Mixed-sneutrino dark matter at the LHC

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work in progress
with S. Chang and N. Weiner

Nice things about susy

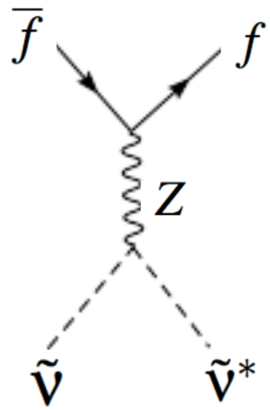
- Solves hierarchy problem
- Gauge coupling unification
- Dark matter from R-parity: obvious candidates are neutralino and sneutrino.

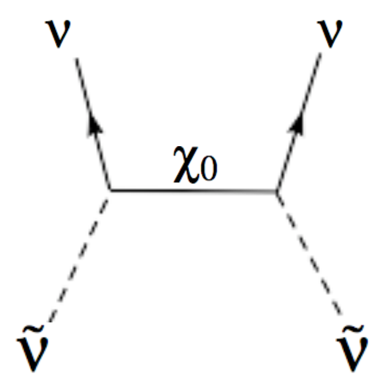
	times mentioned in Atlas physics TDR	times mentioned in CMS physics TDR
slepton	130	41
squark	104	54
gluino	89	54
neutralino	46	48
chargino	29	33
sneutrino	1	0

"... these events and their rejection is more difficult. The rate of direct production of $\tilde{\chi}_2^0$ pairs is comparable with the H/ A $\rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0$, also the background from the direct production of slepton/ sneutrino pairs is non-negligible. "

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

- Introduce right-handed neutrinos with vanishing or small Majorana masses (so add chiral superfields N).

- Include a weak-scale A-term

$$A_\nu \, LNH_u$$

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

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

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

Neutrino masses from susy breaking?

- Suppose X, $\overline{X}$ develop F-term vevs.

$$\frac{1}{M^2}[X^\dagger L N H_u]_D \qquad \frac{1}{M}[\overline{X} L N H_u]_F$$

These operators generate Dirac neutrino masses, A term.

- Can do something similar to get Majorana masses. Now let X get A and F-term vevs of comparable size.

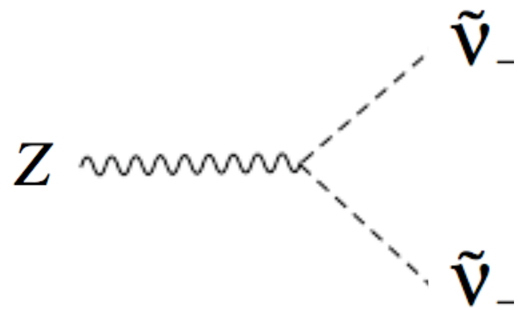
$$\frac{1}{M}[X^\dagger N N]_D \qquad \frac{1}{M}[X L N H_u]_F$$

These generate A-terms and a weak-scale see-saw.

In this framework, natural to expect lepton-number violating mass-squared for $\tilde{n}$

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 $\tilde{\nu}_1$

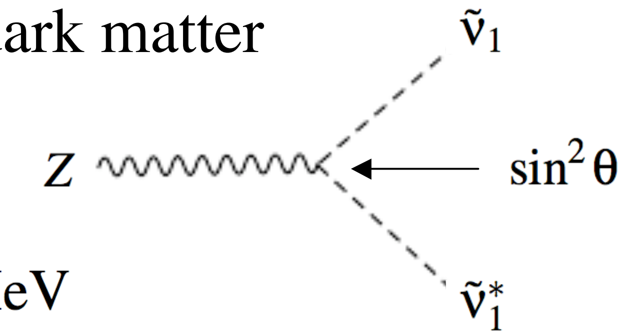


does not exist!

- If mass splitting is greater than ~100 keV, scattering is strongly suppressed at direct-detection experiments.

Hall, Moroi, Murayama

Implications of mixings for dark matter



- Z-width constraint:

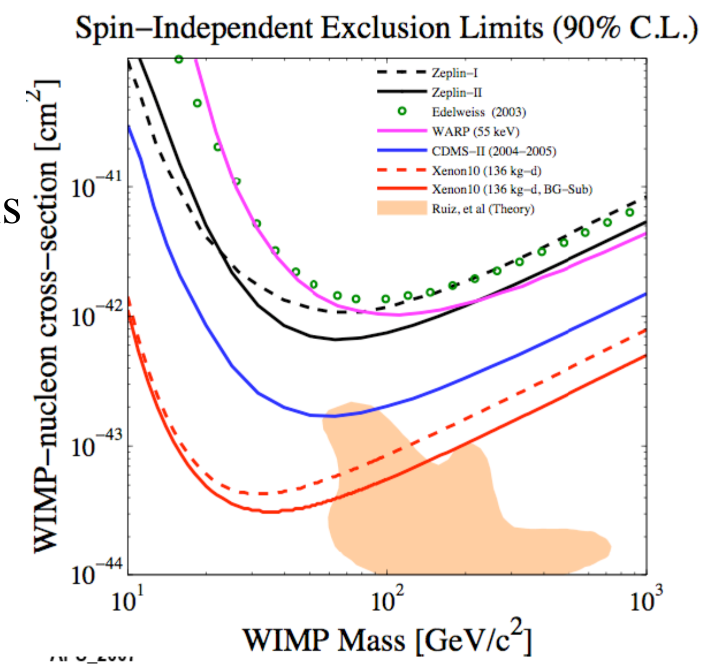
$$\delta\Gamma = \frac{\sin^4\theta}{2}\left[1-(2m_{\tilde{\nu}_1}/m_z)^2\right]^{3/2}\Gamma_\nu < 2\ \text{MeV}$$

- 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

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

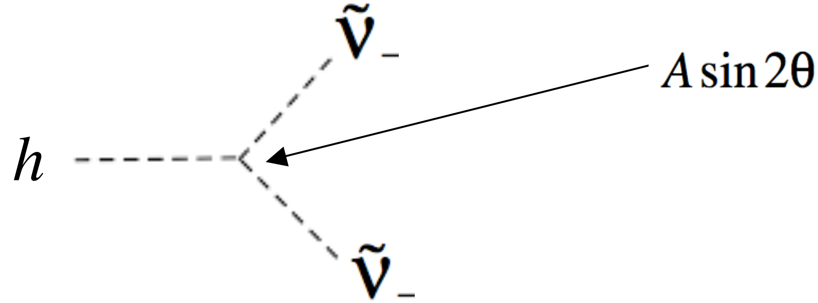
If $\sin\theta < 0.06$, no constraint on mass . . .



Alena Aprile, for the XENON collaboration, talk at APS 2007

Elastic scattering, annihilation from Higgs exchange

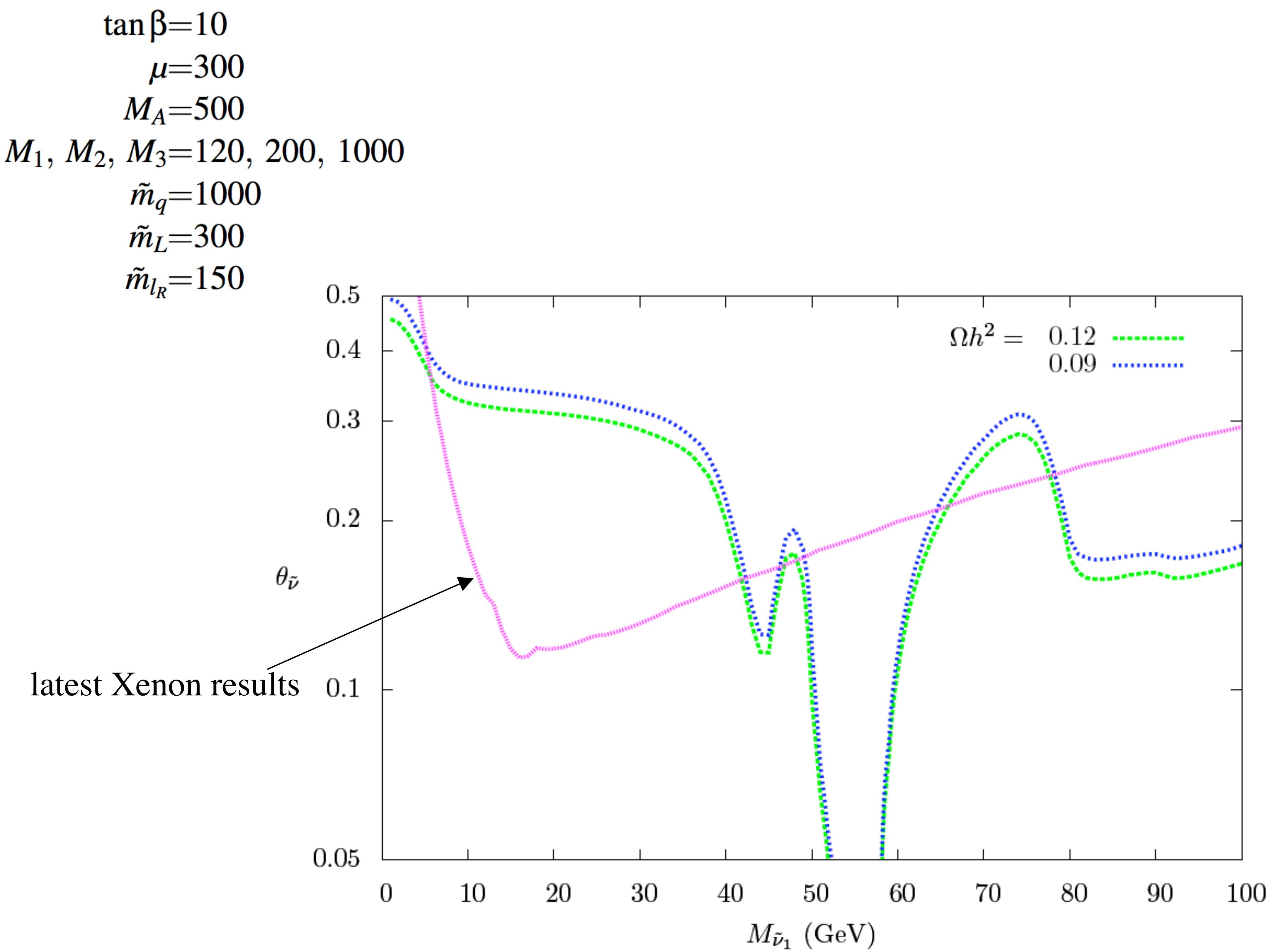
- Even if elastic scattering by Z exchange is turned off, still have



- If A terms are sizeable, s-channel Higgs exchange can give efficient annihilation (especially if W+W- is kinematically accessible).

