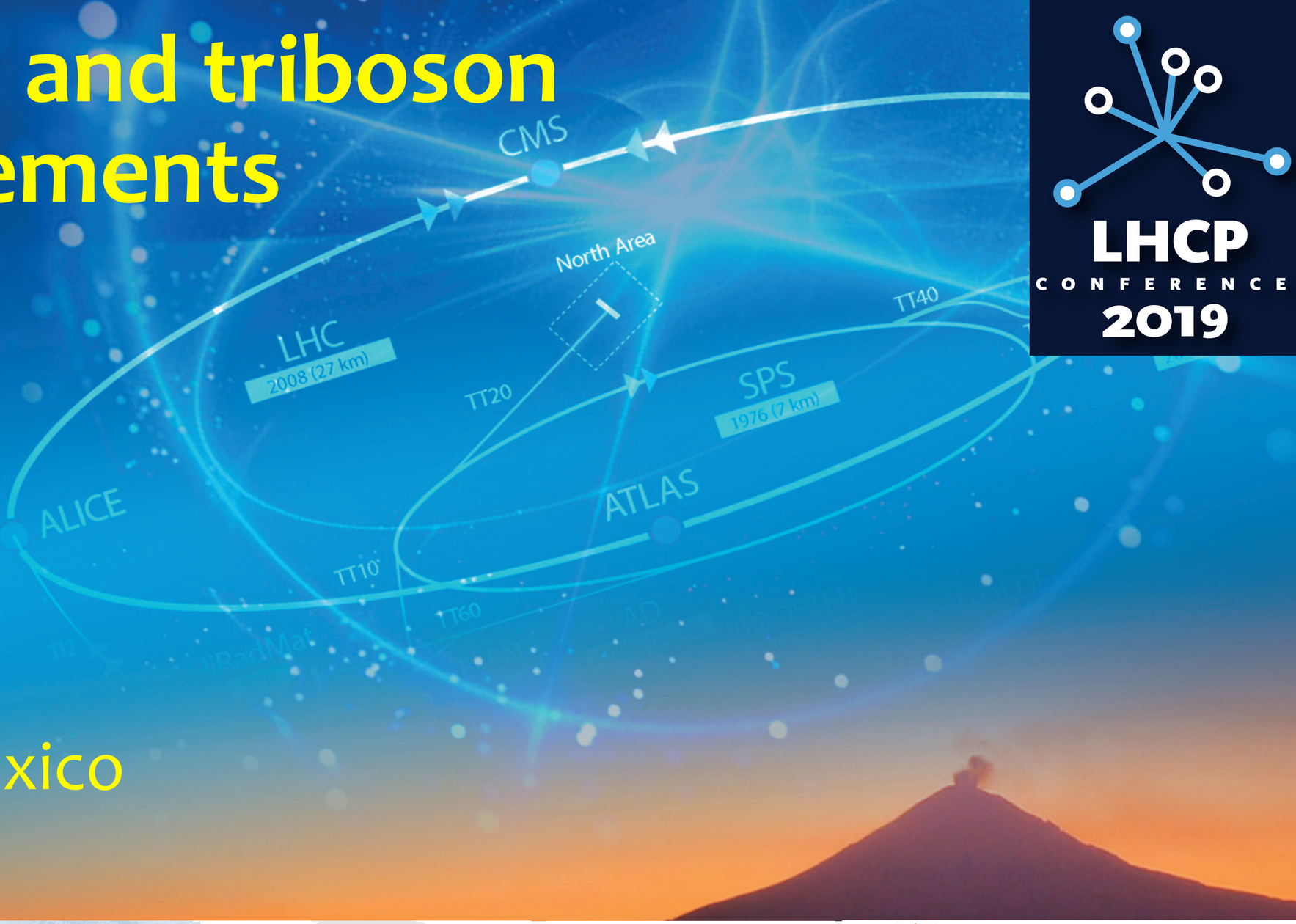
Diboson and triboson measurements



LHCP CONFERENCE 2019

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Universität Bonn

LHCP@Puebla, México
20–25 May 2019

BMBF-Forschungsschwerpunkt
ATLAS-EXPERIMENT
Physik bei höchsten Energien mit dem ATLAS-Experiment am LHC
FSP 103 ATLAS
Bundesministerium für Bildung und Forschung
erc
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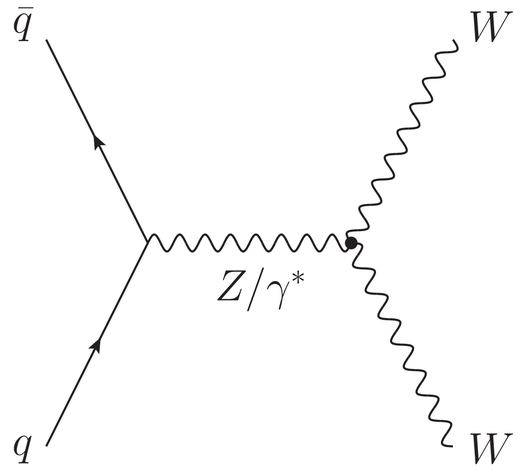
Analyses presented today

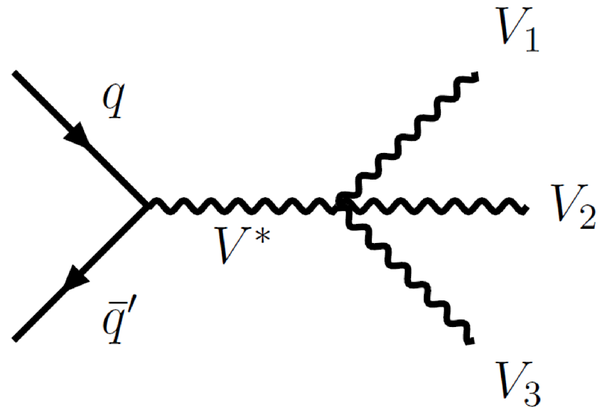
Diboson – using 2015–2016 data (36.1 fb^{-1})

- WW → $e^{\pm}\nu\mu^{\mp}\nu$ 1905.04242
- WZ → $\ell'\nu\ell\ell$ 1902.05759
- ZZ → $\ell\ell\nu\nu$ 1905.07163
- 4ℓ inclusive JHEP 04 (2019) 048



Triboson – using 2015–2017 data (79.8 fb^{-1})

- WWW → $\ell\nu\ell\nu\ell\nu$, $\ell\nu\ell\nu qq$ 1903.10415
- WVZ → $\ell\nu qq\ell\ell$, $\ell\nu\ell\nu\ell\ell$, $qq\ell\ell\ell\ell$ 1903.10415



Cross section

Motivation

- test of pQCD, EWK corrections, constrain aTGC/EFT

Measured in fiducial volume and extrapolated to total phase space

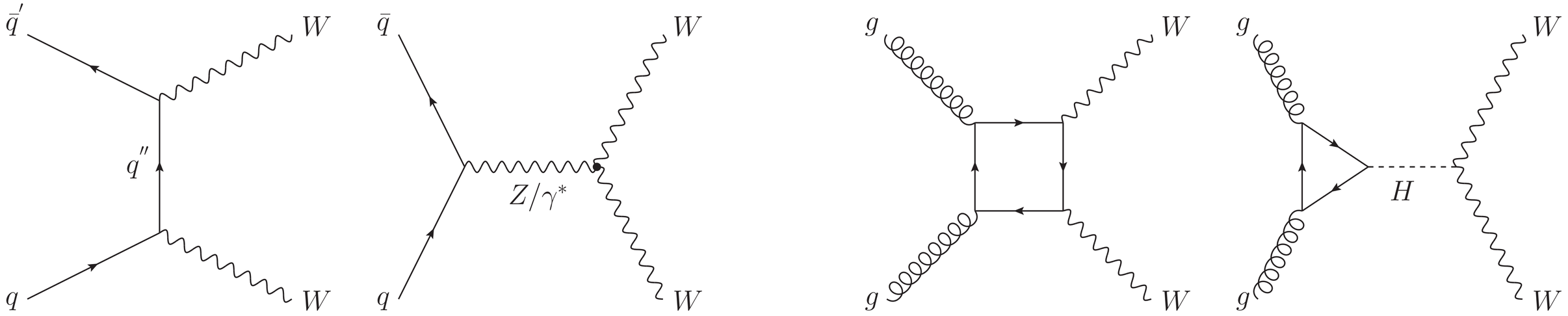
$$\sigma_{\text{fid}} = \frac{N_{\text{data}} - N_{\text{bkg}}}{\mathcal{L} \cdot C} \qquad \sigma_{\text{tot}} = \frac{N_{\text{data}} - N_{\text{bkg}}}{\mathcal{L} \cdot C \cdot A}$$

- C corrects for detector inefficiency and resolution
- A is the signal acceptance in the fiducial volume

Differential measurements

- background subtracted kinematic distributions
- corrected from detector effects

Dibosons: WW



WW→eμνν

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Highlights

- investigation of long-standing discrepancies with predictions
- first differential diboson measurement at 13 TeV

Analysis

- eμ final state, veto jet ($p_T > 35$ GeV) and b-jets
- unfolded differential cross sections in:
  - $p_T(\ell_1)$, $p_T(e\mu)$, $m_{e\mu}$
  - $|y_{e\mu}|$, $\Delta\varphi_{e\mu}$, $|\cos\theta^*| = |\tanh(\Delta\eta_{e\mu}/2)|$
- σ(fid.) also as function of veto jet p_T
- aTGC limits from unfolded $p_T(\ell_1)$ in EFT framework

