# 超対称模型の現状

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Supersymmetry (SUSY): boson  $\Leftrightarrow$  fermion symmetry.

黎明期:

- Miyazawa ('66): baryons & mesons ∈ supermultiplet.
- Volkov & Akulov ('72): supertranslation (nonlinear realization).

Beyond the Standard Model としての SUSY:

• Wess & Zumino ('74): renormalizable quantum field theory (4-dim. N = 1)

以後、"realistic" model building へ。

Minimal Supersymmetric Standard Model (MSSM)の現象論が詳しく調べられている。

SUSY 模型を研究する動機:

- 豊富な新粒子、新現象を予言 ⇒ 面白い。
- 統一理論の可能性
  - ▷ Local SUSY = supergravity: 重力を含む
    - \* SUSY algebra  $\supset$  spacetime translation (Poincaré group)

⇒ local SUSY transformation  $\supset$  一般座標変換

▷ MSSM  $\rightarrow$  GUTと相性がいい。

- (ゲージ) 階層性問題の緩和
  - ▷ Electroweak scale (~ 100 GeV)  $\Leftrightarrow$  Planck (GUT) scale (~ 10<sup>16-19</sup> GeV)
    - \* "軽い" スピン 0 粒子を対称性で保証
      - ·スピン  $1 \rightarrow$ ゲージ対称性
      - ·スピン  $1/2 \rightarrow$ カイラル対称性

Hierarchy problem in SM

● Higgs boson mass への量子補正 → 二次発散



→ 不自然!

Supersymmetry stabilizes the hierarchy.



このセミナーでは、minimal supergravity model (mSUGRA) を中心に、模型の構造と、最近の LHC の結果について紹介する。

# 以下の目次

- Minimal Supersymmetric Standard Model
- Minimal Supergravity scenario
- Constraints from LHC
- Constraints from flavor physics

# Minimal Supersymmetric Standard Model (MSSM)

The Standard Model:

- $SU(3) \times SU(2) \times U(1)$  gauge theory.
- 3 families of quarks/leptons (chiral fermions).
- 1 Higgs doublet (complex scalars).
- 19 (+9) parameters.

 $\triangleright \alpha_s, \alpha, G_F, m_Z, m_{u,c,t}, m_{d,s,b}, m_{e,\mu,\tau}, m_h, V_{\mathsf{CKM}}(\lambda, A, \overline{\rho}, \overline{\eta}), \theta_{\mathsf{QCD}}.$  $\triangleright m_{\nu_1,\nu_2,\nu_3}, U_{\mathsf{MNS}}.$ 

## **MSSM:** field contents

## 標準模型を超対称化する: superpartners の導入。

- $SU(3) \times SU(2) \times U(1)$  gauge fields:  $g_{\mu}$ ,  $W_{\mu}$ ,  $B_{\mu}$
- $\Rightarrow$  vector supermultiplets  $(g_{\mu}, \tilde{g})$ ,  $(W_{\mu}, \tilde{W})$ ,  $(B_{\mu}, \tilde{B})$ 
  - $\triangleright \tilde{g}, W, B$ : Majorana fermions (gauginos).
- Quarks, leptons:  $q_L$ ,  $(u_R)^c$ ,  $(d_R)^c$ ,  $\ell_L$ ,  $(e_R)^c$
- $\Rightarrow$  (left-handed) chiral supermultiplets
  - $Q(q_L, \ \tilde{q}_L), U^c((u_R)^c, \ \tilde{u}_R^*), D^c((d_R)^c, \ \tilde{d}_R^*), L(\ell_L, \ \tilde{\ell}_L), E^c((e_R)^c, \ \tilde{e}_R^*)$
  - $\triangleright \tilde{q}_L, \tilde{u}_R^*, \tilde{d}_R^*, \tilde{\ell}_L, \tilde{e}_R^*$ : complax scalars (squarks, sleptons).
  - ▷ 全部3世代。
- Higgs doublet H
- $\Rightarrow$  (left-handed) chiral supermultiplets  $H_1(h_1, \tilde{h}_1), H_2(h_2, \tilde{h}_2)$ 
  - $\triangleright \tilde{h}_1$ ,  $\tilde{h}_2$ : chiral fermions (higgsinos)

#### **MSSM:** field contents

Chiral supermultiplets (SU(3), SU(2), U(1)):

$$egin{aligned} Q_i(3,\,2,\,rac{1}{6}), & U_i^c(\overline{3},\,1,\,-rac{2}{3}), & D_i^c(\overline{3},\,1,\,rac{1}{3}), & L_i(1,\,2,\,-rac{1}{2}), \ & E_i^c(1,\,1,\,1), & H_1(1,\,2,\,-rac{1}{2}), & H_2(1,\,2,\,rac{1}{2}). \end{aligned}$$

i = 1, 2, 3.

