Entering the next phase of our fantastic journey…

LHC13 Part 2

Is this still natural? Surely we're getting close?

WHERE'S SUSY?

The Fantastic Journey

Christopher Rogan - SUSY16 - University of Melbourne, July 6, 2016
Entering the next phase of our fantastic journey…

LHC13
Part 2

Is this still natural? Surely we're getting close?

WHERE'S SUSY?

The Fantastic Journey

Christopher Rogan - SUSY16 - University of Melbourne, July 6, 2016
Not quite the right analogy…

...“SUSY” isn’t one signature that we simply look for
Rather: Is this what LHC13 is supposed to look like?…

…Are our observations consistent with the SM?

LHC13
Part 2

Is this still natural?
Surely we're getting close?
Searching Collider Phase Space for SUSY

Less like searching for a single person

More like exploring a previously unvisited landscape, searching for new flora/fauna/geographical features
Searching Collider Phase Space for SUSY

The elevation represents the rate of production of different types of collision events.

The lateral distance from the center of the mountain represents what’s in those collision events, i.e. how rare they are.

Christopher Rogan - SUSY16 - University of Melbourne, July 6, 2016
Searching Collider Phase Space for SUSY

- Particles decaying to $W/Z/\gamma/\text{leptons/}\text{top quarks/b-jets}$
- Cascading decays through SM spectrum (BSM?) can lead to high/conspicuous object multiplicities

More heavy particles

More jets

More leptons

LHC Phase-space

Christopher Rogan - SUSY16 - University of Melbourne, July 6, 2016
Searching Collider Phase Space for SUSY

- Heavy BSM particles decaying to SM particles → large visible momenta
- New symmetry conservation → large missing momenta
- Resonances, kinematic edges, mass sensitive variables…

more mass ⇒ more energy

Christopher Rogan - SUSY16 - University of Melbourne, July 6, 2016
more integrated luminosity (more data) reveals more of the phase-space

LHC Phase-space

from A. Askew’s talk

from D. Costanzo’s talk

10 events produced / 10 fb⁻¹

[1411.1427]
Searching for rare events

- BSM physics can potentially produce event topologies rarely seen in the SM
- Must control/measure object fake-rates and validate/understand simulation of rare SM processes

$Z + \text{jets, } ZZ, Z\gamma, WZ, \ldots$

LHC Phase-space
Searching for general excesses

- BSM can produce an excess of events with interesting kinematic features (large missing transverse energy, momentum, mass)

- Final states with weakly interacting particles can lead to ‘broad’ excesses in the tails of these kinematic distributions

CMS-EXO-16-013
(C. Peña’s talk)
Searching for general excesses

- BSM can produce an excess of events with interesting kinematic features (large missing transverse energy, momentum, mass)

- Final states with weakly interacting particles can lead to ‘broad’ excesses in the tails of these kinematic distributions

CMS-EXO-16-013
(C. Peña’s talk)

- Must have an accurate reference expectation for the SM to see subtle features!
Searching for general excesses

Nearby regions of phase space are often necessary to contextualize our observations in signal sensitive regions sidebands, control regions, …
The view from the pole(s)

- SUSY searches begin at ‘the pole’: W/Z bosons, tops, quarkonia candles
- Used to: select control samples of leptons, photons, b-jets, …
calibrate/measure object reconstruction performance,
fake-rates, energy scales
validate our understanding of the SM in new phase-space

JINST 10 (2015) P02006
The view from the peak

- BSM searches begin at ‘the rate peak’: QCD mult-ijets
- Used to:
  - select control samples of leptons, photons, b-jets, …
  - calibrate/measure object reconstruction performance, fake-rates, energy scales
  - validate our understanding of the SM in new phase-space

Searching for kinematic features

- New physics can produce kinematic features that are not expected in the SM – bumps, edges…

- Understanding/measuring/improving physics object reconstruction essential for being able to resolve these features

