An effective theory approach to physics beyond (MS)SM

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Research interests:

- Physics beyond (MS)SM:

(model building, susy/sugra, effective operators parametrization of “new physics”....)

- Effective theories of compactification (“field theory orbifolds”):

(implications for 4D model building, regularization and re-summation techniques, loop corrections, and link with string models at $\alpha' \rightarrow 0$ limit, phenomenology of string models).

- Higher dimensional operators (HDO): origin & motivation:

$$\mathcal{L}_{eff} = \mathcal{L}_{[SM\ or\ MSSM]} + \sum_{i,n\geq 1} \frac{\rho_{i,n}}{M_*^n}\, \mathcal{O}_{i,n}(\phi,\psi,....), \qquad dim\,\mathcal{O}_i = 4+n$$

M_*: the scale of "new physics". $\rho_{i,n} \sim \mathcal{O}(1)$ coefficients.

- generated by:

(a): integrating "new physics" at $M_* \gg m_Z$, in renormalisable models

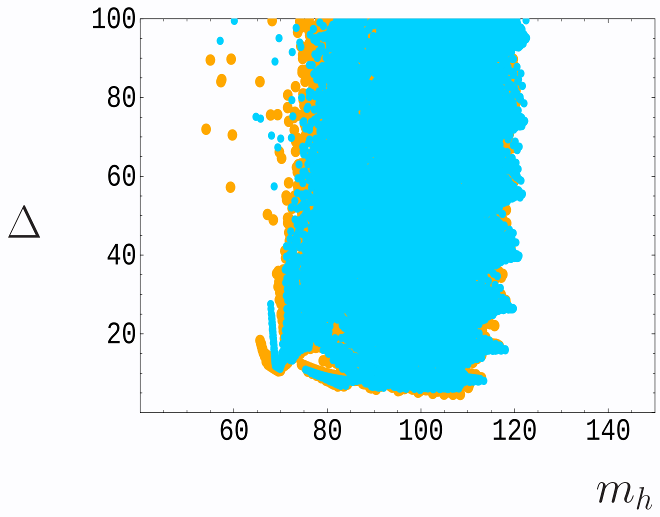
(b): dynamically by compactification, on (MS)SM brane. [DG, H.M. Lee, S.Groot Nibbelink]

$\Rightarrow$ HDO's parametrize and capture "new physics" ($>$TeV, beyond SM/MSSM), due to a more fundamental theory (massive states, extra dimensions....)

• Applications: (a): MSSM Higgs:

LEPII: $m_h \geq 114.4$ GeV; $m_h \leq m_Z$; $\Rightarrow$ Large Q.C. $\Rightarrow$ EW scale fine-tuning: $v^2 = -m^2_{soft}/\lambda$

$$\Delta \equiv \max \left| \frac{\partial \ln v^2}{\partial \ln p^2} \right|_{p=\{\mu_0, m_0, ...\}} > 20 - 50 \;\; \text{(one-loop)} \quad (m_h > 114.4 \; GeV)$$



$\Rightarrow$ "new physics?"; parametrise it by HDO .....

$\Rightarrow$ HDO effects on m_h and EW fine-tuning?

$\Rightarrow$ Examine: MSSM with $d = 5$ and $d = 6$ operators.

• MSSM + (d=5) + (d=6) operators:

$$\mathcal{L} = \mathcal{L}_{MSSM} + \mathcal{L}_{(d=5)} + \mathcal{L}_{(d=6)}$$

$$\mathcal{L}_1 = \frac{1}{M_*} \int d^2\theta \ \zeta(S) \ (H_1.H_2)^2 + h.c., \qquad S \equiv \theta\theta \, m_0, \quad \frac{1}{M_*} \zeta(S) = \zeta_{10} + \zeta_{11} \, S,$$

