Gauge Higgs Unification Phenomenology in Warped Dimensions

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Warped Extra Dimensions

- Warped Extra Dimensions (RS1):
  Naturally solves hierarchy problem (kL~30)

- Branes at $x_5 = 0$ (UV) and $x_5 = L$ (IR):

- UV IR $SO(5) \times U(1)$

$a(x_5)=e^{-kx_5}$

$\longrightarrow$ $SU(2)_L \times U(1)_Y$

$SO(4) \times U(1)_Y$

$T^i \longrightarrow T^{La}, T^{Ra}, T^{\hat{a}}$

Gauge Fields

- Gauge fields live in bulk.
- Break SO(5) via following boundary conditions (BC):

$$\partial_5 A_\mu^{a_L} = \partial_5 A_\mu^{Y} = A_\mu^{\prime 3_R} = A_\mu^{1,2_R} = A_\mu^{\hat{a}} = A_5^{a_L, Y, 1, 2_R, \prime 3_R} = \partial_5 A_5^{\hat{a}} \quad = \quad 0\,, \qquad x_5 = 0$$

$$\partial_5 A_\mu^{a_L} = \partial_5 A_\mu^{Y} = \partial_5 A_\mu^{\prime 3_R} = \partial_5 A_\mu^{1,2_R} = A_\mu^{\hat{a}} = A_5^{a_L, Y, 1, 2_R, \prime 3_R} = \partial_5 A_5^{\hat{a}} \quad = \quad 0\,, \qquad x_5 = L\,.$$

- Leads to A_5 acquiring a vacuum expectation value (vev) at one loop.

→ **HIGGS** $H \propto (h^{\hat{1}} + i h^{\hat{2}}, h^{\hat{4}} - i h^{\hat{3}})^t.$

Gauge Fields

- To get proper EWS breaking $< h^4 >= h.$
- Equations of motion in presence of vev for *h* mix Neumann and Dirichlet modes.
- Can use following gauge transformation, which relates the solutions with *h* =0:

$$f^\alpha(x_5, h)T^\alpha = \Omega^{-1}(x_5, h) f^\alpha(x_5, 0) T^\alpha \Omega(x_5, h),$$

$$\Omega(x_5, h) = \exp\left[-iC_h h T^4 \int_0^{x_5} dy\, a^{-2}(y)\right].$$

Gauge Fields

- **Basis functions (warped generalization of sin and cosine functions) satisfy initial conditions:**

$$C(0,z) = 1,\; C'(0,z) = 0,\; S(0,z) = 0 \quad S'(0,z) = z.$$

- **KK profiles satisfying UV BC can be written as:**

$$f_n^{a_L}(x_5,0) = C_{n,a_L} C(x_5,m_n) \qquad f_n^{\hat{a}}(x_5,0) = C_{n,\hat{a}} S(x_5,m_n)$$

$$f_n^{Y}(x_5,0) = C_{n,Y} C(x_5,m_n) \qquad f_n^{(1,2_R,3_{\rm R})}(x_5,0) = C_{n,(1,2_R,3_{\rm R})} S(x_5,m_n)$$

Gauge Fields

- Imposing BC on IR brane and demanding a non-trivial solution (determinant=0), we arrive at the quantization equation for the gauge masses:

$$1 + F_{W,Z}(m_n^2)\sin^2\left(\frac{\lambda_G h}{f_h}\right) = 0\,, \qquad F_W(z^2) = \frac{z}{2a_L^2 C'(L,z)S(L,z)}$$

$$s_\phi^2 \simeq \tan^2\theta_W = (0.23/0.77) \simeq 0.2987, \qquad F_Z(z^2) = \frac{(1+s_\phi^2)z}{2a_L^2 C'(L,z)S(L,z)}\,.$$

Fermion Fields

- Realistic model requires 3 vector-like fermion multiplets living in the bulk:

$$\xi^i_{1L} \sim Q^i_{1L} = \begin{pmatrix} \chi^{u_i}_{1L}(-,+)_{5/3} & q^{u_i}_L(+,+)_{2/3} \\ \chi^{d_i}_{1L}(-,+)_{2/3} & q^{d_i}_L(+,+)_{-1/3} \end{pmatrix} \oplus u'^i_L(-,+)_{2/3} ,$$

$$\xi^i_{2R} \sim Q^i_{2R} = \begin{pmatrix} \chi^{u_i}_{2R}(-,+)_{5/3} & q'^{u_i}_R(-,+)_{2/3} \\ \chi^{d_i}_{2R}(-,+)_{2/3} & q'^{d_i}_R(-,+)_{-1/3} \end{pmatrix} \oplus u^i_R(+,+)_{2/3} ,$$

$$\xi^i_{3R} \sim$$

$$T^i_{1R} = \begin{pmatrix} \psi'^i_R(-,+)_{5/3} \\ U'^i_R(-,+)_{2/3} \\ D'^i_R(-,+)_{-1/3} \end{pmatrix} \oplus T^i_{2R} = \begin{pmatrix} \psi''^i_R(-,+)_{5/3} \\ U''^i_R(-,+)_{2/3} \\ D^i_R(+,+)_{-1/3} \end{pmatrix} \oplus Q^i_{3R} = \begin{pmatrix} \chi^{u_i}_{3R}(-,+)_{5/3} & q''^{u_i}_R(-,+)_{2/3} \\ \chi^{d_i}_{3R}(-,+)_{2/3} & q''^{d_i}_R(-,+)_{-1/3} \end{pmatrix} ,$$

