Measurement of gauge boson polarisation in inclusive WZ events

Based on [ATLAS-CONF-2018-034], and PhD thesis of Angela Burger

From theory to reality ...

➘ First measurement of polarisation in diboson production in pp collisions

- Exercise and develop methods first in inclusive VV production
- WZ final state (fully leptonic): a good compromise between background, reconstruction problems and statistics
- A precursor for VVjj
- An new degree of freedom for NP searches

Inclusive WZ production

- Analysis based on 36 fb^{-1} (2015-2016) of data

- Definition of phase spaces

Variable	Total	Fiducial and aTGC
Lepton $\|\eta\|$	—	< 2.5
p_T of ℓ_Z, p_T of ℓ_W [GeV]	—	> 15, > 20
m_Z range [GeV]	$66 - 116$	$\|m_Z - m_Z^{PDG}\| < 10$
m_T^W [GeV]	—	> 30
$\Delta R(\ell_Z^-, \ell_Z^+)$, $\Delta R(\ell_Z, \ell_W)$	—	> 0.2, > 0.3

- Main analysis caracteristics
  - ➔ Select events with only 3 leptons
  - ➔ Optimised lepton isolation criteria to reduce the reducible background
  - ➔ no cut on E_T^{miss}, replaced by a cut on m_T^W
  - ➔ Data-driven estimate of reducible backgrounds (matrix method)
  - ➔ Powheg+Pythia signal MC, rescaled to NNLO (MATRIX)

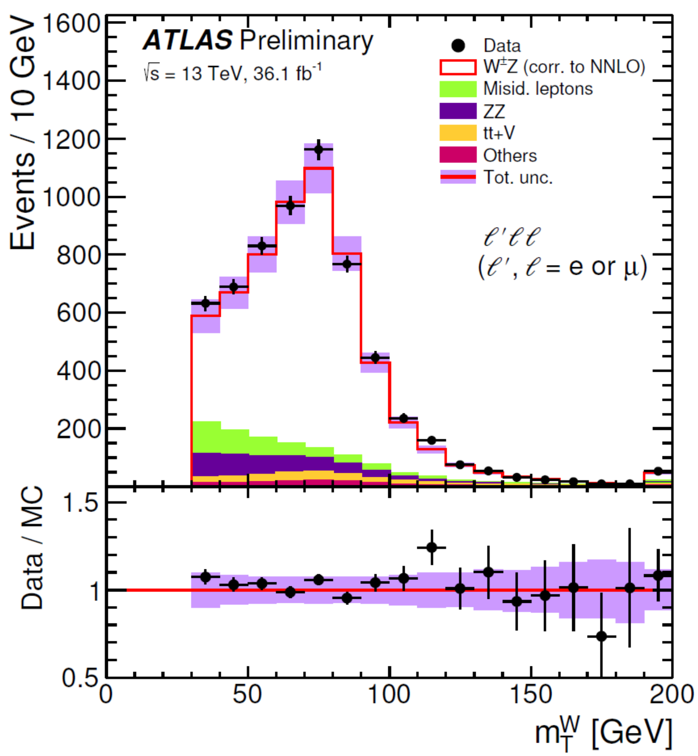
Selected WZ candidate events

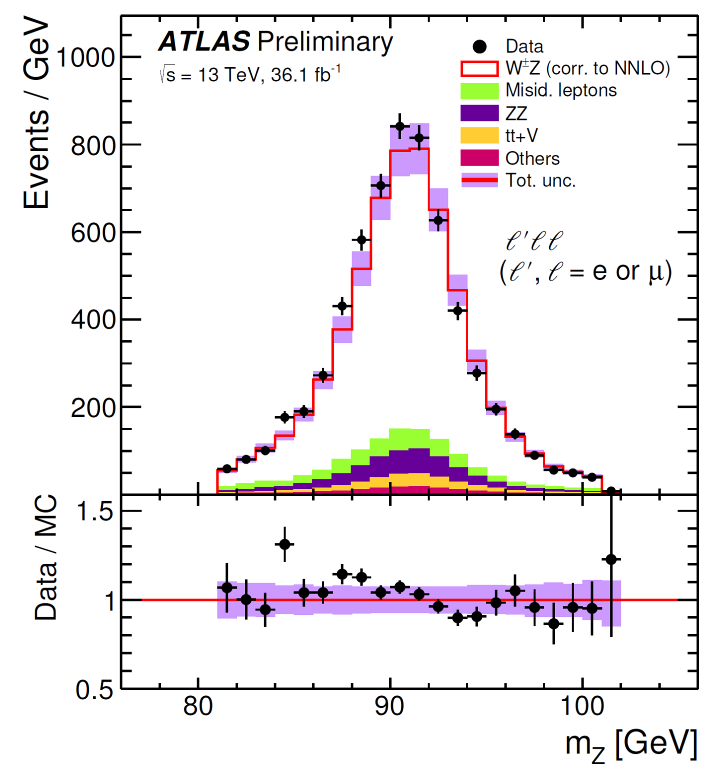
Channel	eee	μee	$e\mu\mu$	$\mu\mu\mu$	All
Data	1279	1281	1671	1929	6160
Total Expected	1221 ± 7	1281 ± 6	1653 ± 8	1830 ± 7	5986 ± 14
WZ	922 ± 5	1077 ± 6	1256 ± 6	1523 ± 7	4778 ± 12
Misid. leptons	138 ± 5	34 ± 2	193 ± 5	71 ± 2	436 ± 8
ZZ	86 ± 1	89 ± 1	117 ± 1	135 ± 1	426 ± 3
$t\bar{t}$+V	50.0 ± 0.7	54 ± 0.7	56.1 ± 0.7	63.8 ± 0.8	225 ± 1
tZ	23.1 ± 0.4	24.8 ± 0.4	28.8 ± 0.4	33.5 ± 0.5	110 ± 1
VVV	2.5 ± 0.1	2.8 ± 0.1	3.2 ± 0.1	3.6 ± 0.1	12.0 ± 0.2

