A Robust Measure of Event Isotropy at Colliders

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(2004.06125) w/ J. Thaler, MIT

FCC-ee Webinar

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Motivation

There is enormous capacity for precision SM measurements & discovery potential at colliders

$\longrightarrow$ Could be new physics at electroweak scale hiding with rare kinematic signatures

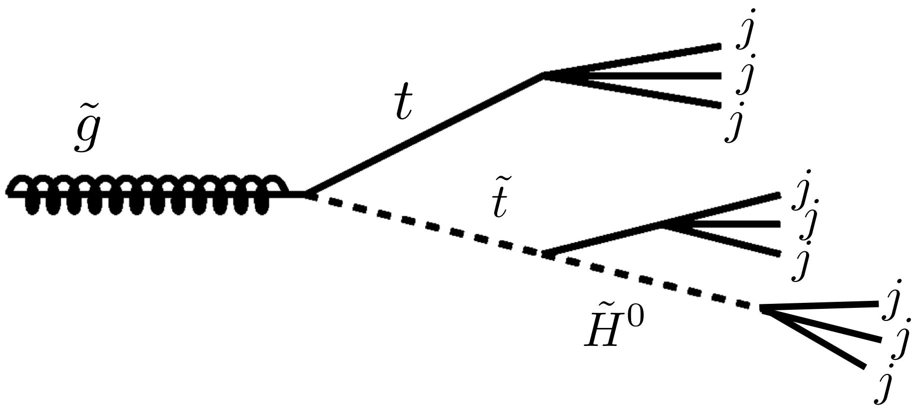
$\longrightarrow$ Strategy for new physics searches: identify signatures *fundamentally* different from QCD backgrounds

Motivation

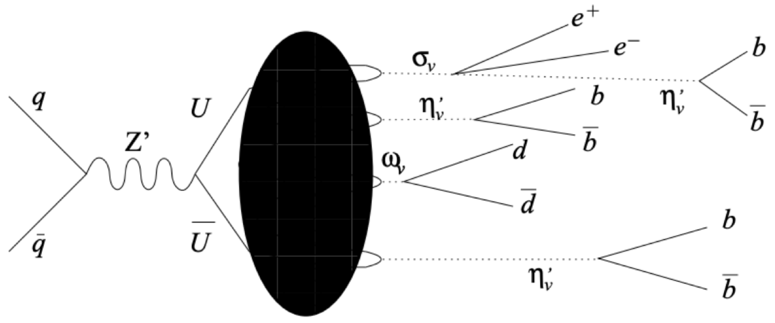
QCD at TeV scale is characterized by soft, collinear splittings, and therefore looks very *jetty*

But many new physics signatures look quasi-isotropic:

RPV SUSY



Hidden Valleys/Dark Showers



Strassler, Zurek 2006

Also:

- Black holes
- Soft bomb (SUEPs)
- Many more…

Motivation

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

When trying to quantify event shape

- Event shape observables designed to measure distance from *dijet*
  - *Thrust, C/D-parameter, sphericity, spherocity, superspherо…*
- Want distance from *isotropy*

Event Isotropy

(CC, J. Thaler, 2004.06125)

Part 1: Defining Event Isotropy

Part 2: Applications of Event Isotropy
at FCC-ee

Energy Mover's Distance

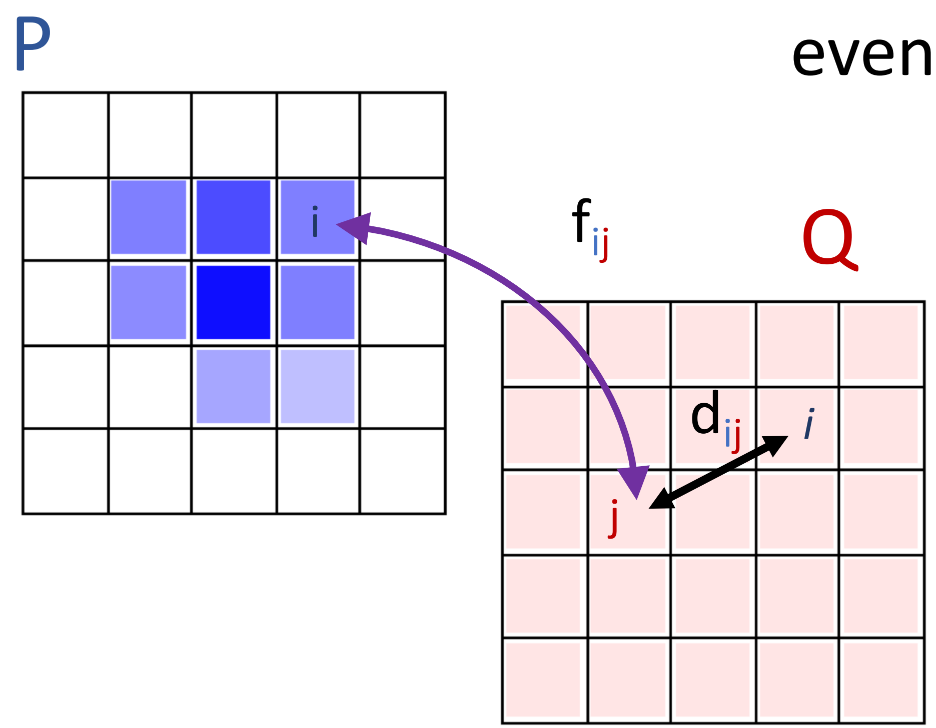
We propose a new event shape observable: event isotropy

CC, J. Thaler 2004.06125

Energy mover's distance (EMD):

What is the minimum work to rearrange the energy distribution in event *P* to look like event *Q*?

P. Komiske, E. Metodiev, J. Thaler 2019



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

f_{ij} : energy transported

d_{ij} : distance measure

$$f_{ij} \geq 0 \qquad \sum_{ij} f_{ij} = E_P^{\mathrm{tot}} = E_Q^{\mathrm{tot}} = 1$$

Energy Mover’s Distance

We propose a new event shape observable: event isotropy

CC, J. Thaler 2004.06125

Energy mover’s distance (EMD):

