Discerning SUSY In Cascade Decay Correlations

or: How much fun can you have with two fermions?

Jessie Shelton

Rutgers

work in progress

with S. Thomas and M. Graesser

KITP LHC08, February 22, 2008

New physics and cascade decays

- **Most anticipated signal at LHC:**

$$pp \to XX \to (n \text{ jets}) + (m \text{ leptons}) + MET$$

- **Even without full reconstruction invariant mass distributions probe underlying model:**
  - endpoints (masses)
  - shapes (spins)
  - relative normalizations (couplings)
- **Post-discovery: distribution shapes key to discriminating between models**

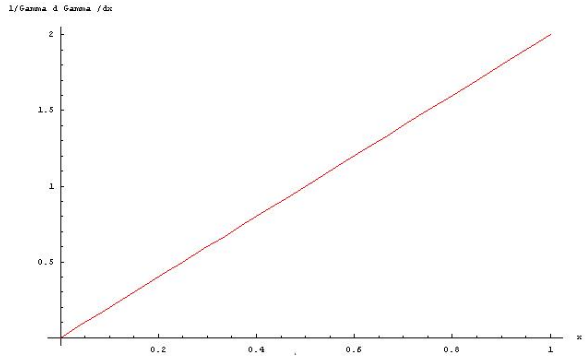
SUSY Dileptons

- **Ur-example: mSUGRA dileptons,**

$$\chi_2^0 \rightarrow \ell^\pm \tilde{\ell}_R^\mp \rightarrow \ell^\pm \ell^\mp \chi_1^0$$

  - Dilepton invariant mass $m_{\ell\ell}$ measures angular correlation of leptons
  - Range set by kinematics: $0 \leq m_{\ell\ell} \leq M_{max}$
  - Intermediate scalar, so $|\mathcal{M}|^2 = \text{constant}$
  - Channel set by quantum numbers of intermediate state: OS, SF only

- **Dilepton "triangle":**
  - with $x = m_{\ell\ell}/M_{max}$,
  - $\frac{1}{\Gamma}\frac{d\Gamma}{dm} = 2x$



- **Shapes of invariant mass distributions are a powerful tool**
  - Clearly necessary for discerning underlying model, but useful to examine even assuming SUSY
  - mSUGRA-like spectra: mostly triangles.
  - Other spectra can give wider variety of dilepton shapes in SUSY
  - Other final states $(\ell\ell, \ell\tau, \tau\tau; b\ell)$
- **Restrict attention to: adjacent fermions on decay chain, on-shell intermediate states**
- **Make minimal assumptions about spectrum, model parameters, global symmetries; study consequences of relaxation**

Intermediate fermions

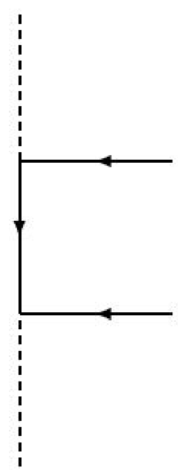
- **Distributions depend on helicity state of intermediate particle** A. Barr

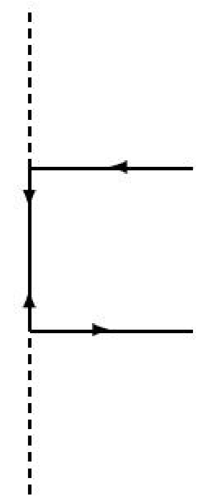
"Hump"

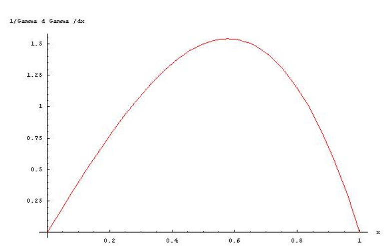
$$\frac{1}{\Gamma}\frac{d\Gamma}{dm} = 4x(1-x^2)$$

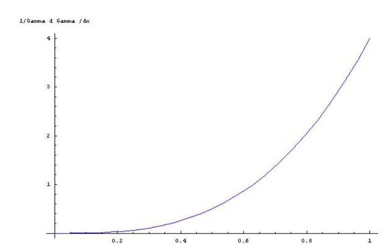
"Cusp"

$$\frac{1}{\Gamma}\frac{d\Gamma}{dm} = 4x^3$$









- **hump + cusp = triangle: must be able to separate channels to observe**

(–must also have spectrum allowing this chain)

