# Gauge-mediated supersymmetry breaking with generalized messenger sector at LHC

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# Outline

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4. $Q + \bar{Q}$ messenger scenario
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# 1. Introduction

## Low-energy supersymmetry (SUSY)

Standard model $\Rightarrow$ Minimal SUSY standard model (MSSM)

Appealing points:

- Cancellation of the quadratic divergence
- Dark matter (R-parity)
- Gauge coupling unification

## Unsolved problem: SUSY breaking mechanism

The mass spectrum of the sparticles is highly dependent on the mechanism which provides the soft SUSY breaking terms!

# Gauge-mediated SUSY breaking (GMSB)

The SUSY breaking effects are communicated to the MSSM fields through the interaction with the messenger fields.

SUSY breaking $\langle S \rangle = \theta^2 F_S \neq 0$ — Messengers $\Phi + \bar{\Phi}$ — Gauge interaction — MSSM fields matter + Higgs

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

## Gaugino mass

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

## Sfermion mass

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

$n_a$: Dynkin index

$n_a$ is determined by the quantum number of the messenger field.

# 2. Generalized messenger fields

The messenger fields affect the running of the gauge couplings.

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

$\Rightarrow$ The Gauge coupling unification may be spoiled!

## How to preserve the gauge coupling unification

- If the messengers are degenerate among the $SU(5)$ multiplet,
  $n_1 = n_2 = n_3$
  $\Rightarrow$ GUT relation
  $$M_1(m_Z) : M_2(m_Z) : M_3(m_Z) \sim 1 : 2 : 6$$

- Another scenario:
  If the masses of messenger fields are controlled by some symmetry, coupling unification may be retained even with different $n_a$s.

## Anomalous $U(1)$ GUT (GUT with anomalous $U(1)$ gauge symmetry)

Under the assumptions;

- The (simple) unification group $G \supset SU(3)_C \times SU(2)_L \times U(1)_Y$.
- $G$-singlet operator $O_i$ with anomalous $U(1)$ charge $o_i$ obtains the VEV

$$\langle O_i \rangle \sim \begin{cases} \lambda^{-o_i}\Lambda & \text{for } o_i \leq 0 \\ 0 & \text{for } o_i > 0 \end{cases} \qquad (\lambda \ll 1,\ \Lambda\text{: cutoff}).$$

- At low-energy, the MSSM is realized.

the gauge coupling unification is naturally explained, even if the mass spectrum of superheavy fields does not respect $SU(5)$ symmetry.

N. Maekawa and T. Yamashita, Phys. Rev. Lett. **90**, 121801 (2003).

$\Rightarrow$ If one of the messengers gives the larger contribution compared with others, the situation of different $n_a$s is naturally realized in anomalous $U(1)$ GUT.

## Typical multiplets in $SU(5)$ GUT

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

If the $SU(5)$ multiplets are degenerated, $n_1 = n_2 = n_3$ is satisfied.

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

We investigate the scenario where one pair of the messenger fields dominates the contribution of GMSB.

# Typical multiplets in $SU(5)$ GUT

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

If the $SU(5)$ multiplets are degenerated, $n_1 = n_2 = n_3$ is satisfied.

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

We investigate the scenario where one pair of the messenger fields dominates the contribution of GMSB.

$\Rightarrow$ $X + \bar{X}$ and $Q + \bar{Q}$ are the candidates.

The impact of the different $n_a$s is apparent for the gaugino masses.

Bino: $M_1$ Wino: $M_2$ Gluino: $M_3$

GUT relation: $M_1 : M_2 : M_3 \simeq 1 : 2 : 6$

- $X + \bar{X}$ messenger scenario
  $n_1 = 5,\ n_2 = 3,\ n_3 = 2 \quad \Rightarrow \quad M_1 : M_2 : M_3 \simeq 5 : 6 : 12$
- $Q + \bar{Q}$ messenger scenario
  $n_1 = 1/5,\ n_2 = 3,\ n_3 = 2 \quad \Rightarrow \quad M_1 : M_2 : M_3 \simeq 1/5 : 6 : 12$

By the measurement of gaugino masses at LHC, it may be possible to discriminate these models from the one which satisfy the GUT relation.

