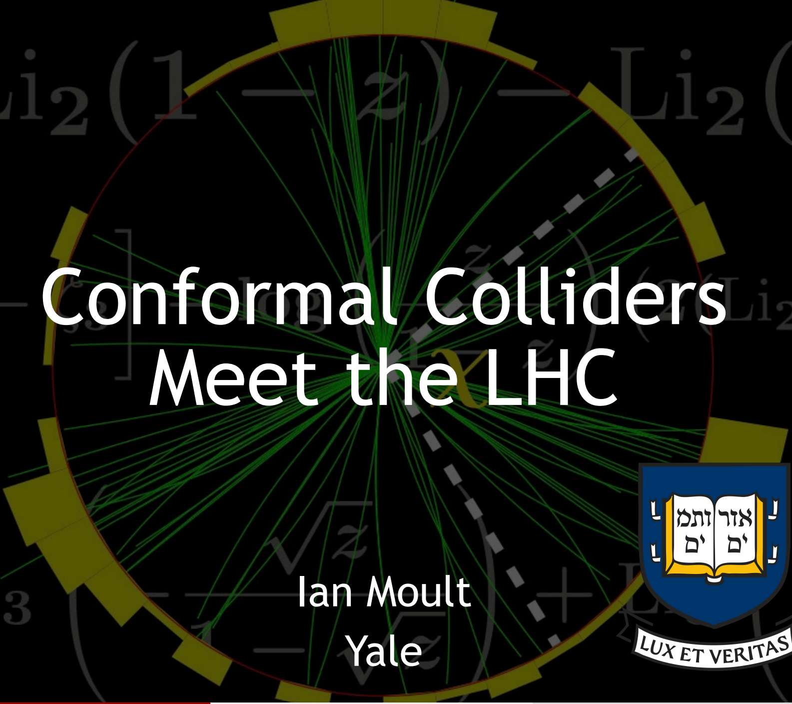
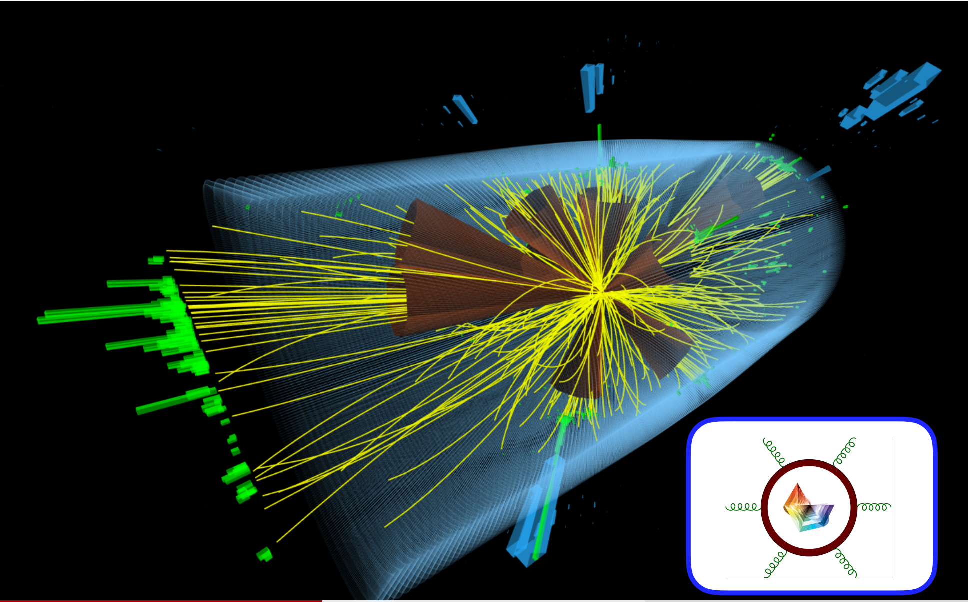


Conformal Colliders Meet the LHC

Ian Moult

Yale

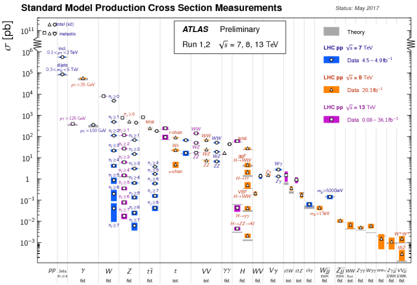
Jets!

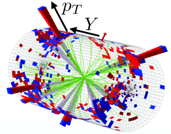


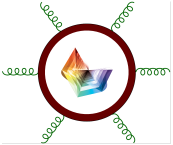
Jets at the LHC

- Obtaining a precise description of jet cross sections has been a significant driver of theory developments in Quantum Field Theory.

