Determining the Mass for an Ultralight Gravitino at the LHC

arXiv:0712.2462

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Collaborated with
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Tsutomu Yanagida (Tokyo U, IPMU)

$m_{3/2} = \mathcal{O}(1)$ eV

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Plan

1. Why such a light gravitino
2. Gravitino at the LHC
3. Gravitino Mass Measurement
4. Summary

1. Why such a light gravitino

Gravitino

(Local) SUSY → Gravitino

SUSY breaking → $m_{3/2} \sim \frac{\Lambda^2}{M_P}$

$M_P = 2.4 \times 10^{18}$ GeV

Λ : SUSY breaking scale.

$$m_{3/2} = 1 \text{ eV} - 100 \text{ TeV}$$

Gravitino Problem

1. **Heavy case** $m_{3/2} > \mathcal{O}(100)$ GeV

   Unstable. Spoilage of BBN.

2. **Light case** $\mathcal{O}(10)$ GeV $> m_{3/2} > \mathcal{O}(1)$ MeV

   Stable. Overclosure of Universe.

3. **Ultralight case** $m_{3/2} = \mathcal{O}(1)$ eV

   Strength of interaction $\propto \dfrac{1}{m_{3/2} M_P}$

Gravitino Problem

1. Heavy case $m_{3/2} > \mathcal{O}(100)$

Unstabl

Gravitino Problem

$m_{3/2} > \mathcal{O}(1)$ MeV

: Overclosure of Universe.

3. Ultralight case $m_{3/2} = \mathcal{O}(1)$ eV

Strength of interaction $\propto \frac{1}{m_{3/2} M_P}$

Gravitino Problem

1. Heavy case $m_{3/2} > \mathcal{O}(100$

Unstabl

Gravitino Problem

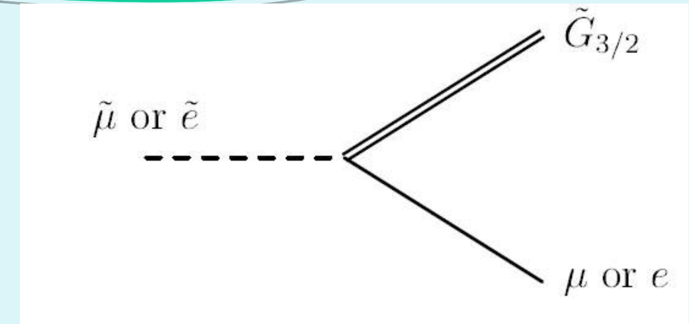
$_{3/2} > \mathcal{O}(1)$ MeV

: Overclosure of Universe.

3. Ultralight case $m_{3/2} = \mathcal{O}(1)$ eV

Strength of interaction $\propto \dfrac{1}{m_{3/2} M_P}$

Gravitino LSP at LHC



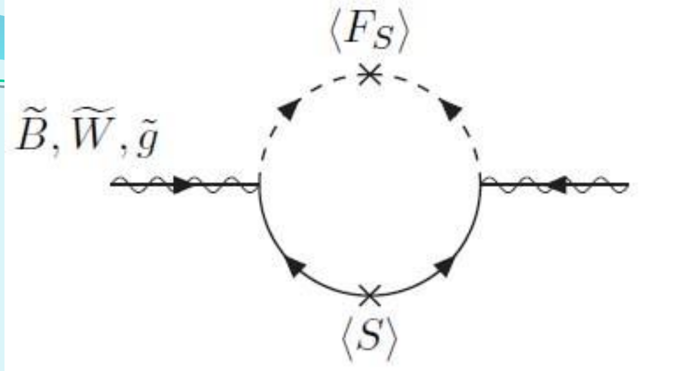
$$\tilde{\chi}_1^0 \to \gamma + \tilde{G}_{3/2}, \quad \tilde{\ell} \to \ell + \tilde{G}_{3/2}, \cdots$$

$$c\tau \simeq 20\ \mu\text{m} \left(\frac{m_{3/2}}{1\ \text{eV}}\right)^2 \left(\frac{m_{\text{NLSP}}}{100\ \ \text{GeV}}\right)^{-5}$$

All MSSM particles decay inside of detector.

2. Gravitino at the LHC

$\tilde{G}_{3/2}$ LSP Scenario



Model : (minimal) Gauge Mediation (mGMSB)

At Messenger scale

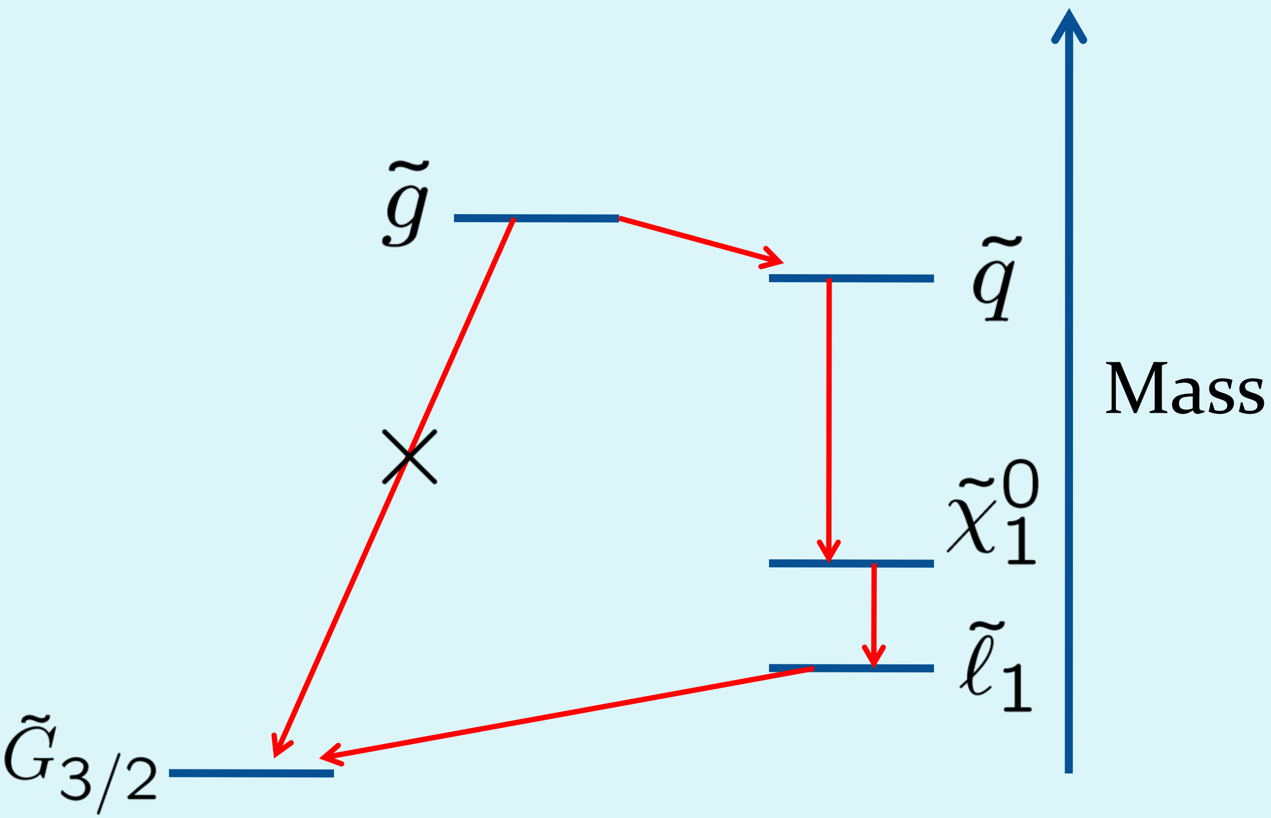
$$m^2_{\text{scalar}} \approx 2N_{\text{mess}} \left(\frac{\alpha}{4\pi}\right)^2 \Lambda^2$$

$$m_{\text{gaugino}} \approx N_{\text{mess}} \left(\frac{\alpha}{4\pi}\right) \Lambda$$

