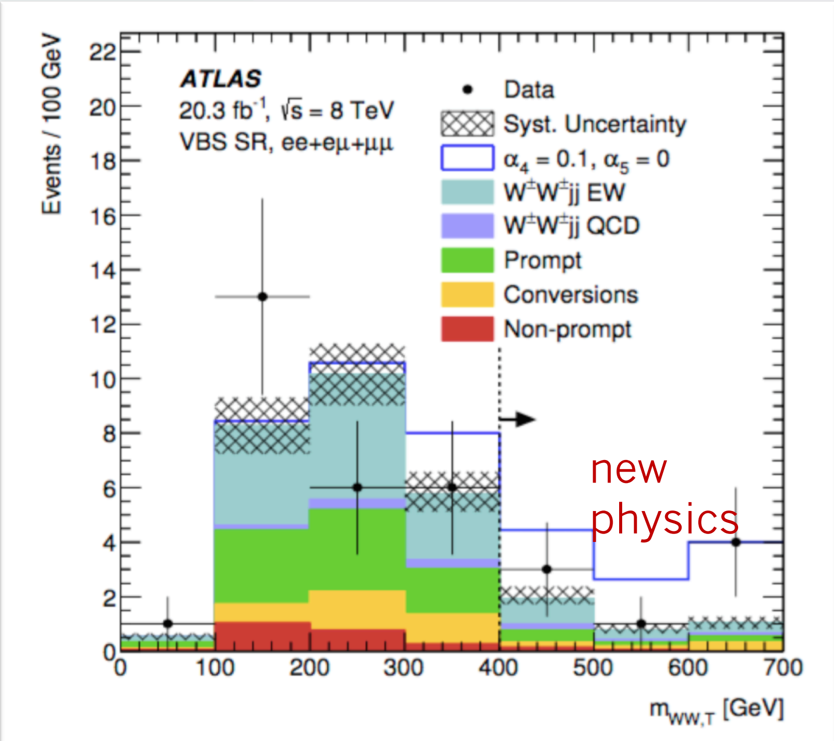


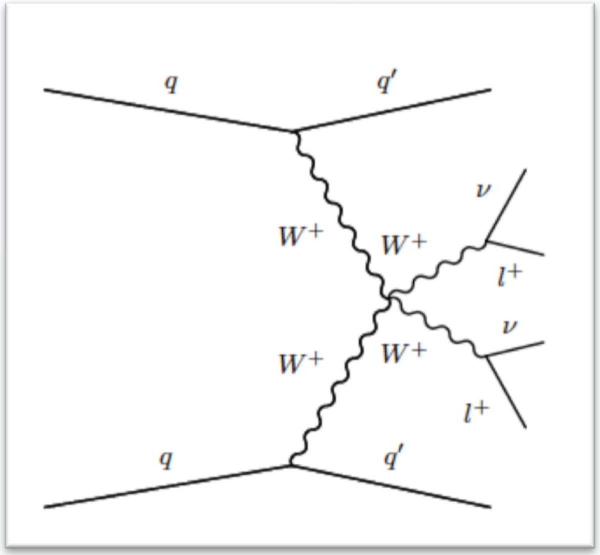




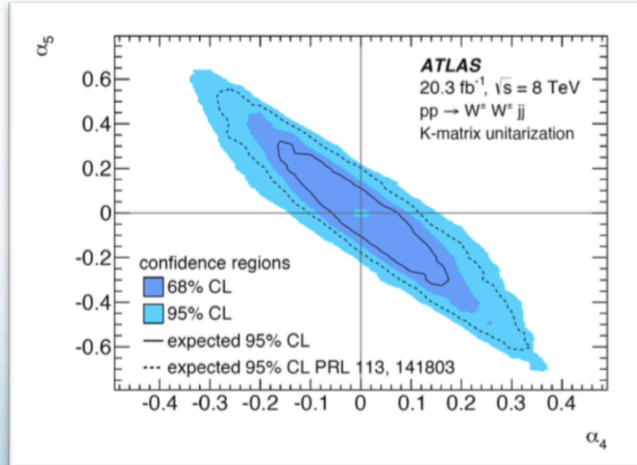
Measuring interactions of four gauge bosons: 1) Vector Boson Scattering

Example: VBS ssWW (8TeV)



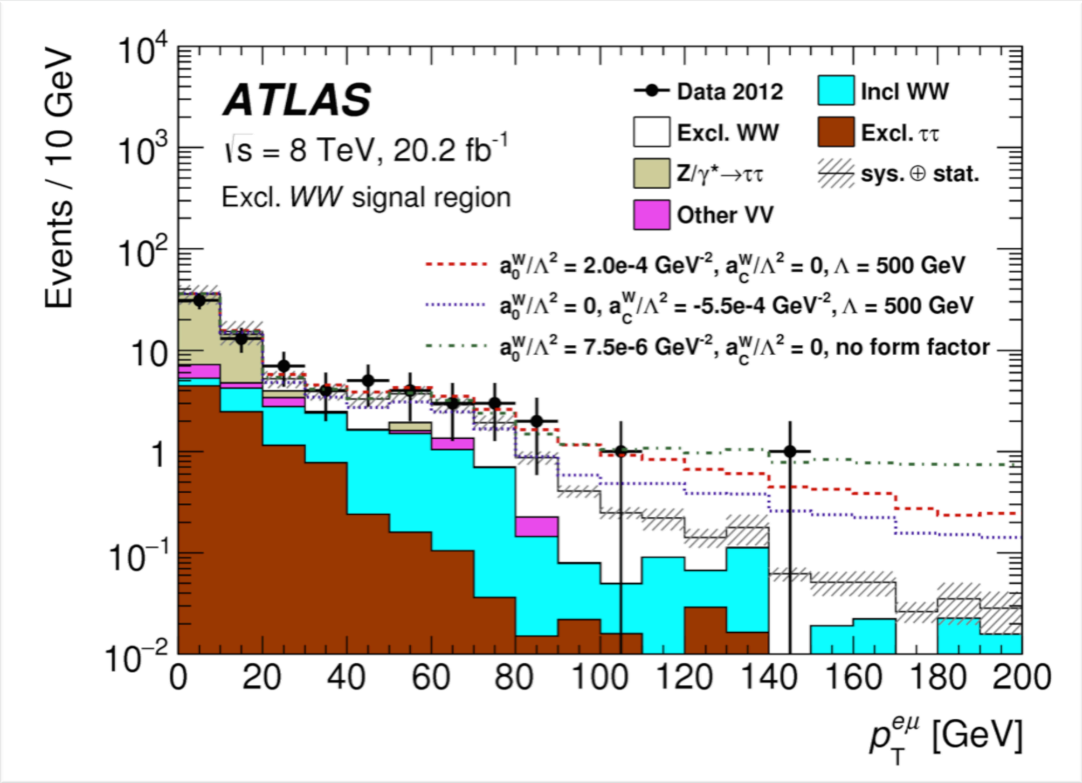


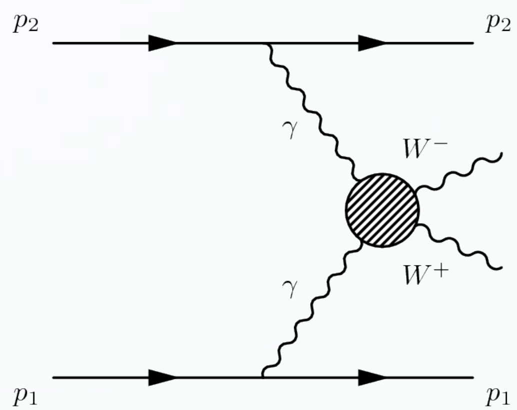
$$m_{WW,T} = \sqrt{\left(\mathbf{P}_{\ell_1} + \mathbf{P}_{\ell_2} + \mathbf{P}_{E_T^{miss}}\right)^2}$$

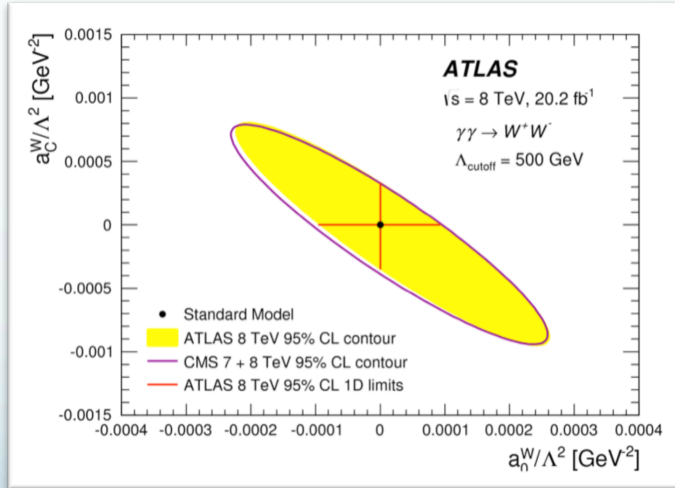


Phys. Rev. D 96 (2017) 012007

Example: exclusive WW production



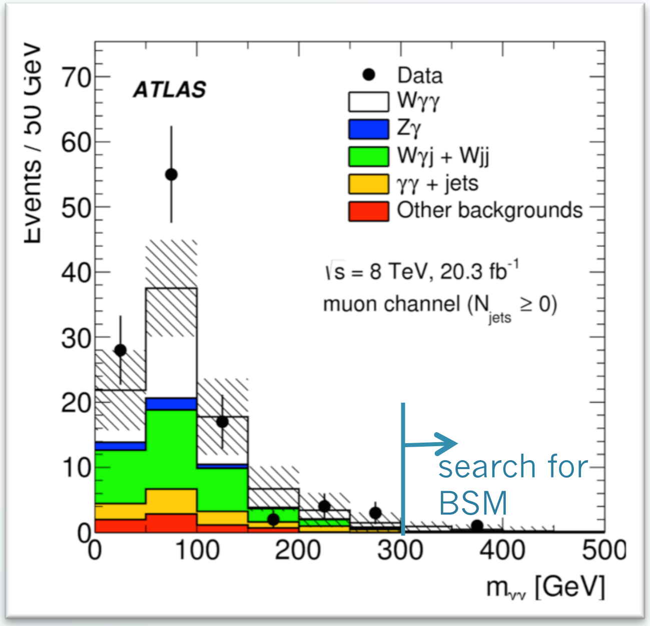




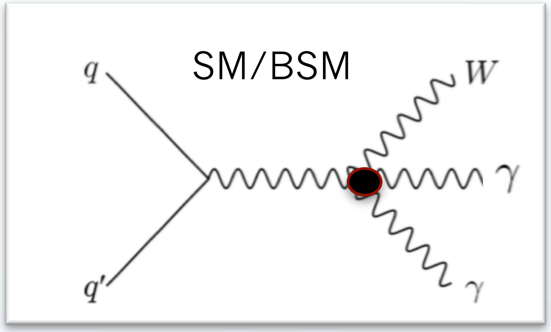
Here: Phys. Rev. D 94 (2016) 032011
CMS paper: JHEP 07 (2013) 116

