FeynRules Implementation of Z' Model

M.Sc. THESIS

by

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to

DEPARTMENT OF PHYSICS

INDIAN INSTITUTE OF TECHNOLOGY

INDORE - 453 552, INDIA

June, 2023

FeynRules Implementation of Z' Model

A THESIS

Submitted in partial fulfilment of the

requirements for the award of the degree

of

Master of Science

by

Joginder

DISCIPLINE OF PHYSICS

INDIAN INSTITUTE OF TECHNOLOGY, INDORE

June, 2023

INDIAN INSTITUTE OF TECHNOLOGY INDORE

CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **FeynRules Implementation of Z' Model** in the partial fulfillment of the requirements for the award of the degree of **Master of Science** and submitted in the **Discipline of Physics, Indian Institute of Technology Indore**, is an authentic record of my own work carried out during the time period from July 2022 to June 2023 under the supervision of **Dr Dipankar Das, Assistant professor, Indian Institute of Technology Indore.**

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any institute.

Joginder

Signature of the student with date

29/05/23 **(Joginder)**

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

Dipankar Das 7/6/23

Signature of the Supervisor of M.Sc. thesis (with date)

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Date: 7/06/23

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Date: 07/06/23

Acknowledgements

I want to express my gratitude to the people who have helped and supported me throughout the project. I am very grateful to my supervisor, Dr Dipankar Das, for his continuous support and ongoing advice and encouragement. I have learned a lot from him. I am thankful to my committee members, Prof. Subhendu Rakshit and Dr Debajyoti Sarkar , who are a guiding light and gave valuable suggestions that helped me improve my work. I am very thankful to my labmates especially Anugrah Prasad for the valuable discussions. I am very thankful to my family and friends for their constant love, support, and kindness.

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Chapter 1

Introduction

Standard Model has been proved experimentally to be a good model for explaining the behavior of subatomic particles. The gauge group of the Standard Model is $SU(3)_C \times SU(2)_L \times U(1)_Y$. The Standard Model describes three of the four fundamental forces of nature: the strong force, the weak force, and the electromagnetic force. The fundamental particles in the Standard Model are divided into two groups: fermions and bosons. Fermions include quarks and leptons, which make up all matter. Bosons include force carriers such as photons, W and Z bosons, and gluons. In the scalar sector, Standard Model have Higgs Doublet. But there are some phenomena which cannot be explained on the basis of Standard Model. There are many theories and models trying to explain these phenomena. One of these is the Z' model which is an extension of the Standard Model of particle physics. Here, I have worked on a minimal Z' model[1]. The gauge group for Z' model is $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_X$. There is an extra gauge boson in Z' model in addition to the ones in Standard Model. In the scalar sector, Z' Model (used here) have Higgs Doublet and an additional Higgs scalar. This also adds an extra Higgs particle apart from that of the Standard Model. The model can be implemented using FeynRules which is a powerful tool for generating Feynman rules and amplitudes for particle physics models. Feynrules requires model file and Lagrangian written in the Wolfram language. Model file contains various classes like particle class, parameter class, Gauge group class etc. We can have a single model file or different files separately like parameter file and particle file. The Lagrangian is written during the mathematica session. The output of FeynRules is input to MadGraph which is a software package to generate simulated events. Events generated at colliders can be simulated with the help of Monte Carlo generators. Madgraph can be used to obtain cross-section and various histogram plots. By selecting a suitable process involving Z' particle, we can obtain the cross-section results. If mass of the Z' particle is changed, the cross-section also changes. We can draw graph of cross-section versus mass of the Z' particle. This graph from simulation can be compared with the graph obtained from experiments[2].

1.1 Implementation Flow

The implementation flow of the procedure used here can be understood from the following diagram :-

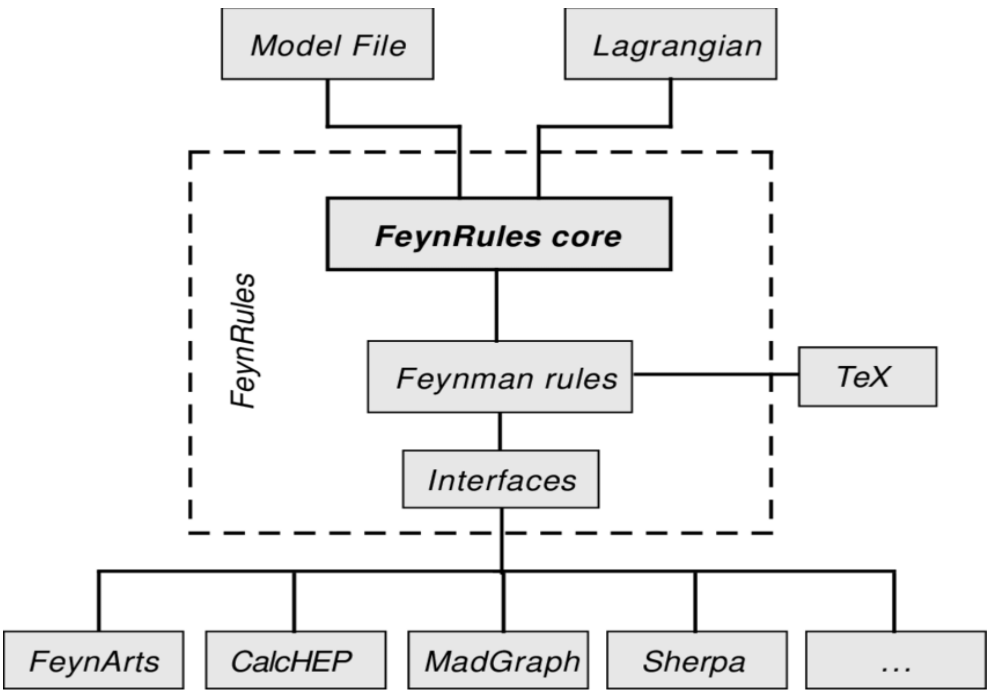

Figure 1.1: Flow Chart

FeynRules is a Mathematica-based package which addresses the implementation of particle physics models. For implementing a new model in FeynRules, we need two things : Model File and Lagrangian. In Feyn-

Rules, a model file is a text file that contains the information needed to define a particular model, including its particle content, interactions, and symmetry properties. The Lagrangian is a mathematical function that describes the dynamics of a system. It includes the interaction terms which define a particular theory. The model file have various classes. The classes have information of fields, parameters and gauge group of model which. All the fields including scalar, Dirac and vector fields are defined in a particle class. After running the FeynRules, a FeynRule file is created. It is written in the Universal FeynRules Output (UFO) format (interface), which is a standardized format used by various software tools to generate Feynman diagrams and perform other calculations related to the model. The FeynRules file typically includes information about the particle content of the model, including the masses, quantum numbers, and interactions of each particle. It also includes information about the vertices and couplings between particles, as well as any additional parameters that are relevant for the model. A Feynrule can be now used for anyone of the Monte Carlo generators. We don't have to write different codes for different Monte Carlo generators.

Chapter 2

Z' Model

In Beyond Standard Model physics, Z' Models are the most common. Here , we will discuss minimal Z' model. We have to add one more symmetry group (U(1)) which is the simplest thing we can do. The gauge group is $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_X$. The consequence is that we get a new vector boson Z' in addition to three vector bosons of the standard model.

2.1 Gauge Sector

Since we have an extra symmetry group in Z' Model, there are four gauge bosons in the theory. The Lagrangian[3] is given by :-

$$L_{Gauge} = -\frac{1}{4}W_a^{\mu\nu}W_{\mu\nu}^a - \frac{1}{4}B^{\mu\nu}B_{\mu\nu} - \frac{1}{4}X^{\mu\nu}X_{\mu\nu} - \frac{\sin\chi}{2}B^{\mu\nu}X_{\mu\nu} \tag{2.1}$$

Here, $W_a^{\mu\nu}$ is for SU(2) group (**a** goes from 1 to 3 for three W gauge bosons), $B^{\mu\nu}$ for $U(1)_Y$ and $X^{\mu\nu}$ for $U(1)_X$ symmetry group. The last term in Lagrangian depicts that we have a gauge kinetic mixing term for two U(1) group gauge bosons and it can be controlled through the χ parameter. This gauge kinetic mixing term is the only possible gauge invariant term for the Lagrangian. So, all the other possible combinations are not allowed. But, we want our kinetic terms in the Lagrangian to be canonically diagonal. So, we perform a linear transformation as following :-

$$\begin{pmatrix} B'_\mu \\ X'_\mu \end{pmatrix} = \begin{pmatrix} 1 & \sin\chi \\ 0 & \cos\chi \end{pmatrix} \begin{pmatrix} B_\mu \\ X_\mu \end{pmatrix} \tag{2.2}$$

Such a transformation leads to a U(1) charge shift[4]. The inverse transformation can be written as follows :-

$$B_\mu = B'_\mu - \tan\chi X'_\mu \tag{2.3}$$

$$X_\mu = \sec\chi X'_\mu \tag{2.4}$$

The definitions for covariant derivatives are as :-

$$D^\mu \Phi = (\partial_\mu - ig\frac{\tau_a}{2}W^a_\mu - i\frac{g_Y}{2}B_\mu - ig_x\frac{x_\phi}{2}X_\mu)\Phi \tag{2.5}$$

$$D^\mu S = (\partial_\mu - i\frac{g_x}{2}X_\mu)S \tag{2.6}$$

After the linear transformation, the expressions for covariant derivatives are changed which are as following :-

$$D^\mu \Phi = (\partial_\mu - i\frac{g}{2}(\tau_a W^a_\mu - \tan\theta_w B'_\mu - \tan\theta_x x'_\phi X'_\mu))\Phi \tag{2.7}$$

$$D^\mu S = (\partial_\mu - ig\tan\theta_x\frac{x_\phi}{2}X'_\mu)S \tag{2.8}$$

Where we have defined,

$$\tan\theta_w = \frac{g_Y}{g} \tag{2.9}$$

$$\tan\theta_x = \frac{g'_x}{g} \tag{2.10}$$

$$g'_x = g_x \sec\chi \tag{2.11}$$

$$x'_\phi = x_\phi - \frac{g_Y}{g_x} \sin\chi \tag{2.12}$$

After spontaneous symmetry breaking, the scalar fields in the unitary gauge can be written as following:-

$$\Phi = \begin{pmatrix} 0 \\ \frac{v+\phi_0}{\sqrt{2}} \end{pmatrix} \tag{2.13}$$

$$S = \frac{v_s + s}{\sqrt{2}} \tag{2.14}$$

where v and v_s are vacuum expectation values of Φ and S respectively. The mass terms for the gauge bosons can be found out as following :-

$$L = (D^\mu \Phi)^\dagger (D_\mu \Phi) + (D^\mu S)^\dagger (D_\mu S) \tag{2.15}$$

We can write the neutral gauge boson mass matrix in the basis where the gauge kinetic terms are diagonal (means selecting W^3_μ ,B'_μ and X'_μ). The next step is to make this matrix diagonal. Here, unphysical gauge bosons W^3_μ, $B^{'}_\mu$ and $X^{'}_\mu$ furthur mix to give the required physical gauge bosons A_μ, Z_μ and $Z^{'}_\mu$. Since there are three fields to be changed, we need two rotation angles here (namely Weinberg angle(θ_w) and Z-Z' mixing angle(α_z)).

$$L_{Mass} = \frac{1}{2}(W^3_\mu \quad B'_\mu \quad X'_\mu) M^2 \begin{pmatrix} W^3_\mu \\ B'_\mu \\ X'_\mu \end{pmatrix} \tag{2.16}$$

where M^2 is given by :-

$$M^2 = \frac{g^2 v^2}{4} \begin{pmatrix} 1 & -\tan(\theta_w) & -x'_\phi \tan(\theta_x) \\ -\tan(\theta_w) & \tan^2(\theta_w) & x'_\phi \tan(\theta_x)\tan(\theta_w) \\ -x'_\phi \tan(\theta_x) & x'_\phi \tan(\theta_x)\tan(\theta_w) & \tan^2(\theta_x)(r^2 + x'^2_\phi) \end{pmatrix} \tag{2.17}$$