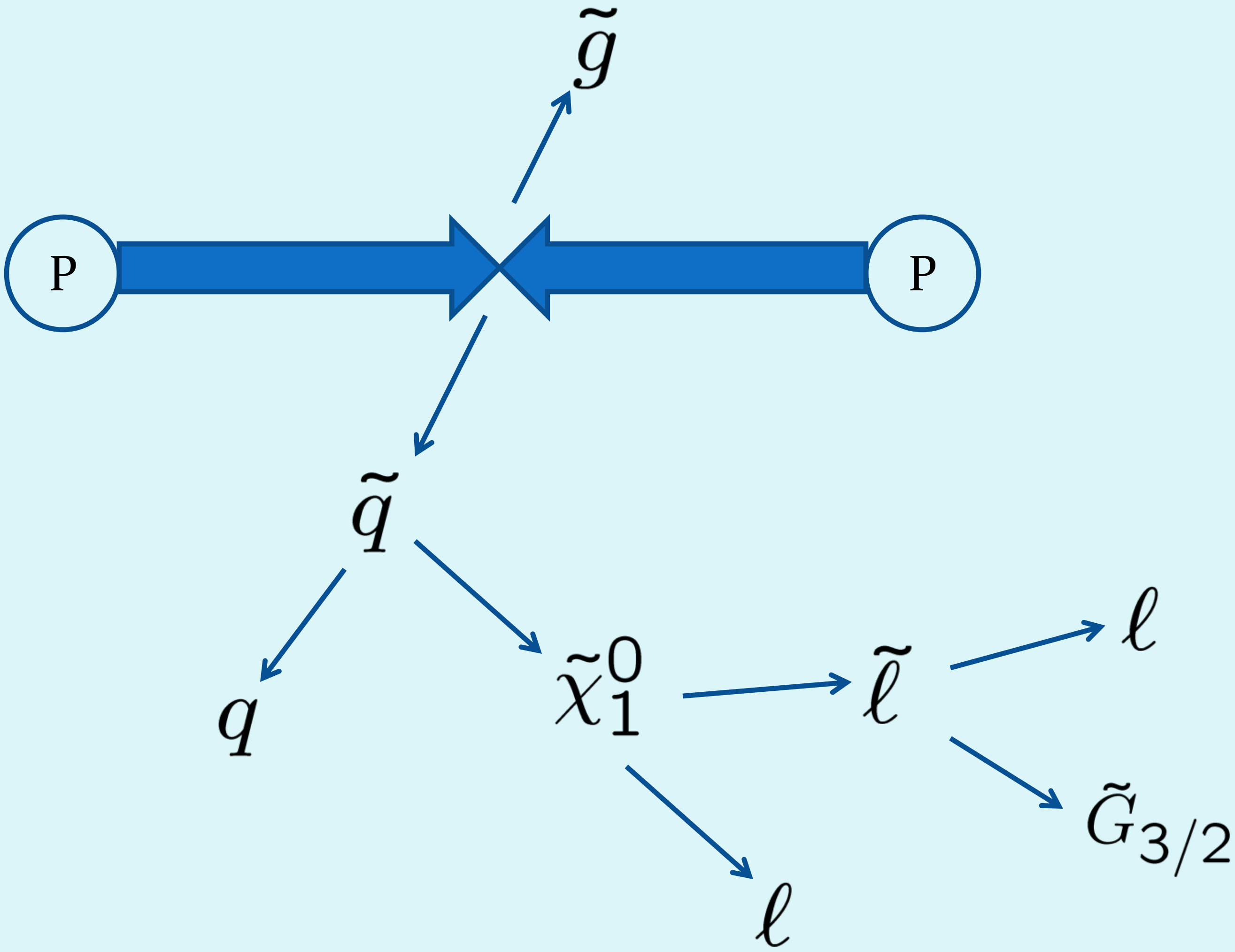
RG evolution

Physical Mass

SUSY Particles' decays



Event Topology at LHC



Sparticle's Mass

Kinematical Method

⬇

Mass Determination

$$m_{\mathrm{soft}} = \mathcal{O}(100) \pm \mathcal{O}(1)\ \mathrm{GeV}$$

How about $m_{3/2} = \mathcal{O}(1)\ \mathrm{eV}$ gravitino case?

3. Garivitino Mass Measurement

Importance of Gravitino Mass

$$m_{3/2} \sim \frac{\Lambda^2}{M_P}$$

Λ : SUSY breaking scale.

Gravitino Mass Measurement

||

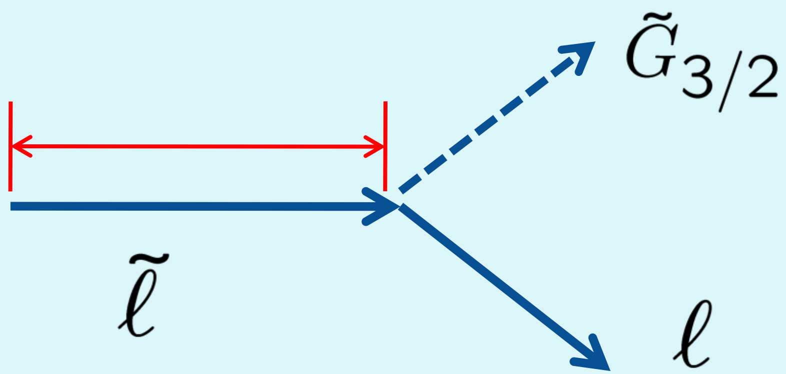
Measuring SUSY Breaking Scale

Gravitino Mass and Decay Width

$$\Gamma_{\text{2body}} \equiv \Gamma(\tilde{\ell}_1 \to \ell + \tilde{G}_{3/2}) = \frac{m_{\tilde{\ell}_1}^5}{48\pi M_P^2 m_{3/2}^2}$$

Slepton's life time depends on gravitino mass.

Decay length = Gravitino mass.



Decay Length

However,

$$c\tau \simeq 20\ \mu\text{m} \left(\frac{m_{3/2}}{1\ \text{eV}}\right)^2 \left(\frac{m_{\text{NLSP}}}{100\ \text{GeV}}\right)^{-5}$$

too short to be measured !

Gravitino Mass

When decay length is very short,

how can we measure

$$\Gamma_{\text{2body}} \equiv \Gamma(\tilde{\ell}_1 \to \ell + \tilde{G}_{3/2}) \propto m_{3/2}^{-2}$$