Belanger, Boudjema, Pukhov, Semenov

- Calculate relic abundance using Micromegas 2.0, see what comologically preferred regions are still allowed . . .



tan β=10
μ=300
M_A=500
M_1, M_2, M_3=120, 200, 1000
$\tilde{m}_q$=1000
$\tilde{m}_L$=300
$\tilde{m}_{l_R}$=150
$\Omega h^2 =$ 0.12
0.09
$\theta_{\tilde{\nu}}$
latest Xenon results
$M_{\tilde{\nu}_1}$ (GeV)
0.5
0.4
0.3
0.2
0.1
0.05
0
10
20
30
40
50
60
70
80
90
100

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M_A=500
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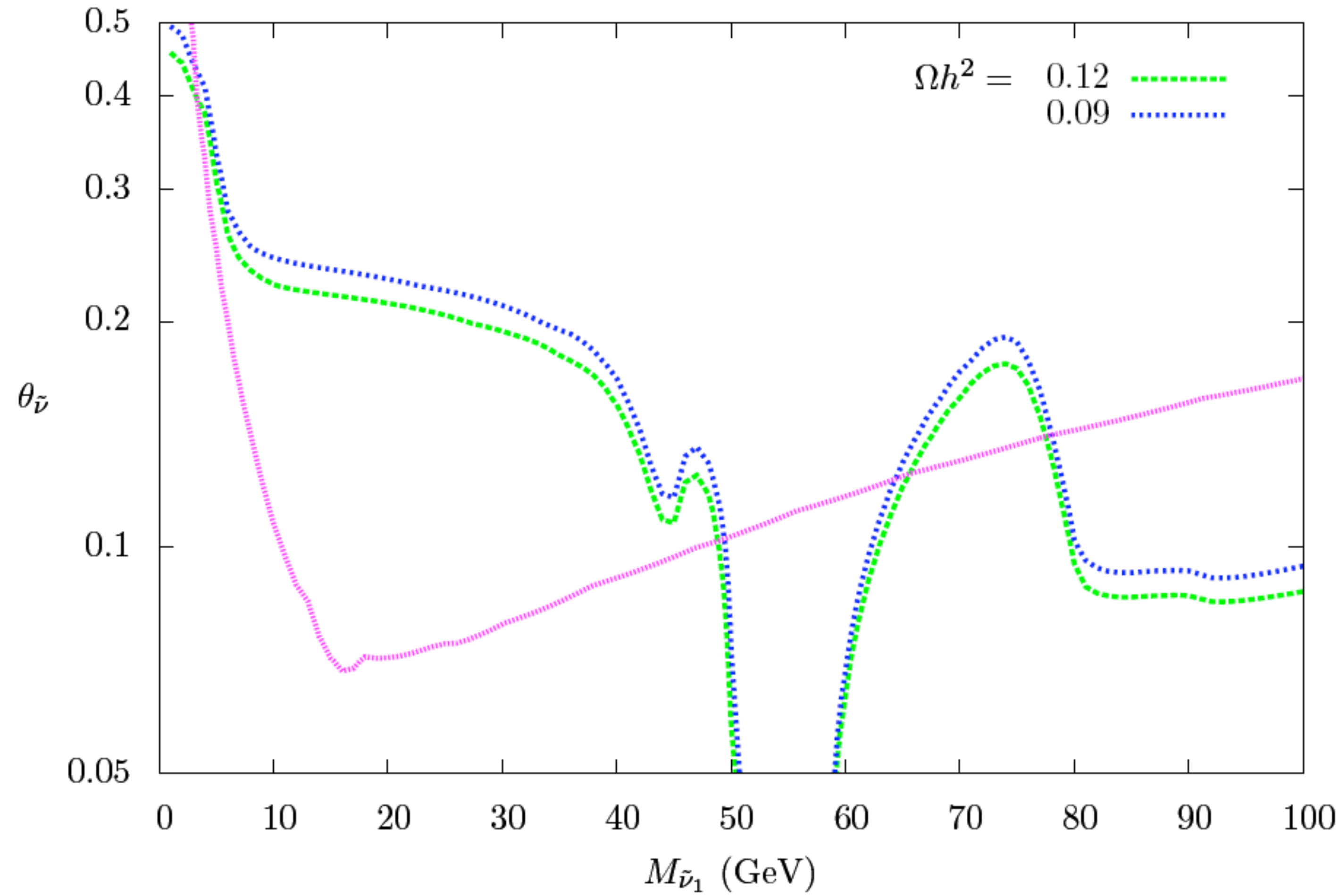

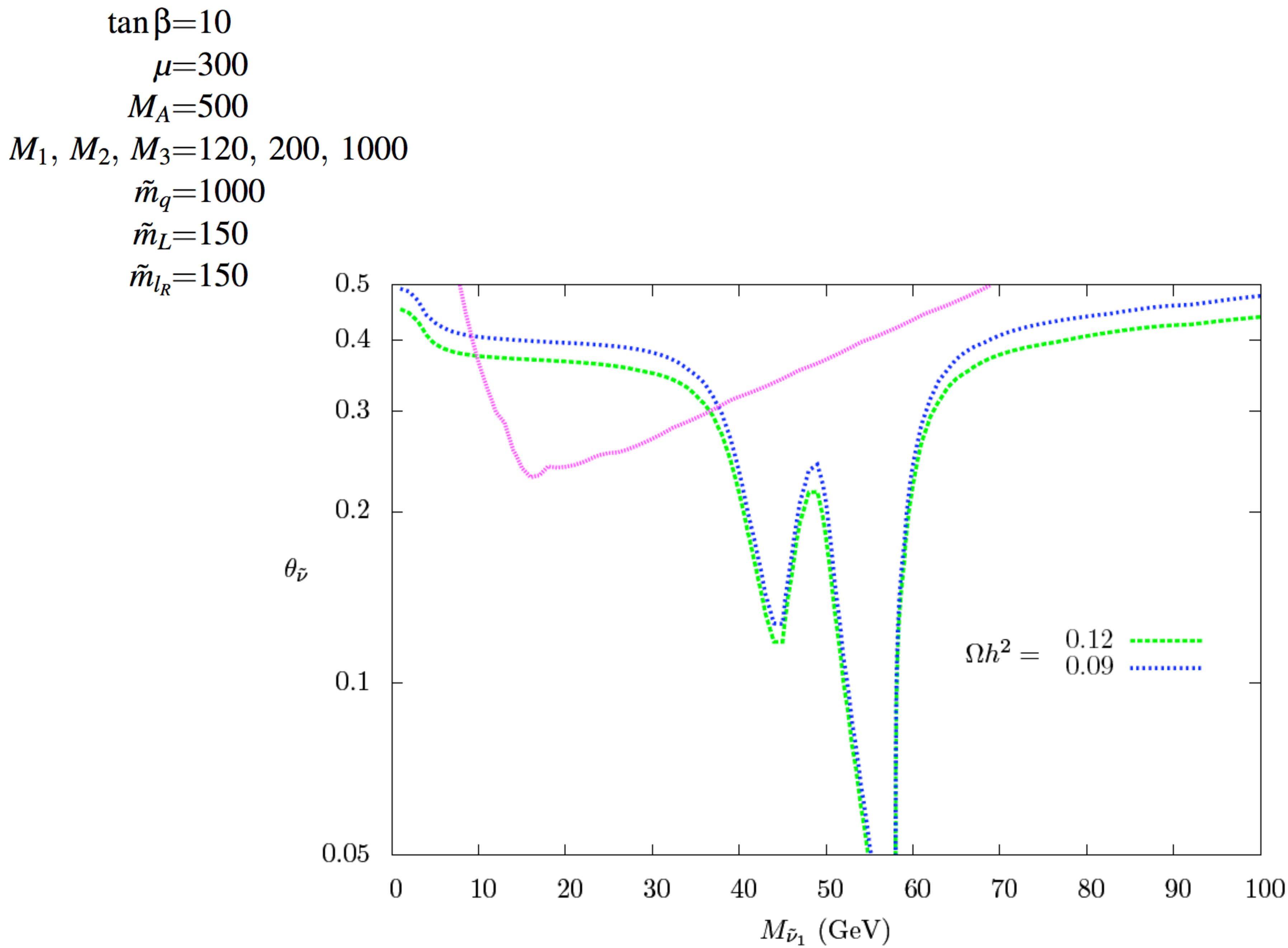

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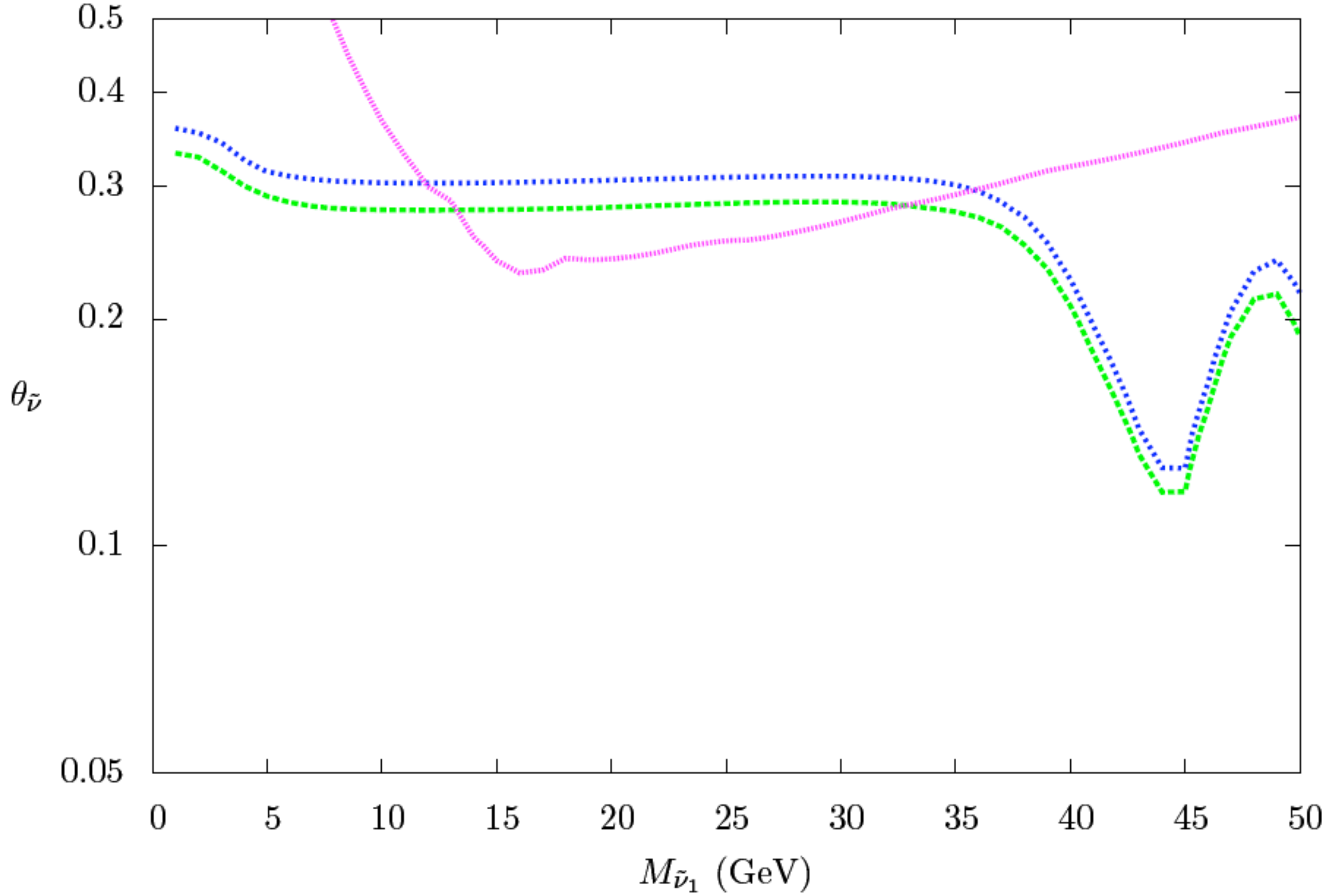
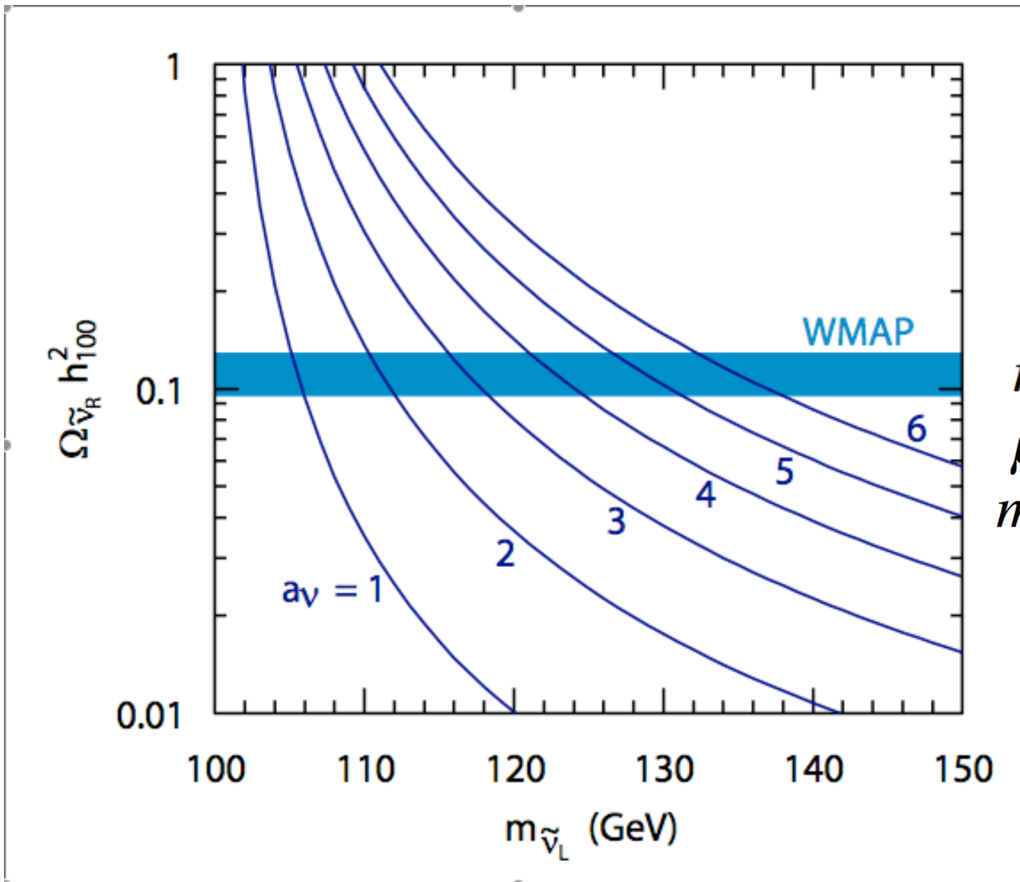