80% of WZ signal

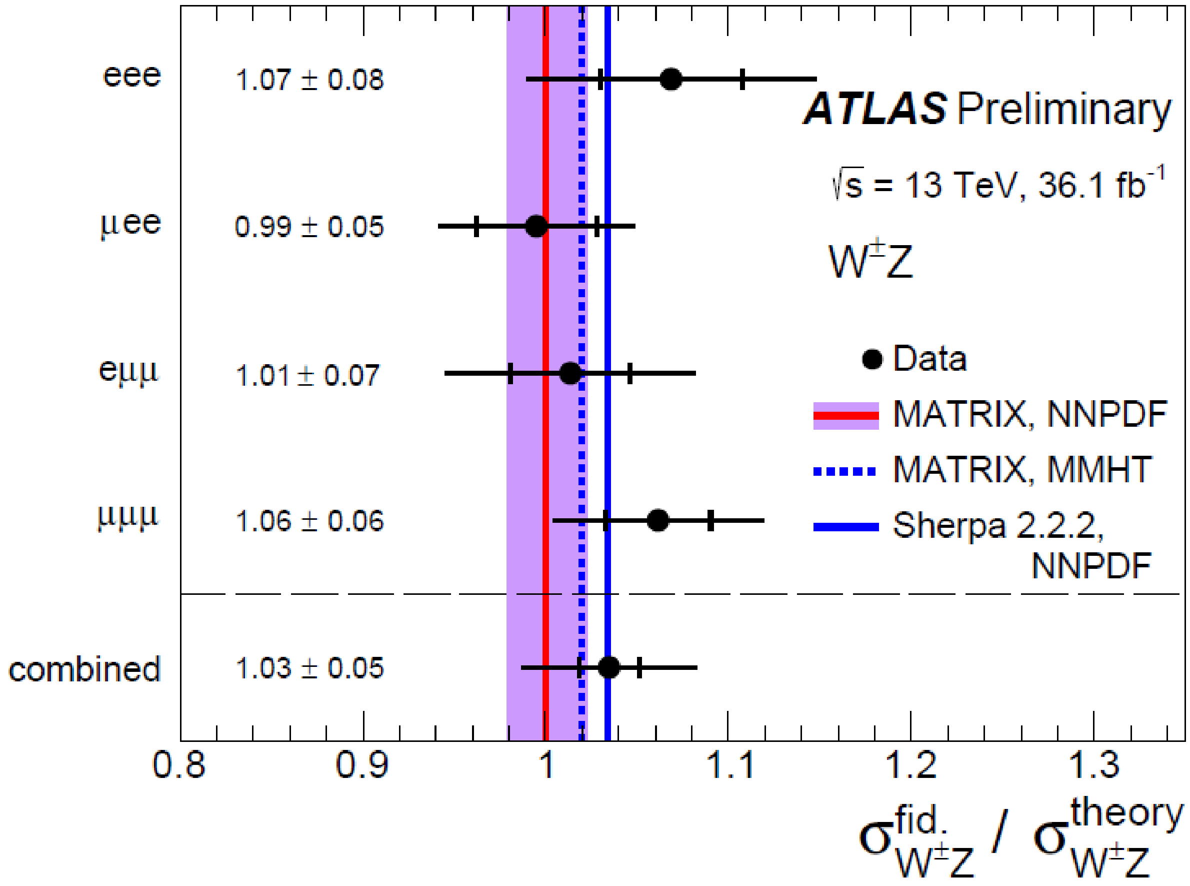
7.3% reducible bkg. (fakes)

7.1% irrreducible bkg. (ZZ)





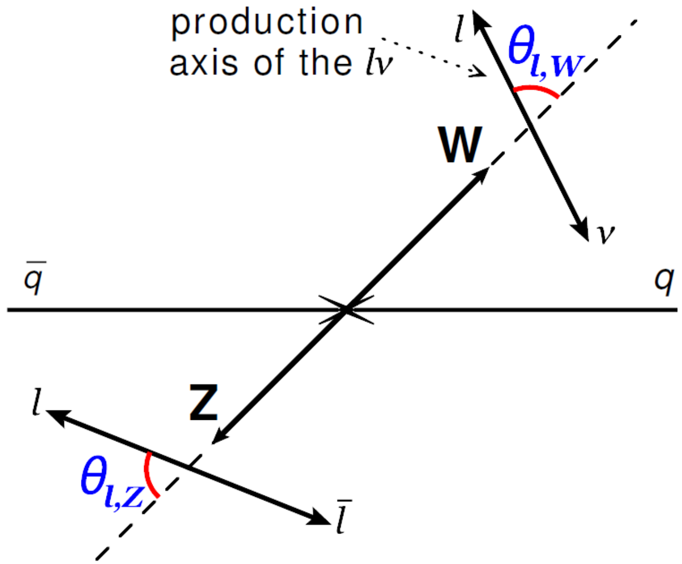
- Analysis used to measure integrated fiducial WZ cross section



➘ Total experimental precision of 4.6%

Polarisation observables

- Decay angles of leptons
- $\cos\theta_{l,W(Z)}$ = lepton decay angle in W(Z) rest frame wrt. th W(Z) direction in the WZ c.m.s.
  - ➔ Helicity frame used
  - ➔ In the WZ rest frame
  - ➘ Helicity fractions depends on the frame



W boson:

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

Z boson:

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

$$\alpha = \frac{2c_\nu c_a}{c_\nu^2+c_a^2} \qquad c_\nu = -\tfrac{1}{2} + 2\sin^2\theta_W^{\text{eff}}$$

