
# U(1)’ seesaw and RHsN DM

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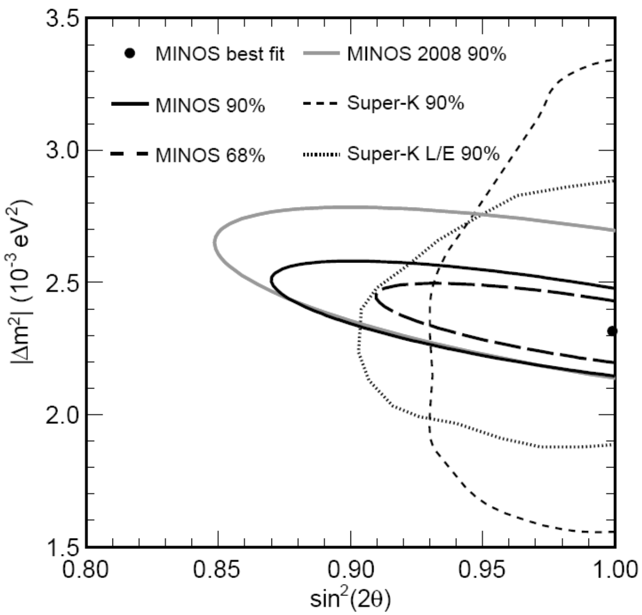
P. Bandyopadhyay, EJC, J.C. Park, arXiv:1105.1652 [hep-ph]

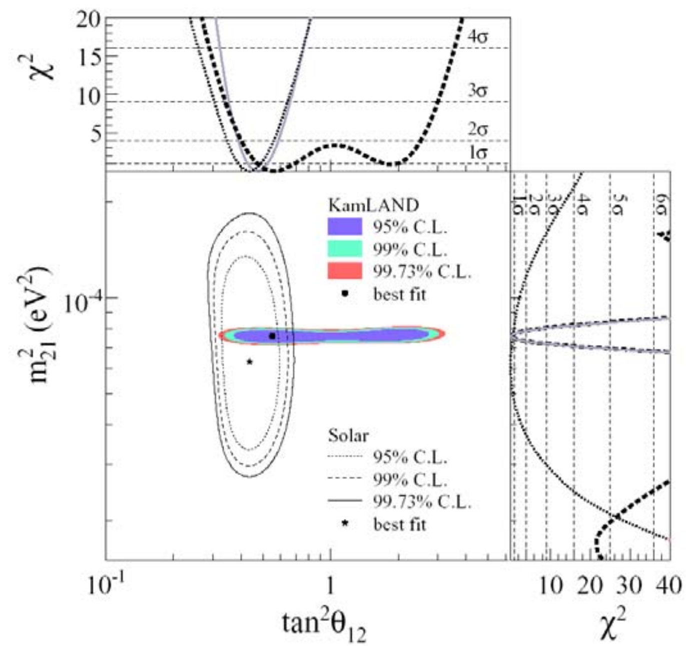
# Neutrinos

## MINOS (2011)




$$|\Delta m^2_{31}| = 2.32^{+0.12}_{-0.08} \times 10^{-3}\ \mathrm{eV}^2$$
$$\sin^2 2\theta_{23} > 0.90$$

## KAMLAND (2008)




$$\Delta m^2_{21} = 7.59^{+0.21}_{-0.21} \times 10^{-5}\ \mathrm{eV}^2$$
$$\tan^2\theta_{12} = 0.47^{+0.06}_{-0.05}$$

# First results from the Double Chooz experiment

H. De Kerret

LowNu, Seoul, Nov. 11

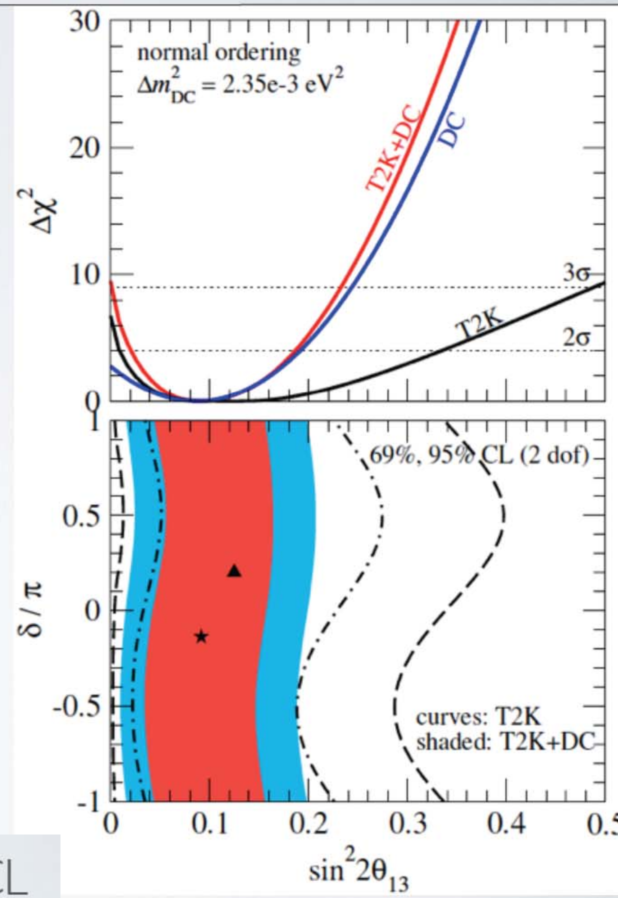
# $\theta_{13}$

## Global $\theta_{13}$ Hunt

DC results consistent with T2K results

Major impact in $\theta$13 knowledge today by DC

Combined effect: $\sin^2(2\theta_{13}) > 0$ @ $3\sigma$

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$\sin^2(2\theta_{13}) = 0.085 \pm 0.029(\text{stat}) \pm 0.042(\text{syst})$ @ 68%CL

# Status of the RENO Reactor Neutrino Experiment

**RENO = Reactor Experiment for Neutrino Oscillation**

**(For RENO Collaboration)**

**(Inauguration for RENO Experiment)**


**K.K. Joo**
**Chonnam National University**

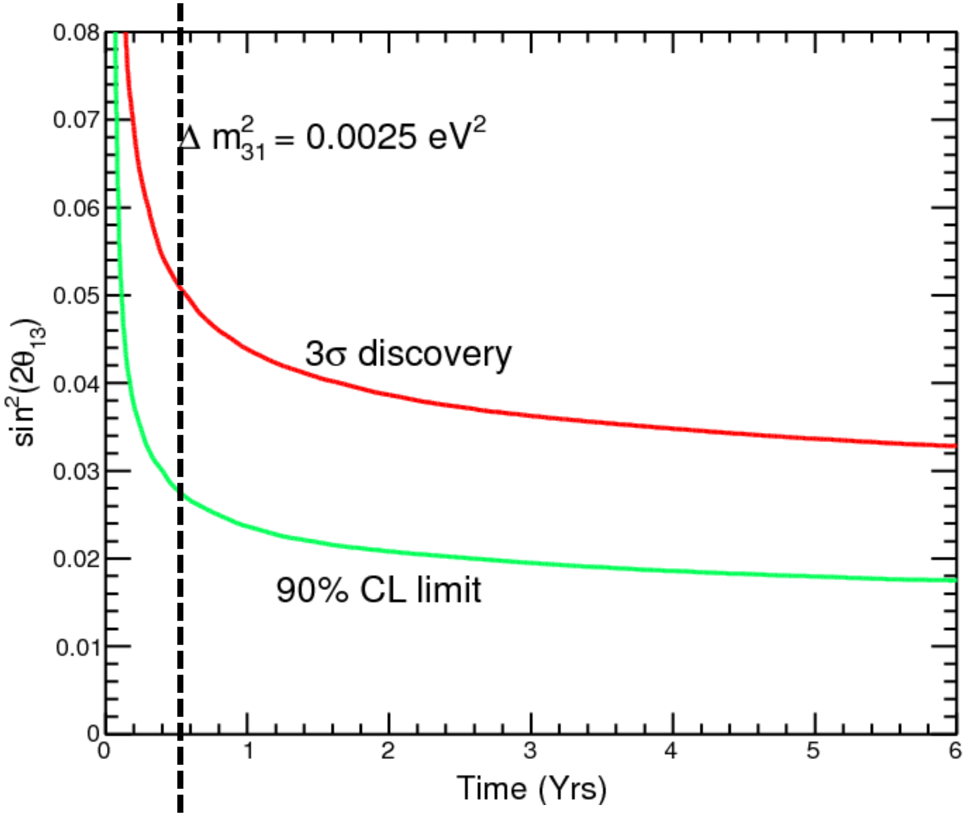
**November 09, 2011**

KNRC Korea Neutrino Research Center

RENO

$6^{th}$ Low Energy Neutrino Physics, November 09-12 2011, SNU

- First results on $\sin^2(2\theta_{13})$ ~0.05 are expected to be available within a half year
  - Goal: ~0.07 (end of this yr)
  ~0.05 (March, 2012)




- RENO group hope to tell the value of $\sin^2(2\theta_{13})$ at the anticip ated time
  - Goal: Neutrino 2012 @ Kyoto (June, 2012)

# Dark Matter

- Unidentified dark matter 23%

$\Omega_{DE}\, h^2 = 0.361$ +/- 0.008

$\Omega_m\, h^2 = 0.1349$ +/- 0.004

$\Omega_B\, h^2 = 0.0226$ +/- 0.0008

$\Omega_\nu\, h^2 = 0.0005 \sim 0.0047$

**$\Omega_{DM}\, h^2 = 0.1123$ +/- 0.0035**

$\Omega_r\, h^2 = 2.469\times10^{-5}$

WMAP7 + BAO + $H_0$
Komatsu et al. 2010

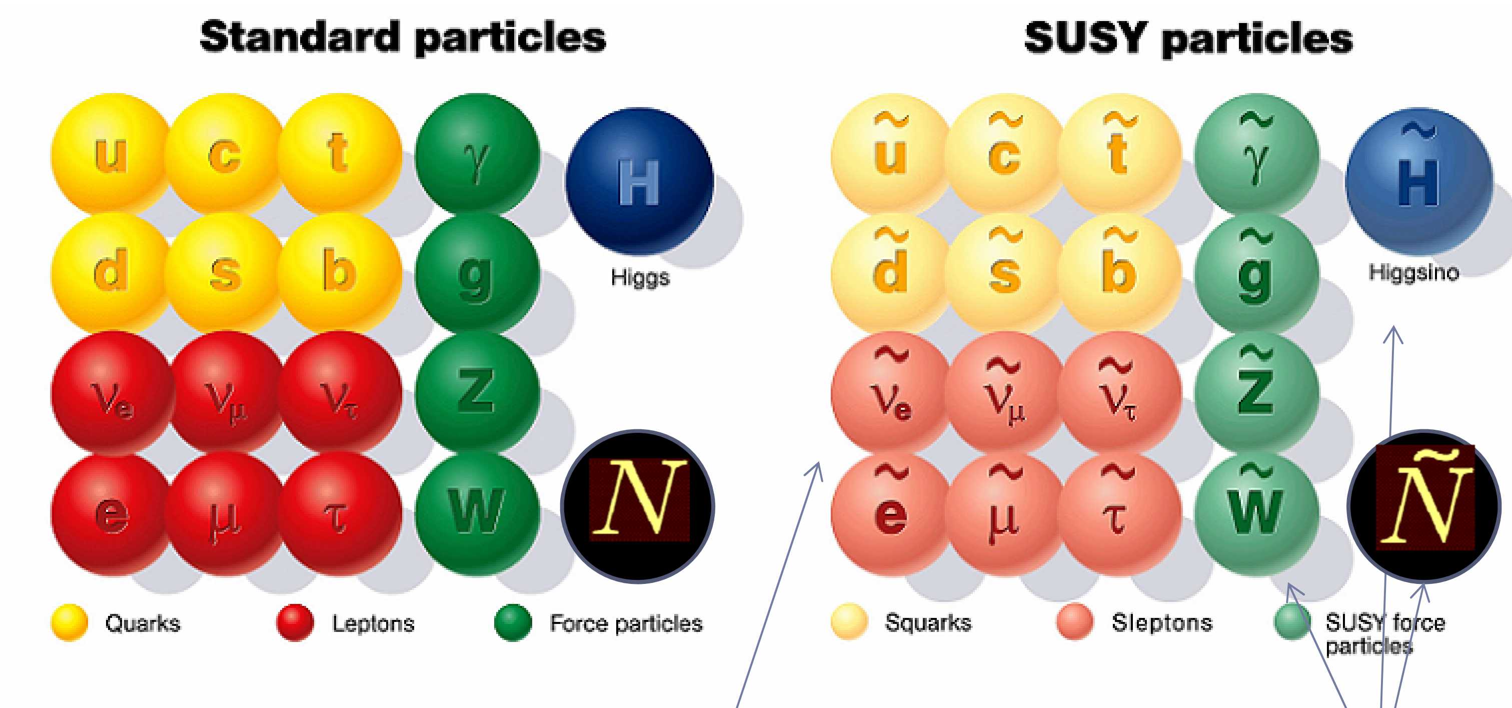
# Why RHsN DM?

