Gauge Higgs Unification Phenomenology in Warped Dimensions

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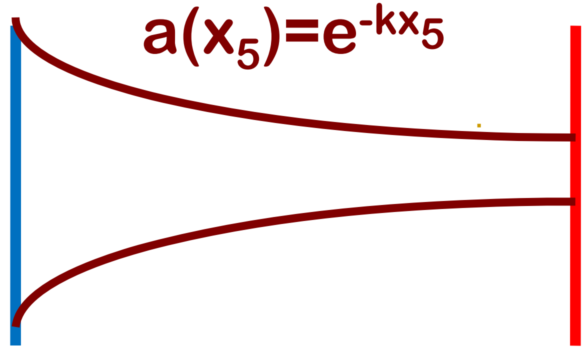
Warped Extra Dimensions

- Warped Extra Dimensions (RS1):
  Naturally solves hierarchy problem ($kL \sim 30$)

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

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



$x_5=0$ $x_5=L$

→ $SU(2)_L \times U(1)_Y$

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

T^i → T^{La}, T^{Ra}, $T^{\hat{a}}$

Gauge Fields

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

$$\partial_5 A_\mu^{a_{\rm L},Y} = A_\mu^{a_{\rm R},\hat{a}} = A_5^{a_{\rm L},Y} = 0\,, \qquad x_5 = 0$$

$$\partial_5 A_\mu^{a_{\rm L},a_{\rm R},Y} = A_\mu^{\hat{a}} = A_5^{a_{\rm L},a_{\rm R},Y} = 0\,, \qquad x_5 = L\,.$$

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

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

Gauge Fields

- To get proper EWSB: $< h^{\hat{4}} >= h$.
- 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 to the ones 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 sine and cosine functions) satisfy initial conditions:**

$$C(0,z)=1,\ C'(0,z)=0,\ S(0,z)=0 \text{ and } S'(0,z)=z.$$

- **Since $\Omega = 1$ at $x_5 = 0$, KK profiles satisfying UV BC can be written as:**

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

$$f_n^{Y}(x_5,0) = C_{n,Y} C(x_5, m_n), \qquad f_n^{a_R}(x_5,0) = C_{n,a_R} S(x_5, m_n)$$

Gauge Fields

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

$$1 + F_{W,Z}(m_n^2)\sin^2\left(\frac{\lambda_G h}{f_h}\right) = 0\,,$$

$$F_W(z^2) = \frac{z}{2a_L^2 C'(L,z)S(L,z)}$$

$$s_\phi^2 \simeq \tan^2\theta_W \simeq (0.23/0.77) \simeq 0.2987,$$

$$F_Z(z^2) = \frac{(1+s_\phi^2)z}{2a_L^2 C'(L,z)S(L,z)}\,.$$

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:**

$$\mathcal{L}_m = 2\delta(x_5 - L)\left[\bar{u}'_L M_{B_1} u_R + \bar{Q}_{1L} M_{B_2} Q_{3R} + \bar{Q}_{1L} M_{B_3} Q_{2R} + \text{h.c.}\right]$$

- **Similar procedure as for the gauge bosons:**

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

$$1 + F_{t_1}(m_n^2)\sin^2\left(\frac{\lambda h}{f_h}\right) + F_{t_2}(m_n^2)\sin^4\left(\frac{\lambda h}{f_h}\right) = 0$$

Effective Potential

- At tree level due to its gauge origin, the Higgs potential is 0. The 1-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 ($f_h \sim k\, e^{-kL}$, $\lambda^2 = 1/2$):

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

$$\rho_b(z^2) = 1 + F_b(z^2) \sin^2\left(\frac{\lambda h}{f_h}\right) \qquad \rho_t(z^2) = 1 + F_{t_1}(z^2) \sin^2\left(\frac{\lambda h}{f_h}\right) + F_{t_2}(z^2) \sin^4\left(\frac{\lambda h}{f_h}\right)$$