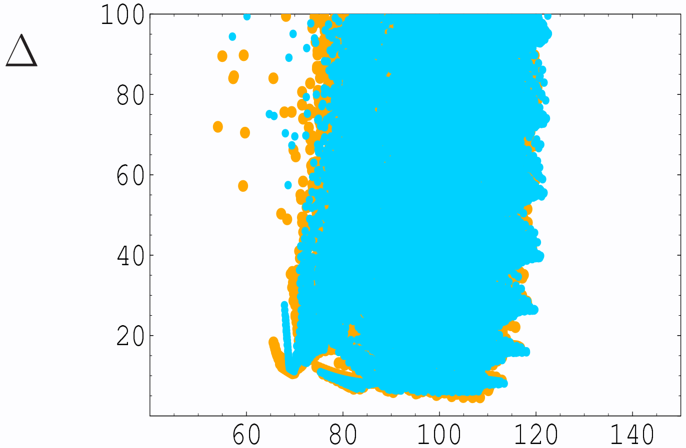
$$\mathcal{L}_2 = \frac{1}{M_*} \int d^4\theta \ a(S, S^\dagger) \, D^\alpha \left[b(S, S^\dagger) \, H_2 \, e^{-V_1} \right] D_\alpha \left[c(S, S^\dagger) \, e^{V_1} \, H_1 \right] + h.c.$$

$\mathcal{L}_1$: massive gauge singlet. $\mathcal{L}_2$: massive Higgs doublets $H_{3,4}$. $M_* \gg \mu$

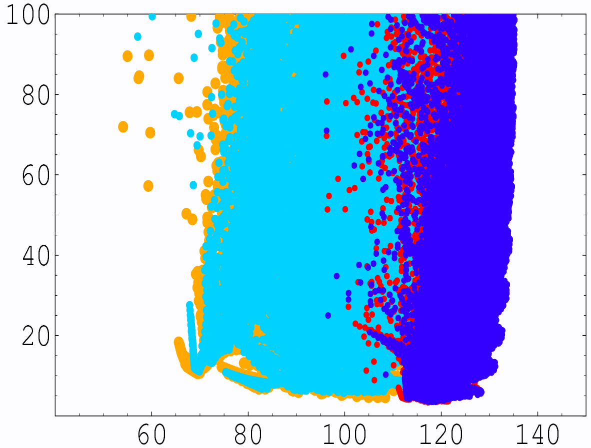
$\mathcal{L}_2$: "removable" by non-linear field redefinitions

$\Rightarrow$ increase m_h closer to LEPII bound. [Dine, Seiberg, Thomas]

- Impact on fine-tuning: MSSM+(d=5) operators: [S. Cassel, Graham Ross, D.G.]



MSSM: m_h



MSSM$_5$: $\zeta_{10}\,\mu_0 = 0.035,\ m_0\zeta_{11} = 0.005$

- $1 < \tan\beta < 6$; quartic coupling λ increased by HDO, $v^2 = -(\sum_i m^2_{soft,i})/\lambda \Rightarrow \Delta$ reduced
- $114.4 \leq m_h \leq 130$ GeV, $\Delta < 10$. $M_* \approx 1/\zeta_{10} \approx (28\,\text{to}\,65) \times \mu_0 \ \Rightarrow\ M_* \sim 8 - 10$ TeV...
- new physics: massive gauge singlet or $SU(2)$ triplet. large $\tan\beta$: d=6 op's important!

• Include all $d = 6$ operators: $\mathcal{L} = \mathcal{L}_{MSSM} + \mathcal{L}_{(d=5)} + \mathcal{L}_{(d=6)}$:

[I. Antoniadis, E.Dudas, P.Tziveloglou, D.G.]

$$\begin{aligned}
\mathcal{O}_1 &= \frac{1}{M_*^2} \int d^4\theta \; \mathcal{Z}_1(S, S^\dagger) \; (H_1^\dagger \, e^{V_1} \, H_1)^2, && (T, U(1)) \\
\mathcal{O}_2 &= \frac{1}{M_*^2} \int d^4\theta \; \mathcal{Z}_2(S, S^\dagger) \; (H_2^\dagger \, e^{V_2} \, H_2)^2, && (T, U(1)) \\
\mathcal{O}_3 &= \frac{1}{M_*^2} \int d^4\theta \; \mathcal{Z}_3(S, S^\dagger) \; (H_1^\dagger \, e^{V_1} \, H_1) \, (H_2^\dagger \, e^{V_2} \, H_2), && (T, U(1)) \\
\mathcal{O}_4 &= \frac{1}{M_*^2} \int d^4\theta \; \mathcal{Z}_4(S, S^\dagger) \; (H_2 \, H_1) \, (H_2 \, H_1)^\dagger, && (S, T) \\
\mathcal{O}_5 &= \frac{1}{M_*^2} \int d^4\theta \; \mathcal{Z}_5(S, S^\dagger) \; (H_1^\dagger \, e^{V_1} \, H_1) \, (H_2 \, H_1 + h.c.) \\
\mathcal{O}_6 &= \frac{1}{M_*^2} \int d^4\theta \; \mathcal{Z}_6(S, S^\dagger) \; (H_2^\dagger \, e^{V_2} \, H_2) \, (H_2 \, H_1 + h.c.) \\
\mathcal{O}_7 &= \frac{1}{M_*^2} \int d^2\theta \; \mathcal{Z}_7(S, 0) \; W^\alpha \, W_\alpha \, (H_2 \, H_1) + h.c., \\
\mathcal{O}_8 &= \frac{1}{M_*^2} \int d^4\theta \; \Big[\mathcal{Z}_8(0, S^\dagger) \; (H_2 \, H_1)^2 + h.c. \Big]
\end{aligned}$$

