

タウ・レプトン物理研究センター研究発表会

Gauge-mediated supersymmetry breaking with generalized messenger sector at LHC

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Outline

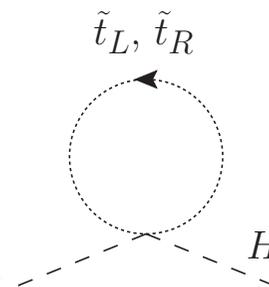
1. Introduction
2. Gauge-mediated SUSY breaking
3. $X + \bar{X}$ messenger scenario
4. $Q + \bar{Q}$ messenger scenario
5. Summary

Supersymmetry (SUSY)

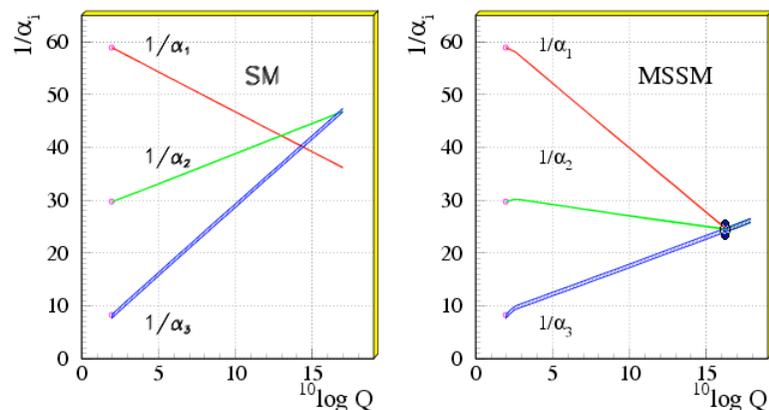
高エネルギーで boson と fermion の間の対称性が実現？

標準模型 \Rightarrow Minimal SUSY standard model (MSSM)

- quark, lepton \Leftrightarrow squark, slepton
- Higgs \Leftrightarrow higgsino
- gauge 場 \Leftrightarrow gaugino



Higgs 質量の二次発散は相殺！



Gauge coupling unification

\Rightarrow GUT の存在を示唆！

現実的なモデルでは SUSY は破れている必要がある

Soft SUSY breaking (二次発散を導かずに SUSY を破る)

$$\begin{aligned}\mathcal{L}_{\text{soft}} = & -\frac{1}{2} \left(M_3 \tilde{G} \tilde{G} + M_2 \tilde{W} \tilde{W} + M_1 \tilde{B} \tilde{B} \right) + \text{h.c.} && \text{gaugino mass} \\ & - \left[(A_u)_{ij} \tilde{U}_i \tilde{Q}_j H_u + \dots \right] + \text{h.c.} && \text{スカラー三点 (A-term)} \\ & - (m_Q^2)_{ij} \tilde{Q}_i^\dagger \tilde{Q}_j + \dots && \text{sfermion mass} \\ & - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - (b H_u H_d + \text{h.c.}) && \text{Higgs mass}\end{aligned}$$

bino \tilde{B} , wino \tilde{W} , higgsino \tilde{H} の質量固有状態

Neutralino: $(\tilde{B}, \tilde{W}^3, \tilde{H}_d^0, \tilde{H}_u^0) \Rightarrow (\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0)$

Chargino: $(\tilde{W}^+, \tilde{H}_u^+, \tilde{W}^-, \tilde{H}_d^-) \Rightarrow (\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm)$

2. Gauge-mediated SUSY breaking

$SU(3)_C \times SU(2)_L \times U(1)_Y$ の量子数を持つ messenger 場を導入することで SUSY の破れを伝搬

$$W = m_\Phi \Phi \bar{\Phi} + \theta^2 F_\Phi \Phi \bar{\Phi} \quad (\Phi, \bar{\Phi} : \text{messenger 場})$$

Gaugino mass

$$M_a \simeq n_a \left(\frac{\alpha_a}{4\pi} \right) \frac{F_\Phi}{m_\Phi}$$

Sfermion mass

$$m_{\tilde{f}}^2 \simeq \sum_{a=1}^3 n_a C_a^{\tilde{f}} \left(\frac{\alpha_a}{4\pi} \right)^2 \frac{F_\Phi^2}{m_\Phi^2}$$

n_a : Dynkin index ($n_a = 1$ for $\mathbf{5} + \bar{\mathbf{5}}$ of $SU(5)$ GUT)

$$\mathbf{5} = D(\mathbf{3}, \mathbf{1})_{-1/3} + \bar{L}(\mathbf{1}, \mathbf{2})_{1/2}, \quad \bar{\mathbf{5}} = \bar{D}(\bar{\mathbf{3}}, \mathbf{1})_{1/3} + L(\mathbf{1}, \mathbf{2})_{-1/2}$$

