Using Object Correlations to Extract New Physics from the LHC

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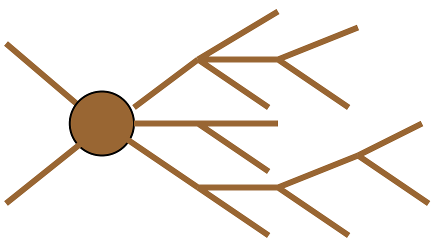
Rutgers HEX + HET

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" SM Particles

Relatively Long Lived Intermediate States: Γ/m ¿ 1

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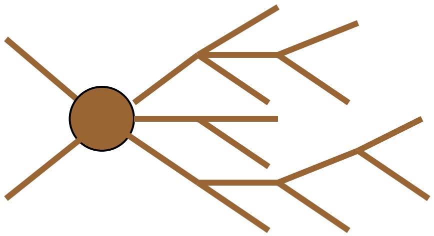


Hard Scattering Processes -
Produce Low Multiplicity States -
Decay to “Stable” SM Particles

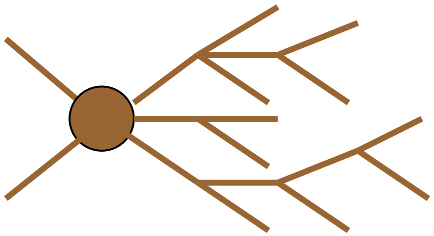
Relatively Long Lived Intermediate States: Γ/m ¿ 1

- Most Direct Route to Interpretation - Direct Measurements

  Masses

  Quantum Numbers (Gauge, Global, Spin, …)

  Interactions

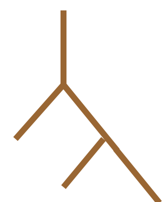


$S\text{-Matrix} = f(m_{ijk\ldots}^2)$ (Unpolarized, Spins Unobserved, T-Invariance)

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

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

True of Subprocess Also



Depend Directly on Masses, Quantum Numbers, Interactions

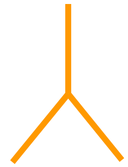
- Exploit (Subprocess) Correlations to Make Direct Measurements …

Compare: Indirect Interpretation of Signatures

Cuts + Number Counts

Correlations Within Decay Trees Γ/m ¿ 1

3-Point Interaction



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

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

J = ½, ½, 0 $\qquad \psi_i \psi_j \phi \ + \ \text{h.c.}$

J = ½, ½, 1 $\qquad \psi_i^* \sigma^\mu \psi_j A_\mu$

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

……

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

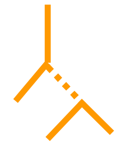
Consistent OnShell Effective Theory (COSET)

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

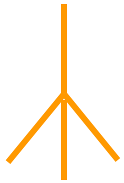
Momentum Expansion p^2/M^2 , $p^2=0$

- 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

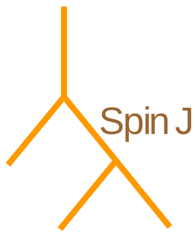
COSET Must be Supplemented by "Model"
for 4 or more-Point Interactions

(Constant Amplitude Not Good Model with Fermions)

Cascade Decay Tree of Sequential 2-Body Decays 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



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

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

$x = m_{23}/m_{23}^{max}$ Have (Almost) Complete List

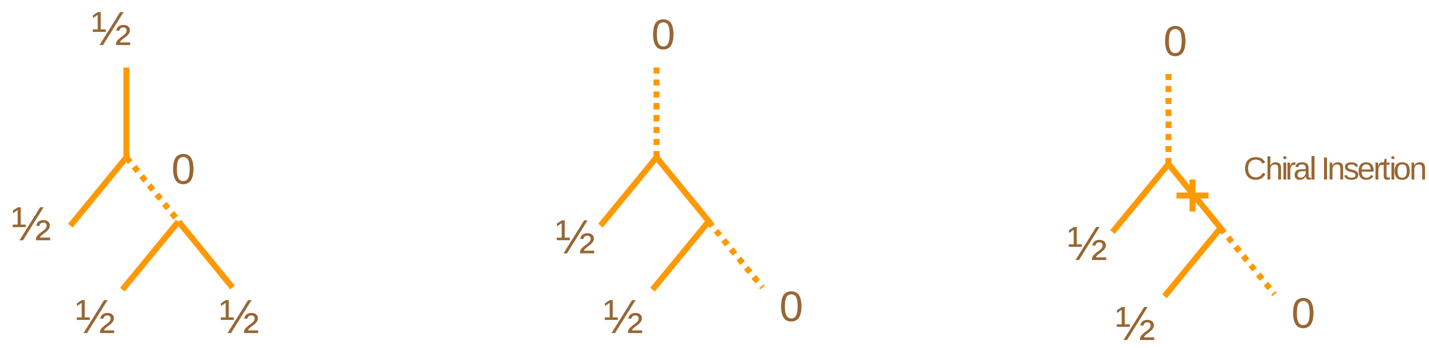
J = 0 , ½ Shape Independent of Masses

J ¸1 Shape Depends on Masses

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

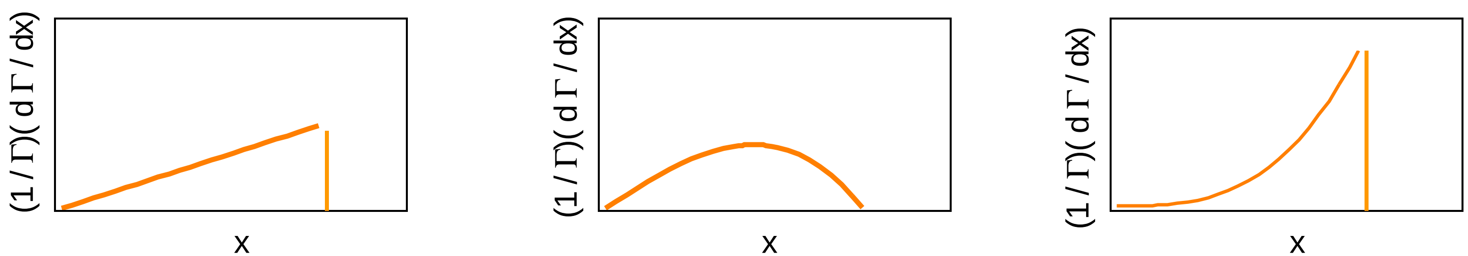
(Suggests Method for Determining Top Mass from m_{lb}
Independent of b-Jet Energy Scale Uncertainty)

COSET 2-Body Cascade Decay Correlations



$2x$ $\qquad$ $4x(1-x^2)$ $\qquad$ $4x^3$

Triangle $\qquad$ Hump $\qquad$ Half-Cusp



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

See Michael's Talk on COSET Interpretation of Signatures Within SUSY

Determining the Spin of Partner Particles

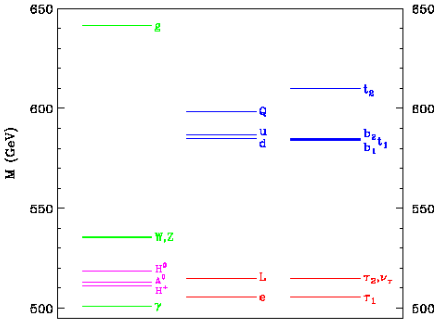
Assume Underlying Theoretical Framework:

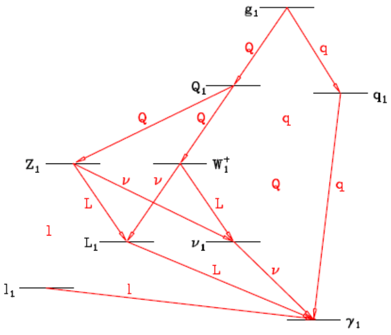
Quadratic Divergences Cancelled by Partner Particles

