Mixed-sneutrino dark matter at the LHC

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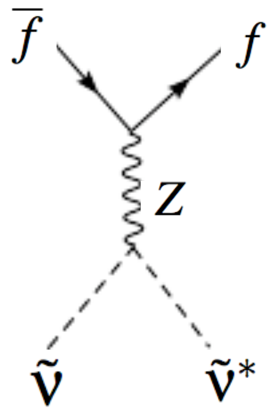
Work in progress with Spencer Chang, Zachary Thomas, and Neal Weiner

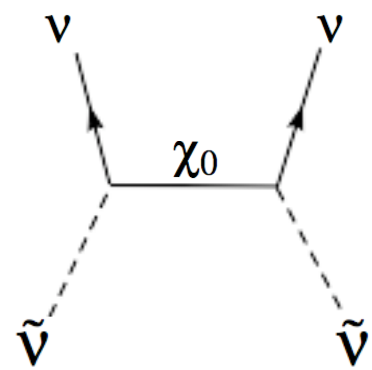
	times mentioned in Atlas physics TDR	times mentioned in CMS physics TDR
slepton	130	41
squark	104	54
gluino	89	54
neutralino	46	48
chargino	29	33
sneutrino	1	0

"... 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 → $\tilde{\chi}_2^0 \tilde{\chi}_2^0$, 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 $M_{\tilde{\nu}} < \text{few GeV or} > 600\ \text{GeV}$

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

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

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

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 $A_\nu \, LNH_u$

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

$$\tilde{\nu}_1 = -\sin\theta \, \tilde{\nu} + \cos\theta \, \tilde{n}^*$$
$$\tilde{\nu}_2 = \cos\theta \, \tilde{\nu} + \sin\theta \, \tilde{n}^*$$

(Other ideas: tiny A-terms and non-thermal production, tiny A-terms and thermalization via a Z')

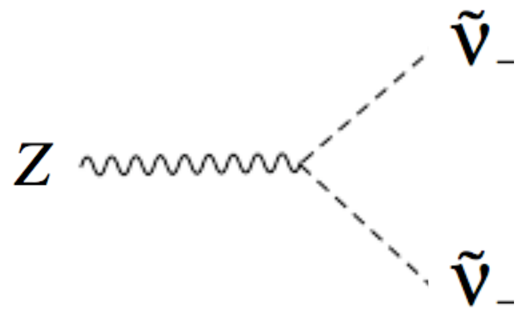
Asaka, Ishiwata, and Moroi

Gopalakrishna, de Gouvea, and Porod

Lee, Matchev, Nasri

Mass splittings and inelastic scattering

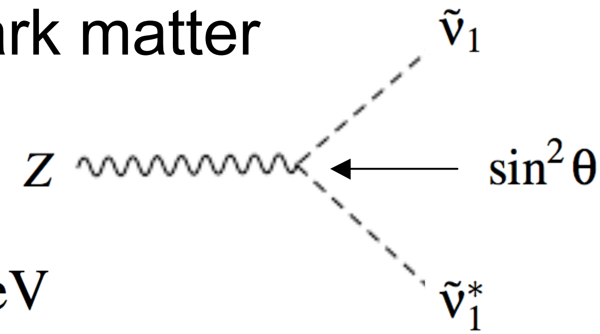
- A small lepton-violating mass term $\tilde{n}\tilde{n}$ will introduce a mass splitting between the CP-even and CP-odd parts of $\tilde{\nu}_1$



does not exist!

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

Implications of mixing for dark matter



- Z-width constraint:

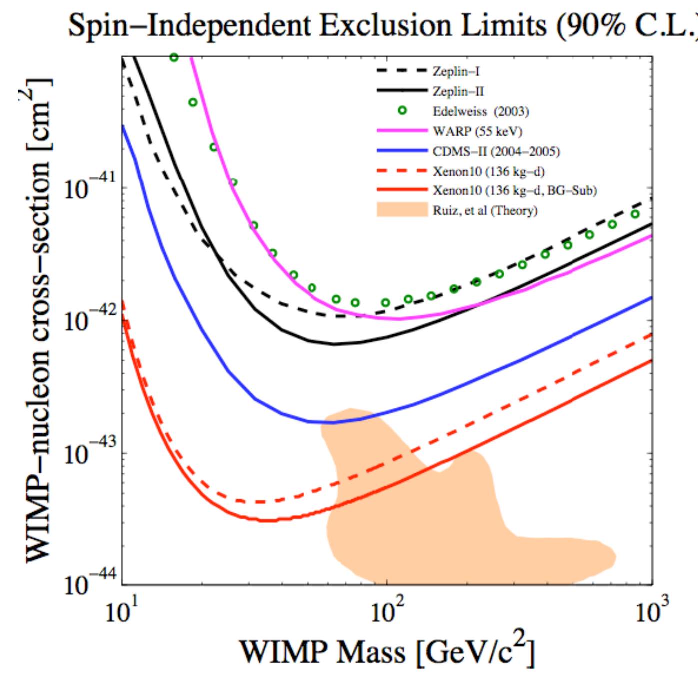
$$\delta\Gamma = \frac{\sin^4\theta}{2}[1-(2m_{\tilde{\nu}_1}/m_z)^2]^{3/2}\Gamma_\nu < 2\text{ MeV}$$

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

- Without inelasticity, cross section for scattering via Z-exchange is

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

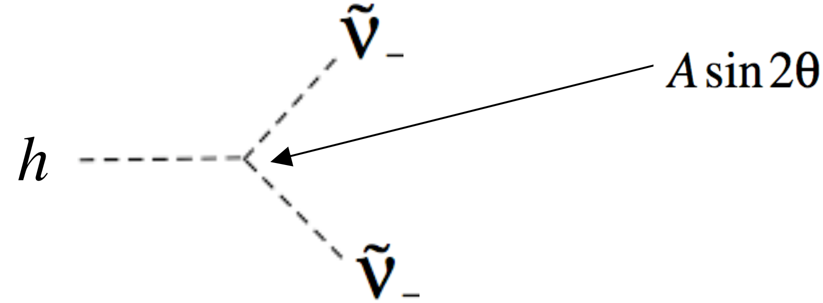
If $\sin\theta < 0.06$, no constraint on mass . . .



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

Elastic scattering, annihilation from Higgs exchange

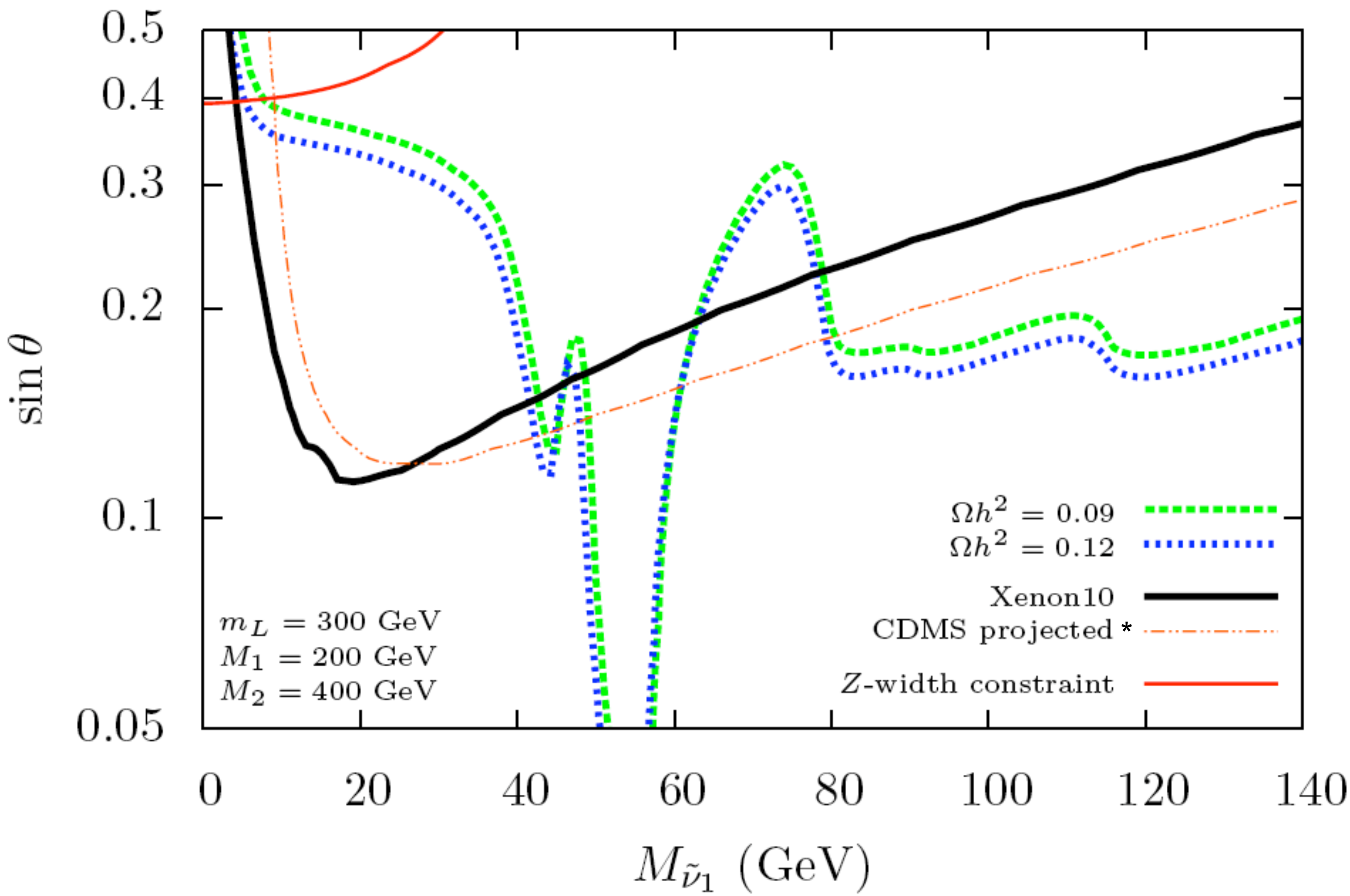
- Even if elastic scattering by Z exchange is turned off, still have



