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Lectures III and IV

SUMMER SCHOOL IN HIGH ENERGY PHYSICS AND COSMOLOGY

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SUPERSTRING PHENOMENOLOGY

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Please note: These are preliminary notes intended for internal distribution only.

NON-PERTURBATIVE EFFECTS I

- GAUGINO CONDENSATION -

Phenomenological Problems in Perturbation Theory:

- vacuum degeneracy
- gauge and Yukawa couplings are free parameters
- only one scale M_{Pl}
- supersymmetry and electroweak symmetry unbroken

hope: Non-perturbative effects provide solution

- induce $V(S, T^i)$ such that

  $g^{-2}(\langle S \rangle)$ and $Y_{IJK}(\langle T \rangle)$ are fixed at phenomenologicaly acceptable values

  supersymmetry is broken with a vanishing cosmological constant

  electroweak symmetry breaking is induced

3 possibilities to proceed:

① understand non-perturbative regime of String Theory

- Matrix models
- strong/weak coupling duality
- String Field Theory

② assume that <u>dominant</u> non-perturbative effects originate well below M_{Pl} and can be described in Field Theory

- example: gaugino condensation -

③ parametrize unknown non-perturbative physics and study possible signals at the weak scale M_W

<u>Gaugino condensation in supergravity</u> (before strings

Witten
Nilles
Ibañez

possible explanation for hierarchy $M_{Pl} \to M_S \to M_W$

supergravity as an effective theory of "some" more fundamental theory of M_{Pl} physics

- observable sector: contains quarks and leptons in N=1 multiplets

- hidden sector: (no renormalizable interaction with observable sector)

asymptotically free non-Abelian gauge theory weakly coupled at M_{Pl} - becomes strong at

$$\Lambda_c \sim M_{Pl}\, e^{-\frac{8\pi^2}{b g^2}} \ll M_{Pl}$$

$\Rightarrow$ gauginos of hidden sector condense

$$\langle \lambda\lambda \rangle \sim \Lambda_c^3 \qquad (\lambda_\alpha = W_\alpha|_{\theta=0})$$

↑ topological correlator

$\swarrow$ and can induce supersymmetry breaking

Once supersymmetry is broken in hidden sector gravitational (and other non-renormalizable) interaction communicate break-down to observable sector

scale of supersymmetry breaking in observable sector:

$$m_{3/2} \equiv \frac{M_s^2}{M_{Pl}} = \frac{\Lambda_c^3}{M_{Pl}^2}$$

For $\Lambda_c \sim 10^{13} - 10^{14}$ GeV

$\Rightarrow M_s \sim 10^{10} - 10^{11}$ GeV

$\Rightarrow m_{3/2} \sim 10^{1} - 10^{3}$ GeV $\sim M_W$

Once supersymmetry is broken it can induce electroweak symmetry breaking radiatively

(supersymmetric Coleman-Weinberg mechanism)

(requires a large top quark Yukawa coupling generically. Goes well with CDF data)

In String Theory:

- hidden sectors do exist (eg. E_8)
- gauge coupling is field dependent

$$g^{-2}(S,T) \Rightarrow \Lambda_c(S,T) \Rightarrow V_{eff}(S,T)$$

- $V(S,T)$ is induced

warm up: hidden sector without matter

$$g^{-2}(\mu) = \mathrm{Re} f + \frac{b}{8\pi^2} \ln \frac{M_{Pl}}{\mu} + \frac{T(G)}{8\pi^2} \ln g^{-2}(\mu) - \frac{T(G)}{16\pi^2} K \quad (*)$$

$$\Rightarrow \mu \frac{dg}{d\mu} = -\frac{g^3}{16\pi^2} \frac{3T(G)}{1 - \frac{T(G)}{8\pi^2} g^2}$$

exact β-function Shifman Vainshtein (to all orders)

gauge coupling becomes strong at scale Λ_c where

$$g^{-2}(\Lambda_c) - \frac{T(G)}{8\pi^2} \ln g^{-2}(\Lambda_c) = 0$$

$$\Rightarrow \boxed{\Lambda_c = \mu \cdot e^{\frac{8\pi^2}{b} g^{-2}(\mu)} \cdot g^{-\frac{2T(G)}{b}}(\mu) \overset{(*)}{=} M_{Pl}\, e^{\frac{8\pi^2}{b}\mathrm{Re} f}\, e^{K/b}}$$

$\frac{d\Lambda_c}{d\mu} = 0$ (RG-invariant scale)