Spin Differs by Δ J = ½ SUSY

Same Spin Δ J =0 One-Loop GIM

Example: Minimal Universal Extra Dimension



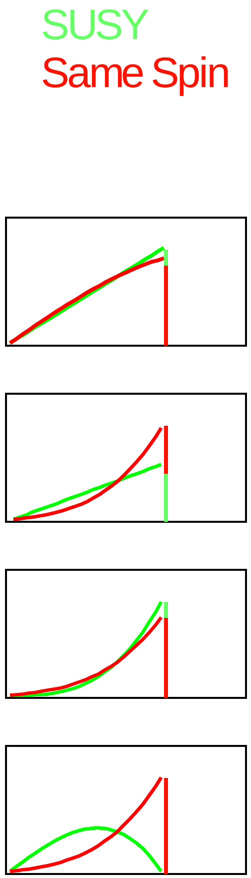


mSUGRA like Mass Ordering :

Adjacent Lepton-Lepton and Lepton-Jet in Decay Tree

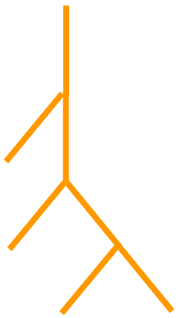
Determining the Spin of Partner Particles

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



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

COSET Decay Trees



To Leading Order in Γ/m - Three Invariant m_{23}^2 m_{34}^2 m_{24}^2

$$(1/\Gamma)(d^3\Gamma / dx\, dy\, dz) = f(x,y,z)$$

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

$$y = m_{34}/m_{34}^{max}$$

$$z = m_{24}/m_{24}^{max}$$

In General $f(x,y,z) \neq f(x)f(y)f(z)$ Although Possible

(Reconstructed) Objects

Objects:

Leptons
Photons
Missing Transverse Energy
Jets

(Reconstructed) Object p^{μ}

Exotic Objects: New (Long Lived) States

Displaced Vertices - Leptons, Photons, Jets
Highly Ionizing Tracks
Highly Ionizing to Minimum Ionizing Kinks
Highly Ionizing Stopped Track
Out of Time Decays
Charge Exchange Tracks
Charge Changing Tracks
.....
High Multiplicity Mush

To 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:

Incorrect Association – Invariants Unrestricted

2. Enhances Signal/Background Purity:

SM Background Tends to be at Worst Similar to Combinatoric Confusion

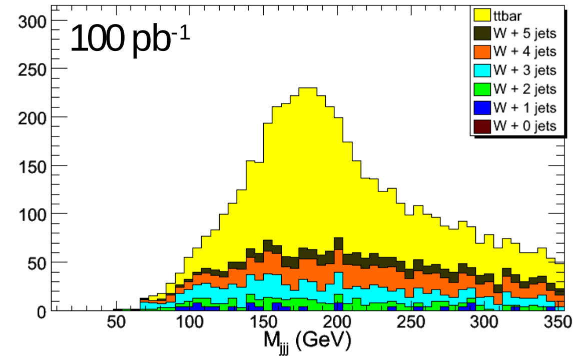
Invariants of “Unrelated” Objects

Object Correlation Ensembles Extract Leading Order Trees (OCELOT)

Semi-Leptonic Top Decay

pp t t
l j l ν
j j j

CMSSW



N_{jets} ¸4 with p_T > 30 GeV

N_{muon} ¸1 with p_T > 20 GeV

H_T jets+muon+MET > 300 GeV

m_{jjj} : Choose 3 jets with highest vector $| \sum p_{Tjeti} |$

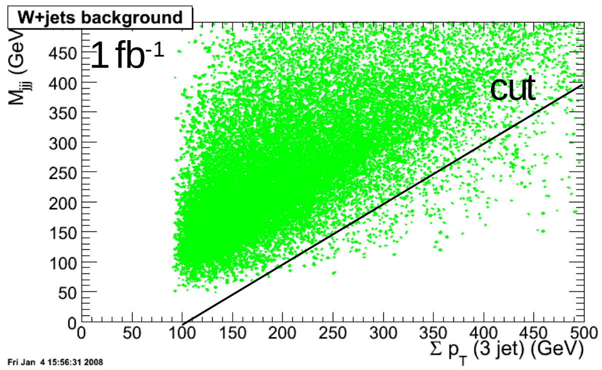
Semi-Leptonic Top Decay - OCELOT

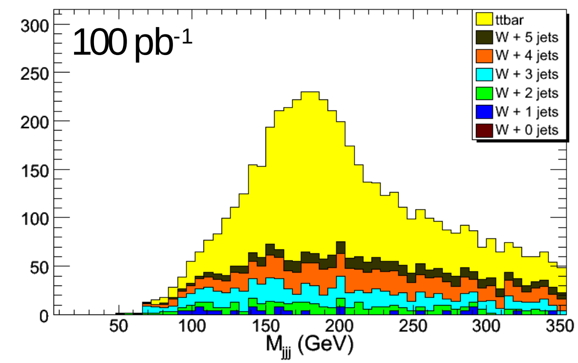
pp → t t̄
→ l ν j ... j l ν
→ j j j

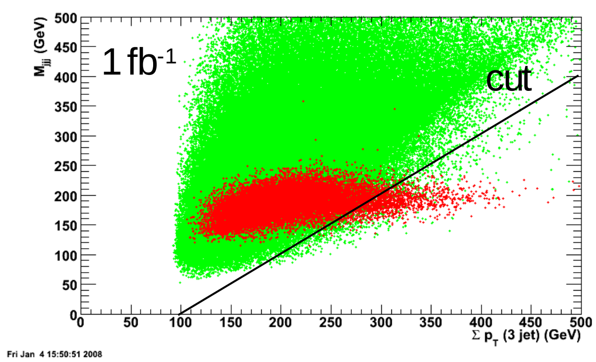
Correlation: $f(\, m_{jjj} \,,\, \Sigma_{i=1,3} \, |p_{T,jeti}|)$

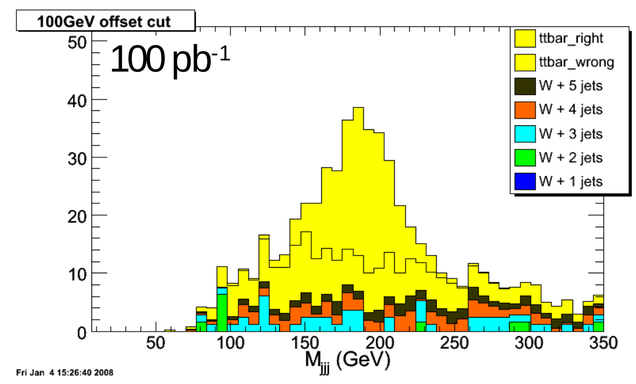
Ensemble All jets p_T > 30 Gev

CMSSW









Note SM Background and Combinatoric Confusion (In Tails)

Purity Crucial in Reconstructing More Branches of Decay tree – SUSY, b', ….