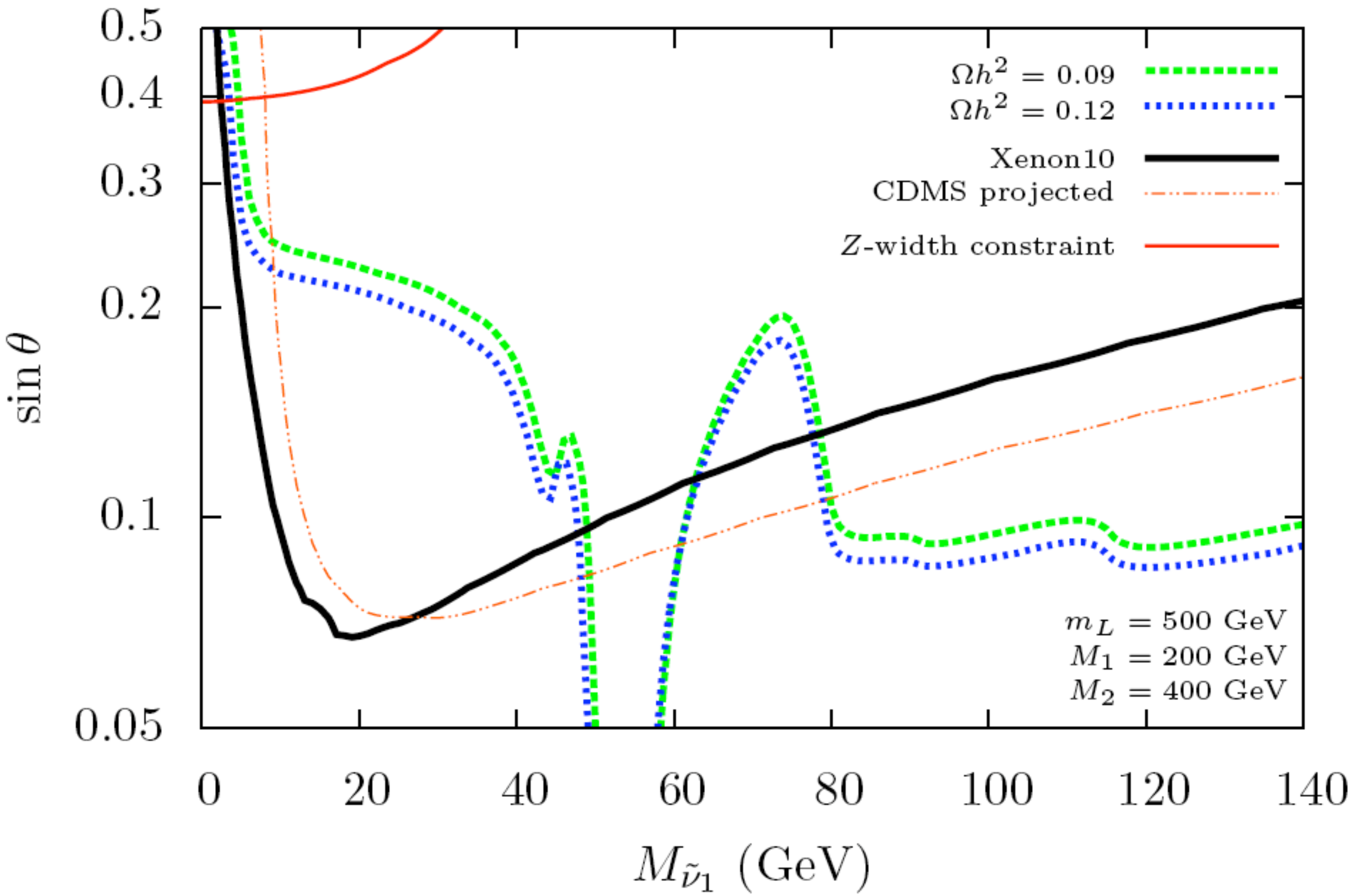
- If A terms are sizeable, s-channel Higgs exchange can give efficient annihilation (especially if W+W- is kinematically accessible).

Belanger, Boudjema, Pukhov, Semenov

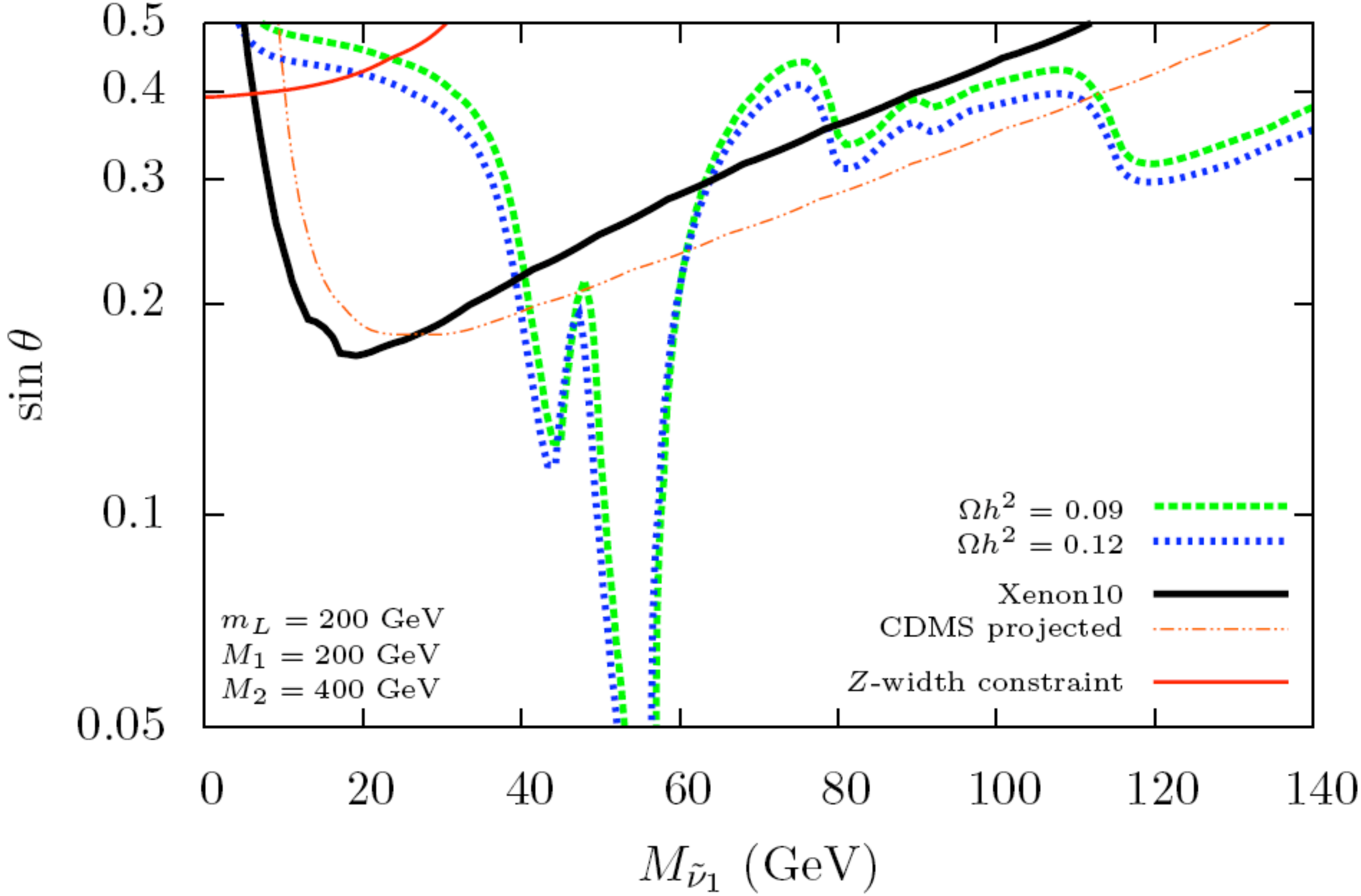
- Calculate relic abundance using Micromegas 2.0, see what comologically preferred regions are still allowed . . .



* K. Ni and L. Baudis, astro-ph/0611124



0.5
0.4
0.3
0.2
0.1
0.05
$\sin\theta$
0
20
40
60
80
100
120
140
$M_{\tilde{\nu}_1}$ (GeV)
$\Omega h^2 = 0.09$
$\Omega h^2 = 0.12$
Xenon10
CDMS projected
Z-width constraint
$m_L = 500$ GeV
$M_1 = 200$ GeV
$M_2 = 400$ GeV