- Combines two evidences for physics BSM.
- It may be the LSP.
- It may be tested at LHC.

  clean seesaw signatures:

  same-sign dileptons, displaced vertices + MET

# SUSY DM




Large $Z^0$ interaction excluded by direct detection

Good DM candidates

# The Model: SUSY U(1)' seesaw at TeV

- U(1)' = $U(1)_{B-L}$, $U(1)_\chi$, or $U(1)_\psi$ from GUT.

$$W = y_\nu L H_2 N + \frac{1}{2}\lambda S N N$$

$$m_N = \lambda \langle S \rangle$$

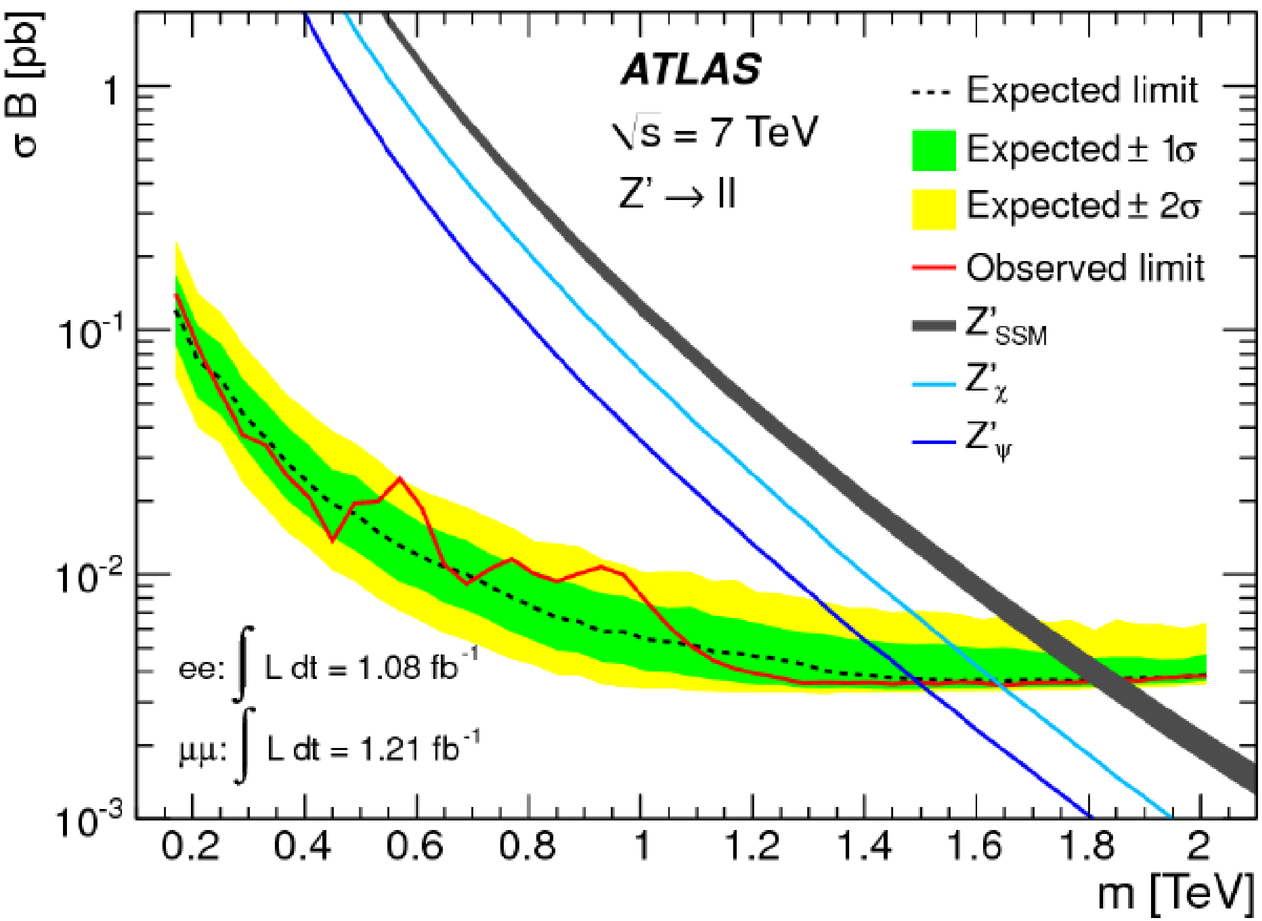
- TeV seesaw: $M_N \sim 10^{2:3}$ GeV.

$$W = y_\nu L H_2 N + \frac{1}{2} m_N N N$$

$$m_\nu = \frac{y_\nu^2 \langle H_2^0 \rangle^2}{m_N} \quad \Rightarrow \quad y_\nu \sim 10^{-6:7}$$

- DM: Right-Handed sNeutrino $\tilde{N}$
- LHC: $Z'/N, \tilde{Z}'/\tilde{N}$

# LHC pushes up Z'




arXiv:1108.1582

# EWPD and Tevatron

| $Z'$ | $M_{Z'}$ [GeV] | | | | $\sin\theta_{ZZ'}$ | | | $\chi^2_{\rm min}$ |
|---|---|---|---|---|---|---|---|---|
| | electroweak | CDF | DØ | LEP 2 | $\sin\theta_{ZZ'}$ | $\sin\theta_{ZZ'}^{\rm min}$ | $\sin\theta_{ZZ'}^{\rm max}$ | |
| $Z_\chi$ | 1,141 | 892 | 800 | 673 | −0.0004 | −0.0016 | 0.0006 | 47.3 |
| $Z_\psi$ | 147 | 878 | 763 | 481 | −0.0005 | −0.0018 | 0.0009 | 46.5 |
| $Z_\eta$ | 427 | 982 | 810 | 434 | −0.0015 | −0.0047 | 0.0021 | 47.7 |
| $Z_I$ | 1,204 | 789 | 692 | | 0.0003 | −0.0005 | 0.0012 | 47.4 |
| $Z_S$ | 1,257 | 821 | 719 | | −0.0003 | −0.0013 | 0.0005 | 47.3 |
| $Z_N$ | 623 | 861 | 744 | | −0.0004 | −0.0015 | 0.0007 | 47.4 |
| $Z_R$ | 442 | | | | −0.0003 | −0.0015 | 0.0009 | 46.1 |
| $Z_{LR}$ | 998 | 630 | | 804 | −0.0004 | −0.0013 | 0.0006 | 47.3 |
| $Z_{\not L}$ | (803) | (740) | | | −0.0015 | −0.0094 | 0.0081 | 47.7 |
| $Z_{SM}$ | 1,403 | 1,030 | 950 | 1,787 | −0.0008 | −0.0026 | 0.0006 | 47.2 |
| $Z_{string}$ | 1,362 | | | | 0.0002 | −0.0005 | 0.0009 | 47.7 |
| SM | $\infty$ | | | | 0 | | | 48.5 |

Langacker,0801.1345

# How to produce? Dirac neutrino (I)

- Nonthermal production.
- Thermal regeneration.

Asaka, et.al., 0512118

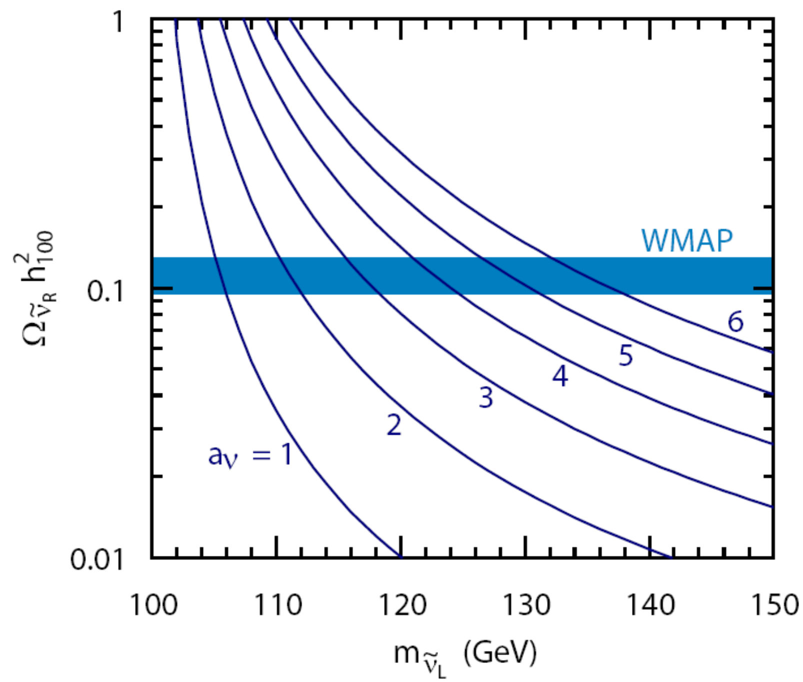
$$W = y_\nu L H_2 N$$

$$m_\nu = y_\nu \langle H_2^0 \rangle \quad \Rightarrow \quad y_\nu \sim 10^{-13}$$

$$\mathcal{L}_A = A_\nu H_u \tilde{L} \tilde{\nu}_R^c + \text{h.c.}$$

$$A_\nu \;=\; a_\nu y_\nu m_{\tilde{L}}$$

$$\Gamma_{\tilde{W}^0 \to \tilde{\nu}_R \bar{\nu}_L} = \frac{\beta_{\rm f}^2 g_2^2}{64\pi} \left[ \frac{A_\nu v_T}{m_{\tilde{\nu}_L}^2 - m_{\tilde{\nu}_R}^2} \right]^2 m_{\tilde{W}}$$

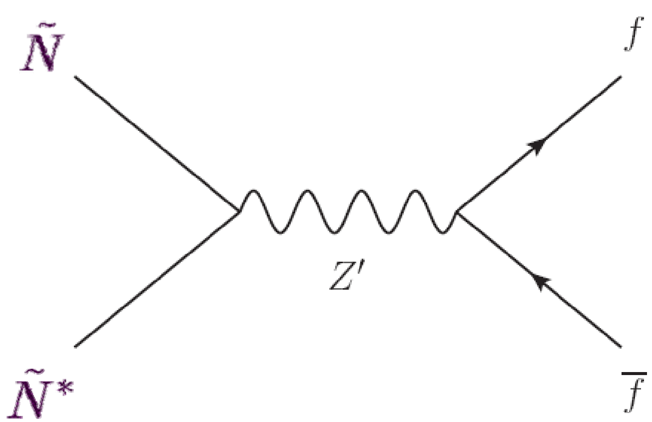



$$m_{\tilde{\nu}_R} = 100 \text{ GeV}, \; m_{\tilde{W}} = 300 \text{ GeV}, \text{ and } \mu_H = 150 \text{ GeV}$$