WW→eμνν

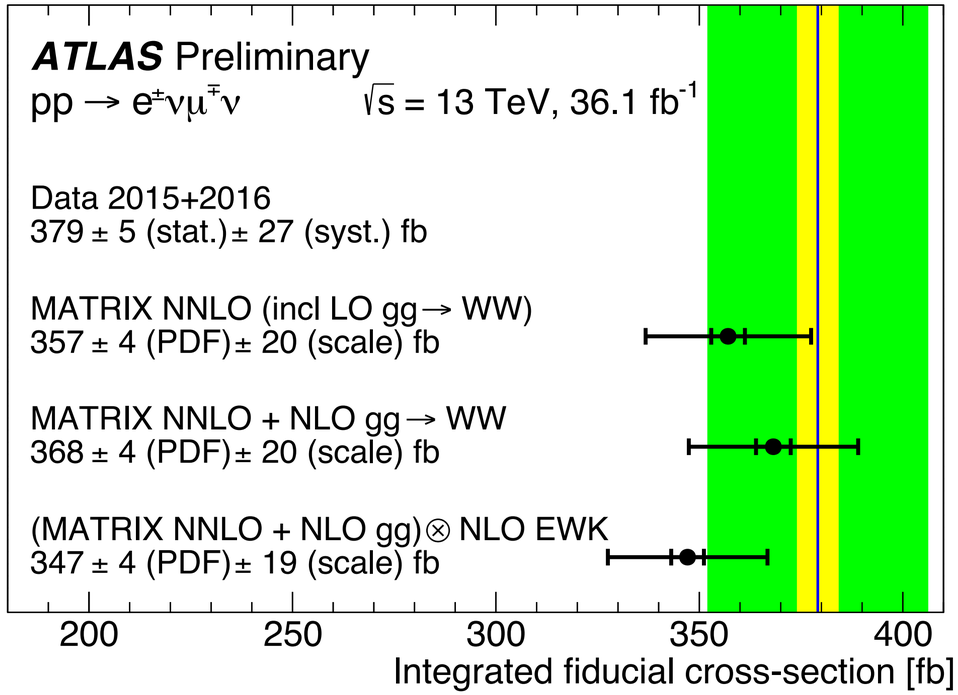
Fiducial cross section

- compared to MATRIX NNLO

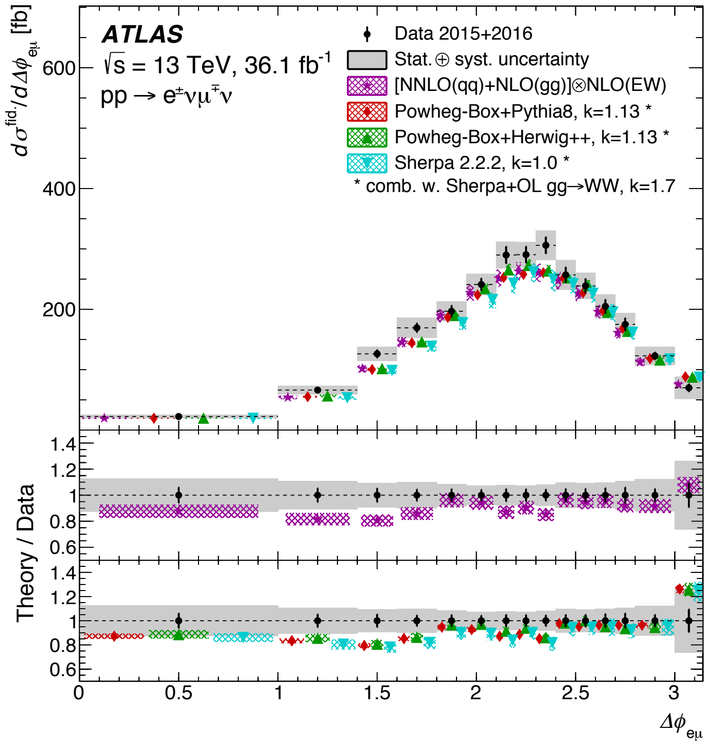
Uncertainties

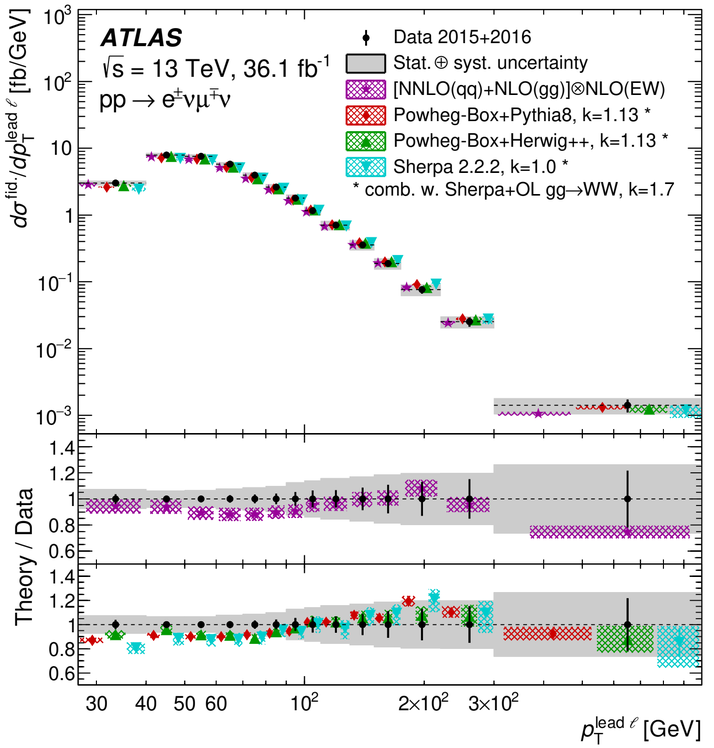
- 1.3% stat.; 6.7% syst., 2.1% lumi.

$$\sigma_{\text{fid}} = (379.1 \pm 5.0\,(\text{stat}) \pm 25.4\,(\text{syst}) \pm 8.0\,(\text{lumi}))\ \text{fb}$$



Differential cross section

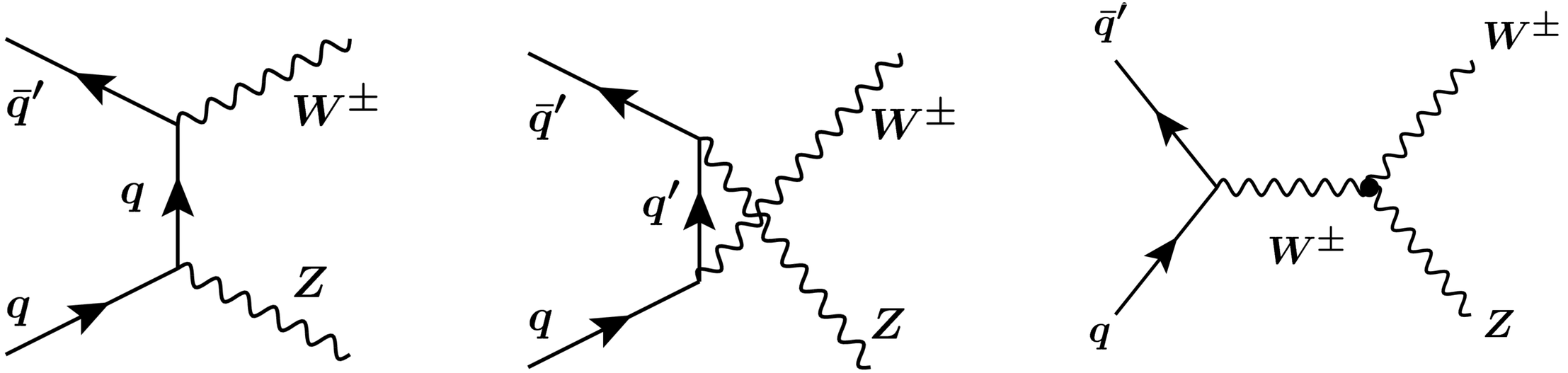




Limits on EFT from $p_T(\ell_1)$ distribution

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]

Dibosons: WZ



$WZ \to \ell\nu\ell'\ell'$

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Selection

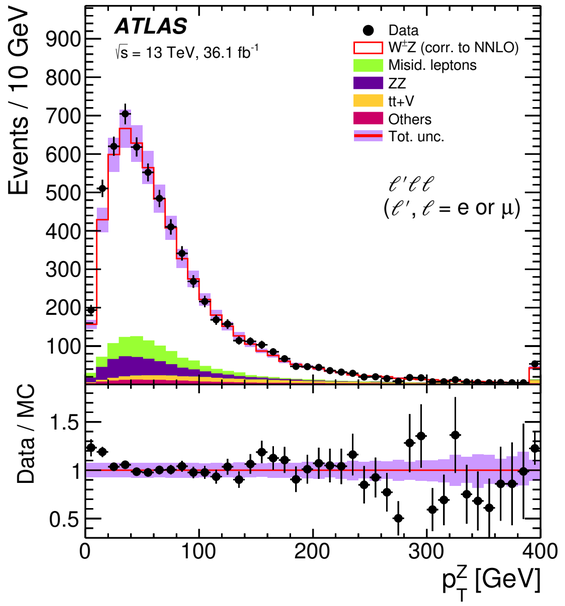
- one OSSF 2ℓ compatible with m_Z
- $m_T^W > 30$ GeV

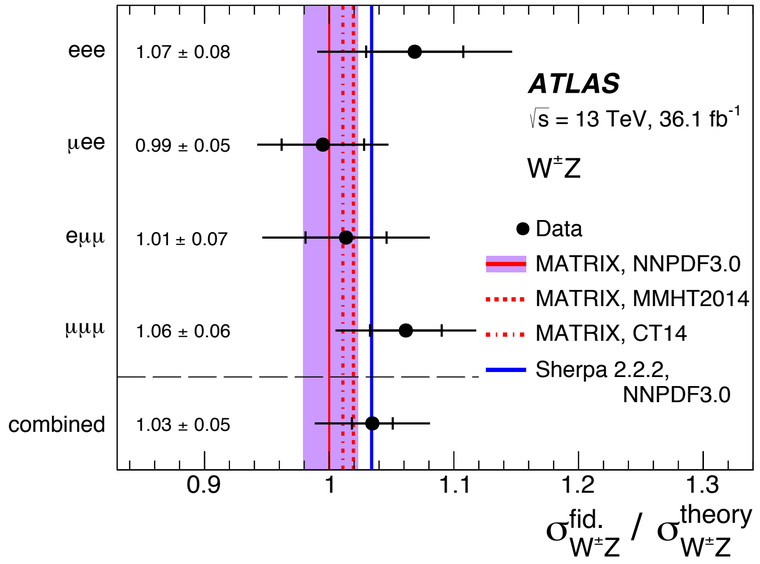
Backgrounds

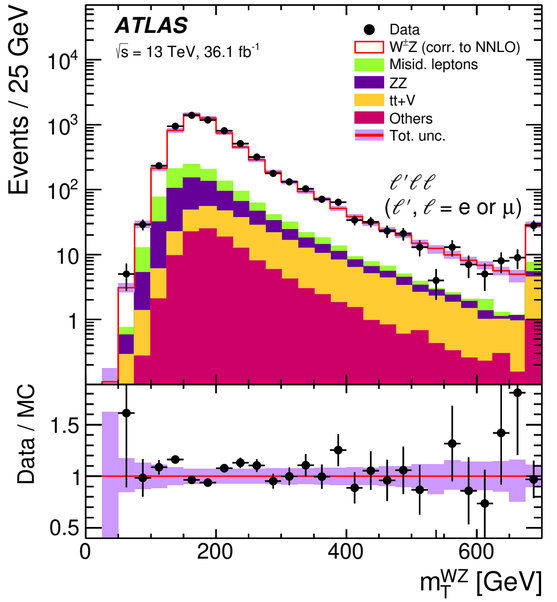
- misid. leptons, ZZ, $t\bar{t}$+X

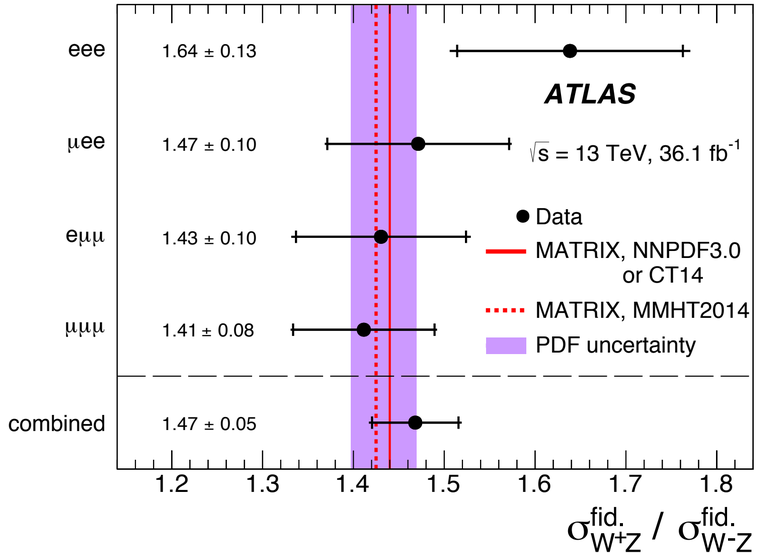
Fiducial cross section

- compared with models
- differential in
  - $p_T(Z)$, $p_T(W)$, $p_T(\nu)$, $m_T(WZ)$
  - $\Delta\varphi(W,Z)$
  - n_{jets}, m_{jj} (anti-k_T; R=0.4; $p_T > 25$ GeV)
  - $|y_Z - y_{\ell,W}|$