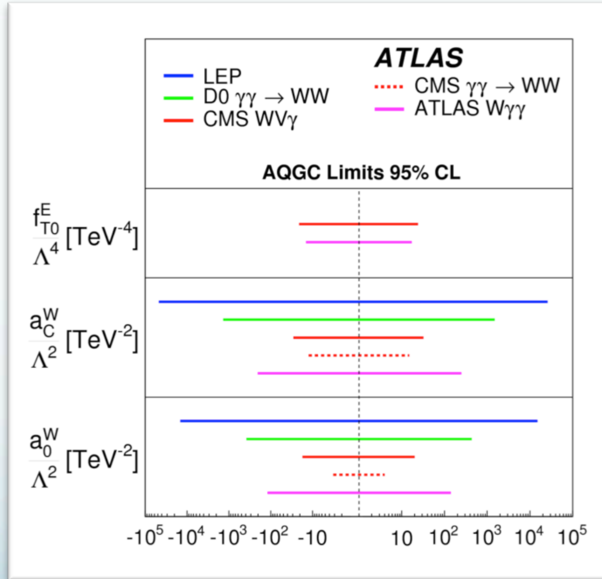
Measuring interactions of four gauge bosons: 2) Tri-Boson production

First Triboson measurements: Wγ γ



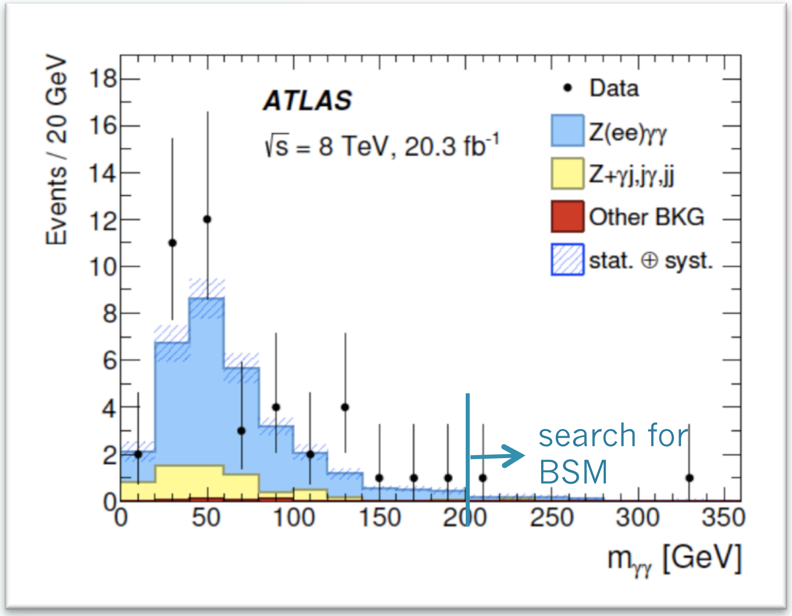
	σ^{fid} [fb]	σ^{MCFM} [fb]
Inclusive ($N_{\text{jet}} \geq 0$)		
$\mu\nu\gamma\gamma$	$7.1\ ^{+1.3}_{-1.2}$ (stat.) ± 1.5 (syst.) ± 0.2 (lumi.)	2.90 ± 0.16
$e\nu\gamma\gamma$	$4.3\ ^{+1.8}_{-1.6}$ (stat.) $^{+1.9}_{-1.8}$ (syst.) ± 0.2 (lumi.)	
$\ell\nu\gamma\gamma$	$6.1\ ^{+1.1}_{-1.0}$ (stat.) ± 1.2 (syst.) ± 0.2 (lumi.)	
Exclusive ($N_{\text{jet}} = 0$)		
$\mu\nu\gamma\gamma$	3.5 ± 0.9 (stat.) $^{+1.1}_{-1.0}$ (syst.) ± 0.1 (lumi.)	1.88 ± 0.20
$e\nu\gamma\gamma$	$1.9\ ^{+1.4}_{-1.1}$ (stat.) $^{+1.1}_{-1.2}$ (syst.) ± 0.1 (lumi.)	
$\ell\nu\gamma\gamma$	$2.9\ ^{+0.8}_{-0.7}$ (stat.) $^{+1.0}_{-0.9}$ (syst.) ± 0.1 (lumi.)	

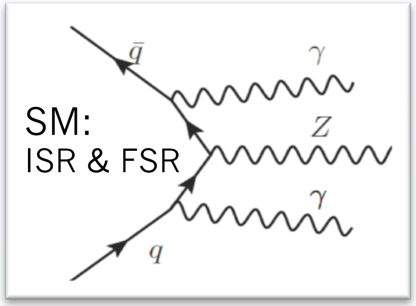


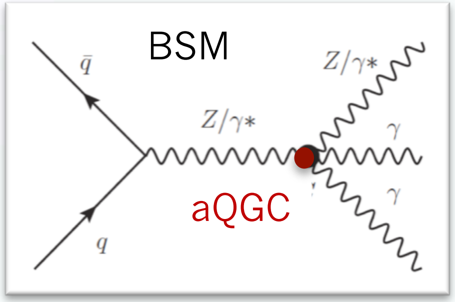


Here: Phys. Rev. Lett. 115, 031802 (2015)
CMS paper: JHEP 10 (2017) 072

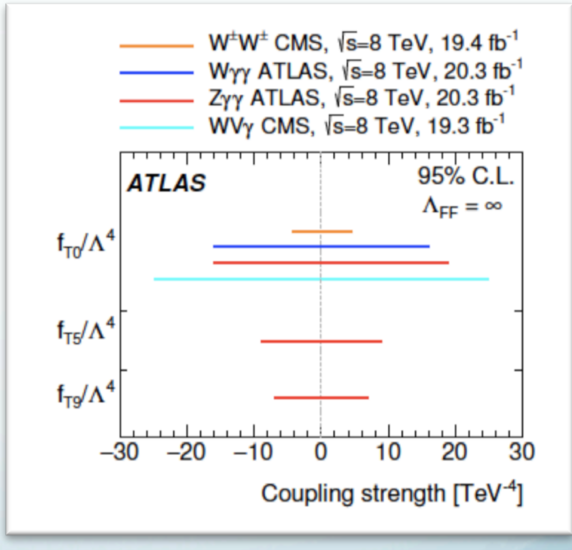
First Triboson measurements: Zγ γ







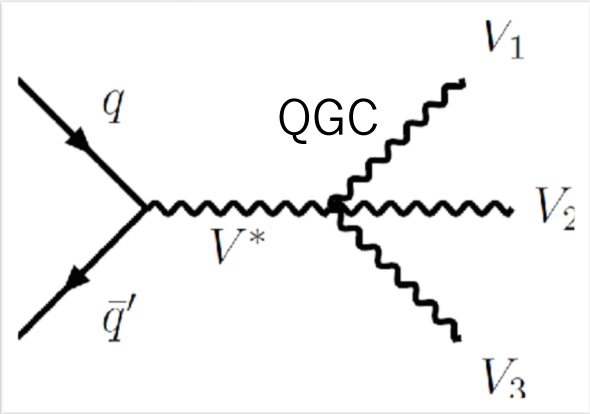
Channel	Measurement [fb]	MCFM Prediction [fb]
$e^+e^-\gamma\gamma$	$6.2\ ^{+1.2}_{-1.1}(\text{stat.}) \pm 0.4(\text{syst.}) \pm 0.1(\text{lumi.})$	$3.70^{+0.21}_{-0.11}$
$\mu^+\mu^-\gamma\gamma$	$3.83\ ^{+0.95}_{-0.85}(\text{stat.})^{+0.48}_{-0.47}(\text{syst.}) \pm 0.07(\text{lumi.})$	
$\ell^+\ell^-\gamma\gamma$	$5.07\ ^{+0.73}_{-0.68}(\text{stat.})^{+0.41}_{-0.38}(\text{syst.}) \pm 0.10(\text{lumi.})$	
$\nu\bar{\nu}\gamma\gamma$	$2.5\ ^{+1.0}_{-0.9}(\text{stat.}) \pm 1.1(\text{syst.}) \pm 0.1(\text{lumi.})$	$0.737^{+0.039}_{-0.032}$



Here: Phys. Rev. D 93, 112002 (2016)
CMS paper: JHEP 10 (2017) 072

Production of 3 massive vector bosons

Production of 3 heavy gauge bosons

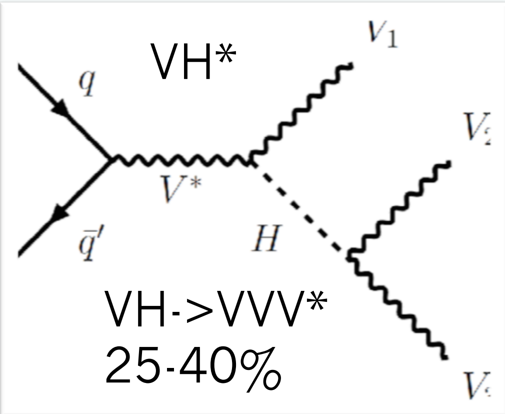


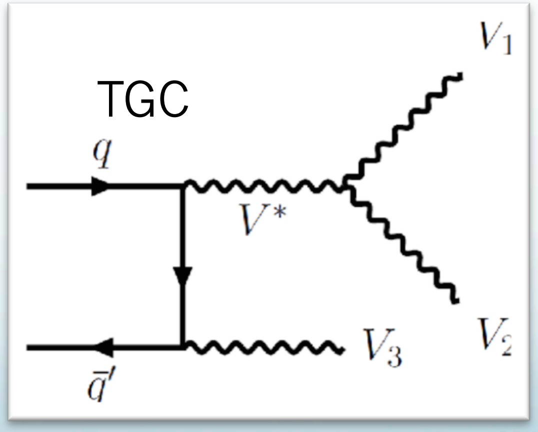
Simulation:

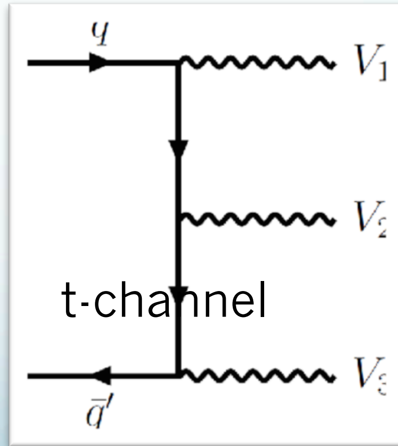
- VVV: Sherpa 2.2.2
- WH → WWW* Powheg+Pythia8
- WH -> WZZ*, ZH → ZWW*: Pythia8

