SUSY breaking parameters and underlying theory.

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§1. Introduction

§2. Gaugino masses

§3. Scalar masses

§4. Fermion masses

◎ Summary

Superparthers の発見

$\Downarrow$

(Low-energy) SUSY は正しい。

S-spectrum

$\Downarrow$

◎ その先の "Underlying Theory" が見えてくる。

(GUTs, Supergravity, String, ...)

◎ Fermion masses

$m_t = 174\ \text{GeV}$

$m_b \approx 5\ \text{GeV}$

$\vdots$

$m_e = 0.5\ \text{MeV}$

Why? "理由" がわかる。

§1 Introduction

Supersymmetry ⇐ several motivations
- Superstring
- Hierarchy problem
- gauge coupling unification
- ⋮

⇓

Superpartner の存在.
- gaugino λ^a
- Squark, slepton $\phi_{\tilde{q}_i}, \phi_{\tilde{l}_i}$
- Higgsino.

⇒ Table

結果 → S-particle は重い.

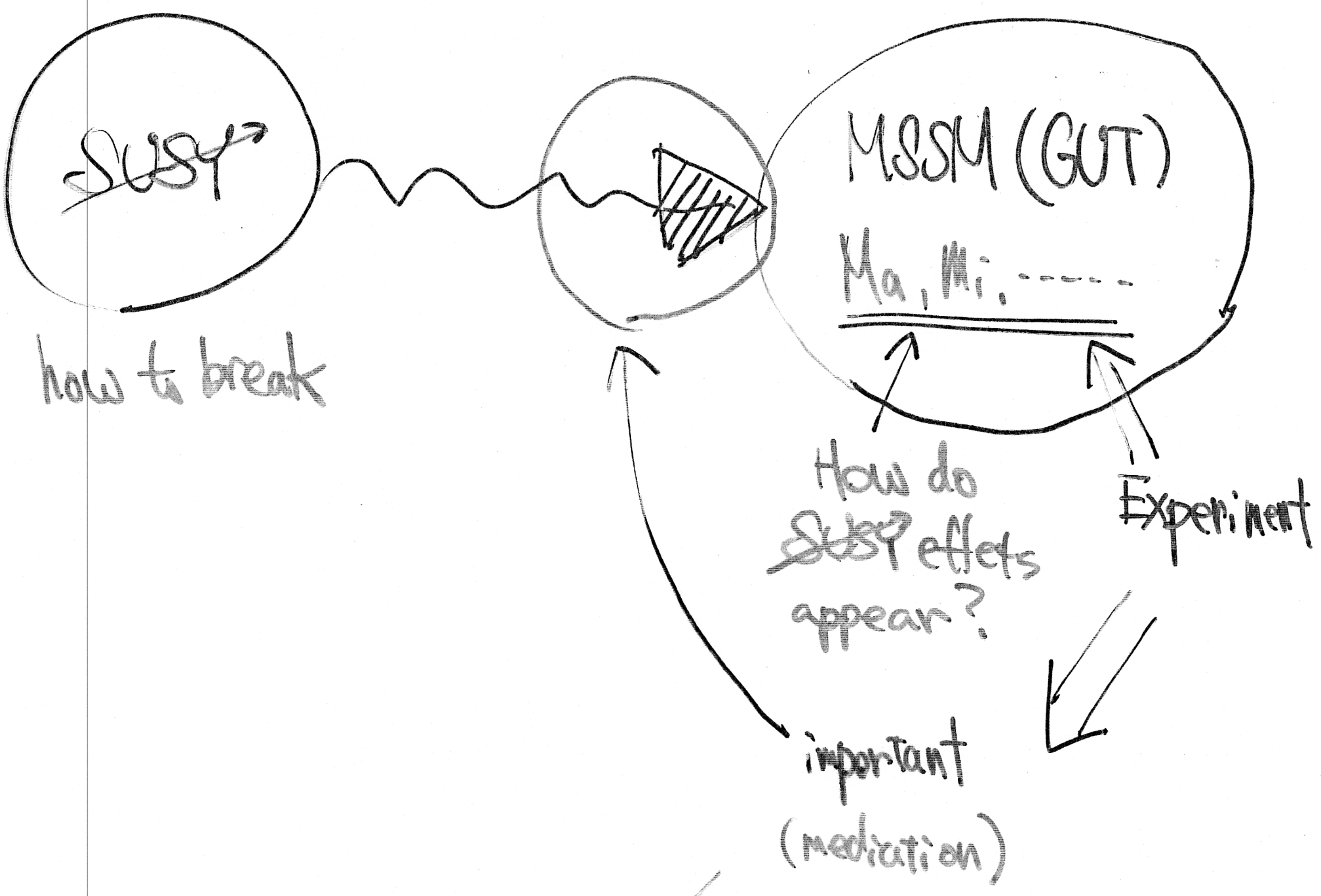
⇓

SUSY は破れている.

- M_a: gaugino masses
- m_i: scalar masses
- ⋮

$a = SU(3), SU(2), U(1)_Y$

$i = \tilde{Q}, \tilde{u}, \tilde{d}, \tilde{L}, \tilde{e}$



How ~~SUSY~~ effects appear depends on underlying theory.