The diagonalization can be done as following :-

$$M^2 = O_g^T M_D^2 O_g \tag{2.18}$$

Where M_D^2 is the squared diagonal gauge boson mass matrix. The diagonalization is a two step process here with rotation angles namely Weinberg angle(θ_w) and Z-Z' mixing angle(α_z). Here, M_D^2 and O_g are given by :-

$$M_D^2 = \begin{pmatrix} M_A^2 & 0 & 0 \\ 0 & M_Z^2 & 0 \\ 0 & 0 & M_{Z'}^2 \end{pmatrix} \tag{2.19}$$

$$O_g = \begin{pmatrix} \cos\theta_w & \sin\theta_w & 0 \\ -\sin\theta_w \sin\alpha_z & \cos\theta_w \cos\alpha_z & \sin\alpha_z \\ \sin\theta_w \sin\alpha_z & -\cos\theta_w \sin\alpha_z & \cos\alpha_z \end{pmatrix} \tag{2.20}$$

Photon mass (M_A) is zero in the equation 2.19. The expression for the transformed fields are given by :-

$$B_\mu^{'} = \cos\theta_w A_\mu - \sin\theta_w \cos\alpha_z Z_\mu + \sin\theta_w \sin\alpha_z Z_\mu^{'} \tag{2.21}$$

$$W_\mu^3 = \sin\theta_w A_\mu + \cos\theta_w \cos\alpha_z Z_\mu - \cos\theta_w \sin\alpha_z Z_\mu^{'} \tag{2.22}$$

$$X_\mu^{'} = \sin\alpha_z Z_\mu + \cos\alpha_z Z_\mu^{'} \tag{2.23}$$

2.2 Scalar Sector

In the standard model, we have a scalar doublet (Higgs Doublet). Here in the Z' Model, we have an additional singlet scalar. The $U(1)_X$ group is broken by this singlet scalar. The scalars are defined as following :-

$$\phi = (1, 2, 1/2, \frac{x_\phi}{2}) \tag{2.24}$$

$$S = (1, 1, 0, 1/2) \tag{2.25}$$

The quantities inside the parentheses characterize the transformation properties under the gauge group of the Z' Model. The first two numbers tell that whether the multiplet is a singlet or a doublet under $SU(3)_C$ and $SU(2)_L$ groups. The last two numbers are hypercharges of $U(1)_Y$ and $U(1)_X$ groups respectively. The Lagrangian for the scalar sector is given by :-

$$L_{Scalar} = (D^\mu \Phi)^\dagger (D_\mu \Phi) + (D^\mu S)^\dagger (D_\mu S) - V(\Phi, S) \tag{2.26}$$

Where V(Φ,S) , Φ and S are given by :-

$$V(\Phi, S) = -\mu_\phi^2 (\Phi^\dagger \Phi) - \mu_s^2 (S^\dagger S) + \lambda_\phi (\Phi^\dagger \Phi)^2 + \lambda_s (S^\dagger S)^2 + \lambda_{\phi s} (\Phi^\dagger \Phi)(S^\dagger S) \tag{2.27}$$

$$\Phi = \begin{pmatrix} -iG_W \\ \frac{v+\phi_0+iG_Z}{\sqrt{2}} \end{pmatrix} \tag{2.28}$$

$$S = \frac{v_s + s + iG_{Z'}}{\sqrt{2}} \tag{2.29}$$

Here, G_θ, G_P and $G_{Z'}$ are the Goldstone bosons corresponding to Z, W and Z' bosons respectively. In the Unitary Gauge and after spontaneous symmetry breaking, Φ and S become as following :-

$$\Phi = \begin{pmatrix} 0 \\ \frac{v+\phi_0}{\sqrt{2}} \end{pmatrix} \tag{2.30}$$

$$S = \frac{v_s + s}{\sqrt{2}} \tag{2.31}$$

When the equations 2.30 and 2.31 are put in equation 2.27, the mass terms have mixing term for fields ϕ_0 and **s**. So, we need to diagonalize the mass matrix to get the physical Higgs Scalars. The mass terms in the Lagrangian are as following :-

$$V_{Scalar} = \lambda_\phi v^2 \times \phi_0^2 + \lambda_{\phi s} v \times v_s \times s \times \phi_0 + \frac{\lambda_s v_s^2 \times s^2}{2} \tag{2.32}$$

The diagonalization involves rotation through one angle only (namely θ_s) which is done as following :-

$$\begin{pmatrix} 2\times\lambda_\phi v^2 & \lambda_{\phi s} v\times v_s \\ \lambda_{\phi s} v\times v_s & 2\times\lambda_s v_s^2 \end{pmatrix} = O_s^T \begin{pmatrix} M_H^2 & 0 \\ 0 & M_{H'}^2 \end{pmatrix} O_s \tag{2.33}$$

Here, M_H and $M_{H'}$ are the masses of physical Higgs masses. $\mathbf{O}_s$ is the rotation matrix with Higgs mixing angle (θ_s) defined as following :-

$$O_s = \begin{pmatrix} \cos\theta_s & \sin\theta_s \\ -\sin\theta_s & \cos\theta_s \end{pmatrix} \tag{2.34}$$

From the equations 2.33 and 2.34, we get

$$\begin{pmatrix} 2\times\lambda_\phi v^2 & \lambda_{\phi s} v\times v_s \\ \lambda_{\phi s} v\times v_s & 2\times\lambda_s v_s^2 \end{pmatrix} = \begin{pmatrix} M_H^2\cos^2\theta_s + M_{H'}^2\sin^2\theta_s & \sin\theta_s\cos\theta_s(M_H^2 - M_{H'}^2) \\ \sin\theta_s\cos\theta_s(M_H^2 - M_{H'}^2) & M_H^2\sin^2\theta_s + M_{H'}^2\cos^2\theta_s \end{pmatrix} \tag{2.35}$$

The coefficients of fields in the scalar potential (in equation 2.32) are related to the physical Higgs masses. The relations are as following :-

$$2\times\lambda_\phi v^2 = M_H^2\cos^2\theta_s + M_{H'}^2\sin^2\theta_s \tag{2.36}$$

$$2\times\lambda_s v_s^2 = M_H^2\sin^2\theta_s + M_{H'}^2\cos^2\theta_s \tag{2.37}$$

$$\lambda_{\phi s} v\times v_s = \sin\theta_s\cos\theta_s(M_H^2 - M_{H'}^2) \tag{2.38}$$

The Spontaneous Symmetric Breaking occur as following :-

$$SU(2)_L\times U(1)_Y\times U(1)_X \to U(1)_{EM} \tag{2.39}$$

Here we can see that only the electromagnetic symmetry group is left unbroken. This is evident from the selection of electric charge expression as following :-

$$Q = T_{3L} + Y \tag{2.40}$$

, where T_{3L} and Y are the third generator of $SU(2)_L$ and the hypercharge related to $U(1)_Y$ respectively.

Chapter 3

FeynRules

FeynRules is a Mathematica-based package which addresses the implementation of particle physics models and provides a set of functions for defining particle content, interactions, and parameters of a new model. We have used the **Wolfram Mathematica 12.0** version here. It calculates the underlying Feynman rules and outputs them to a form appropriate for various programs such as CalcHep, FeynArts, MadGraph5, Sherpa and Whizard. Since Feynman rules produced can be output to various event generators, an interface is required (e.g. UFO Interface). Here, I have implemented Z' Model. We need FeynRules for the following reasons:

1. Each event generator uses its own syntax for a new model. Learning one syntax did not transfer to another generator.

2. Implementing a new model often required the modification of the event generator code itself. These implementations did not transfer well between theorists or to experimentalists.

FeynRules Specifications

Version: 2.3.49

Authors: A. Alloul, N. Christensen, C. Degrande, C. Duhr, B. Fuks

Website: http://feynrules.phys.ucl.ac.be

3.1 Model Description

To use FeynRules [5], the user must start by entering the details of the new model in a valid mathematica syntax (Wolfram Language). Model file contains all of the information needed for a model or a theory. These definitions can be placed in a pure text file with **.fr** extension. The different type of information is included in various classes. All classes can be in a single file or we can make separate files for classes (e.g. for parameters, fields(particles), etc.). The main model file **ZPrime**.fr is shown in figure 3.1 and 3.2 .

```
(*************  This is the FeynRules mod-file for Z-prime Model   *********)
(*************  Author: Joginder ***********)


M$ModelName = "Z Prime Model";

(*************  Model Information    ***********)

M$Information = {
   Authors      -> {"Joginder"},
   Version      -> "1.0",
   Date         -> "01. 01. 2023",
   Institutions -> "Indian Institute of Technology Indore",
   Emails       -> {"jogindergoswami77@gmail.com"}
};

FeynmanGauge = True;

(* ***** NLO Variables ****** *)

FR$LoopSwitches = {{Gf, MW}};
FR$RmDblExt = { ymb -> MB, ymc -> MC, ymdo -> MD, yme -> Me,
   ymm -> MMU, yms -> MS, ymt -> MT, ymtau -> MTA, ymup -> MU};

(* *****      vevs      ***** *)

M$vevs = { {Phi[2],vev},{Su,vevs} };

(* *****  Gauge groups   ***** *)

M$GaugeGroups = {
  U1Y  == {
    Abelian          -> True,
    CouplingConstant -> g1,
    GaugeBoson       -> B,
    Charge           -> Y
  },
(* ======================New Group U1X Added===================== *)
U1X  == {
    Abelian          -> True,
    CouplingConstant -> gx,
    GaugeBoson       -> X,
    Charge           -> Yp
  },
SU2L == {
    Abelian           -> False,
    CouplingConstant  -> gw,
    GaugeBoson        -> Wi,
    StructureConstant -> Eps,
    Representations   -> {Ta,SU2D},
    Definitions       -> {Ta[a_,b_,c_]->PauliSigma[a,b,c]/2, FSU2L[i_,j_,k_]:> I Eps[i,j,k]}
  },
SU3C == {
    Abelian           -> False,
    CouplingConstant  -> gs,
    GaugeBoson        -> G,
    StructureConstant -> f,
    Representations   -> {T,Colour},
    SymmetricTensor   -> dSUN
  }
};
```

Figure 3.1: Model file describing general model information, vacuum expectation values and Gauge groups (Screenshot 1)

```
63  (* *****    Indices     ***** *)
64
65  IndexRange[Index[SU2W      ]] = Unfold[Range[3]];
66  IndexRange[Index[SU2D      ]] = Unfold[Range[2]];
67  IndexRange[Index[Gluon     ]] = NoUnfold[Range[8]];
68  IndexRange[Index[Colour    ]] = NoUnfold[Range[3]];
69  IndexRange[Index[Generation]] = Range[3];
70
71  IndexStyle[SU2W,       j];
72  IndexStyle[SU2D,       k];
73  IndexStyle[Gluon,      a];
74  IndexStyle[Colour,     m];
75  IndexStyle[Generation, f];
76
77  (* *** Interaction orders *** *)
78  (* ***  (as used by mg5)  *** *)
79
80  M$InteractionOrderHierarchy = {
81    {QCD, 1},
82    {QED, 2}
83  };
84
85  (************* Calling for paramter and particles files   ***********)
86
87  Get["parameterszp.fr"];
88
89  Get["particleszp.fr"];
```

Figure 3.2: Model file describing indices , interaction order hierarchy and calling of parameter and particle files (Screenshot 2)

1. **Model Information**

   Just like any programming language, the model information is stored in some variables. The variables in Wolfram language are defined with **M$Variablename** This contains general information about the model. It includes model name. The model information have options such as authors, institute, date and email IDs etc. The variable M$Information acts as an electronic signature of the model. **Lorentz and Spin** indices are defined by default in FeynRules. Indices are defined by **Index**[].

2. **Gauge Group**

   The structure of the interactions of a model is in general dictated by gauge symmetries. In Z' model, Gauge group is $\mathrm{SU}(3)\times\mathrm{SU}(2)\times\mathrm{U}(1)\times\mathrm{U}(1)$. The options used in this class are Abelian, Coupling Constant, Charge etc. Since, we have doublets for SU(2) group, generators are used in the two-dimensional representation ($\frac{\tau_a}{2}$). These are defined in line number 51.