Another possibility

- Tiny A-terms and non-thermal production

Asaka, Ishiwata, and Moroi

Gopalakrishna, de Gouvea, and Porod

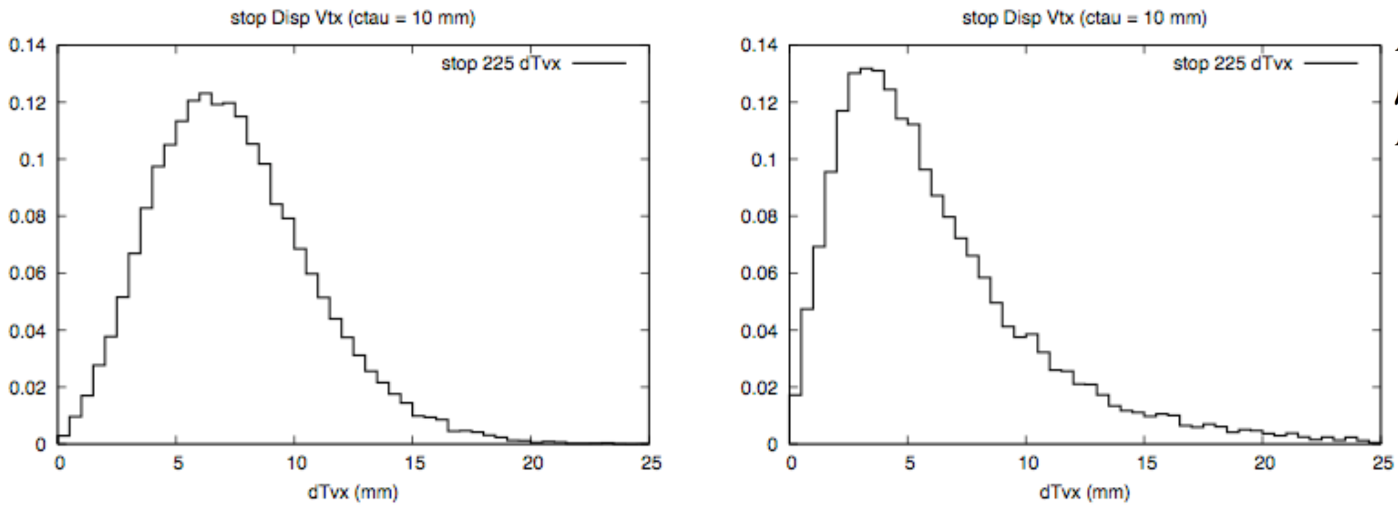


$m_{\tilde{\nu}_R} = 100$ GeV
$\mu = 150$ GeV
$m_{\tilde{W}} = 300$ GeV

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
$\lambda_\nu = 10^{-6}$

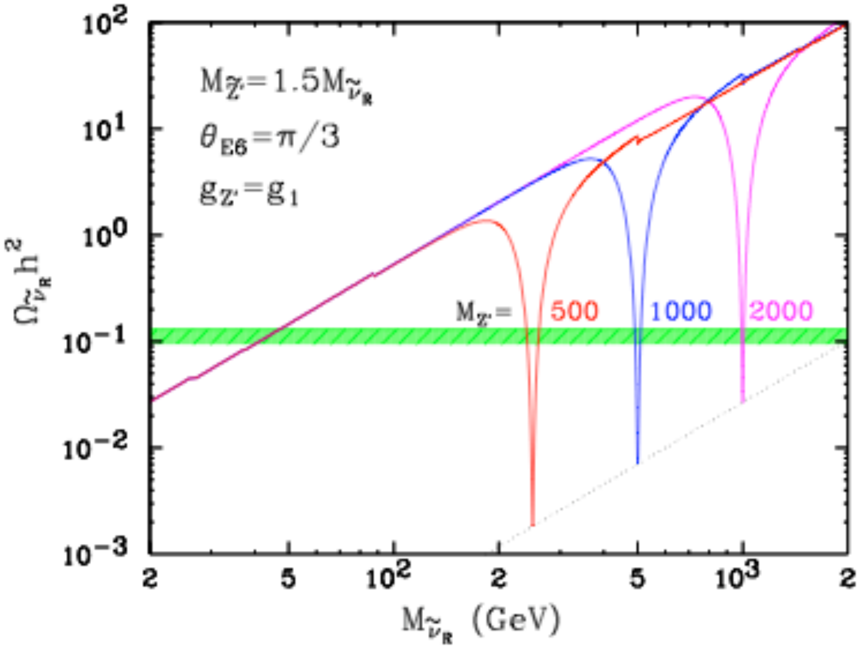
FIG. 4: The distributions of the transverse displacement of the stop (in mm), at the Tevatron (left) and the LHC (right).

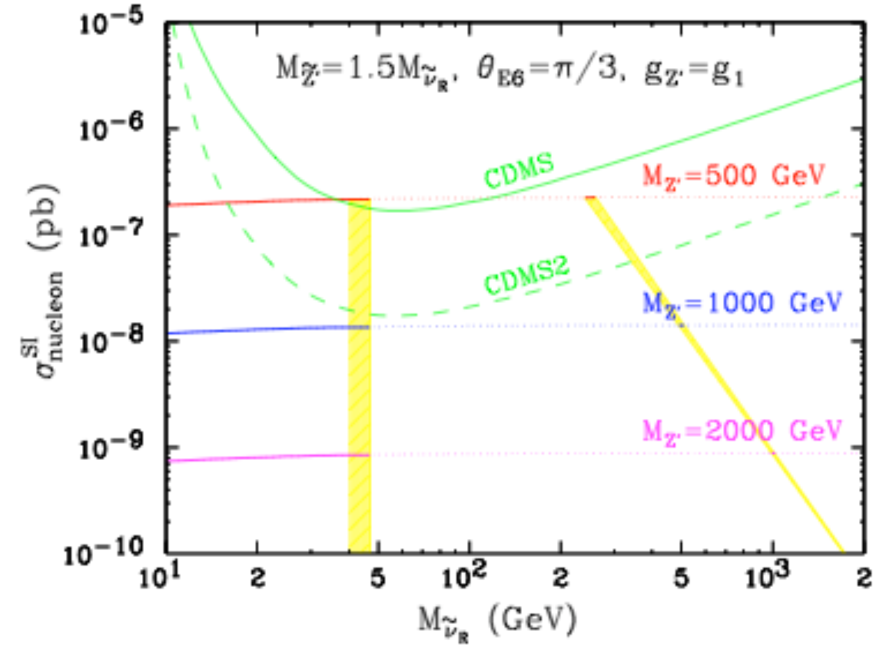
- Or, tracks from nlsp staus? Gupta, Mukhopadhyaya, Kumar Rai

Another possibility

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

Lee, Matchev, Nasri





Back to mixed sneutrino lsp

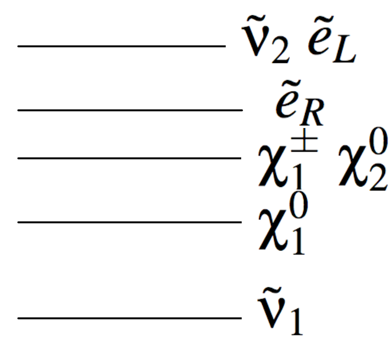
- What is the impact on collider phenomenology? Studies of MSSM signatures tend to be dominated by neutralino LSP hypothesis.

- Two quick illustrations, with mixed sneutrino "tacked on" to more conventional MSSM spectra:

1. neutralino LSP -> neutralino NSLP:

$$\tan\beta = 10$$
$$M_{1/2} = 300$$
$$M_0 = 200$$
$$M_{H_u},\ M_{H_D} = 0$$
$$A_\tau,\ A_b = 0$$
$$A_t = -500$$

$$\tilde{m}_N = 100$$
$$\theta_{\tilde{\nu}} = 0.2$$



MSSM case: $\chi_1^\pm$ and χ_2^0 decay dominantly to W χ_1^0 and Z χ_1^0

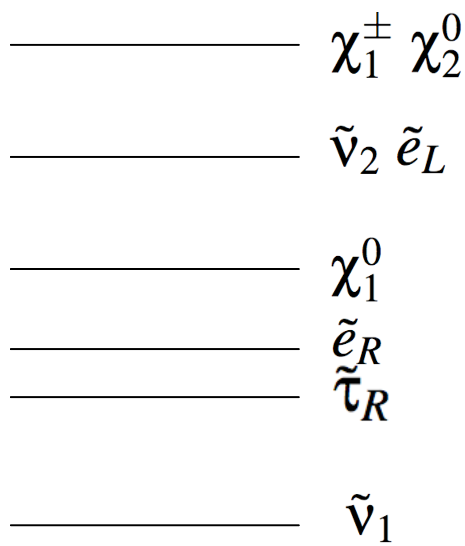
Mixed snu case: χ_2^0 decays invisibly, and $\chi_1^\pm$ decays to $\tilde{\nu}_1 l$

2. Slepton NLSP

These parameters make right-handed sleptons lighter than χ_1^0 -- to avoid stau LSP, raise right-handed soft mass to 200 GeV for MSSM case.

