# Polarisation measurement concept

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- Measure fractions of longitudinal & transverse polarization of W & Z-bosons
- Test of SM, MC modelling & PDF prediction : Boson polarization dependent on hadronic dynamic of boson production meachanism
- New interactions can cause different polarization states, can probe aTGCs
- Goal :
  - Measure polarization fractions of W & Z-bosons
  - Look for correlated states among W & Z boson
  - Interested especially in longitudinal polarization which is connected to massive character of gauge boson

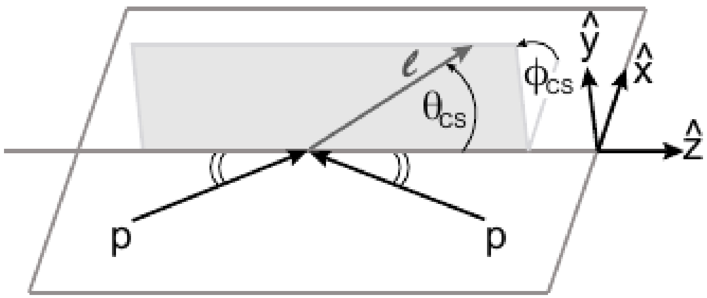
# Previous polarization measurements in ATLAS

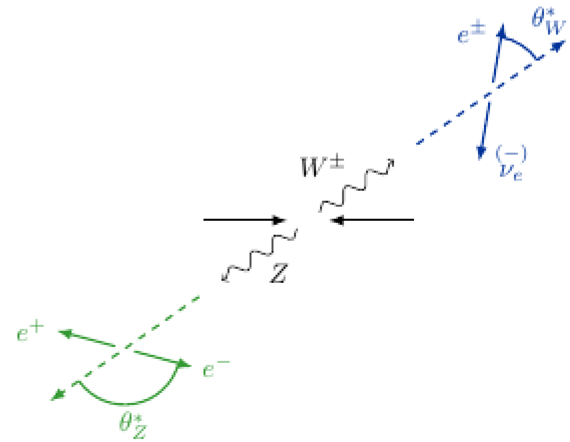
- W-polarisation @ 7TeV : arXiv:1203.2165
- Z-polarisation @ 8TeV (full angular coefficients measurement) : arXiv:1606.00689
- Diboson polarization never measured before, first (internal) studies for WZ @ 8TeV, current studies by Elena (see for example : slides)
- W-boson polarization & previous WZ polarization studies based on **fitting templates** of pure longitudinal and left- and right-handed transverse **polarizations** to **decay lepton angular distribution**

Will propose new method to measure polarization based on arXiv:1606.00689 (Z-boson angular coefficient extraction)

# Note on the reference frame

- All angles and momenta are defined in the Collins-Soper reference frame :




  - Z-Axis : bisector of the two colliding protons, direction of positive longitudinal Z-boson momentum
  - Y-Axis : Normal to incoming protons-plane
  - X-axis : Complete the coordinate system that have right-handed Carthesian coordinate system

- Angle $\theta$ is the angle between the boson direction in the laboratory frame & the lepton from the boson's decay in the boson rest frame

- Angle $\Phi$ is the azimuthal angle

# Theory

- Spin correlations between boson decay products described by 3x3 spin-density matrix
  - Diagonal elements : polarization fractions
  - Off-diagonal elements : interferences between single helicity states → introduce dependence on azimutal angle $\Phi$
- Cross section can be decomposed in sum of nine harmonic potentials dependent on $\Phi$ and cos($\theta$) :

$$\frac{3}{16\pi}\frac{d\sigma^{U+L}}{dp_T dy^Z dm^Z} \times ((1+cos^2\theta) + \sum_i A_i P_i(cos\theta, \phi)) =$$

(Eq. 1)

$$\frac{d\sigma}{dp_T^Z\, dy^Z\, dm^Z\, d\cos\theta\, d\phi} = \frac{3}{16\pi}\frac{d\sigma^{U+L}}{dp_T^Z\, dy^Z\, dm^Z}$$
$$\Big\{(1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1\ \sin 2\theta\ \cos\phi$$
$$+\frac{1}{2}A_2\ \sin^2\theta\ \cos 2\phi + A_3\ \sin\theta\ \cos\phi + A_4\ \cos\theta$$
$$+A_5\ \sin^2\theta\ \sin 2\phi + A_6\ \sin 2\theta\ \sin\phi + A_7\ \sin\theta\ \sin\phi\Big\}.$$