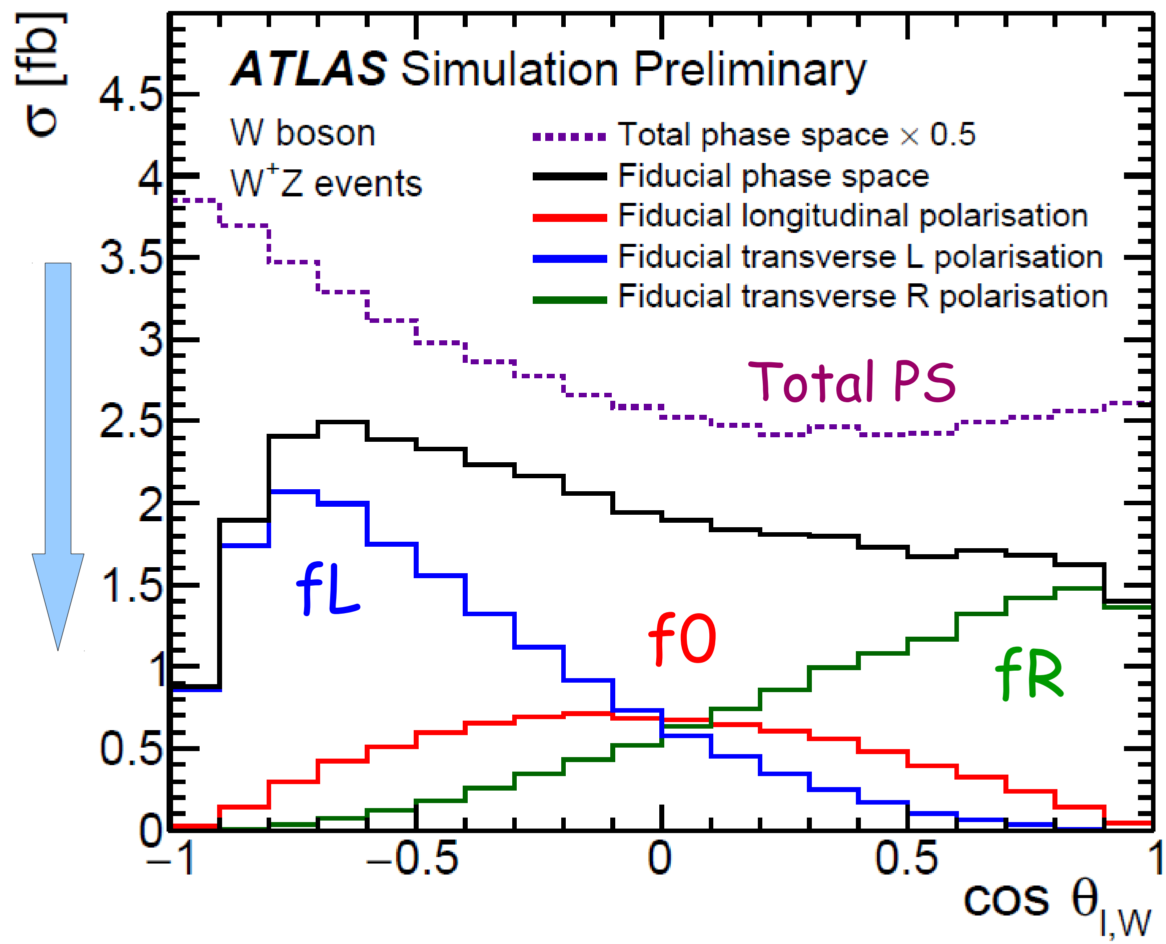
- Effective Weinberg angle used $\sin^2\theta_W^{\text{eff}} = 0.23152$ (value affects Z-polarisation)
- Constraint: $f_0 + f_L + f_R = 1$

From total to fiducial Phase Space

- Previous formulae valid only in a total phase space
  - ➔ Shape of cos θ_V modified by acceptance cuts on leptons
    - ➘ Reason to avoid a cut on E_T^{miss}

W+ boson, MC truth

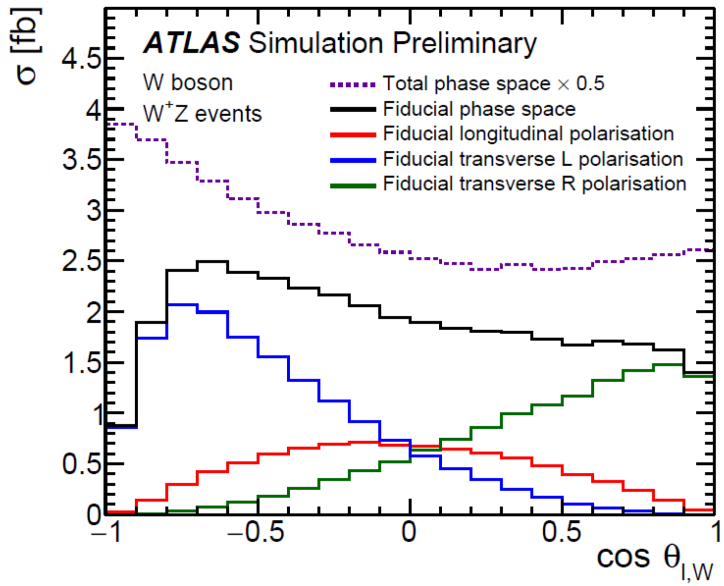
Lepton pT cut (pT > 20 GeV)