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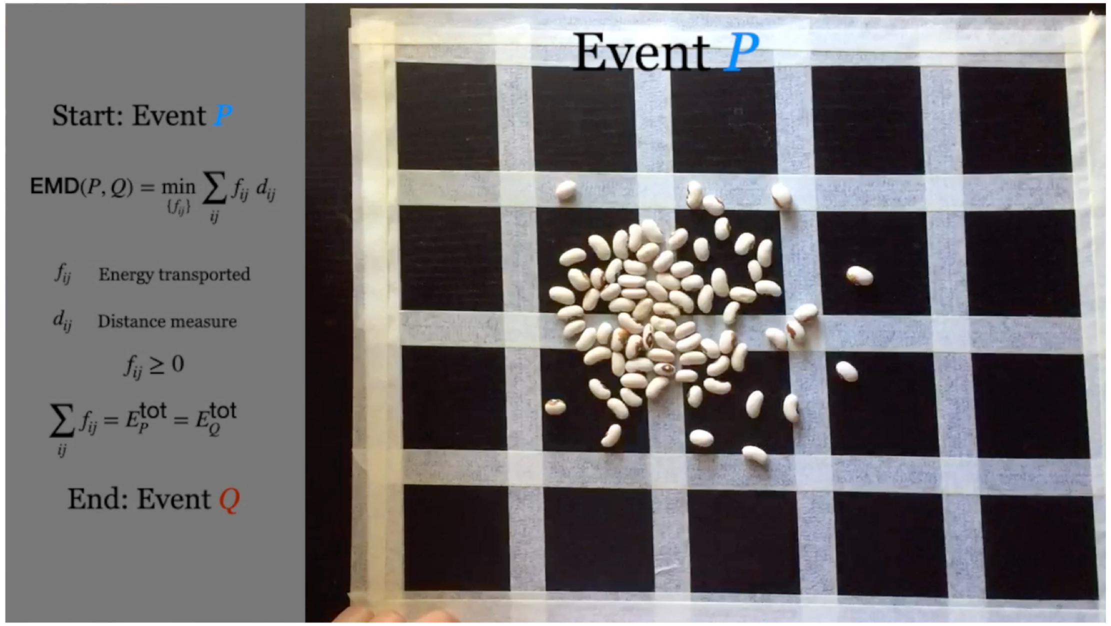
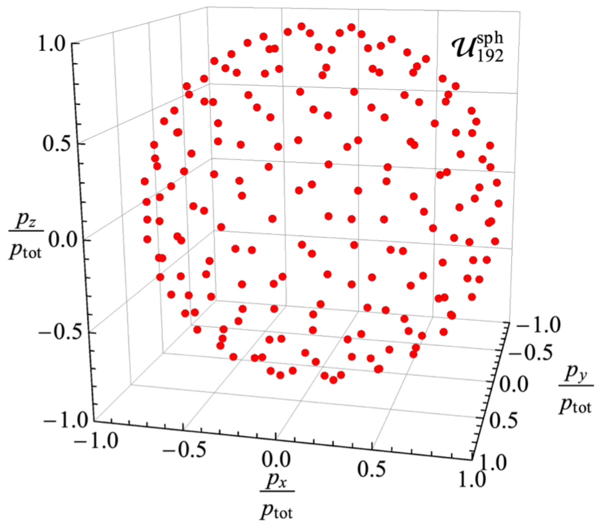


Event Isotropy: EMD of an event to uniform radiation pattern

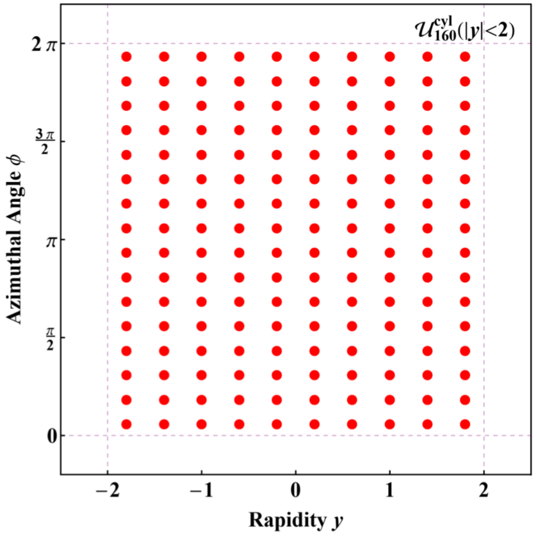
$$\mathcal{I}_n^{\text{geo}}(\mathcal{E}) = \text{EMD}_{\text{geo}}(\mathcal{U}_n^{\text{geo}}, \mathcal{E})$$

- *Geo*: Geometry of isotropic radiation pattern (sphere, cylinder, ring)
  - Associated energy weight w_i (moved with f_{ij}) and distance measure d_{ij}
- *n*: Number of particles in quasi-uniform sample

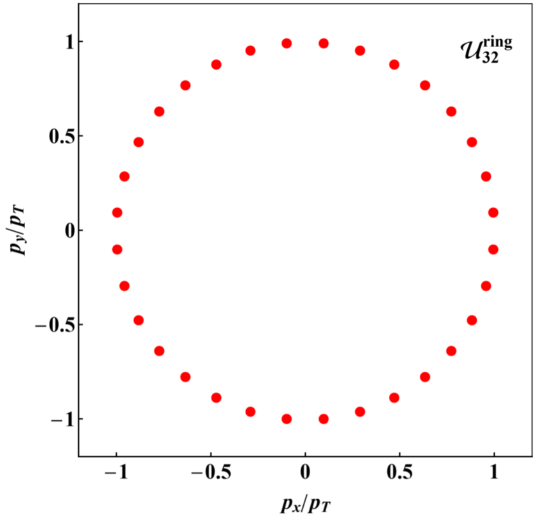
Sphere n = 192



Cylinder n = 160



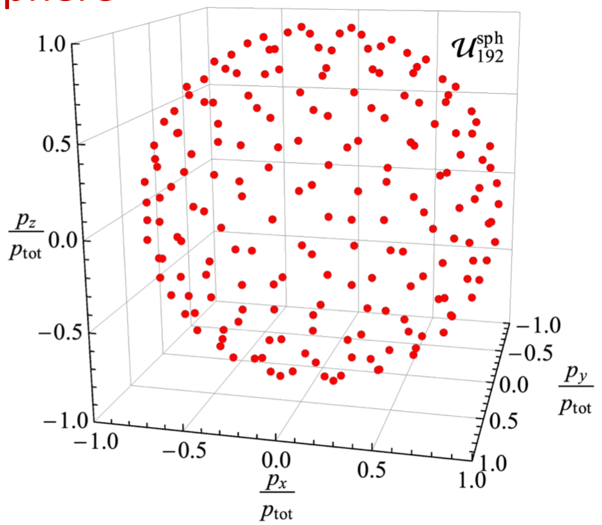
Ring n = 32



Event Isotropy

$$\mathcal{I}_n^{\text{geo}}(\mathcal{E}) = \text{EMD}_{\text{geo}}(\mathcal{U}_n^{\text{geo}}, \mathcal{E})$$

