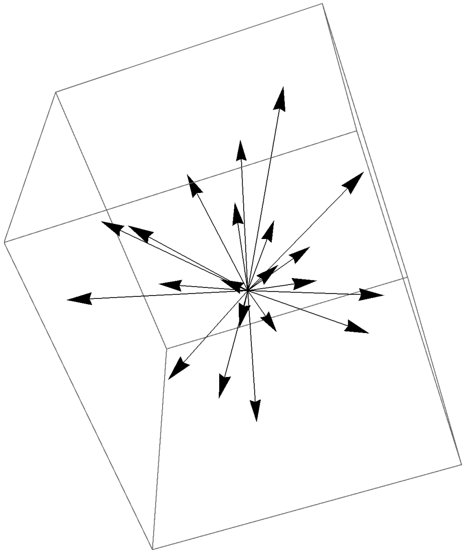
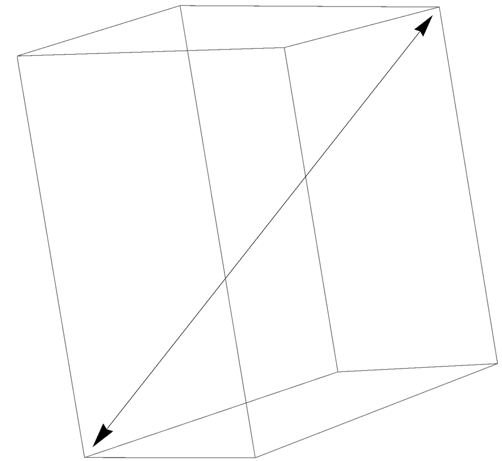




SUEPs* to Jets: Parameterizing the Theory

Cari Cesarotti

Harvard University

In Collaboration with Matt Reece, Matt Strassler

LLP Trieste, October 20 2017

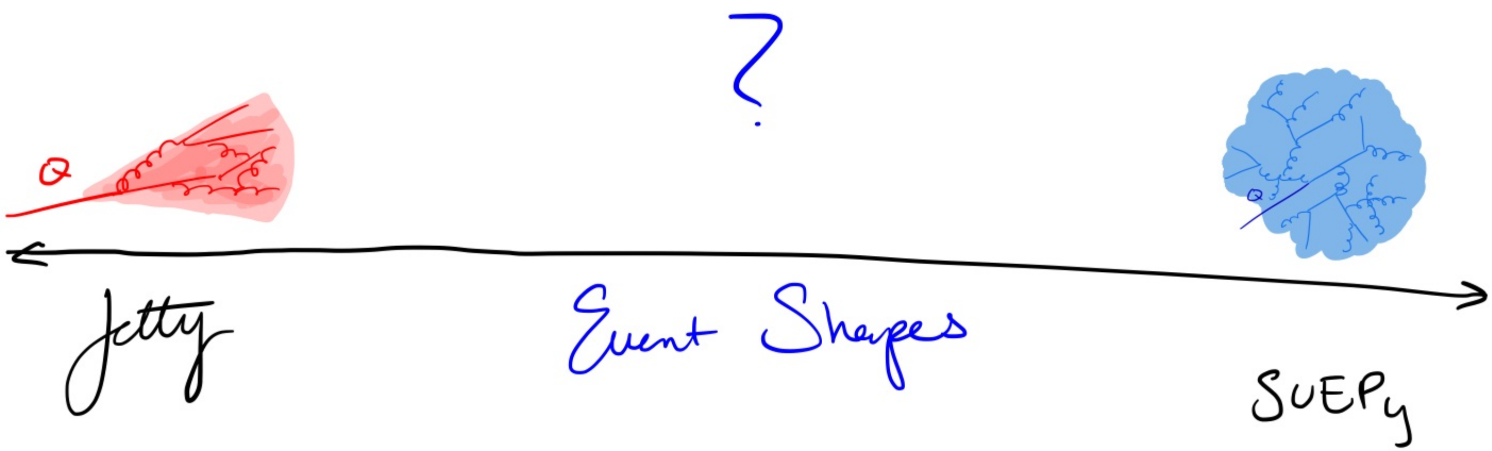
*Soft unclustered energy patterns

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 → Weak coupling (QCD)
- SUEPy Events → Strong Coupling
- Intermediate regime?



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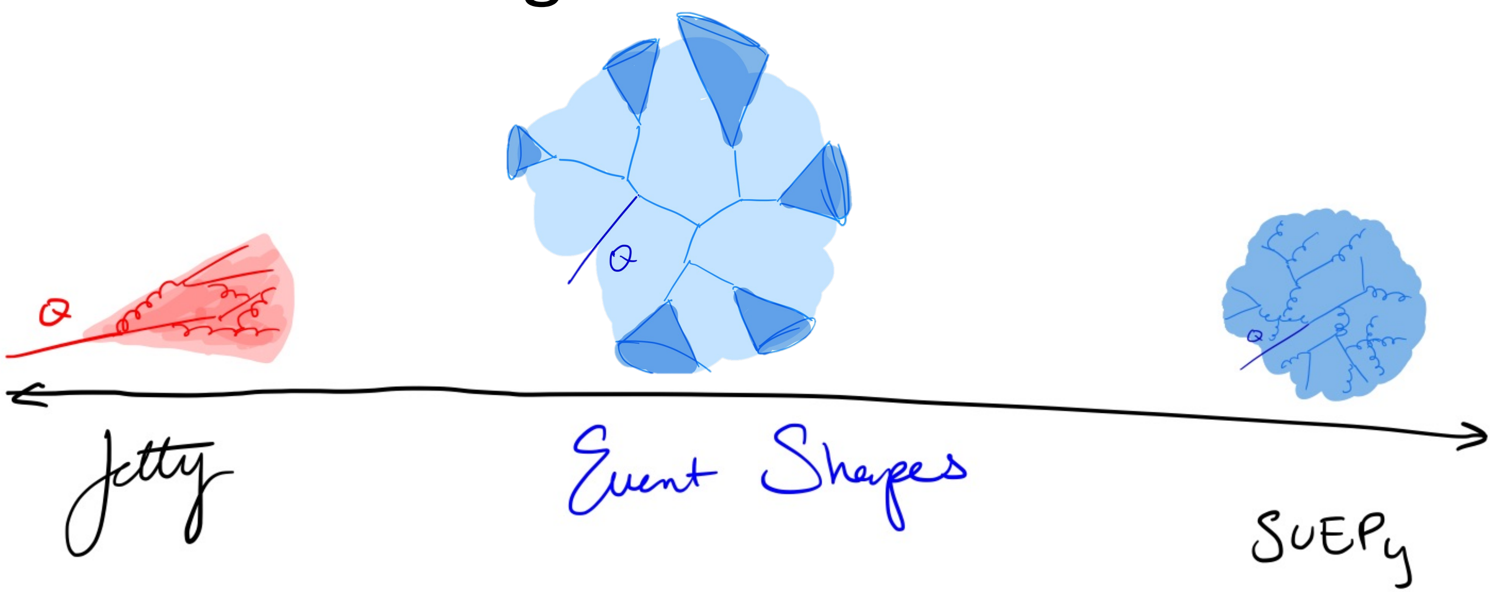

