LECTURE 3.

END OF SUSY
EXTRA DIMENSIONS

SUSY BREAKING

EFFECTIVE DESCRIPTION OF ~~SUSY~~

$S \leftarrow$ field in hidden sector

$\uparrow$

$\langle S \rangle = \dots \quad + \theta^2 \langle F \rangle$

Want a catalog of leading non-renormalizable terms connecting S to ϕ

$$\frac{1}{M^2}\int \phi^\dagger \phi\, S^\dagger S\, d^4\theta \longrightarrow m_\varphi^2 = |\varphi|^2 \frac{F^2}{M^2}$$ scalar mass

$$S^\dagger S \to \bar\theta^2 F^*,\quad \theta^2 F$$

$$b\,\frac{1}{M^2}\int \phi^2\, S^\dagger S\, d^4\theta + h.c. \longrightarrow b\,\varphi^2 \frac{F^2}{M^2}$$ B-term

$$\frac{1}{M}\int \phi^3\, S\, d^2\theta \longrightarrow a\,\varphi^3 \frac{F}{M}$$ A-term

$$\frac{1}{M}\int W_\alpha W^\alpha S\, d^2\theta \longrightarrow \frac{F}{M}\lambda_\alpha \lambda^\alpha$$ gaugino mass

$$m_{soft} = \frac{F}{M}$$

$A \sim m_{soft}$

$B \sim m_{soft}^2$

$m_\varphi^2 = m_{soft}^2$

$m_\lambda \sim m_{soft}$

$m_{soft} \sim$ few hundred GeV – TeV

$$\mathcal{L} = \mathcal{L}_{SUSY} + \mathcal{L}_{soft}$$

$$\mathcal{L}_{soft} = -\frac{1}{2}\left(M_3 \, \tilde{g}\tilde{g} + M_2 \, \tilde{W}.\tilde{W} + M_1 \, \tilde{B}\tilde{B}\right)$$

$$+ \Big(A_u \, \tilde{Q} H_u \tilde{\bar{u}} + A_d \, (\quad) + A_e \, (\quad)$$

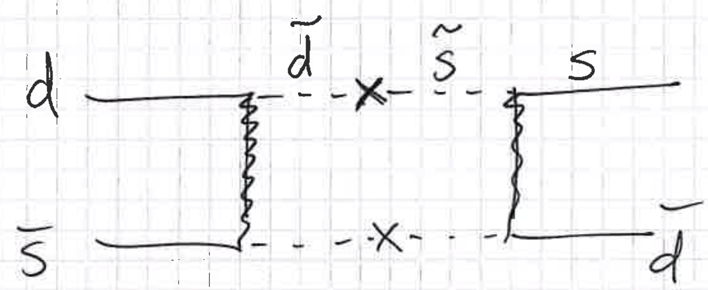
$$+ \tilde{Q}^{+} \underbrace{\tilde{m}_Q^2} \tilde{Q} + \tilde{\bar{u}}^{+} \tilde{m}_u^2 \tilde{\bar{u}} + \ldots$$

$$+ m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + B_\mu H_u H_d + h.c.$$

105 new param's.

Very strong flavor constraints on flavor structure of soft breaking terms!

E.g. squarks can contribute to $K-\bar{K}$ mixing



$$\frac{\Delta m^2_{ds}}{m^2_{SUSY}} \lesssim 4 \cdot 10^{-3} \left(\frac{m_{SUSY}}{500\,\text{GeV}} \right)$$

<u>Assume</u> : organizing principle: soft breaking universality

At <u>some</u> scale all soft breaking terms are flavor universal

EWSB in SUSY

Only source for Higgs quartic in MSSM

$$V_D = \frac{1}{2} g^2 \left| H_u^\dagger H_d \right|^2 + \frac{1}{8}\left(g^2+g'^2\right)\left(|H_u|^2 - |H_d|^2\right)^2$$

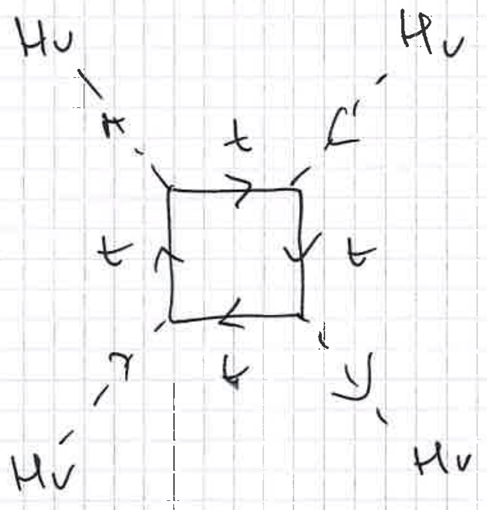
In SM $\sim \sqrt{\lambda}\, v$

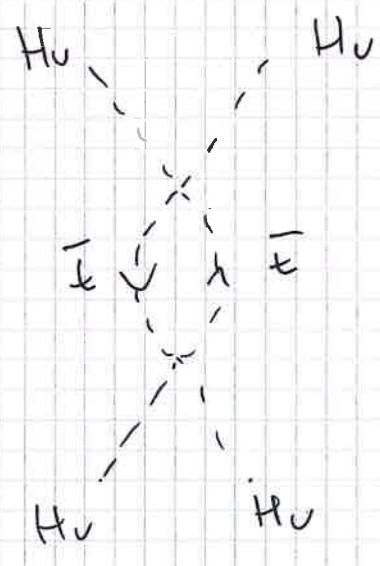
$$V_H = V_D + \left(\mu^2 + m_{H}^2\right)|H_u|^2 + \left(\mu^2 + m_{H_d}^2\right)|H_d|^2 - B_\mu H_u H_d + \text{h.c.}$$

$H_u, H_d \longrightarrow 8$ comp's -3 eaten

$\longrightarrow 5$
- h, H ⟵
- CP-odd neutral
- charged Higgs

<u>Way out:</u> <u>include radiative corrections!</u>





$$\lambda = \lambda_{SUSY} + \frac{6\,|y_t|^4}{16\pi^2} \log\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right)$$

to make this large → need to split stop & top a lot.

to get 125 GeV $m_{\tilde{t}} \sim$ multi TeV!