- **SUSY: hump = SS, cusp = OS**

- **theoretical assumptions:**
  - neglect Yukawa couplings
  - no L-R slepton mixing
  - flavour structure

Cross-channel comparison

	Triangle	Hump	Half-Cusp
Opposite-Sign Same-Flavor	$\chi_i^0 \to \tilde{\ell}^{\mp}_{L,R}\ell^{\pm}$ $\hookrightarrow \chi_j^0 \ell^{\mp}\ell^{\pm}$		$\tilde{\ell}^{\pm}_{L,R} \to \chi_i^0 \ell^{\pm}$ $\hookrightarrow \tilde{\ell}^{\pm}_{R,L}\ell^{\mp}\ell^{\pm}$
Opposite-Sign Opposite-Flavor			$\tilde{\ell}^{\pm}_{L,R} \to \chi_i^0 \ell^{\pm}$ $\hookrightarrow \tilde{\ell}'^{\pm}_{R,L}\ell'^{\mp}\ell^{\pm}$
Same-Sign Same-Flavor		$\tilde{\ell}^{\pm}_{L,R} \to \chi_i^0 \ell^{\pm}$ $\hookrightarrow \tilde{\ell}^{\mp}_{R,L}\ell^{\pm}\ell^{\pm}$	
Same-Sign Opposite-Flavor		$\tilde{\ell}^{\pm}_{L,R} \to \chi_i^0 \ell^{\pm}$ $\hookrightarrow \tilde{\ell}'^{\mp}_{R,L}\ell'^{\pm}\ell^{\pm}$	

- *Simultaneous* hump SS and cusp OS, with same normalizations and endpoints. Flavour structure: sfermion degeneracy; L-R ordering.

- **Observing correlations a useful check on theoretical assumptions: SUSY beyond MSSM**
- **Eg: Flavour universality**
  - Near-degeneracy of selectrons and smuons: edges of ee, $\mu\mu$, $e\mu$ should be identical
  - Universality of gauge couplings fixes relative normalizations
- **Eg: models with continuous $U(1)_R$.**
  - Neutralinos acquire Dirac mass by marrying new chiral adjoints
  - Right and left handed sleptons have opposite $U(1)_R$ charges
    $\Rightarrow$ decay $\tilde{\ell}_L^- \to \tilde{\ell}_R^+ \ell^- \ell^+$ is forbidden
  - Therefore no cusp OS distributions; only hump SS.

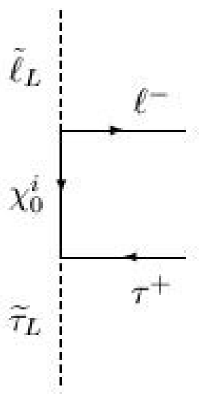
- **More flavour: “left-right ordering”**
  - The decays $\tilde{\ell}_{L,R} \to \chi_i^0 \ell \to \tilde{\ell}'_{R,L} \ell' \ell$ always give hump = SS, cusp = OS
  - But if $\tilde{\ell}_L \to \chi_i^0 \ell \to \tilde{\ell}'_L \ell' \ell$ is possible then sign-shape correlation is reversed: hump = OS, cusp = SS
  - Signal only seen in different-flavour dileptons

τ final states

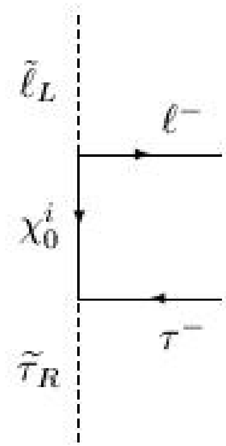
- **Theoretically, τ final states give window into interesting physics:**
  - λ_τ can be appreciable (large $\tan\beta$)
  - $\Rightarrow$ L-R stau mixing
  - $\Rightarrow$ gaugino-higgsino mixing
- **Experimentally, full four-momentum of τ not reconstructed**
  - compute modified line shapes: folding theoretical distributions with energy spectra of daughter particles
  - ditau triangle analysis (mSUGRA, few 100 pb^{-1} (Mangeol and Goerlach, CMS))
  - τ polarization measurable

