Polarization studies in WZ production at the LHC

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Outline

- Motivation
- Definition of inclusive polarization observables
- Definition of fiducial polarization observables
- Results for inclusive observables (vs. ATLAS)
- Results for fiducial observables
- Summary

Motivation

- The process $pp \to WZ \to 3\ell + \nu$ is important in the physics program at the LHC.
- Sensitive to triple-gauge couplings.
- High statistics $\rightsquigarrow$ precision!
- To search for hints of new physics: polarization observables can be important.
- To find new physics effects: good understanding of theoretical and experimental errors is needed.

Diboson is important!

- Helicity correlations between the 2 gauge bosons first occur here. For example, the double longitudinal fraction $f_{LL} = d\sigma(V_L V_L)/d\sigma(VV)$ is interesting.
- We have to understand the polarizations here before moving to vector boson scatterings (VBS).

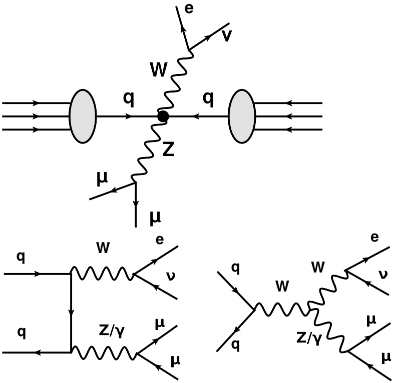
The status of $pp \to WZ + X$

- NLO QCD: [Ohnemus 1991]; [Frixione, Nason, Ridolfi 1992].
- NLO EW on-shell: [Bierweiler, Kasprzik, Kühn 2013]; [Baglio, LDN, Weber 2013 (with $q\gamma$ induced)].
- NNLO QCD: [Grazzini, Kallweit, Rathlev, Wiesemann 1604.08576, 1703.09065].
- full NLO EW off-shell: [Biedermann, Denner and Hofer 1708.06938].

There is still another step to go from those inclusive results (cross sections, angular distributions) to polarization observables.
Latest experimental results: ATLAS arXiv:1902.05759 with measurements of individual gauge boson polarizations.
It is now time for throughout comparisons between measurements and theoretical predictions.

The focus of this talk is on individual gauge boson polarizations.

$W^{\pm}Z$ production at the LHC



- Intial beams: unpolarized
- Only left-handed quarks interact with W (max. asymmetry)
- Z interacts with both left- and right-handed quarks, but with different coupling strength:
  $g_R^f = -(s_W Q_f)/c_W$,
  $g_L^f = (I_f^3 - s_W^2 Q_f)/(s_W c_W)$.
- $\rightsquigarrow$ W and Z produced at the LHC are polarized!

Remark: those polarized W and Z induce an asymmetry in angular distributions of the final-state leptons!

The master equation

Consider $V \to \ell_1 \bar{\ell}_2$, θ and ϕ are the angles of ℓ_1 in the V rest frame.

$$\frac{d\sigma}{dp_T^V dy^V dm^V d\cos\theta d\phi} = \frac{3}{16\pi} \frac{d\sigma}{dp_T^V dy^V dm^V}$$

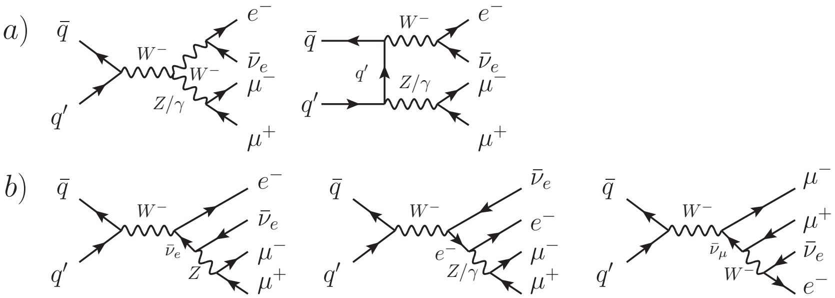
$$\times \Big[(1+\cos^2\theta) + A_0 \frac{1}{2}(1-3\cos^2\theta) + A_1 \sin(2\theta)\cos\phi$$

$$+ A_2 \frac{1}{2}\sin^2\theta\cos(2\phi) + A_3 \sin\theta\cos\phi + A_4\cos\theta$$

$$+ A_5 \sin^2\theta\sin(2\phi) + A_6\sin(2\theta)\sin\phi + A_7\sin\theta\sin\phi\Big],$$