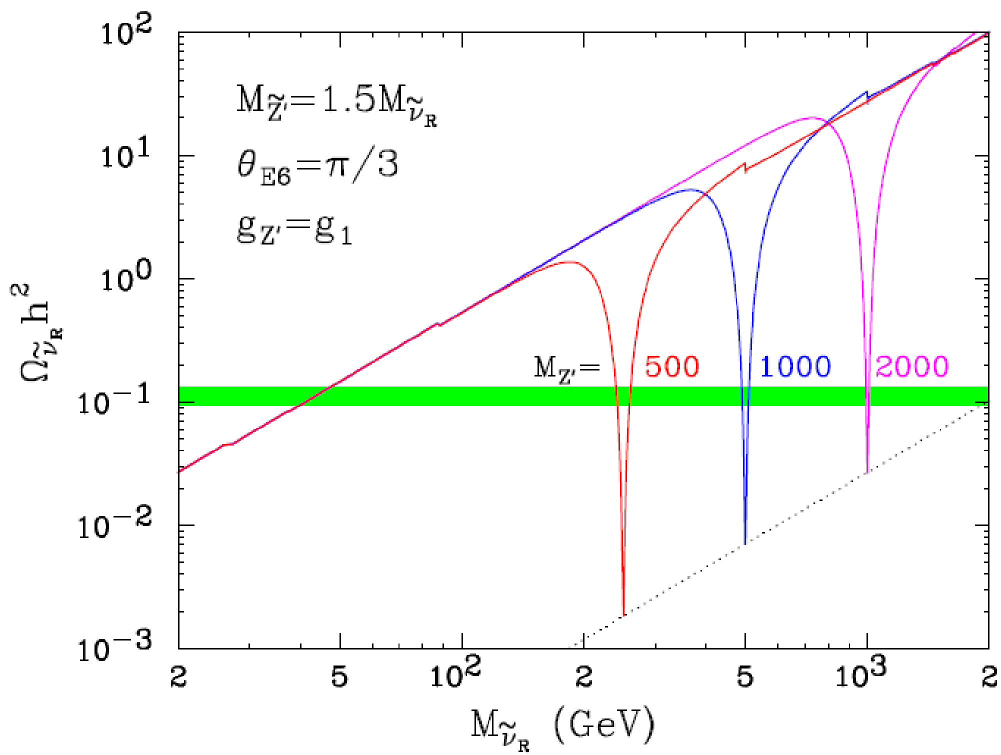
# How to produce? Dirac neutrino (II)

- U(1)': $Q' = Q_\chi \cos\theta_{E6} + Q_\psi \sin\theta_{E6}$

$$\tilde{N}\tilde{N}^* \to Z' \to f\bar{f}$$




Lee, et.al., 0702223



# How to produce? Majorana neutrino (I)

- Too huge thermal regeneration:

  $y_\nu \sim 10^{-7} \rightarrow \Omega_{DM} >> 1.$

- Need thermalization: large Yukawa or gauge.
- Large A term:

Arkani-Hamed, et.al., 0006312
Borzumati-Nomura, 0007018

$$V_{soft} = A_\nu \tilde{l} H_u \tilde{N} \text{ with } A_\nu \sim 100\text{GeV}$$

Usually, $A_\nu \sim y_\nu m_{3/2}$

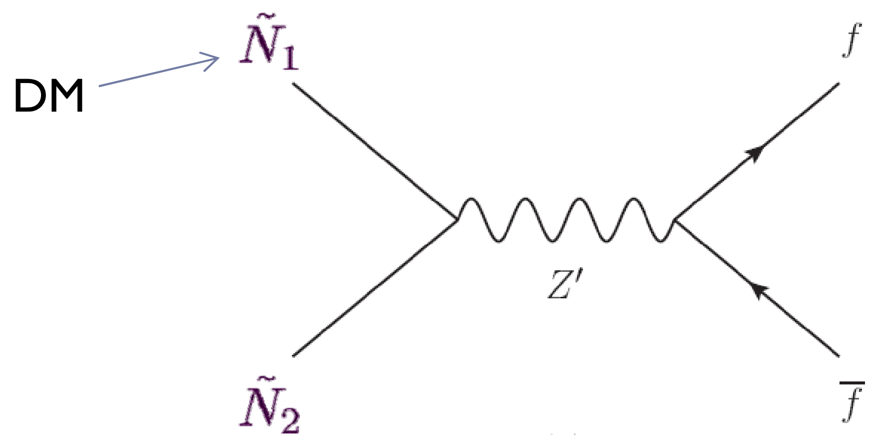
# How to produce? Majorana neutrino (II)

- Z'?
- RHsN mass splitting: $\tilde{N} = \tilde{N}_1 + i\tilde{N}_2$

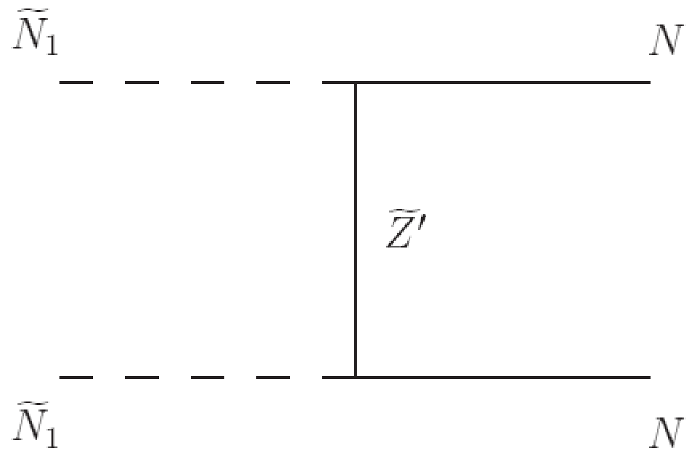
$$V_{mass} = (m_N^2 + m_{\tilde{N}}^2 - \frac{1}{4} m_{Z'}^2 c_{2\beta'})|\tilde{N}|^2 - \frac{1}{2} B_N m_N (\tilde{N}\tilde{N} + \tilde{N}^*\tilde{N}^*)$$

$$m_{\tilde{m}_{1,2}}^2 = m_N^2 + m_{\tilde{N}}^2 - \frac{1}{4} m_{Z'}^2 \mp B_N m_N$$

- Z': too heavy, off-diagonal coupling.



# Can U(1)' gaugino help?




- Yes! How?

# $U(1)_\chi$ model

- New fields and anomaly-free charge assignment:

| $SU(5)$ | $10_F$ | $\bar{5}_F$ | $1(N)$ | $5_H$ | $\bar{5}_H$ | $1(X)$ | $1(S_1)$ | $1(S_2)$ |
|---|---|---|---|---|---|---|---|---|
| $2\sqrt{10}Q'$ | $-1$ | $3$ | $-5$ | $2$ | $-2$ | $0$ | $10$ | $-10$ |

- Gauge invariant Yukawas:

$$W_{seesaw} = y_{ij} L_i H_u N_j + \frac{\lambda_{N_i}}{2} S_1 N_i N_i$$

$$W' = \mu' S_1 S_2 \quad \text{or} \quad W' = \lambda X S_1 S_2 + \frac{\kappa}{3} X^3$$

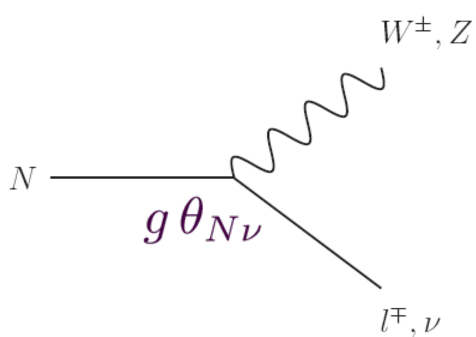
# Left-Right Mixing

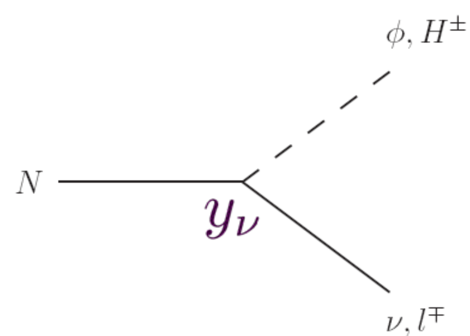
- L-R mixing (Dirac) mass leads to a small mixing between LH neutrino/sneutrino and RH neutrino/sneutrino:

$$\mathcal{L}_{mixing} = m_D \nu N + \tilde{m} m_D \tilde{\nu} \tilde{N}$$

$$\theta_{N\nu} \approx \frac{y_\nu v_u}{\sqrt{2} m_N} \qquad \theta_{\tilde{N}_{1,2}\tilde{\nu}_{R,I}} = y_\nu \frac{(m_N \pm A_L \mp \mu \cot\beta) v_u}{\sqrt{2}(m^2_{\tilde{N}_{1,2}} - m^2_{\tilde{\nu}_{R,I}})}$$

- RH neutrino/sneutrino couples not only to Higgs bosons but also to Z/W bosons through mixing:



# RHN decays

$$\Gamma(N \to \nu h) = \Gamma(N \to \bar{\nu} h) = \frac{1}{8}\frac{y_\nu^2 m_N}{8\pi}\left(1-\frac{m_h^2}{m_N^2}\right)^2 \cos^2\alpha \; ,$$

$$\Gamma(N \to \nu H) = \Gamma(N \to \bar{\nu} H) = \frac{1}{8}\frac{y_\nu^2 m_N}{8\pi}\left(1-\frac{m_H^2}{m_N^2}\right)^2 \sin^2\alpha \; ,$$

$$\Gamma(N \to \nu A) = \Gamma(N \to \bar{\nu} A) = \frac{1}{8}\frac{y_\nu^2 m_N}{8\pi}\left(1-\frac{m_A^2}{m_N^2}\right)^2 \cos^2\beta \; ,$$

$$\Gamma(N \to l H^+) = \Gamma(N \to \bar{l} H^-) = \frac{1}{4}\frac{y_\nu^2 m_N}{8\pi}\left(1-\frac{m_{H\pm}^2}{m_N^2}\right)^2 \cos^2\beta \; ,$$

$$\Gamma(N \to \nu Z) = \Gamma(N \to \bar{\nu} Z) = \frac{1}{8}\frac{y_\nu^2 m_N}{8\pi}\left(1-\frac{M_Z^2}{m_N^2}\right)^2 \left(1+2\frac{M_Z^2}{m_N^2}\right) \sin^2\beta \; ,$$

$$\Gamma(N \to l W^+) = \Gamma(N \to \bar{l} W^-) = \frac{1}{8}\frac{y_\nu^2 m_N}{8\pi}\left(1-\frac{M_W^2}{m_N^2}\right)^2 \left(1+2\frac{M_W^2}{m_N^2}\right) \sin^2\beta \; .$$

# U(1)' gaugino $\tilde{Z}'$

- U(1)' gaugino-Higgsino mass matrix:

$$(\tilde{Z}', \tilde{S}'_1, \tilde{S}'_2)$$

$$\mathcal{M} = \begin{bmatrix} m_M & M_{Z'} c_{\beta'} & -M_{Z'} s_{\beta'} \\ M_{Z'} c_{\beta'} & 0 & \mu' \\ -M_{Z'} s_{\beta'} & \mu' & 0 \end{bmatrix}$$