$m_{\tilde{t}}$ [illegible] feeds into quadratic term!

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix} \qquad \langle H_u \rangle = \begin{pmatrix} 0 \\ v_u \end{pmatrix}$$

VEV's.

$$\frac{v_u}{v_d} = \tan\beta$$

$$H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix} \qquad \langle H_d \rangle = \begin{pmatrix} v_d \\ 0 \end{pmatrix}$$

minimize the full Higgs pot'l

$$\boxed{\frac{M_Z^2}{2} = -\mu^2 + \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1}}$$

$$\sin 2\beta = \frac{2B_\mu}{2|\mu|^2 + m_{H_u}^2 + m_{H_d}^2}$$

$$m_h^2 = \frac{1}{2}\left[M_Z^2 + m_A^2 \pm \sqrt{(M_Z^2 + m_A^2) - 4 m_A^2 M_Z^2 \cos^2 2\beta}\right]$$

$$m_A^2 = \frac{B_\mu}{\sin\beta\cos\beta} \qquad m_{h^0} \leq M_Z |\cos 2\beta|$$

$$\Delta m_{H_u}^2 = -\frac{3 y_t^2}{4\pi^2} \, m_{\tilde{t}}^2 \, \log\left(\frac{\Lambda}{m_{\tilde{t}}}\right)$$

Little hierarchy of SUSY!

EXTRA DIMENSIONS

IDEA: more S-T dimensions than we observe
additional dimensions should be compact!

1.) Kaluza-Klein tower

Assume 1 ED, compact $\rightarrow$ radius R

Free scalar ϕ massless

$$S = \int d^5x \; \frac{1}{2} \partial_M \phi \, \partial^M \phi \qquad x_5 = y$$

Write in terms of Fourier modes

$$\phi(x,y) = \frac{1}{\sqrt{2\pi R}} \sum_n \phi^{(n)}(x) \, e^{i \frac{n}{R} y}$$

$$(\phi^{n})^{+} = \phi^{(-n)} \qquad \text{(to keep it real)}$$

$$\partial_M \phi \partial^M \phi = \partial_\mu \phi \partial^\mu \phi - (\partial_y \phi)^2$$

orthogonal

$m = -n$

$$S = \int d^4x \sum_{m,n} \int dy \frac{1}{2\pi R} e^{\frac{i(m+n)}{R} y} \cdot \frac{1}{2} \left[\partial_\mu \phi^{(m)}(x) \partial^\mu \phi^n(x) + \frac{m \cdot n}{R^2} \phi^m \cdot \phi^n \right]$$

$$= \frac{1}{2} \sum_n \int d^4x \left[\partial_\mu \phi^{(-n)} \partial^\mu \phi^{(n)} - \frac{n^2}{R^2} \phi^{(-n)} \phi^n \right]$$

infinite tower of massive 4D fields $m^{(n)} = \frac{n}{R}$

more extra dim's

$$m^2_{n_5, n_6} = m_0^2 + \frac{n_5^2}{R_5^2} + \frac{n_6^2}{R_6^2}$$

$$A_M \longrightarrow \begin{pmatrix} A_\mu \\ \hline A_5 \end{pmatrix} \longrightarrow A_\mu^{(n)}$$ KK-tower for spin 1 particles.

A_5: only have a zero mode.

$$\left(\begin{array}{c|c} g_{\mu\nu} & A_\mu \\ \hline & g_{55} \end{array}\right)$$

<u>Matching of couplings</u> 5D gauge theory g_5

$$D_\mu = \partial_\mu - i g_5 \underbrace{A_\mu}_{\text{5D field}} \xrightarrow{4D} \partial_\mu - i \frac{g_5}{\sqrt{2\pi R}} A_\mu^{(0)} + \dots$$

Effectively like a 4D gauge theory with coupling

$$\boxed{g_4 = \frac{g_5}{\sqrt{2\pi R}}}$$

Matching of gravitational coupling

$$M_{Pl}^2 \int \sqrt{g}\, R\, d^4x$$

4D action

$$M_*^{2+n} \int \sqrt{g^{(4+n)}}\, R^{(4+n)}\, d^{4+n}x$$

Planck scale in 4+n dimensions

$$\boxed{M_{Pl}^2 = M_*^{2+n} \cdot V_n}$$

volume of extra dimensions.

Large extra dimensional theories

1.) Only fundamental scale in nature exists

$$\boxed{M_* \sim 1\,\mathrm{TeV}}$$

A way to introduce the observed Planck scale:

make volume of extra dim. gigantic?

$$\boxed{r \sim 2 \cdot 10^{-17}\ 10^{\frac{32}{n}}\ \mathrm{cm}}$$

$n=1$ $r = 10^{15}$ cm ✗

$n=2$ $r = 0.1$ cm