Missing transverse energy

Two plots from my SUSY10 conference talk…

we turned the LHC on in 2010 hoping to see this…

Christopher Rogan - SUSY16 - University of Melbourne, July 6, 2016
Missing transverse energy

Two plots from my SUSY10 conference talk…

\[ \sqrt{s} = 14 \text{ TeV MC} \]

CERN-LHCC-2006-021

Minimum bias data

\[ \int L \, dt = 11.7 \, \text{nb}^{-1} \]

…and we got this
Missing transverse energy

Two plots from my SUSY10 conference talk…

Missing transverse energy is a powerful observable for inferring the presence of weakly interacting particles in events…

…but, it only tells us about their transverse momenta – often we can better resolve quantities of interest by using additional information.
Missing Transverse Energy

$\vec{E}_{T}^{miss}$

Missing transverse energy only tells us about the momentum of weakly interacting particles in an event…

Christopher Rogan - SUSY16 - University of Melbourne, July 6, 2016
…not about the identity or mass of weakly interacting particles, or about the particle(s) they may decay from…
Missing Transverse Energy

…not about the identity or mass of weakly interacting particles, or about the particle(s) they may decay from…
Missing Transverse Energy

We can learn more by using other information in an event to contextualize the missing transverse energy and resolve additional information.
Resolving the invisible $W(e\nu)$

$m_T(l\nu)$ has kinematic edge at $m_W \sim 80$ GeV

Can use visible particles in events to contextualize missing transverse energy and better resolve mass scales

Christopher Rogan - SUSY16 - University of Melbourne, July 6, 2016
Missing Transverse Energy

We can learn more by using other information in an event to contextualize the missing transverse energy ⇒ what about multiple weakly interacting particles?
Example: slepton pair-production

Experimental signature: di-lepton final states with missing transverse momentum
Example: slepton pair-production

Main background:

Christopher Rogan - SUSY16 - University of Melbourne, July 6, 2016
Example: slepton pair-production

What quantities, if we could calculate them, could help us distinguish between signal and background events?

\[ \sqrt{\hat{s}} = 2 \gamma^{\text{decay}} m_{\tilde{\ell}} \]

\[ M_\Delta \equiv \frac{m^2_{\tilde{\ell}} - m^2_{\tilde{\chi}^0}}{m_{\tilde{\ell}}} \]
Example: slepton pair-production

What information are we missing?

We don’t observe the weakly interacting particles in the event. We can’t measure their momentum or masses.
Example: slepton pair-production

What do we know?

We can reconstruct the 4-vectors of the two leptons and the transverse momentum in the event.
Example: slepton pair-production

Can we calculate anything useful?

With a number of simplifying assumptions…

\[ \sum p_T \tilde{\chi}^0 \quad m_{\tilde{\chi}^0} = 0 \]

…we are still 4 d.o.f. short of reconstructing any masses of interest
‘Singularity’ Mass Variables

- State-of-the-art for LHC Run I was to use *singularity variables* as observables in searches.

- Derive observables that *bound a mass or mass-splitting of interest* by:
  - Assuming knowledge of event decay topology
  - “Extremizing” over under-constrained kinematic degrees of freedom associated with weakly interacting particles.
Singularity Variable Example: $M_{T2}$

Generalization of transverse mass to two weakly interacting particle events

$$M^2_{T2}(m_\chi) = \min_{\not{p}_T^{x1} + \not{p}_T^{x2} = E_{miss}^T} \max \left[ m^2_T(\not{p}_T^{\ell_1}, \not{p}_T^{\chi_1}, m_\chi), m^2_T(\not{p}_T^{\ell_2}, \not{p}_T^{\chi_2}, m_\chi) \right]$$

with: $m^2_T(\not{p}_T^{\ell_i}, \not{p}_T^{\chi_i}, m_\chi) = m_\chi^2 + 2 \left( E_T^{\ell_i} E_T^{\chi_i} - \not{p}_T^{\ell_i} \cdot \not{p}_T^{\chi_i} \right)$

