WZ polarization and WZjj-EW measurements with ATLAS

F. Costanza, *on behalf of the* **ATLAS collaboration**
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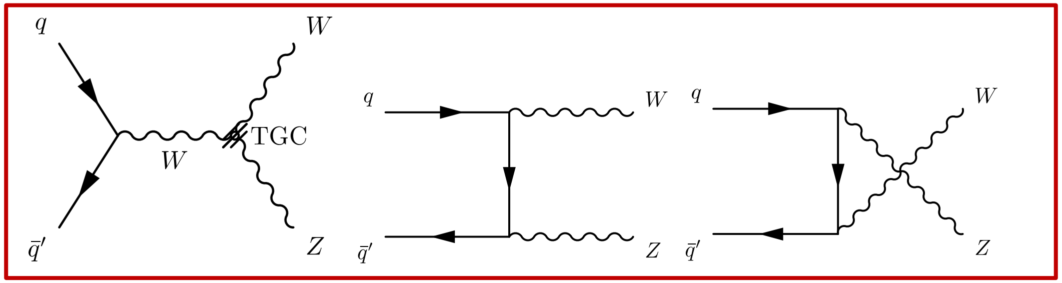
- The study of WZ diboson production is an important test of the SM for its sensitivity to gauge boson self-interactions (TGCs and QGCs).
- The measurement of polarization in diboson production is also important for its connection to the electroweak symmetry breaking mechanism.
- In the long term, measuring the scattering of longitudinally polarized vector bosons will be the ultimate test of the EWSB.

- In this talk:
  - Single boson polarization measurements in the $W^{\pm}Z$ production as reported by the ATLAS Collaboration in ***Phys. Lett. B 793 (2019) 469***.
  - $W^{\pm}Z$ Vector Boson Scattering (VBS) measurements as reported by the ATLAS Collaboration in ***Eur. Phys. J. C 79 (2019) 535***.
  - Problematics faced by these analyses to improve their results with the full LHC Run2 data sample.

WZ Inclusive: Analysis Overview

- Precise inclusive and differential cross section measurement (out of the scope of this talk/workshop).
- Measurement of single boson polarization fractions.
- Possibility to investigate aTGCs.



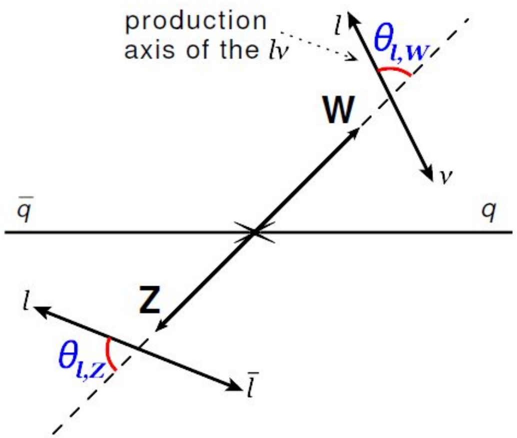
- Clear leptonic final state, 3 leptons (*e* or *μ*):
  - 2ℓ OSSF with $p_T > 15GeV$ and $|m(\ell\ell) - M_{Z\ PDG}| < 10GeV$
  - 1ℓ with $p_T > 20GeV$ and $m_T > 30GeV$.
- Backgrounds:
  - **Reducible** (~40%): Z+j, Zγ, ttbar, and WW. Data-driven estimation with matrix method.
  - **Irreducible**: ZZ, ttbar+V, VVV, tZ(j). Estimated from MC.
- Unfolding to assess differential distribution in fiducial PS.

Channel	All	
Data	6160	
Total Expected	5986	± 14
WZ	4778	± 12
Misid. leptons	436	± 8
ZZ	426	± 3
$t\bar{t}$+V	225	± 1
tZ	110	± 1
VVV	12.0	± 0.2

- Polarization fractions are extracted from a **template fit on reco distributions**.
  - At the time of the analysis, no MC event generator available for polarization states. **Need to extract polarization templates from unpolarized MC sample**.
- At Born level, the expected angular distribution for massless fermions in the rest frame of the parent $W^{\pm}$ boson is given in terms of the polarization fractions as:

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

where $\theta_{\ell,W}$ is defined in the helicity frame as the **decay angle of the charged lepton in the *W* rest frame relative to the $W^{\pm}$ direction in the *WZ* com** and f_0, f_L, and f_R are the longitudinal, left-handed and right-handed helicity fractions.



- **Challenge: such equation is valid only when the full phase space is accessible.**

Analysis strategy: Reweighting method

- For each of the gauge bosons, the predicted helicity fractions are extracted from a fit in the total phase space from the PowHeg+Pythia MC in bins of p_T and y.
- The MC templates at detector level are obtained by reweighting the PowHeg+Pythia MC events according to:

$$\boxed{\frac{\left.\frac{1}{\sigma_{W^\pm Z}}\frac{d\sigma_{W^\pm Z}}{d\cos\theta_{\ell,W}}\right|_{L/0/R}}{\frac{3}{8}f_L^{\text{gen.}}(1\mp\cos\theta_{\ell,W})^2+\frac{3}{8}f_R^{\text{gen.}}(1\pm\cos\theta_{\ell,W})^2+\frac{3}{4}f_0^{\text{gen.}}\sin^2\theta_{\ell,W}}}$$