Sphere

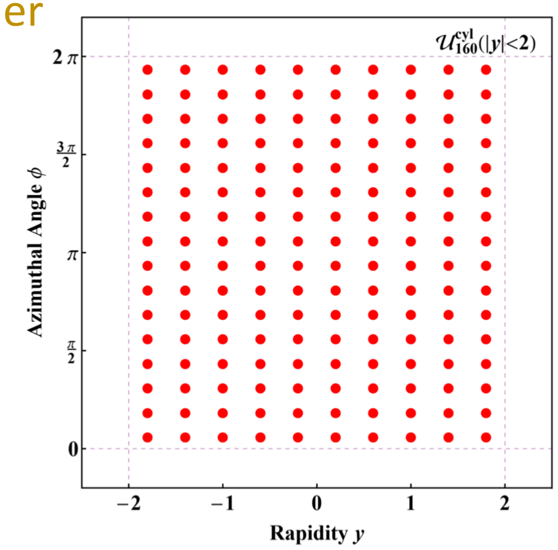


e^+e^-

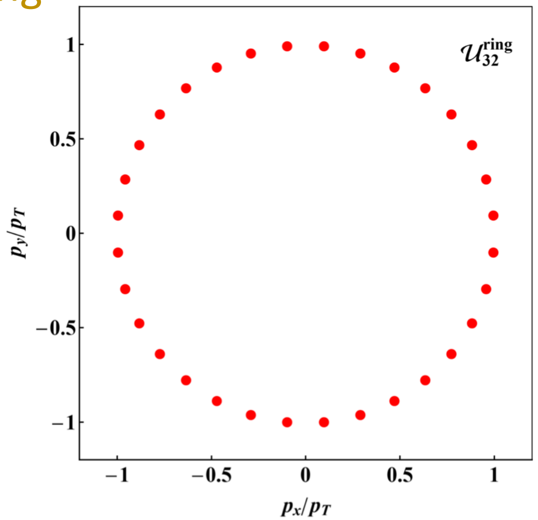
$$w_i = E_i/E_{\text{tot}}$$

$$d_{ij} = 2\,(1 - \cos\theta_{ij})$$

Cylinder



Ring



pp

$$w_i = p_{T,i}/p_{T,tot}$$

$$d_{ij} = \frac{12}{\pi^2 + 16y_{\text{max}}^2}\,(y_{ij}^2 + \phi_{ij}^2)$$

$$d_{ij} = \frac{\pi}{\pi - 2}\,(1 - \cos\phi_{ij})$$

Event Isotropy

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

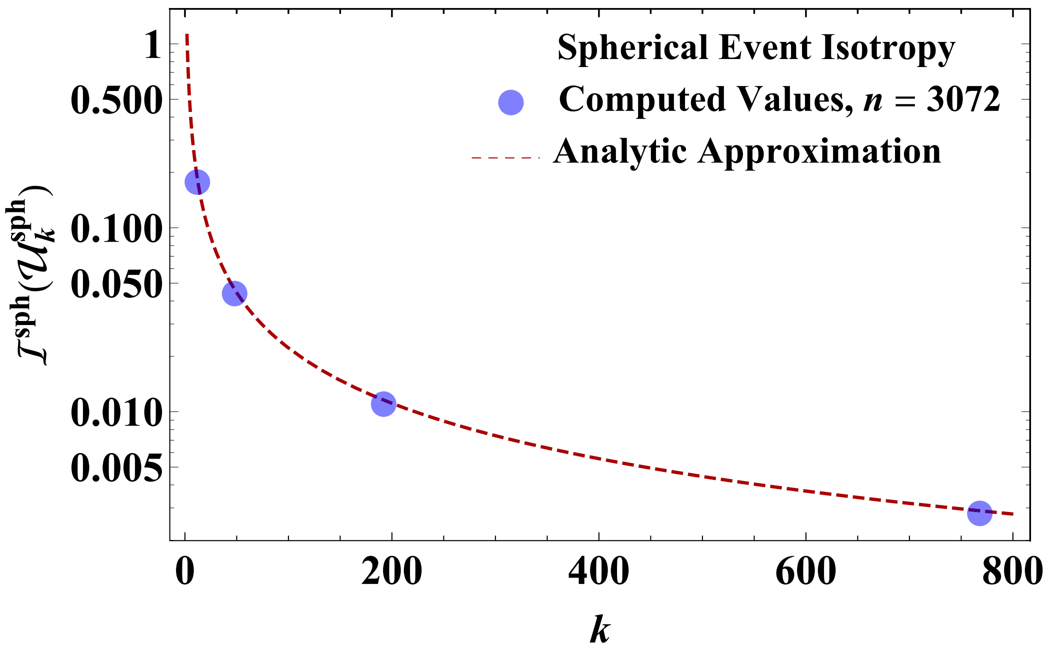
$$\mathcal{I}_n^{\text{geo}}(\mathcal{E}) = \text{EMD}_{\text{geo}}(\mathcal{U}_n^{\text{geo}}, \mathcal{E})$$

$\mathcal{I}^{\text{sph}} = 0$ $\mathcal{I}^{\text{sph}} = 1$

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



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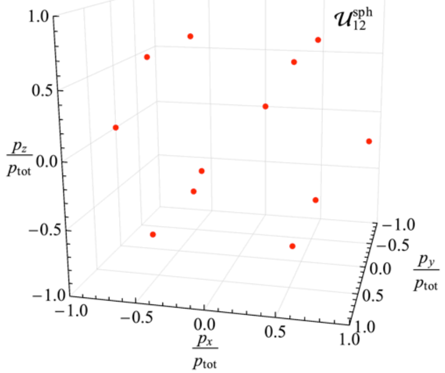
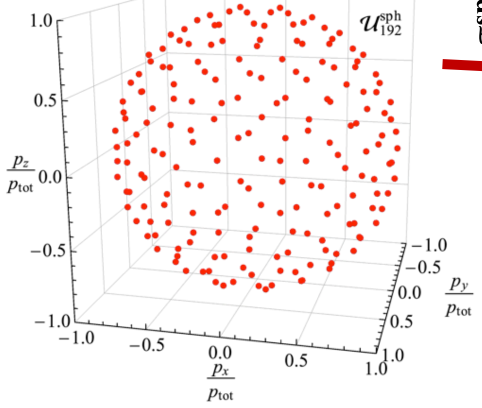
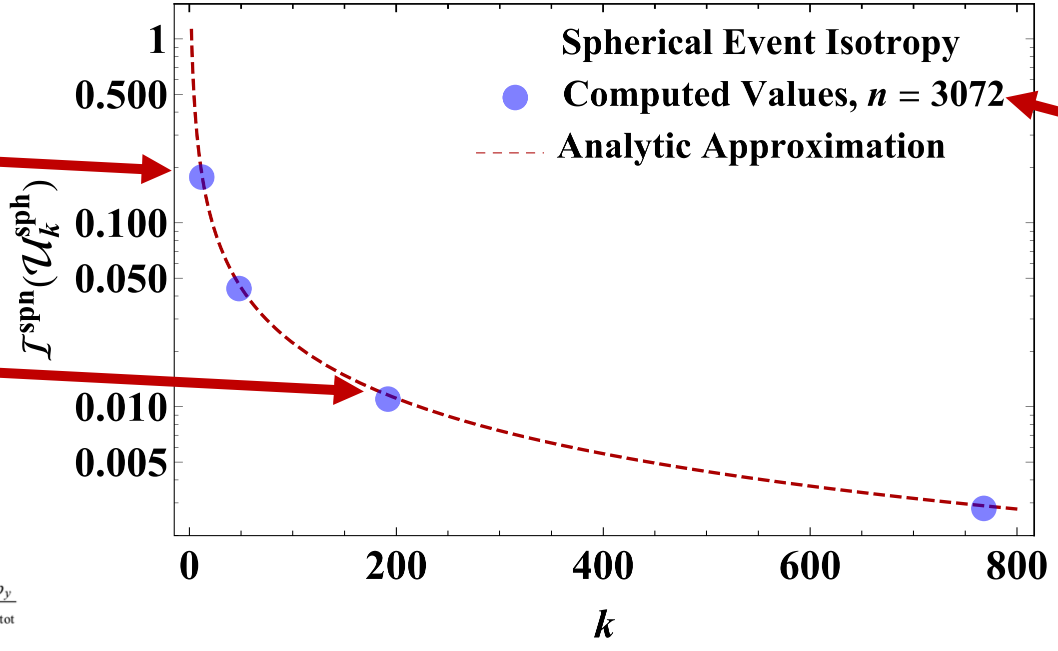
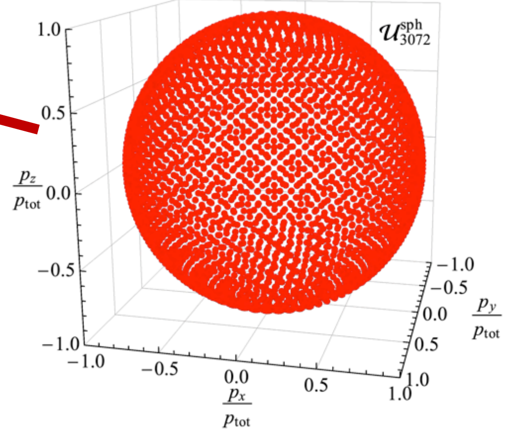