From:
Singularity Variable Example: $M_{T2}^2$

Generalization of transverse mass to two weakly interacting particle events

LSP ‘test mass’

Extremization over under-constrained d.o.f.

$$M_{T2}^2(m_\chi) = \min \left( \frac{m_\chi^2}{\vec{p}_T^{x_1} + \vec{p}_T^{x_2} = E_T^{miss}} \right) \max \left[ m_T^2(\vec{p}_T^{\ell_1}, \vec{p}_T^{\chi_1}, m_\chi), m_T^2(\vec{p}_T^{\ell_2}, \vec{p}_T^{\chi_2}, m_\chi) \right]$$

Subject to constraints

with: $$m_T^2(\vec{p}_T^{\ell_i}, \vec{p}_T^{\chi_i}, m_\chi) = m_\chi^2 + 2 \left( E_T^{\ell_i} E_T^{\chi_i} - \vec{p}_T^{\ell_i} \cdot \vec{p}_T^{\chi_i} \right)$$

From:


Christopher Rogan - SUSY16 - University of Melbourne, July 6, 2016
Singularity Variable Example: $M_{T2}$

Generalization of transverse mass to two weakly interacting particle events

Extremization over under-constrained d.o.f.

$LSP \text{ ‘test mass’}$

\[
M_{T2}^2(m_\chi) = \min \left[ \frac{m_{T}^2(p_T^{\ell_1}, p_T^{\chi_1}, m_\chi), m_{T}^2(p_T^{\ell_2}, p_T^{\chi_2}, m_\chi)}{p_T^{\chi_1} + p_T^{\chi_2} = E_T^{\text{miss}}} \right] \\
\text{Subject to constraints}
\]

with: $m_{T}^2(p_T^{\ell_i}, p_T^{\chi_i}, m_\chi) = m_\chi^2 + 2 \left( E_T^{\ell_i} E_T^{\chi_i} - p_T^{\ell_i} \cdot p_T^{\chi_i} \right)$

Constructed to have a kinematic endpoint
(with the right test mass) at: $M_{T2}^{\text{max}}(m_\chi) = m_\tilde{\ell}$ \quad $M_{T2}^{\text{max}}(0) = M_\Delta \equiv \frac{m_\tilde{\ell}^2 - m_\chi^2}{m_\tilde{\ell}}$

From:

Christopher Rogan - SUSY16 - University of Melbourne, July 6, 2016
$M_{T2}$ in practice

From:

ATLAS-CONF-2013-049

Backgrounds with di-leptonic W’s fall steeply once $M_{T2}$ exceeds the W mass Jacobian edge

Searches based on singularity variables have sensitivity to new physics signatures with mass splittings larger than the analogous SM ones
The Family of Singularity Variables

- Transverse mass-bounding variables
  \[ M_{2T}, M_{T2}, M_{\circ2} \text{ and } M_{2\circ} \]
  PRD 84, 095031 [1108.5182]

- 3D (3+1) generalizations, possibly with constraints
  JHEP 1408 070 [1401.1449]

Example:

\[ M_{2CC} \equiv \min \{ \max [M_{P1}(\vec{q}_1, \tilde{m}), M_{P2}(\vec{q}_2, \tilde{m})] \} \]

Extremization over 3D momenta

\[ \vec{q}_1T + \vec{q}_2T = \vec{p}_T \]
\[ M_{P1} = M_{P2} \]
\[ M_{R1}^2 = M_{R2}^2 \]

subject to constraints

test masses
The Family of Singularity Variables

- Transverse mass-bounding variables
  \[ M_{2T}, M_{T2}, M_{02} \text{ and } M_{20} \]
  PRD 84, 095031 [1108.5182]

- 3D (3+1) generalizations, possibly with constraints
  JHEP 1408 070 [1401.1449]

