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Z' generation with PYTHIA

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Abstract

This document is intended as a guide for getting started with the Z' generation with PYTHIA[1]. Several different conventions used in literature are discussed, and the conversion among these is given. The Z' couplings to fermions are given for the sequential Z', the Z' model-lines of Ref. [2], and the popular E6 Z' models.

1 Notations and Conventions

The interaction of the Z' boson to Standard Model (SM) fermions f can be generally written as:

$$\mathcal{L} = g_{Z'} \bar{f} \gamma^{\mu} (z_{f_L} P_L + z_{f_R} P_R) f Z'_{\mu} \tag{1}$$

where $g_{Z'}$ is the $U(1)_{Z'}$ gauge coupling, z_{f_L} and z_{f_R} are the left and right handed fermion charges, and $P_L = (1 - \gamma^5)/_2$ and $P_R = (1 + \gamma^5)/_2$ are the projectors for left and right-handed chiral fields. In the above equation, it is customary to separate the chiral operator γ^5 term; we list below the main conventions used in literature:

$$
\begin{aligned}
& g_{Z'}\bar{f}\gamma^\mu(z_{f_L}P_L + z_{f_R}P_R)fZ'_\mu \\
& = g_{Z'}\bar{f}\gamma^\mu\left(\frac{z_{f_L}+z_{f_R}}{2} - \frac{z_{f_L}-z_{f_R}}{2}\gamma^5\right)fZ'_\mu = \\
& \equiv g_{Z'}\bar{f}\gamma^\mu(C_{f_V} - C_{f_A}\gamma^5)fZ'_\mu && \text{CDDT [2]} \quad (2) \\
& \equiv g_{Z'}\bar{f}\gamma^\mu\frac{1}{2}(\mathcal{C}_{f_\mathcal{V}} - \mathcal{C}_{f_\mathcal{A}}\gamma^5)fZ'_\mu && \text{Halzen+Martin [3]} \quad (3) \\
& \equiv -\bar{f}\gamma^\mu(C_{V_{Z',f}} + C_{A_{Z',f}}\gamma^5)fZ'_\mu && \text{Rosner87 [4]} \quad (4) \\
& \equiv \frac{g}{4\cos\theta_W}\bar{f}\gamma^\mu(C_V - C_A\gamma^5)fZ'_\mu && \text{PYTHIA [1]} \quad (5)
\end{aligned}
$$

where $g = 0.626$ is the $\mathrm{SU}(2)_L$ gauge coupling, and θ_W is the Weinberg angle. Note the slightly different notations used to identify the four conventions. The axial and vector couplings defined above can be expressed as:

$$
\begin{aligned}
& C_{f_V} = (z_{f_L}+z_{f_R})/2 && C_{f_A} = (z_{f_L}-z_{f_R})/2 && \text{CDDT [2]} \quad (6) \\
& \mathcal{C}_{f_\mathcal{V}} = z_{f_L}+z_{f_R} && \mathcal{C}_{f_\mathcal{A}} = z_{f_L}-z_{f_R} && \text{Halzen+Martin [3]} \quad (7) \\
& C_{V_{Z',f}} = -g_{Z'}(z_{f_L}+z_{f_R})/2 && C_{A_{Z',f}} = g_{Z'}(z_{f_L}-z_{f_R})/2 && \text{Rosner87 [4]} \quad (8) \\
& C_V = 2\cos\theta_W(z_{f_L}+z_{f_R})g_{Z'}/g && C_A = 2\cos\theta_W(z_{f_L}-z_{f_R})g_{Z'}/g && \text{PYTHIA [1]} \quad (9)
\end{aligned}
$$

From these conversion relations, it is now easy to express the input couplings to PYTHIA needed to implement various Z' models. As seen in Eqns. (4) and (5) (or Eqns. (8) and (9)), for the Rosner paper and PYTHIA cases the $g_{Z'}$ is included in the V and A couplings.

f	Q_f	$T_f^3 = \mathcal{C}_{f_\mathcal{A}}$	$\mathcal{C}_{f_\mathcal{V}}$
ν_e, $\nu_{mu}, \ldots$	0	1/2	1/2
e^-, $\mu^-, \ldots$	-1	-1/2	-1/2 + 2sin$^2\theta_W$
$u, c, \ldots$	2/3	1/2	1/2 - 4sin$^2\theta_W/3$
$d, s, \ldots$	-1/3	-1/2	-1/2 + 2sin$^2\theta_W/3$

Table 1: SM couplings, from page 301 of Halzen+Martin [3].

d		u		e		ν_e	
V	A	V	A	V	A	V	A
PARU(121)	PARU(122)	PARU(123)	PARU(124)	PARU(125)	PARU(126)	PARU(127)	PARU(128)
$-1+\frac{4}{3}\sin^2\theta_W$	-1	$1-\frac{8}{3}\sin^2\theta_W$	1	$-1+4\sin^2\theta_W$	-1	1	1
-0.693	-1	0.387	1	-0.08	-1	1	1

Table 2: SM couplings - PYTHIA implementation.

