Discerning New Physics in Cascade Decay Correlations

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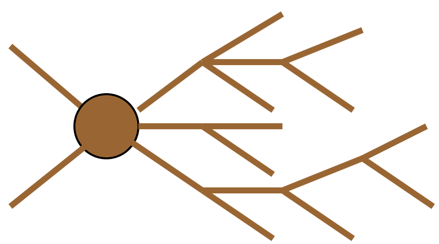
New Physics at the Large Hadron Collider

- Extract Signatures from Data
- Interpret Signatures
- Determine Underlying Theoretical Framework



Hard Scattering Processes -
Produce Low Multiplicity States
- Decay to "Stable" Particles

Relatively Long Lived Intermediate States: Γ/m ¿ 1

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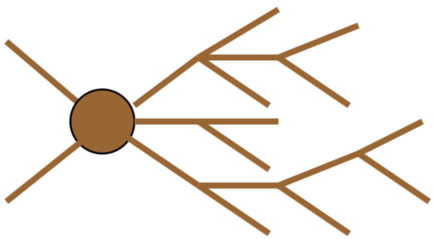

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- **Object Correlations Within (and Between) Events**

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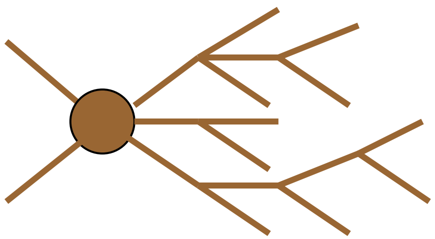

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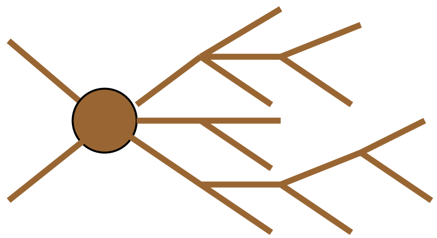
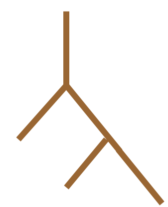


$S\text{-Matrix} = f(m_{ijk\ldots}^2)$ (Unpolarized, Spins Unobserved, T-Invariance)

$m_{ijk\ldots}^2 = f(m_{ij}^2)$

- Correlations in Generalized Dalitz Space m_{ij}^2 i,j = All Pairs

True of Subprocesses Also



Depend Directly on Masses, Quantum Numbers, Interactions

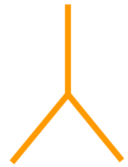
- Exploit (Subprocess) Correlations to Make "Direct" Measurements …

Compare: Indirect Interpretation of Signatures

Cuts + Number Counts

Correlations Within Decay Trees Γ/m ¿ 1

3-Point Interaction



$f(p_1^2, p_2^2, p_3^2)$

Amplitude (Almost) Uniquely Determined Determined by
Lorentz Invariance up to Momentum Dependent Form Factor

$J = \frac{1}{2}, \frac{1}{2}, 0$

$$\psi_i \psi_j \phi \; + \; \mathrm{h.c.}$$

$J = \frac{1}{2}, \frac{1}{2}, 1$

$$\psi_i^* \sigma^\mu \psi_j A_\mu$$

$$\psi_i \sigma^{\mu\nu} \psi_j F_{\mu\nu} \; + \; \mathrm{h.c.}$$

……

Near Mass
Shell

$$f(p_i^2) = f_0 + (p_i^2 - m_i^2) \frac{\partial f(p_i^2)}{\partial(p_i^2 - m_i^2)} \; + \; \cdots \qquad i = 1, 2, 3$$

Form Factor Nearly Constant Γ/m ¿ 1

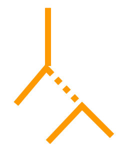
Consistent OnShell Effective Theory (COSET)

OnShell fields $\Psi_0, \phi_0, \ldots.$ $\langle \Psi_0(p) \Psi_0(-p) \rangle = -2\pi i \delta(p^2 - m^2) + \cdots$