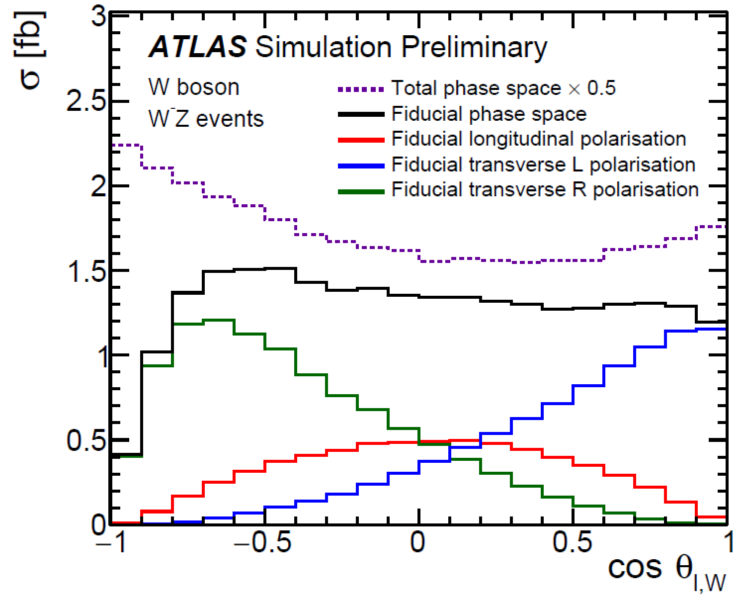
Neutrino pT cut

Fiducial PS cos θ_V distributions

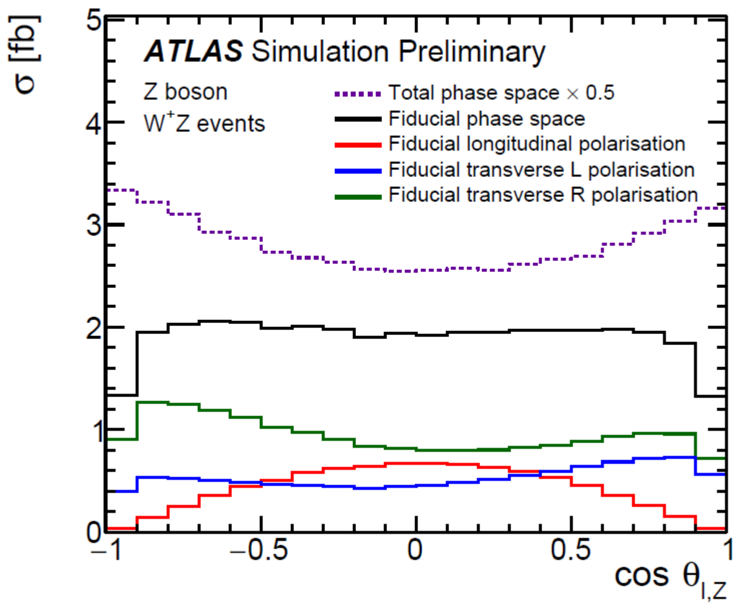
W+ boson



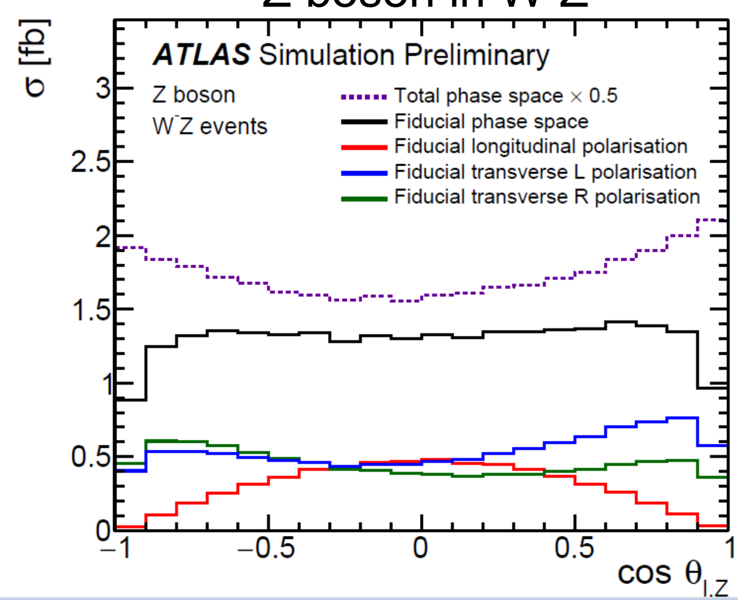
W- boson



Z boson in W+Z

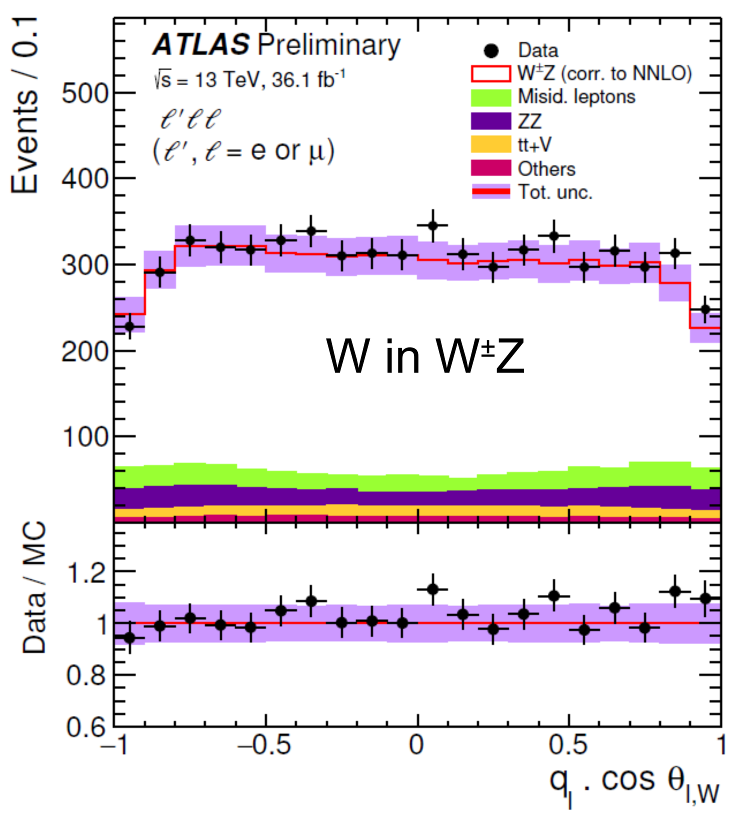


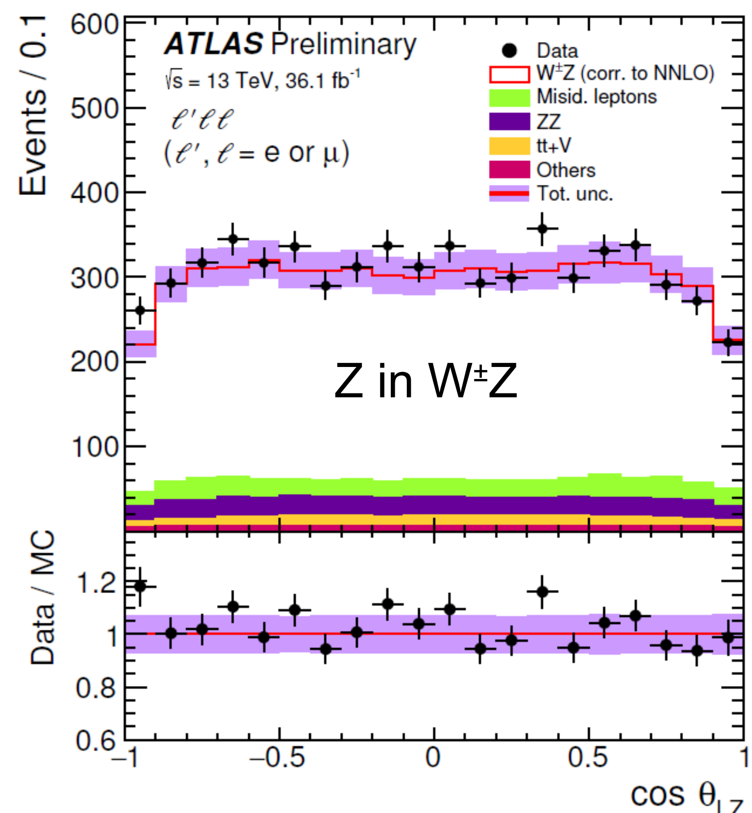
Z boson in W-Z



Detector-level observables

- Moving to detector level:
  - ➔ Detector resolution
  - ➔ Reconstruction of the longitudinal momentum of the neutrino
    - Use W-mass constrain → choose solution with smaller p_z^{ν}
    - If no real solution: real part of the complex solution with smaller magnitude