- Note: $A_i = A_i(p_T^V, y^V, m^V)$.
- A_i are independent of the decay angles θ and ϕ.
- Remark: The above equation can be proved for $V \to \ell_1 \bar{\ell}_2$ type diagrams. Is it still hold for radiative decays $V \to 2\ell +$ photons ? and for $\ell \to \ell_1 V' \to \ell_1 \bar{\ell}_2 \ell_3$ diagrams ? There are higher-order and interference effects.
- The present measurements are done under the assumption that the master equation is true. Are results sensitive to those small effects ?

Leading-order diagrams



Note 1: The Z boson does not appear in the last diagram. The angular information of the μ^- there comes from the W boson. Calling this information Z polarization is therefore misleading.

Note 2: there are interference effects between a) and b).

Definition using projections

Integrating over p_T^V, y^V, m^V to get:

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

Projections (or expectations):

$$< f(\theta) > = \int_{-1}^{1} d\cos\theta f(\theta)\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta},$$

$$< f(\theta,\phi) > = \int_{-1}^{1} d\cos\theta \int_{0}^{2\pi} d\phi f(\theta,\phi)\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta d\phi}.$$

Inclusive (no cuts on individual leptons) polarization observables:

$$A_0 = 4 - \langle 10\cos^2\theta\rangle,\ A_1 =< 5\sin 2\theta\cos\phi >,\ \ldots$$

Fiducial polarization observables

Note: $d\sigma/(d\cos\theta d\phi)$ is now calculated using the full matrix elements with arbitrary cuts on the individual leptons as usual. Radiative decays and interference effects are all included.
Projections:

$$< f(\theta) > = \int_{-1}^{1} d\cos\theta f(\theta) \frac{1}{\sigma}\frac{d\sigma}{d\cos\theta},$$
$$< f(\theta,\phi) > = \int_{-1}^{1} d\cos\theta \int_{0}^{2\pi} d\phi f(\theta,\phi) \frac{1}{\sigma}\frac{d\sigma}{d\cos\theta d\phi}.$$

Fiducial (arbitrary cuts on leptons) polarization observables:

$$A_0 = 4 - \langle 10\cos^2\theta\rangle,\ A_1 =< 5\sin 2\theta\cos\phi >,\ \ldots$$

Comparison to the inclusive polarizations:

- Same definition using projections.
- The 8 fiducial coefficients A_i are no longer enough to describe the $g = d\sigma/(\sigma d\cos\theta)$ distribution, since some information is lost after the projections. E.g. $< \cos\theta >= \int \cos\theta(g + \cos^{2n}\theta) d\cos\theta$.

Polarization fractions: $f_L + f_R + f_0 = 1$

Notation: $e = 3$, $\mu^- = 6$, $\theta_i = \angle(\vec{p}'_{\ell_i}, \vec{z}')$ in the V rest frame, integrate out ϕ:

$$\frac{d\sigma}{\sigma d\cos\theta_3} \equiv \frac{3}{8}\left[(1 \mp \cos\theta_3)^2 f_L^{W^\pm} + (1 \pm \cos\theta_3)^2 f_R^{W^\pm} + 2\sin^2\theta_3 f_0^{W^\pm}\right], \quad (2)$$

$$\frac{d\sigma}{\sigma d\cos\theta_6} \equiv \frac{3}{8}\left[(1 + \cos^2\theta_6 + 2c\cos\theta_6) f_L^Z + (1 + \cos^2\theta_6 - 2c\cos\theta_6) f_R^Z + 2\sin^2\theta_6 f_0^Z\right], \quad (3)$$

