Collider physics of sneutrino dark matter

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work in progress
with S. Chang and N. Weiner

Nice things about susy

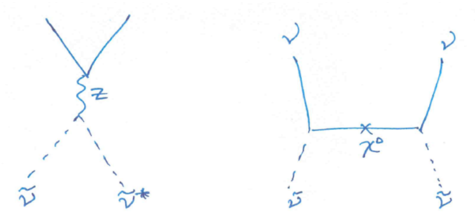
- Solves hierarchy problem

- Gauge coupling unification

- Dark matter from R-parity: obvious candidates are neutralino and sneutrino.

What's wrong with sneutrino dark matter?

- Sneutrinos annihilate rapidly in the early universe.



- To get interesting abundance, need $M_{\tilde{\nu}}$ < few GeV or > 600 GeV

  Hagelin, Kane, Raby; Ibanez   Falk, Olive, Srednicki

- Direct detection experiments rule out $M_{\tilde{\nu}} > 10$ GeV

- Z-width constraint rules out $M_{\tilde{\nu}} < 45$ GeV

One way to save sneutrino dark matter

Arkani-Hamed, Hall, Murayama, Smith,Weiner

- Adopt framework with Dirac neutrino masses (so introduce chiral superfields N).

- Include a weak-scale A-term $A_\nu LNH_u$

$$M^2_{\tilde{\nu}} = \begin{pmatrix} M_L^2 + \frac{1}{2}\cos 2\beta\, M_Z^2 & A_\nu\, v \sin\beta \\ A_\nu\, v \sin\beta & M_R^2 \end{pmatrix}$$

$$\tilde{\nu}_1 = -\sin\theta\,\tilde{\nu} + \cos\theta\,\tilde{n}^*$$

$$\tilde{\nu}_2 = \cos\theta\,\tilde{\nu} + \sin\theta\,\tilde{n}^*$$

- Assume no NN term in superpotential.

- Why are neutrino masses so small? Could be related to susy breaking.

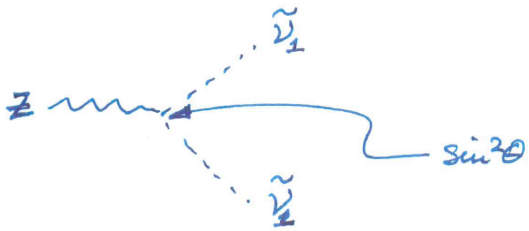
$$[X^\dagger L H_u N]_D$$

$$[\bar{X} L H_u N]_F$$

Give neutrino masses, A term, once X develops F-term vev.

Implications for dark matter

- Z-width constraint:



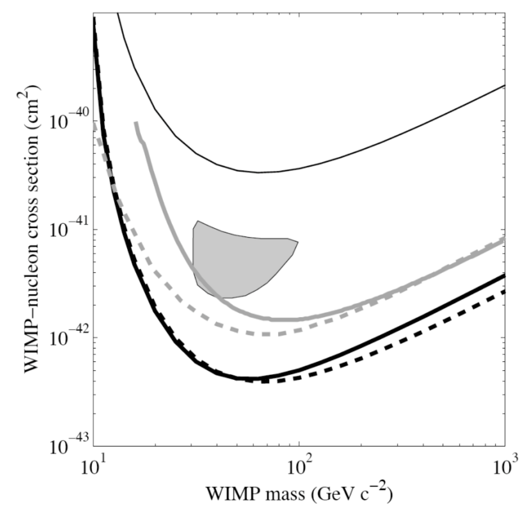
$$\delta\Gamma = \frac{\sin^4\theta}{2}[1-(2m_{\tilde{\nu}_1}/m_z)^2]^{3/2}\Gamma_\nu < 2\ \mathrm{MeV}$$

- If $\sin\theta < 0.4$ no constraint on mass -- light sneutrino dark matter opens up as possibility.

- Rate for direct detection (via Z-exchange) is

$$\sigma = \frac{G_F^2}{2\pi}\mu^2\left((A-Z)-(1-4\sin^2\theta_W)Z\right)^2 \times \sin^4\theta$$

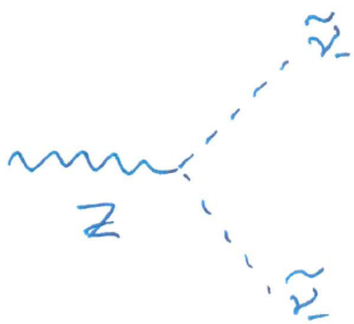
If $\sin^4\theta < 0.11$, no constraint on mass . . .



CDMS collaboration, Phys.Rev.D73:011102,2006

Mass splittings and inelastic scattering

- A small lepton-violating mass term $\tilde{n}\tilde{n}$ will introduce a mass splitting between the CP-even and CP_odd parts of $\tilde{\nu}_1$



does not exist

- If mass splitting is greater than ~20 keV, scattering is strongly suppressed.

Abundance for light sneutrino

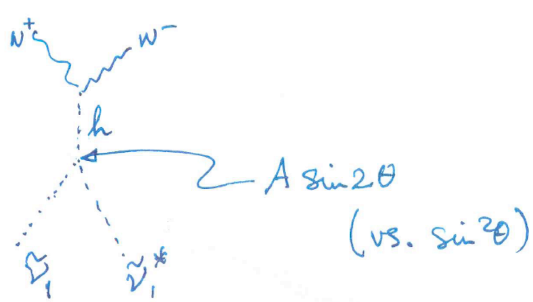
Assume t-channel Wino exchange dominates:

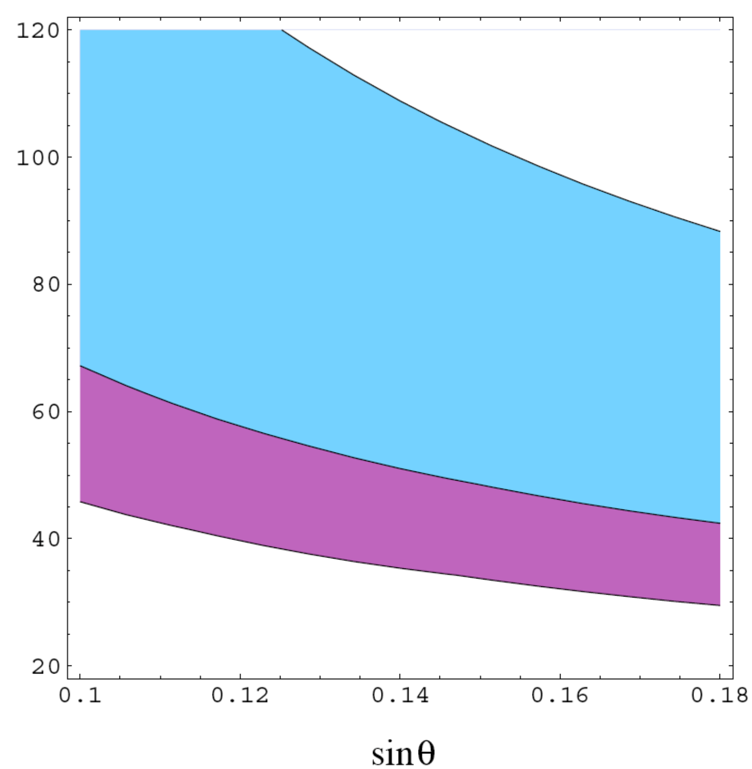
$$\Omega_{\tilde{\nu}_1} h^2 \approx \left(\frac{M_{\tilde{W}}}{100\text{GeV}}\right)^2 \left(\frac{0.19}{\sin\theta}\right)^4$$

Rather constrained . . .

Abundance for heavier sneutrino

- Higgs-mediated annihilations can help get rid of sneutrinos





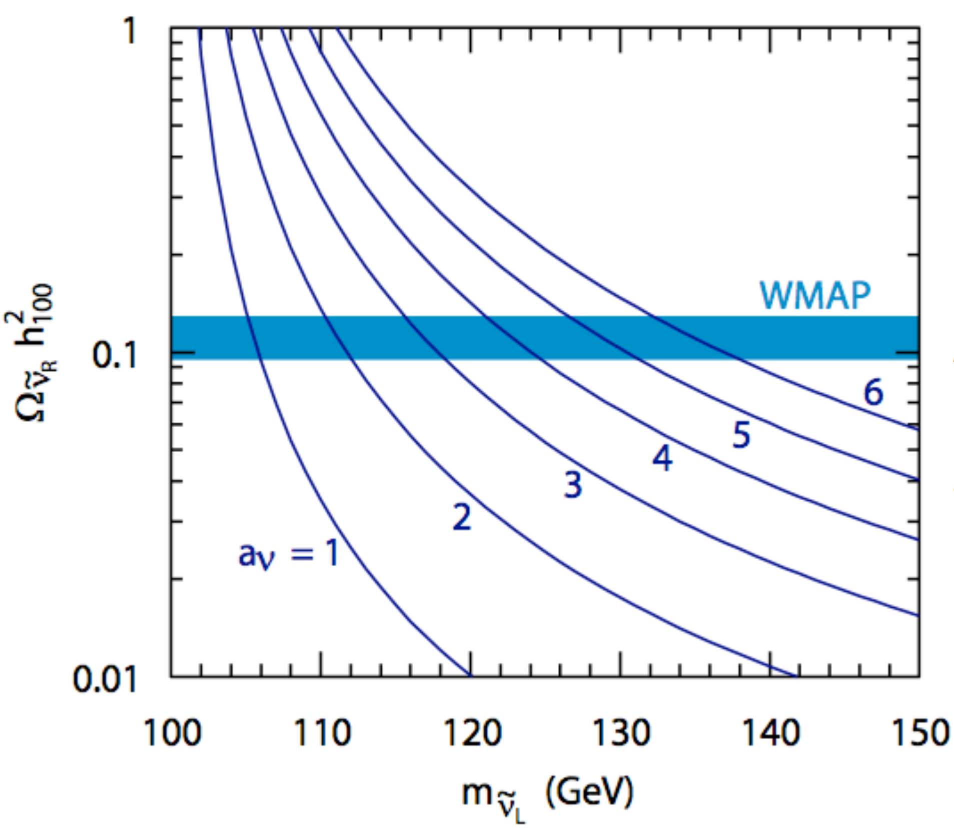
$m_{\tilde{\nu}_1} = 100$ GeV

Another possibility

- Tiny A-terms and non-thermal production

Asaka, Ishiwata, and Moroi

Gopalakrishna, de Gouvea, and Porod



$m_{\tilde{\nu}_L} = 100$ GeV

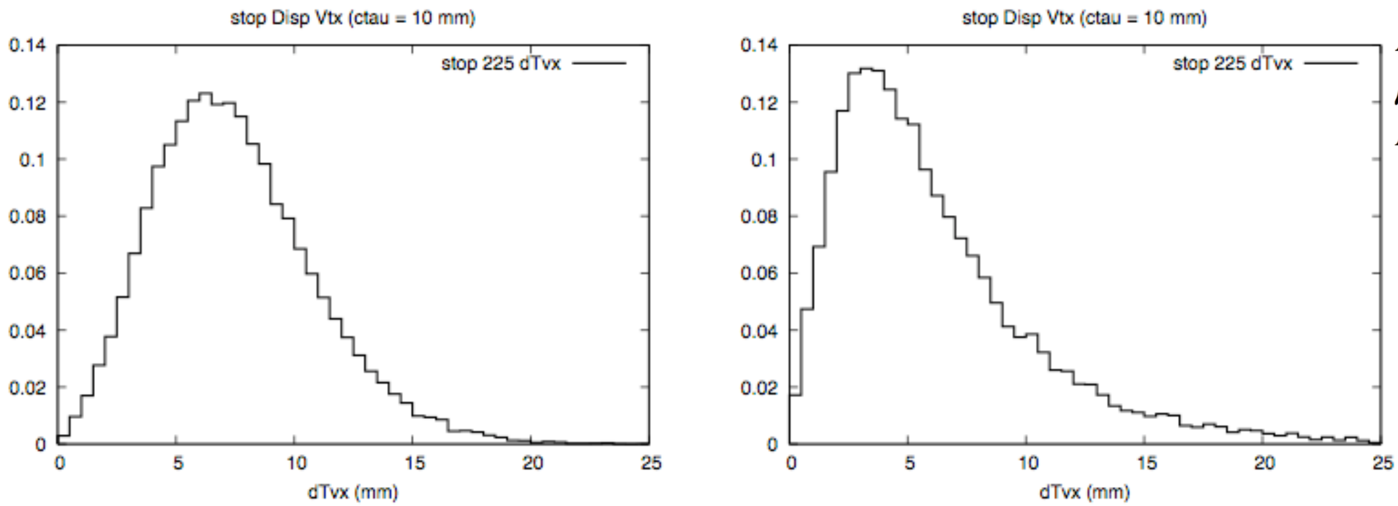
$\mu = 150$ GeV

$m_{\tilde{W}} = 300$ GeV

Asaka, Ishiwata, and Moroi

- Displaced vertices from nlsp stops?

de Gouvea and Gopalakrishna



$M_{\tilde{t}_R} = 225$ GeV
$\mu = 250$ GeV
$M_{\tilde{\nu}_R} = 100$ GeV
$\lambda_\nu = 10^{-6}$

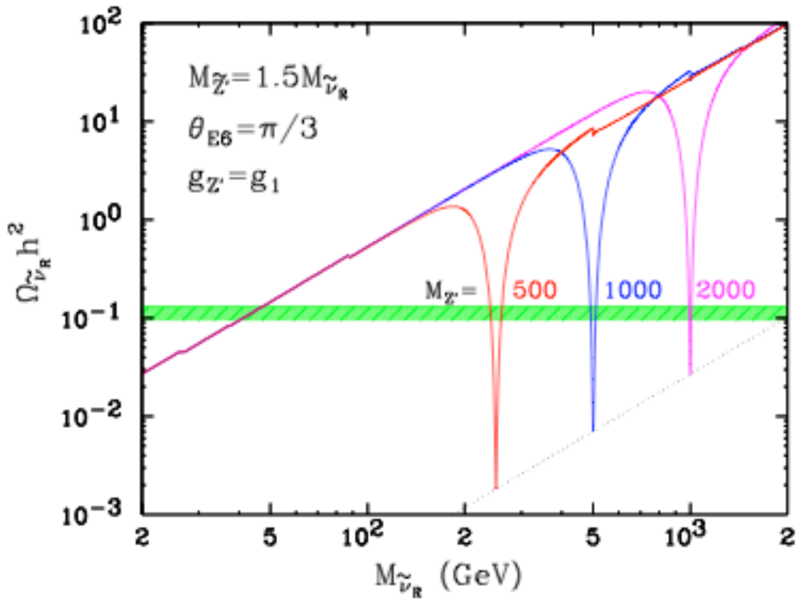
FIG. 4: The distributions of the transverse displacement of the stop (in mm), at the Tevatron (left) and the LHC (right).

