Third-Generation Fermions and Precision Measurements at the LHC

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work in progress

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New physics and cascade decays

- **Highly anticipated signal at LHC:**

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

- **Typically do not expect to fully reconstruct events.**
  - Invariant mass distributions can be a powerful tool
  - Lorentz-invariant characterization of object correlations.
  - Directly computable relation between observables and underlying model parameters

- **Post-discovery: distribution shapes important to discriminate between models**
  - earlier: iteratively generate and test hypotheses
  - later: detailed measurements

SUSY On-Shell Cascade Decays

- **Basic process: cascade** $X \to \Psi_1 Y \to \Psi_1 \Psi_2 M$
- **Distribution shape** $\frac{1}{\Gamma}\frac{d\Gamma}{dm} = P_k^{(4J+1)}(m)$ **sensitive to spin of intermediate particle** Y**:**
  - $J_i = 0, 1/2$: coefficients independent of masses
  - $J_i \geq 1$: coefficients depend on masses: different couplings of longitudinal, transverse degrees of freedom
- **SUSY models: theoretical distributions are simple and universal.**
  - three shapes: intermediate scalar (1), intermediate fermion (2)
  - Starting point for analysis aimed at measuring NP properties (couplings, masses, spins, ...)
  - Similar analyses for same-spin partner models are possible and desirable.

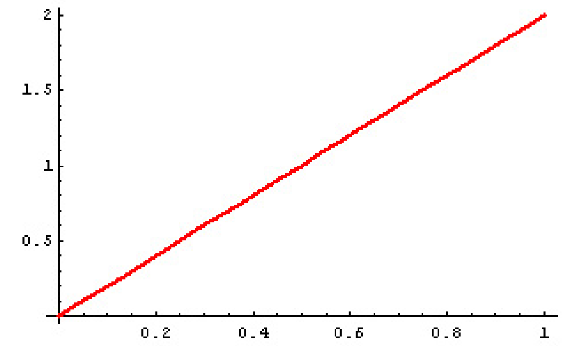
An Example

- **A simple example: mSUGRA dileptons,**

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

  - 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 $|\mathcal{M}|^2 =$ constant
  - Channel determined by quantum numbers of intermediate state: OS, SF only

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

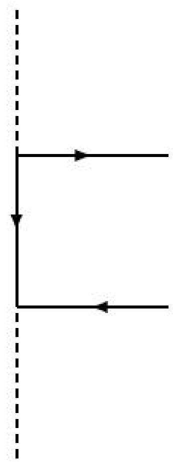


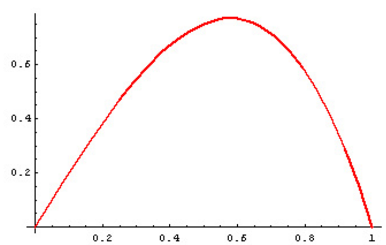
Intermediate fermions

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

"Hump"

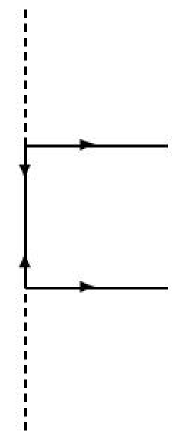
$$\frac{1}{\Gamma}\frac{d\Gamma}{dx} = 4x(1-x^2)$$

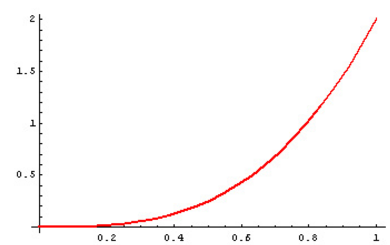




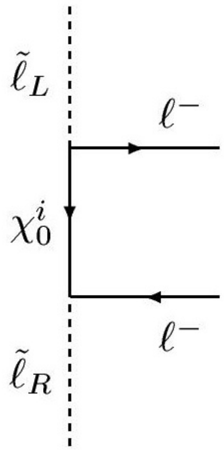
"Cusp"

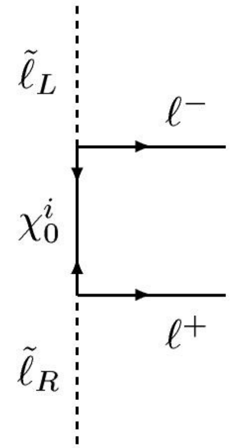
$$\frac{1}{\Gamma}\frac{d\Gamma}{dx} = 4x^3$$





- **SUSY: chiral couplings to leptons $\Rightarrow$ hump $=$ same-sign, cusp $=$ opposite-sign**





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

- **Importance of cross-channel correlations:** *Simultaneous* **hump SS and cusp OS**
  - same normalizations and endpoints
  - same distributions in OF, SF channels
  - check of theoretical assumptions (R-parity, flavor structure, ...)