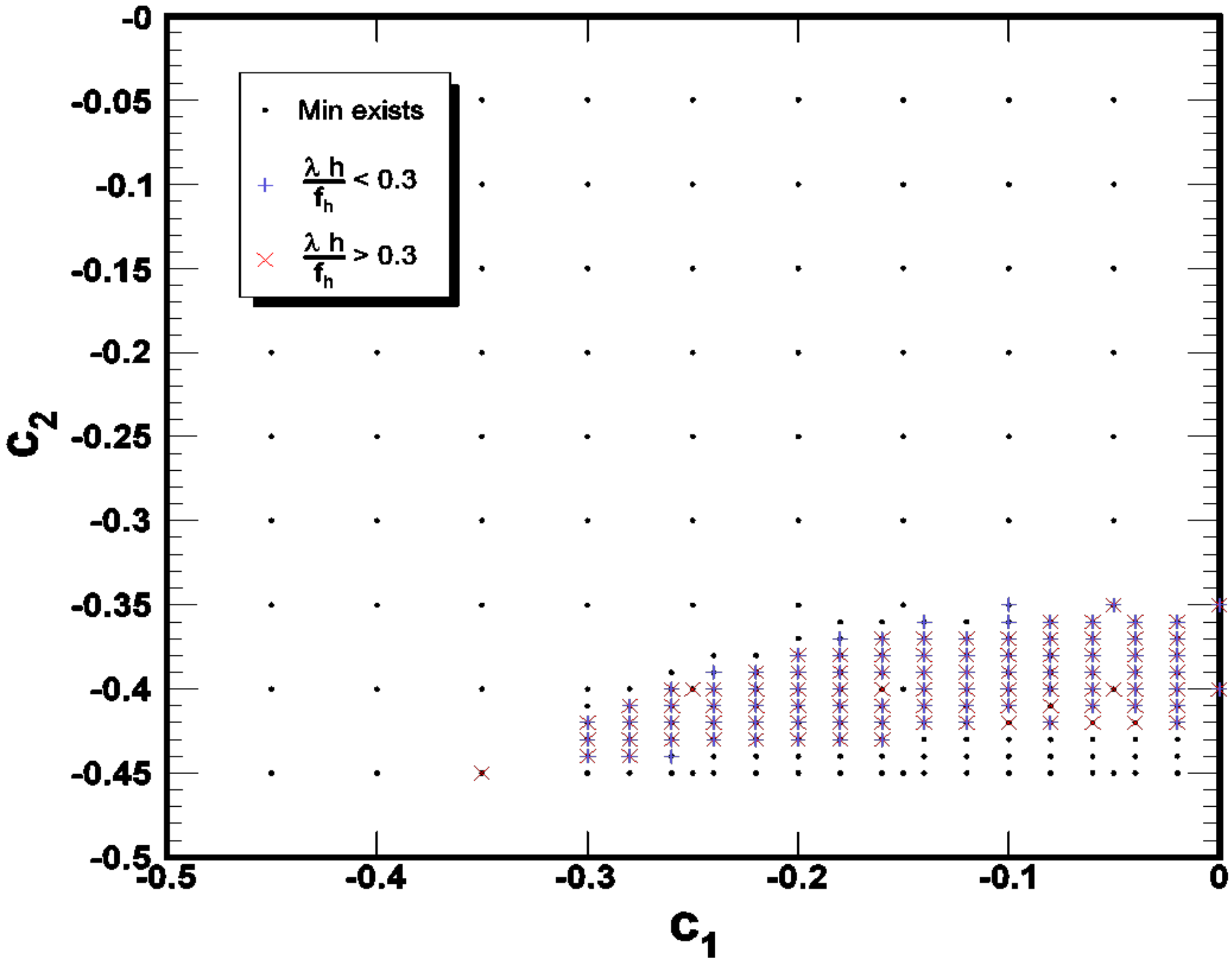
Effective Potential

- 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~ >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 the Higgs coupling to gauge bosons goes to 0.