0.5
0.4
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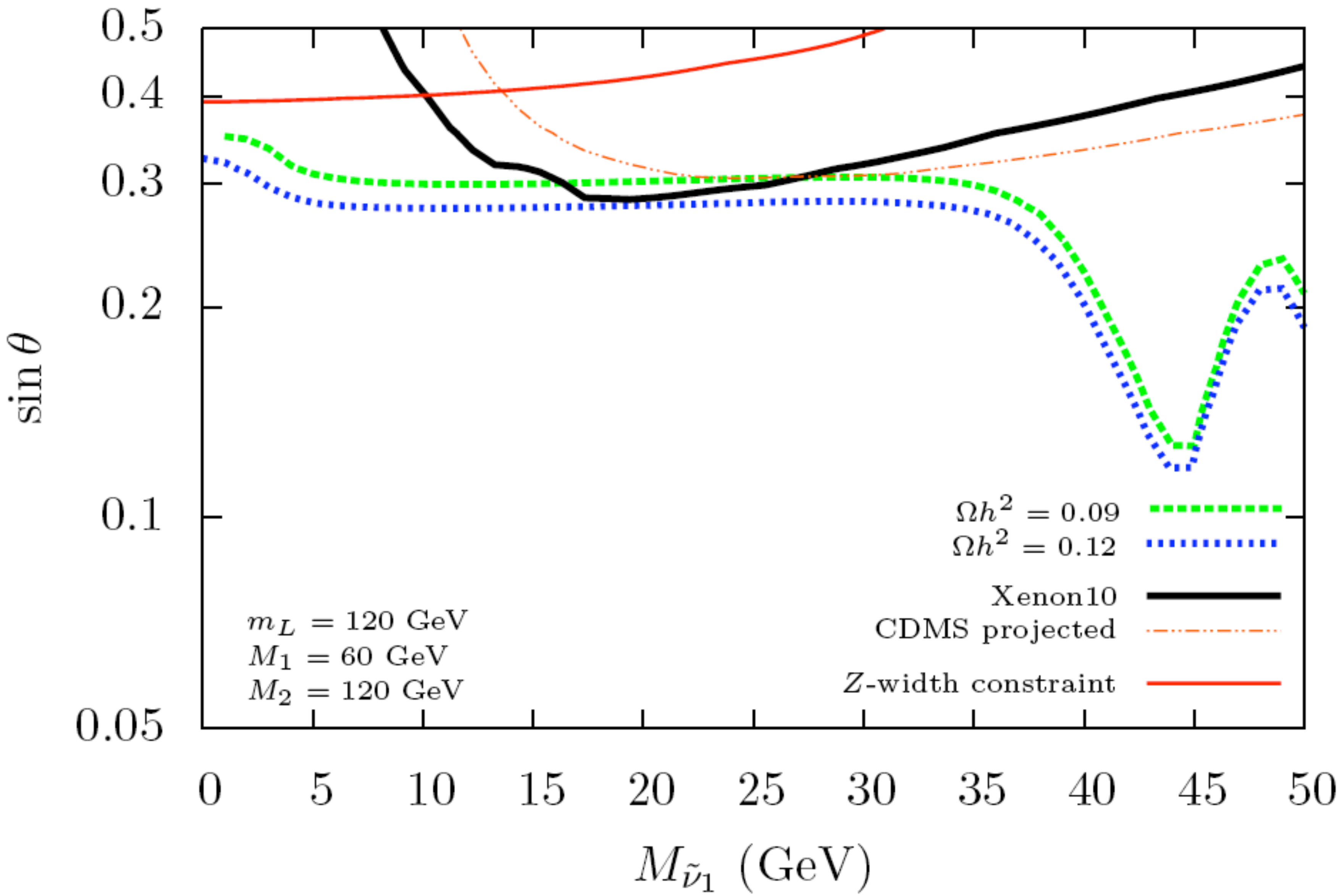

0.5
0.4
0.3
0.2
0.1
0.05
$\sin\theta$
0
5
10
15
20
25
30
35
40
45
50
$M_{\tilde{\nu}_1}$ (GeV)
$\Omega h^2 = 0.09$
$\Omega h^2 = 0.12$
Xenon10
CDMS projected
Z-width constraint
$m_L = 120$ GeV
$M_1 = 60$ GeV
$M_2 = 120$ GeV

Dark matter summary

- Mixed sneutrino is a viable dark matter candidate -- encourages us to investigate collider pheno of mixed-sneutrino LSP.
- With lepton-# violation, elastic scattering through Z exchange can be suppressed, but scattering through Higgs exchange still places important constraints.
- Interesting regions: above threshold for annihilation into W pairs, near Z/higgs poles, small lsp masses with light gauginos.
- In lepton-# conserving case 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).

Implications for LHC physics

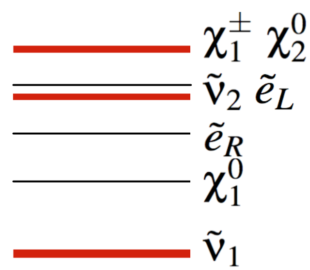
- Case with θ very tiny, and χ_1^0 NLSP: no change for collider physics.

  BUT new regions of MSSM parameter space become viable for cosmology

- With $\tilde{l}_R$ NLSP, opposite-sign same-flavor (OSSF) dilepton signature from χ_1^0 decay.

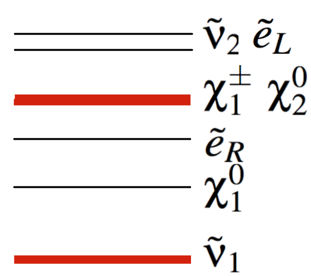
- Case with larger θ ($\gtrsim$0.1)

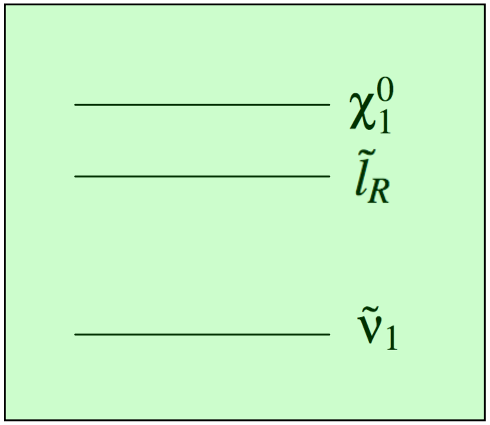
  – Direct decays $\tilde{\nu}_2 \to \tilde{\nu}_1 Z\,,\;\; \tilde{\nu}_2 \to \tilde{\nu}_1 h$



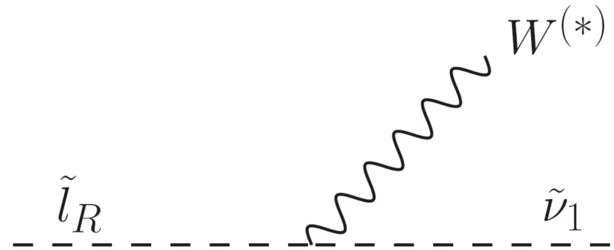
  – Direct decays $\tilde{\chi}_1^\pm \to \tilde{\nu}_1 l$

  $\tilde{\chi}_2^0,\ \tilde{\chi}_1^0 \to \tilde{\nu}_1 \nu$



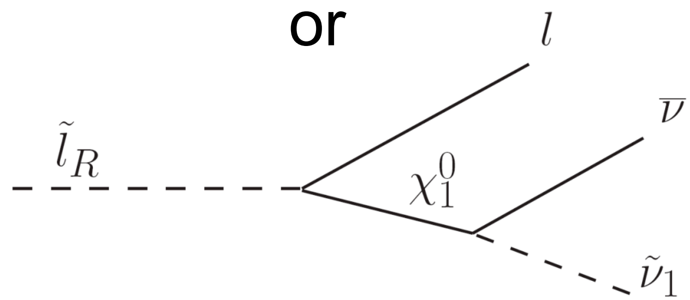


Decays of a $\tilde{l}_R$ NLSP

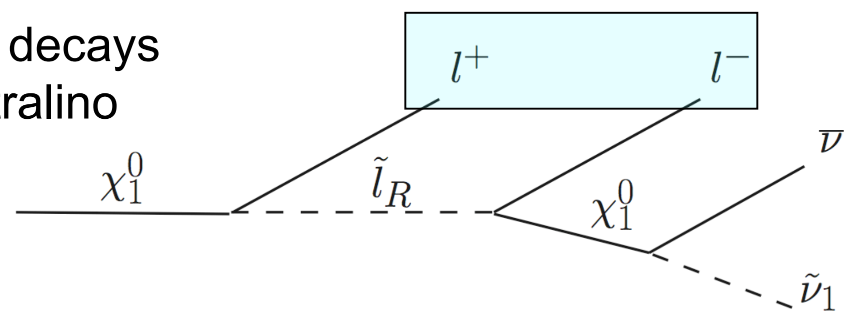


dominates in absence of LR slepton mixing (not for $\tilde{\tau}_1$, typically)

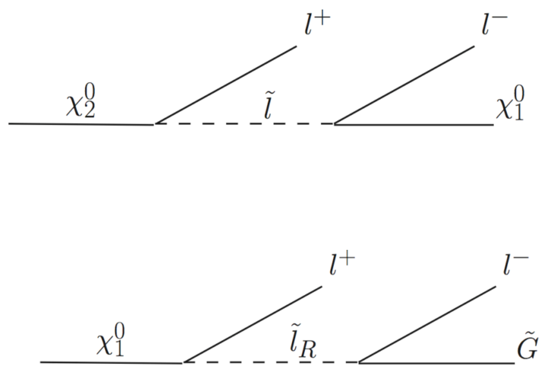
or



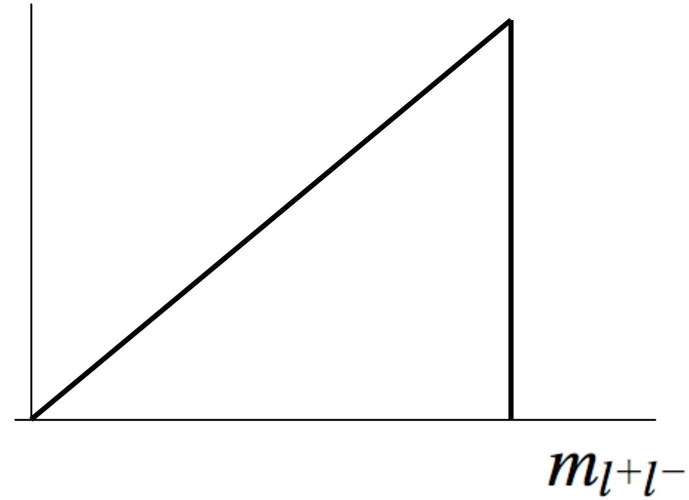
OSSF dilepton signature from decays of lightest neutralino