....and operators involving extra derivatives

$$
\begin{aligned}
\mathcal{O}_9 &= \frac{1}{M_*^2}\int d^4\theta\ \mathcal{Z}_9(S,S^\dagger)\ H_1^\dagger\,\overline{\nabla}^2\,e^{V_1}\,\nabla^2\,H_1\\
\mathcal{O}_{10} &= \frac{1}{M_*^2}\int d^4\theta\ \mathcal{Z}_{10}(S,S^\dagger)\ H_2^\dagger\,\overline{\nabla}^2\,e^{V_2}\,\nabla^2\,H_2\\
\mathcal{O}_{11} &= \frac{1}{M_*^2}\int d^4\theta\ \mathcal{Z}_{11}(S,S^\dagger)\ H_1^\dagger\,e^{V_1}\,\nabla^\alpha\,W_\alpha^{(1)}\,H_1\\
\mathcal{O}_{12} &= \frac{1}{M_*^2}\int d^4\theta\ \mathcal{Z}_{12}(S,S^\dagger)\ H_2^\dagger\,e^{V_2}\,\nabla^\alpha\,W_\alpha^{(2)}\,H_2\\
\mathcal{O}_{13} &= \frac{1}{M_*^2}\int d^4\theta\ \mathcal{Z}_{13}(S,S^\dagger)\ H_1^\dagger\,e^{V_1}\ W_\alpha^{(1)}\,\nabla^\alpha\,H_1\\
\mathcal{O}_{14} &= \frac{1}{M_*^2}\int d^4\theta\ \mathcal{Z}_{14}(S,S^\dagger)\ H_2^\dagger\,e^{V_2}\ W_\alpha^{(2)}\,\nabla^\alpha\,H_2
\end{aligned}
$$

(plus extra spurion under $\nabla_\alpha \equiv e^{-V}\,D_\alpha\,e^V$).

$$
\frac{1}{M_*^2}\,\mathcal{Z}_j(S,S^\dagger) = \alpha_{j0} + \alpha_{j1}\,m_0\,\theta\theta + \alpha_{j1}^*\,m_0\,\overline{\theta\theta} + \alpha_{j2}\,m_0^2\,\theta\theta\overline{\theta\theta}, \qquad \alpha_{jk}\sim 1/M_*^2.
$$

- Implications for m_h in MSSM Higgs+(d=5)+(d=6) operators: $(\zeta_{10}, \zeta_{11} \sim 1/M_*, \quad \alpha_{ij} \sim 1/M_*^2)$

[I. Antoniadis, E.Dudas, P. Tziveloglou, D.G.]

$$m_{h,H}^2 = m_h^{MSSM}\Big|_{1-loop} + \delta m_h^2\Big|_{\mathcal{O}(1/M)} + \delta m_h^2\Big|_{\mathcal{O}(1/M^2)}$$

$$\delta m_h^2\Big|_{\mathcal{O}(1/M)} = (2\,\zeta_{10}\,\mu_0)\,v^2\,\sin 2\beta\left[1 \pm \frac{m_A^2 + m_Z^2}{\sqrt{\tilde{w}}}\right] + \frac{(-2\,\zeta_{11}\,m_0)\,v^2}{2}\left[1 \mp \frac{(m_A^2 - m_Z^2)\,\cos^2 2\beta}{\sqrt{\tilde{w}}}\right]$$

