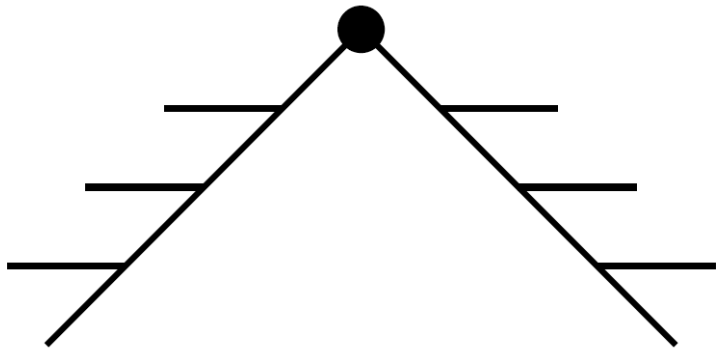
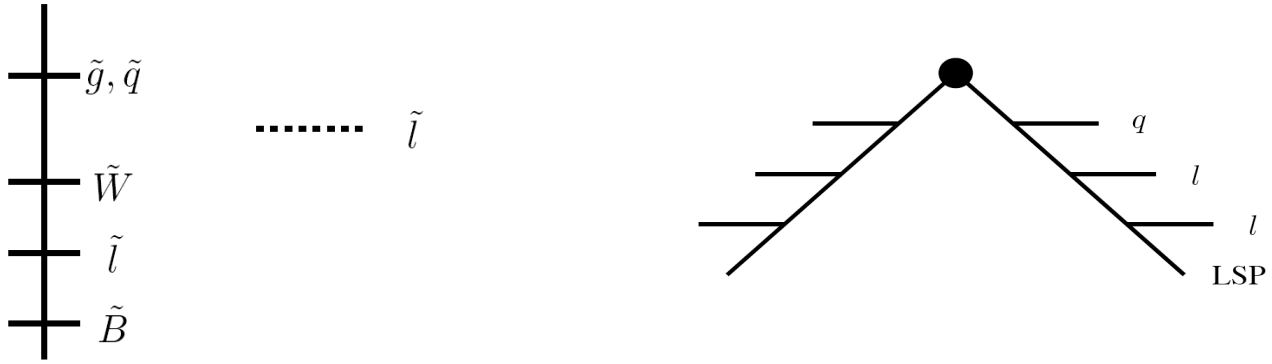
``Correlations in Supersymmetric Cascade Decays''

New LHC Signatures Workshop: Jan 5-12 University of Michigan

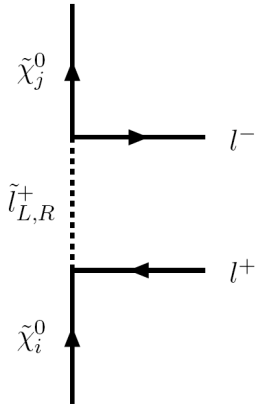
Michael Graesser (LANL)
work in progress with Jessie Shelton and Scott Thomas



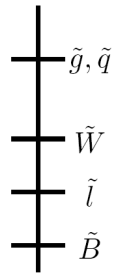
- susy cascade decays provide abundant information on underlying susy model
- post-discovery:shapes of invariant distributions useful tool to discriminate between models
- Correlations between distributions provides useful check on theoretical assumptions



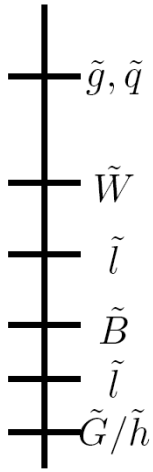
- Dilepton studies mostly focus on minimal sugra-like spectrum that has a particular ordering of neutralinos and sleptons
  - LM1-6' study points
- Dilepton distributions are ``triangles''
- other shapes in susy?