SUSY Dileptons

	Triangle	Hump	Half-Cusp
Opposite-Sign Same-Flavor			
Opposite-Sign Opposite-Flavor			
Same-Sign Same-Flavor			
Same-Sign Opposite-Flavor			

- Minimal assumptions: neglect Yukawa couplings, L-R slepton mixing; L-R ordering

SUSY Dileptons

	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			

- Minimal assumptions: neglect Yukawa couplings, L-R slepton mixing; L-R ordering

SUSY Dileptons

	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		$\tilde{\ell}^{\pm}_{L,R} \to \chi_i^0 \ell^{\pm}$ $\hookrightarrow \tilde{\ell}'^{\mp}_{R,L}\ell'^{\pm}\ell^{\pm}$	

- Minimal assumptions: neglect Yukawa couplings, L-R slepton mixing; L-R ordering

Third-generation final states

- **Leptons (e, μ) are "easy": observed distribution very close to theoretical distribution**

- **Final states with third-generation fermions (τ, b) are more complicated:**
  - more complicated as experimental objects
  - must work harder to connect underlying theoretical distribution to experimentally observed distribution
  - richer phenomenology: an excellent laboratory for measuring model parameters

b-ℓ distributions

- **Processes giving b, ℓ on adjacent steps of a cascade:**
  - $\tilde{b}^{\pm} \to b^{\pm}\chi^{0} \to b^{\pm}\ell^{\pm}\tilde{\ell}^{\mp},\ b^{\pm}\ell^{\mp}\tilde{\ell}^{\pm}$
  - $\tilde{t}^{\pm} \to b^{\mp}\chi^{\pm} \to b^{\mp}\ell^{\pm}\widetilde{\nu}$
- **Typically expect third-generation squarks will be appreciably mixed.**
  - b-ℓ distributions will depend on the mixing
  - for the moment set mixings to zero for clarity
- **Sensitivity depends on whether or not b-jet is signed.**

Unsigned b-ℓ distributions

- **Sbottom decay via Dirac neutralino:**
  - Models with unbroken R-symmetry: neutralinos acquire Dirac mass by marrying new chiral adjoint
  - Compatibility with EWSB requires all sfermions have equal R-charge; thus (e.g.) $\tilde{b}_L \to b^- \ell^- \tilde{\ell}^+_R$ is allowed but $\tilde{b}_L \to b^- \ell^+ \tilde{\ell}^-_R$ is forbidden.
  - $\Rightarrow$ only one process contributes to any given $b - \ell^\pm$ final state, and the observed distribution is a hump.

Unsigned b-ℓ distributions

- **Stop decay via chargino:**
  - If chargino is pure gaugino: $\tilde{t}_L \to b\chi^{\pm} \to b\ell\widetilde{\nu}$ gives a hump distribution.
  - If chargino is partly higgsino, the couplings are no longer purely chiral, and the spin correlations are partially washed out but typically still significant.

Unsigned b-ℓ distributions

- **Sbottom decay via (Majorana) neutralino:**
  - the process $\tilde{b}_{L,R} \to b\chi^0 \to b\ell\tilde{\ell}_{R,L}$ gives a hump distribution in the same-sign channel and a cusp distribution in the opposite-sign channel, just as for dileptons.
  - the process $\tilde{b}_{L,R} \to b\chi^0 \to b\ell\tilde{\ell}_{L,R}$ gives a cusp distribution in the same-sign channel and a hump distribution in the opposite-sign channel.
  - If one does not sign either the b-quark or the lepton, then the observed distribution is a triangle. (Of course, this is still an interesting kinematic feature!)
  - Separately considering b-ℓ^+ and b-ℓ^- gives sensitivity to any production asymmetry favoring squarks over anti-squarks.

