Revisiting gravitino dark matter in thermal leptogenesis

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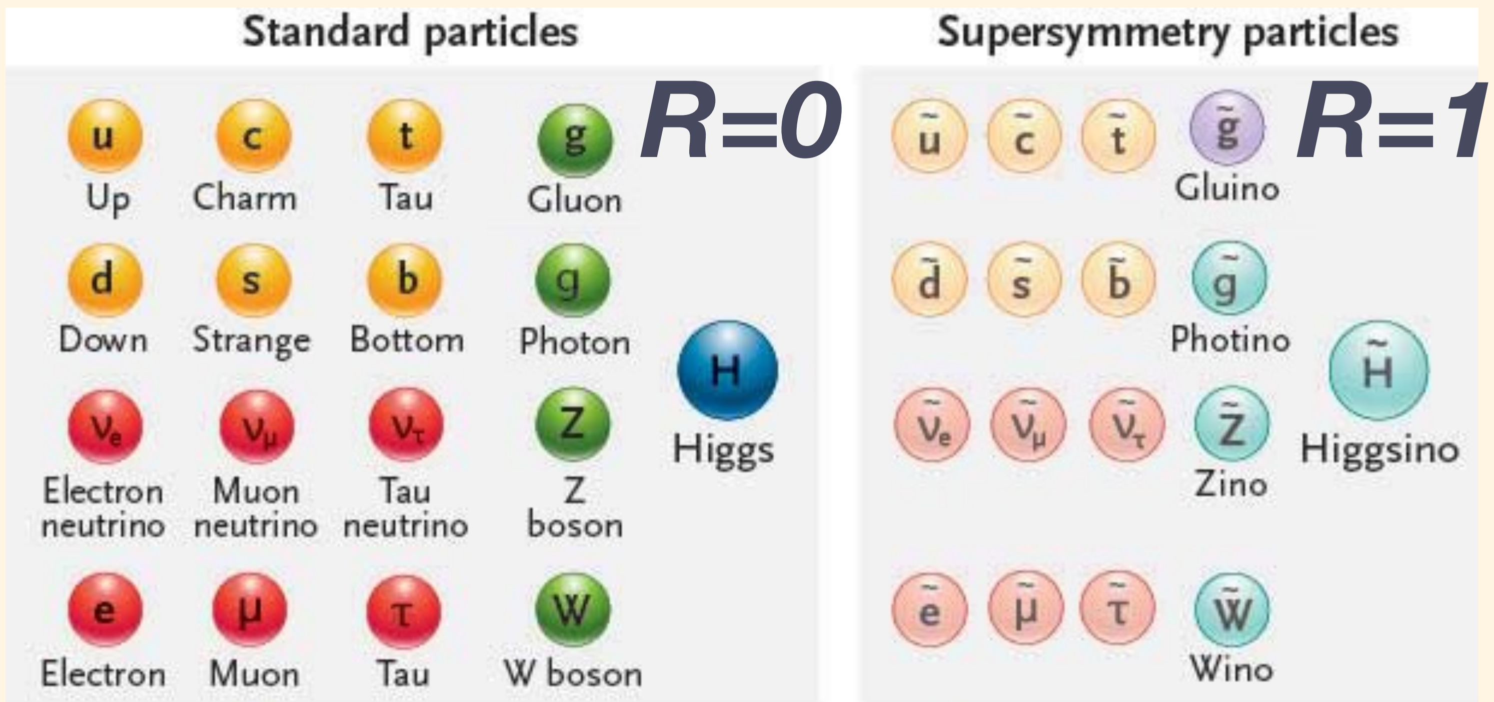
In collaboration with Masahiro ibe and Tsutomu. T. Yanagida

R-parity

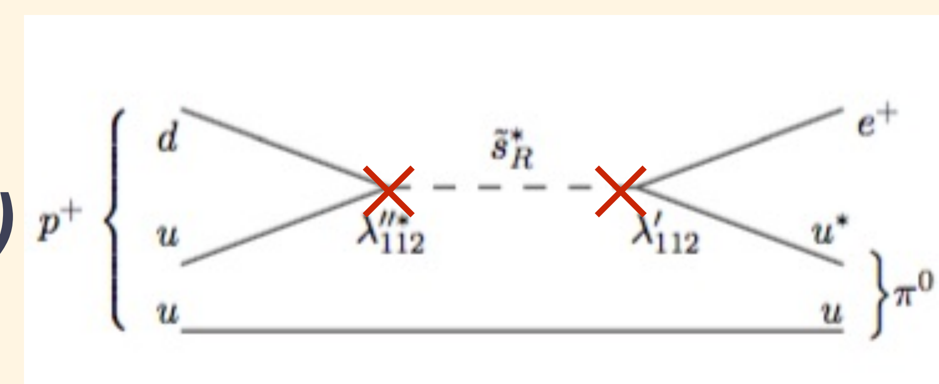
R-parity is introduced *for* ***phenomenological consistency***
in Minimal Supersymmetric Standard Model (MSSM)

R-parity charge assignment



http://www7b.biglobe.ne.jp/~kcy05t/supersymmetry.html

A. ***Prohibiting rapid proton decay***
B. ***Stable lightest SUSY particle (dark matter)***



https://arxiv.org/abs/hep-ph/9709356

Do we have
theoretical ground *on* ***R-parity?***

Theoretical ground on R-parity

Gravity breaks all global symmetry

↓

R-parity can be embedded into gauge symmetry

e.g. $U(1)_{B-L}$ gauge symmetry (adding N_R)

B-L parity $(-1)^{B-L}$ accidentally introduce R-parity

$$SO(10) \supset U(1)_{B-L} \supset \text{R-parity } (-1)^{B-L}$$

R-parity is acceptable!!

However…

Theoretical ground on R-parity

However…

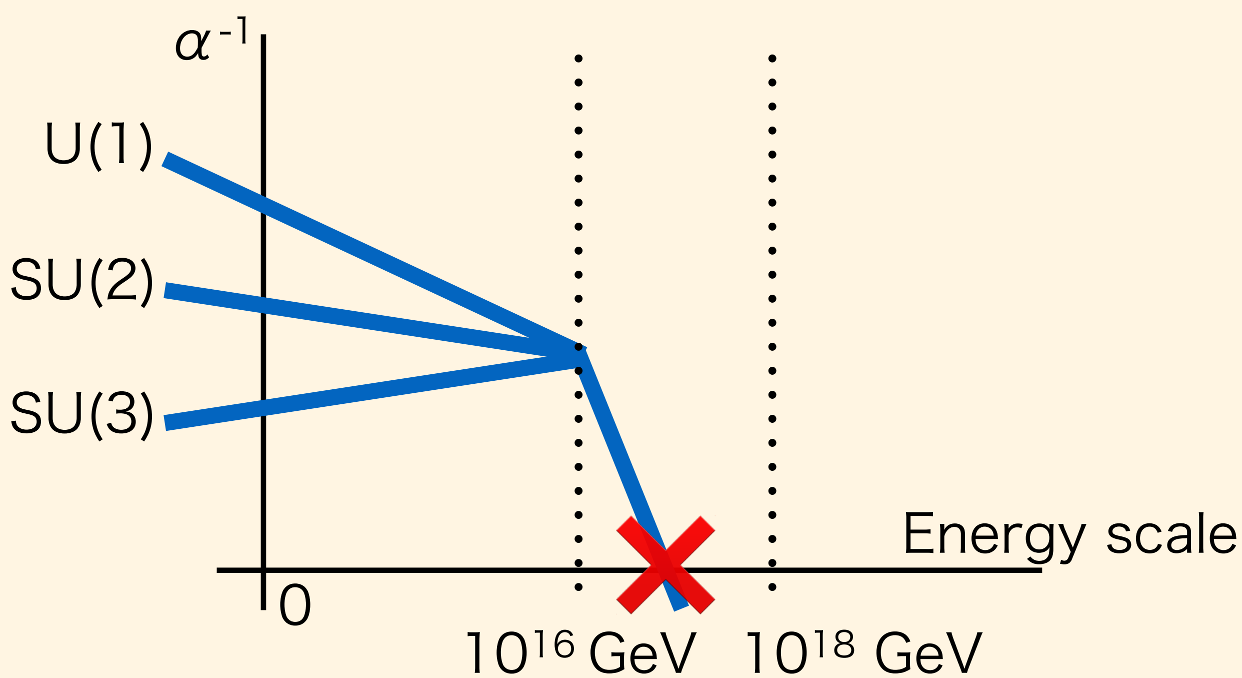
this framework has ***tension*** with **"perturbative *SO(10)* GUT"**

There are ***two possibilities*** in R-parity breaking (and neutrino mass)