Fermion Fields

- Also allowed boundary mass terms:

$$\mathcal{L}_m = \delta(x_5 - L)\left[\bar{u}'_L M_{B1} u_R + \bar{Q}_{1L} M_{B2} Q_{3R} + \bar{Q}_{1L} M_{B3} Q_{2R} + \text{h.c.}\right]$$

- Similar procedure as for the gauge bosons:

$$1 + F_b(m_n^2)\sin^2\left(\frac{\lambda_r h}{f_h}\right) = 0\,,$$

$$1 + F_{t1}(m_n^2)\sin^2\left(\frac{\lambda_r h}{f_h}\right) + F_{t2}(m_n^2)\sin^4\left(\frac{\lambda_r h}{f_h}\right) = 0$$

Exotic Fermions

- This procedure also gives rise to exotic fermions.
- Mass spectrum given by:

$$S'^{3}_{-M_2} = 0$$

$$S'^{5}_{-M_3} = 0$$

$$\left[M_{B2}^2 S_{M_1} S_{-M_3} + S'_{M_1} S'_{-M_3}\right]^2 = 0$$

Effective Potential

- At tree level due to its gauge origin, the Higgs potential is 0. The one-loop Coleman-Weinberg Potential is given by:

$$V(h) = \sum_r \pm \frac{N_r}{(4\pi)^2} \int_0^\infty dp p^3 \log(\rho(-p^2))$$

- Spectral functions ($f_h \sim k\, e^{-kL}$, $\lambda^2 = 1/2$):

$$\rho_W(z^2) = 1 + F_W(z^2)\sin^2\left(\frac{\lambda h}{f_h}\right) \qquad \rho_Z(z^2) = 1 + F_Z(z^2)\sin^2\left(\frac{\lambda h}{f_h}\right),$$

$$\rho_b(z^2) = 1 + F_b(z^2)\sin^2\left(\frac{\lambda h}{f_h}\right) \qquad \rho_t(z^2) = 1 + F_{t1}(z^2)\sin^2\left(\frac{\lambda h}{f_h}\right) + F_{t2}(z^2)\sin^4\left(\frac{\lambda h}{f_h}\right)$$