Wilsonian Re f appears

relation of $\langle\lambda\lambda\rangle$ to Λ_c depends on normalization

in superspace $\lambda_\alpha^{(S)} = W_\alpha|_{\theta=\bar\theta=0}$

canonically normalized $\lambda_\alpha^{phys} = \lambda_\alpha^{S} \cdot e^{K/4}$

$$\Rightarrow \boxed{\langle\lambda\lambda\rangle^{phys} = \Lambda_c^3 = M_{Pl}^3 \, e^{\frac{24\pi^2}{b}\mathrm{Re}f} \, e^{K/2}}$$

$$= e^{K/2}\langle\lambda\lambda\rangle^{(S)}$$

$$\Rightarrow \boxed{\langle\lambda\lambda\rangle^{(S)} = M_{Pl}^3 \, e^{\frac{24\pi^2}{b}\mathrm{Re}f}}$$

exact to all orders but only need to compute f to 1 loop

Veneziano & Yankielowicz:

$U := \frac{1}{16} W^\alpha W_\alpha$ composite chiral superfield

$$\langle U\rangle = \langle\lambda\lambda\rangle^{(S)} = M_{Pl}^3 \, e^{\frac{24\pi^2}{b} f}$$

Effective superpotential for U:

$$W(U,S,T) = \frac{1}{4} U f(S,T) + U\left[\frac{T(G)}{32\pi^2}\ln\frac{U}{M_{Pl}^3} + \text{const.}\right]$$

Minimum of potential

$$V = e^K\left[|DW|^2 - 3|W|^2\right] = \underbrace{e^K\left|\frac{\partial W}{\partial U}\right|^2}_{O(\Lambda_c^9)} + O\left(\frac{\Lambda_c^6}{M_{Pl}^6}\right)$$

$\Rightarrow$ at leading order $\frac{\partial W}{\partial U} = 0 \Leftrightarrow \langle U\rangle = M_{Pl}^3 \, e^{-\frac{8\pi^2}{T(G)} f(S,T)}$ ✓

$$W_{mod}(S,T) := W(\langle U\rangle, S, T) = -\frac{T(G)}{32\pi^2}\langle U\rangle = -\frac{T(G)}{32\pi^2} M_{Pl} \, e^{-\frac{8\pi^2}{T(G)} f(S,T)}$$

$U \ln U$-term can also be determined from Kähler transformations:

$$W_\alpha \to W_\alpha e^{-\frac{\Xi}{3}} \Rightarrow U \to U e^{-F}$$

$$f \to f + \frac{T(G)}{8\pi^2} F$$

$$\Rightarrow W(U,S,T) \to e^{-F} W(U,S,T) \quad ✓$$

Include hidden matter fields Q^I

$$W^{tree} = \tfrac{1}{2} M_{IJ}(T)\, Q^I Q^J + \tfrac{1}{3} Y_{IJK}(T)\, Q^I Q^J Q^K + \dots$$
$$\equiv \sum_t Y_t(T)\, \tilde{Q}^t$$

In addition $\langle \lambda\lambda \rangle$ matter condensate can form $\langle \tilde{Q}^t \rangle$ — not relevant

$$W(U, \tilde{Q}, S, T) = W^{tree}(\tilde{Q}, T) + \tfrac{1}{4} U f(S,T) - \Xi(U, \tilde{Q})$$

W should be invariant under all symmetries (also anomalous)

demand Kähler invariance: $U \to U e^{-F}$

$f \to f - \frac{c}{8\pi^2} F$

$\tilde{Q} \to \tilde{Q}$

$$\Rightarrow \Xi = \frac{U}{32\pi^2}\left[c \ln \frac{U}{M_{Pl}^3} - P(\tilde{Q}) \right]$$

demand coordinate invariance:

$$f \to f - \sum_R \frac{T(R)}{4\pi^2} \ln \det \gamma^{(R)}$$

$$\Rightarrow \boxed{P(\tilde{Q}) \to P(\tilde{Q}) + 2 \sum_R T(R) \ln \det \gamma^{(R)}}$$

transformation of Q^I is known

$\Rightarrow$ $P(\tilde{Q})$ is of the determinantal variety

Example 1: SQCD, $G = SU(N_c)$, $N_f < N_c$

$$W^{tree} = M_{IJ}\, Q_L^I \cdot Q_R^J \qquad N \otimes \bar{N}$$

$c = N_f - N_c$
$b = N_f - N_c$

only condensate: $\tilde{Q}^{IJ} = \langle Q_L^I \cdot Q_R^J \rangle$

coordinate transf.: $Q_L^I \to \gamma_{L,J}^I\, Q^J$

$Q_R^I \to \gamma_{R,J}^I\, Q_R^J$

$$\Rightarrow P = \frac{\ln \det \tilde{Q}}{\Lambda^{2N_f}} + \text{const.}$$

Taylor Veneziano Yankielowicz Affleck Dine seiberg

Example 2: $N_f = 1$, singlet A

$$W^{tree} = Y_1(T)\, A\, Q_L \cdot Q_R - \tfrac{1}{3} Y_2(T) A^3$$

P as before

$$\left.\begin{aligned} \frac{\partial W}{\partial A} &= 0 \\ \frac{\partial W}{\partial Q} &= 0 \\ \frac{\partial W}{\partial A} &= 0 \end{aligned}\right\} \Rightarrow$$