Interactions $\Psi_0 \Psi_0 \phi_0 + \ldots.$

Expansion Parameters Γ/m, m/M

OffShell fields $\Psi, \phi, \ldots.$



(+ Radiation)

Effective Theory – Distinct from - Wilsonian Effective Theory

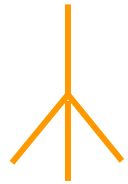
Momentum Expansion p^2/M^2 , $p^2=0$

- Heavy Field Expansion

Two Body Decay Interactions Determined to Leading Order Completely in Terms of One or Two Parameters

Resummation of Wilsonian Effective Theory – Very Close Measured Experimentally

4-Point Interaction



$f(p_1^2, p_2^2, p_3^2, p_4^2, p_{23}^2, p_{34}^2)$

Amplitude Not Uniquely Determined -
Form Factor Depends on Two Invariants Even On Shell

COSET Must be Supplemented by "Model"
for 4 or more-Point Interactions

(Constant Amplitude Never Good Model with Fermions)

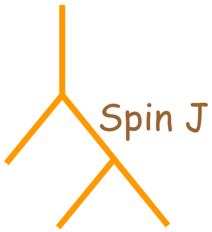
Cascade Decay Tree of Sequential 2-Body Decays
Through Well Defined States

COSET: Functional Form of the Leading Order Correlations are (Almost) Uniquely Determined by the Quantum Numbers and Masses

COSET 2-Body Cascade Decay Correlations

Strongest Correlations - Adjacent Branches of Decay Tree

To Leading Order in Γ/m - Single Invariant m_{23}^2



$(1 / \Gamma)(d \Gamma / dx) = f(x)$ Odd Order Polynomial Degree 4J+1

$x = m_{23}/m_{23}^{max}$

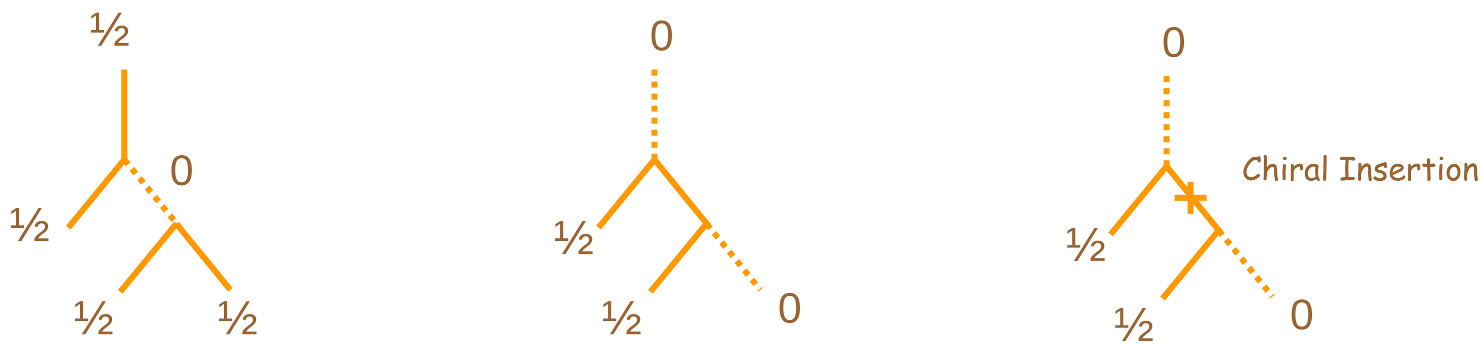
$J = 0 , \frac{1}{2}$ Shape Independent of Masses