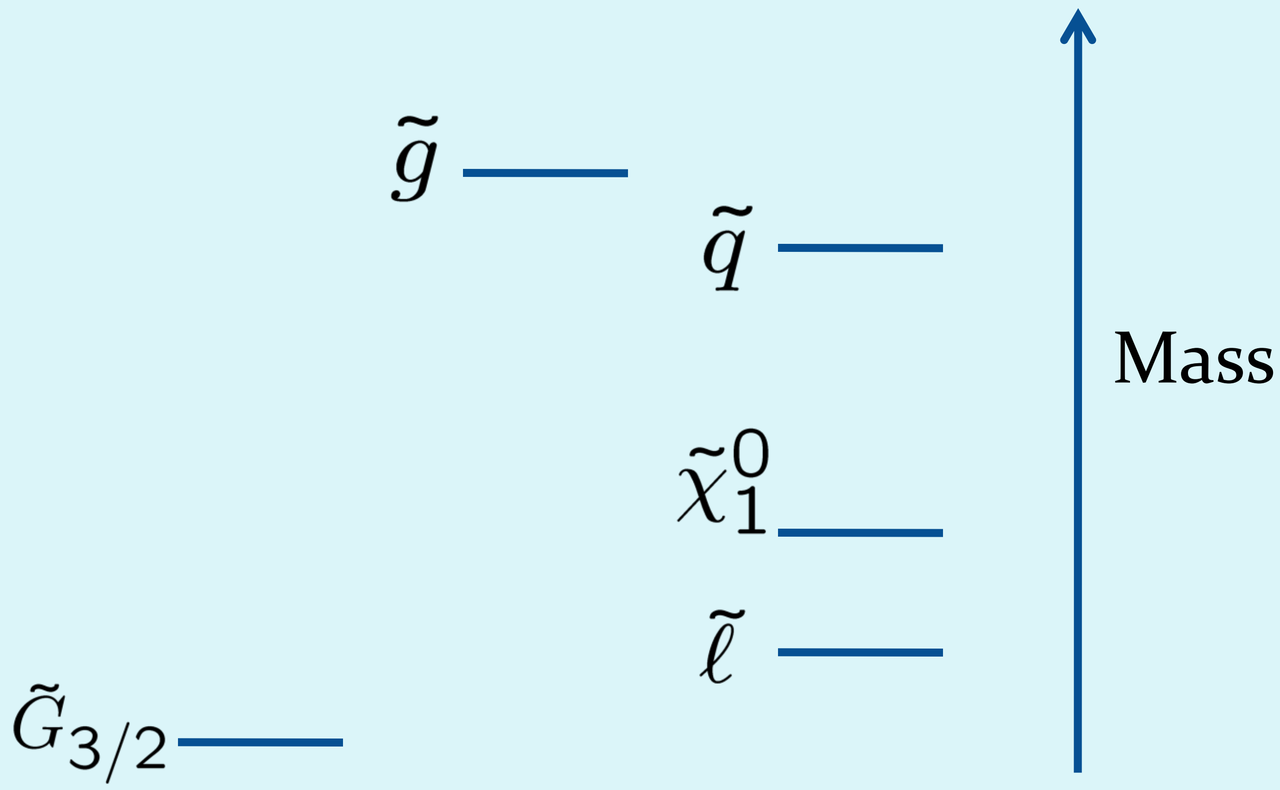
↓

Decay branching fraction

K. Hamaguchi, S. S, T. T. Yanagida '07

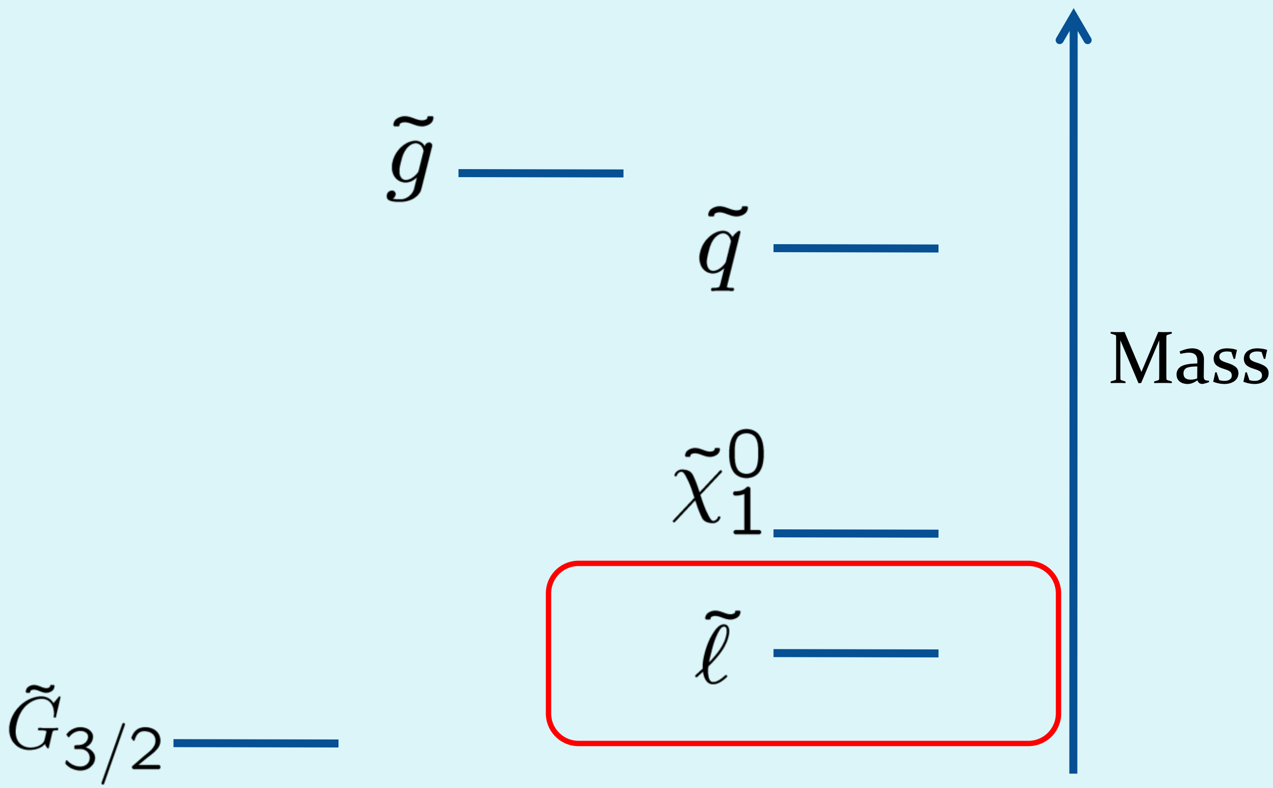
Mass Spectrum

Gauge mediated SUSY breaking spectrum



Mass Spectrum

Gauge mediated SUSY breaking spectrum



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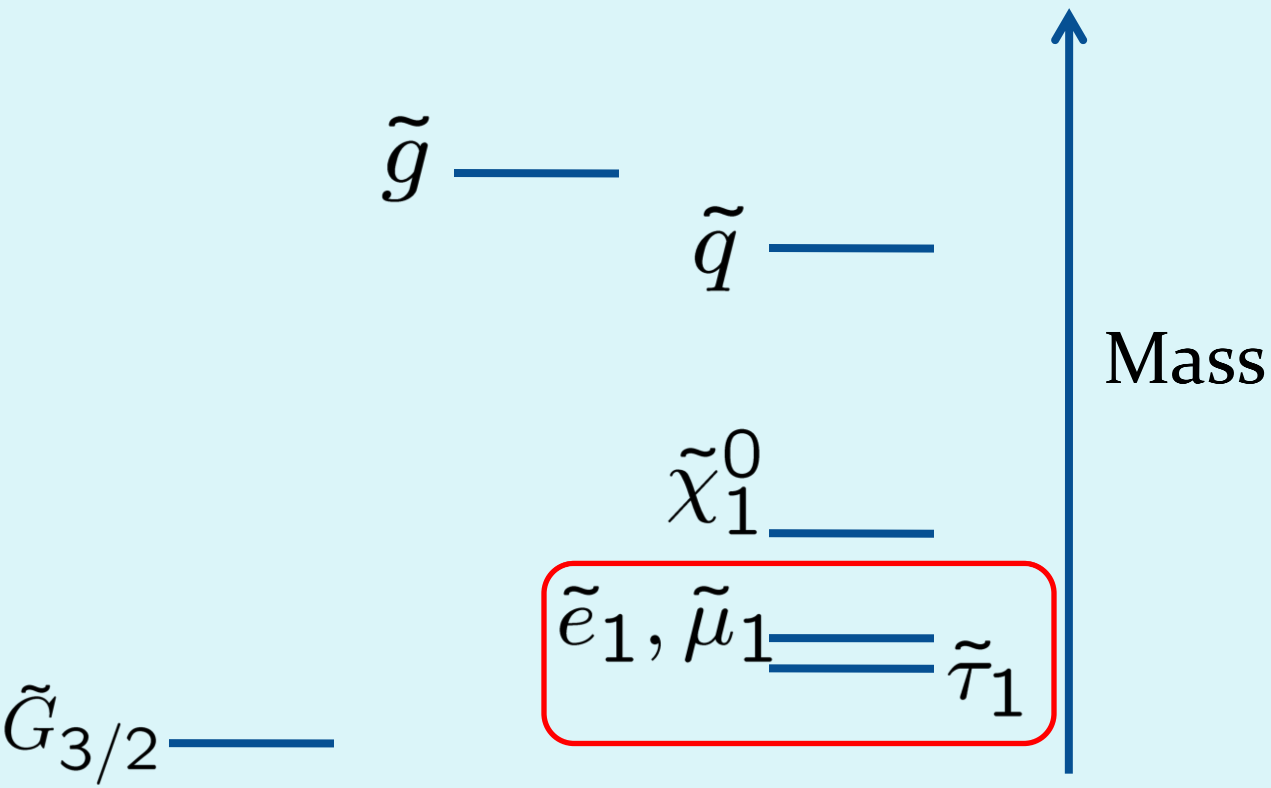
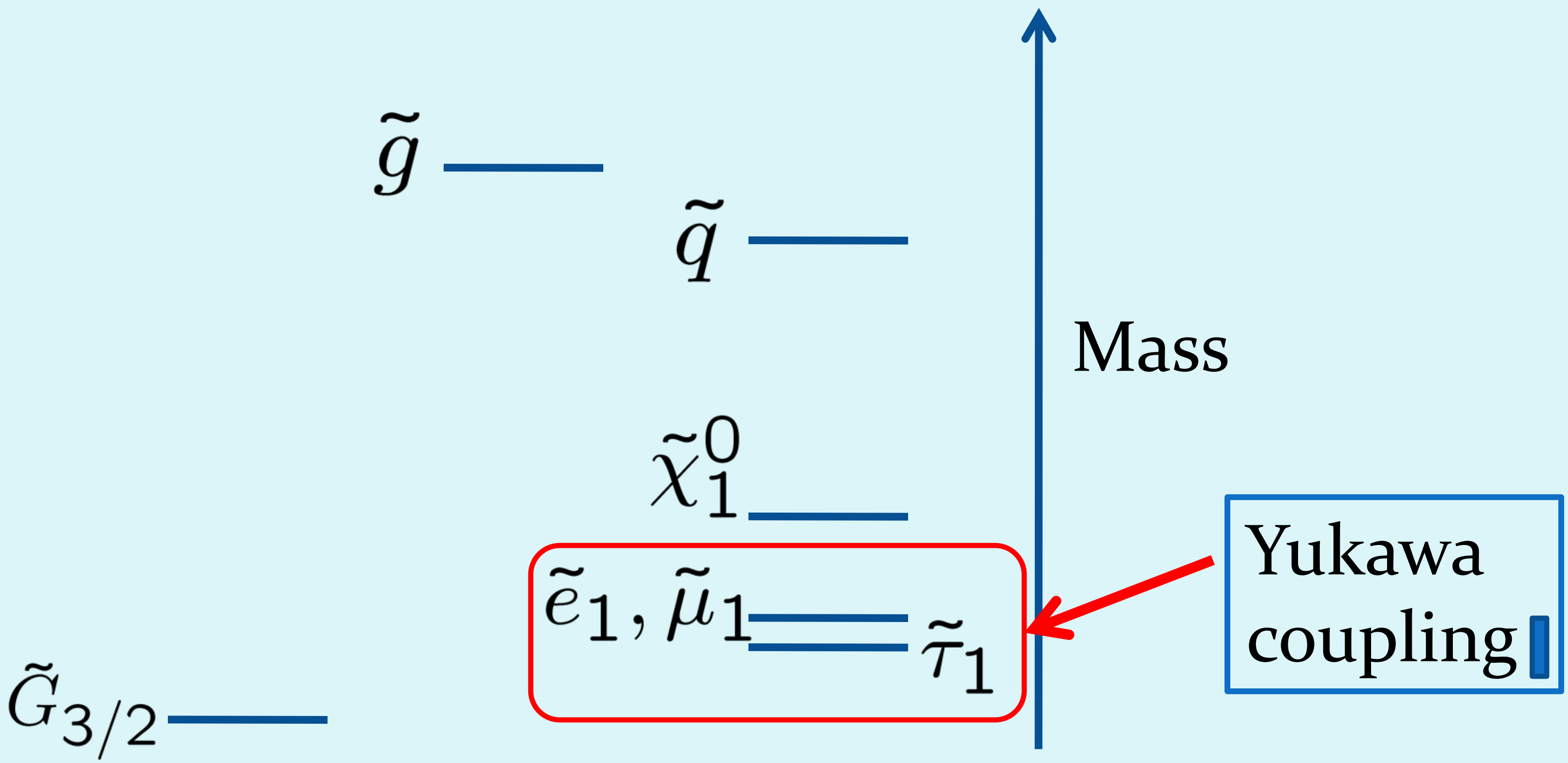


