A measurement of Neutralino Mass at the LHC in Light Gravitino Scenarios

Koichi Hamaguchi (Tokyo U. and IPMU)

at LHC focus week, IPMU, June ’08

with Eita Nakamura and Satoshi Shirai (Tokyo U.),

arXiv: 0805.2502
Summary:

- We considered SUSY models with
We considered SUSY models with a very light gravitino LSP
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- We considered SUSY models with a very light gravitino LSP and a neutralino NLSP.
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- and presented a neutralino mass measurement.
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• We considered SUSY models with a very light gravitino LSP and a neutralino NLSP.

• we presented a neutralino mass measurement based on $M_{T2}$ method.
Summary:

- We considered SUSY models with a very light gravitino LSP and a neutralino NLSP.
- and presented a neutralino mass measurement based on $M_{T2}$ method.

- independent of other masses / cascade patterns
- complementary to (better than) other methods
**$M_{T2}$ method**

Lester, Summers, '99
Barr, Lester, Stephens, '03

$m_A = ?$

$X$ (missing)

$P_{T,\text{miss}}$
$M_{T2}$ method

Lester, Summers, '99
Barr, Lester, Stephens, '03

$m_A = ?$
\( M_{T2} \) method

Lester, Summers, ’99
Barr, Lester, Stephens, ’03

\[
(M_{T2})^2 = \min_p \left[ \max \left\{ (M_{T}^{(1)})^2, (M_{T}^{(2)})^2 \right\} \right],
\]

\[
(M_{T}^{(i)})^2 = m_B^2 + m_X^2 + 2(E_{T}^{\text{miss},i} E_{T}^{B,i} - p_{T}^{\text{miss},i} \cdot p_{T}^{B,i}) \quad \text{for} \quad i = 1, 2
\]
\[ (M_{T2})^2 = \min_{p_T^{\text{miss},1} + p_T^{\text{miss},2} = p_T^{\text{miss}}} \left[ \max \left\{ (M_T^{(1)})^2, (M_T^{(2)})^2 \right\} \right], \]

\[ (M_T^{(i)})^2 = m_B^2 + m_X^2 + 2(E_T^{\text{miss},i} E_T^{B,i} - p_T^{\text{miss},i} \cdot p_T^{B,i}) \quad \text{for} \quad i = 1, 2 \]

is designed to have the endpoint at \( m_A \),

\[ m_A \text{ determination !!!} \]
$M_{T2}$ method

Lester, Summers,’99
Barr, Lester, Stephens,’03

$$\begin{align*}
(M_{T2})^2 &= \min_{p_T^{miss,1} + p_T^{miss,2} = p_T^{miss}} \left[ \max \left\{ (M_T^{(1)})^2, (M_T^{(2)})^2 \right\} \right], \\
(M_T^{(i)})^2 &= m_B^2 + m_X^2 + 2(E_T^{miss, i} E_T^{B,i} - p_T^{miss, i} \cdot p_T^{B,i}) \text{ for } i = 1, 2
\end{align*}$$

is designed to have the endpoint at $m_A$.

......when we input the correct value of $m_X$. 

events
The $M_{T2}$ method is designed to have the endpoint at $m_A$, when we input the correct value of $m_X$. But in general, we don’t know $m_X$. Only a relation $m_A(m_X^{\text{trial}})$ is obtained.

$$\begin{align*}
(M_{T2})^2 &= p_{T,\text{miss}}^1 + p_{T,\text{miss}}^2 = p_{T,\text{miss}}^\text{miss} \left[ \max \left\{ (M_{T}^{(1)})^2, (M_{T}^{(2)})^2 \right\} \right], \\
(M_{T}^{(i)})^2 &= m_B^2 + m_X^2 + 2(E_{T}^{\text{miss},i} E_{T}^{B,i} - p_{T}^{\text{miss},i} \cdot p_{T}^{B,i}) \quad \text{for} \quad i = 1, 2
\end{align*}$$
\( (M_{T2})^2 \equiv \min \left( p_{T,miss,1}^2 + p_{T,miss,2}^2, p_{miss}^2 \right) \max \left\{ (M_T^{(1)})^2, (M_T^{(2)})^2 \right\} \),

\( (M_T^{(i)})^2 = m_B^2 + m_X^2 \pm 2(E_{Tmiss,i} E_{T,B,i} - p_{Tmiss,i} \cdot p_{T,B,i}) \) for \( i = 1, 2 \)

is designed to have the endpoint at \( m_A \),

events

\( m_A \)

......when we input the correct value of \( m_X \).