messenger を導入すると gauge coupling の
スケール依存性が変更を受ける

$$\frac{d}{d \ln Q} \alpha_a^{-1} = -\frac{b_a}{2\pi} + \mathcal{O}(\alpha^2) \quad \Rightarrow \quad b'_a = b_a + n_a$$

coupling unification を損なわないためには
 $n_1 = n_2 = n_3$ であればよい

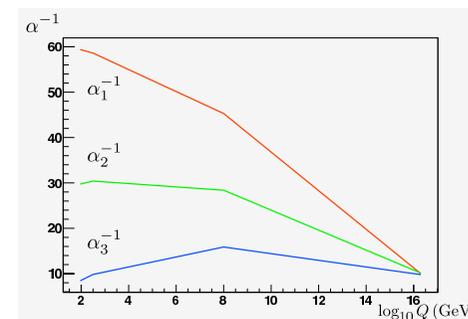
\Rightarrow GUT relation

$$M_1(m_Z) : M_2(m_Z) : M_3(m_Z) \sim 1 : 2 : 6$$

しかし $n_1 = n_2 = n_3$ が満たされない場合でも
unification が実現している可能性はある！

(例：anomalous $U(1)$ GUT)

その場合には GUT relation は成り立っていない！



Typical multiplets in $SU(5)$ GUT

$$\bar{\mathbf{5}} = \bar{D} + L, \quad \mathbf{10} = Q + \bar{U} + \bar{E}, \quad \mathbf{24} = G + W + X + \bar{X}$$

	$(SU(3)_C, SU(2)_L)_{U(1)_Y}$	n_1	n_2	n_3
$Q + \bar{Q}$	$(\mathbf{3}, \mathbf{2})_{1/6} + (\bar{\mathbf{3}}, \mathbf{2})_{-1/6}$	1/5	3	2
$U + \bar{U}$	$(\mathbf{3}, \mathbf{1})_{2/3} + (\bar{\mathbf{3}}, \mathbf{1})_{-2/3}$	8/5	0	1
$D + \bar{D}$	$(\mathbf{3}, \mathbf{1})_{-1/3} + (\bar{\mathbf{3}}, \mathbf{1})_{1/3}$	2/5	0	1
$L + \bar{L}$	$(\mathbf{1}, \mathbf{2})_{-1/2} + (\mathbf{1}, \mathbf{2})_{1/2}$	3/5	1	0
$E + \bar{E}$	$(\mathbf{1}, \mathbf{1})_{-1} + (\mathbf{1}, \mathbf{1})_1$	6/5	0	0
G	$(\mathbf{8}, \mathbf{1})_0$	0	0	3
W	$(\mathbf{1}, \mathbf{3})_0$	0	2	0
$X + \bar{X}$	$(\mathbf{3}, \mathbf{2})_{-5/6} + (\bar{\mathbf{3}}, \mathbf{2})_{5/6}$	5	3	2

一組の messenger 場の寄与だけが主要な場合を考える

⇒ $X + \bar{X}$ と $Q + \bar{Q}$ が messenger 場の候補

模型を LHC で確認するには？

SUSY @ LHC

- R-parity

(SM 粒子) \rightarrow (SM 粒子)

(SUSY 粒子) \rightarrow $-($ SUSY 粒子)