A. Unbroken R-parity

e.g. VEV of fields in 126 representation

NR mass : $\overline{126}_H . 16_M . 16_M$
B-L : -2 +1 +1

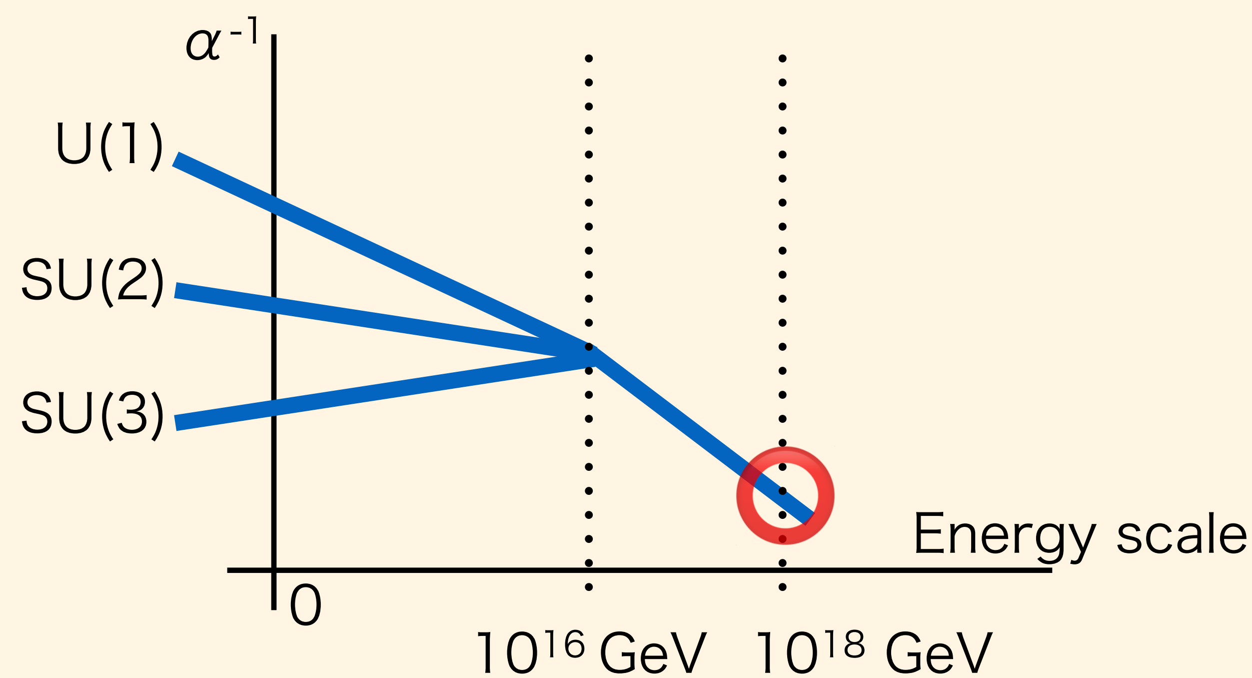


Non-perturbative

B. Broken R-parity

e.g. VEV of fields in 16 representation

NR mass : $(\overline{16}_H . 16_M)(\overline{16}_H . 16_M)$
B-L : -1 +1 -1 +1



R-parity is broken

in perturbative SO(10) GUT!!

Theoretical ground on R-parity

However…

this framework has ***tension*** with **"perturbative *SO(10) GUT*"**

There are ***two possibilities*** in R-parity breaking (and neutrino mass)

R parity is broken in perturbative SO(10) GUT!!

A. Unbroken R-parity

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NR mass : $\overline{126}_H . 16_M . 16_M$

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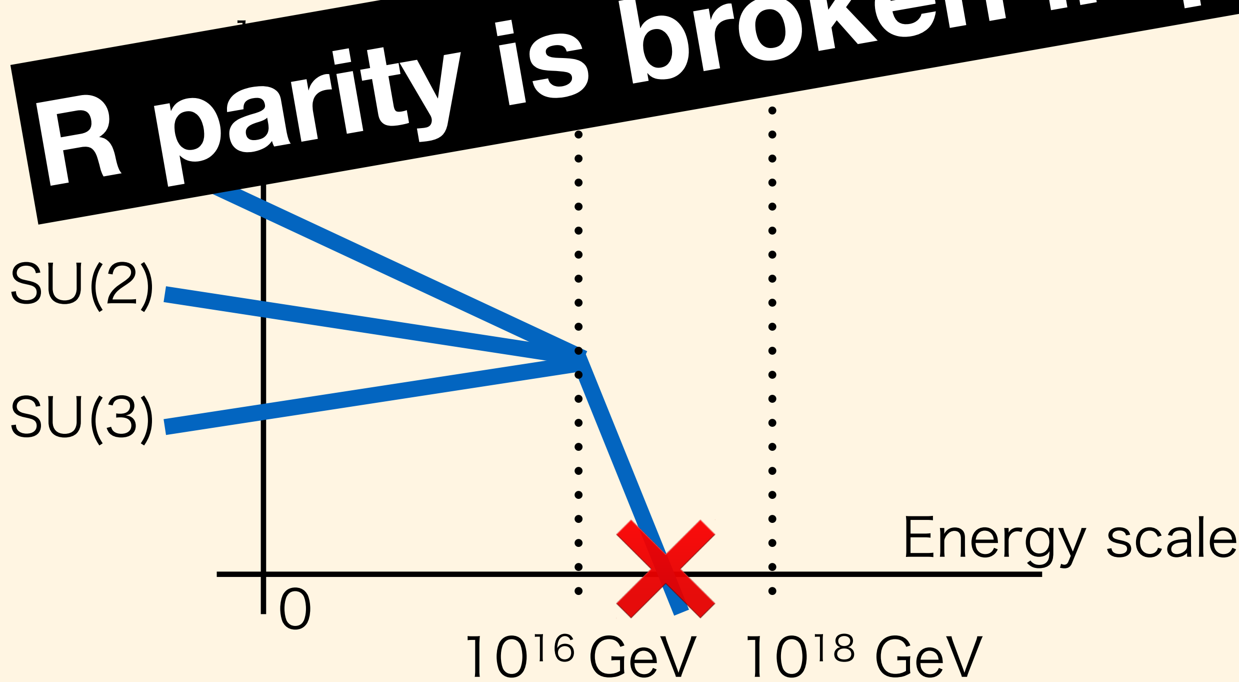


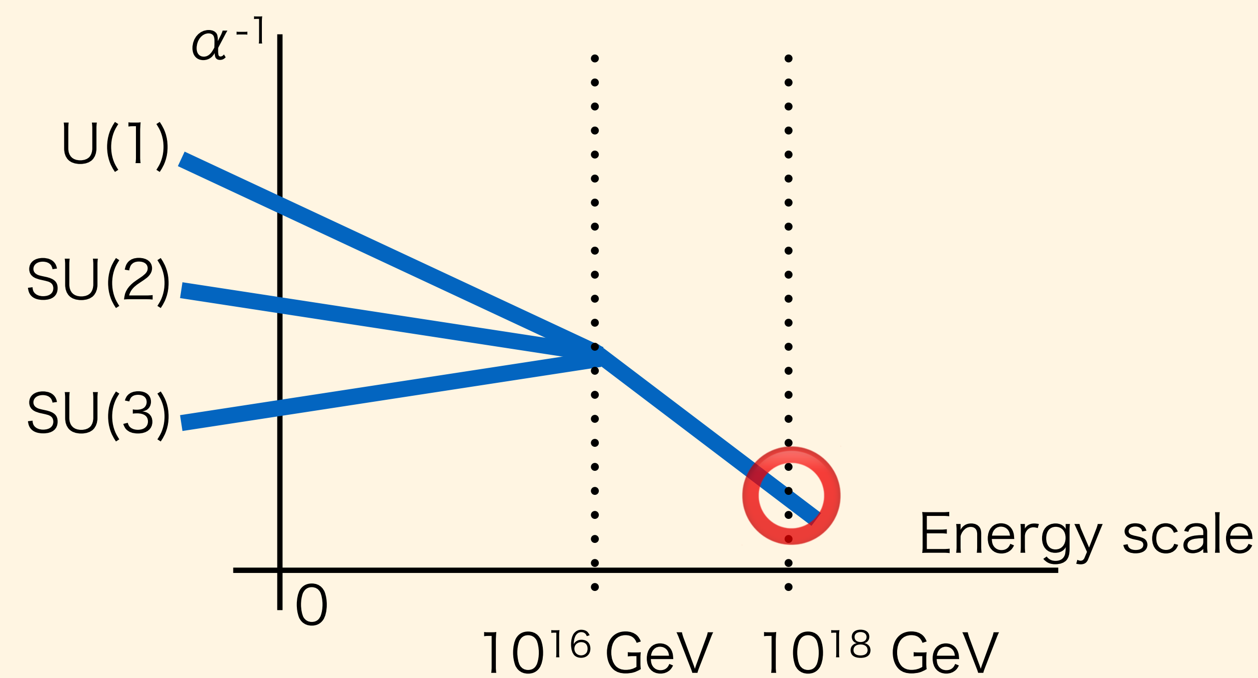
Non-perturbative

B. Broken R-parity

e.g. VEV of fields in 1

$)(16_H . 16_M)$

-1 +1 -1 +1



R-parity is broken in perturbative SO(10) GUT!!

What is dark matter candidate in R-parity violation?

In the following,

consider bilinear R-parity dominated case $W_{\not R} = \mu'_i L_i H_u$

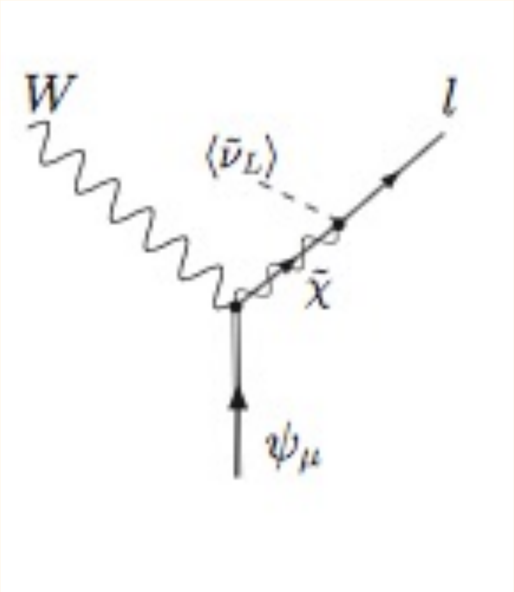
- ***Neutralino LSP cannot be dark matter***

  Neutralino lifetime << the age of universe (e.g. for $\frac{\mu'}{\mu} \sim 10^{-7}$ ***)***

- ***Gravitino LSP can be dark matter***

$$\Gamma[\psi_{3/2} \to Z\nu, h\nu, Wl] \sim \frac{m_{3/2}^3}{192\pi M_{\rm PL}^2} \left(\frac{\mu'}{\mu}\right)^2$$

K. Ishiwata, S. Matsumoto, and T. Moroi (2008)



Long Lifetime

$$\tau_{3/2} \simeq 10^{20}{\rm sec} \times \left(\frac{1{\rm TeV}}{m_{3/2}}\right)^3 \left(\frac{10^{-7}\mu}{\mu'}\right)^2$$
$$>> \mathcal{O}(10^{17}{\rm sec})$$

Gravitino dark matter !!