The effects of mixing

- **Stau L-R mixing:**



$\Rightarrow$

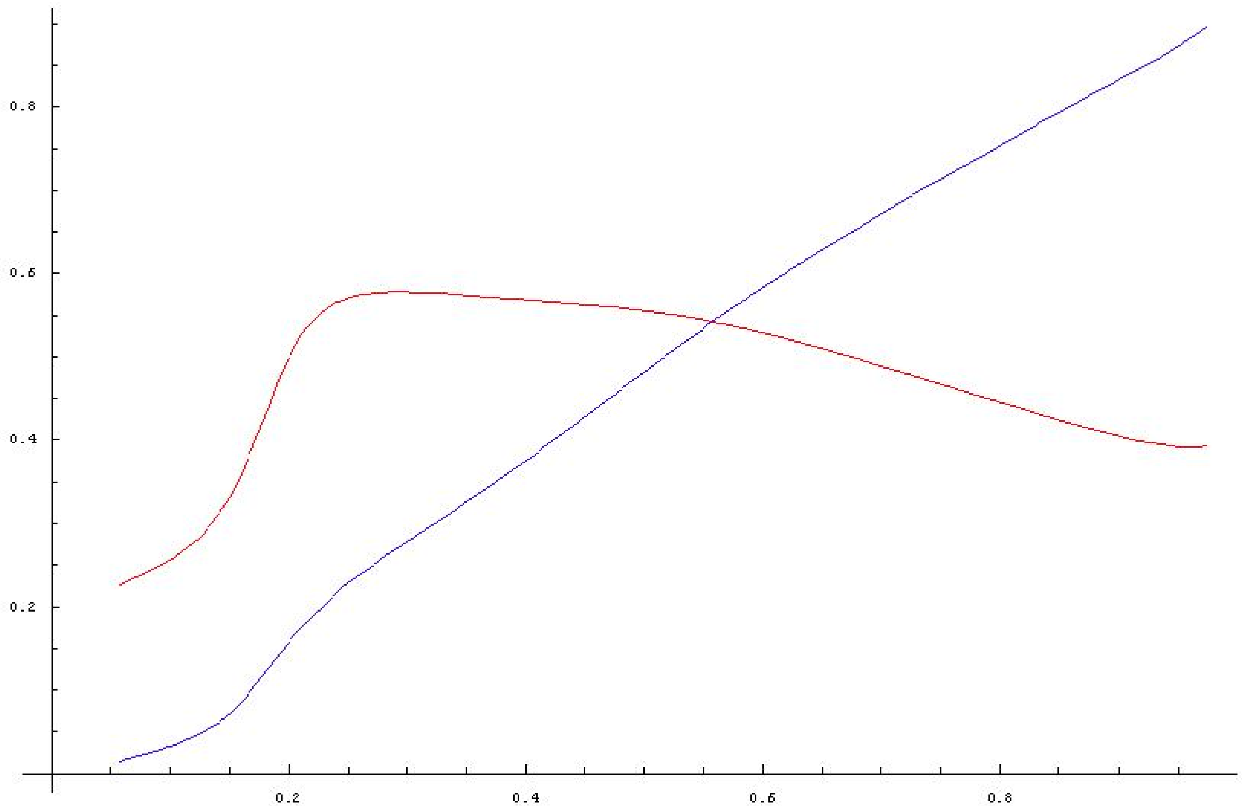


- **Relative normalization of distributions set by $\widetilde{\tau}$ mixing angle**
- **Gaugino-higgsino mixing qualitatively similar**