But in general, we don’t know \( m_X \).

only a relation \( m_A(m_X^{\text{trial}}) \) obtained.

recent developments:

“kink” in \( m_A(m_X^{\text{trial}}) \) may determine \( m_A \) and \( m_X \) simultaneously!

(Lester, Barr, 0708;
Cho, Choi, Kim, Park, 0709 + 0711;
Barr, Gripaios, Lester, 0711;
Nojiri, Shimizu, Okada, Kawagoe, 0802;
............)

☛ See Wednesday Talks by Y.G.Kim, C.Lester, Y.Shimizu.
The $M_{T2}$ method is designed to have the endpoint at $m_A$, when we input the correct value of $m_X$. But in general, we don't know $m_X$. Only a relation $m_A(m_X^{\text{trial}})$ obtained.

Here, we discuss an interesting case in that we will know $m_X = 0$. 

\begin{align*}
(M_{T2})^2 &= p_{T,\text{miss}}^1 + p_{T,\text{miss}}^2 = p_{T,\text{miss}}^\text{min} \left[ \max\left\{ (M_T^{(1)})^2, (M_T^{(2)})^2 \right\} \right], \\
(M_T^{(i)})^2 &= m_B^2 + m_X^2 + 2(E^{\text{miss},i}_T E^{B,i}_T - p_T^{\text{miss},i} \cdot p_{T,B,i}^{}) \quad \text{for} \quad i = 1, 2
\end{align*}
Suppose that large missing $P_T$ signals at the LHC will be accompanied by two high $P_T$ photons.
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➔ a natural candidate for the underlying model is a SUSY model with gravitino LSP
Suppose that large missing $P_T$ signals at the LHC will be accompanied by two high $P_T$ photons.

→ a natural candidate for the underlying model is a SUSY model with gravitino LSP + neutralino NLSP.
decay length of NLSP (into gravitino)

\[ c\tau_{\text{NLSP}} \sim 20\mu m \left( \frac{m_{\tilde{G}}}{1\text{ eV}} \right)^2 \left( \frac{m_{\text{NLSP}}}{100\text{ GeV}} \right)^{-5} \]

\[
\begin{array}{cccc}
\text{m}_{\tilde{G}} & \text{eV} & \text{keV} & \text{MeV} & \text{GeV} \\
\text{m}_{\tilde{\tau}} & \text{mm} & \text{m} & \text{km} \\
\end{array}
\]

We can assume \( m_X = m_{\text{Gravitino}} \approx 0 \) in \( M_{T2} \) method
We can assume $m_X = m_{\text{Gravitino}} \approx 0$ in $M_{T2}$ method and therefore directly measure $m_{\text{neutralino}}$ by the $M_{T2}$ method.
• $\geq 4$ jets with $p_T > 50$ GeV and $p_{T,1,2} > 100$ GeV.
• $\geq 2$ photons with $p_T > 20$ GeV.
• $M_{\text{eff}} > 500$ GeV ($M_{\text{eff}} = \sum_{\text{jets}} p_{T,j} + p_{T,\text{miss}}$).
• $p_{T,\text{miss}} > 0.2M_{\text{eff}}$.

example 1: SPS8

- $H^+, A^0, H^0$
- $\tilde{g}, \tilde{t}_3, \tilde{t}_1, \tilde{b}_2, \tilde{t}_1, \tilde{\nu}_e, \tilde{\tau}_R, \tilde{\tau}_L$
- $h^0, \tilde{\chi}_1^0$

(a) parton level

(b) detector level
example 2: SIGM

- $\geq 4$ jets with $p_T > 50$ GeV and $p_{T,1,2} > 100$ GeV.
- $\geq 2$ photons with $p_T > 20$ GeV.
- $M_{\text{eff}} > 500$ GeV ($M_{\text{eff}} = \sum_{\text{jets}} p_T + p_{T,\text{miss}}$).
- $p_{T,\text{miss}} > 0.2 M_{\text{eff}}$.

