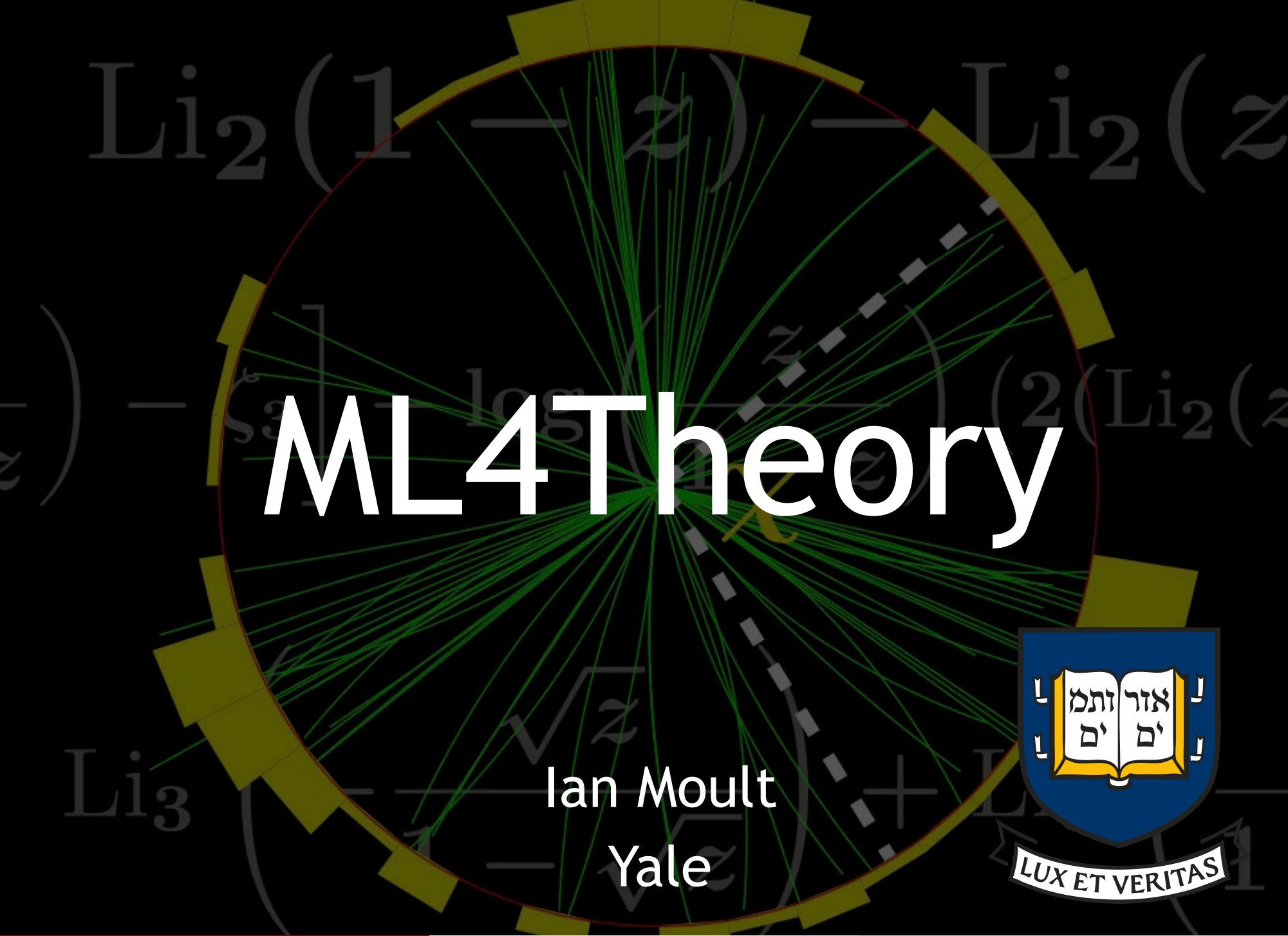


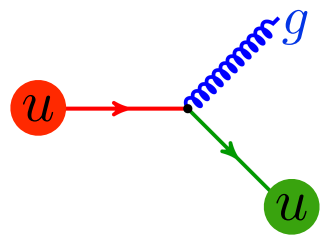
ML4Theory

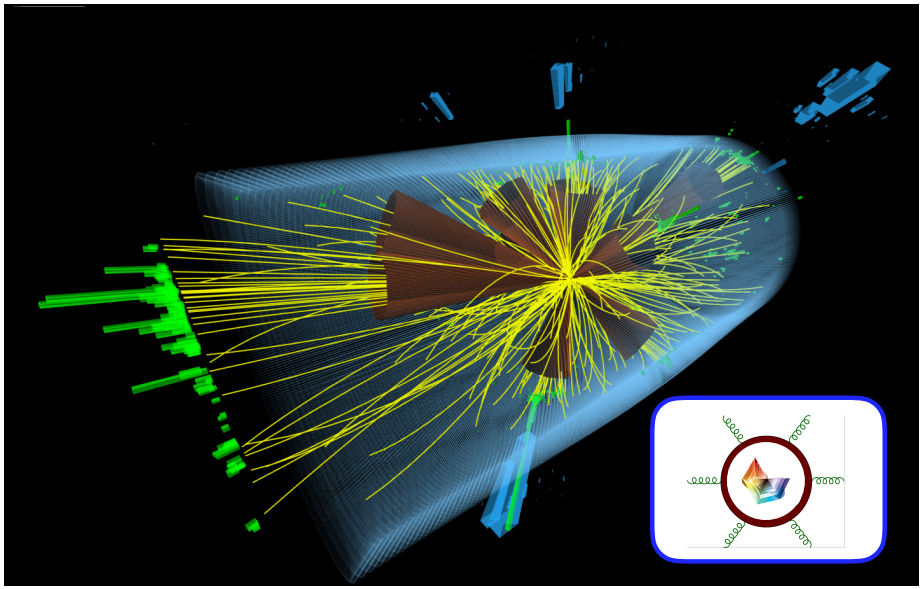
Ian Moult
Yale

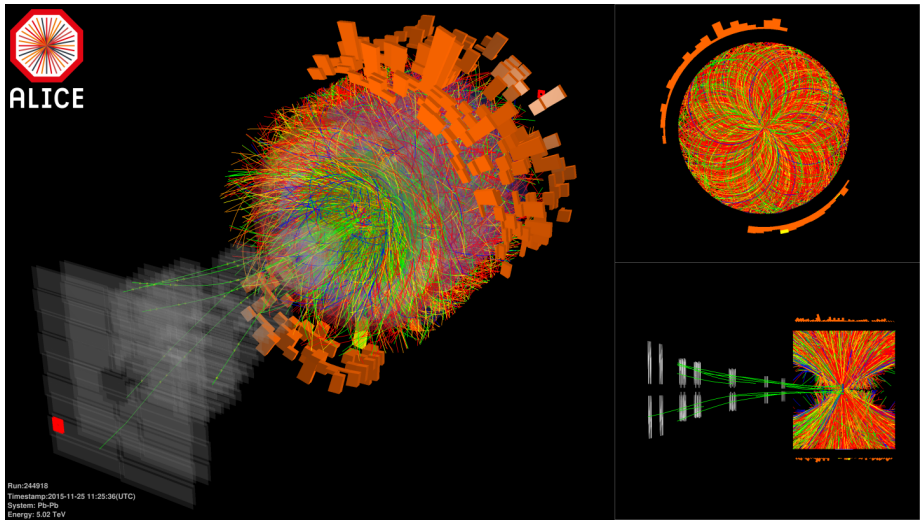
Particle Colliders

- Particle colliders provide one of the most spectacular examples of a simple underlying theory producing remarkably complicated data sets.

$$\mathcal{L}_{\text{QCD}} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu a} + \sum_f \bar{q}_f (i \not{D} - m_f) q_f$$



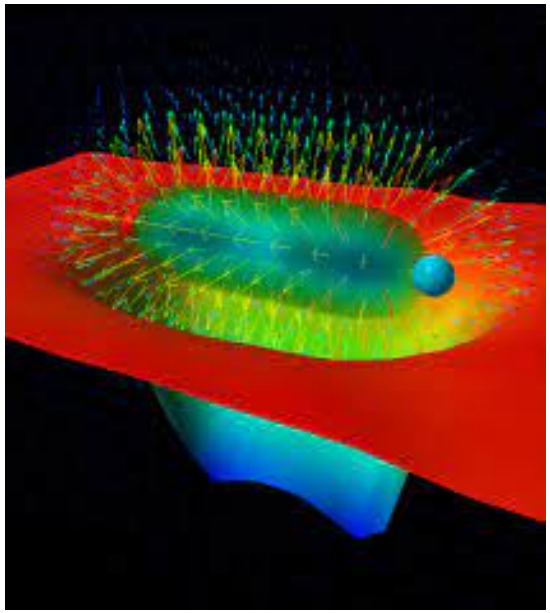


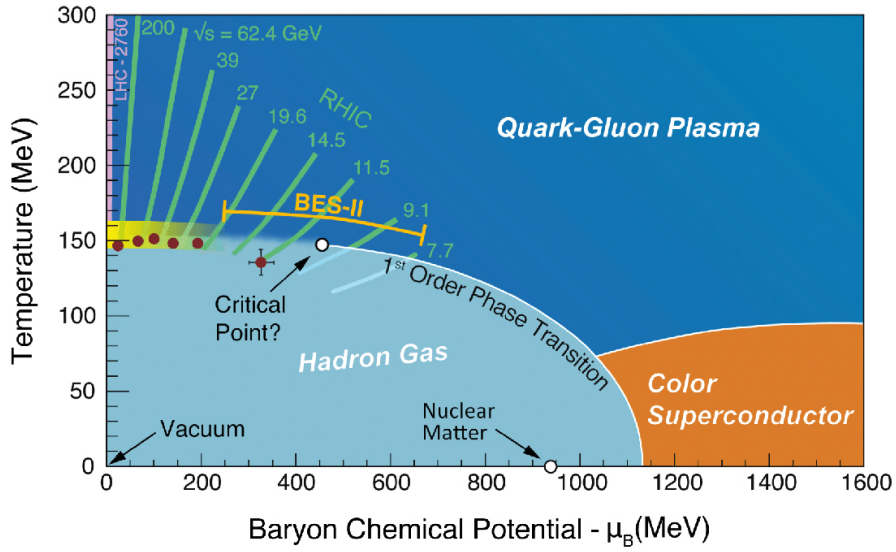


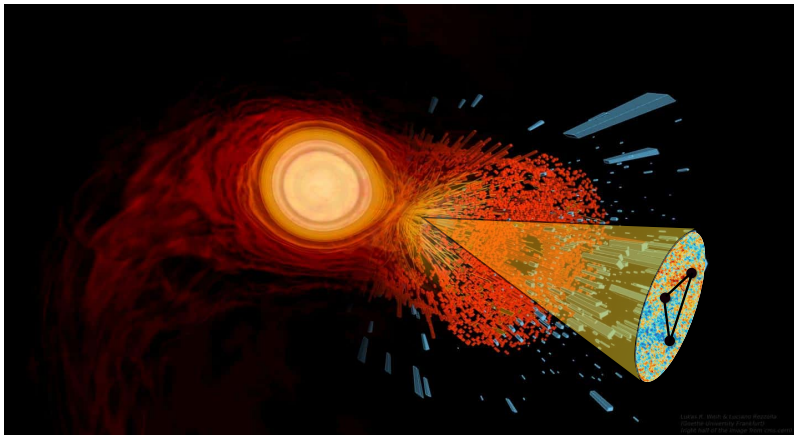
- Provide a unique opportunity to learn about relativistic QFTs in general, and QCD in particular.

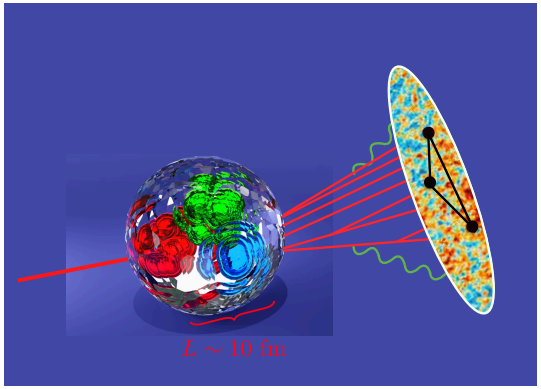
A Laboratory for Quantum Field Theory

- In addition to searches for new physics, the answers to much more subtle questions are imprinted in collider energy flux:



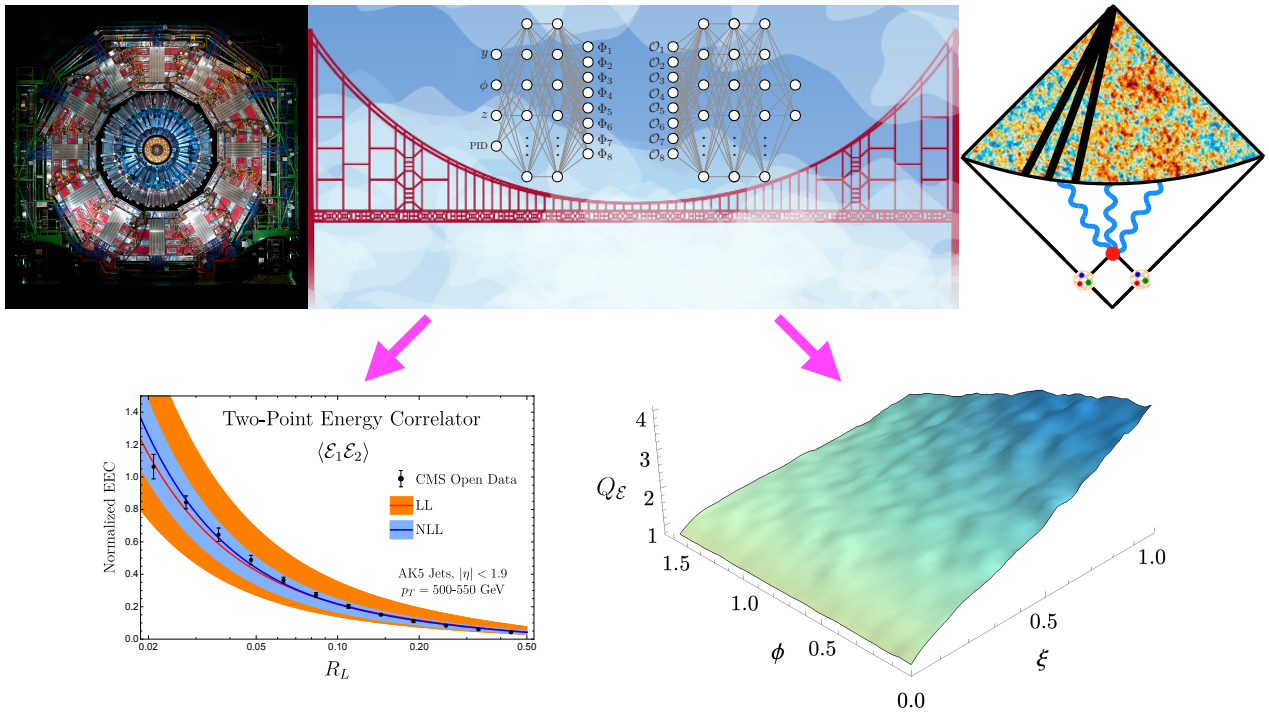






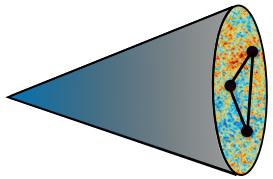
Formal Theory Progress

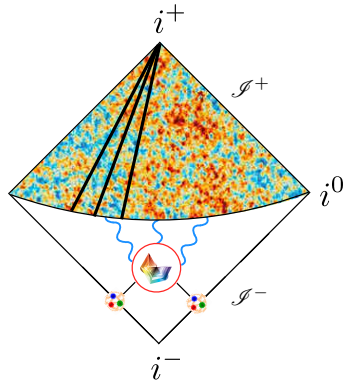
- Recent progress in formal Quantum Field Theory has provided powerful new jet observables and ways to relate them to the parameters of the underlying theory.
- Remarkably, their introduction coincides with the introduction of powerful new ML based analysis techniques, required for their experimental study.