Higgs doublets は2つ必要。

- 湯川相互作用の超対称化(後述)
- Gauge anomaly cancellation
  - ▷  $\tilde{h}_1$  は  $\ell_L$  と同じ量子数。これだけを追加すると gauge anomaly が生じる。 $\tilde{h}_2$  で相殺。

## **MSSM:** field contents

大統一理論 (GUT) と相性が良い。

- GUT は
  - $\triangleright Q_e = -Q_p$
  - $\triangleright g_3 > g_2 > g_1$
  - をゲージ対称性と関連づける点で魅力的。



## **MSSM:** interactions

相互作用の超対称化

SUSY gauge interactions



Superpotential (Yukawa couplings & " $\mu$ "): holomorphic  $W_{\text{MSSM}} = \epsilon_{ab} \left[ (Y_E)_{ij} H_1^a L_i^b E_j^c + (Y_D)_{ij} H_1^a Q_i^b D_j^c + (Y_U)_{ij} H_2^b Q_i^a U_j^c - \mu H_1^a H_2^b \right],$ 

• SUSY: scalar にも chirality.  $\Rightarrow h_1^{\dagger}$  で  $h_2$  の代用不可。



#### MSSM: *R*-parity

Gauge invariance だけだと

 $W_{\mathsf{RPV}} = \epsilon_{ab} \left[ \frac{1}{2} \lambda_{ijk} L^a_i L^b_j E^c_k + \lambda'_{ijk} L^a_i Q^b_j D^c_k - \kappa_i L^a_i H^b_2 \right] + \frac{1}{2} \lambda''_{ijk} U^c_i D^c_j D^c_k,$ も可能。これらはバリオン数、レプトン数を破る ⇒ 短寿命で陽子崩壊。

*R*-parity

- Even: SM particles
- Odd: SUSY particles ( $\tilde{g}$ ,  $\tilde{W}$ ,  $\tilde{B}$ ,  $\tilde{q}_{L,R}$ ,  $\tilde{\ell}_{L,R}$ ,  $\tilde{h}_i$ )

で禁止 ( $L_i$  と  $H_1$  に異なる量子数を割当)。

⇒ Lightest *R*-odd particle (Lightest SUSY Particle, LSP) は安定。

#### MSSM: SUSY breaking

超対称性は破れている。これを soft SUSY breaking terms として取り入れる。

• Gaugino masses

$$\mathcal{L}_G = \frac{1}{2} \left[ M_1 \tilde{B} \tilde{B} + M_2 \tilde{W}^A \tilde{W}^A + M_3 \tilde{g}^X \tilde{g}^X \right] + \text{H.c.}$$

Scalar masses

$$V_{2} = \tilde{q}_{iLa}^{*} (m_{\tilde{Q}}^{2})_{ij} \tilde{q}_{jL}^{a} + \tilde{\ell}_{iLa}^{*} (m_{\tilde{L}}^{2})_{ij} \tilde{\ell}_{jL}^{a} + \tilde{u}_{iR} (m_{\tilde{u}}^{2})_{ij} \tilde{u}_{jR}^{*} + \tilde{d}_{iR} (m_{\tilde{d}}^{2})_{ij} \tilde{d}_{jR}^{*} + \tilde{e}_{iR} (m_{\tilde{e}}^{2})_{ij} \tilde{e}_{jR}^{*} + m_{H_{1}}^{2} h_{1a}^{*} h_{1}^{a} + m_{H_{2}}^{2} h_{2a}^{*} h_{2}^{a} - \left[ m_{3}^{2} \epsilon_{ab} h_{1}^{a} h_{2}^{b} + \text{H.c.} \right],$$

• Trilinear scalar couplings (holomorphic)

 $V_{3} = \epsilon_{ab} \left[ (T_{E})_{ij} h_{1}^{a} \tilde{\ell}_{iL}^{b} \tilde{e}_{jR}^{*} + (T_{D})_{ij} h_{1}^{a} \tilde{q}_{iL}^{b} \tilde{d}_{jR}^{*} + (T_{U})_{ij} h_{2}^{b} \tilde{q}_{iL}^{a} \tilde{u}_{jR}^{*} \right],$ Soft = 2次発散を生じない (Girardello & Grisaru, '82)。

## **MSSM: SUSY** breaking

SUSY breaking mechanism を特定しない場合、

- 105 new parameters. "MSSM-124"
  - ▷ Standard Model はパラメータ19個。
  - ▷ 大半(97個)が squark/slepton mass matrices (SUSY breaking)
    - $\Rightarrow$  flavor/CPV sector.
- ⇒ 最初から大問題。

MSSM + "SUSY breaking parameters の構造の種"で模型を定義する。

## Flavor mixing in the MSSM

- quark の質量行列  $\leftarrow$  Electroweak gauge symmetry breaking  $(\langle h \rangle)$ ,
- squark の質量行列  $\leftarrow$  EW symmetry breaking  $\oplus$  SUSY breaking.

quark と squark の質量行列は一般には同時対角化できない。



- squark の相互作用に CKM 行列とは一般に異なる混合行列が現れる。
- SUSY breaking に特別な構造(universality, etc.) があれば、混合行列が 一致する場合もある。

## SUSY Flavor "Problem"

SUSY breaking のフレイバー構造は既に制限されている。(Ellis & Nanopoulos, '82)



• Lepton sector では  $\mu \rightarrow e \gamma$  が強い制限を与える。

# SUSY breaking scenarios: minimal supergravity

Spontaneous breaking of global SUSY の問題点

- Vacuum energy > 0  $\Rightarrow$  huge cosmological constant?  $\triangleright H = Q^{\dagger}Q \ (Q: \text{ supercharge}) \Longrightarrow Q|0\rangle \neq 0 \Leftrightarrow \langle 0|H|0\rangle > 0.$
- Massless Nambu-Goldstone fermion (goldstino).
- Supertrace relation (tree level):  $\sum m^2(boson) \sum m^2(fermion) = 0$ .
- $\Rightarrow$  Local SUSY = supergravity (SUGRA) で解決。
  - Supertrace relation は loop で解決する方法も (gauge mediation 等)。