2 PYTHIA Generation of Different Z' Models

2.1 Sequential Z'

The parameters available[1] in PYTHIA to implement the couplings for a given Z'model are PARU(121)-PARU(128) for the 1^{st} generation quarks and leptons, PARJ(180)-PARJ(187) for the 2^{nd} generation, and PARJ(188)-PARJ(195) for the 3^{rd} generation, respectively. The default values are those of a sequential Z', which are the same as for the Standard Model Z boson. In Halzen+Martin, these couplings are expressed as: $\mathcal{C}_{f_\mathcal{V}} = T_f^3 - 2Q_f\sin^2\theta_W$ and $\mathcal{C}_{f_\mathcal{A}} = T_f^3$ (see Table 1).

We can use Eqns. (7) and (9), plugging in the Standard Model $g_{Z'} = g/\cos\theta_W$, to obtain the PYTHIA coefficients: $C_V = 2\mathcal{C}_{f_\mathcal{V}}$ and $C_A = 2\mathcal{C}_{f_\mathcal{A}}$, respectively. The exact values of the vector (V) and axial (A) couplings are given in the fourth row of Table 2. If one uses the PYTHIA value $\sin^2\theta_W = 0.23$, one obtains the values listed in the fifth (last) row, which coincide with the defaults listed in the PYTHIA manual. The couplings to the 2^{nd} and 3^{rd} families must be set to the same values, i.e. PARU(121)=PARJ(180)=PARJ(188), etc.

2.2 CDDT model-lines

In the CDDT paper [2], four general classes of Z' models (or model-lines) are discussed. Table 3 presents the fermion charges for these models-lines. These charges are plugged in

[1] In addition to these, one can also set the Z' mass via PMAS(32) parameter, etc.

	$\mathrm{U}(1)_{B-xL}$	$\mathrm{U}(1)_{q+xu}$	$\mathrm{U}(1)_{10+x\bar{5}}$	$\mathrm{U}(1)_{d-xu}$
q_L	$1/3$	$1/3$	$1/3$	0
u_R	$1/3$	$x/3$	$-1/3$	$-x/3$
d_R	$1/3$	$(2-x)/3$	$-x/3$	$1/3$
l_L	$-x$	-1	$x/3$	$(-1+x)/3$
e_R	$-x$	$-(2+x)/3$	$-1/3$	$x/3$
ν_R	0	0	0	0

Table 3: The fermion gauge charges (adapted from Ref.[2]).

d		u		e		ν_e	
V	A	V	A	V	A	V	A
PARU(121)	PARU(122)	PARU(123)	PARU(124)	PARU(125)	PARU(126)	PARU(127)	PARU(128)
$B-xL$ model-line							
$\frac{4}{3}\gamma_{Z'}$	0	$\frac{4}{3}\gamma_{Z'}$	0	$-4x\gamma_{Z'}$	0	$-2x\gamma_{Z'}$	$-2x\gamma_{Z'}$
$d-xu$ model-line							
$\frac{2}{3}\gamma_{Z'}$	$-\frac{2}{3}\gamma_{Z'}$	$-\frac{2x}{3}\gamma_{Z'}$	$\frac{2x}{3}\gamma_{Z'}$	$\frac{2(2x-1)}{3}\gamma_{Z'}$	$-\frac{2}{3}\gamma_{Z'}$	$\frac{2(x-1)}{3}\gamma_{Z'}$	$\frac{2(x-1)}{3}\gamma_{Z'}$
$q+xu$ model-line							
$-\frac{2(x-3)}{3}\gamma_{Z'}$	$\frac{2(x-1)}{3}\gamma_{Z'}$	$\frac{2(x+1)}{3}\gamma_{Z'}$	$-\frac{2(x-1)}{3}\gamma_{Z'}$	$-\frac{2(x+5)}{3}\gamma_{Z'}$	$\frac{2(x-1)}{3}\gamma_{Z'}$	$-2\gamma_{Z'}$	$-2\gamma_{Z'}$
$10+x5$ model-line							
$-\frac{2(x-1)}{3}\gamma_{Z'}$	$\frac{2(x+1)}{3}\gamma_{Z'}$	0	$\frac{4}{3}\gamma_{Z'}$	$\frac{2(x-1)}{3}\gamma_{Z'}$	$\frac{2(x+1)}{3}\gamma_{Z'}$	$\frac{2x}{3}\gamma_{Z'}$	$\frac{2x}{3}\gamma_{Z'}$