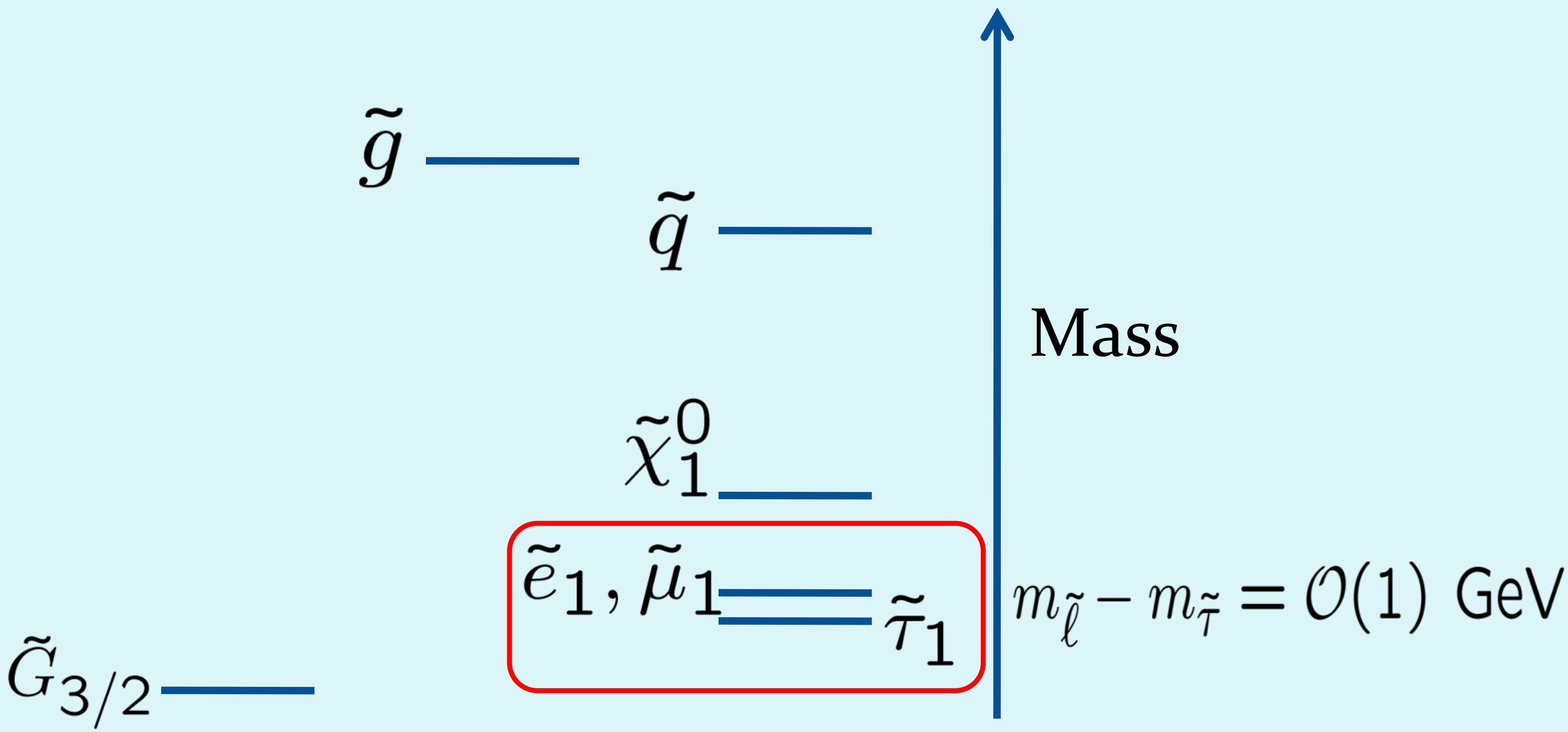
Mass Spectrum

Gauge mediated SUSY breaking spectrum



Mass Spectrum

Gauge mediated SUSY breaking spectrum



Slepton's decay

$$m_{\tilde{e}_1} \approx m_{\tilde{\mu}_1} > m_{\tilde{\tau}_1} + m_\tau$$

$$\tilde{\ell}_1 \to \tilde{\tau}_1 + \tau + \ell$$

$$\tilde{\ell}_1 \to \ell + \tilde{G}_{3/2}$$

$\ell = e$ or μ

Two decay modes

Slepton's decay

$$m_{\tilde{e}_1} \approx m_{\tilde{\mu}_1} > m_{\tilde{\tau}_1} + m_\tau$$

$$\Gamma(\tilde{\ell} \to \ell + \tilde{\tau} + \tau) \approx \mathcal{O}(0.1)\ \mathrm{eV} \left(\frac{m_{\tilde{\ell}}}{100\ \mathrm{GeV}}\right)^{-4} \left(\frac{\Delta m}{2\ \mathrm{GeV}}\right)^{5}$$

$$\Gamma(\tilde{\ell} \to \ell + \tilde{G}_{3/2}) = 0.011\ \mathrm{eV} \left(\frac{m_{\tilde{\ell}}}{100\ \mathrm{GeV}}\right)^{5} \left(\frac{m_{3/2}}{1\ \mathrm{eV}}\right)^{-2}$$

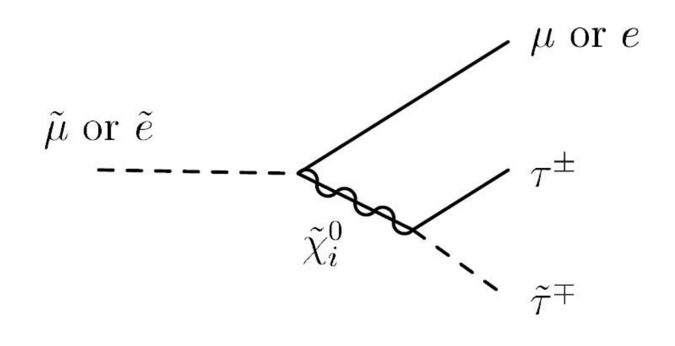
Two decay modes

Two-body Decay

$$\Gamma_{2\text{body}} \equiv \Gamma(\tilde{\ell}_1 \to \ell + \tilde{G}_{3/2}) \propto m_{3/2}^{-2}$$

Unknown value

Three-body Decay



$$\Gamma_{\text{3body}} \equiv \Gamma(\tilde{\ell}_1 \to \tilde{\tau}_1 + \tau + \ell)$$

SM gauge interaction

If gauginos and sleptons' masses are known, we can calculate this value.