- worthwhile to consider two classes of spectrum, differ on ordering of sleptons relative to neutralinos
  - Msugra-like:



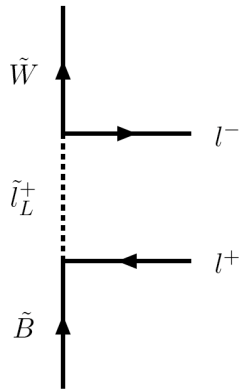
Interlaced:

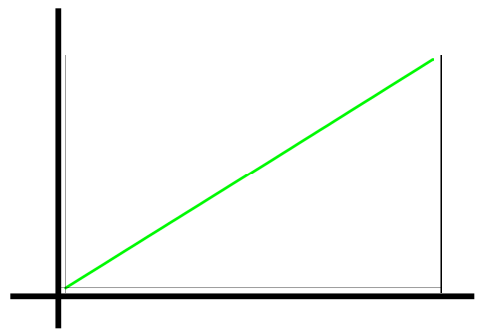


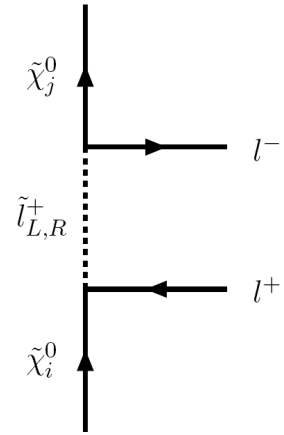
- ``interlaced'' spectrum can occur with gauge mediated susy breaking
- requirement that decays of squarks, gluinos populate sleptons
- patterns to di-fermion invariant mass distributions?
  - ll,lτ,ττ
  - bl

- relax theoretical assumptions :
  - flavor alignment and universality
  - gaugino-higgsino mixing
  - Yukawa couplings, L-R mixing
  - R-parity vs. U(1) R-symmetry

Decays Through Intermediate Scalars







- Features:
  - OS only
  - M_ll distribution is a ``triangle''
  - one endpoint, one gauge slepton only
  - SF only, but equal numbers of ee, uu; all with same endpoint

    and each with same ``triangle distribution''
  - no eu events

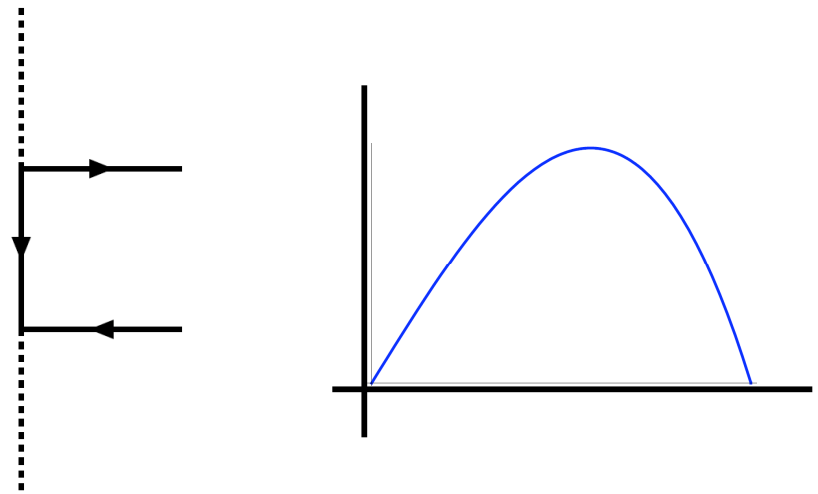
- include gaugino-higgsino mixing:
  - possibly multiple intermediate sleptons (2)
  - distribution sum of triangles, each with different endpoints
  - areas under two triangles give information on branching ratios