Table 4: The four CDDT model-lines - PYTHIA implementation. The parameter $\gamma_{Z'}$ is given by Eqn. (10), or $\gamma_{Z'} = 1.402 \cdot g_{Z'}$ (using the PYTHIA $\sin^2\theta_W = 0.23$ and $g = 0.626$ values).

Eqn. (9) to obtain the corresponding PYTHIA parameters, listed in Table 4. The following linear change of variable has been made:

$$g_{Z'} = \gamma_{Z'} \cdot \frac{g}{\cos\theta_W} \qquad \text{with} \qquad \gamma_{Z'} \equiv \frac{g_{Z'}}{g}\cos\theta_W \tag{10}$$

For example, for a $q+xu$ family Z' with $g_{Z'} = 0.1$ and $x = 1.0$, we have PARU(121) = PARJ(180) = PARJ(188) = $-2(1-3) \cdot 1.402 \cdot 0.1/3 = 0.187$, etc.

2.3 E6 Z''s

In the E6 models, the SM structure is extended to include the $\mathrm{U}(1)_\psi\times$ $\mathrm{U}(1)_\chi$ groups[5]. The gauge fields corresponding to these groups Z'_ψ and Z'_χ can be massive, and are not true mass eigenstates since these states can mix. Let us define the mass eigenstates by:

$$Z'(\theta) \equiv Z'_\psi \cos\theta + Z'_\chi \sin\theta, \qquad Z''(\theta) \equiv Z'_\psi \sin\theta - Z'_\chi \cos\theta \tag{11}$$

with θ being a parameter dependent on the Higgs vev's and the gauge couplings g_ψ and g_χ corresponding to $\mathrm{U}(1)_\psi$ and $\mathrm{U}(1)_\chi$. Different definitions of θ exist in the literature; however, this is irrelevant if one restricts the discussion only to Z'_ψ, Z'_χ, Z'_η, and Z'_I as it is customarily the case in experimental searches. In what follow we assume the θ definition from Ref. [4] (Rosner). As we will show, other definitions [2, 5] lead to the same results. To simplify the problem, we assume that $Z''(\theta)$ is heavy enough to decouple from the Z and $Z'(\theta)$, and will not be discussed further. The $Z'(\theta)$ is light enough to mix with the standard model Z. According to Eqn. (3) of Ref. [4], we can write:

$$g_\theta = \sqrt{\frac{5}{3}}\, g_Z \sin\theta_W = \sqrt{\frac{5}{3}}\, g \tan\theta_W \equiv \sqrt{\frac{5}{3}}\, \gamma \tag{12}$$

where $g = 0.626$ is the $\mathrm{SU}(2)_L$ gauge coupling. In this notation, and using Table I of Ref. [4], we can calculate the fermion couplings for the $Z'(\theta)$, listed in Table 5. For this Table, to get the neutrino couplings we used the e couplings and Eqn. (8) to calculate the z_{ν_L} charge ($z_{\nu_L} = z_{e_L}$, $z_{\nu_R} = 0$). To get the PYTHIA parameters, we used the relations from Eqns. (8) and (9).

Comparing to the $10 + x\bar{5}$ results from the last row of Table 4, the following conversion relations can be written down:

$$\gamma_{Z'} = \frac{\sqrt{10}\cos\theta + \sqrt{6}\sin\theta}{4}\, s, \qquad \text{with} \quad s \equiv \sin\theta_W \tag{13}$$

$$x\gamma_{Z'} = \frac{\sqrt{10}\cos\theta - 3\sqrt{6}\sin\theta}{4}\, s, \qquad \text{with} \quad s \equiv \sin\theta_W \tag{14}$$