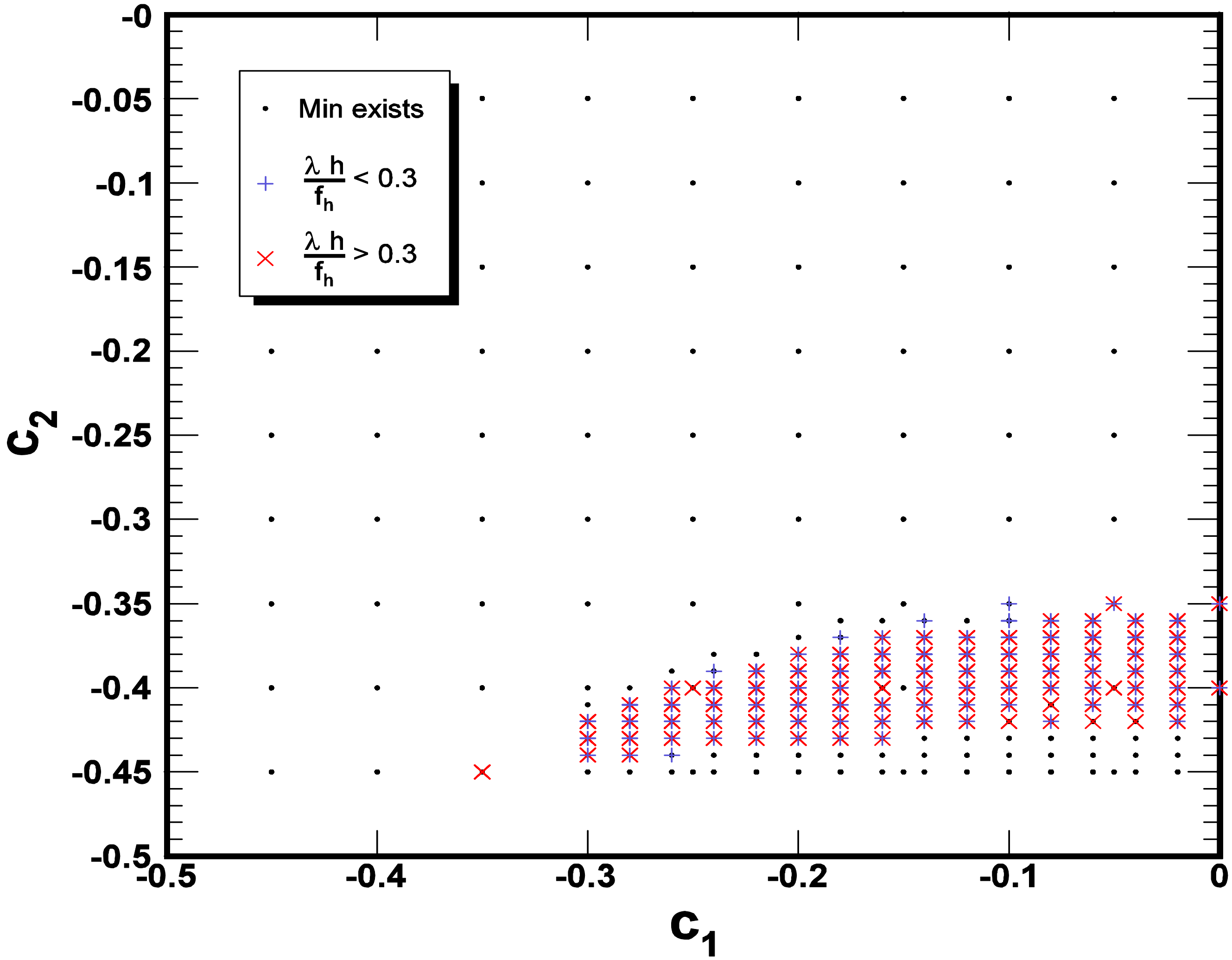
Effective Potential

- Numerical investigation showed V(h) to be a smooth function of all parameters.
- Minimum symmetric with c_1 and skew symmetric with c_2 and c_3. Independent for B_1, $B_2 \sim > 5$, $|c_1|$, $|c_2|$, $|c_3| > 1$.
- h = 0 min ignored since no symmetry breaking.
- $\lambda h/f_h = \pi/2$ min ignored since linear coupling goes to 0.