(Much) More Efficient Than Merged Top Jets

Multi-jet Hadronic Resonances - OCELOT

Standard Techniques Inadequate Even for Extracting Hadronic Signal from QCD Background

See Eva's Talk on OCELOT for Purely Hadronic Multi-jet Resonances

Di-Lepton Correlations (Edges)

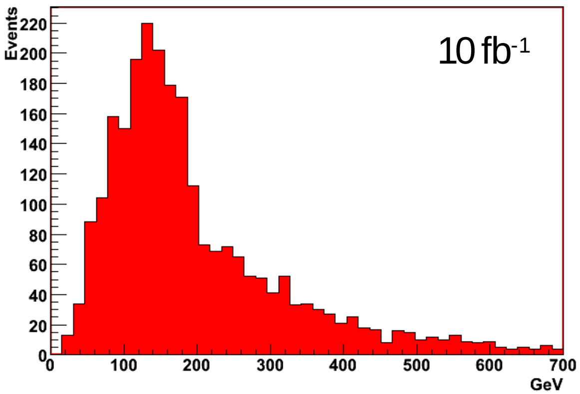
Standard SUSY Spectrum

$N_{Jets} > 2$ with $p_T > 40$ GeV

$N_{Leptons} > 3$ with $p_T > 25$ GeV

MET > 150 GeV

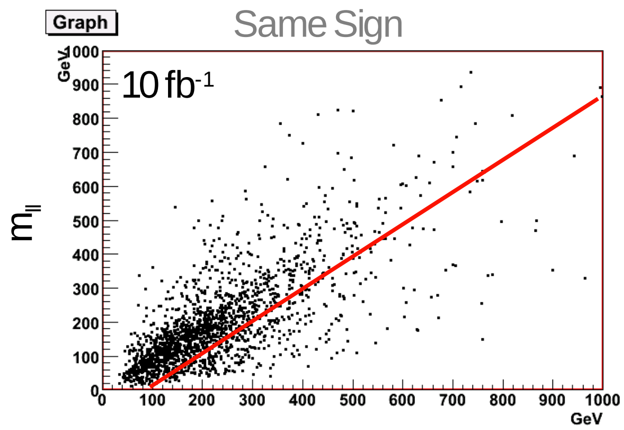
PGS

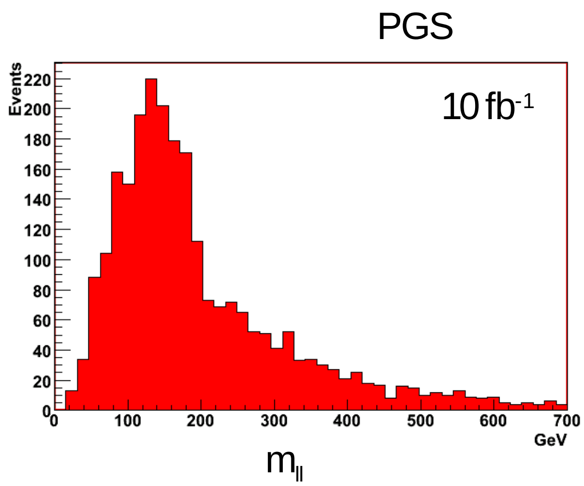


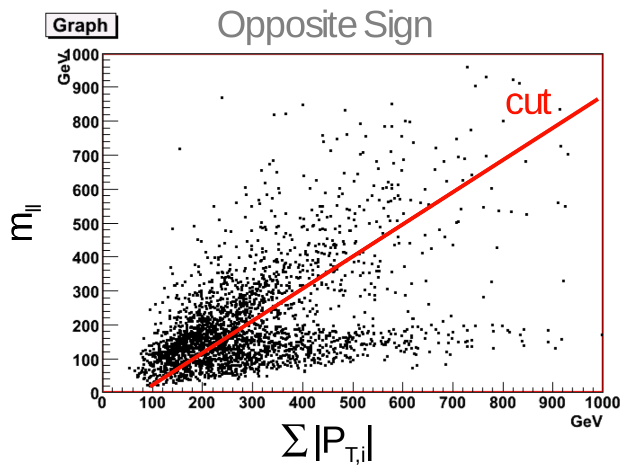
m_{ll}

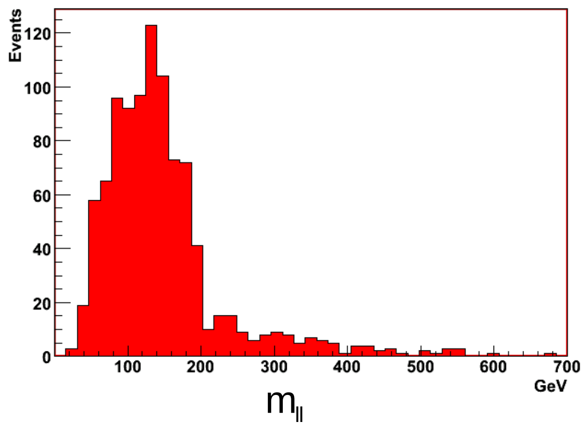
Di-Lepton Correlations (Edges) – OCELOT

Correlation: $f(\, m_{ll} \,, \sum_{i=1,2} |p_{T,i}| \,)$







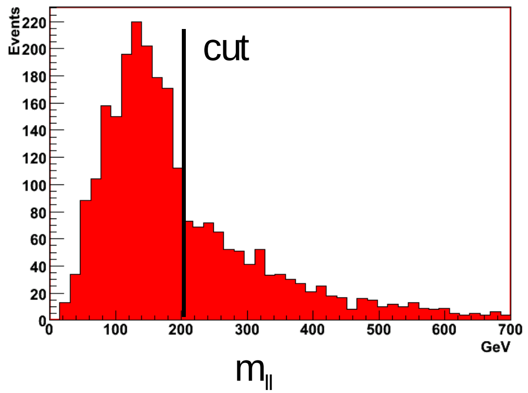


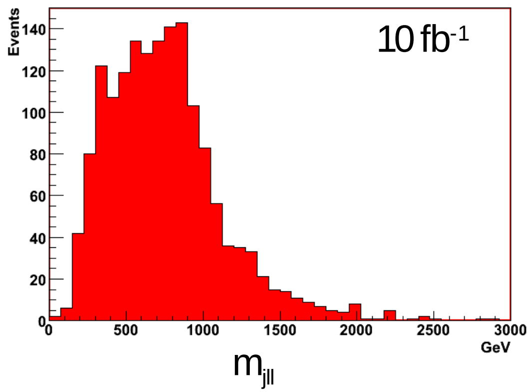
Horizontal Branch
Diagonal Branch

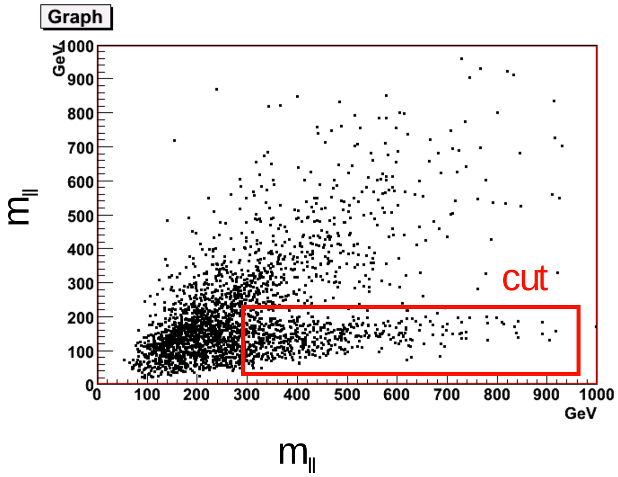
Note: Tails - Edges at 150 and 190 GeV

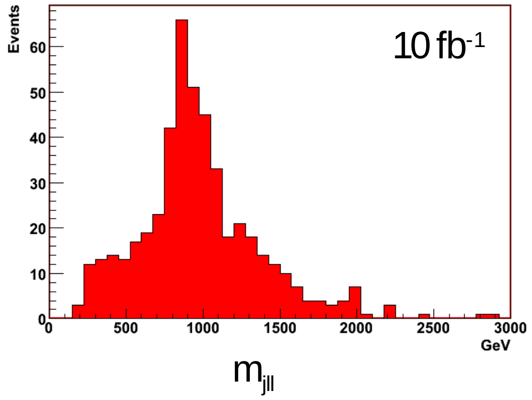
Di-Lepton-Jet Correlations (Edges) – OCELOT