- $M_1 \simeq m_{\tilde{\chi}_1^0}$ (Bino $\tilde{B}$) $\simeq$ (Lightest neutralino $\tilde{\chi}_1^0$)
- $M_2 \simeq m_{\tilde{\chi}_2^0}$ (Wino $\tilde{W}$) $\simeq$ (Second lightest neutralino $\tilde{\chi}_2^0$)
- $M_3 \simeq m_{\tilde{g}}$ (Gluino $\tilde{g}$)

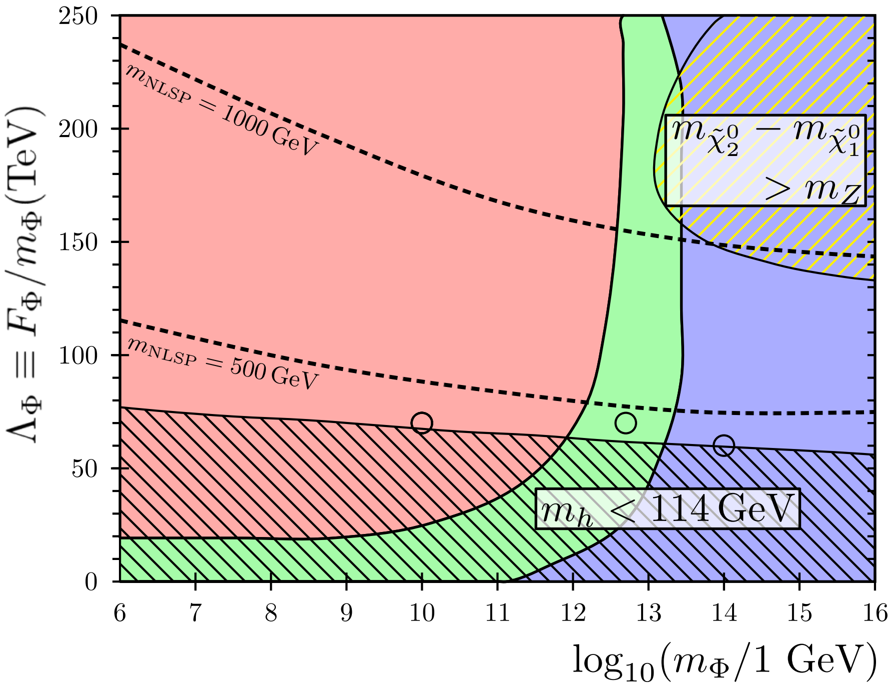
# 3. $X + \bar{X}$ messenger scenario

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

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

Mild hierarchy among the gaugino masses is achieved.