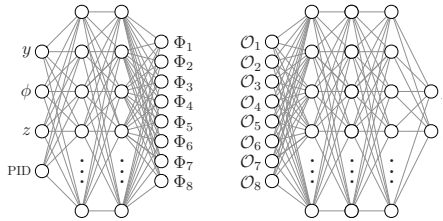


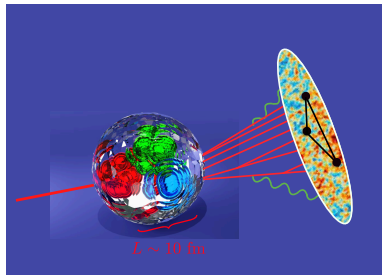
Outline

- Rethinking Jets
- Field Theoretic Foundations
- ML4Theory
- The Frontiers of Jet Physics

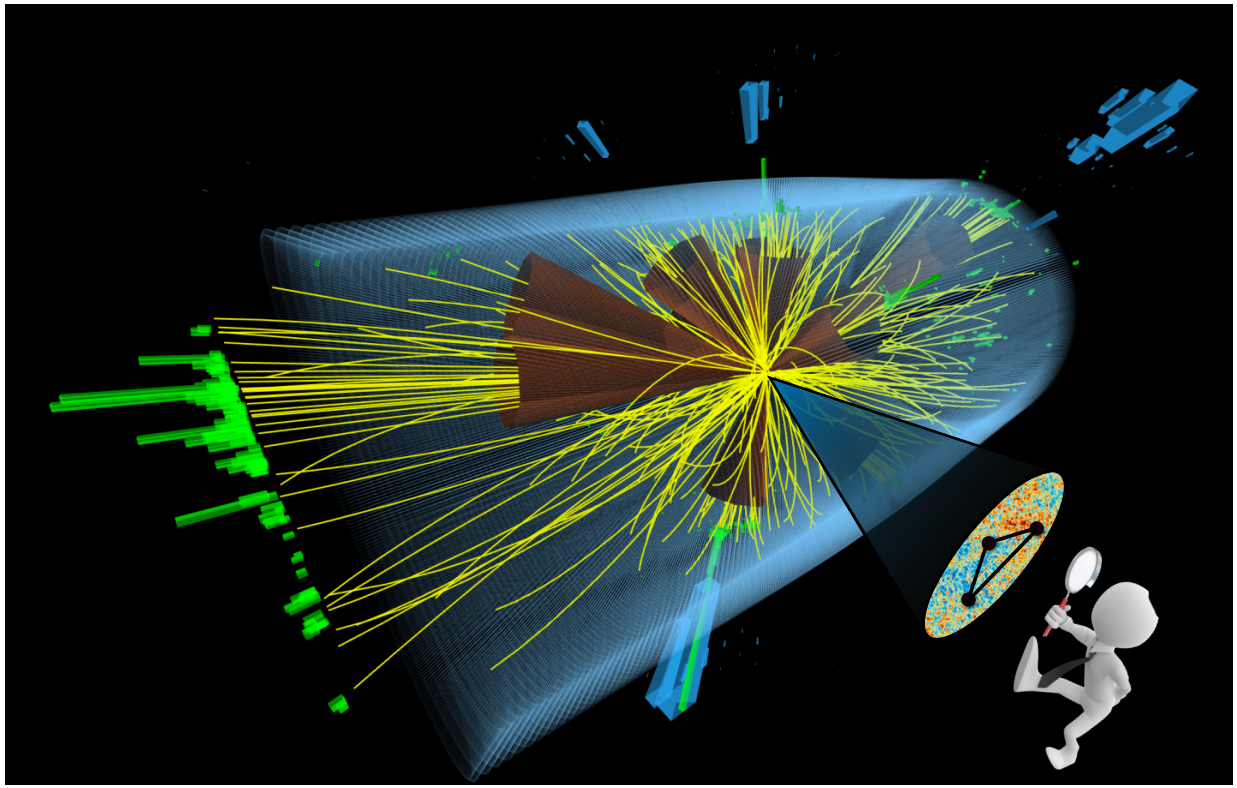




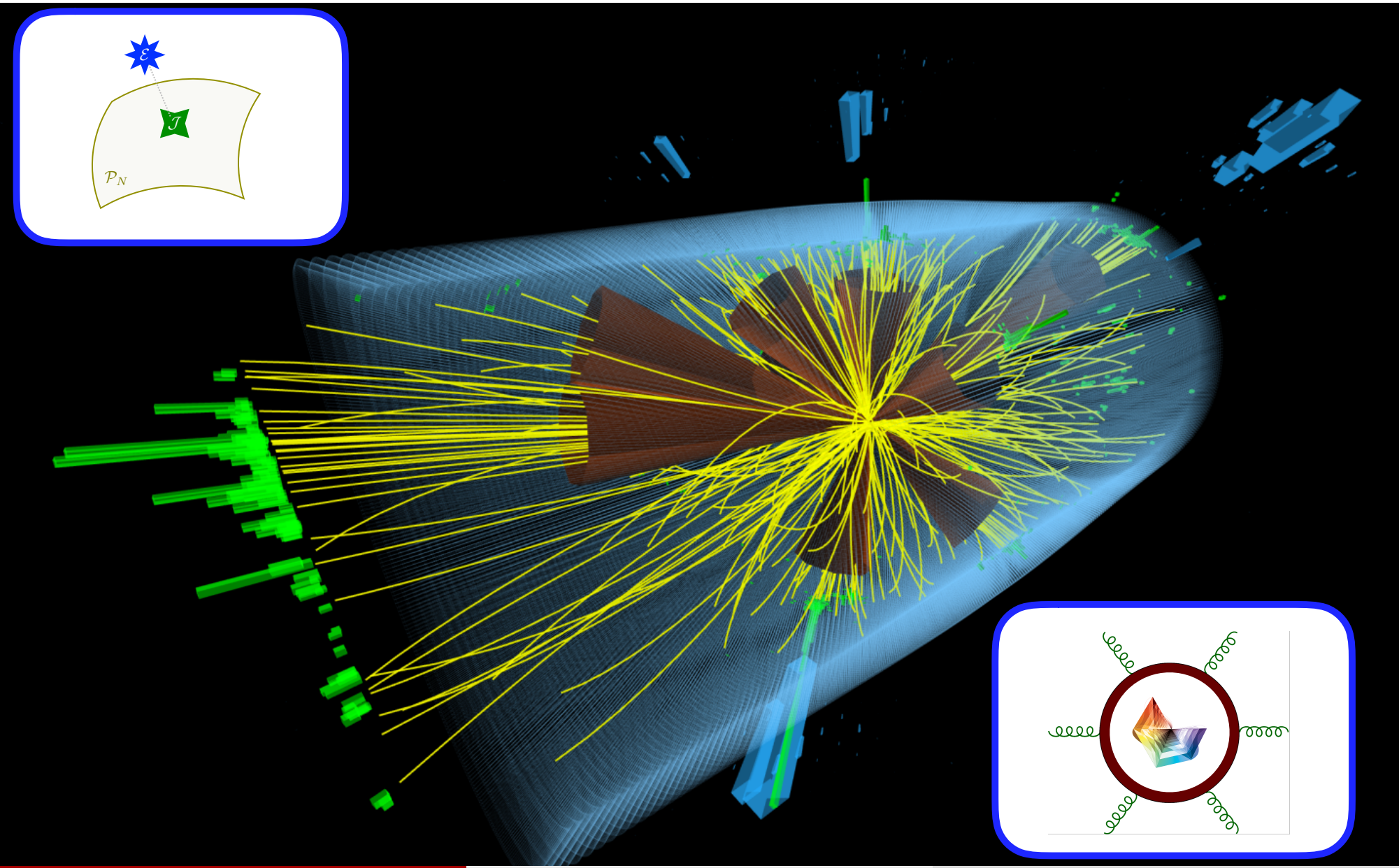




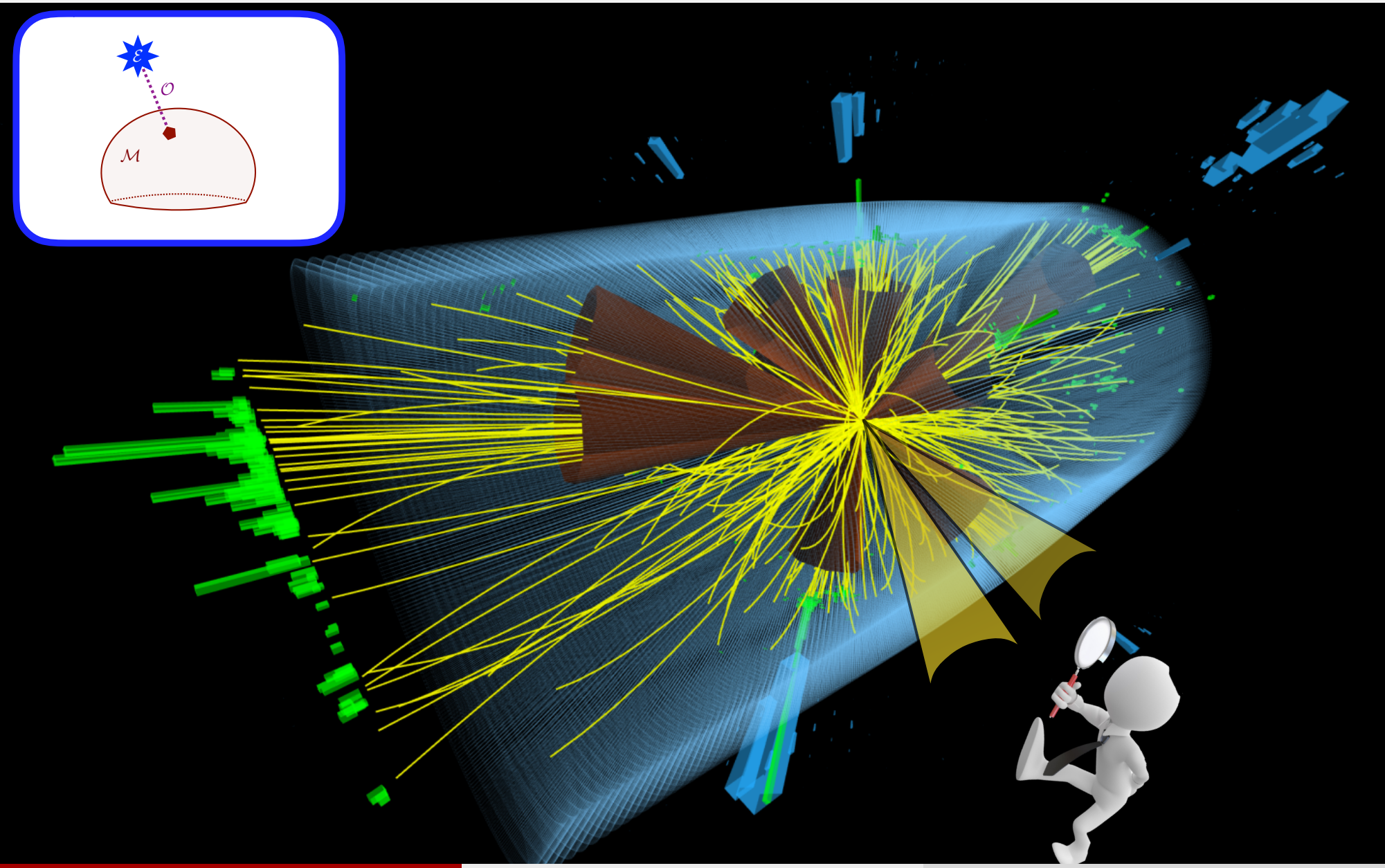
Rethinking Jet Substructure



Jets at the LHC

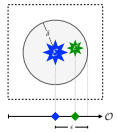
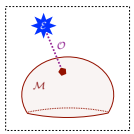
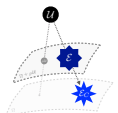


Jet Substructure at the LHC

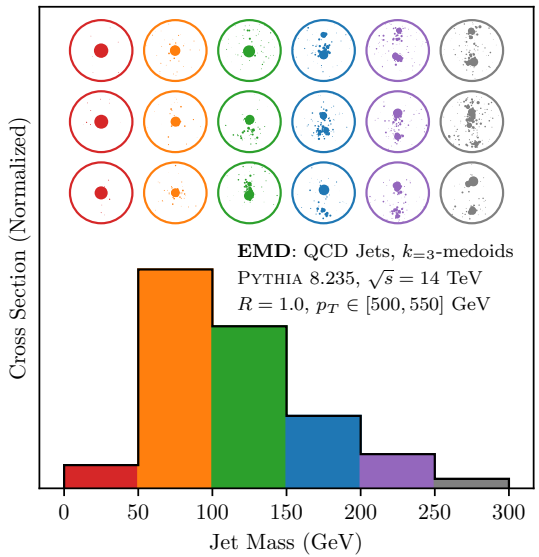


The Jet Shape Paradigm

- This approach of projecting events to lower dimensional manifolds has dominated our thinking about jets for 50 years.

Infrared and Collinear Safety [27–39]	$\mathrm{EMD}(\mathcal{E},\mathcal{E}') < \delta \implies$ $\lvert\mathcal{O}(\mathcal{E}) - \mathcal{O}(\mathcal{E}')\rvert < \epsilon$	
Observables Event Shapes [40–45] Jet Shapes [46–48]	$\mathcal{O}(\mathcal{E}) = \min_{\mathcal{E}'\in\mathcal{M}} \mathrm{EMD}(\mathcal{E},\mathcal{E}')$	
Jets Cone Finding [49, 50] Seq. Rec. [51–54]	$\mathcal{J}(\mathcal{E}) = \arg\min_{\mathcal{J}\in\mathcal{P}_N} \mathrm{EMD}(\mathcal{E},\mathcal{J})$	
Pileup Subtraction [55–61]	$\mathcal{E}_C(\mathcal{E},\rho) = \arg\min_{\mathcal{E}'\in\Omega} \mathrm{EMD}(\mathcal{E},\mathcal{E}' + \rho\mathcal{U})$	

Jet Mass



- Dates back to the introduction of "thrust" by Farhi in 1977.

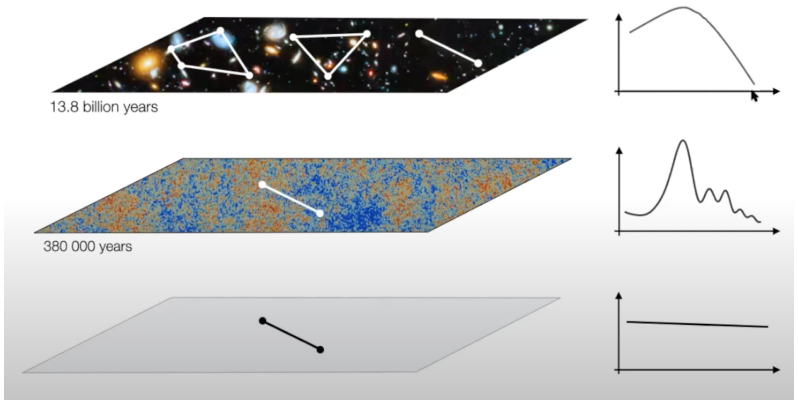
Disrupting the Jet Shape Paradigm

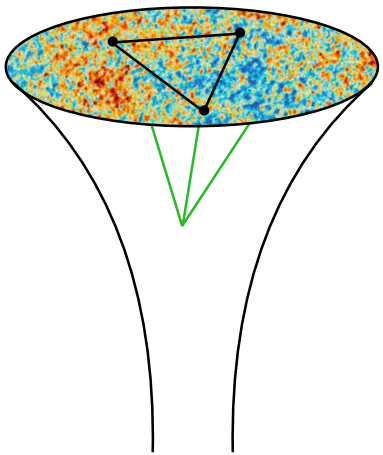
- Machine Learning is supposed to be a disruptive technology.
- It has fundamentally changed the way we think about many aspects of our lives.