## Minimal supergravity

Matter coupled supergravity (Cremmer, Julia, Scherk *et al.*, '79) ⊕ gauge (Cremmer, Ferrara, Girardello & van Proeyen, '83)

Lagrangian La

- Kähler potential  $K(\varphi, \varphi^*)$ ,
- superpotential  $W(\varphi)$ ,
- gauge kinetic function  $f_{ab}(\varphi)$ ,

で記述される。

$$\mathcal{L}_{\mathsf{kin}} = K_{j}^{i} \partial^{\mu} \varphi_{i}^{*} \partial_{\mu} \varphi^{j} - \frac{1}{4} \operatorname{Re} f_{ab}(\varphi) F^{a\mu\nu} F_{\mu\nu}^{b} + \cdots,$$

$$V = e^{G} \left[ G^{i} (G^{-1})_{i}^{j} G_{j} - 3 \right] + (\mathsf{gauge}), \qquad G = K + \log |W|^{2},$$

$$G_{i} = \frac{\partial G(\varphi, \varphi^{*})}{\partial \varphi^{i}}, \qquad G_{j}^{i} = \frac{\partial^{2} G(\varphi, \varphi^{*})}{\partial \varphi_{i}^{*} \partial \varphi^{j}} = K_{j}^{i},$$

# Minimal supergravity

- Spontaneous SUSY breaking with vanishing cosmological constant.
  - ▷ Supersymmetric cosmological term < 0 ("-3" in V).
  - $\Rightarrow$  cancels positive contributions due to SUSY breaking.
    - \* Fine-tuning だが、宇宙項問題を悪化させてはいない。
- Super-Higgs mechanism: goldstino eaten by gravitino.
  - Supergravity multiplet: graviton (spin 2) & gravitino (spin 3/2): gauge field of local supersymmetry.
    - \* SUSY unbroken  $\rightarrow$  massless gravitino, helicity  $\pm 3/2$  only.
    - \* SUSY broken  $\rightarrow$  massive gravitino  $m_{3/2}$ , helicity  $\pm 3/2 \& \pm 1/2$ . helicity  $\pm 1/2$  components  $\Leftarrow$  goldstino.
    - \* Massless goldstino disappear.
- $\sum m^2$ (boson)  $-\sum m^2$ (fermion)  $\propto m_{3/2}^2 > 0$ .
  - ▷ Realistic mass spectrum m(squark) > m(quark) possible.

## Minimal supergravity

(Barbieri, Ferrara & Savoy, '82)

Field contents: "visible" sector (MSSM,  $\phi$ ) and "hidden" sector (z)

- Simplest Käler potential:  $K = \varphi_i^* \varphi^i \to K_i^j = \delta_i^j$ .
- $W = W_{\text{hid}}(z) + W_{\text{vis}}(\phi)$ .
- SUSY breaking occurs in the "hidden" sector.

 $\Downarrow$  flat limit ( $M_{\text{Planck}} \rightarrow \infty$  with  $m_{3/2}$  fixed)

- Lagrangian for the "visible" sector: softly broken (global) SUSY with:
  - ▷ universal scalar mass  $m_0 = m_{3/2}$ .
    - \* degenerate squarks  $\rightarrow$  flavor problem resolved.
  - ▷ universal trilinear coupling  $T_{U,D,E} = A_0 Y_{U,D,E} \propto m_{3/2}$ .
  - ▷ minimal gauge kinetic function ( $f_{ab} = \delta_{ab}$ ) では gaugino mass は 出ない (tree level)。
    - \* loop correction, or nonminimal  $f_{ab}$ .

#### Electroweak symmetry breaking (EWSB)

Higgs potential (neutral component)

$$\begin{split} V_{\text{Higgs}} &= m_1^2 |h_1|^2 + m_2^2 |h_2|^2 - \left(m_3^2 h_1 h_2 + \text{H.c.}\right) + \frac{g_1^2 + g_2^2}{8} \left(|h_1|^2 - |h_2|^2\right)^2 \\ m_i^2 &= |\mu|^2 + m_{H_i}^2, \qquad i = 1, 2, \end{split}$$

- Quartic coupling ⇐ SUSY gauge interaction.
   ▷ Flat direction |h<sub>1</sub>| = |h<sub>2</sub>|.
- EWSB conditions:

$$m_1^2 m_2^2 - \left| m_3^2 \right|^2 < 0, \qquad m_1^2 + m_2^2 - 2 \left| m_3^2 \right| > 0.$$

$$\langle h_1 \rangle = v \cos \beta, \qquad \langle h_2 \rangle = v \sin \beta, \qquad m_W^2 = \frac{g_2^2}{2}v^2.$$
  
 $m_{H_1}^2 = m_{H_2}^2 = m_0^2$  では実現しない。

 $\triangleright$ 

#### Radiative electroweak symmetry breaking

量子補正 ⇒ Lagrangian のパラメータは繰り込み群方程式に従うrunning parameters.