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




Parameters of the messenger fields

$$m_\Phi, \quad \Lambda_\Phi \equiv F_\Phi/m_\Phi$$

Case 1. $m_{\tilde{\chi}_1^0} < m_{\tilde{\chi}_2^0} < m_{\tilde{l}_R}$

Case 2. $m_{\tilde{\chi}_1^0} < m_{\tilde{l}_R} < m_{\tilde{\chi}_2^0}$

Case 3. $m_{\tilde{l}_R} < m_{\tilde{\chi}_1^0} < m_{\tilde{\chi}_2^0}$

# Discrimination of the model at the LHC

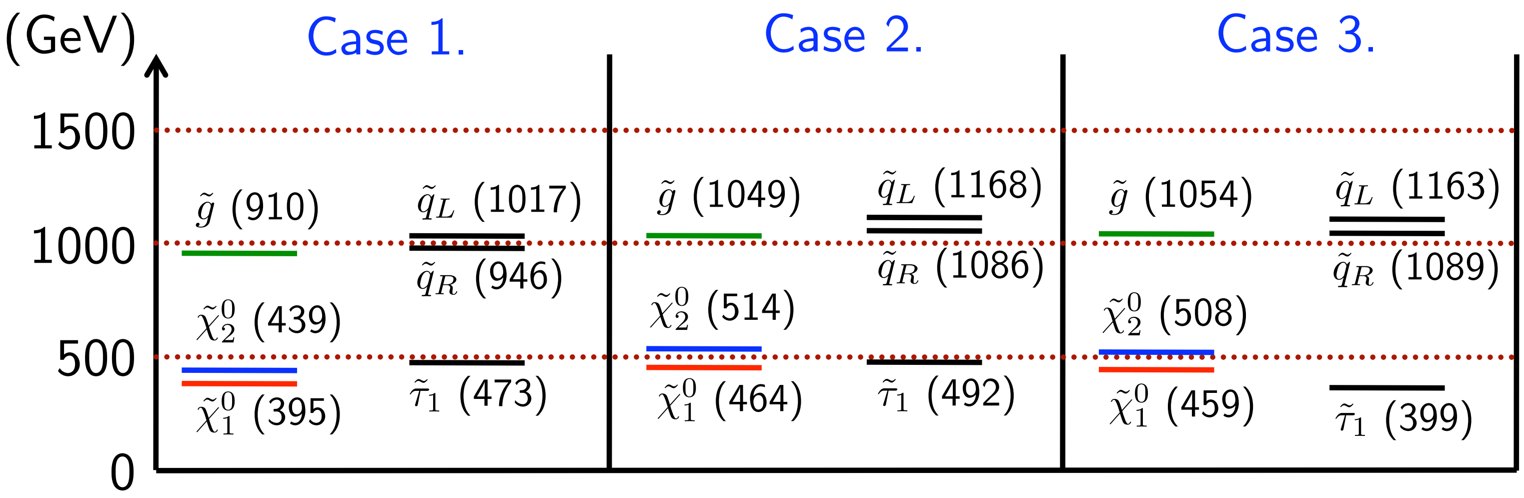
The lightest SUSY particle (LSP) is gravitino in GMSB model.

$\Rightarrow$ The next to LSP (NLSP) is important in collider physics.

- Case 1. and Case 2. Neutralino $\tilde{\chi}_1^0$ NLSP
- Case 3. Stau $\tilde{\tau}_1$ NLSP

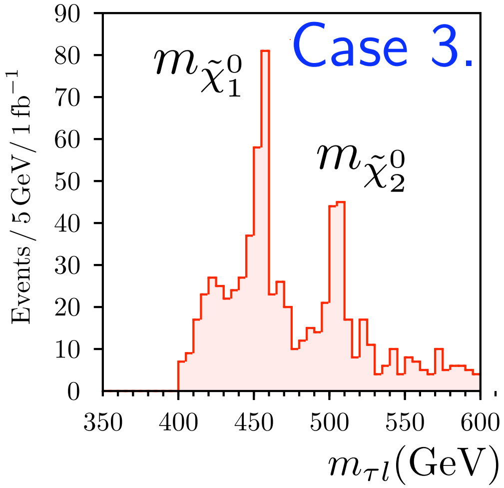
In our model points, NLSP is long-lived. $\Rightarrow$ NLSPs penetrate the detector.

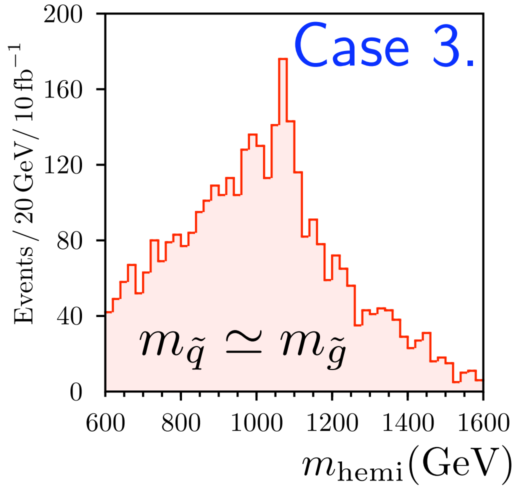
# Model points



If we measure the smallness of the difference between $M_1$ and $M_2$ compared with the overall mass scale of the sparticles, the deviation from the GUT relation can be checked!