$$\langle U \rangle \sim M_{Pl}^3\, e^{+\frac{2\pi^2}{b} f} \left(\frac{Y_1^3}{Y_2}\right)^{-\frac{1}{b}}$$

$$\langle Q \rangle \sim M_{Pl}^2\, e^{\frac{4\pi^2}{b} f}\, Y_1^{\frac{3-3N_c}{3N_c-1}}\, Y_2^{\frac{N_c-1}{3N_c-1}}$$

$$\langle A \rangle \sim M_{Pl}\, e^{\frac{2\pi^2}{b} f}\, Y_1^{-\frac{1}{b}}\, Y_2^{\frac{N_c}{b}}$$

$$W_{eff}(S,T) \sim M_{Pl}^3\, e^{\frac{2\pi^2}{b} f(S,T)} \left(\frac{Y_1^3}{Y_2}\right)^{-\frac{1}{b}}$$

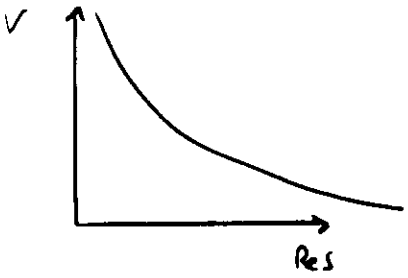
Applying to String Theory: (no hidden matter)

$$f(S,T) = S + \frac{f^{(1\text{loop})}(T)}{16\pi^2}$$

$$W(S,T) = -\frac{T(G)}{32\pi^2} M_{Pl}^3 \, e^{-\frac{8\pi^2}{T(G)} S} \, e^{-\frac{1}{2} f^{(1\text{loop})}(T)}$$

$$V(S,T) = e^{K}\left[D_i W \, g^{i\bar{j}} \, D_{\bar{j}} \bar{W} - 3|W|^2 \right]$$

$$D_i W = \partial_i W + (\partial_i K) W$$



Minimum at $\langle \mathrm{Re}S \rangle = \infty$
$\hat{=}$ $g^2 = 0$

Dilaton problem

Stabelizing the dilaton: Krasnikov mechanism ("racetrack" models)

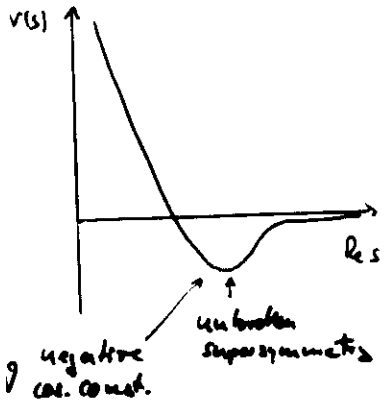
Krasnikov
Kaplunovsky
Casas
Lalak
Munoz
Ross
Taylor

2 hidden gauge groups $G_1 \otimes G_2$

$$W = -\frac{M_{Pl}^3}{32\pi^2}\left\{ T_1(G_1)\, e^{-\frac{8\pi^2}{T_1(G)} S - \frac{1}{2} f_1} + T_2(G_2)\, e^{-\frac{8\pi^2}{T_2(G)} S - \frac{1}{2} f_2} \right\}$$

Look for minimum of V at weak coupling (large S)

$f_{1,2}$ = const for starts



$$\mathrm{Re}S \simeq \frac{1}{8\pi^2} \frac{T_1 \cdot T_2}{T_2 - T_1}\left[\ln \frac{T_1}{T_2} + \frac{1}{2}\left(\frac{f_1}{T_1} - \frac{f_2}{T_2} \right) \right]$$

(leading order)

need: T_1, T_2 large and $T_1 \sim T_2$
f_1 - f_2 large

e.g. $SU(10) \otimes SU(9)$ $\Rightarrow$ $\alpha_{GUT} \sim \frac{1}{25}$

possible improvements:

- add hidden matter → large S easier to achieve
- more than 2 condensates → cos. const. can be tuned to zero (only local minimum)
- demand S-duality (Horne + Moore)

$f^{(1\text{loop})}(T)$

include untwisted moduli of $N=1$ orbifolds

Font Ibanez Lüst Quevedo Ferrara Majumdar Veneziano Taylor Nilles Olechowski

$$f = S + \frac{T(G)}{8\pi^2} \ln \eta^2(iT)$$

$$\Rightarrow \boxed{W(S,T) = -\frac{T(G)}{32\pi^2} M_{Pl}^3 \, e^{-\frac{8\pi^2}{T(G)} S} \, \eta^{-2}(iT)}$$

(one condensate)

same dilaton problem but

$$|W(S,T)| \xrightarrow{Re\,T \to \infty} e^{\frac{\pi}{12}(T+\bar{T})}$$

$\Rightarrow$ V has a minimum at small T, no runaway in T ?