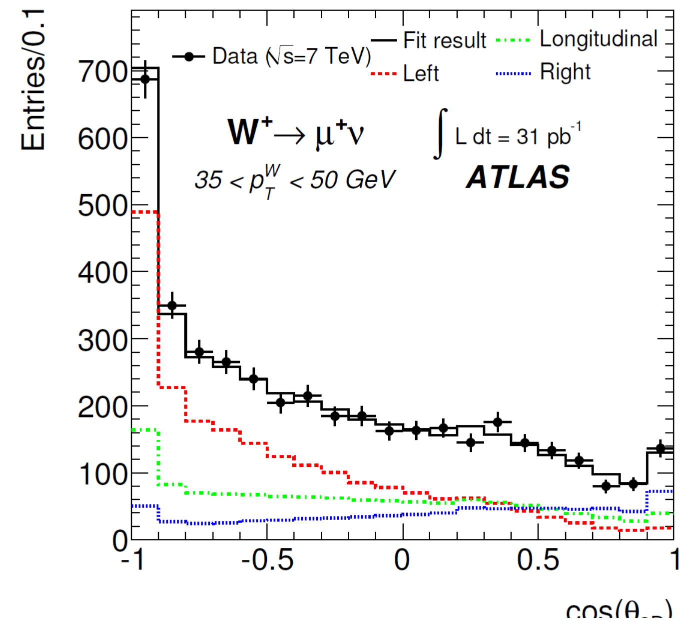
➔ For W multiply cos θ_W by the charge of the W

Comment on W reconstruction

- To avoid the neutrino pz reconstruction:
  - ➔ "Project" cos θ_ν on the transverse plane

$$\cos\theta_{2D} = \frac{\overrightarrow{p}^{\ell*}_{T} \cdot \overrightarrow{p}^{W}_{T}}{|\overrightarrow{p}^{\ell*}_{T}|\,|\overrightarrow{p}^{W}_{T}|}$$

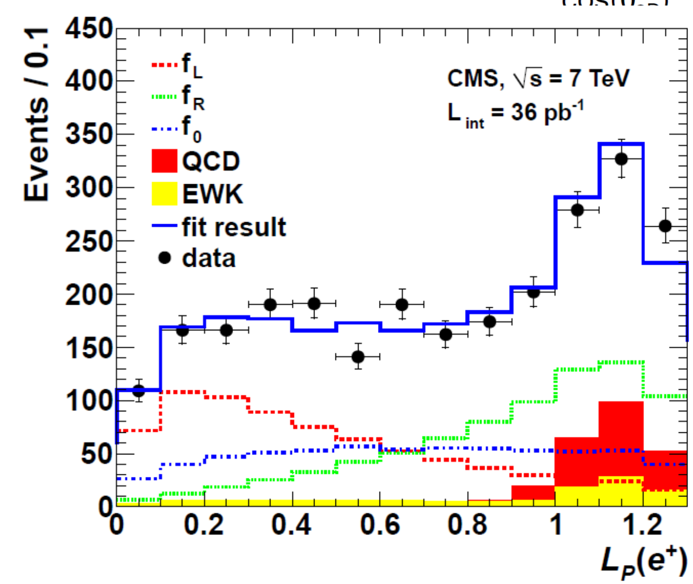
Used for single W polarisation measurement [EPJC 72(2012)2001]



  - ➔ "Lepton projection variable" Lp: projection of $\vec{p}_T(\ell)/|\vec{p}_T(\mathrm{W})|$ onto $\vec{p}_T(\mathrm{W})/|\vec{p}_T(\mathrm{W})|$

$$L_P = \frac{\vec{p}_T(\ell)\cdot\vec{p}_T(\mathrm{W})}{|\vec{p}_T(\mathrm{W})|^2}$$

[PRL 107 (2011) 021802]