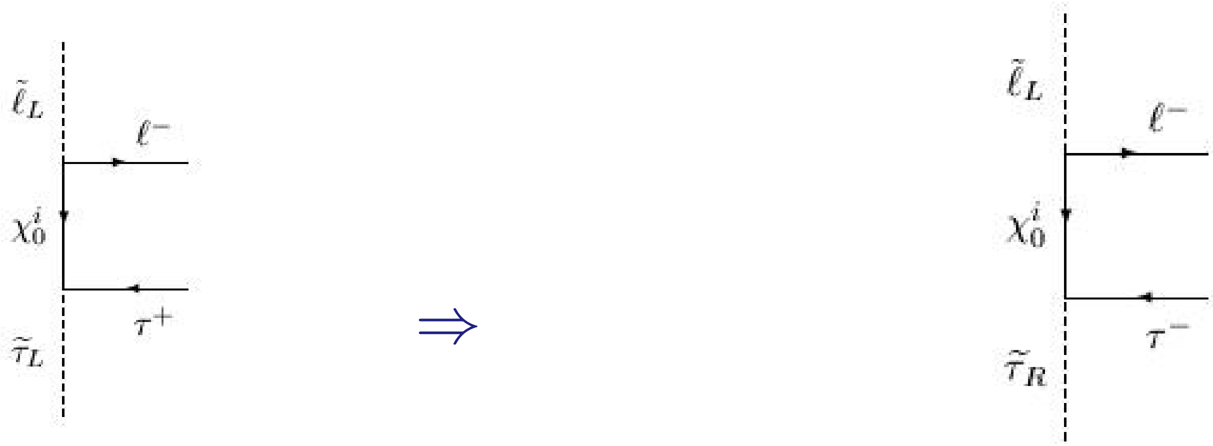
b-jet signing

- **Sign information a powerful lever! Signing the b-jet allows separate resolution of opposite-sign, same-sign distributions.**
  - measure Majorana neutralino
  - measure relative handedness of sbottom, slepton
- **Possibility of signing b-jets using muon from $b \to cW$ allows nontrivial spin correlations to be seen in the quark sector *without* the need for overall production asymmetry.**
  - $\mathcal{O}(10\%)$ of b-jets can be signed;
  - mis-sign rate $\mathcal{O}(30\%)$ reported in ATLAS TDR, D0; optimistic this can be improved (S. Schnetzer, Y. Lin)
  - irreducible mis-sign fraction $\mathcal{O}(13\%)$ due to neutral B meson oscillation

Mixings

- **Expect mixings (R-L sfermions and gauginos-higgsinos) to be typically non-negligible**
  - Effect of mixings is to reduce chirality of vertices. Total distribution in given channel contains admixture of "wrong" distribution, depending on mixing angles

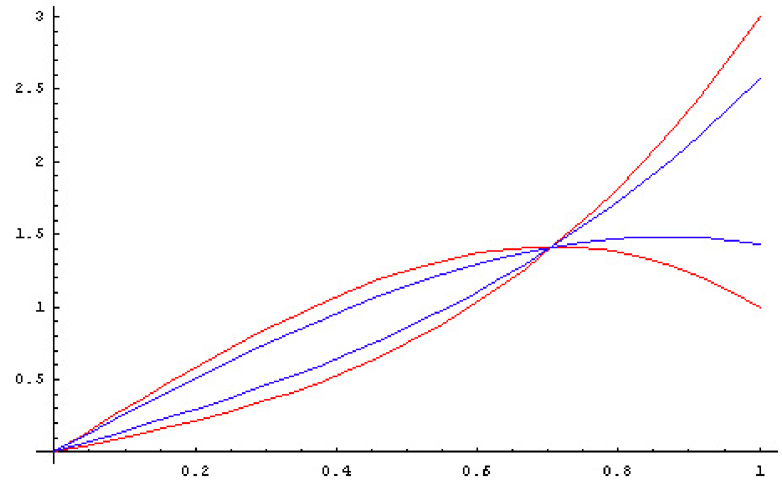
- **Sfermion L-R mixing:**



  - Relative normalization of distributions set by sfermion mixing angle
  - Gaugino-higgsino mixing qualitatively similar