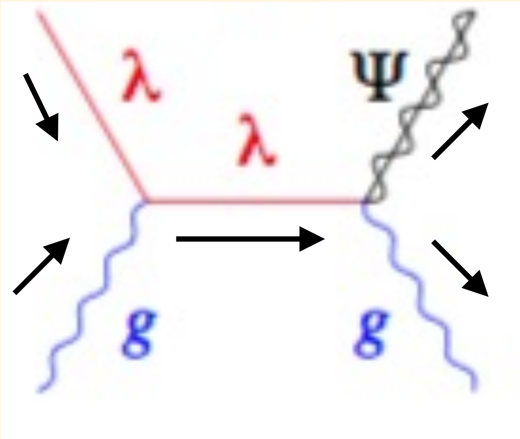
Consistency
between gravitino dark matter and baryon asymmetry

- ***dark matter abundace***

$$\Omega_{3/2}h^2(m_{3/2}, m_{\tilde{g}}, T_R) \sim 0.12$$

Planck (2015)

e.g. $T_R \sim 10^9\text{GeV},\ m_{3/2} \sim m_{\tilde{g}} \sim 1\ \text{TeV}$



g: gluon
λ: gluino
Ψ: gravitino

https://arxiv.org/pdf/hep-ph/

e.g. ***gluon*** and ***gluino*** collisions produce ***gravitino*** dark matter

- ***Successful thermal leptogenesis occurs in following reheating temperature range***

$$10^9\text{GeV} \lesssim T_R \lesssim 10^{10}\text{GeV}$$

W. Buchmuller *et al*. (2003) K. Kohri *et al*. (1999)

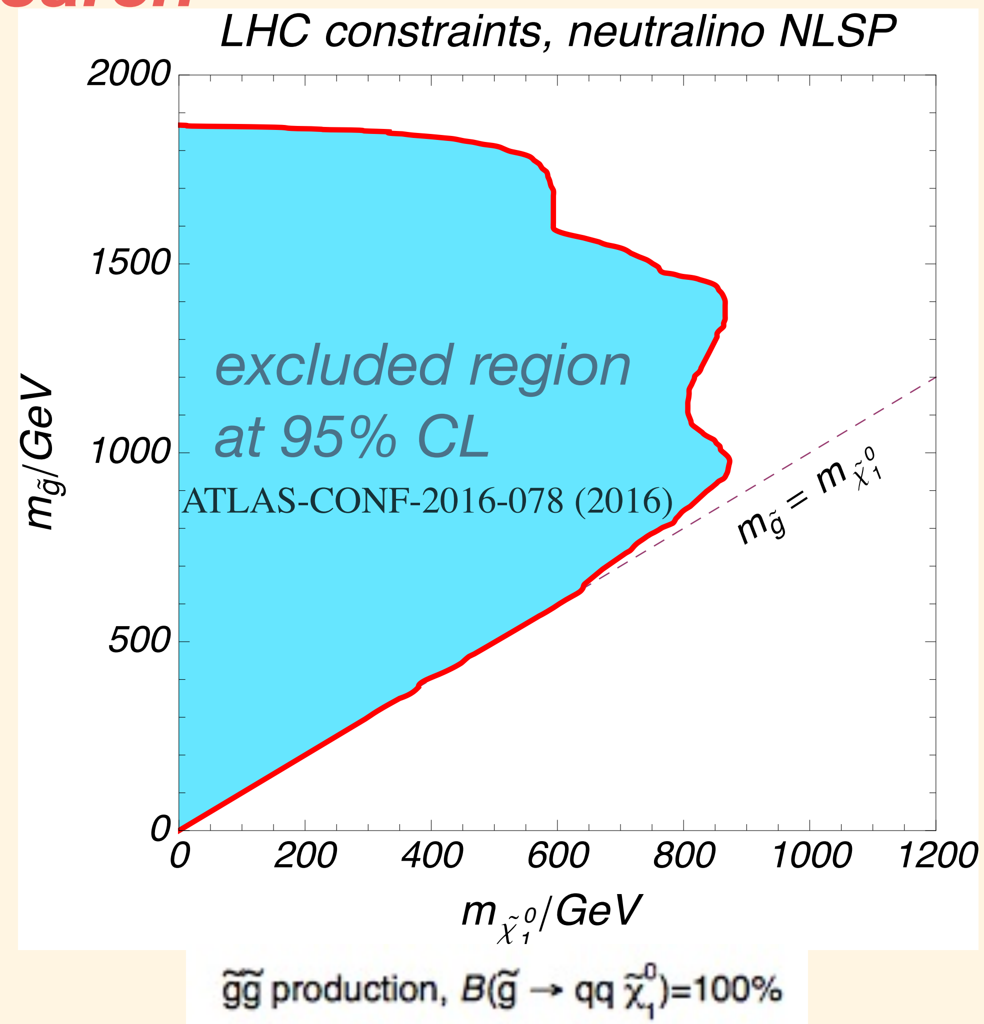
✓ ***Dark matter abundance***

✓ ***Baryon asymmetry***

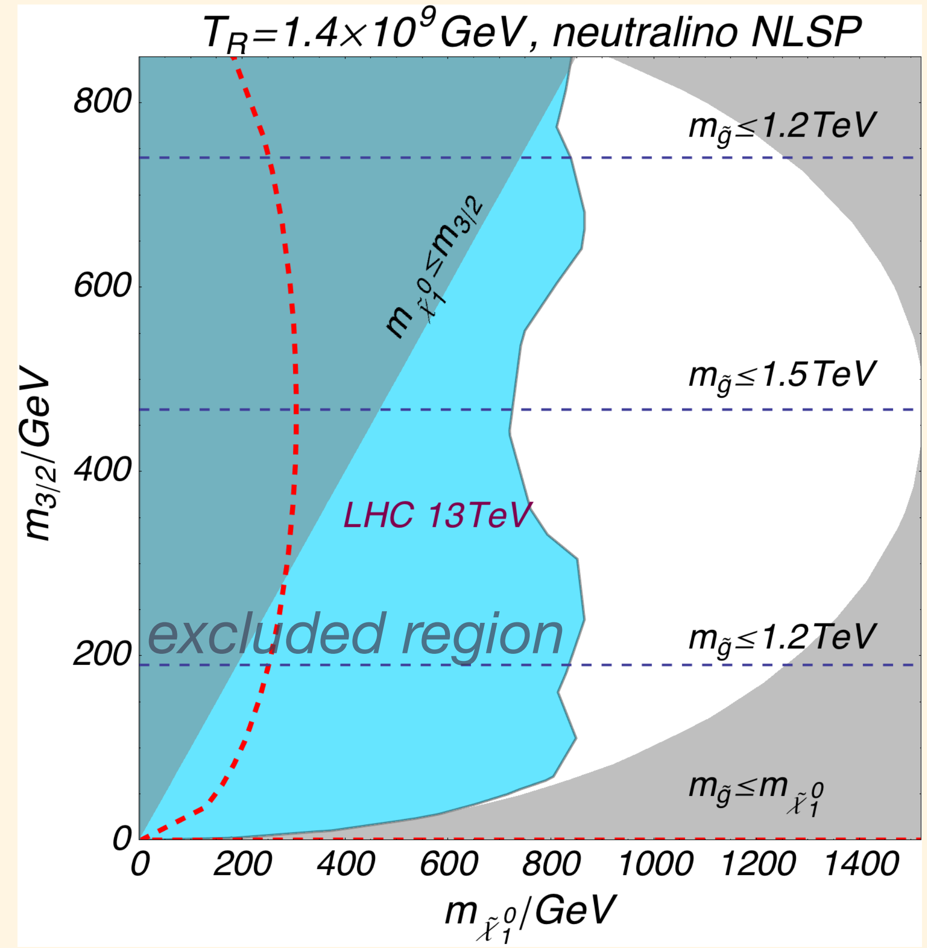
Constraining gravitino dark matter in thermal leptogenesis