$$\begin{aligned}\delta m_h^2\Big|_{\mathcal{O}(1/M^2)} &= -2\,v^2\left[\alpha_{22}\,m_0^2 + (\alpha_{30}+\alpha_{40})\mu_0^2 + 2\alpha_{61}\,m_0\,\mu_0 - \alpha_{20}\,m_Z^2\right] - \frac{(2\,\zeta_{10}\,\mu_0)^2\;v^4}{m_A^2 - m_Z^2}\\ &+\frac{v^2}{\tan\beta}\left[\frac{1}{(m_A^2-m_Z^2)}\Big(4\,m_A^2\,\big((2\alpha_{21}+\alpha_{31}+\alpha_{41}+2\alpha_{81})\,m_0\,\mu_0+(2\alpha_{50}+\alpha_{60})\,\mu_0^2+\alpha_{62}\,m_0^2\big)\right.\\ &-\left.(2\alpha_{60}-3\alpha_{70})\,m_A^2\,m_Z^2-(2\alpha_{60}+\alpha_{70})\,m_Z^4\Big)+\frac{8\,(m_A^2+m_Z^2)\;(\mu_0\,m_0\,\zeta_{10}\,\zeta_{11})\,v^2}{(m_A^2-m_Z^2)^2}\right]\\ &+\;\mathcal{O}(1/\tan^2\beta)\end{aligned}$$

- $m_h > 114.4$ GeV even for $M_* > 10$ TeV. $\mathcal{O}_{2,3,4}$ dominant; $\alpha_{20} > 0$, $\alpha_{30} < 0$, $\alpha_{40} < 0$.
- $\mathcal{O}_{3,4}$ avoid ρ-constraints. $\Rightarrow$ Massive U(1) or gauge singlet preferred.

- Living with ghosts: 4^{th}-order $\Rightarrow$ a 2^{nd}-order theory [I. Antoniadis, E. Dudas, P. Tziveloglu, D.G.]

$$\mathcal{L} = \int d^4\theta \Big[\Phi^\dagger \, (1 + \Box/M_*^2)\, \Phi \Big] + \Big\{ \int d^2\theta \; W[\Phi] + h.c. \Big\} + \mathcal{O}(1/M_*^3),$$

$$\mathcal{L} \; = \int d^4\theta \left[\Phi_1^\dagger \Phi_1 - \Phi_2^\dagger \Phi_2 - \Phi_3^\dagger \, \Phi_3 \right] + \int d^2\theta \left[W[\Phi(\Phi_{1,2,3})] - (m^2/M_*)\, \Phi_1 \, \Phi_3 - M_* \Phi_2 \, \Phi_3 \right] + h.c. + \mathcal{O}(1/M_*^3)$$

$$\Phi = a_1 \, \Phi_1 + a_2 \, \Phi_2,$$

$$(1/m)\overline{D}^2 \, \Phi^\dagger = b_1 \, \Phi_1 + b_2 \, \Phi_2.$$

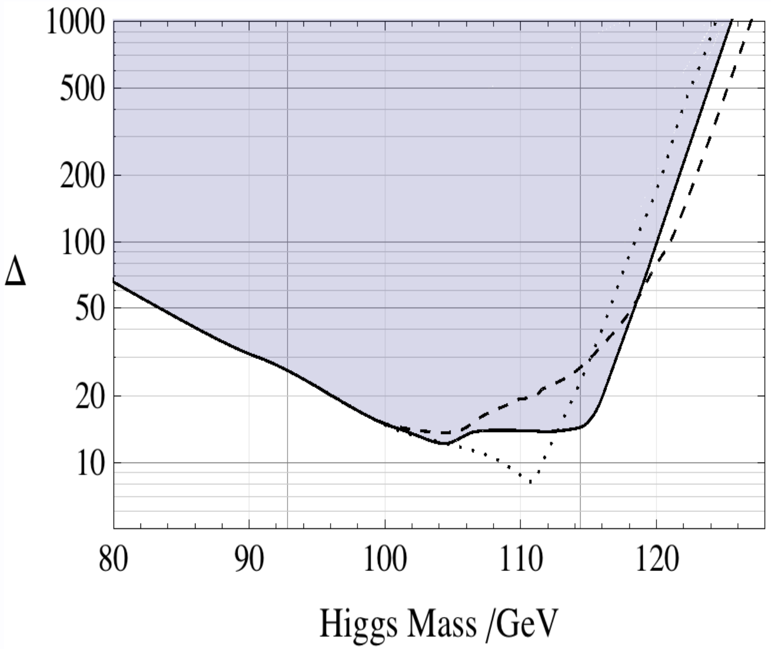
$$\Phi(\Phi_{1,2,3}) = (1 + m^2/M_*^2)^{-1/4} \, (-\Phi_2 + \Phi_1)$$