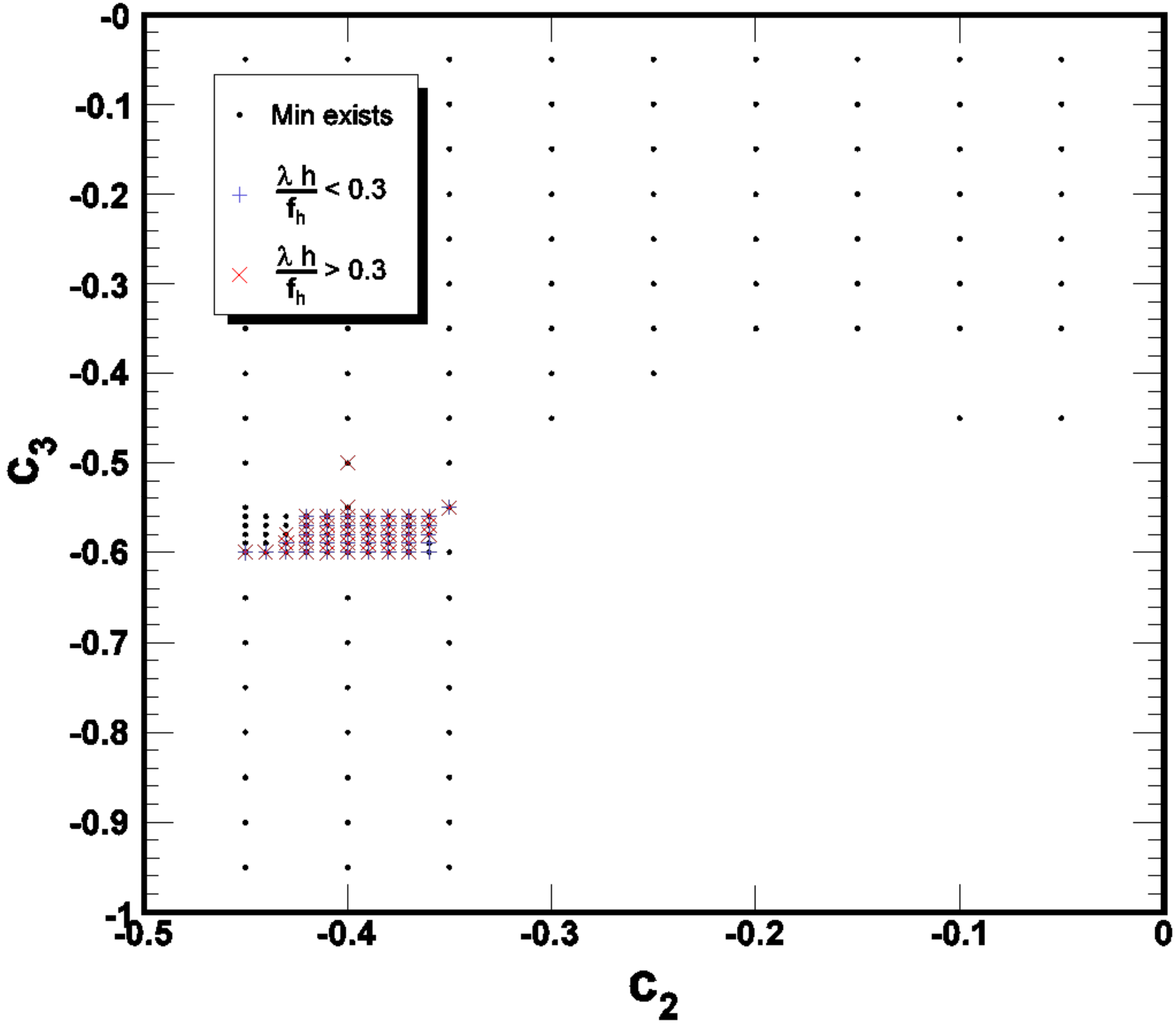
Effective Potential

- $f_h \sim k\, e^{-kL}$ → As $\lambda h/f_h$ ↑, KK scale ↓.
- Simultaneously, linear couplings of the Higgs to the gauge bosons are 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.