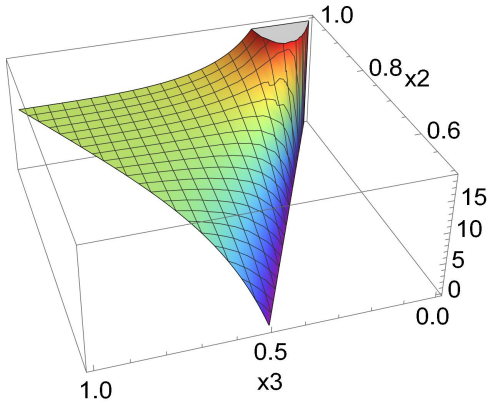
- It is therefore interesting to ask the following question:
  If one had arbitrarily good experimental and data analysis capabilities, how would one talk theoretically about jets?
- Perhaps surprisingly, it is completely differently from what is currently done!

Correlation Functions

- In other areas of physics, one studies statistical correlations (correlation functions) on the full unprojected dataset.
- e.g. Non-Gaussianities allow one to distinguish models of inflation.
- These are the natural theoretical objects associated with the underlying field theory.



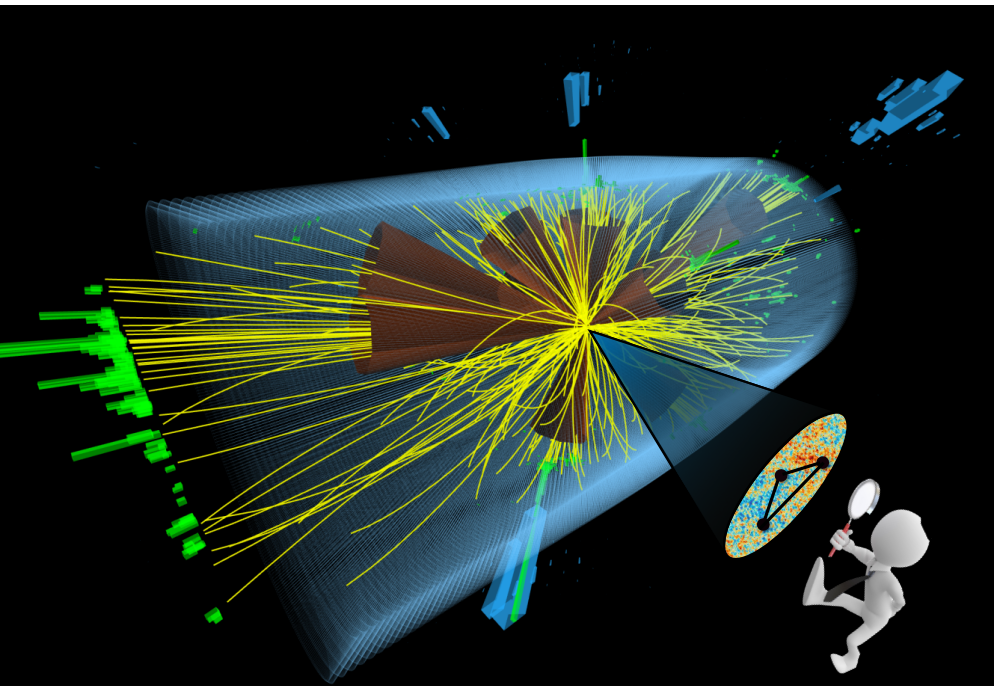


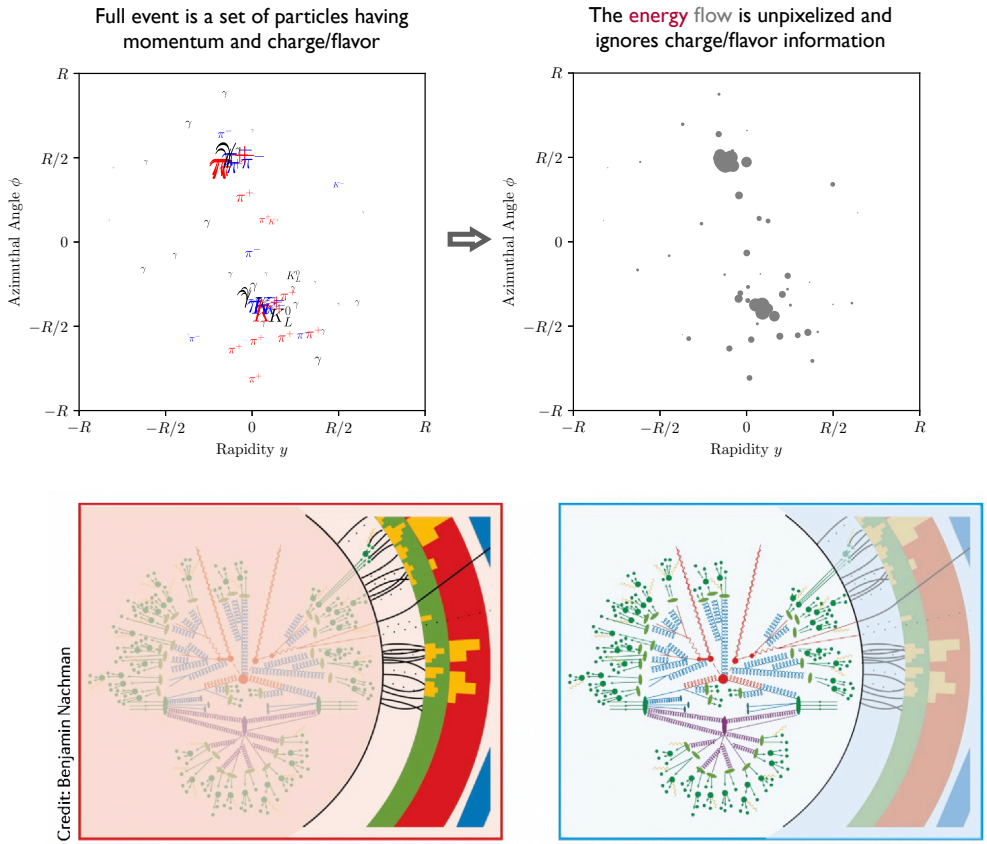


- Why don't we study non-gaussianities of energy flux?

Rethinking Jet Substructure

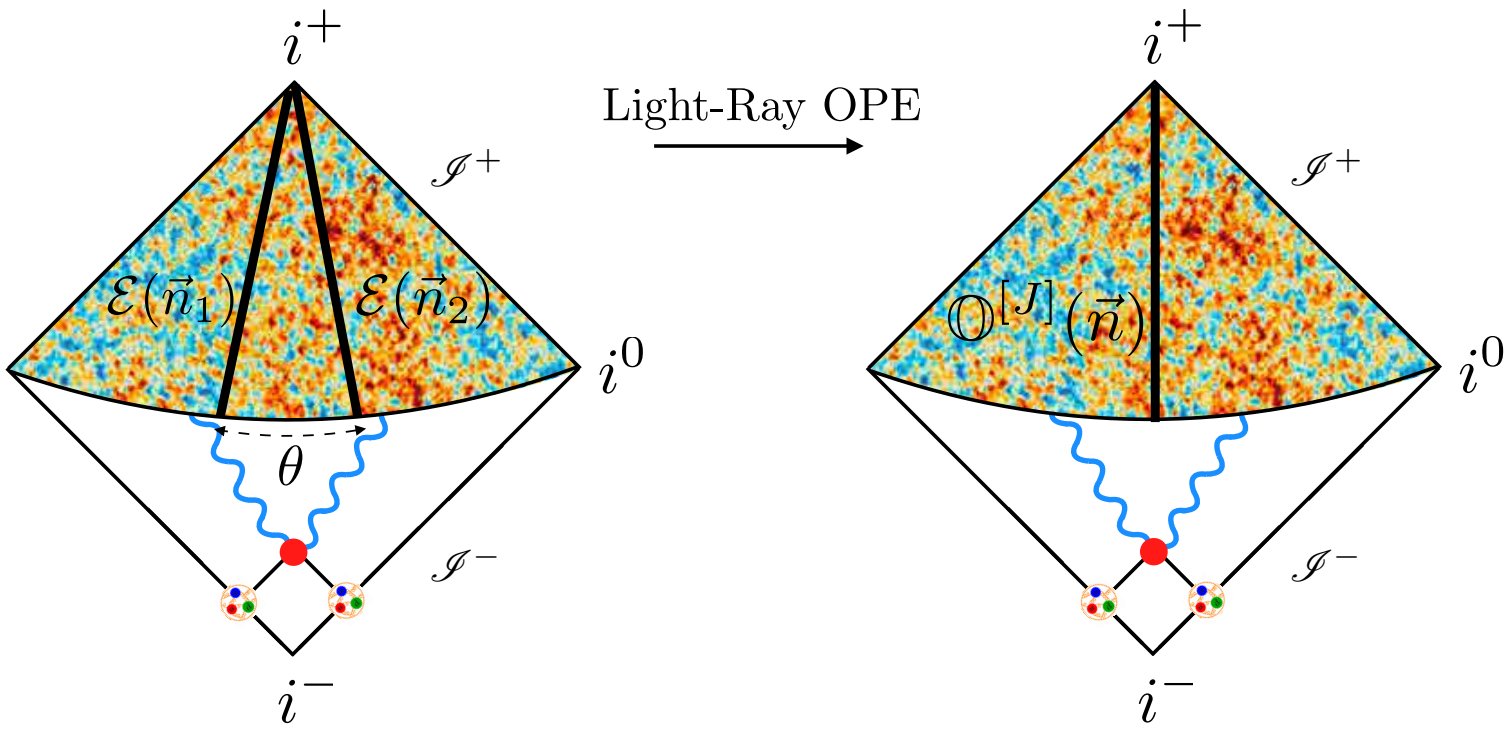
- Why don't we study statistical properties (correlation functions) on the full phase space of collider events?





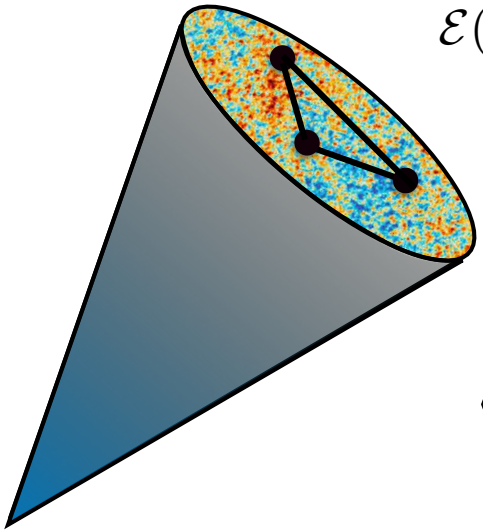
- Lets imagine that we could, and see where it gets us.

The Field Theoretic Foundations of Jet Substructure



Formal Theory to the Rescue

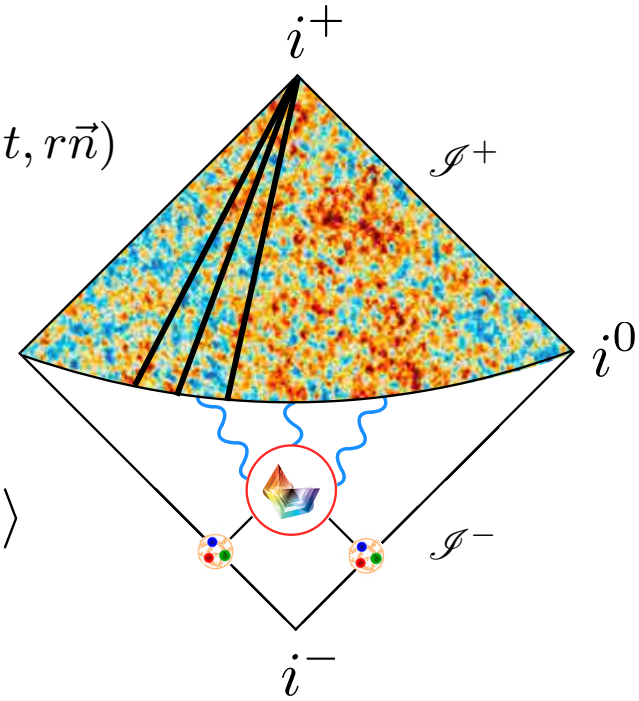
- Calorimeter cells can be given a field theoretic definition in terms of light-ray operators. [Hofman, Maldacena] [Korchemsky, Sterman] [Ore, Sterman]



$$\mathcal{E}(\vec{n}) = \lim_{r\to\infty} r^2 \int_0^\infty dt n^i T_{0i}(t, r\vec{n})$$

$$\langle \Psi | \mathcal{E}(\hat{n}_1) \cdots \mathcal{E}(\hat{n}_k) | \Psi \rangle$$

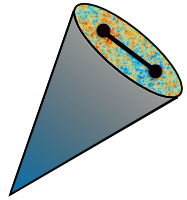
[Figure from DSD]



- From the perspective of QFT, jet substructure is the study of correlation functions of energy flow operators.

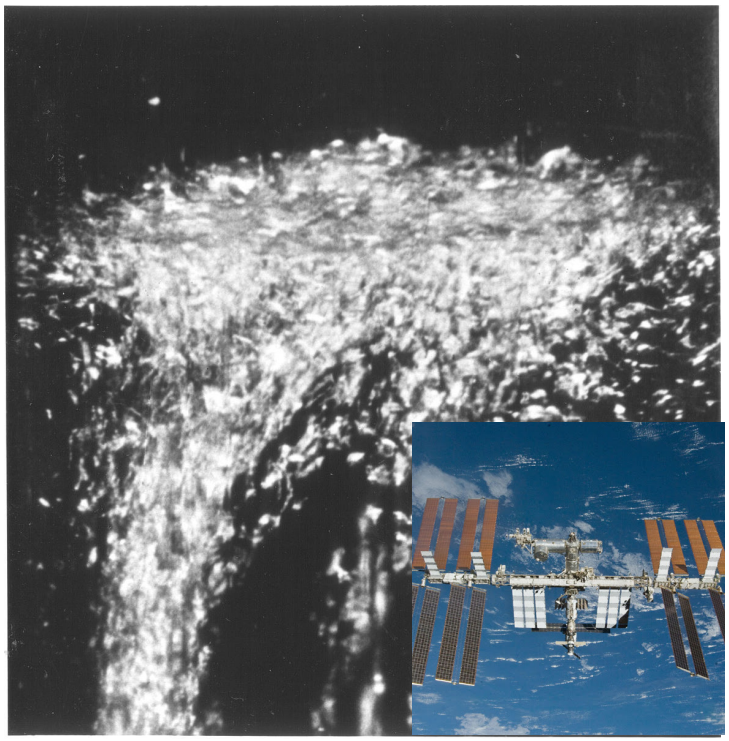
Scaling Behavior in QFT

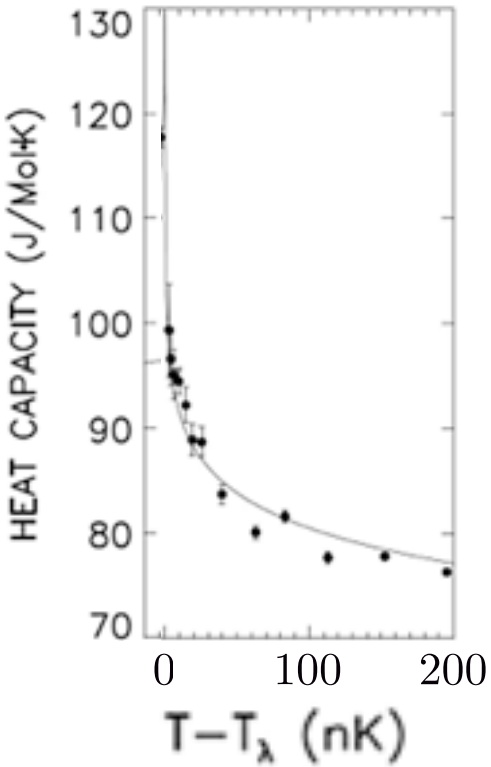
- Why is jet substructure theoretically interesting?