model from
KH, Shirai, Nakamura, Yanagida, ’08
Summary:

- We considered SUSY models with a very light gravitino LSP and a neutralino NLSP.
- and presented a neutralino mass measurement based on $M_{T2}$ method.
- independent of other masses / cascade patterns.
- complementary to other methods.
Motivation:

Why gravitino LSP ??
Why such a light gravitino ??
## Gravitino Problems

### Thermal History

<table>
<thead>
<tr>
<th>Time</th>
<th>Temperature</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>??</td>
<td>$\sim 0$</td>
<td>Inflation</td>
</tr>
<tr>
<td>??</td>
<td>$T_R$</td>
<td>Reheating</td>
</tr>
<tr>
<td>$\approx$</td>
<td></td>
<td>Baryogenesis</td>
</tr>
<tr>
<td>$\sim 1 \text{ sec}$</td>
<td>$\sim 1 \text{ MeV}$</td>
<td>Big Bang Nucleosynthesis</td>
</tr>
<tr>
<td>$\approx$</td>
<td></td>
<td>$n_B/s \sim 10^{-10}$</td>
</tr>
<tr>
<td>14 Gyr</td>
<td>2.7 K</td>
<td>Observed</td>
</tr>
</tbody>
</table>
stable (LSP) gravitino

unstable gravitino

Gravitino Problems

Moroi, Murayama, Yamaguchi,'93
Bolz, Brandenburg, Buchmuller,'00
Fig. from Steffen and Pradler,'06
Pagels and Primack,'82,
Viel, Lesgourgues, Haehnelt, Matarrese, Riotto,'05

Weinberg,'82 + many others
Fig. from Kawasaki, Kohri, Moroi, Yotsuyanagi,'08
Gravitino Problems

stable (LSP) gravitino

 unstabl e gravitino

\[ \Omega_{3\sigma} h^2 = 0.105 \pm 0.021 \]

\[ m/2 = 2 \text{ TeV} \]

\[ m/2 = 500 \text{ GeV} \]

\[ Tr \text{ [GeV]} \]

\[ m_{\tilde{G}} \text{ [GeV]} \]

\[ 10^6 \quad 10^9 \quad 10^{10} \]

\[ 10^7 \quad 10^8 \quad 10^9 \]

\[ 10^2 \quad 10^3 \quad 10^4 \quad 10^5 \]

Gravitino Mass (GeV)

Reheating Temperature (GeV)

BBN

allowed

Moroi, Murayama, Yamaguchi,'93

Bolz, Brandenburg, Buchmuller,'00

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Gravitino Problems

stable (LSP) gravitino

\[ \Omega \bar{G} < \Omega_{\text{CDM}} \]

unstable gravitino

BBN

\[ \text{allowed} \]

Moroi, Murayama, Yamaguchi,’93
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Gravitino Problems

- **Stable (LSP) Gravitino**
  - BBN (NLSP)
  - $\Omega \bar{G} < \Omega_{CDM}$
  - Allowed

- **Unstable Gravitino**
  - BBN
  - Allowed

---

**Fig. from:**
- Moroi, Murayama, Yamaguchi,'93
- Bolz, Brandenburg, Buchmuller,'00
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Gravitino Problems

stable (LSP) gravitino

unstable gravitino

BBN (NLSP)

hot DM

allowed

\[ \Omega_{\tilde{G}} < \Omega_{CDM} \]

allowed

16 eV

Moroi, Murayama, Yamaguchi, '93
Bolz, Brandenburg, Buchmuller, '00
Fig. from Steffen and Pradler, '06

Pagels and Primack, '82,
Viel, Lesgourgues, Haehnelt, Matarrese, Riotto, '05

10^2 10^3 10^4 10^5
Gravitino Mass (GeV)

10^5 10^6 10^7 10^8 10^9 10^{10}
Reheating Temperature (GeV)

BBN

allowed

Weinberg, '82 + many others
Fig. from Kawasaki, Kohri, Moroi, Yotsuyanagi, '08
Gravitino Problems

stable (LSP) gravitino

16 eV

unstable gravitino

allowed

\[ \Omega_{\text{dm}} h^2 = 0.105 \pm 0.021 \]

\[ m_{1/2} = 500 \text{ GeV} \]

\[ m_{1/2} = 2 \text{ TeV} \]

\[ \Omega_{\text{LSP}} \]