Collider constraints in neutralino NLSP

Neutralino NLSP stable in detector : multi-jet with missing momentum search



$$\overrightarrow{m_{\tilde g} \to m_{3/2}}$$



$$\Omega_{3/2}h^2(m_{3/2}, m_{\tilde g}, T_R)|_{\text{fixed } T_R} \sim 0.12$$

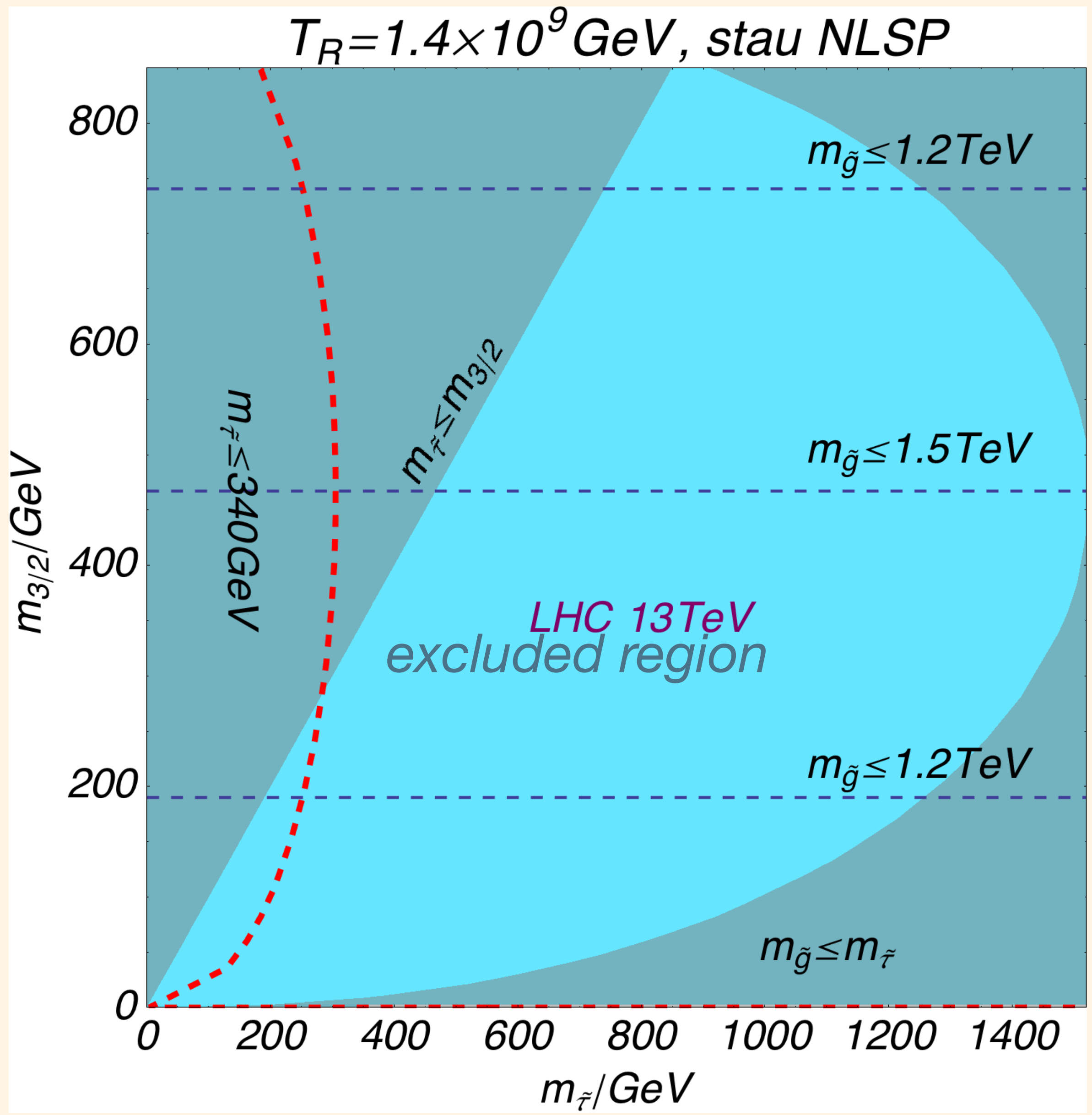
neutralino-gluino → mass relation → neutralino-gravitino

neutralino mass < 700 GeV is excluded !!

Future LHC experiment may be able to search entire region !!

Collider constraints in stau NLSP

Stau NLSP stable in detector : ***long-lived charged particle searches***

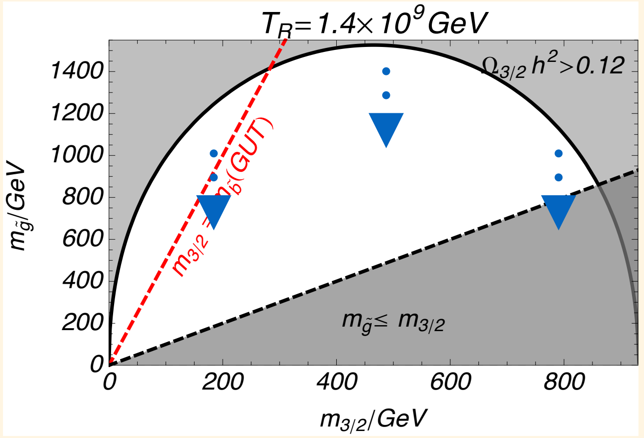


Current LHC experiment exclude entire region !!

Conclusions

- R-parity can be embeded into B-L gauge symmetry
- However, R-parity can be broken in perturbative SO(10) GUT
- In R-parity violation model, gravitino is dark matter candidate
- Furthermote, gravitino dark matter consistent with thermal leptogenesis
- Future LHC may settle down this scenario; gravitino dark matter with leptogenesis
- ***If R-parity is conserved, constraints get more severe***
  because NLSP always contributes gravitino dark matter abundance

$$\Omega^{\rm tot}_{3/2}h^2 = \Omega_{3/2}h^2 + \underbrace{Br_{3/2}}_{=1} \times \frac{m_{3/2}}{m_{\rm NLSP}}\Omega_{\rm NLSP}h^2$$



Back Up

Gravitino and gluino mass relation

- ***Theoretically predicted gravitino dark matter abundance***

$$\Omega_{3/2}h^2 \simeq 0.09\left(\frac{m_{3/2}}{100\,\mathrm{GeV}}\right)\left(\frac{T_R}{10^{10}\,\mathrm{GeV}}\right)\left(\left(1+0.558\frac{r_{\tilde{g}}^{-2}m_{\tilde{g}}^2}{m_{3/2}^2}\right)\right.$$
$$\left. -0.011\left(1+3.062\frac{r_{\tilde{g}}^{-2}m_{\tilde{g}}^2}{m_{3/2}^2}\right)\log\left[\frac{T_R}{10^{10}\,\mathrm{GeV}}\right]\right)$$

$$m_{\tilde{g}} = r_{\tilde{g}} m_{1/2}$$
$$r_{\tilde{g}} \sim 2.5$$

- ***Gravitino and gluino mass relation from dark matter abundance***

$$\Omega_{3/2}h^2\big|_{T_R} \sim 0.12$$

$$m_{3/2} \leftrightarrow m_{\tilde{g}}$$

B-L parity breaking and R-parity breaking

Broken B-L parity

$$\langle 16_H \rangle = v_{\mathrm{B-L}}$$

Broken B-L parity induce Broken R parity

e.g.

$$\begin{aligned} W &\sim \epsilon\ 16_H 16_M 10_H \\ &\sim \epsilon\ v_{\mathrm{B-L}} 16_M 10_H \\ &\sim \epsilon v_{\mathrm{B-L}} L H_u \end{aligned}$$

Bilinear R-parity breaking!!

10_H : SM higgs
16_M : SM matter
16_H : B-L breaking higgs
ε : (small) coupling

B-L parity breaking $\longleftrightarrow$ ***Bilinear R-parity breaking***

R parity is broken in perturbative SO(10) GUT!!

R-parity violation and its constraints

R-parity violating superpotential

$$W_{\not R} = \lambda_{ijk} D_i^c Q_j L_k + \frac{1}{2}\lambda'_{ijk} L_i E_j^c L_k^c + \frac{1}{2}\lambda''_{ijk} D_i^c U_j^c D_k^c$$

$\not{B}\text{-}\not{L}$ → $\not{L}$ $\not{L}$ $\not{B}$

$$+ \mu'_i L_i H_u \quad i, j, k : \text{generation indices}$$

$\not{L}$

Constraints

- ***Erase of baryon asymmetry*** K. Hamaguchi *et al*. (2010)

$$\lambda, \lambda', \lambda'', \mu'/\mu < \mathcal{O}(10^{-(6-7)})$$

- ***Rapid proton decay***

$$|\lambda'\lambda''| < 10^{-25} \left(\frac{m_{\rm SUSY}}{1\,{\rm TeV}}\right)^2 \quad (\tau_{p^+ \to e^+ \pi^0} \gtrsim 10^{34}\,{\rm year})$$

K. Abe *et al*. (2011)

R-parity violation must be small

What is dark matter candidate in R-parity violation?

In the following,

*consider **bilinear R-parity dominated case***

- ***Neutralino LSP cannot be dark matter***

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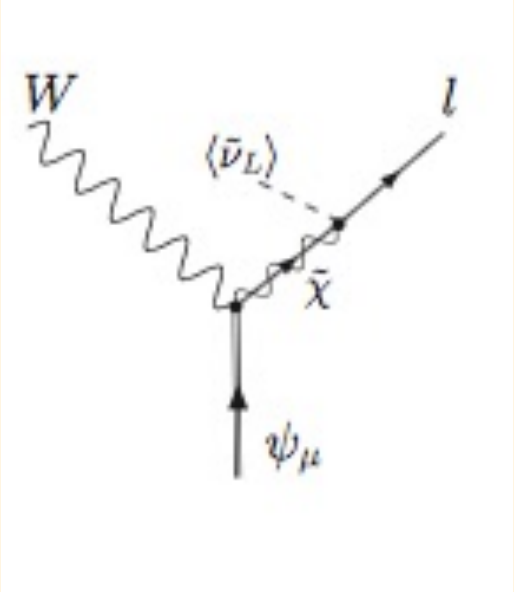

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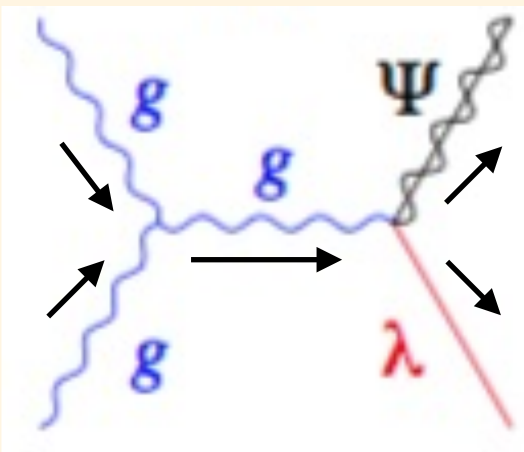
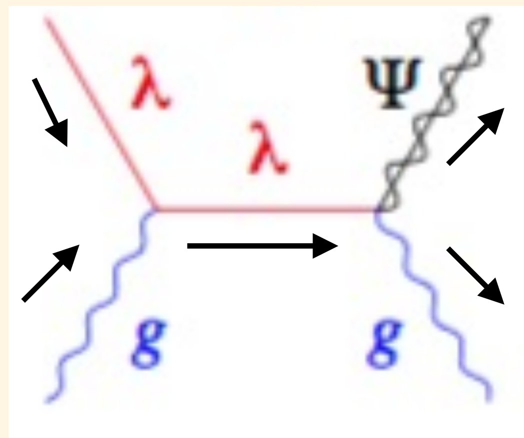
Gravitino dark matter !!