3. **Model Parameters**

Lagrangian is in terms of parameters and fields. So, for listing all the parameters, we need a parameter class. Parameters can be internal or external. The parameters directly taken from the experiments are external and the parameters derived from the external or/and internal parameters are internal parameters. There are various options for a particular parameter like value, parameter type, complex parameter type, interaction order etc. There are total 46 parameters in Z' model. The external parameters are defined from line numbers **7** to **150**. Apart from the Standard Model model file, we have four new external parameters in Z' model namely sa_z, r_s, st_s and tx. Here, the details are included in **parameterszp.fr** file which is given by :-

```
(* *****    Parameters    ***** *)

M$Parameters = {

  (* External parameters *)

  aEWM1 == {
    ParameterType    -> External,
    BlockName        -> SMINPUTS,
    OrderBlock       -> 1,
    Value            -> 127.9,
    InteractionOrder -> {QED,-2},
    Description      -> "Inverse of the EW coupling constant at the Z pole"
  },
  Gf == {
    ParameterType    -> External,
    BlockName        -> SMINPUTS,
    OrderBlock       -> 2,
    Value            -> 1.16637*^-5,
    InteractionOrder -> {QED,2},
    TeX              -> Subscript[G,f],
    Description      -> "Fermi constant"
  },
  aS    == {
    ParameterType    -> External,
    BlockName        -> SMINPUTS,
    OrderBlock       -> 3,
    Value            -> 0.13,
    InteractionOrder -> {QCD,2},
    TeX              -> Subscript[\[Alpha],s],
    Description      -> "Strong coupling constant at the Z pole"
  },
  ymdo == {
    ParameterType -> External,
    BlockName     -> YUKAWA,
    OrderBlock    -> 1,
    Value         -> 5.04*^-3,
    Description   -> "Down Yukawa mass"
  },
  ymup == {
    ParameterType -> External,
    BlockName     -> YUKAWA,
    OrderBlock    -> 2,
    Value         -> 2.55*^-3,
    Description   -> "Up Yukawa mass"
  },
  yms == {
    ParameterType -> External,
    BlockName     -> YUKAWA,
    OrderBlock    -> 3,
    Value         -> 0.101,
    Description   -> "Strange Yukawa mass"
  },
  ymc == {
    ParameterType -> External,
    BlockName     -> YUKAWA,
    OrderBlock    -> 4,
    Value         -> 1.27,
    Description   -> "Charm Yukawa mass"
  },
```

Figure 3.3: Parameter file describing parameters aEWM1, Gf, aS, ymdo, ymup, yms and ymc (Screenshot 1)

```
  ymb == {
    ParameterType -> External,
    BlockName     -> YUKAWA,
    OrderBlock    -> 5,
    Value         -> 4.7,
    Description   -> "Bottom Yukawa mass"
  },
  ymt == {
    ParameterType -> External,
    BlockName     -> YUKAWA,
    OrderBlock    -> 6,
    Value         -> 172,
    Description   -> "Top Yukawa mass"
  },
  yme == {
    ParameterType -> External,
    BlockName     -> YUKAWA,
    OrderBlock    -> 11,
    Value         -> 5.11*^-4,
    Description   -> "Electron Yukawa mass"
  },
  ymm == {
    ParameterType -> External,
    BlockName     -> YUKAWA,
    OrderBlock    -> 13,
    Value         -> 0.10566,
    Description   -> "Muon Yukawa mass"
  },
  ymtau == {
    ParameterType -> External,
    BlockName     -> YUKAWA,
    OrderBlock    -> 15,
    Value         -> 1.777,
    Description   -> "Tau Yukawa mass"
  },
  cabi == {
    ParameterType -> External,
    BlockName     -> CKMBLOCK,
    OrderBlock    -> 1,
    Value         -> 0.227736,
    TeX           -> Subscript[\[Theta], c],
    Description   -> "Cabibbo angle"
  },

(*========================saz Added==========================*)

  saz == {
    ParameterType -> External,
    BlockName     -> MIXBLOCK,
    OrderBlock    -> 1,
    Value         -> 0.0001,
    TeX           -> Subscript[sa,z],
    Description   -> "Sine of Z-Zp Mixing Angle"
  },
```

Figure 3.4: Parameter file describing ymb, ymt, yme, ymm, ymtau, cabi and saz (Screenshot 2)

Here, g_s, α_{EW} and ee are strong coupling constant in natural units, fine structure constant in natural units and electric coupling constant respectively. $'ee'$ defined here is equivalent to electric charge(e). $'\alpha_s'$ is the strong coupling constant at the Z pole (an experimental or external parameter). At the line numbers **154**, **163** and **170**, g_s, α_{EW} and ee are defined respectively as :-

$$g_s = \sqrt{4\pi \times \alpha_s} \tag{3.1}$$

$$\alpha_{EW} = \frac{1}{aEWM1} \tag{3.2}$$

$$ee = \sqrt{4\pi \times \alpha_{EW}} \tag{3.3}$$

```
(*============================rs added============================*)

 rs == {
   ParameterType -> External,
   BlockName     -> MIXBLOCK,
   OrderBlock    -> 2,
   Value         -> 500,
   TeX           -> Subscript[r,s],
   Description   -> "Ratio of Singlet to Doublet VEVs"
 },

(*============================st added============================*)

 st == {
   ParameterType -> External,
   BlockName     -> MIXBLOCK,
   OrderBlock    -> 6,
   Value         -> 0.2,
   TeX           -> Subscript[st,s],
   Description   -> "Sin of Higgs Mixing Angle"
 },

 (*============================tx Added============================*)

tx == {
   ParameterType -> Internal,
   BlockName     -> MIXBLOCK,
   OrderBlock    -> 7,
   Value         -> 1,
   TeX           -> tx,
   Description   -> "Tan of U1X Mixing Angle"
 },


(* Internal Parameters *)
 gs == {
   ParameterType    -> Internal,
   Value            -> Sqrt[4 Pi aS],
   InteractionOrder -> {QCD,1},
   TeX              -> Subscript[g,s],
   ParameterName    -> G,
   Description      -> "Strong coupling constant at the Z pole"
 },

aEW == {
   ParameterType    -> Internal,
   Value            -> 1/aEWM1,
   InteractionOrder -> {QED,2},
   TeX              -> Subscript[\[Alpha], EW],
   Description      -> "Electroweak coupling contant"
 },
 ee == {
   ParameterType    -> Internal,
   Value            -> Sqrt[4 Pi aEW],
   InteractionOrder -> {QED,1},
   TeX              -> e,
   Description      -> "Electric coupling constant"
 },
```

Figure 3.5: Parameter file describing rs, st, gs, aEW and ee (Screenshot 3)

Fermi constant (G_f) is related to vacuum expectation value (vev) of scalar doublet and vev is expressed in terms of G_f at line number **180**.

$$G_f = \frac{1}{\sqrt{2} \times vev^2} \tag{3.4}$$

We know, Weinberg angle(θ_w) is related to mass of W and Z bosons as :

$$\cos\theta_w = \frac{M_W}{M_Z} \tag{3.5}$$

$$M_W = \frac{g_w \times vev}{2} \tag{3.6}$$

$'g_w'$ is weak coupling constant of $SU(2)_L$ group (At the line number 47 in ZPrime.fr). From equations 3.5 and 3.6, Ge2 is defined at line number **188** as :-

$$Ge2 = \frac{g_w}{2 \times \cos g_w} = \frac{M_Z}{vev} \tag{3.7}$$

We know,

$$ee = g_w \times \sin\theta_w \tag{3.8}$$

Using equations 3.5, 3.7 and 3.8, we get

$$\sin 2\theta_w = \frac{ee}{Ge2} \tag{3.9}$$

From equation 3.9, Weinberg angle (θ_w) is defined at line number **196** (th) as :-

$$\theta_w = \frac{\arcsin \frac{ee}{Ge2}}{2} \tag{3.10}$$

From th (θ_w), internal parameters c_w, s_w and t_w are defined at line numbers **204**, **212** and **220** respectively. Parameter M_W is defined at the line number **229** as :-

$$M_W = M_Z \times c_w \tag{3.11}$$

```
(*===========================vev modified===========================*)
  vev == {
    ParameterType    -> Internal,
    Value            -> Sqrt[1/(Sqrt[2]*Gf)],
    InteractionOrder -> {QED,-1},
    Description      -> "Scalar Doublet vacuum expectation value"
  },

(*===========================Ge2 added===========================*)
  Ge2 == {
    ParameterType    -> Internal,
    Value            -> MZ/vev,
    InteractionOrder -> {QED,1},
    Description      -> "Extra paramter 1"
  },

(*===========================th added===========================*)
  th == {
    ParameterType    -> Internal,
    Value            -> ArcSin[ee/Ge2]/2,
    TeX              -> Subscript[\[Theta], w],
    Description      -> "Weinberg angle"
  },

(*===========================cw modified===========================*)
  cw == {
    ParameterType -> Internal,
    Value         -> Cos[th],
    TeX           -> Subscript[c,w],
    Description   -> "Cosine of the Weinberg angle"
  },

(*===========================sw modified===========================*)
  sw == {
    ParameterType -> Internal,
    Value         -> Sin[th],
    TeX           -> Subscript[s,w],
    Description   -> "Sine of the Weinberg angle"
  },

(*===========================tw added===========================*)
  tw == {
    ParameterType -> Internal,
    Value         -> Tan[th],
    TeX           -> Subscript[t,w],
    Description   -> "Tan of the Weinberg angle"
  },

(*===========================W Mass Modified===========================*)

 MW == {
    ParameterType -> Internal,
    Value         -> MZ*cw,
    TeX           -> Subscript[M,W],
    Description   -> "W mass"
  },
```

Figure 3.6: Parameter file describing vev, Ge2, th, cw, sw, tw and MW (Screenshot 4)

We know, mass of W boson is given by :-

$$M_W = \frac{g_w \times vev}{2} \tag{3.12}$$

From equations 3.11 and 3.12, g_w is defined at the line number **237** as:-

$$g_w = \frac{2 \times MW}{vev} \tag{3.13}$$

$U(1)_Y$ coupling constant (g_1) is the coupling constant of $U(1)_Y$ group (At the line number 34 in ZPrime.fr). $U(1)_Y$ coupling constant (g_1) and scalar singlet vacuum expectation value (vevs) are defined at line numbers **247** and **256** respectively as :-

$$g_1 = g_w \times t_w \tag{3.14}$$

$$vevs = r_s \times vev \tag{3.15}$$

From the diagonalization procedure of gauge boson mass matrix (here r_s is the ratio of Higgs singlet to doublet vacuum expectation values), the following relations are obtained :-

$$M_Z^2 \cos^2 \alpha_z + M_{Z'}^2 \sin^2 \alpha_z = \frac{M_W^2}{\cos^2 \theta_z} \tag{3.16}$$

$$M_{Z'}^2 \cos^2 \alpha_z + M_Z^2 \sin^2 \alpha_z = M_W^2 \tan^2 \theta_x \times (r_s^2 + x_\phi'^2) \tag{3.17}$$

$$(M_{Z'}^2 - M_Z^2) \sin 2\alpha_z = \frac{2x_\phi' \tan \theta_x M_W^2}{\cos \theta_w} \tag{3.18}$$