- For the stau $\tilde{\tau}_1$ NLSP scenario, (Case 3.)
  4-momentum of $\tilde{\tau}_1$ can be measured by the muon system.
  G. Polesello and A. Rimoldi, ATL-MUON-99-006
  $\Rightarrow$ The invariant masses of sparticles can be measured directly.



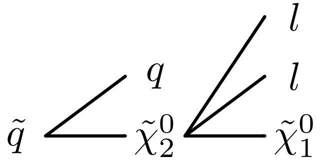




- For the neutralino NLSP scenario, (Case 1. and Case 2.)
  NLSP is invisible and we need some technique to measure the masses of the sparticles.

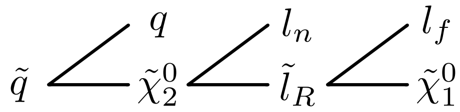
The endpoint of the invariant mass is determined from the kinematics.

## 1) Dilepton invariant mass measurement

Case 1. Three-body decay




Case 2. Two-body decay




Dilepton invariant mass

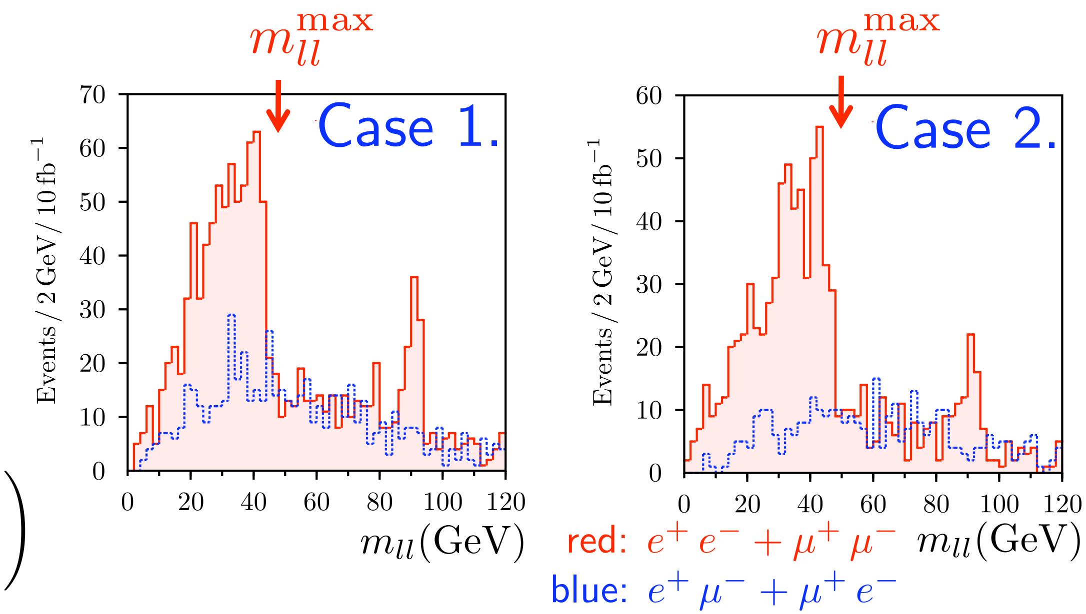
$$m_{ll}^2 \equiv (p_{l_1} + p_{l_2})^2$$

Case 1.

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

Case 2.