- Gaugino lighter than Z': $m_M, M_{Z'} << \mu'$

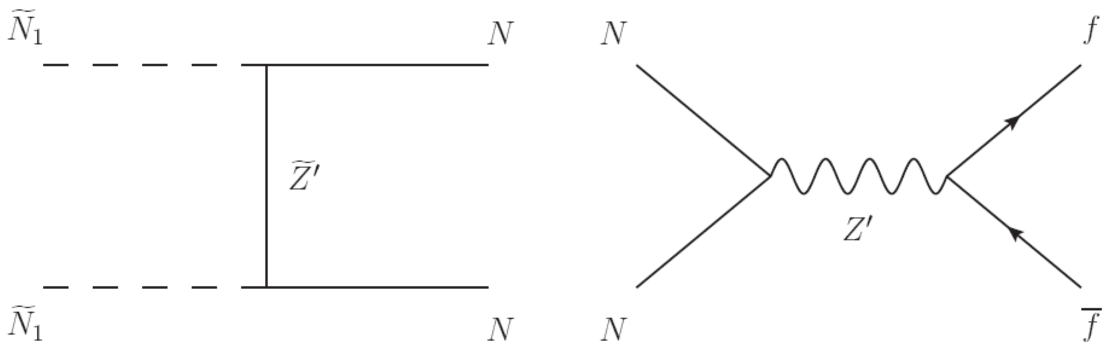
$$m_{\tilde{Z}'} \approx m_M - \frac{M_{Z'}^2}{\mu'} << 1TeV$$

# U(1)’ gauge interactions

| | | | |
|---|---|---|---|
| $\bar{f} f Z'$ | $ig'(Q'_{f_L} P_L - Q'_{f_R^\dagger} P_R)\gamma^\mu$ | $hAZ'$ | $-ig' Q'_{H_u} \sin(\alpha+\beta) q^\mu$ |
| $\tilde{f} \tilde{f}^* Z'$ | $ig' Q'_f q^\mu$ | $HAZ'$ | $ig' Q'_{H_u} \cos(\alpha+\beta) q^\mu$ |
| $\tilde{f}_L \bar{f} \tilde{Z}'$ | $-i\sqrt{2} g' Q'_{f_L} P_R$ | $H^+ H^- Z'$ | $ig' Q'_{H_u} q^\mu$ |
| $\tilde{f}_R \bar{f} \tilde{Z}'$ | $-i\sqrt{2} g' Q'_{f_R^\dagger} P_L$ | $hZZ'$ | $-i\sqrt{2} g' M_Z Q'_{H_u} \cos(\alpha+\beta) g^{\mu\nu}$ |
| $\tilde{N}_1 \tilde{N}_2 Z'$ | $ig' Q'_N q^\mu$ | $HZZ'$ | $-i\sqrt{2} g' M_Z Q'_{H_u} \sin(\alpha+\beta) g^{\mu\nu}$ |
| $\bar{N} \tilde{N}_1 \tilde{Z}'$ | $-ig' Q'_N P_R$ | $h \bar{\chi}_i^0 \tilde{Z}'$ | $-ig' Q'_{H_u} (N_{4i} \cos\alpha + N_{3i} \sin\alpha) P_R$ |
| $\bar{N} \tilde{N}_2 \tilde{Z}'$ | $g' Q'_N P_R$ | $H \bar{\chi}_i^0 \tilde{Z}'$ | $-ig' Q'_{H_u} (N_{4i} \sin\alpha - N_{3i} \cos\alpha) P_R$ |
| $S_{1,2} S^*_{1,2} Z'$ | $ig' Q'_{S_{1,2}} q^\mu$ | $A \bar{\chi}_i^0 \tilde{Z}'$ | $g' Q'_{H_u} (N_{4i} \cos\beta - N_{3i} \sin\beta) P_R$ |
| $\bar{\tilde{S}}_{1,2} \tilde{S}_{1,2} Z'$ | $ig' Q'_{S_{1,2}} \gamma^\mu$ | $H^+ \bar{\chi}_i^+ \tilde{Z}'$ | $-i\sqrt{2} g' Q'_{H_u} (V^*_{2i} \cos\beta\, P_R - U_{2i} \sin\beta\, P_L)$ |
| $S_{1,2} \bar{\tilde{S}}_{1,2} \tilde{Z}'$ | $-i\sqrt{2} g' Q'_{S_{1,2}} P_R$ | | |

# Thermal abundance of RHsN (I)

- RHsN annihilation to RHN; RHN to the usual thermal fermions:

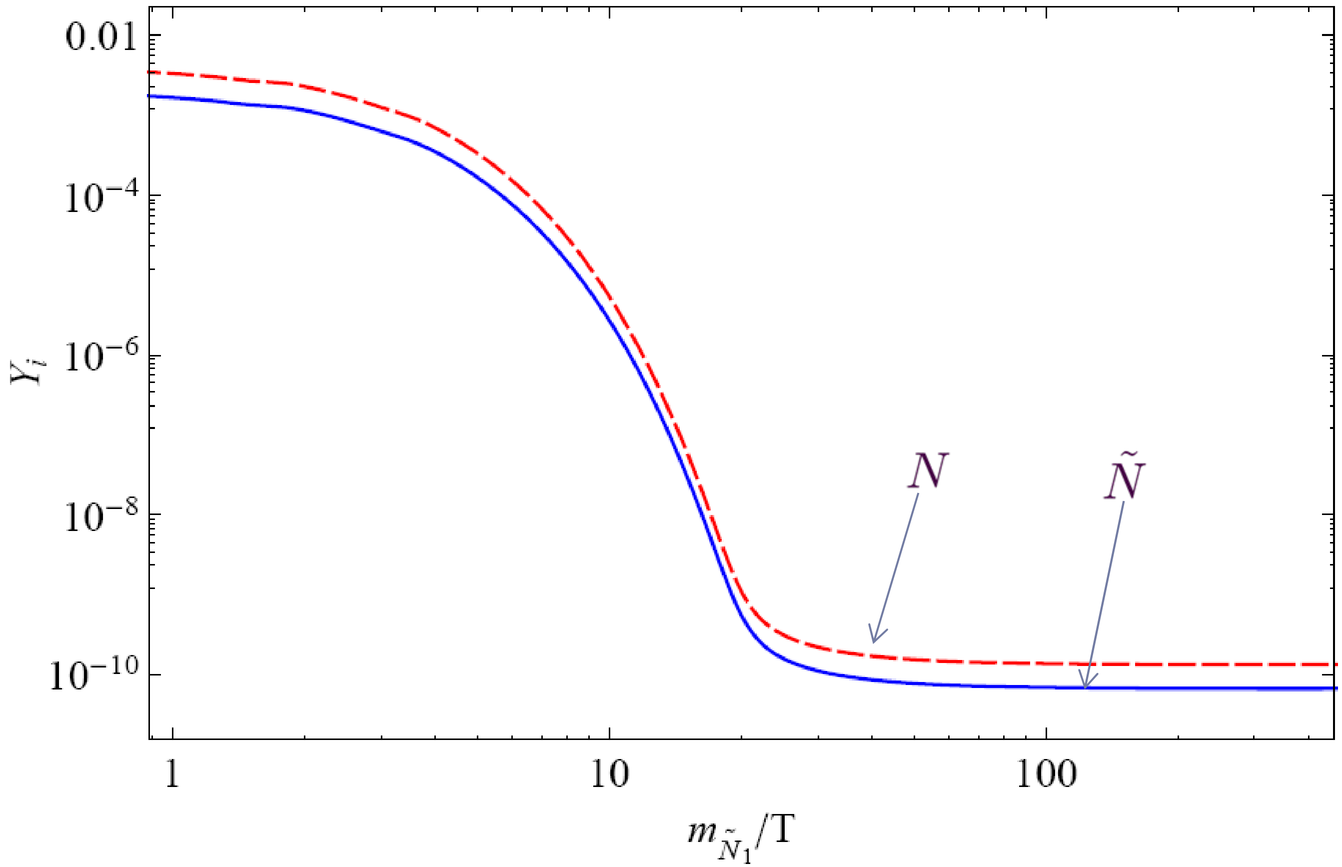



- Boltzmann equations to solve:

$$\frac{dn_{\widetilde{N}_1}}{dt} = -3Hn_{\widetilde{N}_1} - \langle \sigma_{\widetilde{N}_1} v_{\widetilde{N}_1} \rangle \left[ (n_{\widetilde{N}_1})^2 - \left( \frac{g_{\widetilde{N}_1}}{g_N} n_N \right)^2 \right]$$

$$\frac{dn_N}{dt} = -3Hn_N - \langle \sigma_N v_N \rangle \left[ (n_N)^2 - (n_N^{\rm eq})^2 \right] + \langle \sigma_{\widetilde{N}_1} v_{\widetilde{N}_1} \rangle \left[ (n_{\widetilde{N}_1})^2 - \left( \frac{g_{\widetilde{N}_1}}{g_N} n_N \right)^2 \right]$$

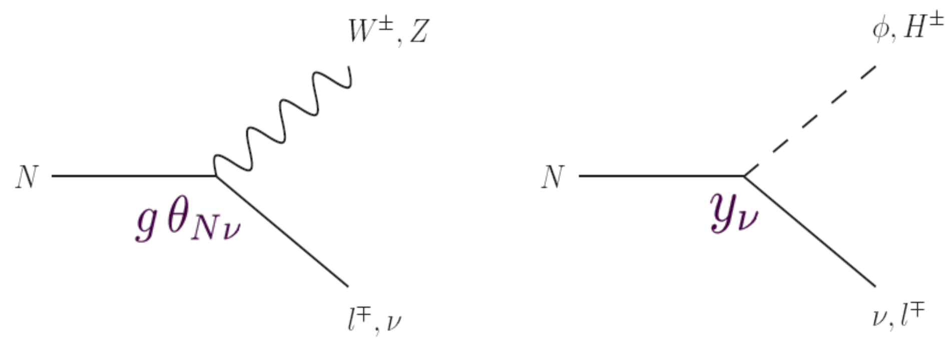
# Solution (I): too large!

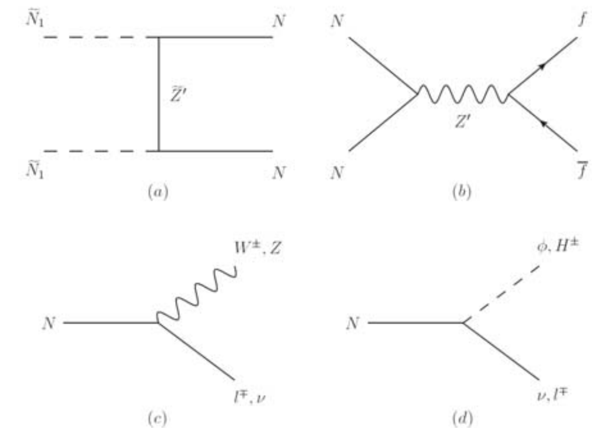



$$m_{\tilde{Z}'} = 600\mathrm{GeV},\ m_{Z'} = 1200\mathrm{GeV}$$

# Thermal abundance of RHsN (II)

- Include the decay and inverse-decay of RHN:




- Boltzmann equations:

$$\frac{dn_{\tilde{N}_1}}{dt} = -3Hn_{\tilde{N}_1} - \langle \sigma_{\tilde{N}_1} v_{\tilde{N}_1} \rangle \left[ (n_{\tilde{N}_1})^2 - \left( \frac{g_{\tilde{N}_1}}{g_N} n_N \right)^2 \right]$$