- QFTs exhibit universal behavior as operators are brought together.

λ-point of Helium

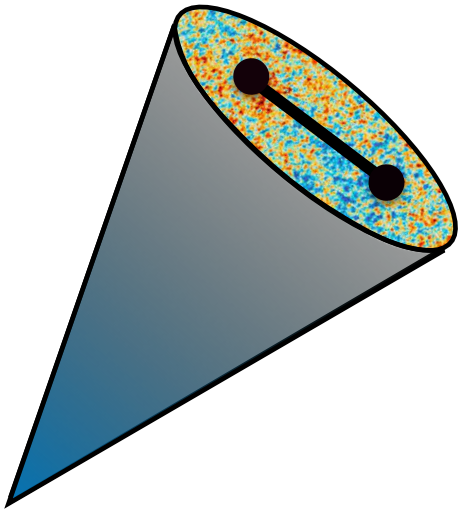


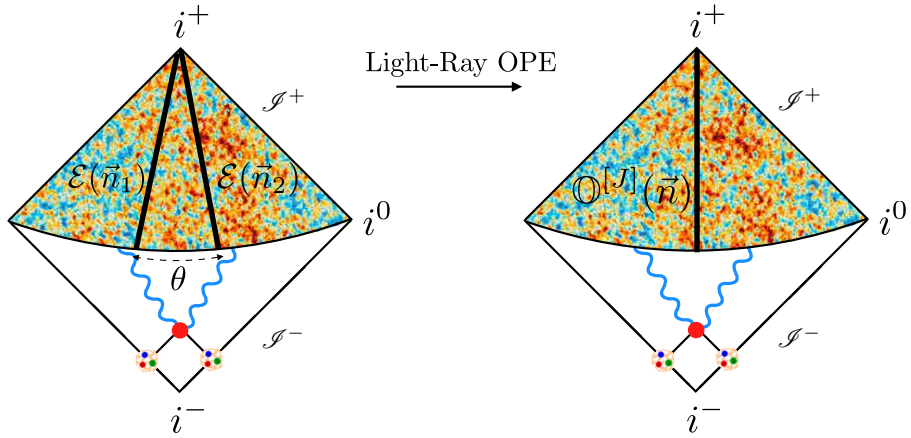


$$\mathcal{O}(x)\mathcal{O}(0) = \sum x^{\gamma_i} c_i \mathcal{O}_i$$

Jet Substructure as Scaling Behavior

- Energy flow operators also admit an OPE!
- The substructure of jets is determined by the OPE structure of lightray operators.





$$\mathcal{E}(\hat{n}_1)\mathcal{E}(\hat{n}_2) \sim \sum \theta^{\tau_i - 4}\mathbb{O}_i(\hat{n}_1)$$

[Hofman, Maldacena]
[Chang, Kologlu, Kravchuk, Simmons Duffin, Zhiboedov]
[See Also: Konishi, Ukawa, Veneziano]

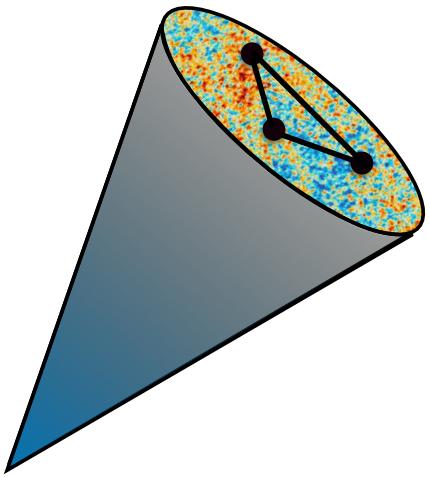
- Allows a reformulation of jet substructure as the study of the symmetry and OPE structure of these operators.

Non-Gaussianities of Energy Flux

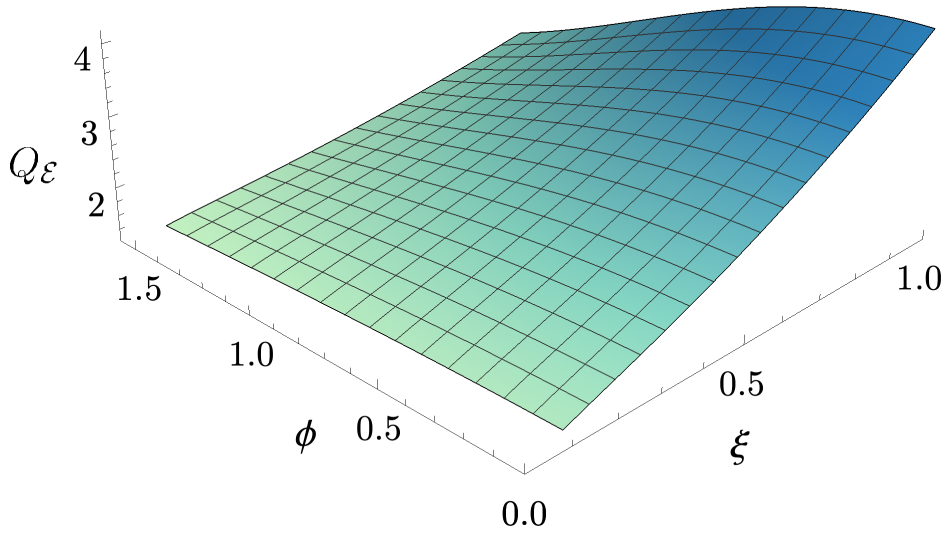
- Non-gaussianities of energy flux have beautiful theoretical structure, encoding details of the interactions of the underlying theory!

[Chen, Luo, Moult, Yang, Zhang, Zhu]

$$
\begin{aligned}
G_{\mathcal{N}=4}(z) &= \frac{1+u+v}{2uv}(1+\zeta_2) - \frac{1+v}{2uv}\log(u) - \frac{1+u}{2uv}\log(v) \\
&- (1+u+v)(\partial_u+\partial_v)\Phi(z) + \frac{(1+u^2+v^2)}{2uv}\Phi(z) + \frac{(z-\bar{z})^2(u+v+u^2+v^2+u^2v+uv^2)}{4u^2v^2}\Phi(z) \\
&+ \frac{(u-1)(u+1)}{2uv^2}D_2^+(z) + \frac{(v-1)(v+1)}{2u^2v}D_2^+(1-z) + \frac{(u-v)(u+v)}{2uv}D_2^+\left(\frac{z}{z-1}\right)
\end{aligned}
$$

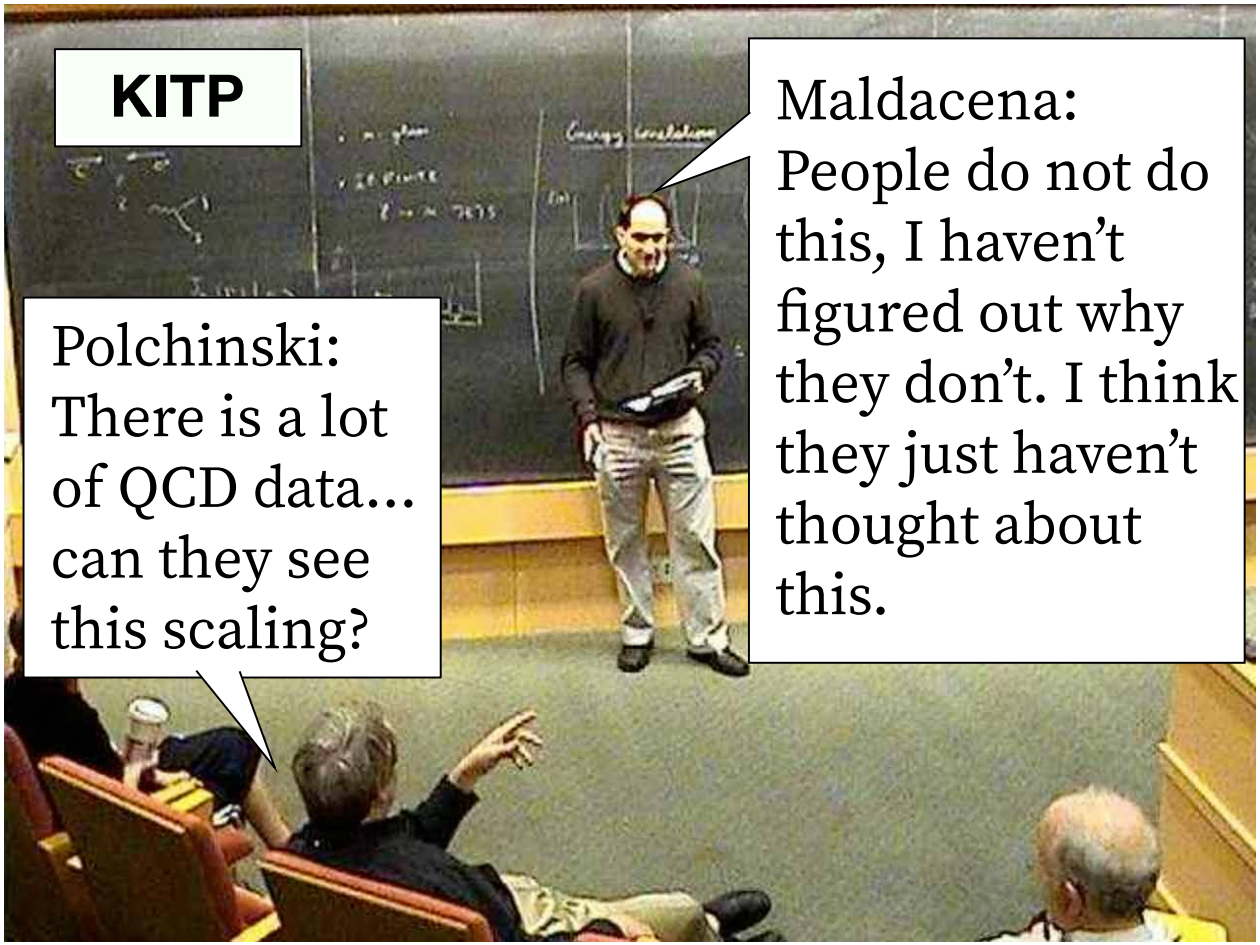


LL + LO prediction, $R_L = 0.35$



Theory-Experiment Gap

- The extraordinary complexity of the LHC dataset, has produced a gap between what theorists want, and what can be measured.



*Exact transcription

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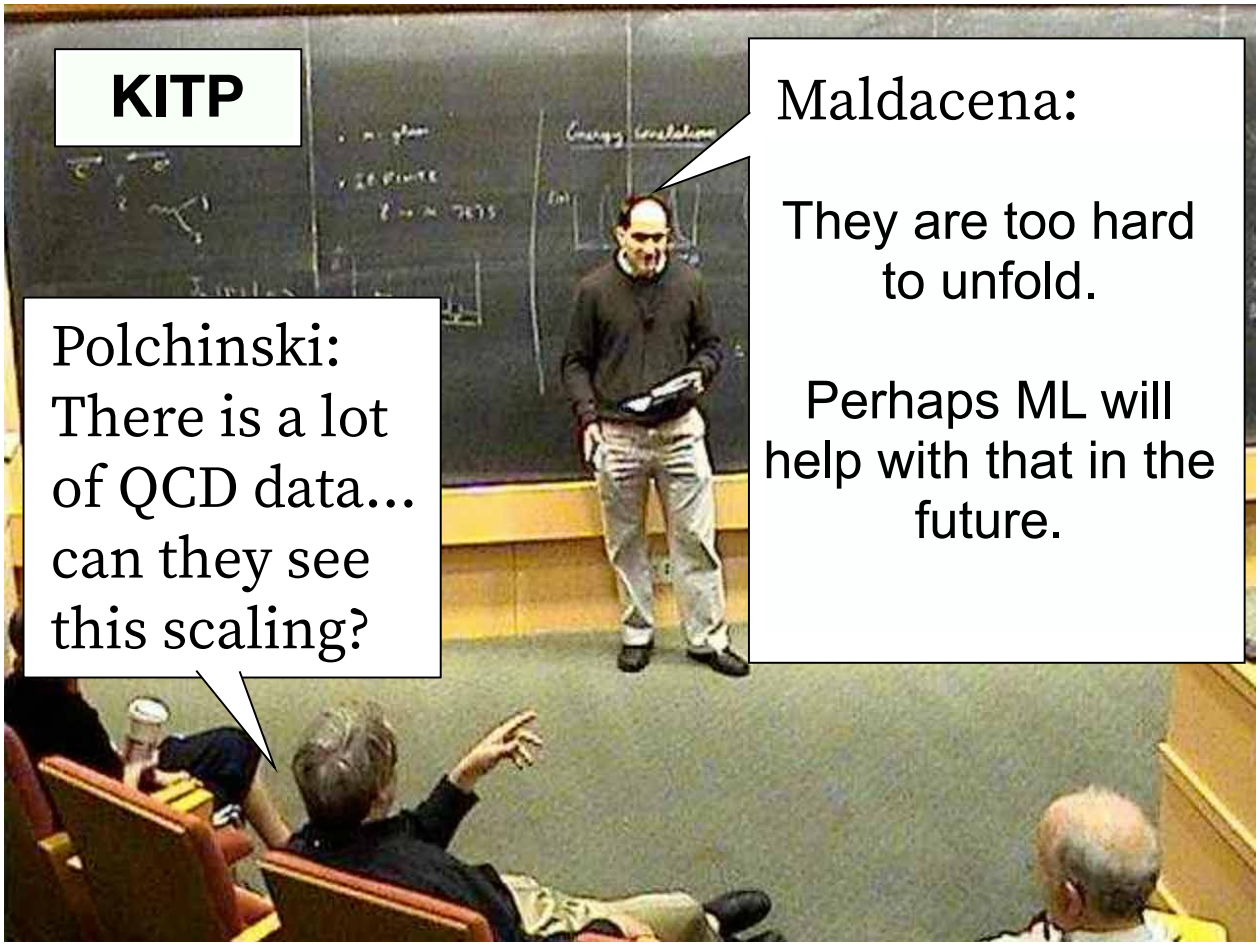