Invariant Momentum of Three Adjacent Branches jll in Decay Tree



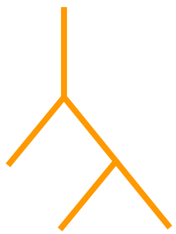






Purity Important for Reconstructing Multi-Branches in Decay Tree

Contained Decay Trees – OCELOT



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

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

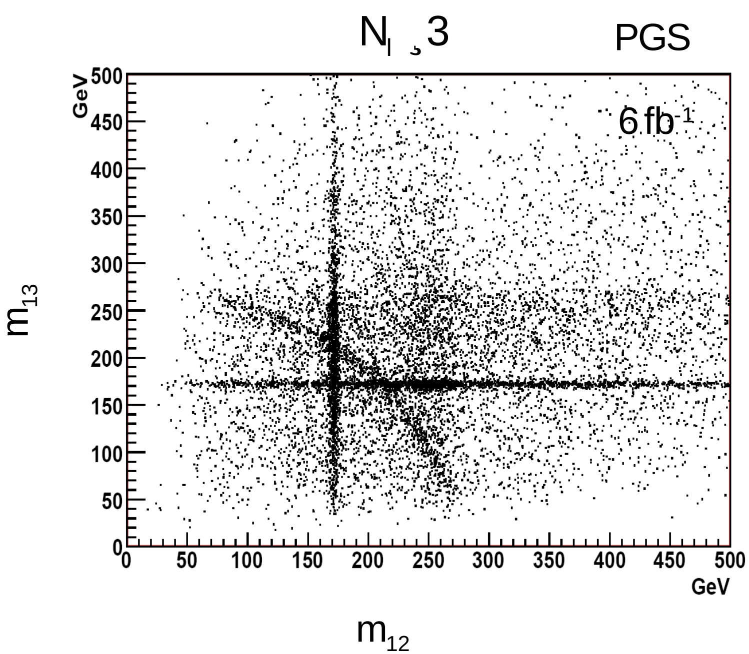
Doesn't Hurt to Loose 3rd Branch to Missing Energy

(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

Contained Decay Trees – OCELOT

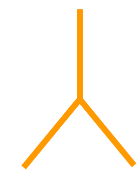
- New Physics Sample
  - N_l = 2-6
  - N_{jet} ¸ 2
  - Backgrounds Unimportant



- Enhanced $S/B_{Combinatoric}$ Constrast

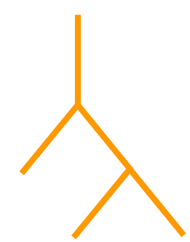
  $D_S < D_B$ (D=1 Histrogram $D_S = D_B$)

- Two Body Resonant Tree



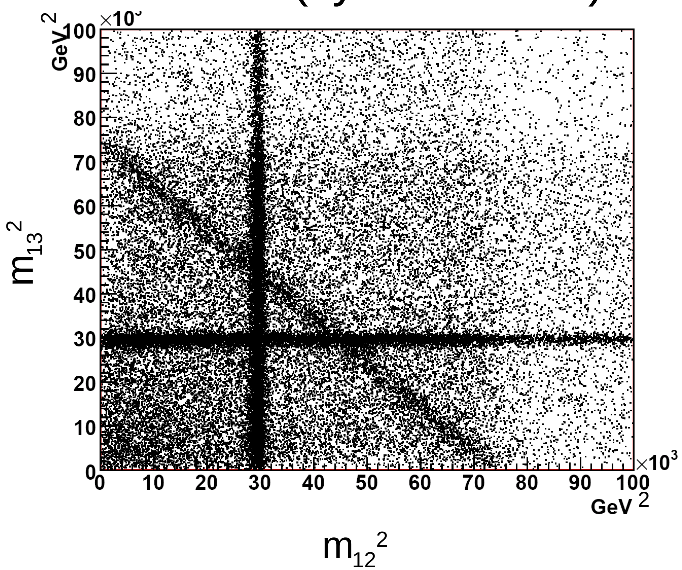
- Correlation $m_{12}^2 + m_{13}^2$ = Constant

  (Some of) The Two Body Resonances Arise from Three Body Decay



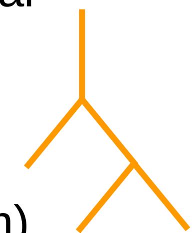
Contained Decay Trees – OCELOT

Dalitz (symmetrized)



- Uniform $|M|^2$ on Two Body Resonances

  Consistent with Intermediate Scalar



- Edges

  Three Body Tree (Only feature in D=1 Histogram)

  Coincide with Endpoint of Resonant Two Body Correlation

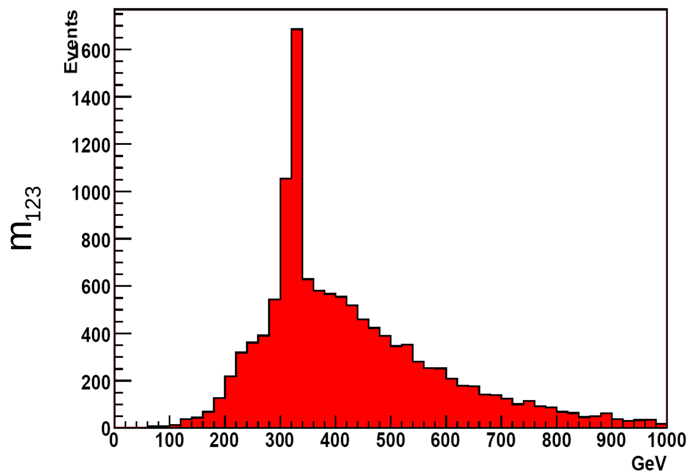
  - Arise from “Missing” Lepton
  - Anything Else Contributing to Edge is massless

- Relative Density of Two Body Resonances, Resonant Two Body <u>Correlation</u>, and Edge Contrast

  - Br (Φ lll) / Br(Φ llX)