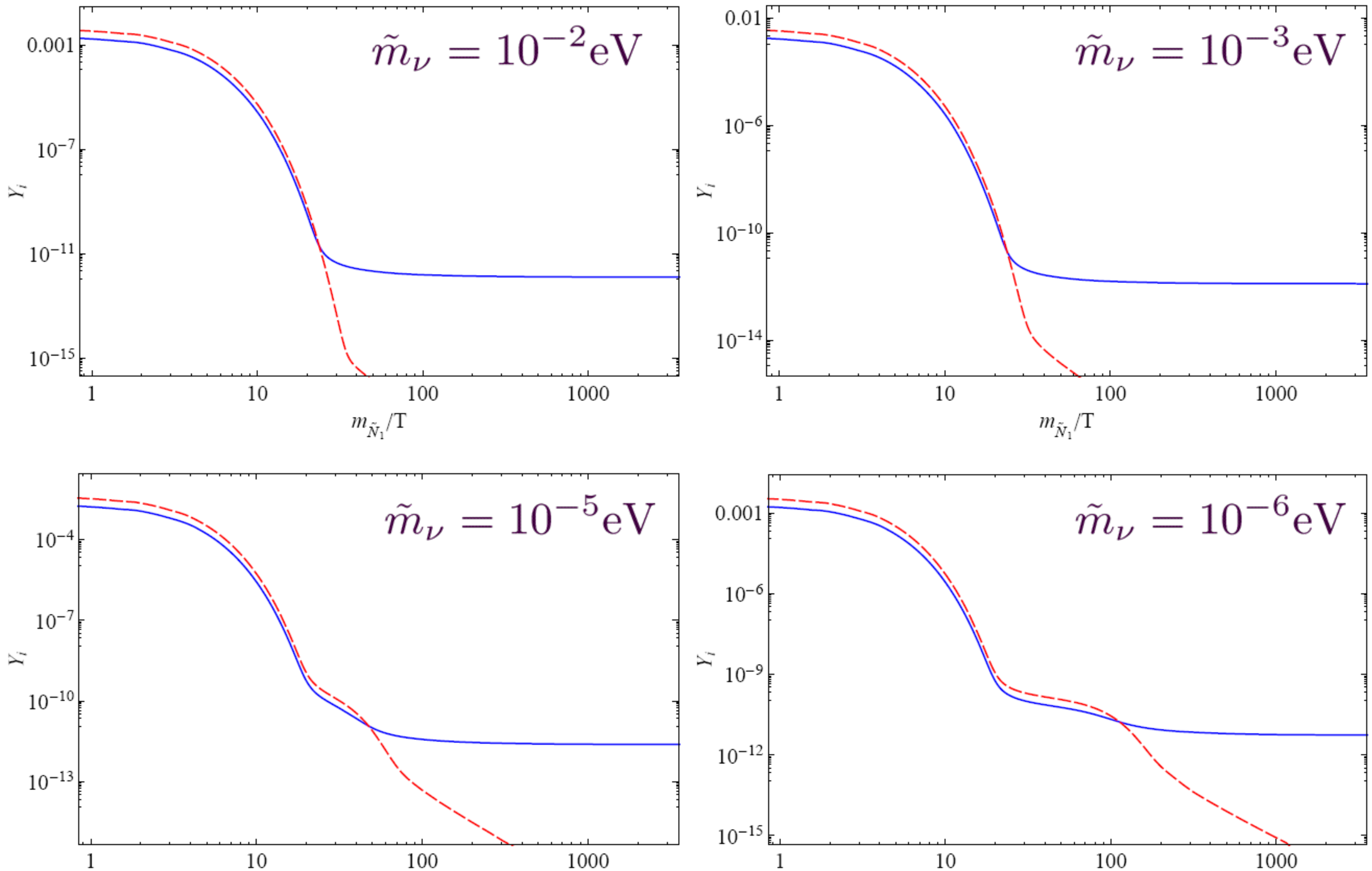
$$\frac{dn_N}{dt} = -3Hn_N - \langle \sigma_N v_N \rangle \left[ (n_N)^2 - (n_N^{\rm eq})^2 \right] + \langle \sigma_{\tilde{N}_1} v_{\tilde{N}_1} \rangle \left[ (n_{\tilde{N}_1})^2 - \left( \frac{g_{\tilde{N}_1}}{g_N} n_N \right)^2 \right]$$
$$- \Gamma_N (n_N - n_N^{\rm eq}) \, ,$$

# Solution (II)

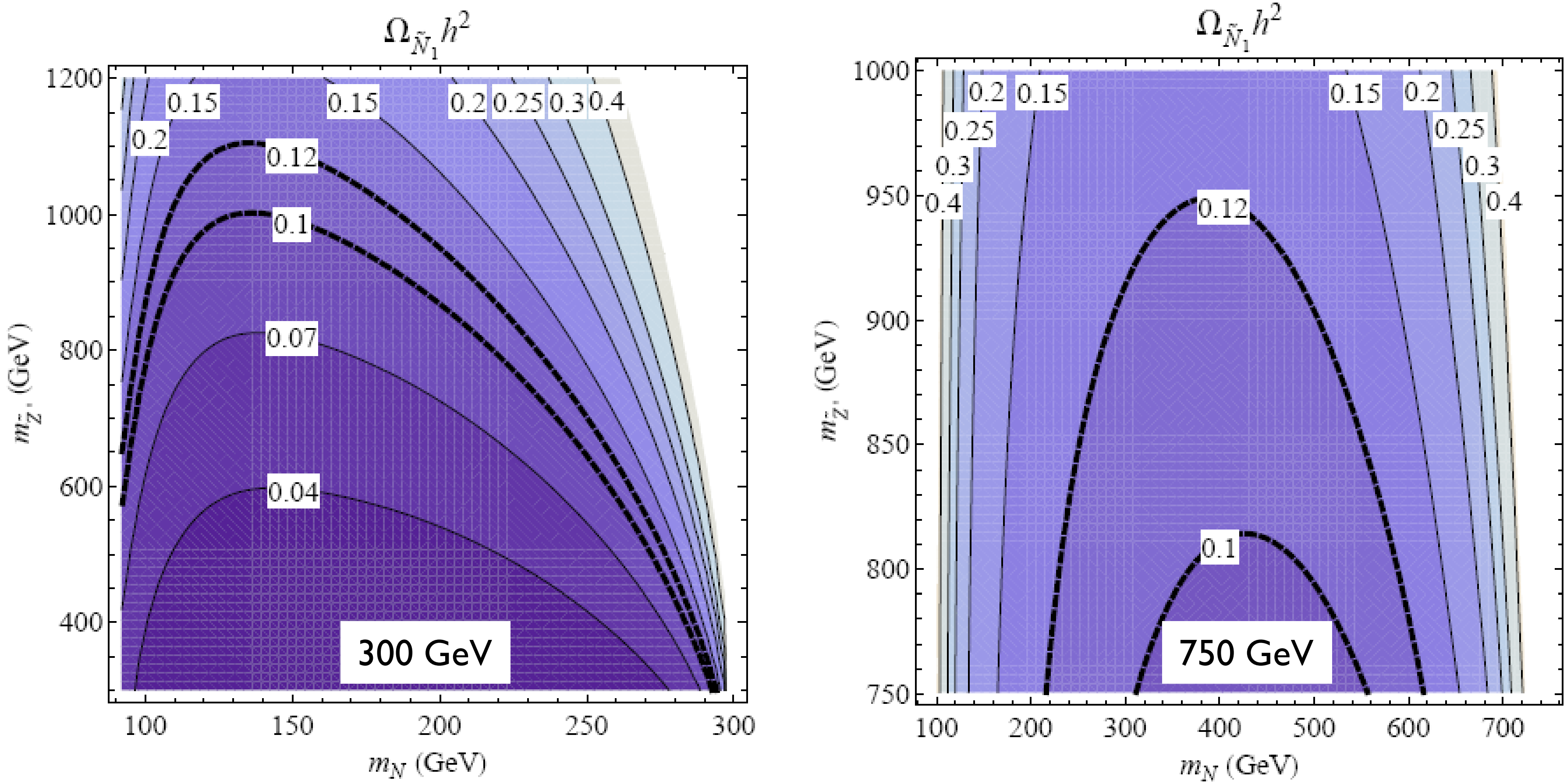
- Although suppressed by small Yukwas $y_\nu \sim 10^{-6}$, the decay and inverse-decay processes maintain in thermal equilibrium longer the RHN and thus also the RHsN.
- The RHsN DM relic density can be in the right range unless $y_\nu$ is small.
- To see a peculiar dependence on $y_\nu$ , define an effective neutrino mass:

$$\tilde{m}_\nu \equiv \frac{|y_\nu|^2 v^2}{M}$$

# Decay/inverse-decay effect

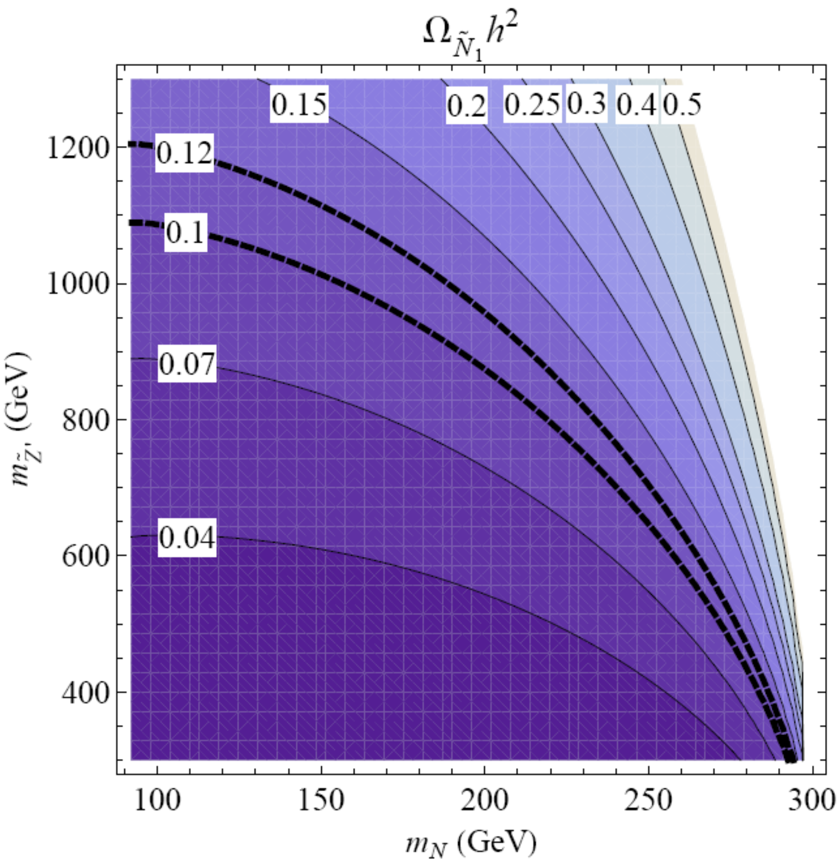


# DM mass dependence $\tilde{m}_\nu = 10^{-3}\text{eV},\ m_{Z'} = 1.2\text{TeV}$

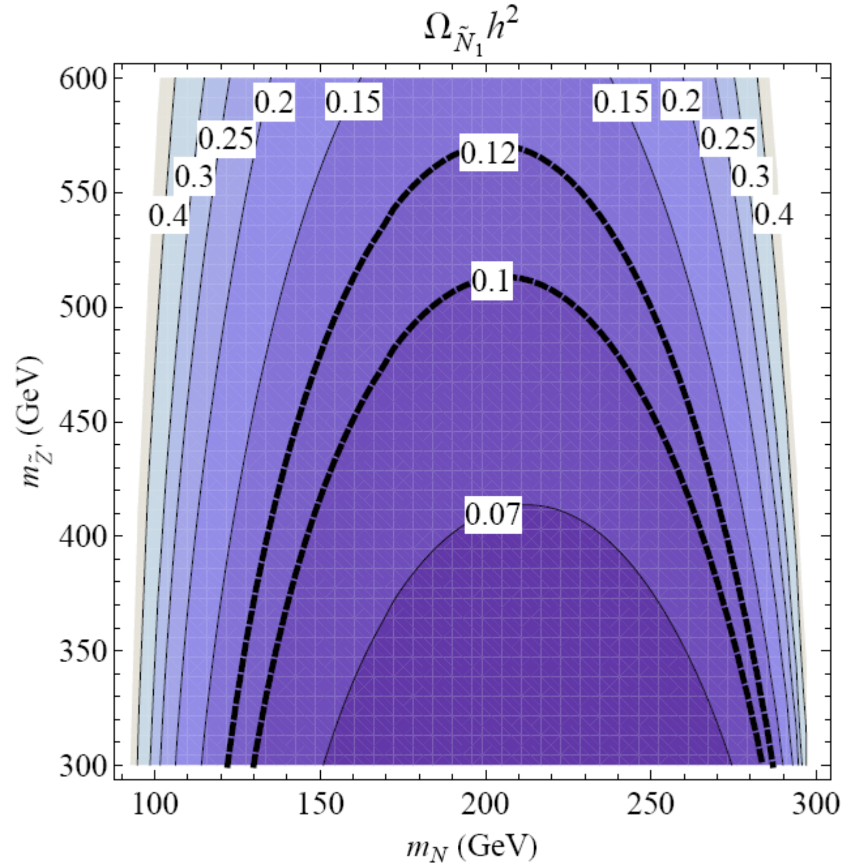


# Dependency on $y_\nu$

$m_{\tilde{N}_1} = 300\text{GeV},\ m_{Z'} = 1.2\text{TeV}$

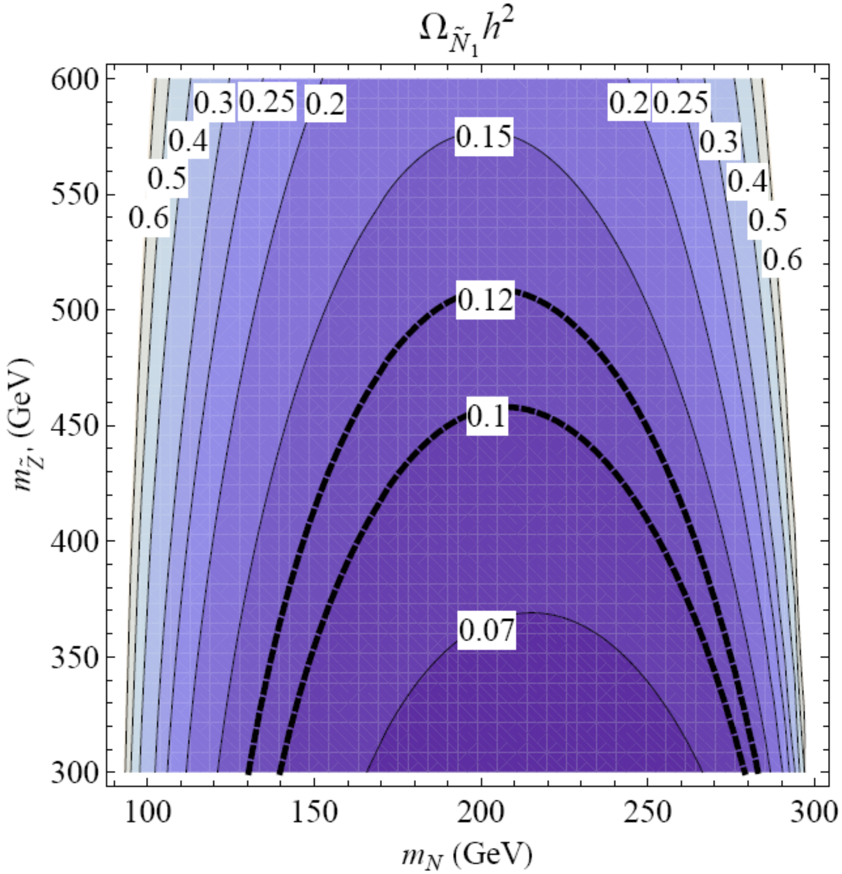



$\tilde{m}_\nu = 10^{-1}\text{eV}$

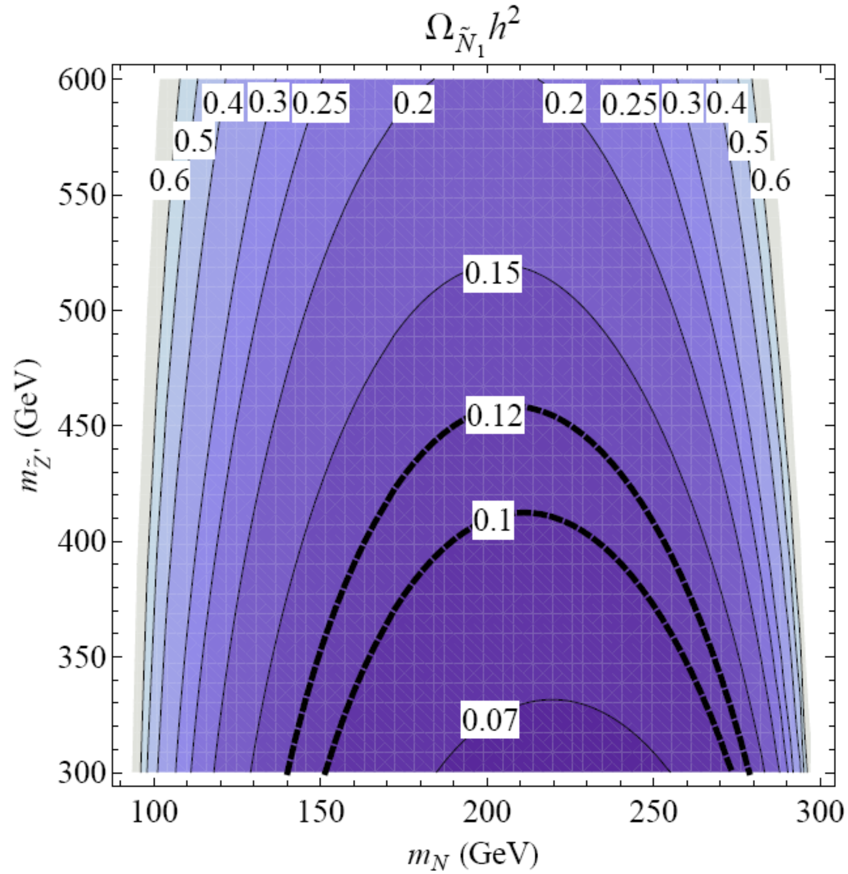



$\tilde{m}_\nu = 10^{-5}\text{eV}$

# Dependency on Z' mass $m_{\tilde{N}_1} = 300\text{GeV},\ \tilde{m}_\nu = 10^{-3}\text{eV}$




$m_{Z'} = 2\text{TeV}$

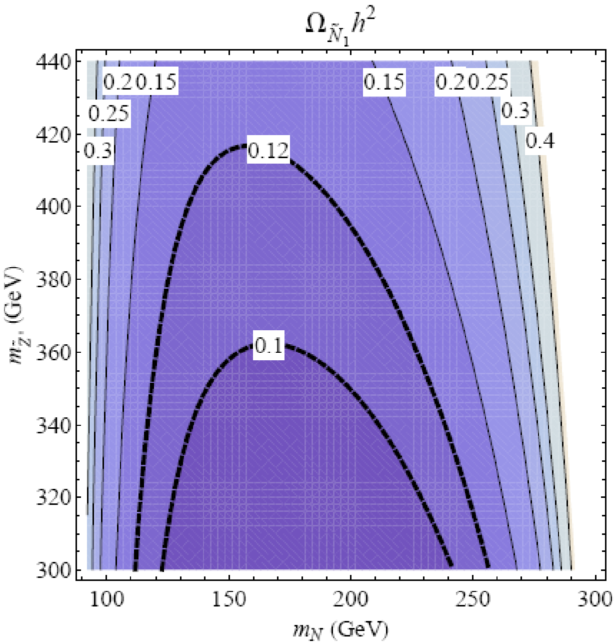



$m_{Z'} = 4\text{TeV}$

# Dependency on g'

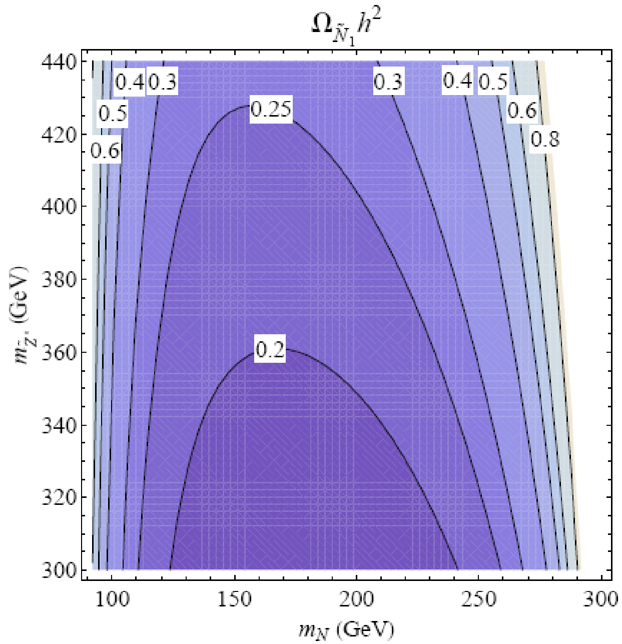
$m_{Z'} = 1.2\text{TeV},\ \tilde{m}_\nu = 10^{-3}\text{eV}$

$$g'_{\text{standard}} = \sqrt{5/3}g_2 \tan\theta_W = 0.46$$



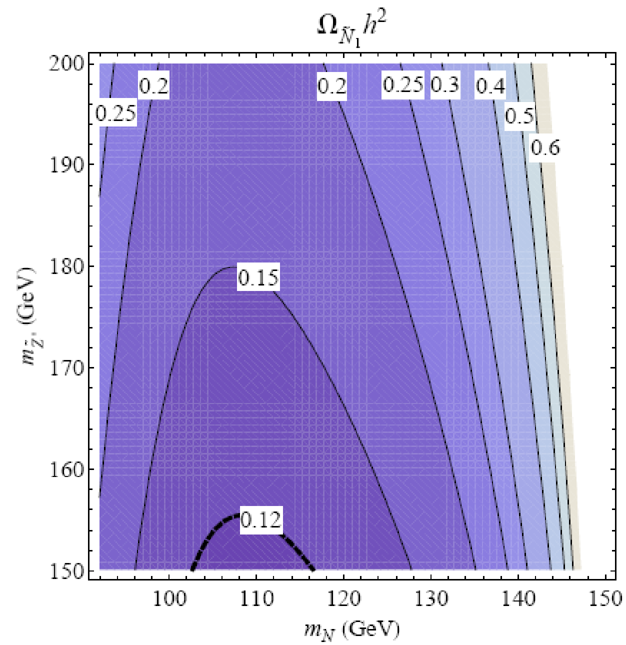

$g' = 0.3$

$m_{\tilde{N}_1} = 300\text{GeV}$




$g' = 0.25$

$m_{\tilde{N}_1} = 300\text{GeV}$




$\boxed{g' = 0.2}$

$m_{\tilde{N}_1} = 150\text{GeV}$

# LHC signatures

- Discover RHN: SSD and/or displaced vertices

$$pp \to Z' \to NN \to l^\pm l^\pm W^\mp W^\mp (4j)$$

$$N \to lW, \nu Z, \nu h, \nu H, \nu A, lH^+$$

Probe Majorana nature of neutrino

- Similar with large missing $E_T$:

$$pp \to \tilde{Z}'\tilde{Z}' \to NN\tilde{N}_1\tilde{N}_1 \to l^\pm l^\pm 4j + \not{E}_T$$

- Probe the Higgs channel(s) (with MET)?

$$pp \to Z'(\tilde{Z}'\tilde{Z}') \to l^\pm W^\mp \nu h \ (+\not{E}_T)$$
$$\to l^\pm W^\mp l^\pm H^\mp \ (+\not{E}_T)$$