where

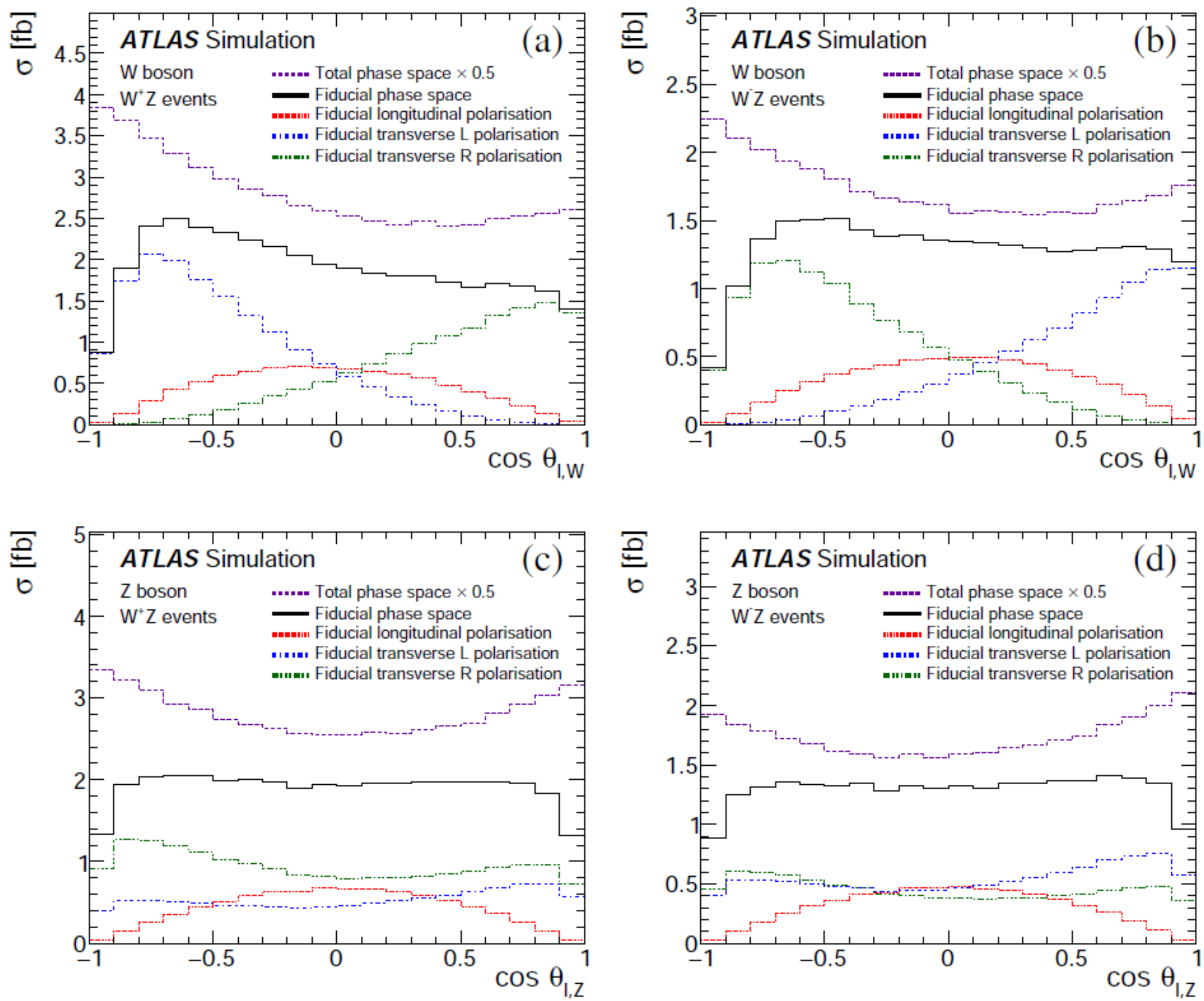
$$\left.\frac{1}{\sigma_{W^\pm Z}}\frac{d\sigma_{W^\pm Z}}{d\cos\theta_{\ell,W}}\right|\begin{matrix}L\\0\\R\end{matrix} = \frac{3}{8}\begin{cases}(1\mp\cos\theta_{\ell,W})^2\\ 2\sin^2\theta_{\ell,W}\\ (1\pm\cos\theta_{\ell,W})^2\end{cases}$$

and the $f_{L/0/R}^{\text{gen.}}$ helicity fraction are extracted by the fit at generator level.