Total cross section:

WWW: 0.50 pb, WWZ: 0.29 pb
uncertainty: 10%







Production of 3 heavy gauge bosons

WWW → **$l^{\pm}\nu+l^{\pm}\nu+qq$** or $l\nu+l\nu+l\nu$ no SFOS: reject backgrounds with Z

WWZ → $l\nu+qq+ll$ or $e\nu+e\nu+ll$ / $\mu\nu+\mu\nu+ll$ / **$e\nu+\mu\nu+ll$**

WZZ → $l\nu+qq+ll$ or $qq+ll+ll$

Here: arXiv:1903.10415, subm to PLB
CMS: search for WWW in 2015/16 data: PRD 100 (2019) 012004

Production of 3 heavy gauge bosons

		1)			2)
WWW	→	**$l^{\pm}\nu+l^{\pm}\nu+qq$**	or	lν+lν+lν	no SFOS: reject backgrounds with Z
WWZ	→	lν+qq+ll	or	eν+eν+ll / μν+μν+ll / **eν+μν+ll**	
WZZ	→	lν+qq+ll	or	qq+ll+ll	
		3)		4)	

Here: arXiv:1903.10415, subm to PLB
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Production of 3 heavy gauge bosons

		1)			2)
WWW	→	**$l^{\pm}\nu+l^{\pm}\nu+qq$**	or	**lν+lν+lν**	no SFOS: reject backgrounds with Z
WWZ	→	lν+qq+ll	or	eν+eν+ll / μν+μν+ll / **eν+μν+ll**	
WZZ	→	lν+qq+ll	or	qq+ll+ll	
		3)		4)	

→ Signatures:

- 1) WWW → **ll+2jets**: **2SS leptons+2jets**, binned in m(jj)
- 2) WWW → 3l: **1 inclusive bin**
- 3) WVZ → 3l+jets 3 BDTs: 3l+1/2/3jets:
- 4) WVZ → 4l (+jets): 3 BDTs: Z + SF ll off-shell / on-shell / **Z+DF ll**

nearly no WZ/ZZ bkg

→ Combined fit of all channels: 186 bins

Data set used: 2015+2016+2017: 80/fb

Here: arXiv:1903.10415, subm to PLB
CMS: search for WWW in 2015/16 data: PRD 100 (2019) 012004

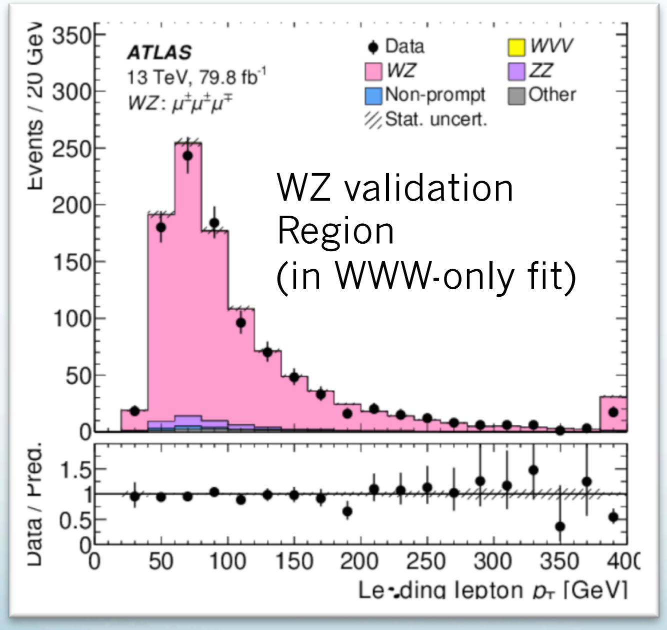
WWW selection

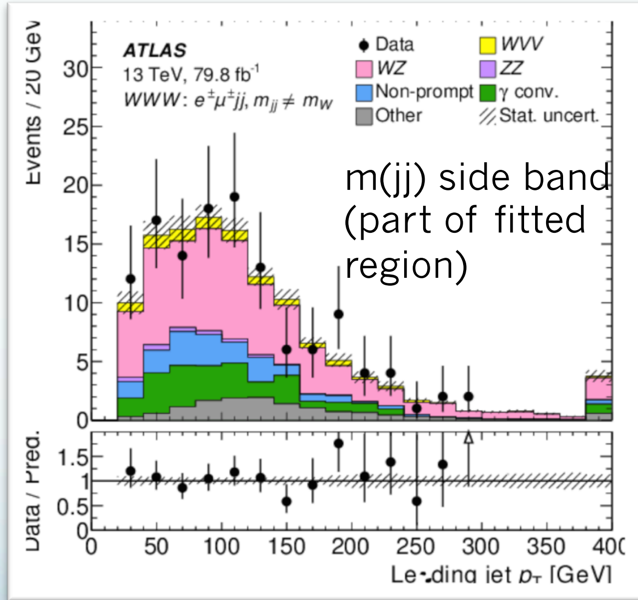
	$WWW \to \ell\nu\ell\nu qq$	$WWW \to \ell\nu\ell\nu\ell\nu$
Lepton	Two leptons with $p_T > 27(20)$ GeV and one same-sign lepton pair	Three leptons with $p_T > 27(20, 20)$ GeV and no same-flavour opposite-sign lepton pairs
$m_{\ell\ell}$	$40 < m_{\ell\ell} < 400$ GeV	–
Jets	At least two jets with $p_T > 30(20)$ GeV and $\lvert\eta\rvert < 2.5$	–
m_{jj}	$m_{jj} < 300$ GeV	–
$\Delta\eta_{jj}$	$\lvert\Delta\eta_{jj}\rvert < 1.5$	–
E_T^{miss}	$E_T^{miss} > 55$ GeV (only for ee)	–
Z boson veto	$m_{ee} < 80$ GeV or $m_{ee} > 100$ GeV (only for ee and μee)	
Lepton veto	No additional lepton with $p_T > 7$ GeV and $\lvert\eta\rvert < 2.5$	
b-jet veto	No b-jets with $p_T > 25$ GeV and $\lvert\eta\rvert < 2.5$	

WWW → **$l^{\pm}\nu+l^{\pm}\nu+qq$** or $l\nu+l\nu+l\nu$ no SFOS: reject backgrounds with Z

WWW: backgrounds

- Dominant WZ → lνll+jets (ll+2jets), lν τ τ (lll)
- → from MC, Jet multiplicity reweighted
- Non-prompt: mostly from ttbar: sample with one fake lepton
- fake factor from b-tagged CR
- Photon conversion in V γ jj: sample with photon-like electron
  fake factor from Z→ μμ γ



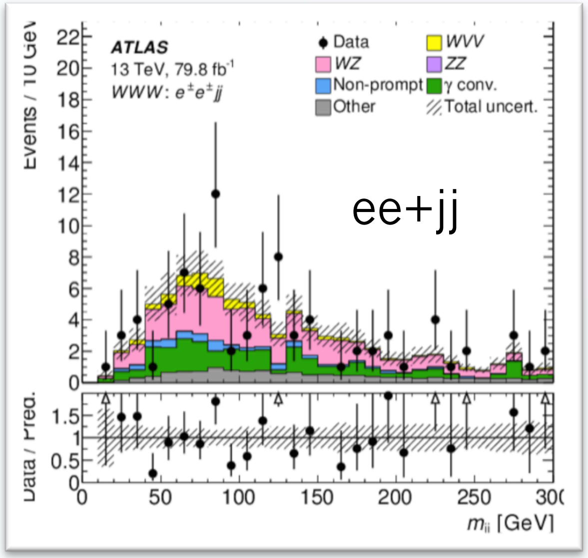


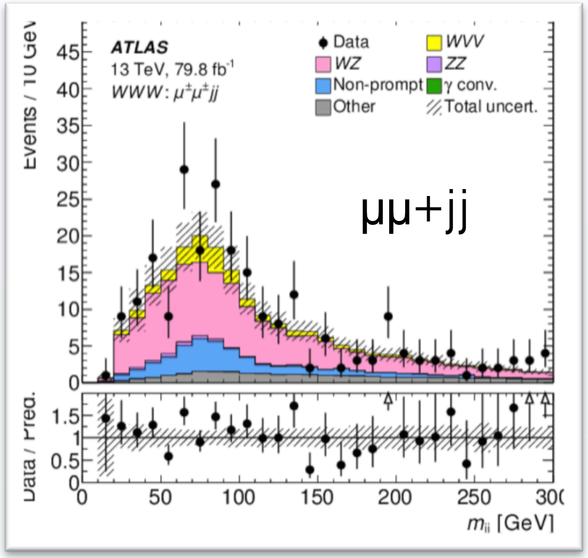
WWW: backgrounds

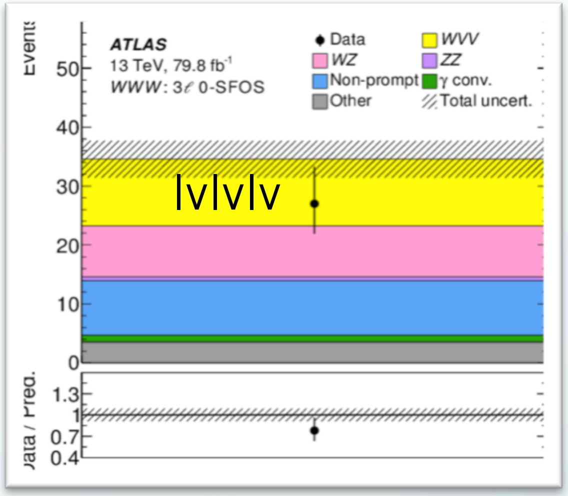
- Dominant WZ → lνll+jets (ll+2jets), lν $\tau\ \tau$ (lll)
- → from MC, Jet multiplicity reweighted
- Non-prompt: mostly from ttbar: sample with one fake lepton
- fake factor from b-tagged CR
- Photon conversion in V γ jj: sample with photon-like electron
  fake factor from Z→ μμ γ