final: (numerically)
- $\langle T \rangle \sim O(1)$ T is stabelized
- supersymmetry is broken $\langle F_T \rangle \neq 0$!
- negative cos. const.
- dilaton problem

Font Ibanez Lüst Quevedo

$W(S,T)$ can also be derived directly by demanding $SL(2,\mathbb{Z})$ without relying on gaugino condensation

$$W(T) \to W(T)\, e^{-F}, \quad F = \ln(icT+d)$$

$\Rightarrow$ W is modular form of $SL(2,\mathbb{Z})$

$$\Rightarrow W(T) = \frac{H[j(T)]}{\eta^2(iT)}$$

H is arbitrary polynom of j-function

in gaugino condensation : $H = const$

for other "stringy" non-perturbative effects:

$H \neq const.$

$\Rightarrow$ singularity at finite T or exponential blow up at large T

but can tune cos. const $= 0$

Put it all to gether:

de Carlos
Casas
Muñoz

- Large S is much easier to obtain with hidden matter present. This is the more realistic case any way. supersymmetry never broken by hidden matter

① one condensate, no $f(T)$

$\langle F_s \rangle = 0$, $\langle S \rangle = \infty$, $\langle V \rangle = 0$

② two condensates, no $f(T)$

$\langle F_S \rangle = 0$, $\langle S \rangle$ fixed, $\langle V \rangle < 0$

③ one condensate, $f(T) = \frac{c}{8\pi^2} \ln \eta^{-2}(iT)$

$\langle F_S \rangle = 0$, $\langle S \rangle = \infty$, $\langle F_T \rangle \neq 0$, $\langle T \rangle$ fixed

$\langle V \rangle < 0$

④ two condensates, $f(T) = \frac{c}{8\pi^2} \ln \eta^{-2}(iT)$

$\langle F_S \rangle = 0$, $\langle S \rangle$ fixed, $\langle F_T \rangle \neq 0$, $\langle T \rangle$ fixed

$\langle V \rangle < 0$

Note: always $\langle F_S \rangle = 0$, almost always $\langle V \rangle < 0$

Summary

Gaugino condensation in string theory

- induces $V(S,T)$
- large $\langle S \rangle$ and $\langle T \rangle \sim O(1)$ can be arranged
- supersymmetry can be broken
- cos. const. can be tuned to zero

But: There is no model at present where it all happens at the same time

Lesson: Study of gaugino condensation shows that non-perturbative effects might indeed solve some of the phenomenological problems left by the perturbative analysis

NON-PERTURBATIVE EFFECTS II

alternative 2

Parametrize the unknown non-perturbative effects

Brignole Ibanez Kaplunovsky Lüst Muñoz T.L.

will we learn anything?

- many "signatures" at M_{weak} are encoded in perturbative string couplings and can be computed

- interesting "lessons" for susy phenomenology

SPECTRUM (N=1 supersymmetric)

- graviton, gauge bosons
- observable sector:

$$SU(3) \times SU(2) \times U(1) \times ?$$

matter Q^I (quarks, leptons, Higgs, ... ?)

- hidden sector:

$G^{(hid)}$

hidden matter A^α

- moduli ϕ^i

flat directions of $V^{(eff)}$ at perturbation level

ASSUMPTIONS about non-perturbative physics

- Non-perturbative potential has stable minimum
- Hidden fields become massive or confined at $M_{(hid)}$: $M_W \ll M_{(hid)} \ll M_{Pl}$
- $\langle F^{(hid)} \rangle = \langle D^{(hid)} \rangle = 0$

$\Rightarrow$ "integrate out" hidden sector

supersymmetric $V^{(eff)}(Q, \phi)$ induced

- $V^{(eff)}_{(Q,\phi)}$ has no flat directions, (S, T^i are fixed)
- cos. constant vanishes
- $\langle F^i \rangle \neq 0$, i.e. supersymmetry spontaneously broken in the moduli sector

The couplings of $\mathcal{L}_{eff}(\phi, Q)$: W, K, f

$$W = W^{(tree)} + W^{(ind)}$$

($W^{(tree)}$: can be computed)

$$W^{(tree)} = \frac{1}{3} \tilde{y}_{IJK}(\phi)\, Q^I Q^J Q^K + \cdots$$

$$W^{(ind)} = \hat{W}(\phi) + \frac{1}{2} \tilde{\mu}_{IJ}(\phi)\, Q^I Q^J + \cdots$$

($\hat{W}$: "unknown"; $\tilde{\mu}$: "known")

$$K = \kappa^{-2} \hat{K}(\phi, \bar{\phi}) + Z_{I\bar{J}}(\phi, \bar{\phi})\, Q^I \bar{Q}^{\bar{J}}$$

("known")

$$+ \left[\frac{1}{2} H_{IJ}(\phi, \bar{\phi})\, Q^I Q^J + \text{h.c.} \right]$$

$$+ O(Q^3) + \cdots$$

$G = \prod_a G_a$

("known")

$$g_a^{-2}(\phi) = \mathrm{Re}\, f_a(\phi) + \frac{b_a}{8\pi^2} \ln \frac{M_P}{P}$$