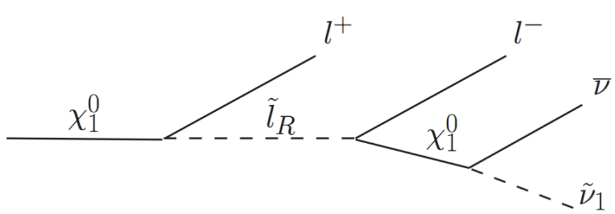


Invariant mass distributions



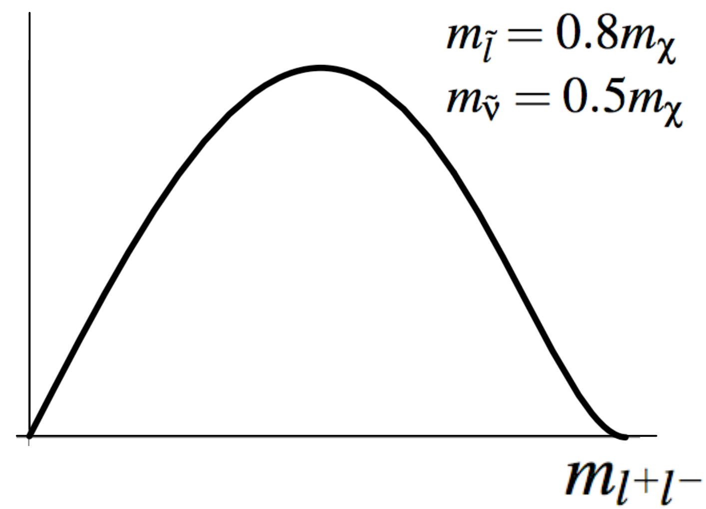
2 body - 2 body

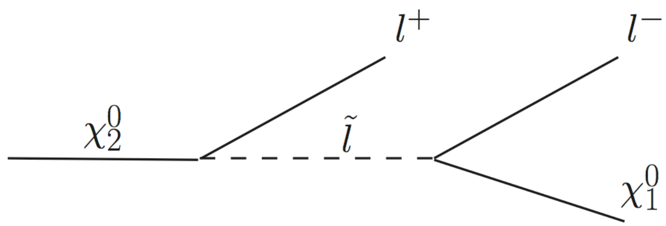




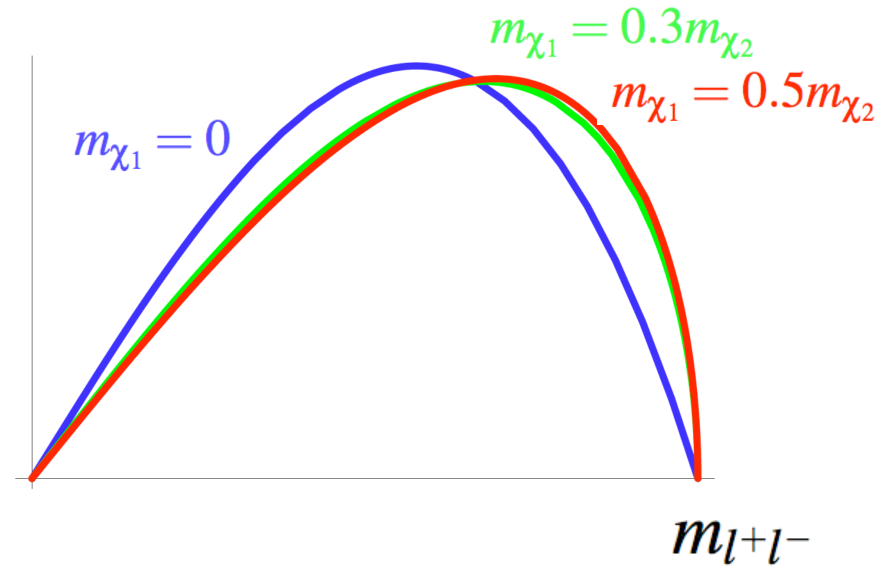
2 body - 3 body

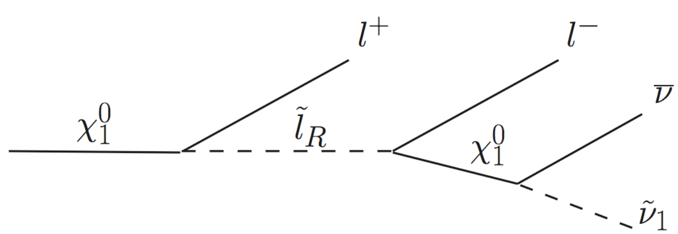
(assume constant amplitude for now)



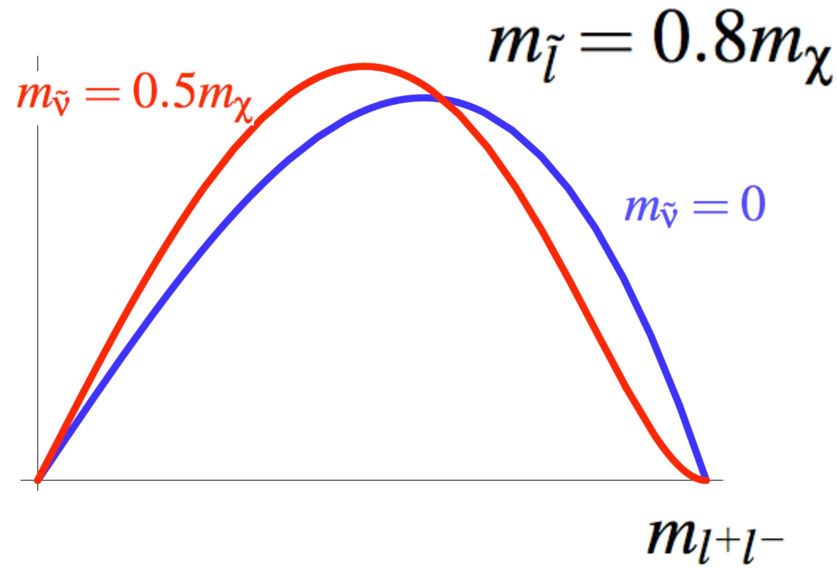


3 body





2 body - 3 body



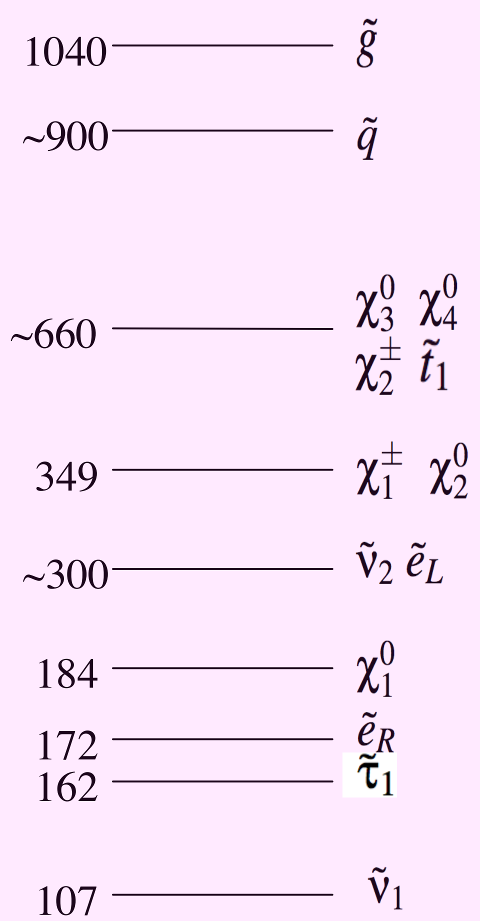
(assume constant amplitude for now)

A sample point

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

$\tilde{m}_{\tilde{\nu}_1} = 106$
$\theta_{\tilde{\nu}} = 0.2$

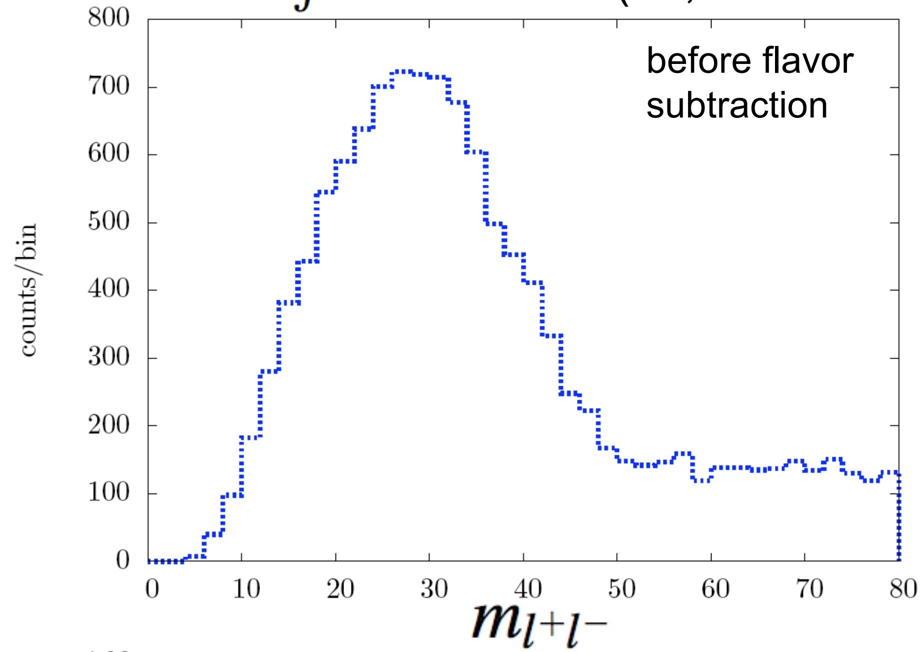
For spectrum, decay branching ratios,
adapted SUSY-HIT package to accommodate mixed sneutrino.
Djouadi, Muhlleitner, Spira