$\tan\beta = 10$
$M_{1/2} = 450$
$M_0 = 10$
$A_{b,\tau} = 0$
$A_t = -500$

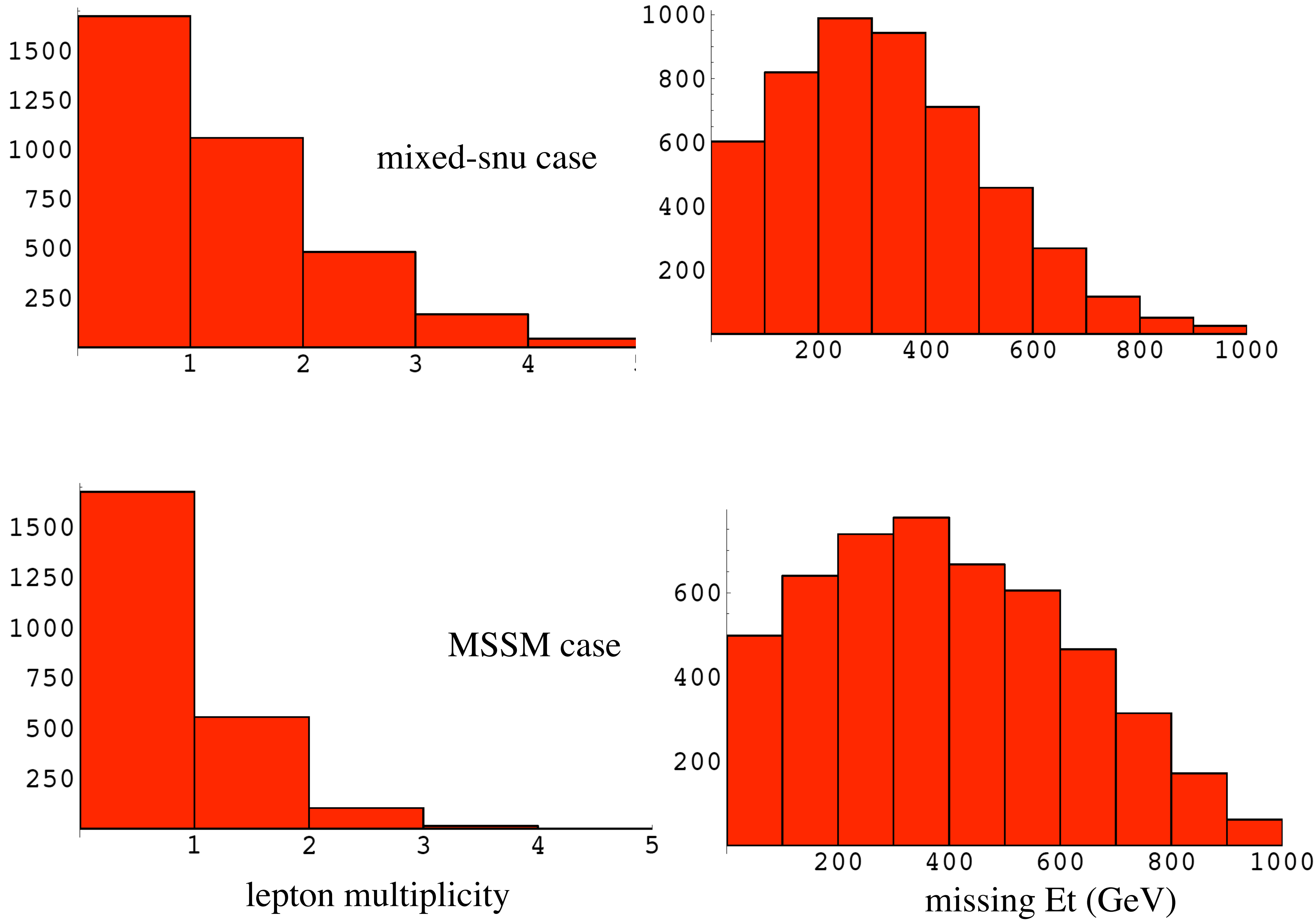
$\tilde{m}_N = 120$
$\theta_{\tilde{\nu}} = 0.2$



mixed snu case:

$Br(\chi_1^0 \to \tilde{l}_R l) = 40\%$
$Br(\chi_1^0 \to \tilde{\nu}_1 \nu) = 5\ \%$

$Br(\tilde{l}_R \to l \tilde{\nu}_1 \nu) = 96\%$



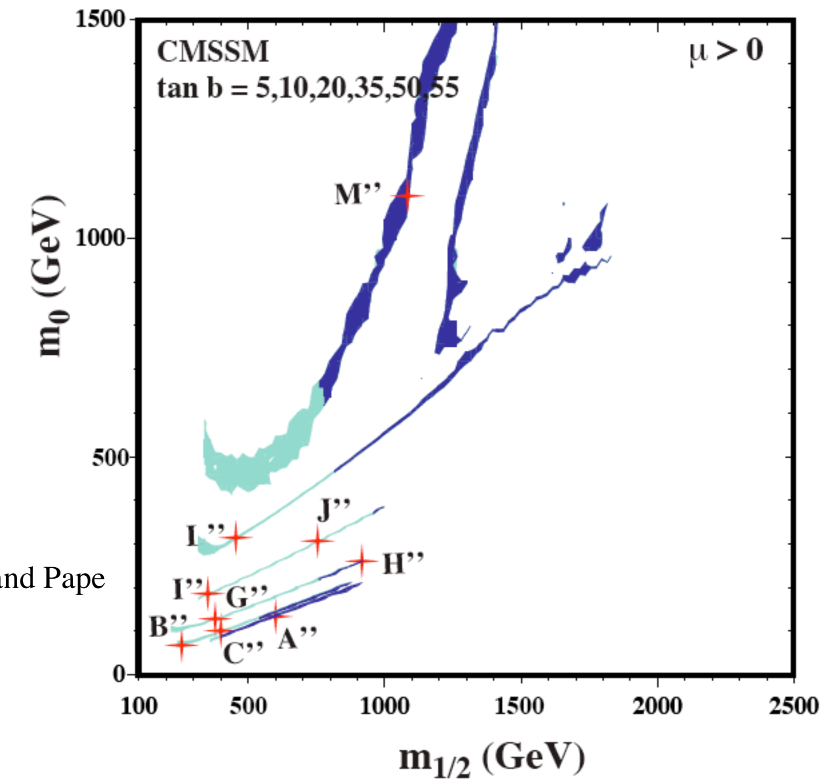
mixed-snu case
MSSM case
lepton multiplicity
missing Et (GeV)

The small angle limit

- If the sneutrino mixing angle is small enough, particles will only decay to the LSP when they have no other choice.

- In this limit, the slepton NLSP case can still have very distinctive collider phenomenology.

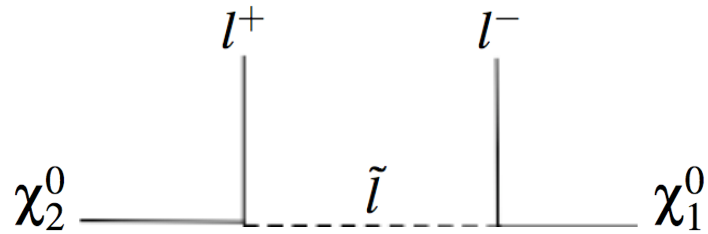
- In this limit, the neutralino NLSP case looks identical to MSSM with neutralino LSP . . . But the input from cosmology is completely different!



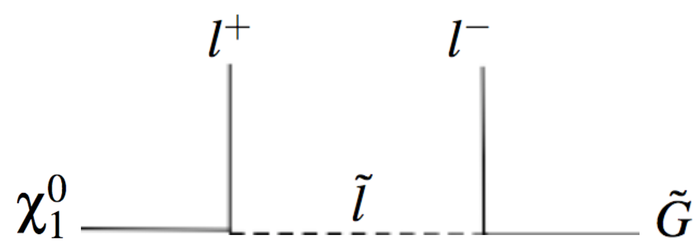
DeRoeck, Ellis, Gianotti, Moortgat, Olive, and Pape

A: opposite-sign dileptons

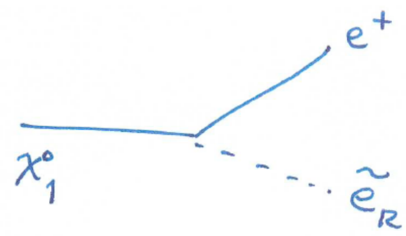
MSSM with
neutralino LSP:



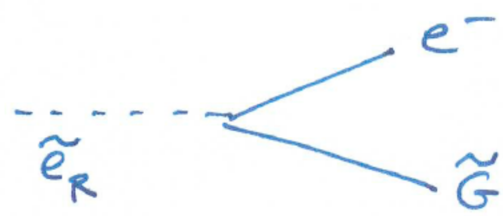
MSSM with
gravitino LSP,
slepton NLSP:



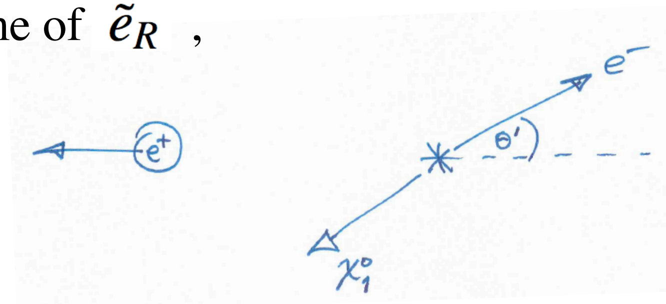
Consider the decay



. . .followed by



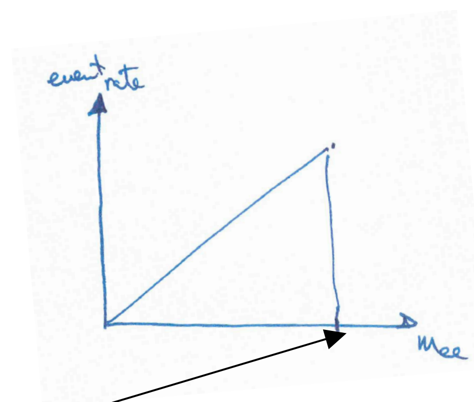
In rest frame of $\tilde{e}_R$,



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

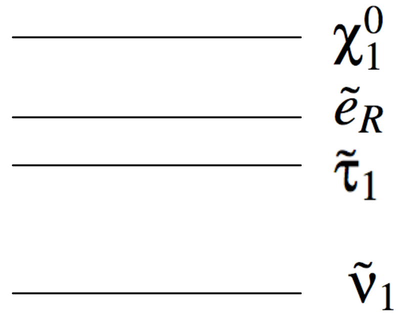
$$m_{ee}^2 \propto E_{e^-}(1+\cos\theta) \propto E'_{e^-}(1+\cos\theta')$$

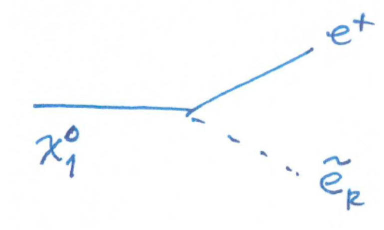
So, $d\Gamma/dm_{ee} \propto m_{ee}$



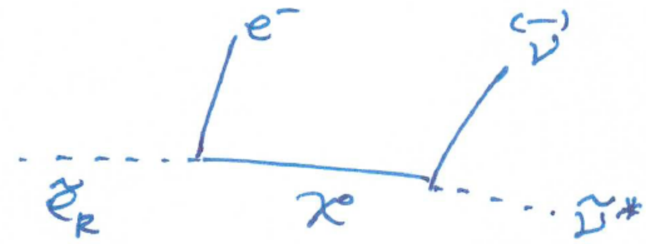
$$(m_{ee})_{max} = m_{\chi_1^0}\sqrt{1-(m_{\tilde{e}_R}/m_{\chi_1^0})^2}\sqrt{1-(m_{\tilde{G}}/m_{\tilde{e}_R})^2}$$