Shifman, Vainshtein, Dine, Seiberg, Ferrara, Kounnas, Zwirner, ...

$$+ \frac{C_a}{16\pi^2} \hat{K}(\phi, \bar{\phi}) + \frac{T(G)}{8\pi^2} \ln g_a^{-2}(\phi, \bar{\phi}, P)$$

$$- \sum_r \frac{T_a(r)}{8\pi^2} \ln \det Z^{(r)}(\phi, \bar{\phi}, P)$$

Supersymmetry breaking in the moduli/dilaton sector

$$V(\phi, \bar{\phi}, Q=0) = e^{K(\phi,\bar{\phi})} \left[D_i \hat{W}\, g^{i\bar{j}}\, D_{\bar{j}} \hat{W}^* - 3 |\hat{W}|^2 \right]$$

order parameter for supersymmetry breaking

$$F_i := D_i \hat{W} = \partial_i \hat{W} + (\partial_i K) \hat{W}$$

$\langle F_i \rangle \neq 0 \Rightarrow$ spontaneous supersymmetry breaking

<u>assume</u> $\hat{W}(\phi)$ is such that

- some $\langle F_i \rangle \neq 0$
- all $\langle \phi^i \rangle$ fixed
- $\langle V \rangle = 0$ (vanishing cos. const.)
- $m_{3/2} = O(1\ \mathrm{TeV})$

$\Rightarrow$ ompak effects in the observable sector

parameters to appear: $\langle \hat{W} \rangle \sim m_{3/2}$

$\langle \partial_i \hat{W} \rangle \sim F_i$

In the observable sector one finds at leading order (neglecting $\frac{m_{3/2}}{M_{Pl}}$ contributions) (flat limit)

Barbieri Ferrara Savoy Soni Weldon

soft supersymmetry breaking terms

- $\tilde{m}_a = F^i \partial_i \ln g_a^{-2}$ gaugino mass

- $W^{eff} = \frac{1}{2} \mu_{IJ} Q^I Q^J + \frac{1}{3} Y_{IJK} Q^I Q^J Q^K$

  effective μ-term $\quad \| \quad e^{\hat{\kappa}/2} \hat{Y}_{IJK}$

$$u_{IJ} = e^{\hat{\kappa}/2} \hat{\mu}_{IJ} + \underbrace{m_{3/2} H_{IJ} - \bar{F}^{\bar{i}} \bar{\partial}_{\bar{i}} H_{IJ}}_{O(m_{3/2})}$$

Goldstino mass-term

$\hat{\mu}_{IJ}$: can be large; dangerous Kim, Nilles

- $V^{eff} = \sum_a \frac{g_a^2}{2} [\bar{Q}^I Z_{IJ} T_a Q^J]^2 + \underbrace{\partial_I W^{eff} Z^{IJ} \partial_J \bar{W}^{eff}}_{\text{globally supersymmetric potential}}$

$+ m^2_{I\bar{J}} Q^I \bar{Q}^J + \frac{1}{3} A_{IJK} Q^I Q^J Q^K + h.c.$

scalar mass ↑; A_{IJK}: A-terms

$+ \frac{1}{2} B_{IJ} Q^I Q^J + h.c.$

↑ ⊥

soft terms are expressed as geometrical quantities on the moduli space

- $m^2_{I\bar{J}} = m^2_{3/2} Z_{I\bar{J}} - F^i \bar{F}^{\bar{j}} R_{I\bar{J}i\bar{j}}$

  ↑ non-universal (flavor dependent) scalar mass

Non-universality is controlled by perturbative coupling: $R_{I\bar{J}i\bar{j}} = \partial_i \partial_{\bar{j}} Z_{I\bar{J}} - \Gamma^N_{iI} Z_{N\bar{J}} \bar{\Gamma}^{\bar{L}}_{\bar{j}\bar{J}}$

- $A_{IJK} = F^i \mathcal{D}_i Y_{IJK} \neq A \cdot Y_{IJK}$

$\mathcal{D}_i Y_{IJK} = \partial_i Y_{IJK} + \frac{1}{2} \hat{K}_i Y_{IJK} - \Gamma^N_{i(I} Y_{JK)N}$

↑ non-universality controlled by perturbative couplings

- $B_{IJ} = F^i \mathcal{D}_i \mu_{IJ} - m_{3/2} \mu_{IJ} \neq B \cdot \mu_{IJ}$

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non-perturbative parameters: $m_{3/2}$, F^i

12 perturbative couplings: $\hat{K}$, Z_{IJ}, H_{IJ}, Y_{IJK}, f_a

String Theory

$\phi^i = (S, T^i)$

perturbative couplings:

$\hat{K}(S,T^i) = -\ln(S+\bar{S}) + \hat{K}(T^i,\bar{T}^i)$ + loop corrections

$f_a(S,T) = k_a S + f_a^{(1)}(T^i)$

S-independent:

$Z_{I\bar{J}}(T^i,\bar{T}^i)$, $H_{IJ}(T^i,\bar{T}^i)$, $Y_{IJK}(T^i)$

non-perturbative couplings:

$\hat{W}(S,T^i)$, $\tilde{K}_{I\bar{J}}(S,\bar{T}^i)$

$H_{IJ}(T^i,\bar{T}^i) \neq 0$ generically

Antoniadis
Gava
Narain
Taylor

$\Rightarrow$ contribution to μ-term of $O(m_{3/2})$

Supersymmetry Breaking

2 limits:

(a) $\langle F^S \rangle \gg \langle F^T \rangle$

(b) $\langle F^S \rangle \ll \langle F^T \rangle$

occurs in gaugino condensation

((a)+(b): Brignole
Ibanez
Muñoz)

Barbieri
Hall
Horetti
T.L.

(a) $\langle F^S \rangle \gg \langle F^{III} \rangle$

$$m_a = \frac{\sqrt{3}}{m} \, m_{3/2}$$

$$m^2_{IJ} = m^2_{3/2} \, Z_{IJ}$$

$$A_{IJK} = -\sqrt{3} \, m_{3/2} \, (\tfrac{1}{3} \underbrace{e^{\hat{\alpha}_m} \tilde{Y}_{IJK}}_{Y_{IJK}})$$

$\Rightarrow$ 3 independent parameters: $m_{3/2}, \mu_{IJ}, B_{IJ}$
(MSSM: 5 parameters)

if $\tilde{\mu} = 0 \Rightarrow B_{IJ} = 2 m^2_{3/2} \mu_{IJ}$

$\Rightarrow$ 2 independent parameters: $m_{3/2}, \mu_{IJ}$

Next:

- assume MSSM
- assume $M_g \sim 3 \cdot 10^{16}$ GeV

- Spectrum of MSSM: additional Higgs doublet

$$W = \mu H_1 H_2 + \sum_{\text{generations}} Y_u Q_L U_R H_2 + Y_d Q_L D_R H_1 + Y_e L_L E_R H_1$$

- Higgs potential: $H_1 = \begin{pmatrix} h_1^+ \\ h_1^0 \end{pmatrix}$, $H_2 = \begin{pmatrix} h_2^- \\ h_2^0 \end{pmatrix}$

$$V = \frac{1}{8}(g_1^2 + g_2^2)\left[|h_1|^2 - |h_2|^2\right]^2 + m_1^2 |h_1|^2 + m_2^2 |h_2|^2 - m_3^2 h_1 h_2 + \text{h.c.}$$

$$m_1^2 = m_2^2 = m_{3/2}^2 + \mu^2, \qquad m_3^2 = -2 m_{3/2} \mu$$

- RG-analysis: only keep Y_{top}

$$m_i \to m_i(Y_{top})$$

- electroweak symmetry breaking induced: Ibanez Ross ⋮

$$2 m_3^2 < m_1^2 + m_2^2, \qquad m_1^2 \cdot m_2^2 < m_3^4$$

$$M_Z^2 = 2 \frac{m_1^2 - m_2^2 \tan^2\beta}{\tan^2\beta - 1}$$

$$\tan\beta = \frac{\langle h_2 \rangle}{\langle h_1 \rangle}, \qquad \sin 2\beta = \frac{2 m_3^2}{m_1^2 + m_2^2}$$

(b) $\langle F^{\mathbb{1}} \rangle \gg \langle F^{5} \rangle$

- encountered in "string-inspired" gaugino cond.
- model dependent
- $m_{IS}^2 = O(m_{3/2})$

  $A_{ISk} = O(m_{3/2}\, Y_{ISk})$

  m_a generated by string loops

  Coste, Font, Ibañez, Lust, Quevedo, Carlos Casas Muñoz

  $\Rightarrow$ suppressed:

$$m_a = C_a \cdot \frac{\alpha_a}{4\pi} \cdot m_{3/2} \ll m_{3/2}$$

C_a: $O(1)$

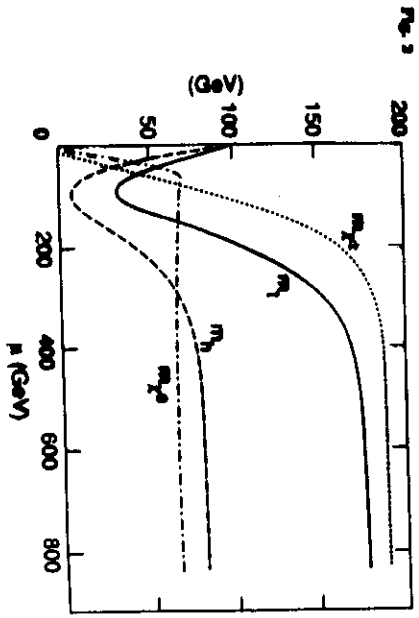
- $H_{IS}(T,F) \neq 0$ generically $\Rightarrow$ μ-term is generated
- m_{IS}^2 is non-universal