Gravitino dark matter abundance

e.g. ***gluon*** and ***gluino*** collisions produce ***gravitino*** dark matter





g: gluon
λ: gluino
Ψ: gravitino

https://arxiv.org/pdf/hep-ph/0701104.pdf

Thermally produced gravitino dark matter abundance

J. Ellis *et al*. (2016)

$$\Omega_{3/2}h^2 \simeq 0.09\left(\frac{m_{3/2}}{100\,\mathrm{GeV}}\right)\left(\frac{T_R}{10^{10}\,\mathrm{GeV}}\right)\left(\left(1+0.558\frac{r_{\tilde{g}}^{-2}m_{\tilde{g}}^2}{m_{3/2}^2}\right)\right.$$
$$\left. -0.011\left(1+3.062\frac{r_{\tilde{g}}^{-2}m_{\tilde{g}}^2}{m_{3/2}^2}\right)\log\left[\frac{T_R}{10^{10}\,\mathrm{GeV}}\right]\right)$$

$$m_{\tilde{g}} = r_{\tilde{g}} m_{1/2}$$

Assumption

A. **Bilinear R-parity violation**

$$\frac{\mu'}{\mu} < 10^{-11} \times \left(\frac{1\mathrm{TeV}}{m_{3/2}}\right)^{3/2}$$

E, Carquin *et.al*. (2016)
S. Ando and K. Ishiwata(2016)

B. **gravitino dark matter in thermal leptogenesis**

C. **$m_{3/2} < 1$ TeV, 10^9GeV < T_R < 10^{10} GeV**

Searching this scenario

Gluino mass upper bound

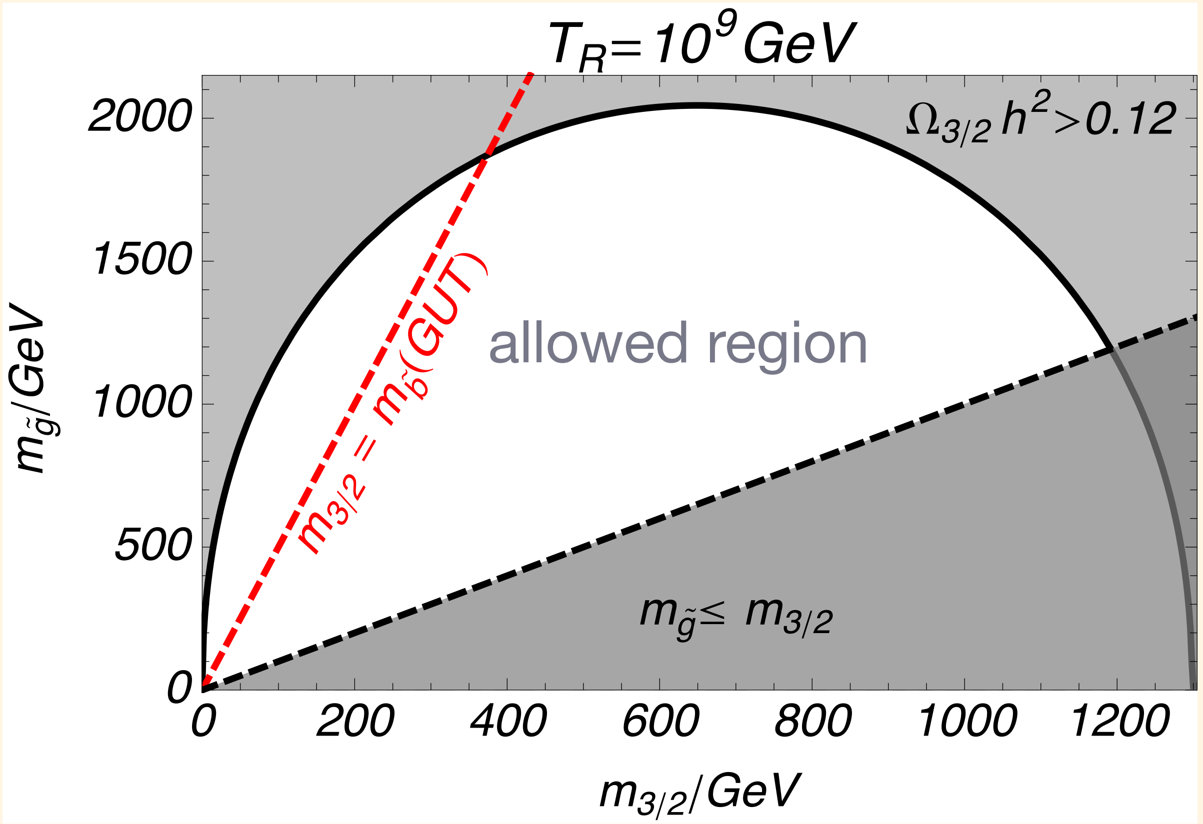
Gluino mass upper bound

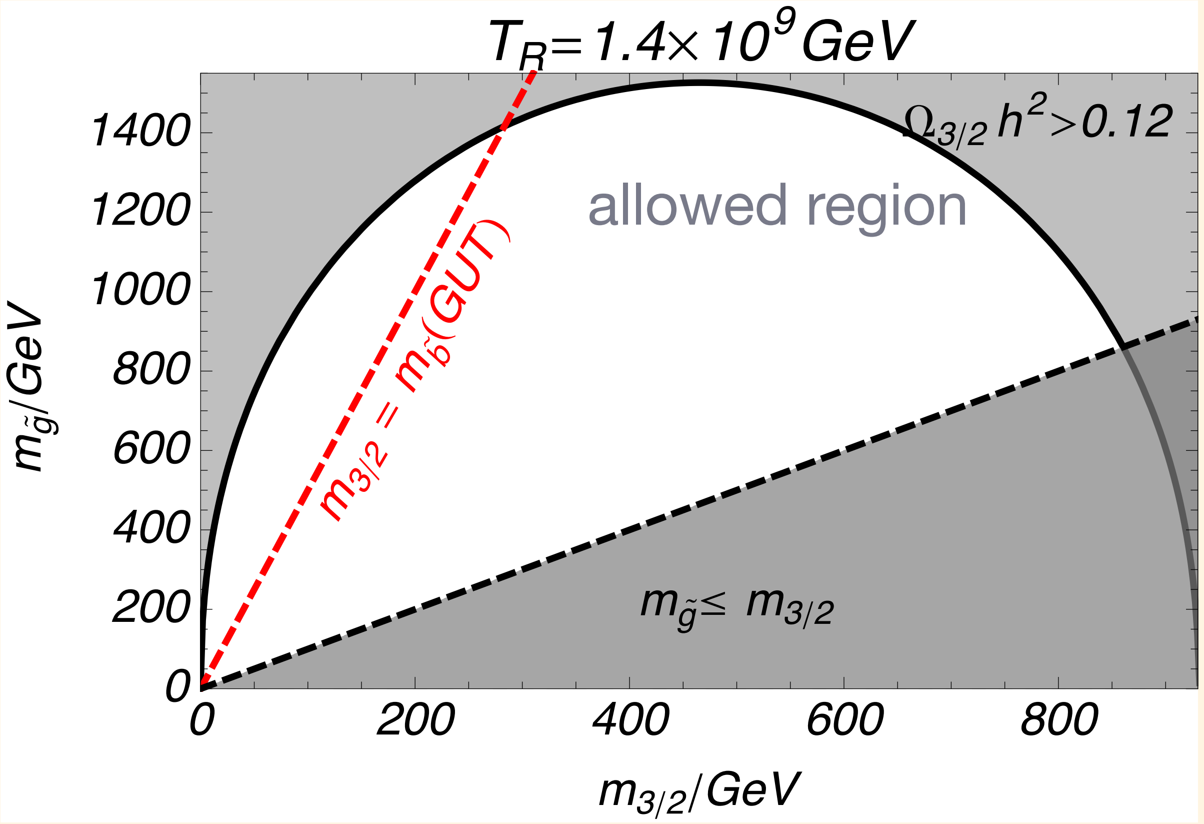
$$\Omega_{3/2}h^2|_{T_R} \sim 0.12$$

Latest reheating temperature upper bound in thermal leptogenesis

$$T_R \lesssim 1.4 \times 10^9 \mathrm{GeV}$$

S. Antusch and A. M. Teixeira (2006)





$m_{\tilde{g}}$ **< 2 TeV**

$m_{\tilde{g}}$ **< 1.6 TeV**

LHC constraints

NLSP contribution into dark matter abundance

Gravitino dark matter abundance from NLSP decay

$$\Omega_{3/2}^{\rm tot} h^2 = \Omega_{3/2} h^2 + Br_{3/2} \times \frac{m_{3/2}}{m_{\rm NLSP}} \Omega_{\rm NLSP} h^2 \ .$$