Part 1: Defining Event Isotropy

Part 2: Applications of Event Isotropy
at FCC-ee

Standard Model Benchmark

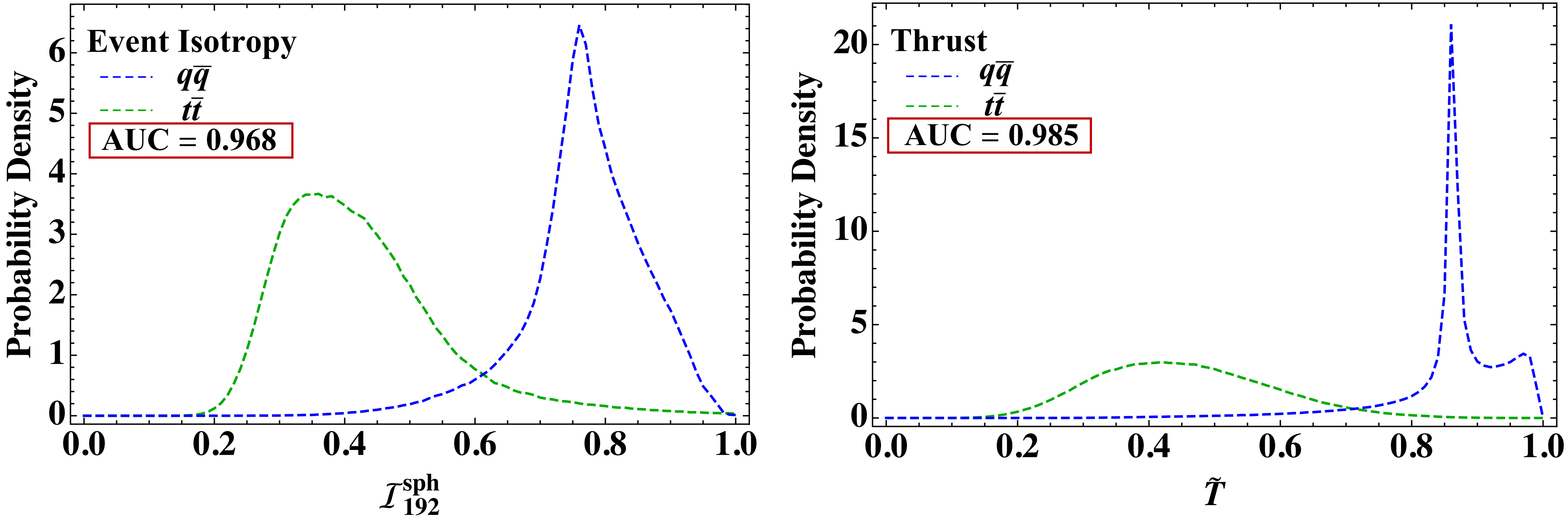
Sphere Geometry

QCD dijet vs. top pair production

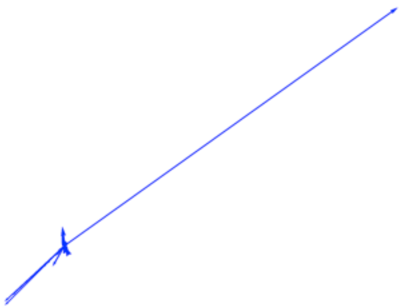
e^+e^- Collisions at $\sqrt{s}$ = 350 GeV

Event isotropy

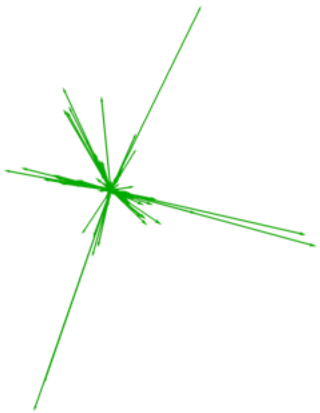
Scaled thrust



QCD Dijet



Top pair



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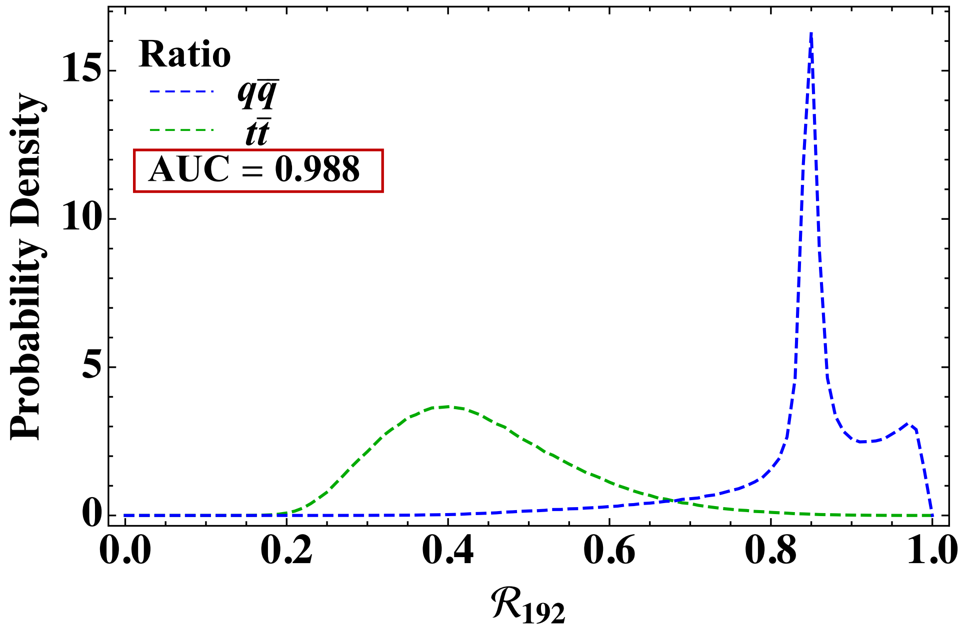
Standard Model Benchmark