Branching Fraction

$$\Gamma_{2body} = \left(\frac{\Gamma_{2body}}{\Gamma_{3body}}\right)\Gamma_{3body}$$

Branching Fraction

Determined by $m_{\tilde{\ell}_1}$, $m_{\tilde{\tau}_1}$, $m_{\tilde{\chi}}$

$$\Gamma_{\mathrm{2body}} = \left(\frac{\Gamma_{\mathrm{2body}}}{\Gamma_{\mathrm{3body}}}\right) \Gamma_{\mathrm{3body}}$$

Determined by experiments

Two Slepton's Decays

$$\tilde{\ell}_1 \to \tilde{\tau}_1 + \tau + \ell$$

$$\tilde{\ell}_1 \to \ell + \tilde{G}_{3/2}$$

Two Slepton's Decays

$$\tilde{\ell}_1 \rightarrow \tilde{\tau}_1 + \tau + \ell$$

$$\downarrow$$

$$\tau + \tilde{G}_{3/2}$$

$$\tilde{\ell}_1 \rightarrow \ell + \tilde{G}_{3/2}$$

Two Slepton's Decays

soft tau

$$\tilde{\ell}_1 \rightarrow \tilde{\tau}_1 + \boxed{\tau} + \ell$$

$$\downarrow$$

$$\boxed{\tau} + \tilde{G}_{3/2}$$

hard tau

$$\tilde{\ell}_1 \rightarrow \ell + \tilde{G}_{3/2}$$

Two Slepton's Decays

soft tau

$$\tilde{\ell}_1 \rightarrow \tilde{\tau}_1 + \boxed{\tau} + \ell$$