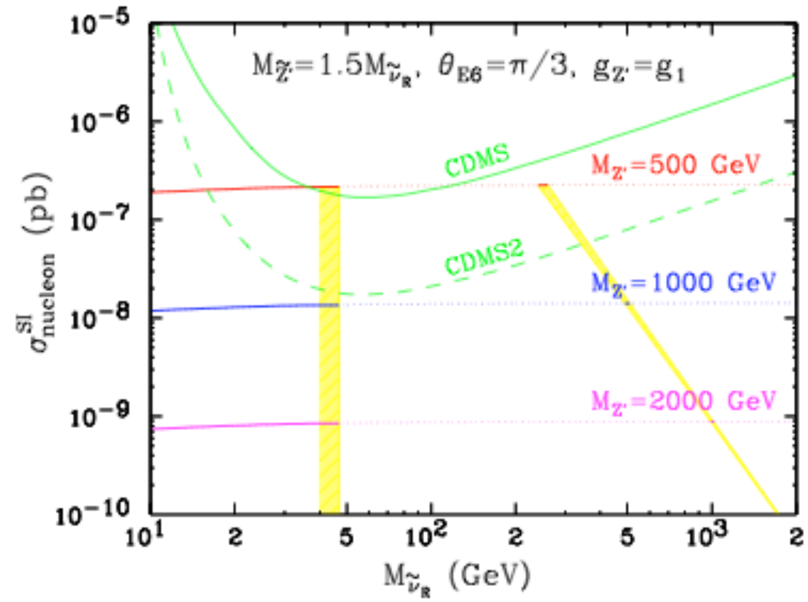
- Or, tracks from nlsp staus? Gupta, Mukhopadhyaya, Kumar Rai

Another possibility

- Tiny A-terms, thermalization via an extra U(1) gauge boson.

Lee, Matchev, Nasri

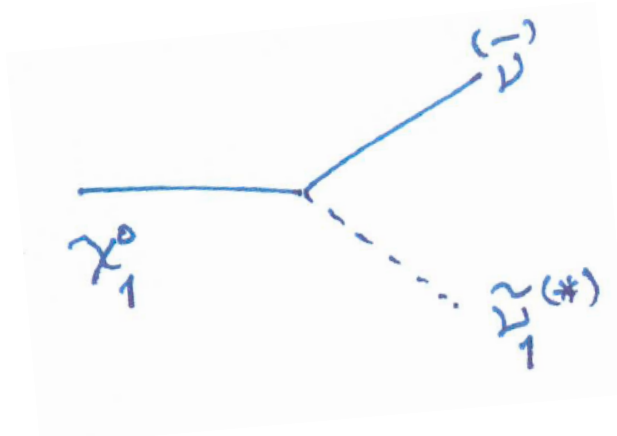




Back to mixed sneutrino lsp: collider signatures?

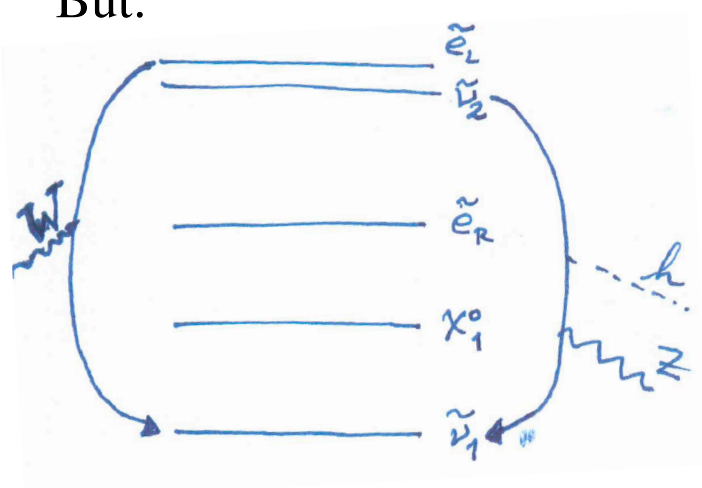
- Two ways to produce rh sneutrinos:
  - (1) in the decays of the NLSP
  - (2) in the decays of heavier particles
- If $\theta \ll 1$, only (1) matters.
- (2) may give more direct information about A, θ, and possibly more characteristic signatures.

χ_1^0 NLSP



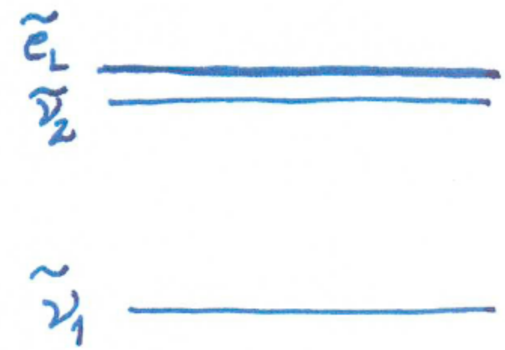
- Get no information from NLSP decays.

- But:

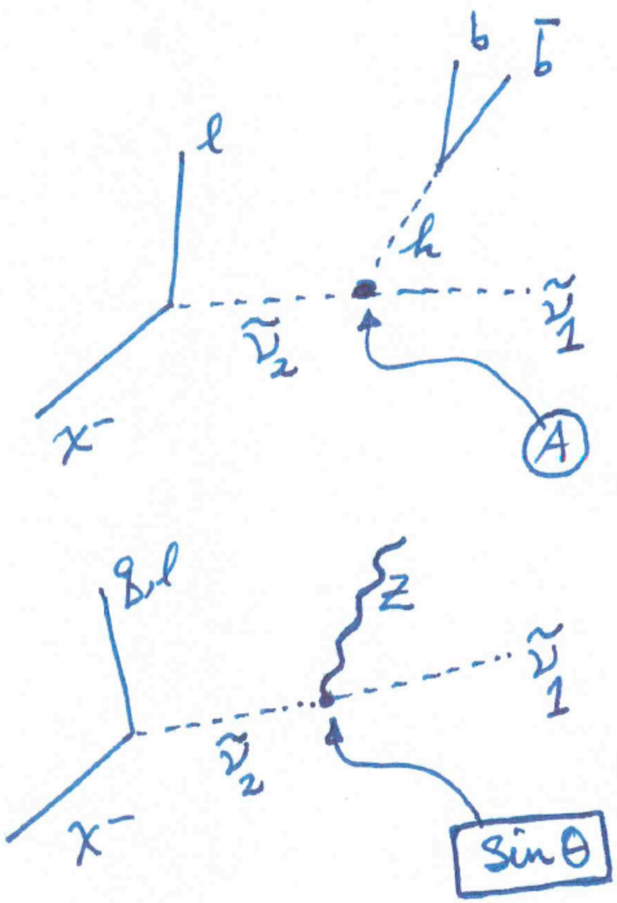


. . . can be competitive, depending on parameters

$\tilde{\nu}_2$ NLSP



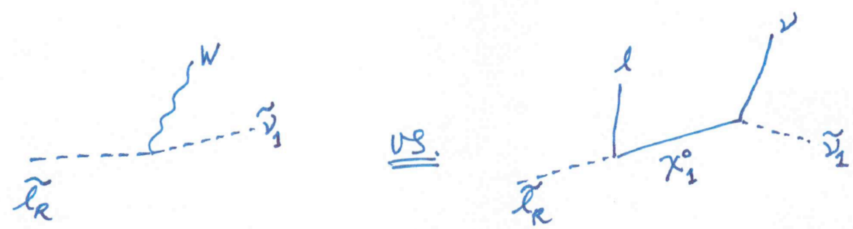
- Now NLSP decays are very interesting:

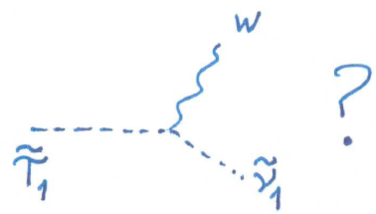


$\tilde{l}_R$ NLSP

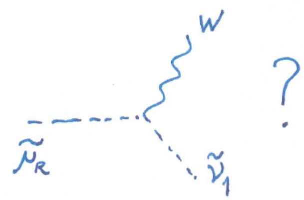
- Take to be nearly degenerate:

- An important competition:

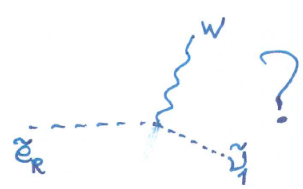




Quite possible, depending on lsp flavor(s), $\tan\beta$, etc.



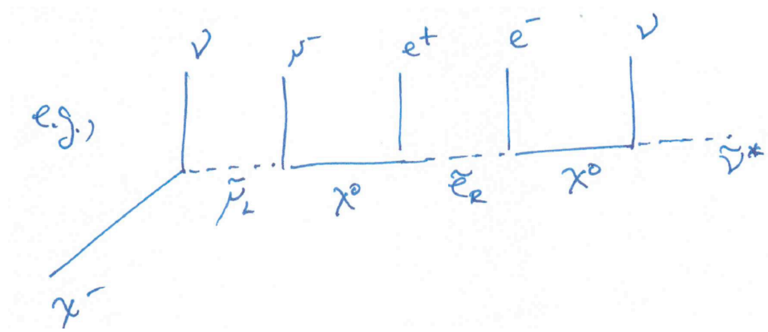
Much less likely, but not insignificant at large $\tan\beta$



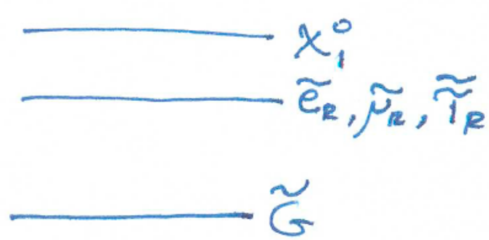
Ignore.

Signals?

- Lots of leptons.



- Other ways to get lots of leptons?

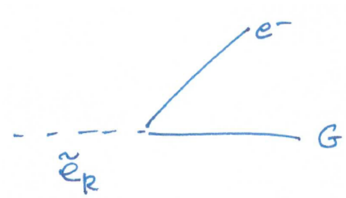


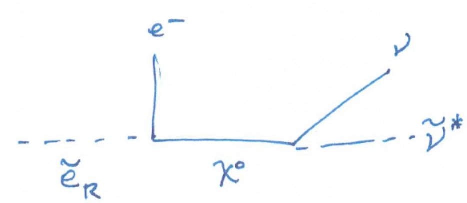
Assume prompt decay (low $\sqrt{F}$)

How to distinguish?

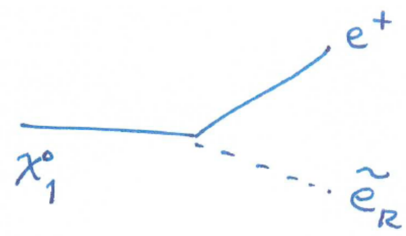
- Can look for evidence for direct decays of non-NLSP to LSP.

- Or, can try to use NLSP decays alone.

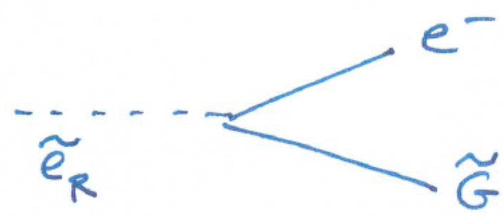
Just replacing 

with 

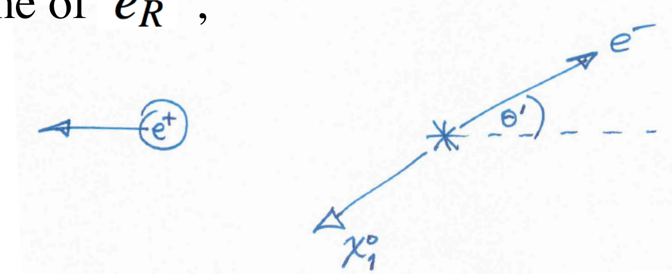
Consider the decay



. . .followed by



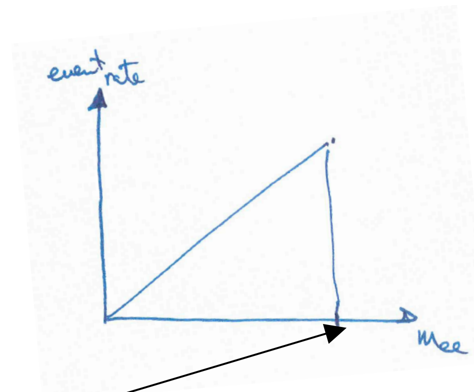
In rest frame of $\tilde{e}_R$,



$$d\Gamma \propto d\cos\theta'$$

$$m_{ee}^2 \propto E_{e^-}(1+\cos\theta) \propto E'_{e^-}(1+\cos\theta')$$

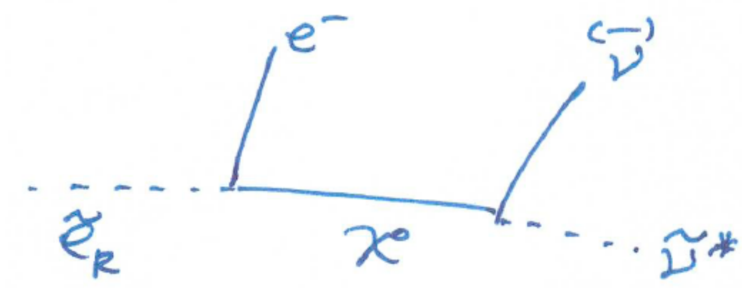
So, $\quad d\Gamma/dm_{ee} \propto m_{ee}$



$$(m_{ee})_{max} = m_{\chi_1^0}\sqrt{1-(m_{\tilde{e}_R}/m_{\chi_1^0})^2}\sqrt{1-(m_{\tilde{G}}/m_{\tilde{e}_R})^2}$$

