Gauge-Higgs Unification Phenomenology in Warped Extra Dimensions

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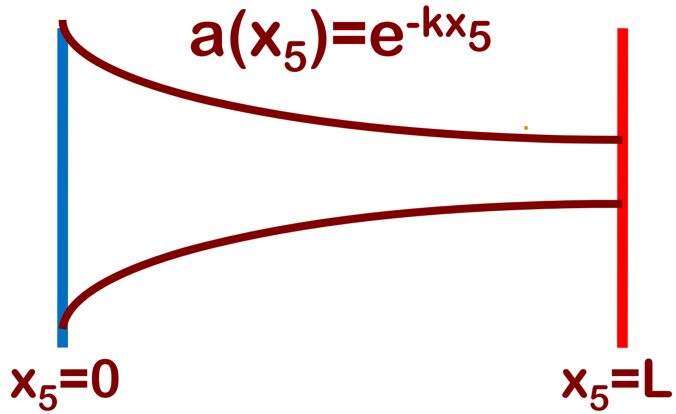
Warped Extra Dimensions

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

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

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



$\rightarrow$ $SU(2)_L \times U(1)_Y$
$SO(4) \times U(1)_Y$

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

Gauge Fields

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

$$\partial_5 A_\mu^{a_L, Y} = A_\mu^{a_R, \hat{a}} = A_5^{a_L, Y} = 0\,, \qquad x_5 = 0$$
$$\partial_5 A_\mu^{a_L, a_R, Y} = A_\mu^{\hat{a}} = A_5^{a_L, a_R, Y} = 0\,, \qquad x_5 = L\,.$$

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

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

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

- **Bessel 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:**

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

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

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:**

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

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

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

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

Fermion Fields

- **Realistic model requires 3 vector-like fermion multiplets living in the bulk. Localization parameterized by c_i:**

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

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

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

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

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

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

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

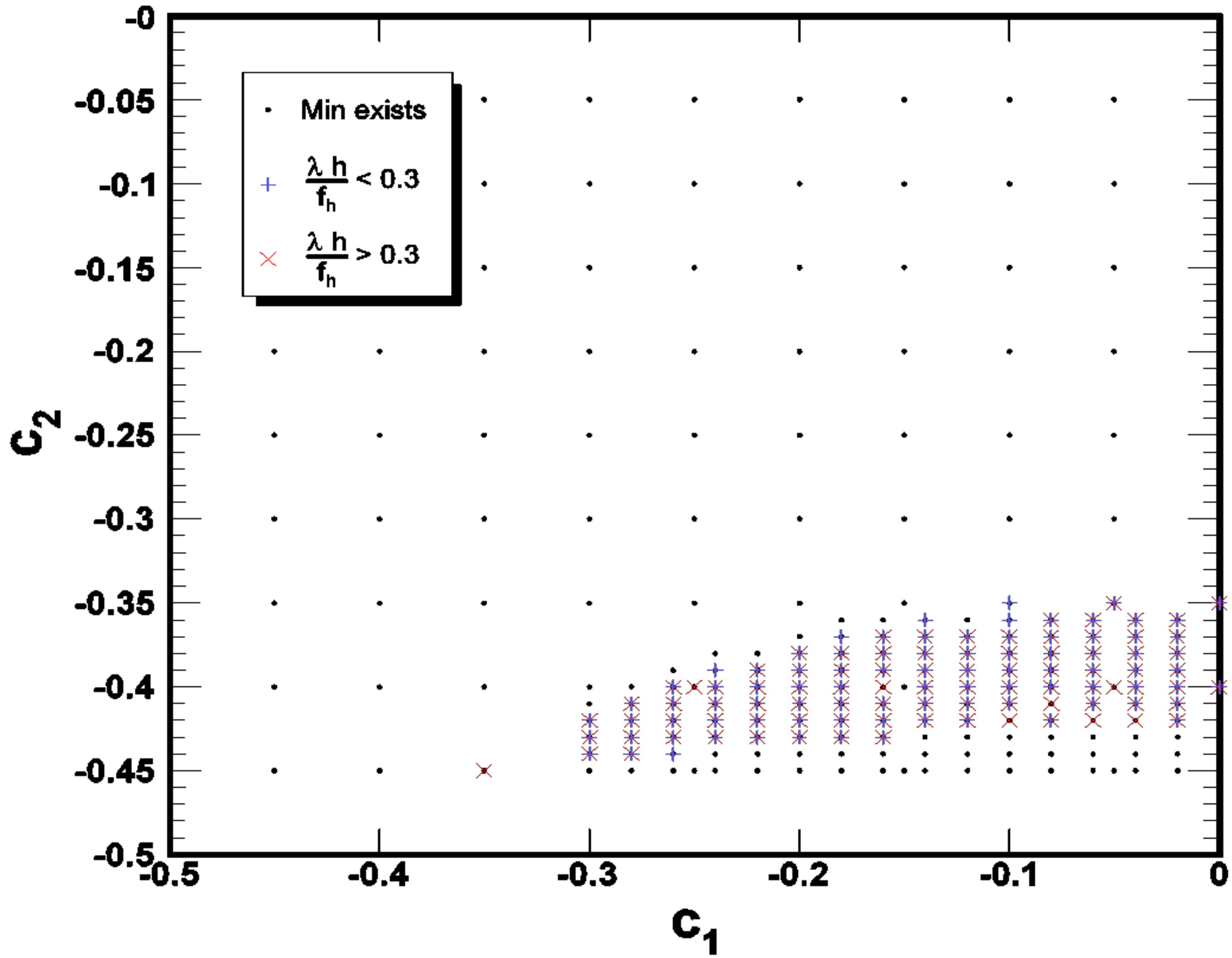
Effective Potential

- 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 M_{B_1}, $M_{B_2} \sim > 5$, $|c_1|$, $|c_2|$, $|c_3| > 1$.
- $h = 0$ min ignored since no EW symmetry breaking.
- $\lambda h/f_h = \pi/2$ min ignored since the Higgs coupling to gauge bosons goes to 0.