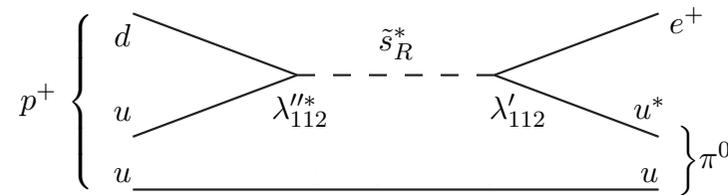
MSSM で陽子崩壊を導く相互作用を禁止するために導入

\Rightarrow 最も軽い SUSY 粒子 (LSP: Lightest SUSY Particle) は安定

LSP は dark matter の候補

GMSB model では典型的に gravitino \tilde{G} が LSP

\Rightarrow GMSB では Next to LSP (NLSP) が重要！

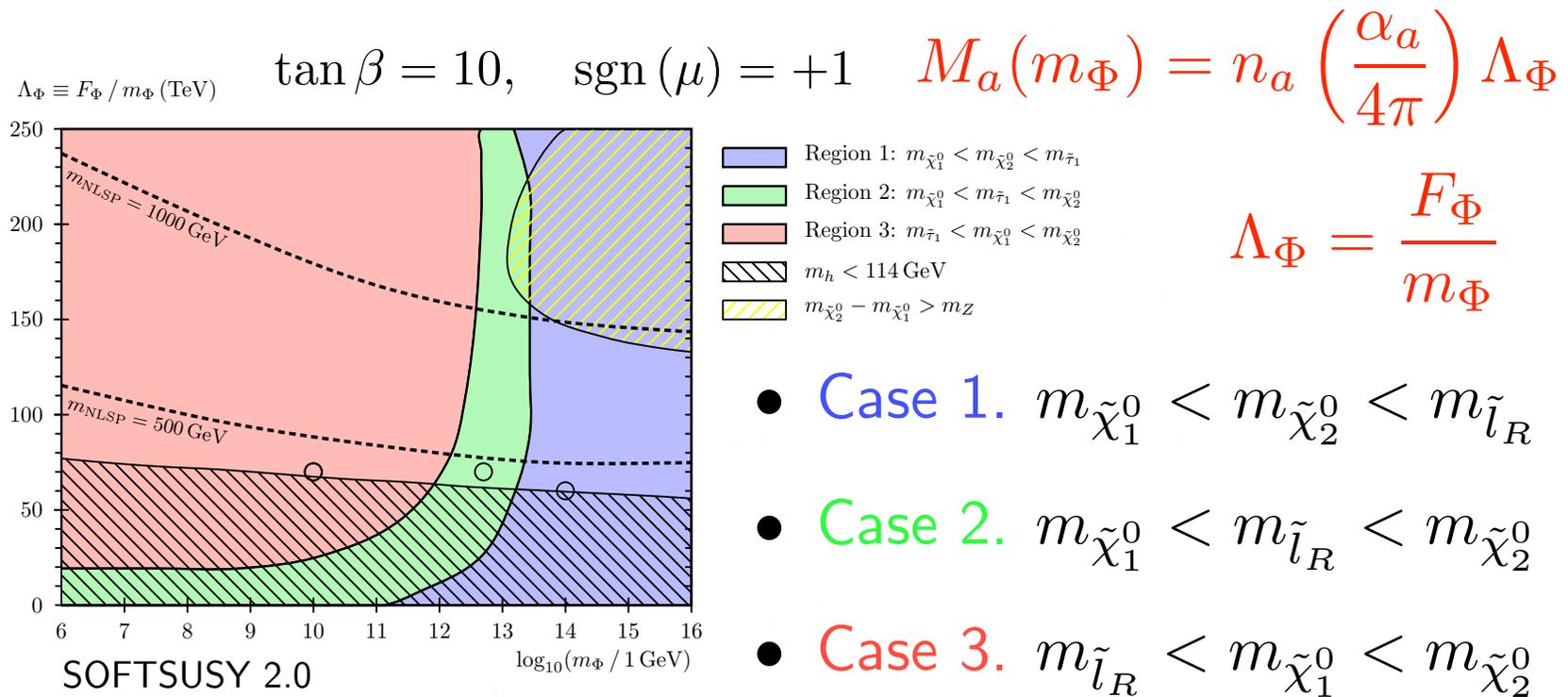


3. $X + \bar{X}$ messenger scenario

$$n_1 = 5, \quad n_2 = 3, \quad n_3 = 2$$

$$M_1(m_Z) : M_2(m_Z) : M_3(m_Z) \sim 5 : 6 : 12$$

⇒ Mild hierarchy among gauginos is achieved.



Case 1. and Case 2.

Neutralino $\tilde{\chi}_1^0$ NLSP

Case 3.

Stau $\tilde{\tau}_1$ NLSP

具体的な model point

Case 1. $\Lambda_\Phi = 60$ TeV, $m_\Phi = 1.0 \times 10^{14}$ GeV

Case 2. $\Lambda_\Phi = 70$ TeV, $m_\Phi = 5.0 \times 10^{12}$ GeV

Case 3. $\Lambda_\Phi = 70$ TeV, $m_\Phi = 1.0 \times 10^{10}$ GeV

今考えている model point では

NLSP は detector 内で崩壊しない！

$$\Gamma(\text{NLSP} \rightarrow \tilde{G} + \text{SM 粒子}) \propto F_\Phi^{-2}$$

Model Points

	Case 1	Case 2	Case 3
\tilde{g}	910	1049	1054
\tilde{u}_L	1017	1168	1163
\tilde{u}_R	946	1086	1089
\tilde{d}_L	1022	1173	1169
\tilde{d}_R	905	1047	1063
\tilde{b}_1	894	1036	1053
\tilde{b}_2	929	1073	1085
\tilde{t}_1	704	831	879
\tilde{t}_2	957	1097	1107
$\tilde{\nu}_l$	564	621	556
$\tilde{\nu}_\tau$	562	619	555
\tilde{e}_L	569	626	561
\tilde{e}_R	478	497	403
$\tilde{\tau}_1$	473	492	399
$\tilde{\tau}_2$	568	625	561
$\tilde{\chi}_1^0$	395	464	459
$\tilde{\chi}_2^0$	439	514	508
$\tilde{\chi}_3^0$	530	595	562
$\tilde{\chi}_4^0$	571	640	621
$\tilde{\chi}_1^\pm$	433	506	496
$\tilde{\chi}_2^\pm$	568	636	618
h^0	114	115	114
H^0	766	852	783
A^0	765	851	783
H^\pm	770	856	787