From equations 3.16, 3.17 and 3.18, internal parameters dm_1, dm_2 , xpp_2 and xpp are defined at the line numbers **264**, **273**, **283** and **292** respectively. These are given by :-

$$dm_1 = 2(M_{Z'}^2 - M_Z^2) \times sa_z \times \sqrt{1 - sa_z^2} \tag{3.19}$$

$$dm_2 = M_{Z'}^2 \cos^2 \alpha_z + M_Z^2 \sin^2 \alpha_z \tag{3.20}$$

$$xpp_2 = \frac{r_s^2 \cos^2 \theta_w \times dm_1^2}{4M_W^2 \times dm_2 - \cos^2 \theta_w \times dm_1^2} \tag{3.21}$$

$$xpp = \sqrt{xpp_2} \tag{3.22}$$

```
(*============================gw Modified===========================*)
  gw == {
    ParameterType    -> Internal,
    Definitions      -> {gw->(2*MW)/vev},
    InteractionOrder -> {QED,1},
    TeX              -> Subscript[g,w],
    Description      -> "Weak coupling constant at the Z pole"
  },


(*============================g1 Modified===========================*)
  g1 == {
    ParameterType    -> Internal,
    Definitions      -> {g1->gw*tw},
    InteractionOrder -> {QED,1},
    TeX              -> Subscript[g,1],
    Description      -> "U(1)Y coupling constant at the Z pole"
  },

  (*============================vevs added===========================*)
  vevs == {
    ParameterType    -> Internal,
    Value            -> rs*vev,
    Description      -> "Singlet Scalar vacuum expectation value"
  },

  (*============================dm1 Added===========================*)

 dm1 == {
    ParameterType -> Internal,
    Value         -> (MZp*MZp-MZ*MZ)*2*saz*(Sqrt[1-saz*saz]),
    TeX           -> Subscript[dm,1],
    Description   -> "Extra Paramter 2 for Diagonalization"
  },

(*============================dm2 Added===========================*)

 dm2 == {
    ParameterType -> Internal,
    Value         -> MZp*MZp*(1-saz*saz)+MZ*MZ*saz*saz,
    TeX           -> Subscript[dm,2],
    Description   -> "Extra Paramter 3 for Diagonalization"
  },


(*============================xpp2 added===========================*)

xpp2 == {
    ParameterType    -> Internal,
    Definitions      -> {xpp2->(rs*rs*cw*cw*dm1*dm1)/(4*MW*MW*dm2-cw*cw*dm1*dm1)},
    TeX              -> Subscript[xpp,2],
    Description      -> "Square of Modified U(1)X Hyperharge of Higgs Doublet"
},

(*============================xpp added===========================*)

xpp == {
    ParameterType    -> Internal,
    Definitions      -> {xpp->Sqrt[xpp2]},
    TeX              -> xpp,
    Description      -> "Modified U(1)X Hyperharge of Higgs Doublet"
},
```

Figure 3.7: Parameter file describing gw, g1, vevs, dm1, dm2, xpp2 and xpp (Screenshot 5)

```
299  (*===========================gxp added===========================*)
300  gxp == {
301      ParameterType    -> Internal,
302      Definitions      -> {gxp->gw*tx},
303      InteractionOrder -> {QED,1},
304      TeX              -> Subscript[g,xp],
305      Description      -> "Modified U(1)X coupling constant"
306  },
307
308  (*===========================chi Added===========================*)
309
310   chi == {
311      ParameterType -> Internal,
312      Value         -> ArcTan[(-xpp*gxp)/g1],
313      TeX           -> chi,
314      Description   -> "chi Parameter"
315    },
316
317  (*===========================sc added===========================*)
318
319  sc == {
320      ParameterType    -> Internal,
321      Definitions      -> {sc->Sin[chi]},
322      TeX              -> sc,
323      Description      -> "Sin of Chi Parameter"
324  },
325
326  (*===========================tc added===========================*)
327
328  tc == {
329      ParameterType    -> Internal,
330      Definitions      -> {tc->Tan[chi]},
331      TeX              -> tc,
332      Description      -> "Tan of Chi Parameter"
333  },
334
335
336  (*===========================gx added===========================*)
337
338  gx == {
339      ParameterType    -> Internal,
340      Definitions      -> {gx->gxp*(1-sc*sc)},
341      InteractionOrder -> {QED,1},
342      TeX              -> Subscript[g,x],
343      Description      -> "U(1)X coupling constant"
344  },
```

Figure 3.8: Parameter file describing tx, gxp, chi, sc, tc and gx (Screenshot 6)

We know , the relation between modified coupling constant of $U(1)_X$ group (g_x') and weak coupling constant (g_w) as :

$$\tan\theta_x = \frac{g_x'}{g_w} \tag{3.23}$$

So, g_x' is defined in parameter file by g_{xp} at line number **302** using equation 60 as :

$$g_{xp} = g_w \times tx \tag{3.24}$$

We know,

$$g'_x = \frac{g_x}{\cos\chi} \tag{3.25}$$

$$x'_\phi = x_\phi - \frac{g_1 \times \tan\chi}{g'_x} \tag{3.26}$$

Using 3.26 and 3.27, χ is expressed as :

$$\chi = \arctan\frac{(x'_\phi - x_\phi)g'_x}{g1} \tag{3.27}$$

It is defined at the line number **312**. The internal parameters sc, tc and g_x are defined at the line numbers **321**, **330** and **340** respectively as :-

$$sc = \sin\chi \tag{3.28}$$

$$tc = \tan\chi \tag{3.29}$$

$$g_x = g'_x \times \sqrt{1 - sc^2} \tag{3.30}$$

$'g'_x$ is the coupling constant of $U(1)_X$ group (At the line number 41 in ZPrime.fr). Using the equations 2.36, 2.37 and 2.38, ls, μ_S, l_{HS}, lh, μ_H are defined at the line numbers **351**, **361**, **370**, **381** and **390** respectively. $'\mu'_S$ and $'\mu'_H$ are the coefficients of quadratic piece of the scalar singlet potential and scalar doublet potential (scalar sector) respectively. $'ls'$ and $'lh'$ are the coefficients of quartic piece of the scalar singlet potential and scalar doublet potential respectively. $'l'_{HS}$ is the coefficient of mixing term between scalar singlet and scalar doublet fields in the scalar potential part of the Lagrangian. These are given by :-

$$ls = \frac{st_s^2 \times M_H^2 + (1 - st_s^2) \times M_{H'}^2}{2 \times vevs \times vev} \tag{3.31}$$

$$\mu_S = \sqrt{vevs^2 \times ls + \frac{l_{HS} \times vevs^2}{2}} \tag{3.32}$$

$$l_{HS} = \frac{\sqrt{1 - st_s^2} \times st_s \times M_H^2 \times M_{H'}^2}{vev \times vevs} \tag{3.33}$$

$$lh = \frac{(1 - st_s^2)M_H^2 + st_s^2 \times M_{H'}^2}{2 \times vev^2} \tag{3.34}$$

$$\mu_H = \sqrt{vev^2 \times lh + \frac{l_{HS} \times vev^2}{2}} \tag{3.35}$$

```
(*===========================ls Added===========================*)

ls == {
    ParameterType    -> Internal,
    Value            -> (st*st*MH*MH+(1-st*st) MHp*MHp)/(vevs*vevs*2),
    InteractionOrder -> {QED,2},
    TeX              -> ls,
    Description      -> "Singlet Scalar Quartic Coupling"
  },

(*===========================muS Added===========================*)

muS == {
    ParameterType -> Internal,
    Value         -> Sqrt[vevs^2 ls+(lHS*vevs*vevs/2)],
    TeX           -> Subscript[\[Mu],s],
    Description   -> "Coefficient of the quadratic piece of the Singlet Scalar Potential"
  },


(*===========================lHS Added===========================*)
lHS == {
    ParameterType -> Internal,
    Value         -> (Sqrt[1-(st^2)]*st*(MH^2-MHp^2))/(vev*vevs),
    InteractionOrder -> {QED, 2},
    TeX           -> Subscript[l,HS],
    Description   -> "Coefficient of the mixing of the Singlet Scalar and Higgs field"

  },

(*===========================lh modified ===========================*)

lh == {
    ParameterType    -> Internal,
    Value            -> ((1-st^2)*MH*MH + st*st*MHp*MHp)/(2*vev*vev),
    InteractionOrder -> {QED, 2},
    Description      -> "Higgs quartic coupling"
  },

(*=========================== muH modified===========================*)

 muH == {
    ParameterType -> Internal,
    Value         -> Sqrt[vev*vev*lh +(lHS*vev*vev)/2],
    TeX           -> Subscript[\[Mu],H],
    Description   -> "Coefficient of the quadratic piece of the Higgs potential"
  },

 yl == {
    ParameterType    -> Internal,
    Indices          -> {Index[Generation], Index[Generation]},
    Definitions      -> {yl[i_?NumericQ, j_?NumericQ] :> 0  /; (i =!= j)},
    Value            -> {yl[1,1] -> Sqrt[2] yme / vev, yl[2,2] -> Sqrt[2] ymm / vev, yl[3,3] -> Sqrt[2] ymtau / vev},
    InteractionOrder -> {QED, 1},
    ParameterName    -> {yl[1,1] -> ye, yl[2,2] -> ym, yl[3,3] -> ytau},
    TeX              -> Superscript[y, l],
    Description      -> "Lepton Yukawa couplings"
  },
```

Figure 3.9: Parameter file describing ls, muS, lHS, lh, muH and yl (Screenshot 7)

The internal parameters y_l, y_u, y_d and V_{CKM} are defined at the line numbers **399**, **410**, **421** and **434** respectively. The parameters y_l, y_u, y_d are the lepton, up-type quark and down-type quark Yukawa couplings respectively. $'V'_{CKM}$ is the CKM matrix parameter in our model.

```
406    yu == {
407      ParameterType    -> Internal,
408      Indices          -> {Index[Generation], Index[Generation]},
409      Definitions      -> {yu[i_?NumericQ, j_?NumericQ] :> 0  /; (i =!= j)},
410      Value            -> {yu[1,1] -> Sqrt[2] ymup/vev, yu[2,2] -> Sqrt[2] ymc/vev, yu[3,3] -> Sqrt[2] ymt/vev},
411      InteractionOrder -> {QED, 1},
412      ParameterName    -> {yu[1,1] -> yup, yu[2,2] -> yc, yu[3,3] -> yt},
413      TeX              -> Superscript[y, u],
414      Description      -> "Up-type Yukawa couplings"
415    },
416
417    yd == {
418      ParameterType    -> Internal,
419      Indices          -> {Index[Generation], Index[Generation]},
420      Definitions      -> {yd[i_?NumericQ, j_?NumericQ] :> 0  /; (i =!= j)},
421      Value            -> {yd[1,1] -> Sqrt[2] ymdo/vev, yd[2,2] -> Sqrt[2] yms/vev, yd[3,3] -> Sqrt[2] ymb/vev},
422      InteractionOrder -> {QED, 1},
423      ParameterName    -> {yd[1,1] -> ydo, yd[2,2] -> ys, yd[3,3] -> yb},
424      TeX              -> Superscript[y, d],
425      Description      -> "Down-type Yukawa couplings"
426    },
427
428  (* N. B. : only Cabibbo mixing! *)
429
430    CKM == {
431      ParameterType -> Internal,
432      Indices       -> {Index[Generation], Index[Generation]},
433      Unitary       -> True,
434      Value         -> {CKM[1,1] -> Cos[cabi],  CKM[1,2] -> Sin[cabi], CKM[1,3] -> 0,
435                        CKM[2,1] -> -Sin[cabi], CKM[2,2] -> Cos[cabi], CKM[2,3] -> 0,
436                        CKM[3,1] -> 0,          CKM[3,2] -> 0,         CKM[3,3] -> 1},
437      TeX         -> Superscript[V,CKM],
438      Description -> "CKM-Matrix"
439
440    }
441  };
```

Figure 3.10: Parameter file describing yu, yd and CKM (Screenshot 8)

4. **Particle Classes**

   The fields used in the Lagrangian are described in model file by particle classes. The particle classes are labeled according to the spins of the particles.(E.g. S-Scalar Field ,F-Dirac Field,V-Vector Field). The options used in particle class are like Class Name, SelfConjugate, Mass, PDG, Width etc. This all information is included in file **particleszp.fr** which is as following :-