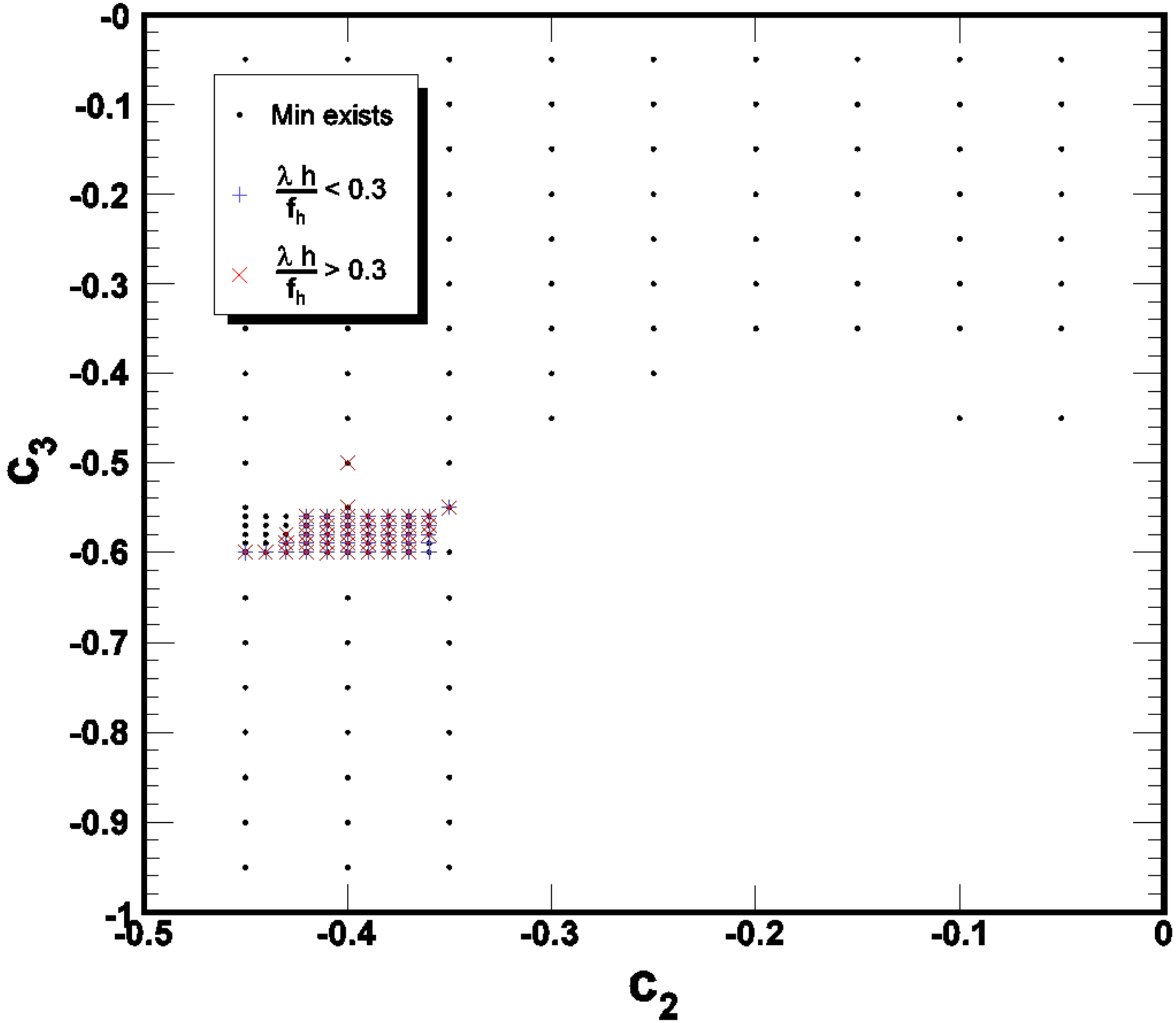
Effective Potential

- $f_h \sim k\, e^{-kL}$ $\longrightarrow$ As $\lambda h/f_h \uparrow$, KK scale $\downarrow$.
- 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.