See talks from Partha Konar and Abhaya Kumar Swain at SUSY16
SUSY Search Variables

- A list (incomplete) of observables used in the collider searches described at SUSY16:

\[ E_{T}^{\text{miss}}, \ H_{T}^{\text{miss}}, \ H_{T}, \ S_{T}, \ L_{T}, \ M_{\text{eff}}, \ \frac{E_{T}^{\text{miss}}}{M_{\text{eff}}} \]

\[ E_{T}^{\text{miss}} \ \sqrt{H_{T}}, \ M_{T2}, \ M_{CT}, \ M_{CT\perp}, \ M_{R}, \ R \]

\[ L_{p}, \ \min \Delta \phi_{\text{jet}}, \ E_{T}^{\text{miss}}, \ \alpha_{T}, \ dE/dx, \ \beta \]

\[ M_{jj}, \ \Sigma M_{\text{jet}}, \ \bar{M}_{\text{jet}}, \ M_{\text{fat jet}}, \ M_{\gamma\gamma}, \ M_{\ell\ell} \]

\[ N_{\text{jet}}, \ N_{b-\text{tag}}, \ N_{\ell}, \ N_{\gamma}, \ \cdots \]

- See the many experimental/pheno talks in this conference for descriptions/explanations
SUSY Search Variables

- Which variables is/are the best?
  - Depends on final state, background composition, sparticle/particle masses, instantaneous luminosity, integrated luminosity, …

[Cohen et al, 1605.01416]

Study of Jets and MET searches for $n$-parton simplified models

Varying $n$, sparticle masses, compression and comparing different variables/combinations

Cohen et al, 1605.01416

See Matt Dolen’s SUSY16 talk for more details
SUSY Search Variables

- Which variable is/are the best? wrong question
  - Depends on final state, background composition, sparticle/particle masses, instantaneous luminosity, integrated luminosity, …

[1605.01416]
Study of Jets and MET searches for $n$-parton simplified models

Varying $n$, sparticle masses, compression and comparing different variables/combinations

Cohen et al, 1605.01416

See Matt Dolen’s SUSY16 talk for more details

- Which combination/basis is the best?
SUSY Search Variable Basis “wish-list”

- Complete
  - contains all the event information that’s useful
- Always well-defined
  - not over-constrained as to prevent real solutions
- Orthogonal/~uncorrelated
  - as little redundant information as possible (“minimal”)
- “Diagonalized”
  - Ideally, matched to the particle masses, decay angles, etc. that we hope to study/discover
SUSY Search Variable Basis “wish-list”

- **Complete**
  - contains all the event information that’s useful

- **Always well-defined**
  - not over-constrained as to prevent real solutions

- **Orthogonal/~uncorrelated**
  - as little redundant information as possible (“minimal”)

- **“Diagonalized”**
  - Ideally, matched to the particle masses, decay angles, etc. that we hope to study/discover

- **Recursive Jigsaw Reconstruction** [P. Jackson, CR,1607.xxxx]
  - is a systematic prescription for deriving such a basis
Recursive Jigsaw Reconstruction

Example: single W production

four unknown d.o.f. associated with neutrino

\( (\vec{p}_\nu, T, p_{\nu, z}, m_\nu) \)

subject to three constraints

\[ \vec{E}_T^{\text{miss}} = \vec{p}_\nu, \ T \quad m_\nu = 0 \]
Recursive Jigsaw Reconstruction

Example: single W production

four unknown d.o.f. associated with neutrino

\((\vec{p}_\nu, T, p_{\nu, z}, m_\nu)\)

subject to three constraints

\(E_T^{\text{miss}} = \vec{p}_\nu, T \quad m_\nu = 0\)

re-express under-constrained d.o.f.
in terms of unknown velocity
along beam-line to W rest frame