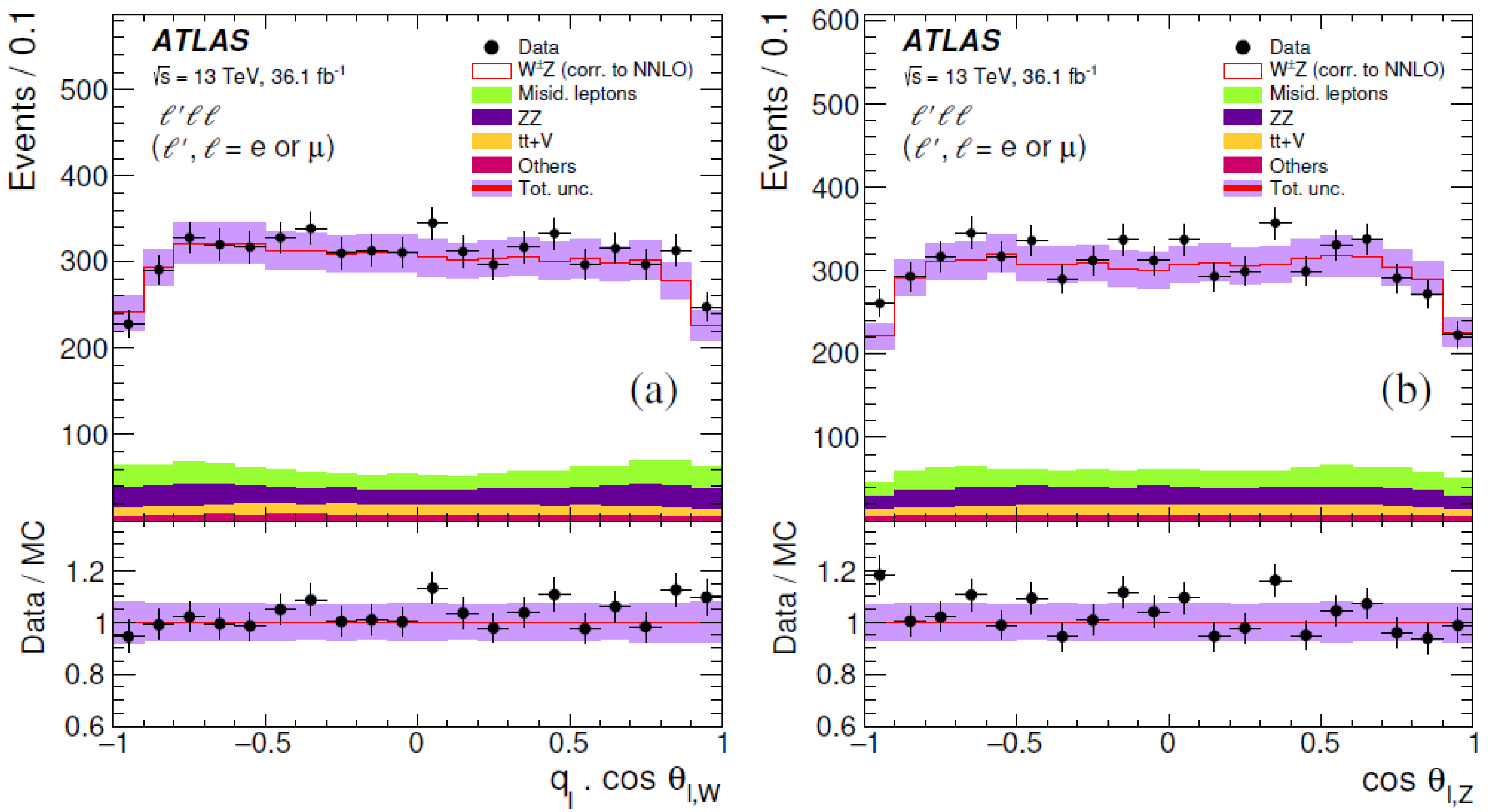
- Similar equations hold for the *Z* boson, when the corresponding axial-vector $c_a = -1/2$ and vector $c_v = 1/2 + 2\sin^2\theta_W^{\text{eff}}$ couplings are taken into account.

Polarization templates

- Restriction on the p_T and η value of the leptons suppress events at $|\cos\theta_{\ell,W(Z)}| \sim 1$
- Confirmation that simulated templates must be used.



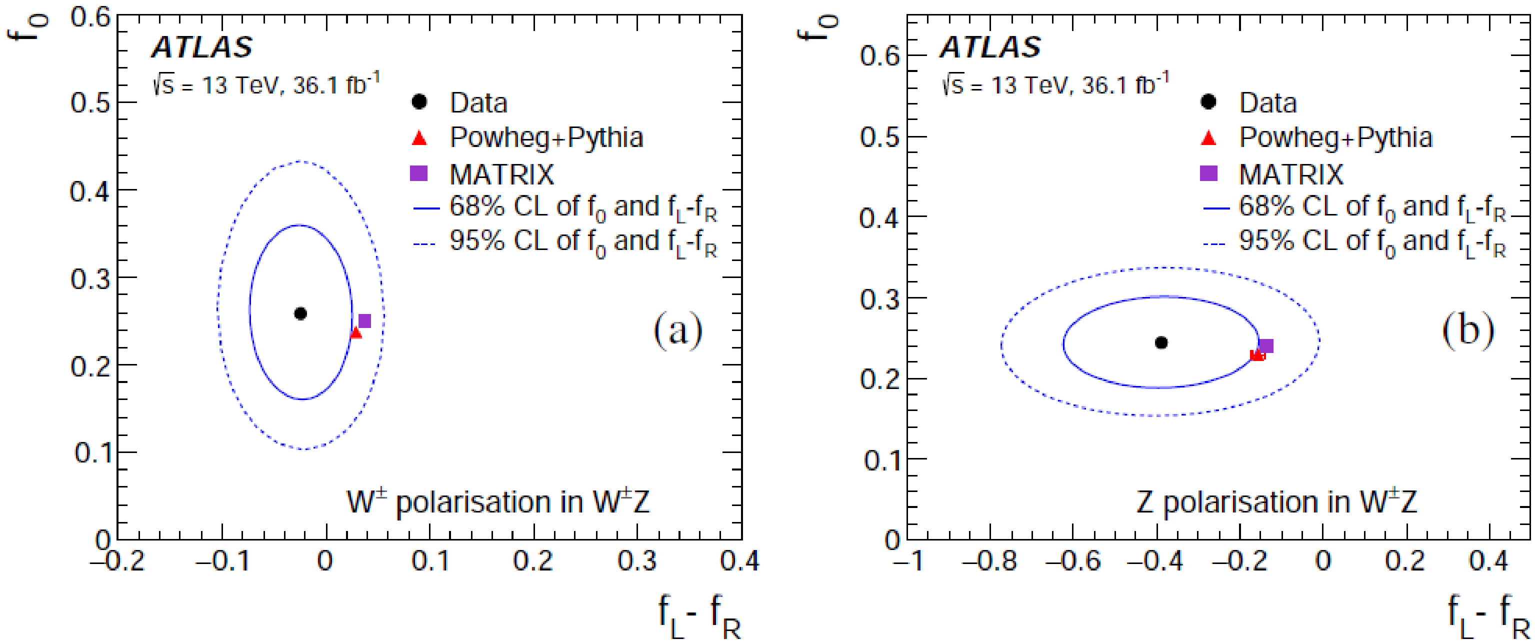
- $\cos\theta_{\ell,W}$ is **multiplied by the charge of the lepton** to allow the polarization measurement with the $W^{\pm}Z$ events using the combination of the datasets of both *W* boson charges.