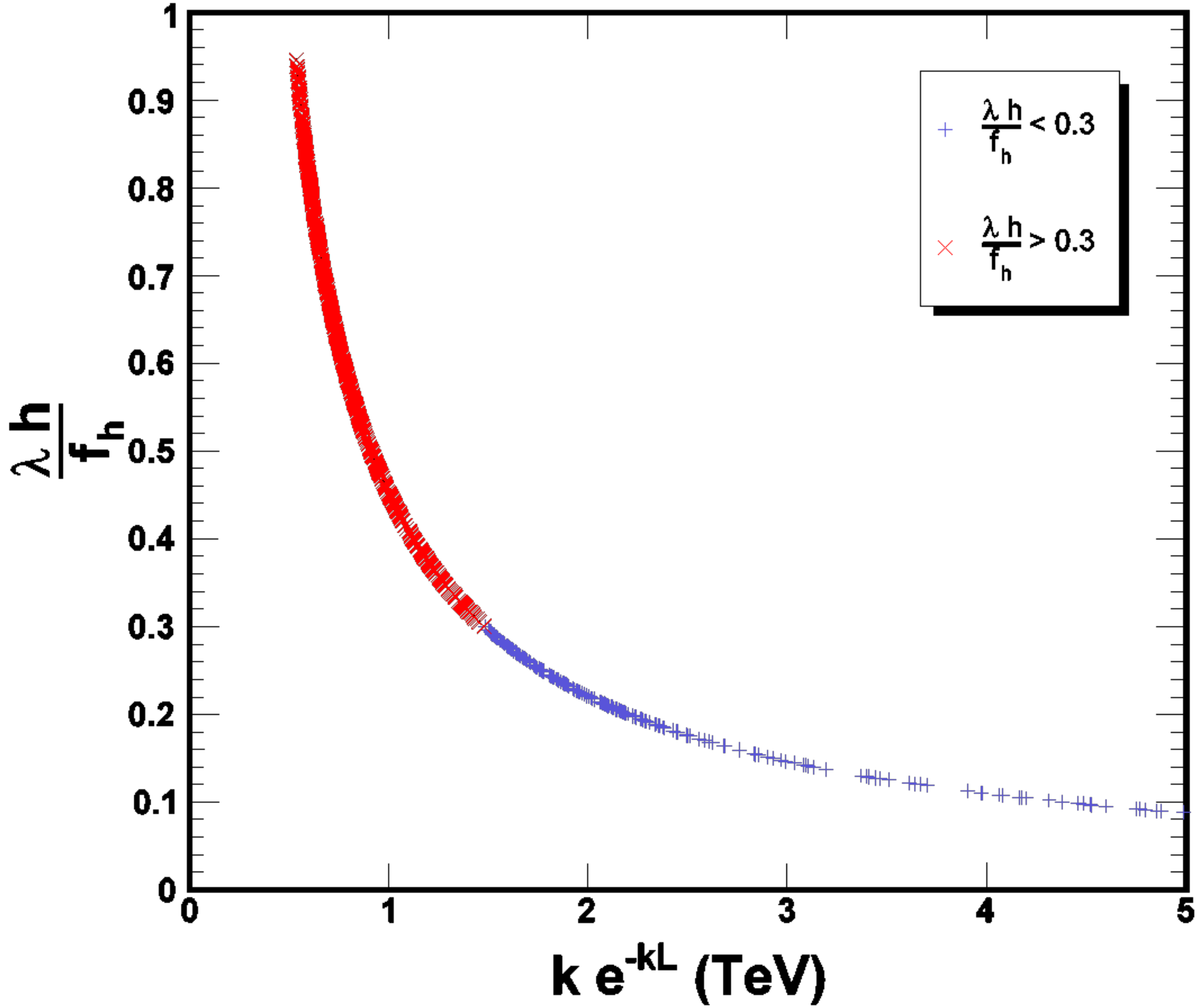


c_2 vs. c_3



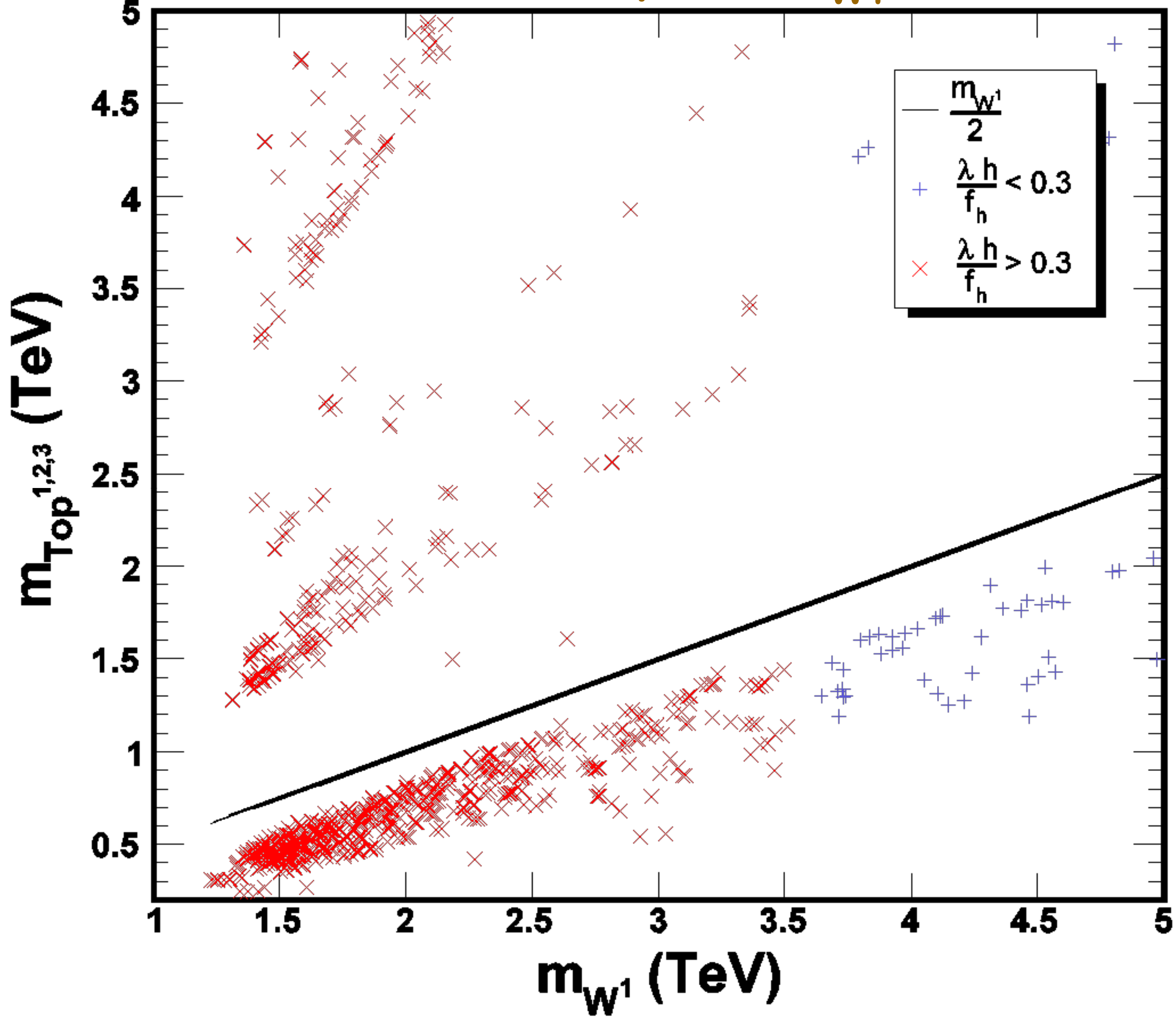
Min exists
$\frac{\lambda\, h}{f_h} < 0.3$
$\frac{\lambda\, h}{f_h} > 0.3$
-0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1
c_3
-0.5
-0.4
-0.3
-0.2
-0.1
0
c_2

k e^{-kL} vs. min.