- "Universal" soft SUSY breaking (← SUGRA): Planck スケール (GUT スケール) 付近の値。
- 現象論に必要なのはEWスケール付近 (O(100) GeV O(1) TeV) の値。

⇒ Top Yukawa coupling の効果が重要 (Alvarez-Gaumé, Polchinski & Wise, '83, Inoue, Kakuto & Takeshita, '84 )。

RGEs (3rd gen.):

$$(4\pi)^{2} \mu \frac{d}{d\mu} m_{Q}^{2} = 2y_{t}^{2} \left( m_{Q}^{2} + m_{U}^{2} + m_{H_{2}}^{2} \right) - \frac{32}{3} g_{3}^{2} |M_{3}|^{2} + \cdots,$$
  

$$(4\pi)^{2} \mu \frac{d}{d\mu} m_{U}^{2} = 4y_{t}^{2} \left( m_{Q}^{2} + m_{U}^{2} + m_{H_{2}}^{2} \right) - \frac{32}{3} g_{3}^{2} |M_{3}|^{2} + \cdots,$$
  

$$(4\pi)^{2} \mu \frac{d}{d\mu} m_{H_{2}}^{2} = 6y_{t}^{2} \left( m_{Q}^{2} + m_{U}^{2} + m_{H_{2}}^{2} \right) + \cdots,$$

## **RG** running of sparticle masses



 $\Rightarrow$  considered as a realistic scenario.

# mSUGRA scenario

- MSSM with *R*-parity.
- SUGRA-induced (gravity-mediated) SUSY breaking.
  - ▷ SUSY breaking parameters at GUT scale:
    - \* universal scalar mass  $m_0$ ,
    - \* universal trilinear coupling  $A_0$ .
    - $\Rightarrow$  flavor problem under control.
    - \* universal (unified) gaugino mass  $m_{1/2}$ ,
  - ▷ EW scale input parameters:  $\tan \beta = \langle h_2 \rangle / \langle h_1 \rangle$ ,  $\operatorname{sgn}(\mu)$ .
- Radiative EWSB.

基本要素は80年代前半に出揃っていた。

# その後の発展: 定量的精密化

- Loop correction to Higgs boson mass (1-loop: Okada, Yamaguchi & Yanagida, '91) → 2-loop.
- 2-loop RGE (Jack, Jones, Martin, Vaughn & Yamada, '94).

## **MSSM** particles

- *R*-even
  - $\triangleright$  Quarks: u, c, t; d, s, b.
  - $\triangleright$  Leptons:  $e, \mu, \tau; \nu_e, \nu_\mu, \nu_\tau$ .
  - $\triangleright$  Gauge bosons:  $g, W^{\pm}, Z, \gamma$ .
  - ▷ Higgs bosons:  $h^0$ ,  $H^0$ ,  $A^0$ ,  $H^{\pm}$  (< 2-Higgs doublet model).

 $\bullet$  *R*-odd

- $\triangleright$  Squarks:  $\tilde{u}_L$ ,  $\tilde{u}_R$ ,  $\tilde{c}_L$ ,  $\tilde{c}_R$ ,  $\tilde{t}_L$ ,  $\tilde{t}_R$ ;  $\tilde{d}_L$ ,  $\tilde{d}_R$ ,  $\tilde{d}_L$ ,  $\tilde{d}_R$ ,  $\tilde{b}_L$ ,  $\tilde{b}_R$ .
- $\triangleright$  Sleptons:  $\tilde{e}_L$ ,  $\tilde{e}_R$ ,  $\tilde{\mu}_L$ ,  $\tilde{\mu}_R$ ,  $\tilde{\tau}_L$ ,  $\tilde{\tau}_R$ ;  $\tilde{\nu}_{eL}$ ,  $\tilde{\nu}_{\mu L}$ ,  $\tilde{\nu}_{\tau L}$ .
  - \* 一般に世代、Left-Right の混合有り。
- $\triangleright$  Gluino:  $\tilde{g}$ .
- ▷ Chargino = mixture of charged gauginos & higgsinos:  $\tilde{\chi}_1^{\pm}$ ,  $\tilde{\chi}_2^{\pm}$  (Dirac).
- ▷ Neutralino = mixture of neutral gauginos & higgsinos:  $\tilde{\chi}_1^0$ ,  $\tilde{\chi}_2^0$ ,  $\tilde{\chi}_3^0$ ,  $\tilde{\chi}_4^0$  (Majorana).

## **MSSM** particles

LSP: stable, neutral.  $\Rightarrow$  Lightest neutralino or sneutrino.

mSUGRA では、 $m(\tilde{\nu}) > m(\tilde{\tau})$  になりやすい (RG running  $\oplus$  Left-Right mixing)。

 $\Rightarrow$ 大半の場合 neutralino LSP  $\tilde{\chi}_1^0$ .

## **Constraints from LHC**

CERN Large Hadron Collider: proton-proton collider at  $\sqrt{s} = 7 \text{ TeV}$  (2010-2011),  $\sqrt{s} = 8 \text{ TeV}$  (2012).

Experiments:

- SUSY/Higgs search: ATLAS, CMS.
- *B* physics: LHCb.

Main target: colored SUSY particles = squark  $\tilde{q}$ , gluino  $\tilde{g}$ .

Production:  $q g \to \tilde{q} \tilde{g}$ ,  $g g \to \tilde{q} \tilde{q}^*$ ,  $g g \to \tilde{g} \tilde{g}$ .

• R-parity  $\rightarrow$  sparticles are produced in pairs.

Decay:  $\tilde{q} \to q \, \tilde{\chi}_1^0$ ,  $\tilde{g} \to q \, \bar{q} \, \tilde{\chi}_1^0$ .

- LSP (lightest neutralino  $\tilde{\chi}_1^0$ ) は見えない。  $\Rightarrow$  missing momentum. ▷ Missing transverse energy ( $\mathcal{E}_T$ ) を測る。
- high-energy quark  $\rightarrow$  hadronic "jet".

Typical signal: excess in jets  $+ \not\!\!\!E_T + 0$  lepton ( $\mu$  or e).