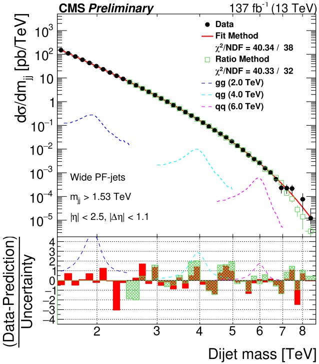
Jet Kinematic Distributions





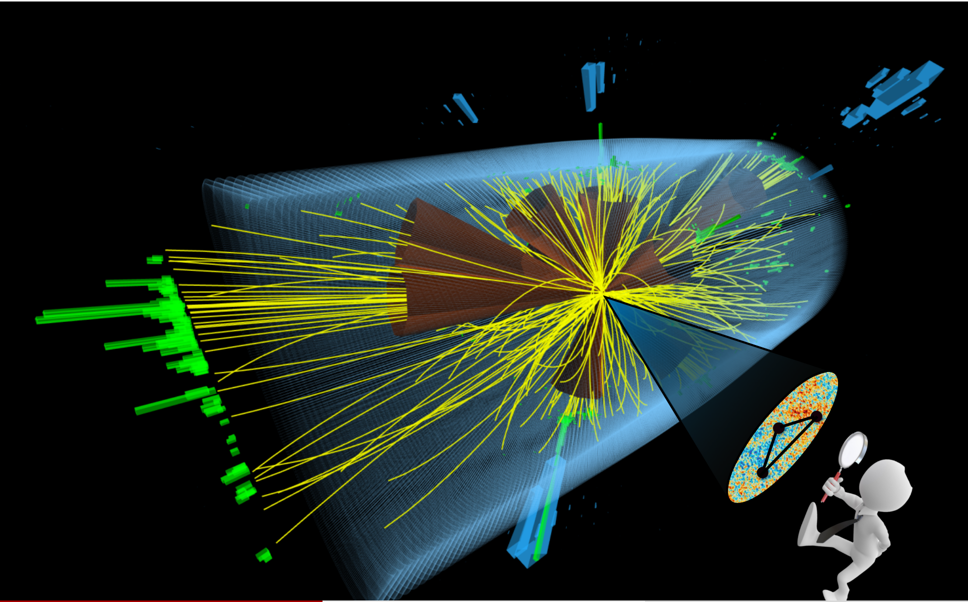


Dijet Mass



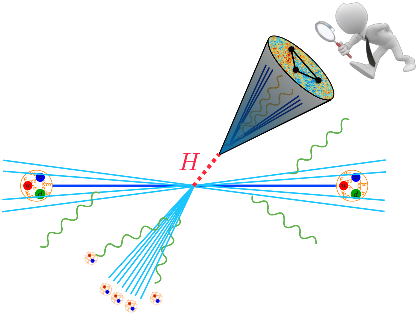
- Enables precision tests of QCD and searches for new physics.

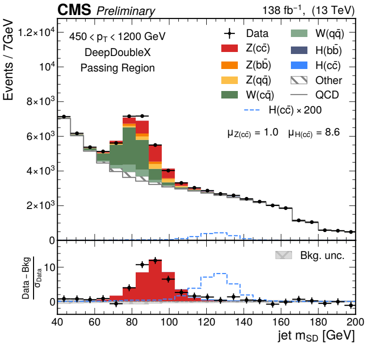
Jet Substructure!



Jet Substructure: Searches

- Jet Substructure uses the internal structure of jets to provide qualitatively new ways to study physics at the LHC.

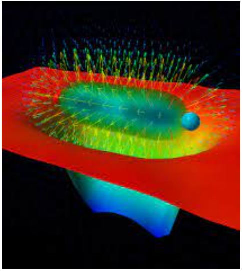


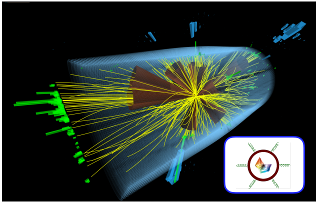


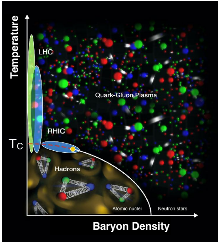
- Its introduction in 2008 by Butterworth, Davison, Rubin and Salam, along with anti-k_T by Cacciari, Soyez, Salam reinvigorated the study of jets in QCD.

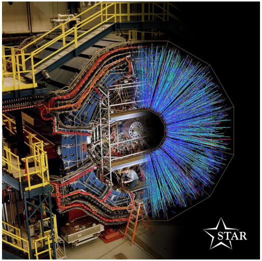
Jet Substructure: Quantum Field Theory

- Beyond searching for new physics, much more subtle questions about QCD are imprinted in collider energy flux:



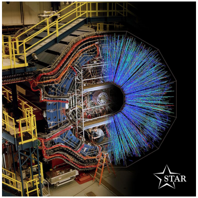


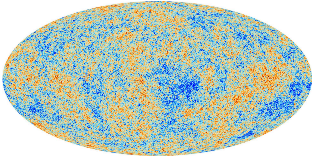


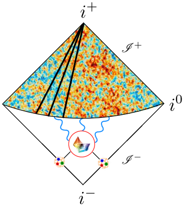


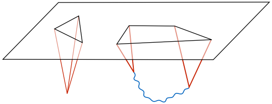
Decoding Energy Flux

- Much like in cosmology, we must infer microscopic (early time) physics from asymptotic (late time) energy flux.