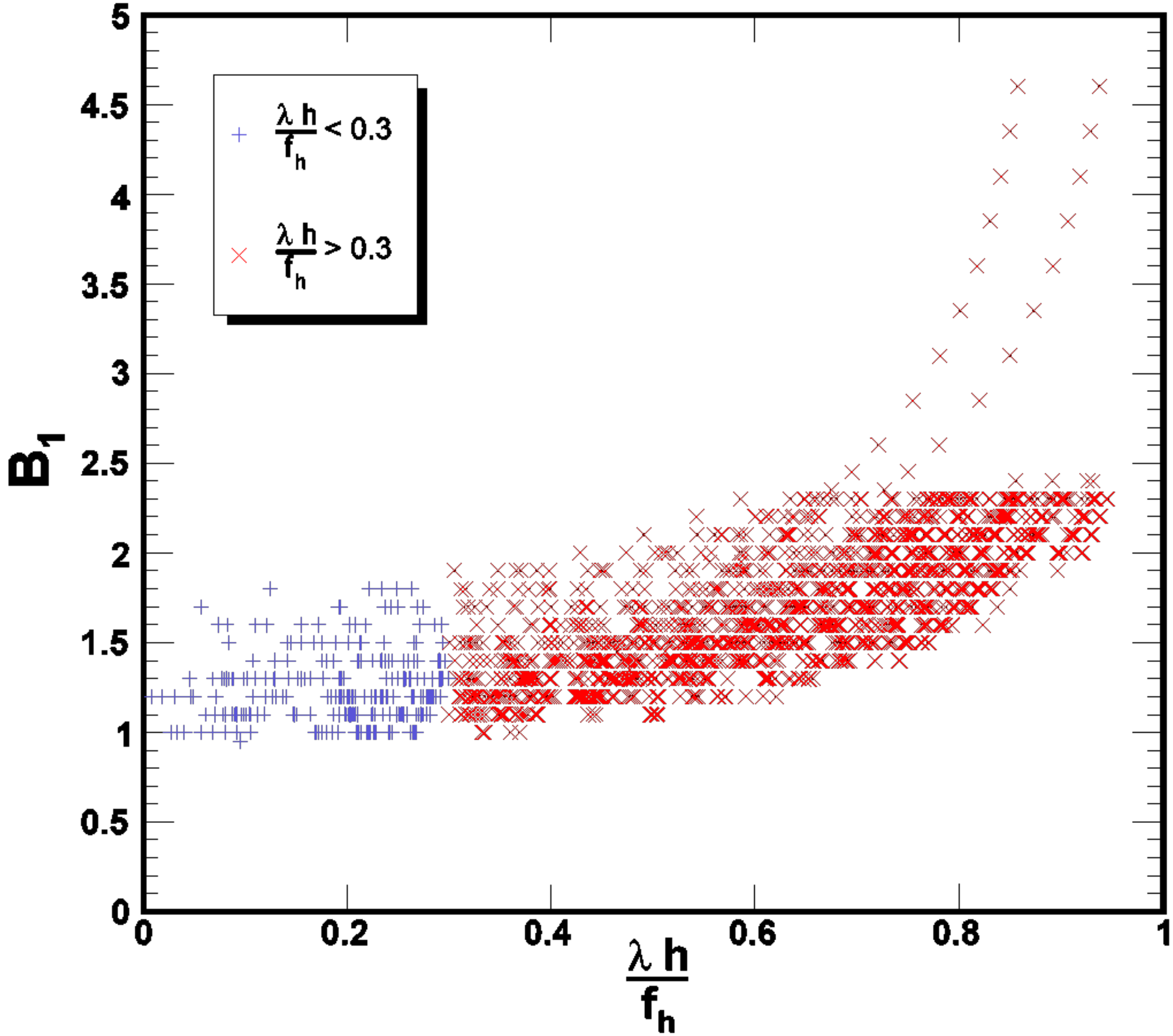


c_2 VS. c_3

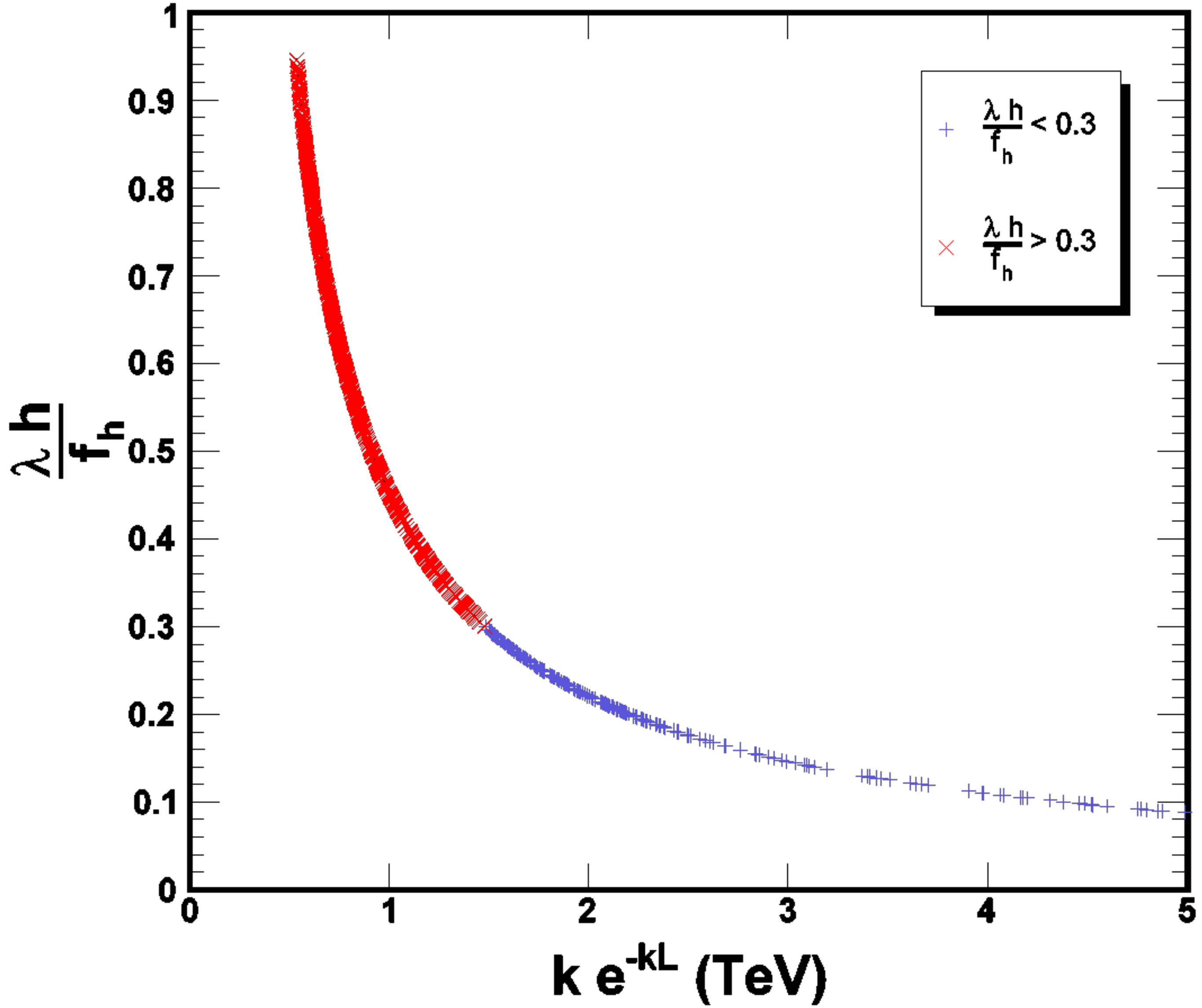


Min exists
λ h / f_h < 0.3
λ h / f_h > 0.3