J ¸ 1 Shape Depends on Masses

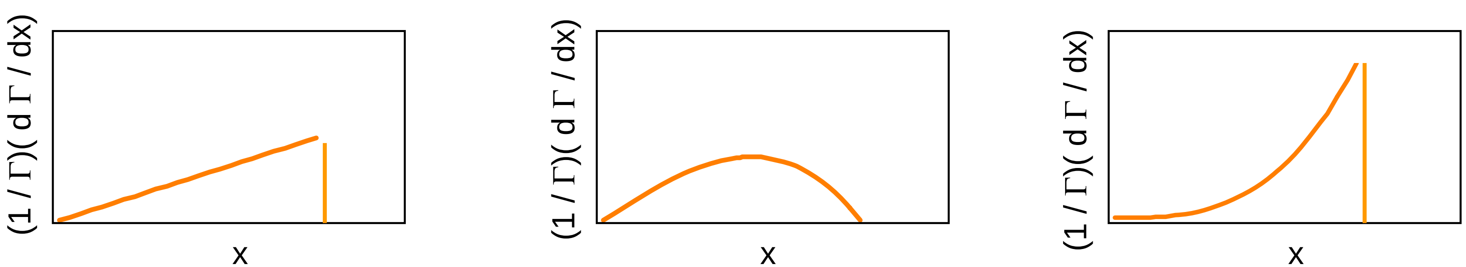
Gain Mass Through (Generalized) Higgs Mechanism :
Coupling Through Longitudinal and Transverse
Components Give Different Distributions

(Suggests Method for Determining Top Mass from m_{lb}
Independent of b-Jet Energy Scale Uncertainty)

COSET 2-Body Cascade Decay Correlations



$2x$	$4x(1-x^2)$	$4x^3$
Triangle	Hump	Half-Cusp

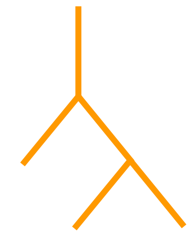


Chiral Structure Unique - Independent of Majorana/Weyl, Dirac, PseudoDirac, ...

Only Possibilities for Adjacent Branch Correlations with J=0, $\frac{1}{2}$

Discerning New Physics in Cascade Decay Correlations

Adjacent Branches of Decay Tree



$$\frac{1}{\Gamma}\frac{d\Gamma}{dx} = x\sum_{n=0}^{J} c_{2n}x^{2n}$$

$$c_{2n} = f(m_i^2/m_j^2) \quad \text{for} \quad J \geq 1$$

Have (Almost) Complete List for J · 1

(Template) Search for Correlations in Data

Non-Unique Interpretations Possible ….

Triangle = (1/2) (Hump + Half-Cusp)

Limiting forms and (Contrived) Coincidences
of J ¸ 1 Distributions

Hypothesis Testing …

Discerning Supersymmetry in Cascade Decay Correlations

Limited Set of Possible Adjacent Branch Correlations : J=0, $\frac{1}{2}$

Adjacent Di-Lepton Distributions - All Possible SUSY Spectra

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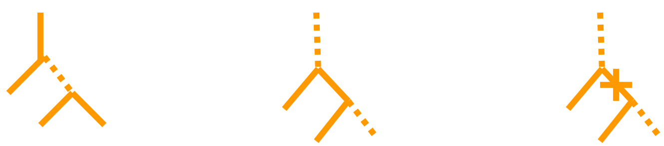

(No Gaugino-Higgsino mixing, No L-R mixing, L-R ordering, Flavor Conservation)

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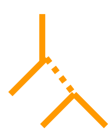
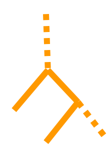
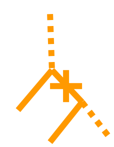

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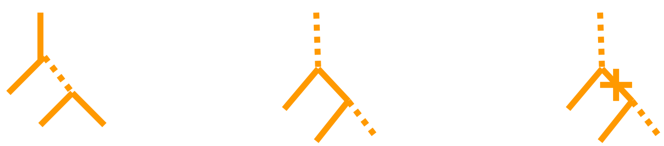

U(1)$_R$ Conservation: Half Cusp Absent

Similar Correlation Table for Di-Jet Correlations – (No Charge)