Case 3. Stau ($\tilde{\tau}_1$) NLSP

電荷を持つ $\tilde{\tau}_1$ が detector 内で崩壊しない場合

muon system を利用して測定が可能！

G. Polesello and A. Rimoldi, ATL-MUON-99-006

J. Ellis et al., ATL-PHYS-PUB-2007-016

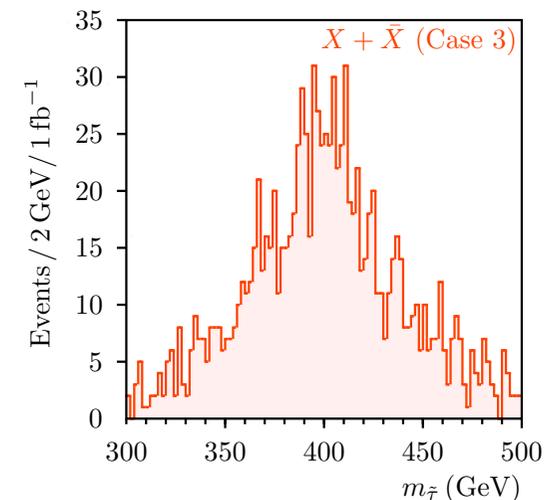
Stau ($\tilde{\tau}_1$) identification

- High ionization rate
- Time-of-Flight (ToF) measurement

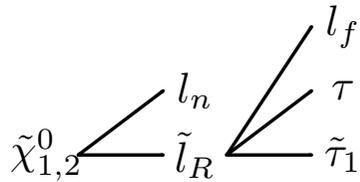
$\tilde{\tau}_1$ の速度が測定できる

$$m = \frac{p}{\beta\gamma} \quad \gamma = (1 - \beta^2)^{-1/2}$$

HERWIG 6.5 + AcerDET 1.0

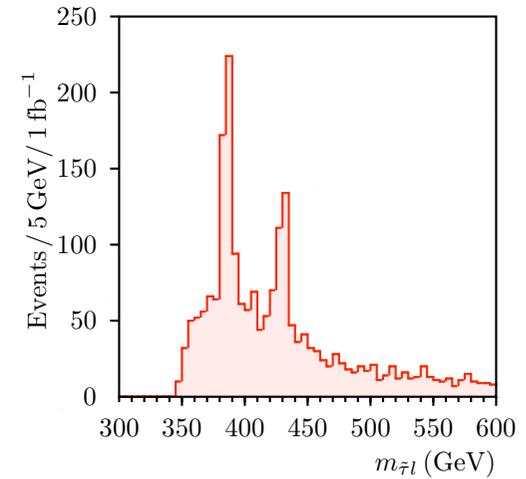


$m_{\tilde{\chi}_1^0} \simeq M_1, m_{\tilde{\chi}_2^0} \simeq M_2$ の測定



$$p_{\tilde{l}_R} = p_{\tilde{\tau}_1} + p_{\tau} + p_{l_f} \simeq p_{\tilde{\tau}_1}$$

$$\Rightarrow m_{\tilde{\chi}_{1,2}^0}^2 \simeq (p_{\tilde{\tau}_1} + p_{l_n})^2$$

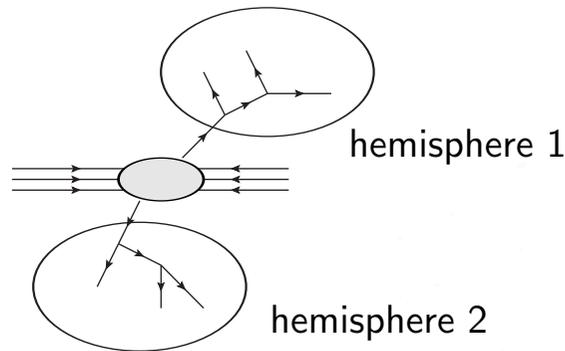


$m_{\tilde{g}}$ の測定

LHC における main production process は $pp \rightarrow \tilde{g}\tilde{g}, \tilde{q}\tilde{g}, \tilde{q}\tilde{q}$