➘ Tested, but no sensitivity improvements observed

Measurement methodology

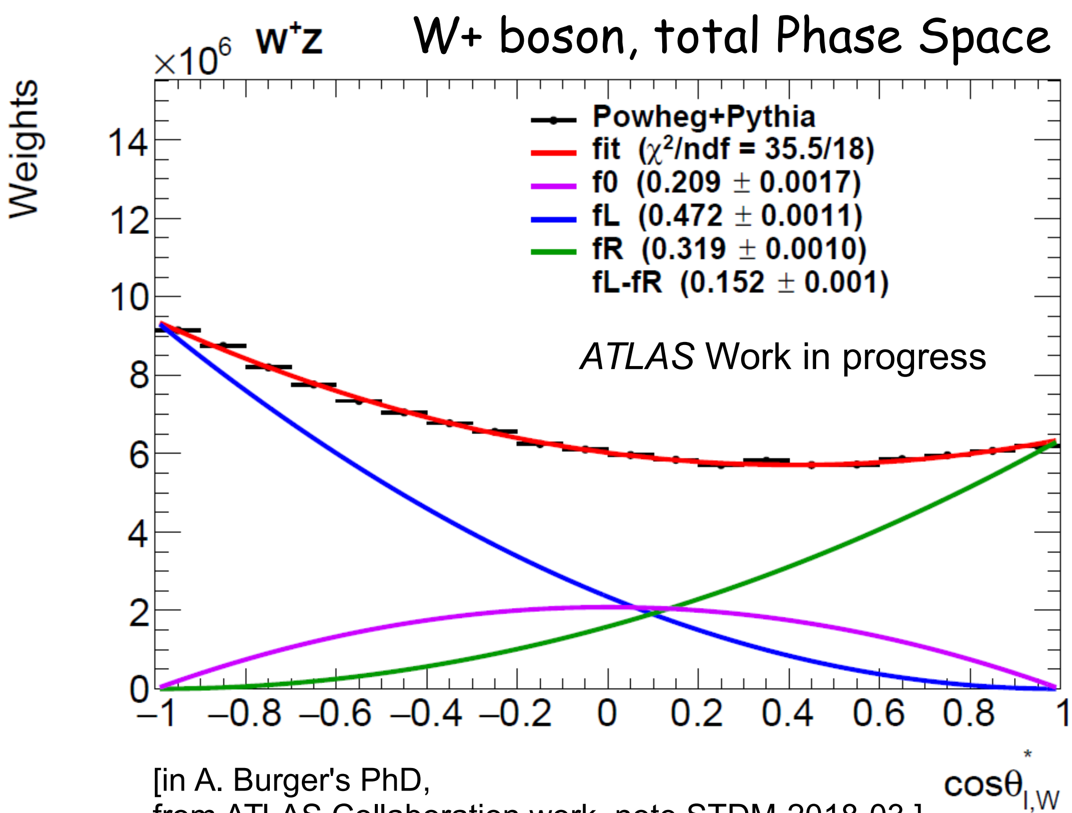
- Measure separatly W and Z polarisations
- Template fit at detector-level using MC templates for fL, fR and f0
  - ➔ Need to generate the MC detector-level templates
- Use a binned profile-likelihood fit
- Use the constraint fL+fR+f0 = 1
  - ➔ 3 parameters fit : f0, fL-fR and the total cross section
- Unfold to fiducial phase space and Born-level leptons
  - ➔ Correct for efficiency differences of each helicity states

Monte Carlo polarisation templates

- No MC available with events of single helicity state
  - ➔ Use standard Powheg+Pythia WZ MC and reweight it to single f0, fL and fR states
  - ➔ Same technique as for single W and Z polarisation measurements

    [EPJC 72(2012)2001] and [JHEP 08(2016)159]

- Determine f0, fL and fR using analytical fits, in (p_T^V,y_V) bins

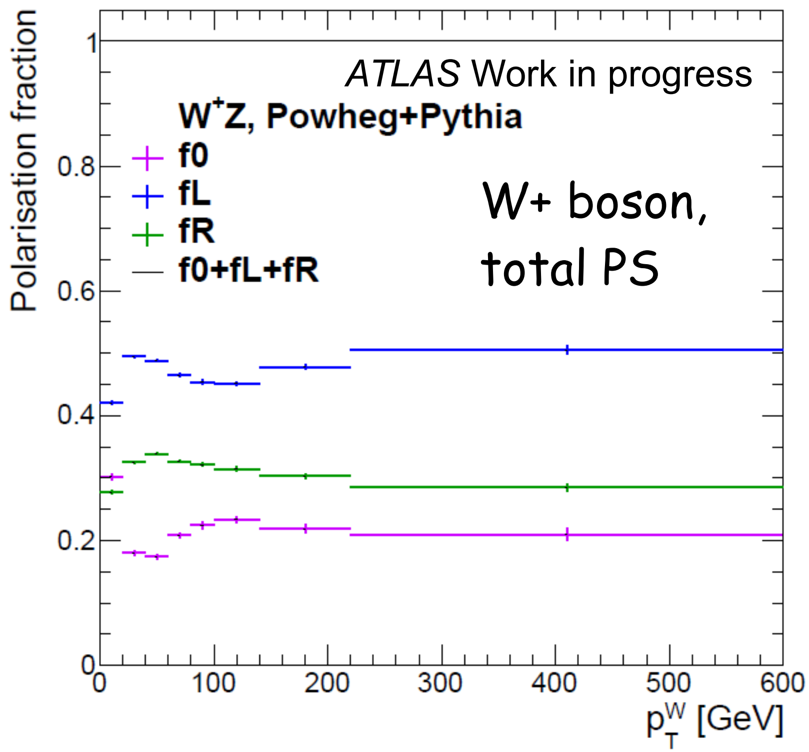


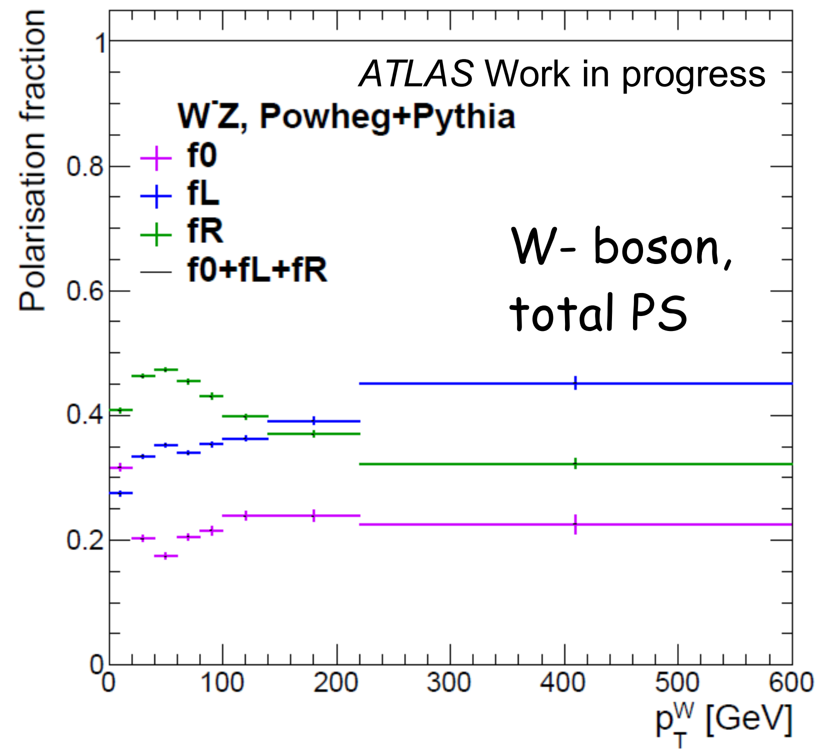
[in A. Burger's PhD,
from ATLAS Collaboration work, note STDM-2018-03]

Monte Carlo polarisation templates

- Exemple of evolution with p_T^V (integrated over y_V)