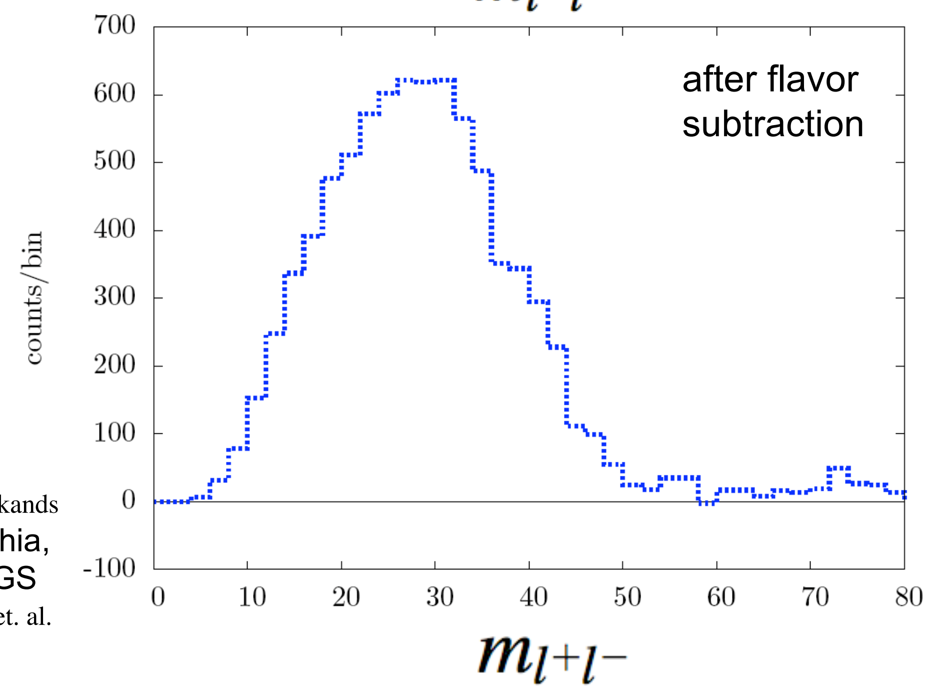


$Br(\chi_1^0 \to \tilde{l}_R l) = 40\,\%$
$Br(\chi_1^0 \to \tilde{\tau}_R \tau) = 50\,\%$
$Br(\chi_1^0 \to \tilde{\nu}_1 \nu) = 10\,\%$

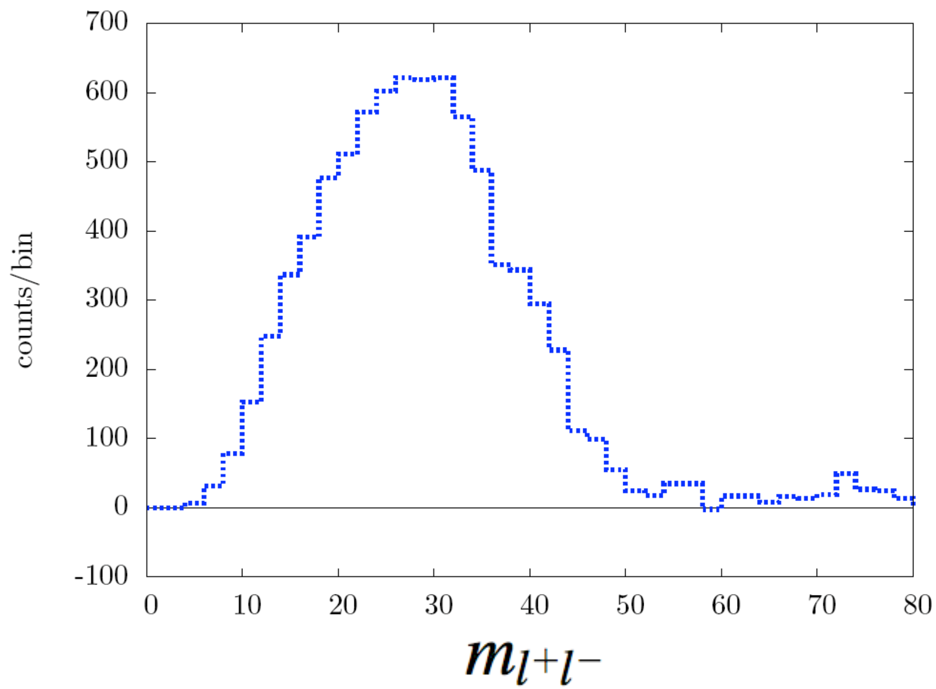
$Br(\tilde{l}_R \to l \tilde{\nu}_1 \nu) = 99\,\%$

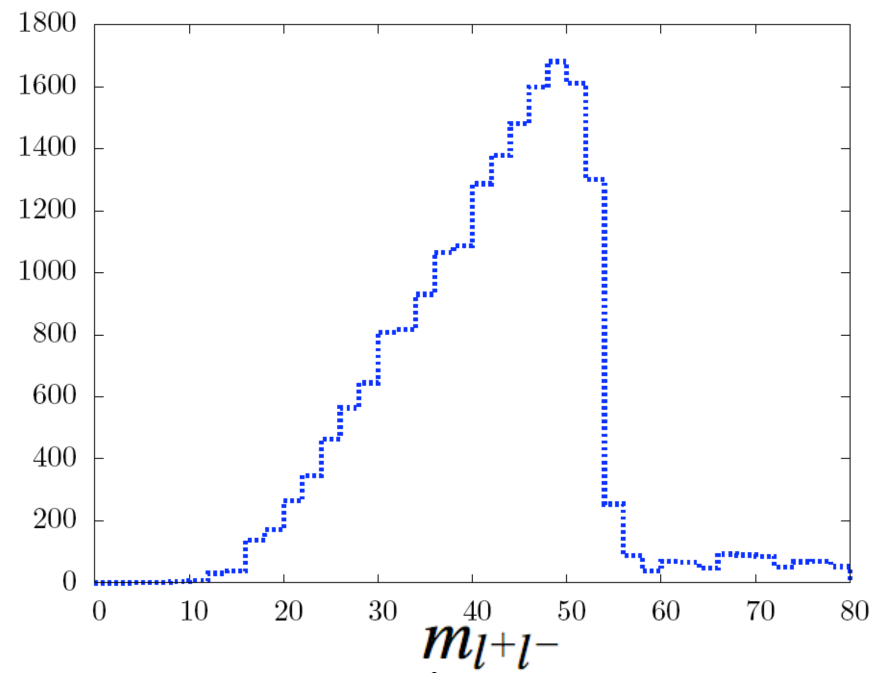
$\int L \sim 30\ \text{fb}^{-1}$ (80,000 events)



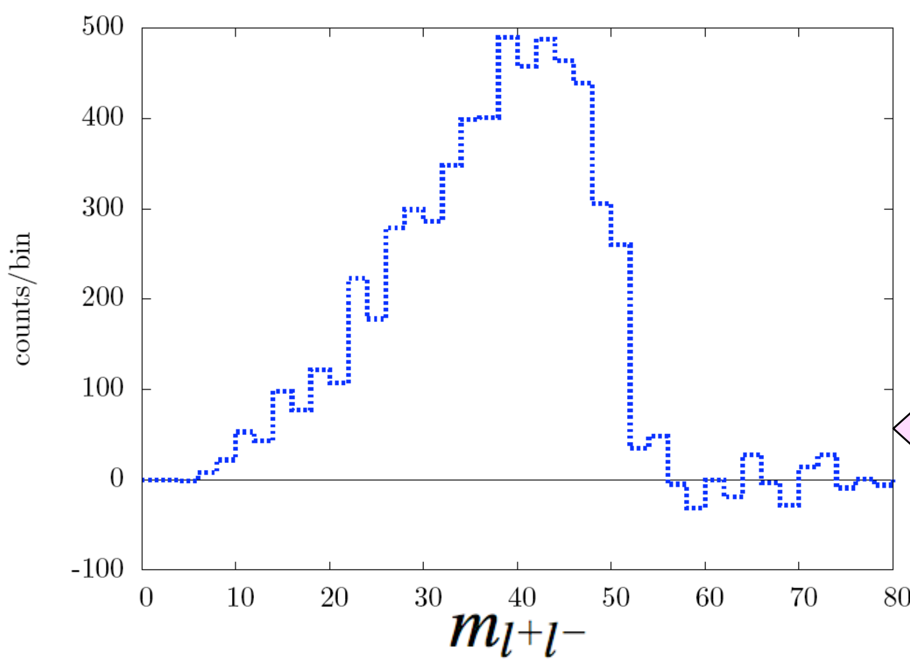


Sjostrand, Mrenna, Skands
Events generated with Pythia,
detector simulation with PGS
Conway et. al.





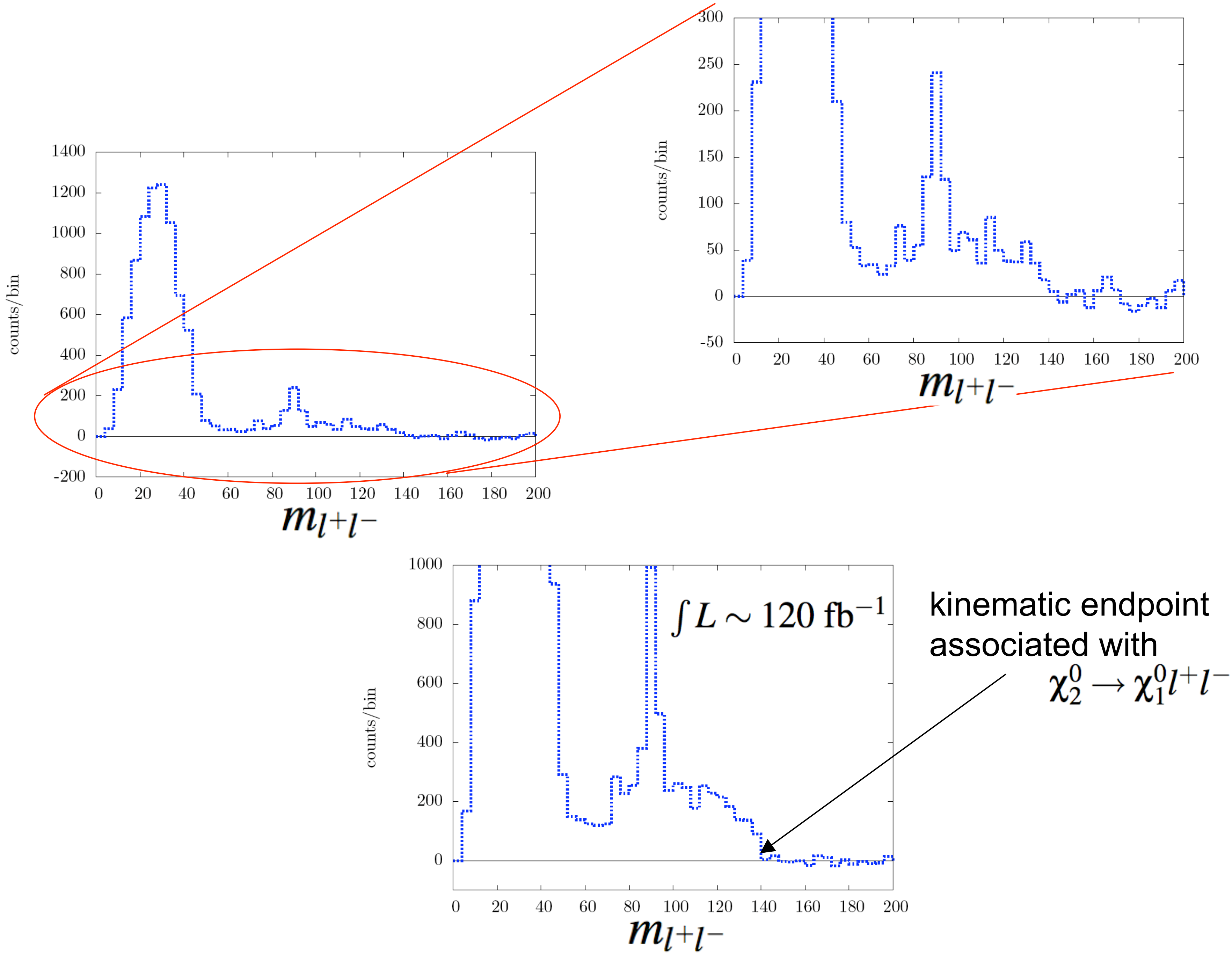
replace mixed-sneutrino LSP with gravitino