Sphere Geometry

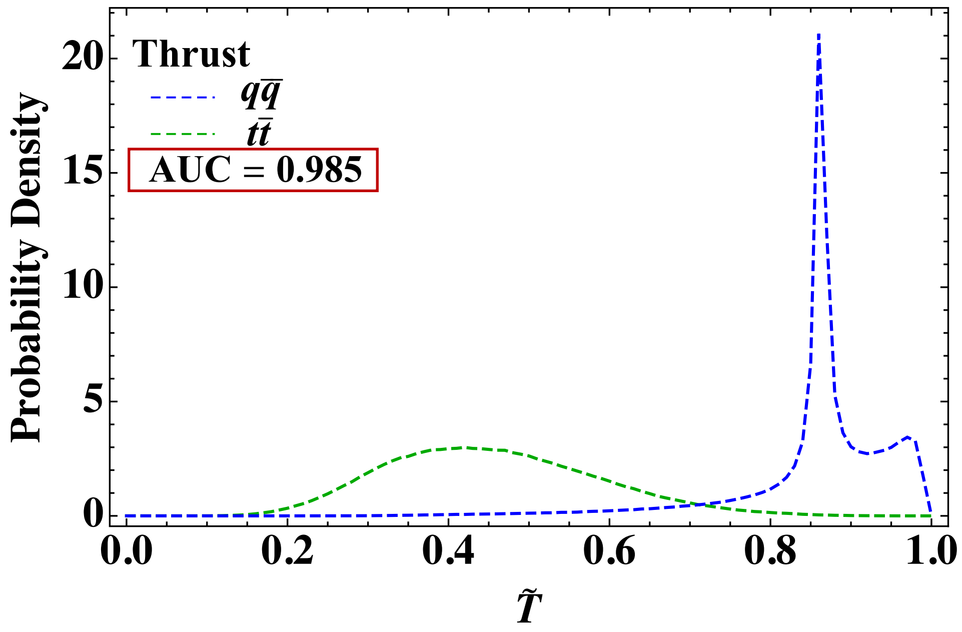
QCD dijet vs. top pair production

e^+e^- Collisions at $\sqrt{s}$ = 350 GeV

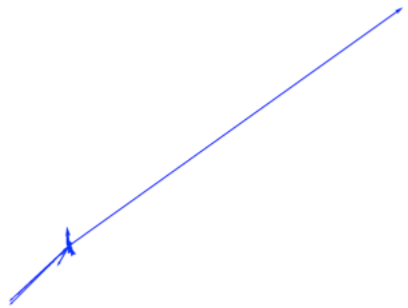
$$\mathcal{R}_{192} = \frac{\mathcal{I}_{192}^{\text{sph}}}{\mathcal{I}_{192}^{\text{sph}} + (1 - \tilde{T})}$$



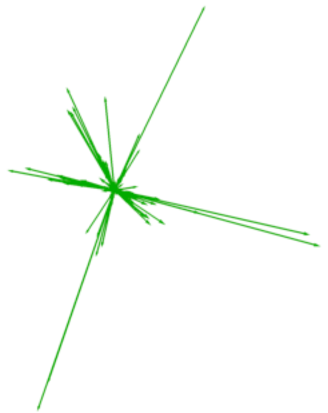
Scaled thrust



QCD Dijet



Top pair



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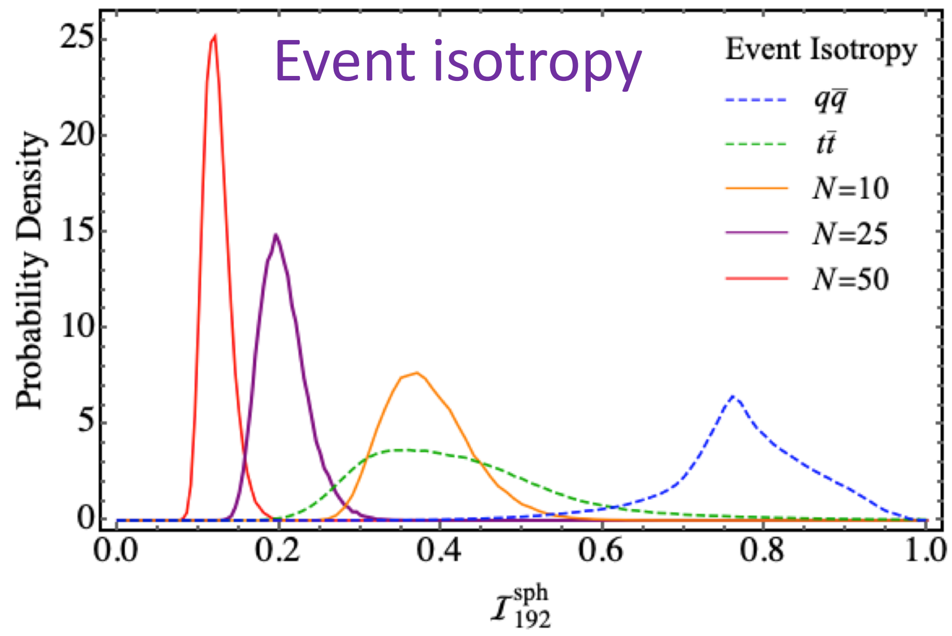
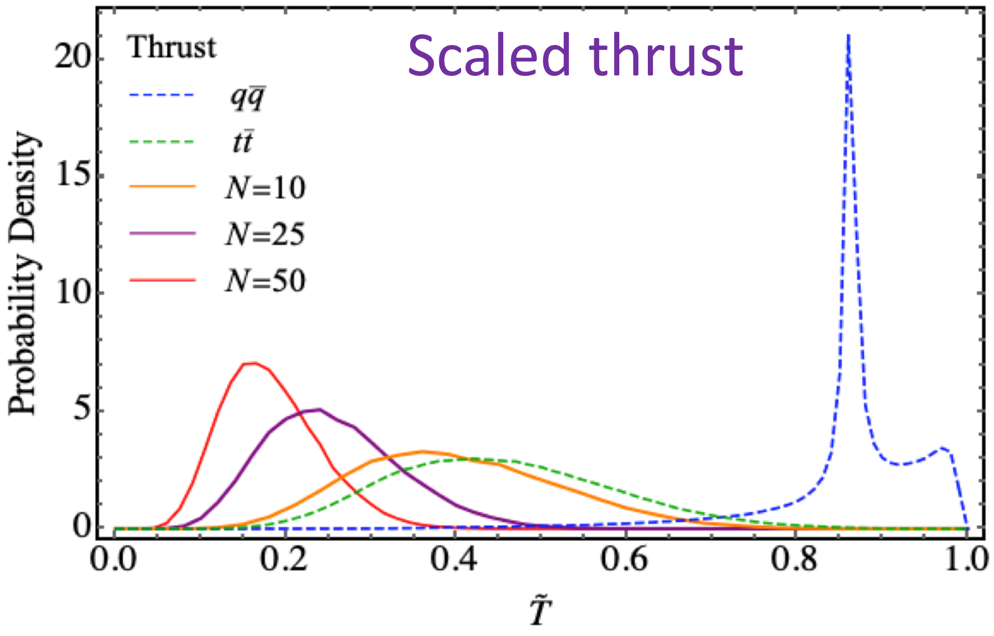
Toy Model: Uniform *N*-body Phase space