[in A. Burger's PhD,
from ATLAS Collaboration work, note STDM-2018-03]





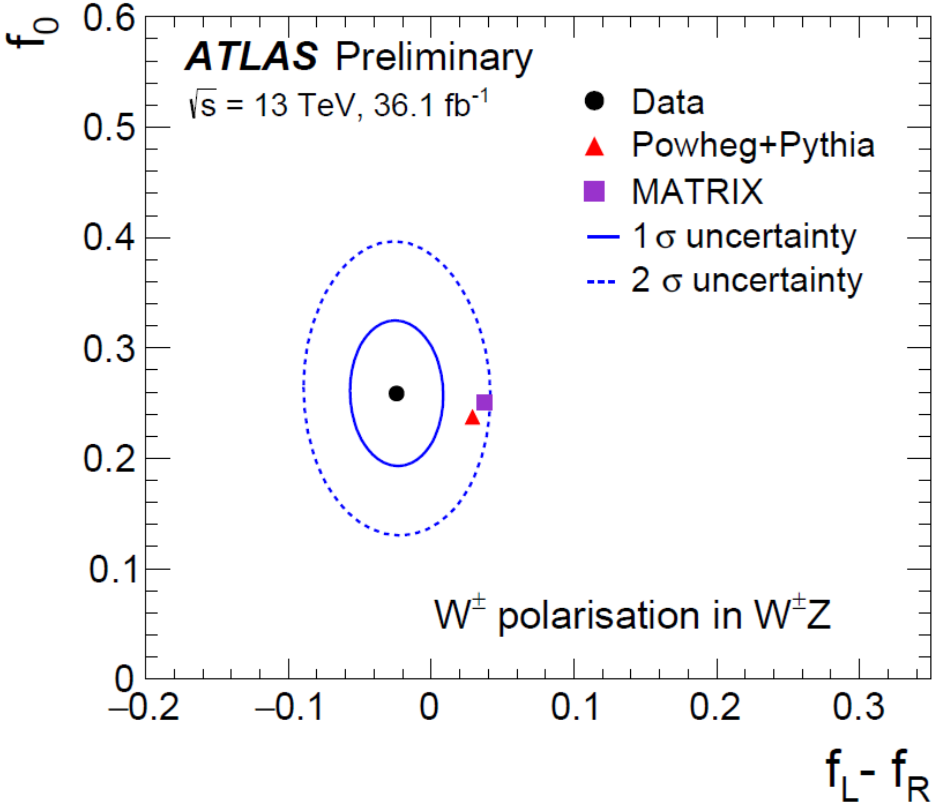
- Event by event weights of MC events

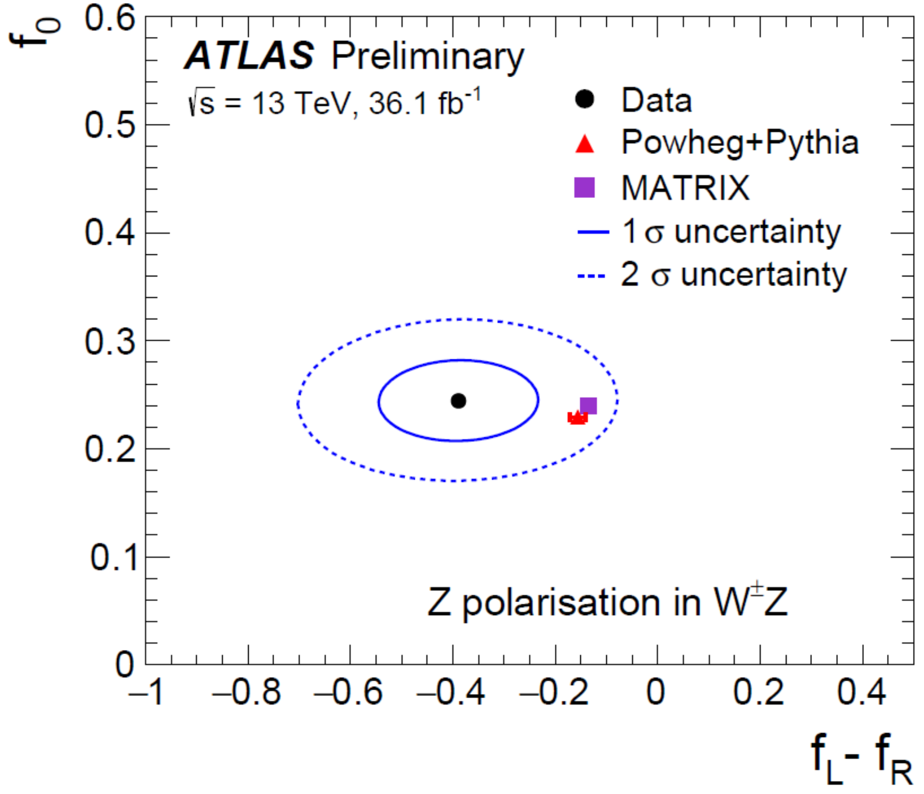
$$\frac{\frac{1}{\sigma_{W^\pm Z}} \frac{d\sigma_{W^\pm Z}}{d\cos\theta_{\ell,W}}\Big|_{\mathrm{L/0/R}}}{\frac{3}{8} f_{\mathrm{L}}^{\mathrm{gen.}} (1 \mp \cos\theta_{\ell,W})^2 + \frac{3}{8} f_{\mathrm{R}}^{\mathrm{gen.}} (1 \pm \cos\theta_{\ell,W})^2 + \frac{3}{4} f_0^{\mathrm{gen.}} \sin^2\theta_{\ell,W}}$$

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

Results of the fit

- Evidence of f0 for W boson : 4.2 σ obs. (3.8 σ expected)
- Observation of f0 for Z boson : 6.5 σ obs. (6.1 σ expected)





➔ Agreement with predictions (low sensitivity on fL-fR)