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





followed by



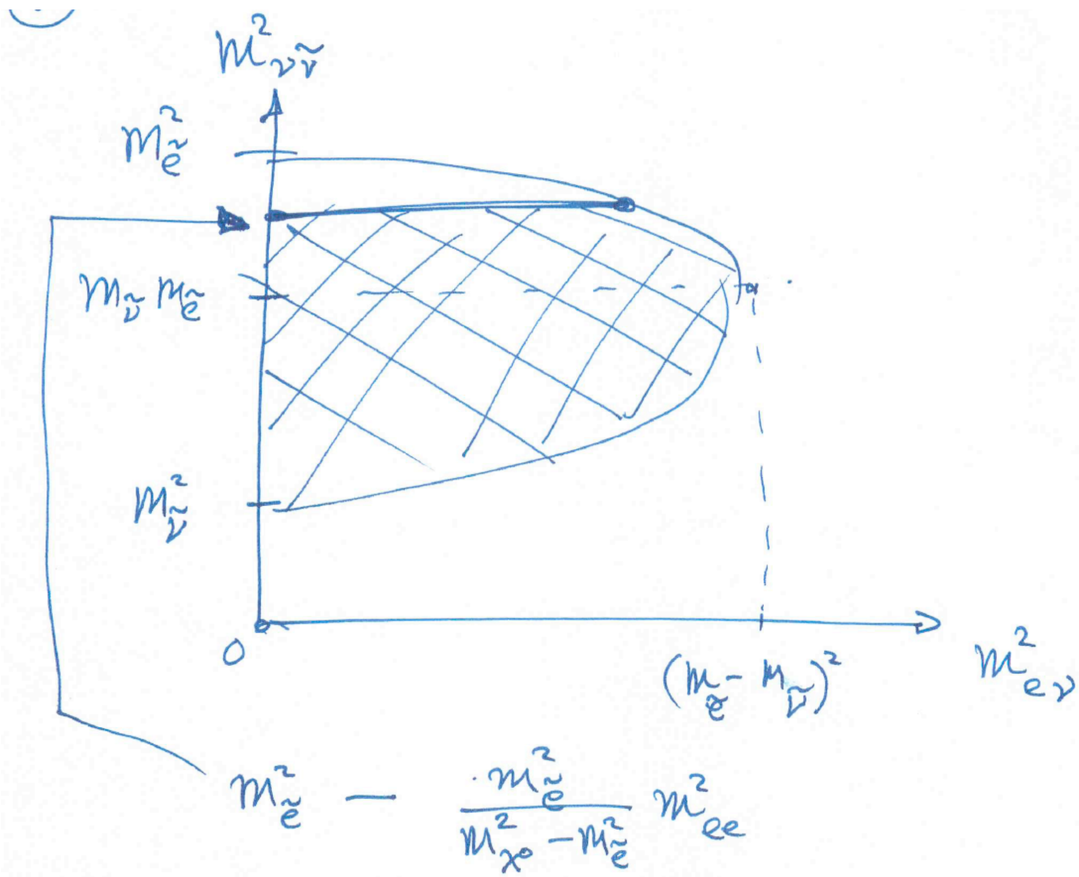
In rest frame of $\tilde{e}_R$,

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

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

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

(take constant amplitude for now)

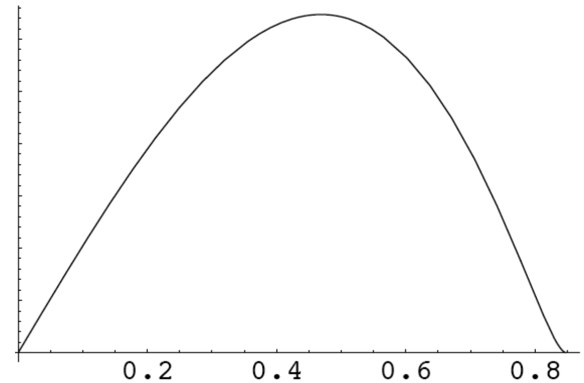


In the massless sneutrino limit,

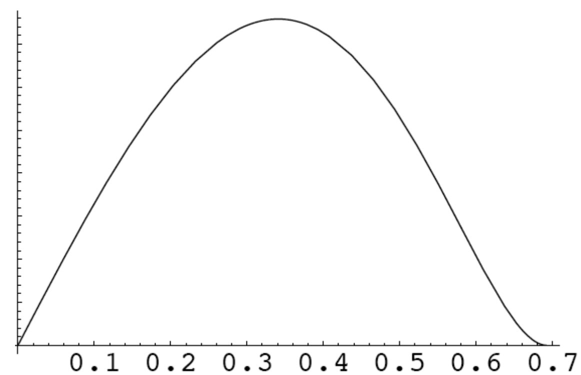
$$\frac{d\Gamma}{dm_{ee}} \propto m_{ee}\left[(m_{ee})^2_{max} - (m_{ee})^2\right]$$

Distribution shifts to lower values as sneutrino mass increases.

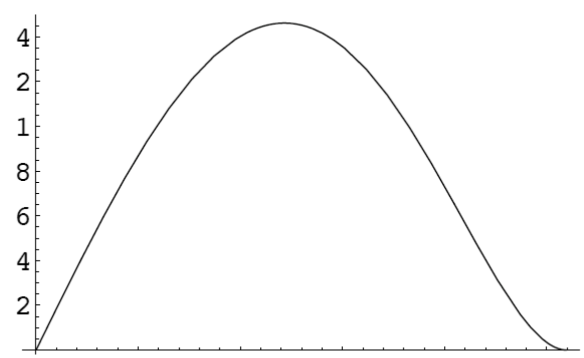
$\frac{m_{\tilde{e}}}{m_{\chi}} = 0.5$



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



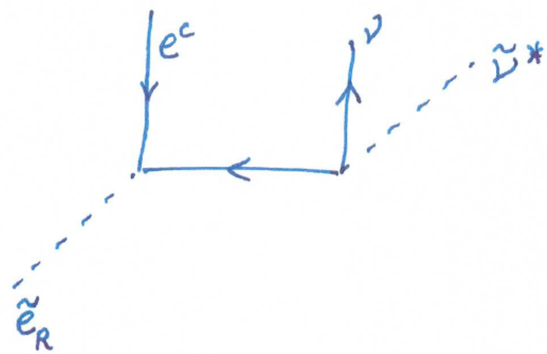
$\frac{m_{\tilde{\nu}}}{m_{\chi}} = 0.3$



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

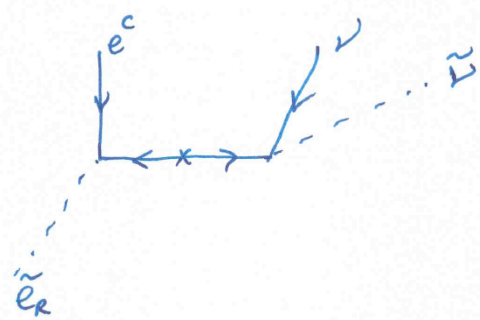
Include full $|\mathcal{M}|^2$

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



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

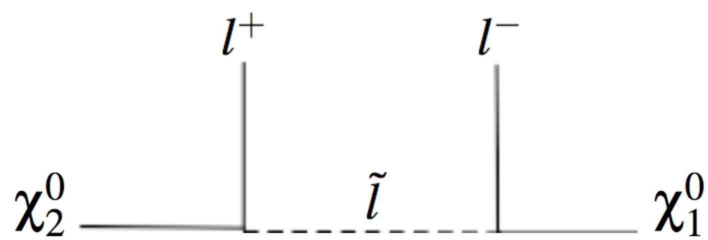
$\tilde{e}_R \to e^- \bar{\nu} \tilde{\nu}$



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

Ways to get a similar shape?

Suppose this is a 3-body decay:

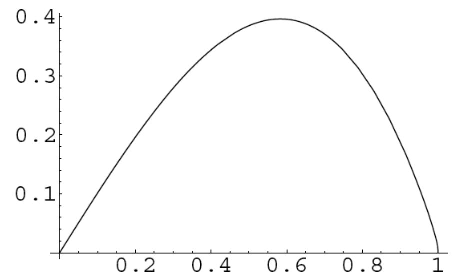


For constant amplitude,

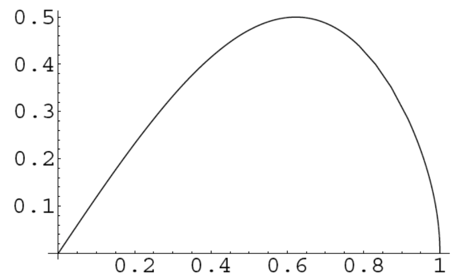
$$\frac{d\Gamma}{dm_{ee}} \propto x\sqrt{(1-x^2)((1+2K)^2-x^2)}$$

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

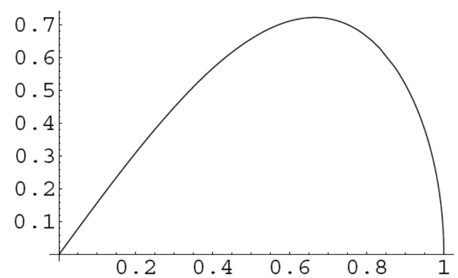
K=0



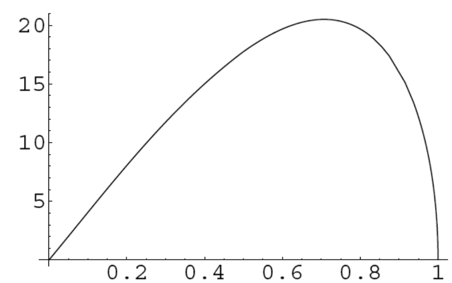
K=0.1

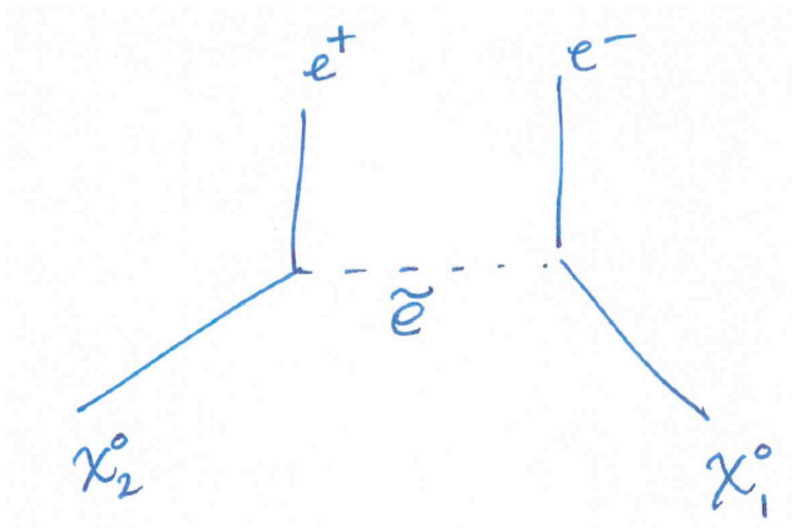


K=0.3



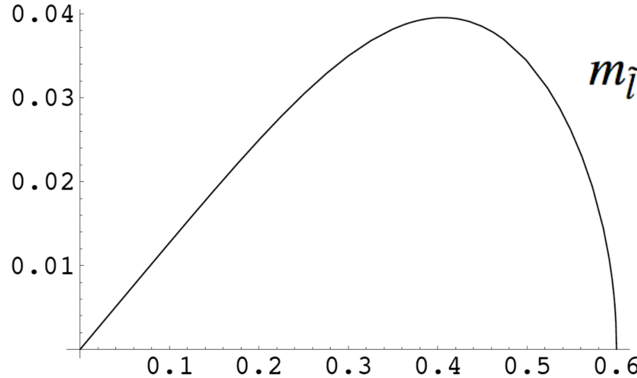
K=inf





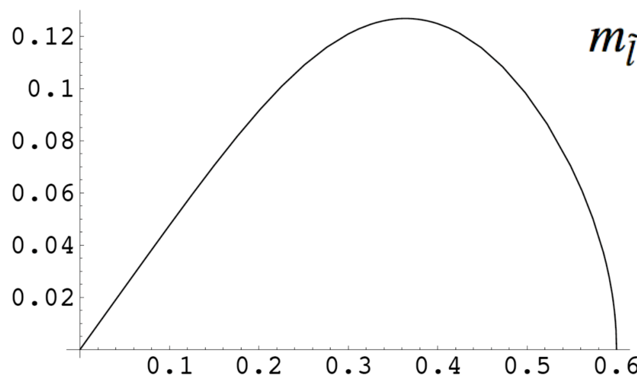
$$|\mathcal{M}|^2 \propto \frac{m^2_{e^-\chi_1}(m^2_{\chi_2} - m^2_{e^-\chi_1})}{(m^2_{e^-\chi_1} - m^2_{\tilde{e}})^2}$$