-0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1
-0.5
-0.4
-0.3
-0.2
-0.1
0
c_3
c_2

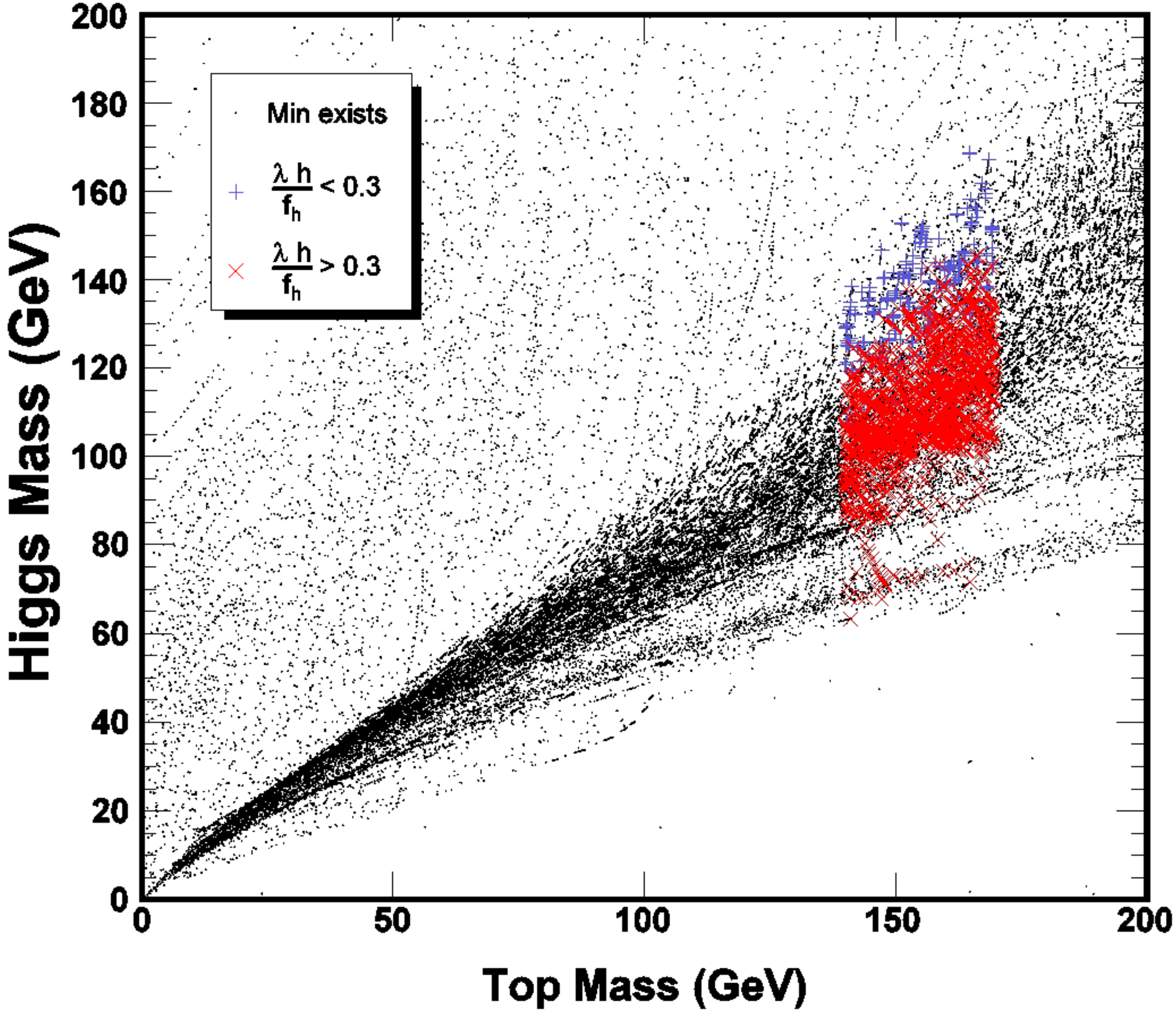
B_1 vs. min.