Compare with $\tilde{\nu}$ case:

followed by



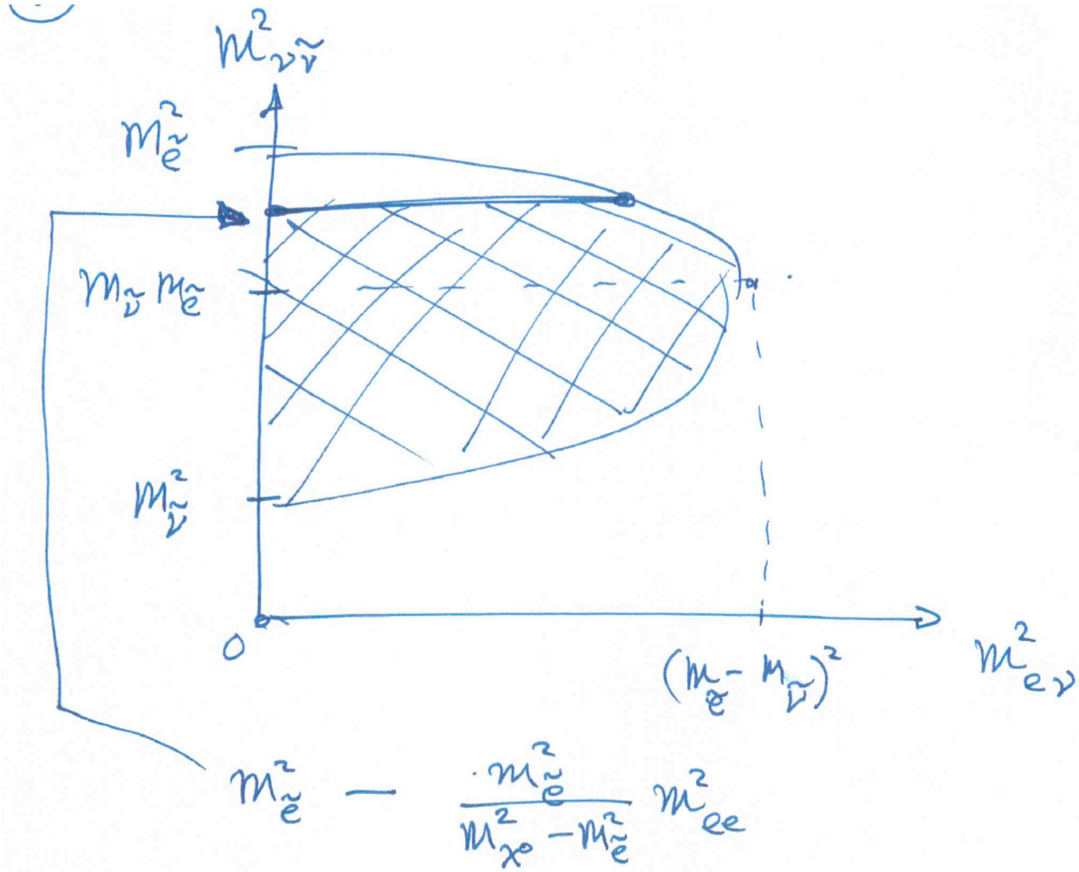
In rest frame of $\tilde{e}_R$

$$m_{ee}^2 \propto E'_{e^-}(1+\cos\theta') = \frac{m_{\tilde{e}}^2 - m_{\nu\tilde{\nu}}{}^2}{2m_{\tilde{e}}}(1+\cos\theta')$$

$$d\Gamma \propto dE'_{e^-}\, dE'_{\nu}\, d\cos\theta' \propto dE'_{e^-}\, dE'_{\nu}\, \frac{dm_{ee}^2}{E'_{e^-}}$$

$$\frac{d\Gamma}{dm_{ee}} \propto m_{ee} \int \frac{dm_{e\nu}^2\, dm_{\nu\tilde{\nu}}^2}{m_{\tilde{e}}^2 - m_{\nu\tilde{\nu}}^2}$$

(take constant amplitude for now)

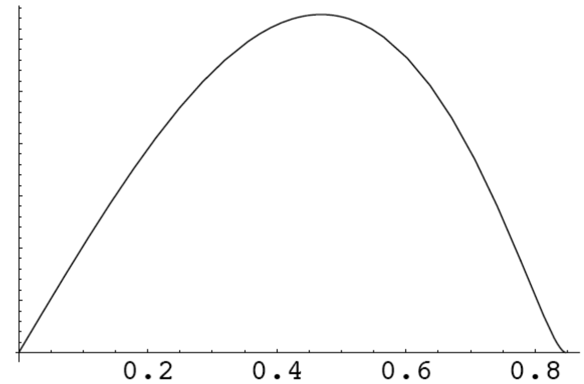


In the massless sneutrino limit,

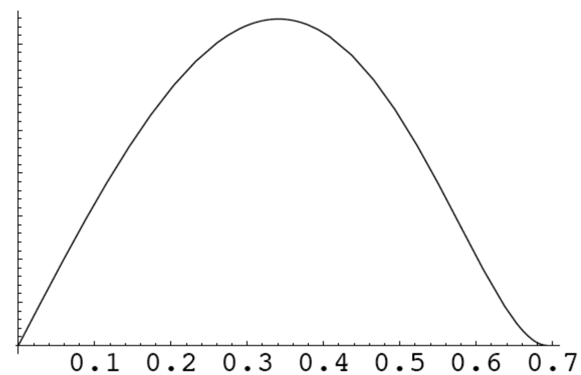
$$\frac{d\Gamma}{dm_{ee}} \propto m_{ee}[(m_{ee})^2_{max} - (m_{ee})^2]$$

Distribution shifts to lower values as sneutrino mass increases.

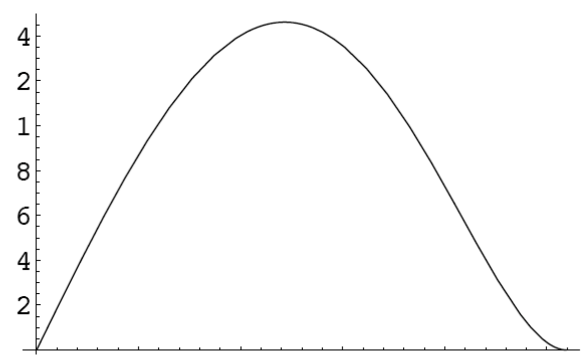
$$\frac{m_{\tilde{e}}}{m_\chi} = 0.5$$



$$\frac{m_{\tilde{\nu}}}{m_\chi} = 0.1$$



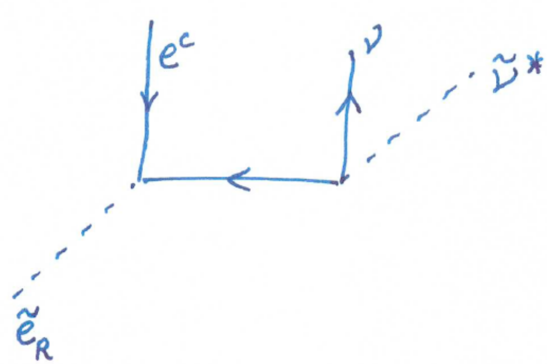
$$\frac{m_{\tilde{\nu}}}{m_\chi} = 0.3$$



$$\frac{m_{\tilde{\nu}}}{m_\chi} = 0.4$$

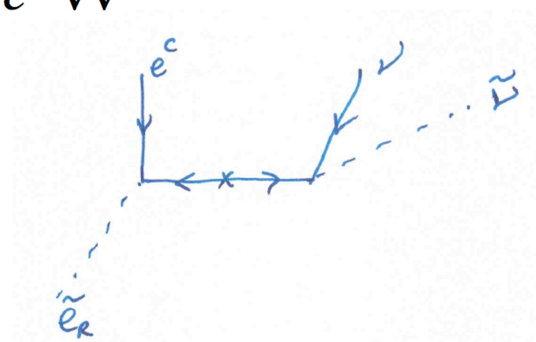
Include full $|\mathcal{M}|^2$

$\tilde{e}_R \rightarrow e^- \nu \tilde{\nu}^*$



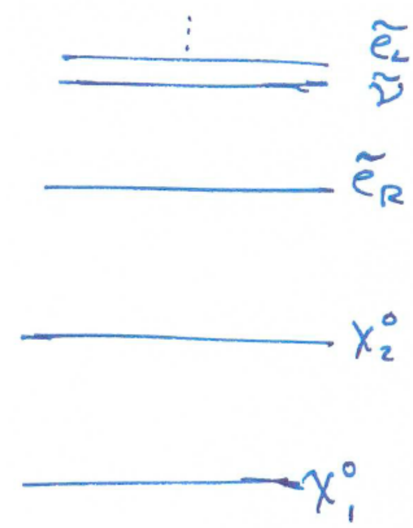
$$|\mathcal{M}|^2 \propto \frac{(4E_e E_\nu - m_{e\nu}^2) m_{\tilde{e}}^2}{(m_\chi^2 - m_{\nu\tilde{\nu}}^2)^2}$$

$\tilde{e}_R \rightarrow e^- \bar{\nu} \tilde{\nu}$

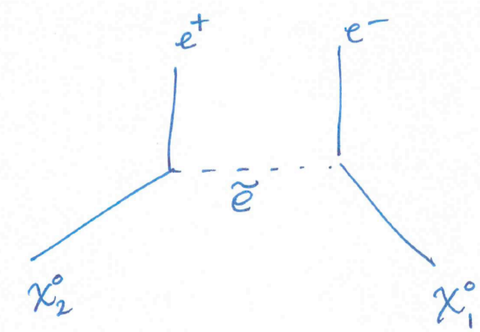


$$|\mathcal{M}|^2 \propto \frac{m_{e\nu}^2 m_\chi^2}{(m_\chi^2 - m_{\nu\tilde{\nu}}^2)^2}$$

Other ways to get lots of leptons?



Suppose this 3-body decay dominates:

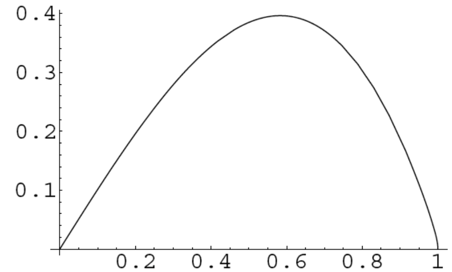


For constant amplitude,

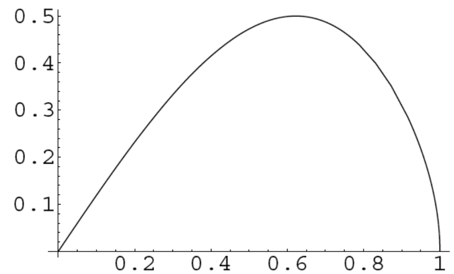
$$\frac{d\Gamma}{dm_{ee}} \propto x\sqrt{(1-x^2)((1+2K)^2) - x^2}$$

$$x = \frac{m_{ee}}{(m_{ee})_{max}} \qquad K = \frac{m_{\chi_1}}{m_{\chi_2} - m_{\chi_1}}$$

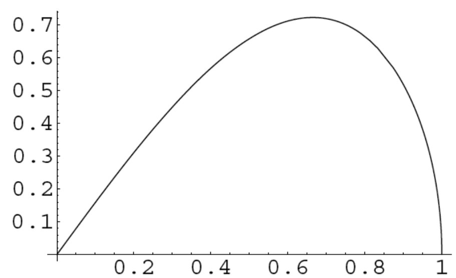
K=0



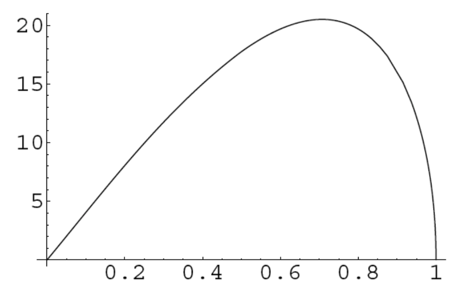
K=0.1

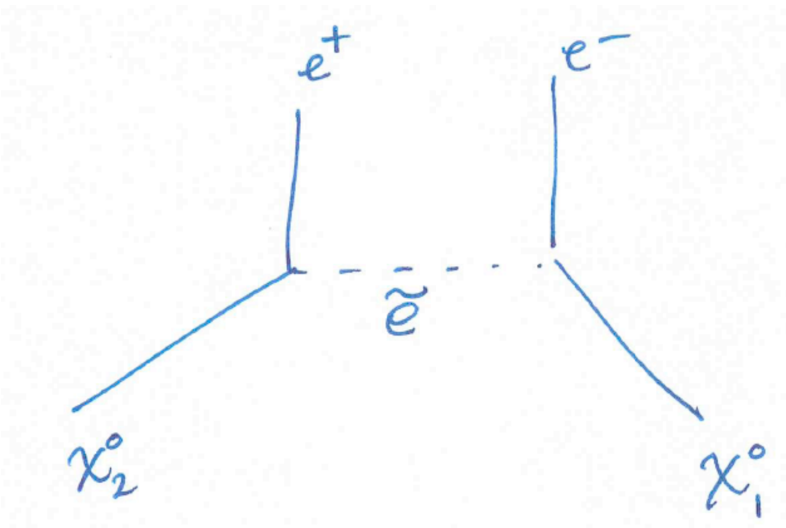


K=0.3



K=inf

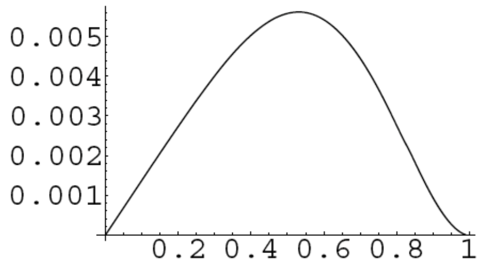




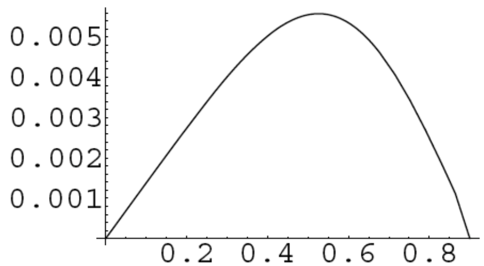
$$|\mathcal{M}|^2 \propto \frac{m^2_{e^-\chi_1}(m^2_{\chi_2} - m^2_{e^-\chi_1})}{(m^2_{e^-\chi_1} - m^2_{\tilde{e}})^2}$$

$m_{\tilde{e}}/m_{\chi_2},\ m_{\chi_1}/m_{\chi_2} =$

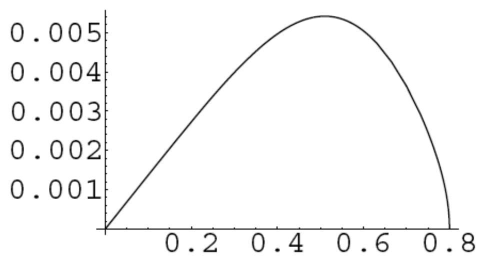
(2, .01)



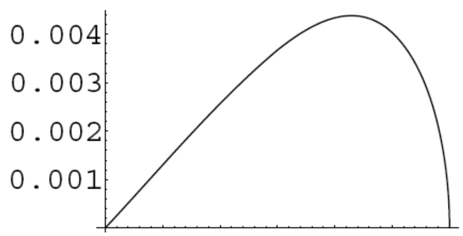
(2, 0.1)



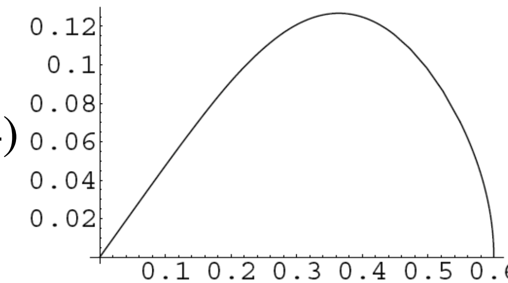
(2, 0.2)



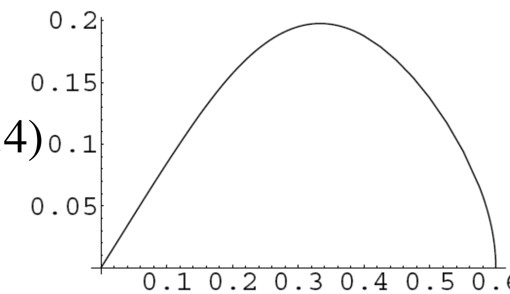
(2, 0.4)



(1.1, 0.4)



(1.01, 0.4)



- Expect dilep invariant mass distributions to effectively distinguish $\tilde{\nu}_1$ lsp scenario with $\tilde{e}_R$ nlsp from gravitino lsp case.