Discerning Partner Spin in Cascade Decay Correlations

Adjacent Di-Lepton Distributions $J = \frac{1}{2}, 1$

All Possible Nearly Degenerate Spectra

	Modified Triangle	Modified Hump	Modified Half-Cusp
Opposite-Sign Same-Flavor	$\hat{V}_2 \to \hat{\ell}^{\mp}_{L,R}\ell^{\pm}$ $\hookrightarrow \hat{V}_1 \ell^{\mp}\ell^{\pm}$	$\hat{\ell}^{\pm}_{L,R} \to \hat{V}_1 \ell^{\pm}$ $\hookrightarrow \hat{\ell}^{\pm}_{R,L}\ell^{\mp}\ell^{\pm}$	
Opposite-Sign Opposite-Flavor		$\hat{\ell}^{\pm}_{L,R} \to \hat{V}_1 \ell^{\pm}$ $\hookrightarrow \hat{\ell}'^{\pm}_{R,L}\ell'^{\mp}\ell^{\pm}$	
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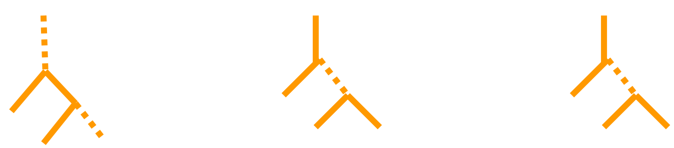
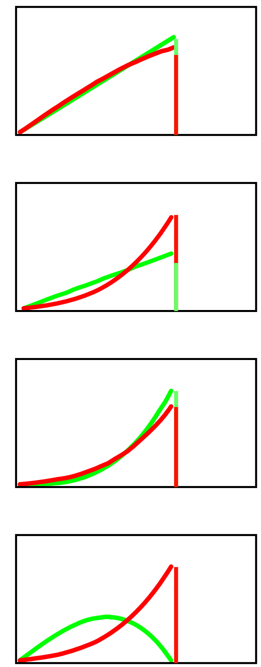


(No Gauge mixing, No L-R mixing, L-R ordering, Flavor Conservation)

Discerning Partner Spin in Cascade Decay Correlations

	Super-Partners	Same Spin-Partners (Nearly Degenerate)	Same Spin-Partners (General)
Opposite-Sign Same-Flavor Lepton-Lepton	$2x$	$\frac{20}{9}x(1-\frac{1}{5}x^2)$	$x(c_0+c_2x^2)$
Jet-Lepton	$2x$	$\frac{2}{3}x(1+4x^2)$	$x(c_0+c_2x^2+c_4x^4)$
Opposite-Sign b-Jet-Lepton	$4x^3$	$\frac{2}{3}x(1+4x^2)$	$x(c_0+c_2x^2+c_4x^4)$
Same-Sign b-Jet-Lepton	$4x(1-x^2)$	$\frac{2}{3}x(1+4x^2)$	$x(c_0+c_2x^2+c_4x^4)$

SUSY
Same Spin
(Nearly Degenerate)



Modified Triangle

Modified Half-Cusp

Modified Half-Cusp

Note: No Initial State Charge Asymmetry Required
Better Discrimination with non-Degenerate States – $O(x^5)$ Polynomial
Even Easier Discrimination with Other Mass Orderings

Exploit Correlations – Extract (Segment) of Decay Tree

In Addition to Standard Cuts ….