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

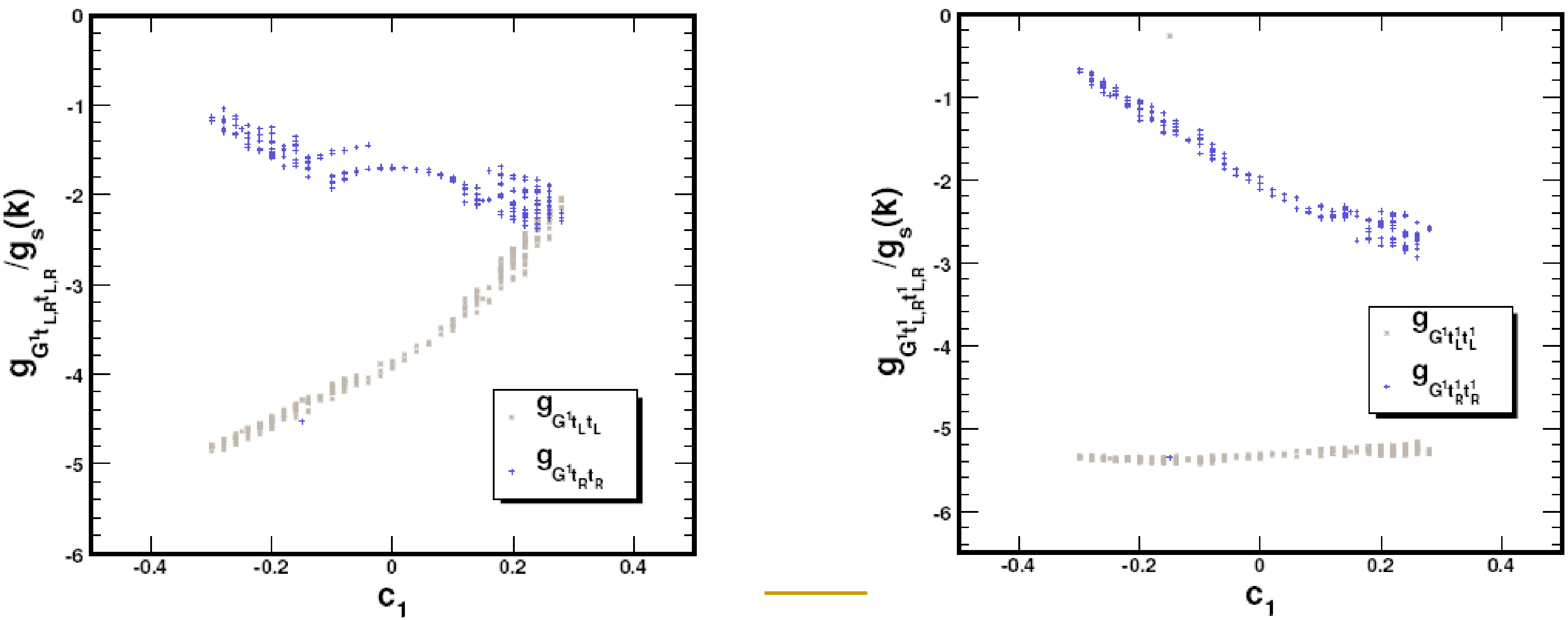
First few KK mode of the Top vs. m_{W1}



Decays of G^1 into pairs of excited tops, t^1. Improve reach to probe t^1-masses further than direct QCD production.

- Pairs of t^1 decay into either $W^+ b$, $H\, t$ or $Z\, t$.
- Example of important couplings to consider

$$g_{G^1\bar{t}t} \;=\; g_{5s} N_{G^1} \int_0^L \left(\sum_i f^{2/3*}_{F,i,m_t}(x_5,h).f^{2/3}_{F,i,m_t}(x_5,h) \right) C[x_5, m_{G^1}] dx_5$$



t^1 and G^1 decays branching ratios

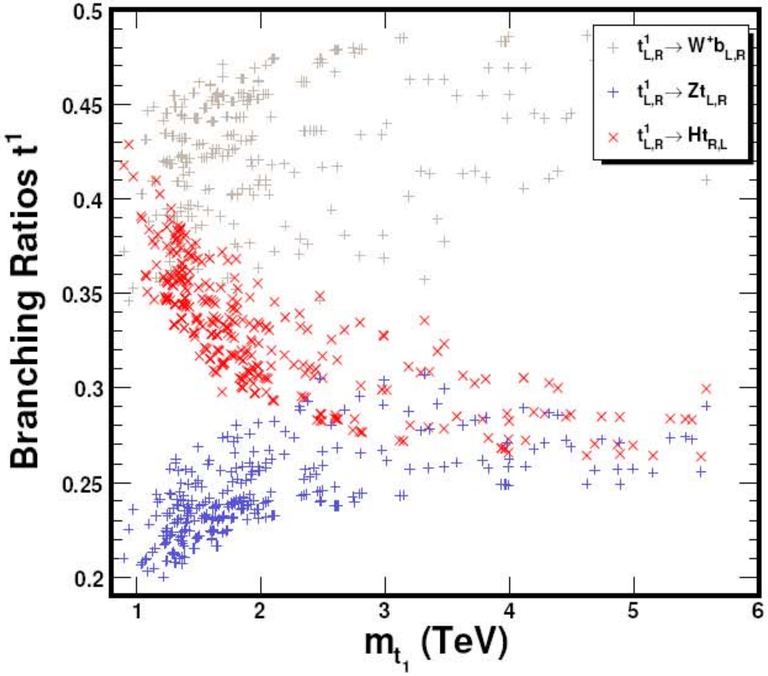


Figure 4: Branching ratios for the decay of t^1 vs m_{t^1} (GeV). Notice that the 2:1:1 relations holds for large m_{t^1}.