	Hump	Half-Cusp
Opposite-Sign Same-Flavor	$\widetilde{\tau}_2^{\pm} \to \tau^{\pm}\chi_i^0$ $\hookrightarrow \widetilde{\tau}_1^{\pm}\tau^{\mp}\tau^{\pm}$	$\widetilde{\tau}_2^{\pm} \to \tau^{\pm}\chi_i^0$ $\hookrightarrow \widetilde{\tau}_1^{\pm}\tau^{\mp}\tau^{\pm}$
Opposite-Sign Opposite-Flavor	$\widetilde{\ell}_L^{\pm} \to \ell^{\pm}\chi_i^0$ $\hookrightarrow \widetilde{\tau}_1^{\pm}\tau^{\mp}\ell^{\pm}$ $\hookrightarrow \widetilde{\tau}_2^{\pm}\tau^{\mp}\ell^{\pm}$	$\widetilde{\ell}_L^{\pm} \to \ell^{\pm}\chi_i^0$ $\hookrightarrow \widetilde{\tau}_1^{\pm}\tau^{\mp}\ell^{\pm}$ $\hookrightarrow \widetilde{\tau}_2^{\pm}\tau^{\mp}\ell^{\pm}$
Same-Sign Same-Flavor	$\widetilde{\tau}_2^{\pm} \to \tau^{\pm}\chi_i^0$ $\hookrightarrow \widetilde{\tau}_1^{\mp}\tau^{\pm}\tau^{\pm}$	$\widetilde{\tau}_2^{\pm} \to \tau^{\pm}\chi_i^0$ $\hookrightarrow \widetilde{\tau}_1^{\mp}\tau^{\pm}\tau^{\pm}$
Same-Sign Opposite-Flavor	$\widetilde{\ell}_L^{\pm} \to \ell^{\pm}\chi_i^0$ $\hookrightarrow \widetilde{\tau}_1^{\mp}\tau^{\pm}\ell^{\pm}$ $\hookrightarrow \widetilde{\tau}_2^{\mp}\tau^{\pm}\ell^{\pm}$	$\widetilde{\ell}_L^{\pm} \to \ell^{\pm}\chi_i^0$ $\hookrightarrow \widetilde{\tau}_1^{\mp}\tau^{\pm}\ell^{\pm}$ $\hookrightarrow \widetilde{\tau}_2^{\mp}\tau^{\pm}\ell^{\pm}$

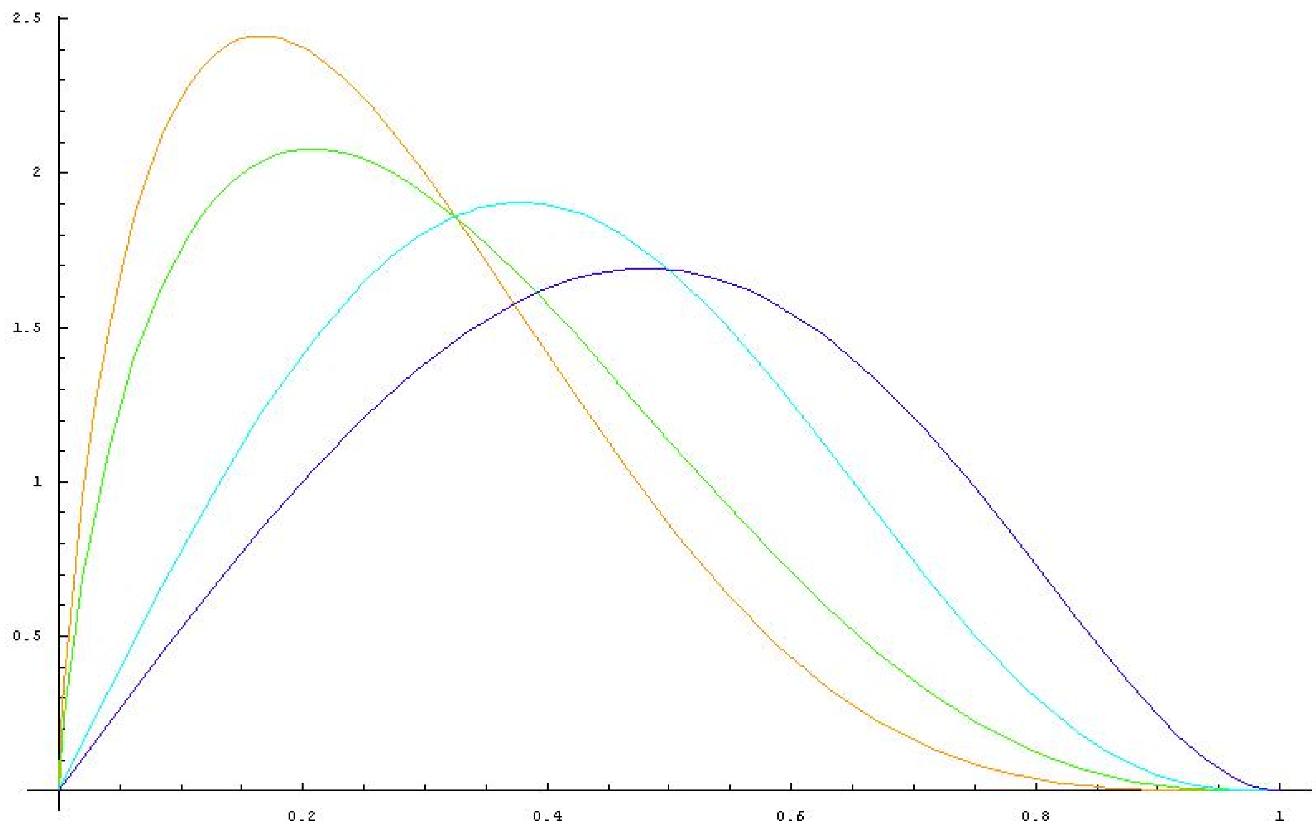
- comparing relative normalizations of hump, cusp distributions in given channel measures calculable function of mixings: a precision question