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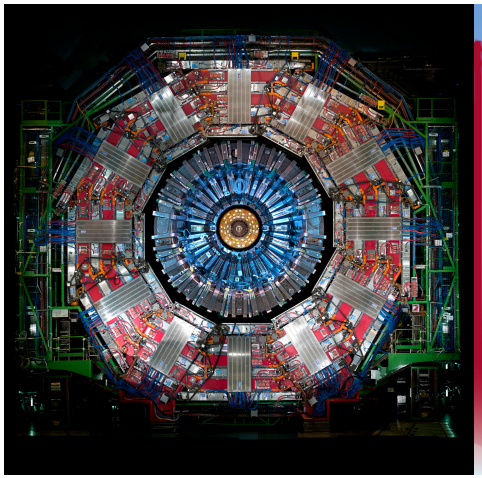
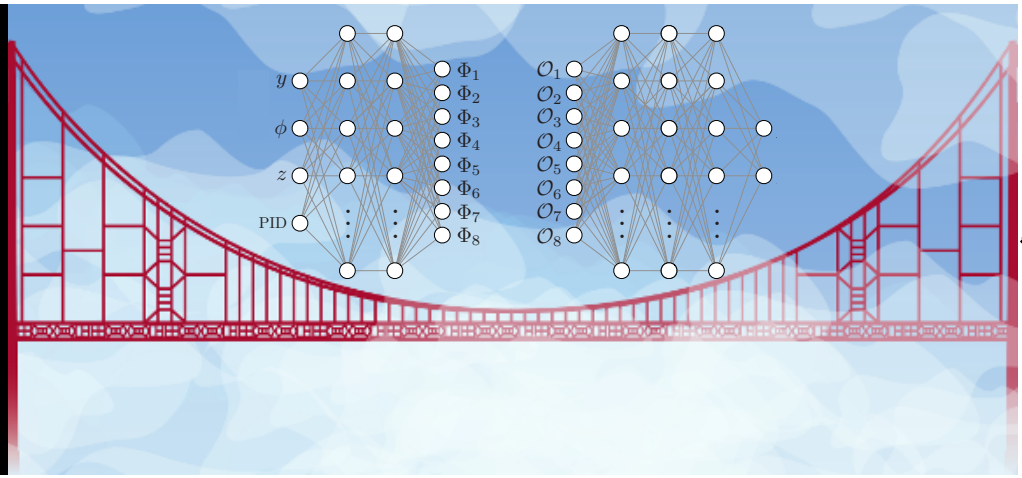
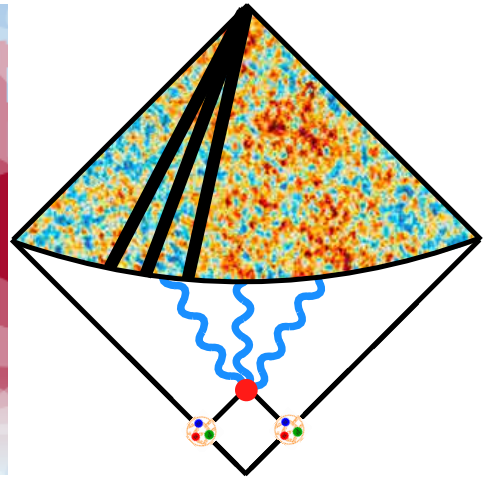
Machine Learning:
The Bridge Between Theory and Experiment

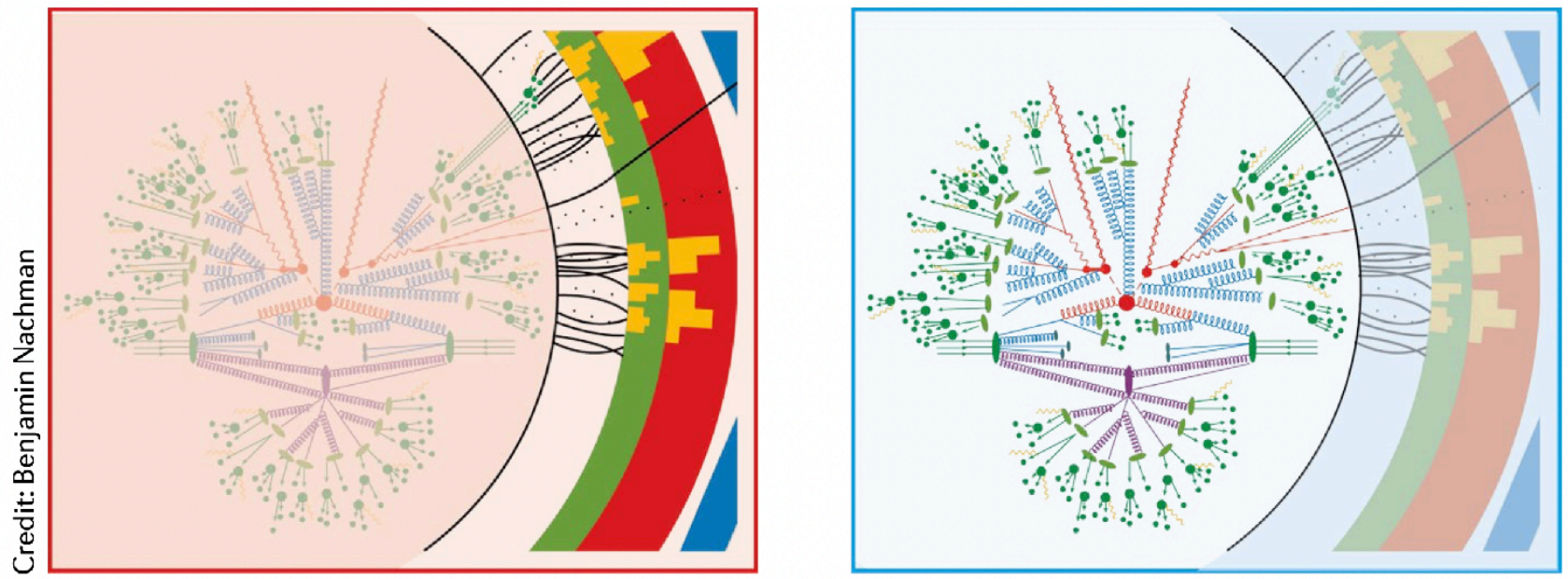






From Detector Data to Theory Comparisons

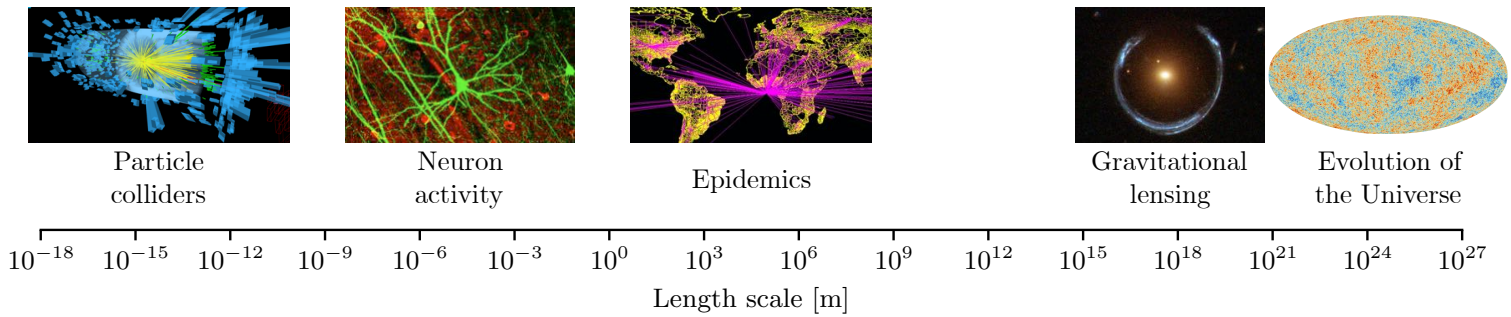
- To be interpreted theoretically, measurements must "invert" the effects of the detector: Unfolding.
- "Simple" if one projects to low dimensional features such as jets.
- To measure statistical properties of energy flux requires unfolding the full particle phase space.



Likelihood Free Inference

- Traditional approaches to unfolding that explicitly determine the likelihood fail:
  - High dimensional input space - full phase space of detector effects.
  - High dimensional output space - space of energy correlations.
- This is a common feature of many modern data sets in the physical sciences, for which we have high fidelity simulations:

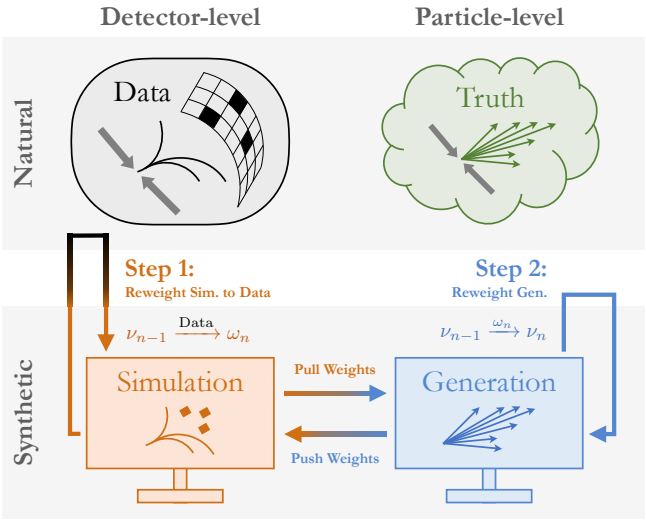
  $\Longrightarrow$ "Likelihood Free Inference"



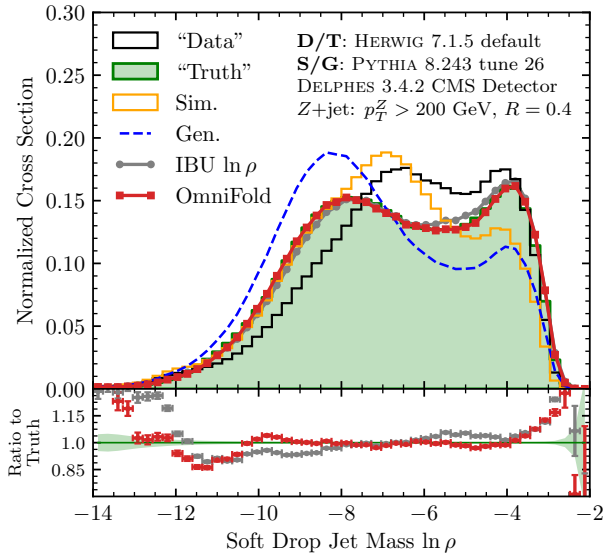
[Cranmer, Brehmer, Louppe]
[Karagiori, Kasieczka, Kravitz, Nachman, Shih]

Omnifold

- Seminal advance in unfolding for collider physics: Omnifold



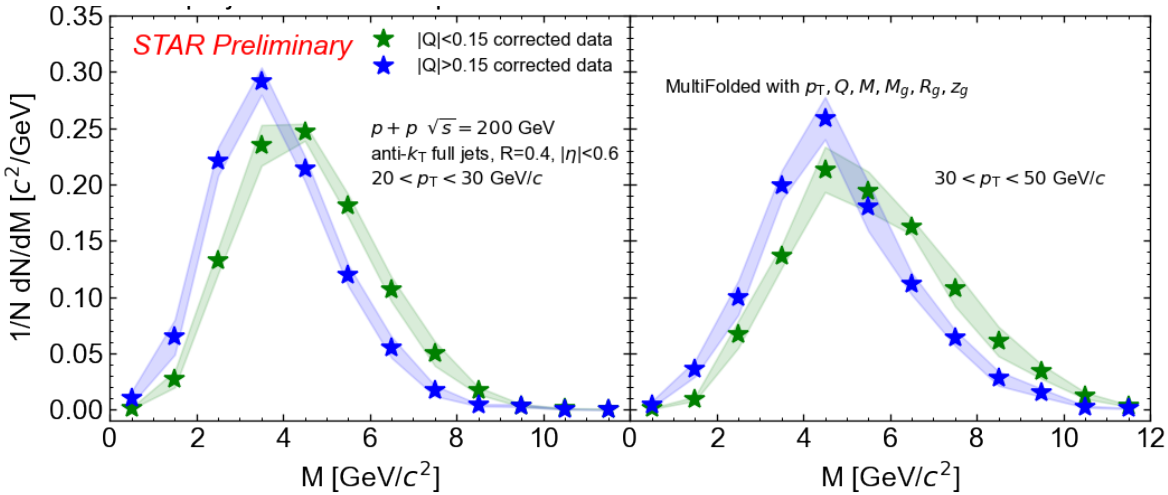
[Andreassen, Nachman]
[Andreassen, Komiske, Metodiev, Nachman, Thaler]



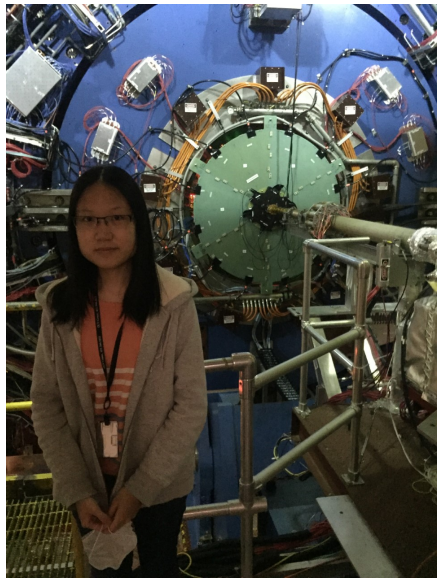
- Rigorously proven to reduce to Iterative Bayesian Unfolding.
- Explicit expression for likelihood intractable in high dimension
  $\Longrightarrow$ circumvented by classification task.
- Unfolding of full phase space, combined with theory progress
  $\Longrightarrow$ transformative progress in QCD.

An Unbiased Test User

- Simultaneous unfolding of p_T, Q_κ, M, R_g, z_g, M_g at STAR!



Mean and spread of jet M distribution both increase with decreasing $|Q|$

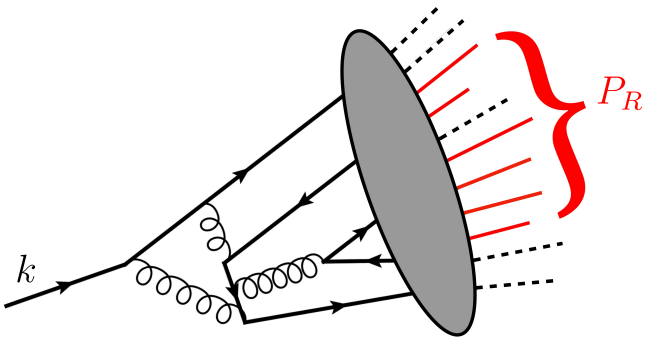


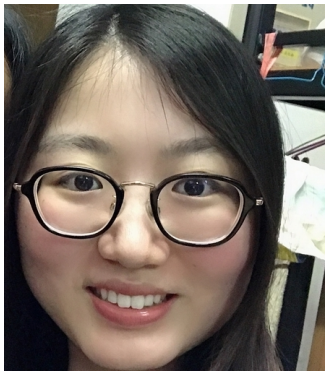
Youqi Song

- No outside influence from Ben, Eric, Patrick or Jesse
  $\Longrightarrow$ trustworthy!