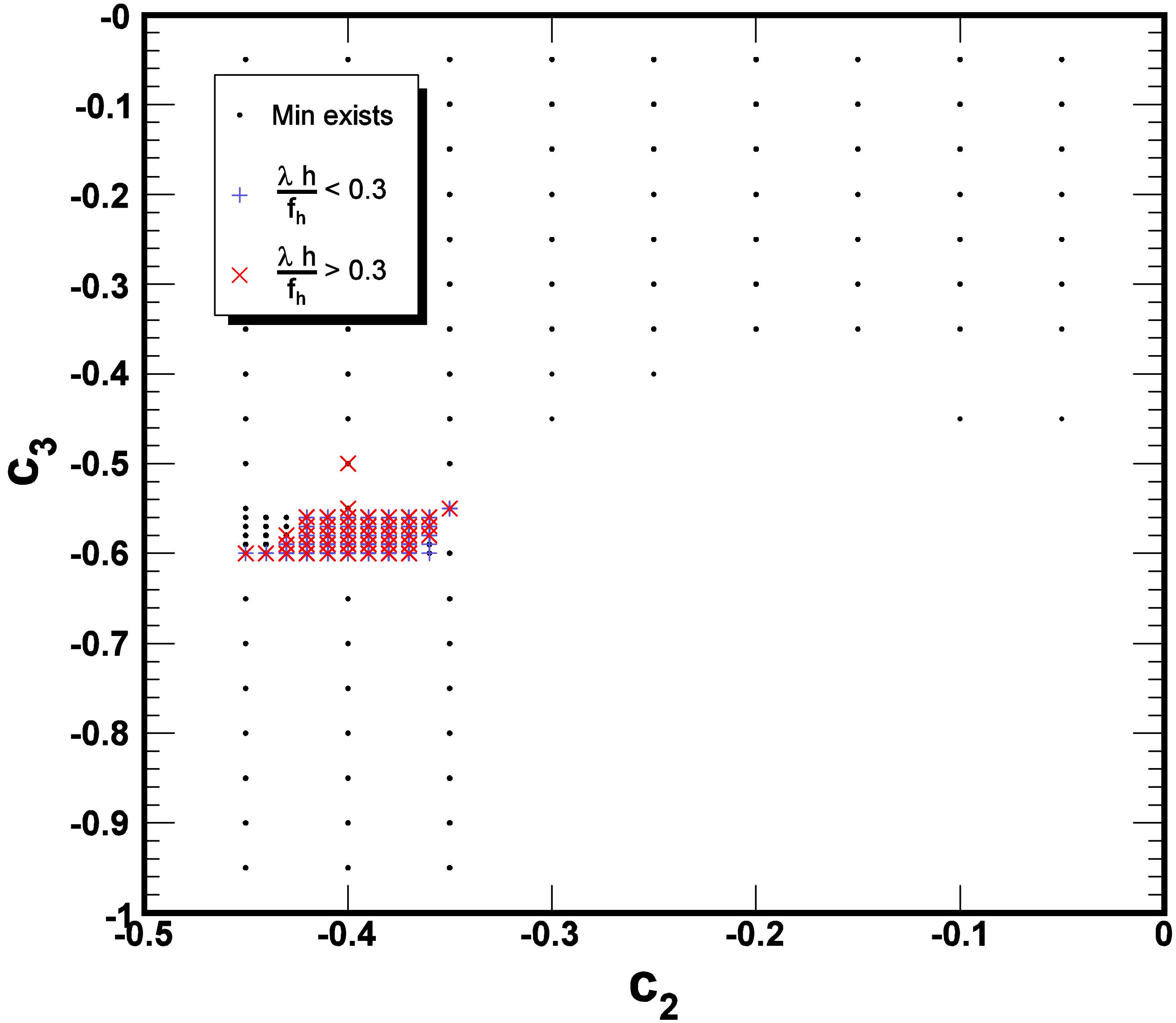
Effective Potential

- $f_h \sim k\, e^{-kL} \longrightarrow$ As $\lambda h/f_h \uparrow$, KK scale $\downarrow$.
- Simultaneously, linear coupling of the Higgs to the gauge bosons is suppressed compared to the SM.
- Correct W, Z, Top and Bottom masses marked by blue and red.
- We will denote values of $\lambda h/f_h$ less than or greater then 0.3, as linear (blue) and non-linear (red) approximations.

Masses in the phenomenological range only when c_1, c_2 in the range allowed by EWPT.