- τ polarization can be determined from spectrum of its daughters:

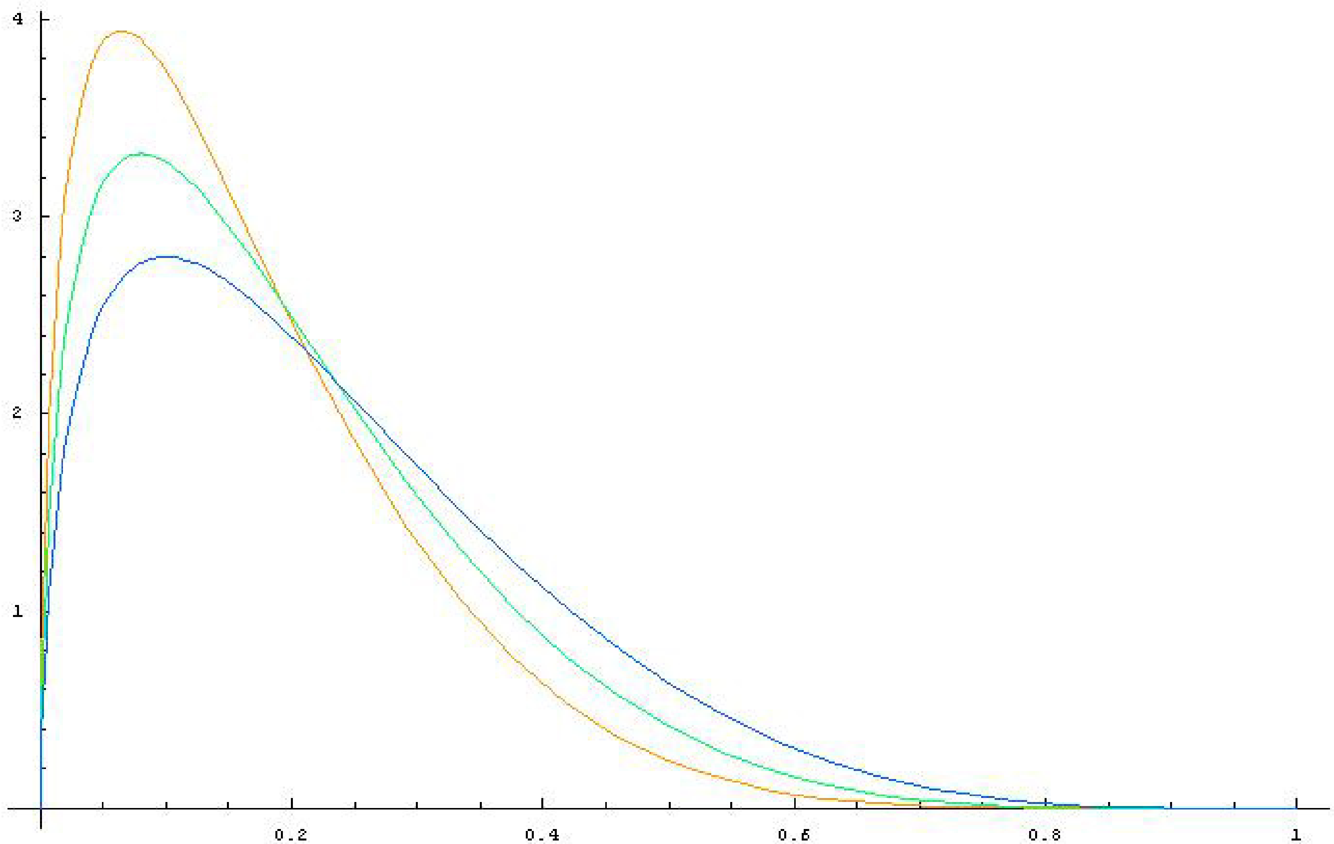


Fractional energy distribution for reconstructed 1-prong τs

- use to further distinguish final states and probe model parameters more closely



Lepton-τ hump and cusp distributions, for leptonically-decaying τs. Notice different polarizations. Distinguishability at $> 10\%$ level



Di-τ triangles, again for leptonically-decaying τs. Different polarizations are distinguishable at $> 10\%$ level

- **Quantitative study necessary (statistics, efficiencies)**
- **Potentially difficult measurements: Need to understand high energy tail**
  - Selection efficiency must be good: combinatoric background
- **Worthwhile: sensitivity to broad range of model parameters**

Ditau triangles

	Process	Weight
$\tau_L^+\tau_L^-$	$\chi_j^0 \to \tau_L^\pm \widetilde{\tau}_2^\mp$	
	$\hookrightarrow \tau_L^\pm \tau_L^\mp \chi_i^0$	$\cos^4\theta \lvert y_{Lj} y_{Li} \rvert^2$
	$\chi_j^0 \to \tau_L^\pm \widetilde{\tau}_1^\mp$	
	$\hookrightarrow \tau_L^\pm \tau_L^\mp \chi_i^0$	$\sin^4\theta \lvert y_{Lj} y_{Li} \rvert^2$
$\tau_R^+\tau_R^-$	$\chi_j^0 \to \tau_R^\pm \widetilde{\tau}_2^\mp$	
	$\hookrightarrow \tau_R^\pm \tau_R^\mp \chi_i^0$	$\sin^4\theta \lvert y_{Rj} y_{Ri} \rvert^2$
	$\chi_j^0 \to \tau_R^\pm \widetilde{\tau}_1^\mp$	
	$\hookrightarrow \tau_R^\pm \tau_R^\mp \chi_i^0$	$\cos^4\theta \lvert y_{Rj} y_{Ri} \rvert^2$