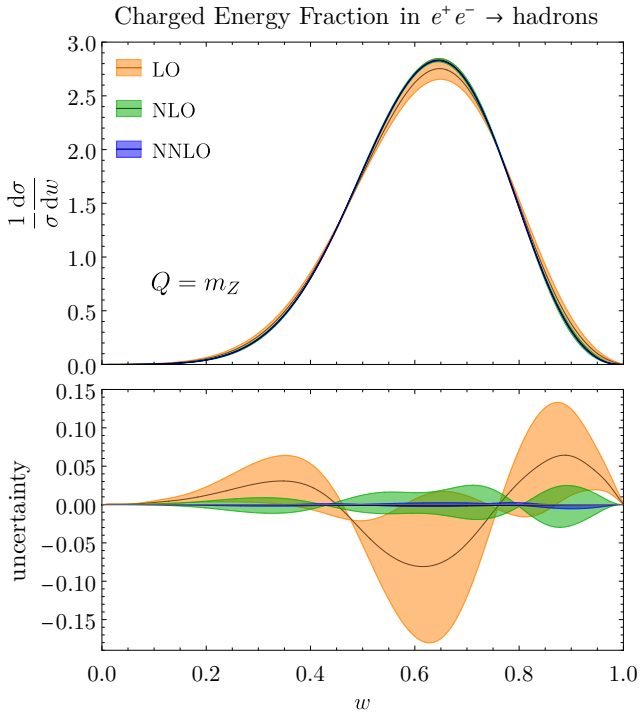
A Slightly Biased Test User

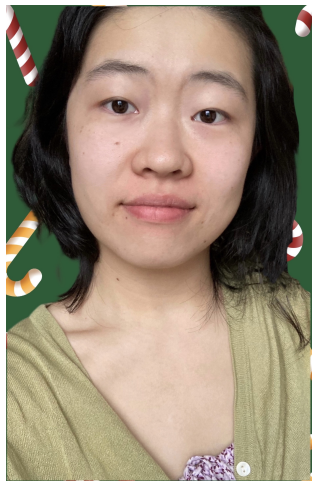
- Can be used to perform unbinned measurements of foundational QCD quantities: Track Functions





Yibei Li

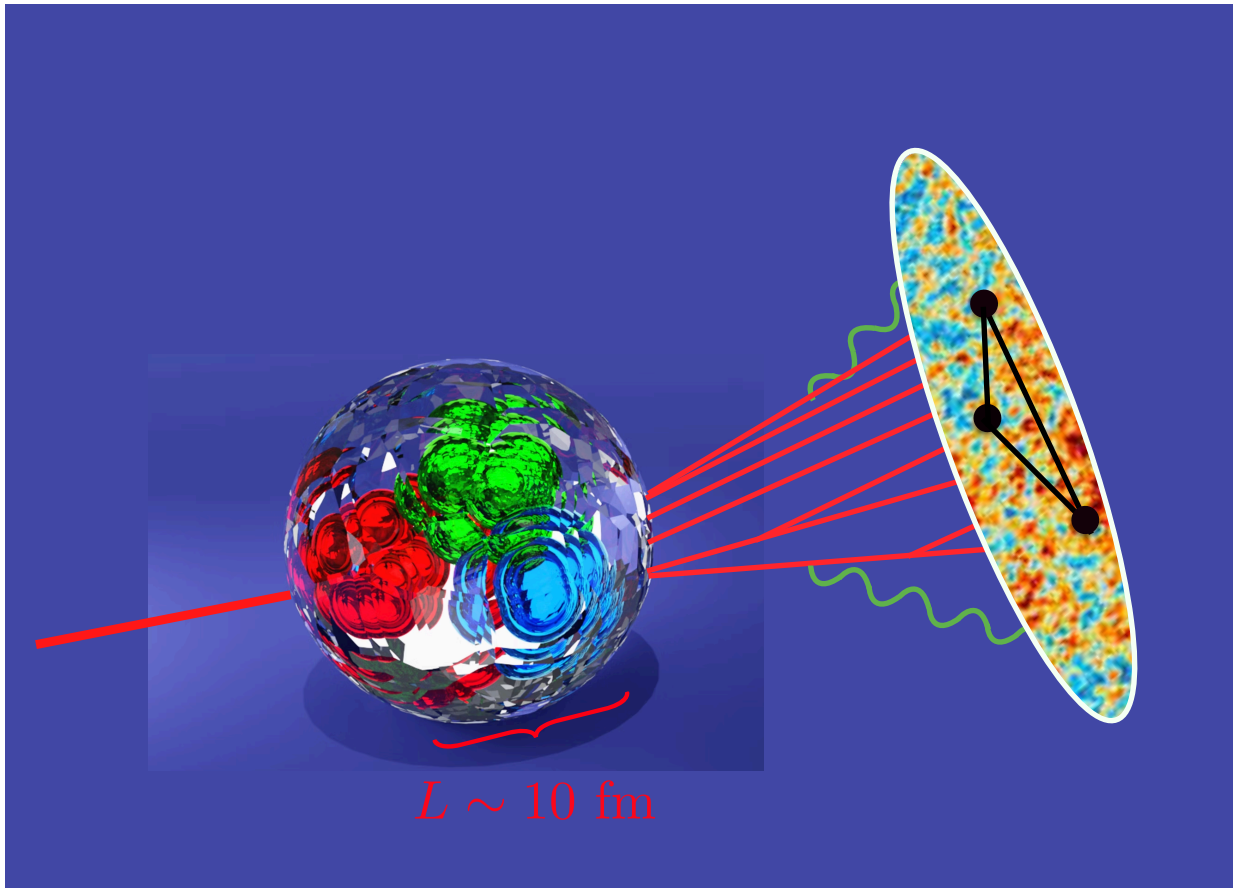




Jingjing Pan

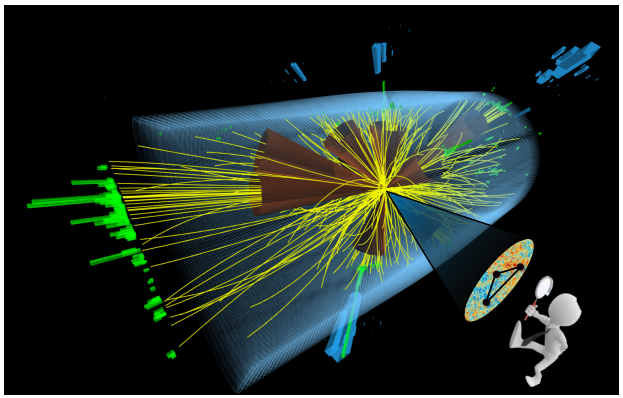
- Will enable a wide variety of jet substructure calculations on tracks!

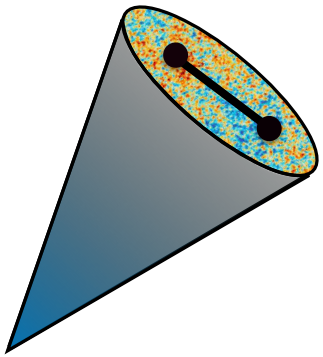
The Frontiers of Jet Physics

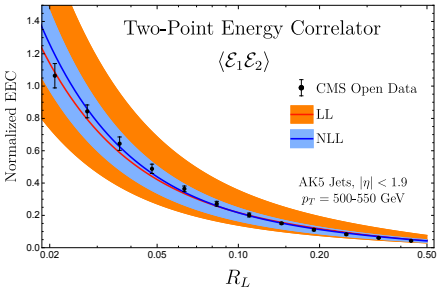


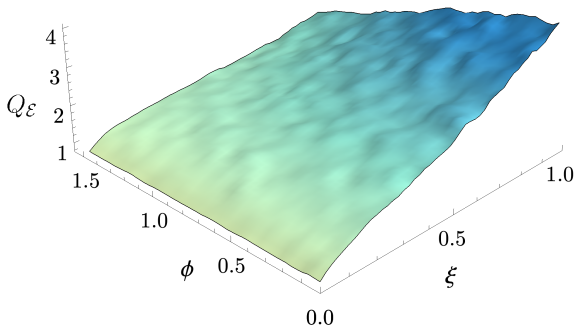
Conformal Colliders Meet the LHC

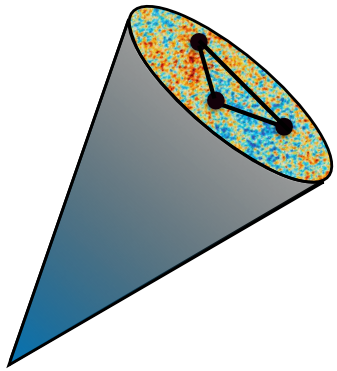
- This new class of observables, obtained from the statistical properties of the entire phase space, provides a completely new perspective on jet substructure.









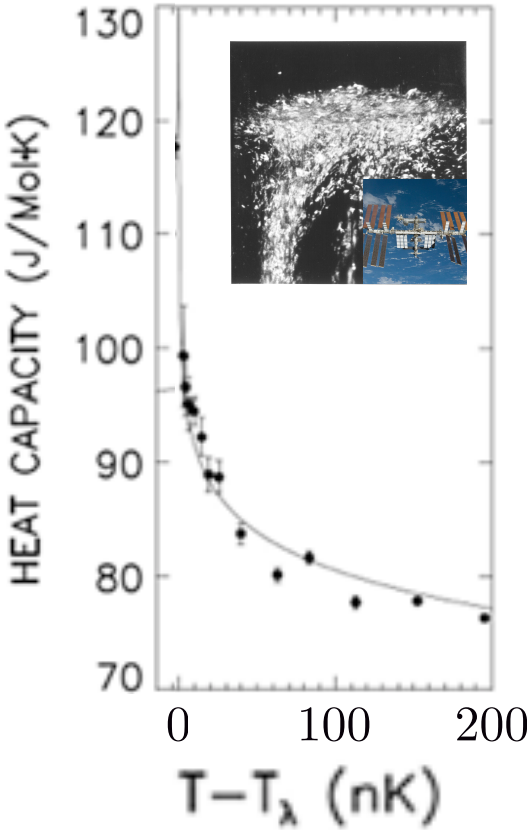


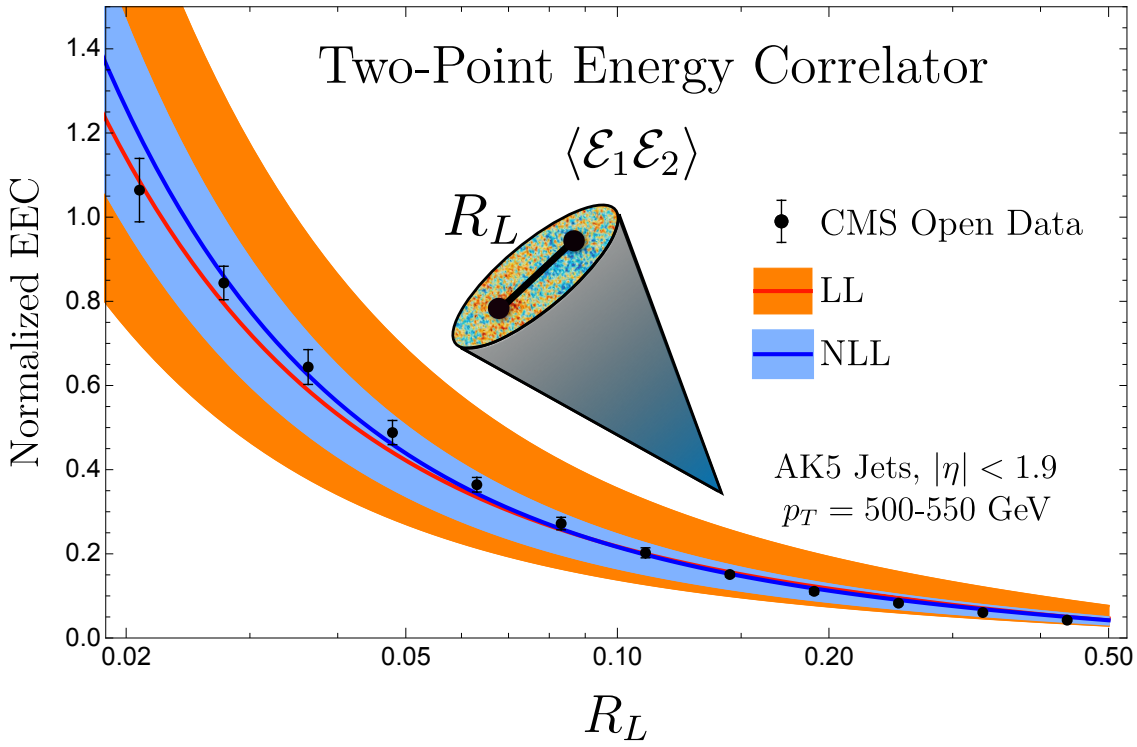
- Allows a direct relation between experimental measurements and the properties of the underlying field theory.

Scaling Behavior in Jets

[Komiske, Moult, Thaler, Zhu]
[Dixon, Moult, Zhu]
[Lee, Mecaj, Moult]

- The $\mathcal{E}(\hat{n}_1)\mathcal{E}(\hat{n}_2)$ OPE inside high-energy jets!



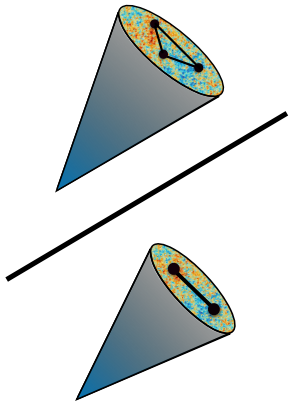


- Beautiful scaling behavior in energy flux, provides a common language from superfluid helium to jet substructure!

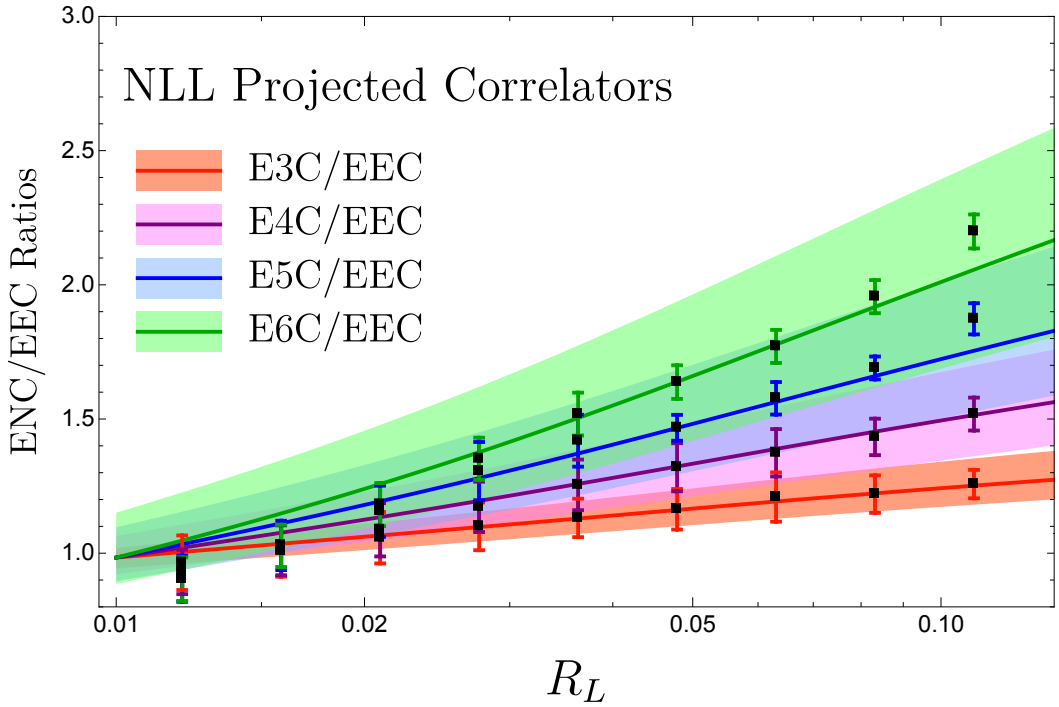
The Spectrum of a Jet

[Chen, Moult, Zhang, Zhu]
[Lee, Mecaj, Moult]

- Measurements of asymptotic energy flux directly extract the spectrum of (twist-2) lightray operators in QCD at the quantum level!



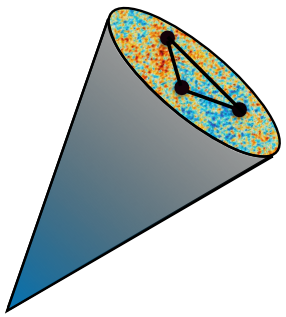
$$\frac{\langle \mathcal{E}_1 \mathcal{E}_2 \cdots \mathcal{E}_{J-1} \rangle}{\langle \mathcal{E}_1 \mathcal{E}_2 \rangle} \sim \frac{\langle \mathbb{O}^{[J]} \rangle}{\langle \mathbb{O}^{[3]} \rangle}$$



- A never before observed feature of QFT, accessible due to the high energies and remarkable detectors of the LHC.