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

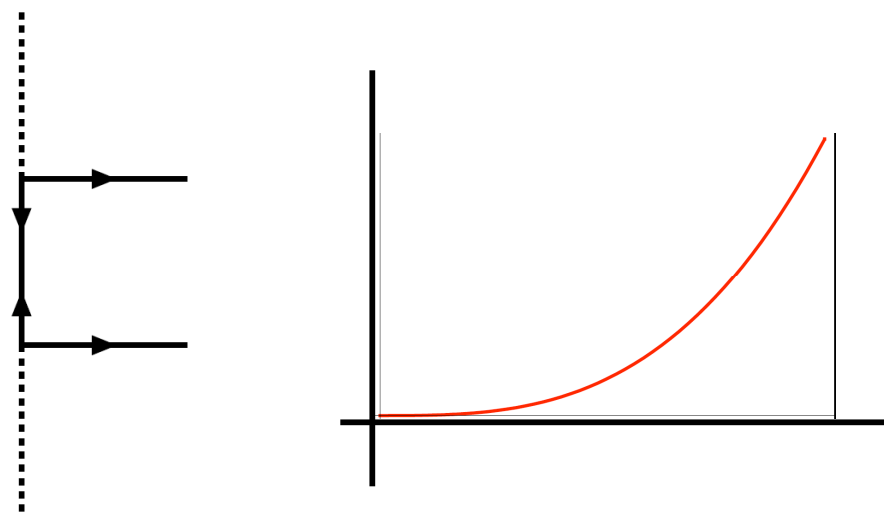
Table 1: SUSY di-leptons. First two generations. Neglect Yukawa couplings. No L-R mixing, no flavor violation.

Decays through intermediate neutralino(s) occurring with an interlaced spectrum:

``hump'': $$\frac{1}{\Gamma}\frac{d\Gamma}{dx} = 4x(1-x^2)$$



``half-cusp'': $$\frac{1}{\Gamma}\frac{d\Gamma}{dx} = 4x^3$$



(A.Barr;C.Athansiou,C.Lester & J.Smillie,B.Webber;Wang&Yavin;Killic,Wang and Yavin)

- No gaugino-higgsino mixing:
  - should see both OS and SS
  - OS has ``half-cusp'' but SS has ``hump'' distributions
  - endpoints of both OS and SS the same
  - In Same-Flavor and Opposite-Flavor channels: number of OS equals the number of SS
  - Opposite Flavor: ee, ue, uu all with same endpoints and number of ee+uu=eu
- including gaugino-higgsino mixing patterns are robust and generalize:

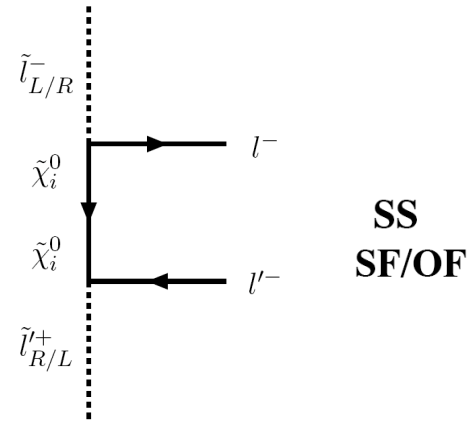
  OS is a sum of half-cusp distributions with several endpoints

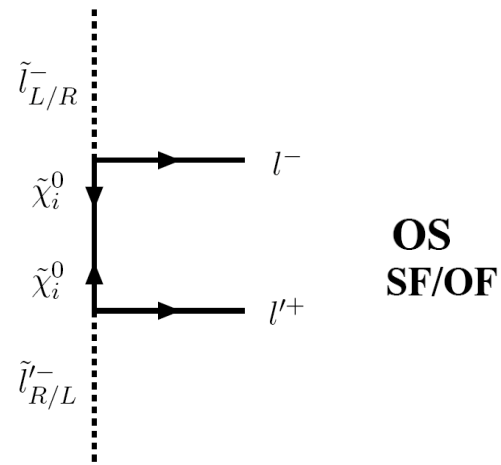
  SS is a sum of hump distributions with same endpoints as OS

  relative areas or locations of peaks provides information on relative branching fractions . Equal for OS and SS

- signing of leptons crucial: ``hump"+"half-cusp"=``triangle'' (A.Barr)