- R-parity conserving decay into gravitino

$$\tau_{\rm NLSP}^{R} \simeq 5 \times 10^3 {\rm sec} \left(\frac{m_{3/2}}{100{\rm GeV}} \right)^2 \left(\frac{1\,{\rm TeV}}{m_{\rm NLSP}} \right)^5 \ .$$

- R-parity violating decay into the other SM particles

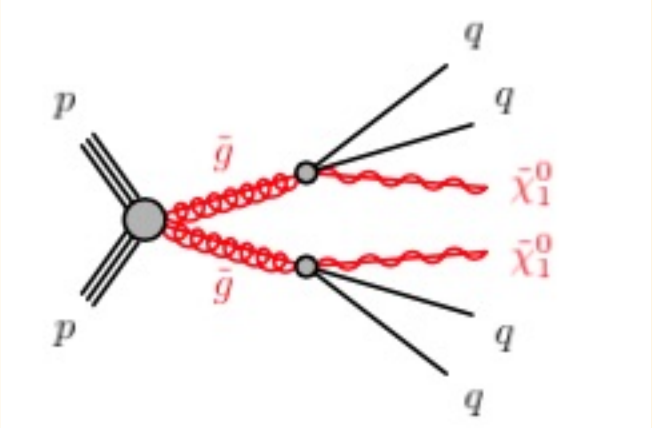
$$\tau_{\rm NLSP}^{\not R} \simeq 10^{-12}\ {\rm sec} \left(\frac{10^{-7} \mu}{\mu'} \right)^2 \left(\frac{1{\rm TeV}}{m_{\rm NLSP}} \right)$$

$$\tau_{\rm NLSP}^{\not R} << \tau_{\rm NLSP}^{R}$$

NLSP contribution is neglibible for dark matter abundance

Neutralino NLSP

- ***Neutralino production by gluino decay***
  - *all squark decoupled limit*
  - *no mass degeneracy*
  - *gluino decaying into two squarks and a neutralino*

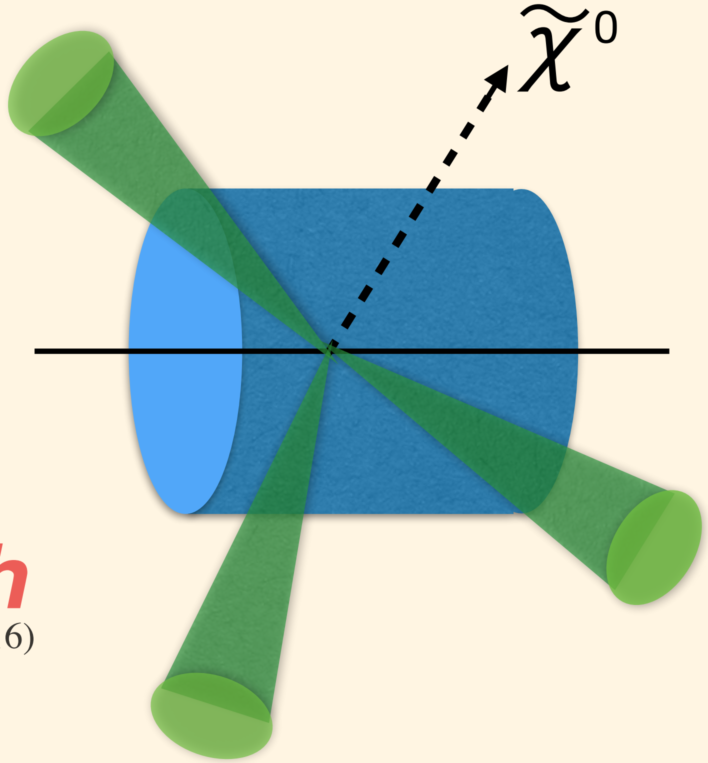


ATLAS-CONF-2016-078 (2016)

- ***Neutralino stable in detector***

$$c\tau_{\tilde{\chi}_1^0} \gtrsim 10^6\,\mathrm{m} \times \left(\frac{1\mathrm{TeV}}{m_{\tilde{\chi}_1^0}}\right)^3 \left(\frac{10^{-11}\mu}{\mu'}\right)^2 \left(\frac{10}{\tan\beta}\right)^2 .$$

K. Hamaguchi *et al.* (2007)

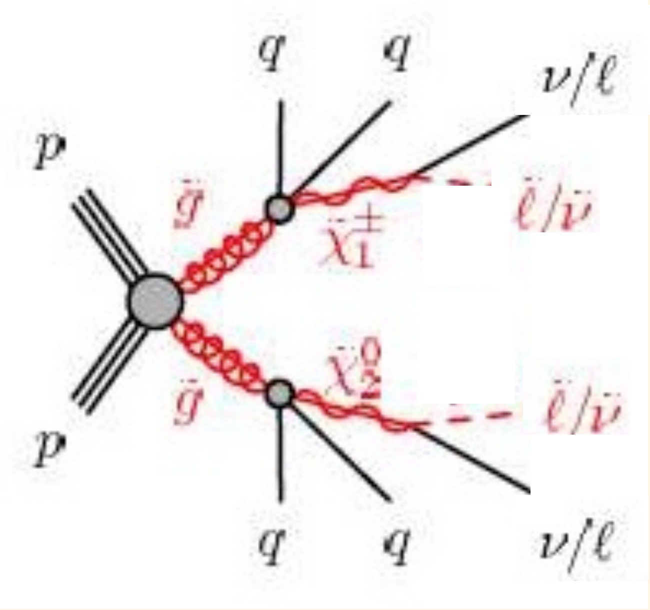


→ ***multi-jet with missing momentum search***

ATLAS-CONF-2016-078 (2016)

Stau NLSP

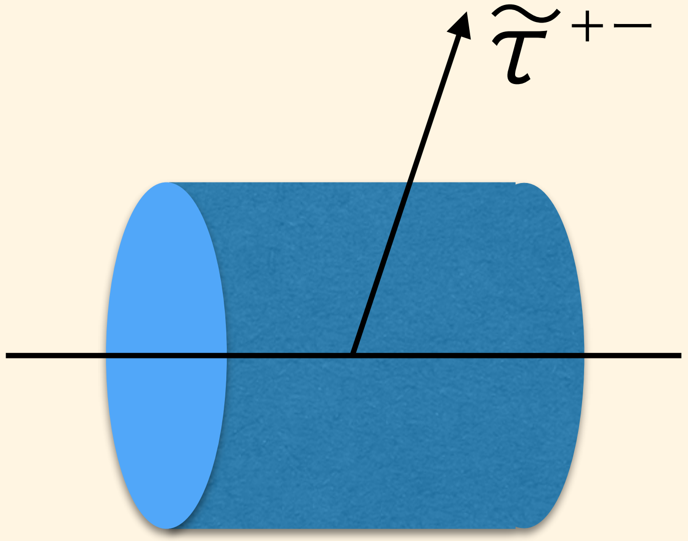
- ***Stau production***
  - *all squark decoupled limit*
  - *no mass degeneracy*
  - *stau cross section ← gluino cross section*
  - *direct Drell-Yan stau pair production*



- ***Stau stable in detector***

$$c\tau_{\tilde{\tau}} \gtrsim 10^7\,\mathrm{m} \times \left(\frac{1\mathrm{TeV}}{m_{\tilde{\tau}}}\right)\left(\frac{10^{-11}\mu}{\mu'}\right)^2\left(\frac{10}{\tan\beta}\right)^2 .$$