The physical vector fields (Gauge Bosons) A, Z, W, G and Zp are defined at the line numbers **7**, **19**, **31**, **45** and **61** respectively.

```
1    (* **** Particle classes **** *)
2
3    M$ClassesDescription = {
4
5    (* Gauge bosons: physical vector fields *)
6
7      V[1] == {
8        ClassName        -> A,
9        SelfConjugate    -> True,
10       Mass             -> 0,
11       Width            -> 0,
12       ParticleName     -> "a",
13       PDG              -> 22,
14       PropagatorLabel  -> "a",
15       PropagatorType   -> W,
16       PropagatorArrow  -> None,
17       FullName         -> "Photon"
18     },
19     V[2] == {
20       ClassName        -> Z,
21       SelfConjugate    -> True,
22       Mass             -> {MZ, 91.1876},
23       Width            -> {WZ, 2.4952},
24       ParticleName     -> "Z",
25       PDG              -> 23,
26       PropagatorLabel  -> "Z",
27       PropagatorType   -> Sine,
28       PropagatorArrow  -> None,
29       FullName         -> "Z"
30     },
31     V[3] == {
32       ClassName         -> W,
33       SelfConjugate     -> False,
34       Mass              -> {MW, Internal},
35       Width             -> {WW, 2.085},
36       ParticleName      -> "W+",
37       AntiParticleName  -> "W-",
38       QuantumNumbers    -> {Q -> 1},
39       PDG               -> 24,
40       PropagatorLabel   -> "W",
41       PropagatorType    -> Sine,
42       PropagatorArrow   -> Forward,
43       FullName          -> "W"
44     },
45     V[4] == {
46       ClassName         -> G,
47       SelfConjugate     -> True,
48       Indices           -> {Index[Gluon]},
49       Mass              -> 0,
50       Width             -> 0,
51       ParticleName      -> "g",
52       PDG               -> 21,
53       PropagatorLabel   -> "G",
54       PropagatorType    -> C,
55       PropagatorArrow   -> None,
56       FullName          -> "G"
57     },
```

Figure 3.11: Particle file describing physical vector fields A, Z, W and G (Screenshot 1)

Using equations 2.2, 2.21 , 2.22 and 2.23, unphysical vector fields B, Bp, X, Xp and Wi (W_1, W_2 and W_3) are defined at the line numbers **85**, **94**, **103**, **112** and **123** respectively. Fields W_1 and W_2 combine to give physical fields W^+ and W^- (As in the Standard Model)

```
59   (* =====================Zp Added==================== *)
60
61    V[5] == {
62      ClassName       -> Zp,
63      SelfConjugate   -> True,
64      Mass            -> {MZp,500},
65      Width           -> {WZp,10},
66      ParticleName    -> "Zp",
67      PDG             -> 32,
68      PropagatorLabel -> "Zp",
69      PropagatorType  -> Sine,
70      PropagatorArrow -> None,
71      FullName        -> "Zp"
72    },
73
74  (* Ghost fields for physical vector fields not added *)
75
76
77  (* Gauge bosons: unphysical vector fields *)
78
79  (* =============New definition of B Added============= *)
80
81    V[11] == {
82      ClassName     -> B,
83      Unphysical    -> True,
84      SelfConjugate -> True,
85      Definitions   -> { B[mu_] -> Bp[mu]-tc Xp[mu]}
86    },
87
88  (* =======================Bp Added==================== *)
89
90    V[12] == {
91      ClassName     -> Bp,
92      Unphysical    -> True,
93      SelfConjugate -> True,
94      Definitions   -> { Bp[mu_] -> cw A[mu] - sw Sqrt[1-saz*saz] Z[mu] + sw*saz Zp[mu]}
95    },
96
97  (* =======================X Added==================== *)
98
99    V[13] == {
100     ClassName     -> X,
101     Unphysical    -> True,
102     SelfConjugate -> True,
103     Definitions   -> { X[mu_] -> (1/Sqrt[1-sc*sc]) Xp[mu]}
104   },
105
106 (* =======================Xp Added==================== *)
107
108   V[14] == {
109     ClassName     -> Xp,
110     Unphysical    -> True,
111     SelfConjugate -> True,
112     Definitions   -> { Xp[mu_] -> saz Z[mu] + Sqrt[1-saz*saz] Zp[mu]}
113   },
```

Figure 3.12: Particle file describing fields Zp, B, Bp, X and Xp (Screenshot 2)

Fields vl and l are defined at the line numbers **132** and **149** respectively. Physical fields 'vl' and 'l' are the neutrino and lepton fields (for three generations) respectively.

```
115 (* ==============New definition of W3 Added============== *)
116
117   V[15] == {
118     ClassName     -> Wi,
119     Unphysical    -> True,
120     SelfConjugate -> True,
121     Indices       -> {Index[SU2W]},
122     FlavorIndex   -> SU2W,
123     Definitions   -> { Wi[mu_,1] -> (Wbar[mu]+W[mu])/Sqrt[2], Wi[mu_,2] -> (Wbar[mu]-W[mu])/(I*Sqrt[2]),
124      Wi[mu_,3] -> sw A[mu]+cw Sqrt[1-saz*saz] Z[mu]-cw*saz Zp[mu]}
125   },
126
127  (* Ghost fields for unphysical vector fields not added *)
128
129
130  (* Fermions: physical fields *)
131
132   F[1] == {
133     ClassName        -> vl,
134     ClassMembers     -> {ve,vm,vt},
135     Indices          -> {Index[Generation]},
136     FlavorIndex      -> Generation,
137     SelfConjugate    -> False,
138     Mass             -> 0,
139     Width            -> 0,
140     QuantumNumbers   -> {LeptonNumber -> 1},
141     PropagatorLabel  -> {"v", "ve", "vm", "vt"} ,
142     PropagatorType   -> S,
143     PropagatorArrow  -> Forward,
144     PDG              -> {12,14,16},
145     ParticleName     -> {"ve","vm","vt"},
146     AntiParticleName -> {"ve~","vm~","vt~"},
147     FullName         -> {"Electron-neutrino", "Mu-neutrino", "Tau-neutrino"}
148   },
149   F[2] == {
150     ClassName        -> l,
151     ClassMembers     -> {e, mu, ta},
152     Indices          -> {Index[Generation]},
153     FlavorIndex      -> Generation,
154     SelfConjugate    -> False,
155     Mass             -> {Ml, {Me,5.11*^-4}, {MMU,0.10566}, {MTA,1.777}},
156     Width            -> 0,
157     QuantumNumbers   -> {Q -> -1, LeptonNumber -> 1},
158     PropagatorLabel  -> {"l", "e", "mu", "ta"},
159     PropagatorType   -> Straight,
160     PropagatorArrow  -> Forward,
161     PDG              -> {11, 13, 15},
162     ParticleName     -> {"e-", "mu-", "ta-"},
163     AntiParticleName -> {"e+", "mu+", "ta+"},
164     FullName         -> {"Electron", "Muon", "Tau"}
165   },
```

Figure 3.13: Particle file describing fields Wi, vl and l (Screenshot 3)

Fields uq, dq, LL and lR are defined at the line numbers **166**, **183**, **285** and **215** respectively. 'LL' fields are lepton doublets defined for all the three generations. Fields in 'LL' field are operated with **ProjM[,]** to get the left handed part of the field. 'uq' and 'dq' are the physical fields corresponding to up-type quarks and down-type quarks respectively. 'lR' are the right handed lepton fields (for electron, muon and tau). The right handed neutrino is not included in our Z' model. These are given by :-

$$LL = \begin{pmatrix} vl \\ l \end{pmatrix}_L \tag{3.36}$$

Where L stands for left handed part. Fields QL, uR, dR, H and Hp are defined at the line numbers **224**, **235**, **244**, **260** and **275** respectively. QL fields are quark doublets defined for all the three generations. 'uq' and 'dq' in 'QL' field are operated with **ProjM[,]** operator to get the left handed part of the field. For getting the right handed part of the field, we need **ProjP[,]** operator. 'uR' and 'dR' are right handed part of the fields 'uq' and 'dq' respectively (for three generations). These are given by :-

$$QL = \begin{pmatrix} uq \\ CKM \times dq \end{pmatrix}_L \tag{3.37}$$

Where L stands for left handed part of the field.

```
  F[3] == {
    ClassName        -> uq,
    ClassMembers     -> {u, c, t},
    Indices          -> {Index[Generation], Index[Colour]},
    FlavorIndex      -> Generation,
    SelfConjugate    -> False,
    Mass             -> {Mu, {MU, 2.55*^-3}, {MC,1.27}, {MT,172}},
    Width            -> {0, 0, {WT,1.50833649}},
    QuantumNumbers   -> {Q -> 2/3},
    PropagatorLabel  -> {"uq", "u", "c", "t"},
    PropagatorType   -> Straight,
    PropagatorArrow  -> Forward,
    PDG              -> {2, 4, 6},
    ParticleName     -> {"u",  "c",  "t" },
    AntiParticleName -> {"u~", "c~", "t~"},
    FullName         -> {"u-quark", "c-quark", "t-quark"}
  },
  F[4] == {
    ClassName        -> dq,
    ClassMembers     -> {d, s, b},
    Indices          -> {Index[Generation], Index[Colour]},
    FlavorIndex      -> Generation,
    SelfConjugate    -> False,
    Mass             -> {Md, {MD,5.04*^-3}, {MS,0.101}, {MB,4.7}},
    Width            -> 0,
    QuantumNumbers   -> {Q -> -1/3},
    PropagatorLabel  -> {"dq", "d", "s", "b"},
    PropagatorType   -> Straight,
    PropagatorArrow  -> Forward,
    PDG              -> {1,3,5},
    ParticleName     -> {"d",  "s",  "b" },
    AntiParticleName -> {"d~", "s~", "b~"},
    FullName         -> {"d-quark", "s-quark", "b-quark"}
  },


(* Fermions: unphysical fields *)


  F[11] == {
    ClassName      -> LL,
    Unphysical     -> True,
    Indices        -> {Index[SU2D], Index[Generation]},
    FlavorIndex    -> SU2D,
    SelfConjugate  -> False,
    QuantumNumbers -> {Y -> -1/2 , Yp -> -1/4},
    Definitions    -> { LL[sp1_,1,ff_] :> Module[{sp2}, ProjM[sp1,sp2] vl[sp2,ff]], LL[sp1_,2,ff_]
     :> Module[{sp2}, ProjM[sp1,sp2] l[sp2,ff]] }
  },
  F[12] == {
    ClassName      -> lR,
    Unphysical     -> True,
    Indices        -> {Index[Generation]},
    FlavorIndex    -> Generation,
    SelfConjugate  -> False,
    QuantumNumbers -> {Y -> -1 , Yp -> -1/4},
    Definitions    -> { lR[sp1_,ff_] :> Module[{sp2}, ProjP[sp1,sp2] l[sp2,ff]] }
  },
```

Figure 3.14: Particle file describing fields uq, dq, LL and lR (Screenshot 4)

Fields H and Hp are the physical scalar fields of Z' Model.

```
  F[13] == {
    ClassName      -> QL,
    Unphysical     -> True,
    Indices        -> {Index[SU2D], Index[Generation], Index[Colour]},
    FlavorIndex    -> SU2D,
    SelfConjugate  -> False,
    QuantumNumbers -> {Y -> 1/6 , Yp -> 1/12},
    Definitions    -> {
      QL[sp1_,1,ff_,cc_] :> Module[{sp2}, ProjM[sp1,sp2] uq[sp2,ff,cc]],
      QL[sp1_,2,ff_,cc_] :> Module[{sp2,ff2}, CKM[ff,ff2] ProjM[sp1,sp2] dq[sp2,ff2,cc]] }
  },
  F[14] == {
    ClassName      -> uR,
    Unphysical     -> True,
    Indices        -> {Index[Generation], Index[Colour]},
    FlavorIndex    -> Generation,
    SelfConjugate  -> False,
    QuantumNumbers -> {Y -> 2/3 , Yp -> 1/12},
    Definitions    -> { uR[sp1_,ff_,cc_] :> Module[{sp2}, ProjP[sp1,sp2] uq[sp2,ff,cc]] }
  },
  F[15] == {
    ClassName      -> dR,
    Unphysical     -> True,
    Indices        -> {Index[Generation], Index[Colour]},
    FlavorIndex    -> Generation,
    SelfConjugate  -> False,
    QuantumNumbers -> {Y -> -1/3 , Yp -> 1/12},
    Definitions    -> { dR[sp1_,ff_,cc_] :> Module[{sp2}, ProjP[sp1,sp2] dq[sp2,ff,cc]] }
  },

 (* Scalars *)

(* Higgs: Physical scalars  *)

(* ========================H Added==================== *)

S[1] == {
    ClassName       -> H,
    SelfConjugate   -> True,
    Mass            -> {MH,125},
    Width           -> {WH,0.00407},
    PropagatorLabel -> "H",
    PropagatorType  -> D,
    PropagatorArrow -> None,
    PDG             -> 25,
    ParticleName    -> "H",
    FullName        -> "H"
  },

(* ========================Hp Added==================== *)

  S[2] == {
    ClassName       -> Hp,
    SelfConjugate   -> True,
    Mass            -> {MHp,455},
    Width           -> {WHp,0.00407},
    PropagatorLabel -> "Hp",
    PropagatorType  -> D,
    PropagatorArrow -> None,
    PDG             -> 1111,
    ParticleName    -> "Hp",
    FullName        -> "Hp"
  },
```