Hemisphere method

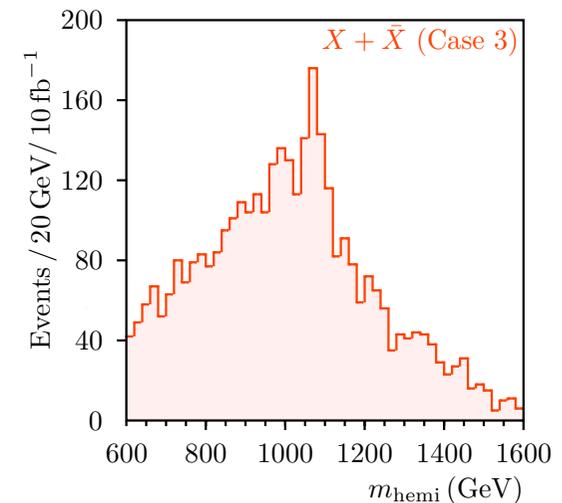
G. L. Bayatian et al.
J. Phys. G 34 (2007) 995



$$p_{\text{hemi}}^{(i)} \equiv \sum_{\text{hemisphere } i} p$$

$m_{\text{hemi}}^2 \equiv p_{\text{hemi}}^2$ から $m_{\tilde{g}}$ の見当がつく

$\Rightarrow M_1 : M_2 : M_3 \sim 5 : 6 : 12$ が確認できそう



Case 1. and 2. Neutralino ($\tilde{\chi}_1^0$) NLSP

- NLSP $\tilde{\chi}_1^0$ の運動量は直接測定できない
- parton の initial momentum は不明
- 生成粒子のビーム軸に垂直な方向の全運動量はほぼ 0

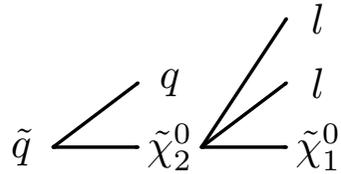
$$\mathbf{p}_T^{\text{mss}} \equiv - \sum \mathbf{p}_T^{\text{vis}} = \mathbf{p}_T^{\text{NLSP(1)}} + \mathbf{p}_T^{\text{NLSP(2)}}$$

標準模型の事象に対するカット

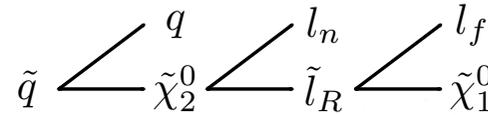
- $p_T^{(1)} > 100 \text{ GeV}$ and $p_T^{(2,3,4)} > 50 \text{ GeV}$
- $M_{\text{eff}} \equiv p_T^{(1)} + p_T^{(2)} + p_T^{(3)} + p_T^{(4)} + E_T^{\text{miss}} > 400 \text{ GeV}$
- $E_T^{\text{miss}} > \max\{100 \text{ GeV}, 0.2M_{\text{eff}}\}$
- 2 isolated leptons with $p_T^e > 20 \text{ GeV}$ and $p_T^\mu > 5 \text{ GeV}$

1) Kinematical endpoint measurement

Case 1. 3体崩壊



Case 2. 2体崩壊



Dilepton invariant mass

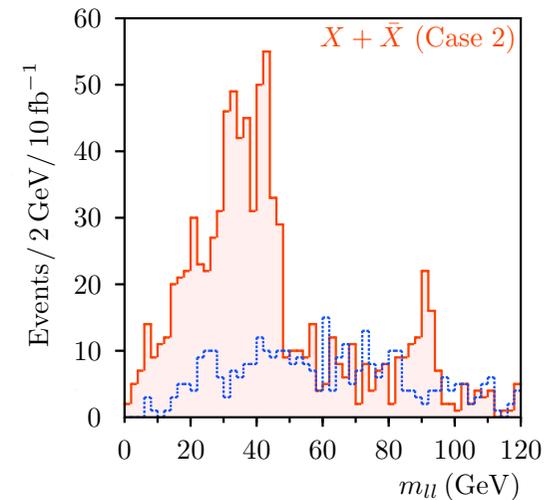
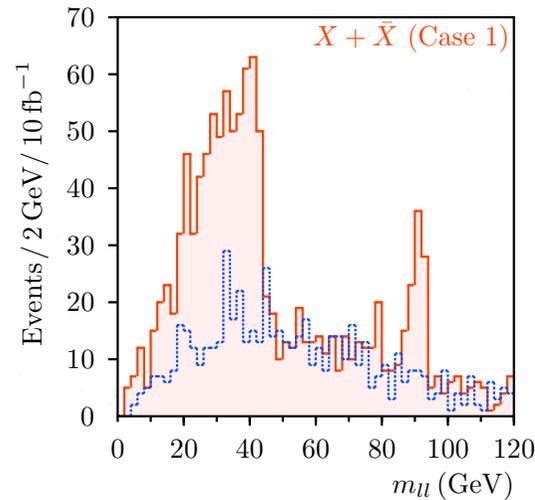
$$m_{ll}^2 \equiv (p_{l_1} + p_{l_2})^2$$

Case 1.