# Discovery channels

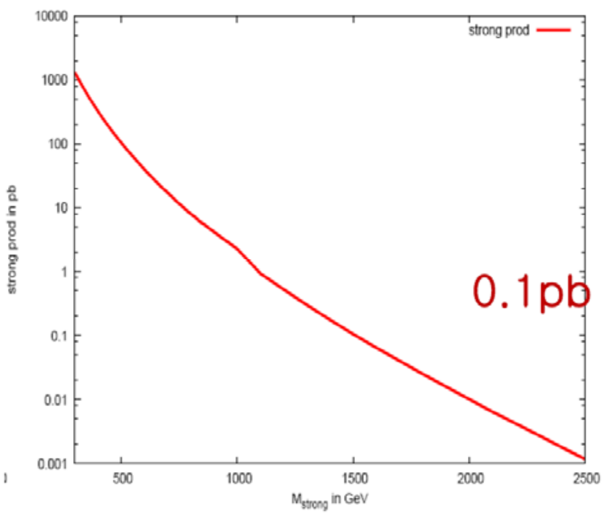
$$\tilde{q} \to q\bar{\tilde{Z}}_{B-L}$$

$$\to N\tilde{N}$$

$$\to \nu h, l^{\pm}W^{\mp}, \nu Z$$

$$\to b\bar{b}$$

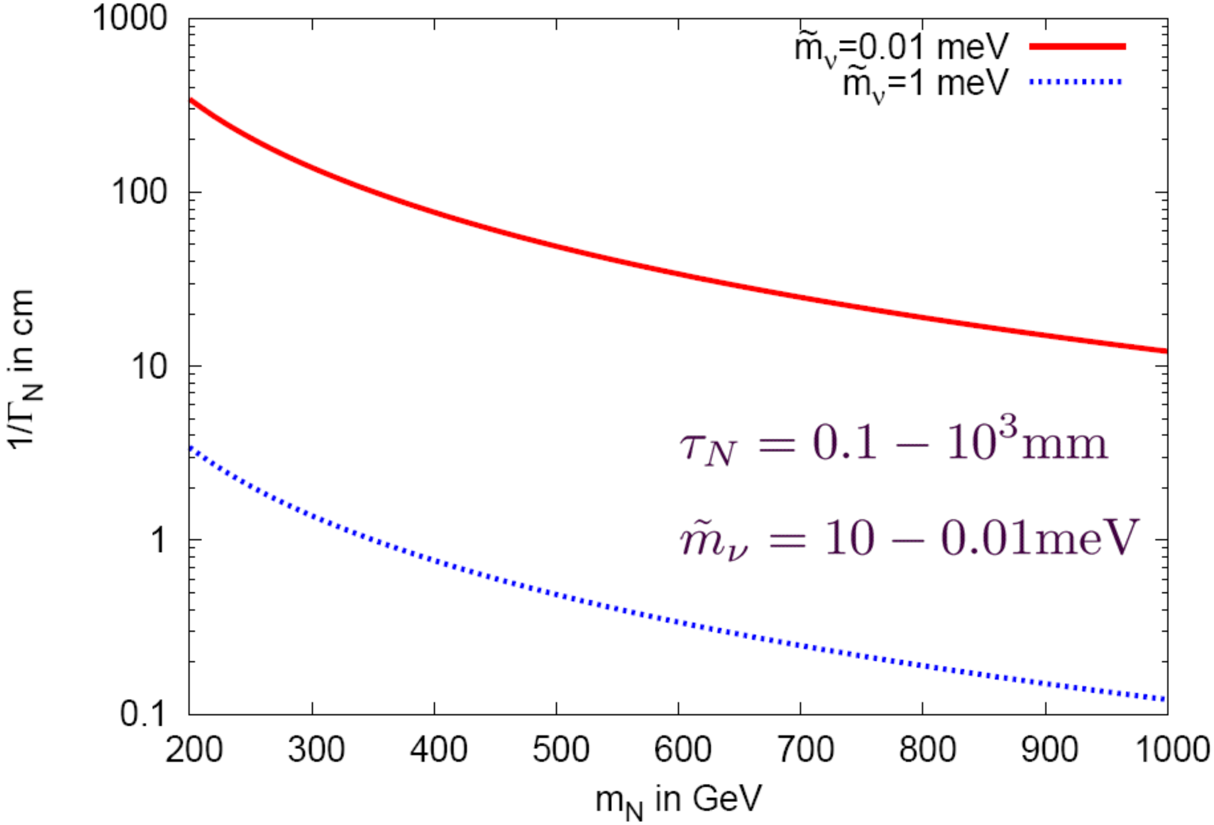
Dijet, same-sign dilepton, MET
Dijet, displaced b-jet(s), MET




0.1pb for $m_{squark}$=1.5 TeV

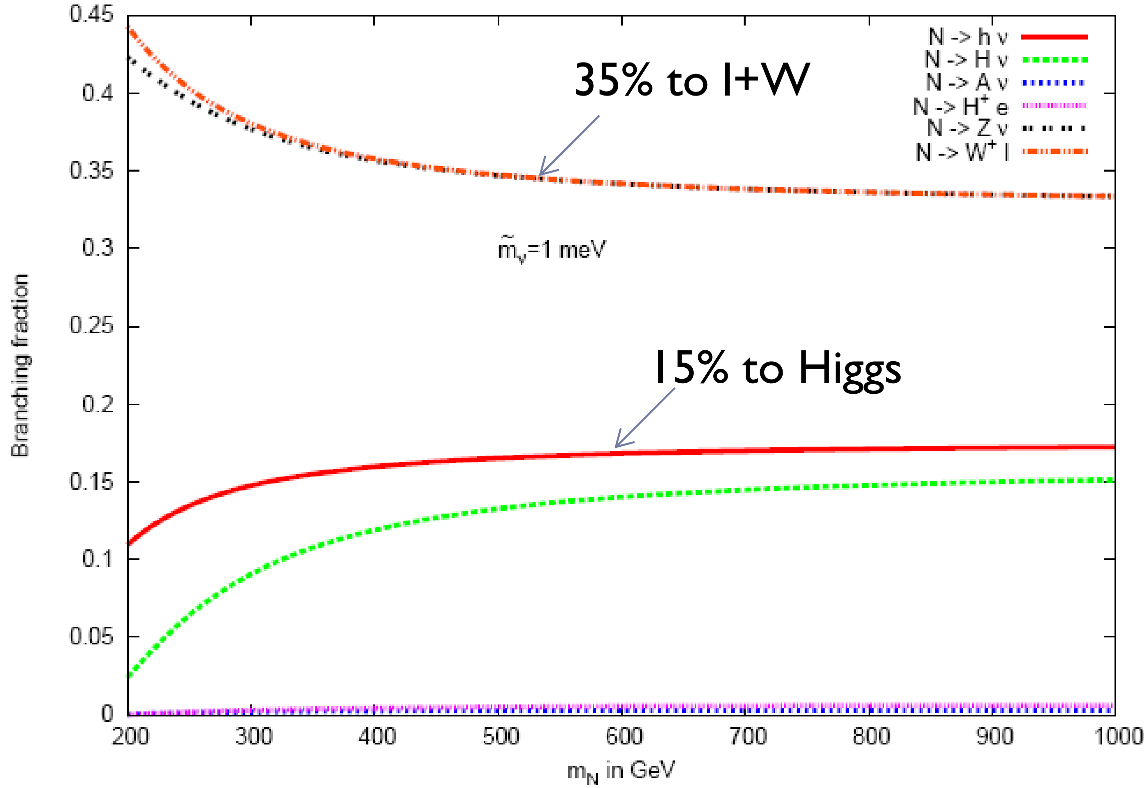
$\tau$=0.2cm
for $m_\nu=10^{-3}$eV and $m_N$=200GeV