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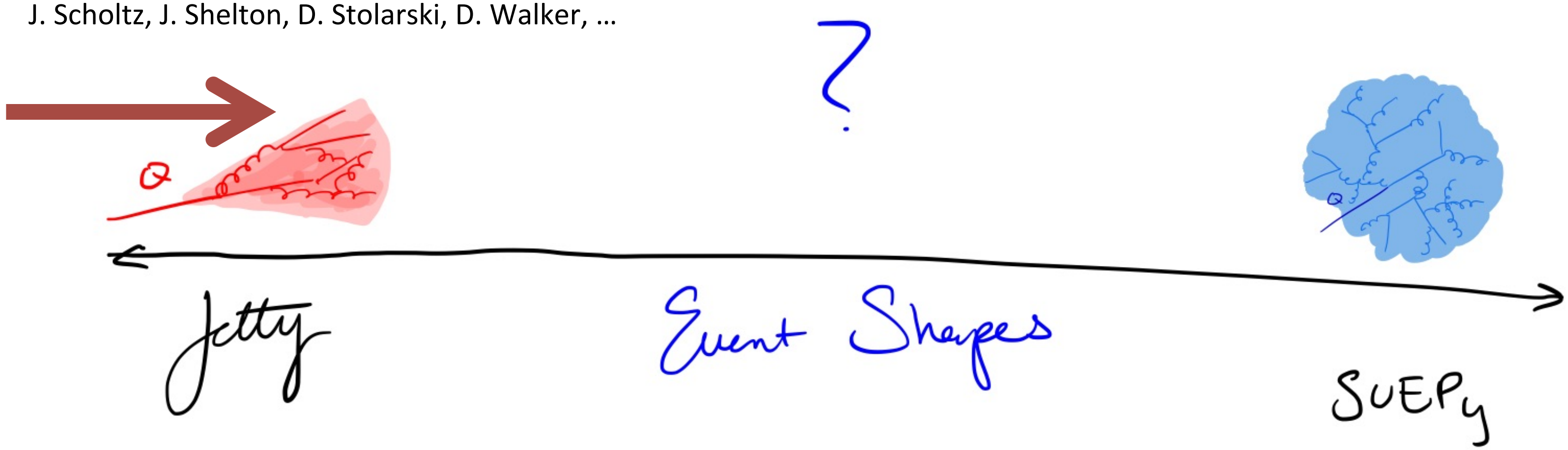
M. Adersberger, J. Beacham, M. Buschmann, J. Evans, M. Freytsis, S. Knapen, D. Linthorne, S. Renner, P. Schwaller, J. Scholtz, J. Shelton, D. Stolarski, D. Walker, …



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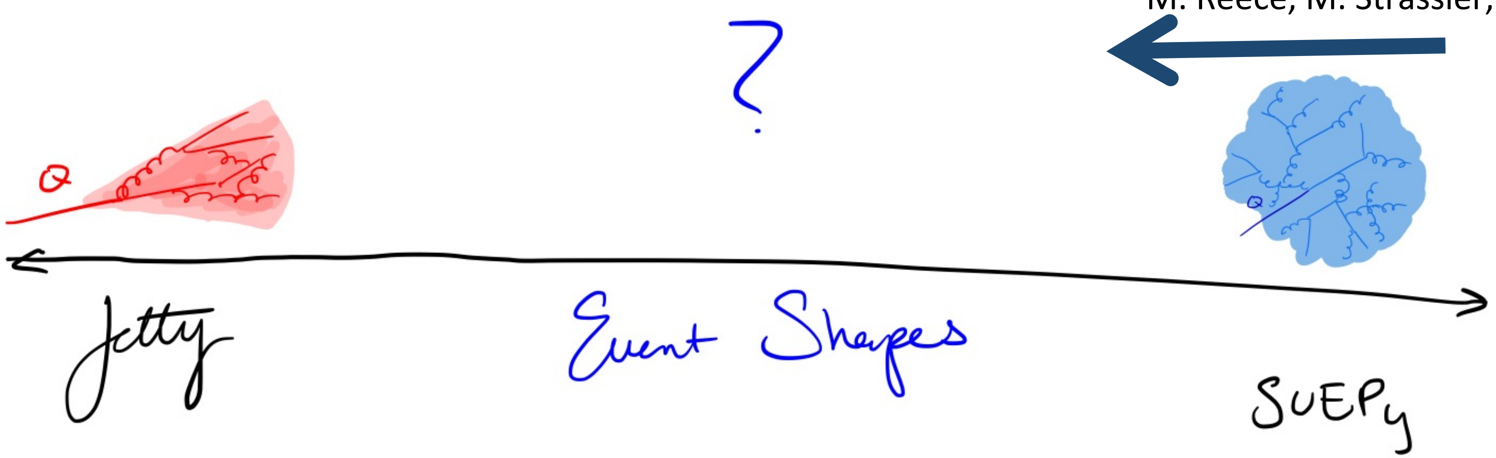
M. Reece, M. Strassler, CJC



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AdS/CFT Correspondence

AdS		**CFT**
(toy)		(want to understand)
Slice in AdS_5	⟺	4D Confined Theory
Bulk scalar field		Field operators
Kaluza-Klein Modes		Hidden Sector Hadrons