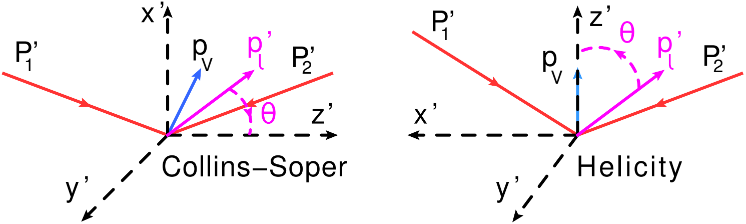
$$f_L^V = \frac{1}{4}(2 - A_0^V + d_V A_4^V), \quad f_R^V = \frac{1}{4}(2 - A_0^V - d_V A_4^V), \quad f_0^V = \frac{1}{2}A_0^V,$$

$$f_L^V - f_R^V = \frac{d_V}{2}A_4^V, \quad d_Z = \frac{1}{c}, \quad d_{W^\pm} = \mp 1,$$

$$c = \frac{g_L^2 - g_R^2}{g_L^2 + g_R^2} = \frac{1 - 4s_W^2}{1 - 4s_W^2 + 8s_W^4} \approx 0.21, \quad s_W^2 = 1 - \frac{M_W^2}{M_Z^2}. \quad (4)$$

- Values of f_L, f_R depend on the coordinate system.
- Note: $A_4^Z \propto c$, $\rightsquigarrow f_{L,R}^Z$ do not depend much on s_W^2.

Coordinate systems

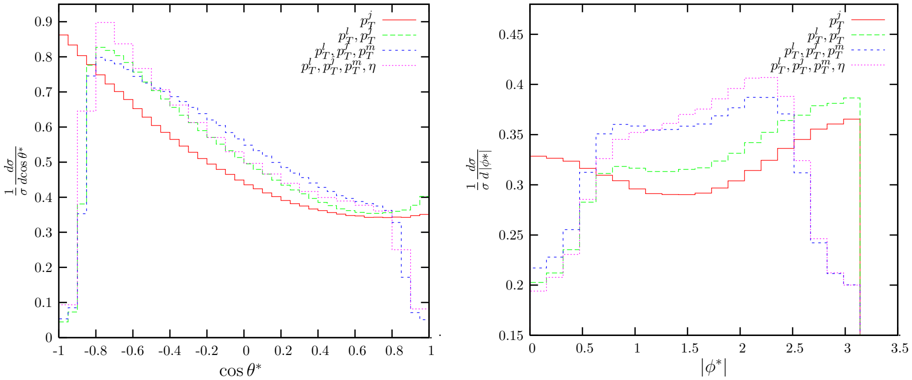


- Collins-Soper coordinate system [CS, 1977]: z' is the bisector of $\vec{P}'_1$ and $-\vec{P}'_2$, points into the hemisphere of $\vec{p}_V$ (in the lab frame).
- Helicity c.s [Bern et al, arXiv:1103.5445]: $z' = \vec{p}_{V,Lab}$.
- Modified helicity c.s [ATLAS WZ 2019]: $z' = \vec{p}_{V,WZ-c.m}$. (THIS TALK)
- f_0 is the longitudinal fraction in the (modified) helicity coordinate systems, but not in the Collins-Soper system.

Effects of cuts (I)

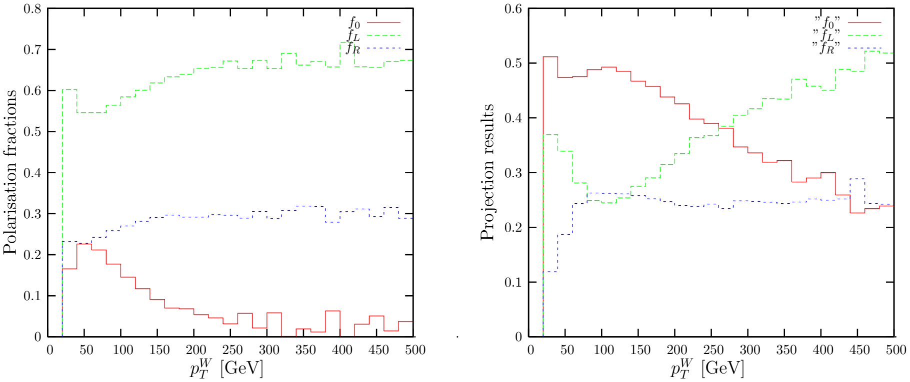
W^+ + 1jet [Stirling, Vryonidou 1204.6427]:

$$p_{T,j} > 20\,\text{GeV},\ p_{T,\ell} > 20\,\text{GeV},\ E_{T,m} > 20\,\text{GeV},\ |\eta_{\ell,j}| < 2.5.$$