# Displaced vertex



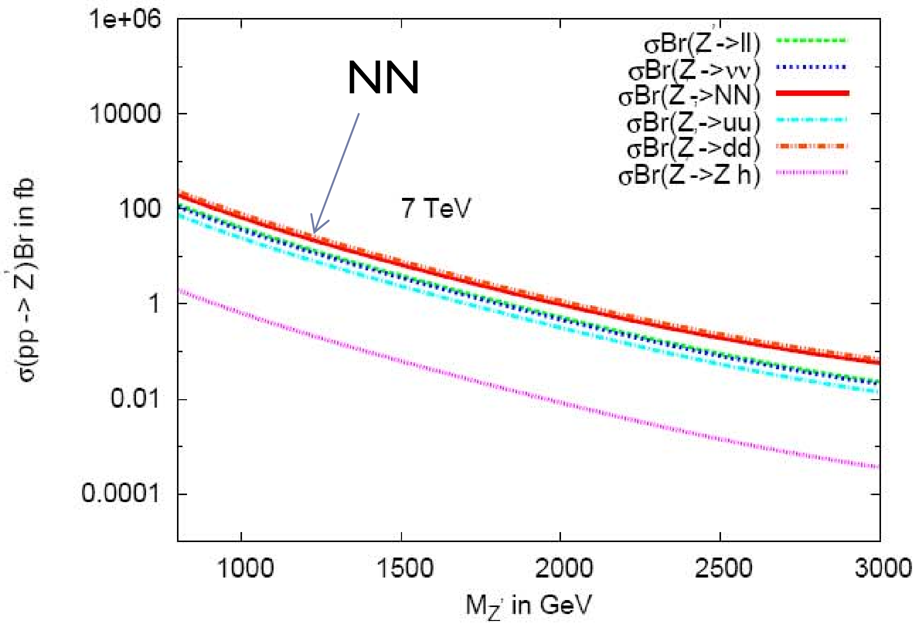

$$\Gamma_N \sim y_\nu^2 m_N \sim \tilde{m}_\nu m_N^2 / v$$

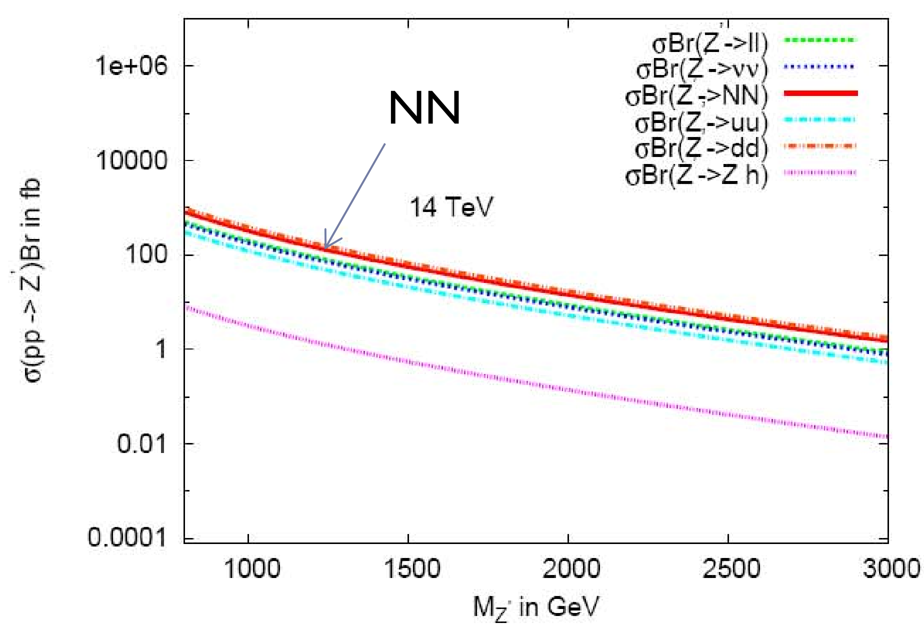
# N decay branching fraction



# Z' production and decay

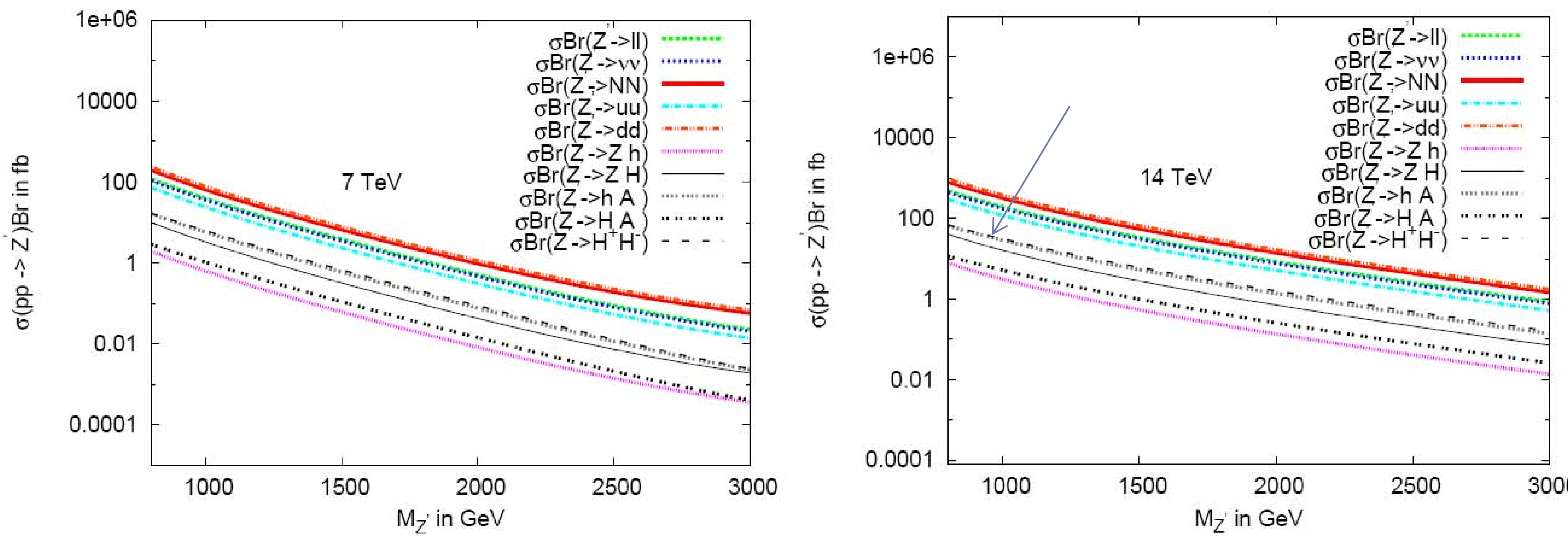
Heavy Higges decoupled



# Z' production and decay at LHC

Heavy Higges non-decoupled




$$m_A = 162\mathrm{GeV},\ m_{H^\pm} = 180\mathrm{GeV},\ m_H = 164\mathrm{GeV}$$

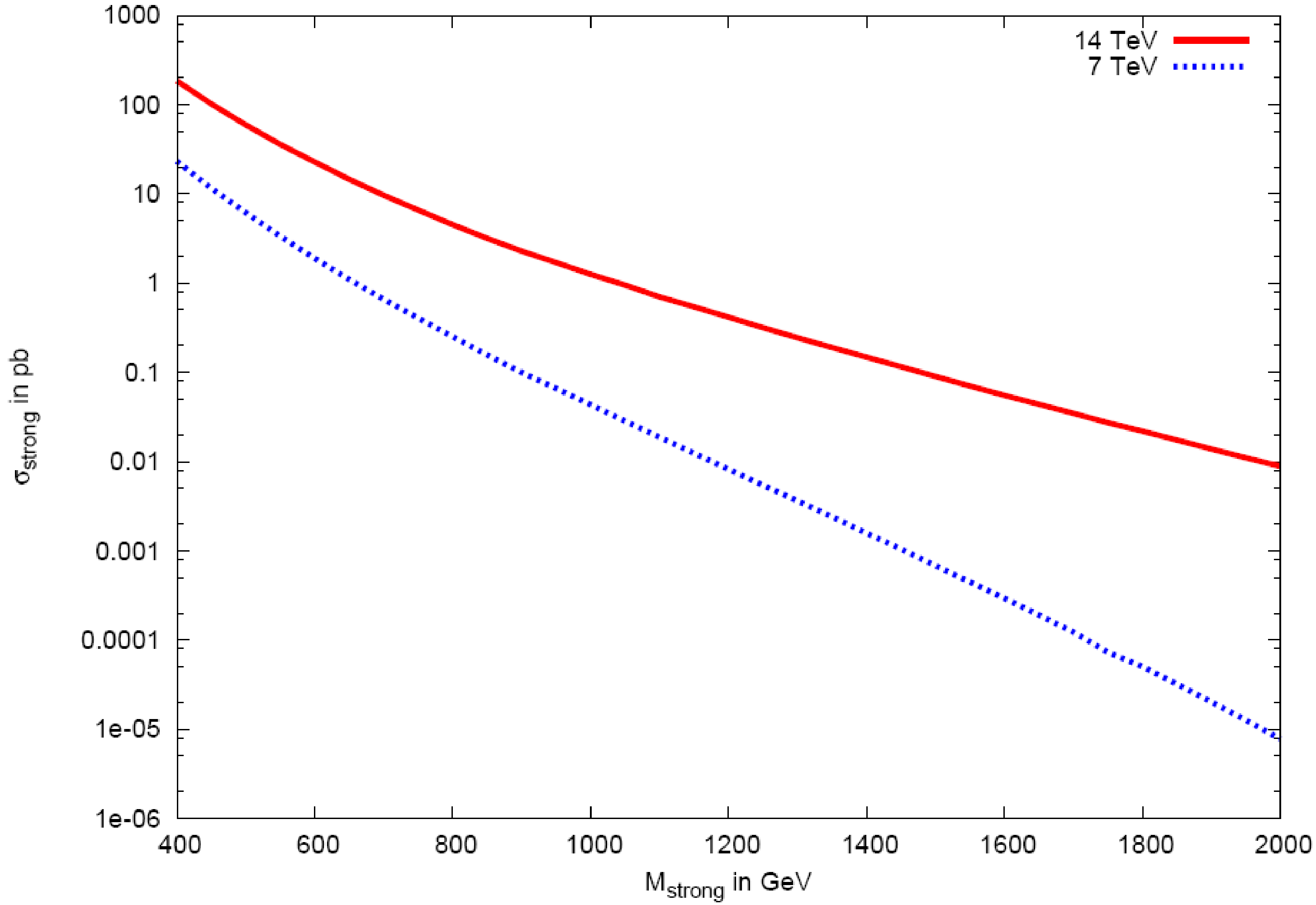
# U(1)' gaugino production

- Cascade decay from gluinos/squarks:

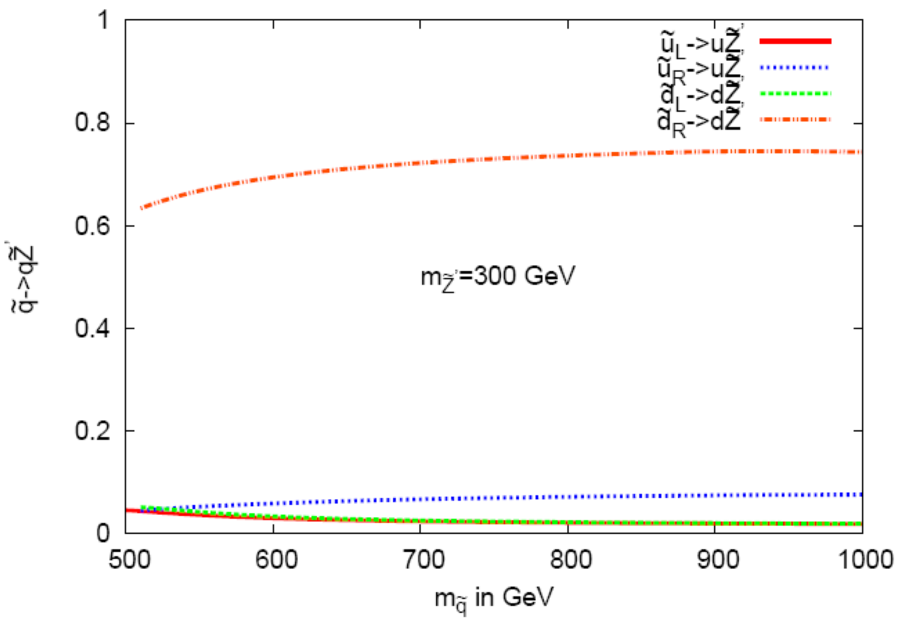
$$pp \to \tilde{q}\tilde{q} \to qq\tilde{Z}'\tilde{Z}' \to qqNN\tilde{N}_1\tilde{N}_1$$

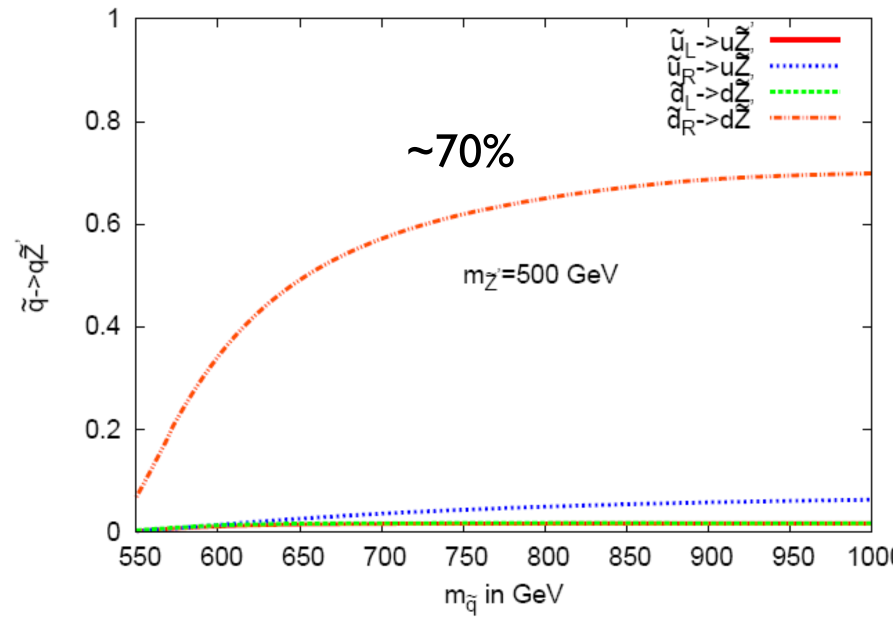
- Maximied if U(1)' gaugino is the NLSP.

# Cascade production of U(1)' gaugino



# Squark decay to U(1)' gaugino



# Discovery prospect: rough numbers

- SSD channel: BR(NN-> l l W W)~12%
- Higgs channel: BR(NN-> h$\nu$ l W)~10% .
- For U(1)' gaugino as NLSP:

LHC7

$$\sigma(pp \to Z' \to NN) \approx 10 \text{ fb for } m_{Z'} = 1.5 \text{ TeV}$$

$$\sigma(pp \to \tilde{Z}'\tilde{Z}' \to NN) \approx 1 \text{ fb for } m_{\text{strong}} = 1.5 \text{ TeV}$$

$$\Rightarrow \sigma(hlW(+MET)) \approx 1\ (0.1) \text{ fb}$$

LHC14

$$\Rightarrow \sigma(hlW(+MET)) \approx 10\ (10) \text{ fb}$$

- Needs a careful background study.

# Conclusion

- RHsN: a good dark matter candidate in U(1)' seesaw.
- Right freeze-out relic density from U(1)' gaugino exchange + Z' scattering, decay and inverse-decay of the RHN.
- Unique LHC signatures: SSD w/ and w/o MET.
- Probe the Higgs channel, h → bb, associated with lepton+W, in particular, at displaced vertices.