d		u	e		ν_e	
Rosner convention						
$C_{V_{Z',d}}$	$C_{A_{Z',d}}$	$C_{A_{Z',u}}$	$C_{V_{Z',e}}$	$C_{A_{Z',e}}$	$C_{V_{Z',\nu}}$	$C_{A_{Z',\nu}}$
$-\frac{\sin\theta}{\sqrt{6}}\gamma$	$\frac{\sqrt{5}\cos\theta-\sqrt{3}\sin\theta}{6\sqrt{2}}\gamma$	$\frac{\sqrt{5}\cos\theta+\sqrt{3}\sin\theta}{6\sqrt{2}}\gamma$	$\frac{\sin\theta}{\sqrt{6}}\gamma$	$\frac{\sqrt{5}\cos\theta-\sqrt{3}\sin\theta}{6\sqrt{2}}\gamma$	$-\frac{\sqrt{5}\cos\theta-3\sqrt{3}\sin\theta}{12\sqrt{2}}\gamma$	$\frac{\sqrt{5}\cos\theta-3\sqrt{3}\sin\theta}{12\sqrt{2}}\gamma$
PYTHIA implementation						
PARU(121)	PARU(122)	PARU(124)	PARU(125)	PARU(126)	PARU(127)	PARU(128)
$\frac{4\sin\theta}{\sqrt{6}}s$	$\frac{\sqrt{10}\cos\theta-\sqrt{6}\sin\theta}{3}s$	$\frac{\sqrt{10}\cos\theta+\sqrt{6}\sin\theta}{3}s$	$-\frac{4\sin\theta}{\sqrt{6}}s$	$\frac{\sqrt{10}\cos\theta-\sqrt{6}\sin\theta}{3}s$	$\frac{\sqrt{10}\cos\theta-3\sqrt{6}\sin\theta}{6}s$	$\frac{\sqrt{10}\cos\theta-3\sqrt{6}\sin\theta}{6}s$

Table 5: The general E6 fermion couplings as function of θ, following Rosner's definition of θ. We used the shorthand notations $\gamma \equiv g\tan\theta_W$, and $s \equiv \sin\theta_W$, respectively. To fit all values in the Table, we omitted the $C_{V_{Z',u}}$ column, as this parameter is zero; that is, PARU(123)=0 for all E6 models.

The next step is to particularize the general $Z'(\theta)$ to obtain the popular models. Table 6 lists the couplings for these models; the values were obtained simply by plugging each θ value in the expressions from Table 5. Given Eqns. (13)-(14), the same results from Table 6 can also be found if one particularizes the CDDT model-lines as follows [6]:

- Z'_ψ is obtained in the $10 + x\bar{5}$ model-line (last row in Table 4), for $x = 1$ and $\gamma_{Z'} = \sqrt{\frac{5}{8}}\,\sin\theta_W$.
- Z'_χ is obtained in the $10 + x\bar{5}$ model-line (last row in Table 4), for $x = -3$ and $\gamma_{Z'} = \sqrt{\frac{3}{8}}\,\sin\theta_W$.
- Z'_η is obtained in the $10 + x\bar{5}$ model-line (last row in Table 4), for $x = -1/2$ and $\gamma_{Z'} = \sin\theta_W$.
- Z'_I is obtained[2] in the $d - xu$ model-line (eighth row in Table 4), for $x = 0$ and $\gamma_{Z'} = \frac{\sqrt{15}}{2}\,\sin\theta_W$.
- Z'_{sq} is obtained in the $10 + x\bar{5}$ model-line (last row in Table 4), for $x = -8$ and $\gamma_{Z'} = \frac{1}{4}\sin\theta_W$.

[2]This is also the special $10 + x\bar{5}$ case: $\gamma_{Z'} \to 0$, and $x\gamma_{Z'} = -\frac{\sqrt{15}}{2}\,\sin\theta_W$ (as $x \to \infty$).