Reheating Temperature (GeV)

Gravitino Mass (GeV)

allowed

\[ ^3\text{He} \]

\[ ^6\text{Li} \]

\[ ^7\text{Li} \]

\[ ^4\text{He} \]

\[ ^5\text{D} \]
Gravitino Problems

stable (LSP) gravitino

unstable gravitino

thermal leptogenesis

16 eV
Gravitino Problems

stable (LSP) gravitino

unstable gravitino

thermal leptogenesis

nonthermal leptogenesis

16 eV
Gravitino Problems

- stable (LSP) gravitino
- unstable gravitino

In addition, direct production of gravitinos from inflaton $\Rightarrow$ exclude most inflation models

16 eV
Gravitino Problems

stable (LSP) gravitino  unstable gravitino

allowed

16 eV

In addition, direct production of gravitinos from inflaton $\rightarrow$ exclude most inflation models

note: low TR doesn't help.

Fig. from Endo, Takahashi, Yanagida, ’07

FIG. 3: Constraints from the gravitino production by the inflaton decay, for $m_{3/2} = 1\,\text{TeV}$ with $B_h = 1$ (case A), $m_{3/2} = 1\,\text{TeV}$ with $B_h = 10^{-3}$ (case B), $m_{3/2} = 100\,\text{TeV}$ (case C), and $m_{3/2} = 1\,\text{GeV}$ (case D). The region above the solid (gray) line is excluded for each case. For
Gravitino Problems

Gravitino Problems

stable (LSP) gravitino
unstable gravitino

allowed

thermal leptogenesis
nonthermal leptogenesis

In addition, direct production of gravitinos from inflaton ➜ exclude most inflation models

solutions:

• inflation with zero VEV (Z₂)
• gravitino LSP
• very heavy gravitino

note: low TR doesn’t help.

FIG. 3: Constraints from the gravitino production by the inflaton decay, for $m_{3/2} = 1$ TeV with $B_h = 1$ (case A), $m_{3/2} = 1$ TeV with $B_h = 10^{-3}$ (case B), $m_{3/2} = 100$ TeV (case C), and $m_{3/2} = 1$ GeV (case D). The region above the solid (gray) line is excluded for each case. For
Gravitino Problems

stable (LSP) gravitino

unstable gravitino

\[ \Omega_{\text{LSP}}^{3\sigma} h^2 = 0.105^{+0.021}_{-0.030} \]

\[ m_{1/2} = 500 \text{ GeV} \]

\[ m_{1/2} = 2 \text{ TeV} \]

Reheating Temperature (GeV)

Gravitino Mass (GeV)

16 eV

allowed

\[ \text{allowed} \]

\[ \text{allowed} \]

\[ \text{allowed} \]
Gravitino Problems

- Stable (LSP) gravitino
  - Allowed
  - Peak at 16 eV

- Unstable gravitino
  - Allowed

Ultralight gravitino is completely free from cosmological problems!!
We considered SUSY models with a very light gravitino LSP and a neutralino NLSP. And presented a neutralino mass measurement based on $M_{T2}$ method, independent of other masses / cascade patterns and complementary to other methods.
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This work
### Gravitino and NLSP at the LHC

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*KH, Shirai, Yanagida,’07 cf. talk at previous focus week (Dec.’07)*

This work

F determination
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Gravitino and NLSP at the LHC

\[ \tilde{G} \]

\[ \tilde{\chi}^0 \] NLSP

\[ 2\gamma + E_{T,\text{miss}} \]

non-pointing photon

F determination

This work

the same as \( \tilde{\chi}^0 \) LSP signal....

Kawagoe, Kobayashi, Nojiri, Ochi, ’03

FIG. 7: Estimated resolution of the lifetime \( \tau \) for an integrated luminosity of 13.9 fb\(^{-1}\) from (a) the average \( \beta_0/\gamma_0 \) and (b) the number of \( e\gamma \) pairs \( N_{e\gamma} \). The input \( m_f \) and \( m_{\tilde{g}} \) are used for the reconstruction and their errors are ignored.
### Gravitino and NLSP at the LHC

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- K.H, Shirai, Yanagida, '07 (cf. talk at previous focus week (Dec.'07))
- “kink” in charged track
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- F determination
- This work
- charged track

- talk by R. Kitano on Thursday!
- the same as $\tilde{\chi}^0$ LSP signal....
null
Gravitino and NLSP at the LHC

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K.H. Shirai, Yanagida,'07

cf. talk at previous focus week (Dec.'07)

"kink" in charged track

F determination

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\tilde{\chi}^0 NLSP

This work

charged track

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non-pointing photon

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F determination

the same as LSP signal....