Invariant Correlations Can Also be Useful in Increasing Purity of Particular Decay Tree Within an Event Sample

Develop Discriminating Correlations Between Some Invariant Momenta or Correlation that Arises Within a Decay Tree (and Some Other Variable(s))

Apply Correlation to an Ensemble of Objects Within a Given Event

1. Reduces Combinatoric Confusion:

   Correct Association – Invariants Restricted

   Incorrect Associations – Invariants Unrestricted

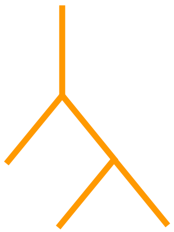
2. Enhances Signal/Background Purity:

   SM Background Tends to be at Worst Similar to Combinatoric Confusion

   Invariants of "Unrelated" Objects

Object Correlation Ensembles Extract Leading Order Trees (OCELOT)

Contained Decay Trees



To Leading Order in Γ/m - Single Invariant m_{23}

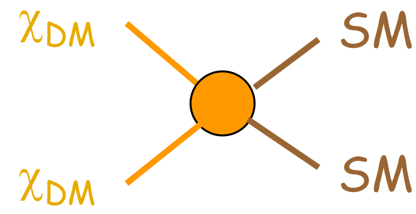
Invariant Momentum of Two Branches m_{23} Completely Determines Correlations Within this Subprocess

Doesn't Hurt to Loose 3rd Branch to Missing Energy

(If Visible) Can Still use m_{12} and m_{13} to Form Additional Correlations

1. Extract More Information Directly from Correlations
2. Further Improve Signal to Background Contrast – Higher Dimensional Correlations

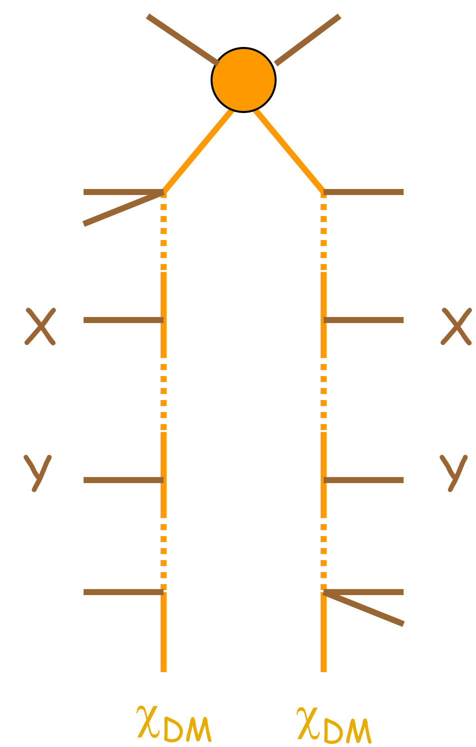
Determining the WIMP Dark Matter Stabilizing Symmetry



WIMP Dark Matter – Freeze Out

Requires Stabilizing (Exact) Symmetry

$m \chi \chi$ Allowed - SM Uncharged



Symmetry

Continuous	$(X^+Y)(X^-Y)$	Opposite Sign
Discrete	$(X^+Y)(X^-Y)$	Opposite Sign
	$(X^+Y)(X^+Y)$	Same Sign

(Small Caveats)