$$m_{\chi_1}/m_{\chi_2} = 0.4$$



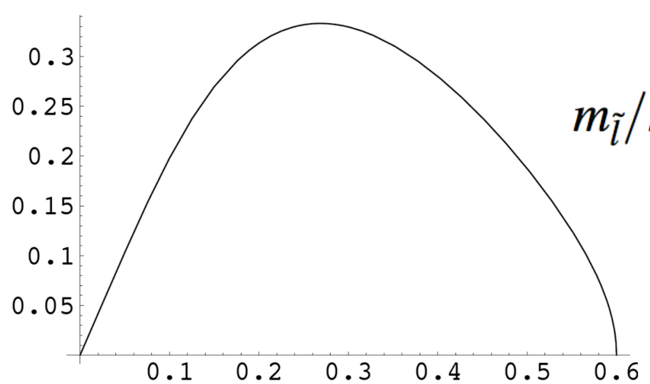
$$m_{\tilde{l}}/m_{\chi_2} = 1.3$$

44]= - Graphics -



$$m_{\tilde{l}}/m_{\chi_2} = 1.1$$

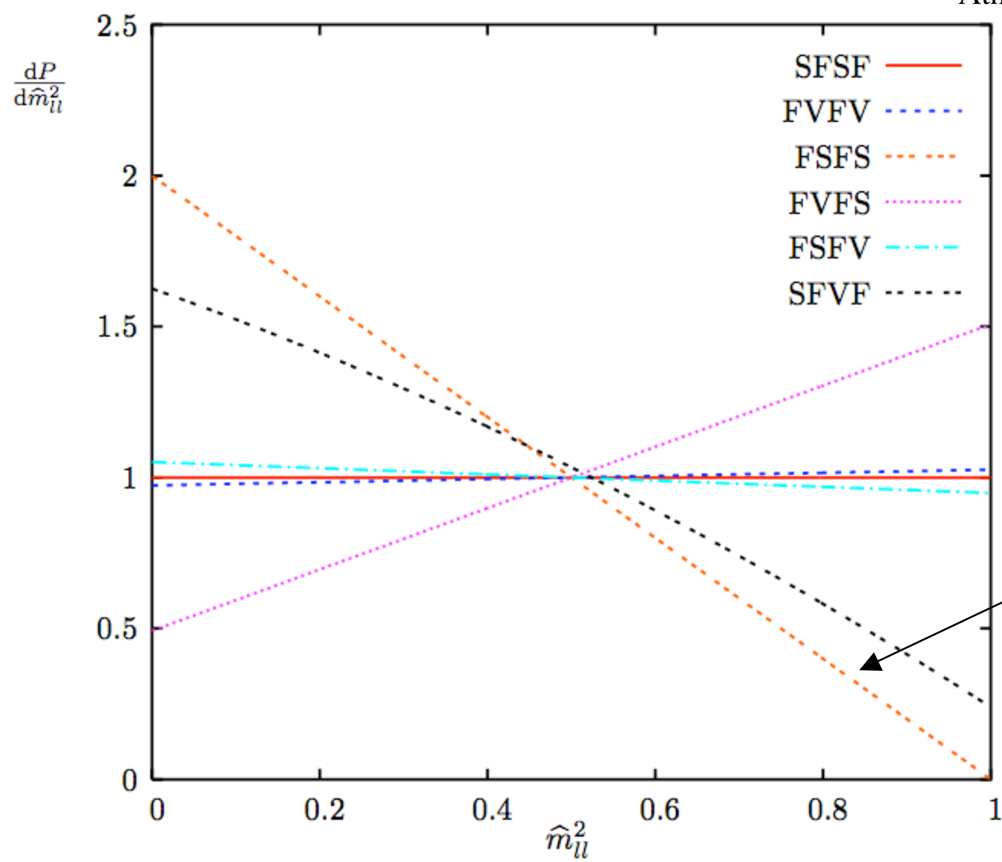
45]= - Graphics -



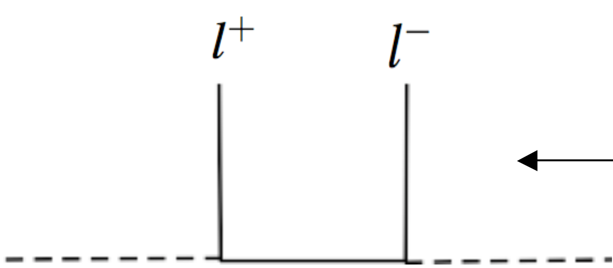
$$m_{\tilde{l}}/m_{\chi_2} = 1.01$$

Effects of spin on invariant mass distributions

Athanasioiu, Lester, Smillie, and Webber



what you get with massless sneutrino, slepton nlsp.



gives distribution with same shape as mixed sneutrino in massless sneutrino limit

- Dilep invariant mass distributions effectively distinguish $\tilde{\nu}_1$ lsp scenario with $\tilde{l}_R$ nlsp from gravitino lsp case.

- Also can distinguish 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 $\tilde{l}_L, \chi_2$ are nearly degenerate.

- If $(m_{ee})_{max}$ is small, becomes more challenging to invoke these.

About the simulations

- (Almost) no backgrounds yet.
- Adapted SUSY-HIT package to accommodate mixed sneutrino.
  Djouadi, Muhlleitner, Spira
- Generated SUSY events with initial/final-state radiation, hadronization using Pythia. Sjostrand, Mrenna, Skands
- Ran showered events through PGS detector simulator. Conway et. al.

A sample point

$\tan\beta = 10$

$M_{1/2} = 450$

$M_0 = 10$

$A_{b,\tau} = 0$

$A_t = -500$

$\tilde{m}_N = 120$

$\theta_{\tilde{\nu}} = 0.2$

1040	$\tilde{g}$
~900	$\tilde{q}$
~660	$\chi_3^0 \; \chi_4^0 \; \chi_2^\pm \; \tilde{t}_1$
349	$\chi_1^\pm \; \chi_2^0$
~300	$\tilde{\nu}_2 \; \tilde{e}_L$
184	χ_1^0
172	$\tilde{e}_R$
162	$\tilde{\tau}_R$
107	$\tilde{\nu}_1$

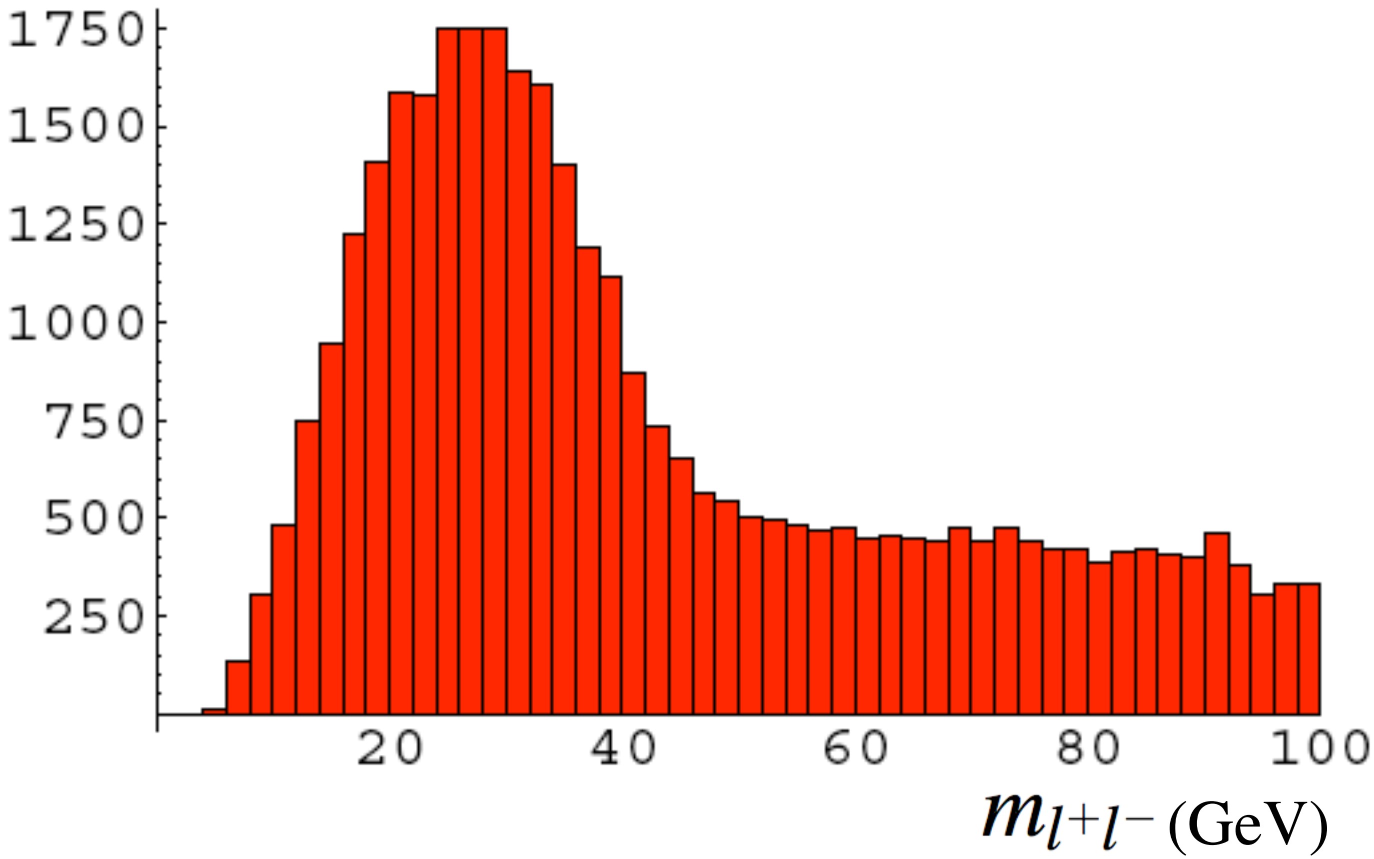
$Br(\chi_1^0 \to \tilde{l}_R l) = 40\%$

$Br(\chi_1^0 \to \tilde{\nu}_1 \nu) = 5\,\%$

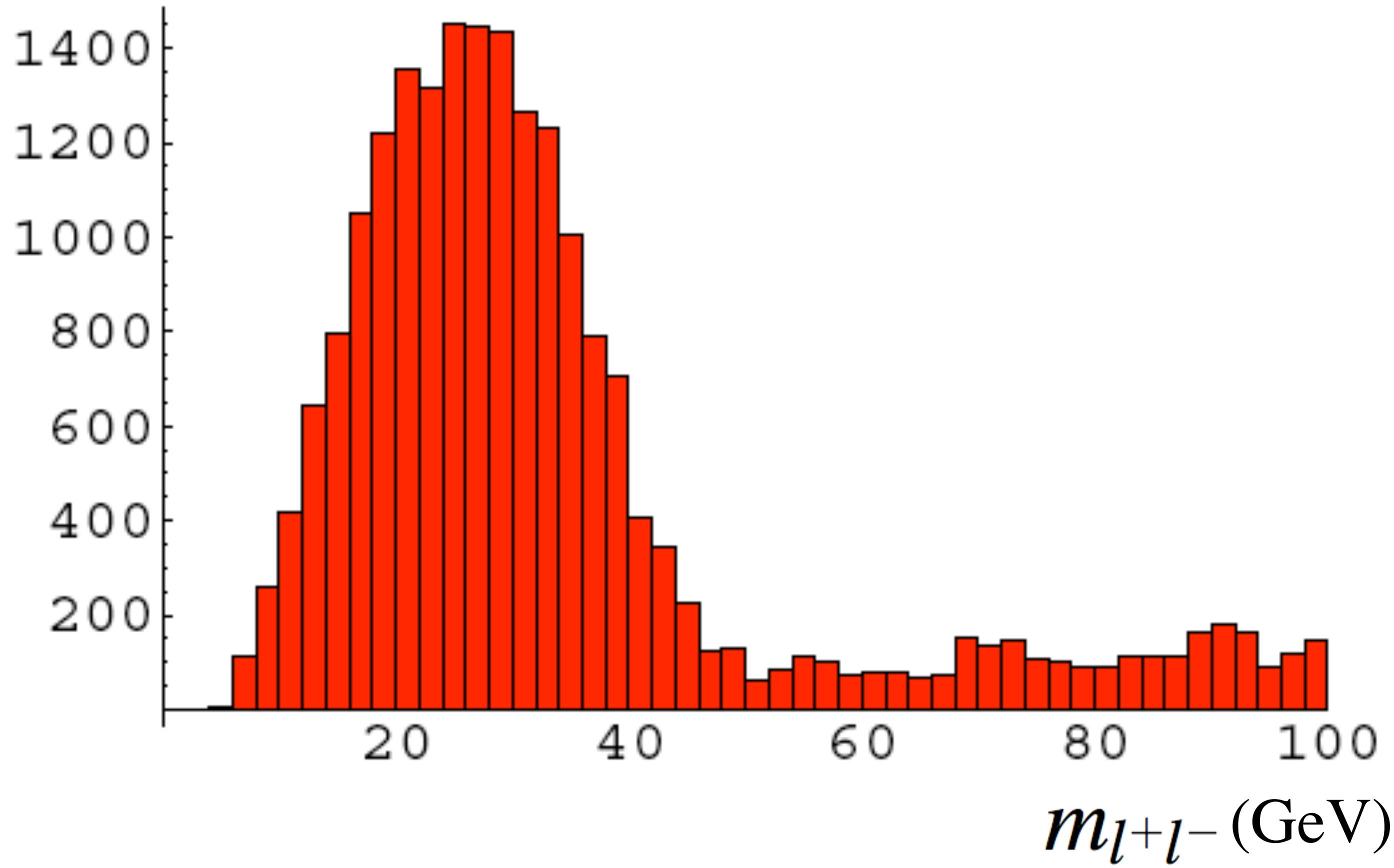
$Br(\tilde{l}_R \to l \tilde{\nu}_1 \nu) = 96\%$