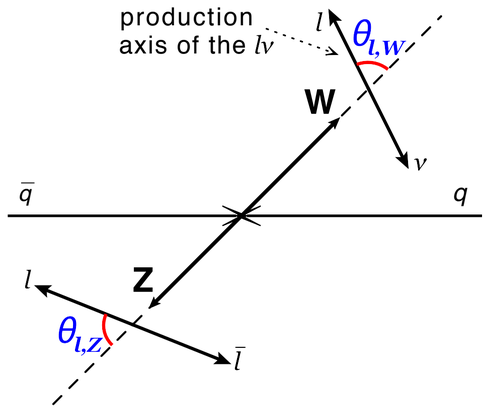






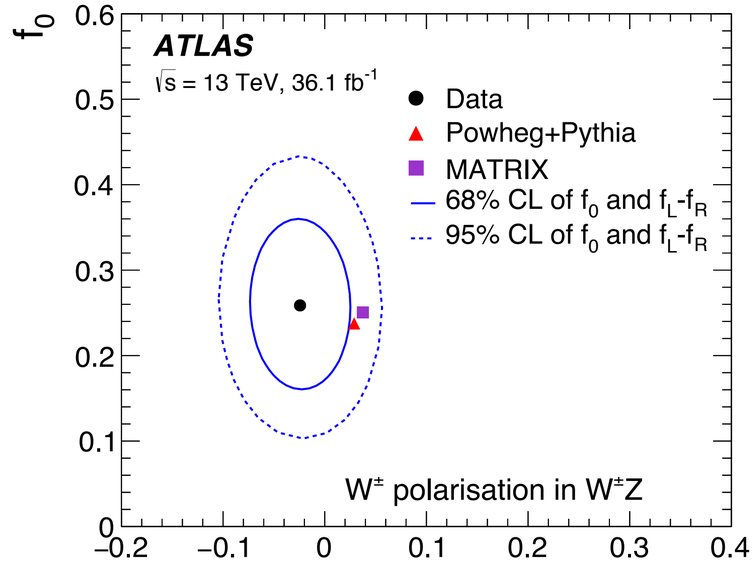
WZ production – polarisation

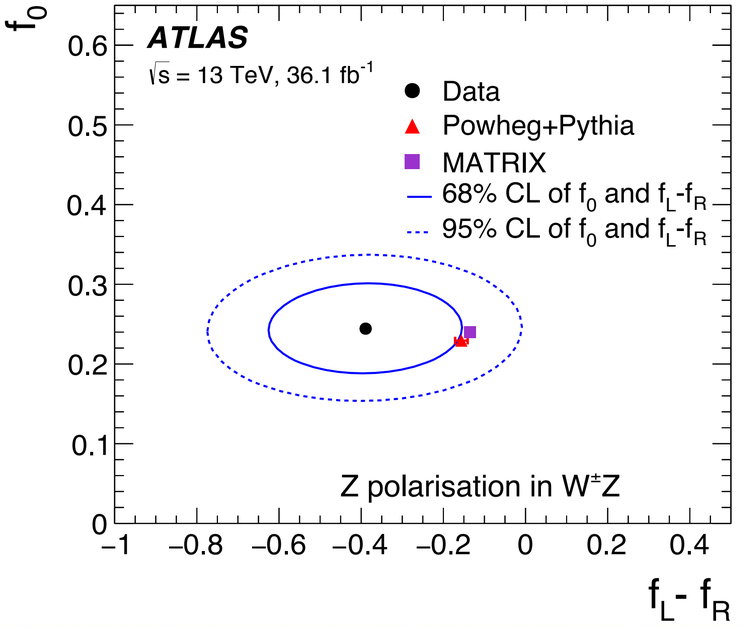
$$\frac{1}{\sigma_{W^\pm Z}}\frac{\mathrm{d}\sigma_{W^\pm Z}}{\mathrm{d}\cos\theta_{\ell,W}} = \frac{3}{8}f_L[(1\mp\cos\theta_{\ell,W})^2] + \frac{3}{8}f_R[(1\pm\cos\theta_{\ell,W})^2] + \frac{3}{4}f_0\sin^2\theta_{\ell,W}$$



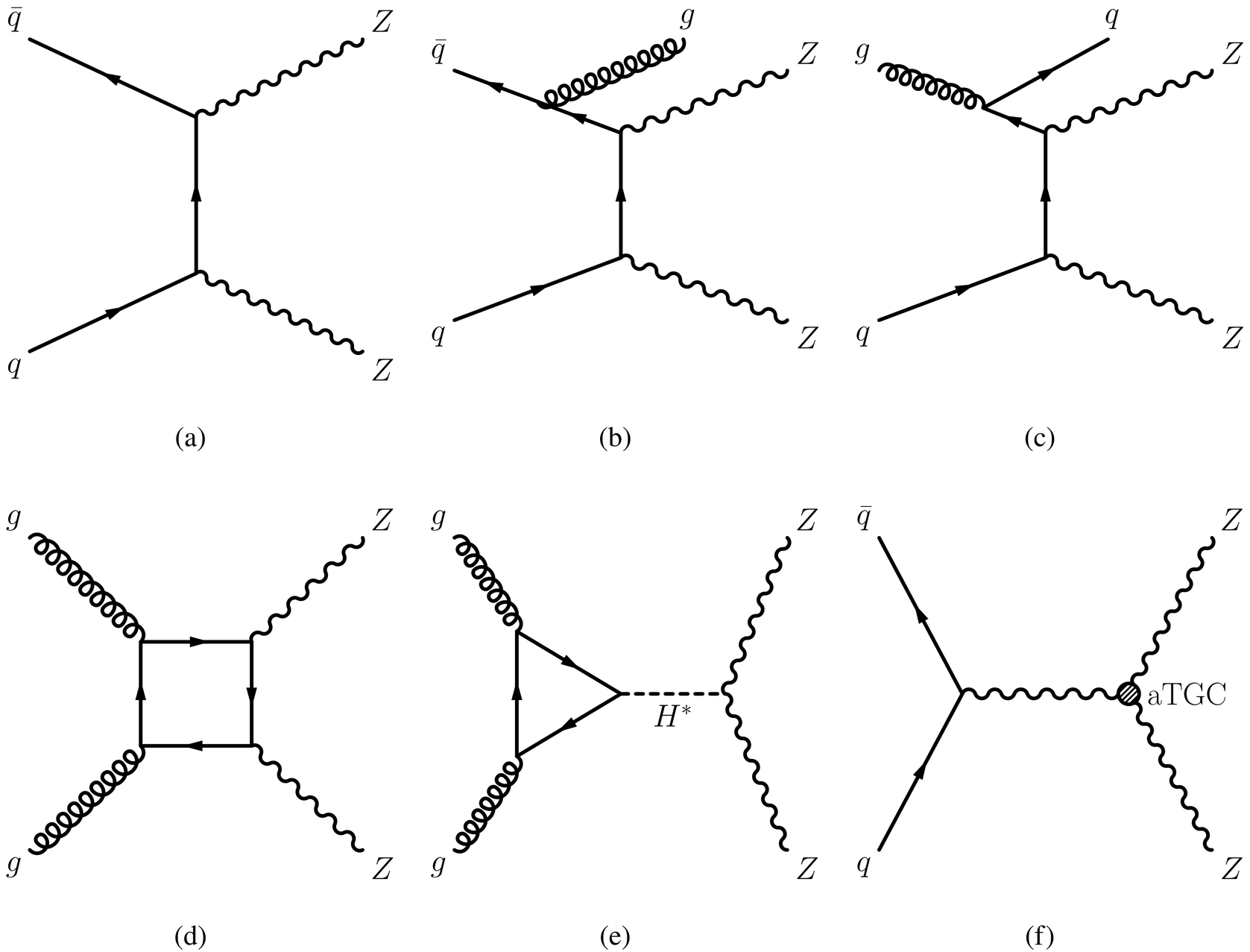
- **Measurement**
  - **extract polarisation from fit of $q_\ell \cdot \cos\theta(\ell,W)$ and $\cos\theta(\ell,Z)$**
  - **f_0 (longitudinal) and $f_L - f_R$ (transverse)**

f_0	Measured	SM (NLO QCD)	Significance	Expected
W	0.26 ± 0.06	0.238 ± 0.003	4.2σ	3.8σ
Z	0.24 ± 0.24	0.230 ± 0.003	6.5σ	6.1σ





ZZ



$ZZ \to \ell\ell\nu\nu$

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Larger BF, larger background than 4ℓ

- high-p_T Z bosons, good sensitivity to TGC

Selection

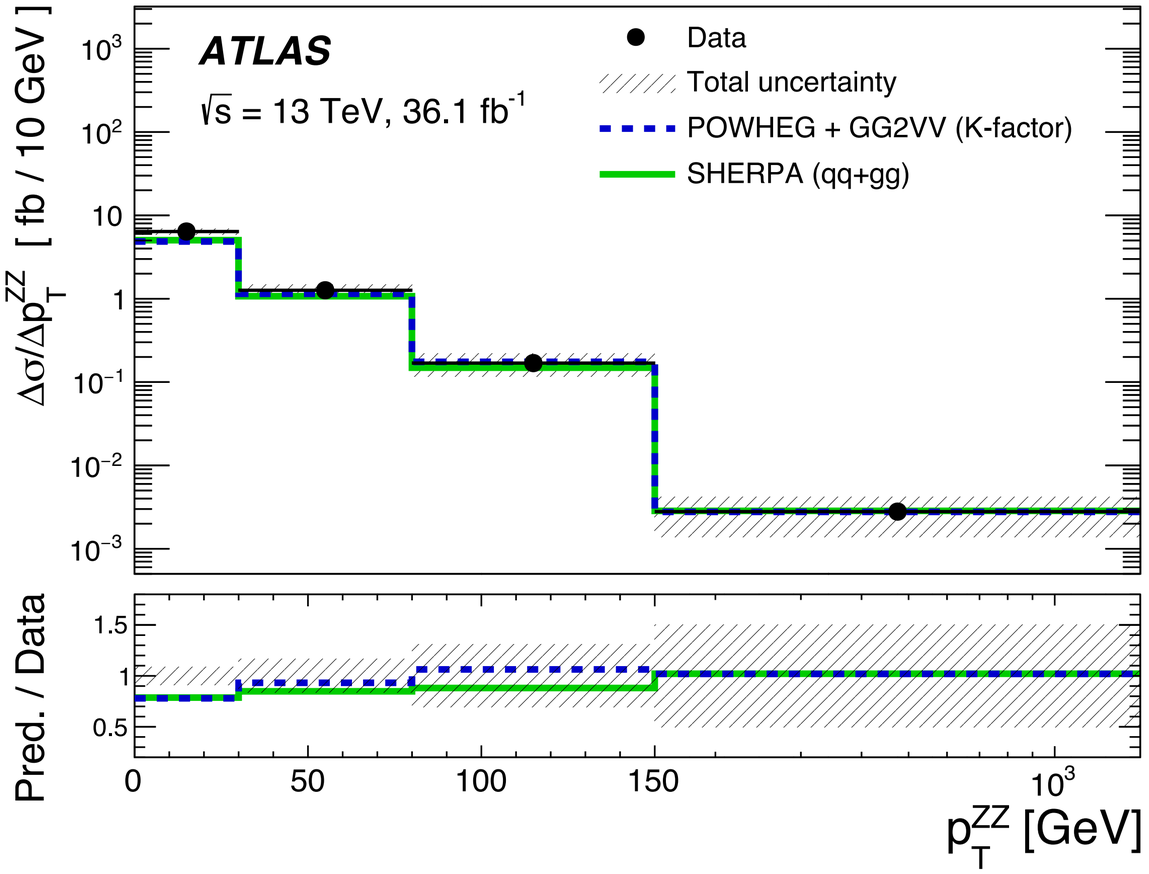
- no extra leptons or b-tagged jets
- E_T^{miss} > 110 GeV, V_T / S_T [1]> 0.65 + angular req.

Backgrounds to control

- WZ, Z+jets, other ZZ, VVV, $t\bar{t}V$

Differential cross section in

- p_T of leading lepton and leading jet
- $\ell\ell$ system: p_T, $|y|$, $\Delta\varphi$
- ZZ system: p_T, m_T
- number of jets



[1] S_T = scalar sum, V_T = vector sum of p_T of leptons and jets

ZZ → ℓℓνν

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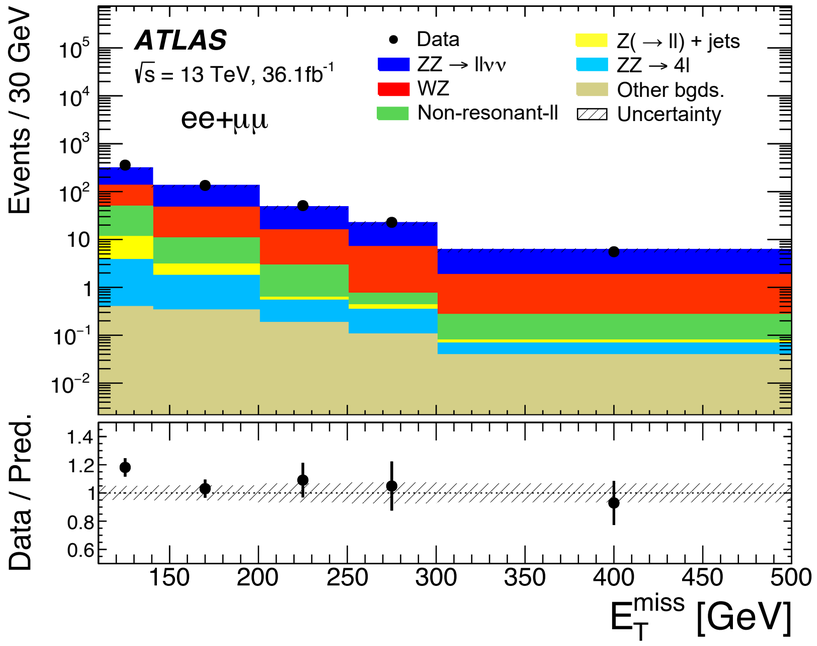
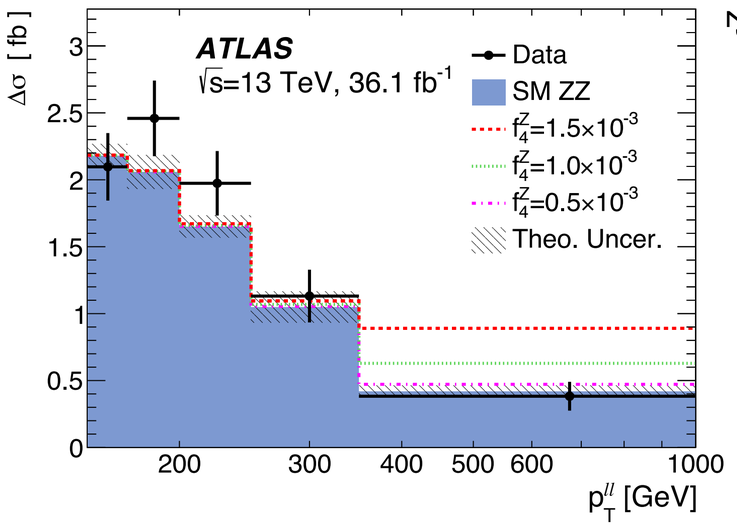
Total cross section