- **Correction factors** for **detector efficiencies** and **QED final-state radiation** effects are extracted from simulation and used to express the helicity fractions at particle level in the **fiducial phase space**.

	f_0 Data	f_0 POWHEG+PYTHIA	f_0 MATRIX	$f_L - f_R$ Data	$f_L - f_R$ POWHEG+PYTHIA	$f_L - f_R$ MATRIX
W^+ in W^+Z	0.26 ± 0.08	0.233 ± 0.004	0.2448 ± 0.0010	-0.02 ± 0.04	0.091 ± 0.004	0.0868 ± 0.0014
W^- in W^-Z	0.32 ± 0.09	0.245 ± 0.005	0.2651 ± 0.0015	-0.05 ± 0.05	-0.063 ± 0.006	-0.034 ± 0.004
$W^\pm$ in $W^\pm Z$	0.26 ± 0.06	0.2376 ± 0.0031	0.2506 ± 0.0006	-0.024 ± 0.033	0.0289 ± 0.0022	0.0375 ± 0.0011
Z in W^+Z	0.27 ± 0.05	0.225 ± 0.004	0.2401 ± 0.0014	-0.32 ± 0.21	-0.297 ± 0.021	-0.262 ± 0.009
Z in W^-Z	0.21 ± 0.06	0.235 ± 0.005	0.2389 ± 0.0015	-0.46 ± 0.25	0.052 ± 0.023	0.0468 ± 0.0034
Z in $W^\pm Z$	0.24 ± 0.04	0.2294 ± 0.0033	0.2398 ± 0.0014	-0.39 ± 0.16	-0.156 ± 0.016	-0.135 ± 0.006

- The **longitudinal helicity fraction** of the ***Z* boson** in measured with an observed (expected) significance of **6.5(6.1)σ**.
- The **longitudinal helicity fraction** of the ***W* boson** in measured with an observed (expected) significance of **4.2(3.8)σ**.



- The **PowHeg+Pythia and MATRIX** predictions are at **NLO and NNLO in QCD**, respectively, but both calculations use only **LO electroweak matrix elements**.
- No stringent constraints nor clear inconsistencies between measurements and predictions are observed, also due to the still **large statistical uncertainties**.