We could see
some information on underlying theory.

- GUTs
- String
- ⋮

② SUSY breaking

F-term

$\langle F \rangle \neq 0$

$\Downarrow$

$\cancel{\text{SUSY}}$

$\Downarrow$

M_a, m_i, ……

c.f. Higgs mechanism

$\langle H \rangle \neq 0$

$\Downarrow$

$\cancel{\text{Symmetry}}$. $SU(2)\times U(1)_Y \rightarrow U(1)_{em}$

M_Z, M_W, m_t, m_b, …… , m_e

SUSY multiplet Φ

$\phi \leftrightarrow \psi \leftrightarrow F_\Phi$

scalar　spinor

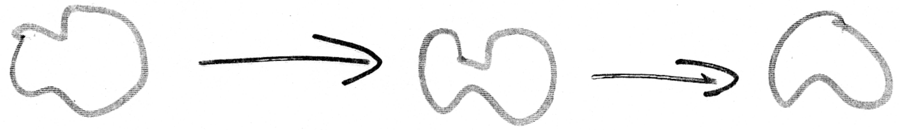
- どのΦが $\langle F_\Phi \rangle \neq 0$ となるか？
- Gauge, Quark, Lepton Supermultiplets が Φ, F_Φ とどう結合しているか？

重要.

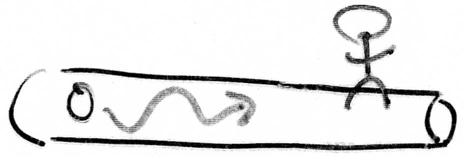
||

underlying theory

① Superstring (Theory of Everything)



Consistent construction → "10次元分"



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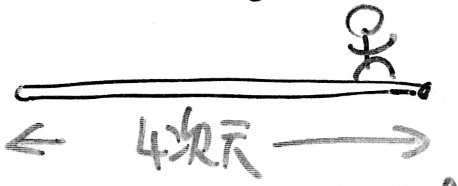


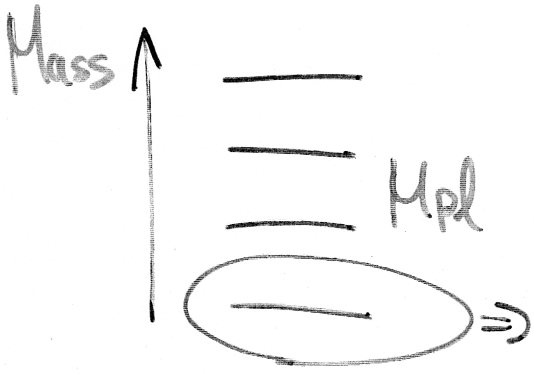
※6次元

Compactification

Compactification
~~SUSY~~ } pure stringy calculation?