- Also can distinuish from χ_1^0 lsp with three-body decay $\chi_2^0 \longrightarrow \chi_1^0 e^+ e^-$ unless
  - $m_{\chi_1^0}/m_{\chi_2^0}$ is small
  - and/or $\tilde{e}, \chi_2$ are nearly degnerate.

- Note: if $(m_{ee})_{max}$ is small, becomes problematic to invoke first; in second case get lots of soft leptons.

About the simulations

- No backgrounds yet
- Adapted SUSY-HIT package to accommodate mixed sneutrino.
  Djouadi, Muhlleitner, Spira
- Parameters set at weak scale.
- Generated SUSY events with initial/final-state radiation, hadronization using Pythia. Sjostrand, Mrenna, Skands
- Ran showered events through PGS detector simulator. Conway et. al.

$\tan\beta = 10$

$\mu = 350$

$M_A = 350$

$M_3 = 600$

$M_2 = 400$

$M_1 = 200$

$\tilde{m}_Q = 500$

$\tilde{m}_u = 500$

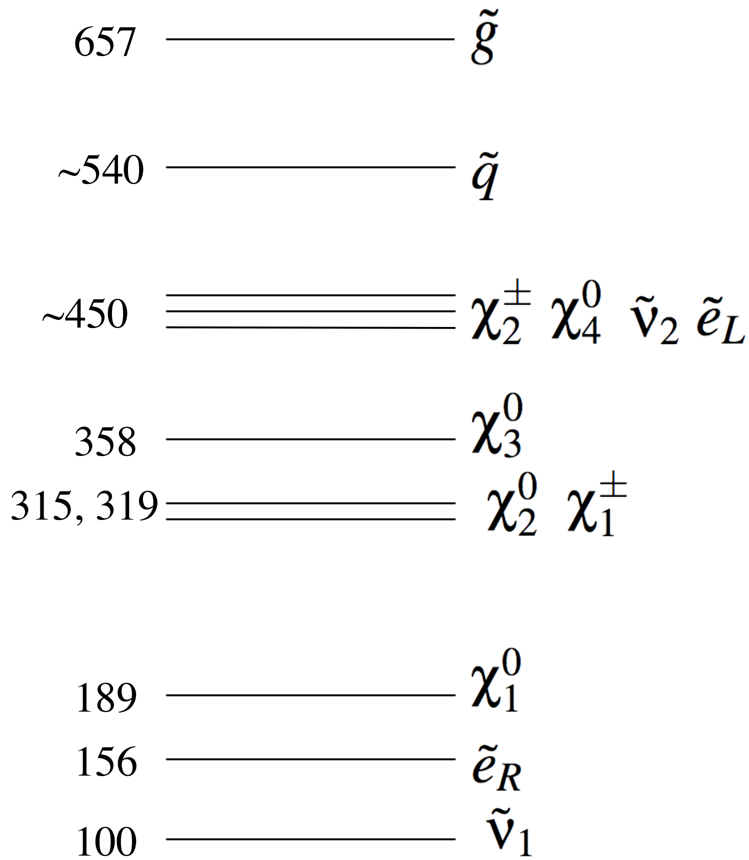
$\tilde{m}_d = 500$

$\tilde{m}_L = 450$

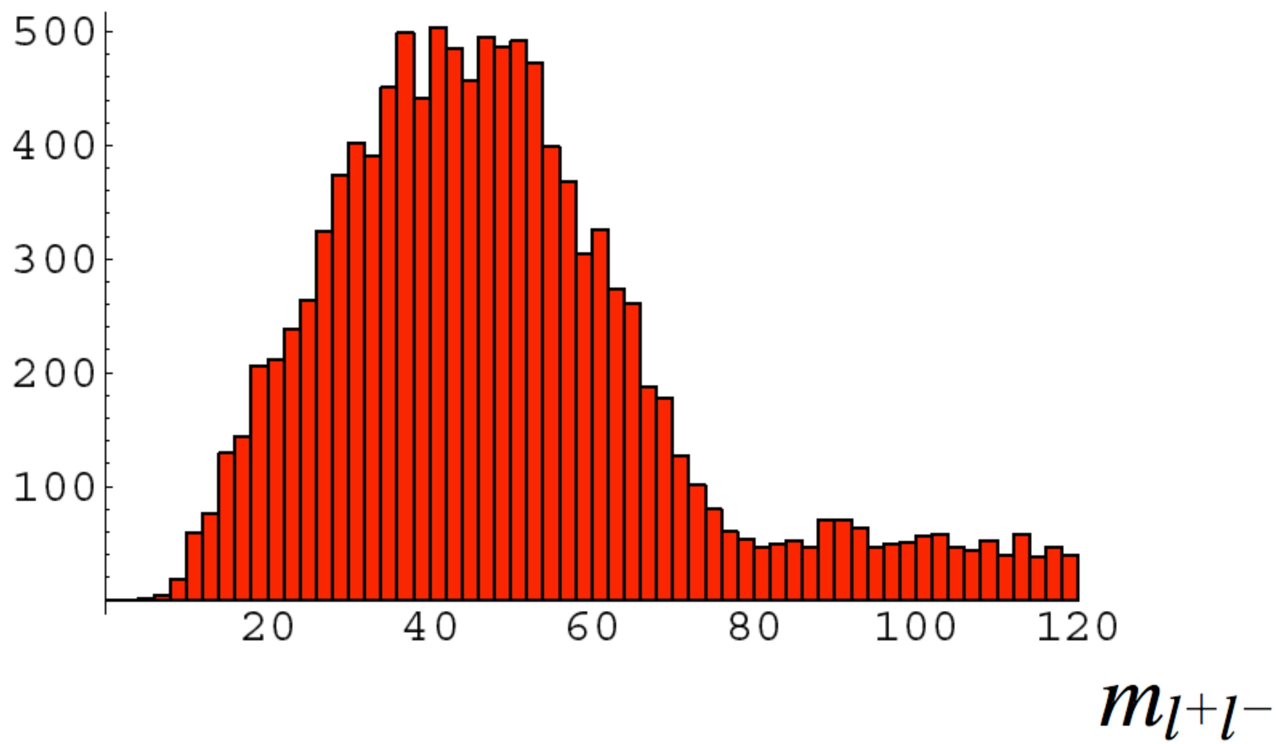
$\tilde{m}_e = 150$

$\tilde{m}_n = 110$

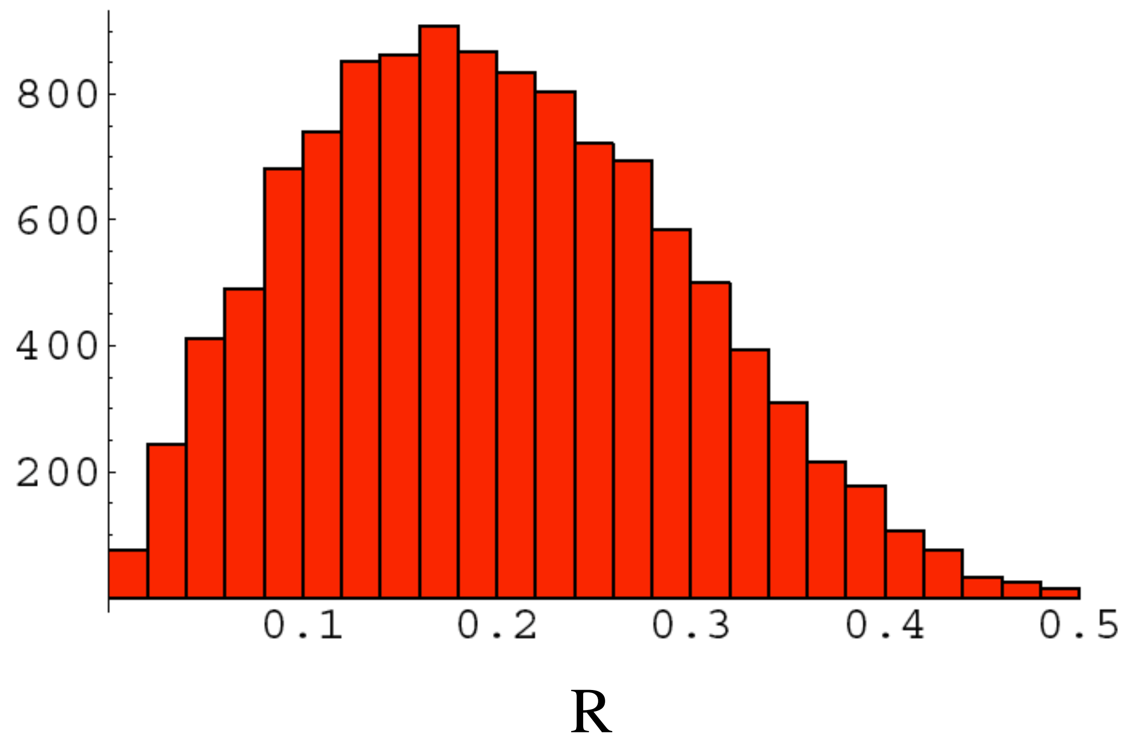
A sample point



Take events with an e+e- pair and/or a mu+mu- pair . . .

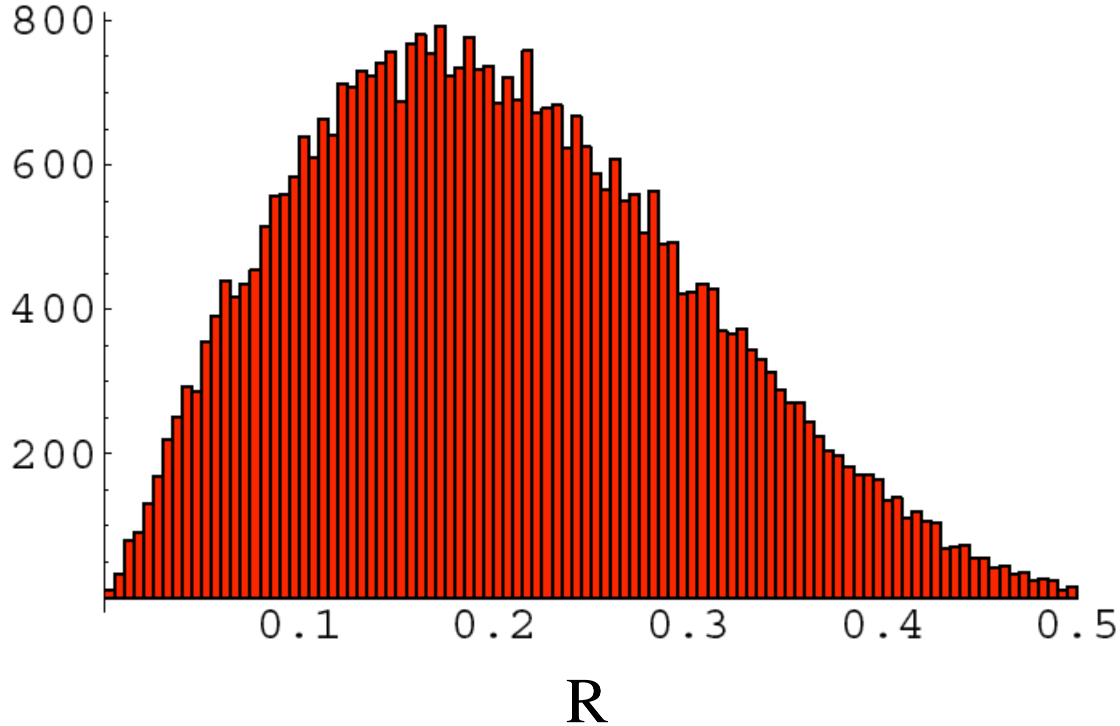


R = missing pT/(scalar sum of pT's + missing pT)