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



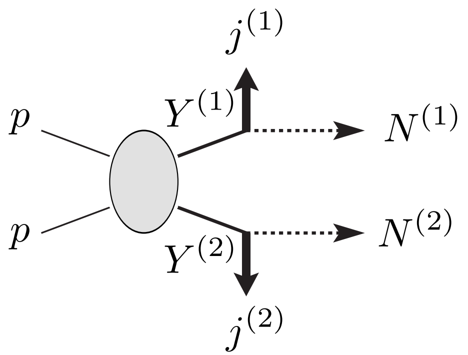

Small $m_{ll}^{\max}$ is characteristic in the $X + \bar{X}$ messenger scenario.
($m_{\tilde{\chi}_1^0} \simeq M_1$, $m_{\tilde{\chi}_2^0} \simeq M_2$ and $(M_2 - M_1)/M_1 \ll 1$)

**The mass scale of the sparticles can be roughly measured by $m_{T2}$ variable.**

## 2) $m_{T2}$ measurement

For the process $p\,p \to Y\,Y \to N\,j\,N\,j$, the maximal value of $m_{T2}$ variable is given as a function of the masses of $Y$ and $N$.

($Y$: Parent particle, $N$: invisible particle, $j$: visible particle)



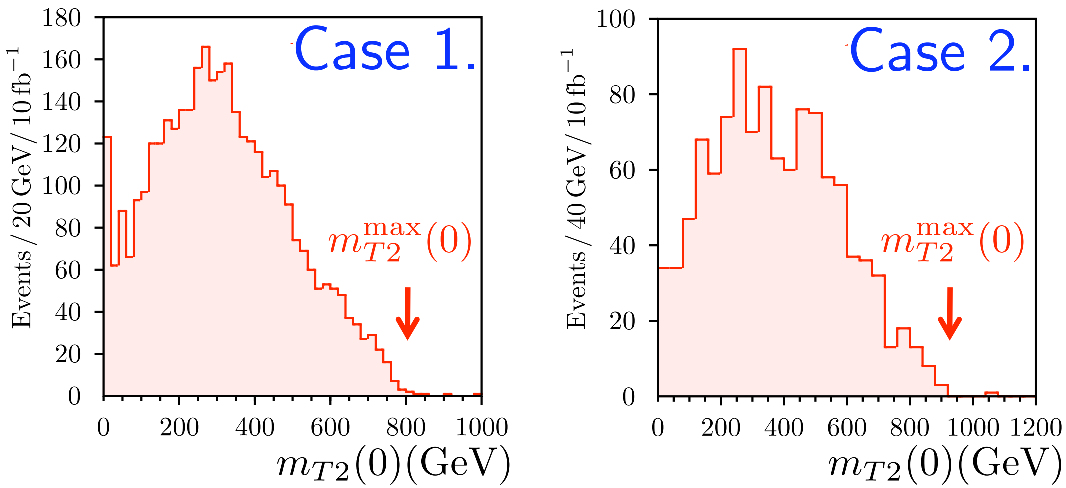

$$m_{T2}(0) \equiv \min_{\boldsymbol{p}_T^{\text{miss}} = \boldsymbol{p}_T^{N(1)} + \boldsymbol{p}_T^{N(2)}} \left[ \max \left\{ m_T^{(1)}, m_T^{(2)} \right\} \right]$$

$$m_T^2(\boldsymbol{p}_T^j, \boldsymbol{p}_T^N) \equiv m_j^2 + 2(E_T^j \cdot E_T^N - \boldsymbol{p}_T^j \cdot \boldsymbol{p}_T^N)$$

**Squark pair production**

$$p\,p \to \tilde{q}_R\,\tilde{q}_R \to \tilde{\chi}_1^0\,q\,\tilde{\chi}_1^0\,q$$