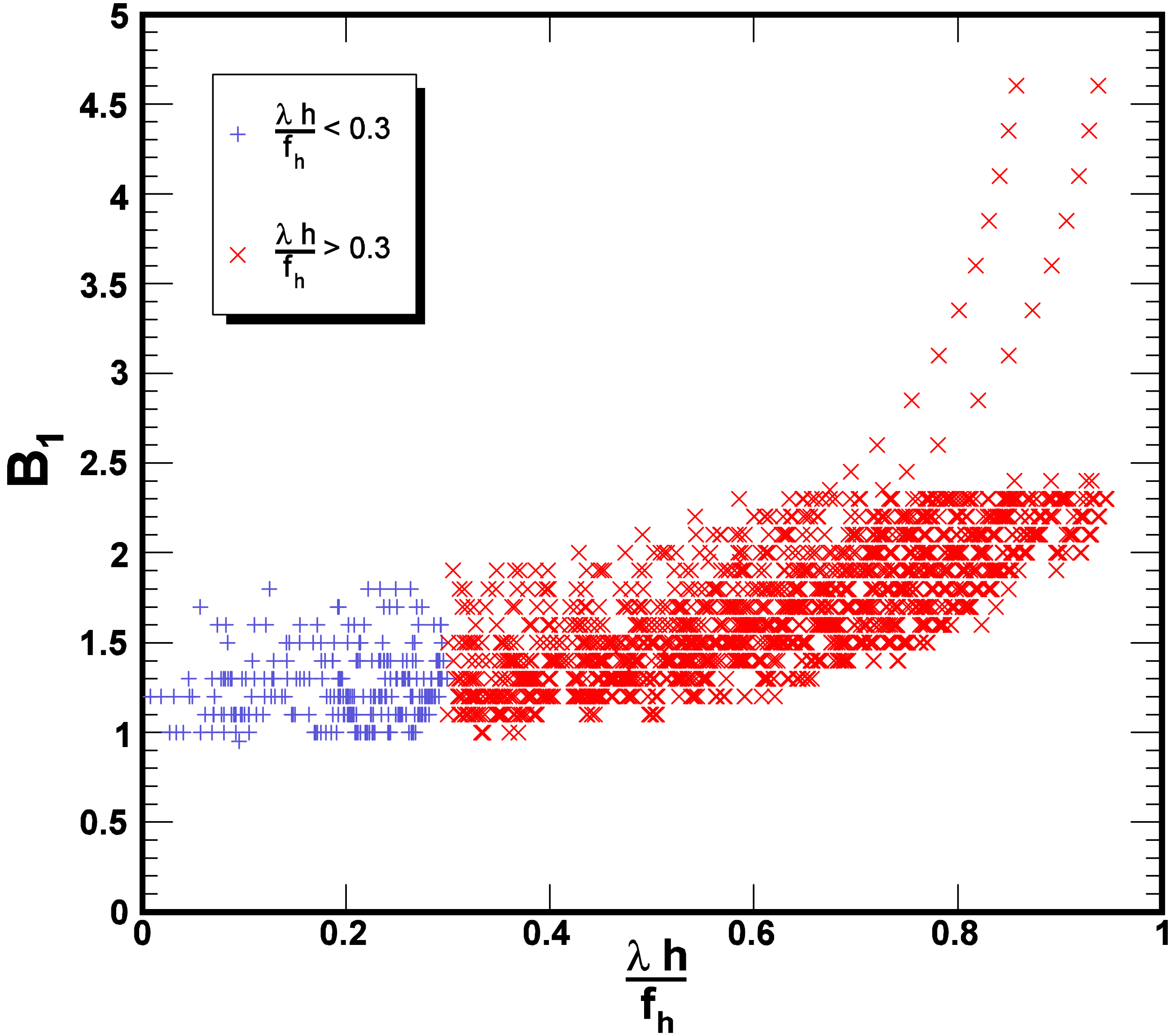


c_2 VS. c_3



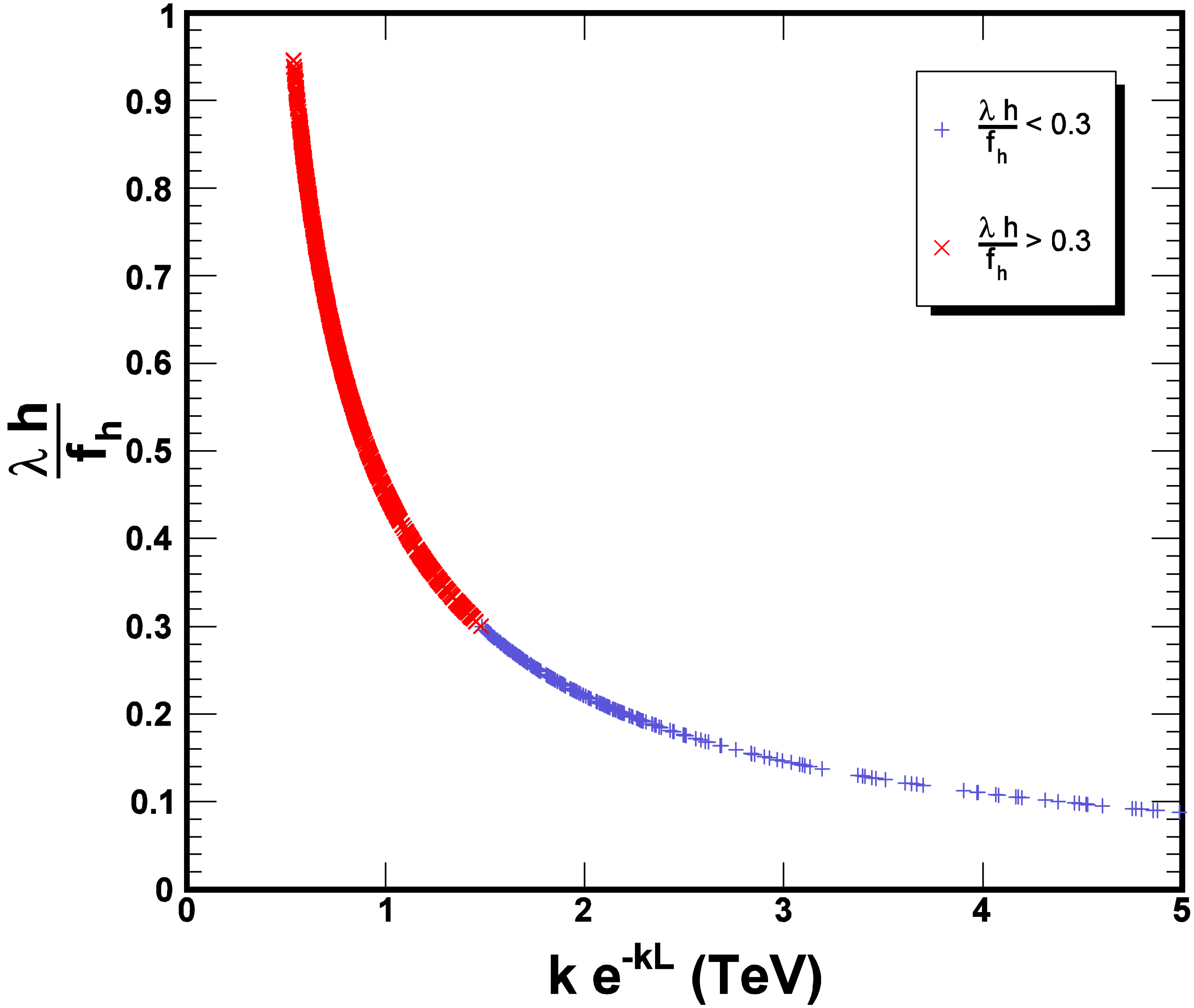
Min exists
λ h / f_h < 0.3
λ h / f_h > 0.3
-0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1
c3
-0.5
-0.4
-0.3
-0.2
-0.1
0
c2

B_1 vs. min.