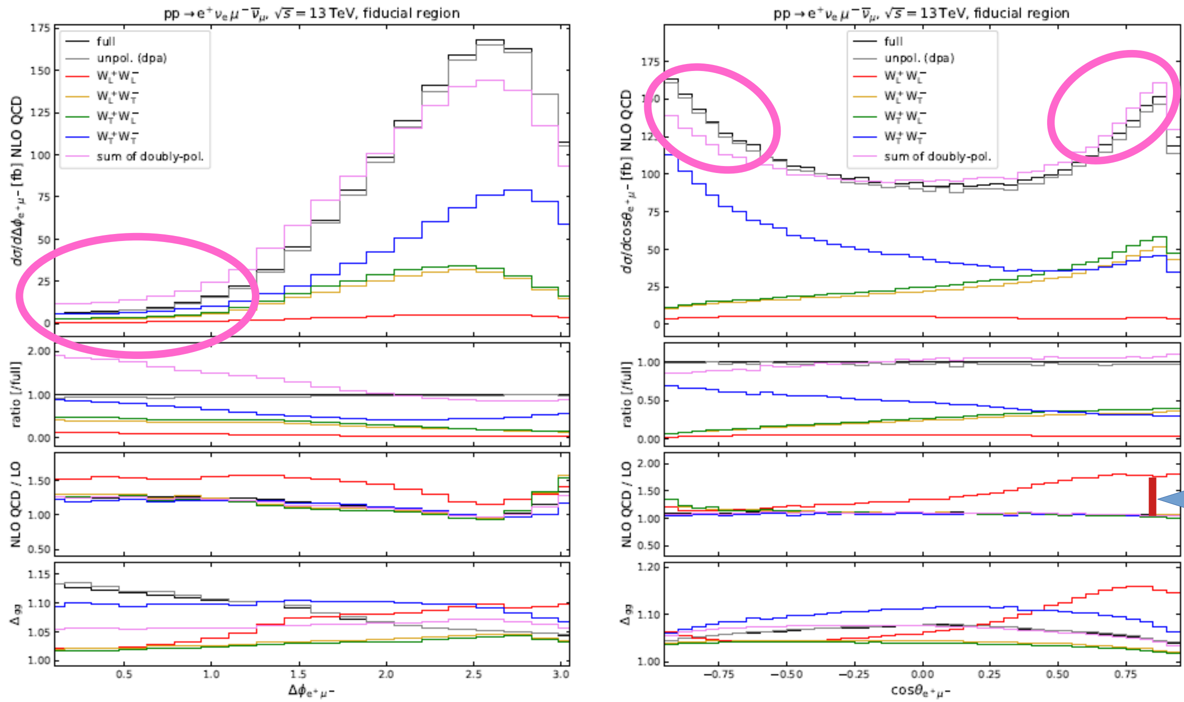
	$W^\pm$ in $W^\pm Z$		Z in $W^\pm Z$	
	f_0	$f_L - f_R$	f_0	$f_L - f_R$
e energy scale and id. efficiency	0.0024	0.0004	0.005	0.0021
μ momentum scale and id. efficiency	0.0013	0.0027	0.0018	0.008
E_T^{miss} and jets	0.0024	0.0010	0.0017	0.005
Pile-up	0.005	0.00009	0.0014	0.005
Misid. lepton background	0.031	< 0.001	0.007	0.019
ZZ background	0.009	0.0004	0.0007	0.0012
Other backgrounds	0.0012	0.0005	0.0018	0.005
QCD scale	0.0008	0.0013	0.0004	0.008
PDF	0.0011	0.0009	0.00004	< 0.00001
Modelling	0.004	0.007	0.0015	0.0028
Total systematic uncertainty	0.033	0.008	0.009	0.024
Luminosity	0.0015	< 0.0001	< 0.0001	0.0008
Statistics	0.06	0.032	0.04	0.15
Total	0.06	0.033	0.04	0.16

- Statistically dominated measurement (at LHC Run2).

WZ polarization problematics (1)

- The extension of the reweighting method for double-boson polarization measurements is challenging.
- NLO corrections for polarized distributions are needed for *WZ* (not yet available as event generator MCs). Example for W^+W^-:

A. Denner & G. Pelliccioli, 2006.14867

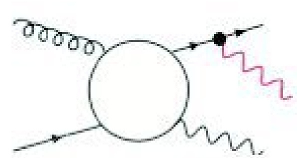


Big interference effects. Not a good variable for polarization measurements.

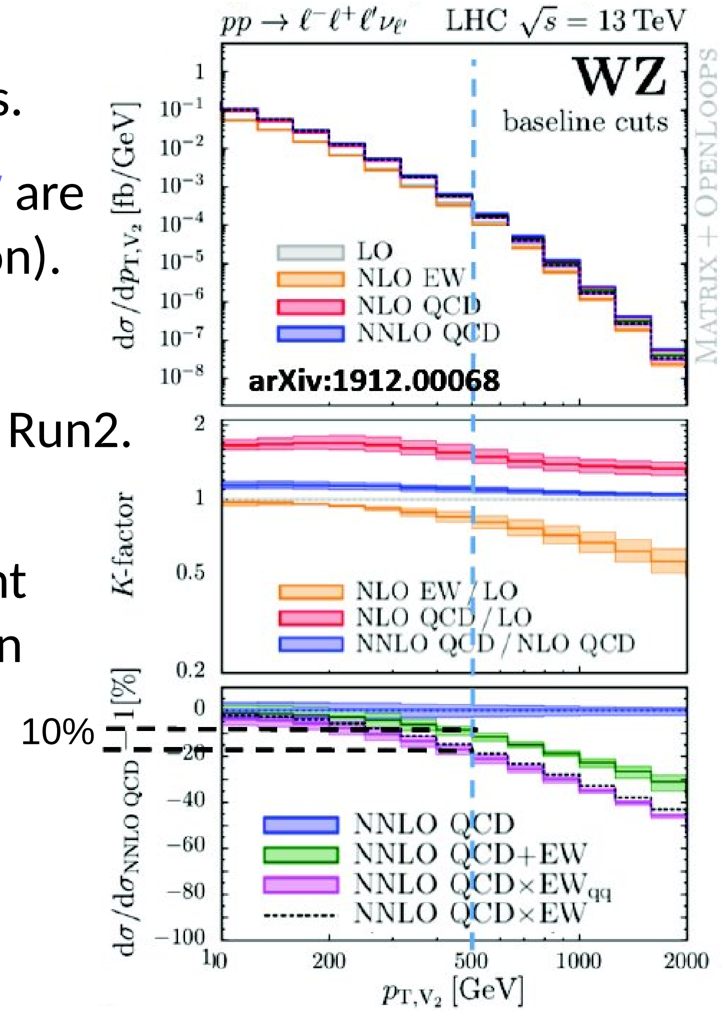
Big and not-flat NLO corrections to $W_L W_L$.

- How to take into account theory uncertainties? NLO/LO too conservative?

- Reference frame and phase space definition to:
  - Decrease the impact of theory uncertainties.
  - Eg. predictions @NNLO QCD and @NLO EW are published (and will be publicly available soon).
    - ~10% unc for p_{TV}=500GeV.
    - ~same size as expected stat unc for full Run2.
    - To suppress the hard *Vj* topology with a soft vector boson which leads to geant k-factors, a cut on r_{21}, the ratio between the non-leading and leading boson p_T, was suggested.