Extra Dimensions

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

$$ds^2 = \left(\frac{R}{z}\right)^2 \left(\eta^{\mu\nu} dx_\mu dx_\nu + dz^2\right)$$

Kaluza-Klein (KK) Modes

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

$$\Phi(x^\mu, z) = \sum_n \phi_n(x^\mu)\psi_n(z)$$

- Up to quadratic Lagrangian

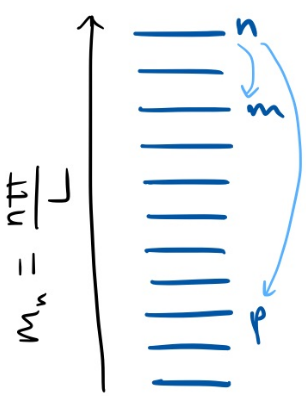
$$\mathcal{L}_5^{(\text{Quad})} = -g_{MN}\partial^M\Phi\partial^N\Phi - m_5^2|\Phi|^2$$

- Study 5^{th} dim effects (KK modes) on 4D theory

$$\mathcal{L}_{int} \supset -\frac{g_4}{3!}\phi_i\phi_j\phi_k$$
$$= -\frac{g_5}{3!}\phi_i\phi_j\phi_k\int_{z_{UV}}^{z_{IR}}\sqrt{-g}\,dz\,\psi_i\psi_j\psi_k$$

KK Modes → 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



$$\int dz\, \psi_n(z)\psi_m(z)\psi_p(z) = 0$$

$$\text{for} \quad n \neq m + p$$

- KK number 'n' is conserved
- No phase space left

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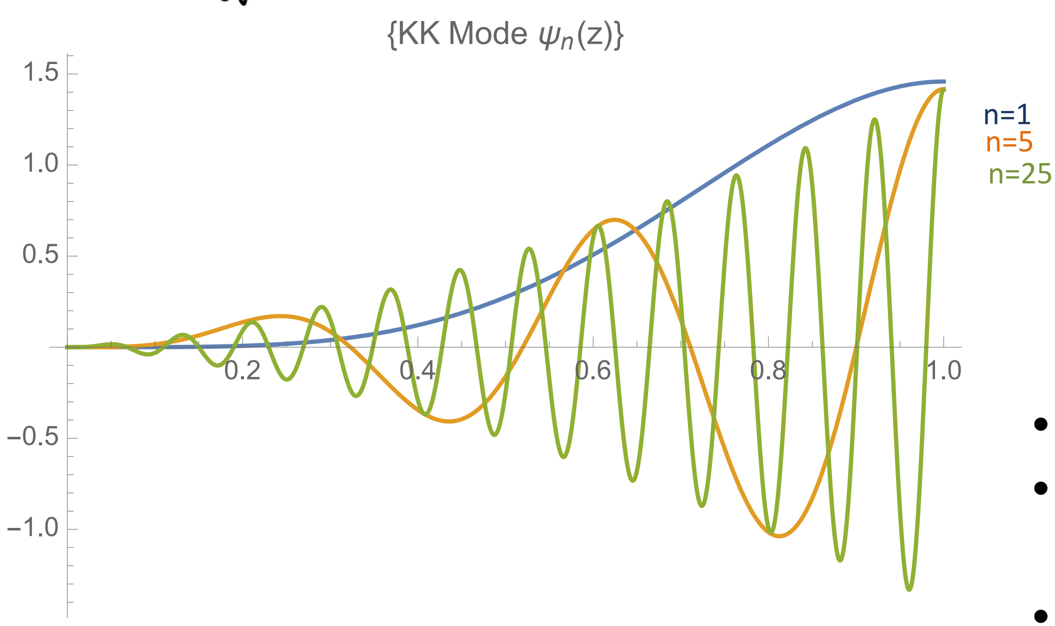
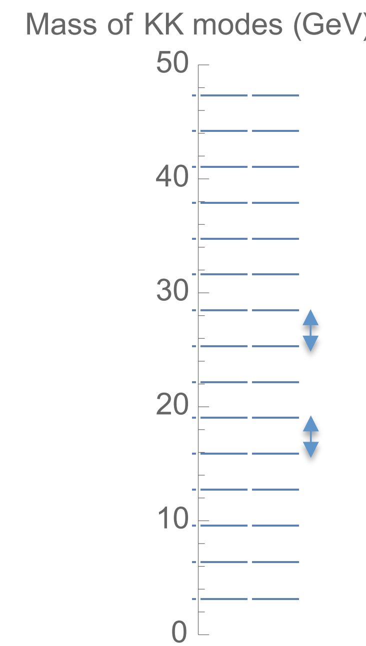
KK Modes → Jetty or SUEPy