Mixing and b-ℓ

- **To measure spin and mixings, fit b-ℓ distributions to a sum of hump and cusp distributions:**
  - $D_{theory}(x) = fH(x) + (1-f)C(x)$, where f depends on ratios of Yukawas
  - fit observed distribution with correction for mis-sign rate
  - fit f in both opposite-sign and same-sign channels
- **Example, for intermediate pure bino and $\cos\theta_b = .78$.**



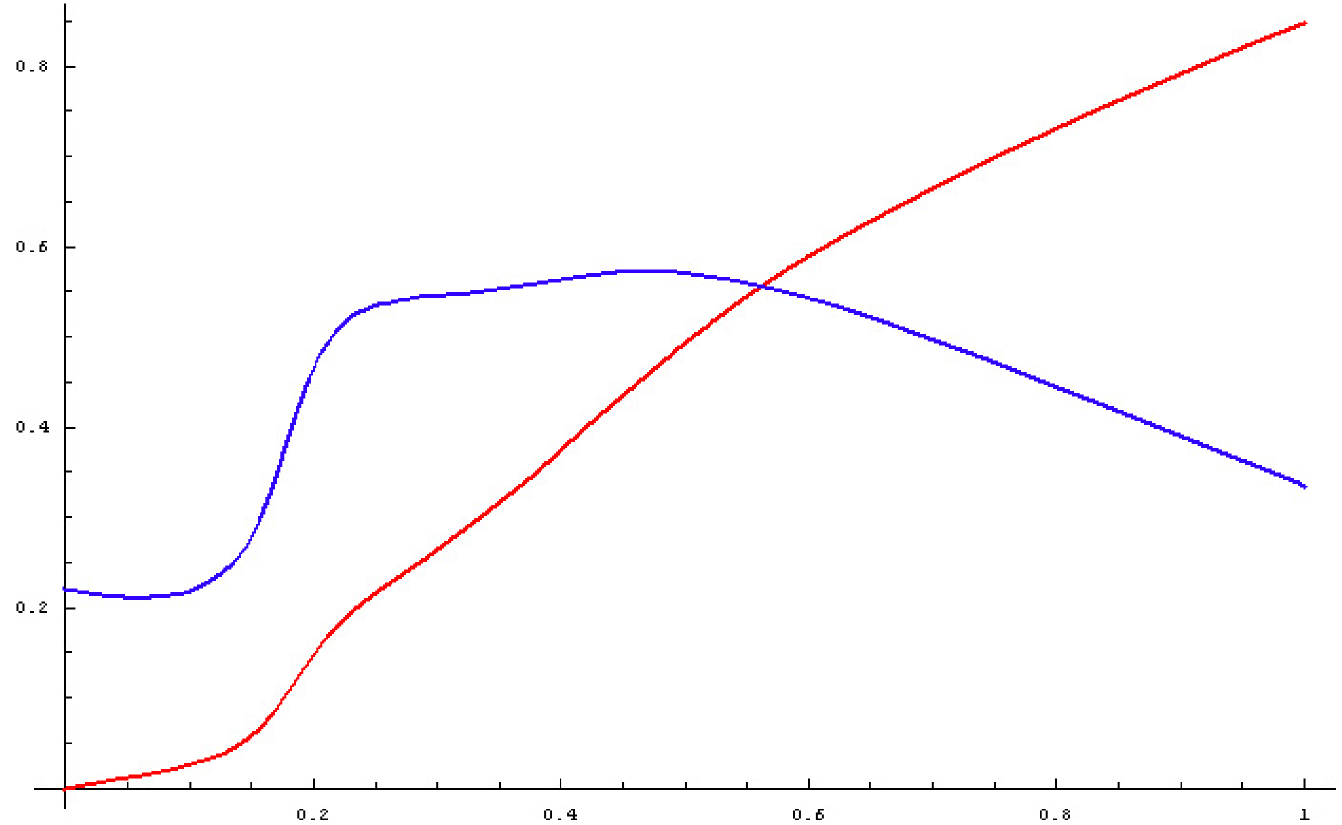
b-ℓ distributions with 15% (red) and 30% (blue) mis-sign fraction

ℓ-τ and di-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
  - In many models, stau LSP leads to τ-rich final states
- **Experimentally, full four-momentum of τ not reconstructed**
  - compute modified distributions: folding theoretical distributions with energy spectra of daughter particles
  - τ polarization statistically measurable