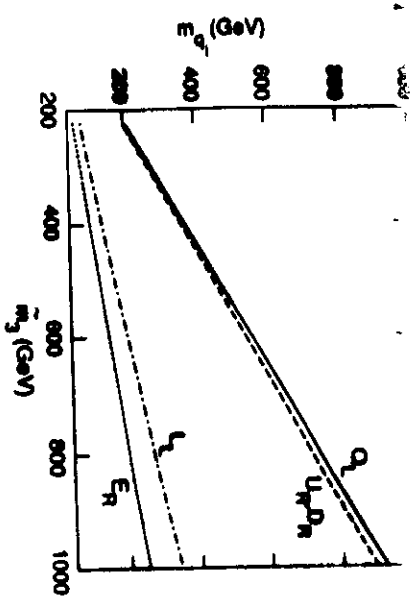
  $\Rightarrow$ constraint on R_{ISij} from FCNC

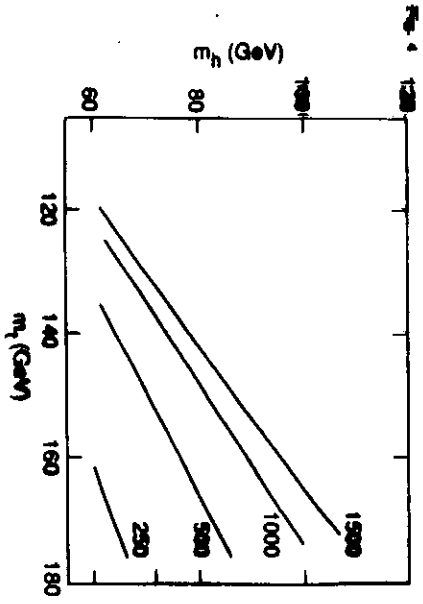
  Dine, Kagan, Samuel, Nir, Seiberg, ...

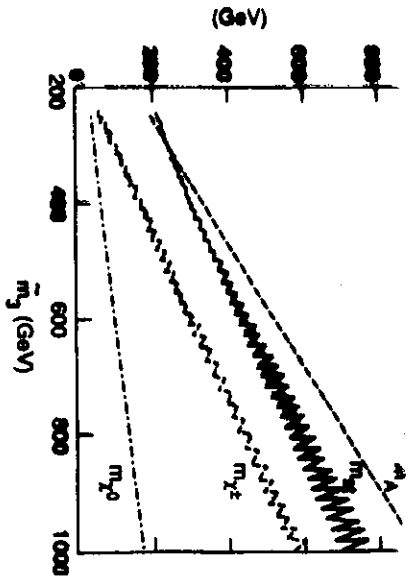
- m_a is non-universal due to C_a
- $m_{gaugino} \sim O(m_{3/2})$ $\Rightarrow$ problem with nucleosynthesis

  Banks, Kaplan, Nelson







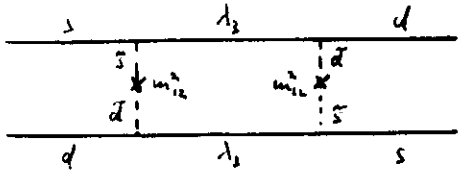


Problems with FCNC

constraints on off-diagonal m^2_{IJ} from gluino (photino) exchange in box (Penguin) diagrams

Donoghue
Nilles
Wyler
Gabbiani
Masiero

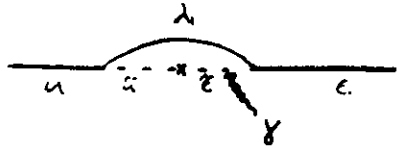
e.g. $K-\bar{K}$ mixing



$$\frac{m^{2\,(d)}_{12}}{m^2_{av}} \approx 6\cdot 10^{-3} \left(\frac{\tilde{m}_{av}}{1\,TeV}\right)^2$$

↖ average squark mass

- $\mu \to e\gamma$



$$\frac{m^{2\,(d)}_{12}}{m^2_{av}} \simeq 0.1 \cdot \left(\frac{\tilde{m}_{av}}{1\,TeV}\right)^2$$

2) Can we tolerate non-universal scalar masses?