\(p_{\nu, z} \rightarrow \beta_{\text{LAB} \rightarrow W}^z\)

choose \(\beta_z\) such that

\[\frac{\partial M_W(\beta_z)}{\partial \beta_z} = 0\]

equivalent to setting the nu rapidity equal to the lepton’s
Recursive Jigsaw Reconstruction

Example: single W production

Choosing \[ \frac{\partial M_W(\beta_z)}{\partial \beta_z} = 0 \]

we have essentially re-derived the W transverse mass
Recursive Jigsaw Reconstruction

Example: single W production

![Diagram of W mass reconstruction]

**Subtlety:**

\[
\frac{\partial M_W(\beta_z)}{\partial \beta_z} \propto \frac{\partial (\Lambda_{\beta_z} p_\ell)_0}{\partial \beta_z}
\]

Our W mass variable is (manifestly) invariant under longitudinal boosts.

It is also invariant to order \(\beta_T^2\) to transverse boosts.

Our approximation of the W rest frame has these same properties.
Recursive Jigsaw Reconstruction

Example: single W production

with approximations of all the velocities relating the reference frames in our event, we can calculate a complete basis of observables

transverse part of W decay angle

azimuthal angle between W decay plane and \( \vec{p}_{W,T}/\hat{n}_z \) plane
Recursive Jigsaw Reconstruction

Example: single W production

with approximations of all the velocities relating the reference frames in our event, we can calculate a complete basis of observables

\[ \vec{p}_{W,T}, M_W, \phi_W, \Delta \phi_W \]

Observables defined in a particular reference frame inherit derived properties of that frame

\[ \phi_W \] is invariant under longitudinal boosts and up to order \( \beta_T^2 \) in transverse ones
Recursive Jigsaw Reconstruction

Example: charged Higgs production

same unknown d.o.f. and constraints as W case

choose $\beta_z$ such that the rapidity of the neutrino is the same as the $h^0(\gamma\gamma) + \ell$ system (minimizes $M_{H^+}$)

procedure gives us our transverse mass...
Recursive Jigsaw Reconstruction

Example: charged Higgs production

same unknown d.o.f. and constraints as W case

choose $\beta$ such that the rapidity of the neutrino is the same as the $h^0(\gamma\gamma) + \ell$ system (minimizes $M_{H^+}$)

...and a full basis of ~uncorrelated observables
Recursive Jigsaw Reconstruction

Example: charged Higgs production

RJR procedure provides a complete, physics-motivated basis that improves resolution of kinematic features we are interested in

assumes $h^0$ production frame is our $H^+$ rest-frame approximation

assumes $h^0$ production frame is the lab frame

3D neutral Higgs decay angle
Recursive Jigsaw Reconstruction

Example: di-sleptons

- Eight unknown d.o.f. $2 \times 4$
- Associated with LSP’s $(\vec{p}_{\tilde{\chi}}, \vec{p}_{\tilde{\chi}}, \vec{z}, m_{\tilde{\chi}})$

- Four simplifying constraints
  
  $E_T^{\text{miss}} = \vec{p}_{\tilde{\chi}_a}, T + \vec{p}_{\tilde{\chi}_b}, T$
  
  $m_{\tilde{\chi}} = 0$
Recursive Jigsaw Reconstruction

Example: di-sleptons

\[ \begin{align*} 
\text{eight unknown d.o.f.} & \quad 2x \\
\text{associated with LSP’s} & \quad (\vec{p}_{\tilde{\chi}}, T, p_{\tilde{\chi}, z}, m_{\tilde{\chi}}) \\
\text{four simplifying constraints} & \\
E_T^{\text{miss}} = \vec{p}_{\tilde{\chi}, a}, T + \vec{p}_{\tilde{\chi}, b}, T & \quad m_{\tilde{\chi}} = 0 
\end{align*} \]

Tricky mass problem:
The invariant mass is invariant under coherent Lorentz transformations of two particles

\[ m_{\text{inv}}^2(p_1, p_2) = m_1^2 + m_2^2 + 2(E_1 E_2 - \vec{p}_1 \cdot \vec{p}_2) \]