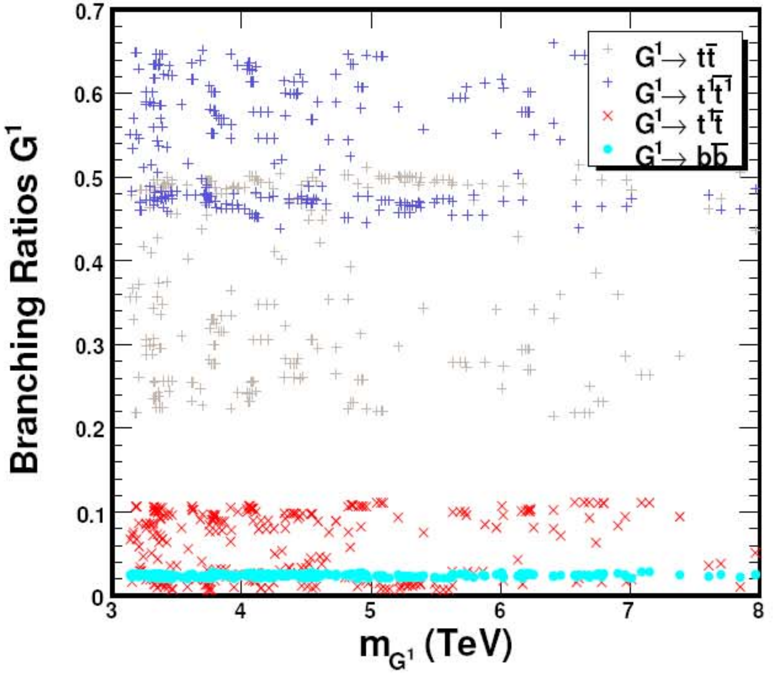


Figure 5: Branching ratios for the decay of G^1 vs m_{G^1} (GeV). Notice that G^1 decays mostly to t^1 pairs.

t^1 production cross section through QCD alone and through QCD+G^1 for M_{G1} = 4 TeV.

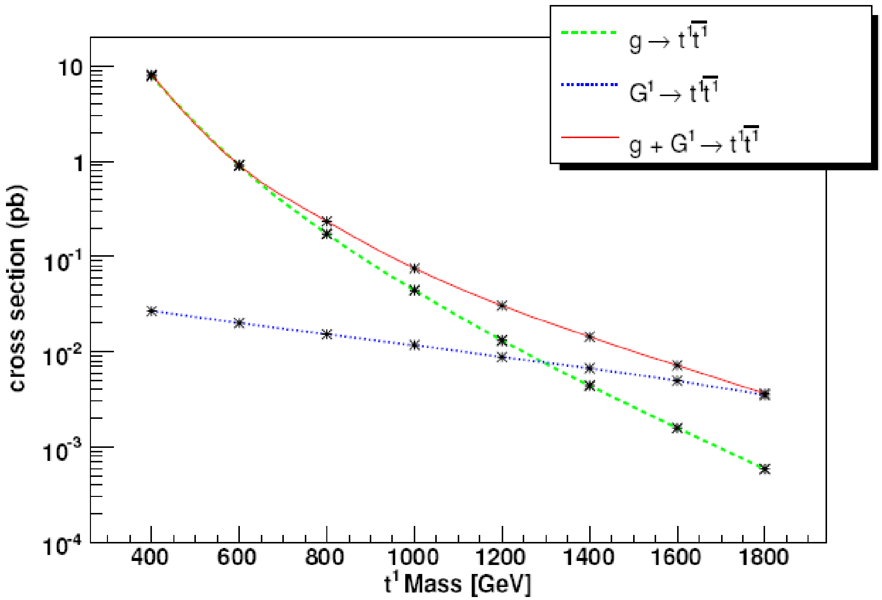


Figure 5: Cross section for $M_{G^1} = 4.0$ TeV with couplings $g_{G^1\bar{t^1}_L t^1_L} = -5.8$ and $g_{G^1\bar{t^1}_R t^1_R} = -3.1$.

Notice that for $m_{t^1} \sim 1.5$ TeV, G^1 induced production contributes significantly to the t^1 production cross section.

Collider Phenomenology

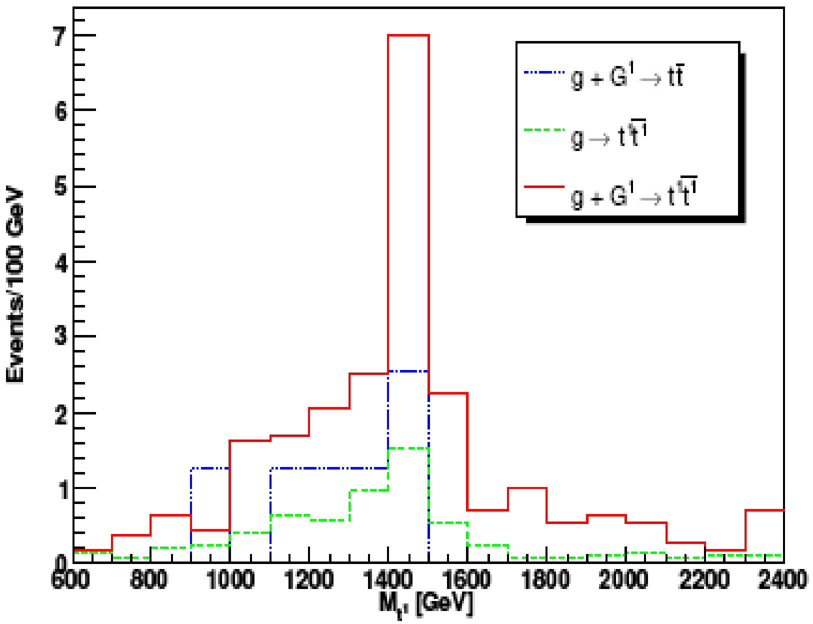
- From the Goldstone Equivalence Theorem ~ 50 % of the time, t^1 decays in W^+ b. We shall therefore concentrate on the channel:

$$pp \to (g + G^1) \to t^1\bar{t}^1 \to W^+ b W^- \bar{b} \to l^- \bar{\nu} b\bar{b} jj, \quad (l = e, \mu)$$