Figure 3.15: Particle file describing fields QL, uR, dR, H and Hp (Screenshot 5)

Fields hd, G0, GP and GZp are defined at the line numbers **298**, **303**, **317** and **336** respectively. G0, GP and GZp are the Goldstone bosons corresponding to Z, W and Z' bosons respectively. We know that,

$$\begin{pmatrix} hd \\ ss \end{pmatrix} = \begin{pmatrix} \cos\theta_s & -\sin\theta_s \\ \sin\theta_s & \cos\theta_s \end{pmatrix} \begin{pmatrix} H \\ Hp \end{pmatrix} \tag{3.38}$$

```
290   (* Higgs: unphysical scalars  *)
291
292  (* ========================New definition of hd Added==================== *)
293
294    S[3] == {
295      ClassName     -> hd,
296      Unphysical    -> True,
297      SelfConjugate -> True,
298      Definitions   -> { hd -> Sqrt[1-(st^2)] H-st Hp }
299    },
300
301
302
303    S[4] == {
304      ClassName       -> G0,
305      SelfConjugate   -> True,
306      Goldstone       -> Z,
307      Mass            -> {MZ, 91.1876},
308      Width           -> {WZ, 2.4952},
309      PropagatorLabel -> "Go",
310      PropagatorType  -> D,
311      PropagatorArrow -> None,
312      PDG             -> 250,
313      ParticleName    -> "G0",
314      FullName        -> "G0"
315    },
316
317    S[5] == {
318      ClassName        -> GP,
319      SelfConjugate    -> False,
320      Goldstone        -> W,
321      Mass             -> {MW, Internal},
322      QuantumNumbers   -> {Q -> 1},
323      Width            -> {WW, 2.085},
324      PropagatorLabel  -> "GP",
325      PropagatorType   -> D,
326      PropagatorArrow  -> None,
327      PDG              -> 251,
328      ParticleName     -> "G+",
329      AntiParticleName -> "G-",
330      FullName         -> "GP"
331    },
332
333
334  (* ========================GZp Added==================== *)
335
336  S[6] == {
337      ClassName        -> GZp,
338      SelfConjugate    -> False,
339      Goldstone        -> Zp,
340      Mass             -> {MZp,500},
341      QuantumNumbers   -> {Q -> 0},
342      Width            -> {WZp,10},
343      PropagatorLabel  -> "GZp",
344      PropagatorType   -> D,
345      PropagatorArrow  -> None,
346      PDG              -> 2222,
347      ParticleName     -> "GZp+",
348      AntiParticleName -> "GZp-",
349      FullName         -> "GZp"
350    },
```

Figure 3.16: Particle file describing fields hd, G0, GP and GZp (Screenshot 6)

Fields ss, Phi and Su are defined at the line numbers **359**, **372** and **383** respectively. 'hd' and 'ss' are the unphysical scalar fields and are defined using the equations 3.38. Fields Phi and Su are the scalar doublet and scalar singlet fields respectively. They are defined using the equations 2.28 and 2.29.

```
353   (* ========================ss Added==================== *)
354
355   S[7] == {
356       ClassName     -> ss,
357       Unphysical    -> True,
358       SelfConjugate -> True,
359       Definitions   -> { ss -> st*H+Sqrt[1-(st^2)] Hp }
360     },
361
362
363   (*================== Higgs doublet and Singlets============*)
364
365     S[11] == {
366       ClassName      -> Phi,
367       Unphysical     -> True,
368       Indices        -> {Index[SU2D]},
369       FlavorIndex    -> SU2D,
370       SelfConjugate  -> False,
371       QuantumNumbers -> {Y -> 1/2 , Yp -> 0},
372       Definitions    -> { Phi[1] -> -I GP, Phi[2] -> (vev+hd+I G0)/Sqrt[2]  }
373     },
374
375
376   (* =======================Su Added====================*)
377
378    S[12] == {
379       ClassName      -> Su,
380       Unphysical     -> True,
381       SelfConjugate  -> False,
382       QuantumNumbers -> {Y -> 0 , Yp -> 1/2},
383       Definitions    -> { Su -> (vevs+ss+I GZp)/Sqrt[2]}
384     }
385    };
386
```

Figure 3.17: Particle file describing fields ss, Phi and Su (Screenshot 7)

3.2 Lagrangian

The Lagrangian in the Wolfram Language (in mathematica) for Z' is shown in the figure **3.18**. The Lagrangian has four parts namely LYukawa, LFermions, LGauge and LScalar. LYukawa and LFermions are the same as that of the Standard Model. The part of the Lagrangian including ghost fields is not included in the model.

```
LYukawa := Block[{sp, ii, jj, cc, ff1, ff2, ff3, yuk, feynmangaugerules}, feynmangaugerules = If[Not[FeynmanGauge],
    {G0 | GP | GPbar → 0}, {}];
  yuk = ExpandIndices[-yd[ff2, ff3] × CKM[ff1, ff2] × QLbar[sp, ii, ff1, cc].dR[sp, ff3, cc] × Phi[ii] -
      yl[ff1, ff3] × LLbar[sp, ii, ff1].lR[sp, ff3] × Phi[ii] - yu[ff1, ff2] × QLbar[sp, ii, ff1, cc].uR[sp, ff2, cc] ×
       Phibar[jj] × Eps[ii, jj], FlavorExpand → SU2D];
yuk = yuk /. {CKM[a_, b_] Conjugate[CKM[a_, c_]] → IndexDelta[b, c], CKM[b_, a_] Conjugate[CKM[c_, a_]] → IndexDelta[b, c]};
  yuk + HC[yuk] /. feynmangaugerules
];

LGauge := Block[{mu, nu, ii, aa}, ExpandIndices[-1/4 FS[B, mu, nu] × FS[B, mu, nu] - 1/4 FS[X, mu, nu] × FS[X, mu, nu] -
    sc/2 FS[B, mu, nu] × FS[X, mu, nu] - 1/4 FS[Wi, mu, nu, ii] × FS[Wi, mu, nu, ii] -  1/4 FS[G, mu, nu, aa] ×
     FS[G, mu, nu, aa], FlavorExpand → SU2W]];


LFermions := Block[{mu}, ExpandIndices[I * (QLbar.Ga[mu].DC[QL, mu] + LLbar.Ga[mu].DC[LL, mu] + uRbar.Ga[mu].DC[uR, mu] +
       dRbar.Ga[mu].DC[dR, mu] + lRbar.Ga[mu].DC[lR, mu]), FlavorExpand → {SU2W, SU2D}] /. {CKM[a_, b_] ×
      Conjugate[CKM[a_, c_]] → IndexDelta[b, c], CKM[b_, a_] Conjugate[CKM[c_, a_]] → IndexDelta[b, c]}];


LScalar := Block[{ii, mu, feynmangaugerules}, feynmangaugerules = If[Not[FeynmanGauge], {G0 | GP | GPbar → 0}, {}];
  ExpandIndices[DC[Phibar[ii], mu] × DC[Phi[ii], mu] + muH^2 Phibar[ii] × Phi[ii] - lh Phibar[ii] ×
      Phi[ii] × Phibar[jj] × Phi[jj] + DC[Subar, mu] × DC[Su, mu] + muS^2 Subar.Su - ls (Subar.Su) * (Subar.Su) -
     lHS Phibar[ii] × Phi[ii] Subar.Su, FlavorExpand → {SU2D, SU2W}] /. feynmangaugerules];


LZPM := LGauge + LFermions + LScalar + LYukawa;
```

Figure 3.18: Lagrangian

3.3 Running The FeynRules

The first thing that must be done when using FeynRules is to load the package into a Mathematica session. This should be done before any of the model file is loaded in the kernel. In order to load FeynRules, the user must first specify the directory where it is stored and then load it. After the FeynRules package has been loaded, the model can be loaded using the command **LoadModel**[].

The Lagrangian is given during the mathematica session. Some points for Lagrangian are :-

1. FeynRules provides functions that can be used while constructing Lagrangians like $DC[\phi, \mu]$ for covariant derivative, $Ga[\mu]$ for Gamma(Dirac) matrix etc.

2. Once the Lagrangian is implemented, several checks are performed by means of the functions like CheckHermiticity[L], GetInteractionTerms[L], GetMassTerms[L] etc.

After the model description is created and the Lagrangian constructed, it can be loaded into FeynRules and the Feynman rules are obtained. The command used is **FeynmanRules**[**L**].

UFO Interface

After issuing this command, UFO files needed for MadGraph5 are created using command **WriteUFO**[**L**]. These files are basically python files(**.py**) files which contain everything about model like parameters, vertices, particles etc. With the UFO files, there is a **logfile** for our model where we can check if there are errors in our model like electric charges are defined correctly or not, lepton number conservation etc.

Chapter 4

MadGraph

MadGraph[6] is a software package which allows physicists to study the properties of particles and their interactions in a simulated environment that can be used to make predictions for experimental results. MadGraph uses Monte Carlo techniques to generate events, which means that it uses random numbers to simulate the behavior of particles in a collision. The simulated events can be compared to experimental data to test theoretical models and make predictions for future experiments. It can be used for finding scattering cross-section and generating events.

4.1 Installation

Here , I have used MadGraph5aMC@NLO. MadGraph5aMC@NLO is the new version of both MadGraph5 and aMC@NLO that unifies the LO and NLO lines of development of automated tools within the MadGraph family. The installation procedure is shown in the figure **4.1**

Website: https://launchpad.net/mg5amcnlo

Software Requirements

Python 3.9, gfortran compiler

Others

MadAnalysis5, lhapdf6 (These can be installed in MadGraph by **Install** command)

The various steps required for generating the events using MadGraph

```
root:~$ sudo apt install software-properties-common
root:~$ sudo apt-get install --reinstall ca-certificates
root:~$ sudo add-apt-repository ppa:deadsnakes/ppa
root:~$ sudo apt update
root:~$ sudo apt install python3.9
root:~$ sudo apt install gfortran
root:~$ python3.9 –version
root:~$ cd Desktop/Joginder/Project/Mad_Graph

tar -xvzf MG5_aMC_v3.4.1.tar.gz

root:~$ Desktop/Joginder/Project/Mad_Graph/MG5_aMC_v3_4_1/bin$ ./mg5_aMC
```

Figure 4.1: Installation

are shown in the figure **4.6**. These are explained as follows :-

1. **Importing model** The UFO Files folder created in the model folder must be copied to the directory of MadGraph (models folder of bin). Then, it can be imported by issuing command : **import model modelname**.

2. **Generating a Process** A process can be generated by **generate p1 p2 > p3 p4**. There must be a space between different symbols of particles used in MadGraph. We can add different processes together. We want a process where somehow Z' boson is involved. There are different ways by which Z' particle can be produced and decayed. It can be produced by pp collision or electron-positron collision. Similarly, it can decay to dilepton pair or to W^+ and W^+ particles. But we have chosen the process in equation **76**. I have used the experimental data of Large Hadron Collider with the ATLAS detector[2]. LHC is a hadron collider and so have used pp collision to produce Z'. The decay width of Z' to dilepton state is maximum or is the dominant channel in Z' decay.

$$pp > zp > e + e- \tag{4.1}$$

When we upload the UFO files of a particular model, the particle definitions and symbols are defined. Here p means proton, zp means Z' boson and e+ e- means positron and electron respectively. In terms of MadGraph, two new particles are included in Z' model apart from the particles in the Standard model (namely **zp** and **hp**).