neutralino LSP with 3-body decay

$$\chi_2^0 \to \chi_1^0 l^+ l^-$$

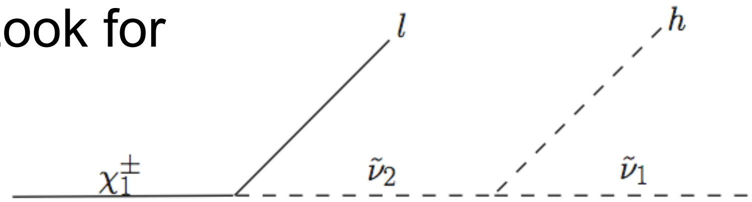
$$m_{\chi_1} = 58 \text{ GeV}$$
$$m_{\chi_2} = 111 \text{ GeV}$$
$$m_{\tilde{\nu}} = 113 \text{ GeV}$$
$$m_{\tilde{l}} = 138 \text{ GeV}$$



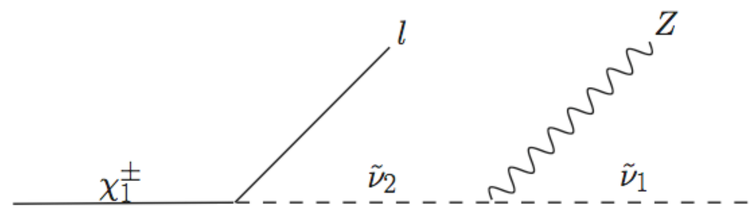
counts/bin
$m_{l^+l^-}$
$\int L \sim 120\ \mathrm{fb}^{-1}$
kinematic endpoint
associated with
$\chi_2^0 \rightarrow \chi_1^0 l^+ l^-$

Decays of $\tilde{\nu}_2$

Look for

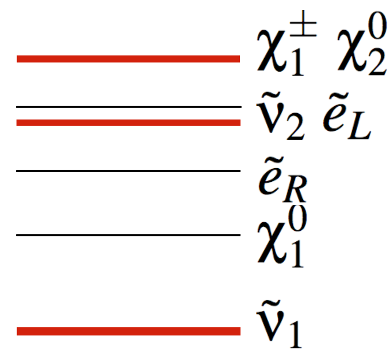


or



Need appreciable branching ratios for

$$\chi_1^+ \to \tilde{\nu}_2 l^+ \quad \text{and} \quad \tilde{\nu}_2 \to \tilde{\nu}_1 + h/Z$$



A sample point (low-energy input):

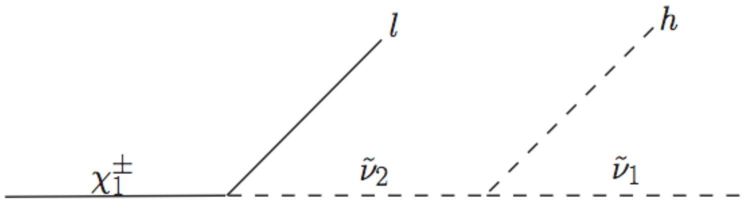
$$\tan\beta = 10$$
$$\mu = 600$$
$$M_A = 350$$
$$M_1,\ M_2,\ M_3 = 200,\ 500,\ 700$$
$$\tilde{m}_q = 600$$
$$\tilde{m}_L = 300$$
$$\tilde{m}_{l_R} = 250$$

$$\tilde{m}_{\tilde{\nu}_1} = 83$$
$$\theta_{\tilde{\nu}} = 0.2$$

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

$$Br(\tilde{\nu}_2 \to \tilde{\nu}_1 Z) = 37\%$$
$$Br(\tilde{\nu}_2 \to \tilde{\nu}_1 h) = 37\%$$

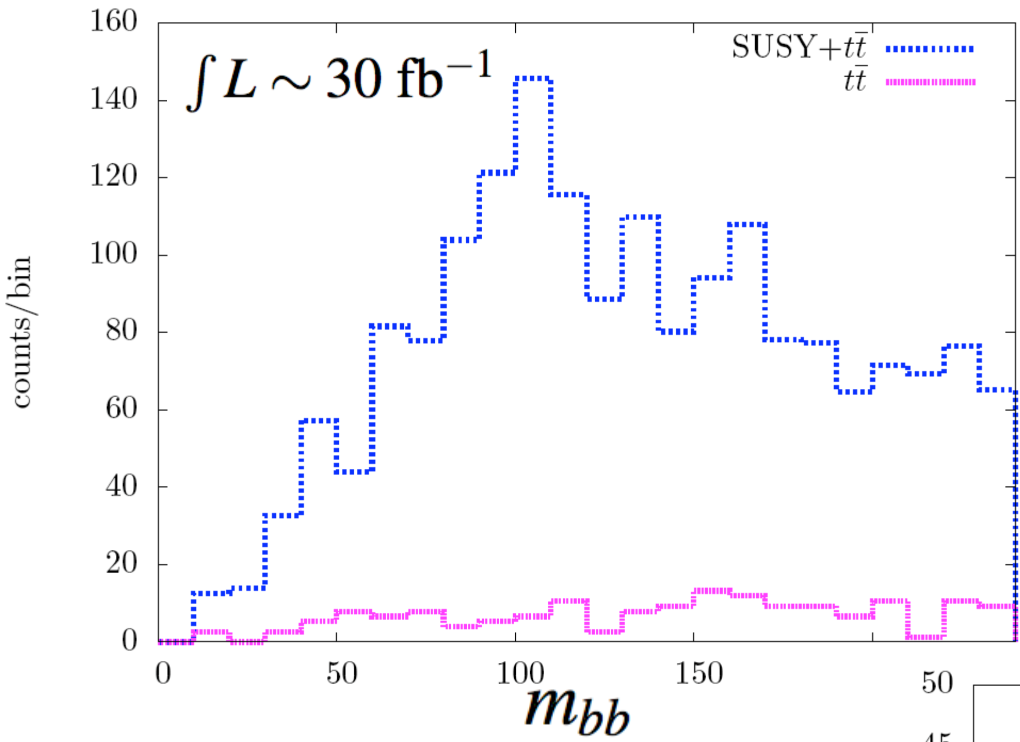
Higgs analysis



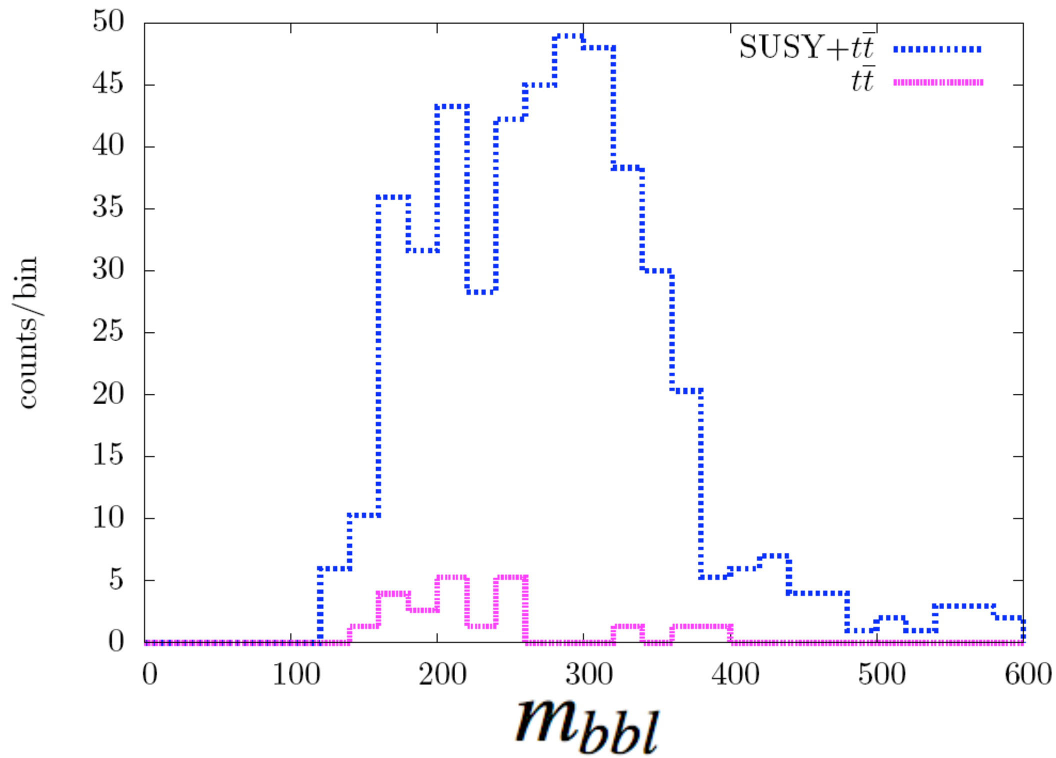
require invariant mass of b-jets to lie in peak, and look for edge in distribution of bbl invariant mass (at ~370 GeV for given parameters).