\nonumber$
\tilde{\chi}^0$

\nonumber$
\tilde{G}$

\nonumber$
\tilde{G}$

\nonumber$
\tilde{G}$

\nonumber$
\text{NLSP}$

\nonumber$
\text{NLSP}$

\nonumber$
\text{NLSP}$

\nonumber$
\chi_0$

\nonumber$
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\chi_0$

\nonumber$\gamma$
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Let's see what the LHC will find......!

This work
backup slides
Another Side Remark

- thermal leptogenesis \( TR > 10^9 \text{GeV} \) \( \rightarrow \) \( m_G > O(10) \text{ GeV} \)
- \( \rightarrow T_{\tau} \gg 1000 \text{ sec.} \) \( \rightarrow \) excluded by CBBN?? (unless
• thermal leptogenesis \( TR > 10^9 \text{GeV} \Rightarrow m_G > O(10) \text{ GeV} \)
• \( \Rightarrow T_{\text{stau}} \gg 1000 \text{ sec.} \) \( \Rightarrow \) excluded by CBBN?? (unless

A solution: a small R-parity violation can help it.

• \( \lambda > 10^{-14} \) is large enough to make \( T_{\text{stau}} < 1000 \text{ sec,} \)
• \( \lambda < 10^{-7} \) is small enough to satisfy the constraints including baryon washout,
• and to make the gravitino stable, i.e. \( T_{\text{gravitino}} > T_{\text{universe}}. \)
• (Buchmuller, Covi, KH, Ibarra, Yanagida,'07; cf. Takayama Yamaguchi,'00)
Another Side Remark

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- (Buchmuller, Covi, KH, Ibarra, Yanagida,’07; cf. Takayama Yamaguchi,’00)

And the gravitino DM decay can be (or has already been?!)
seen by CRs !!!

Ibarra, Tran,’08 ➔
Ishikawa, Matsumoto, Moroi,’08 ➔

$\gamma$ (EGRET) $\Rightarrow$ $e^+$ (HEAT) $\Rightarrow$ $\gamma$ (EGRET) $\Rightarrow$ $e^+$ (HEAT)
Gravitino Interaction: extremely weak
suppressed by $\sim \frac{1}{M_P}$ (or $\sim \frac{1}{F} \sim \frac{1}{M_P m_\tilde{G}}$)

Gravitino Mass: model dependent

\begin{tabular}{ccccc}
eV & keV & MeV & GeV & TeV \\
\hline
\end{tabular}

GMSB

AMSB, mMSB

$\tilde{g}$MSB

gravity-MSB
SUSY models with an ultralight gravitino is

\[ (m_{\tilde{G}} < 10 \text{ eV}) \]

No Cosmological Problem! at all!
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\[(m_{\tilde{G}} \lesssim 10 \text{ eV})\]

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LSP (gravitino) ≠ CDM (too light → hot DM), but....
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\[ m_{\tilde{G}} \sim 10 \text{ eV} \quad \Longrightarrow \quad F = \Lambda^2 \sim (100 \text{ TeV})^2 \]

100 TeV DM \( \Rightarrow \) natural thermal relic DM if strongly interacting
In general, \( \Omega_{X}^{\text{thermal}} \sim 0.2 \left( \frac{\text{pb}}{\sigma_{\text{ann.}}(XX \rightarrow \text{all})} \right) \)

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\]

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\sigma_{\text{ann.}} \sim \mathcal{O}(4\pi) \frac{m^2}{m^2} \quad \rightarrow \quad m \sim \mathcal{O}(10 - 100) \, \text{TeV} \quad \text{strongly self-interacting}
\]

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DM may be 100 TeV composite “baryon” made from strongly self-interacting hidden-sector/messenger particles

Dimopoulos, Giudice, Pomarol '96 / KH, Shirai, Yanagida '07