The Euclidean mass (or contra-variant mass) is invariant under anti-symmetric Lorentz transformations of two particles

\[ m_{\text{eucl}}^2(p_1, p_2) = m_1^2 + m_2^2 + 2(E_1 E_2 + \vec{p}_1 \cdot \vec{p}_2) \]

For two mass observables \( (\sqrt{\hat{s}}, m_\ell) \) we want to capture both types of behavior…

Christopher Rogan - SUSY16 - University of Melbourne, July 6, 2016
di-sleptons

Example: di-sleptons assuming \( \sim \)mass-less leptons

\[
M_{CT}^2 = 2 \left( p_T^{\ell_1} p_T^{\ell_2} + \vec{p}_T^{\ell_1} \cdot \vec{p}_T^{\ell_2} \right)
\]

JHEP 0804:034

contraboost invariant transverse mass has same \( M_\Delta \equiv \frac{m_\ell^2 - m_{\tilde{\chi}^0}^2}{m_\ell} \)

end-point, irrespective of \( \sqrt{\hat{s}} \) …

…but end-point is not invariant under Lorentz boost of CM system

PRD 89, 055020 (2014)
Recursive Jigsaw Reconstruction

Example: di-sleptons

In RJR, rather than determining all under-constrained d.o.f. in one go *a la* singularity variables, we factorize the problem:

Imagine we knew how to get to di-slepton rest-frame:

with the lepton four-vectors in this frame $p_{\ell a} \quad p_{\ell b}$
Recursive Jigsaw Reconstruction

Example: di-sleptons

Imagine we knew how to get to di-slepton rest-frame:

with the lepton four-vectors in this frame $p_{\tilde{\ell}}^a\ p_{\tilde{\ell}}^b$

we choose the velocity to get to the lepton frames $\vec{\beta}\tilde{\ell}\ell\rightarrow\tilde{\ell}_i$

$$\frac{\partial(\Lambda_{\tilde{\beta}}\ p_{\tilde{\ell}}^a+\Lambda_{-\tilde{\beta}}\ p_{\tilde{\ell}}^b)}{\partial\tilde{\beta}}\bigg|_0 = \frac{\partial(E_{\tilde{\ell}}^a+E_{\tilde{\ell}}^b)}{\partial\tilde{\beta}} = 0$$
Recursive Jigsaw Reconstruction

Example: di-sleptons

In RJR, rather than determining all under-constrained d.o.f. in one go a la singularity variables, we factorize the problem:

Imagine we knew how to get to di-slepton rest-frame:

with the lepton four-vectors in this frame $p_{\tilde{\ell}a}$, $p_{\tilde{\ell}b}$
we choose the velocity to get to the lepton frames $\tilde{\beta} \to \tilde{\ell} \to \tilde{\ell}_i$

$$\frac{\partial}{\partial \tilde{\beta}} \left( \Lambda_{\tilde{\beta}} p_{\tilde{\ell}a} + \Lambda_{-\tilde{\beta}} p_{\tilde{\ell}b} \right)_0 = \frac{\partial}{\partial \tilde{\beta}} \left( E_{\tilde{\ell}a} + E_{\tilde{\ell}b} \right) = 0$$

which also sets $M_{\tilde{\chi}\tilde{\chi}} = m_{\ell\ell}$
Recursive Jigsaw Reconstruction

Example: di-sleptons

In RJR, rather than determining all under-constrained d.o.f. in one go
*a la* singularity variables, we factorize the problem:

Imagine we knew how to get to di-slepton rest-frame:

with the lepton four-vectors in this frame $p_{\ell a}^{\tilde{\ell}}$, $p_{\ell b}^{\tilde{\ell}}$

we choose the velocity to get to the lepton frames $\beta^{\tilde{\ell}\ell \rightarrow \ell_i}$

$$\frac{\partial (\Lambda_{\overrightarrow{\beta}} p_{\ell a}^{\tilde{\ell}} + \Lambda_{-\overrightarrow{\beta}} p_{\ell b}^{\tilde{\ell}})_{0}}{\partial \overrightarrow{\beta}} = \frac{\partial (E_{\ell a}^{\tilde{\ell}} + E_{\ell b}^{\tilde{\ell}})}{\partial \overrightarrow{\beta}} = 0$$

which also sets $M^{\tilde{\chi}\tilde{\chi}} = m_{\ell\ell}$

which allows us to determine longitudinal component of $\beta^{LAB \rightarrow CM}$ by minimizing $\sqrt{\hat{s}}$, as in previous examples
Recursive Jigsaw Reconstruction

Example: di-sleptons

Resulting basis of observables are the super-razor variables [PRD 89, 055020 (2014)]

new mass-estimator acts like pT-corrected $M_{CT}$
Recursive Jigsaw Reconstruction

Example: di-sleptons

Resulting basis of observables are the super-razor variables

\[ \text{[PRD 89, 055020 (2014)]} \]

extracts \sim uncorrelated estimators for both mass scales along with complete basis of other observables

\[ \chi_l \rightarrow l \tilde{\chi}^0_1; m_l = 150 \text{ GeV} \]

\[ \chi_l \rightarrow l \tilde{\chi}^0_1; m_l = 150 \text{ GeV} \]

\[ \chi_l \rightarrow l \tilde{\chi}^0_1; m_l = 150 \text{ GeV} \]

\[ \chi_l \sim m_l = 150 \text{ GeV} \]

\[ \chi_l \sim m_l = 70 \text{ GeV} \]

\[ \chi_l \sim m_l = 100 \text{ GeV} \]

\[ \chi_l \sim m_l = 120 \text{ GeV} \]

\[ \chi_l \sim m_l = 8 \text{ TeV} \]

\[ \chi_l \sim m_l = 8 \text{ TeV} \]

\[ \chi_l \sim m_l = 8 \text{ TeV} \]

Christopher Rogan - SUSY16 - University of Melbourne, July 6, 2016
Recursive Jigsaw Reconstruction

New approach to reconstructing final states with weakly interacting particles: *Recursive Jigsaw Reconstruction*

- The strategy is to transform observable momenta iteratively *reference-frame to reference-frame*, traveling through each of the reference frames relevant to the topology.

- **Recursive:** At each step, specify *only the relevant d.o.f. related to that transformation* $\Rightarrow$ *apply a Jigsaw Rule*

  Repeat procedure recursively, using the visible momenta encountered in each reference frame.

- **Jigsaw:** each of these rules is factorizable/customizable/interchangeable like a (strange) jigsaw puzzle pieces.

- Rather than obtaining one observable, get a *complete basis* of useful observables for each event.

- See P. Jackson and L. Lee’s talks for additional applications.
Generalizing Further...

Recursive Jigsaw approach can be generalized to arbitrarily complex final states with weakly interacting particles.
Example: the di-leptonic top basis

\[ \sqrt{s} = 2\gamma M_t \]

\[ E_b \equiv \frac{M_t^2 - M_W^2}{2M_t} \]

\[ E_{\text{lep}} \equiv \frac{M_W^2 - M_\nu^2}{2M_W} \]

In more complicated decay topologies there can be many masses/mass-splittings, spin-sensitive angles and other observables of interest that can be used to distinguish between the SM and SUSY signals.
Mass-sensitive singularity variables are sensitive to mass splittings through end-points, but are not necessarily independent.
The di-leptonic top basis

~independent information about five different masses, and decay angles

Christopher Rogan - SUSY16 - University of Melbourne, July 6, 2016
The di-leptonic top basis
largely independent information about decay angles