$$\downarrow$$

$$\boxed{\tau} + \tilde{G}_{3/2}$$

hard tau

$$\tilde{\ell}_1 \rightarrow \ell + \tilde{G}_{3/2}$$

Problem

Background

Tau-ID efficiency

Two Slepton's Decays

$$\tilde{\ell}_1 \rightarrow \tilde{\tau}_1 + \tau + \boxed{\ell}$$

$$\tilde{\ell}_1 \rightarrow \boxed{\ell} + \tilde{G}_{3/2}$$

Two Slepton's Decays

$$\tilde{\ell}_1 \rightarrow \tilde{\tau}_1 + \tau + \boxed{\ell}$$

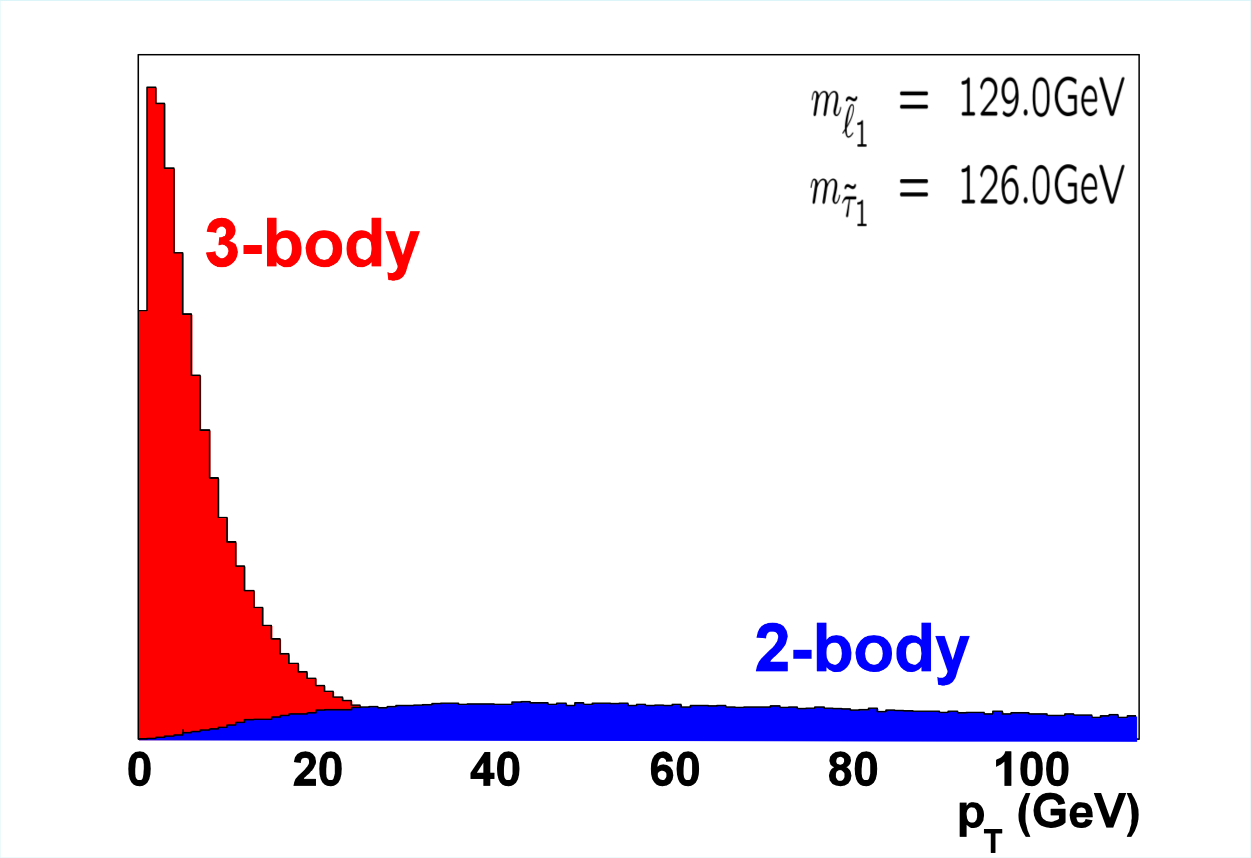
↓ 3-body decay

Different Momentum Distribution

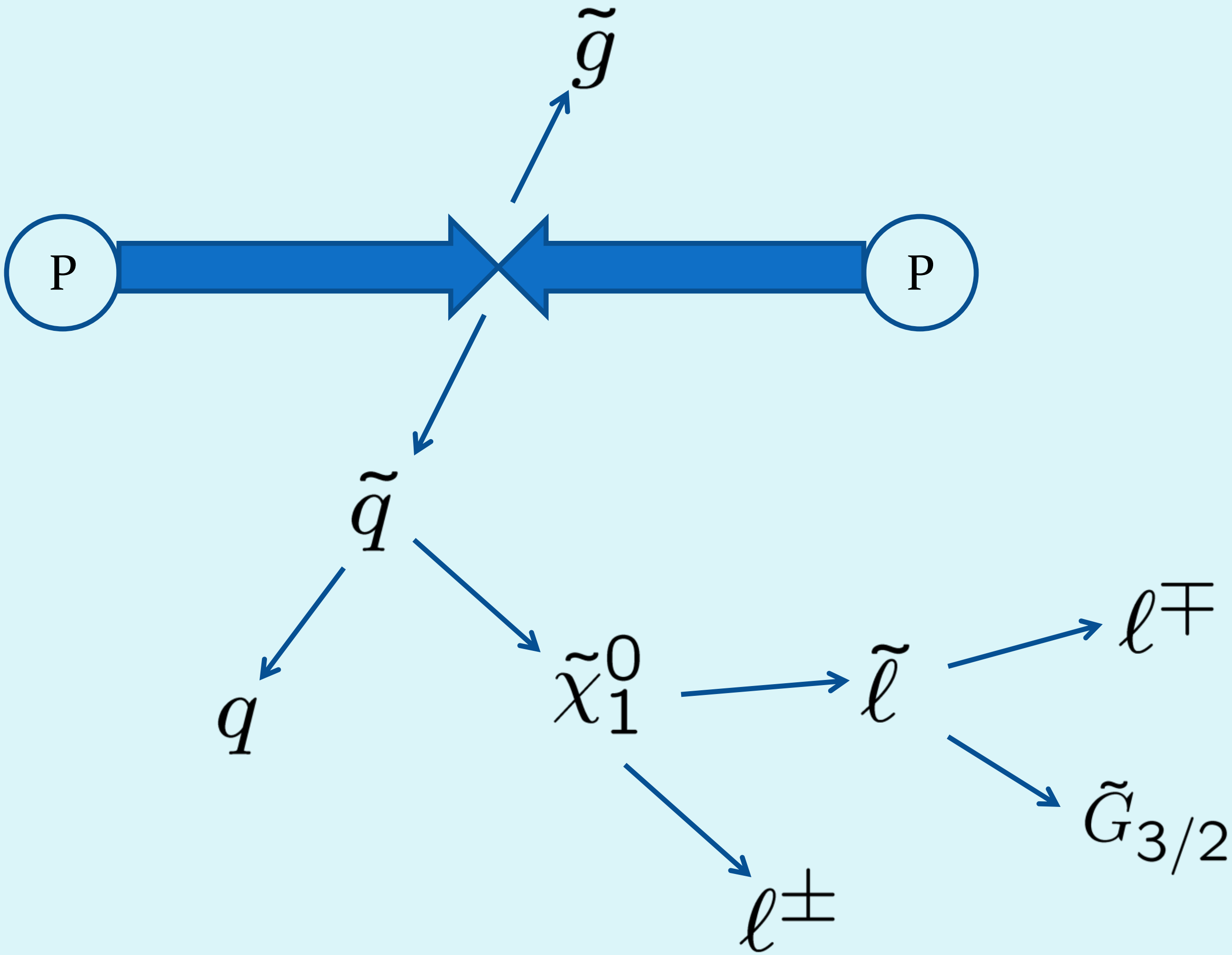
↗ 2-body decay

$$\tilde{\ell}_1 \rightarrow \boxed{\ell} + \tilde{G}_{3/2}$$

Momentum Distribution

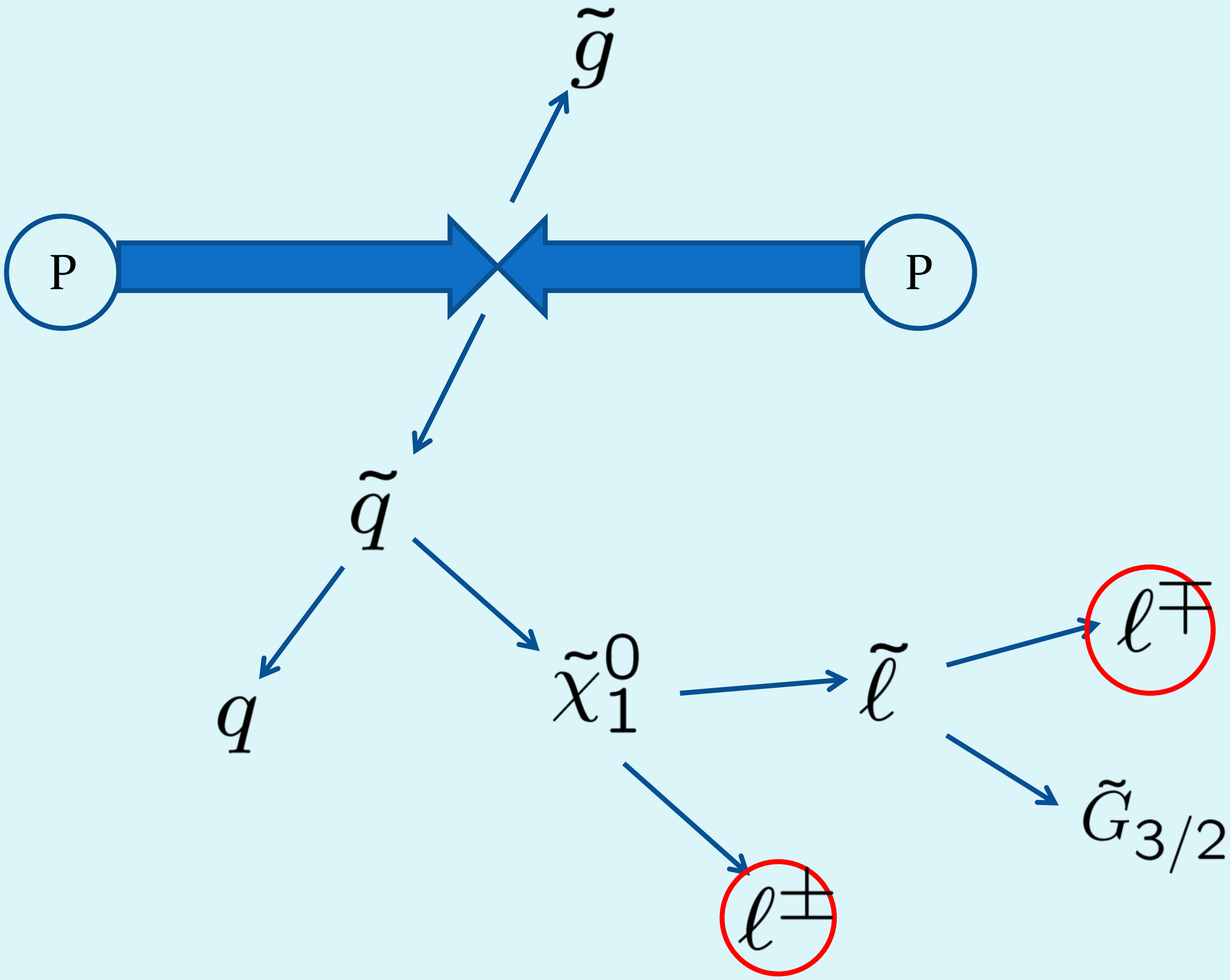


Decay Chain



$\tilde{g}$
P
P
$\tilde{q}$
q
$\tilde{\chi}_1^0$
$\tilde{\ell}$
$\ell^{\mp}$
$\tilde{G}_{3/2}$
$\ell^{\pm}$

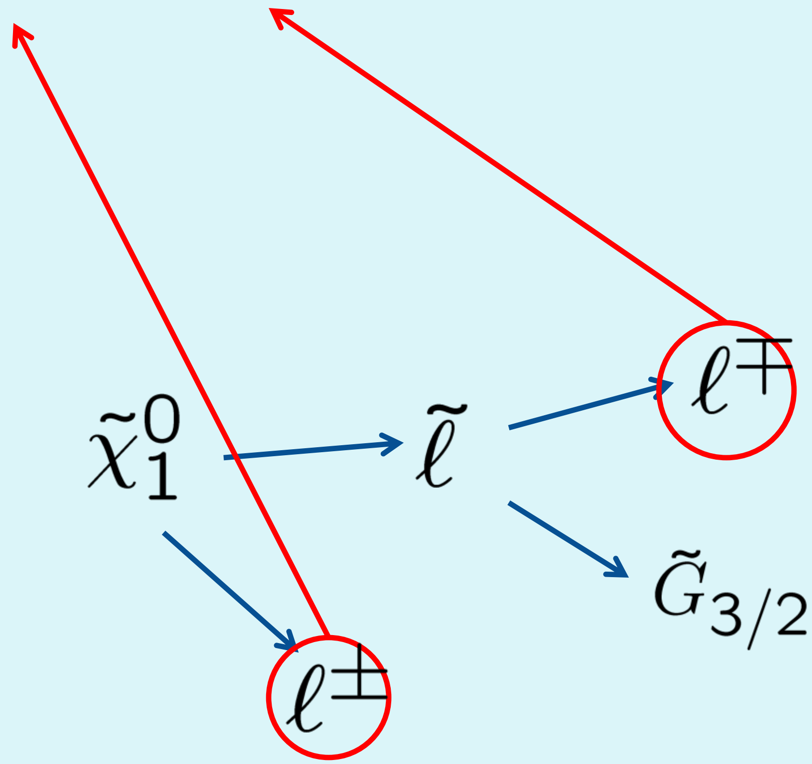
Decay Chain



$\tilde{g}$
P
P
$\tilde{q}$
q
$\tilde{\chi}_1^0$
$\tilde{\ell}$
$\ell^{\mp}$
$\tilde{G}_{3/2}$
$\ell^{\pm}$