 $\Rightarrow$  No excess found.

mSUGRA interpretation:  $m(\tilde{g}) > 1 \text{ TeV}, m(\tilde{q}) > 1.5 \text{ TeV}.$ 



(ATLAS-CONF-2012-109)

## mSUGRA interpretation



mSUGRA interpretation:  $m(\tilde{g}) > 1 \text{ TeV}, m(\tilde{q}) > 1.5 \text{ TeV}.$ 



		ATLAS SUSY	Searches* - 95% CL Lower Limits (Status: S	USY 2012)	
S	MSUGRA/CMSSM : 0 lep + J's + $E_{T,miss}$	L=5.8 fb <sup>-1</sup> , 8 TeV [ATLAS-CONF-2012-109]	<b>1.50 TeV</b> q = g mass		
che	MSUGRA/CMSSM : 1 lep + J's + $E_{T,miss}$	L=5.8 fb <sup>-1</sup> , 8 TeV [ATLAS-CONF-2012-104]	1.24 TeV $q = g \text{ mass}$	$Ldt = (1.00 - 5.8) \text{ fb}^{-1}$	
ear	Pheno model : 0 lep + j's + $E_{T,miss}$	L=5.8 fb <sup>-1</sup> , 8 TeV [ATLAS-CONF-2012-109]	<b>1.18 TeV</b> g mass $(m(\hat{q}) < 2 \text{ TeV}, \text{ light } \chi_1^{\gamma})$		
e Se	Pheno model : 0 lep + J's + $E_{T,miss}$	L=5.8 fb <sup>-1</sup> , 8 TeV [ATLAS-CONF-2012-109]	<b>1.38 TeV Q MASS</b> $(m(\hat{g}) < 2 \text{ TeV}, \text{ light } \chi_1)$	IS = 7,8 IEV	
sive	Gluino med. $\chi$ (g $\rightarrow$ q $\overline{q}\chi$ ) : 1 lep + j's + $E_{T,miss}$	L=4.7 fb <sup>-1</sup> , 7 TeV [ATLAS-CONF-2012-041]	<b>900 GeV g</b> mass $(m(\chi_1) < 200 \text{ GeV}, m(\chi^2) = \frac{1}{2}(m(\chi_1) + 200 \text{ GeV})$	+ <i>m</i> (g)) ΛΤΙΛς	
shire	GMSB: 2 lep (OS) + j's + $E_{T,miss}$	L=4.7 fb <sup>-1</sup> , 7 TeV [Preliminary]	<b>1.24 TeV</b> g mass $(\tan\beta < 15)$	Broliminan	
Inc	GIVISB: $1-2^{T} + 0 - 1$ lep + $JS + E$	L=4.7 fb <sup>-1</sup> , 7 TeV [ATLAS-CONF-2012-112]	$\frac{1.20 \text{ TeV}}{\sim} g \text{ mass } (\tan\beta > 20)$	Freiminary	
	= $=$ $=$ $=$ $=$ $=$ $=$ $=$ $=$ $=$	L=4.8 fb <sup>-1</sup> , 7 TeV [ATLAS-CONF-2012-072]	<b>1.07 TeV</b> g mass $(m(\chi_1) > 50 \text{ GeV})$		
	$g \rightarrow bb\chi_{1}^{\prime}$ (virtual b) $\sim 0$ lep + 1/2 b-j's + $E_{T,miss}$	L=2.1 fb <sup>-1</sup> , 7 TeV [1203.6193]	<b>900 GeV g</b> mass $(m(\chi_1) < 300 \text{ GeV})$		
ks bé	$\tilde{g} \rightarrow bb\chi$ (virtual b) : 0 lep + 3 b-j's + $E_{T,miss}$	L=4.7 fb <sup>-1</sup> , 7 TeV [1207.4686]	1.02 TeV g mass $(m(\chi) < 400 \text{ GeV})$		
lar	$\tilde{g} \rightarrow \tilde{b} b \chi_1 \text{ (real b) : } 0 \text{ lep } + 3 \text{ b-J's } + E_{T, \text{miss}}$	L=4.7 fb <sup>-1</sup> , 7 TeV [1207.4686]	<b>1.00 TeV</b> g mass $(m(\chi_1) = 60 \text{ GeV})$		
sqi	$g \rightarrow tt \chi_{10}(virtual t)$ : 1 lep + 1/2 b-j's + $E_{T,miss}$	L=2.1 fb <sup>-1</sup> , 7 TeV [1203.6193]	<b>710 GeV</b> g mass $(m(\chi_1) < 150 \text{ GeV})$		
n. m	$g \rightarrow tt \chi_1^{-}$ (virtual t) : 2 lep (SS) + j's + $E_{T,miss}$	L=5.8 fb <sup>-1</sup> , 8 TeV [ATLAS-CONF-2012-105]	<b>850 GeV</b> g mass $(m(\chi_1) < 300 \text{ GeV})$		
ge inc	$\tilde{g} \rightarrow t \tilde{t} \chi_1^{\circ}$ (virtual t) : 3 lep + j's + $E_{T,miss}$	L=4.7 fb <sup>-1</sup> , 7 TeV [ATLAS-CONF-2012-108]	<b>760 GeV</b> g mass (any $m(\chi_1) < m(g)$ )		
glu	$\tilde{g} \rightarrow t \tilde{t} \chi_{J}^{\circ}$ (virtual t): 0 lep + multi-j's + $E_{T,miss}$	L=5.8 fb <sup>-1</sup> , 8 TeV [ATLAS-CONF-2012-103]	<b>1.00 TeV g</b> mass $(m(\bar{\chi}_1) < 300 \text{ GeV})$		
	$\tilde{g} \rightarrow t \tilde{\chi}_{L}$ (virtual t) : 0 lep + 3 b-j's + $E_{T,miss}$	L=4.7 fb <sup>-1</sup> , 7 TeV [1207.4686]	940 GeV g mass $(m(\bar{\chi}_1) < 50 \text{ GeV})$		
	$\widetilde{g} \rightarrow t t \widetilde{\chi}_1^\circ$ (real t) : 0 lep + 3 b-j's + $E_{T,miss}$	L=4.7 fb <sup>-1</sup> , 7 TeV [1207.4686]	<b>820 GeV g</b> mass $(m(\chi_1) = 60 \text{ GeV})$		
(a =	bb, $b_1 \rightarrow b \tilde{\chi}_1$ : 0 lep + 2-b-jets + $E_{T,miss}$	L=4.7 fb <sup>-1</sup> , 7 TeV [ATLAS-CONF-2012-106]	<b>480 GeV</b> b mass $(m(\tilde{\chi}_1) < 150 \text{ GeV})$		
ion	bb, $b_1 \rightarrow t \tilde{\chi}_1^{\pm}$ : 3 lep + j's + $E_{T,miss}$	L=4.7 fb <sup>-1</sup> , 7 TeV [ATLAS-CONF-2012-108]	<b>380 GeV</b> $\widetilde{\mathbf{g}}$ mass $(m(\widetilde{\chi_1^{\pm}}) = 2 m(\widetilde{\chi_1^{0}}))$		
lua	tt (very light), t $\rightarrow b\tilde{\chi}_1^{\pm}$ : 2 lep + $E_{T,miss}$	L=4.7 fb <sup>-1</sup> , 7 TeV [CONF-2012-059]135 GeV	t mass $(m(\bar{\chi}_1^{-0}) = 45 \text{ GeV})$		