$\tau_L^\pm\tau_R^\mp$	$\chi_j^0 \to \tau_L^\pm \widetilde{\tau}_{1,2}^\mp$	
	$\hookrightarrow \tau_L^\pm \tau_R^\mp \chi_i^0$	$\cos^2\theta \sin^2\theta \lvert y_{Lj} y_{Ri} \rvert^2$
	$\chi_j^0 \to \tau_R^\mp \widetilde{\tau}_{1,2}^\pm$	
	$\hookrightarrow \tau_R^\mp \tau_L^\pm \chi_i^0$	$\cos^2\theta \sin^2\theta \lvert y_{Rj} y_{Li} \rvert^2$

Lepton-tau distributions

	Hump Process	Weight	Half-Cusp Process	Weight
$\ell^\pm\tau_L^\mp$	$\tilde\ell_L^\pm \to \ell^\pm\chi_i^0 \hookrightarrow \ell^\pm\tau_L^\mp\widetilde{\tau}_1^\pm$	$\sin^2\theta\|y_{Li}\|^2$	$\tilde\ell_R^\pm \to \ell^\pm\chi_i^0 \hookrightarrow \ell^\pm\tau_L^\mp\widetilde{\tau}_1^\pm$	$\sin^2\theta\|y_{Li}\|^2$
$\ell^\pm\tau_R^\mp$	$\tilde\ell_R^\pm \to \ell^\pm\chi_i^0 \hookrightarrow \ell^\pm\tau_R^\mp\widetilde{\tau}_1^\pm$	$\cos^2\theta\|y_{Ri}\|^2$	$\tilde\ell_L^\pm \to \ell^\pm\chi_i^0 \hookrightarrow \ell^\pm\tau_R^\mp\widetilde{\tau}_1^\pm$	$\cos^2\theta\|y_{Ri}\|^2$
$\ell^\pm\tau_L^\pm$	$\tilde\ell_R^\pm \to \ell^\pm\chi_i^0 \hookrightarrow \ell^\pm\tau_L^\pm\widetilde{\tau}_1^\mp$	$\sin^2\theta\|y_{Li}\|^2$	$\tilde\ell_L^\pm \to \ell^\pm\chi_i^0 \hookrightarrow \ell^\pm\tau_L^\pm\widetilde{\tau}_1^\mp$	$\sin^2\theta\|y_{Li}\|^2$
$\ell^\pm\tau_R^\pm$	$\tilde\ell_L^\pm \to \ell^\pm\chi_i^0 \hookrightarrow \ell^\pm\tau_R^\pm\widetilde{\tau}_1^\mp$	$\cos^2\theta\|y_{Ri}\|^2$	$\tilde\ell_R^\pm \to \ell^\pm\chi_i^0 \hookrightarrow \ell^\pm\tau_R^\pm\widetilde{\tau}_1^\mp$	$\cos^2\theta\|y_{Ri}\|^2$