Effects of cuts (II)

W^+ + 1jet [Stirling, Vryonidou 1204.6427]:
$p_{T,j} > 20$ GeV vs. $p_{T,j} > 20$ GeV and $p_{T,\ell} > 20$ GeV,



Note: watch the longitudinal fraction, it decreases with p_T in both cases.

WZ polarization at NLOQCD+EW

Our results presented here:

- NLOQCD: full amplitudes, using VBFNLO.
- NLOQCDEW: NLOQCD + DPA EW.

At LO, the amplitude in the double-pole approximation (DPA) is defined as

$$\mathcal{A}^{ab\to V_1V_2\to 4\ell}_{\text{LO,DPA}} = \sum_{\lambda_1,\lambda_2} \frac{\mathcal{A}^{ab\to V_1V_2}_{\text{LO}}\,\mathcal{A}^{V_1\to \ell_1\ell_2}_{\text{LO}}\,\mathcal{A}^{V_2\to \ell_3\ell_4}_{\text{LO}}}{Q_1Q_2},$$

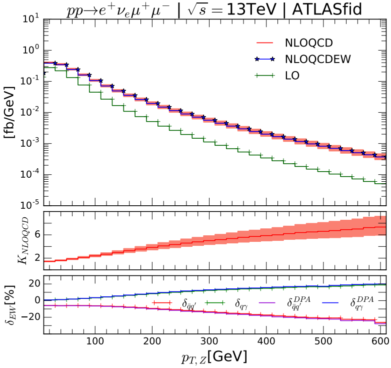
$$Q_i = q_i^2 - M_{V_i}^2 + iM_{V_i}\Gamma_{V_i}, \quad i = 1, 2.$$

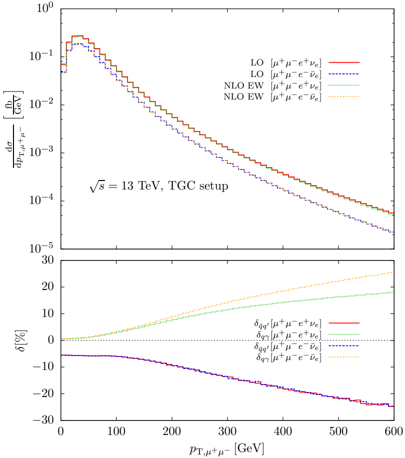
NLO EW corrections in the DPA:

- Virtual and real corrections to the production part included.
- Virtual and real corrections to the decays included.
- Quark-photon induced $q\gamma \to WZq' \to 4lq'$ included.
- Non-factorizable contribution not included.
- Off-shell effects not included.

DPA vs. full NLOEW: $p_{T,Z}$

Full NLOEW: [Biedermann, Denner and Hofer 1708.06938],
`LUXqed17_plus_PDF4LHC15_nnlo`.





- Excellent agreement for $\delta_{q\gamma}$ and $\delta_{\bar{q}q'}$.
- Strong cancellation between $\delta_{q\gamma}$ and $\delta_{\bar{q}q'}$, making the total EW correction small at large p_T. Photon PDF is important here.

Inclusive polarization fractions: comparison with ATLAS

13 TeV, ATLAS cuts (arXiv:1902.05759):

$$p_{T,e} > 20\,\text{GeV}, \quad p_{T,\mu} > 15\,\text{GeV}, \quad |\eta_\ell| < 2.5,$$
$$|m_{\mu^+\mu^-} - M_Z| < 10\,\text{GeV}, \quad \Delta R(\mu^+, \mu^-) > 0.2, \quad \Delta R(e^+, \mu^\mp) > 0.3,$$
$$m_{T,W} = \sqrt{2 p_{T,\nu} p_{T,e} [1 - \cos \Delta\phi(e,\nu)]} > 30\,\text{GeV}$$

- Template fits are used to get polarization fractions.