② String-inspired models (4D effective theory)

振動



⇒ lightest modes

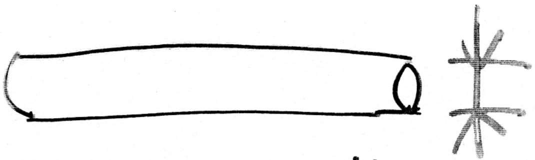
⇓

我々の世界に
顔を出す.

② lightest (massless) modes

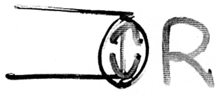
- Gauge multiplets
- Quark, Lepton multiplets
- Higgs multiplets
- graviton multiplets
- dilaton multiplets S : 全体的スケールを支配
- moduli multiplets T_i

コンパクト空間の自由度



すべてのゲージ群に対し singlet

"Theory of Everything"



⇓

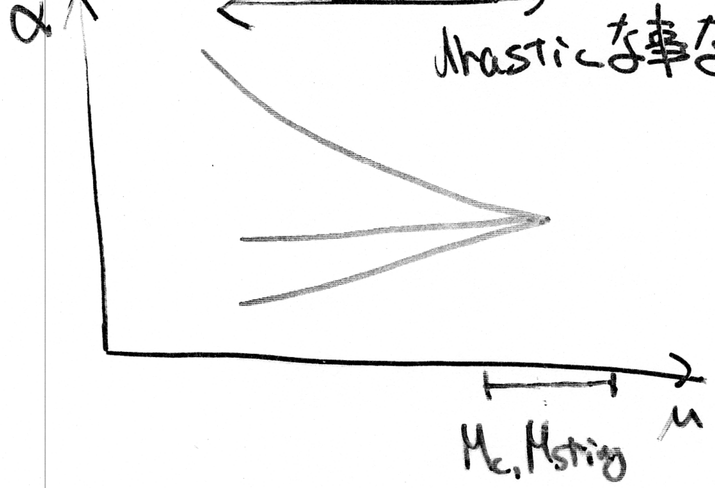
ゲージ結合 g, コンパクト空間の大きさ

⇑ も与えられる ⇑

$\langle S \rangle$ $\langle T \rangle$

scalar場の真空期待値

これらのF-termsが ~~SUSY~~ に寄与すると期待.



drasticな事なし

→ GUTsの様子が見える?

$E_8 \times E_8'$, $SO(32)$, ...

→ $SU(3) \times SU(2) \times U(1)$

stringy breaking

この辺の様子が見える?

$$M_c, M_{string} \sim M_I \sim \text{TeV} \ ?$$

・ある(複数の) F-terms が non-zero

↓

gaugino masses, scalar masses, ...

がどうなるか?

§2 Gaugino masses

3つのGauginoの質量比を知りたい.

$M_3 : M_2 : M_1 = ?$

② <u>Gauge kinetic function</u> $f_a(\Phi)$

$$\int d^2\theta\, f_a(\Phi) W^a W^a \qquad W^a : (\lambda, F^{\mu\nu})$$

$a = SU(3), SU(2), U(1)_Y$

$$= \underbrace{f_a(\phi)}_{=1/g_a^2} F^{a\,\mu\nu} F^a_{\mu\nu} + \underbrace{F f_a}_{=f_a' \cdot F_\Phi} \lambda^a \lambda^a$$

gauge coupling　　　Gaugino mass

$$M_a = \frac{f_a'}{2 f_a} \cdot F_\Phi$$

(どんな理論を考えるか)

理論 $\Rightarrow$ $f_a(\Phi)$

Gaugino masses	理論(の可能性)
Universal $M_3 : M_2 : M_1$ (at M_X) $1 : 1 : 1$	• dilaton-dominat ~~SUSY~~ • Naive GUTs (with $F_{\mathbf{1}}$)
Non-universal $M_3 : M_2 : M_1$ (at M_X)	
$2 : -3 : -1$	SU(5) GUT with F_{24}
$10 : 5 : 1$	Kaluza-Klein mediation (heavy modes の loop 補正)
Free	D-brane