mixing is with tau sneutrino alone

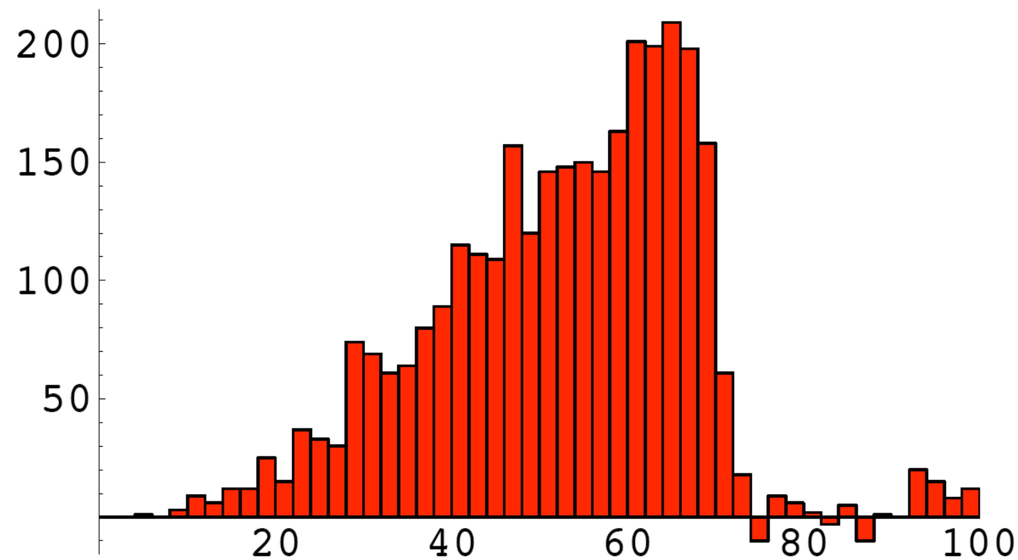
Take events with an e+e- pair and/or a mu+mu- pair . . .



Subtract off invariant mass distributions for e+mu- pair and mu+e- pairs: .



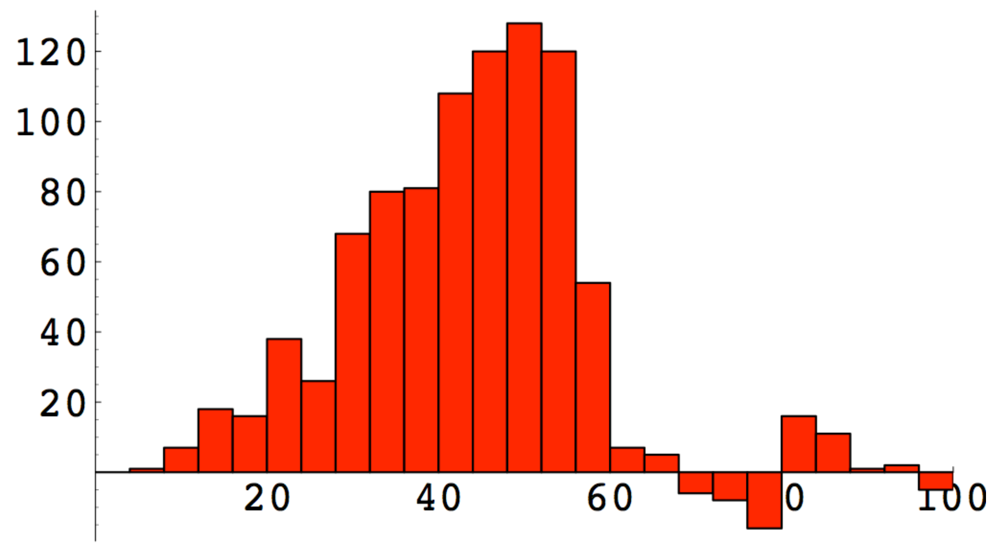
Replace sneutrino lsp with gravitino:



Three-body decay with similar endpoint mass:

$$\chi_2^0 \rightarrow \chi_1^0 e^+ e^-$$

$$m_{\chi_2^0} = 111$$
$$m_{\chi_1^0} = 48$$
$$m_{\tilde{l}_L} = 138$$
$$m_{\tilde{\nu}} = 113$$



B: Chargino-dominated lepton production

- Typical decays of χ_2^0 in MSSM:

$$\tilde{l}l,\ \tilde{\nu}\nu,\ \chi_1^0 Z,\ \chi_1^0 h,\ l^+l^-\chi_1^0,\ q\bar{q}\chi_1^0$$

- With mixed-sneutrino LSP, easy to have ~100% branching ratios for

$$\chi_2^0 \to \tilde{\nu}_1 \nu$$

$$\chi_1^0 \to \tilde{\nu}_1 \nu$$

$$\chi_1^+ \to \tilde{\nu}_1 l^+$$

$\tilde{\nu}_2\ \tilde{e}_L$

$\tilde{e}_R$

$\chi_1^\pm\ \chi_2^0$

χ_1^0

$\tilde{\nu}_1$

Take these parameters:

$\tan\beta = 10$

$M_{1/2} = 300$ $\quad \tilde{m}_N = 100$

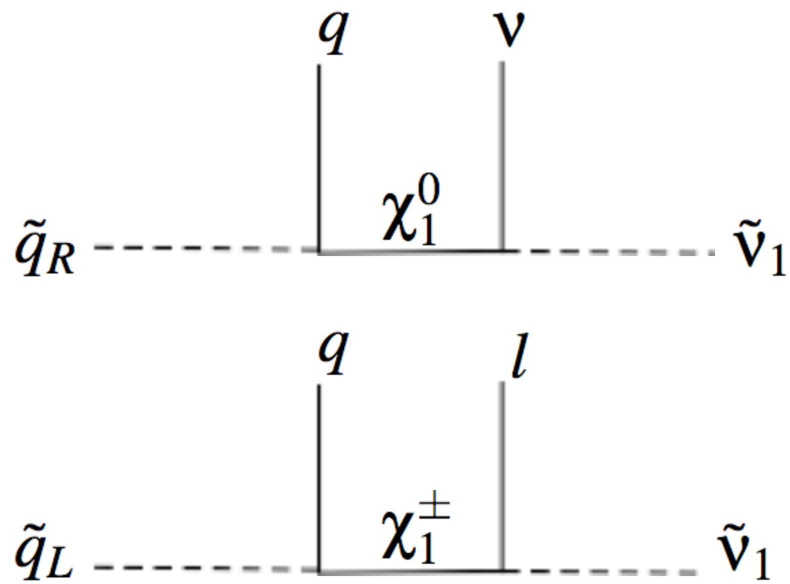
$M_0 = 200$ $\quad \theta_{\tilde{\nu}} = 0.2$

$M_{H_u},\ M_{H_D} = 0$

$A_\tau,\ A_b = 0$ $\quad (\sigma = 15\ \text{pb})$

$A_t = -500$

- Get lots events with



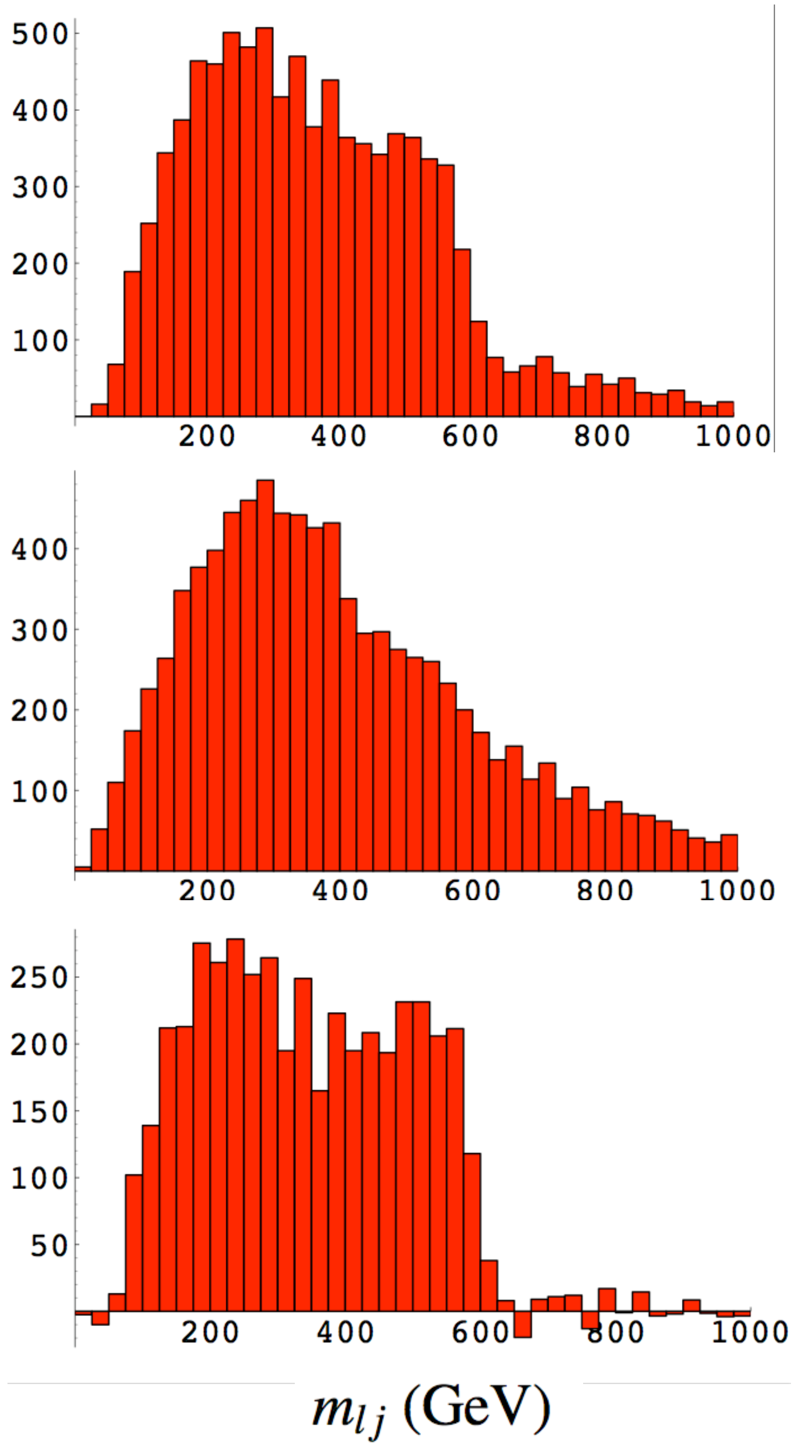
- Signature: hard jets + missing transverse energy + lepton, with kinematic edge in lepton-jet invariant mass.