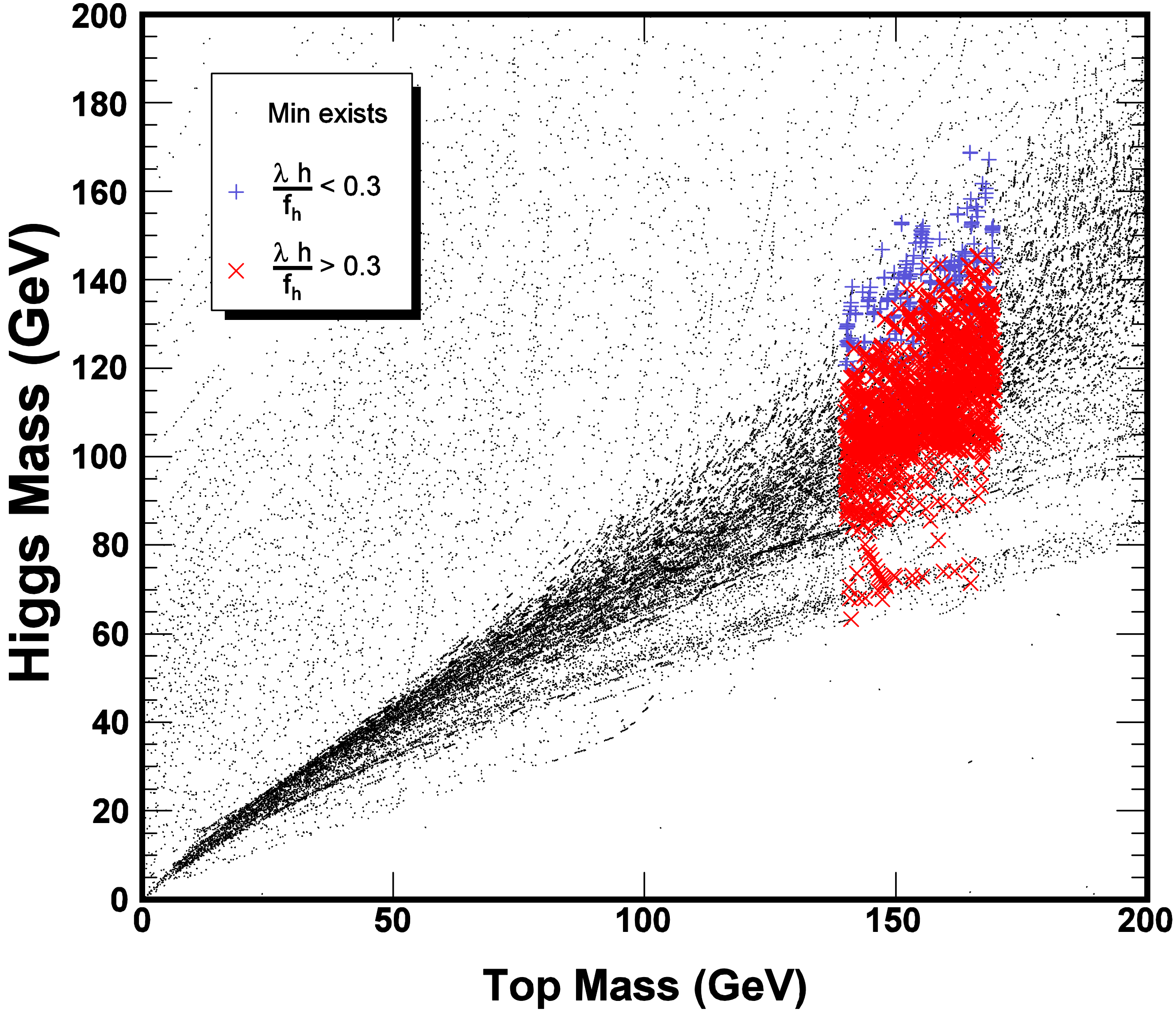
$\frac{\lambda h}{f_h} < 0.3$
$\frac{\lambda h}{f_h} > 0.3$
B_1
$\frac{\lambda h}{f_h}$
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0
0.2
0.4
0.6
0.8
1

k e^{-kL} vs. min.