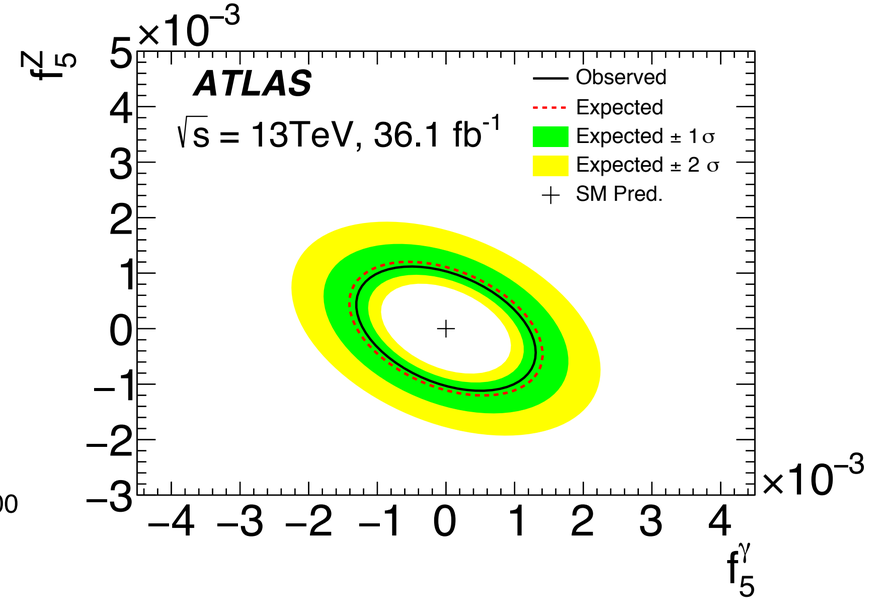
- fit to E_T^{miss} distribution



Interpretation

- from fit to $p_T(\ell\ell)$
- limit to $f_{4,5}^{Z,\gamma}$ varying one or two at the time





		Measured	Predicted
$\sigma^{fid}_{ZZ\to\ell\ell\nu\nu}$ [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

	CP violating		CP conserving	
	f_4^γ	f_4^Z	f_5^γ	f_5^Z
Expected [$\times10^{-3}$]	[−1.3, 1.3]	[−1.1, 1.1]	[−1.3, 1.3]	[−1.1, 1.1]
Observed [$\times10^{-3}$]	[−1.2, 1.2]	[−1.0, 1.0]	[−1.2, 1.2]	[−1.0, 1.0]

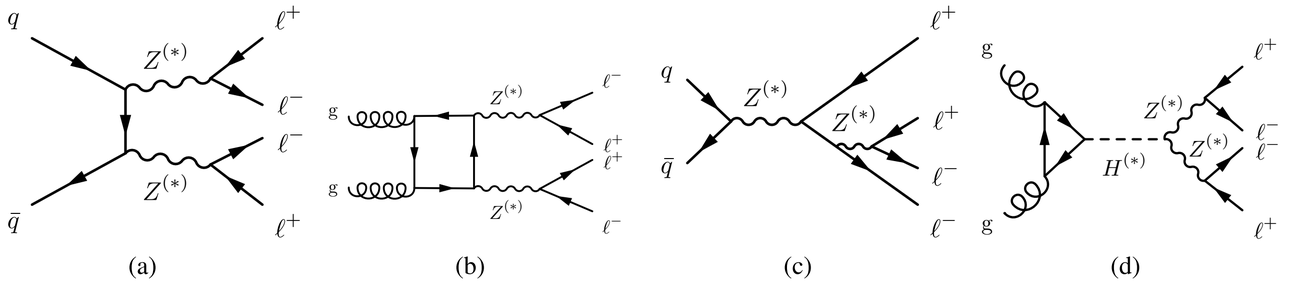
Four leptons

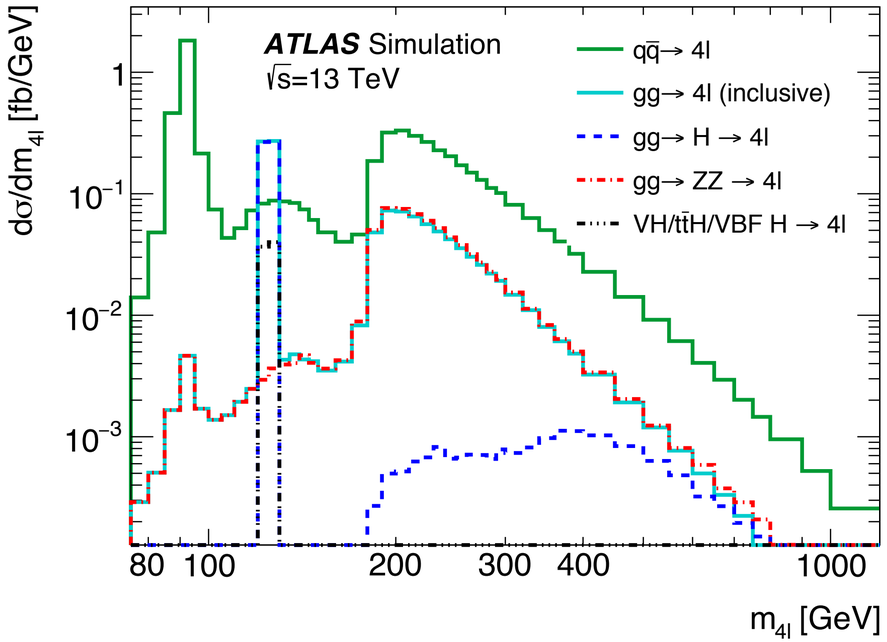
Inclusive final state of 4ℓ

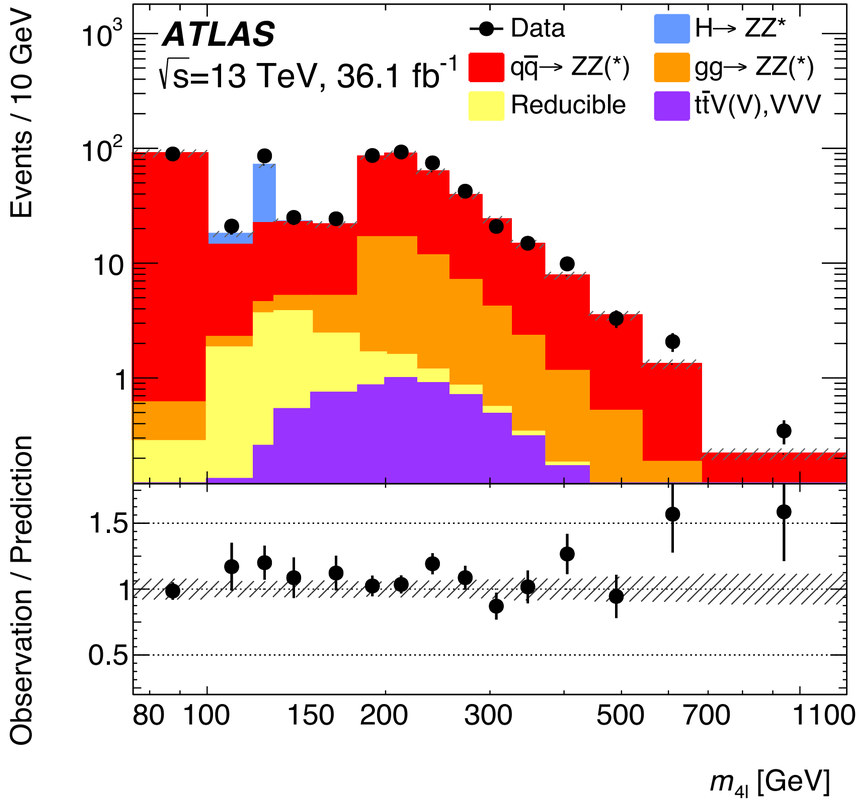
- behaviour of full m(4ℓ) spectrum

Irreducible background

- continuum beneath the Higgs peak
- peak at Z mass from (c)

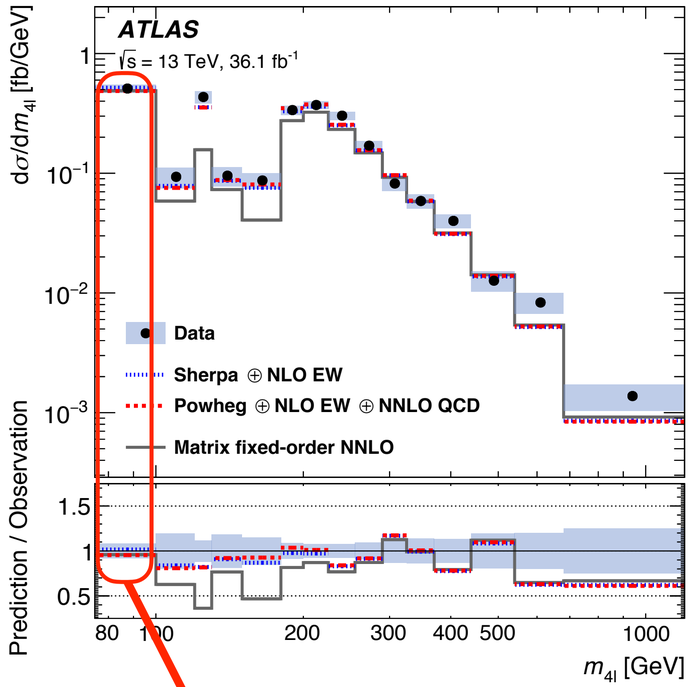






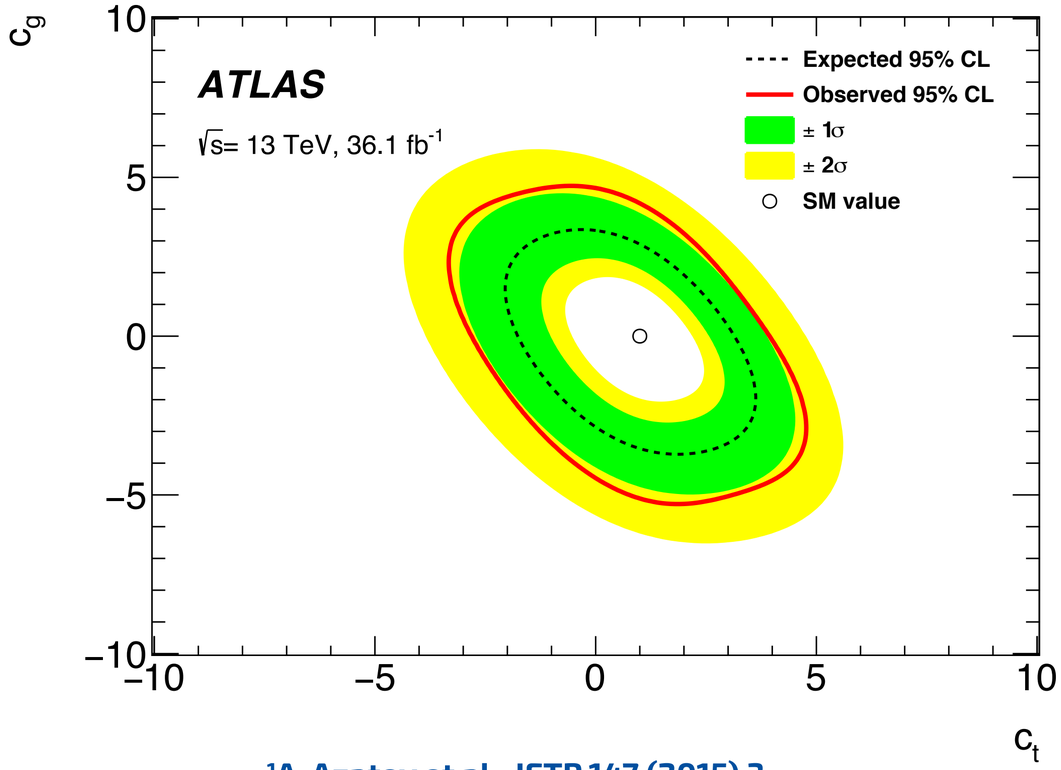
Four leptons

- Unfolded distributions, double differential in $p_T(4\ell)$, $|y_{4\ell}|$, and ℓ flavour
- Extracted $Z \to 4\ell$ total cross section