2-1 Universal gaugino masses

$M_3 : M_2 : M_1 = 1 : 1 : 1$ at M_X

$\int d^2\theta f_a(\Phi) W^a W^a$, f_a : universal

(例) $\int d^2\theta S W^a W^a$ (heterotic) String-inspired model

S : dilaton

$\Downarrow$

$$\underbrace{S}_{= 1/g_a^2} F^{a\mu\nu} F^a_{\mu\nu} + \underbrace{\frac{F_S}{2S}}_{= M_a} \lambda$$

Gauge coupling unification, Universal gaugino mass

① 共通のD-brane (type I string, Type IIB ...)

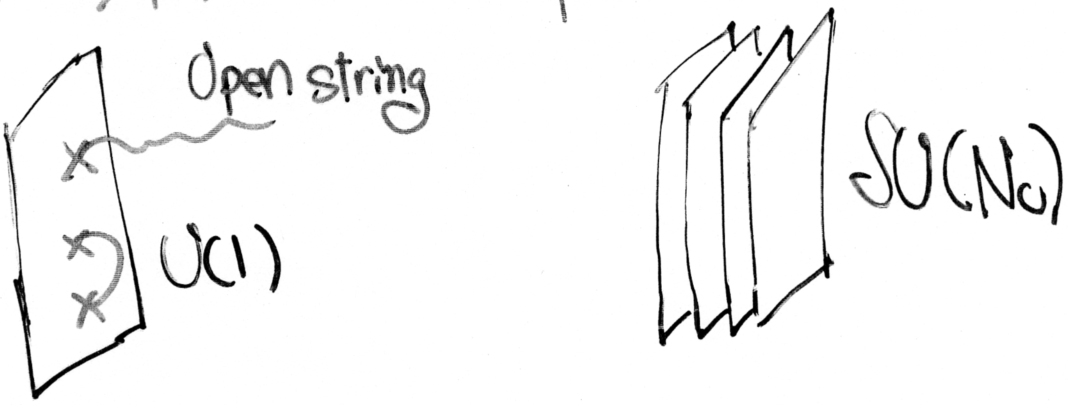
② Naive GUTs

f_a : SU(5) singlet
(SO(10))

2-2 Non-universal gaugino masses

① D-brane

M_3/M_2 = Free parameter



$SU(3)\times SU(2)\times U(1)_Y$ 異なる種類のD-braneから起因

(出どころが異なる)

f_a, M_a は Non-universal

例) D5 brane (我々の3次元空間 + extra 2次元空間)

$$\int d^4x \underbrace{\int^R d^2y}_{\text{extra 空間}} \underbrace{e^{-\phi}}_{\text{共通}} W^a W^a$$

$$f_3 = \int_0^{R_3} d^2y_{4,5}\, e^{-\phi} = e^{-\phi} R_3^2 = T_3$$

$$f_2 = \int_0^{R_2} d^2y_{6,7}\, e^{-\phi} = e^{-\phi} R_2^2 = T_2$$

$SO(3)$ $\int d^2\theta\, T_3 W^3 W^3$

$SO(2)$ $\int d^2\theta\, T_2 W^2 W^2$

$1/g_3^2 : 1/g_2^2 = \langle T_3 \rangle : \langle T_2 \rangle$

free

$M_3 : M_2 = \frac{F_{T_3}}{T_3} : \frac{F_{T_2}}{T_2}$

free

C.f. universal case e.g. $f = S$

$1/g_3^2 \to 1/g_2^2$, $M_3 \to M_2$

$\Rightarrow$ Why g_3/g_2, M_3/M_2 ?

$R_3 : R_2$. $F_{T_3} : F_{T_2}$

Compactifiation.

SUSY breaking ?

一番よくわからないところ?