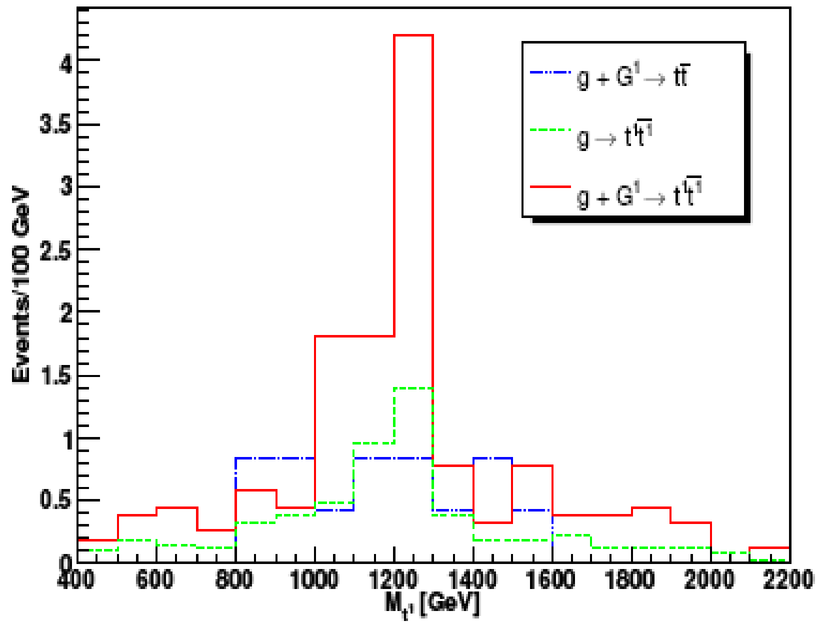
- Backgrounds for this signal:
  - Top quark pair production induced by G^1 in addition to QCD (main background)
  - W + jets
  - Z + jets
- Last two backgrounds are reduced to negligible levels by requiring 2 b-tags and lepton+MET.

- **W-mass reconstructed using two methods:**
  - W → 2 jets. Works well for t^1 masses less than 1 TeV. $\Delta R=0.4$.
  - W → 1 jet. Works well for t^1 masses larger than 1 TeV. Increases signal and decreases background. $\Delta R=0.6$.
- **Reconstructed t^1 invariant mass distribution, choosing b with largest ΔR w.r.t W:**

m_{t1}~1.47 TeV, m_{G1}~3.9 TeV



m_{t1}~ 1.25 TeV, m_{G1}~3.4 TeV



- **Presence of these particles may be found already at 100 fb^{-1} for Point 1 (60 fb^{-1} point 2) and discovery at 300 fb^{-1} for point 1 (200 $fb^{-1}$for point 2).**

Constant cross-section curves in (m_{G1},m_{t1}) plane to estimate reach at 300 fb^{-1}