$$m_{ll}^{\max} = m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$$

Case 2.

$$(m_{ll}^{\max})^2 = m_{\tilde{\chi}_2^0}^2 \left(1 - \frac{m_{\tilde{l}_R}^2}{m_{\tilde{\chi}_2^0}^2} \right) \left(1 - \frac{m_{\tilde{\chi}_1^0}^2}{m_{\tilde{l}_R}^2} \right)$$

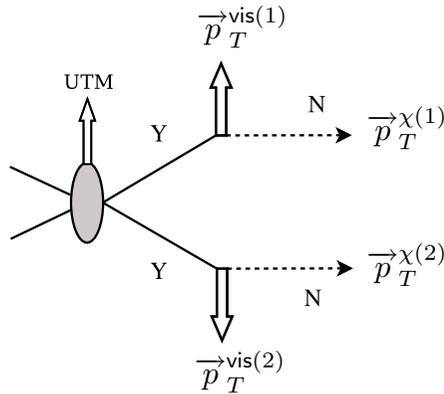


赤 : $e^+ e^- + \mu^+ \mu^-$

青 : $e^+ \mu^- + \mu^+ e^-$

2) m_{T2} measurement

二つの同質量粒子 Y が invisible 粒子 N と visible 粒子に崩壊



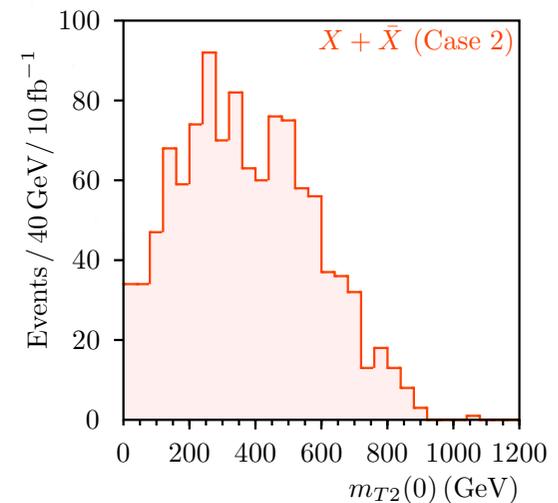
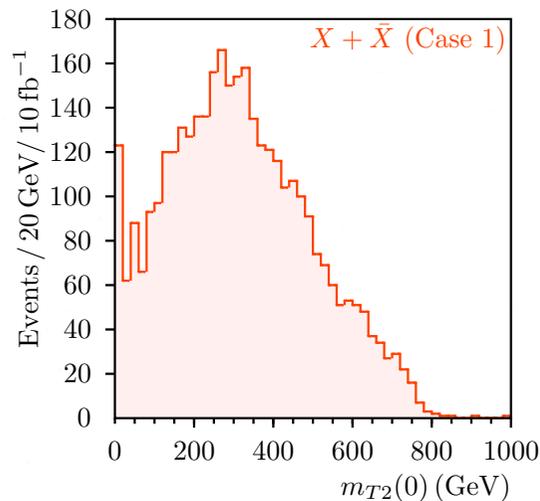
$$m_{T2}(M_{\text{test}}) \equiv \min_{\mathbf{p}_T^{\text{miss}} = \mathbf{p}_T^{\chi(1)} + \mathbf{p}_T^{\chi(2)}} \left[\max \left\{ m_T^{(1)}, m_T^{(2)} \right\} \right]$$

$$\begin{aligned} m_T^2(\vec{p}_T^{\text{vis}}, \vec{p}_T^{\chi}) &\equiv (\vec{p}_T^{\text{vis}} + \vec{p}_T^{\chi})^2 \\ &= m_{\text{vis}}^2 + M_{\text{test}}^2 + 2(E_T^{\text{vis}} \cdot E_T^{\chi} - \mathbf{p}_T^{\text{vis}} \cdot \mathbf{p}_T^{\chi}) \end{aligned}$$

$$\vec{p}_T \equiv (E_T, \mathbf{p}_T), \quad E_T \equiv \sqrt{|\mathbf{p}_T|^2 + m^2}$$

$$pp \rightarrow \tilde{q}_R \tilde{q}_R \rightarrow \tilde{\chi}_1^0 q \tilde{\chi}_1^0 q$$

$$m_{T2}^{\text{max}}(0) = \frac{m_{\tilde{q}}^2 - m_{\tilde{\chi}_1^0}^2}{m_{\tilde{q}}}$$