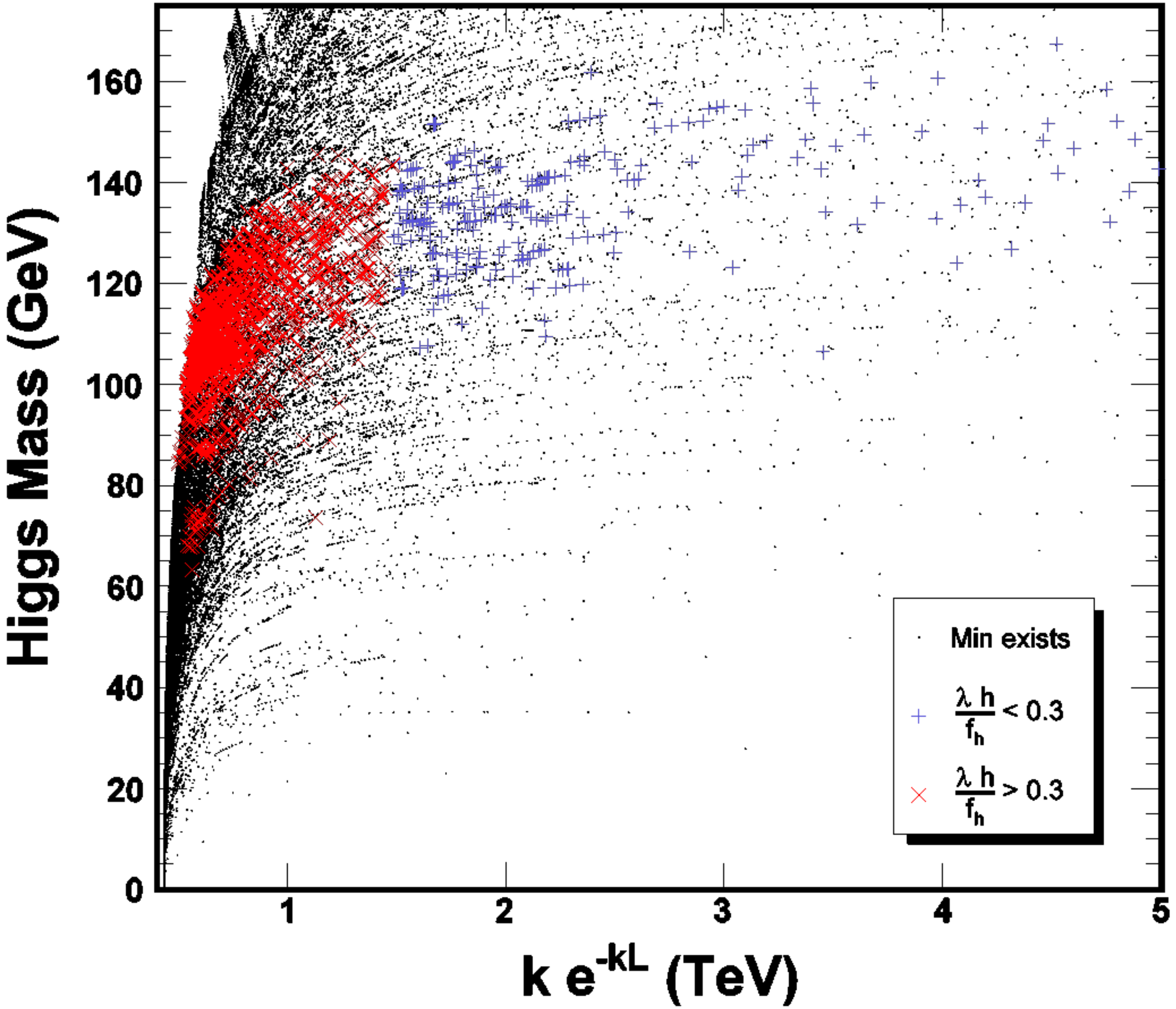
k e^{-kL} vs. min.