$$\psi_n(z) = z^2 A_n J_\nu(m_n \cdot z)$$

$$\int_{z_{UV}}^{z_{IR}} \sqrt{-g}\, |\psi_n(z)|^2 \, dz = 1$$

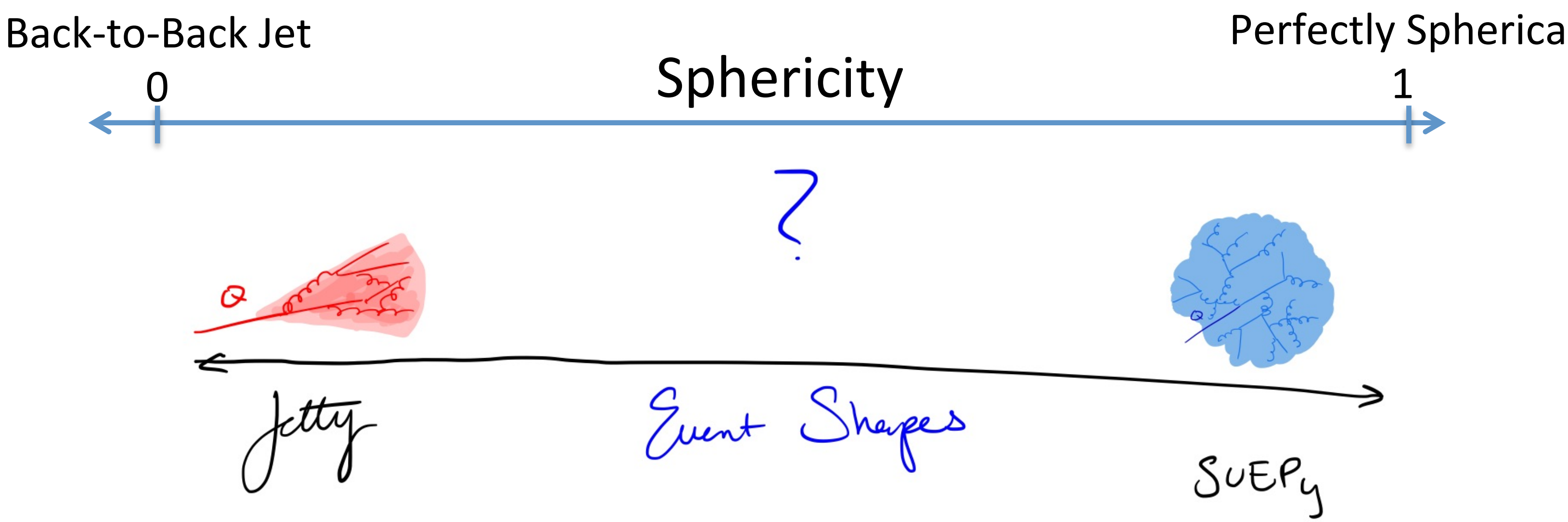


Warped 5D



- Mass spacing ~ linear
- cubic interaction ~ KK number conserving
- Soft decay daughters → SUEPy shape