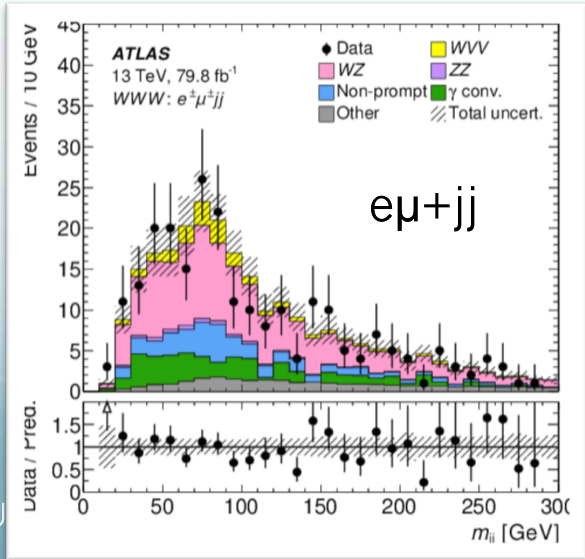
	ee	$e\mu$	μe	$\mu\mu$	$\mu ee + e\mu\mu$
WWW	9.9 ± 3.3	26 ± 9	23 ± 8	30 ± 10	15 ± 5
WZ	37.4 ± 2.2	121 ± 6	96 ± 5	119 ± 6	8.6 ± 0.5
ZZ	0.46 ± 0.05	5.11 ± 0.25	3.44 ± 0.18	4.12 ± 0.24	0.69 ± 0.03
Non-prompt	6.1 ± 3.0	35 ± 5	17 ± 9	37 ± 7	9.4 ± 1.5
γ conv.	20.9 ± 1.9	35.0 ± 3.1	76 ± 7	–	1.06 ± 0.11
Other	12.9 ± 1.0	25.7 ± 1.7	20.3 ± 1.3	25.3 ± 1.6	3.5 ± 0.4
Total	88 ± 4	249 ± 9	237 ± 10	216 ± 9	38 ± 4
Data	87	239	235	237	27

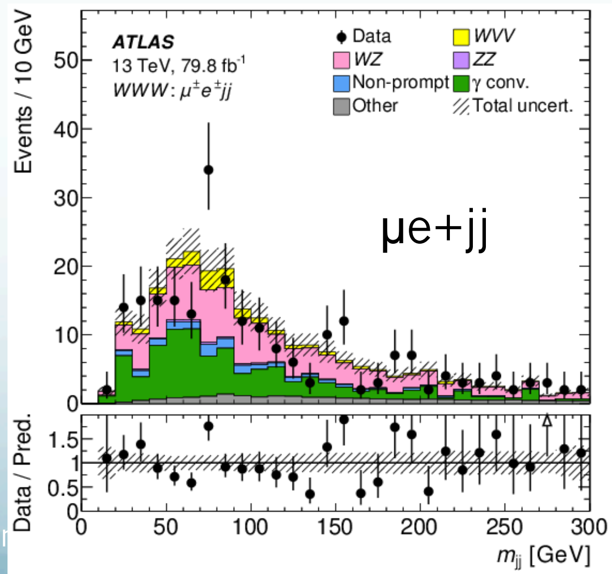
WWW: ll+2jets prefit distributions











WVZ selections

	$WVZ \to \ell\nu qq\ell\ell$	$WVZ \to \ell\nu\ell\nu\ell\ell/qq\ell\ell\ell\ell$
Z boson	At least one OS lepton pair with $\|m_{\ell\ell} - 91.2\,\text{GeV}\| < 10\text{GeV}$	
Low mass veto	$m_{\ell\ell} > 12\,\text{GeV}$ for any OS lepton pair	
b-jet veto	No b-jets with $p_T > 25\,\text{GeV}$ and $\|\eta\| < 2.5$	
Leptons	One additional nominal lepton	One additional OS lepton pair; third and fourth lepton nominal
H_T	$H_T > 200\text{GeV}$	–

WWZ → lv+qq+ll or ev+ev+ll / μv+μv+ll / **ev+μv+ll**

WZZ → lv+qq+ll or qq+ll+ll

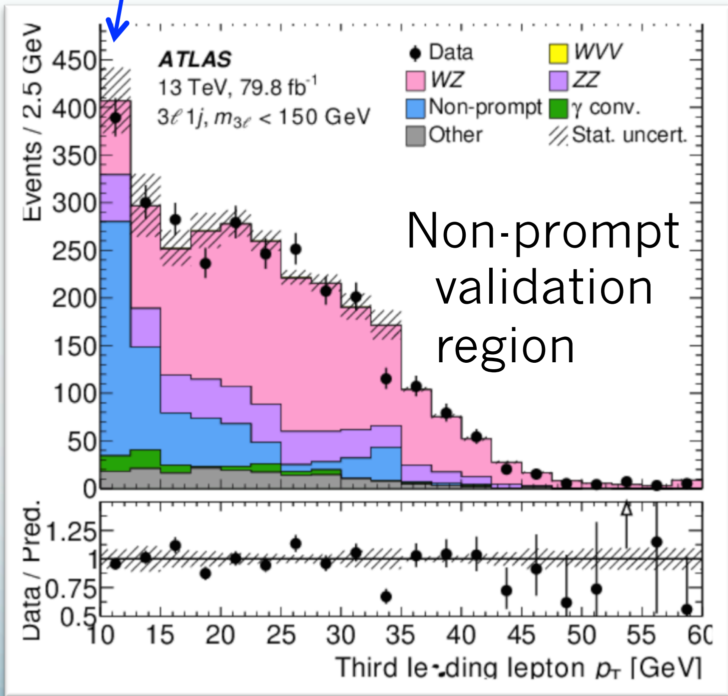
WVZ backgrounds

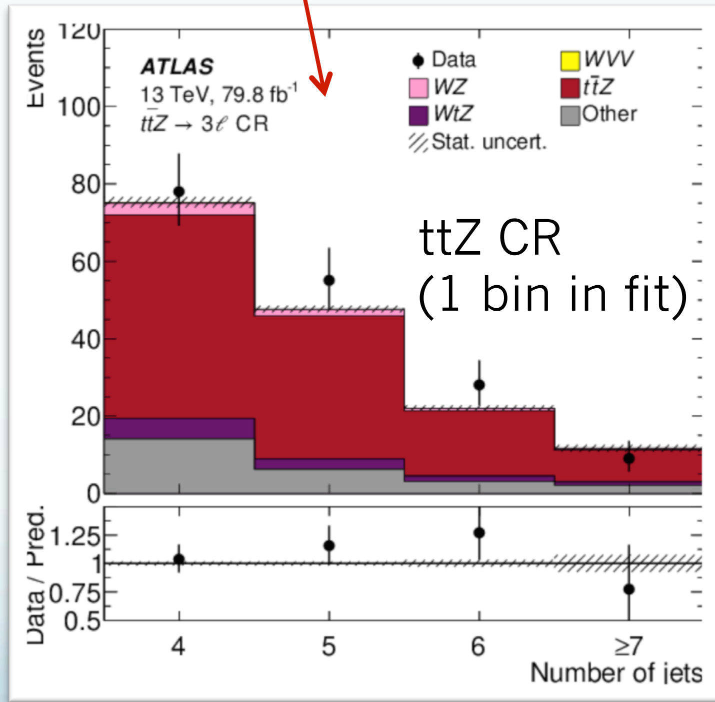
- All backgrounds estimated from MC
- Dominant: ZZ (4l channels), WZ (3l channels):
  → MC jet multiplicity reweighted

	4ℓ-DF	4ℓ-SF-Z	4ℓ-SF-noZ	3ℓ-1j	3ℓ-2j	3ℓ-3j	$t\bar{t}Z$ CR
WVZ	9.6 ± 3.5	5.0 ± 1.8	10 ± 4	62 ± 23	85 ± 30	84 ± 30	–
WZ	1.11 ± 0.13	–	1.08 ± 0.14	2580 ± 80	1830 ± 60	1110 ± 50	5.7 ± 0.4
ZZ	6.7 ± 0.4	933 ± 28	310 ± 10	344 ± 12	182 ± 13	98 ± 12	0.58 ± 0.06
$t\bar{t}Z$	5.1 ± 0.5	0.55 ± 0.08	4.5 ± 0.5	7.6 ± 1.1	22.6 ± 2.5	82 ± 8	122 ± 9
tWZ	1.9 ± 0.4	0.23 ± 0.10	1.6 ± 0.4	4.2 ± 0.9	11.2 ± 2.2	20 ± 4	10.3 ± 0.8
Non-prompt	–	–	0.18 ± 0.12	130 ± 50	77 ± 28	59 ± 24	0.47 ± 0.18
γ conv.	–	–	–	42 ± 8	32 ± 7	9.6 ± 3.4	0.4 ± 0.6
Other	0.4 ± 0.4	1.8 ± 1.1	1.0 ± 0.7	200 ± 15	182 ± 16	120 ± 10	24.4 ± 2.5
Total	24.8 ± 3.5	941 ± 27	329 ± 10	3370 ± 70	2430 ± 40	1580 ± 40	160 ± 10
Data	28	912	360	3351	2438	1572	170

WVZ backgrounds

- All backgrounds estimated from MC
- Dominant: ZZ (4l channels), WZ (3l channels):
  → MC jet multiplicity reweighted
- ttZ: CR without HT cut, 3l+4jets (at least 2b tags), added to fit (1bin)
- Non-prompt: WZ+jets, Z+jets: validated in region w/o HT cut, low pt(l3)