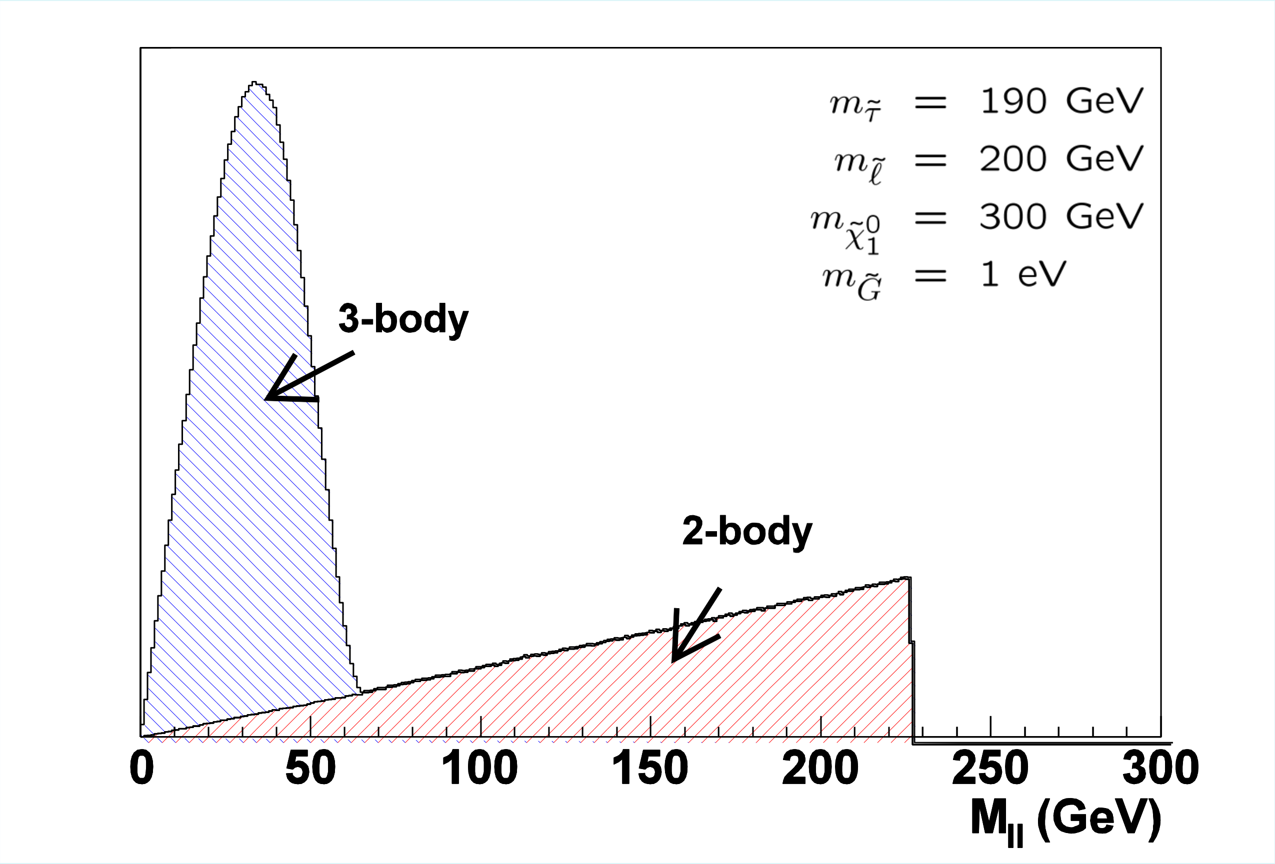
Decay Chain

$$m_{\ell\ell}^2 = (p_{\ell^\pm} + p_{\ell^\mp})^2$$



Two Invariant Masses

$$\frac{\Gamma_{3body}}{\Gamma_{2body}} = 1.23$$



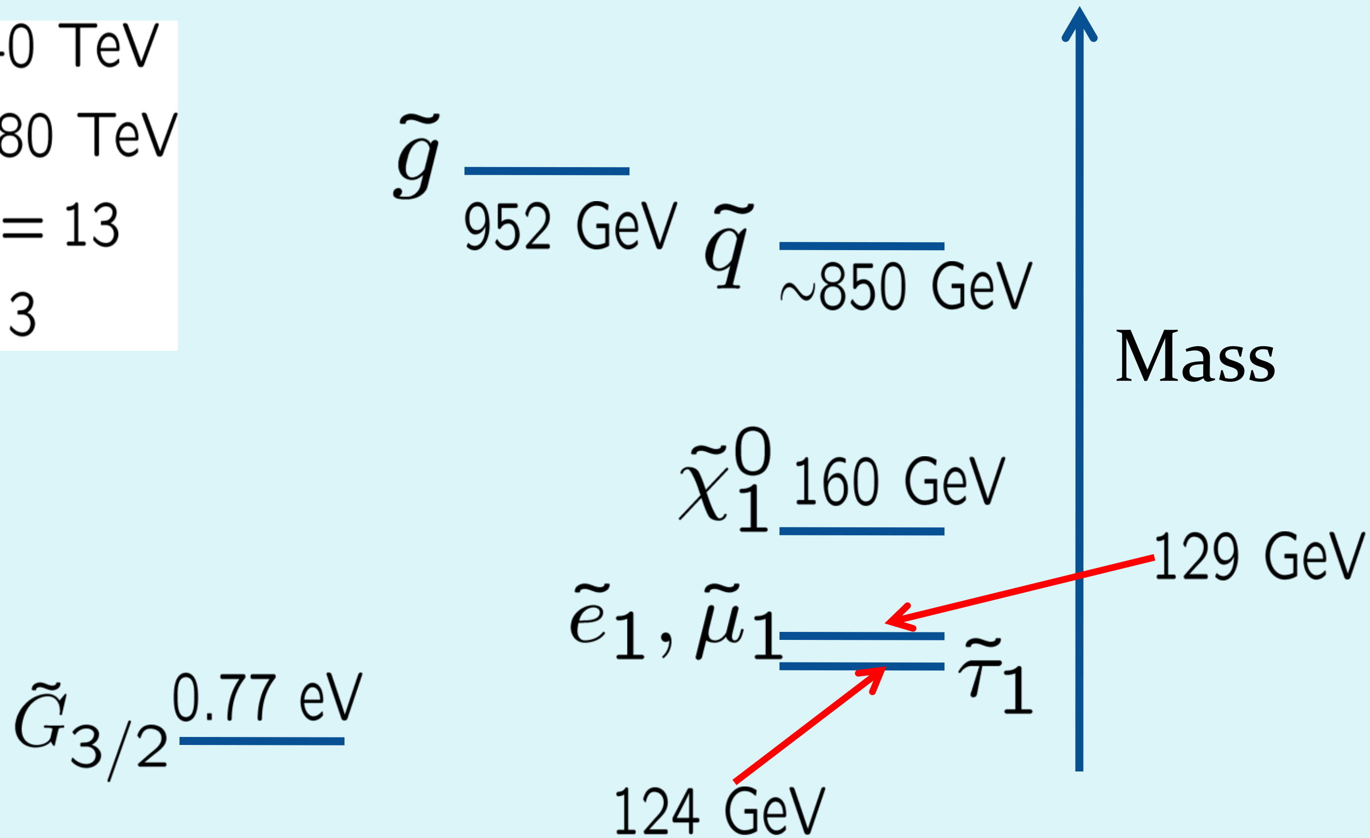
Simulation

$\Lambda = 40$ TeV

$M = 80$ TeV

$\tan\beta = 13$

$N_5 = 3$



Cut

- At least four jets have $p_{\mathrm{T}} \geq 25$ GeV. And for a jet which has the largest transverse momentum, $p_{\mathrm{T}} > 200$ GeV, and for the second, $p_{\mathrm{T}} > 150$ GeV.

- $p_{\mathrm{T,miss}} \geq 100$ GeV.

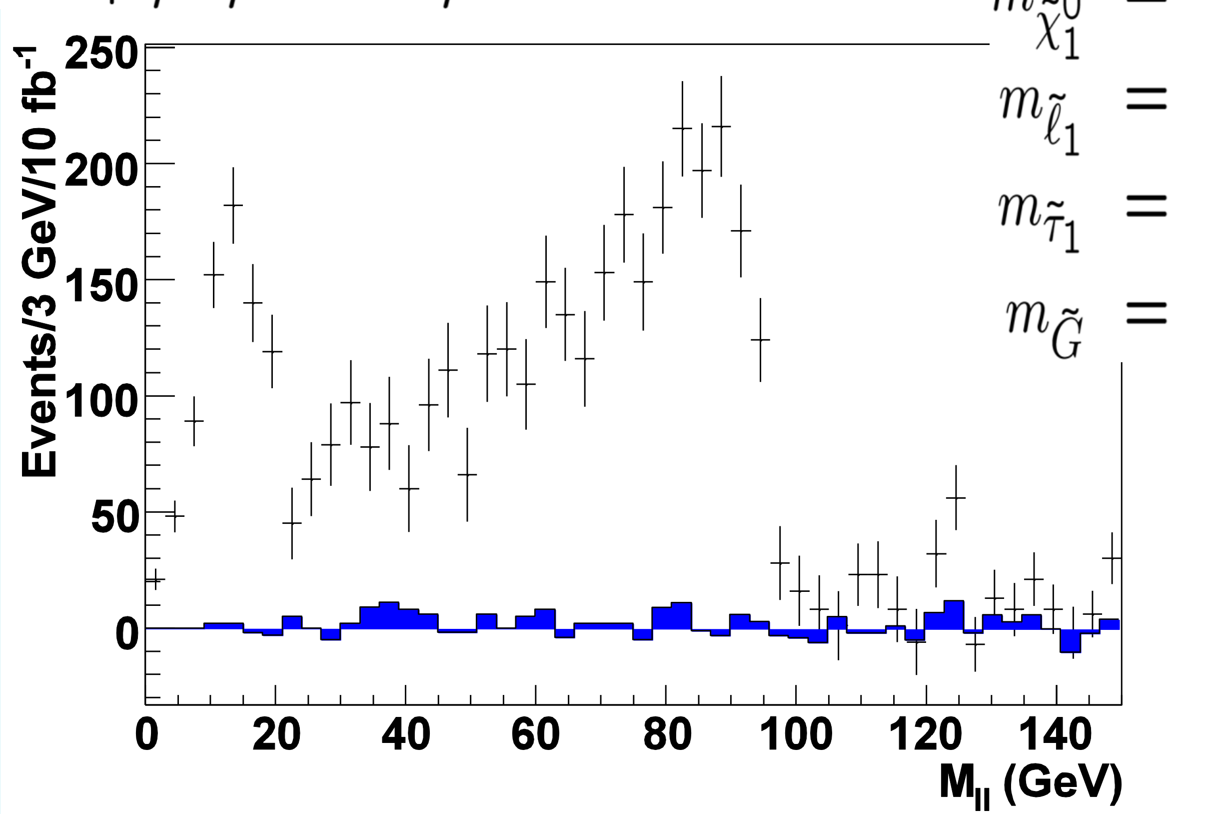
Cut

For $m_{\ell\ell}$, our requirements are as follows:

- two leotons have opposite charge.
- One lepton has $p_T \geq 20$ GeV, and another $p_T \geq 10$ GeV.
- $|\eta| < 2.5$.