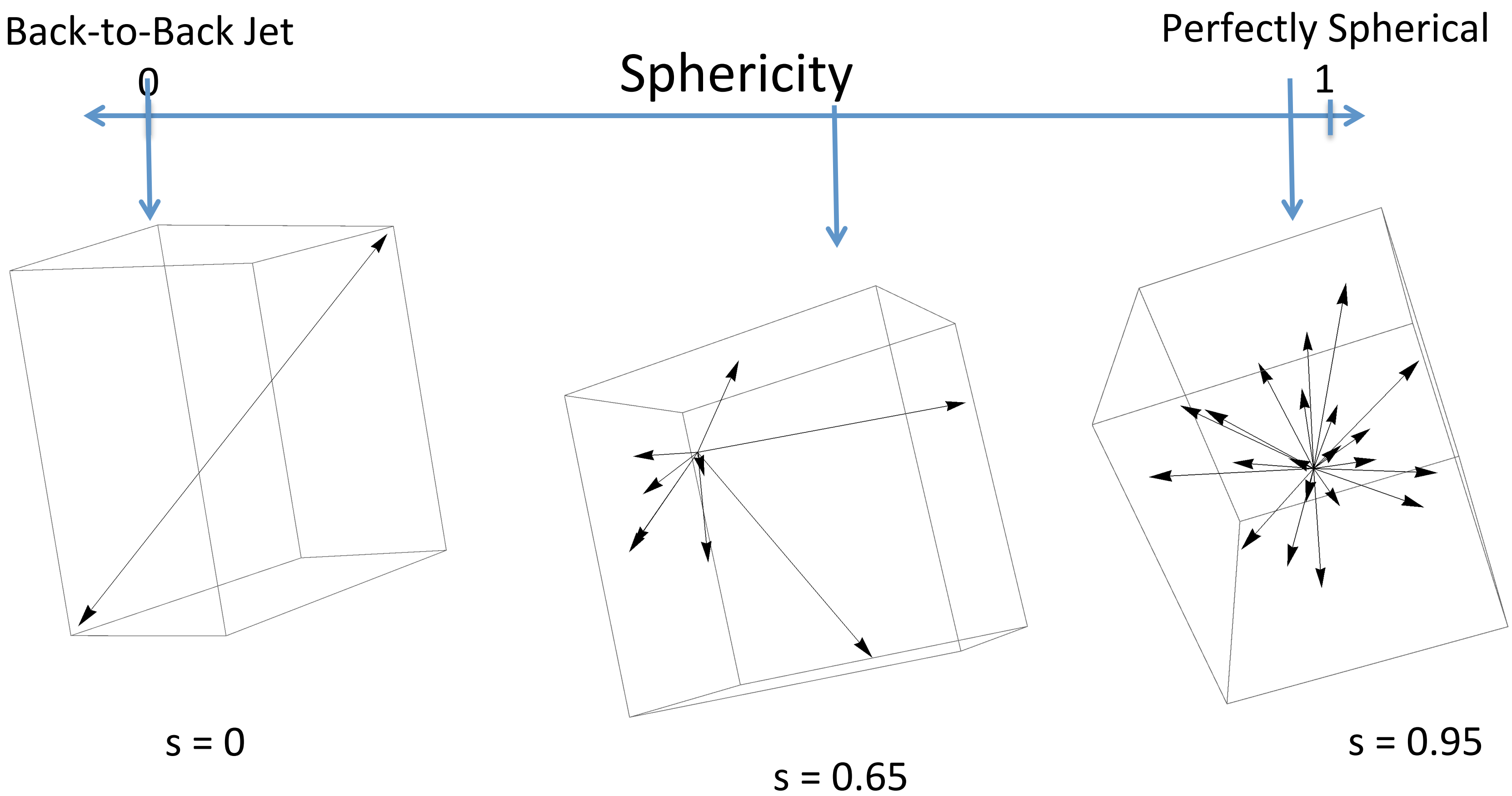
Sphericity of KK Modes



$$S_{ij} = \frac{\sum^{n} p_i^n p_j^n}{|p^n|^2}$$

$$S = \frac{3}{2}(\lambda_1 + \lambda_2)$$

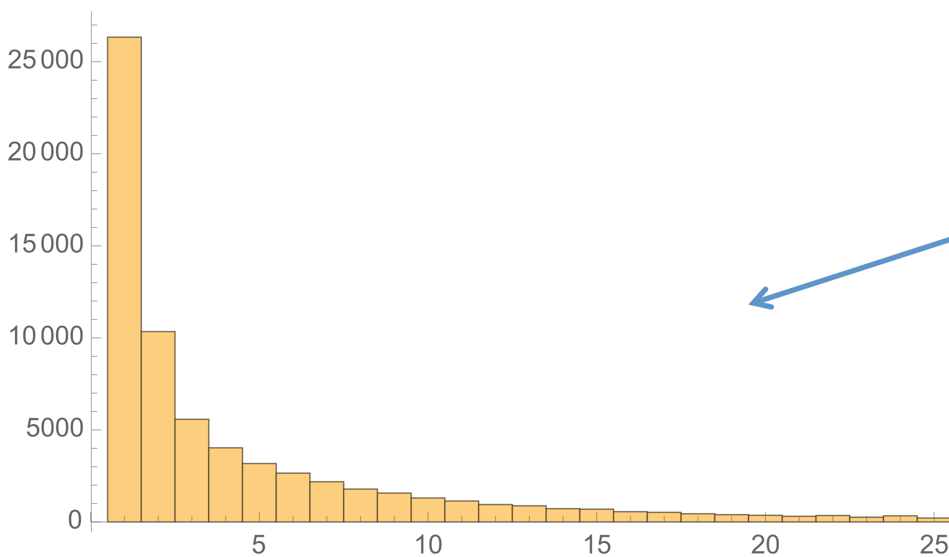
Sphericity of KK Modes



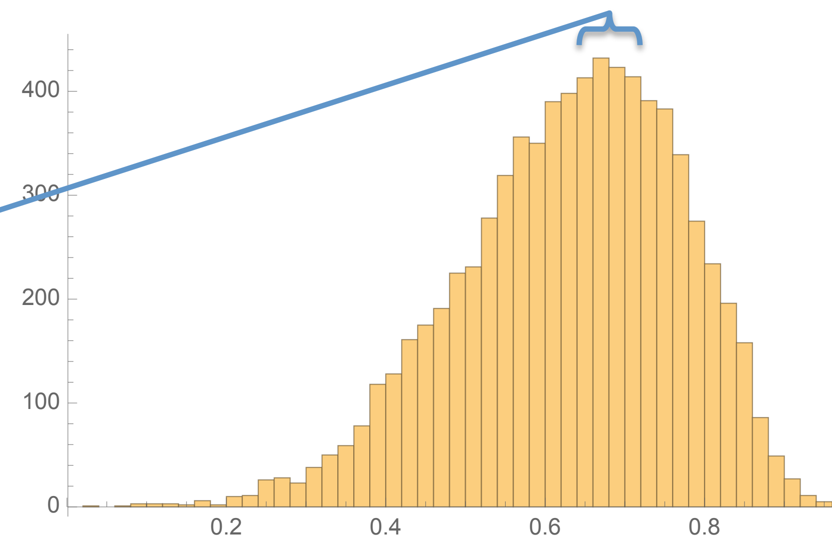
KK Modes – Cubic Interaction

$$\mathcal{L}^{int}_{5} \supset -\frac{g}{3!}\Phi^3$$

7.5×10^3 Trials
Starting at KK # = 50



KK # in decay shower
0.65 < s < 0.75



Sphericity

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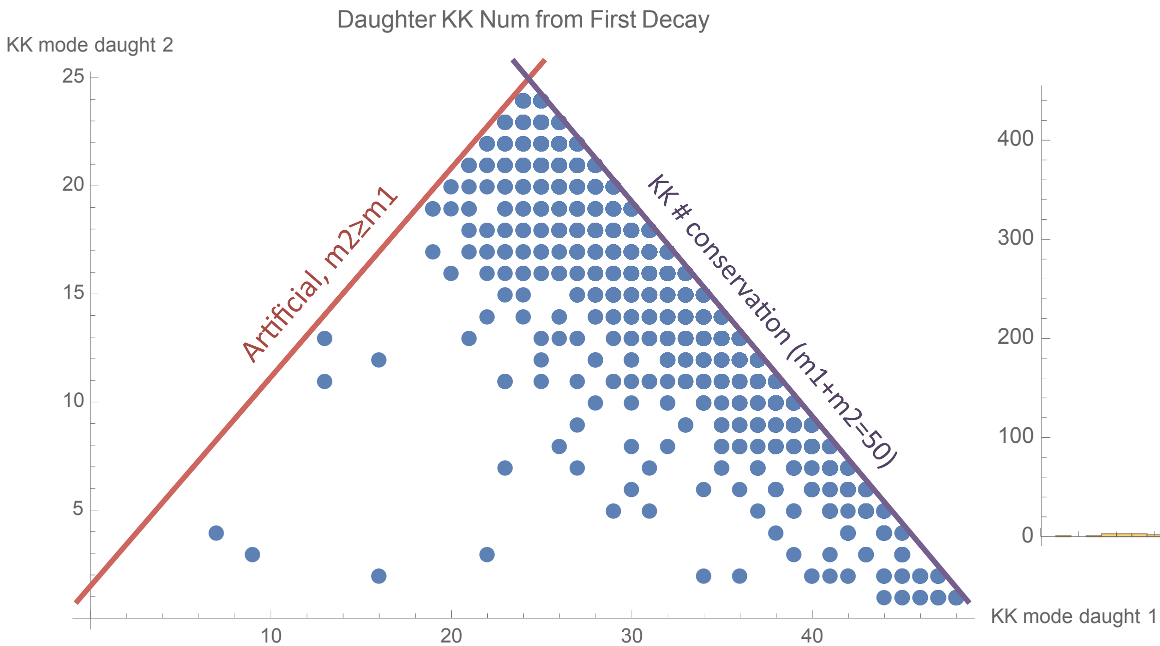
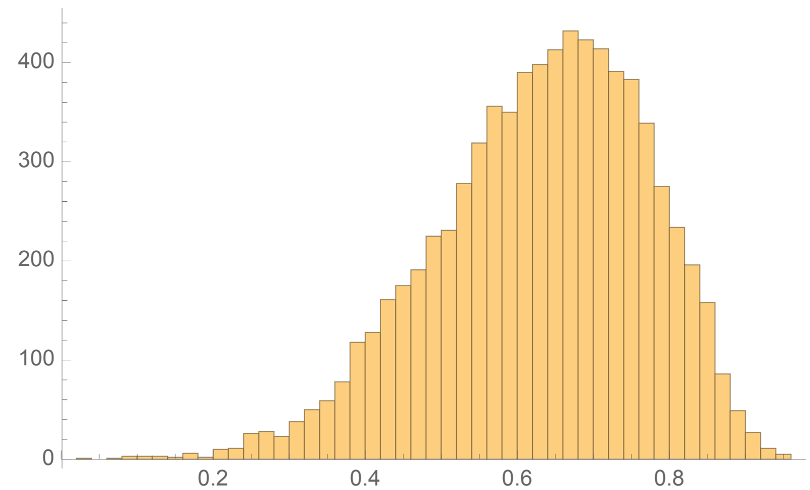
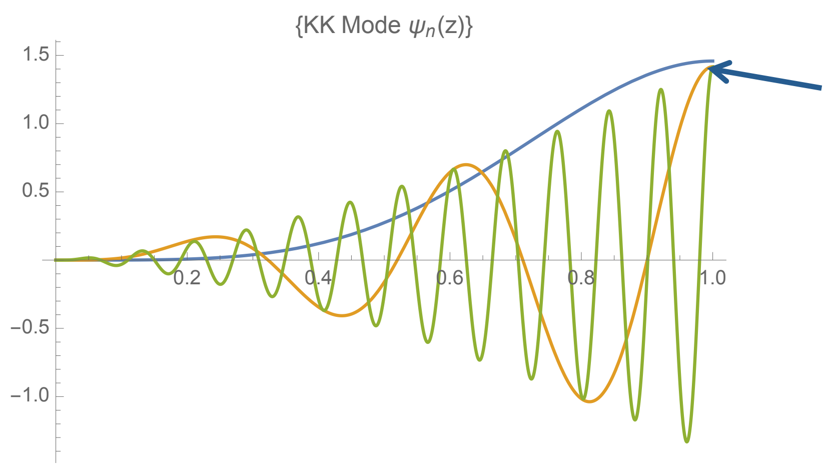