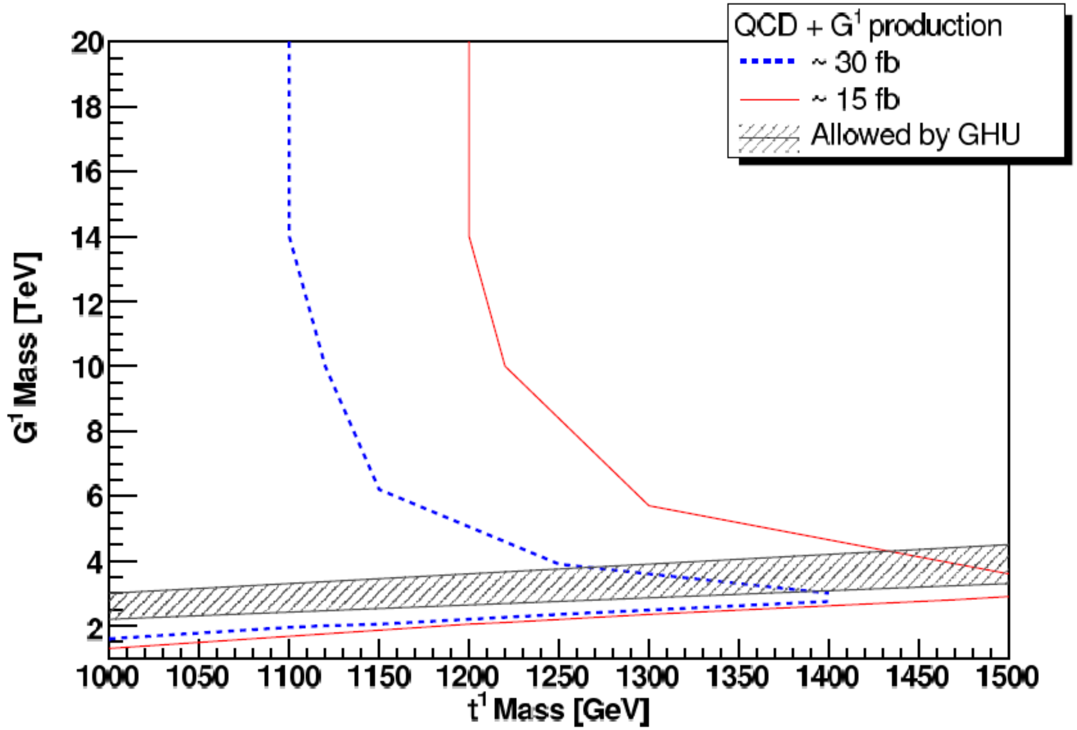
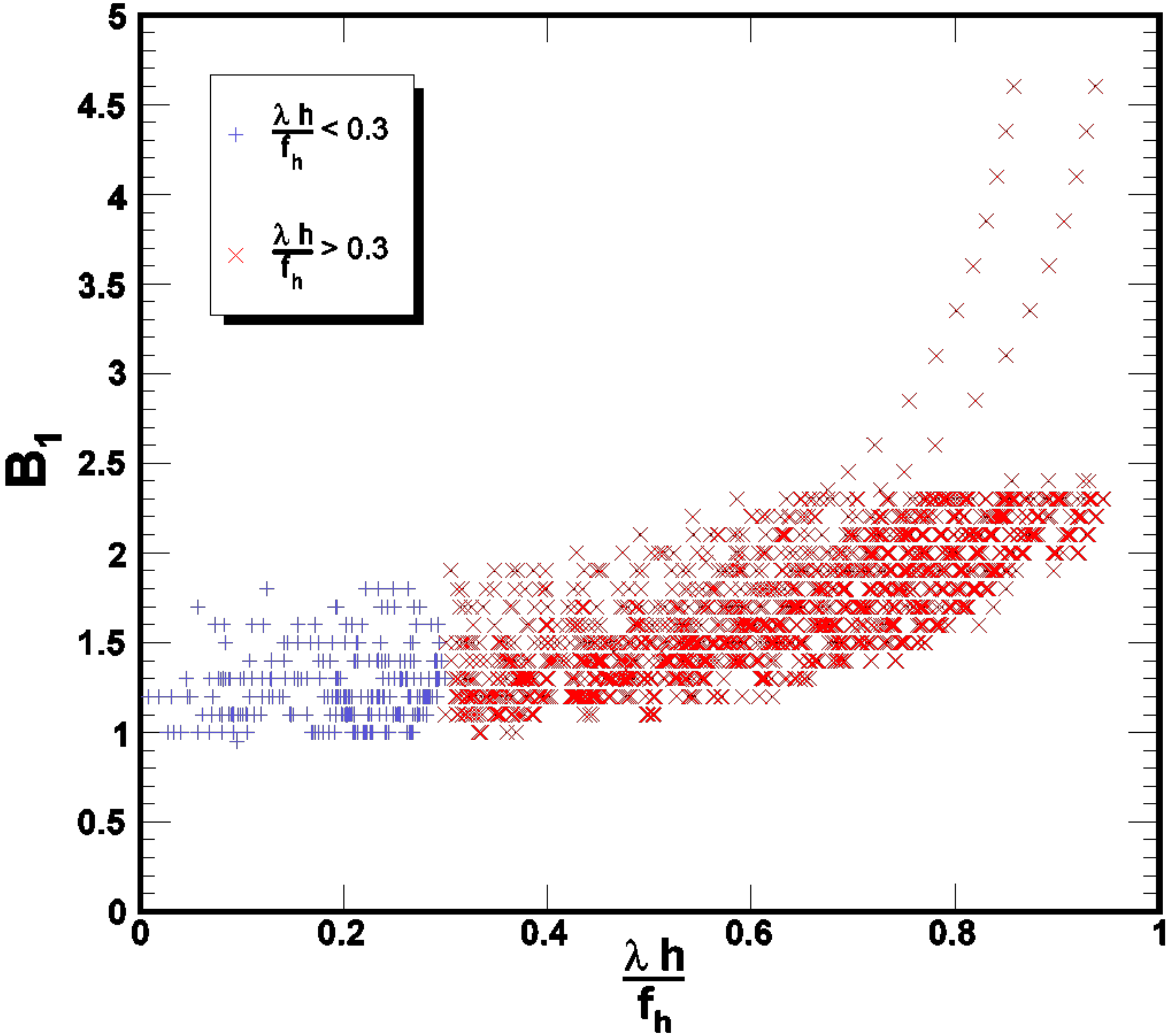


Figure 20: Curves of constant cross section for QCD in addition of G^1 decay, in (m_{G^1}, m_{t^1}) plane.

Conclusions

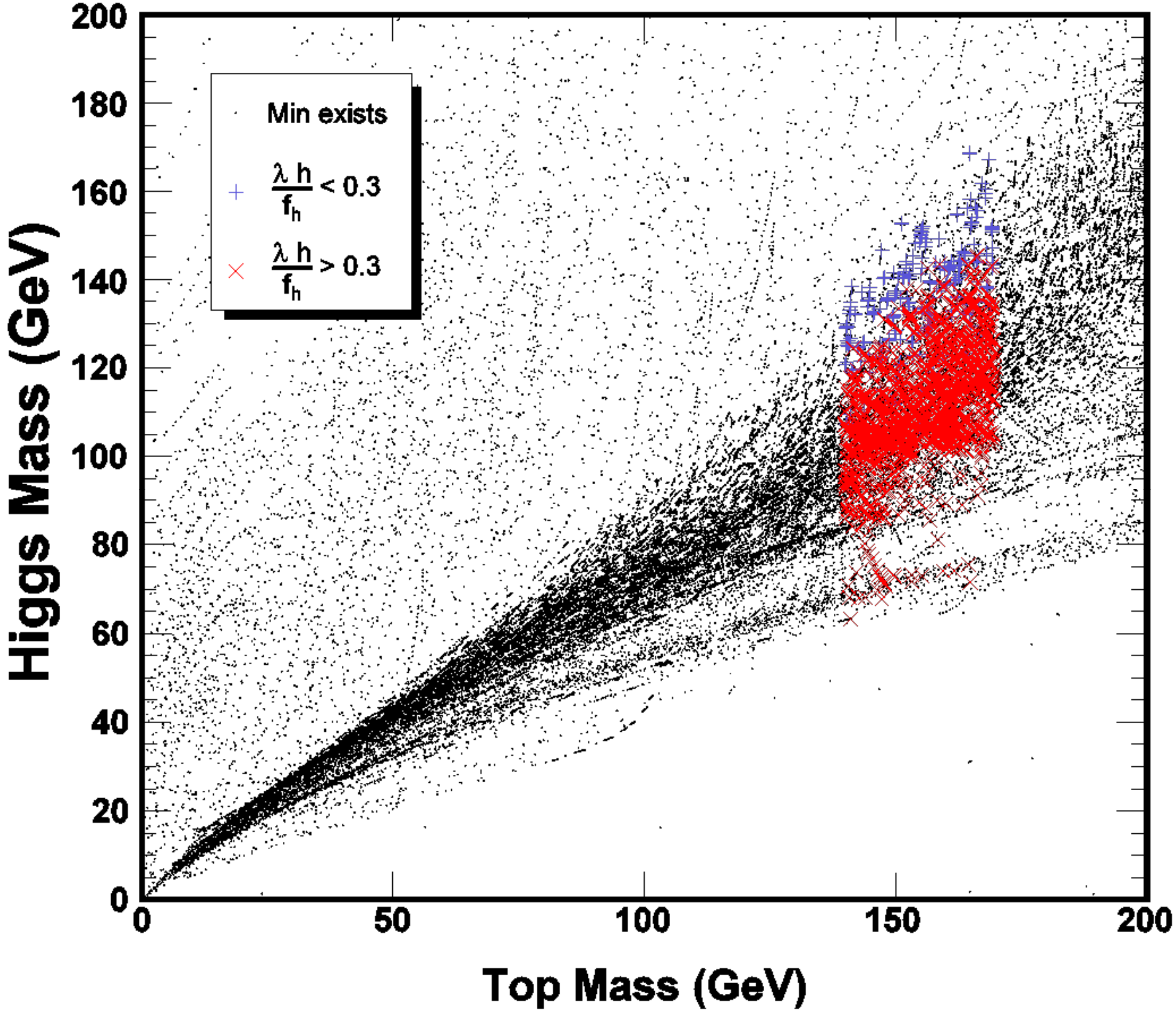
- Higgs constructed from gauge fields.
- Higgs potential generated at one loop with SM consistent matter and gauge content.
- Found conditions for EW symmetry breaking.
- Light Higgs [110-160 GeV].
- First KK mode of the top quark, t^1 , light enough to be produced from decays of first excited KK state of the gluon.
- Interesting collider phenomenology: G^1 decays into t^1 expand the reach of t^1 detection to masses around 1.5 TeV.