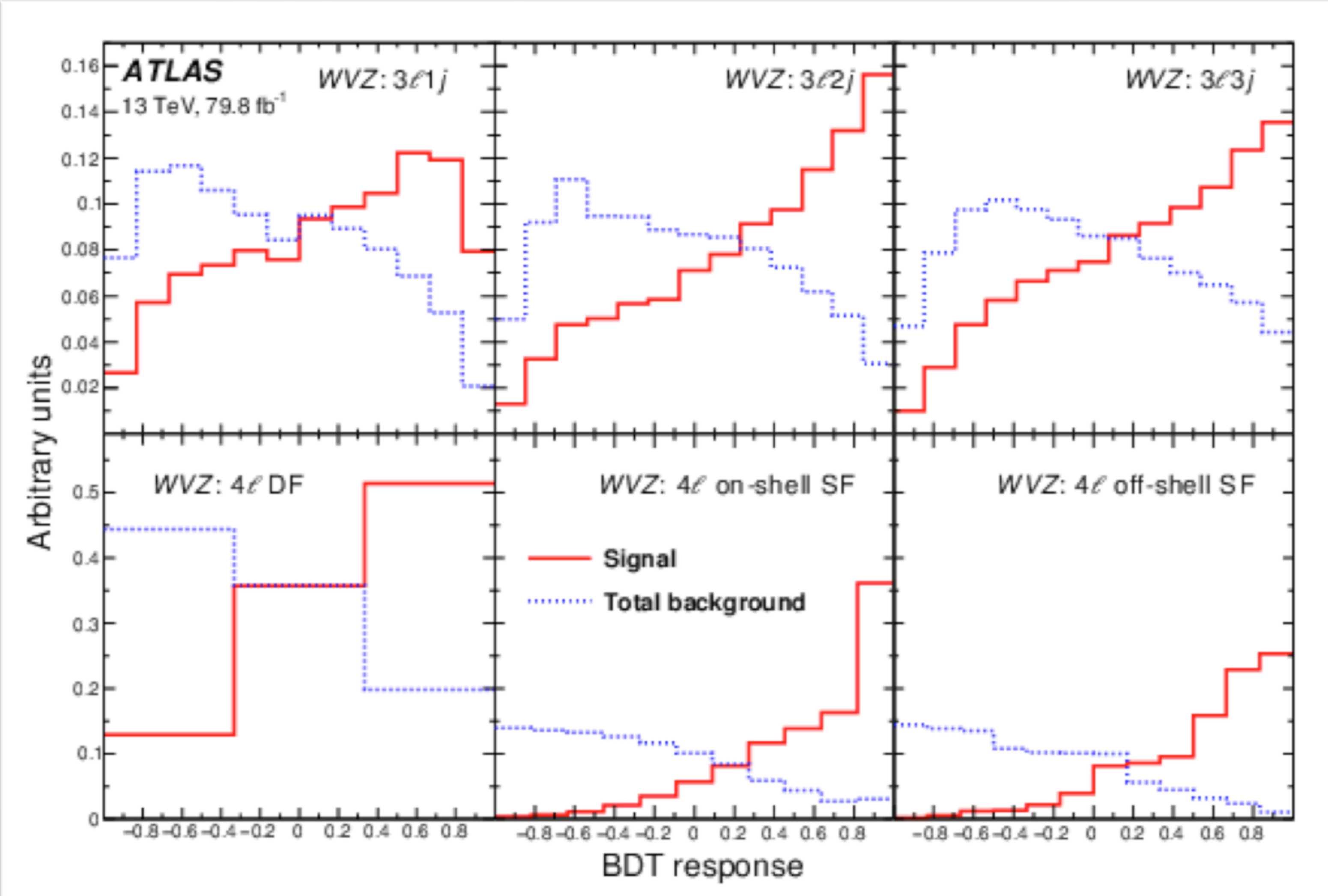


WVZ BDTs

Variable	3ℓ-1j	3ℓ-2j	3ℓ-3j	4ℓ DF	4ℓ SF on-shell	4ℓ SF off-shell
$p_{\mathrm{T}}(\ell_1)$	×	×				
$p_{\mathrm{T}}(\ell_2)$	×	×	×			
$p_{\mathrm{T}}(\ell_3)$	×	×	×			
Sum of $p_{\mathrm{T}}(\ell)$	×	×	×			
$m_{\ell_1\ell_2}$	×	×				
$m_{\ell_1\ell_3}$	×	×				
$m_{\ell_2\ell_3}$	×	×				
$m_{\ell\ell}$ of best Z					×	×
$m_{\ell\ell}$ of other leptons				×	×	×
$m_{3\ell}$	×	×	×			
$m_{4\ell}$				×	×	×
Sum of lepton charges	×	×	×			
$p_{\mathrm{T}}(j_1)$	×	×				
$p_{\mathrm{T}}(j_2)$		×	×			
Sum of $p_{\mathrm{T}}(j)$			×			
Number of jets			×	×	×	×
$m_{j_1j_2}$		×				
$m_{\mathrm{T}}(W_\ell)$		×				
m_{jj} of best W			×			
Smallest m_{jj}			×			
$E_{\mathrm{T}}^{\mathrm{miss}}$		×	×	×	×	×
H_{T}	×	×			×	×
Leptonic H_{T}				×		
Hadronic H_{T}				×		
Invariant mass of all leptons, jets and $E_{\mathrm{T}}^{\mathrm{miss}}$	×		×			
Invariant mass of the best Z leptons and j_1	×					

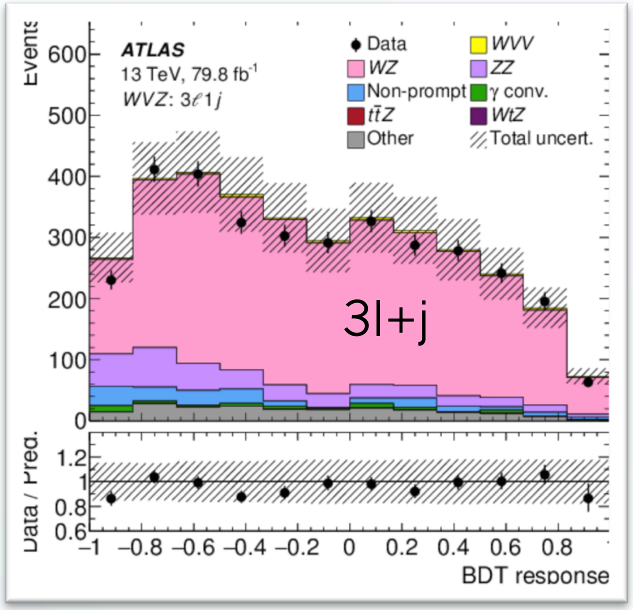
1 BDT per signal region

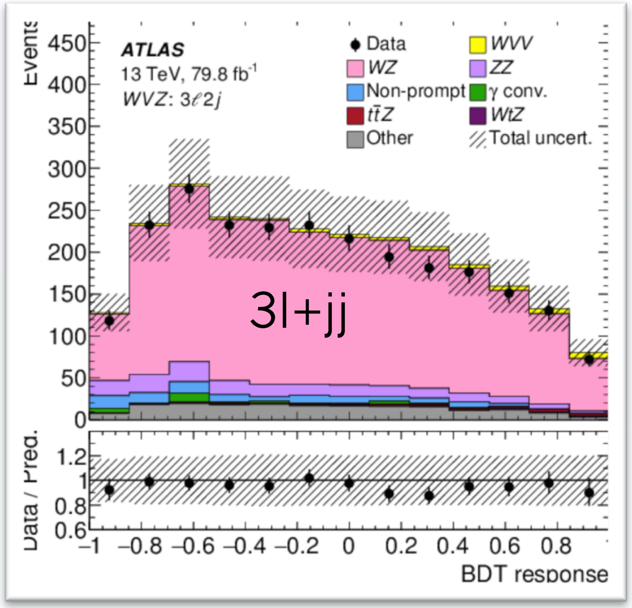
WVZ BDTs

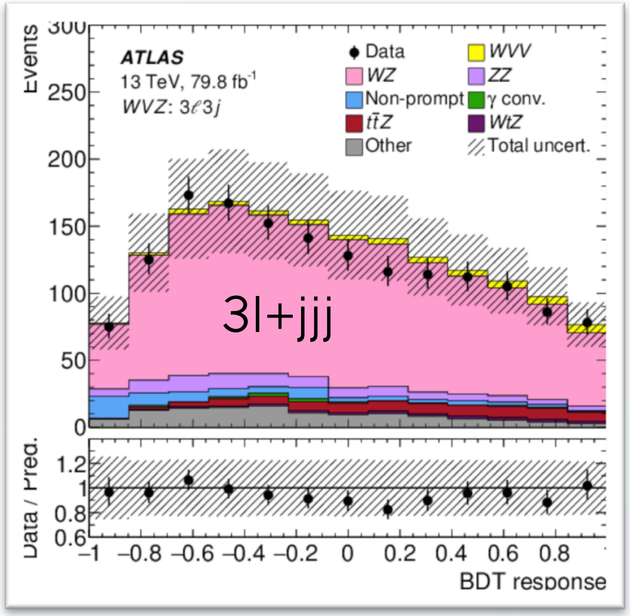


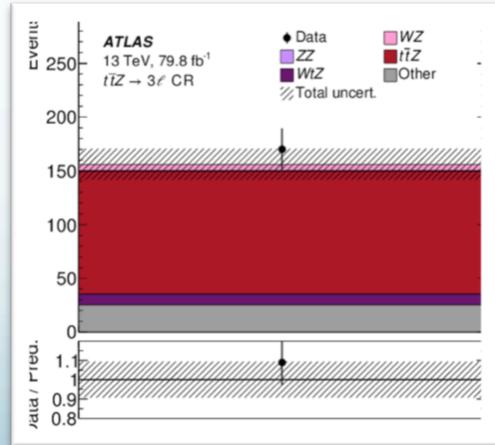
ATLAS
13 TeV, 79.8 fb^{-1}
WVZ: 3ℓ1j
WVZ: 3ℓ2j
WVZ: 3ℓ3j
WVZ: 4ℓ DF
WVZ: 4ℓ on-shell SF
WVZ: 4ℓ off-shell SF
Signal
Total background
Arbitrary units
BDT response