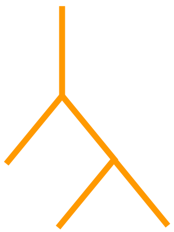
Correlations in Same and Opposite Signs

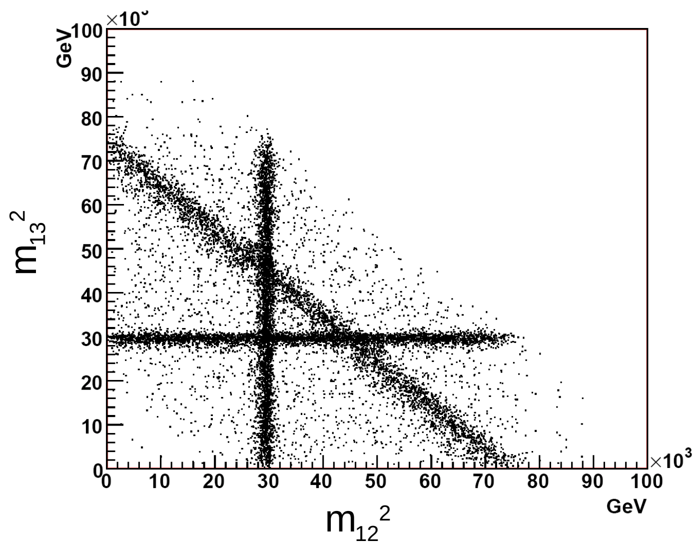
Contained Decay Trees – OCELOT



Three Body Resonant Trees

310 GeV • m_{lll} • 330 GeV

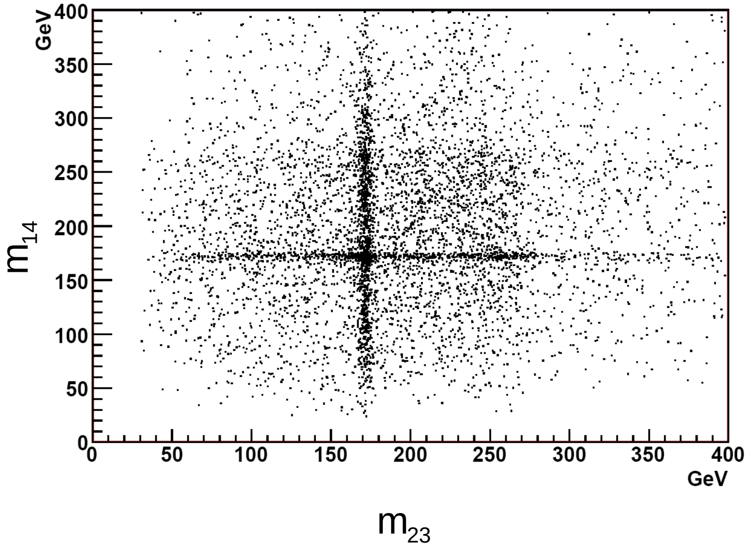




- Further Enhances
  - $S/B_{Combinatoric}$ Contrast

Inter-Tree Correlations – OCELOT

N_l ¸4



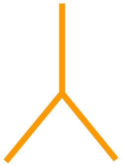
- No Kinematic Correlation (factorize)

  - Consistent with Arising from Different Parent Particle

- $m_{14} = m$ and $m_{23} \neq m$ or

  $m_{14} \neq m$ and $m_{23} = m$

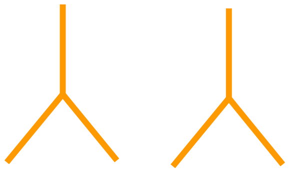
  - Single Resonant Two Body Decay



- $m_{14} = m_{23} = m$

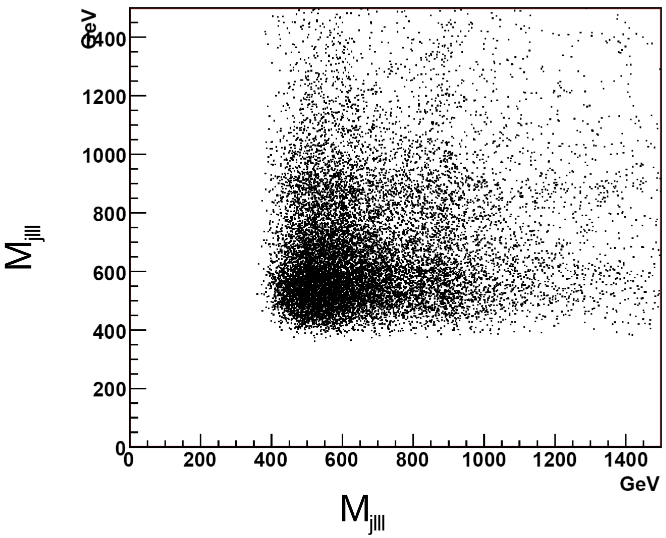
  - If Density at Intersection ¸2 Some Events with (At least) . Two Resonant Two Body Decays

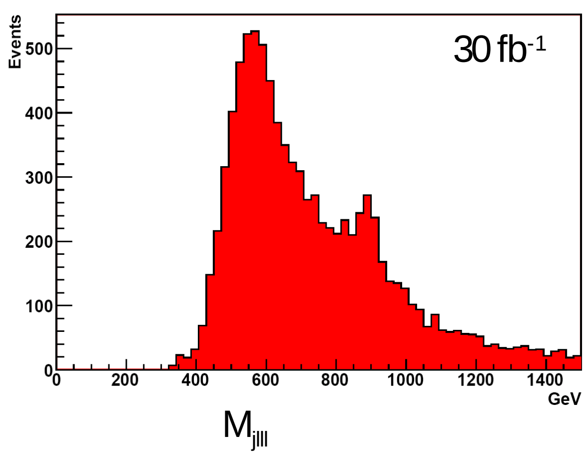
  - Density at Intersection gives Fraction



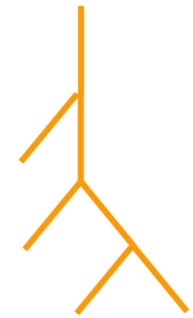
Contained Di-Lepton-Jet Correlations – OCELOT

N_j ¸ 2





- Contrast S/B$_{Combinatoric}$ Contrast Improved
- Two Four Body Resonant Decays



- Density in Bands and Intersections Give

σ Br(Ψ_1 jlll) / σ Br(Ψ_2 jlll)

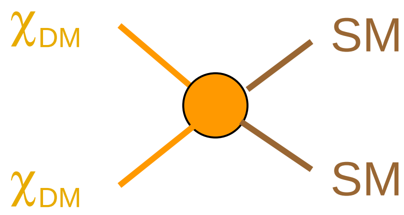
Correlation Could Indicate Resonant

. Five Body Decay ξ jjlll

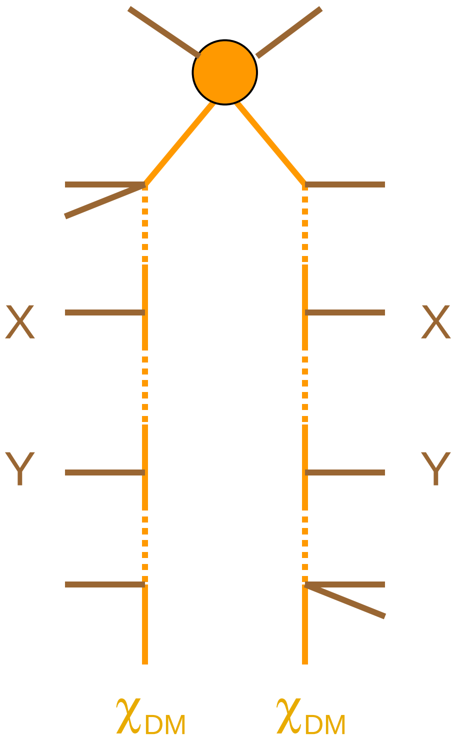
Determining the Stabilizing Symmetry of WIMP Dark Matter

WIMP Dark Matter – Freeze Out

Requires Stabilizing (Exact) Symmetry



$m \chi \chi$ Allowed - SM Uncharged



	Abelian		
Continuous	U(1)	$(X^{+}Y)(X^{-}Y)$	Opposite Sign
Discrete	Z_2	$(X^{+}Y)(X^{-}Y)$	Opposite Sign
		$(X^{+}Y)(X^{+}Y)$	Same Sign

(Small Caveats)