- no charge asymmetry needed if both leptons signed



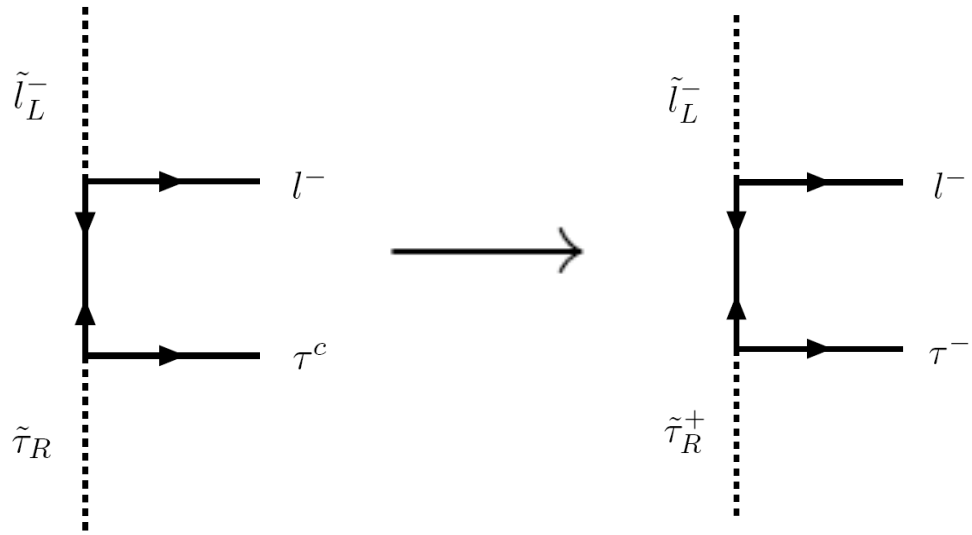


	Triangle	Hump	Half-Cusp
Opposite-Sign Same-Flavor	$\chi_i^0 \to \tilde{\ell}^{\mp}_{L,R}\ell^{\pm}$ $\hookrightarrow \chi_j^0 \ell^{\mp}\ell^{\pm}$		$\tilde{\ell}^{\pm}_{L,R} \to \chi_i^0 \ell^{\pm}$ $\hookrightarrow \tilde{\ell}^{\pm}_{R,L}\ell^{\mp}\ell^{\pm}$
Opposite-Sign Opposite-Flavor			$\tilde{\ell}^{\pm}_{L,R}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

Table 2: SUSY di-leptons. First two generations - neglect first two generation Yukawa couplings. No L-R mixing. No flavor violation.

Staus and taus

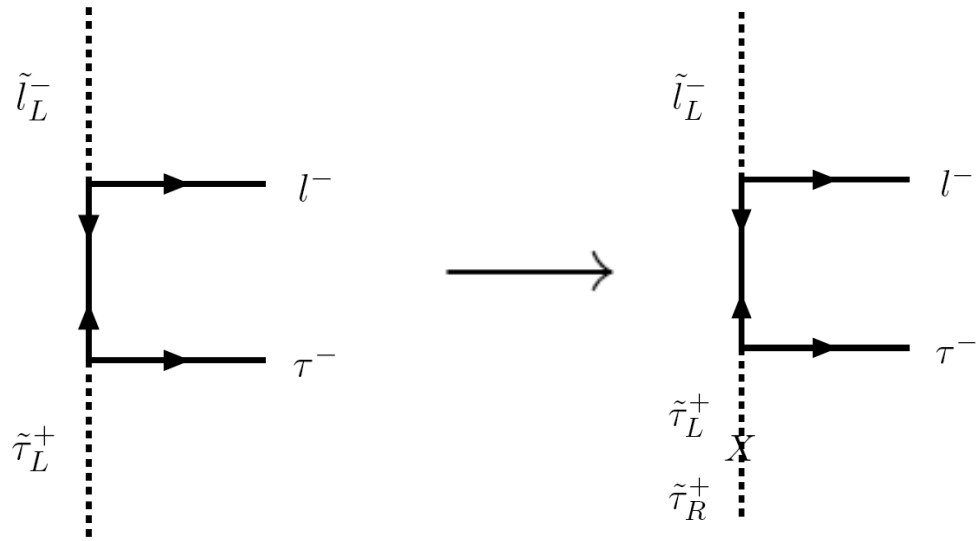
- Calculable modification to shapes :
  - distribution of $l\tau$, di-tau events modified due to missing energy
  - τ polarization
- τ Yukawa coupling cannot be neglected at large tan β
- L-R stau mixing may be important
- Decays involving Yukawa coupling change chirality and therefore charge of the outgoing τ
  - Neutralino decay producing OS ``half-cusp'' distribution gives with $\tau$ Yukawa coupling insertion a SS ``half-cusp'' distribution