$$\not{p}_T > 200 \text{ GeV}$$
$$m_T > 200 \text{ GeV}$$
$$M_{eff} > 800 \text{ GeV}$$

	σ	events generated	two b-tags,one lepton	kinematic cuts	m_{bb} in peak
SUSY	22 pb	640k (~30/fb)	7,776	2,432	451
$t\bar{t}$	830 pb	18.9M (~23/fb)	440k	253	18

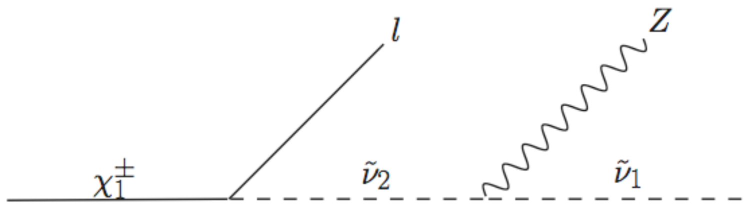


$\int L \sim 30\ \mathrm{fb}^{-1}$
SUSY+$t\bar{t}$
$t\bar{t}$
counts/bin
m_{bb}
0
20
40
60
80
100
120
140
160
0
50
100
150

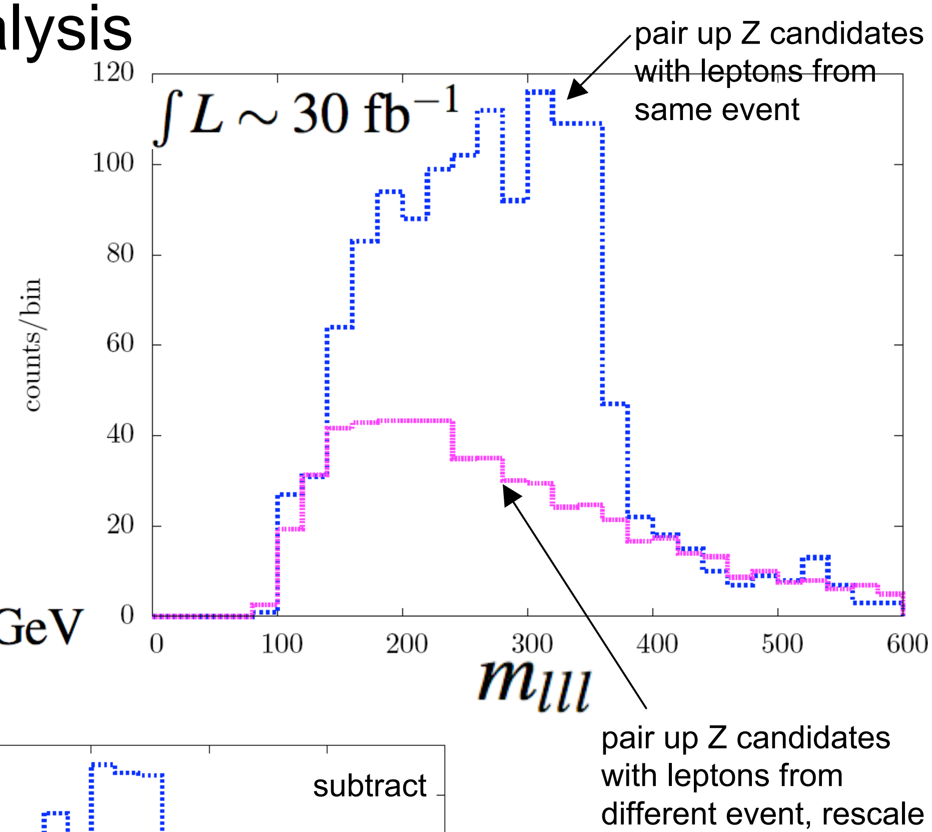


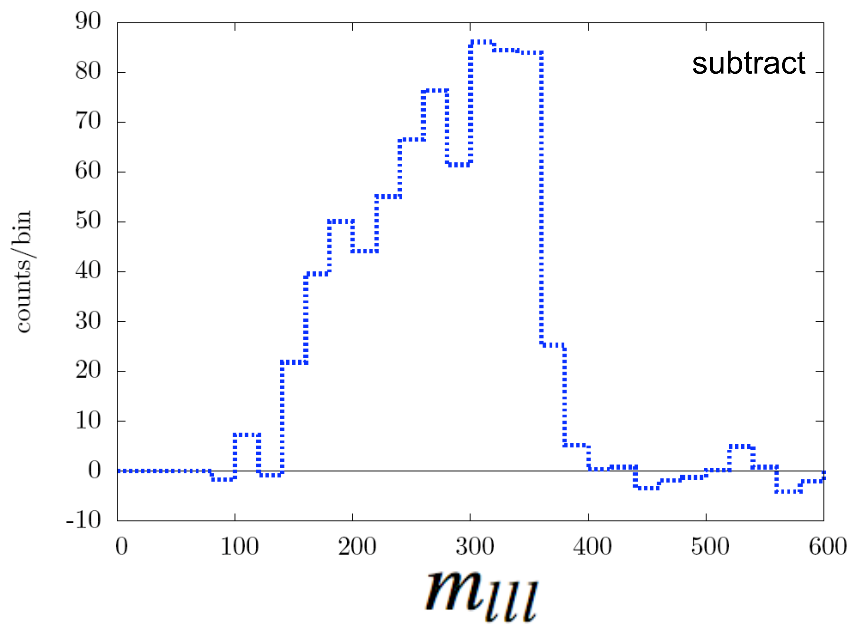
SUSY+$t\bar{t}$
$t\bar{t}$
counts/bin
m_{bbl}
0
5
10
15
20
25
30
35
40
45
50
0
100
200
300
400
500
600

Z analysis



- 5,001 events with three leptons, two OSSF.
- 1,323 after requiring $M_{eff} > 800$ GeV and $|m_{l^+l^-} - m_Z| < 10$ GeV



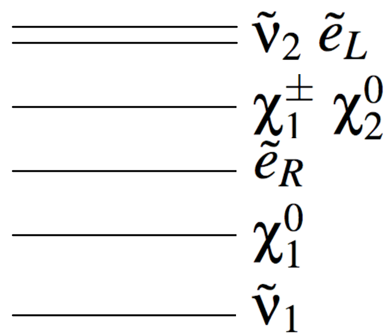


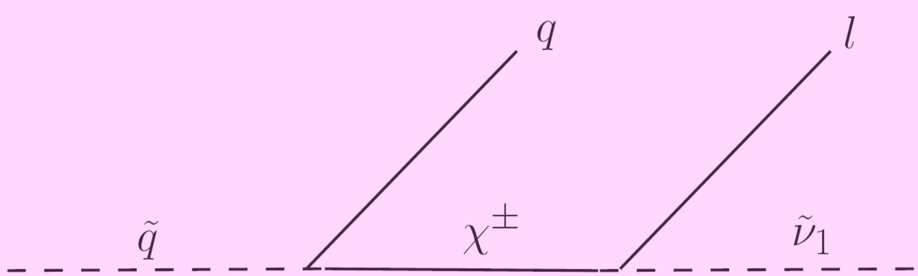
Direct decays of charginos/neutralinos

- Can easily have ~100% branching ratios for

$$\begin{cases} \chi_2^0 \to \tilde{\nu}_1 \nu \\ \chi_1^0 \to \tilde{\nu}_1 \nu \\ \chi_1^+ \to \tilde{\nu}_1 l^+ \end{cases}$$

e.g.





signature: jet-lepton kinematic edge, without OSSF dilepton signal

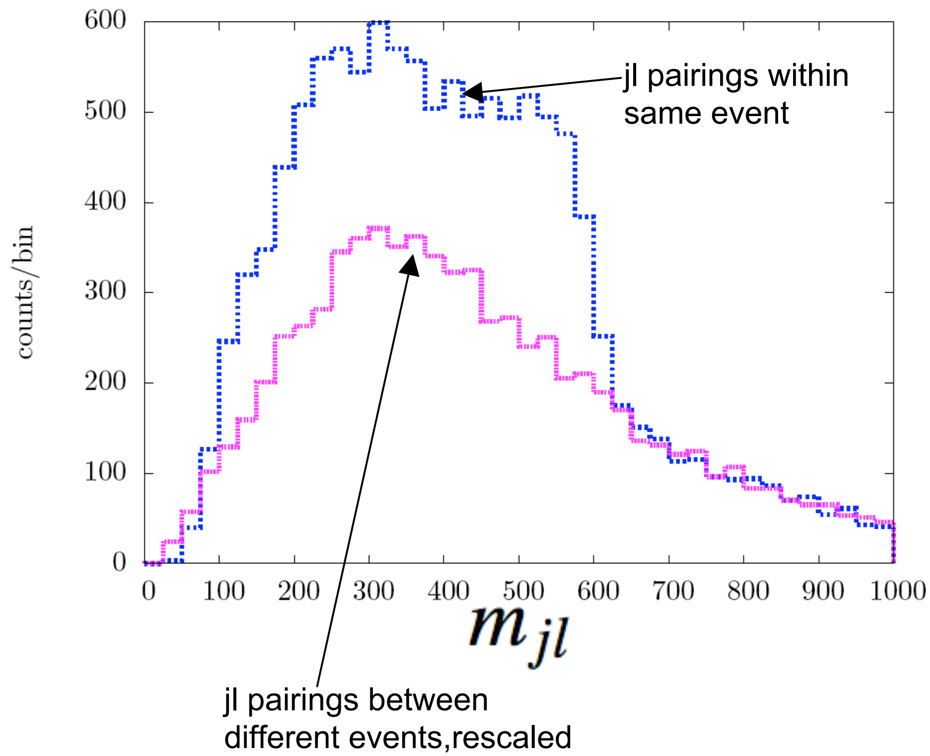
a sample point:

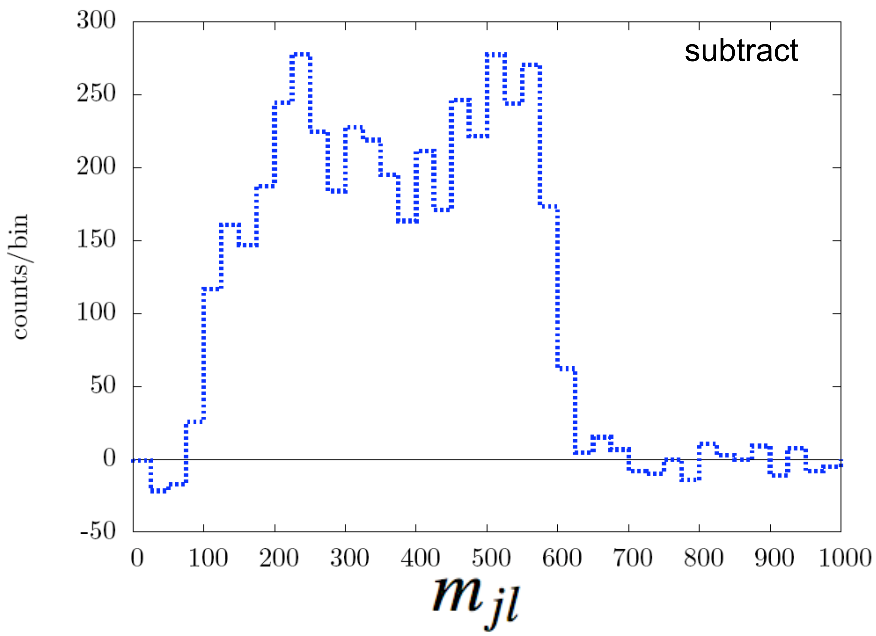
$\tan\beta = 10$
$M_{1/2} = 300$
$M_0 = 200$
$M_{H_u},\ M_{H_D} = 0$
$A_\tau,\ A_b = 0$
$A_t = -500$

$\tilde{m}_{\tilde{\nu}_1} = 86$
$\theta_{\tilde{\nu}} = 0.2$

- Require
  - two jets with pt > 150 GeV
  - one lepton with pt > 10 GeV
  - $\not{E}_T$ > 250 GeV
  - m_T > 250 GeV
- Take invariant mass for both pairings.

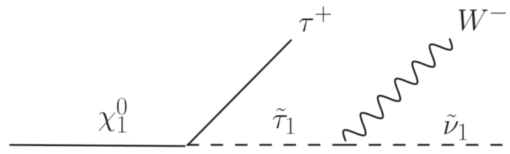
$\int L \sim 8\ \mathrm{fb}^{-1}$(160,000 events, 5,972 pass cuts)



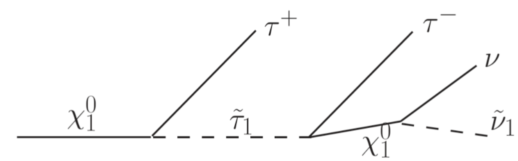


τ signatures

- $\tilde{\tau}_1$ NLSP case: if $\chi_1^0 \to \tilde{\tau}_1 \tau$ dominates, have



or

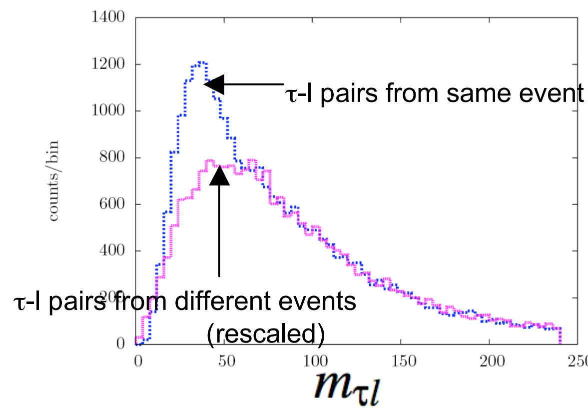


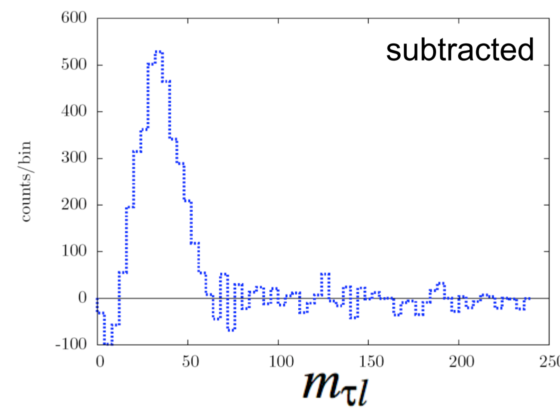
$\tan\beta = 10$
$M_{1/2} = 350$
$M_0 = 10$
$A_{b,\tau} = 0$
$A_t = -500$

$m_{\tilde{\nu}_1} = 40$
$\theta_{\tilde{\nu}} = 0.2$

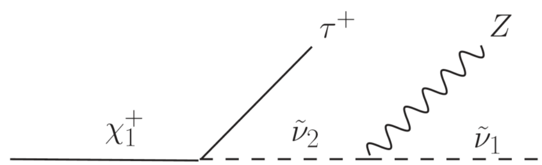
$Br(\tilde{\tau}_1 \to \tilde{\nu}_1 W) = 96\%$

$\int L \sim 60\ \text{fb}^{-1}$ (640k events)

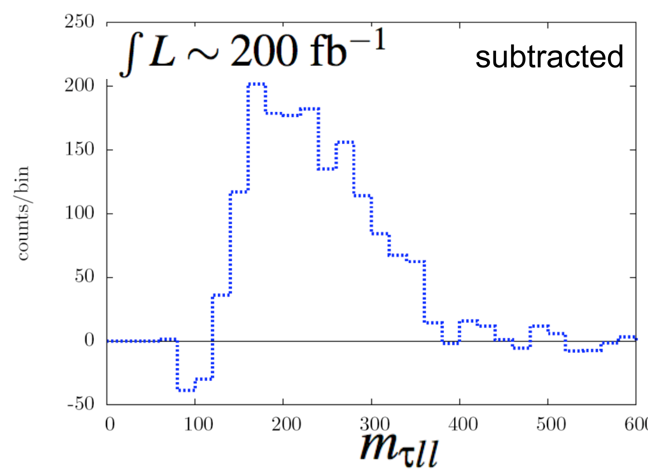




- $\tilde{\nu}_2$ decays: if only $\tilde{\nu}_\tau$ mixes, have

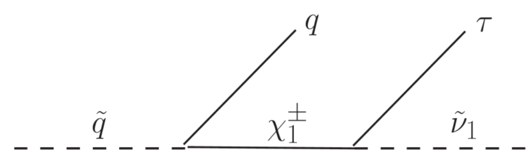


take same parameters as before,
but with only 3rd generation mixing:



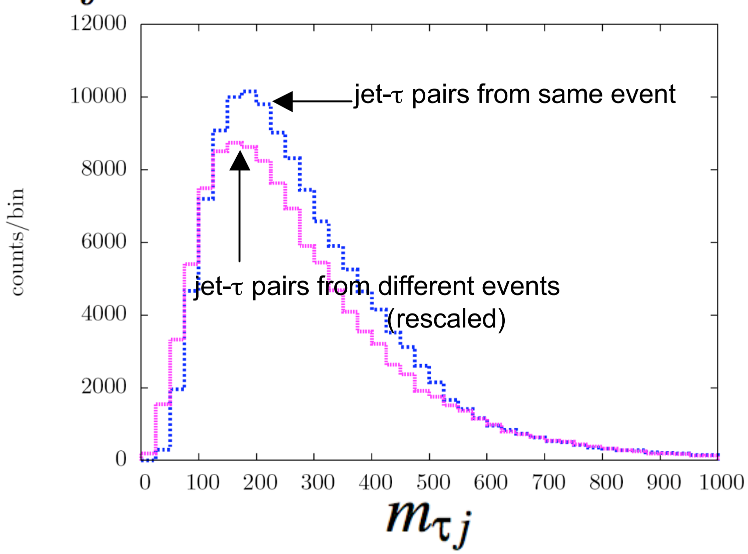
τ signatures, continued

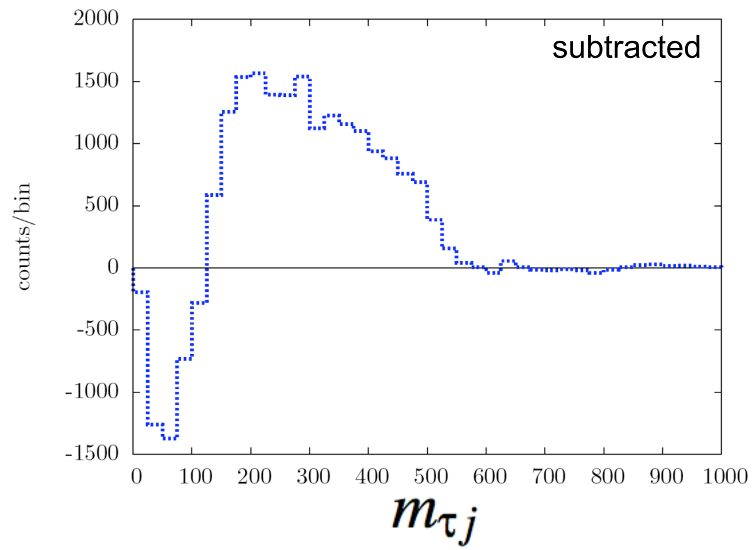
- $\chi_1^{\pm}$ decays: if only $\tilde{\nu}_\tau$ mixes, have



take same parameters as before,
but with only 3rd generation mixing:

$\int L \sim 30\ \text{fb}^{-1}$





Conclusions

- A mixed-sneutrino is a viable dark matter candidate.

- 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).
  - higgs-lepton, Z-lepton production.
  - lepton-jet kinetmatic edge from chargino decay straight to lsp sneutrino, without OSSF dilepton edge.