... and no dilepton invariant mass edge.

- Require
  - exactly two jets with pt > 150 GeV
  - exactly one lepton with pt > 10 GeV
  - $\not{E}_T$ > 250 GeV
  - m_T > 250 GeV
- Take invariant mass for both j-l pairings (so have combinatorial background).

Mangano, Moretti, Piccinini, Pittau, Polosa

- Simulated W+2jets with Alpgen: required pt>100 GeV at generator level, found σ = 150 pb. ~90,000 events generated (~0.6/fb), 0 passed cuts.
- Signal: ~120,000 events generated (~8/fb), 4320 passed cuts.

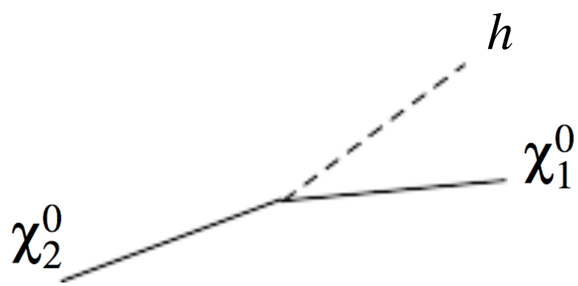


match l and j from different events:

subtract:

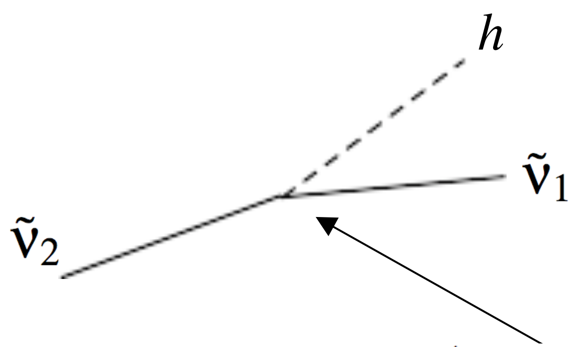
C: Higgs + lepton

- In MSSM, can have



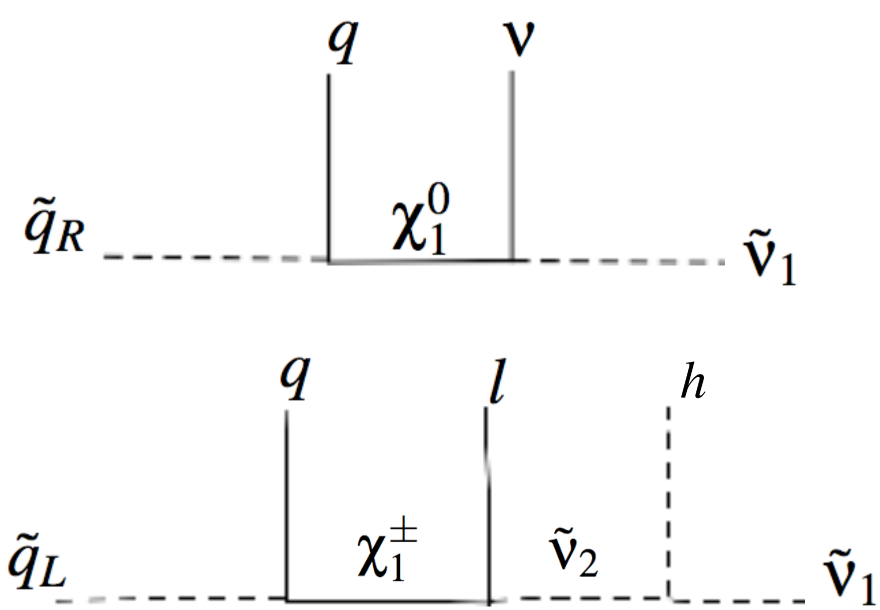
(if kinematically accessible)

- With mixed sneutrinos, can also have



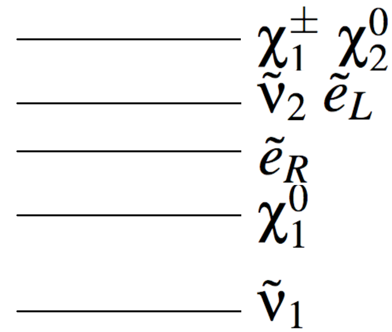
$\frac{A}{\sqrt{2}} \cos\alpha \cos 2\theta$ + D-term contribution

- Look for



- Require $m_{b\bar{b}}$ in peak, hope for edge in $m_{b\bar{b}l}$ distribution.

- To get appreciable signal, need
  - $Br(\chi_1^+ \to \tilde{\nu}_2 l)$ not too small ($\theta_{\tilde{\nu}}$ not too big)
  - $Br(\tilde{\nu}_2 \to \tilde{\nu}_1 h)$ not too small ($\theta_{\tilde{\nu}}$ not too small)



- Sample point (low-energy input):

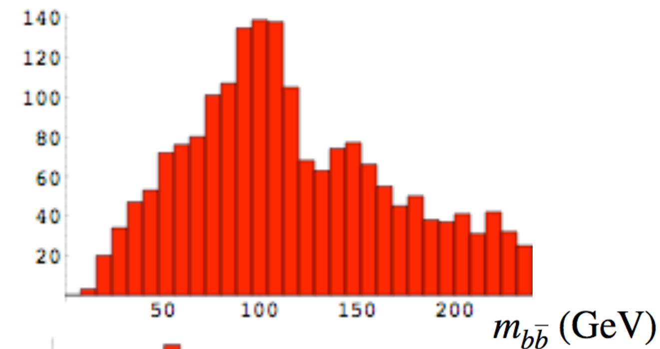
$$\tan\beta = 10$$
$$\mu = 600$$
$$M_A = 350$$
$$M_1,\ M_2,\ M_3 = 200,\ 500,\ 700$$
$$\tilde{m}_q = 600$$
$$\tilde{m}_L = 300$$
$$\tilde{m}_{l_R} = 250$$

$$\theta_{\tilde{\nu}} = 0.2$$
$$\tilde{m}_N = 100$$

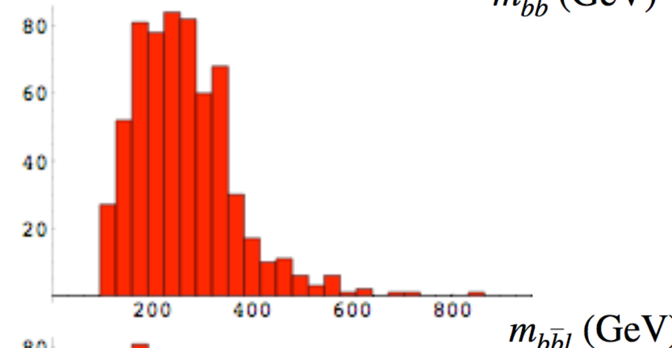
gives

$$Br(\chi_1^+ \to \tilde{\nu}_2 l) = 32\%$$
$$Br(\tilde{\nu}_2 \to \tilde{\nu}_1 h) = 37\%$$

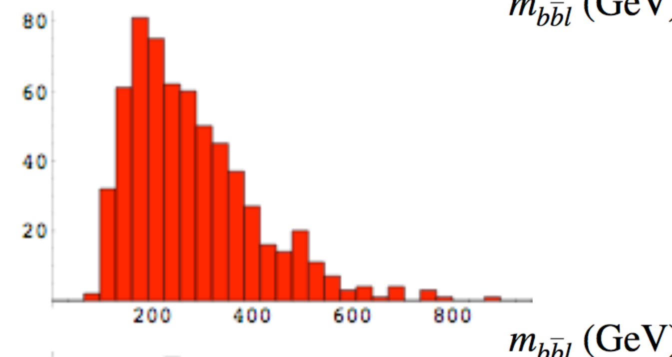
-Generated 120,000 events (~7/fb), required exactly two b tags, and exactly one lepton (2183 events)



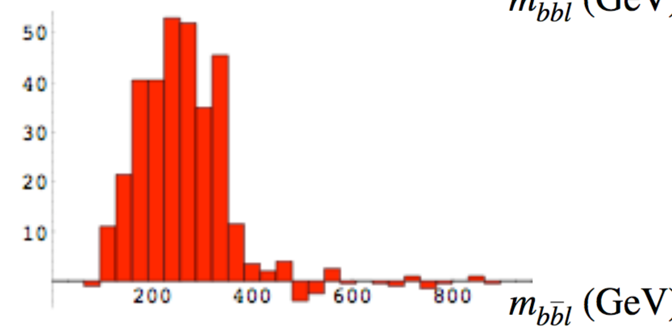
-Forced bb invariant mass to be in 40 GeV interval centered at peak (624 events).



match b's with
lepton from different event:

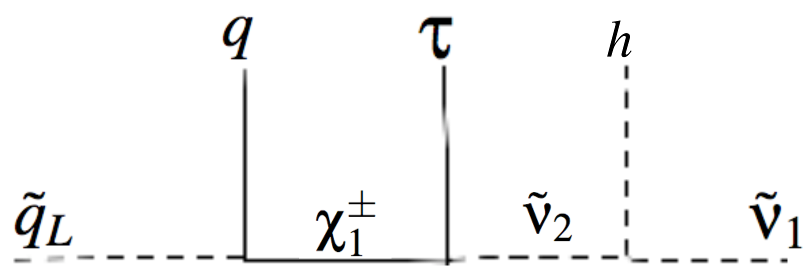


subtract:

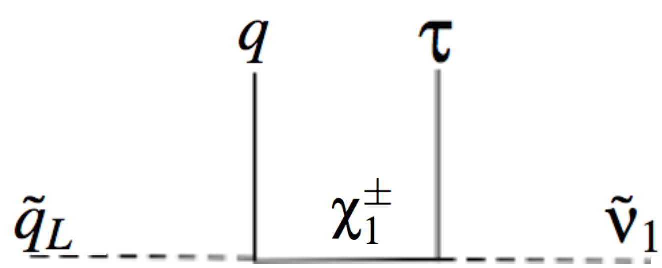


D: tau signatures

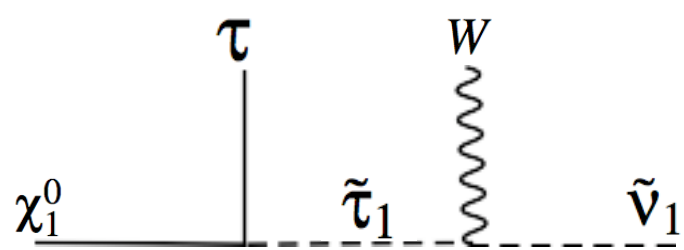
tau-higgs



tau-jet



tau-W



Conclusions

- Mixed sneutrino is a viable dark matter candidate
  - In lepton # conserving case (Dirac neutrinos), mixing angle must be small ($\lesssim$ 0.06) to evade direct detection bounds, except for very small masses ($\lesssim$ few GeV).
  - Then to get interesting abundance, should be in Higgs funnel, or have heavy left-handed sleptons (masses $\gtrsim$ TeV).
  - With lepton-# violation, elastic scattering through Z exchange can be suppressed, but scattering through Higgs exchange still places important constraints.
  - Interesting regions: small lsp masses with light gauginos and $\theta \sim 0.3$, near Z/higgs poles, and above threshold for annihilation into W pairs.

- A mixed sneutrino LSP impacts collider phenomenology.
  - e.g. likely to alter lepton multiplicity, missing energy distribution.
  - At the very least, invites us to reconsider parameter regions thought to be cosmologically disfavored in MSSM.

- Possible signals include
  - opposite-sign dileptons with invariant mass distribution shifted away from endpoint (right-handed slepton NSLP).
  - lepton-jet kinetmatic edge from chargino decay straight to lsp sneutrino.
  - higgs-lepton (or Z-lepton) production.