KK number is almost conserved → higher sphericity

KK Modes → Jetty or SUEPy

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

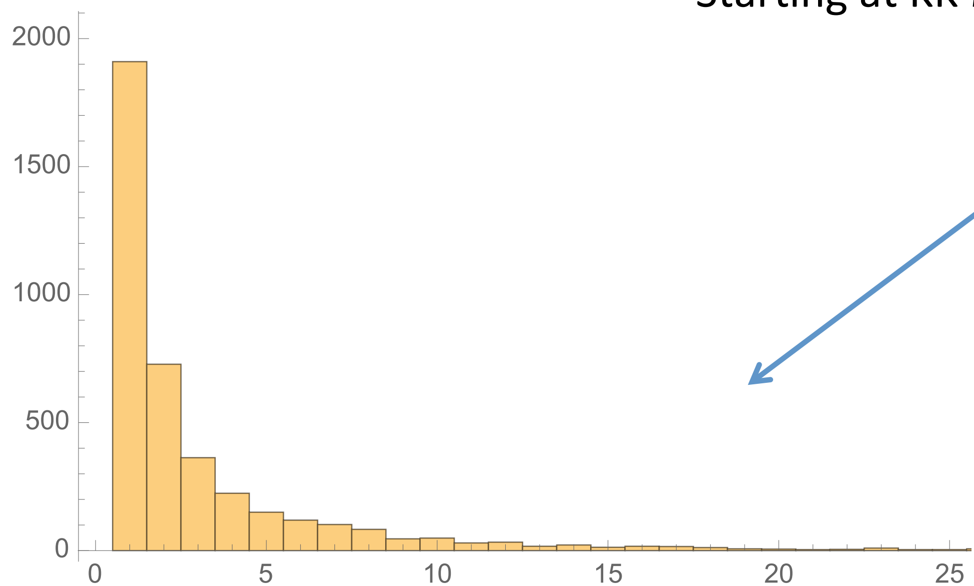


- KK wave functions converge at IR
- Decay widths about equal
- Decay to larger phase space options → Jettier?