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



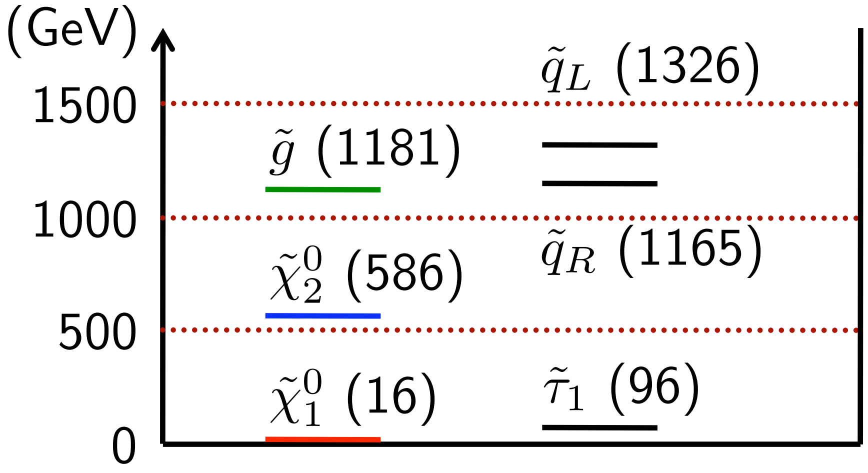
# 4. $Q + \bar{Q}$ messenger scenario

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

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

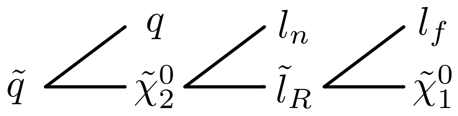
Sparticles with only $U(1)_Y$ charge (i.e., bino and right-handded slepton) are very light compared with other sparticles.

## Model point

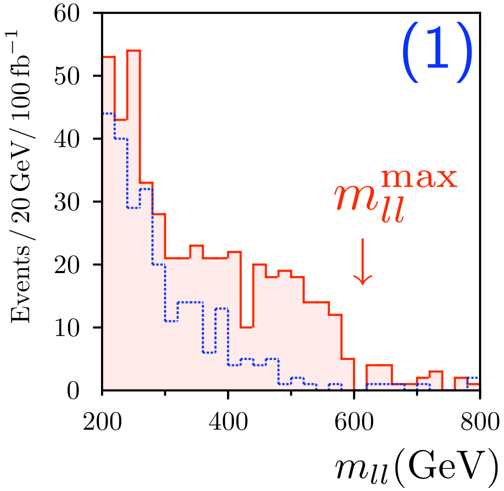


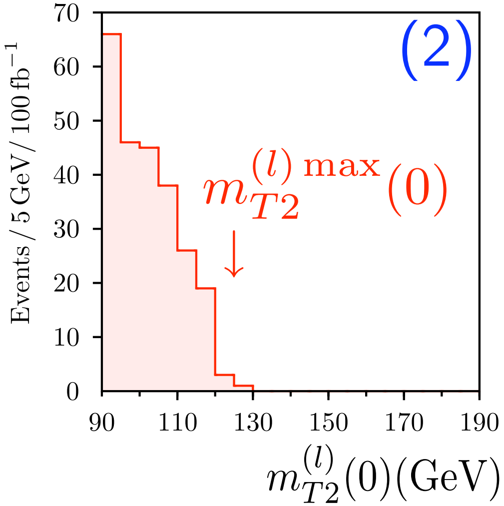

$M_1 \simeq m_{\tilde{\chi}^0_1} \ll m_{\tilde{\chi}^0_2}$ is characteristic in $Q + \bar{Q}$ messenger scenario.

## (1) Dilepton invariant mass measurement




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




## (2) $m_{T2}$ measurement

Leptonic $m_{T2}$

$$p\,p \to \tilde{l}_R^+\,\tilde{l}_R^- \to \tilde{\chi}_1^0\,l^+\,\tilde{\chi}_1^0\,l^-$$

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

Combining these measurements, we can see the large hierarchy between $m_{\tilde{\chi}_1^0}$ and $m_{\tilde{\chi}_2^0}$.

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

$\Rightarrow$ $M_1 \ll M_2$ can be checked!

# 5. Summary

- Most of the GMSB models considered so far are based on messengers which respect $SU(5)$ sym. $(n_1 = n_2 = n_3)$
- We consider the models of messengers with different $n_a$s.
- For $X + \bar{X}$ messenger scenario, small mass splitting between bino and wino is predicted.
- For $Q + \bar{Q}$ messenger scenario, all sparticles other than bino and right-handded slepton are considerably heavier.
- These scenario may be discriminated from the models which satisfy the GUT relation of the gaugino masses through the search at the LHC.

| | 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 |

| | | | |
|---|---|---|---|
| $\tilde{g}$ | 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 | | |