K. Hamaguchi *et al.* (2007)

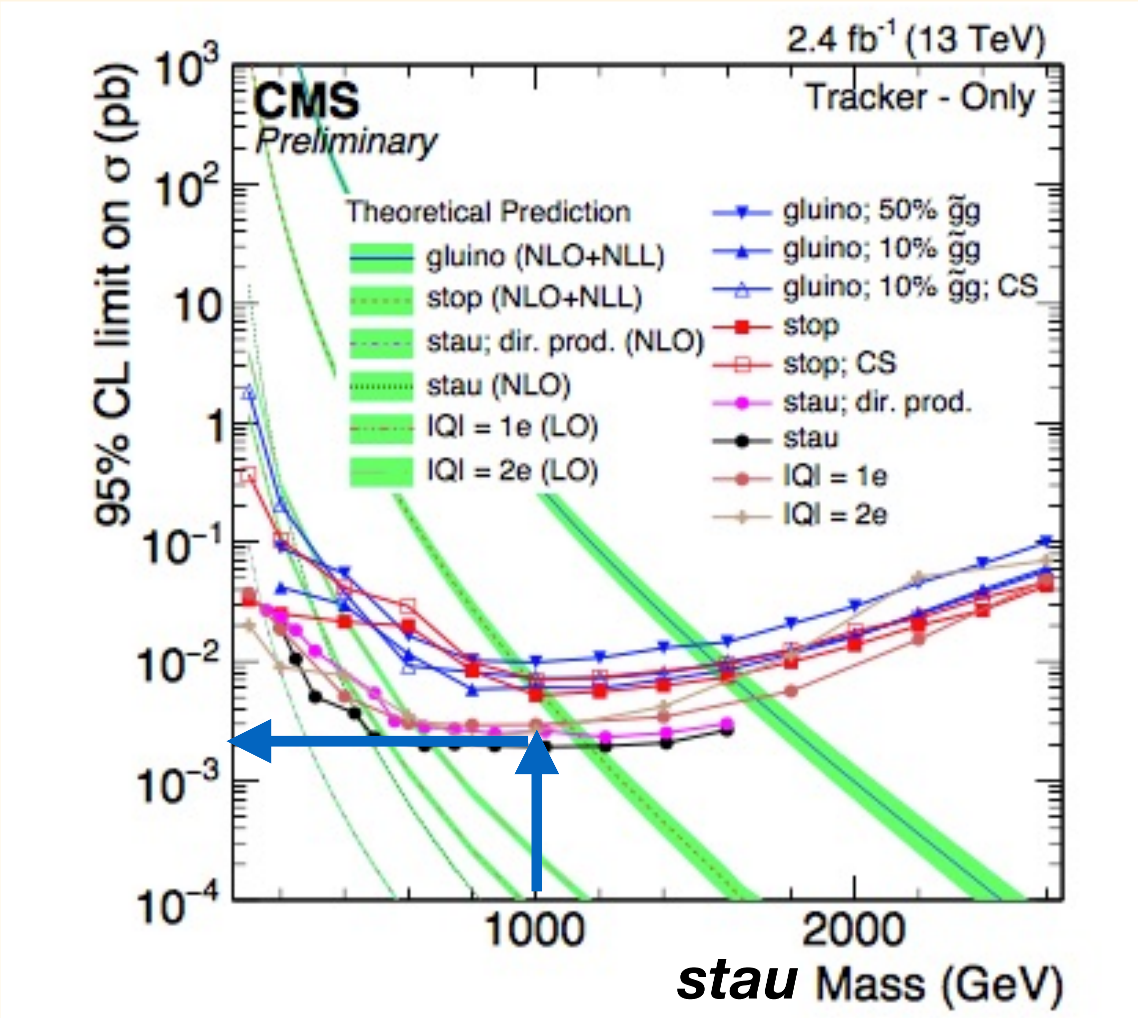


→ ***long-lived charged particle searches***

CMS-PAS-EXO-15-010 (2015)

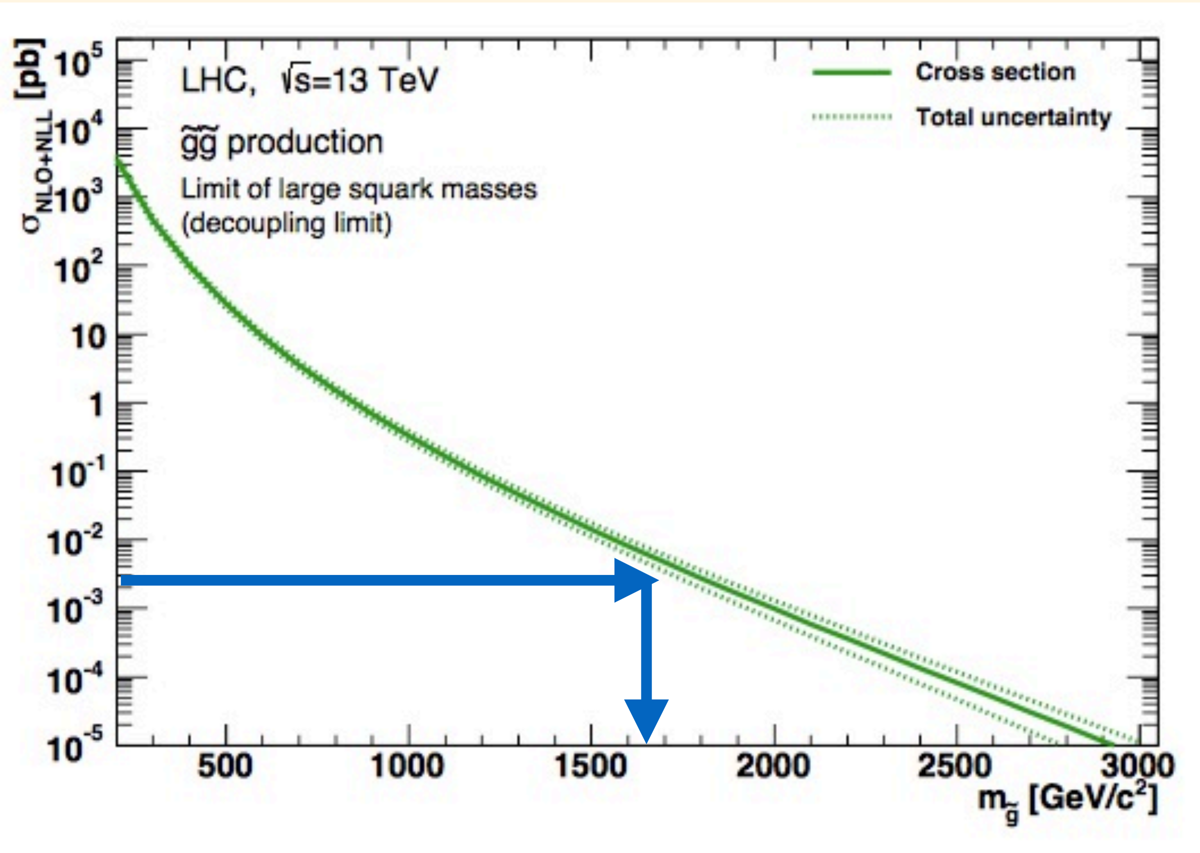
Stau and gluino constraint

Stau cross section upper limit



CMS-PAS-EXO-15-010 (2015)

Gluino production cross section



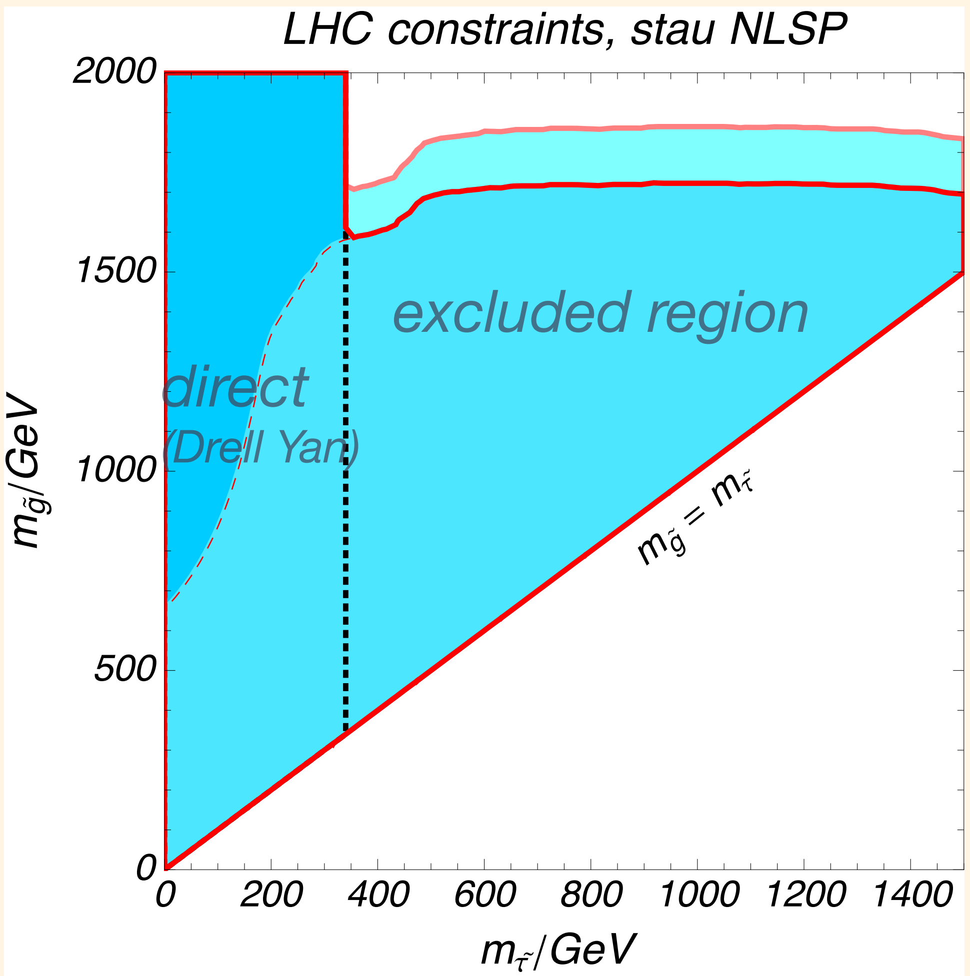
C. Borschensly *et.al*. (2014)