WVZ prefit distributions: 3l +jets

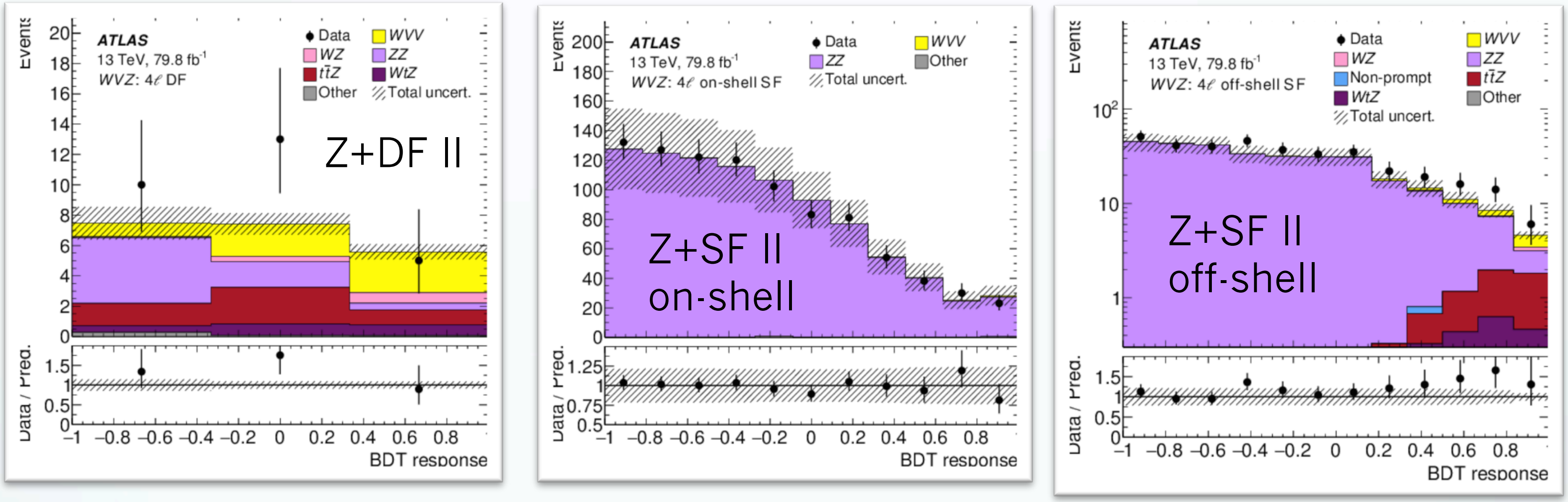






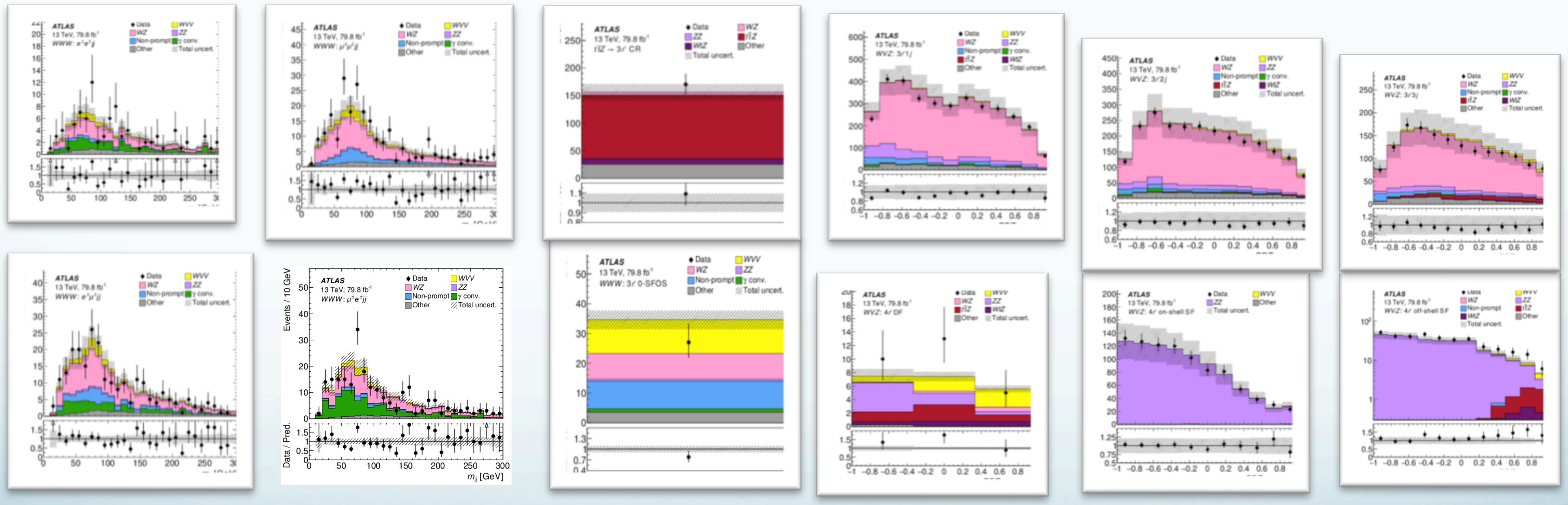


WVZ prefit distributions: 4l channels



Global fit

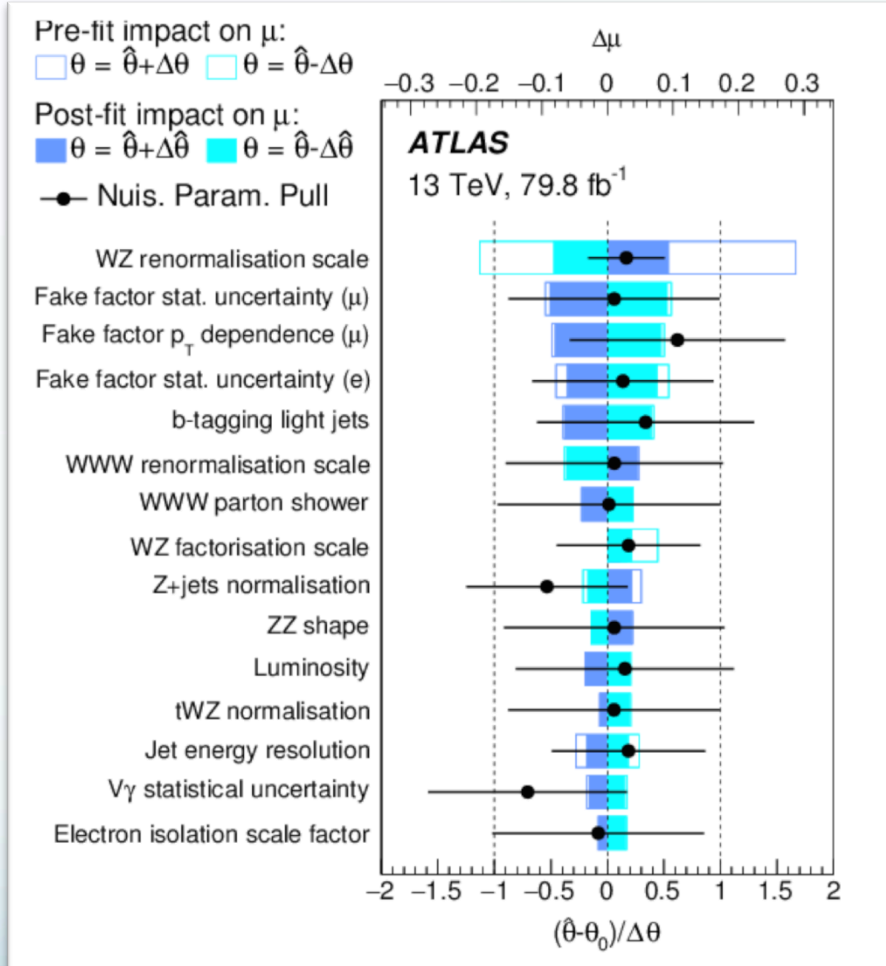
- Profile LLH: 186 bins in 12 regions
- Common signal strength μ fitted for all VVV processes
- Simulated backgrounds: 10%-40% normalisation uncertainty priors
- Shape uncertainties: alternate samples, fac/ren scale uncertainties
- Stat & syst uncertainties on data-driven backgrounds
- Experimental uncertainties on signal & background samples
- Signal shape uncertainties: fac/ren scale, PDF, matching



... additional WWW-only (incl WZ CR) and WWZ-only fits

Global fit: uncertainties

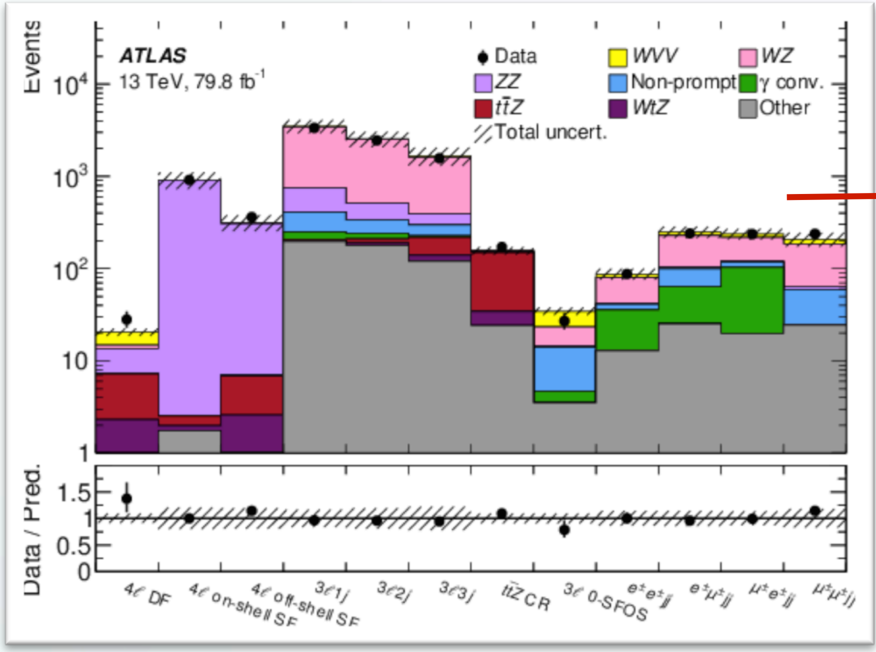
Uncertainty source	$\Delta\mu_{WVV}$	
Data-driven	+0.14	−0.14
Theory	+0.15	−0.13
Instrumental	+0.12	−0.09
MC stat. uncertainty	+0.06	−0.04
Generators	+0.04	−0.03
Total systematic uncertainty	+0.30	−0.27

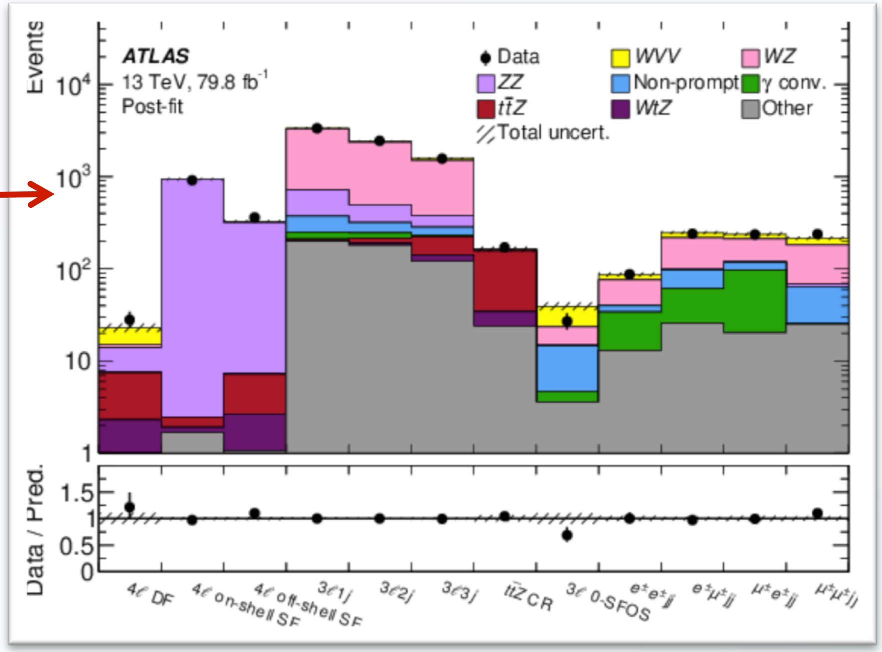


Largest post-fit impact on μ:

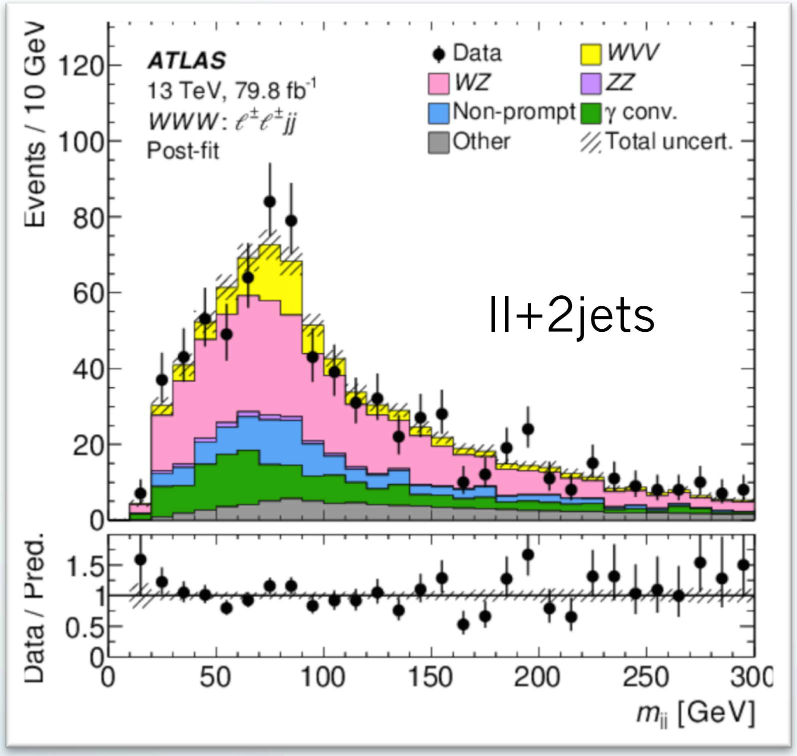
- non-prompt background
- WZ/ZZ shape (constrained in fit)
- VVV modelling