GUT relation が満たされる場合との区別

mSUGRA

同様な m_{ll} 分布を与えるパラメータ

$$m_{1/2} = 150 \text{ GeV}, m_0 = 750 \text{ GeV}$$

$$A_0 = -100 \text{ GeV}, \tan \beta = 10, \text{sgn}(\mu) = +1$$

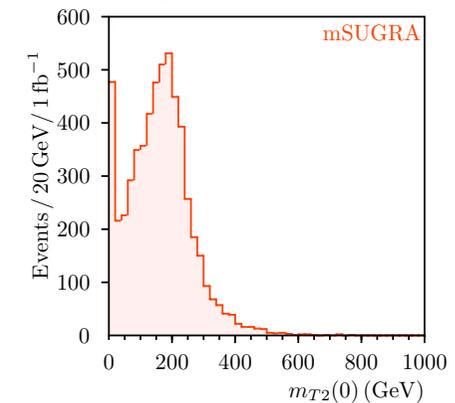
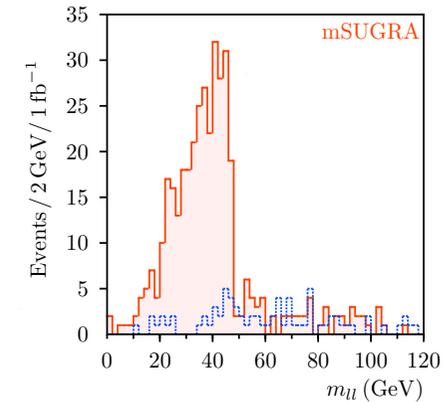
GUT relation $M_1 : M_2 : M_3 \sim 1 : 2 : 6$ が

成り立つため m_{ll}^{\max} が小さいとき

gluino が軽いはず

m_{T2}^{\max} で color を持つ粒子の質量スケールは見える

Case 1 と Case 2 の区別にはさらに詳細な測定が必要



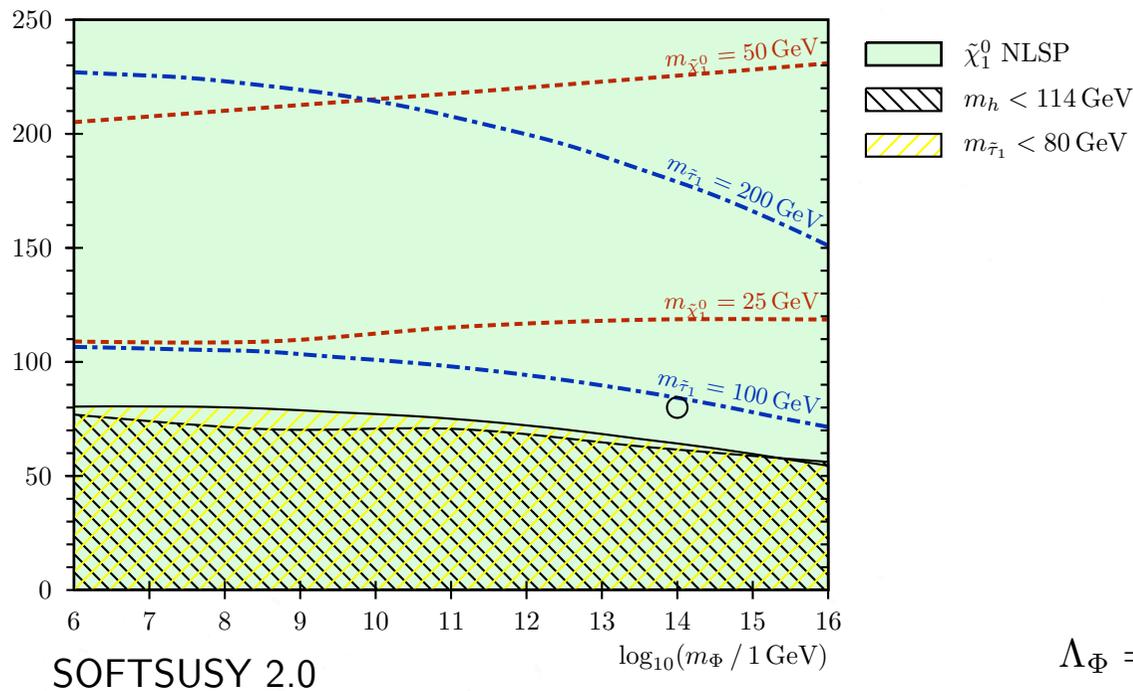
4. $Q + \bar{Q}$ messenger scenario

$$n_1 = 1/5, \quad n_2 = 3, \quad n_3 = 2$$

$$M_1(m_Z) : M_2(m_Z) : M_3(m_Z) \sim 1 : 30 : 60$$

$\Rightarrow U(1)_Y$ charge しか持たない SUSY 粒子が非常に軽い

$$\Lambda_\Phi \equiv F_\Phi / m_\Phi \text{ (TeV)} \quad \tan \beta = 10, \quad \text{sgn}(\mu) = +1$$