- **Angular coefficients $A_0$-$A_7$** (spin density matrix elements) depend on **boson pT and rapidity y**
- Analytic dependenct of the cross section on $\Phi$ and cos($\theta$) => $A_i$ are decoupled from decay kinematics and only depend on hadronic dynamic of production process

- Fit templates of pure polarization to distribution sensitive to polarization
- **Templates of pure polarization** have to be created by **reweighting the MC** :
  1) **Remove all polarization information** about Z-boson : weight each event with $\frac{1.}{\frac{3}{16\pi}((1+cos^2\theta)+\sum_i A_i P_i(cos\theta,\phi))}$
  2) Apply event weights, selection criteria and weight by $A_i P_i(cos\theta,\phi)$

     => obtain **template for each angular coefficient $A_i$** considering modifications of the template shape due to selection criteria

- Need to know coefficients $A_i$ in simulation : calculate **weighted average of each coefficient** :

$$\langle P(\cos\theta,\phi)\rangle = \frac{\int P(\cos\theta,\phi)\mathrm{d}\sigma(\cos\theta,\phi)\mathrm{d}\cos\theta\mathrm{d}\phi}{\int \mathrm{d}\sigma(\cos\theta,\phi)\mathrm{d}\cos\theta\mathrm{d}\phi}.$$

- **Calculate $A_i$** from the following relation obtained from momentum:

$$\langle\frac{1}{2}(1-3\cos^2\theta)\rangle = \frac{3}{20}(A_0-\frac{2}{3}); \quad \langle\sin 2\theta\cos\phi\rangle = \frac{1}{5}A_1; \quad \langle\sin^2\theta\cos 2\phi\rangle = \frac{1}{10}A_2;$$
$$\langle\sin\theta\cos\phi\rangle = \frac{1}{4}A_3; \quad \langle\cos\theta\rangle = \frac{1}{4}A_4; \quad \langle\sin^2\theta\sin 2\phi\rangle = \frac{1}{5}A_5;$$
$$\langle\sin 2\theta\sin\phi\rangle = \frac{1}{5}A_6; \quad \langle\sin\theta\sin\phi\rangle = \frac{1}{4}A_7.$$

- Fit 2-dimensional templates ($\Phi$,cos($\theta$)) to data in bins of pT & y

# Theory 2

- If assume symmetry in $\Phi$, can integrate Eq. 1 over $\Phi$ :

$$\frac{d\sigma}{dp_T^Z\, dy^Z\, dm^Z\, d\cos\theta} = \frac{3}{8}\frac{d\sigma^{U+L}}{dp_T^Z\, dy^Z\, dm^Z}\left\{(1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_4\cos\theta\right\}$$

- Compare to expression for helicity fractions, see Elena's slides :

W-boson: $$\frac{1}{\sigma_{W^\pm\to\ell^\pm\nu}}\frac{d\sigma_{W^\pm\to\ell^\pm\nu}}{d\cos\theta_{3D}} = \frac{3}{8}f_L(1\mp\cos\theta_{3D})^2 + \frac{3}{8}f_R(1\pm\cos\theta_{3D})^2 + \frac{3}{4}f_0\sin^2\theta_{3D}$$

Z-boson: $$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_{3D}} = \frac{3}{8}f_L(1+2A\cos\theta_{3D}+\cos^2\theta_{3D}) + \frac{3}{8}f_R(1+\cos^2\theta_{3D}-2A\cos\theta_{3D})^2 + \frac{3}{4}f_0\sin^2\theta_{3D}$$