· Another example

D9 brane

$f_a = e^{-\phi} R_1 R_2 R_3 \equiv S$

◎ SU(5) GUT with F_{24}

$$M_3 : M_2 : M_1 = 2 : -3 : -1 \quad \text{at } M_X$$

$\Uparrow$

F_{Φ} : SU(5) non-singlet

c.f. $F_{\mathbb{1}}$: SU(5) singlet

$$M_3 : M_2 : M_1 = 1 : 1 : 1$$

・24表現 Higgs Φ_{24}

$$\langle \Phi_{24} \rangle = \begin{pmatrix} 2 & & & & \\ & 2 & & & \\ & & 2 & & \\ & & & -3 & \\ & & & & -3 \end{pmatrix}$$

$$SU(5) \longrightarrow SU(3) \times SU(2) \times U(1)_Y$$

$$f = \frac{1}{g^2} + \frac{\Phi_{24}}{M}$$

$$F_{24} \neq 0 \longrightarrow M_3 : M_2 : M_1 = 2 : -3 : -1$$

同様に

	$M_3 : M_2 : M_1$
F_{75}	$1 : 3 : -5$
F_{200}	$1 : 2 : 10$

§3 Scalar masses

Universal
or
Non-universal
(どんな)

$\Leftarrow \Phi, F_\Phi$ との結合.

Scalar masses	理論
Universal $m_i = m_0$ (at M_X)	
$M_{1/2}^2 = 3m_0^2$ ($M_{1/2} = -A$)	dilaton-dominant ~~SUSY~~
$A = m_0 = 0$ ($M_a \neq 0$)	Gaugino mediation
Non-universal	一般の Supergravity (String-inspired models)
$m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2 + m_{H_u}^2 = M_{1/2}^2$	String models
$M_3^2 + M_2^2 = 3m_{\tilde{t}_L}^2$	D-brane

② Universalな例 $m_i = m_0$

$$3m_i^2 = M_{1/2}^2 \quad \text{at } M_X$$

- Dilaton-dominant SUSY breaking
 (String models)

$\int d^2\theta\, S\, W^a W^a \rightarrow$ universal gaugino mass

- Dilaton → すべての matter fields と universalに結合.

$$m_i^2 = m_0^2 \;\left(= m_{3/2}^2 = \langle e^G \rangle = \langle e^K |W|^2 \rangle \right)$$

$m_{3/2}$: gravitino mass

- Cosmological constant

$$V_0 = \frac{|F_S|^2}{(2S)^2} - 3m_{3/2}^2$$

$$V_0 = 0$$

$$\Downarrow$$

$$m_i^2 = m_{3/2}^2 = \frac{|F_S|^2}{3(2S)^2} = \frac{1}{3} M_{1/2}^2$$

$$A = -M_{1/2} \quad \text{at } M_X$$

② Non-universal masses

Non-universal に結合する F_Φ

→ non-universal scalar masses

$$c_i |F_\Phi|^2 |\phi_i|^2 \longrightarrow m_i^2 |\phi_i|^2$$

その中、なんとか光を見いだそう。

孔係関係式を導こう!!

③ Sum rule

$$m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2 + m_{H_u}^2 = M_{1/2}^2 \quad \text{at } M_X$$

異なる粒子：異なる量子数をもつ

(で区別できる。)

u, d, e, ν は、異なる $U(1)_{em}$

Φ_i :(ある対称性の下で) 量子数 n_i

関係のない F_S 　　関係のある F'