sc	tt (light), $t \rightarrow b \tilde{\chi}_{4}^{\pm}$ : 1/2 lep + b-jet + $E_{T,miss}$	L=4.7 fb <sup>-1</sup> , 7 TeV [CONF-2012-070] 120-173 C	<b>Bev</b> t mass $(m(\tilde{\chi}_1^0) = 45 \text{ GeV})$		
en. t pi	$\widetilde{t}\widetilde{t}$ (heavy), $\widetilde{t} \rightarrow t \widetilde{\chi}_{0}^{0}$ : 0 lep + b-jet + $E_{T,miss}$	L=4.7 fb <sup>-1</sup> , 7 TeV [1208.1447]	<b>380-465 GeV</b> t mass $(m(\tilde{\chi}_{1}^{0}) = 0)$		
d g 'ec	$\widetilde{tt}$ (heavy), $\widetilde{t} \rightarrow t \widetilde{\chi}_{\bullet}$ : 1 lep + b-jet + $E_{T,miss}$	L=4.7 fb <sup>-1</sup> , 7 TeV [CONF-2012-073]	<b>230-440 GeV</b> t mass $(m(\chi_1^{-0}) = 0)$		
3r dii	tt (heavy), t $\rightarrow$ t $\tilde{\chi}_{1}$ : 2 lep + b-jet + $E_{T,miss}$	L=4.7 fb <sup>-1</sup> , 7 TeV [CONF-2012-071]	<b>298-305 GeV</b> t mass $(m(\tilde{\chi}_{1}^{0}) = 0)$		
	tt (GMSB) $Z(\rightarrow II) + b - jet + E_{T miss}$	L=2.1 fb <sup>-1</sup> , 7 TeV [1204.6736]	<b>310 GeV</b> t mass (115 < $m(\tilde{\chi}_1^0)$ < 230 GeV)		
ct /	$\tilde{I}_{L}\tilde{I}_{L}, \tilde{I} \rightarrow \tilde{\chi}_{0}^{0}$ : 2 lep + $E_{T,miss}$	L=4.7 fb <sup>-1</sup> , 7 TeV [CONF-2012-076] 93-180	GeV I mass $(m(\tilde{\chi}_1^0) = 0)$		
EN	$\widetilde{\chi}_{1}^{+}\widetilde{\chi}_{1}^{-}, \widetilde{\chi}_{1}^{+} \rightarrow iv(iv) \rightarrow iv\widetilde{\chi}_{1}^{u}: 2 \text{ lep } + E_{T,\text{miss}}$	L=4.7 fb <sup>-1</sup> , 7 TeV [CONF-2012-076]	<b>120-330 GeV</b> $\widetilde{\chi}_{1}^{\pm}$ <b>MASS</b> $(m(\widetilde{\chi}_{1}^{0}) = 0, m(\widetilde{l}, \widetilde{\nu}) = \frac{1}{2}(m(\widetilde{\chi}_{1}^{\pm}) + m(\widetilde{\chi}_{1}^{0})))$		
	$\widetilde{\chi}_{\lambda}^{\pm}\widetilde{\chi}_{\lambda}^{0} \rightarrow 3I(Ivv) + v + 2\widetilde{\chi}_{\lambda}^{0}$ : 3 lep + $E_{T \text{ miss}}$	L=4.7 fb <sup>-1</sup> , 7 TeV [CONF-201 <mark>2-077]</mark>	<b>60-500 GeV</b> $\widetilde{\chi}_1^{\pm}$ <b>MASS</b> $(m(\widetilde{\chi}_1^{\pm}) = m(\widetilde{\chi}_2^{0}), m(\widetilde{\chi}_1^{0}) = 0, m(\widetilde{l}, \widetilde{v})$ as above)		
Ø	AMSB (direct $\tilde{\chi}_{1}^{\pm}$ pair prod.) : long-lived $\tilde{\chi}_{1}^{\pm}$	L=4.7 fb <sup>-1</sup> , 7 TeV [ATLAS-CONF-2012-111] 2	<b>10 GeV</b> $\widetilde{\chi}_{1}^{\pm}$ <b>MASS</b> (1 < $\tau(\widetilde{\chi}_{1}^{\pm})$ < 10 ns)		
ive les	Stable g R-hadrons : Full detector	L=4.7 fb <sup>-1</sup> , 7 TeV [ATLAS-CONF-2012-075]	985 GeV ĝ mass		
ng-l	Stable t R-hadrons : Full detector	L=4.7 fb <sup>-1</sup> , 7 TeV [ATLAS-CONF-2012-075]	683 GeV t mass		
-on pa	Metastable g R-hadrons : Pixel det. only	L=4.7 fb <sup>-1</sup> , 7 TeV [ATLAS-CONF-2012-075]	<b>910 GeV ğ mass</b> (τ(ğ) > 10 ns)		
-	GMSB : stable 7	L=4.7 fb <sup>-1</sup> , 7 TeV [ATLAS-CONF-2012-075]	<b>310 GeV</b> $\tilde{\tau}$ <b>MASS</b> (5 < tan $\beta$ < 20)		
	RPV : high-mass eµ	L=1.1 fb <sup>-1</sup> , 7 TeV [1109.3089]	<b>1.32 TeV</b> $\tilde{V}_{\tau}$ <b>Mass</b> $(\lambda_{311}^{*}=0.10, \lambda_{312}=0.05)$		
$\sum$	Bilinear RPV : 1 lep + j's + $E_{T,miss}$	L=1.0 fb <sup>-1</sup> , 7 TeV [1109.6606]	<b>760 GeV</b> $\tilde{q} = \tilde{g} \text{ mass } (c\tau_{LSP} < 15 \text{ mm})$		
RF	BC1 RPV : 4 lep + $E_{T,miss}$	L=2.1 fb <sup>-1</sup> , 7 TeV [ATLAS-CONF-2012-035]	1.77 TeV ĝ mass		
	RPV $\tilde{\chi}_{4}^{0} \rightarrow qq\mu$ : $\mu$ + heavy displaced vertex	L=4.4 fb <sup>-1</sup> , 7 TeV [ATLAS-CONF-2012-113]	<b>700 GeV</b> $\tilde{\mathbf{q}}$ mass (3.0×10 <sup>-6</sup> < $\lambda_{211}$ < 1.5×10 <sup>-5</sup> , 1 mm < ct <	1 m, g decoupled)	
5	Hypercolour scalar gluons : 4 jets, $m_{ij} \approx m_{kl}$	L=4.6 fb <sup>-1</sup> , 7 TeV [ATLAS-CONF-2012-110]	100-287 GeV Sgluon mass (incl. limit from 1110.2693)		
)the	Spin dep. WIMP interaction : monojet + $\dot{E}_{T.miss}$	L=4.7 fb <sup>-1</sup> , 7 TeV [ATLAS-CONF-2012-084]	<b>709 GeV</b> M <sup>*</sup> SCale ( $m_{\chi}$ < 100 GeV, vector D5, Dirac $\chi$ )		
<sup>O</sup> Sp	bin indep. WIMP interaction : monojet $+E_{T,miss}$	L=4.7 fb <sup>-1</sup> , 7 TeV [ATLAS-CONF-2012-084]	548 GeV M <sup>*</sup> SCale $(m_{\chi} < 100 \text{ GeV}, \text{ tensor D9}, \text{ Dirac } \chi)$		
		10 <sup>-1</sup>	1 1	0	
*Only	*Only a selection of the available mass limits on new states or phenomena shown. INIASS Scale [10				