- can integrate out the massive super-ghosts:

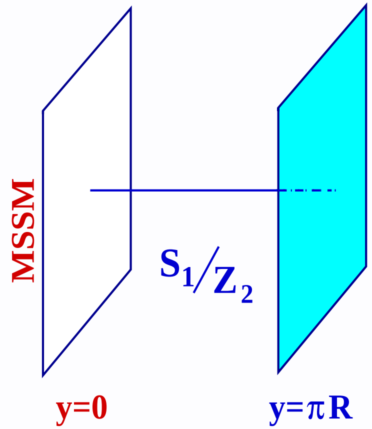
$$\mathcal{L} \; = \; \int d^4\theta \left[\Phi_1^\dagger \Phi_1 - \frac{1}{M_*^2} \, W'^\dagger[\Phi_1] \; W'[\Phi_1] + \Big\{ \int d^2\theta \;\; W[\Phi_1] + h.c. \Big\} + \mathcal{O}(1/M_*^3) \right.$$

• MSSM: a closer look at the fine-tuning: [S. Cassel, Graham Ross, DG]

- Two-loop level analysis (solid line); (one-loop analytical results for Δ).



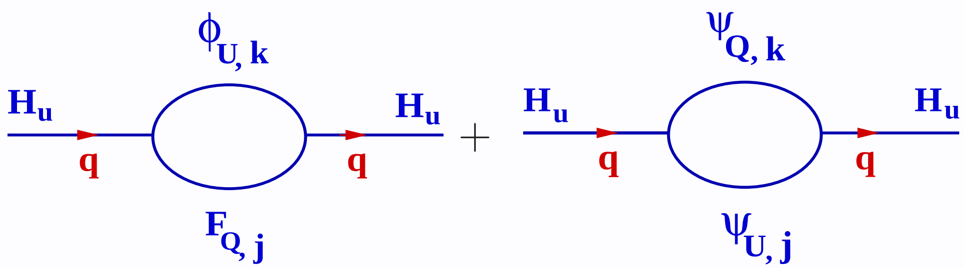
• $m_h = 114.4(\pm 2)$ GeV has minimal fine-tuning, $\Delta \sim 14.5$ (SOFTSUSY) (b): HDO from: Localised interaction (Yukawa) on orbifolds (MSSM on S_1/Z_2, $(T^2/Z_N, ...)$).



$$L_4 = \int dy\, \delta(y) \int d^2\theta \left[\lambda\, Q\, U\, H_u + \lambda_b\, Q\, D\, H_d\right] + \text{h.c.}$$

$N=2 \to N=1\,(Z_2)$; $N=1 \to N=0$ [localised, SS breaking...]

$$m_H^2(q^2) = \sum_{j,k \in \mathbb{Z}}$$



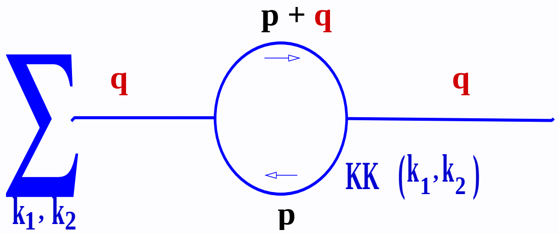
$$= -\frac{y_t^2}{R^2} + y_t^2\, R^2\, \frac{q^4}{\epsilon} + \frac{1}{R^2}\,\mathcal{O}(q^2 R^2), \quad \lambda \equiv (\pi R)^{3/2} y_t$$

[D.G., Hyun Min Lee]

$$\Rightarrow\ L_4 \supset \lambda^2 \int dy\, \delta(y) \int d^4\theta\ H_u^\dagger \Box H_u \sim y_t^2\, R^2\, h_0^\dagger \Box^2 h_0 + \cdots$$

$\Rightarrow$ Localised interactions on orbifolds: $\Rightarrow$ HDO (counterterms) already at one-loop.