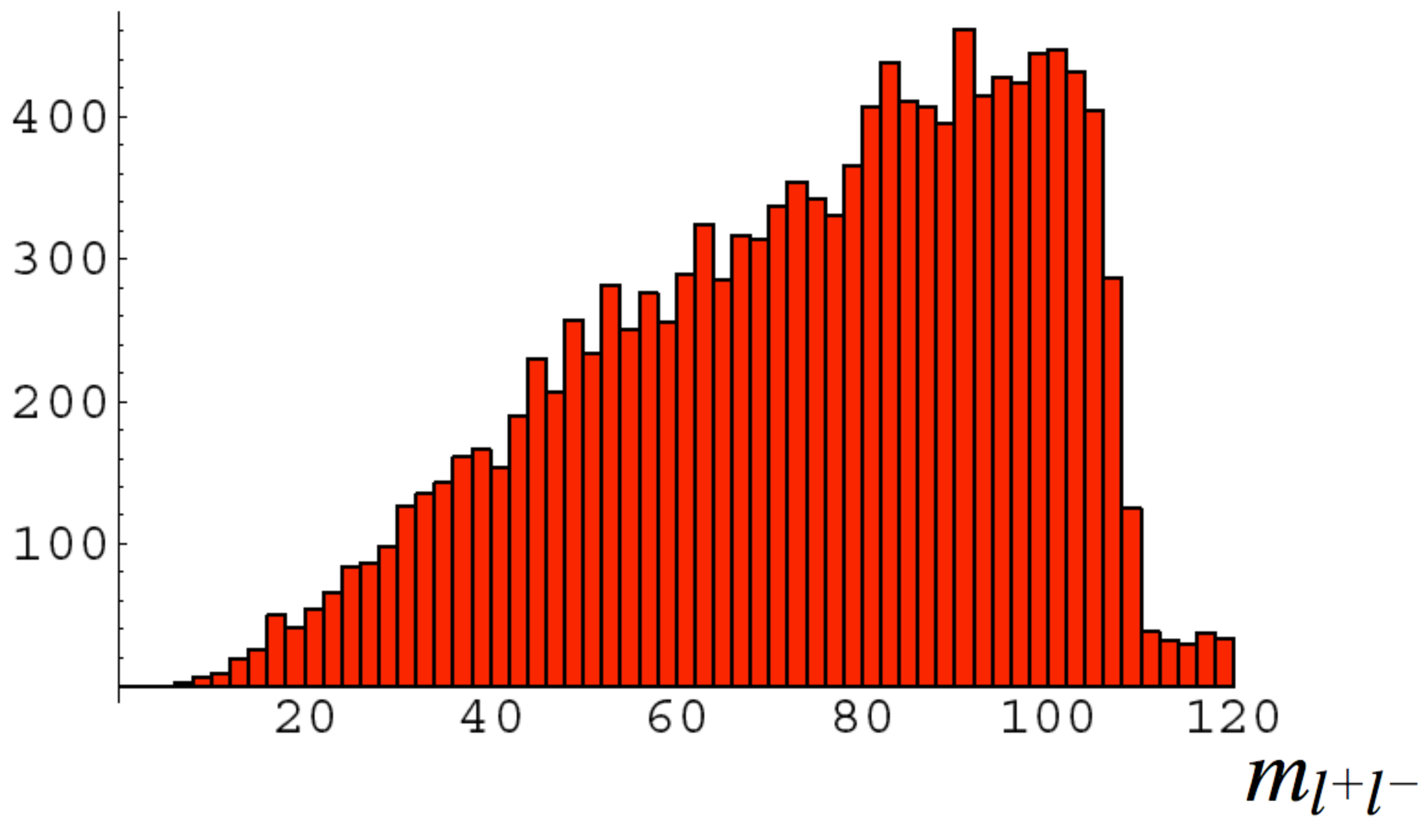
R = missing pT/(scalar sum of pT's + missing pT)

All events
Included

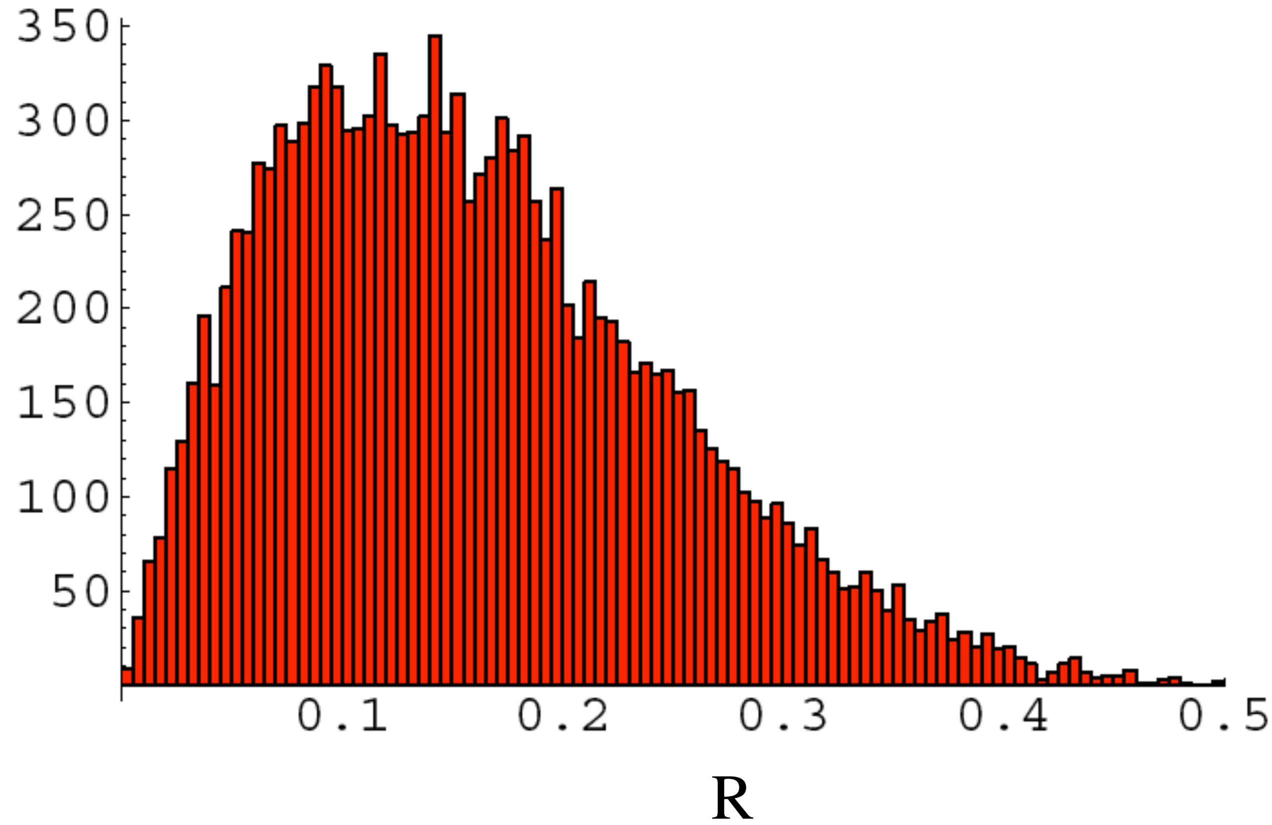


gravitino case

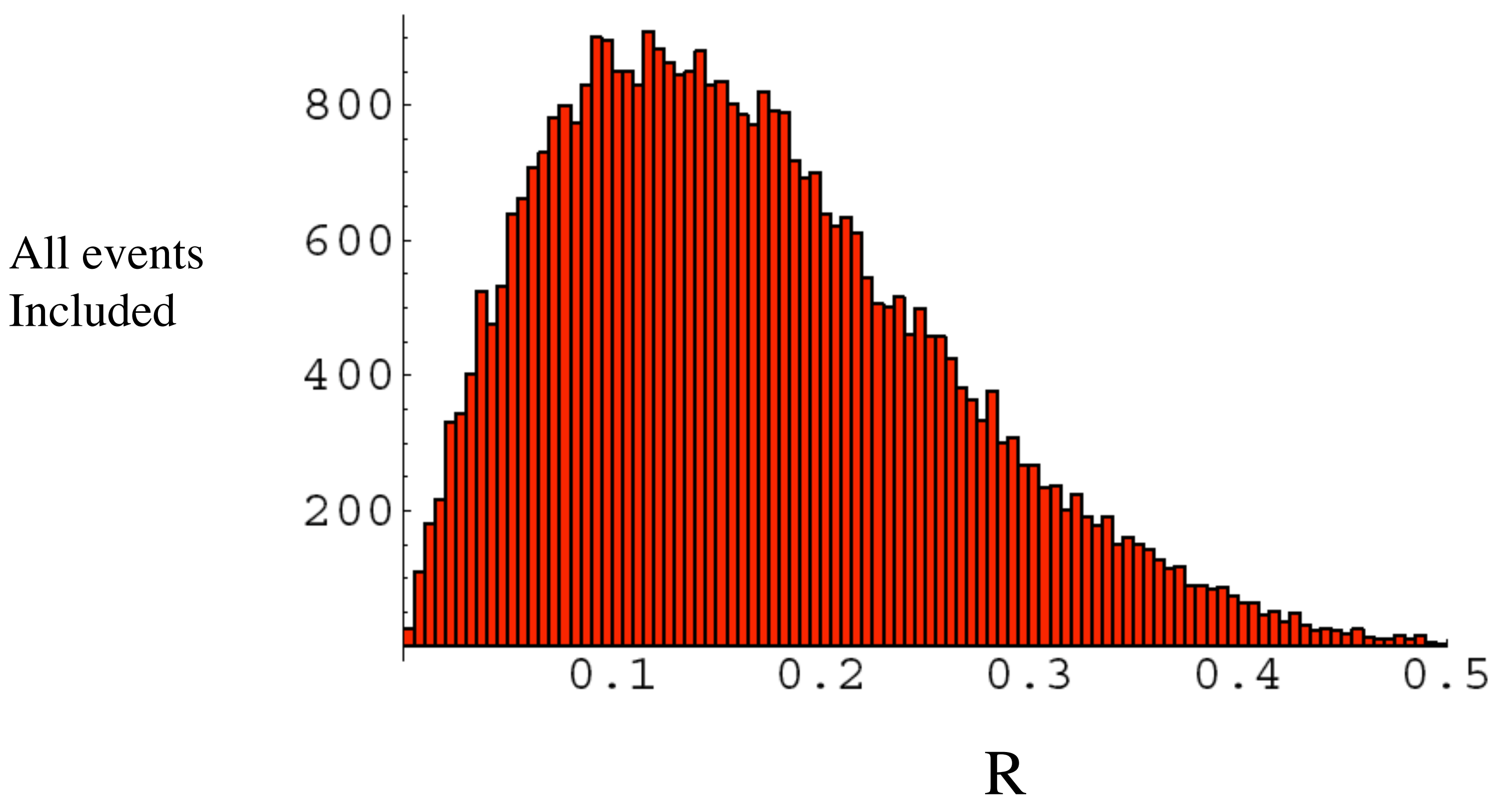
(Keep same spectrum, except lose sneutrino and replace with light gravitino).