τ polarization

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

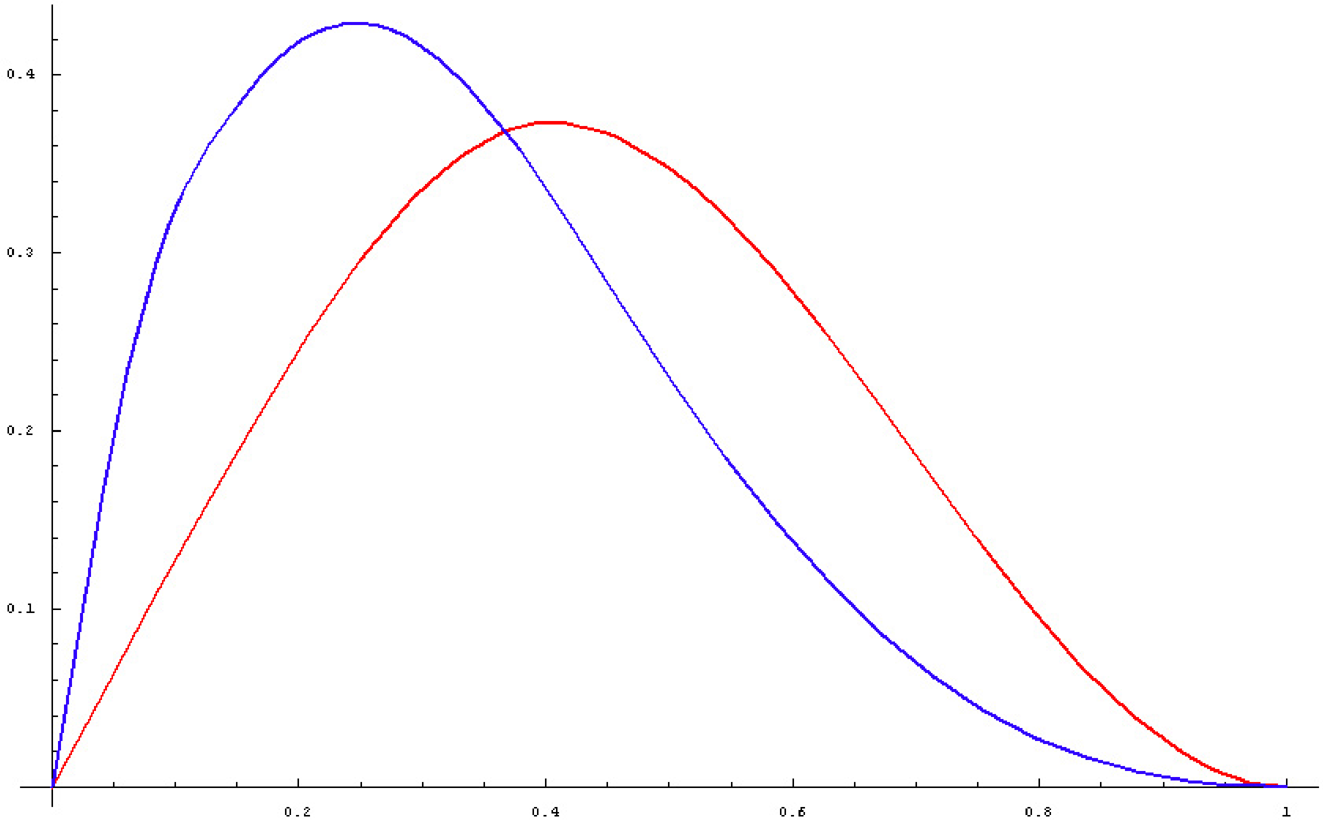


Fractional energy distribution for reconstructed 1-prong τs

- unique window into chiral structure of NP

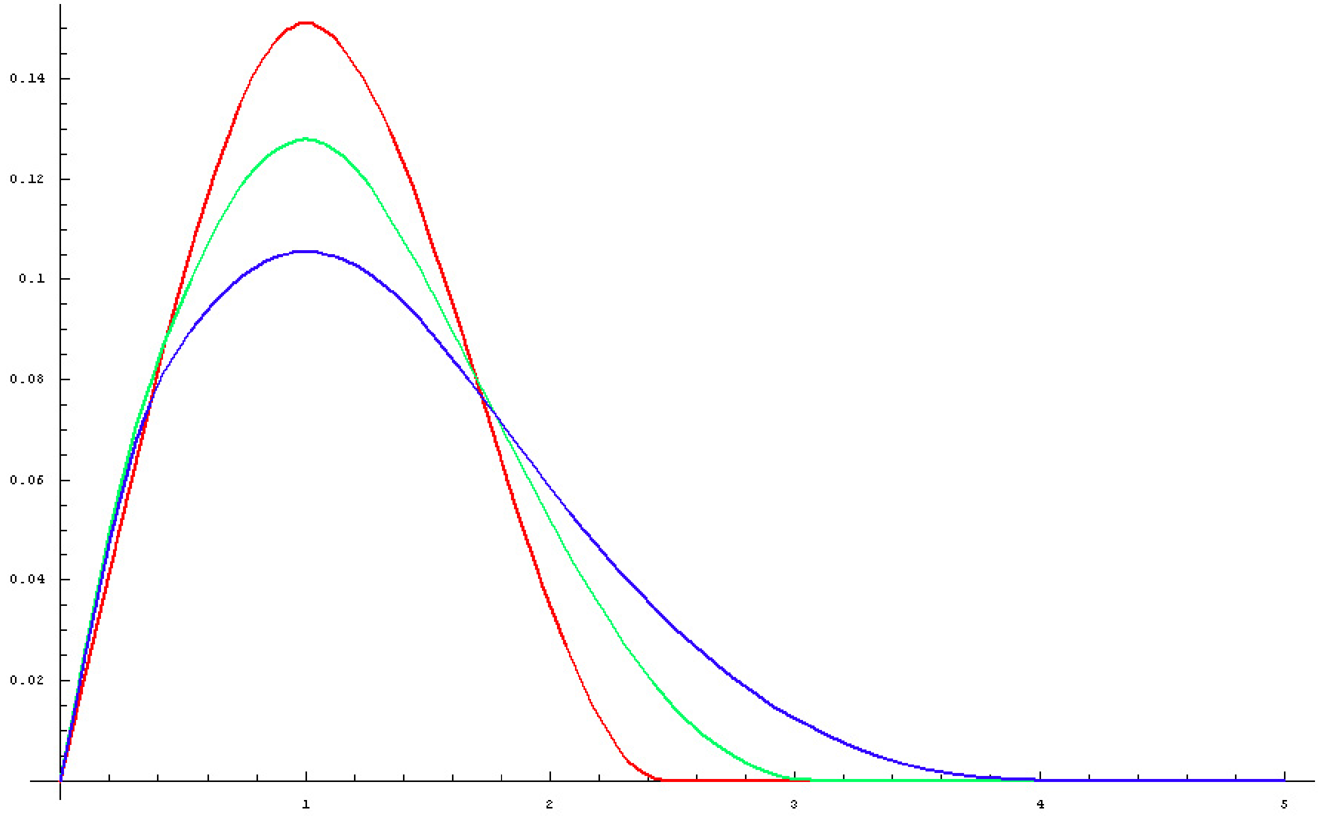
An example: ditau triangle

- **Consider the process $\chi_i^0 \to \tau\widetilde{\tau}_{L,R} \to \tau\tau\chi_j^0$. Different staus give different invariant mass distributions for the reconstructed one-prong taus:**



Di-τ triangle distributions for a pure $\widetilde{\tau}_L$ (blue) and pure $\widetilde{\tau}_R$ (red).

- **Mixing: Now *three* possible distributions, T_{LL}, T_{LR}, T_{RR}.**
- **Two parameter fit measures stau and neutralino identities.**



scaled di-τ triangle distributions; identical areas

- **challenging measurement: requires high statistics, good background characterization**

Conclusions

- **Difermion invariant mass distributions a powerful analysis tool**
  - correlations across channels useful in checking model parameters, assumptions
  - third-generation fermions are challenging but potentially very rewarding: sensitivity to spin, mixing, chiral structure
- **Cascade decays still repay further analytic study (even now!): analyses will require good understanding of additional invariant mass distributions:**
  - Nonadjacent fermions
  - Three-body decays; finite width effects
  - Same-spin partners
  - Other final states: ℓV^{μ}, ℓh, ...