M. Grazzini et al.



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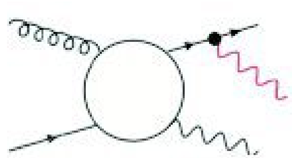
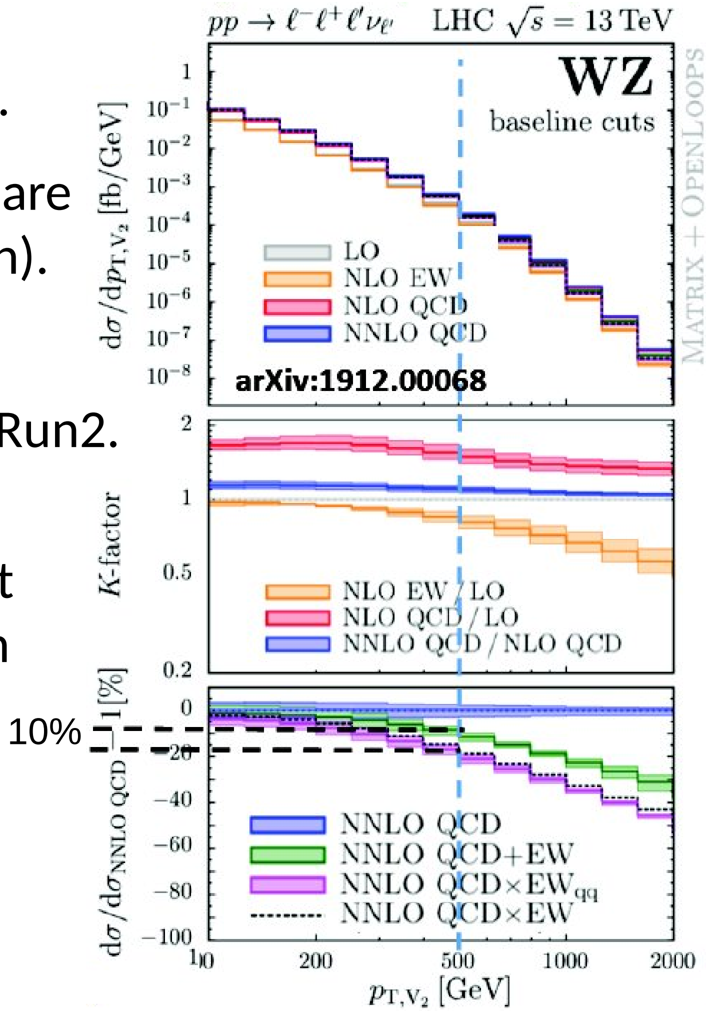




  - Increase the sensitivity to f_{00}.
  - Increase the sensitivity to EFTs.

WZ polarization problematics (3)

Neutrino reconstruction:

- Impossible to measure it at LHC.
  - Very sensitive to boson decay characteristics → polarization.
- Evaluation methods:
  - Assuming $M_W = M_{pole}$: $A\,p_{z,\nu}^2 + B\,p_{z,\nu} + C = 0$

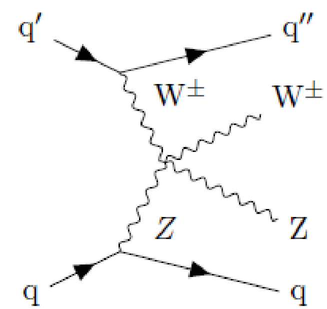
$$A = p_{T,lep}^2$$
$$B = -2\,p_{z,lep}\left(p_{x,lep}\,p_{x,\nu} + p_{y,lep}\,p_{y,\nu} + \frac{M_W^2}{2}\right)$$
$$C = -\left(p_{x,lep}\,p_{x,\nu} + p_{y,lep}\,p_{y,\nu} + \frac{M_W^2}{2}\right)^2 + E_{lep}^2\,p_{T,\nu}^2$$

  - Second order equation → 2 solutions (and can be complex)
- Several methods tested to deal with the ambiguity and to complex solutions.
  - No clear winner.
- Use variables only defined in the ***transverse plane***?
- The "transverse helicity" angle as defined in 1203.2165 was tested with no increase in f_0 sensitivity, $\cos\theta_{2D} = \dfrac{\vec{p}_T^{\,\ell*} \cdot \vec{p}_T^{\,W}}{|\vec{p}_T^{\,\ell*}|\,|\vec{p}_T^{\,W}|}$. Other possibilities?
- DNN reconstruction under test.