Inclusive fractions: vs. ATLAS (W^+Z)

Method	$f_0^{W^+}$	$f_L^{W^+} - f_R^{W^+}$	f_0^Z	$f_L^Z - f_R^Z$
ATLAS data	$0.26\{8\}$	$-0.02\{4\}$	$0.27\{5\}$	$-0.32\{21\}$
ATLAS POWHEG+PYTHIA	$0.233\{4\}$	$0.091\{4\}$	$0.225\{4\}$	$-0.297\{21\}$
ATLAS MATRIX	$0.2448\{10\}$	$0.0868\{14\}$	$0.2401\{14\}$	$-0.262\{9\}$
NLOQCD	0.241	0.082	0.232	-0.307
NLOQCDEW	0.244	0.078	0.237	-0.244

- Note: Our fixed-order results (NLOQCD and NLOQCDEW) are obtained using the templates generated by POWHEG+PYTHIA. This should be OK because the templates are independent of the underlying physical model. The template-fit code and the templates are kindly provided by Emmanuel Sauvan, thanks!
- EW corrections are small for W, but large for $f_L^Z - f_R^Z$, about 20%.
- About 3σ deviation for $f_L^W - f_R^W$, but the error is large.

Inclusive fractions: vs. ATLAS (W^-Z)

Method	$f_0^{W^-}$	$f_L^{W^-} - f_R^{W^-}$	f_0^Z	$f_L^Z - f_R^Z$
ATLAS data	0.32{9}	−0.05{5}	0.21{6}	−0.46{25}
ATLAS POWHEG+PYTHIA	0.245{5}	−0.063{6}	0.235{5}	0.052{23}
ATLAS MATRIX	0.2651{15}	−0.034{4}	0.2389{15}	0.0468{34}
NLOQCD	0.257	−0.049	0.232	0.079
NLOQCDEW	0.259	−0.045	0.236	0.050

- EW corrections are small for W, but large for $f_L^Z - f_R^Z$, about -40%. Origin: EW corrections to $Z \to \mu^+\mu^-$ decay.
- Perfect agreement for $f_L^{W^-} - f_R^{W^-}$, but not as good for $f_L^Z - f_R^Z$ (2σ). The deviation moves from W to Z when changing from W^+Z to W^-Z.

Fiducial polarization fractions

Using the same ATLAS fiducial cuts, but no template fitting this time. Direct projections of lepton angular distributions.

Method	f_0^W	$f_L^W - f_R^W$	f_0^Z	$f_L^Z - f_R^Z$
NLOQCD (W^+Z)	0.483	0.091	0.441	−0.123
NLOQCDEW (W^+Z)	0.485	0.089	0.444	−0.084
NLOQCD (W^-Z)	0.498	0.05	0.422	0.116
NLOQCDEW (W^-Z)	0.498	0.054	0.425	0.099

Note: to compare with data, unfolded angular distributions are needed.

Summary

- Results for individual gauge boson polarizations have been presented at full NLOQCD and EW corrections in the double-pole approximation (DPA) for $pp \to WZ \to 3l + \nu$.
- DPA is an excellent approximation, in particular for polarization observables.
- NLOEW corrections are important for $A^Z_{3,4}$, $f^Z_{L,R}$ due to radiative decay.
- Comparison with ATLAS inclusive fractions: deviation can reach 3σ, but errors are large. Different theoretical tools are in good agreement.
- Similar comparisons for the fiducial fractions can help to identify possible issues.
- Outlook: study W_L-Z_L fraction, sensitivity to ATGC, applications to VBS.

Thank you for your attention!