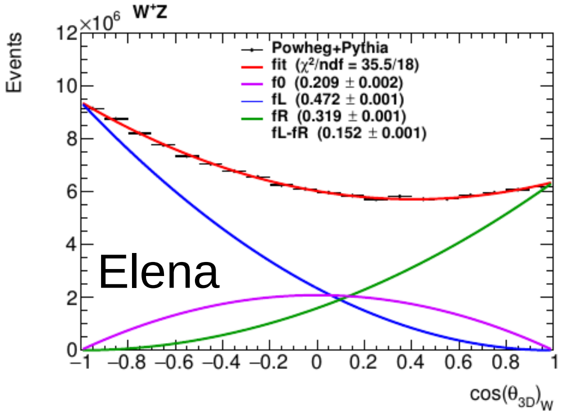
- **Polarization fractions $f_L$, $f_R$ and $f_0$ can be associated to $A_0$ and $A_4$** :
  - $f_0 = ½ A_0$
  - $f_L - f_R = \pm ½ A_4$ ( + : W-, - : W+)
  - $f_L - f_R = \frac{A_4}{2\tilde{A}}$ for Z-boson, where $\tilde{A} = \frac{2c_V c_a}{c_V^2 + c_a^2}$
- Polarisation fractions **only dependent on angular coefficients $A_0$ and $A_4$**
- 3 polarisation fractions, but only two are independent (**$f_L + f_R + f_0 = 1$**)
- = > Fit $A_4$ and $A_0$ templates, fit with less parameters also reduces uncertainty, interested especially in longitudinal polarization

# Polarization measurement concept

- Get templates for angular coefficients $A_0$ & $A_4$ just as in arXiv:1606.00689
- Do not consider $\Phi$ dependence (integrated out), asymmetries in $\Phi$ (limited detector acceptance, selection cuts) taken into account by correcting the templates for selection cuts
- In polarization measurements (for example : arXiv:1203.2165), fit cos($\theta$) distribution as it is very dependent on polarization effects
- Try to fit a different estimator : BDT distribution, feed the BDT with variables sensitive to polarization effects, for example (to be checked) :
  - cos($\theta$) (or projection on transverse plane in case of W-boson)
  - Lepton transverse momentum
  - Etmiss
  - mTW
  - Charge asymmetry ratio
  - Variable used in CMS W-polarization measurement : $\mathrm{L}_p = \frac{\vec{p_\mathrm{T}}(l) \circ \vec{p_\mathrm{T}}(W)}{|p_{\mathrm{T}(W)}|^2}$
- Try to get an estimator which is more sensitive to polarization than cos($\theta$)

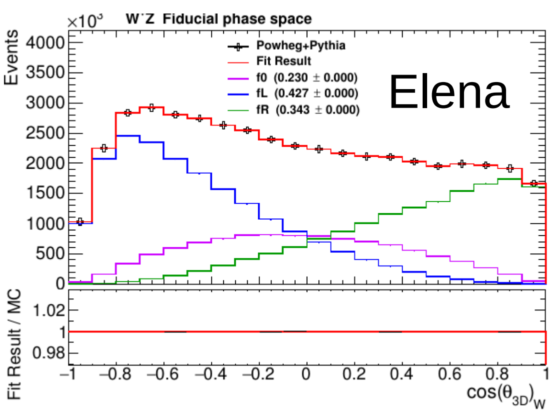
# Methodology comparison : standard method & « angular coefficient method »

Fit functional form of polarization fractions to $\cos(\theta)$ distribution, extract $f_i$




Weight MC events to get polarization templates by

$$w = \frac{f_i P(cos(\theta))}{\sum_i f_i P(cos(\theta))}$$




Fit polarization templates ($f_0$, $f_L$, $f_R$) to $\cos(\theta)$ distribution

Calculate polarization fraction using the momenta :

$$\langle \frac{1}{2}(1 - 3\cos^2\theta) \rangle = \frac{3}{20}(A_0 - \frac{2}{3}); \qquad \langle \cos\theta \rangle = \frac{1}{4}A_4;$$

Remove all polarization information from MC

Apply selection cuts & weight by

$$A_i P_i(cos\theta, \phi)$$

Fit templates for $A_0$ & $A_4$ to BDT-score distribution

# Summary

- Presented concept to extract longitudinal polarization $f_0$ and transverse polarization $f_L$-$f_R$ using the method described in arXiv:1606.00689
- In contrast to conventional polarization measurements, fit only two templates (angular coefficients) in order to reduce uncertainty on fit
- Create templates for the angular coefficients $A_0$ & $A_4$ using the momentum method
- Fit templates to BDT-score distribution with input variable sensitive to polarization effects