OS ``half-cusp'' SS ``half-cusp''

- L-R stau mixing has a similar effect:

- L-R mixing introduces a new feature:



kinematically forbidden SS ``half-cusp''

- Unlike l=e,u dilepton events, once τ Yukawa coupling and/or L-R mixing effects are included, decays to final states involving τ 's do not have simple OS/half-cusp or SS/hump correlations
- SS distribution lτ : hump+ε half-cusp with same endpoint
  e.g. ε=1 for maximal L-R mixing
- correlated modification to OS distribution lτ: half-cusp + ε' hump
- L-R mixing can be an important effect on l τ,$\tau\tau$, distributions

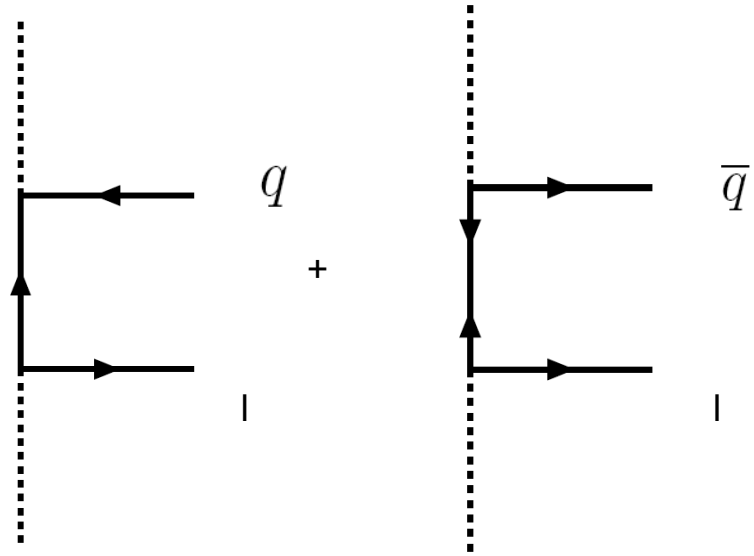
	Triangle	Hump	Half-Cusp
Opposite-Sign Same-Flavor	$\chi_i^0 \to \tilde{\tau}_{1,2}^{\mp}\tau^{\pm}$ $\hookrightarrow \chi_j^0\tau^{\mp}\tau^{\pm}$	$\tilde{\tau}_1^{\pm} \to \ell^{\pm}\chi^0$ $\hookrightarrow \tau^{\pm}\tau^{\mp}\tilde{\tau}_2^{\pm}$	$\tilde{\tau}_1^{\pm} \to \chi_i^0\tau^{\pm}$ $\hookrightarrow \tilde{\tau}_2^{\pm}\tau^{\mp}\tau^{\pm}$
Opposite-Sign Opposite-Flavor		$\tilde{\ell}_{L/R}^{\pm} \to \chi_i^0\ell^{\pm}$ $\hookrightarrow \tau^{\mp}\ell^{\pm}\tilde{\tau}_2^{\pm}$	$\tilde{\tau}_1^{\pm} \to \chi_i^0\tau^{\pm}$ $\hookrightarrow \tilde{\ell}_{R/L}^{\pm}\ell^{\mp}\tau^{\pm}$
		$\tilde{\tau}_1^{\pm} \to \tau^{\pm}\chi_i^0$ $\hookrightarrow \tau^{\pm}\ell^{\mp}\tilde{\ell}_{R/L}^{\pm}$	$\tilde{\ell}_{L/R}^{\pm} \to \chi_i^0\ell^{\pm}$ $\hookrightarrow \tilde{\tau}_2'^{\pm}\tau^{\mp}\ell^{\pm}$
Same-Sign Same-Flavor		$\tilde{\tau}_1^{\pm} \to \chi_i^0\tau^{\pm}$ $\hookrightarrow \tilde{\tau}_2^{\mp}\tau^{\pm}\tau^{\pm}$	$\tilde{\tau}_1^{\pm} \to \tau^{\pm}\chi_i^0$ $\hookrightarrow \tau^{\pm}\tau^{\pm}\tilde{\tau}_2^{\mp}$
Same-Sign Opposite-Flavor		$\tilde{\ell}_{L/R}^{\pm} \to \chi_i^0\ell^{\pm}$ $\hookrightarrow \tilde{\tau}_2^{\mp}\ell^{\pm}\tau^{\pm}$	$\tilde{\ell}_{L/R}^{\pm} \to \ell\chi_i^0$ $\hookrightarrow \tilde{\tau}_2^{\mp}\ell^{\pm}\tau^{\pm}$
		$\tilde{\tau}_1^{\pm} \to \chi_i^0\tau^{\pm}$ $\hookrightarrow \tilde{\ell}_{R/L}^{\mp}\tau^{\pm}\ell^{\pm}$	$\tilde{\tau}_1^{\pm} \to \tau^{\pm}\chi_i^0$ $\hookrightarrow \tilde{\ell}_{R/L}^{\mp}\tau^{\pm}\ell^{\pm}$