Simulation

$e^{\pm}e^{\mp} + \mu^{\pm}\mu^{\mp} - e^{\pm}\mu^{\mp}$



$$m_{\tilde{\chi}_1^0} = 160.0 \text{ GeV}$$
$$m_{\tilde{\ell}_1} = 129.1 \text{ GeV}$$
$$m_{\tilde{\tau}_1} = 124.0 \text{ GeV}$$
$$m_{\tilde{G}} = 0.77 \text{ eV}$$

Herwig + AcerDet

Result

$$m_{\tilde{\chi}_1^0} = 160.0 \text{ GeV}$$
$$m_{\tilde{\ell}_1} = 129.1 \text{ GeV}$$
$$m_{\tilde{\tau}_1} = 124.0 \text{ GeV}$$
$$m_{\tilde{G}} = 0.77 \text{ eV}$$

$$m_{3/2} = (0.76 \pm 0.13) \left(\frac{R_2}{0.76}\right)^{\frac{1}{2}} \left(\frac{R_3}{0.04}\right)^{-\frac{1}{2}} \text{ eV}$$

Result

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Detector effects

$$R_2 = 0.76 \pm 0.05$$
$$R_3 = 0.04 \pm 0.01$$

Result

$$\begin{aligned} m_{\tilde{\chi}_1^0} &= 160.0 \text{ GeV} \\ m_{\tilde{\ell}_1} &= 129.1 \text{ GeV} \\ m_{\tilde{\tau}_1} &= 124.0 \text{ GeV} \\ m_{\tilde{G}} &= 0.77 \text{ eV} \end{aligned}$$

$$m_{3/2} = (0.76 \pm 0.13) \left(\frac{R_2}{0.76}\right)^{\frac{1}{2}} \left(\frac{R_3}{0.04}\right)^{-\frac{1}{2}} \text{ eV}$$

Detector effects

$$\begin{aligned} R_2 &= 0.76 \pm 0.05 \\ R_3 &= 0.04 \pm 0.01 \end{aligned}$$

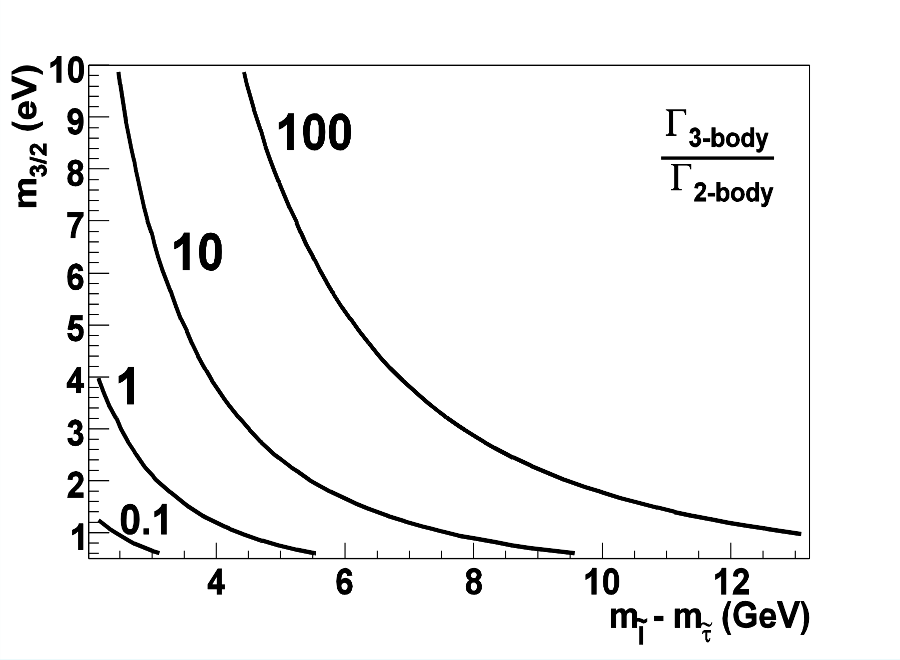
Determined by

$$m_{\tilde{g}}, m_{\tilde{\chi}}, m_{\tilde{q}}, m_{\tilde{\ell}}, m_{\tilde{\tau}}, \cdots$$

Summary

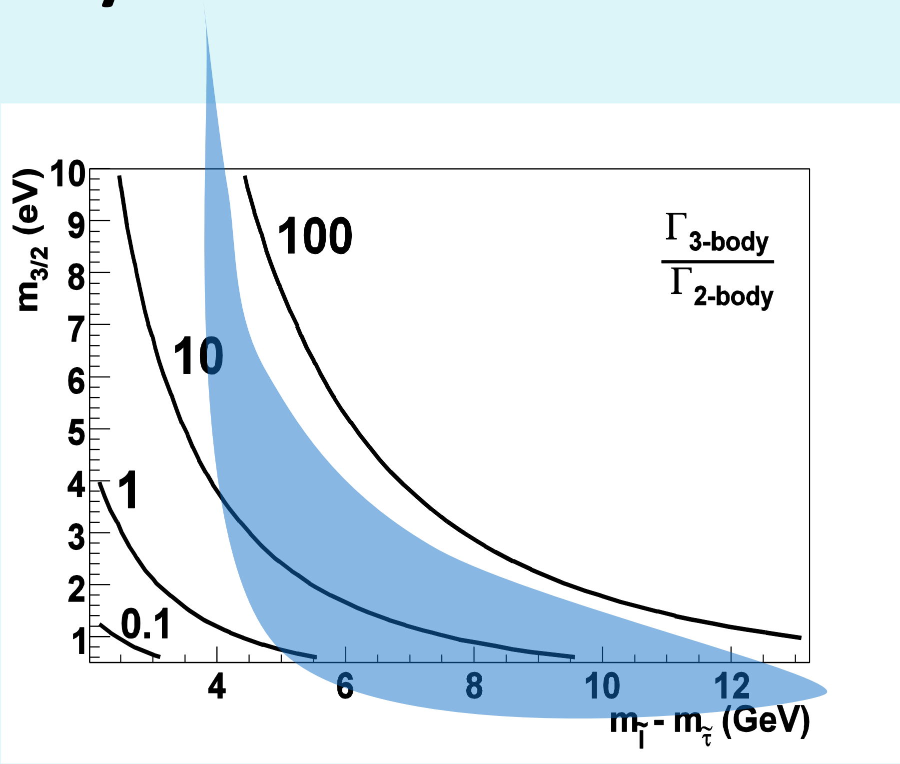
- O(1) eV gravitino is free from cosmological problems.
- Light gravitino plays an important role at LHC.
- If $m_{\tilde{\chi}_1^0} > m_{\tilde{\ell}} > m_{\tilde{\tau}} + m_{\tau}$, gravitino mass can be measured.

Summary



$$m_{\tilde{\chi}_1^0} = 300 \text{ GeV}$$
$$m_{\tilde{\ell}_1} = 200 \text{ GeV}$$

Summary



$$m_{\tilde{\chi}_1^0} = 300\ \text{GeV}$$
$$m_{\tilde{\ell}_1} = 200\ \text{GeV}$$

Outlook

- Soft lepton detection.

- Other NLSP case?

- In the first place, can we know that gravitino is LSP?

Cold Dark Matter (CDM)?

Ultralight gravitino is too light to be CDM

$$m_{3/2} = \mathcal{O}(1)\ \text{eV} \quad \Longrightarrow \quad \Lambda = \mathcal{O}(100)\ \text{TeV}$$

This scale's hidden sector can provide CDM.

see e.g., hep-ph/9607225 and 0712.2462 [hep-ph].

Scalar Lepton

Mass matrix

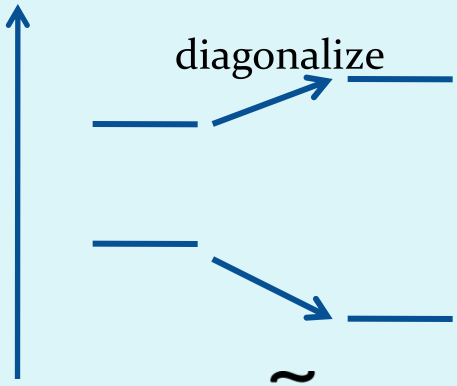
$$\tilde{\ell}_L \qquad\qquad \tilde{\ell}_R$$

$$M^2 = \begin{pmatrix} (m^2_{\tilde{L}})_{ii} + m^2_{e_i} - (\frac{1}{2} - s^2_W) M^2_Z c_{2\beta} & m_{e_i}((A_E)_{ii} - \mu \tan\beta) \\ m_{e_i}((A_E)_{ii} - \mu \tan\beta) & (m^2_{\tilde{e}})_{ii} + m^2_{e_i} - s^2_W M^2_Z c_{2\beta} \end{pmatrix}$$

Diagonalize $\Longrightarrow$ Mass eigenstate $\tilde{\ell}_1, \ \tilde{\ell}_2$

$m_{e,\mu} \ll m_\tau \Longrightarrow m_{\tilde{e}_1} \approx m_{\tilde{\mu}_1} > m_{\tilde{\tau}_1}$

Scalar Lepton



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Diagonalize ⟹ Mass eigenstate $\tilde{\ell}_1, \ \tilde{\ell}_2$

$m_{e,\mu} \ll m_\tau$ ⟹ $m_{\tilde{e}_1} \approx m_{\tilde{\mu}_1} > m_{\tilde{\tau}_1}$