$$m_i^2 = m_{3/2}^2 + n_i m'^2$$

Yukawa 結合 $Y_t t_R Q_3 H_u$

許される ⇓

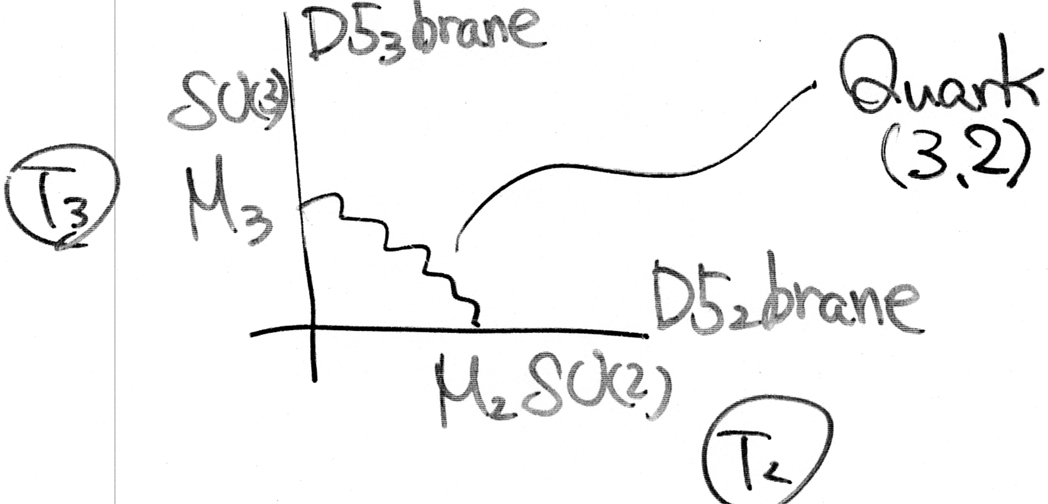
量子数の保存

$$n_{t_R} + n_{Q_3} + n_{H_u} = 0$$

$$m^2_{\tilde{t}_L} + m^2_{\tilde{t}_R} + m^2_{H_u} = 3m^2_{3/2} = M^2_{1/2}$$

at M_X

② D-brane



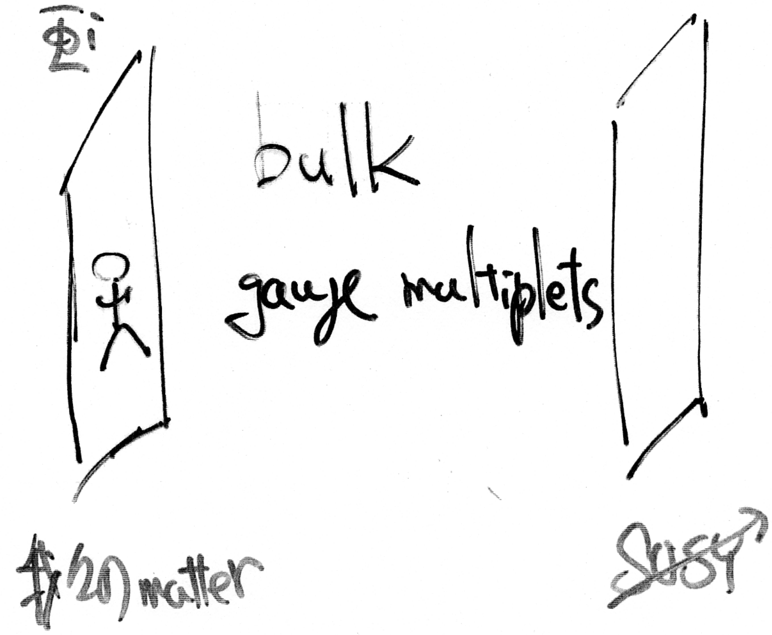
$m^2_{\tilde{Q}}$

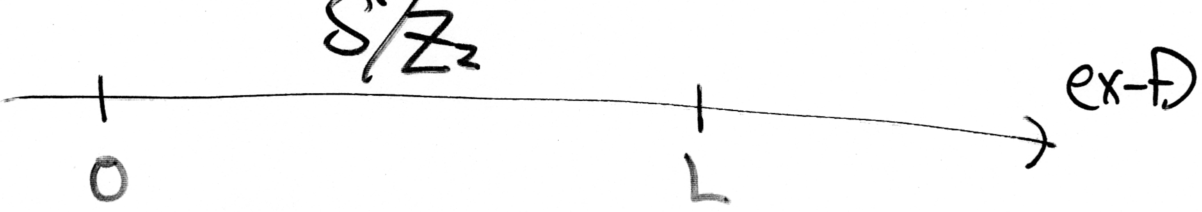
F_{T_3}, F_{T_2} のみ.