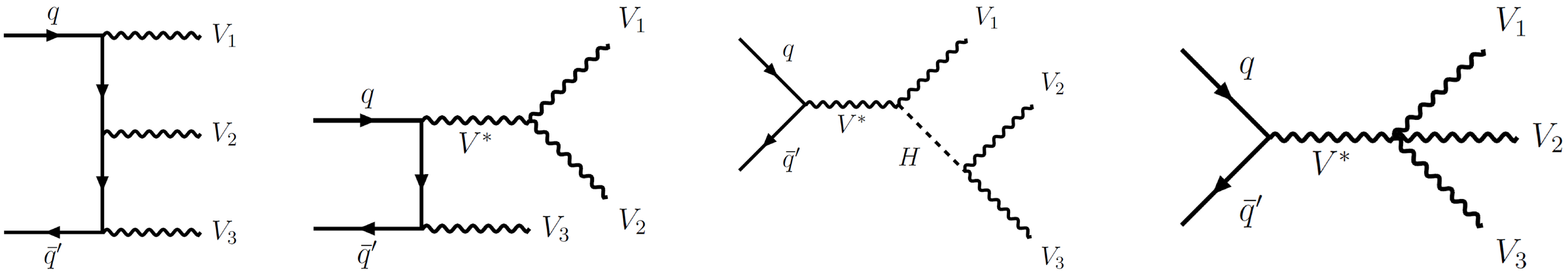
Measurement	$\mathcal{B}_{Z\to 4\ell}/10^{-6}$
ATLAS, $\sqrt{s} = 7$ TeV and 8 TeV [8]	$4.31 \pm 0.34(\text{stat}) \pm 0.17(\text{syst})$
CMS, $\sqrt{s} = 13$ TeV [6]	$4.83\ ^{+0.23}_{-0.22}(\text{stat})\ ^{+0.32}_{-0.29}(\text{syst}) \pm 0.08(\text{theo}) \pm 0.12(\text{lumi})$
ATLAS, $\sqrt{s} = 13$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

- Possible BSM Higgs couplings to top or gluons
- Measured at $m_{4\ell} > 180$ GeV, where c_t and c_g decouple[1]



[1] A. Azatov et al., JETP 147 (2015) 3

Tribosons



Evidence for massive triboson production

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Inclusive analysis on 2015–2017 data

- targeting WWW (2ℓ, 3ℓ) and WVV with Z boson(s) (3ℓ, 4ℓ)
- off-shell production via V/H treated as part of the signal definition

WWW selection

- $\ell\nu\ell\nu qq$: same-sign dilepton, split according to flavour (ee, eμ, μe, μμ)
- $\ell\nu\ell\nu\ell\nu$: trilepton selection, one channel

WWZ and WZZ selection: require one Z candidate

- 3ℓ: split in 1, 2, ≥ 3 jets
- 4ℓ: split in DF, SF-on-shell, SF-off shell

WWW – "fake" lepton background

Misreconstructed j → ℓ

- dominated by $t\bar{t}$

Data-driven estimation

- introduce "fake" lepton definition
- apply correction factors to N+(N)+F events determined in region as 2ℓ and 3ℓ signal regions, but: 1 b-tag ($t\bar{t}$-enriched)

Misreconstructed γ → e

- Vγjj (mostly V=W) important in 2ℓ

Data-driven estimation

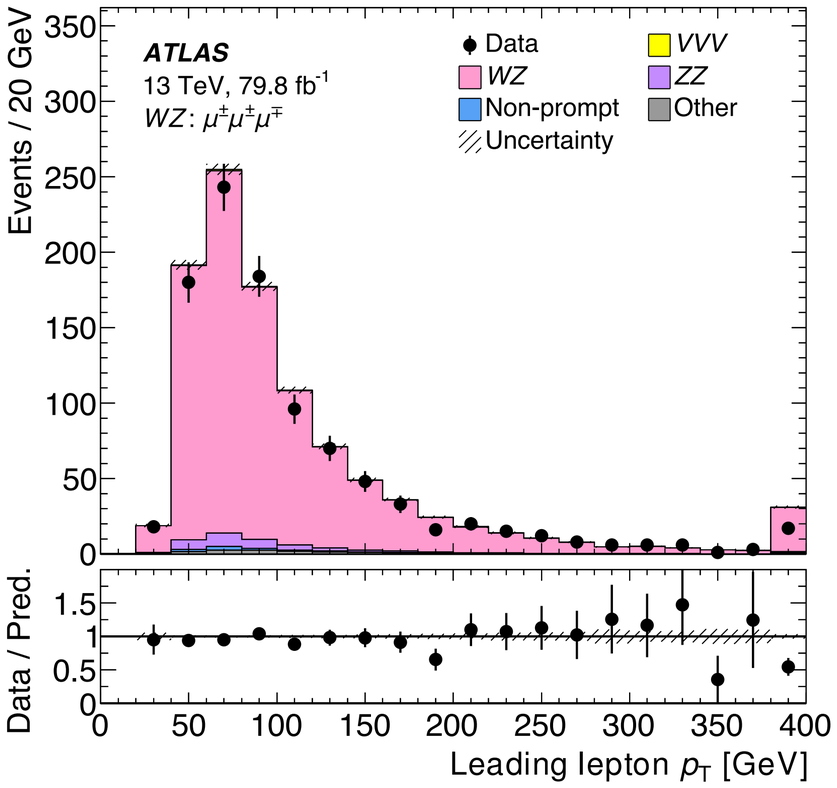
- introduce "photon-like" electrons e_γ
- correction factors from μμe and μμe_γ

Lepton defintion	Quality	Minimum p_T	Isolation	Maximum $\lvert d_0\rvert/\sigma_{d_0}$	Maximum $\lvert z_0 \sin\theta\rvert$	n.p.l. BDT	ch.mis. BDT
Nominal e	Tight		Fix (Loose)	5			yes
Nominal μ WWW	Medium	15 GeV	Gradient	3	0.5 mm	yes	–
Nominal μ WVZ	Loose		FixCutLoose	3			–
Loose e	Loose	15 GeV	no	5	0.5 mm	no	no
Loose μ				3			–
Veto e	Loose	7 GeV	no	no	no	no	no
Veto μ	Loose and $\lvert\eta\rvert < 2.7$						–
Fake e	Medium not Tight	15 GeV	no	5	0.5 mm	no	no
Fake μ	Not nominal WWW			10			–
Photon-like e	Defined as for nominal, but no hit in first pixel layer					no	no

WWW – validation regions

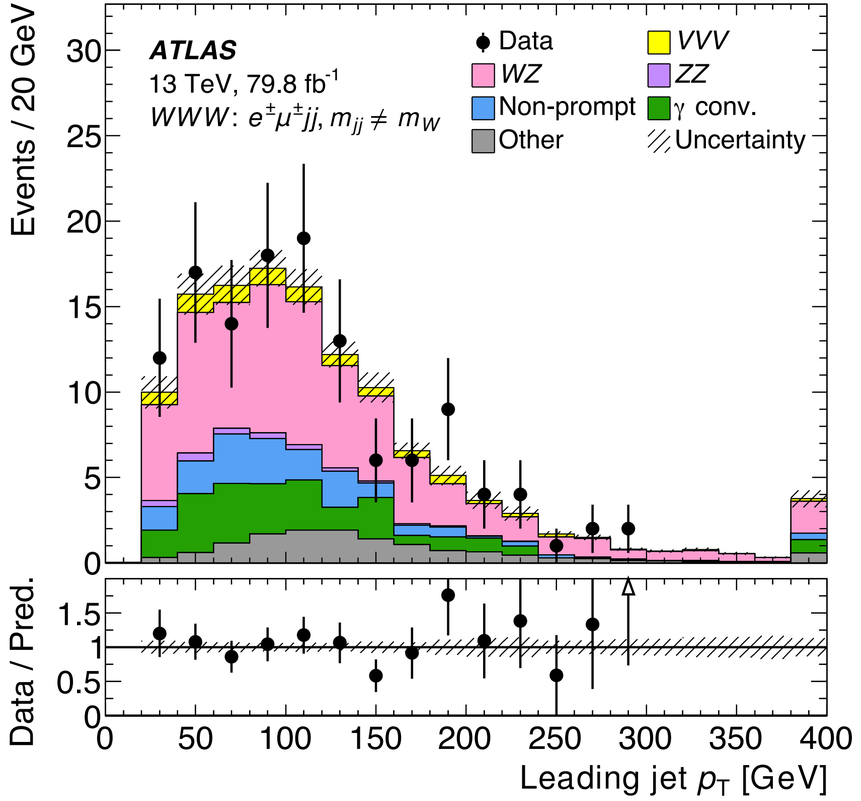
WZ validation region

- 3ℓ, one SFOS lepton pair
- no b-tag, E_T^{miss}> 55 GeV
- $m_{\ell\ell\ell}$ > 110 GeV

