SUEPs* to Jets: Parameterizing the Theory

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*Soft unclustered energy patterns
Dark Shower Phenomenology

• Weakly couple to SM via mediator (scalar, Z’)
• Could be complicated non-abelian theory
• Could be jetty or spherical, or in between

• GOALS:
  – Build a toy model
  – Interpolate between jets and SUEPs
  – Start conversation with experimentalists
Event Shapes

• **Jetty** Events $\rightarrow$ **Weak** coupling (QCD)

• **SUEPy** Events $\rightarrow$ **Strong** Coupling

• Intermediate regime?
Event Shapes

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- **SUEPy Events** $\rightarrow$ **Strong** Coupling
- **Intermediate regime?**
Event Shapes

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- **Intermediate regime?**

M. Adersberger, J. Beacham, M. Buschmann, J. Evans, M. Freytsis, S. Knapen, D. Linthorne, S. Renner, P. Schwaller, J. Scholtz, J. Shelton, D. Stolarski, D. Walker, ...

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hep-th/0803.1467
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Event Shapes

• Jetty Events $\rightarrow$ Weak coupling (QCD)
• SUEPy Events $\rightarrow$ Strong Coupling
• Intermediate regime?
AdS/CFT Correspondence

**AdS**
(toy)
Slice in AdS$_5$
Bulk scalar field
Kaluza-Klein Modes

**CFT**
(want to understand)
4D Confined Theory
Field operators
Hidden Sector Hadrons
Extra Dimensions

• Toy to build intuition for SUEP-to-Jet problem
• Extra finite 5\textsuperscript{th} dimension \((x^\mu, z)\)
• Warp space with \(\Lambda_5 < 0 \rightarrow \text{AdS (RS1)}\)
• Boundary on interval: UV, IR cutoffs
• \textbf{AdS/CFT} to calculate hidden sector dynamics

\[ ds^2 = \left( \frac{R}{z} \right)^z (\eta^{\mu\nu} dx_\mu dx_\nu + dz^2) \]
Kaluza-Klein (KK) Modes

• Solve EOM for scalar field on bulk (5D)

\[ \overline{\Phi}(x^\mu, z) = \sum \phi_n(x^\mu) \psi_n(z) \]

• Up to quadratic Lagrangian

\[ L^{\text{(quad)}}_5 = -g_{\mu\nu} \overline{\Phi} \gamma^\mu \Phi - m_5^2 |\Phi|^2 \]

• Study 5\textsuperscript{th} dim effects (KK modes) on 4D theory

\[ L_{\text{int}} > -\frac{g_4}{3!} \phi_i \phi_j \phi_k \]
\[ = -\frac{g_5}{3!} \phi_i \phi_j \phi_k \int_{z_1}^{z_2} dz \psi_i \psi_j \psi_k \]
KK Modes $\rightarrow$ Jetty or SUEPy

- Interactions to shift from sphere to jet
- Intuition: breaking of KK Number conservation makes jettier events
- Flat Space: KK-modes are cosines

\[ \sum_{n}^{d} \Phi_n(x) \Phi_m(x) \Phi_p(x) = 0 \]
\[ \mu_n \quad n \neq m + p \]

- KK number ‘n’ is conserved
- No phase space left

hep-ph/0811.3001
KK Modes $\rightarrow$ Jetty or SUEPy

\[ \psi_n(z) = z^2 A_n \int_0^z \left( m_n \cdot z \right) \frac{e^{-qz}}{\sqrt{1-q}} |\psi_n(z)|^2 \, dz = 1 \]

\{KK Mode $\psi_n(z)$\}

- Mass spacing $\sim$ linear
- cubic interaction $\sim$ KK number conserving
- Soft decay daughters $\rightarrow$ SUEPy shape

Warped 5D

Mass of KK modes (GeV)

0  10  20  30  40  50

0  10  20  30  40  50
Sphericity of KK Modes

Back-to-Back Jet

0

Sphericity

Event Shapes

Perfectly Spherical

1

Sphericity

\[ S_{ij} = \frac{\sum p_i^\ast \cdot p_j^\ast}{1p^*1^2} \]

\[ A = \frac{3}{2} (\lambda_1 + \lambda_2) \]
Sphericity of KK Modes

Back-to-Back Jet

Perfectly Spherical

Sphericity

s = 0

s = 0.65

s = 0.95
KK Modes – Cubic Interaction

\[ \mathcal{L}_{\infty} > -\frac{g}{3!} \Phi^3 \]

7.5 x 10^3 Trials
Starting at KK # = 50

KK # in decay shower
0.65 < s < 0.75

Sphericity
KK Modes – Cubic Interaction

\[ J^\text{in+} > - \frac{9}{3!} \phi^3 \]

7.5 x 10^3 Trials
Starting at KK # = 50

KK number is almost conserved \( \rightarrow \) higher sphericity
KK Modes $\rightarrow$ Jetty or SUEPy

- Interactions that break KK number
- Competing effects: phase space vs. coupling
- Idea: put interactions on $z_{IR}$ boundary

- KK wave functions converge at IR
- Decay widths about equal
- Decay to larger phase space options $\rightarrow$ Jettier?
KK Modes – Localized Interaction

$\mathcal{L}^\text{int} \supset -\frac{g}{3!} \bar{\Phi}^3$

7.5 x $10^3$ Trials
Starting at KK # = 50

KK # in decay shower
$0 < s < 0.05$

Sphericity

10/20/17
KK Modes – Localized Interaction

\[ L_{\text{int}} = -\frac{g}{3!} \Phi^3 \]

7.5 x 10^3 Trials
Starting at KK # = 50

All allowed states are found! \( \rightarrow \) spectrum of event shapes
Conclusions & Outlook

• Toy provides event shape interpolation
• LHC signatures are dependent on the mediator physics
• Tool to understand shower dynamics for hidden sector
• Theory and experiment
Questions?
Backups
KK Modes – Multiplicity?

$\mathcal{L}_5^{\text{int}} > -\frac{g}{3!} \Phi^3$

# Particles in Shower
Dark Showers

- Strassler & Zurek 2006
- SM weakly coupled to strongly interacting dark sectors
Dark Hadrons?

• **QCD** is very special
• Color **neutral** final states $\rightarrow$ reorganization
• To Consider:
  - $p_{\text{parton}}^\mu \sim p_{\text{jet}}^\mu$
  - hadrons

\[
\text{Rate: } N_f \alpha = \frac{N_f}{N_c}
\]

For SM QCD, $N_f = N_c = 3$
AdS / CFT

- $\text{AdS}_5 \times X_5$
- 10D masses $\rightarrow$ compactify to 5D masses
- Fewer dimensions $\rightarrow$ denser mass states
- More bulk scalar fields $\rightarrow$ closer to confining theory