$$3m^2_{\tilde{Q}} = M_3^2 + M_2^2 \quad \text{at } M_X$$

③ Gaugino mediation

Kaplan, et. al. PRD62 (2000) 035010
Chacko, et. al. JHEP0001 (2000) 003





fixed points

$\Downarrow$

$M_a \neq 0$

$m_i^2 = 0$ "universal" | no-scale type

$A = 0$

§4 Fermion masses & mixing angles

Fermion massesの階層性 (mixing angles) ⇐ Sfermion masses 見れば説明できる.

3 families Quarks Leptons 質量 → Flavor Structure ← Squarks Sleptons 質量

Flavor Structureの一面

Flavor structureを別の方向から見られる.

異なる機構で説明可能(かも) ⇒ Squarks Sleptons (A-terms) masses に特徴が出る.

?

どのように区別する
justify する?

(3)-1 running masses at M_Z

$m_t = 165\,\mathrm{GeV}$, $m_c = 600\,\mathrm{MeV}$, $m_u = 1\sim 3\,\mathrm{MeV}$

Cabibbo angle $\lambda = 0.22$

$m_c \sim \lambda^4 m_t$, $m_u \sim \lambda^4 m_c \sim \lambda^8 m_t$

$(Y_c \sim \lambda^4 Y_t$. $Y_u \sim \lambda^4 Y_c \sim \lambda^8 Y_t$

mixingをなしとすると)

③ Froggatt-Nielsen mechanism 対称性

m_t , $m_c = \varepsilon m_t$, $m_u = \varepsilon^2 m_t$

$\varepsilon \sim \lambda^4$

$\Updownarrow$

squarks

$m_{\tilde{t}}^2$, $m_{\tilde{c}}^2 = m_{\tilde{t}}^2 + m_D^2$, $m_{\tilde{u}}^2 = m_{\tilde{t}}^2 + 2m_D^2$ at M_X

$(300\,\mathrm{GeV})^2$, $(1\,\mathrm{TeV})^2$ $2(1\,\mathrm{TeV})^2$

FCNC dangerous

もっと m_D^2 を大きくする.

$(300\,\mathrm{GeV})^2$ $(5\,\mathrm{TeV})^2$ $2\cdot(5\,\mathrm{TeV})^2$

$(10\,\mathrm{TeV})^2$ $2\cdot(10\,\mathrm{TeV})^2$

FCNC問題へ decoupling solution

② (Infrared) Fixed Point

$Y_t(M_x)$ どんな値でも

くりこみ群 $\Rightarrow$ uniqueな $Y_t(M_I)$ へ at M_I

$\left(Y_t(M_I) / g_3(M_I) \right)$

$\Rightarrow$ Fig.

$\Updownarrow$

$$m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2 + m_{H_u}^2 = M_3^2 \quad \text{at } M_I$$

$\Uparrow$

どんな値 $m_i^2(M_x)$ でも

$\Rightarrow$ Fig.

◎ Nelson-Strassler mechanism

c, u に強く結合したsectorを用意する。
(我々のsector以外)

$$Y_t(M_X) \approx Y_c(M_X) \approx Y_u(M_X)$$

強く結合
(たくりこみ群

at M_I: $\quad Y_t \quad , \quad Y_c = \varepsilon Y_t \quad , \quad Y_u = \varepsilon^2 Y_t$