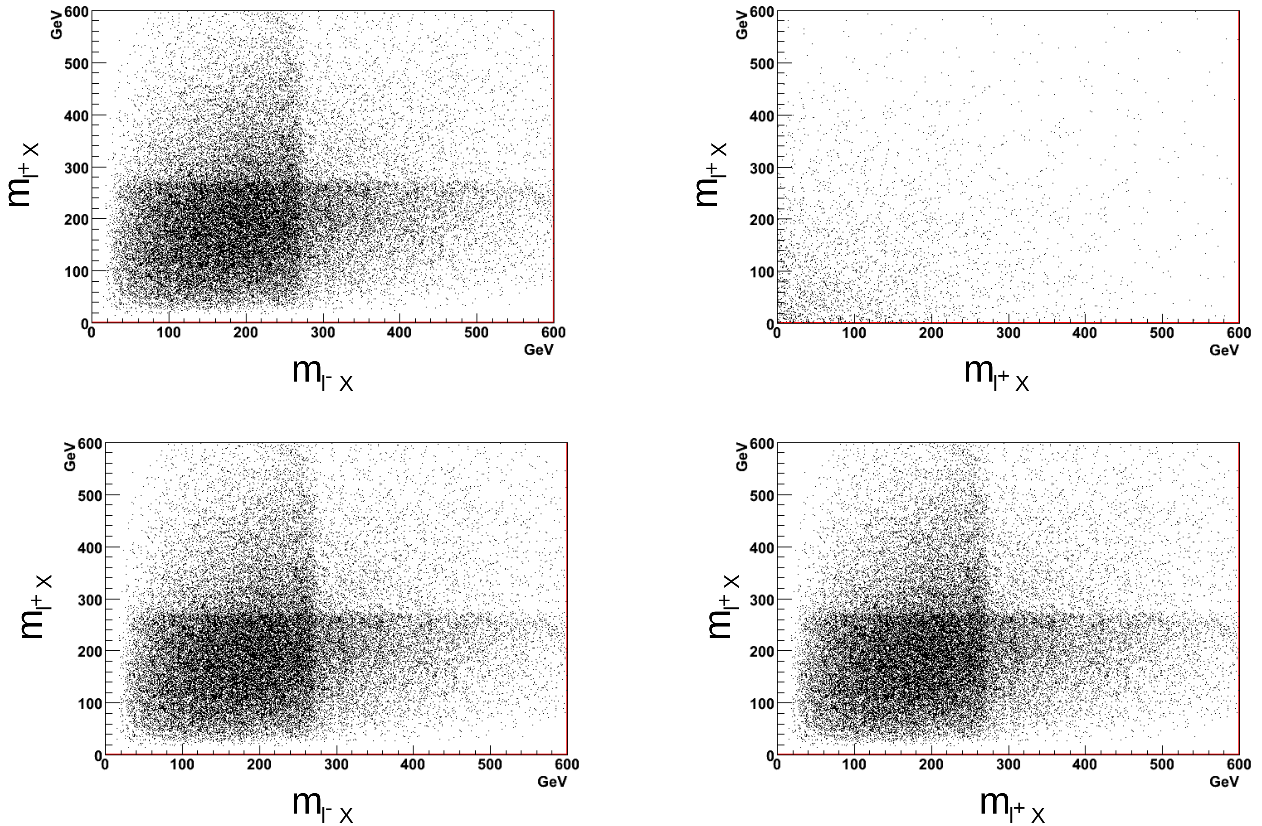
Inter-Tree Correlations - OCELOT

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

Opposite Sign | Same Sign

Continuous

Discrete



$25\ fb^{-1}$

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

Object Correlations

- Correlations in Generalized Dalitz Space m_{ij}^2 Provide Direct Path to Masses, Quantum Numbeers, Spins, and Interactions of New States

  Direct Solution to the Inverse Problem

- Consistent OnShell Effective Theory (COSET) for Decay Tree correlations . (Almost) Uniquely Determines Leading Order Correlations or Sequential . 2-body Decays

  Spin J = 0 + ½ Only Three Correlations for Adjacent Branches

  .Higher Spins Correlations Depend on Masses

  Spin Determination Can be Relatively Easy

- Object Correlation Ensembles for Leading Order Trees (OCELOT)

  Improve Purity of Particular Decay (Sub)Tree within an Event Sample

  Higher Dimenional Correlations can Further Improve ….

- Correlations Can Play a Direct Role in Determining Underlying Theoretical Framework

Rather Direct Path from Data to Interpretation – Early Inverse Problem

Reduce Combinatoric Confusion

Ensemble Technique Very Useful – and Should Have Wide Applicability

Here boosted … Compare Hemisphere --

Correlations in Generalized Dalitz space

Kinematic Correlations Can Enhance Contrast DS < DB

Develop Templates (Neural Nets) for
Generalization to Higher Dimensional Correlations of Edges and Endpoints

Correlations Allow Direct Measurements
Implement Correlations in Fitting Procedure to Decay Trees
. (Fitting to D=1 Counts Misses Many Correlations)

Order for COSET

0. n-body ….. (note constant |M|^2 not good ….)
3. List of COSET amplitudes
4. General polynomial of spin ….
5. Focus on Adject branches spin=0,1/2 – three shapes
6. Pick something(s) – what you learn – completely Mind
7. Determining Partner particle spins (UED as example)
8. Top quark Couplings …… (don’t mention – not “new” Physics)
9. SUSY Michael ……
10. Reconstructing Decay Chains ……

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

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

$$\langle \Psi_0(p)\Psi_0(-p)\rangle = -2\pi i\delta(p^2 - m^2)\ +\ \cdots$$

$$\langle \psi(p)\psi(-p)\rangle = P\left(\frac{1}{p^2 - m^2}\right)$$

$$\psi_i\psi_j\phi\ +\ \text{h.c.}$$

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

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

$$\phi_{(i}\partial^\mu\phi_{j)}A_\mu$$

$$\phi_{[i}\partial^\mu\phi_{j]}A_\mu$$

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

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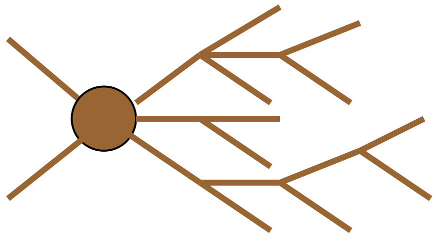
$$\phi_{(i}\partial^\mu\phi_{j)}A_\mu$$

$$\phi_{[i}\partial^\mu\phi_{j]}A_\mu$$

New Physics at the Large Hadron Collider

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

Put what can measure here – then RECO next – with kinematics on same page



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

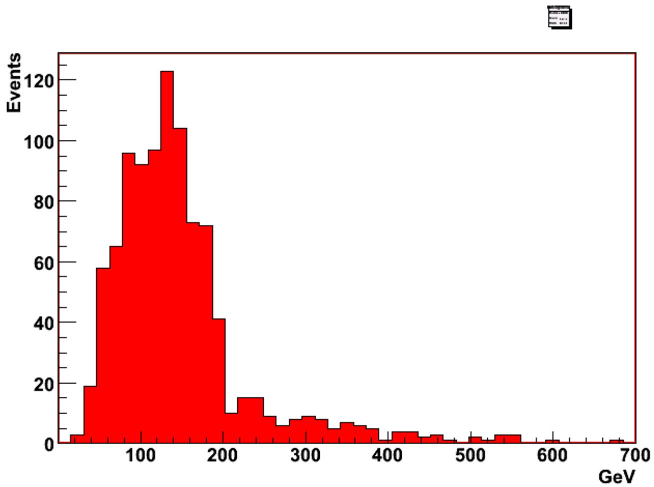
(Reconstructed) Objects

Leptons
Photons
Missing Transverse Energy
Jets

(Reconstructed) Object p^{μ}

Exotic Objects (New Long Lived Particles)