Discriminating N = {10, 25, 50}-body samples

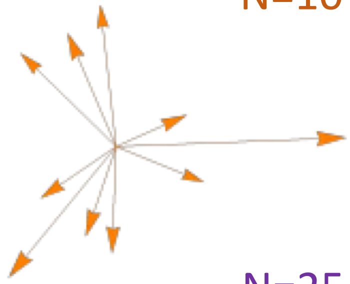
e^+e^- Collisions at $\sqrt{s}$ = 350 GeV

Spherical Geometry

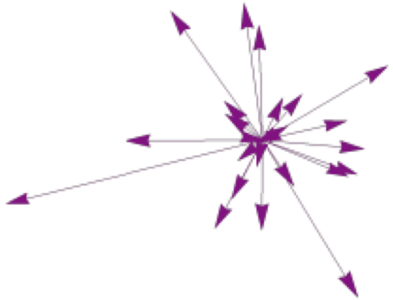




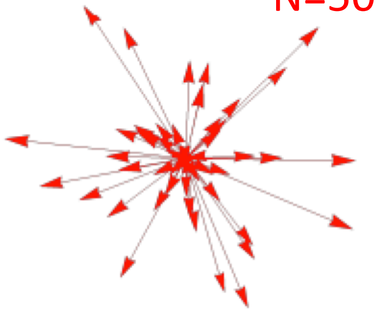
N=10



N=25



N=50



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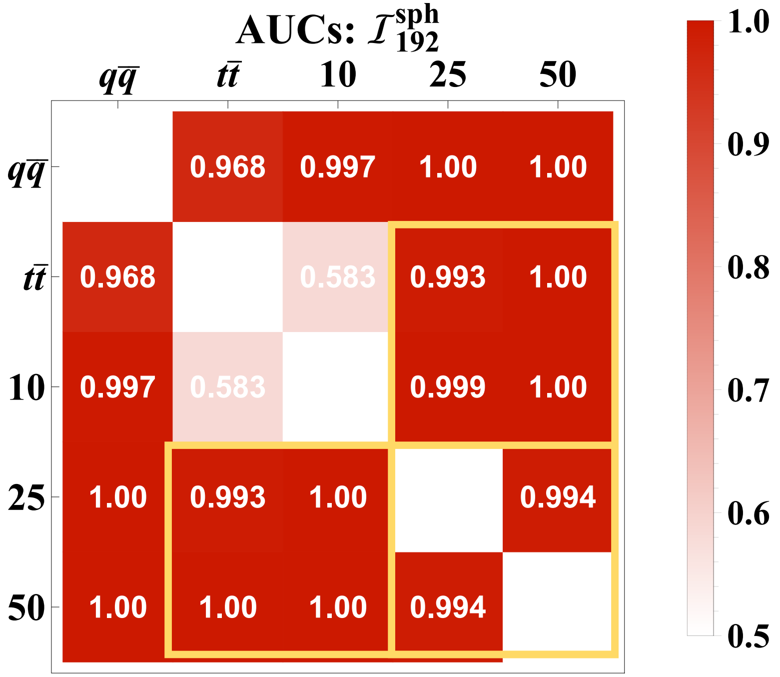
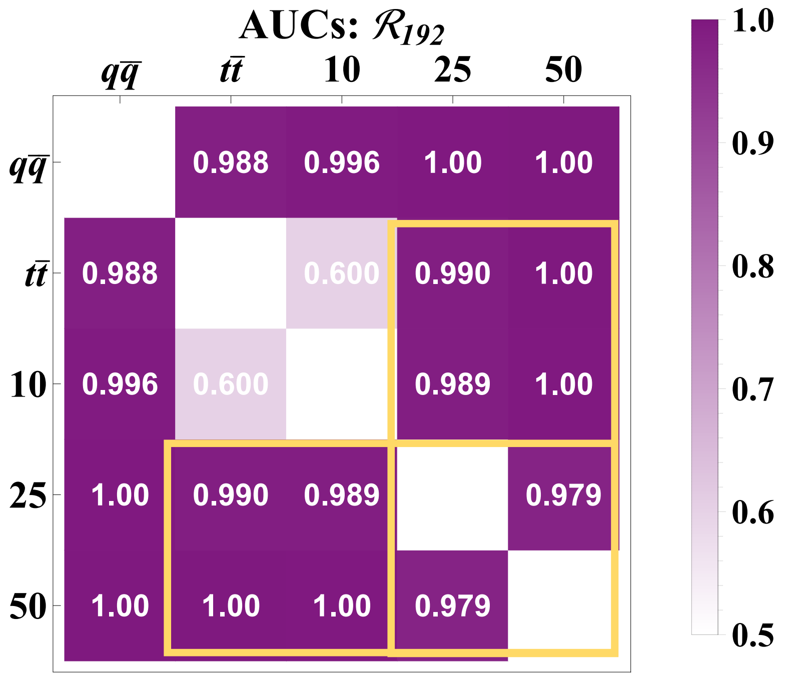
Benchmark Summary

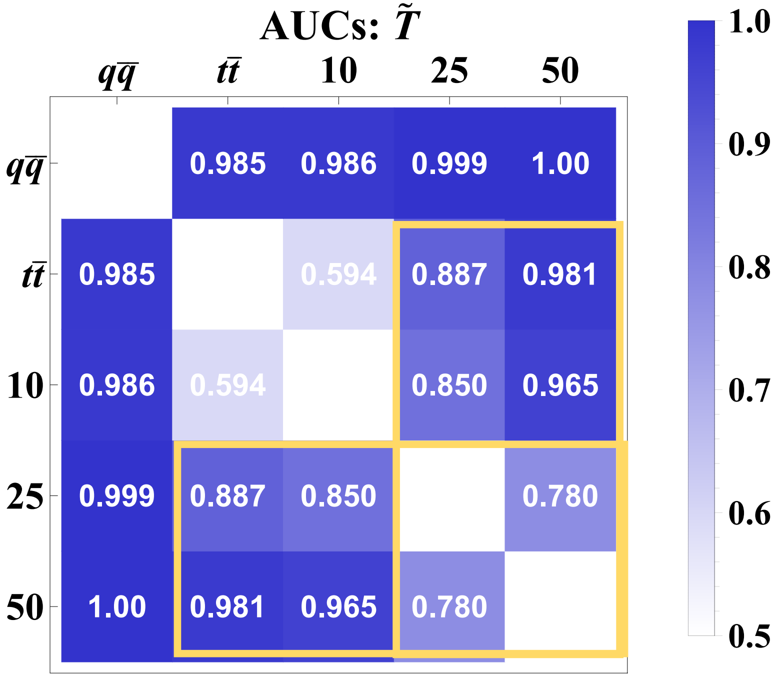
Event isotropy



Ratio



Scaled thrust



Event isotropy excels at differentiating quasi-isotropic event topologies from each other