***Gluino and stau mass constraint* by**

Stau cross section upper bound > Gluino production cross section

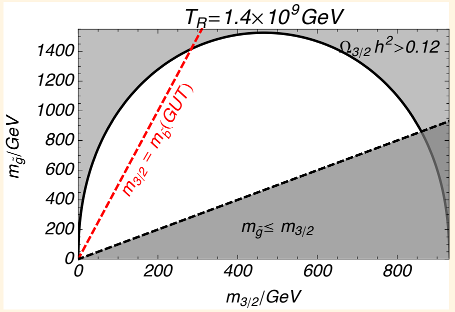
Collider constraints in stau NLSP

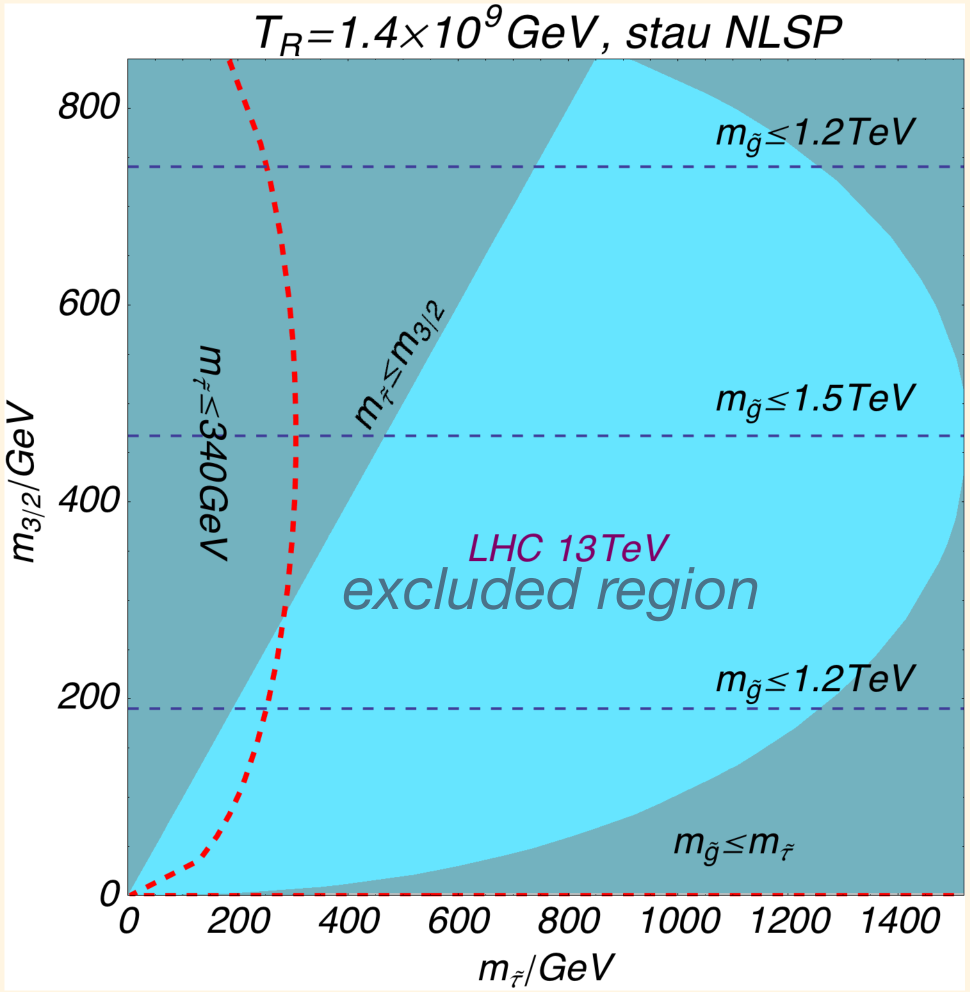
Gluino and stau mass constraint



direct + gluino decay

$m_{\tilde g} \to m_{3/2}$

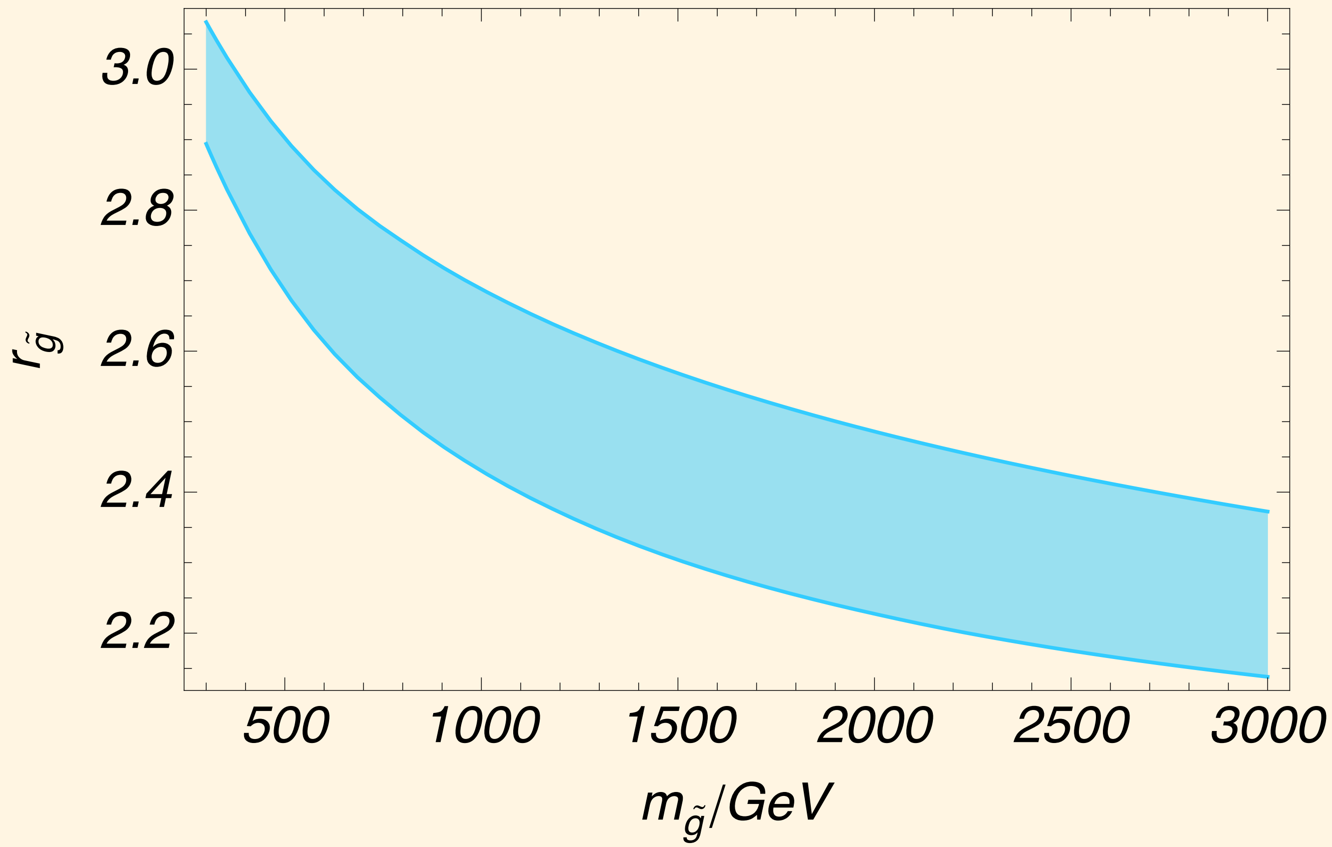




stau-gluino → ***mass relation*** → ***stau-gravitino***

Current LHC experiment exclude entire region !!

Physical gluino mass and gaugino mass at GUT scale



$$m_{\tilde{g}} = r_{\tilde{g}} m_{1/2}$$

$$\Omega_{3/2}h^2 \simeq 0.09 \left(\frac{m_{3/2}}{100\,\mathrm{GeV}}\right)\left(\frac{T_R}{10^{10}\,\mathrm{GeV}}\right)\left(\left(1 + 0.558\frac{r_{\tilde{g}}^{-2} m_{\tilde{g}}^2}{m_{3/2}^2}\right) - 0.011\left(1 + 3.062\frac{r_{\tilde{g}}^{-2} m_{\tilde{g}}^2}{m_{3/2}^2}\right)\log\left[\frac{T_R}{10^{10}\,\mathrm{GeV}}\right]\right)$$

R-parity violation model in SO(10)

	$\mathbf{16}_M$	$\mathbf{10}_H$	$\mathbf{16}_H$	$\overline{\mathbf{16}}_H$	v_{B-L}	X	$m_{3/2}$
R	1	0	$-1/2$	0	$-1/4$	$5/2$	2

Table 1: *R-charges of matter fields, Higgs fields and SO(10) singlets.*

A. Superpotential

$$W = \mathbf{10}_H \mathbf{16}_M \mathbf{16}_M + \overline{\mathbf{16}}_H \overline{\mathbf{16}}_H \mathbf{16}_M \mathbf{16}_M + X(\mathbf{16}_H \overline{\mathbf{16}}_H - v_{B-L}^2)$$

Yukawa term

vR mass term

Bilinear R-parity breaking term

B-L breaking

B. Bilinear R-parity violation by right-handed sneutrino VEV

$$K = v_{B-L}^4 \mathbf{16}_M \overline{\mathbf{16}}_H$$

$$\rightarrow W \sim m_{3/2} v_{B-L}^5 N_R \quad \rightarrow \left\langle \tilde{N}_R \right\rangle \simeq v_{B-L}^3 \times m_{3/2} \rightarrow \quad \mu' = v_{B-L}^3 m_{3/2}$$

C. mu-term

$$W \sim m_{3/2} \mathbf{10}_H \mathbf{10}_H$$

Finally,

$$\frac{\mu'}{\mu} \sim v_{B-L}^3$$

R-parity violation model in SO(10)

	$\mathbf{16}_M$	$\mathbf{10}_H$	$\mathbf{16}_H$	$\overline{\mathbf{16}}_H$	v_{B-L}	X	$m_{3/2}$
R	1	0	$-1/2$	0	$-1/4$	$5/2$	2

Table 1: *R-charges of matter fields, Higgs fields and SO(10) singlets.*

- ***Bilinear R-parity violation***

$$W \sim \mathbf{16}_M \overline{\mathbf{16}}_H$$

- ***Trilinear R-parity violation***

$$W \sim \mathbf{16}_H \mathbf{16}_M \mathbf{16}_M \mathbf{16}_M$$

Small R-parity violation!!

$$\frac{\mu'}{\mu}, \lambda, \lambda', \lambda'' \sim v_{\mathrm{B-L}}^3 \qquad (v_{\mathrm{B-L}} \sim 10^{-3\sim-4})$$