d		u		e		ν_e	
V	A	V	A	V	A	V	A
PARU(121)	PARU(122)	PARU(123)	PARU(124)	PARU(125)	PARU(126)	PARU(127)	PARU(128)
Z'_ψ corresponds to $\theta = 0°$							
0	$\frac{\sqrt{10}\ s}{3}$	0	$\frac{\sqrt{10}\ s}{3}$	0	$\frac{\sqrt{10}\ s}{3}$	$\frac{\sqrt{10}\ s}{6}$	$\frac{\sqrt{10}\ s}{6}$
Z'_χ corresponds to $\theta = 90°$							
$\frac{2\sqrt{6}\ s}{3}$	$-\frac{\sqrt{6}\ s}{3}$	0	$\frac{\sqrt{6}\ s}{3}$	$-\frac{2\sqrt{6}\ s}{3}$	$-\frac{\sqrt{6}\ s}{3}$	$-\frac{\sqrt{6}\ s}{2}$	$-\frac{\sqrt{6}\ s}{2}$
Z'_η corresponds to $\theta = 37.76°$, i.e. $\sin\theta = \sqrt{3/8}$ and $\cos\theta = \sqrt{5/8}$							
s	$\frac{s}{3}$	0	$\frac{4s}{3}$	$-s$	$\frac{s}{3}$	$-\frac{s}{3}$	$-\frac{s}{3}$
Z'_I corresponds to $\theta = 127.76°$, i.e. $\sin\theta = \sqrt{5/8}$ and $\cos\theta = -\sqrt{3/8}$							
$\frac{\sqrt{15}\ s}{3}$	$-\frac{\sqrt{15}\ s}{3}$	0	0	$-\frac{\sqrt{15}\ s}{3}$	$-\frac{\sqrt{15}\ s}{3}$	$-\frac{\sqrt{15}\ s}{3}$	$-\frac{\sqrt{15}\ s}{3}$
Z'_{sq} corresponds to $\theta = 113.28°$, i.e. $\sin\theta = 3\sqrt{6}/8$ and $\cos\theta = -\sqrt{10}/8$							
$\frac{3\ s}{2}$	$-\frac{7\ s}{6}$	0	$\frac{s}{3}$	$-\frac{3\ s}{2}$	$-\frac{7\ s}{6}$	$-\frac{4\ s}{3}$	$-\frac{4\ s}{3}$
Z'_N corresponds to $\theta = -14.48°$, i.e. $\sin\theta = -1/4$ and $\cos\theta = \sqrt{15}/4$							
$-\frac{\sqrt{6}\ s}{6}$	$\frac{\sqrt{6}\ s}{2}$	0	$\frac{\sqrt{6}\ s}{3}$	$\frac{\sqrt{6}\ s}{6}$	$\frac{\sqrt{6}\ s}{2}$	$\frac{\sqrt{6}\ s}{3}$	$\frac{\sqrt{6}\ s}{3}$

Table 6: Popular E6 models - PYTHIA implementation. We used the notation: $s \equiv \sin\theta_W = \sqrt{0.23}$.

- Z'_N is obtained in the $10 + x\bar{5}$ model-line (last row in Table 4), for $x = 2$ and $\gamma_{Z'} = \frac{\sqrt{6}}{4}\sin\theta_W$.

We finally note that Ref. [5] uses a different definition of θ: $Z' = Z_\psi \cos\theta - Z_\chi \sin\theta$. Working out the V and A couplings by using Eqn. (2.7) and Table 2 from [5], we obtain the same PYTHIA couplings as given in our Table 5. Using the definitions (i.e. θ values) of Z'_ψ, Z'_χ, Z'_η, and Z'_I given in Ref. [5], we find the couplings for Z_ψ and Z_η to be identical to the ones listed in our Table 6, while the couplings for the Z_χ and Z_I are equal to the negative of the corresponding values from Table 6 (which is equivalent to the transformation $\theta \to -\theta$). Figure 1 shows a cartoon with several definitions of the E6 angle θ.

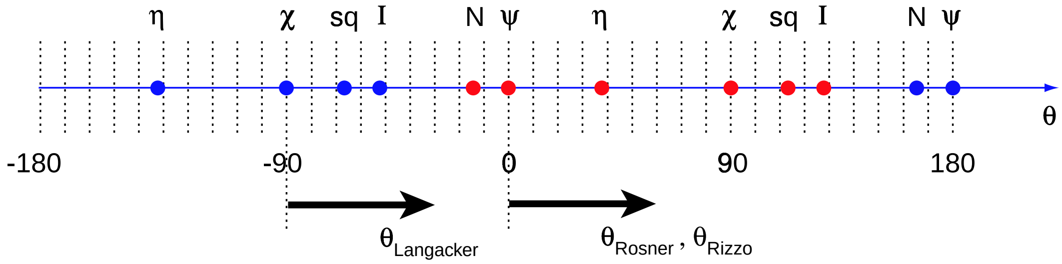

Figure 1: Several definitions of the E6 angle θ.

3 Conclusions

In this document we briefly list several conventions used in the Z' literature, and give the PYTHIA implementation for the sequential Z', the model-lines of Ref. [2], and the popular E6 models. We hope this will serve as a useful first guide for the Z'/PYTHIA beginner. We thank Marcela Carena, Bogdan Dobrescu, Tim Tait, and Muge Karagoz for useful discussions.

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