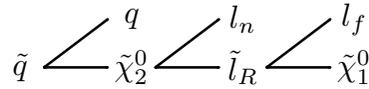


Model Point

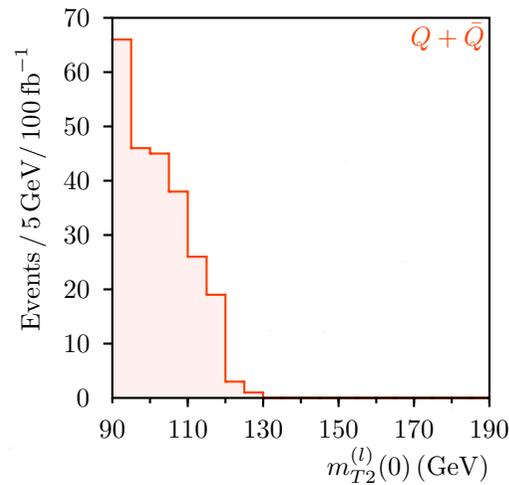
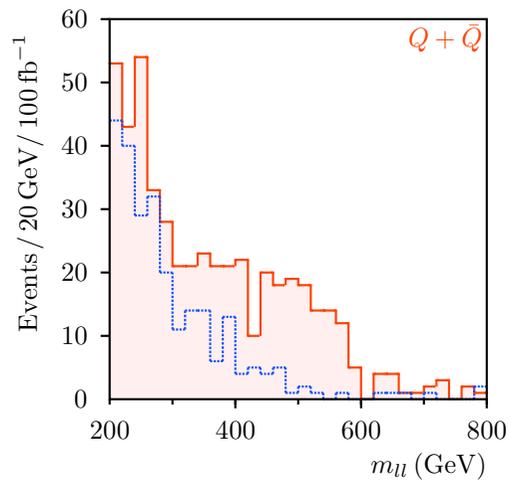
\tilde{g}	1181	$\tilde{\chi}_1^0$	16
\tilde{u}_L	1326	$\tilde{\chi}_2^0$	586
\tilde{u}_R	1165	$\tilde{\chi}_3^0$	682
\tilde{d}_L	1331	$\tilde{\chi}_4^0$	720
\tilde{d}_R	1163	$\tilde{\chi}_1^\pm$	586
\tilde{b}_1	1150	$\tilde{\chi}_2^\pm$	720
\tilde{b}_2	1221	h^0	116
\tilde{t}_1	867	H^0	954
\tilde{t}_2	1240	A^0	954
$\tilde{\nu}_l$	680	H^\pm	958
$\tilde{\nu}_\tau$	679		
\tilde{e}_L	684		
\tilde{e}_R	118		
$\tilde{\tau}_1$	96		
$\tilde{\tau}_2$	682		

$$\Lambda_\Phi = 80 \text{ TeV}, \quad m_\Phi = 1.0 \times 10^{14} \text{ GeV}$$

1) Endpoint measurement



$$(m_{ll}^{\max})^2 = m_{\tilde{\chi}_2^0}^2 \left(1 - \frac{m_{\tilde{l}_R}^2}{m_{\tilde{\chi}_2^0}^2}\right) \left(1 - \frac{m_{\tilde{\chi}_1^0}^2}{m_{\tilde{l}_R}^2}\right)$$



$$\frac{m_{\tilde{\chi}_2^0}^2}{m_{\tilde{\chi}_1^0}^2} > \frac{m_{\tilde{\chi}_2^0}}{m_{\tilde{l}_R}} > \frac{m_{\tilde{\chi}_2^0}^2 - m_{\tilde{l}_R}^2}{m_{\tilde{l}_R}} = \frac{(m_{ll}^{\max})^2}{m_{T2}^{(l)\max}(0)} \sim 2.8 \text{ TeV}$$

$M_1 \ll M_2$ が確認可能！

2) m_{T2} measurement

lepton を用いた m_{T2}

$$pp \rightarrow \tilde{l}_R^+ \tilde{l}_R^- \rightarrow \tilde{\chi}_1^0 l^+ \tilde{\chi}_1^0 l^-$$

$$m_{T2}^{(l)\max}(0) = \frac{m_{\tilde{l}_R}^2 - m_{\tilde{\chi}_1^0}^2}{m_{\tilde{l}_R}}$$

5. Summary

- GMSB model でこれまで主に考えられて来たものは $SU(5)$ sym. を尊重する messenger を用いたものだった
- しかし例えば anomalous $U(1)$ GUT の枠内では異なる n_a を与える messenger による模型もありえる
- $X + \bar{X}$ messenger の場合,
bino と wino の間の mass splitting は小さい
- $Q + \bar{Q}$ messenger の場合,
bino と右巻き slepton が他の粒子に比べて極端に軽い
- これらの特徴が LHC 実験で検証できる可能性は十分ある