Displaced Vertices - Leptons, Photons, Jets
Highly Ionizing Tracks
Highly Ionizing to Minimum Ionizing Kinks
Highly Ionizing Stopped Track
Out of Time Decays
Charge Exchange Tracks
Charge Changing Tracks
.....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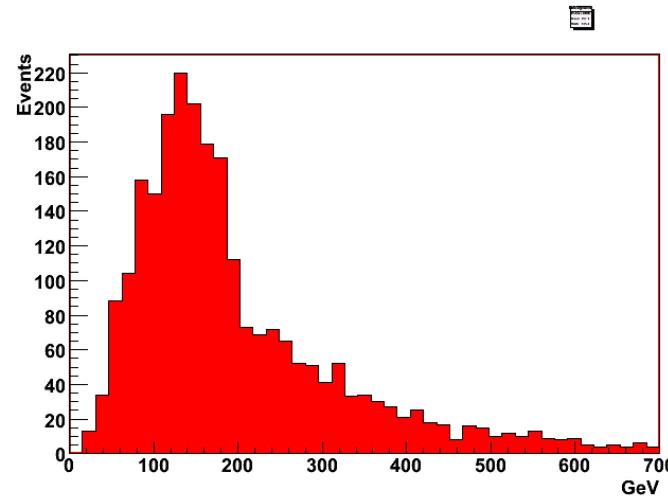
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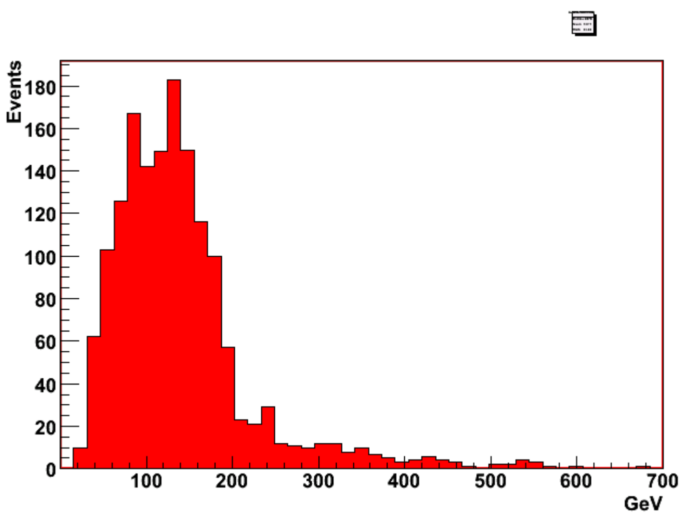
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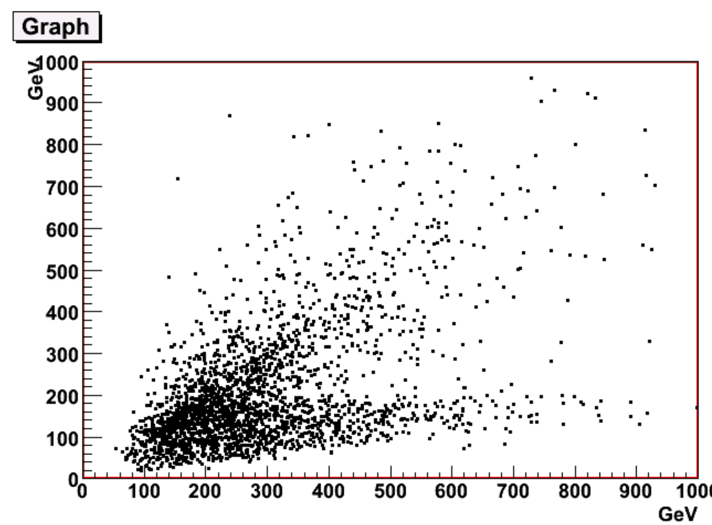
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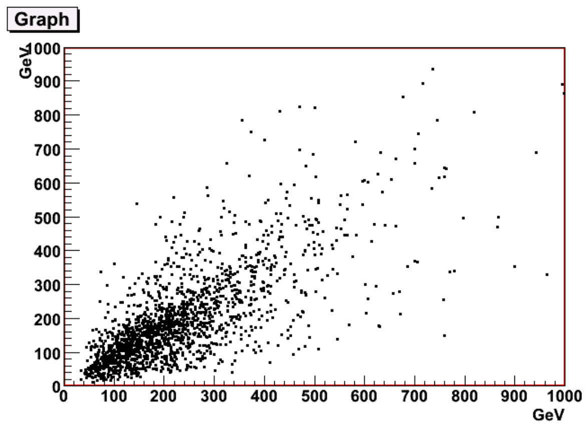
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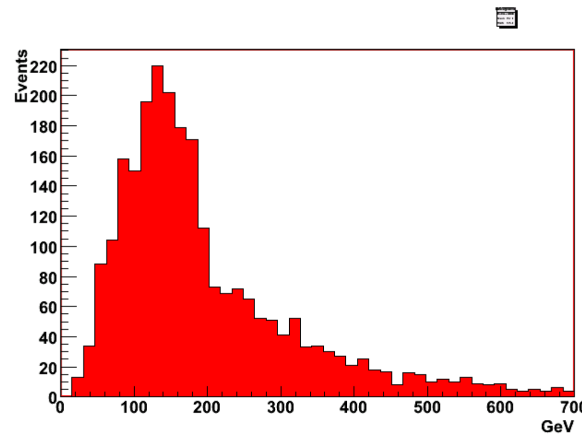
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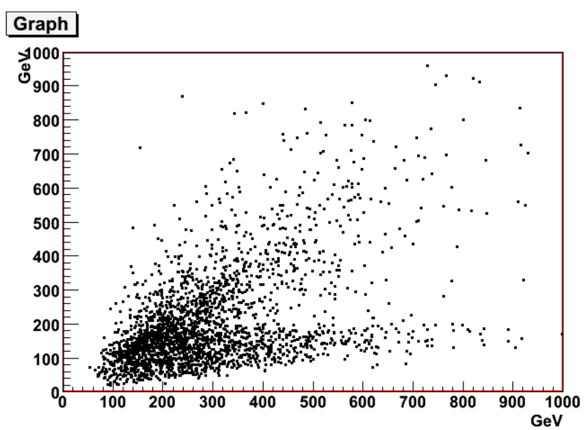
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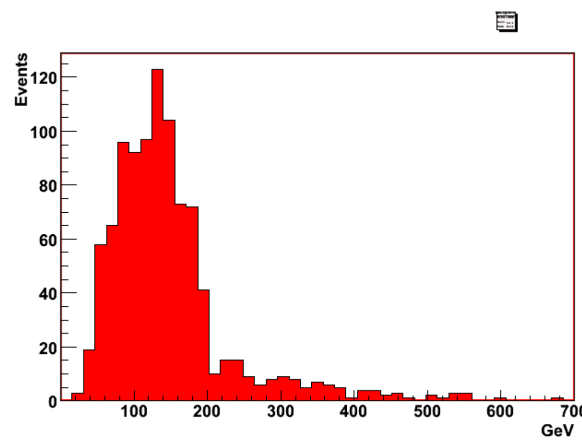
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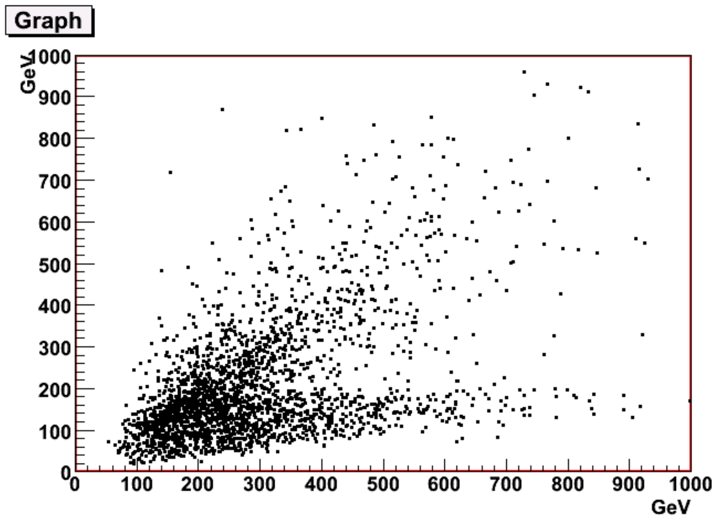
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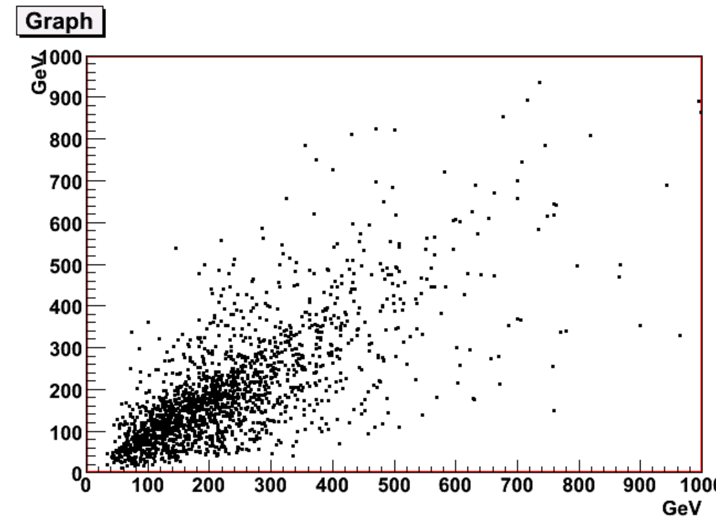
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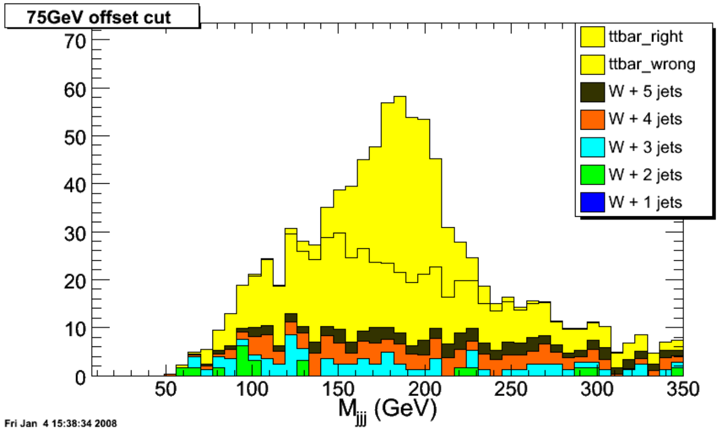