- Regularisation/resummation techniques of radiative corrections to Green functions on orbifolds:

$\mathcal{G}(q,-q) =$ 

[D.G., Hyun Min Lee]

$$\mathcal{G}(q,-q) = \sum_{k_1\geq 0}\sum_{k_2\geq 0}\int \frac{d^{\,4-\epsilon}p}{(2\pi)^d}\,\frac{\alpha\, p^2 + \beta\,(p.q) + \gamma\, q^2 + \delta}{[(q+p)^2 + (k_2+c_2)^2/R^2\,]\,[p^2 + (k_1+c_1)^2 u^2/R^2\,]}$$

$$= \frac{1}{(4\pi)^2}\,\frac{2}{\epsilon}\,\Big[\delta - \frac{\alpha}{3\,R^2}\Big(u^2\,(c_1-1)c_1 + (c_2-1)c_2\Big) + q^2(\gamma-\beta/2)\Big]\Big(c_1-\frac{1}{2}\Big)\Big(c_2-\frac{1}{2}\Big)$$

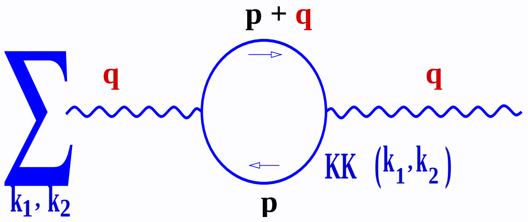
$$+ \frac{1}{(4\pi)^2}\,\frac{2}{\epsilon}\,\Big[-\frac{\pi^2}{32\,u}\,\delta\, q^2 R^2 - \frac{\pi^2}{2^9\,u}\,(2\,\alpha - 8\,\beta + 16\,\gamma\,)\;q^4 R^2\Big]$$

$$+ \;\mathcal{O}(\epsilon^0)\Big[\;\text{(known series of elliptic functions)}\Big]$$

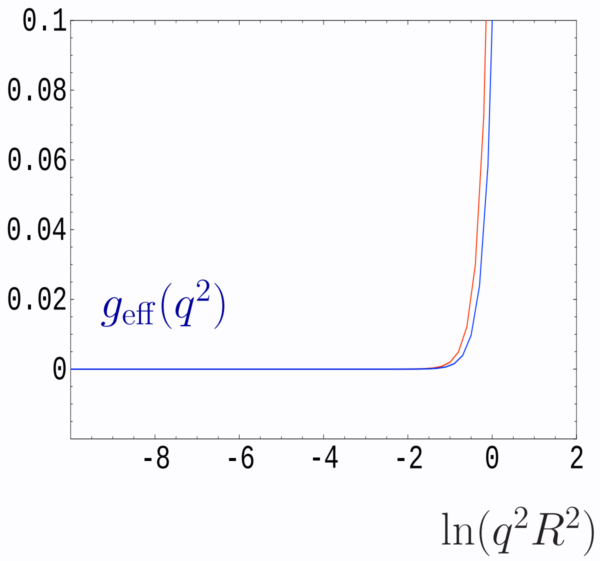
- Casimir energy for T_2/Z_N with Wilson lines [D.G., F. Quevedo, C. Burgess]

- Radiative corrections in gauge theories on orbifolds: T_2/Z_N.... D.G., H.M. Lee, S. Groot-Nibbelink

- non-Abelian gauge theory in 6D N=1 on T_2/Z_2; one-loop (off-shell) effective action



$$\Rightarrow \mathcal{L}_{c.t} = \int d^2z\, d^2\theta \left[\frac{1}{h^2} \mathrm{Tr}\, W^\alpha \Box_6 W_\alpha + \sum_{i=1}^{4} \frac{1}{g^2_{\mathrm{brane},i}} \mathrm{Tr}\, W^\alpha W_\alpha\, \delta^{(2)}(z - z_0^i)\right]$$



$\Rightarrow$ Bulk interactions $\Rightarrow$ "bulk" HDO as counterterms

$$\frac{4\pi}{g^2_{\mathrm{eff}}(q^2)} = \frac{4\pi}{g^2_{\mathrm{tree}}} + \frac{b_1}{4\pi} \ln \frac{\mu^2}{q^2} + \Delta_{KK} - \frac{4\pi\, q^2\, V}{h^2} + \frac{b_2}{4\pi}\, \mathcal{Z}[q^2]$$

$$\Delta_{KK} = -\frac{b_2}{4\pi} \ln \left[4\pi\mu^2\, V\, U_2\, |\eta(U)|^4\right], \quad \mathcal{Z}[q^2] \propto q^2; q^2 < \frac{1}{R^2}$$

- Heterotic string thresholds (T^6/Z_n, $\pm$ Wilson lines) to gauge couplings from a field theory approach

- Conclusion:

- Supersymmetry is getting ......old, we better discover it soon!