3. **Feynman Diagrams** .

   The diagrams can be displayed by issuing the command : **display diagrams**. The Feynman diagrams for our selected process are as shown below :-

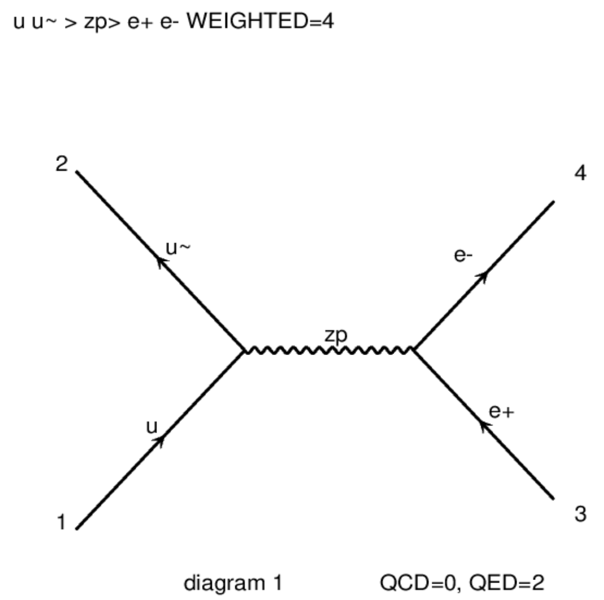

Figure 4.2: Feynman Diagram (Screenshot 1)

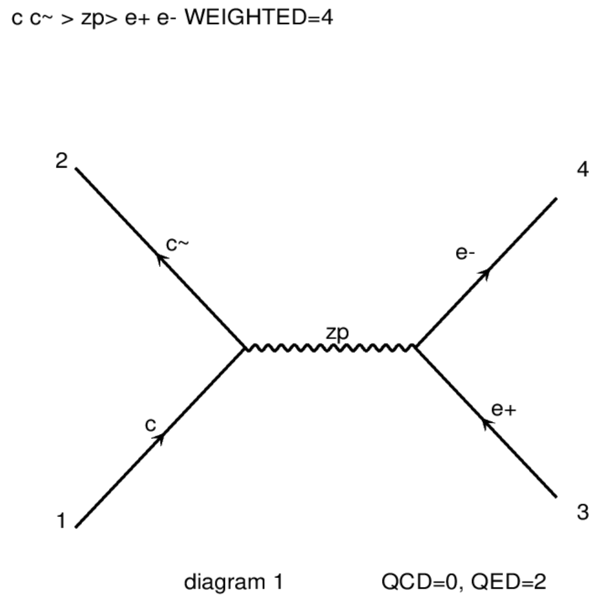

Figure 4.3: Feynman Diagram (Screenshot 2)

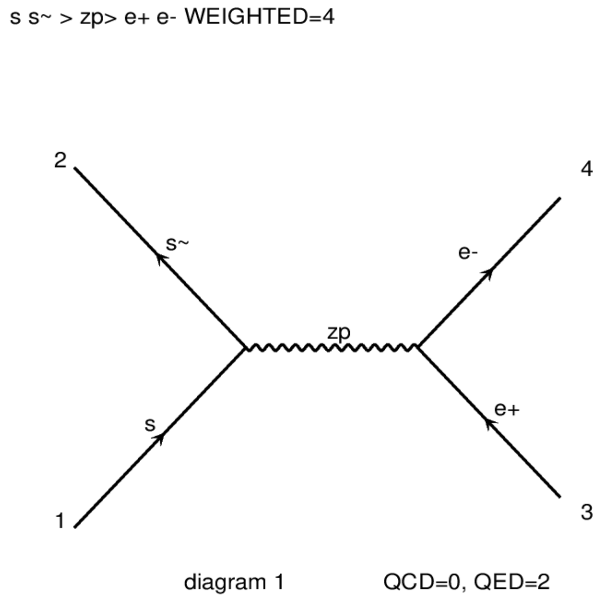

Figure 4.4: Feynman Diagram (Screenshot 3)

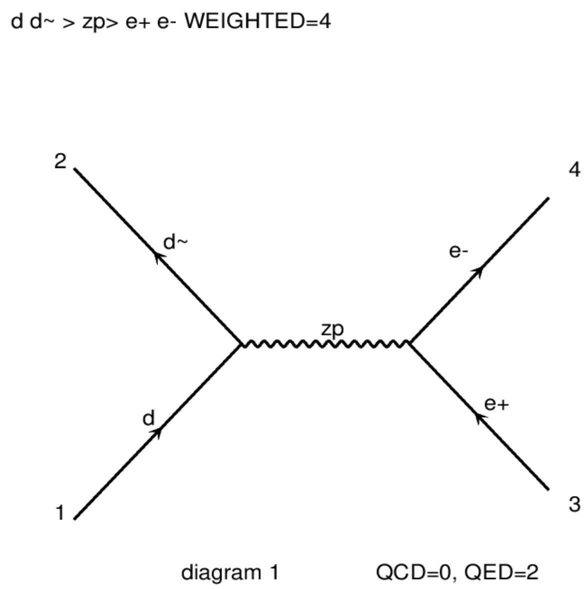

Figure 4.5: Feynman Diagram (Screenshot 4)

4. **Launching the Process** For event generation, our whole event data must be stored in a folder. This is done by **output foldername**(here output zp1). Then we have to launch process by Launch command (**launch foldername**). There are various sub folders in this folder like Cards, Events, bin etc.

```
MG5_aMC>import model Z_Prime_Model_UFO
MG5_aMC>generate p p > zp > e+ e-
MG5_aMC>display diagrams
MG5_aMC>output zp1
MG5_aMC>launch zp1
MG5_aMC>open index.html
```

Figure 4.6: Event Generation

After issuing the command **open index.html**, the results page will be displayed on the browser screen.

A run for our selected process is given by :-

Results in the Z_Prime_Model_UFO1 for p p > zp > e+ e-

Available Results

Run	Collider	Banner	Cross section (pb)	Events	Data	Output	Action
run_01	p p 6500.0 x 6500.0 GeV	tag_1	1.487 ± 0.00093	100000	parton madevent	LHE MA5_report_analysis1	remove run launch detector s

Main Page

Figure 4.7: Sample Run

4.2 Cards Files

Cards files are the input files to the MadGraph. They include all the information regarding event generation and the chosen process. There are many types of card files. The commonly needed ones are run card, parameter card, Mad-analysis parton card, plot card etc. These files can be changed individually or during the run time. For our selected process, the following card files are changed :-

1. **Run Card** In the run card, the number of events and the energy of colliding beams are changed. There are other things also but they are already set by default like rapidity , minimum invariant mass of dilepton pair etc. An example is as following :-

   100000 = nevents ! Number of unweighted events requested

   6500.0 = ebeam1 ! beam 1 total energy in GeV

   6500.0 = ebeam2 ! beam 2 total energy in GeV

2. **Parameter Card** Parameter card contains information of the various parameters of the model. We can change the value of external parameters during the actual run and don't need to upload the model again and again.

3. **Mad-Analysis Parton Card** This card includes the information

regarding plot range and luminosity. An example is as following :-

set main.lumi = 36

plot M(e-[1] e+[1]) 40 0 500 [logY]

4. **Plot Card** This card includes the information of plots and their definitions in the MadGraph.

4.3 Plots

For every run of the process, we get a cross-section value in pico-barns. Each run consists of a number of events which information is given in the run card. The total scattering cross-section depends on various factors like centre-of-mass energy of colliding particles, mass of a particular particle etc. Here, we are changing the mass of Z' particle (MZp name in FeynRules code). Furthur, decay width of Z' particle is also changed as the mass is changed. A single run is done for a particular value of $\sin(\alpha_z)$ and **rs** (ratio of singlet to doublet vacuum expectation values). As MadGraph takes input as python files, we can make a script file written in python to have runs queued one after other. Since mass of Z' particle is changed from 0.5 TeV to 5 TeV, part of script file code for 500 GeV to 700 GeV is as shown below :-

Instead of making a scipt file, we can also give range of the particular parameter in the parameter card file. We have changed mass of Z' particle (or MZp parameter in the code with PDG code of 32) from 500 GeV to 5000 GeV in our runs. It is given by :-

zp1.py

```
launch zp1
   set MZp 500
   set rs 49
   set nevents 100000
   set saz 0.0001
   set decay 32 auto
   set main.lumi = 36
launch zp1
   set MZp 600
   set rs 49
   set nevents 100000
   set saz 0.0001
   set decay 32 auto
   set main.lumi = 36
launch zp1
   set MZp 700
   set rs 49
   set nevents 100000
   set saz 0.0001
   set decay 32 auto
   set main.lumi = 36
```

Figure 4.8: Script File

We will be plotting mainly two types of diagram here. The first one is cross-section times branching ratio ($\sigma\mathbf{B}$ in pico barn) vs mass of Z' boson (**MZp** in TeV) diagram. This type of graph is compared with the experimental data of LHC(Large Hadron Collider) ALICE detector[2] ($\sqrt{s} = 13TeV, 36fb^{-1}$). When compared, there will be a point where both the graph will intersect. This will give a lower limit on the mass of Z' particle. When sine of Z-Z' mixing angle ($\sin(\alpha_z)$) is changed, we get a different lower limit on Z' particle mass (MZp). So, the second type of graph is plotted between MZp vs $\sin(\alpha_z)$.

```
######################################################################
## PARAM_CARD AUTOMATICALY GENERATED BY MG5                       ####
######################################################################
###################################
## INFORMATION FOR CKMBLOCK
###################################
BLOCK CKMBLOCK #
      1 2.277360e-01 # cabi
###################################
## INFORMATION FOR MASS
###################################
BLOCK MASS #
      1 5.040000e-03 # md
      2 2.550000e-03 # mu
      3 1.010000e-01 # ms
      4 1.270000e+00 # mc
      5 4.700000e+00 # mb
      6 1.720000e+02 # mt
      11 5.110000e-04 # me
      13 1.056600e-01 # mmu
      15 1.777000e+00 # mta
      23 9.118760e+01 # mz
      25 1.250000e+02 # mh
      32 scan: [500,600,700,800,900,1000,1100,1200,1300,1400,1500,1600,1700,1800,1900,2000,2100,2200,2300,
      2400,2500,2600,2700,2800,2900,3000,3100,3200,3300,3400,3500,3600,3700,3800,3900,4000,
      4100,4200,4300,4400,4500,4600,4700,4800,4900,5000] # 3.500000e+03 # mzp
      1111 4.550000e+02 # mhp
      12 0.000000e+00 # ve : 0.0
      14 0.000000e+00 # vm : 0.0
      16 0.000000e+00 # vt : 0.0
      21 0.000000e+00 # g : 0.0
      22 0.000000e+00 # a : 0.0
      24 7.982436e+01 # w+ : cw*mz
```

Figure 4.9: Parameter Card

Chapter 5

Results

The data set for all the runs for $\sin(\alpha_z)$=0.0001 and the corresponding graph is shown in the figures 5.2 and 5.1 respectively. The experimental plot[2] in red colour is shown in figure 5.3. This graph tells us that the cross-section values have a maximum (upper limit) for a particular $M_{Z'}$. Only the values of cross-section which are lower than this maximum value are possible. So, when the model and experimental graphs are compared, a lower limit on $M_{Z'}$ is found near the intersection point. The first type of graph between σ**B** and **MZp** is shown for $\sin(\alpha_z)$=0.0001 in the figure 5.5.