D. Choudhury
F. Eberlein
A. Königs
S. Pokorski
J. L.

important point:

| soft terms are generated at <u>high energies</u> M_{GUT} (M_{Pl})
| FCNC constraints hold at <u>M_{weak}</u>

⇒ need to take renormalization effects into account

RG equations:

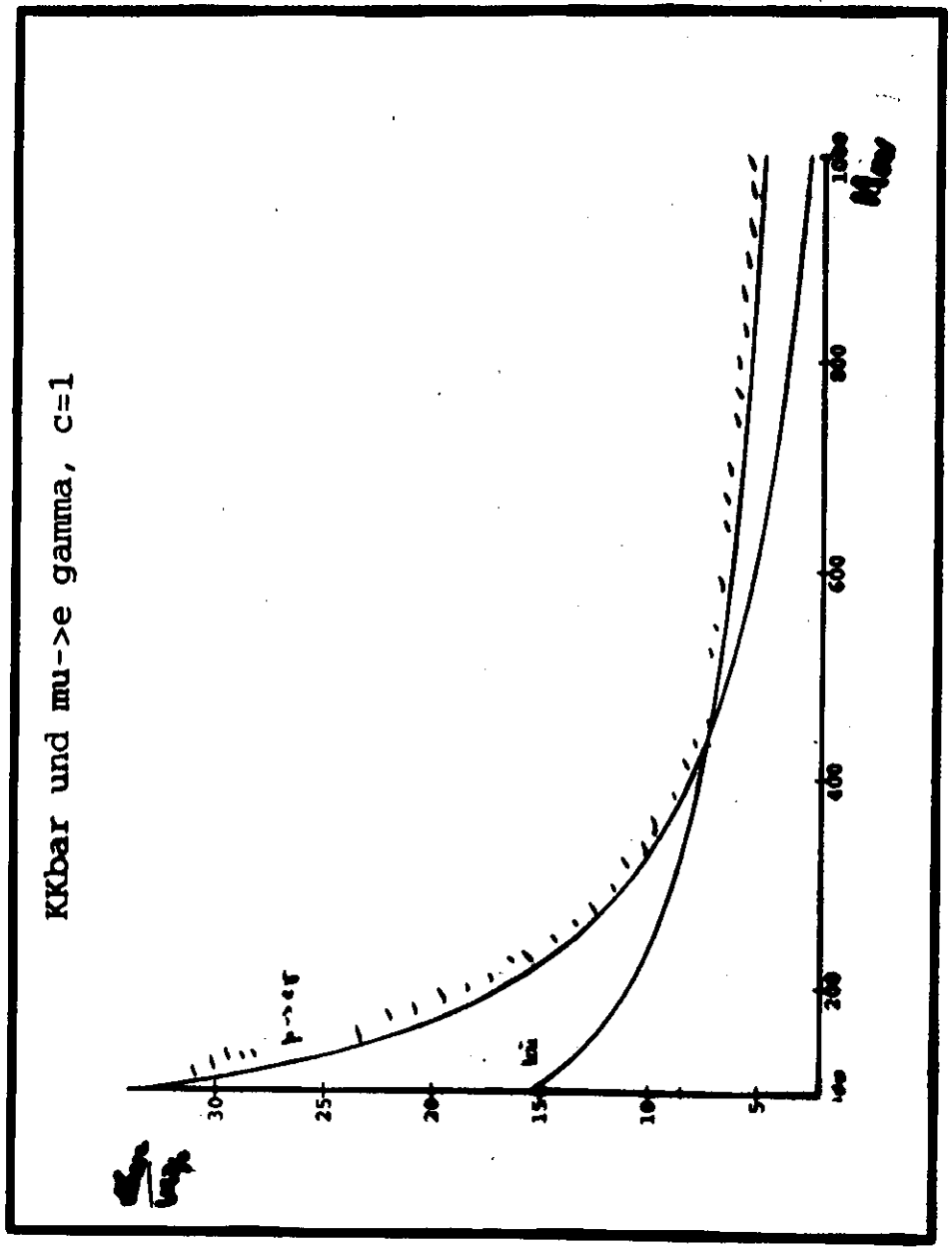
$$\frac{d}{dt} m^2_{IJ} = \frac{4}{3\pi} \delta_{IJ} \alpha_s \tilde{m}^2_{\tilde{g}} - \frac{1}{6\pi^2} m^2_{h} A^2_{IJ} + \dots$$

↑ gaugino mass

observe: diagonal mass terms are enlarged ($\tilde{m}_i$)
off-diagonal terms are diminished (A^2)
iff A-terms are non-universal

⇒ avoid problem with FCNC

- $m_{3/2}$ high — Dine, Kagan, Samuel
- large gluino mass $\tilde{m}_{\tilde{g}}$ — Brignole, Ibanez, Muñoz
- non-universal large A-terms



Summary

- Parametrization of non-perturbative effects
- interesting low energy properties are controlled by perturbative couplings:

  non-universal scalar masses
  non-universal A-terms
  gaugino masses

- μ-term of $O(m_{3/2})$ is generated
- $\langle F_S \rangle$ breaking: universal soft terms
  very constrained but not ruled out
  light Higgs
- $\langle F_T \rangle$ breaking: model dependent
  non-universal scalar masses
  non-universal A-terms
  very light gauginos
  trouble with FCNC

  ⇒ use to constrain possible string vacua