Shape Dependence of Non-Gaussianities

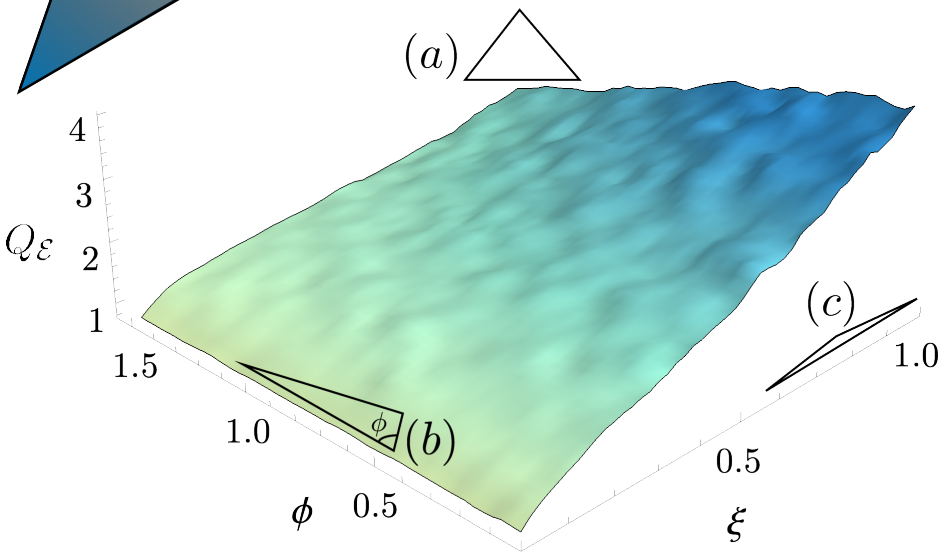
- Can directly study non-gaussianities inside high energy jets.

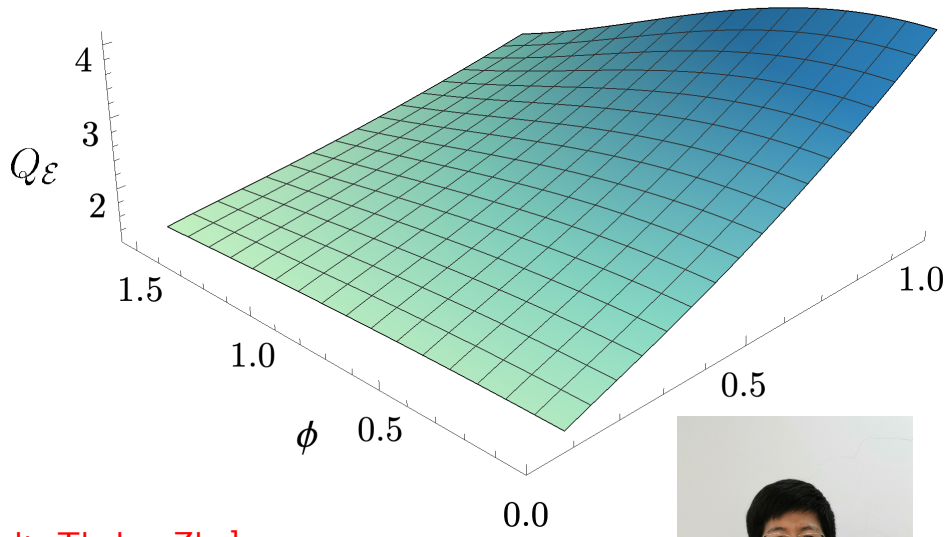


Open Data, $R_L \in (0.3, 0.4)$

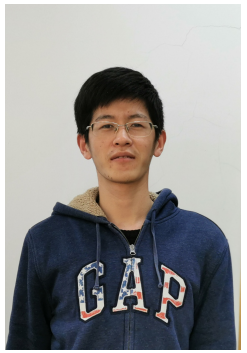
$$G_{N=4}(z) = \frac{1+u+v}{2uv}(1+\zeta_2) - \frac{1+v}{2uv}\log(u) - \frac{1+u}{2uv}\log(v)$$
$$-(1+u+v)(\partial_u+\partial_v)\Phi(z) + \frac{(1+u^2+v^2)}{2uv}\Phi(z) + \frac{(z-\bar{z})^2(u+v+u^2+v^2+u^2v+uv^2)}{4u^2v^2}\Phi(z)$$
$$+\frac{(u-1)(u+1)}{2uv^2}D_2^+(z) + \frac{(v-1)(v+1)}{2u^2v}D_2^+(1-z) + \frac{(u-v)(u+v)}{2uv}D_2^+\left(\frac{z}{z-1}\right)$$

LL + LO prediction, $R_L = 0.35$





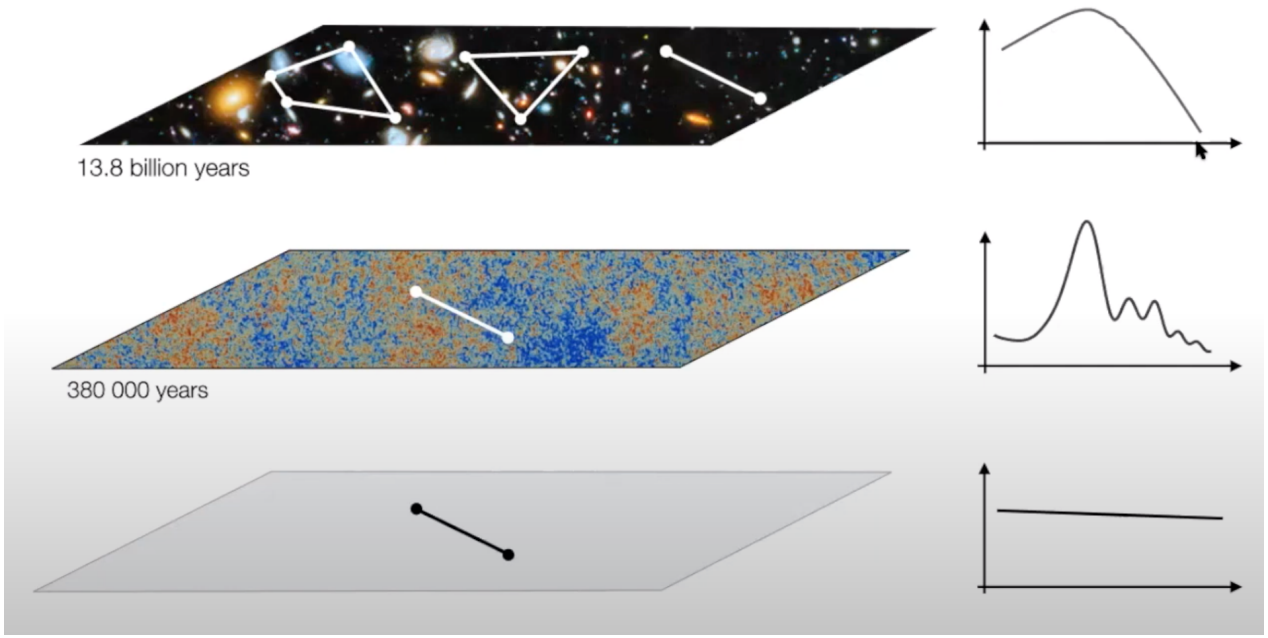
[Chen, Moult, Thaler, Zhu]



- Illustrates theoretical control over multi-point correlations!

Correlation Functions and Scales

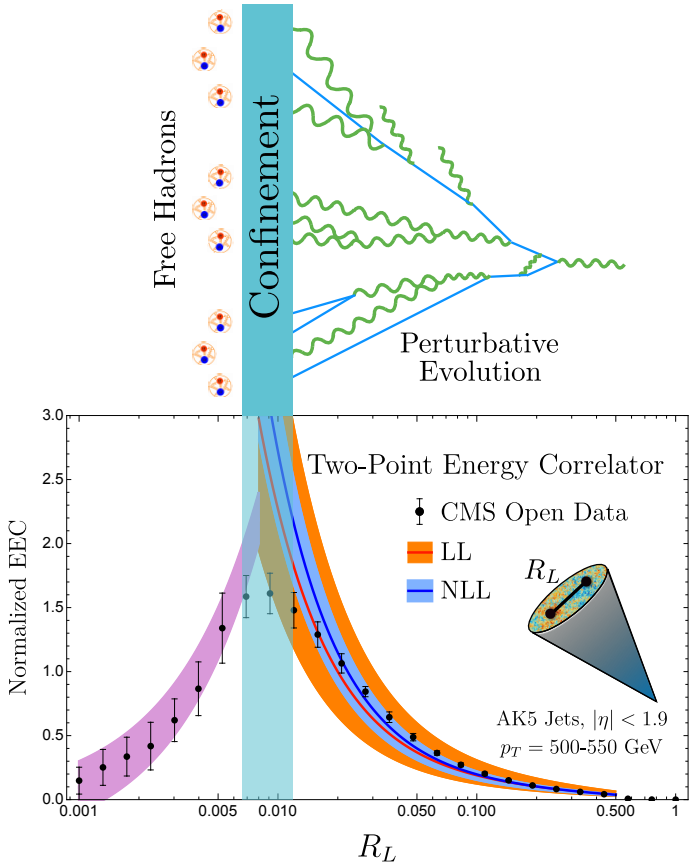
- The beauty of correlation functions (and the reason they are used elsewhere!) is that they isolate the physical phenomena at the scale of correlator.



- Multi-point correlators allow us to image jets at a particular stage in their evolution, and detect the presence of any additional scales.

Application 1: The Confinement Transition

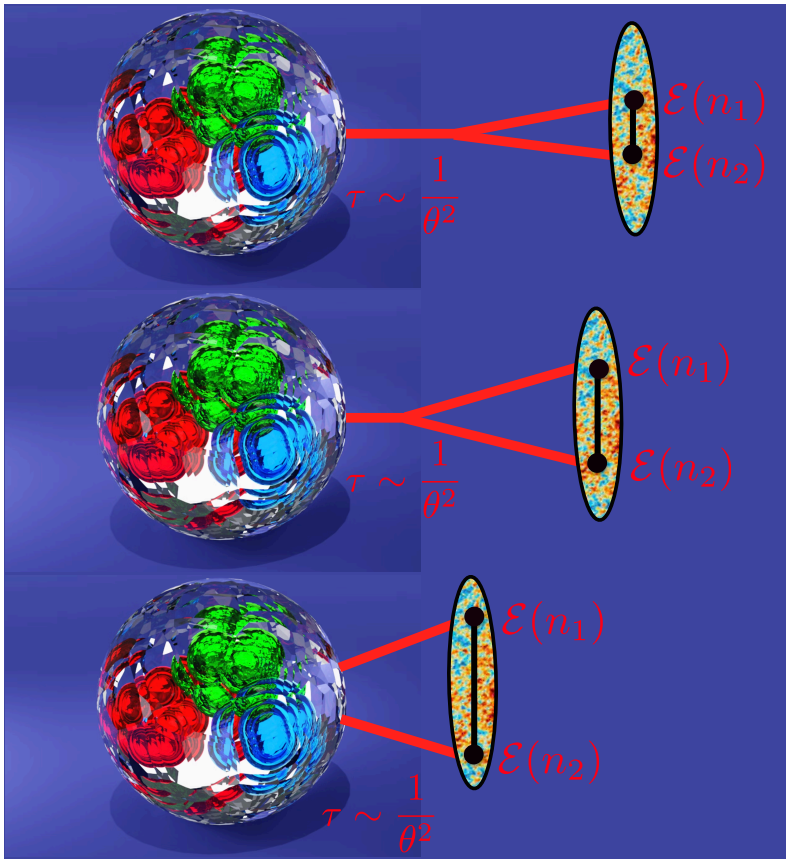
- Energy correlators allow the hadronization process to be directly imaged inside high energy jets: transition from interacting quarks and gluons and free hadrons clearly visible!



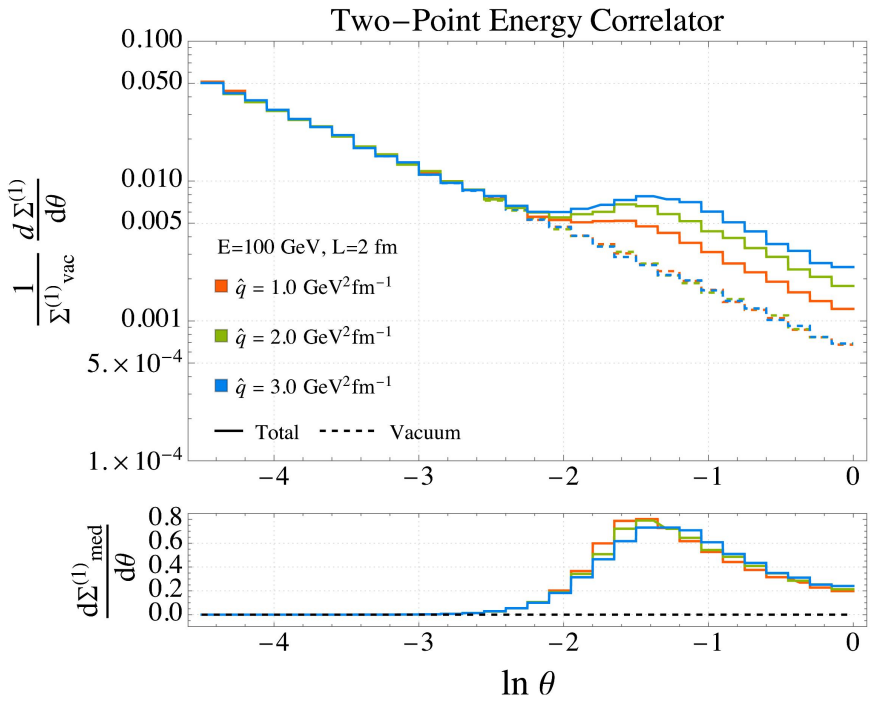
- https://www.youtube.com/watch?v=ORwDv1KTB5U

Application 2: Resolving the Scales of the QGP

- The QGP is cleanly imprinted in two-point correlations.