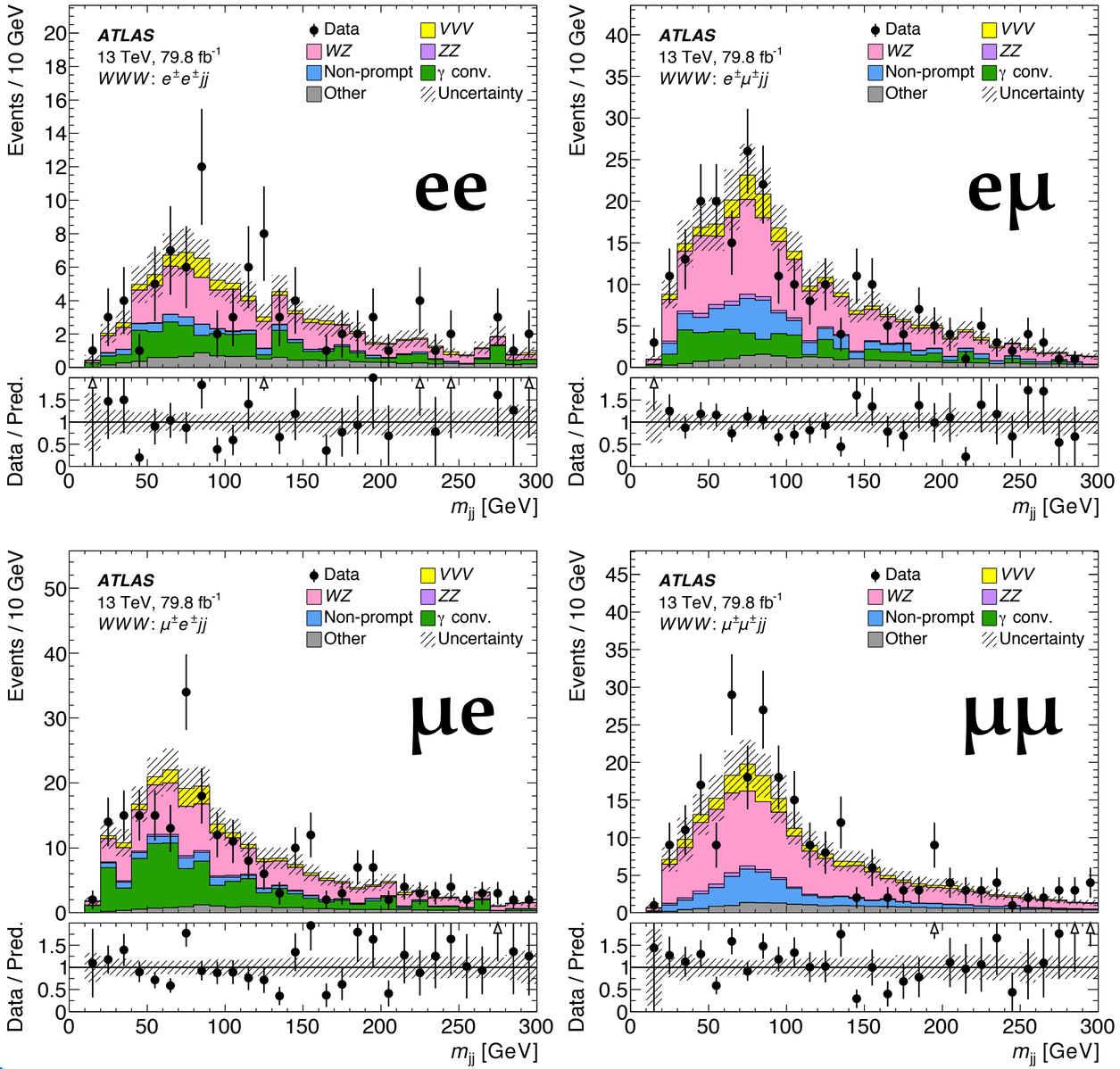


W-sideband region

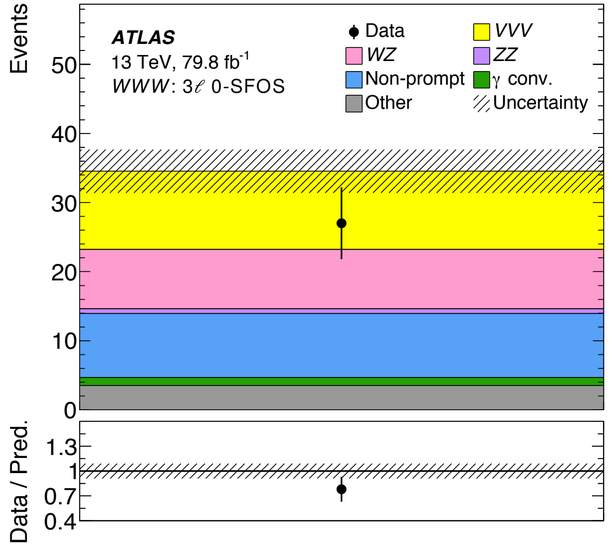
- 2ℓ region with $|m_{jj} - 85\ GeV| > 20\ GeV$



WWW – Pre-fit inputs



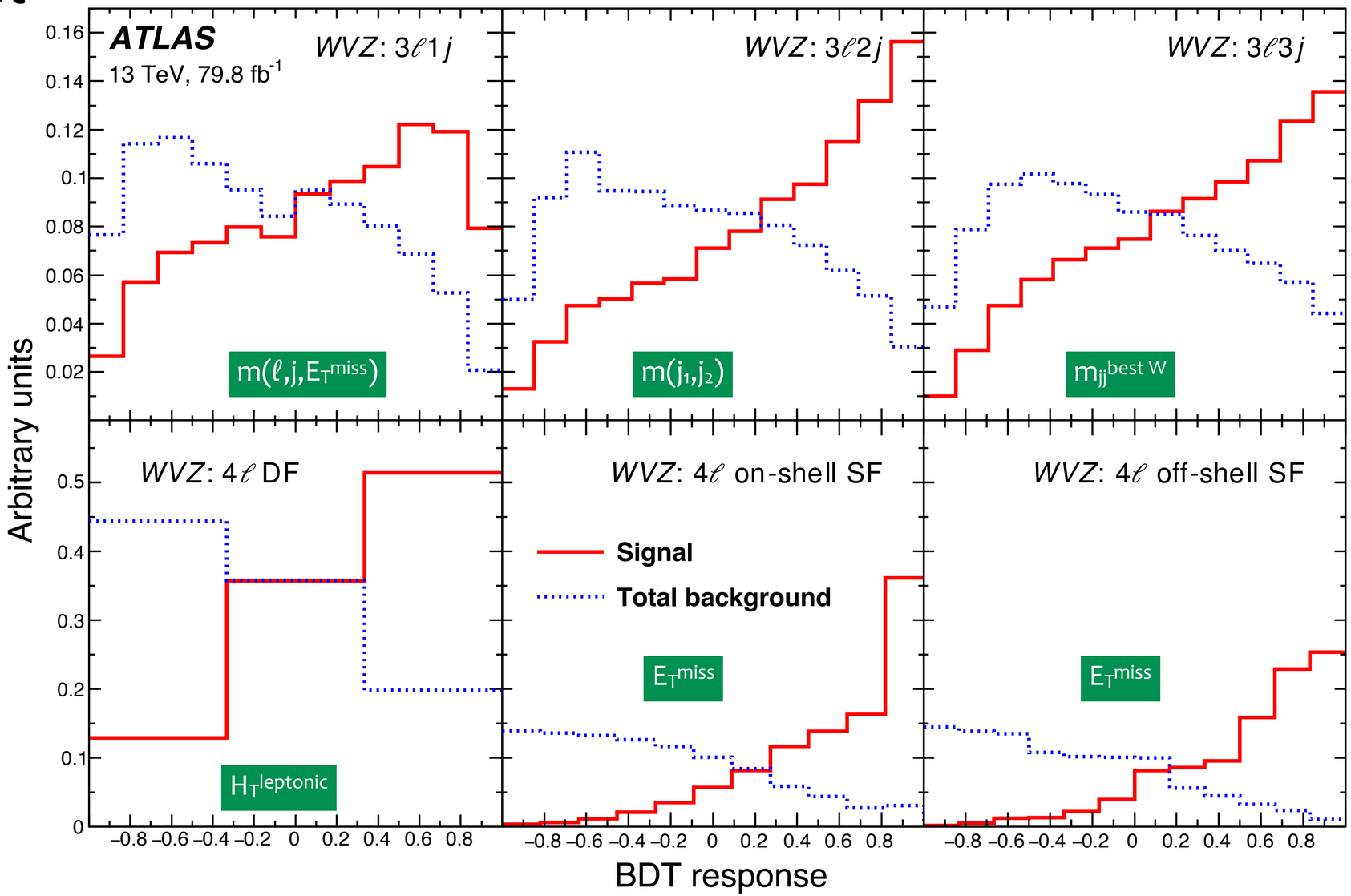
3ℓ



WVZ – analysis strategy

- **Backgrounds mostly prompt**
- **Mainly diboson**
  - **WZ in 3ℓ and ZZ in 4ℓ**
- **All backgrounds from MC**
- **Build a BDT for each of the six signal regions**
  - **trained against diboson**
- **Input variables**
  - **invariant mass, p_T, …**
  - **12–15 variables in 3ℓ regions**
  - **6 variables in 4ℓ regions**

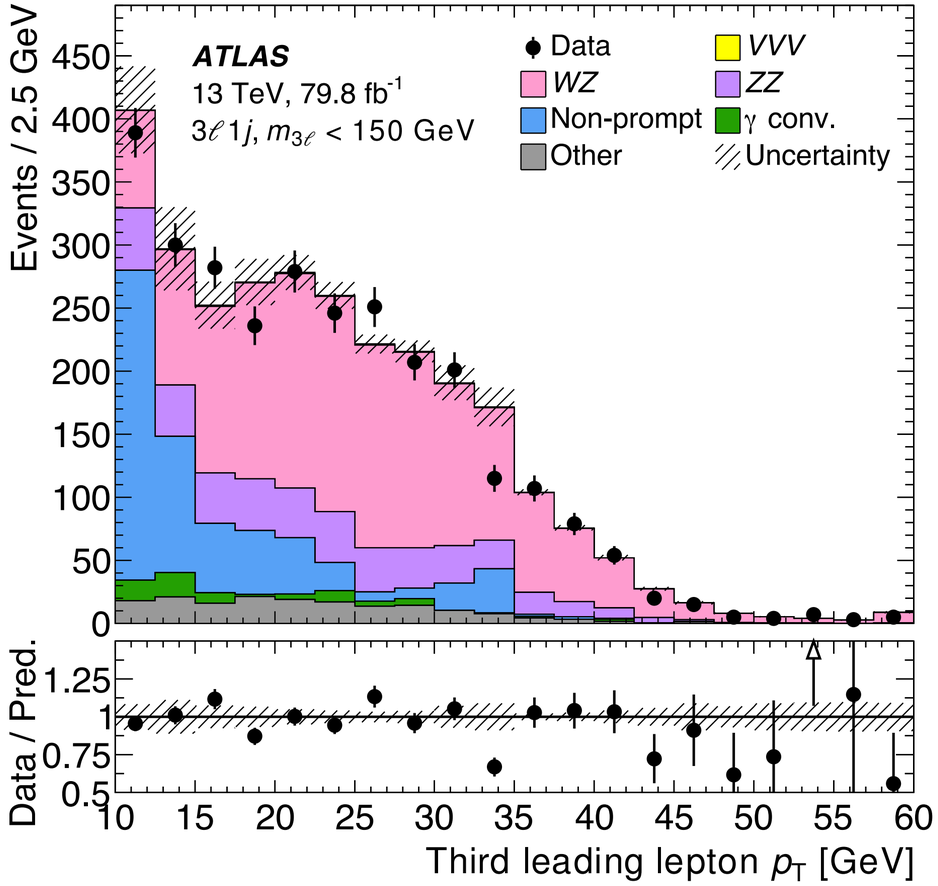
Input variable with best signal-to-background separation



