Searching for New Physics with Event Shape Observables

Cari Cesarotti
Harvard University
(2004.06125) w/ Jesse Thaler
(2009.08981) w/ Matthew Reece, Matthew J. Strassler
(2011.06599) w/ MR, MJS
Motivation

How and where do we look for new physics?

• There is enormous discovery potential at colliders

• New physics at ~ TeV scale hiding with rare kinematic signatures

• Strategy for new physics searches:
Motivation

How and where do we look for new physics?

• There is enormous discovery potential at colliders

• New physics at ~ TeV scale hiding with rare kinematic signatures

• Strategy for new physics searches:

  Identify signatures *fundamentally* different from QCD backgrounds
Motivation

QCD at TeV scale is characterized by soft, collinear splittings

But many new physics signatures look quasi-isotropic:

RPV SUSY

Hidden Valleys/Dark Showers
Motivation

QCD at TeV scale is characterized by soft, collinear splittings

*QCD is jetty*

But many new physics signatures look quasi-isotropic:

RPV SUSY

Hidden Valleys/Dark Showers
Motivation

QCD at TeV scale is characterized by soft, collinear splittings

\[ \text{QCD is jetty} \]

But many new physics signatures look quasi-isotropic:

- RPV SUSY
- Hidden Valleys/Dark Showers

Also:
- Black holes
- Soft bomb (SUEPs)
- Many more...

Strassler, Zurek 2006
Motivation

There are lots of new physics scenarios with quasi-isotropic radiation patterns

We need an observable that is sensitive to different event topologies in this kinematic regime
Motivation

What about existing event shape observables?

• Previous event shape observables designed to measure distance from dijet
  • Thrust, C/D-parameter, sphericity, spherocity, supersphero...
Motivation

What about existing event shape observables?

• Previous event shape observables designed to measure distance from *dijet*
  • *Thrust, C/D-parameter, sphericity, spherocity, supersphero*…

• Want distance from *isotropy*

Event Isotropy

(CC, J. Thaler, 2004.06125)
Part 1: Defining Event Isotropy
Part 2: Event Isotropy & Isotropic Signals
Energy Mover’s Distance

*Energy mover’s distance* (EMD):
What is the minimum work to rearrange the energy distribution in event $P$ to look like event $Q$?

$$EMD(P, Q) = \min_{\{f_{ij}\}} \sum_{ij} f_{ij} d_{ij}$$

- $f_{ij}$: energy transported
- $d_{ij}$: distance measure

\[ f_{ij} \geq 0 \quad \sum_{ij} f_{ij} = E_{P}^{\text{tot}} = E_{Q}^{\text{tot}} = 1 \]
Energy Mover’s Distance

Energy mover’s distance (EMD):
What is the minimum work to rearrange the energy distribution in event $P$ to look like event $Q$?

Start: Event $P$

$\text{EMD}(P, Q) = \min_{(\ell_i)} \sum_{q} \ell_i d_i$

$\ell_i$: Energy transported

$d_i$: Distance measure

$\ell_i \geq 0$

$\sum_{q} \ell_i = E_P^{\text{tot}} = E_Q^{\text{tot}}$

End: Event $Q$
Event Isotropy: EMD of an event to uniform radiation pattern

\[ \mathcal{I}_{n}^{\text{geo}}(\mathcal{E}) = \text{EMD}_{\text{geo}}(\mathcal{U}_{n}^{\text{geo}}, \mathcal{E}) \]

- **Geo**: Geometry of isotropic radiation pattern (sphere, cylinder, ring)
  - Energy fraction moved \( f_{ij} \) by distance measure \( d_{ij} \)
- \( n \): Number of particles in quasi-uniform “reference” sample

**Sphere**
- \( n = 192 \)

**Cylinder**
- \( n = 160 \)

**Ring**
- \( n = 32 \)
Event Isotropy

\[ \mathcal{I}_{\text{geo}}^n(\mathcal{E}) = \text{EMD}_{\text{geo}}(\mathcal{U}_{\text{geo}}^n, \mathcal{E}) \]

Sphere

\[ e^+ e^- \]

\[ f_{ij} = \frac{\Delta E_{ij}}{E_{\text{tot}}} \]

\[ d_{ij} = 2 \left(1 - \cos \theta_{ij} \right) \]

Cylinder

\[ pp \]

\[ f_{ij} = \frac{\Delta p_{T,ij}}{p_{T,\text{tot}}} \]

\[ d_{ij} = \frac{12}{\pi^2 + 16y_{\text{max}}^2} \left(y_{ij}^2 + \phi_{ij}^2 \right) \]

Ring

\[ d_{ij} = \frac{\pi}{\pi - 2} \left(1 - \cos \phi_{ij} \right) \]
Event Isotropy

- IRC safe
- Dimensionless
- Defined on sets of massless particles with zero net momentum
- $I \in [0, 1]$, where 0 is isotropic and 1 is dijet