SUSY: $U(1)_R$ versus R-Parity

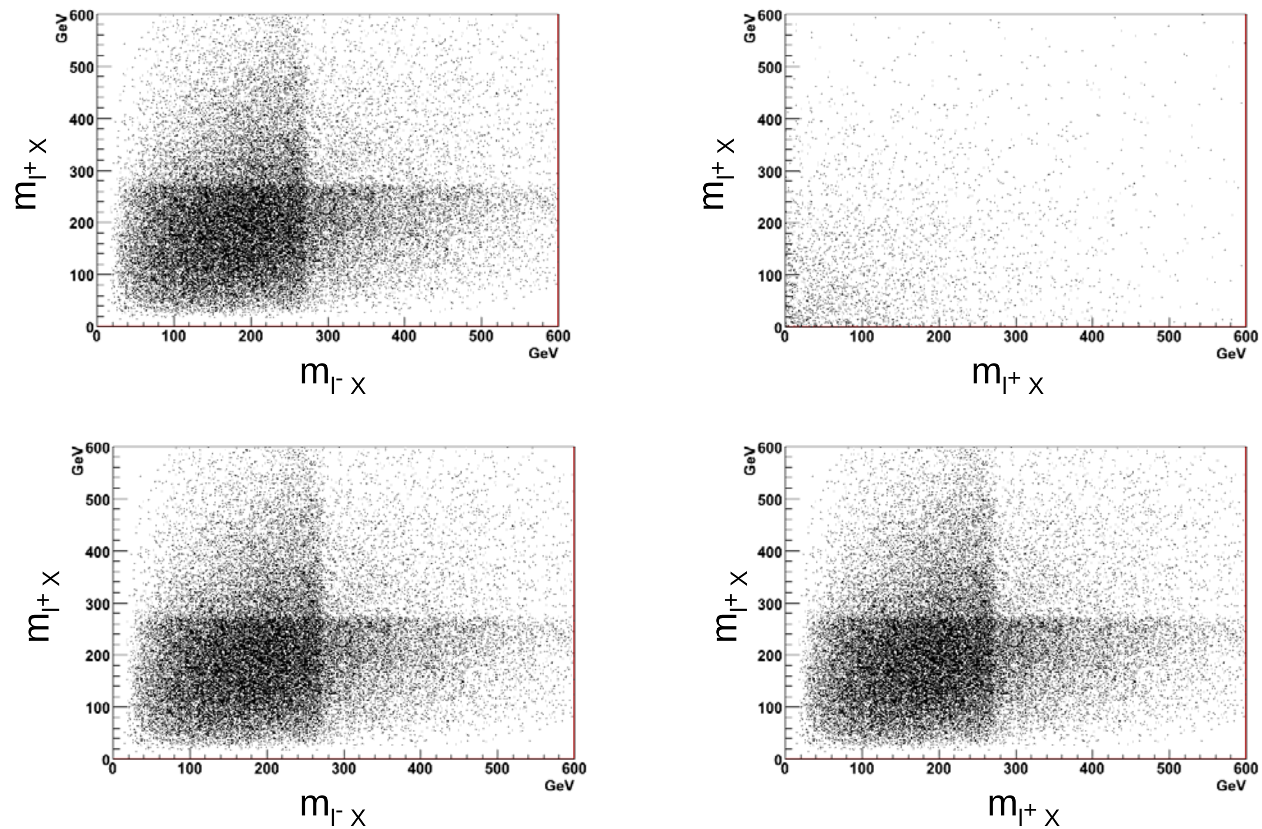
Inter-Tree Correlations

Simultaneous COSET m_{XY} - m_{XY} Inter-Tree Correlation (factorizes)

Opposite Sign | Same Sign

Continuous

Discrete



Note: Same-Sign vs Opposite Sign - Count NOT Necessarily Sufficient

The Use of Object Correlations will Play an Important Role in the New Physics Program at the LHC

- Extract Signatures from Data
- Interpret Signatures
- Determine Underlying Theoretical Framework

Cascade Decay Correlations

- Consistent On-Shell Effective Theory (COSET) Framework

Interpret Signatures → Masses, Quantum Numbers, Spins, Symmetries, ...

With Partial Event Reconstruction / Decay Tree Segments / No MET Reconstruction
Applications to Early Data

	Hump	Half-Cusp
Opposite-Sign	$\tilde{b}_L^\pm \to b^\pm \chi_i^0$ $\hookrightarrow b^\pm \ell^\mp \tilde{\ell}_L^\pm$	$\tilde{b}_R^\pm \to b^\pm \chi_i^0$ $\hookrightarrow b^\pm \ell^\mp \tilde{\ell}_L^\pm$
	$\tilde{t}_L^\pm \to b^\mp \chi_i^\pm$ $\hookrightarrow b^\mp \ell^\pm \tilde{\nu}_L$	
Same-Sign	$\tilde{b}_R^\pm \to b^\pm \chi_i^0$ $\hookrightarrow b^\pm \ell^\pm \tilde{\ell}_L^\mp$	$\tilde{b}_L^\pm \to b^\pm \chi_i^0$ $\hookrightarrow b^\pm \ell^\pm \tilde{\ell}_L^\mp$