WVZ – background modelling

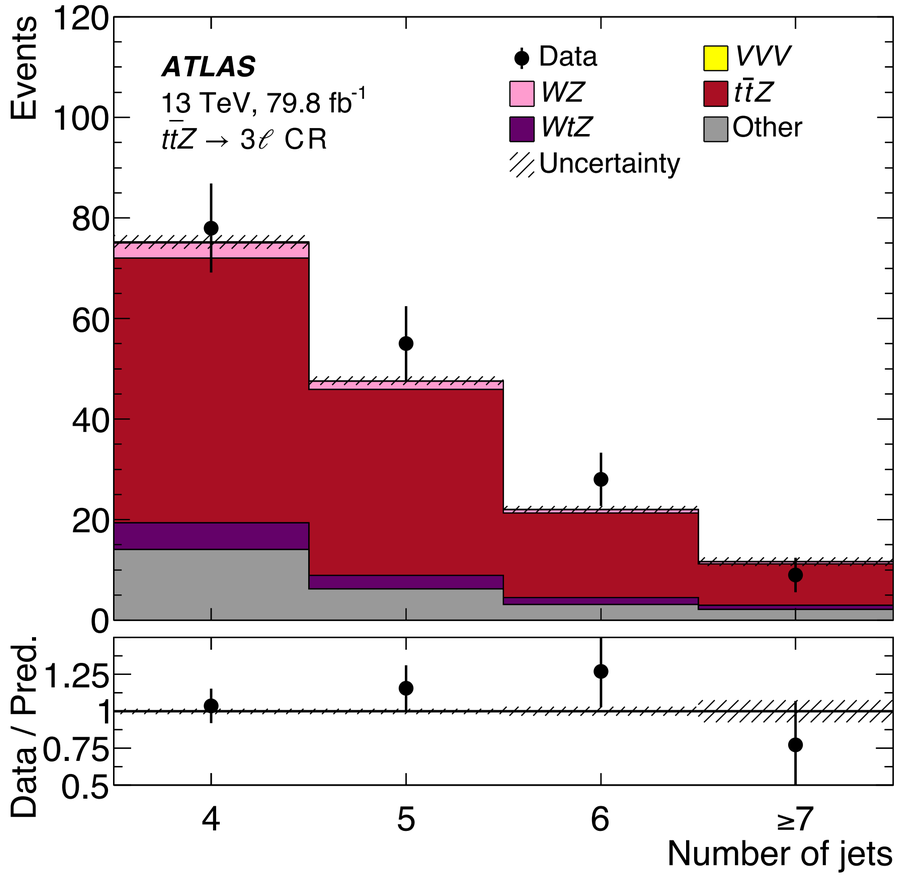
WZ and Z+jets validation

- validation region as 3ℓ-1j SR
- but: no H_T cut; $m_{\ell\ell\ell} < 150$ GeV

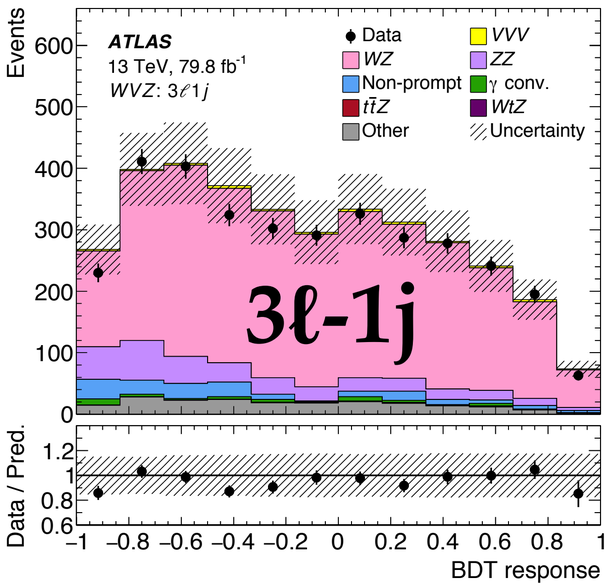


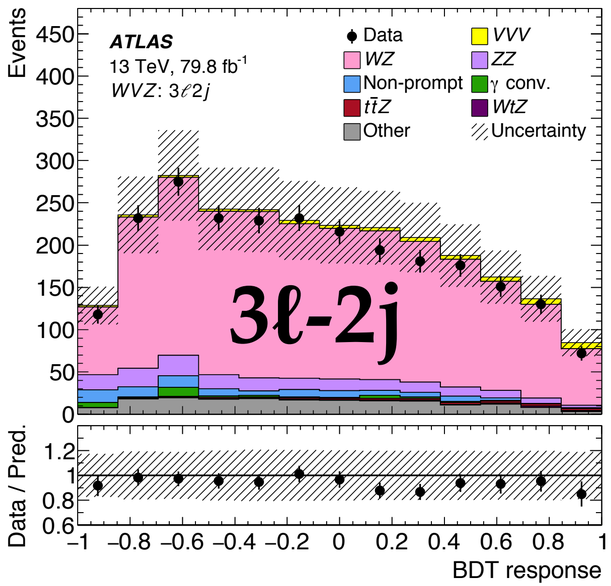
tt̄Z control region

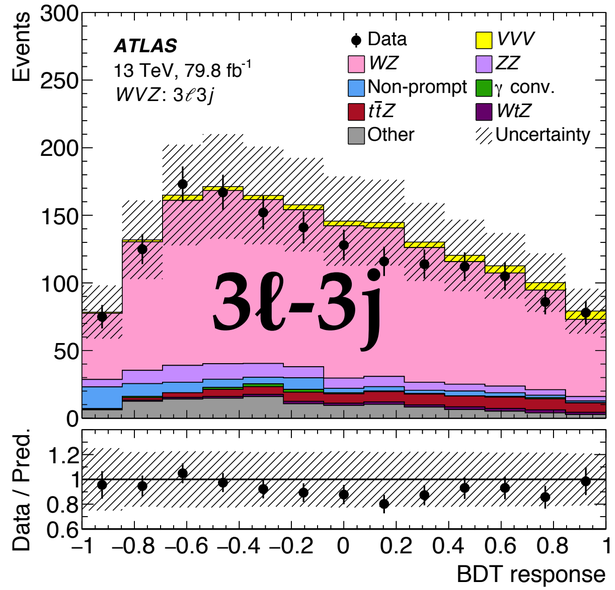
- defined as region as 3ℓ-3j SR
- but: no H_T cut; ≥ 4jets; ≥ 2 b-tags

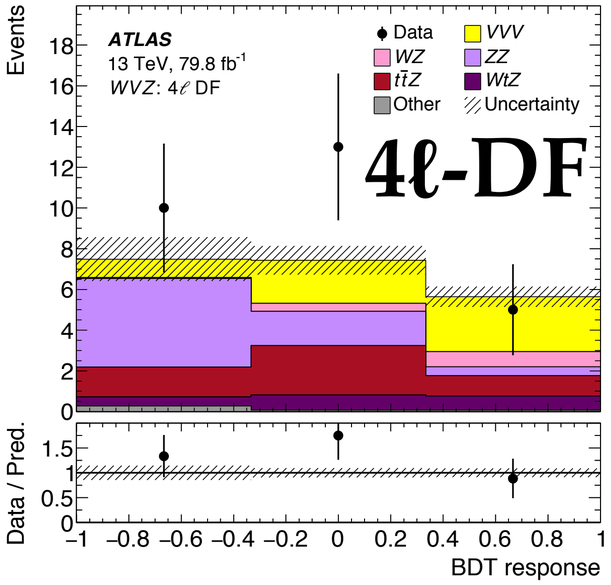


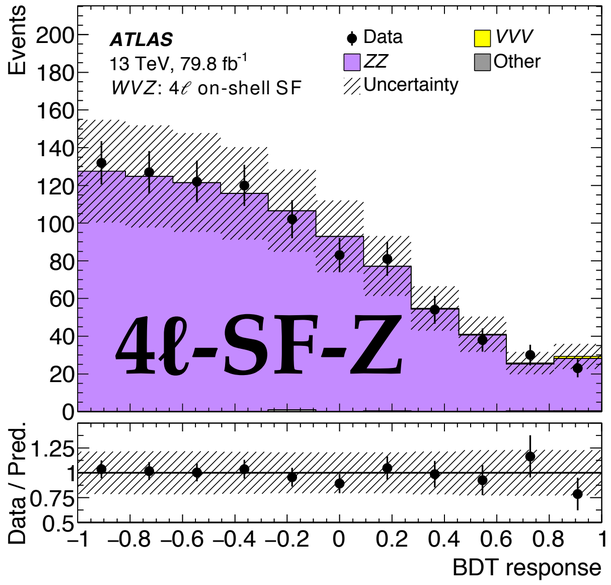
WVZ – Prefit inputs

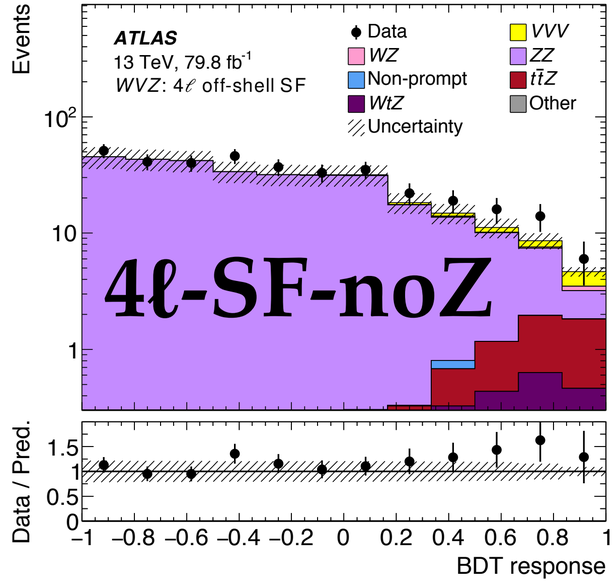












WVV – signal extraction

Binned profile likelihood

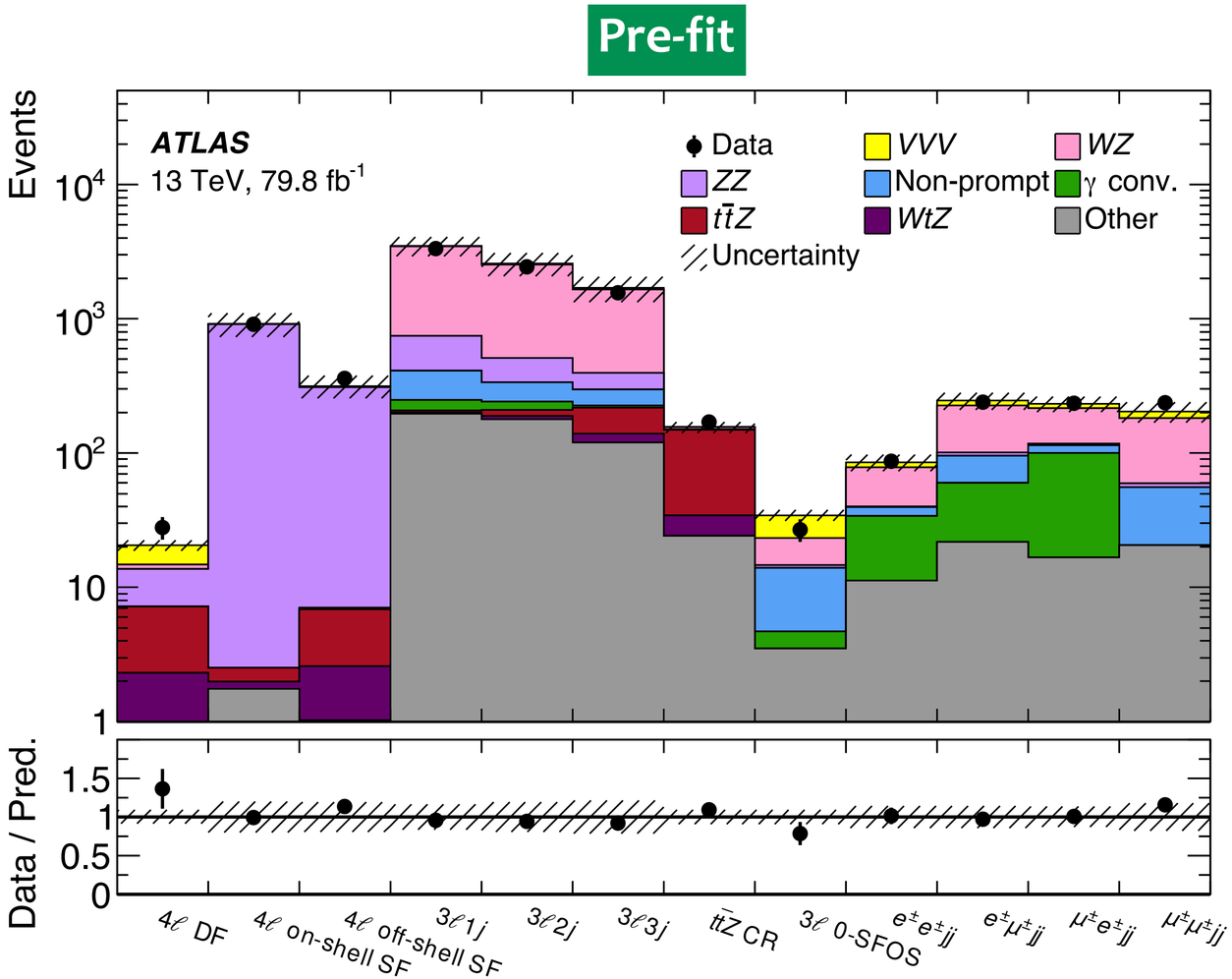
- simultaneous fit to 11 SRs + 1 CR
- one μ_{WVV} assumed for WWW and WVZ
- 186 bins in total

Correlated systematics

- experimental
- irreducible background (theory)
  - signal shape (scale variations)
  - diboson normalisation (constrained to ~5%)
  - diboson shape (Sherpa vs Powheg; scale variations)
- other backgrounds have small impact

Uncorrelated systematics

- data-driven in WWW vs MC in WVZ



WVV – fit results

Expected

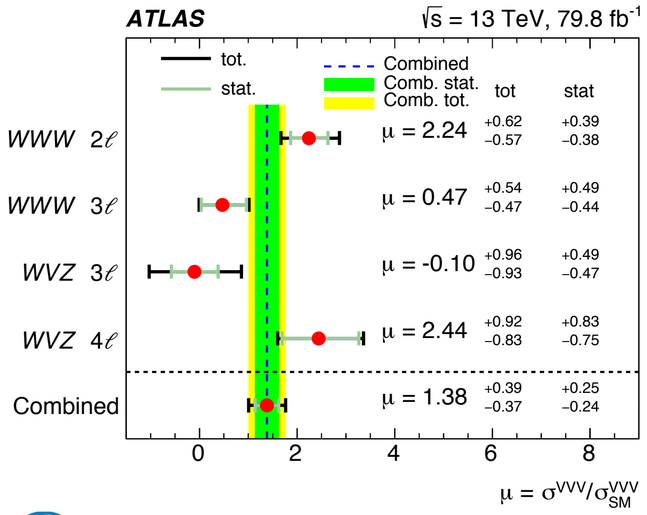
- $\mu_{WVV} = 1.00 \pm 0.24\,(\text{stat.})\,^{+0.27}_{-0.24}\,(\text{syst.})$