$I_{\text{sph}} = 0$

$I_{\text{geo}}(E) = \text{EMD}_{\text{geo}}(U_{\text{geo}}^n, E)$

$I_{\text{sph}} = 1$
Part 1: Defining Event Isotropy

Part 2: Event Isotropy & Isotropic Signals
Standard Model Benchmark

QCD dijet vs. top pair production, \( pp \) Collisions at \( \sqrt{s} = 14 \text{ TeV} \)

**Dijet**

**Top pair**

\[ \Sigma_{p_T} > 400 \text{ GeV} \]

Ring Event Isotropy

- Dijet
- \( t\bar{t} \)

AUC = 0.774

\[ \Sigma_{p_T} > 400 \text{ GeV} \]

Transverse Thrust

- Dijet
- \( t\bar{t} \)

AUC = 0.745

**CC, J. Thaler (2004.06125)**
Standard Model Benchmark

QCD dijet vs. top pair production, $pp$ Collisions at $\sqrt{s} = 14$ TeV

Event isotropy is marginally more effective

CC, J. Thaler (2004.06125)
Toy Model New Physics

Toy Model:
• Generate 1 TeV Z’ in Pythia
• Generate N-body final state in flat phase space
• ’Decay’ Z’ to N-body final state

CC, J. Thaler (2004.06125)
Toy Model New Physics

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$pp$ Collisions at $\sqrt{s} = 14$ TeV

CC, J. Thaler (2004.06125)
Toy Model New Physics

*pp Collisions at $\sqrt{s} = 14$ TeV*

Toy Model:
- Generate 1 TeV $Z'$ in Pythia
- Generate $N$-body final state in flat phase space
- 'Decay' $Z'$ to $N$-body final state

*CC, J. Thaler (2004.06125)*
Event isotropy is a more effective discriminant than previous event shape observables in the quasi-isotropic regime
Event Isotropy vs. Other Observables

_Is event isotropy correlated with other observables?_
Event Isotropy vs. Other Observables

Is event isotropy correlated with other observables?

We test for correlation with 5d simplified model

• Construct a toy model with quasi-isotropic signatures [2009.08981]

• Use this model and other symmetric constructions to stress-test event isotropy [2011.06599]

CC, M. Reece, M. Strassler
Other Event Shape Observables

**Sphericity Tensor**

\[
S^{(r)}_{ij} = \frac{\sum_m |p_m|^r - 2 p^i_m p^j_m}{\sum_m |p_m|^r}
\]

Eigenvalues: \(\lambda_1, \lambda_2, \lambda_3\)

\[
\lambda_1 + \lambda_2 + \lambda_3 = 1
\]

\[
S = \frac{3}{2} (\lambda_2 + \lambda_3) \quad (r = 2)
\]

\[
C = 3 (\lambda_1 \lambda_2 + \lambda_1 \lambda_3 + \lambda_2 \lambda_3) \quad (r = 1)
\]

\[
D = 27 \lambda_1 \lambda_2 \lambda_3
\]

CC, M. Reece, M. Strassler
Other Event Shape Observables

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Not IRC safe
Other Event Shape Observables

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\]

\[
D = 27 \lambda_1 \lambda_2 \lambda_3
\]

Spherical:

\[
\lambda = \frac{1}{3}
\]

\[
C = 1
\]

\[
D = 1
\]
**Other Event Shape Observables**

\[ S(r)^{ij} = \frac{\sum_m |p_m|^{r-2} p^i_m p^j_m}{\sum_m |p_m|^r} \]

Eigenvalues: \( \lambda_1, \lambda_2, \lambda_3 \)

**Sphericity Tensor**

\[ \lambda_1 + \lambda_2 + \lambda_3 = 1 \]

\[ S = \frac{3}{2} (\lambda_2 + \lambda_3) \quad \text{(r = 2)} \]

\[ C = 3 (\lambda_1 \lambda_2 + \lambda_1 \lambda_3 + \lambda_2 \lambda_3) \quad \text{(r = 1)} \]

**Spherical:**

\[ \lambda = \frac{1}{3} \]

\[ C = 1 \]

\[ D = 1 \]

**Azimuthally Symmetric:**

\[ \lambda_2 = \lambda_3 = \frac{1 - \lambda_1}{2} \]

\[ C_{az} = \frac{3}{4} (2\lambda_1 - 3\lambda_1^2 + 1) \]

\[ D_{az} = \frac{27}{4} (1 + \lambda_1^2 - 2\lambda_1) \]

Not IRC safe
Other Event Shape Observables

**Sphericity Tensor**

\[ S(r)_{ij} = \frac{\sum_m |p_m|^r r^{-2} p_i p_j}{\sum_m |p_m|^r} \]

Eigenvalues: \( \lambda_1, \lambda_2, \lambda_3 \)

\[ \lambda_1 + \lambda_2 + \lambda_3 = 1 \]

\[ S = \frac{3}{2} (\lambda_2 + \lambda_3) \quad (r = 2) \]

\[ C = 3 (\lambda_1 \lambda_2 + \lambda_1 \lambda_3 + \lambda_2 \lambda_3) \quad (r = 1) \]