Conclusions

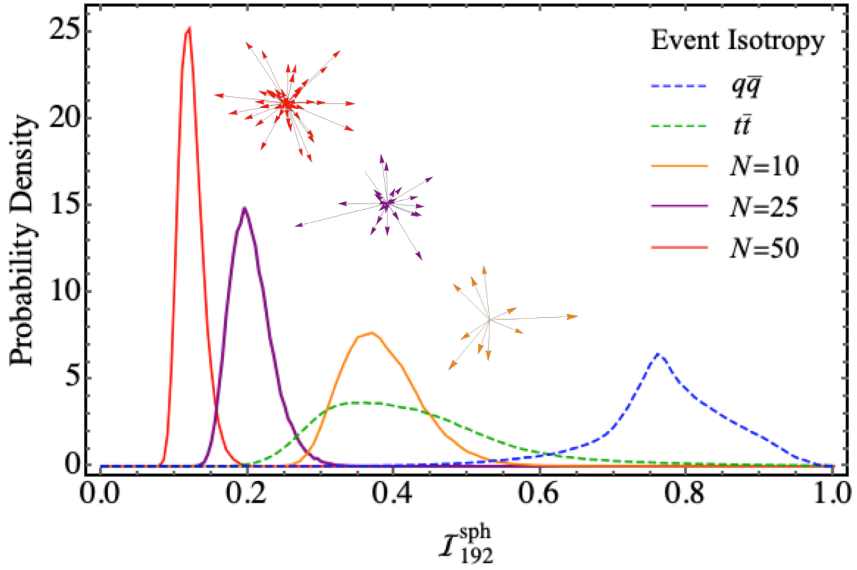
Event isotropy is useful for discriminating and characterizing events in the quasi-isotropic regime

Part 1:

- Application of Energy Mover's Distance
- Calculated with Wasserstein Distance

Part 2:

- Discriminates between quasi-uniform samples
- Characterizes event shape of new physics and high multiplicity SM events



Future Studies

!Jet isotropy: To consider isotropic signatures boosted against a jet, remove jet and boost remaining event backwards by jet momentum

Thank you!

Back ups:
Dark Showers & Event Isotropy

Work in Progress
CJC, M. Reece, M. Strassler

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

Warped Finite Extra Dim.

$$\underbrace{\Phi(x^\mu, z)}_{\text{5d Scalar}} = \sum_{n=1}^{\infty} \underbrace{\phi_n(x^\mu)}_{\text{4d Hadrons}} \underbrace{\psi_n(z)}_{\text{Wave function in } z}$$

Dark Showers from 5d Simplified Models

Including a cubic coupling between 5d field ⟷ infinite cubic couplings between KK modes in 4d

$$\int \sqrt{g}\ \mathrm{d}^4x\ \mathrm{d}z\ \mathcal{L}_{\mathrm{int}} = -\int \sqrt{g}\ \mathrm{d}^4x\ \mathrm{d}z\ c\,\Phi_1\Phi_2\Phi_3$$

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:

$$\mathcal{L}_{4\mathrm{d}} \supset \sum_{i,j,k}^{\infty} c_{ijk}\phi_{1,i}(x)\phi_{2,j}(x)\phi_{3,k}(x),$$

Work in Progress
CJC, M. Reece, M. Strassler

Dark Showers from 5d Simplified Models

5d scalar mass corresponds to different phenomenology in dark shower

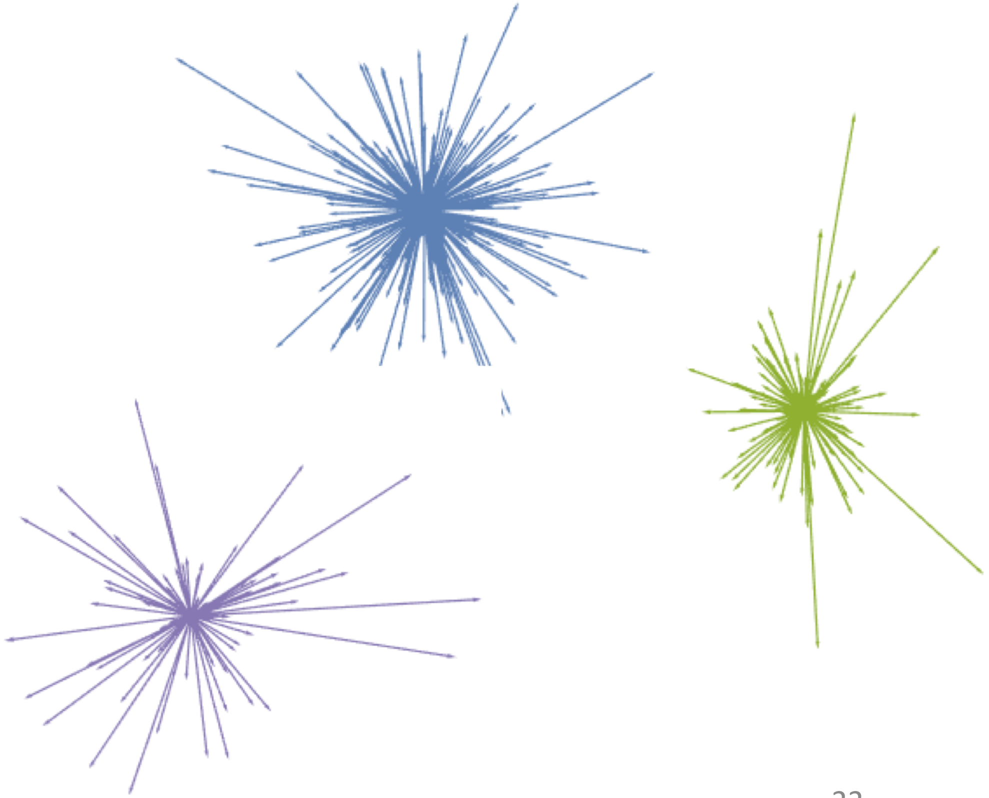
Goal of model: interpolate between *jetty* and *spherical* signatures

Model dark shower as

1. Starting at n_{KK} = 100
2. Two-body decays between modes:

$$\phi_n \to \phi_m \phi_l$$

3. Cascade develops to stable 4d hadrons
4. Split hadrons into 2 massless particles



Work in Progress
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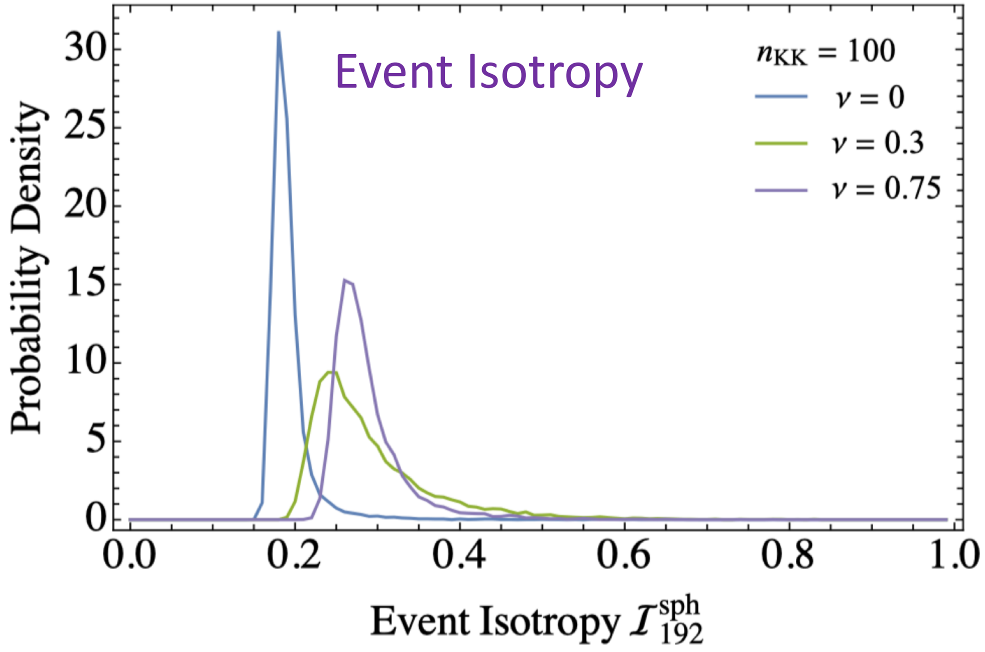
Dark Showers from 5d Simplified Models