Final state	Hump Process	Weight	Half-Cusp Process	Weight
$\tau_L^+\tau_L^-$	$\widetilde{\tau}_2^\pm \longrightarrow \tau_L^\pm \chi_i^0$ $\hookrightarrow \tau_L^\pm \tau_L^\mp \widetilde{\tau}_1^\pm$	$\cos^2\theta \sin^2\theta \lvert y_{Li}\rvert^4$		
$\tau_R^+\tau_R^-$	$\widetilde{\tau}_2^\pm \longrightarrow \tau_L^\pm \chi_i^0$ $\hookrightarrow \tau_R^\pm \tau_R^\mp \widetilde{\tau}_1^\pm$	$\cos^2\theta \sin^2\theta \lvert y_{Ri}\rvert^4$		
$\tau_L^+\tau_R^-$			$\widetilde{\tau}_2^- \longrightarrow \tau_R^- \chi_i^0$ $\hookrightarrow \tau_R^- \tau_L^+ \widetilde{\tau}_1^-$ $\widetilde{\tau}_2^+ \longrightarrow \tau_L^+ \chi_i^0$ $\hookrightarrow \tau_L^+ \tau_R^- \widetilde{\tau}_1^-$	$\sin^4\theta \lvert y_{Ri} y_{Li}\rvert^2$ $\cos^4\theta \lvert y_{Ri} y_{Li}\rvert^2$
$\tau_R^+\tau_L^-$			$\widetilde{\tau}_2^- \longrightarrow \tau_L^- \chi_i^0$ $\hookrightarrow \tau_L^- \tau_R^+ \widetilde{\tau}_1^-$ $\widetilde{\tau}_2^+ \longrightarrow \tau_R^+ \chi_i^0$ $\hookrightarrow \tau_R^+ \tau_L^- \widetilde{\tau}_1^+$	$\cos^4\theta \lvert y_{Ri} y_{Li}\rvert^2$ $\sin^4\theta \lvert y_{Ri} y_{Li}\rvert^2$

- clean, independent measurements of gaugino couplings and stau mixing angle

b-lepton final states

- **Quark sector is more difficult to study: indistinguishability of final states washes out information.**
  - Barr: rely on *overall* squark production asymmetry to generate asymmetry in q-ℓ^-, q-ℓ^+ distributions
- **Possibility of signing b-jets using associated muon allows nontrivial spin correlations to be seen without the need for overall production asymmetry**
  - $\mathcal{O}(10\%)$ of b-jets can be signed;
  - mis-sign rate $\mathcal{O}(30\%)$ (ATLAS TDR, D0); optimistic this can be improved (S. Schnetzer)

- **Expect mixings to be typically non-negligible**
  - Recall τ sector: total distribution contains admixture of "wrong" distribution, depending on mixing angles
  - good: can probe many parameters in the underlying model
  - bad: Spin measurement may require more statistics
- **Quantitative study necessary**

Conclusions

- **Difermions are fun!**
  - crucial analysis tool
  - third-generation fermions are challenging but potentially rewarding
- **Many further aspects of cascade decays which can (even now!) repay further analysis:**
  - Other final states: ℓV^μ, ℓh
  - Nonadjacent fermions
  - Three-body decays; finite width effects
  - Same-spin partners