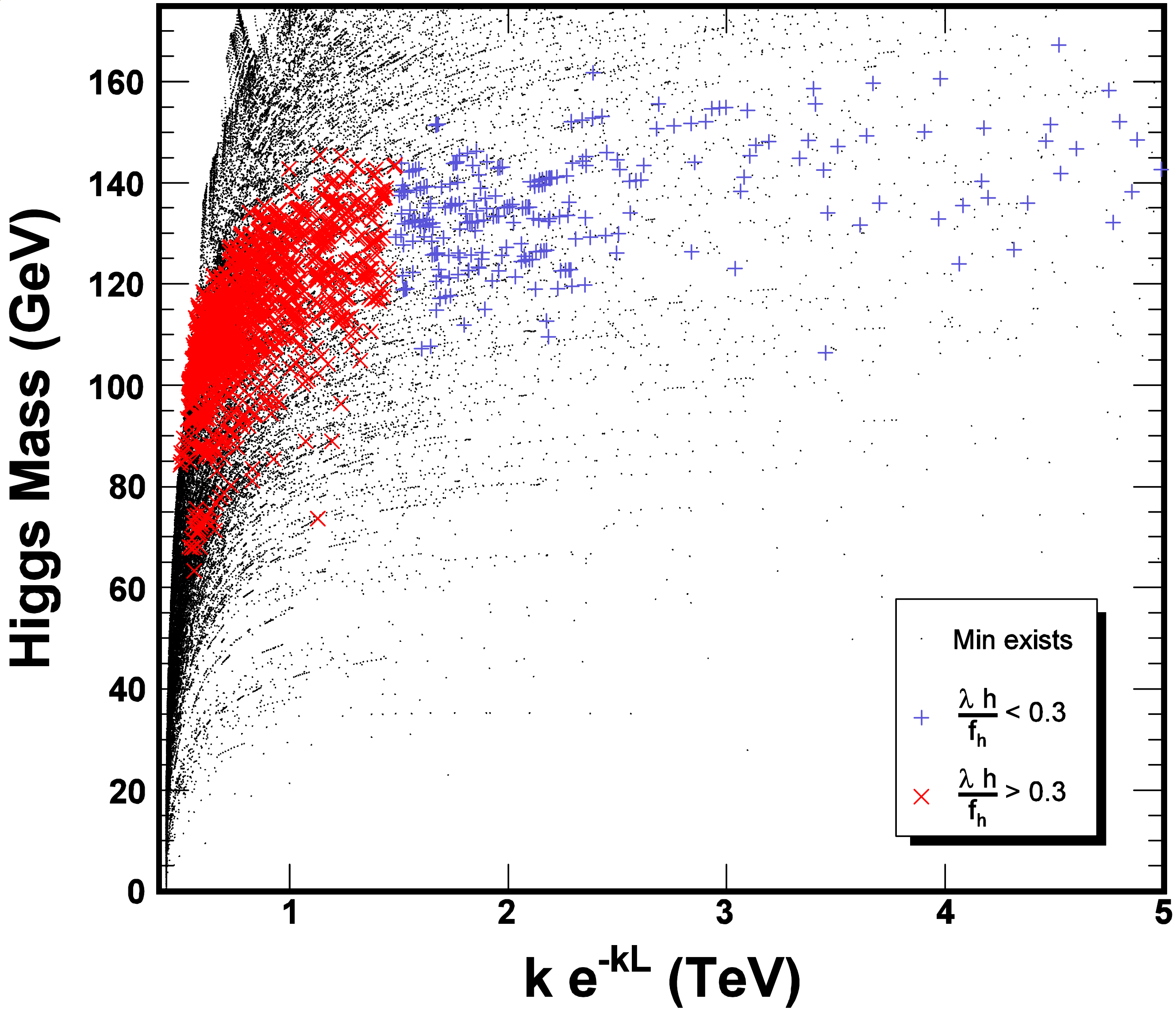


$\frac{\lambda h}{f_h} < 0.3$
$\frac{\lambda h}{f_h} > 0.3$
$\frac{\lambda h}{f_h}$
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
1
2
3
4
5
k e^{-kL} (TeV)