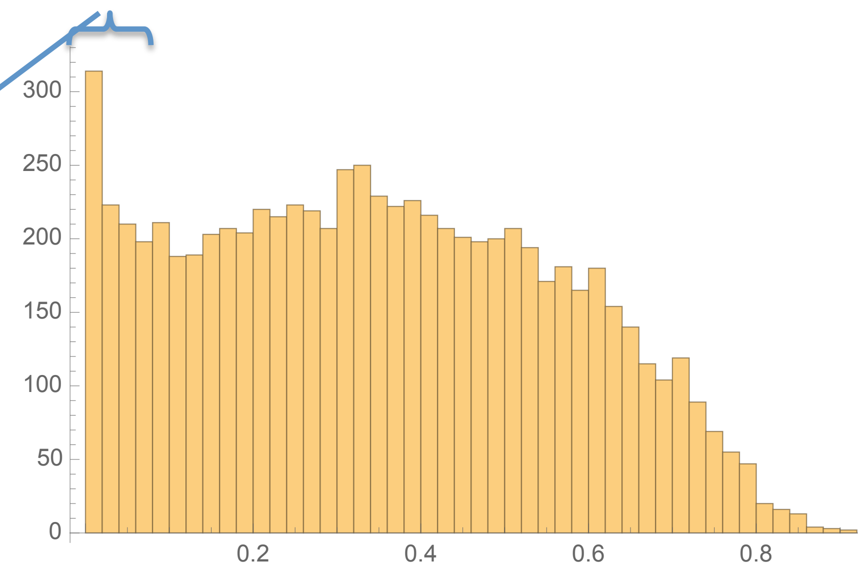
KK Modes – Localized Interaction

$$\mathcal{L}_5^{int} \supset -\frac{g}{3!}\Phi^3\Big|_{z=z_{IR}}$$

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



KK # in decay shower
0 < s < 0.05



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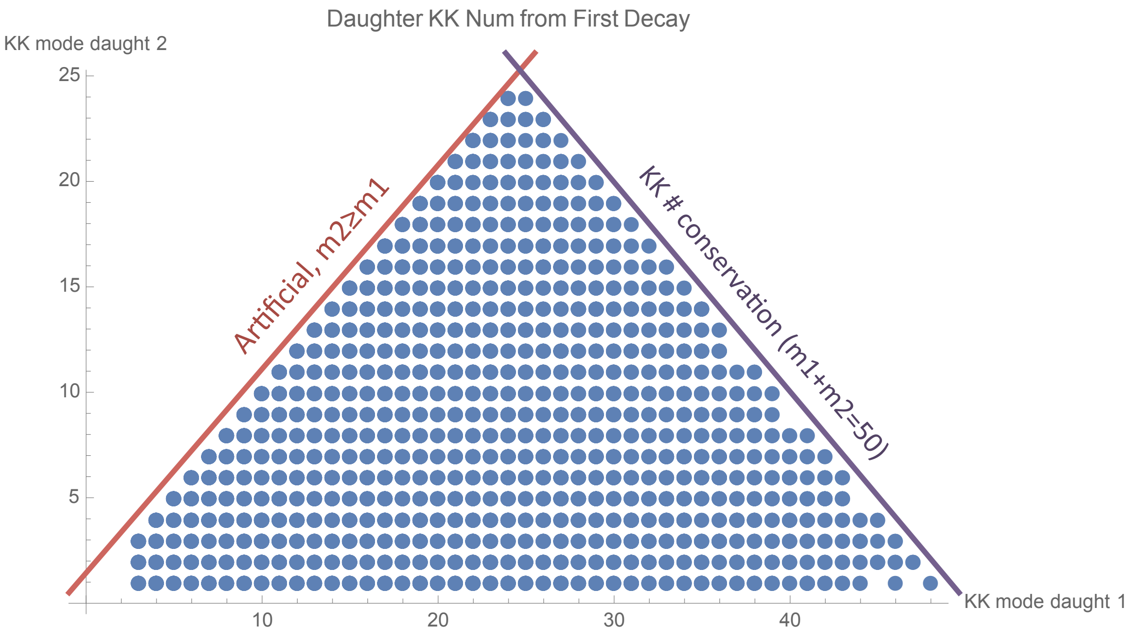
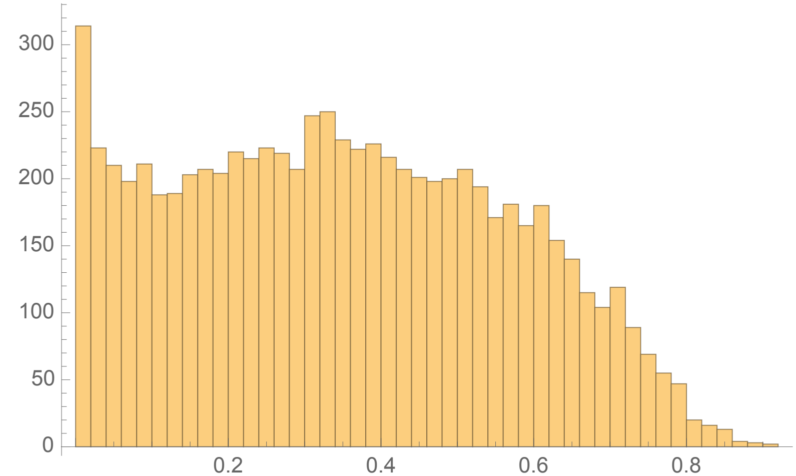




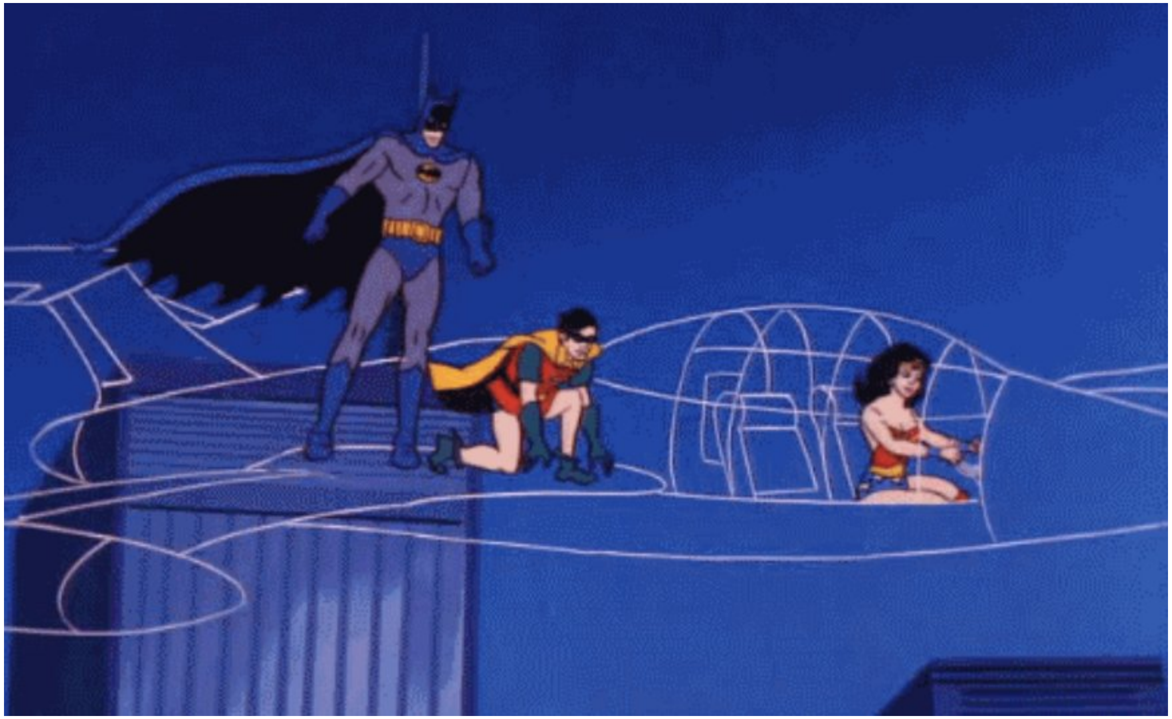
Sphericity

All allowed states are found! → 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