\*Only a selection of the available mass limits on new states or phenomena shown. All limits quoted are observed minus  $1\sigma$  theoretical signal cross section uncertainty.

(ATLAS, SUSY2012)

# SUSY



## Higgs boson search at ATLAS & CMS

SM Higgs(-like) boson discovered:  $m(h) \approx 125 \text{ GeV}$ .

SUSY 模型へのインパクト?

- 基研研究会 標準模型を超えた素粒子理論へ向けて
  - ~新しい実験結果をふまえて~(2012.3.19-23)で議論。[まとめPDF]

#### MSSM Higgs boson masses

$$V_{\text{Higgs}} = m_1^2 |h_1|^2 + m_2^2 |h_2|^2 - \left(m_3^2 h_1 h_2 + \text{H.c.}\right) + \frac{g_1^2 + g_2^2}{8} \left(|h_1|^2 - |h_2|^2\right)^2$$

$$\frac{\partial V_{\text{Higgs}}}{\partial h_i} = 0 \quad \Longrightarrow \quad \langle h_1 \rangle = v \cos \beta, \quad \langle h_2 \rangle = v \sin \beta.$$

Physical Higgs bosons: charged  $H^{\pm}$ , pseudoscalar  $A^{0}$ , scalar  $H^{0}$ ,  $h^{0}$ .