Increasing θ

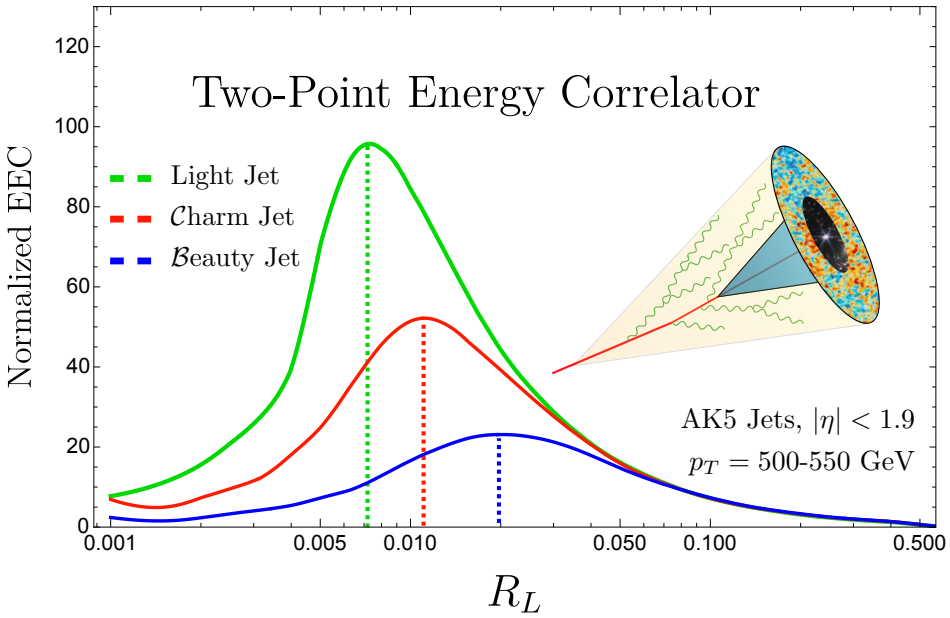


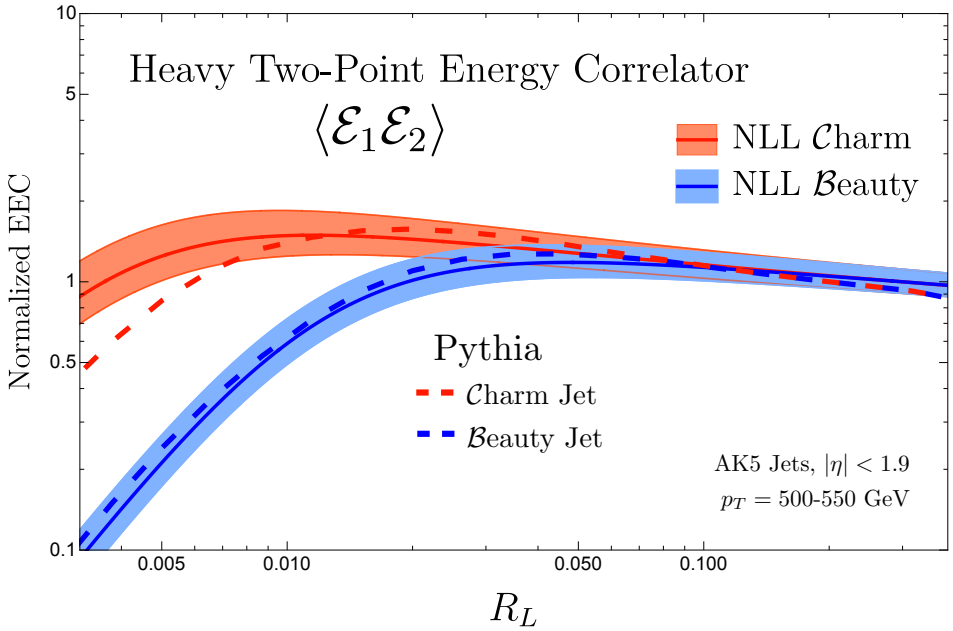
Increasing θ

[Andres, Dominguez, Holguin, Kunnawalkam Elayavalli, Marquet, Moult]

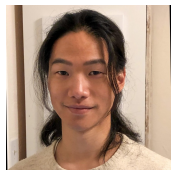
Application 3: Intrinsic Mass Effects

- Intrinsic masses in QCD are imprinted into the correlators, allowing one to study their hadronization.



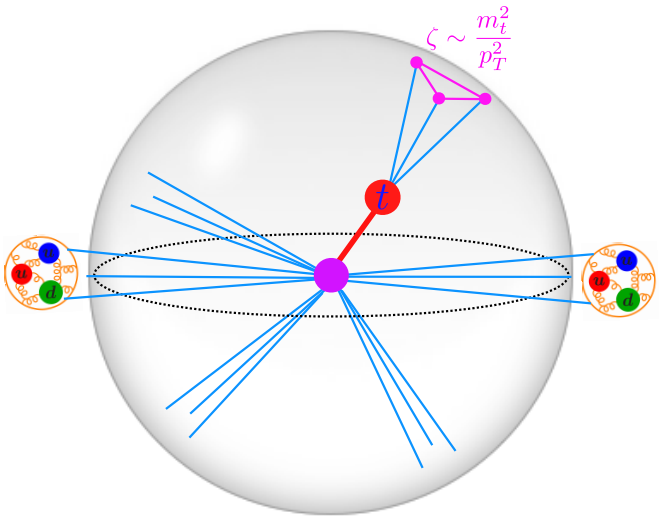


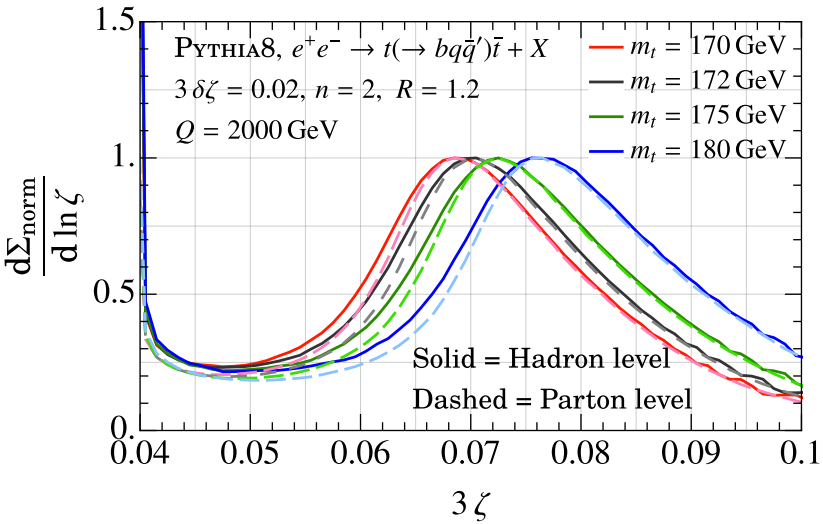
[Craft, Lee, Mecaj, Moult]


Application 4: Top Quark Mass Measurement

- The top quark mass is a central parameter of the SM.
- Mass measurements are subtle: need observables with top mass sensitivity that can be computed from first principles field theory.
- Massive particles break the scaling of the correlators and imprint their existence at a characteristic angular scale $\zeta \sim m^2/Q^2$.

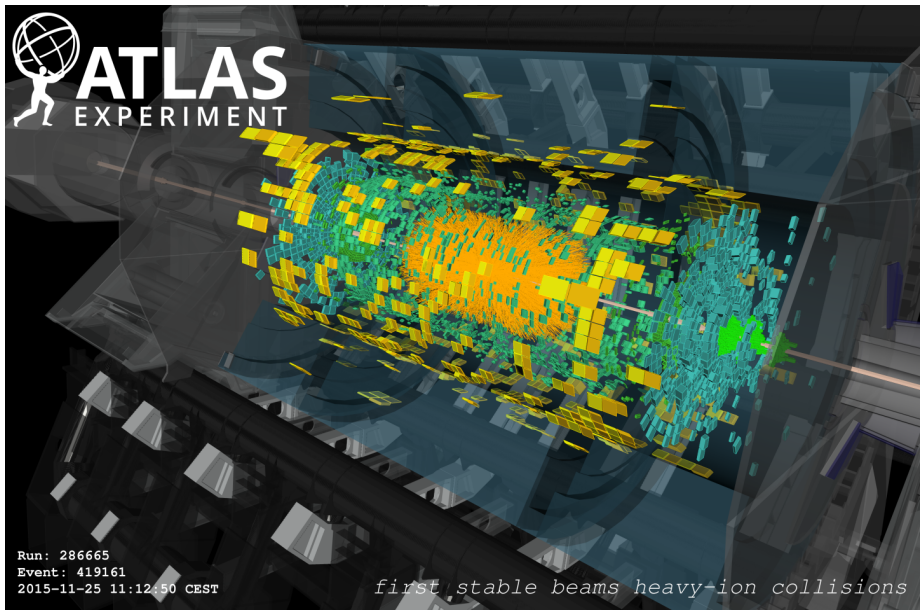


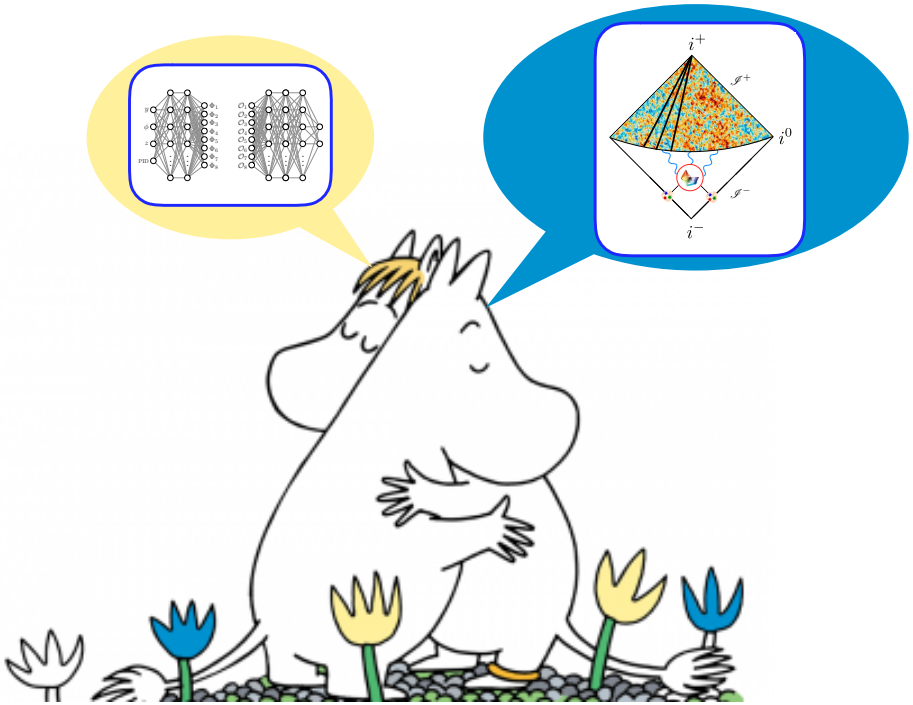


- Optimistic for a precision ($\lesssim 1$ GeV) top mass extraction at LHC from jet substructure! [Holguin, Moult, Pathak, Procura]

ML+QFT for Colliders

- Colliders offer a unique opportunity to study general features of QFT, and specific features of QCD.

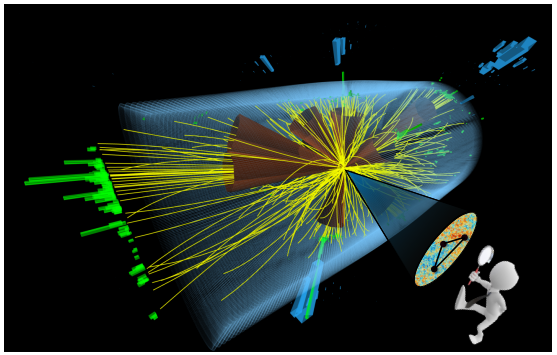




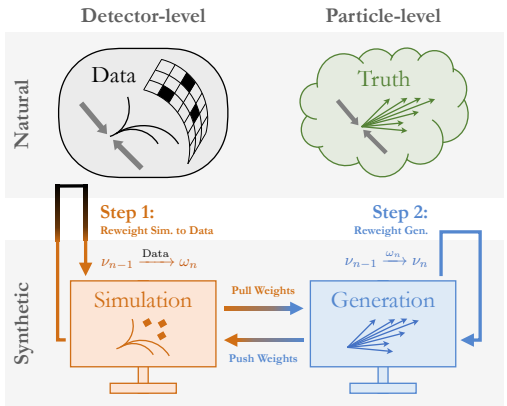
- ML and QFT are both remarkably rich tools that must work hand in hand to unravel the structure of nature.

Summary

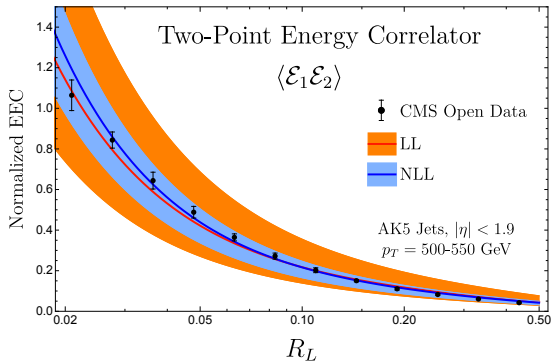
- Collider physics inextricably ties Data Science and Quantum Field Theory.

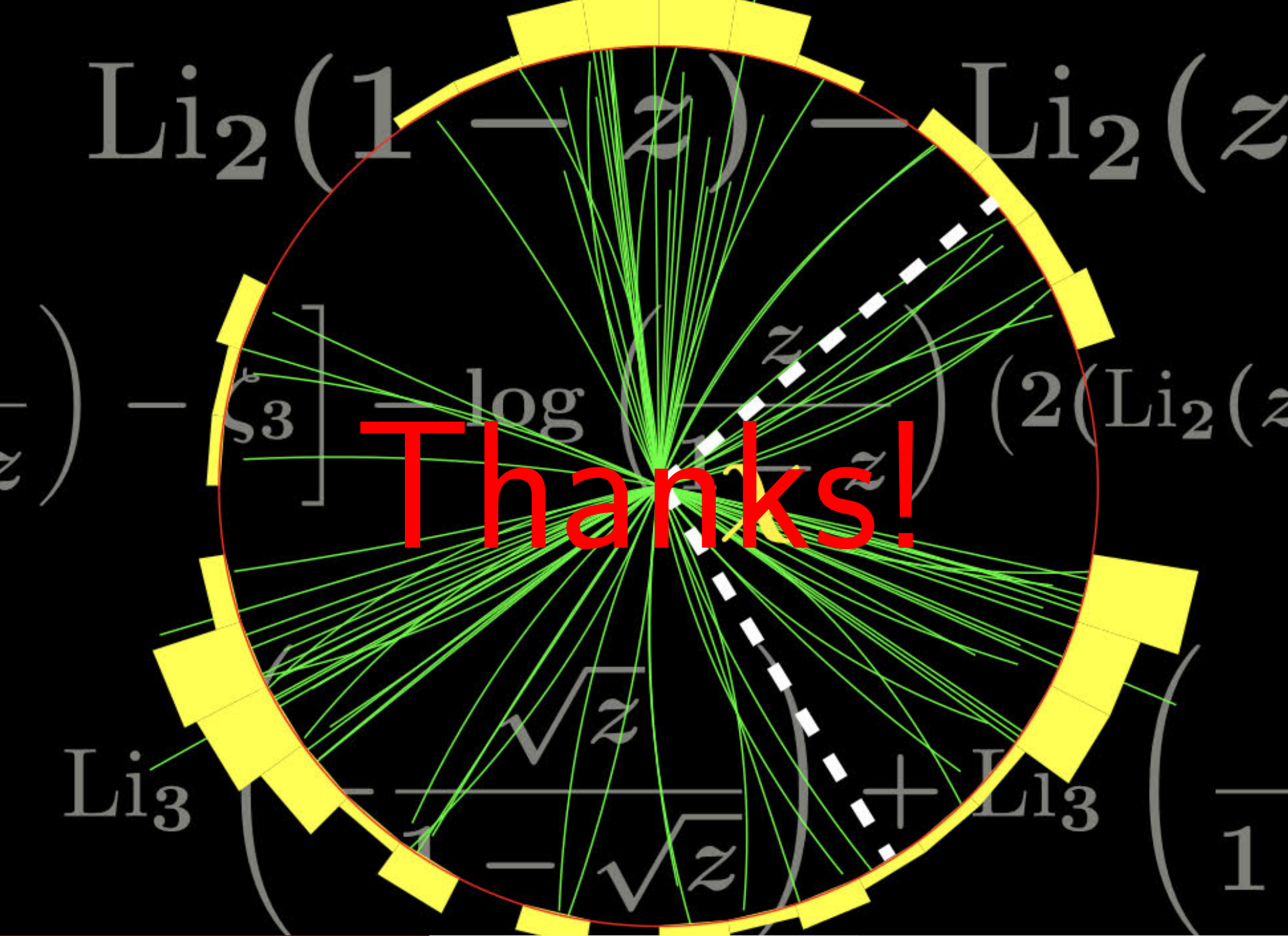


- Progress in Machine Learning enables the measurement of qualitatively new classes of Jet Substructure observables.



- Combined with theory progress, this opens the door to an exciting physics program using jet substructure!




Thanks!