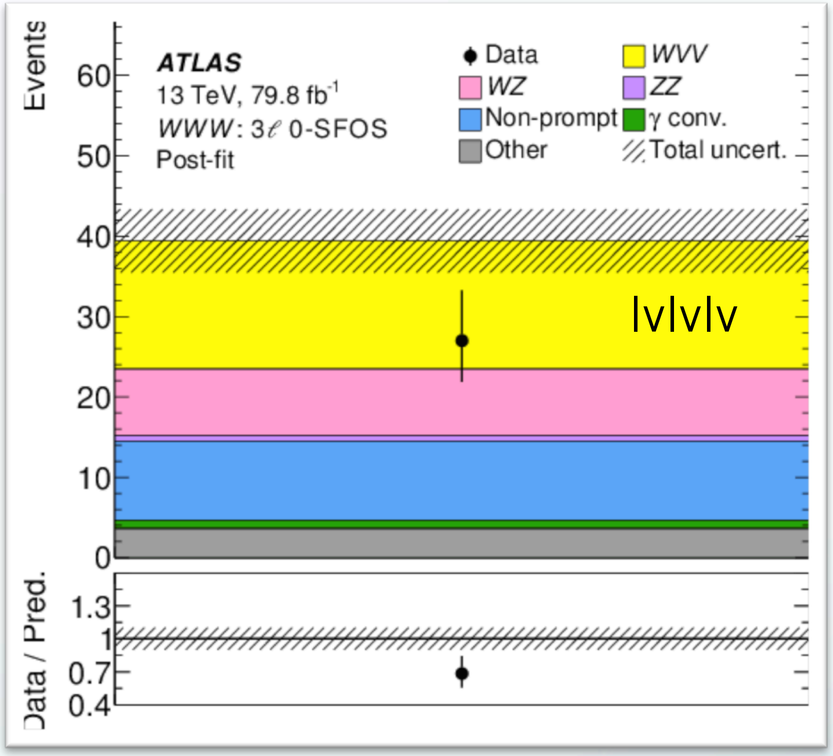
Global fit: summary



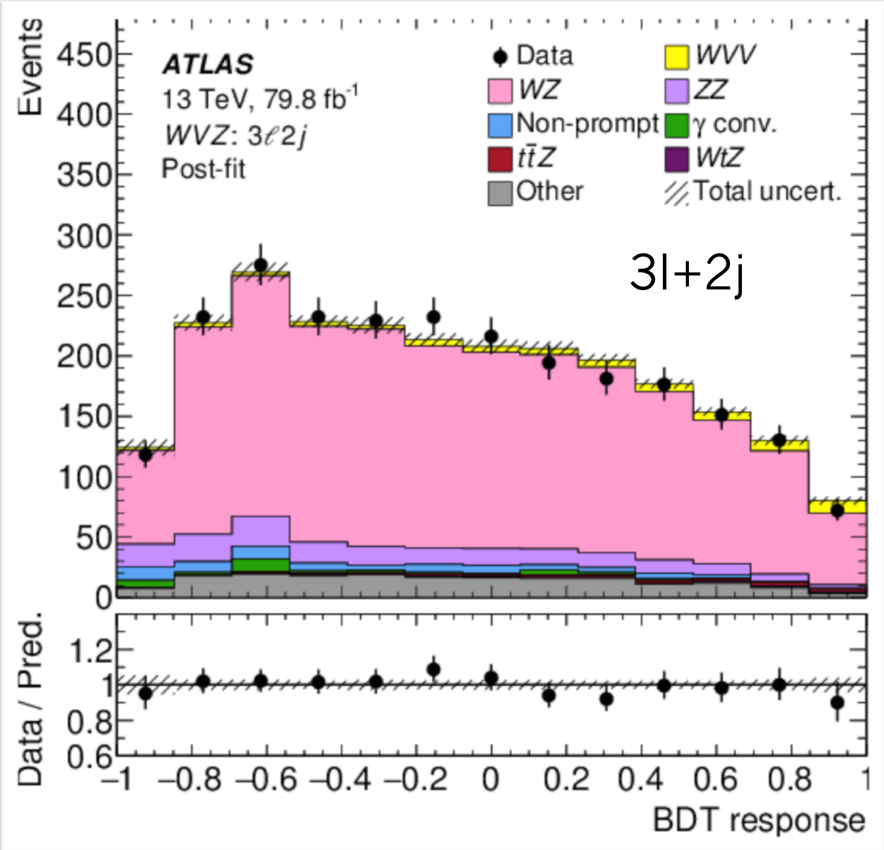


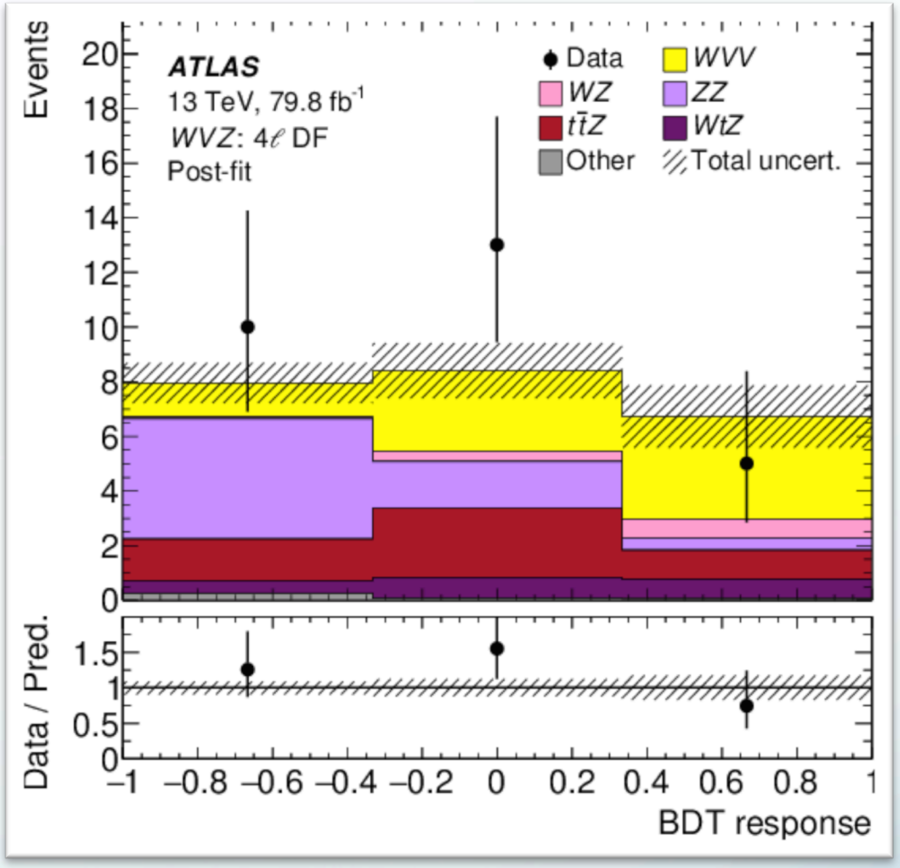
Global fit: post-fit distributions WWW



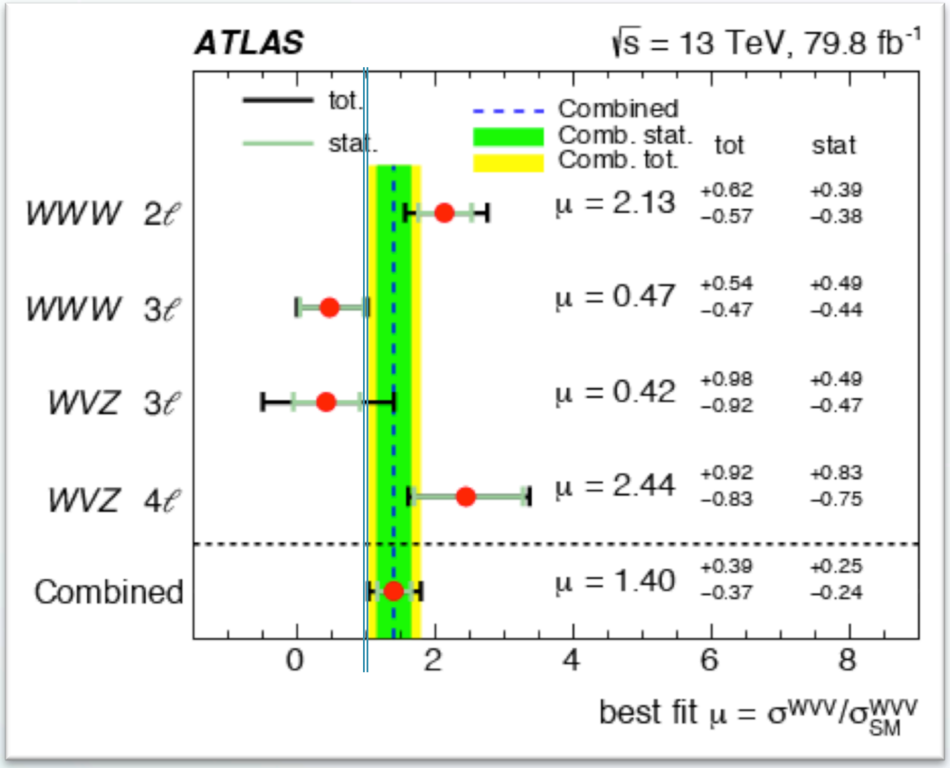


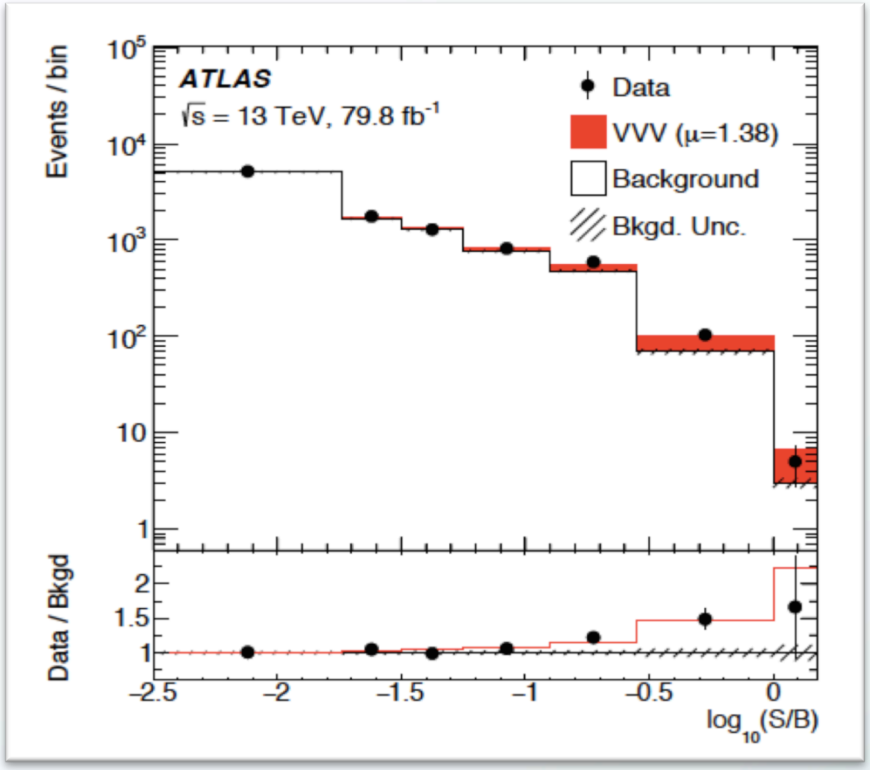
Global fit: post-fit distributions WVZ





Signal strength





Signal strength compatible with SM expectation

Data stat unc and syst unc
At the same level

Events sorted according to S/B of the final discriminant → accumulation of data in bins with high S/B

Significance

First evidence for the joint production of 3 heavy gauge bosons

Decay channel	Significance	
	Observed	Expected
WWW combined	3.3σ	2.4σ
$WWW \to \ell\nu\ell\nu qq$	4.3σ	1.7σ
$WWW \to \ell\nu\ell\nu\ell\nu$	1.0σ	2.0σ
WVZ combined	2.9σ	2.0σ
$WVZ \to \ell\nu qq\ell\ell$	–	1.0σ
$WVZ \to \ell\nu\ell\nu\ell\ell/qq\ell\ell\ell\ell$	3.5σ	1.8σ
VVV combined	4.0σ	3.1σ

Fiducial cross sections

Fitted signal strengths from individual WWW and WWZ fits are converted into fiducial cross sections using the theoretical NLO cross sections from the signal samples.
Assuming SM cross section for WZZ.
Post-fit uncertainties from fit except signal normalisation.

$$\sigma_{WWW} = 0.65^{+0.16}_{-0.15}\,(\text{stat.})\,^{+0.16}_{-0.14}\,(\text{syst.})\text{ pb}$$

$$\sigma_{WWZ} = 0.55 \pm 0.14\,(\text{stat.})\,^{+0.15}_{-0.13}\,(\text{syst.})\text{ pb}$$

Stat and syst uncertainties contribute equally

Expected σ WWW: 0.50 ± 0.05 pb, σ WWZ: 0.29±0.03 pb

Summary

- ◆ First evidence for the production of 3 heavy gauge bosons.
- ◆ Dominated by WWW and WWZ channels.
- ◆ Most sensitive channels: WWW: ss ll+2jets, WVZ: Z+DF lepton pair
- ◆ Dominant backgrounds form WZ and ZZ
- ◆ Dominant syst uncertainties from WZ/ZZ shapes and non-promt bkg
- ◆ Currently equal contributions from stat and syst uncertainty

→ Expect improvement using the full Run2 data set of 139/fb

Parametrizing new physics

EFT approach

$$\mathcal{L}^{\text{eff.}} = \mathcal{L}^{\text{SM}} + \sum_i \frac{c_6^i}{\Lambda^2}\mathcal{O}_6^i + \sum_i \frac{c_8^i}{\Lambda^4}\mathcal{O}_8^i + \cdots$$

Only applicable for scales << Λ

Λ: scale of new physics
SM: Λ -> oo

Fermi theory of the 21st century

Example: Operators for WWV:

CP conserving:

$$\begin{aligned}\mathcal{O}_{WWW} &= \mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W_\rho^\mu] \\ \mathcal{O}_W &= (D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi) \\ \mathcal{O}_B &= (D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi)\end{aligned}$$

C/P violating:

$$\begin{aligned}\mathcal{O}_{\tilde{W}WW} &= \mathrm{Tr}[\tilde{W}_{\mu\nu}W^{\nu\rho}W_\rho^\mu] \\ \mathcal{O}_{\tilde{W}} &= (D_\mu\Phi)^\dagger \tilde{W}^{\mu\nu}(D_\nu\Phi)\end{aligned}$$

In practice, we constrain c_i/Λ^2

- → **Observes the symmetries of the Standard Model**
- → **Higher dimensional terms are automatically suppressed by $1/\Lambda^2$**
- → **Perturbative expansion in $1/\Lambda^2$ possible, renormalizable**

Parametrizing new physics

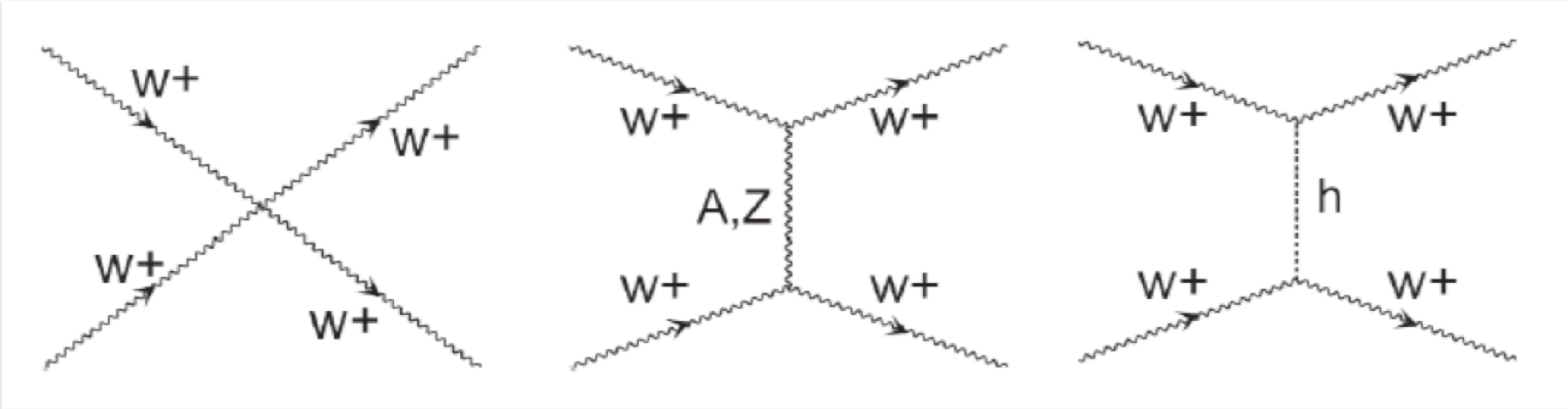
Quartic Gauge couplings:

- Dim6 and Dim8 operators
- Dim 6 operators already constrained by TGC constraints
- Independent: Dim8 operators:

$$O_{S,0} = [(D_\mu\Phi)^\dagger D_\nu\Phi] \times [(D^\mu\Phi)^\dagger D^\nu\Phi]$$
$$O_{S,1} = [(D_\mu\Phi)^\dagger D^\mu\Phi] \times [(D_\nu\Phi)^\dagger D^\nu\Phi]$$
$$O_{S,2} = [(D_\mu\Phi)^\dagger D_\nu\Phi] \times [(D^\nu\Phi)^\dagger D^\mu\Phi]$$
$$O_{M,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$
$$O_{M,1} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$
$$O_{M,2} = \left[\hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$
$$O_{M,3} = \left[\hat{B}_{\mu\nu}\hat{B}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$
$$O_{M,4} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\mu\Phi\right] \times \hat{B}^{\beta\nu}$$
$$O_{M,5} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\nu\Phi\right] \times \hat{B}^{\beta\mu}(+h.c.)$$
$$O_{M,7} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu} D^\nu\Phi\right]$$

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

Boson scattering



$$\mathcal{M}_{Gauge} = -g^2 \frac{s}{4M_W^2} + \mathcal{O}(s^0)$$

$$\mathcal{M}_H = g^2_{HWW} \frac{s}{M_W^4} + \mathcal{O}(s^0)$$

s = squared center-of-mass energy of the interacting bosons

Without the Higgs contribution the cross section diverges for high energies

→ **Higgs contribution cancels divergence if Higgs couples proportional to W mass: $g_{HWW} = gM_W$ … as expected from SM Higgs**

$$\mathcal{M}_{Gauge} + \mathcal{M}_H = g^2 \frac{M_H^2}{4M_W^2}$$

Similar for W+W- scattering, WZ scattering, etc