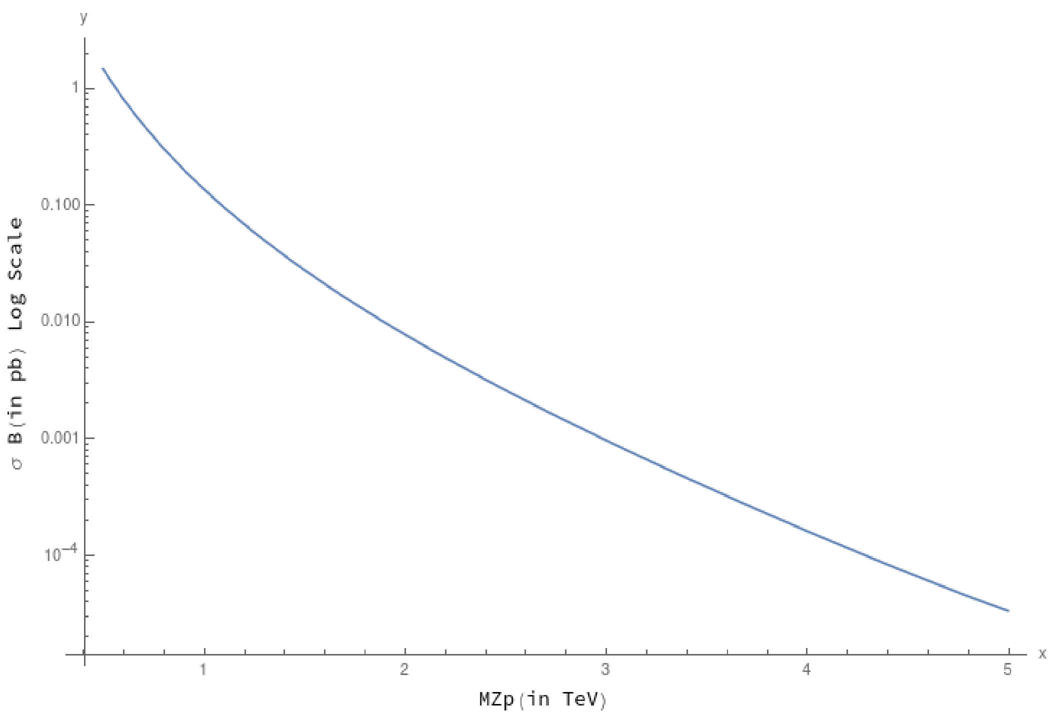

Figure 5.1: Model Data Plot

1	MZp(TeV) GIVEN	Cross-Section(pb) (rs=40)
2	0.5	1.446
3	0.6	0.8027
4	0.7	0.4801
5	0.8	0.3032
6	0.9	0.1995
7	1	0.1357
8	1.1	0.09496
9	1.2	0.06785
10	1.3	0.04951
11	1.4	0.03662
12	1.5	0.02751
13	1.6	0.0209
14	1.7	0.01607
15	1.8	0.01246
16	1.9	0.009751
17	2	0.007694
18	2.1	0.006105
19	2.2	0.004879
20	2.3	0.003917
21	2.4	0.003162
22	2.5	0.002566
23	2.6	0.002087
24	2.7	0.001708
25	2.8	0.001402
26	2.9	0.001154
27	3	0.0009522
28	3.1	0.0007878
29	3.2	0.0006535
30	3.3	0.000544
31	3.4	0.0004533
32	3.5	0.0003797
33	3.6	0.0003174
34	3.7	0.0002664
35	3.8	0.0002237
36	3.9	0.0001883
37	4	0.0001587
38	4.1	0.0001344
39	4.2	0.0001137
40	4.3	9.65E-05
41	4.4	8.20E-05
42	4.5	6.99E-05
43	4.6	5.97E-05
44	4.7	5.12E-05
45	4.8	4.39E-05
46	4.9	3.79E-05
47	5	3.28E-05

Figure 5.2: Model Data Set

.

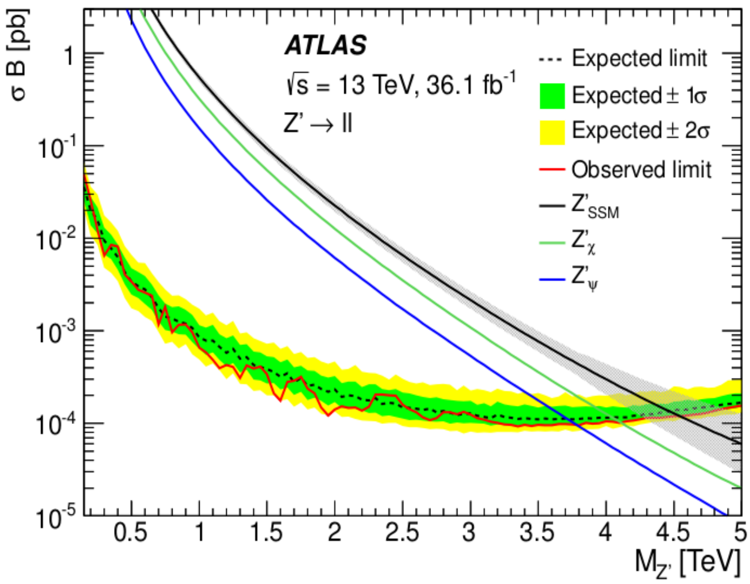

Figure 5.3: Experimental Data Plot 1

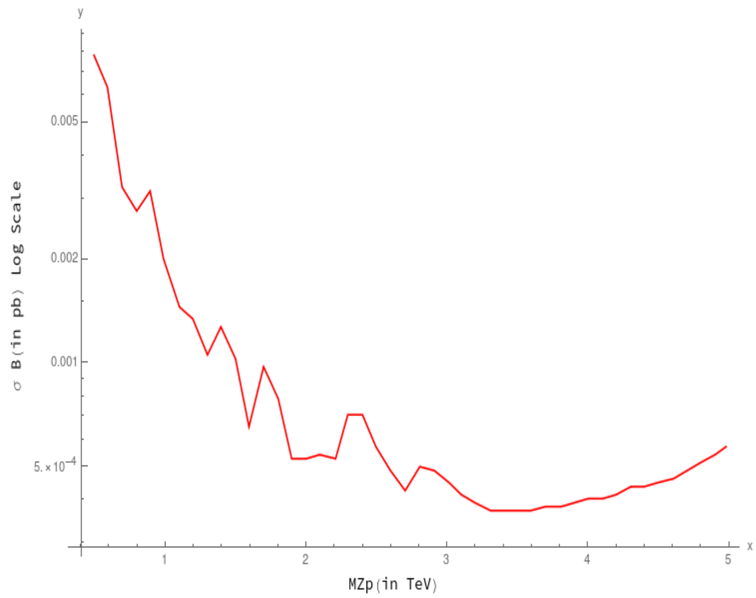

Figure 5.4: Experimental Data Plot 2

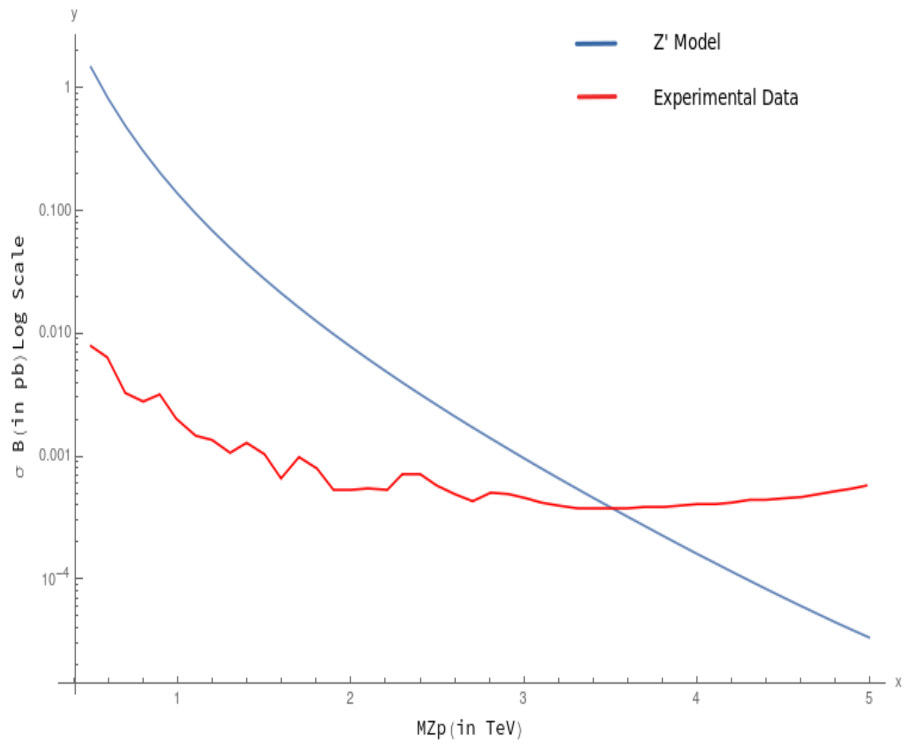

Figure 5.5: Combined Plot

The intersection point for the above graph (figure 5.5) is at MZp=3.50332 TeV. So, according to this, Z' particle cannot have a mass value lower than 3.50332 TeV. Mass limits on Z' are found for different values of $\sin(\alpha_z)$ parameter. In all these runs, rs and $\tan\theta_x$ values are fixed to 40 and 1 respectively. A graph can be plotted between MZp and $\sin(\alpha_z)$. The data set points and the graph are shown in the figures 5.6 and 5.7 respectively.

Sin(alphaz)*10^4	Mzp(Found)
-4	4.77503
-3	4.3091
-2	3.91991
-1	3.5088
0	2.93324
1	3.50332
2	3.91443
3	4.3091
4	4.786

Figure 5.6: Model Data Set 2

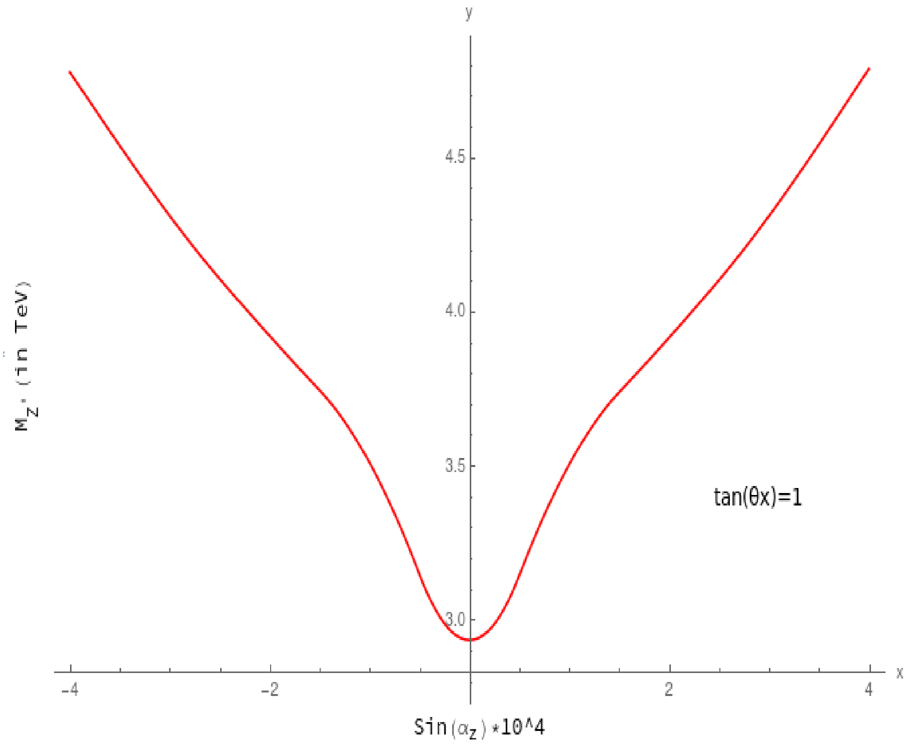

Figure 5.7: Final Plot

5.1 Future

Experimental data has been updated for greater center-of-mass energy and luminosity. We can find the new lower Z' particle mass limits for new experimental data of hadron collider and electron-positron collider.

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