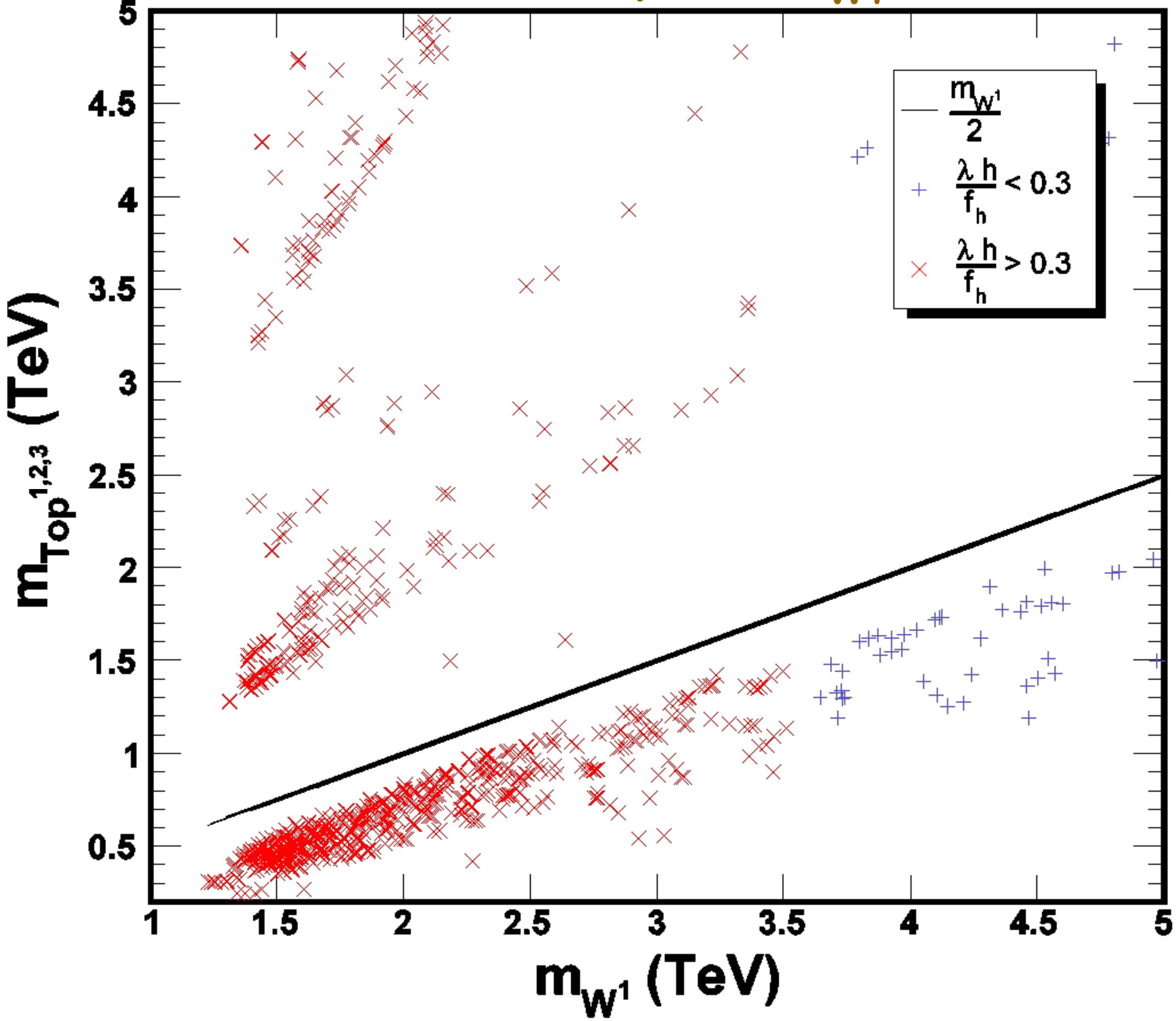
Top mass vs. Higgs Mass



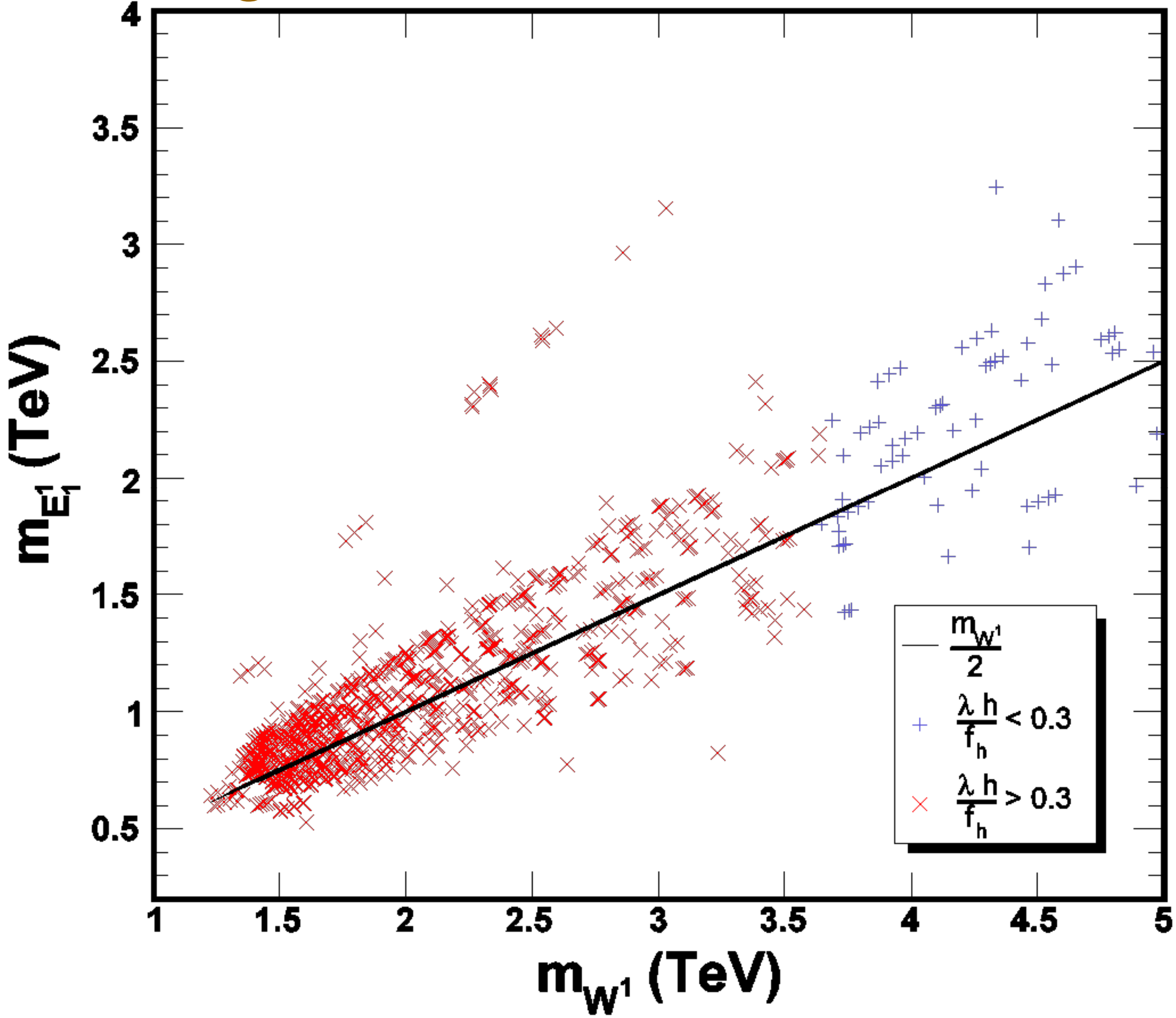
Higgs mass vs. k e^{-kL}



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.