Measured

- $\mu_{WVV} = 1.38\,^{+0.25}_{-0.24}\,(\text{stat.})\,^{+0.30}_{-0.27}\,(\text{syst.})$

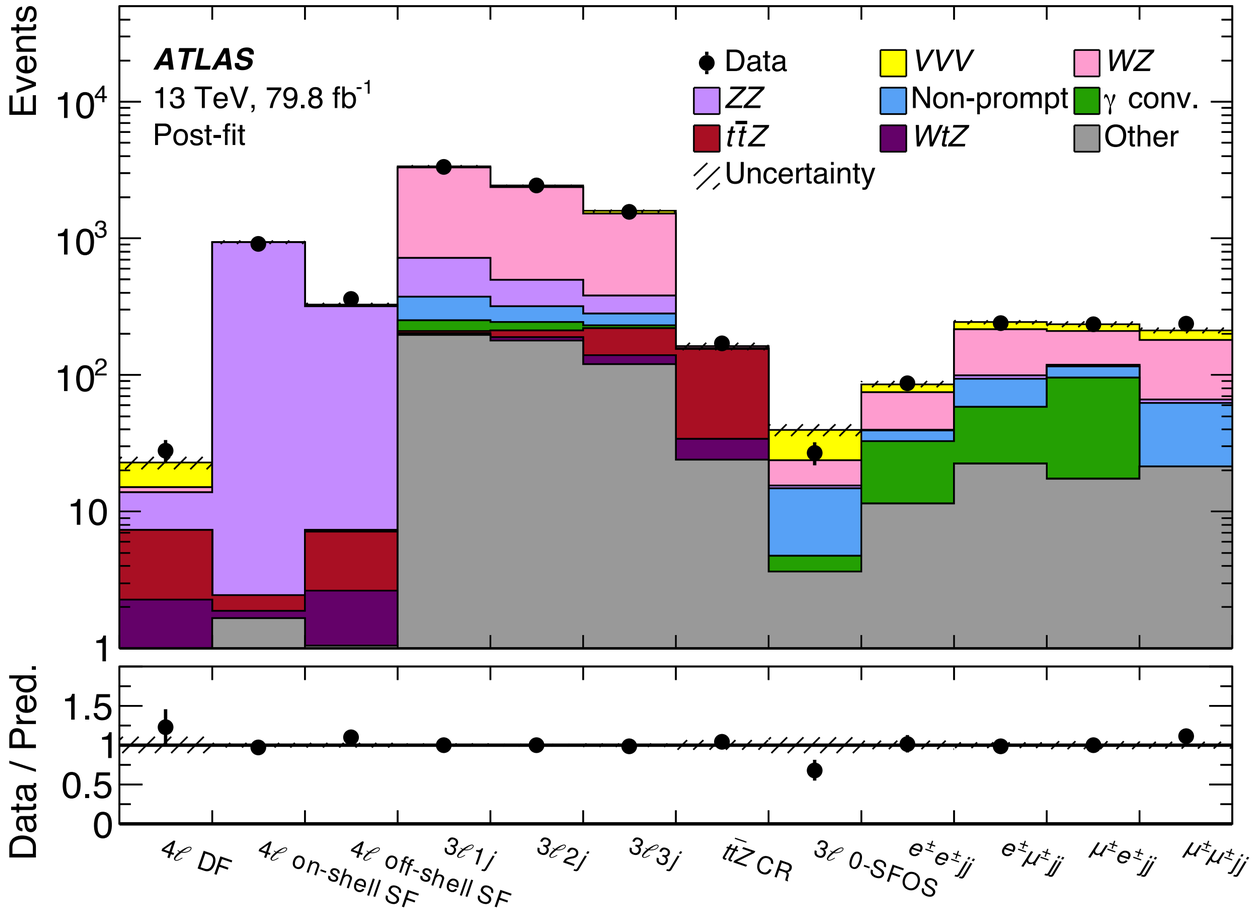
Evidence for 3 massive bosons

- exclusion of bckgnd-only hypothesis

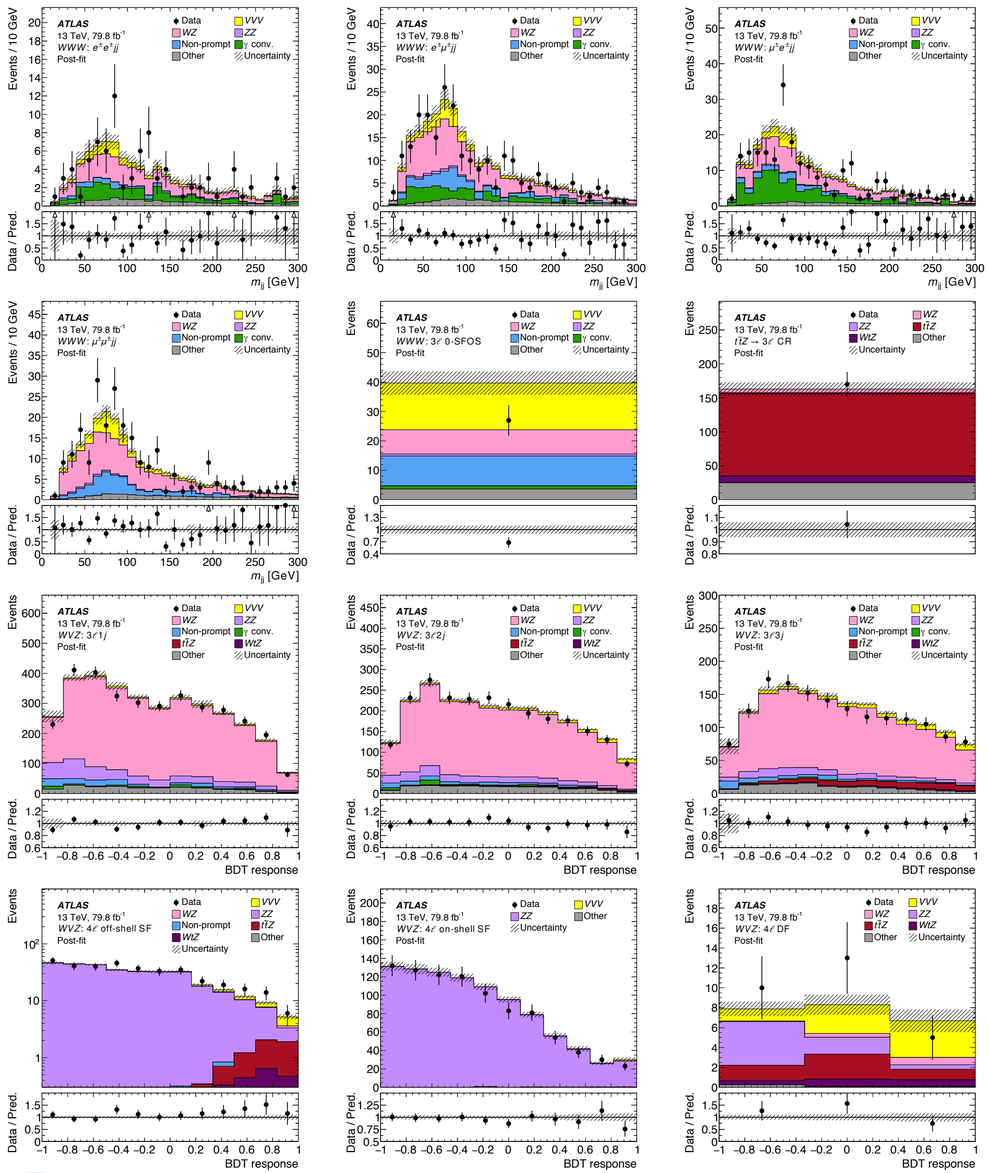


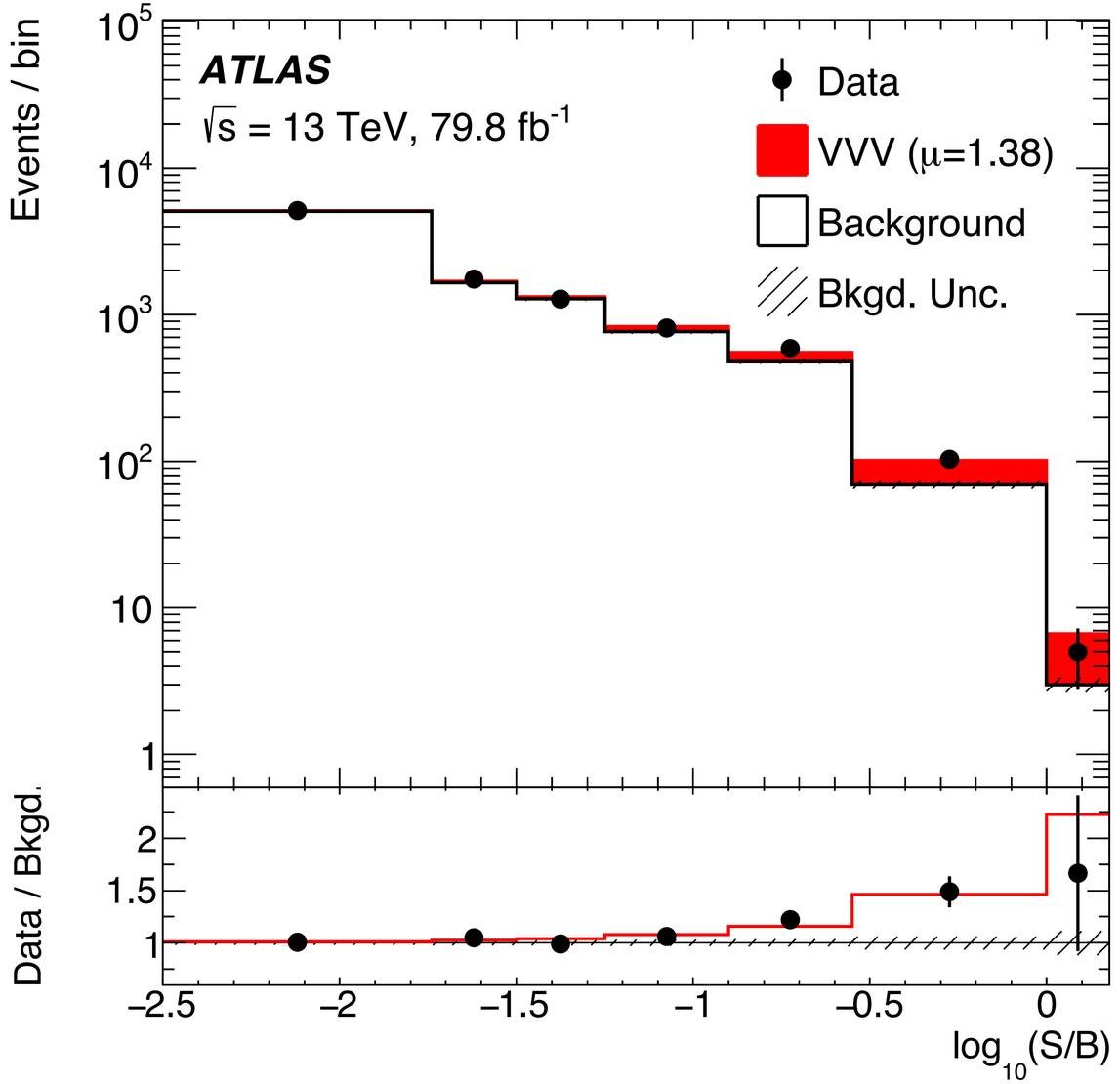
Decay channel	Significance	
	Observed	Expected
WWW combined	3.3σ	2.4σ
$WWW \to \ell\nu\ell\nu qq$	4.3σ	1.7σ
$WWW \to \ell\nu\ell\nu\ell\nu$	1.0σ	2.0σ
WVZ combined	2.9σ	2.0σ
$WVZ \to \ell\nu qq\ell\ell$	–	1.0σ
$WVZ \to \ell\nu\ell\nu\ell\ell/qq\ell\ell\ell\ell$	3.5σ	1.8σ
VVV combined	4.0σ	3.1σ

Post-fit



Visualising the evidence





Conclusions

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Dibosons

- several 13 TeV results
- fiducial & differential
- extracted aTGC/EFT limits and polarisation

Tribosons

- first evidence (4σ) for three massive bosons
- window to QGC

- poster at this conference