gravitino case



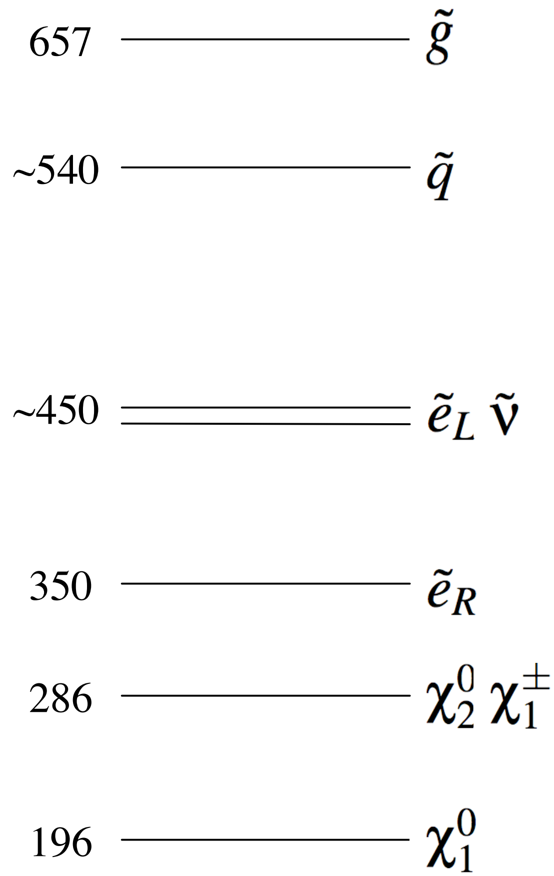
gravitino case



neutralino case

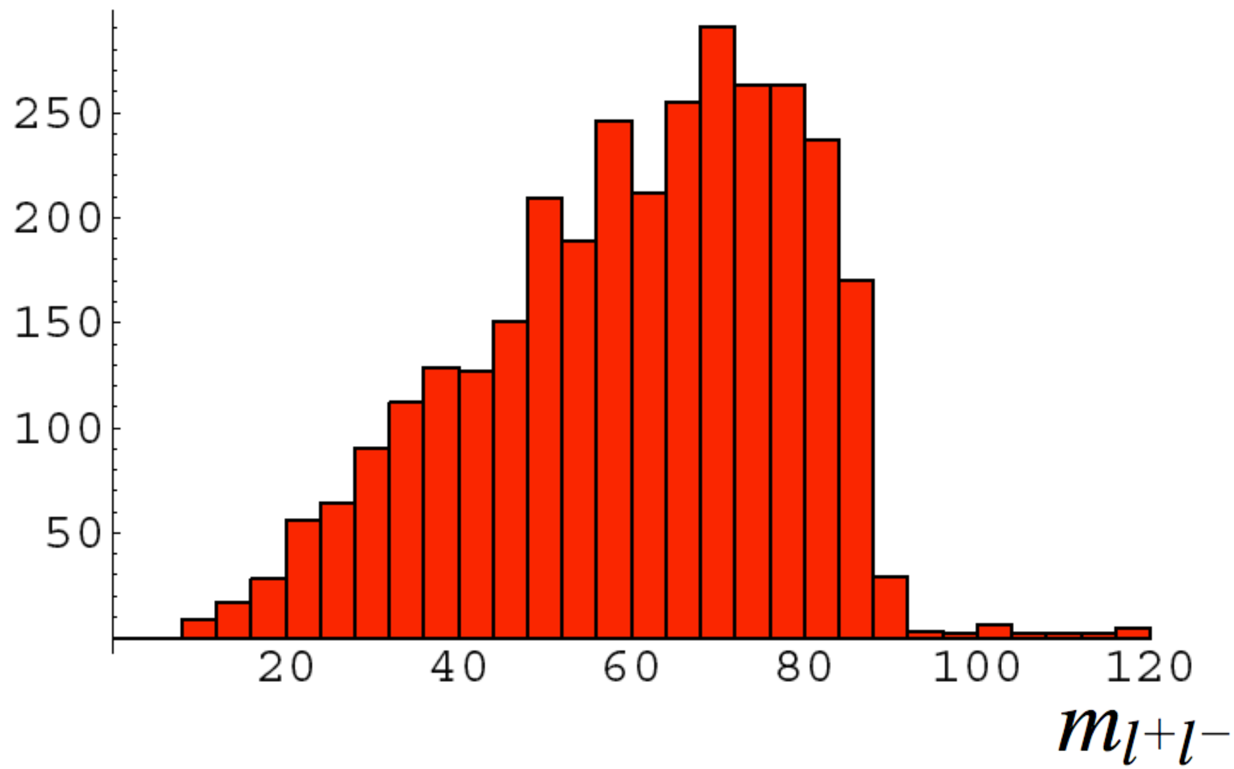
$M_3 = 600$
$M_2 = 280$
$M_1 = 200$

$\tilde{m}_L = 450$
$\tilde{m}_e = 350$

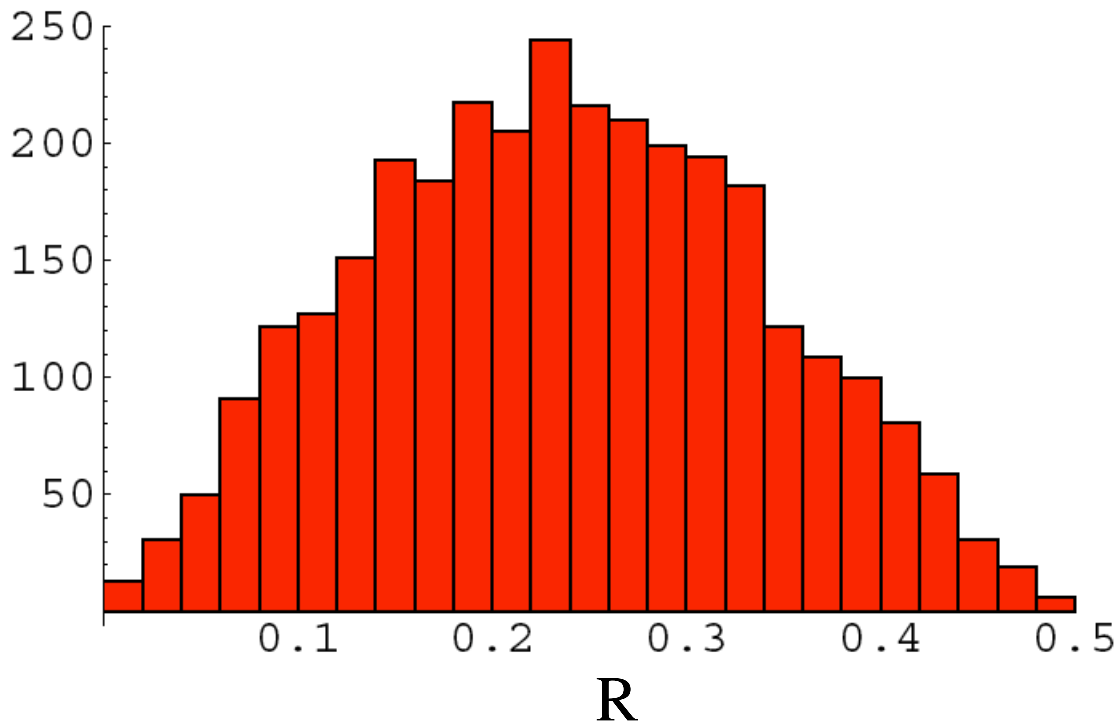


Decouple higgsinos, and to get lots of events with leptons quickly, cheat: keep only leptonic decays of χ_2^0

neutralino case

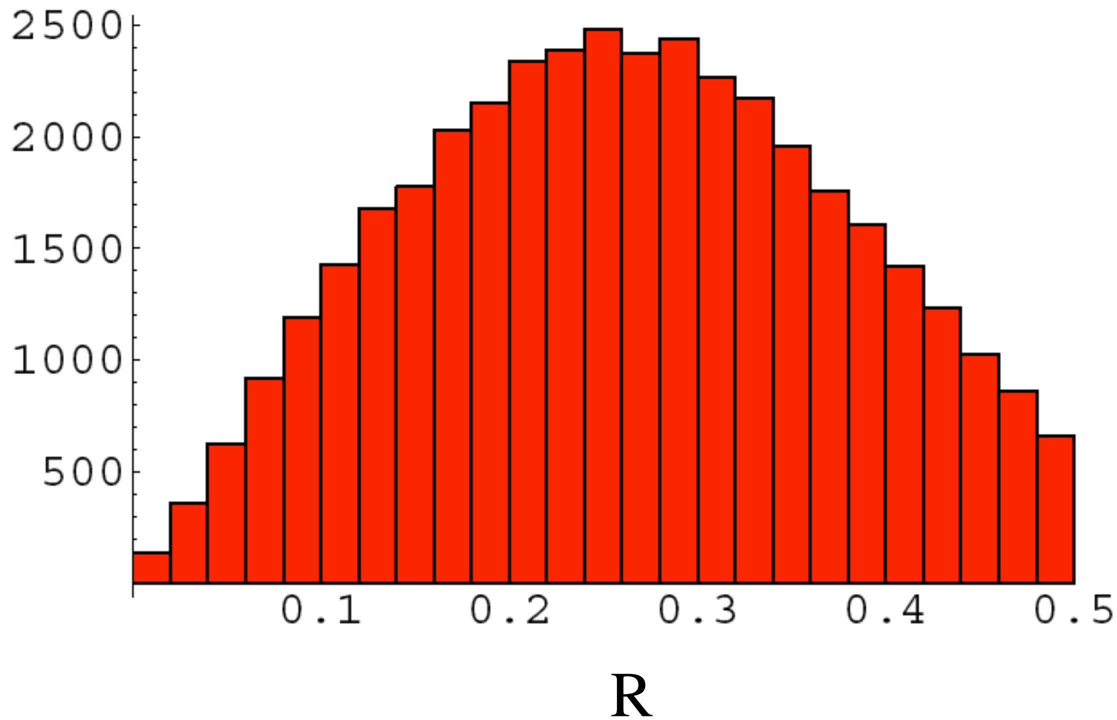


neutralino case

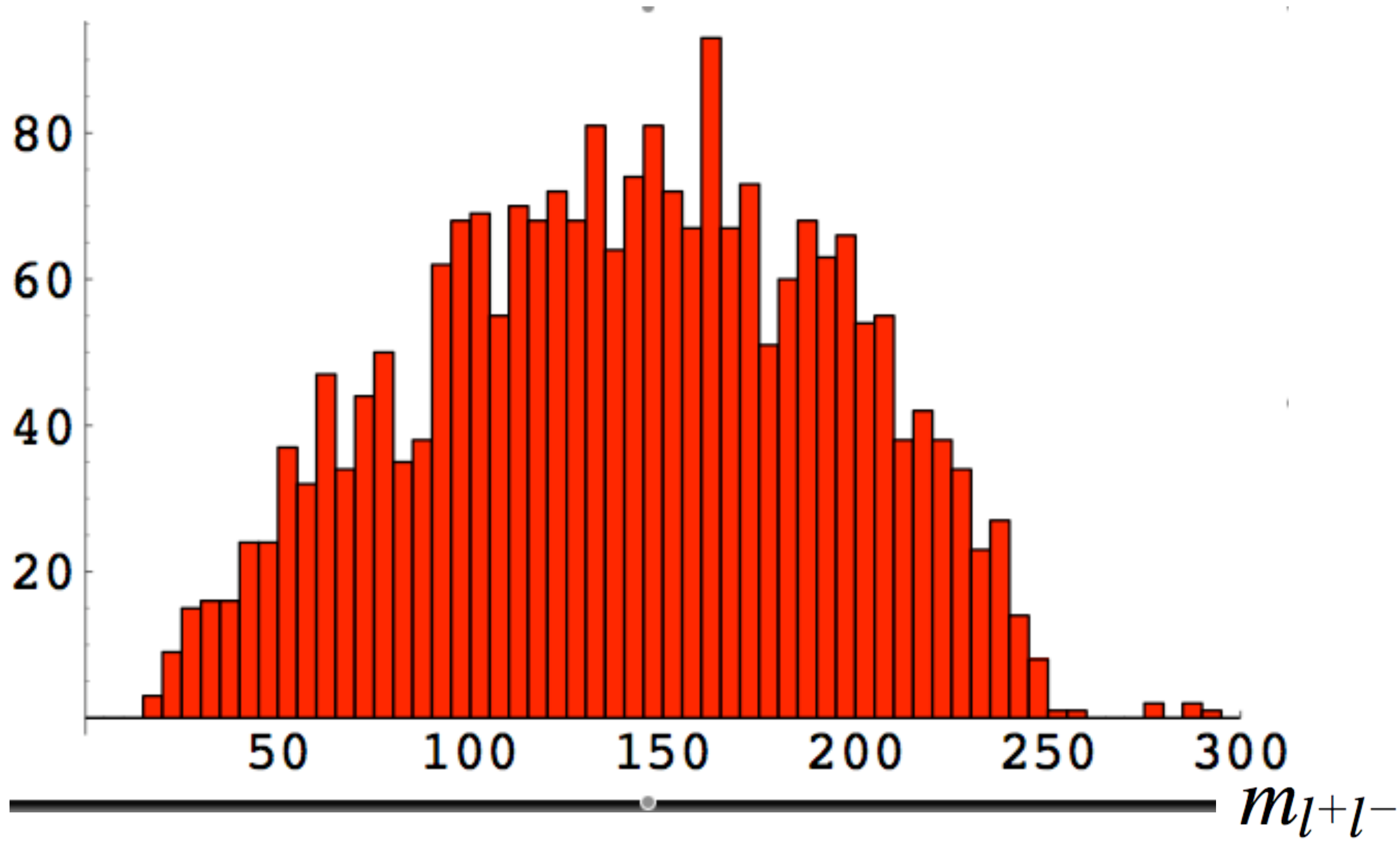


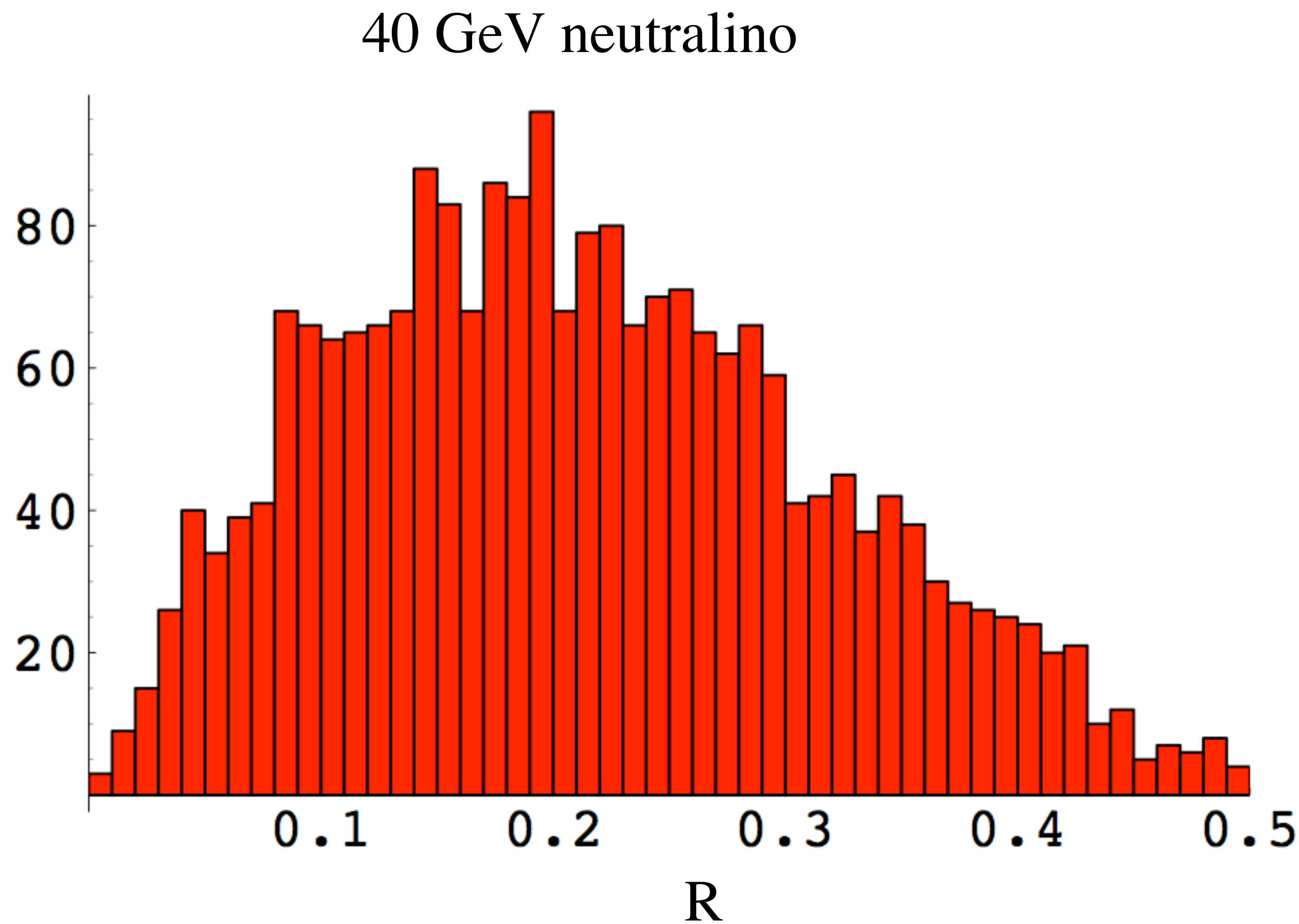
neutralino case

All events
Included:

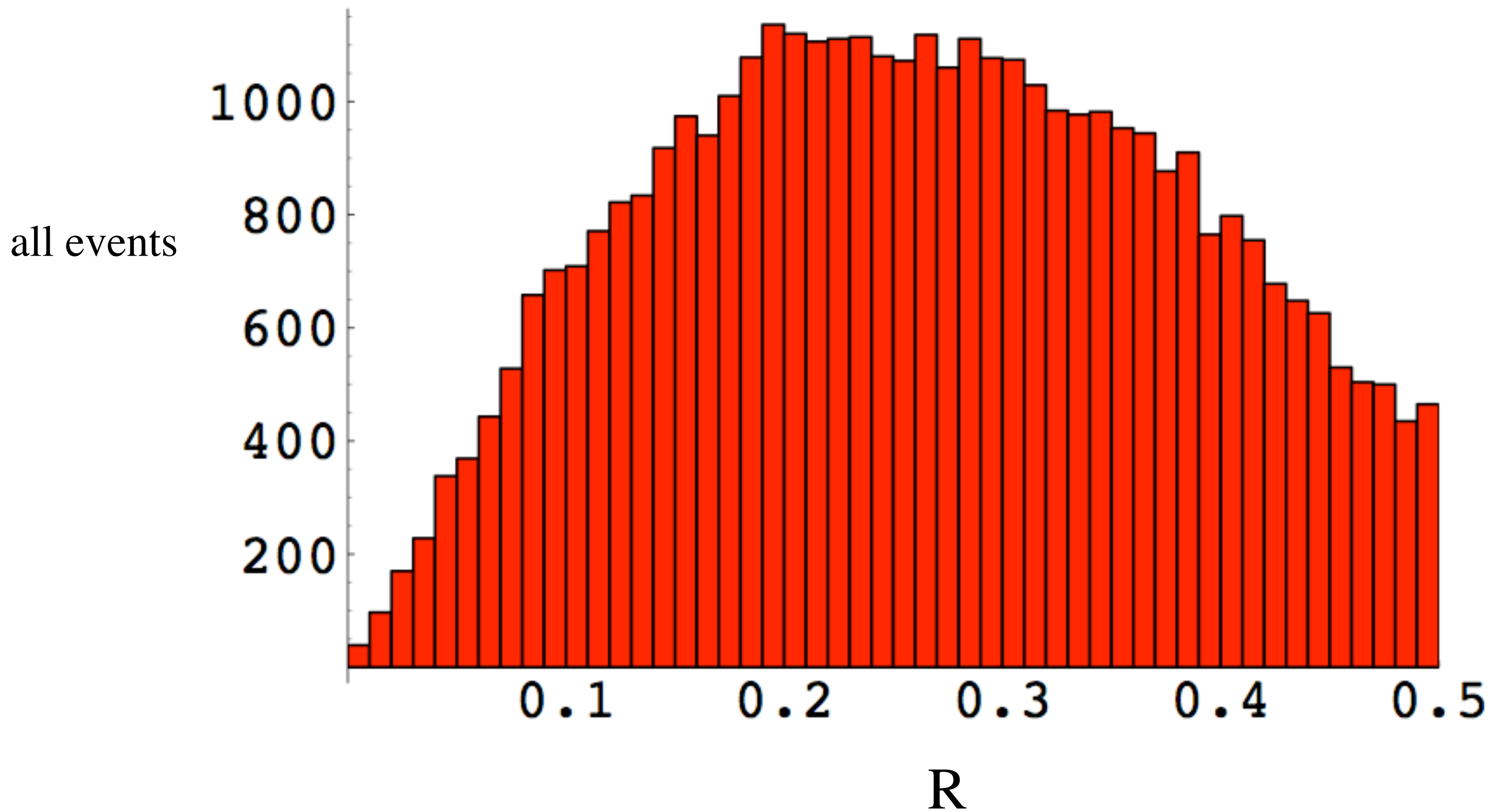


bring mass of neutralino lsp down to 40 GeV

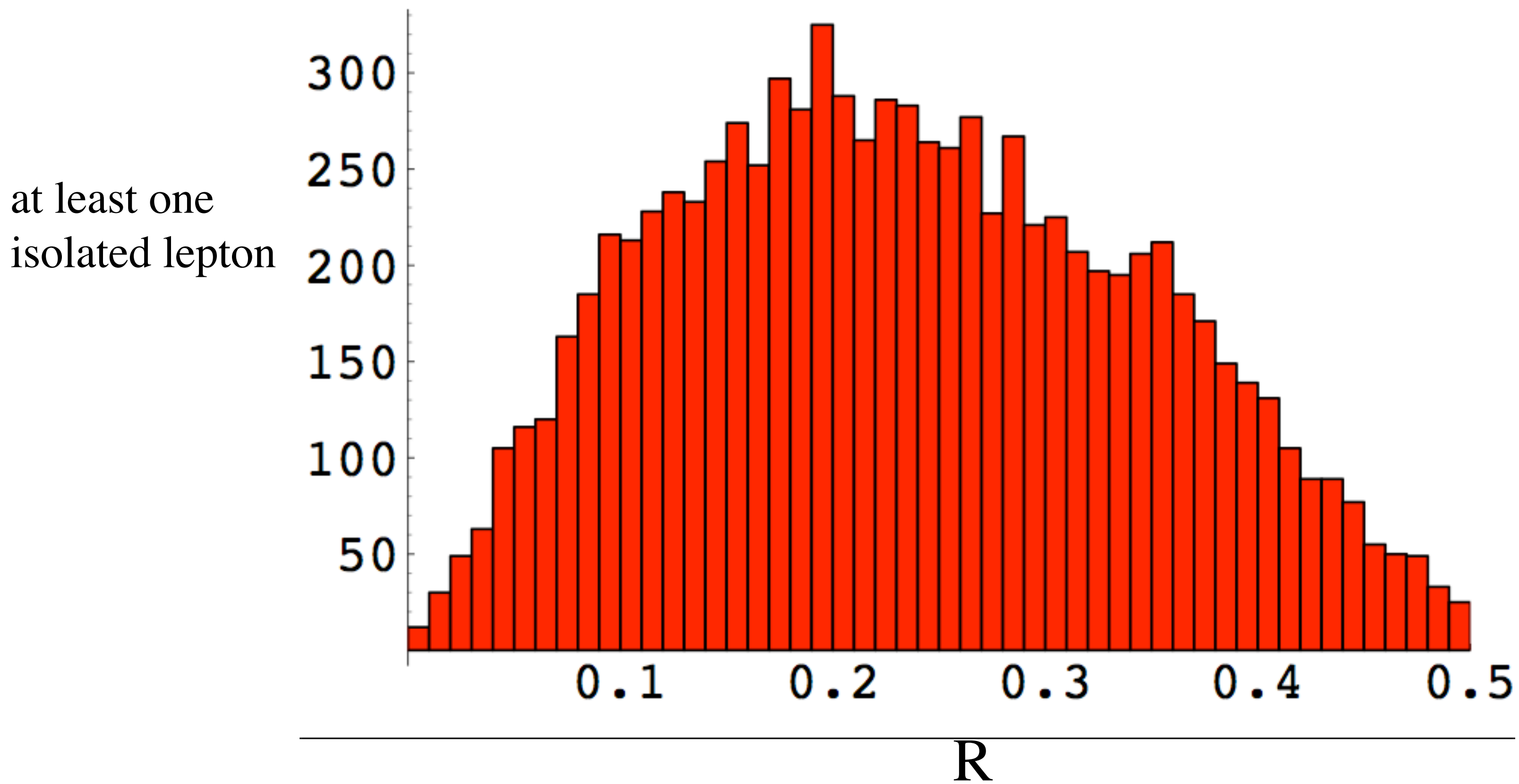



40 GeV neutralino
80
60
40
20
0.1
0.2
0.3
0.4
0.5
R

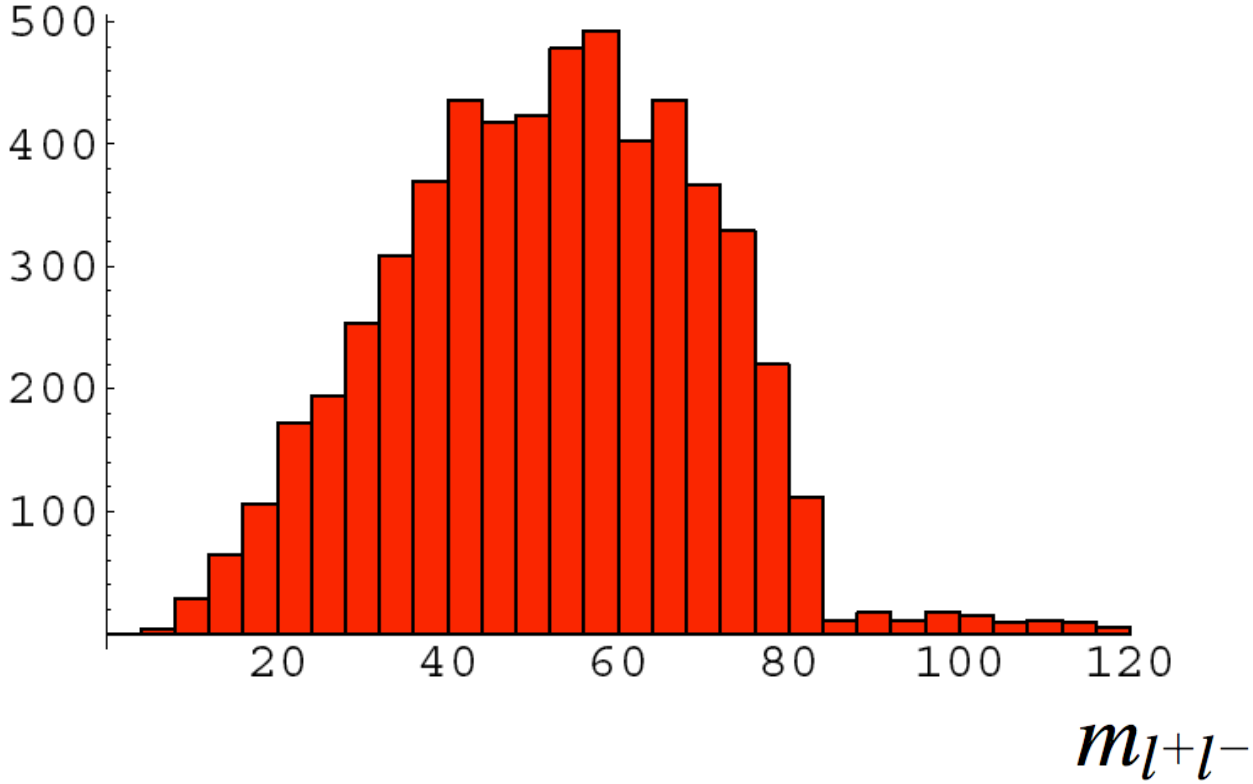
40 GeV neutralino



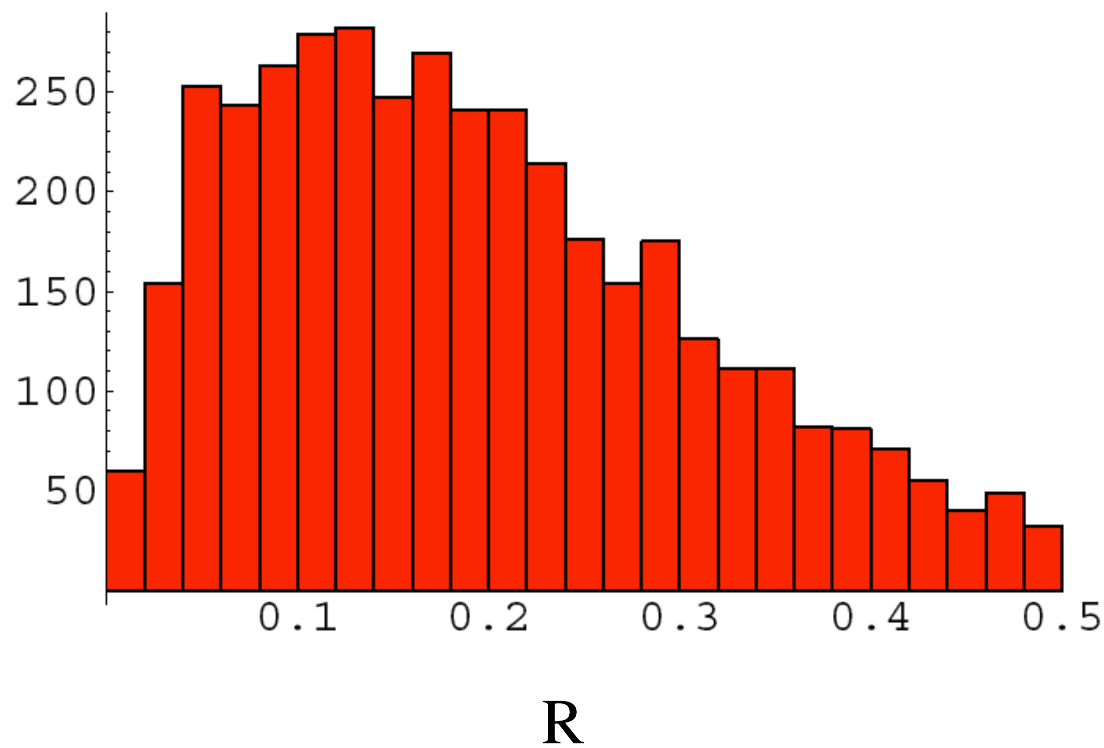
40 GeV neutralino



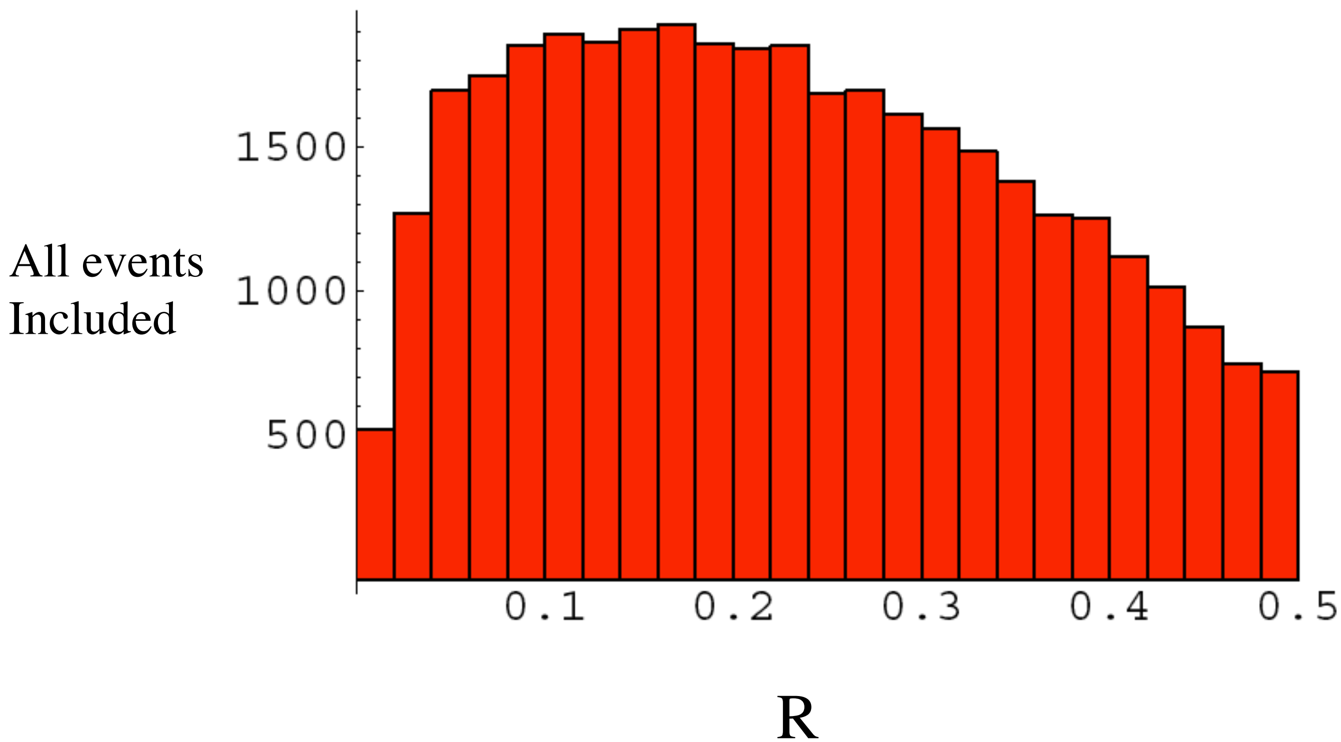
case with very light lsp neutralino (10 GeV)