BACKUP

Spin density matrix

A massive gauge boson (spin = 1) has 3 polarization states!

$$\rho \equiv |\psi><\psi|, \tag{5}$$

$$<A> = <\psi|A|\psi> = \mathrm{Tr}(A\rho), \tag{6}$$

$$|\psi> = \sum_{\lambda=1}^{3} c_\lambda |\lambda>, \tag{7}$$

$$\rho = \sum_{\lambda,\lambda'=1}^{3} \underbrace{c_\lambda c^*_{\lambda'}}_{\rho_{\lambda\lambda'}} |\lambda><\lambda'| \tag{8}$$

- ρ is Hermitian: $\rho^*_{\lambda\lambda'} = \rho_{\lambda'\lambda}$
- Normalization $\mathrm{Tr}(\rho) = 1$

Thus, ρ is described by 8 real parameters!

Angular coefficients (I)

[Ref. Gounaris et al IJMPA1993; Aguilar-Saavedra, Bernabeu, arXiv:1508.04592; Aguilar-Saavedra et al, arXiv:1701.03115]

Consider the case of $W^*(m) \to \ell(\lambda_1)\nu_\ell(\lambda_2)$ decay:

$$|\mathcal{M}|^2 = \sum_{m,m'} \rho_{mm'} \mathcal{M}_{m\lambda_1\lambda_2} \mathcal{M}^*_{m'\lambda_1\lambda_2},$$

$$= \sum_{m,m'} \rho_{mm'} |a_{\lambda_1\lambda_2}|^2 e^{i(m-m')\phi} d^1_{m\lambda}(\theta) d^1_{m'\lambda}(\theta),$$

$$\mathcal{M}_{m\lambda_1\lambda_2} = a_{\lambda_1\lambda_2} e^{im\phi} d^1_{m\lambda}(\theta), \;\; \lambda(W^\pm) = \lambda_1 - \lambda_2 = \pm 1,$$

$$d^1_{11}(\theta) = \frac{1+\cos\theta}{2}, \;\; d^1_{1-1}(\theta) = \frac{1-\cos\theta}{2},$$

$$d^1_{01}(\theta) = \frac{\sin\theta}{\sqrt{2}}, \;\; d^j_{m'm} = (-1)^{m-m'} d^j_{mm'} = d^j_{-m-m'},$$

θ and ϕ are the polar and azimuthal angles of $\vec{p}_e$ in the W boson rest frame.

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

This angular distribution contains all W/Z spin information: 8 (pseudo-)observables!

Angular coefficients (II)

Relations between the angular coefficients and the spin-density matrix:

$$A_0 = 2\rho_{00},\ A_1 = \frac{1}{\sqrt{2}}(\rho_{+0} - \rho_{-0} + \rho_{0+} - \rho_{0-}),$$

$$A_2 = 2(\rho_{+-} + \rho_{-+}),\ A_3 = \sqrt{2}b(\rho_{+0} + \rho_{-0} + \rho_{0+} + \rho_{0-}),$$

$$A_4 = 2b(\rho_{++} - \rho_{--}),\ A_5 = \frac{1}{i}(\rho_{-+} - \rho_{+-}),$$

$$A_6 = -\frac{1}{i\sqrt{2}}(\rho_{+0} + \rho_{-0} - \rho_{0+} - \rho_{0-}),\ A_7 = \frac{\sqrt{2}b}{i}(\rho_{0+} - \rho_{0-} - \rho_{+0} + \rho_{-0}), \tag{9}$$

where $b = 1$ for the $W^\pm$ bosons and $b = -c$ for the Z boson, with

$$c = \frac{g_L^2 - g_R^2}{g_L^2 + g_R^2} = \frac{1 - 4s_W^2}{1 - 4s_W^2 + 8s_W^4} \approx 0.21, \quad s_W^2 = 1 - \frac{M_W^2}{M_Z^2}. \tag{10}$$

- The above simple relations between A_i and the ρ_{ij} were proven at LO.
- A_5, A_6, A_7 come from the imaginary parts of ρ_{ij} $\rightsquigarrow$ expected to be very small.
- A_3^Z, A_4^Z depend also on c, originated from the L-R asymmetry in the $Z^* \to \ell^+\ell^-$ decay.