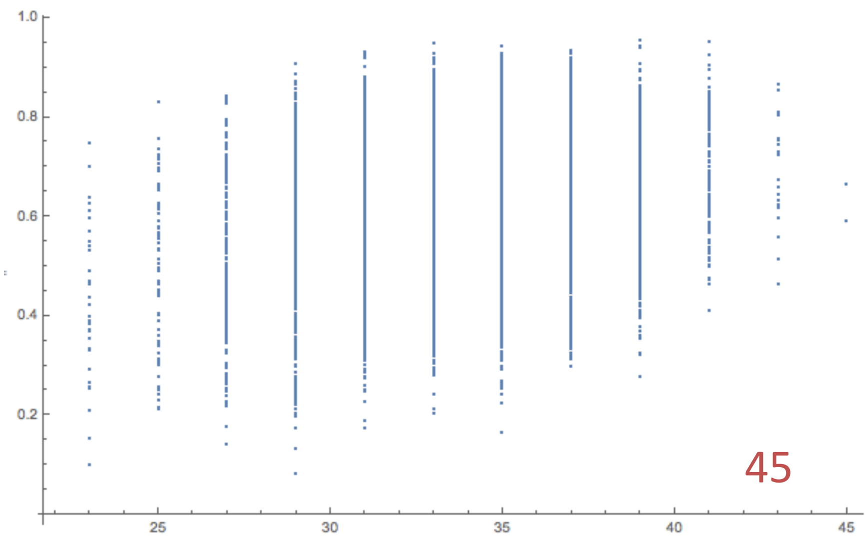
Questions?

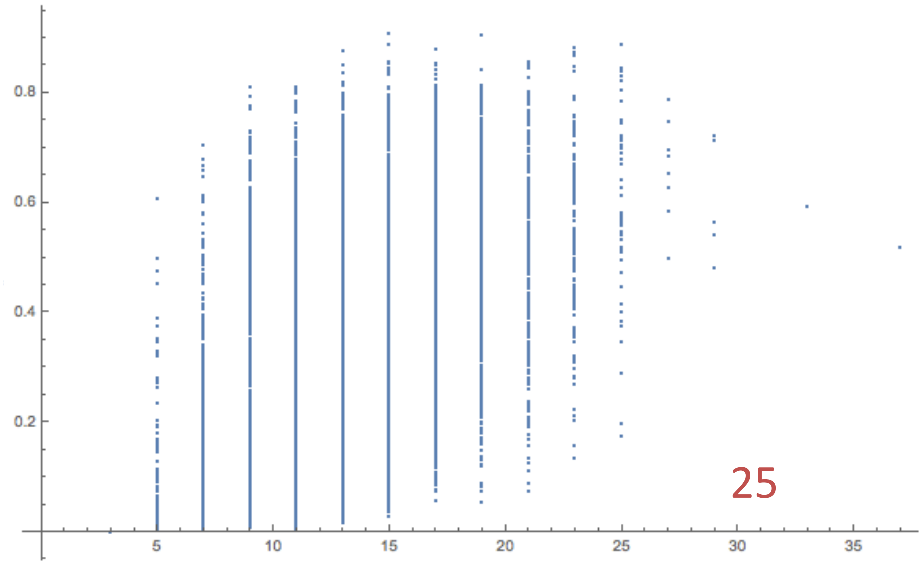


Backups

KK Modes – Multiplicity?

Sphericity





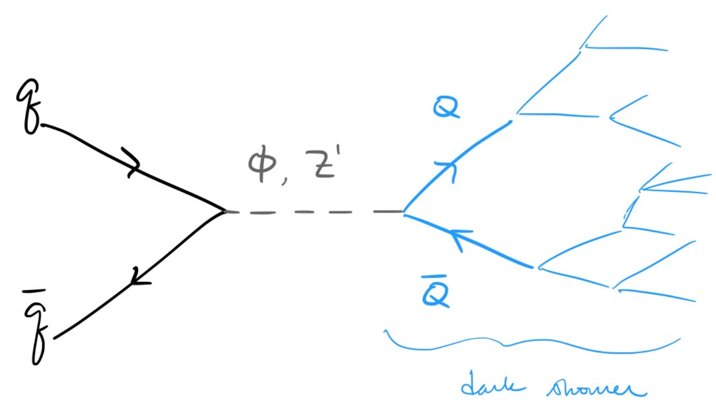
$$\mathcal{L}_5^{int} \supset -\frac{g}{3!}\Phi^3$$

$$\mathcal{L}_5^{int} \supset -\frac{g}{3!}\Phi^3 \Big|_{z=z_{IR}}$$

Particles in Shower

Dark Showers

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



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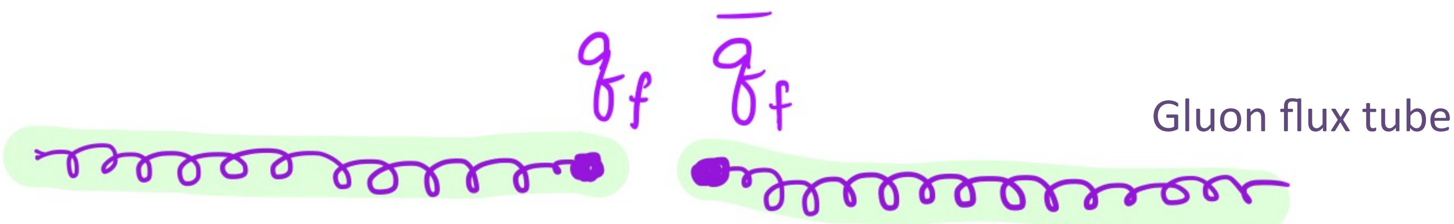
Dark Hadrons?

- QCD is very special
- Color neutral final states →reorganization
- To Consider:
  - $p^{\mu}_{parton} \sim p^{\mu}_{jet}$
  - hadrons



$$\text{Rate: } N_f \alpha \simeq \frac{N_f}{N_c}$$

For SM QCD, $N_f = N_c = 3$

AdS / CFT

- AdS_5 x X_5
- 10D masses → compactify to 5D masses
- Fewer dimensions → denser mass states
- More bulk scalar fields → closer to confining theory