$$m^2_{\tilde{t}}(M_X) \qquad m^2_{\tilde{c}}(M_X) \,,\; m^2_{\tilde{u}}(M_X)$$

どんな量でも

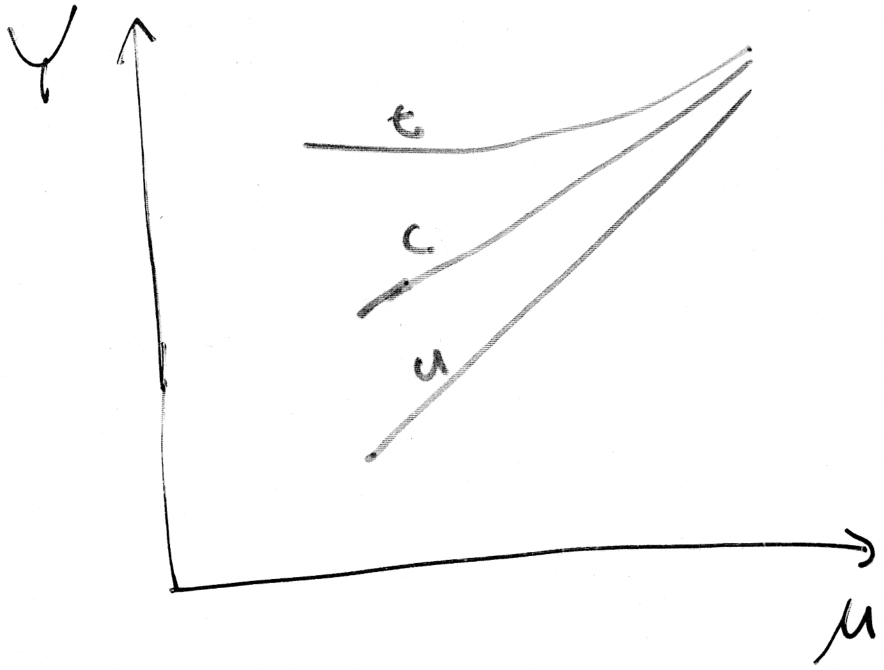
$$m^2_{\tilde{t}}(M_Z) \neq 0 \qquad m^2_{\tilde{c}}(M_Z) \simeq 0 \qquad m^2_{\tilde{u}}(M_Z) \simeq 0$$

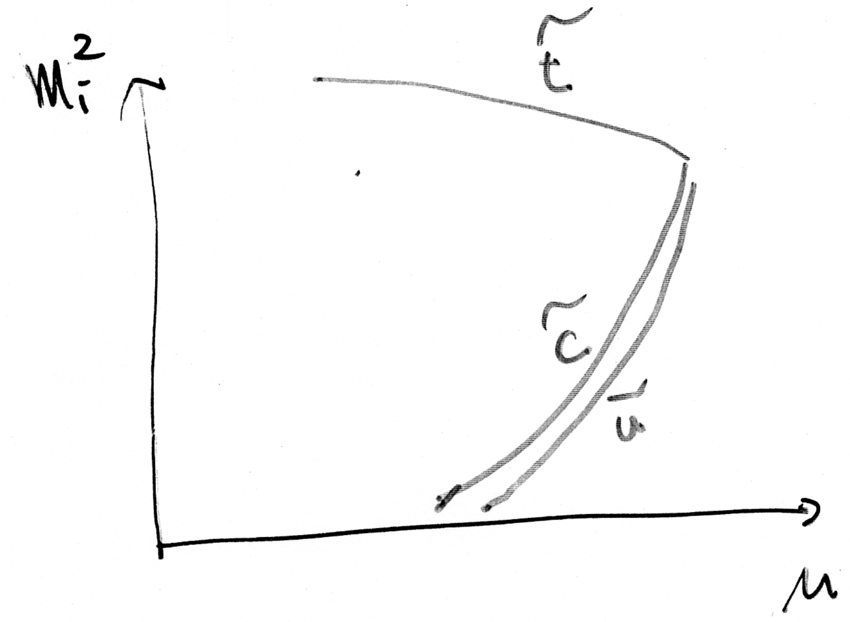
→ Fig.

$$M_I \longrightarrow M_Z$$

M_3 からの量子補正. $m^2_{\tilde{c}}(M_Z) = m^2_{\tilde{u}}(M_Z)$
縮退

FCNC O.K. → Fig.


Y
t
c
u
μ


m_i^2
$\tilde{t}$
$\tilde{c}$
$\tilde{u}$
μ