Here, the decay angle of the top/anti-top system can be used to study resonance structure, along with di-top mass
The di-leptonic top basis

largely independent information about decay angles

Here, the decay angle of the top/anti-top system can be used to study resonance structure, along with di-top mass

Christopher Rogan - SUSY16 - University of Melbourne, July 6, 2016
Recursive Jigsaw Reconstruction

Example:
non-resonant $N W(\ell\nu)$
Recursive Jigsaw Reconstruction

Example: Heavy Higgs to light Higgs to $4W(\ell\nu)$

Implementations of the examples shown in this talk are available in the public software RestFrames (www.RestFrames.com)

Christopher Rogan - SUSY16 - University of Melbourne, July 6, 2016
Summary

- Probing SUSY at colliders (here LHC13) involves understanding a large, new, phase-space
  - Boot-strapping our understanding of the SM and detectors from the poles to the regions where we’re searching for evidence of BSM physics
- Many different way to partition that phase-space
  - Observables designed for every final state, every kinematic feature we hope to exploit. Enormous breadth of techniques стратегies signatures
- We’re getting closer to a discovery, SUSY or other
  - More data reveals more phase-space, increasingly detailed analyses probing more thoroughly.
  - No stone left unexamined - maybe SUSY17?
BACKUP SLIDES
Open vs. closed final states

**CLOSED** \( H \rightarrow Z(\ell\ell)Z(\ell\ell) \)
- Can calculate all masses, momenta, angles
- Can use masses for discovery, can use information to measure spin, CP, etc.

**OPEN** \( H \rightarrow W(\ell\nu)W(\ell\nu) \)
- Under-constrained system with multiple weakly interacting particles – can’t calculate all the kinematic information

What useful information can we calculate?
What can we measure?
Singularity variables

Kinematic Singularities. A singularity is a point where the local tangent space cannot be defined as a plane, or has a different dimension than the tangent spaces at non-singular points.

From:

The guiding principle we employ for creating useful hadron-collider event variables, is that: we should place the best possible bounds on any Lorentz invariants of interest, such as parent masses or the center-of-mass energy $\sqrt{s}$, in any cases where it is not possible to determine the actual values of those Lorentz invariants due to incomplete event information. Such incomplete information...
**p_T corrections for M_{CT}**

Attempts have been made to mitigate this problem:

(i) ‘Guess’ the lab $\rightarrow$ CM frame boost:

$$M_{CT}^{(corr)} = \begin{cases} 
M_{CT} & \text{after boosting by } \beta = p_b/E_{cm} \\
M_{CT} & \text{if } A_{x(lab)} \geq 0 \text{ or } A'_{x(lo)} \geq 0 \\
M_{Cy} & \text{if } A'_{x(hi)} < 0 \\
M_{Cy} & \text{if } A'_{x(hi)} \geq 0
\end{cases}$$

$x$ – parallel to boost

$y$ – perp. to boost

with:

$$A_x = p_x[q_1]E_y[q_2] + p_x[q_2]E_y[q_1]$$

$$M_{Cy}^2 = (E_y[q_1] + E_y[q_2])^2 - (p_y[q_1] - p_y[q_2])^2$$


(ii) Only look at event along axis perpendicular to boost:

$$M_{CT \perp}$$

$M_{\text{CTperp}}$ in practice

‘peak position’ of signal and backgrounds due to other cuts ($p_T$, MET) and only weakly sensitive to sparticle masses

From:
CMS-SUS-PAS-13-006

Christopher Rogan - SUSY16 - University of Melbourne, July 6, 2016
What other info can we extract?

Ex. $M_{T2}$ extremization assigns values to missing degrees of freedom – if one takes these assignments literally, can we calculate other useful variables?

From:
Mass and Spin Measurement with $M(T2)$ and MAOS Momentum - Cho, Won Sang et al.

When we assign unconstrained d.o.f. by extremizing one quantity, what are the general properties of other variables we calculate? What are the correlations among them?