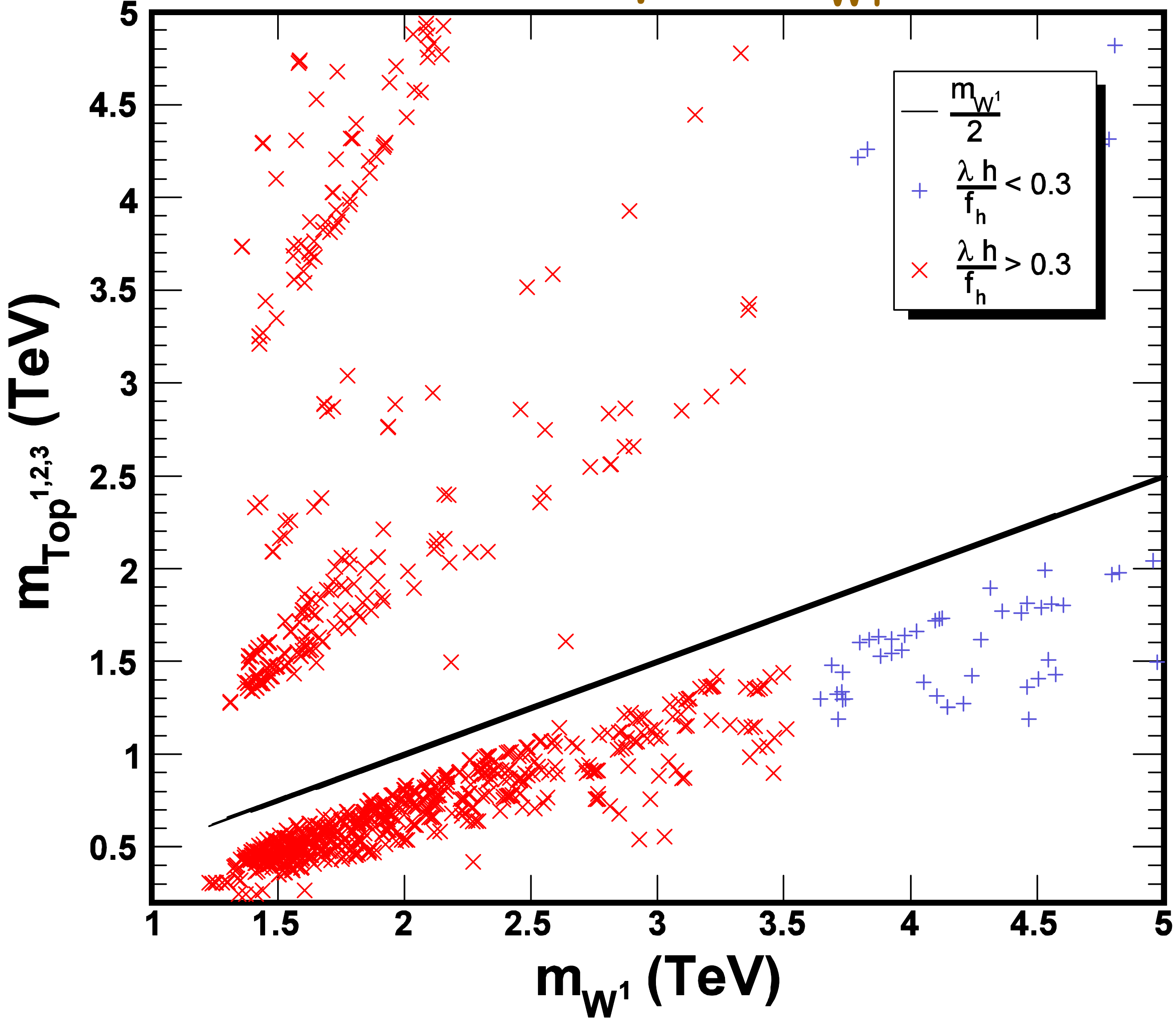
Top mass vs. Higgs Mass



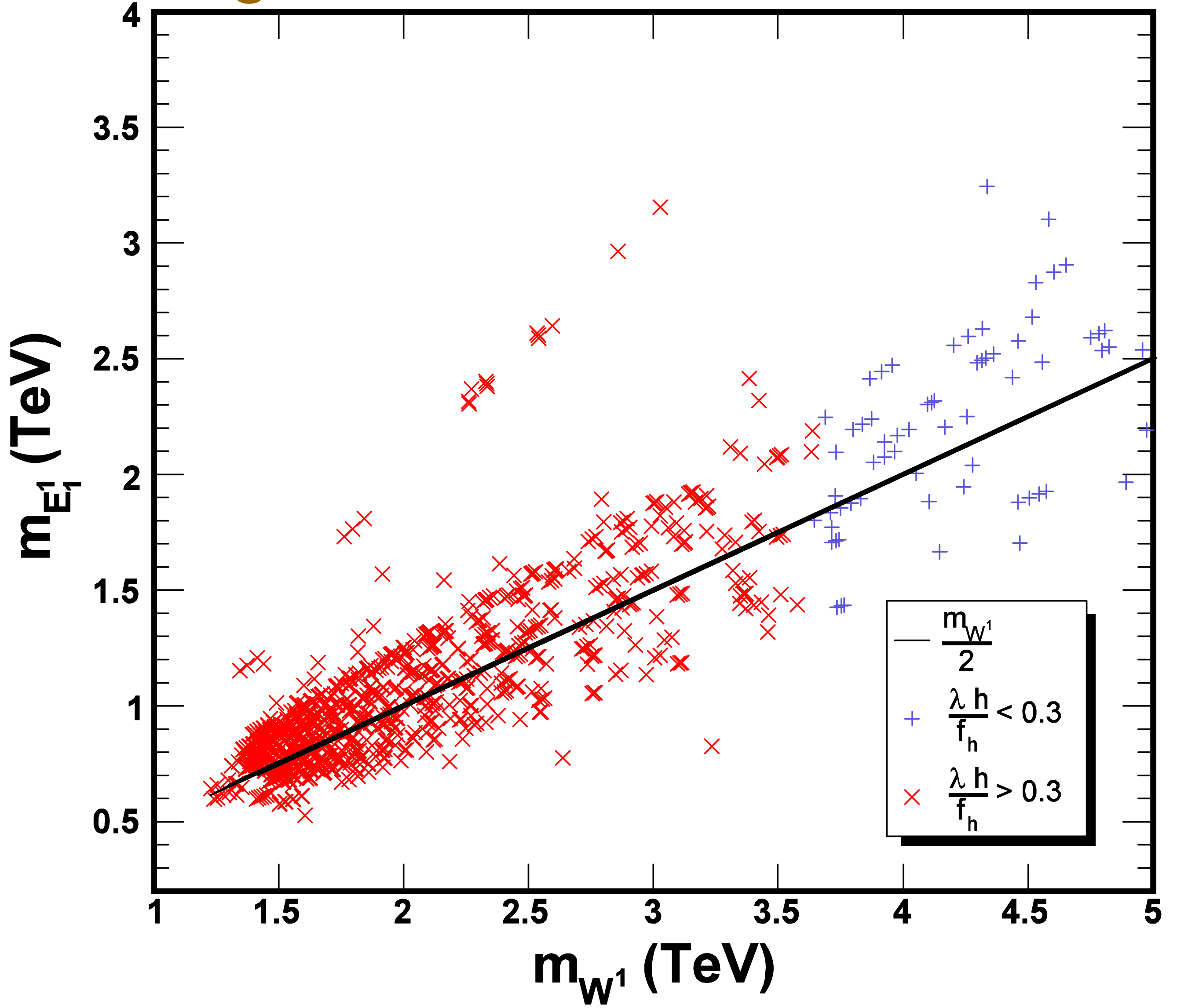
Higgs mass vs. k e^{-kL}



First few KK mode of the Top vs. m_{W1}



Mass of the lightest exotic fermion vs. mass of W^1



Conclusion

- Higgs constructed from gauge fields.
- Higgs potential generated at one loop with SM consistent matter and gauge content.
- Found conditions for breaking symmetry.
- Light Higgs [110-160 GeV].
- KK modes with masses ~ TeV.
- Exotic fermions with masses ~ TeV
- Interesting possibilities for the LHC.