Spherical Geometry

$\nu \leftrightarrow m_{5d}$



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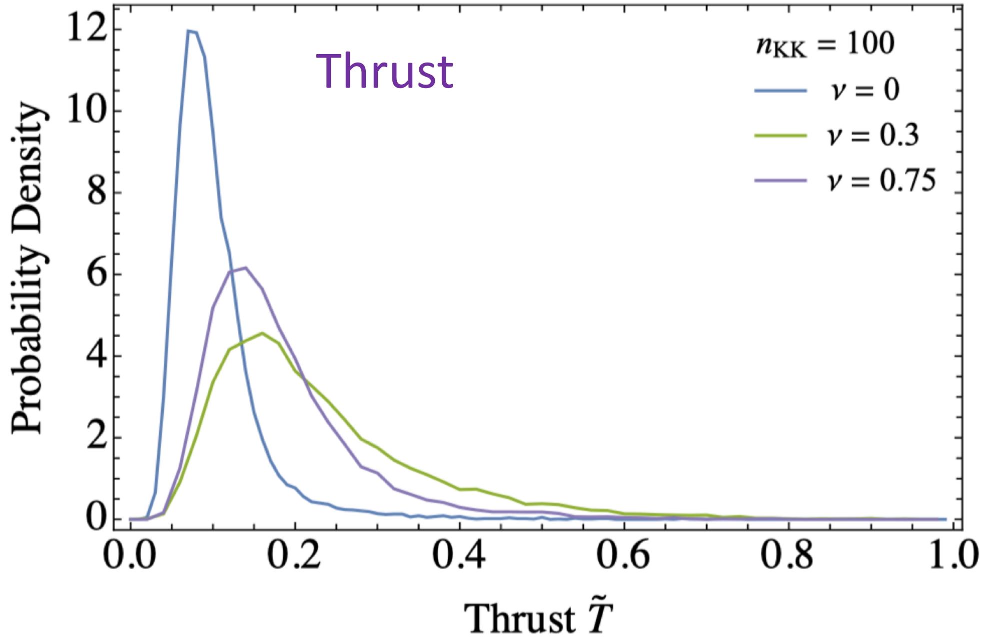

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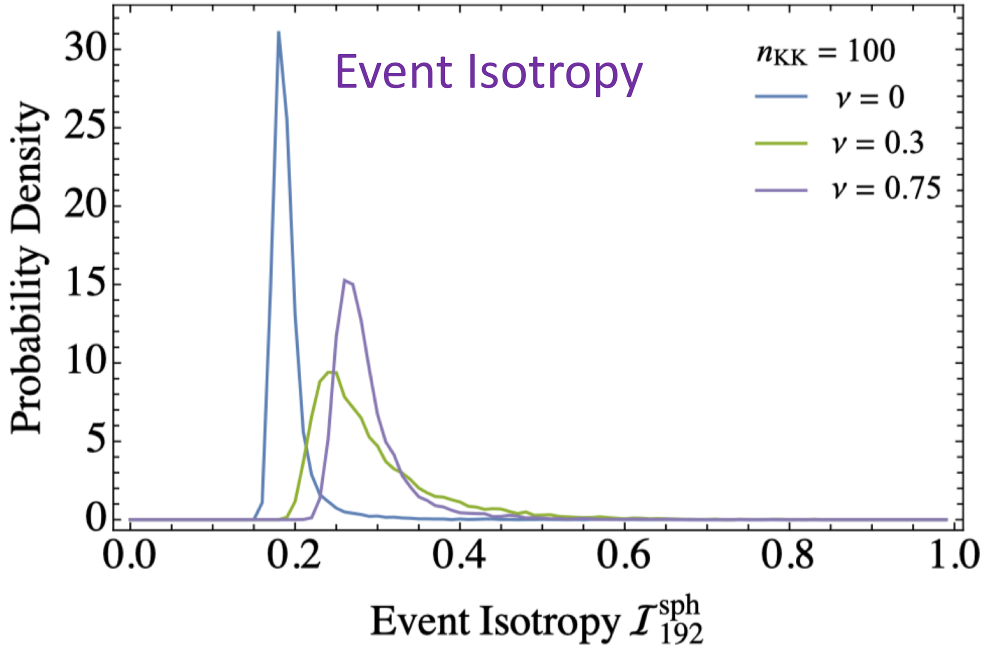
Dark Showers from 5d Simplified Models

Clearly, thrust & event isotropy probe different structure!

Spherical Geometry

$\nu \leftrightarrow m_{5d}$



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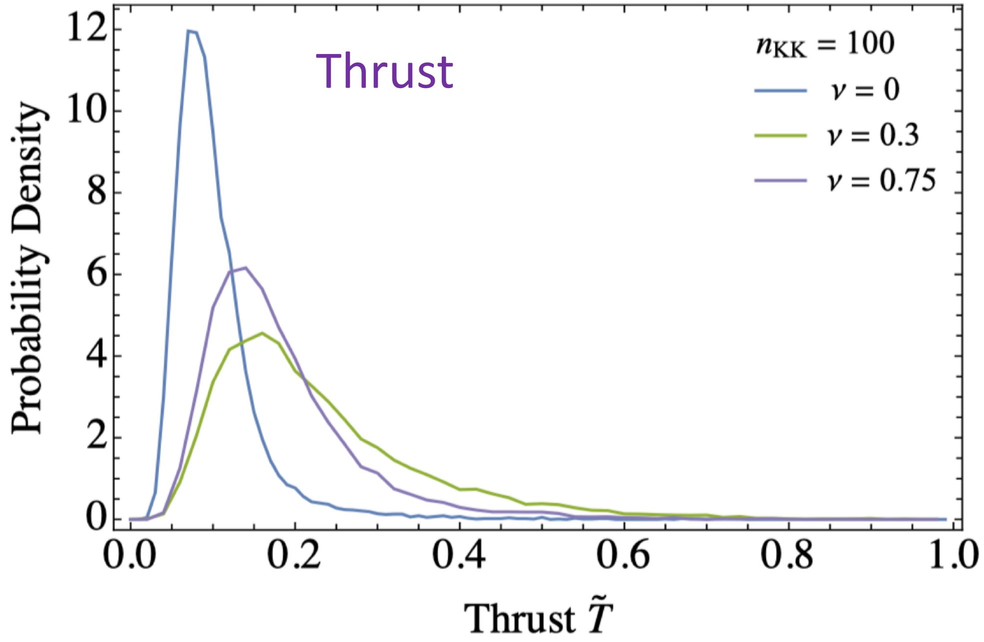

Work in Progress
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