➔ Minor impact of NNLO QCD corrections on prediction

Systematic uncertainties

	$W^\pm$ in $W^\pm Z$		Z in $W^\pm Z$	
	f_0	$f_L - f_R$	f_0	$f_L - f_R$
Electrons	0.0024	0.0004	0.005	0.0021
Muons	0.0013	0.0027	0.0018	0.008
Jets	0.0024	0.0010	0.0017	0.005
Pileup	0.005	0.00009	0.0014	0.005
Misid. lepton background	0.031	0	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
Modelling	0.004	0.007	0.0015	0.0028
Total systematics **13%**	0.033	0.008	0.009	0.024
Luminosity	0.0015	0	0	0.0008
Statistics	0.06	0.032	0.04	0.15
Total	0.06	0.033	0.04	0.16
	23%		**17%**	

→ Dominated by data statistical uncertainties

Polarisation per W charge

- Polarisation also measured for W+Z and W-Z events

	f_0		$f_L - f_R$	
	Data	Prediction	Data	Prediction
W^+ in W^+Z	0.26 ± 0.08	0.233 ± 0.004	-0.02± 0.04	0.083 ± 0.004
W^- in W^-Z	0.32 ± 0.09	0.245 ± 0.005	-0.05± 0.05	-0.061 ± 0.006
$W^\pm$ in $W^\pm Z$	0.26 ± 0.06	0.2376 ± 0.0031	-0.024± 0.033	0.0249 ± 0.0022
Z in W^+Z	0.27 ± 0.05	0.225 ± 0.004	-0.32± 0.21	-0.269 ± 0.021
Z in W^-Z	0.21 ± 0.06	0.235 ± 0.005	-0.46 ± 0.25	0.034 ± 0.023
Z in $W^\pm Z$	0.24 ± 0.04	0.2294 ± 0.0033	-0.39± 0.16	-0.147 ± 0.016

Discussion of NLO EW corrections effects

- A recent calculation for WZ from Julien BAGLIO[1], LE Duc Ninh[2]

  Windows on the universe, Quy Nhon, 7 August 2018 [here]

Method	$f_L^{W^+}$	$f_0^{W^+}$	$f_R^{W^+}$	f_L^Z	f_0^Z	f_R^Z
HE FULL-LO	$0.355(2)^{+2}_{-2}$	$0.513(1)^{+3}_{-3}$	$0.132(2)^{+0.8}_{-0.7}$	$0.222(2)^{+0.8}_{-0.2}$	$0.517(2)^{+1}_{-0.9}$	$0.261(3)^{+1}_{-2}$
HE FULL-NLOQCD	$0.320(3)^{+2}_{-3}$	$0.508(3)^{+2}_{-2}$	$0.172(2)^{+4}_{-3}$	$0.255(8)^{+5}_{-1}$	$0.493(2)^{+2}_{-3}$	$0.252(8)^{+0}_{-3}$
HE FULL-NLOEW	0.355	0.512	0.133	0.217	0.518	0.266

[Note: helicity frame, but differente definition using not the WZ cms. but the laboratory]

- A Tests also on-going using NLO-EW corrections from

  Benedikt Biedermann, Ansgar Denner, Lars Hofer [JHEP10(2017)043]

  ➔ Effects on shape of cos θ_V distributions seems negligible

  ➘ All still understudy, more work needed

Summary and prospects

- A first "full scale" exercise of VV polarisation measurement
- Agreement with predictions (within uncertainties)

Future:

- Analyse full run 2 data (> 3x more statistics)
- Improvements:

  ➔ A better observable than cos θ_V: combination of observables ? with help of NN or BDT ?

  ➔ Jet observables ?

  ➔ Study boson correlations

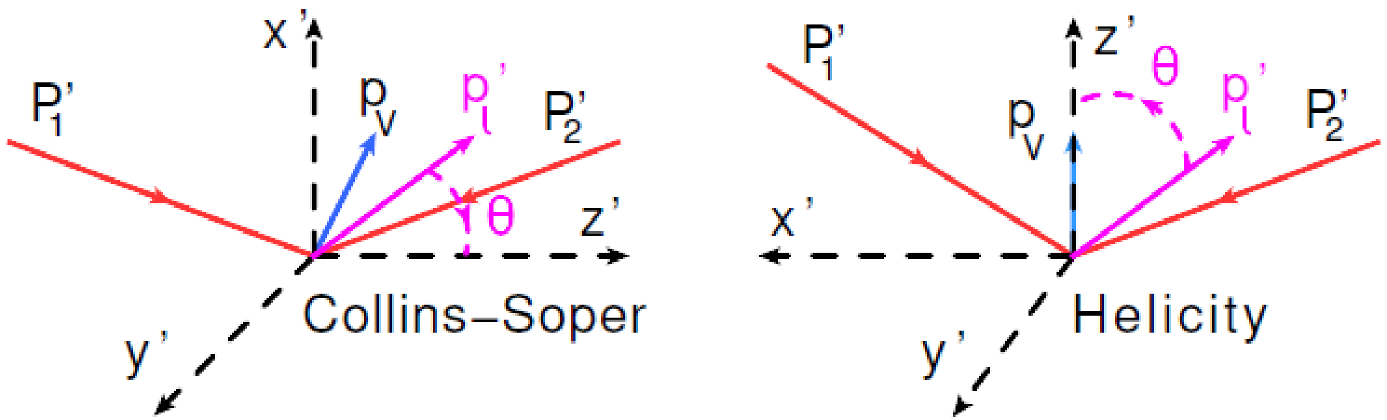
  ➔ Try to apply to WZjj

Additional informations

Polarization observables in two frames

Convention: used by ATLAS and CMS, $l = \mu^-$ for Z, in the V rest frame,

$$\frac{d\sigma}{\sigma d\cos\theta d\phi} = \frac{3}{16\pi}\Big[(1+\cos^2\theta) + A_0\frac{1}{2}(1-3\cos^2\theta) + A_1\sin(2\theta)\cos\phi + A_2\frac{1}{2}\sin^2\theta\cos(2\phi) + A_3\sin\theta\cos\phi + A_4\cos\theta + A_5\sin^2\theta\sin(2\phi) + A_6\sin(2\theta)\sin\phi + A_7\sin\theta\sin\phi\Big],$$



- Collins-Soper frame [CS, 1977]: z' is the bisector of $\vec{P}'_1$ and $-\vec{P}'_2$, points into the hemisphere of $\vec{p}_V$ (in the lab frame).
- Helicity frame [Bern et al, arXiv:1103.5445]: $z' = \vec{p}_V$.
- Integrating over ϕ gives the above polarization fractions $f_{L,0,R}$.

Polarisation per W charge