Not IRC safe

Spherical:

\[ \lambda = \frac{1}{3} \]

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\[ \lambda_2 = \lambda_3 = \frac{1 - \lambda_1}{2} \]

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Quasi-Azimuthally Symmetric:

\[ \lambda_{2,3} = \frac{1 - \lambda_1 \pm \epsilon}{2} \]

\[ C_{quasi} = C_{az} - \frac{3 \epsilon^2}{4} \]

\[ D_{quasi} = D_{az} - \frac{27 \lambda_1}{4} \epsilon^2 \]
Other Event Shape Observables

**Sphericity Tensor**

\[
S = \frac{3}{2 \sum_m |\lambda|^2}
\]

- Eigenvalues: \(\lambda_1, \lambda_2, \lambda_3\)
- Not IRC safe

- Only quadratic sensitivity for perturbations around symmetric configurations

**Spherical:**

\[
\begin{align*}
\lambda &= \frac{1}{3} \\
C &= 1 \\
D &= 1
\end{align*}
\]

**Azimuthally Symmetric:**

\[
\begin{align*}
\lambda_2 &= \lambda_3 = \frac{1 - \lambda_1}{2} \\
C_{az} &= \frac{3}{4} (2\lambda_1 - 3\lambda_1^2 + 1) \\
D_{az} &= \frac{27}{4} (1 + \lambda_1^2 - 2\lambda_1)
\end{align*}
\]

**Quasi-Azimuthally Symmetric:**

\[
\begin{align*}
\lambda_{2,3} &= \frac{1 - \lambda_1 \pm \epsilon}{2} \\
C_{quasi} &= C_{az} - \frac{3\epsilon^2}{4} \\
D_{quasi} &= D_{az} - \frac{27\lambda_1}{4} \epsilon^2
\end{align*}
\]
Other Event Shape Observables

In azimuthally symmetric/ spherical regime, thrust is correlated with $\lambda_1$ as well.

5d Simplified Model (2011.06599)
Event isotropy does not show same degree of correlation

5d Simplified Model (2011.06599)
Event Isotropy vs. Other Observables

Event isotropy is not strongly correlated with other popular observables

5d Simplified Model (2011.06599)
Conclusion

Event isotropy is a complementary probe to existing event shape observables

Most interesting in quasi-isotropic regime

Can be used for robust searches for new physics at LHC and beyond!
Back ups:
Dark Showers & Event Isotropy
Event Isotropy vs. Other Observables

5d Simplified Model (2011.06599)
Dark Showers from 5d Simplified Models

Using 5d simplified models, we can model many particles and interactions with few parameters.

Consider slice of (4+1)d AdS (RS1) with scalars that propagate in the bulk.

- Each scalar has infinite Kaluza-Klein tower scalars.
- Gauge / gravity duality: Interpret KK modes as 4d hadrons.

\[ \Phi(x^\mu, z) = \sum_{n=1}^{\infty} \phi_n(x^\mu)\psi_n(z) \]

Warped Finite Extra Dim. 5d Scalar 4d Hadrons Wave function in z
Dark Showers from 5d Simplified Models

Including a cubic coupling between 5d field $\longleftrightarrow$ infinite cubic couplings between KK modes in 4d

\[
\int \sqrt{g} \, d^4x \, dz \, L_{\text{int}} = - \int \sqrt{g} \, d^4x \, dz \, c \Phi_1 \Phi_2 \Phi_3
\]

plug in expansion

\[
\Phi(x^\mu, z) = \sum_{n=1}^{\infty} \phi_n(x^\mu) \psi_n(z)
\]

\[
= - \int d^4x \, c \sum_{i,j,k} \left( \int \sqrt{g} \, dz \, \psi_{1,i}(z) \psi_{2,j}(z) \psi_{3,k}(z) \right) \phi_{1,i}(x) \phi_{2,j}(x) \phi_{3,k}(x)
\]

Wavefunctions control 4d coupling:

\[
L_{4d} \supset \sum_{i,j,k} \infty c_{ij,k} \phi_{1,i}(x) \phi_{2,j}(x) \phi_{3,k}(x)
\]
Dark Showers from 5d Simplified Models

5d scalar mass corresponds to different phenomenology in dark shower

**Goal of model:** interpolate between *jetty* and *spherical* signatures

Model dark shower as

1. Starting at $n_{KK} = 100$
2. Two-body decays between modes:
   \[ \phi_n \rightarrow \phi_m \phi_l \]
3. Cascade develops to stable 4d hadrons
4. Split hadrons into 2 massless particles
Event Isotropy

Any finite-multiplicity event has a theoretical bound on isotropy which is saturated when the event is symmetrized on the geometry.

Analytic approximations match computation well.