M_{B1} vs. min.

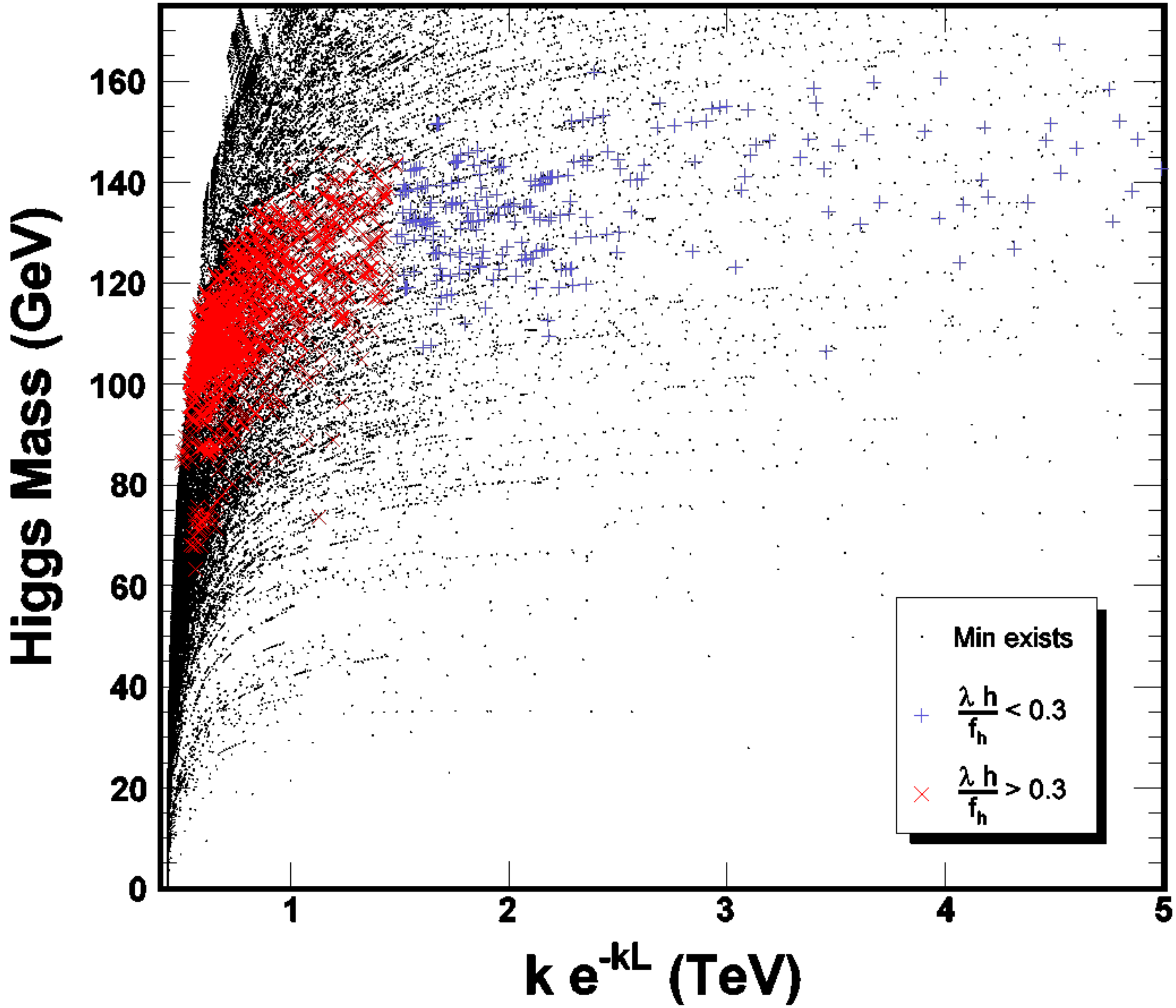


$\frac{\lambda h}{f_h} < 0.3$
$\frac{\lambda h}{f_h} > 0.3$
B_1
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0.2
0.4
0.6
0.8
1
$\frac{\lambda h}{f_h}$

Top mass vs. Higgs Mass



Higgs mass vs. k e^{-kL}



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