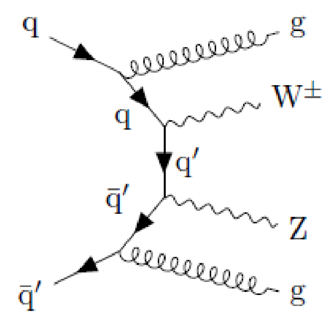
WZjj-EW: Analysis overview

- Target: EW production of $W^{\pm}Z \rightarrow \ell\ell\ell\nu$.
- Identified by 2 jets with large $\Delta\eta$ and $m(jj)$.
- Signal extracted by fitting a BDT discriminant built from 15 variables:
  - Jet kinematics:
    $m(jj)$, $p_T(j_1)$, $p_T(j_2)$, $\Delta\eta$, $\Delta\varphi$, $y(j_1)$, n_{jets}.
  - Diboson kinematics:
    $p_T(W)$, $p_T(Z)$, $\eta(W)$, $|y(Z)-y(\ell_W)|$, $m_T(W)$
  - Combined jet-dibons:
    $\Delta R(j_1,Z)$, R^{hard}_{pT}, ζ_{lep}.

$$\boxed{R^{hard}_{p_T} = \frac{\left(\sum_{l,j} p\right)_T}{\sum_{l,j} p_T}}$$



Electroweak-induced



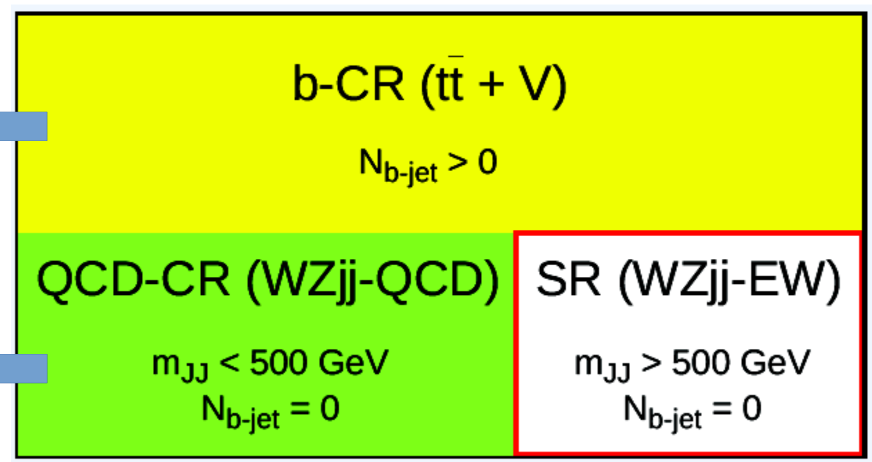
QCD-induced production

- Main backgrounds: QCD-induced production (~75% of bkg in SR) and mis-identified leptons (~7% of bkg in SR), estimated from data in dedicated control regions.
- Main MC samples:
  - Signal: SHERPA-v2.2.2, LO EWK, with up to 2 add. jets @LO.
  - QCD: SHERPA-v2.2.2, one jet @NLO and up to 2 add. jets @LO (norm. in CR and SR).

- Baseline Selection:
  - Exactly 3 well-identified and isolated leptons (electrons or muons):
    - 2 OSSF leptons with $p_T > 15GeV$ and $|m(\ell\ell) - M_{Z\ PDG}| < 10GeV$
    - 1 lepton with $p_T > 20GeV$ and $mT > 30GeV$.
  - 2 jets: $p_T > 40GeV$, $|\eta| < 4.5$, $\eta_{j1} \cdot \eta_{j2} < 0$, $m(jj) > 150GeV$, no b-jet

b-CR (45% purity)
used to normalize ttV (second irreducible background).

QCD-CR (80% purity)
used to normalize WZjj-QCD (main irreducible background)



+ ZZ CR (70% purity)
by requiring a 4th lepton

Results

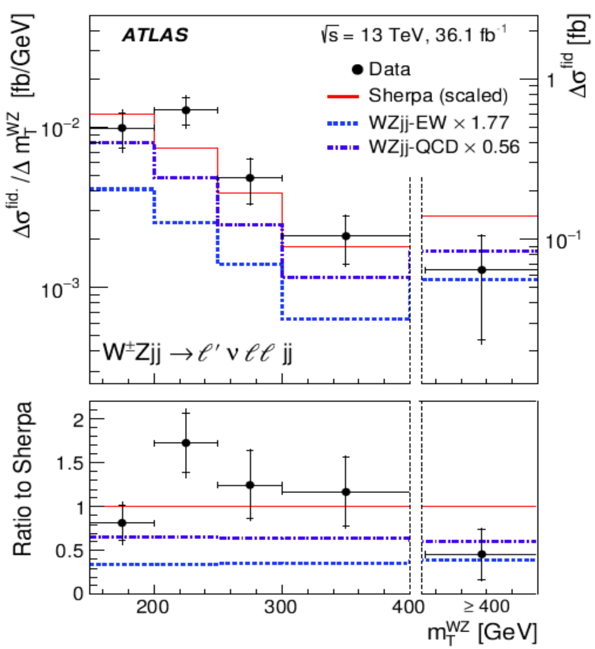
- Overestimation of strong WZjj production by SHERPA-v2.2.2, $\mu_{WZ\text{-}QCD} = 0.56 \pm 0.16$.
- **Background only hypothesis rejected with 5.3σ** (exp. 3.2σ).
- Fiducial cross section:

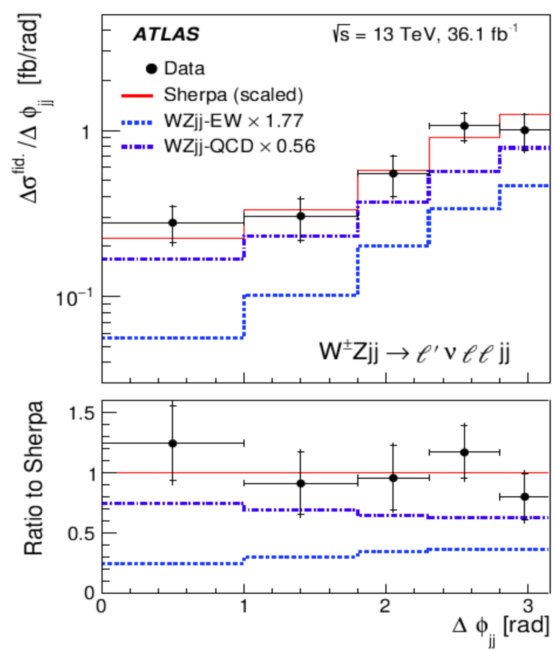
$$\sigma^{fid.}_{WZjj-\mathrm{EW}} = 0.57^{+0.14}_{-0.13}\ (\mathrm{stat.})^{+0.05}_{-0.04}\ (\mathrm{exp.\ syst.})^{0.05}_{-0.04}\ (\mathrm{mod.\ syst.})^{+0.01}_{-0.01}\ (\mathrm{lumi.})\ \mathrm{fb}$$

to be compared to $0.321^{+0.028}_{-0.024}$ fb predicted by SHERPA-v2.2.2.

- Combined QCD+EW differential fiducial cross section:

For EFT interpretations





For QCD studies

Systematic Uncertainties

Source	Uncertainty [%]
$WZjj$–EW theory modelling	4.8
$WZjj$–QCD theory modelling	5.2
$WZjj$–EW and $WZjj$–QCD interference	1.9
Jets	6.6
Pile-up	2.2
Electrons	1.4
Muons	0.4
b-tagging	0.1
MC statistics	1.9
Misid. lepton background	0.9
Other backgrounds	0.8
Luminosity	2.1
Total Systematics	10.9

Main source of sys unc:
jet reconstruction and calibration

Interference:
shape unc computed using MG5_aMC@NLO 2.3 at LO in QCD

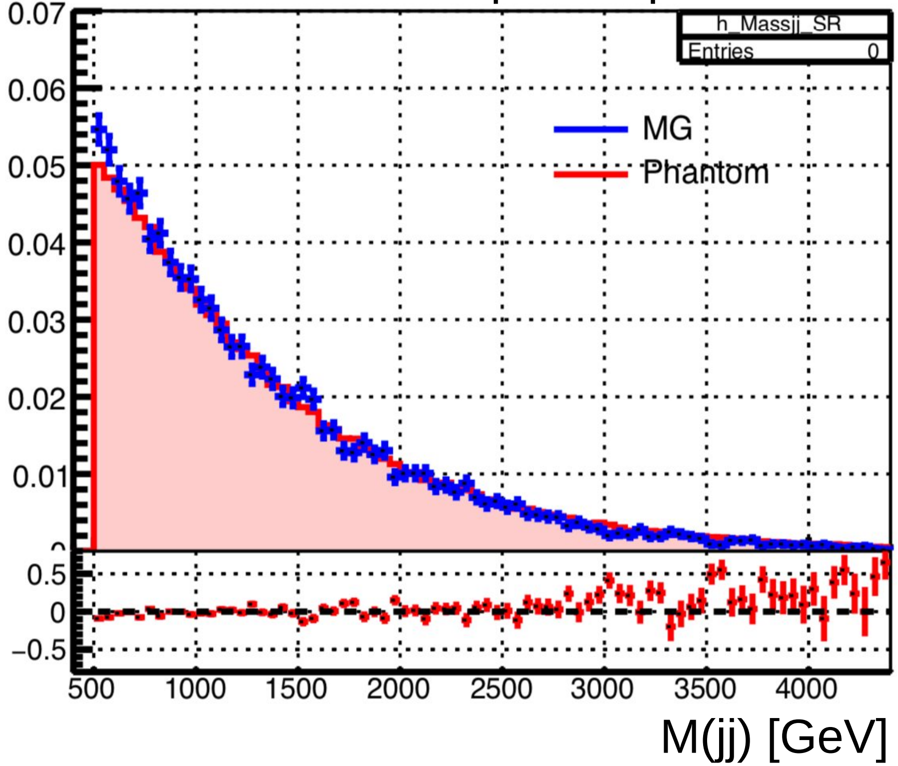
QCD scale:
20-30% for QCD, 5% for signal (flat)
PDF uncertainties: ~1-2%

WZjj-QCD modelling uncertainty:
conservative envelope between parton shower unc. and differences between SHERPA-v2.2.2 at NLO and MG5_aMC@NLO 2.3 at LO in QCD with up to two partons at matrix element.

WZjj-EW modelling uncertainty:
shape differences between SHERPA-v2.2.2 at NLO and MG5_aMC@NLO 2.3 at LO in QCD.

- m(jj) modelling:
  - New comparison between MG and Phantom shows good agreement?
  - Why differencies w.r.t Sherpa-v2.2.2?

L. Di Ciaccio, private production



WZjj-EW probelmatics (2)

- Theory problematics:
  - For polarization measurements, is it enough to assess uncertainties from missing higher orders just with factorization and normalization scale variations?
  - In $V_L V_L \to V_L V_L$, how to interpret polarization fractions for the initial states? Is there any particular prescription for the case in which they are off-shell with negative invariant mass?
  - How interesting are single boson polarization measurements with LHC Run2 dataset?
  - Is it interesting to perform the measurement in different phase-spaces, e.g enriched in α_{EW}^{6} contributions?
- Experimental problematics:
  - Neutrino reconstruction.

Time for discussion..