75GeV offset cut
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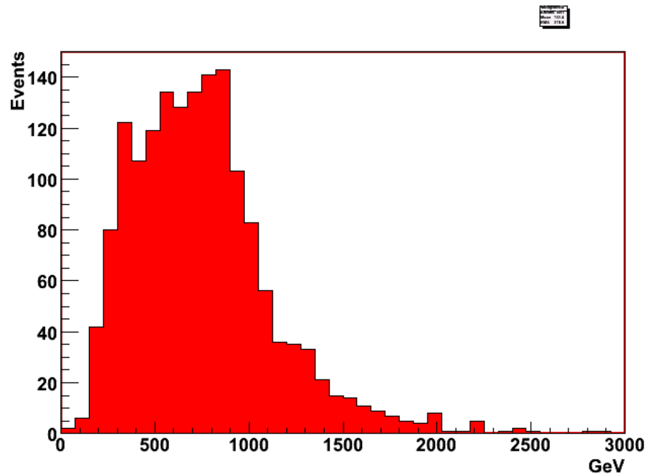
M_jjj (GeV)
ttbar_right
ttbar_wrong
W + 5 jets
W + 4 jets
W + 3 jets
W + 2 jets
W + 1 jets
Fri Jan 4 15:38:34 2008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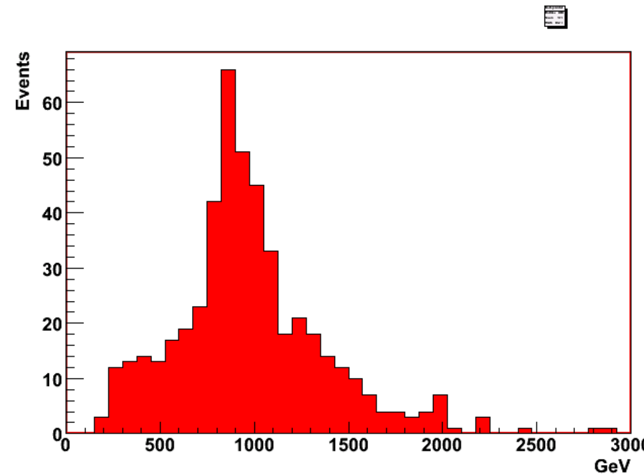
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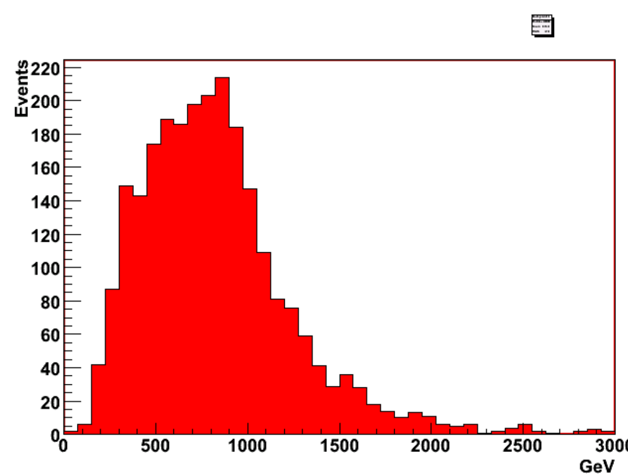
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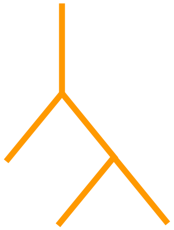
Kinematic Correlations

Decay Trees



Invariant Kinematic Correlations = f($m_{ijk...}^2$)   (Unpolarized,
Spins Unobserved,
T-Invariance)

.

.

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

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

Correlations Isolate … Background and Combinatoric Confusion

Can make use of correlations Also to reduce background

Use Other Variable sPull Apart Correct pairing of signal Always Correct

Don't forget to TITLE OCELO

Order for OCELOT Correlations

RECO FIRST I guess

2. semi-leptonic top Dmitry
3. Jets – Eva ……. (understand efficiency)
4. Lepton edge
5. Llj distribution
6. Resonant stuff If visible redundant – If all visible although redundant can still use to form additional correlations and extract more information but still can make use of it ……. Resonant

8. Dark Matter

Object Correlations to Extract Low Order Trees (OCELOT)

Kinematic Correlations Can Enhance Contrast $D_S < D_B$

Menu of Correlations for Low Order Trees

- Develop Templates to Search for Correlations

Extend to Trees with MET

(Generalization to D > 1 of Edges and Endpoints)

Correlations Allow Direct Measurements

Implement Correlations in Fitting Procedure to Decay Trees

. (Fitting to D=1 Counts Misses Many Correlations)