Tree level mass relations:

$$m_{A^0}^2 = m_1^2 + m_2^2, \quad m_{H^{\pm}}^2 = m_{A^0}^2 + m_W^2,$$
$$m_{H^0,h^0}^2 = \frac{1}{2} \left\{ m_{A^0}^2 + m_Z^2 \pm \sqrt{\left(m_{A^0}^2 + m_Z^2\right)^2 - 4m_{A^0}^2 m_Z^2 \cos^2 2\beta} \right\}.$$
$$\frac{m_{h^0}^2 < m_Z^2 \cos^2 2\beta}{m_{H^0}^2 \cos^2 2\beta}.$$

•  $m_{A^0} \gtrsim 200 \text{ GeV}$  程度なら、 $h^0$  (軽い方)はほぼ SM Higgs とみなしてよい。

## MSSM Higgs boson masses

Top Yukawa による loop correction が重要 (Okada, Yamaguchi & Yanagida, '91)。

1-loop approximate formula:

$$m_{h^0}^2 = m_Z^2 \cos^2 2\beta + \frac{3m_t^4}{4\pi^2 v^2} \left[ \log \frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2} \left( 1 - \frac{X_t^2}{12M_S^2} \right) \right],$$

 $M_S = \sqrt{m_{\widetilde{t}_1} m_{\widetilde{t}_2}}, \qquad X_t$ : Left-right mixing of  $\widetilde{t}$ .

● 現在は 2-loop まで計算されている。

 $m_{h^0} > m_Z$  になるには:

- Heavy stop,
- Large stop left-right mixing (max:  $X_t/M_S = \sqrt{6}$ ),

 $m_{h^0} \approx 125 \, \text{GeV} \Longrightarrow SUSY parameters に制限。$ 

#### **MSSM Higgs boson masses**



#### Constraints from flavor physics

Flavor Changing Neutral Current (FCNC) processes が重要な制限。

mSUGRA (degenerate squark mass  $\oplus$  RG running) では、 Quark 質量行列の構造  $\Rightarrow$  squark 質量行列の構造

$$rac{m_{u,c}}{m_W} \ll 1 \lesssim rac{m_t}{m_W} \; \Rightarrow \; m(\widetilde{u}) pprox m(\widetilde{c}) > m(\widetilde{t})$$

- $K^0 \overline{K}^0$  混合への寄与は抑えられる。
- Squark フレイバー混合は主に  $\tilde{q}_L$ 、 ~  $V_{CKM}$ 。
- *b* の物理には効き得る。
  - $\triangleright b \to s \gamma$  $\triangleright B_s \to \mu^+ \mu^-$

## $b \to s \, \gamma$ in <code>mSUGRA</code>

- $B(b \rightarrow s \gamma)_{exp} = (3.55 \pm 0.24 \pm 0.09) \times 10^{-4}$  (Belle+Babar+CLEO, '10)
- $B(b \to s \gamma)_{SM} = (3.15 \pm 0.23) \times 10^{-4}$  (Misiak, '07,  $O(\alpha_s^2) \pm c$ )



- SM(W) + H<sup>−</sup> と squark-"ino" ループの寄与の相対符号は模型のパラメー タによって決まる (Higgsino mass µ と gaugino mass m<sub>1/2</sub> の相対符号 が主)。
- SUSY 粒子による寄与が標準模型(W)分と同等の大きさになり得る。
  - ▷  $b \rightarrow s \gamma$  はクォークのカイラリティが反転する  $(b_R \rightarrow s_L)$  過程。
    - \* 標準模型では  $m_b$  がカイラリティ反転の最大要因。
    - \* squark- "ino" ループでは gaugino/higgsino の質量等でカイラリティ 反転を生じる。

 $b \to s \, \gamma$  in mSUGRA



SUSY braking パラメータに重要な制限を与えていた。

 $b \to s \, \gamma$  in <code>mSUGRA</code>

(Mahmoudi, '12)



•  $\overline{sk} : CMS exclusion limit with 4.4 fb^{-1} data.$ 

# $B_s \rightarrow \mu^+ \mu^-$ in mSUGRA • $B(B_s \rightarrow \mu^+ \mu^-)_{exp} < 4.5 \times 10^{-9}$ at 95% C.L. (LHCb, '12) • $B(B_s \rightarrow \mu^+ \mu^-)_{SM} = (3.58 \pm 0.36) \times 10^{-9}$

標準模型値に迫って来た。



- SUSY breaking による湯川相互作用への補正が重要な寄与。
   ▷ B<sub>SUSY</sub> ≫ B<sub>SM</sub> になり得るとして注目された。
- B( $B_s \to \mu^+ \mu^-$ )<sub>SUSY</sub>  $\propto \frac{\tan^6 \beta}{m_A^4} \Rightarrow \tan \beta \gtrsim 40$  で強い制限。

$$B_s 
ightarrow \mu^+ \, \mu^-$$
 in mSUGRA

 $\tan \beta = 50$ の場合 (Mahmoudi, '12)



• 黄色: LHCb limit for  $B(B_s \to \mu^+ \mu^-)$ 

## Conclusion

- SUSY は new physics の候補。
- LHC SUSY search でシグナルは見つかっていない。
  - ▷ spectrum に制限:

 $m(\widetilde{g}) > 1 \text{ TeV}, \ m(\widetilde{q}) > 1.5 \text{ TeV}.$ 

- 125 GeV Higgs は MSSM と整合。
- $B_s \rightarrow \mu^+ \mu^-$  で large tan  $\beta$  に直接探索より強い制限。