Table 4: SUSY di-leptons. Decays only involving $\tilde{\tau}$ listed. Gaugino-higgsino, τ Yukawa coupling and L-R mixing included.

Signed bl distributions

- Observation of a non-triangular ql distribution requires that both fermions be signed or charge asymmetry (A.Barr)

otherwise:



= triangle

Signed bl distribution does not need a charge asymmetry, but:

- Signed bl distributions similar to affects of L-R mixing on l τ distributions because both L and R sbottoms may have same decay (but different endpoints)

$$\tilde{b}_{L,R} \rightarrow b\chi_i^0$$

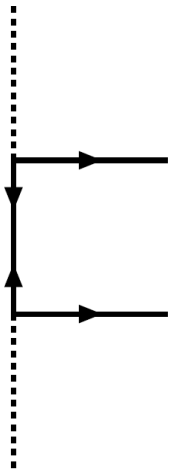
Signed bl distribution contains information on both R and L sbottoms, as well as neutralino decays to either L and R sleptons

Symmetry of Dark Matter

- In the MSSM the LSP is stable because of a discrete symmetry (R-parity). But continuous U(1)_R symmetry well-motivated.
- Suppose a missing energy signal is discovered. Is the symmetry discrete or continuous?
- In U(1)_R symmetric limit gauginos acquire Dirac masses by marrying new chiral adjoints
  - lose U(1)_R violating decay :

$$\tilde{l}_L^- \to \tilde{l}_R^- l^+ l^-$$

  - no adjacent OS ``half-cusp'' distributions in an interlaced spectrum
  - distribution important: dileptons higher up decay chain from intermediate slepton, but those give OS triangle



Superfield	$U(1)_R$
L	$+1$
E^c	$+1$
$H_{u,d}$	0
Component Fields	
$\tilde{G}$	+1
ψ_{SM}	0
$\tilde{l}_L^-$	$+1$
$\tilde{l}_R^-$	-1
$h_{u,d}$	0

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

Table 3: SUSY di-leptons. First two generations - neglect first two generation Yukawa couplings. No L-R mixing. No flavor violation. $U(1)_R$ symmetry conservation.

Summary

- If susy exists, potential for rich pattern of dilepton distributions and correlations between observables
  - ``triangles'' mSUGRA-like points (LM1-LM6'…)
  - ``humps'' and ``half-cusps'' for an ``interlaced'' spectrum (minimal gauge-mediation, higgsino-LSP like,….)
  - Pattern to correlations if susy; complete pattern of correlations not filled out
    - Relaxed number of assumptions: flavor conservation and flavor universality; gaugino-higgsino mixing; Yukawa couplings;
  - $\tau\tau,\tau l$
  - signed bl
- discriminate between continuous and discrete symmetries

- Interesting to apply ``Rutgers Ensemble Method'' to reduce combinatorial confusion (see Eva's talk) ; study required
- signals soon after discovery