case with very light lsp neutralino

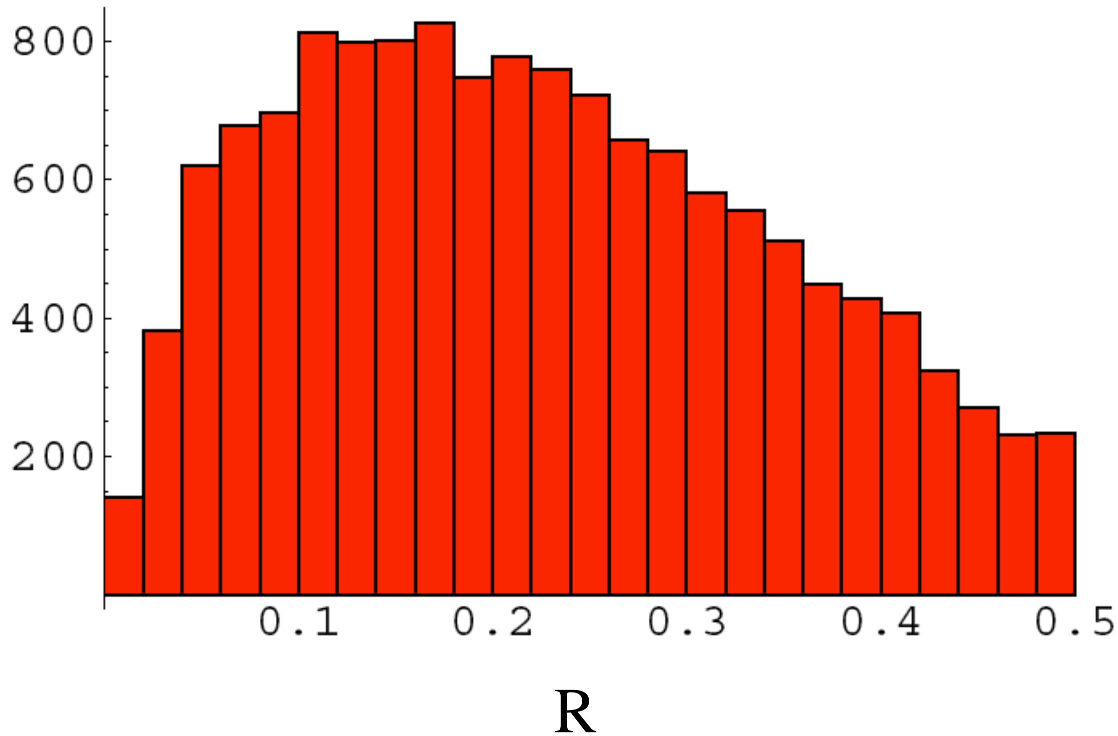


case with very light lsp neutralino

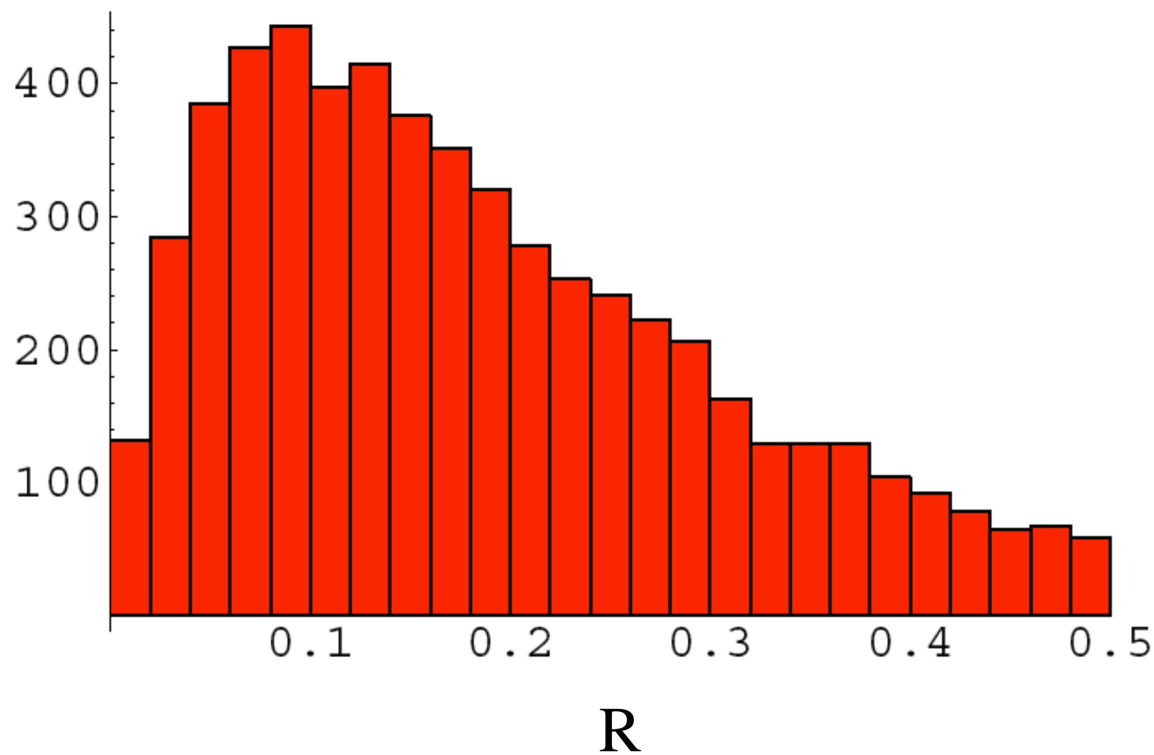


case with very light lsp neutralino

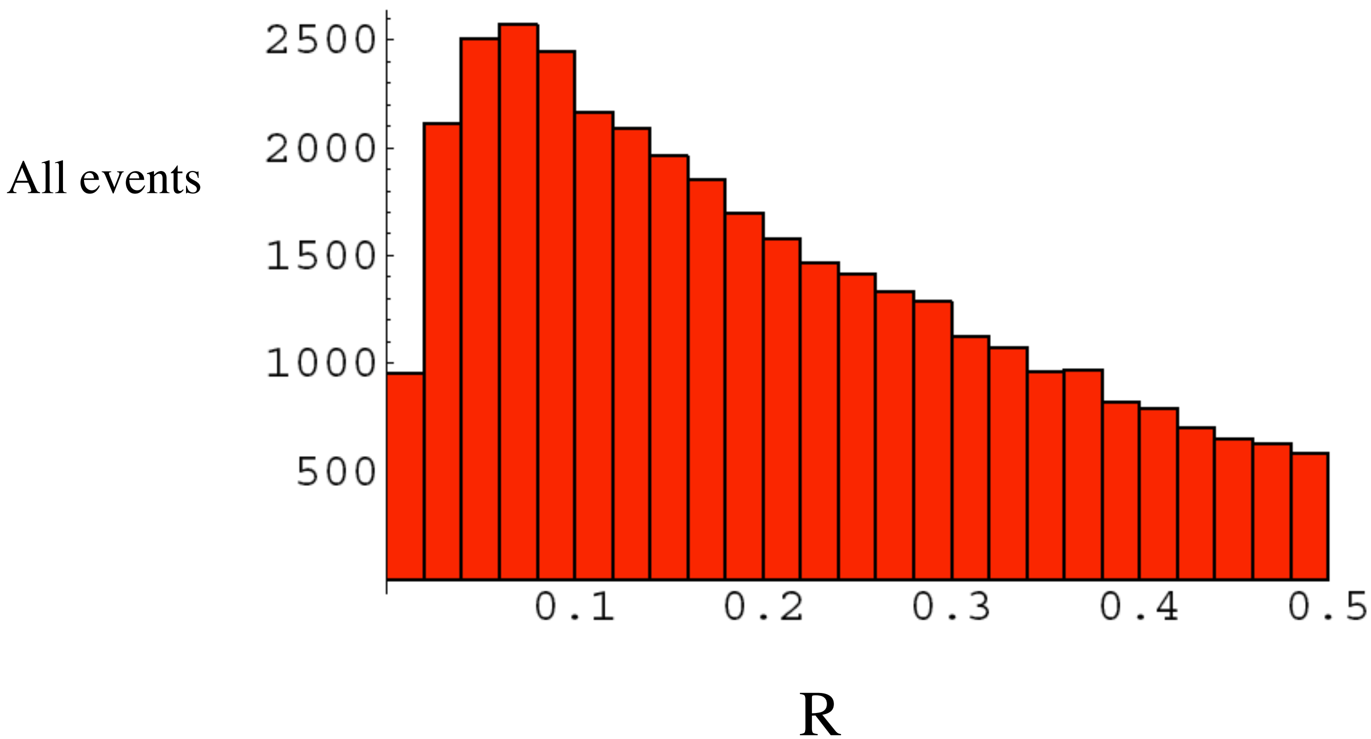
Require at least
one isolated lepton:



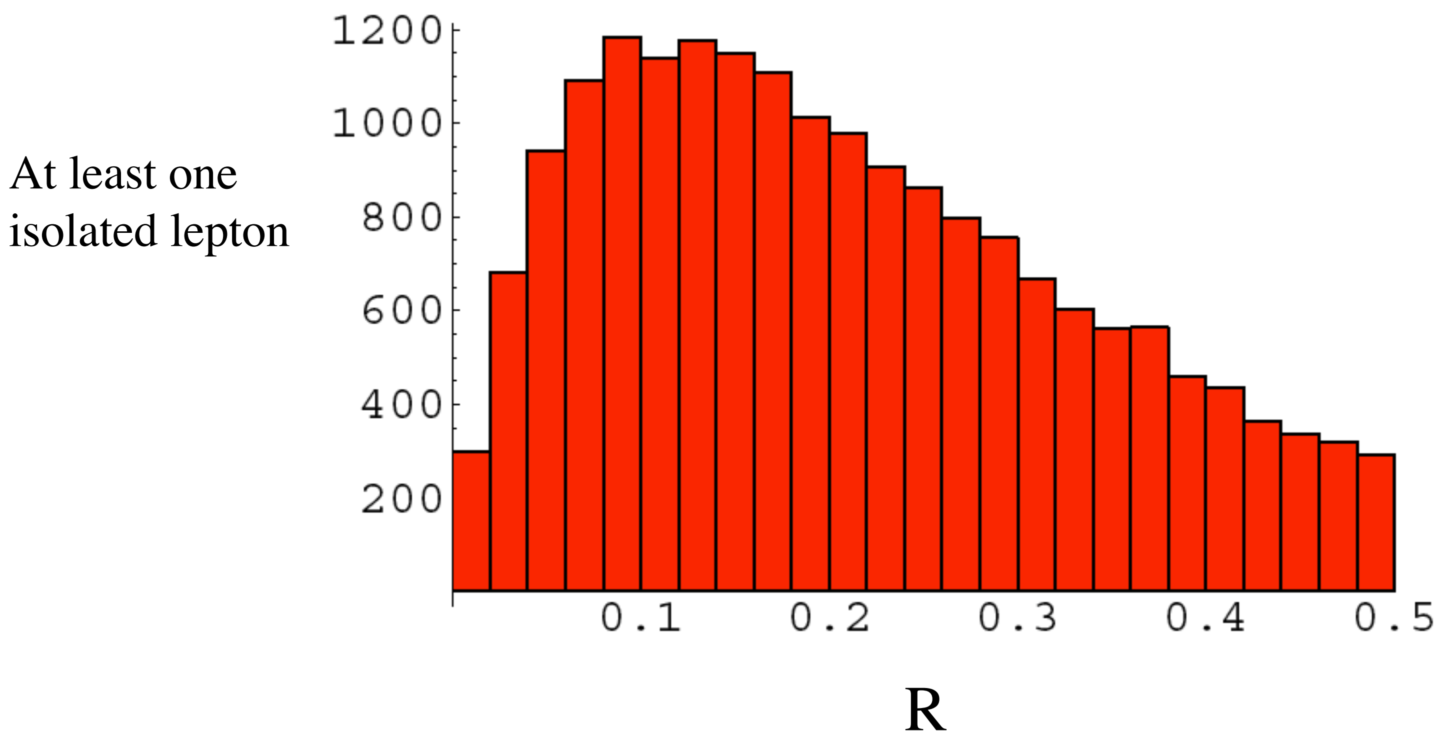
Now decouple right-handed squarks



decouple right-handed squarks



decouple right-handed squarks



Conclusions

- Mixed sneutrino is a viable dark matter candidate

- For the case of a right-handed slepton nlsp, a useful signature at the LHC may be an invariant mass distribution for OSSF dileptons that is shifted away from the kinematic endpoint.

- First priority: backgrounds.

- Second: different signatures, especially those from decays of $\tilde{\nu}_2$