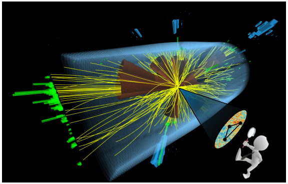




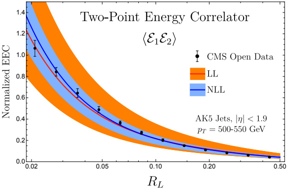
- Requires development of field theoretic techniques to interpret subtle correlations in terms of the dynamics of the underlying field theory.

Outline

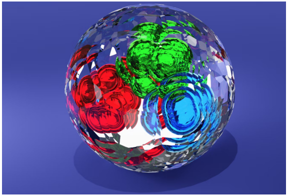
- Decoding Energy Flux



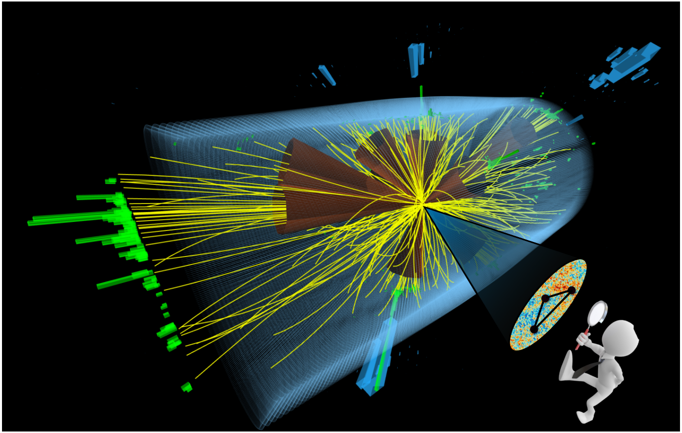
- Scaling Behavior of Quarks and Gluons



- Imaging Intrinsic and Emergent Scales of QCD

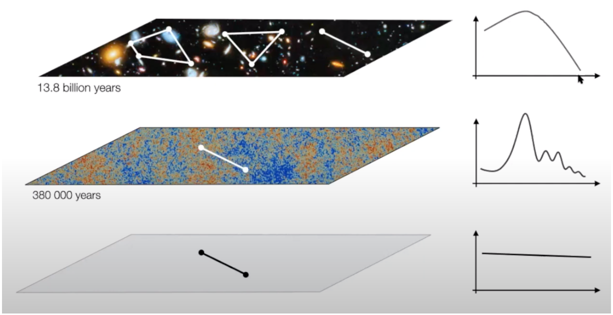


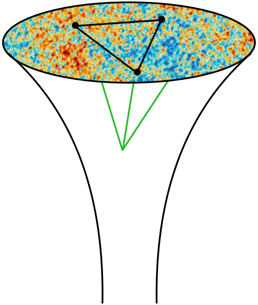
Decoding Energy Flux



Correlation Functions

- In condensed matter physics or cosmology we decode the underlying dynamics using correlation functions.

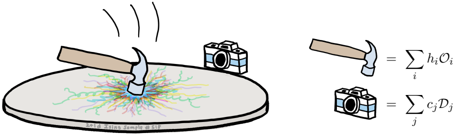




- Can we achieve a similarly coherent picture of collider physics?

Defining the Problem

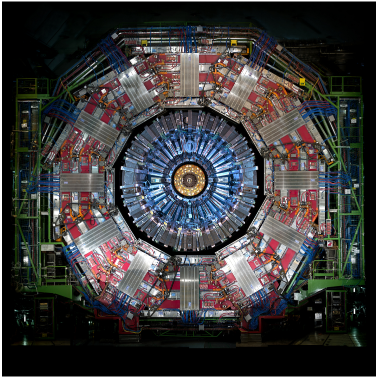
- What is a detector?



$$= \sum_i h_i \mathcal{O}_i$$

$$= \sum_j c_j \mathcal{D}_j$$

[Caron Huot, Kologlu, Kravchuk, Meltzer, Simmons Duffin]

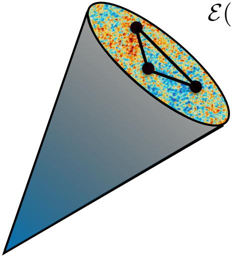


- To be able to understand subtle signals in energy flux, we must understand what a detector is in Quantum Field Theory.

Calorimeter Cells in Field Theory

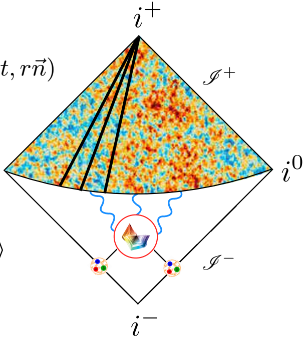
- Calorimeter cells can be given a field theoretic definition in terms of light-ray operators.

[Hofman, Maldacena], [Belitsky, Hohenegger, Korchemsky, Sokatchev, Zhiboedov]
[Korchemsky, Sterman]
[Ore, Sterman]
[Basham, Brown, Ellis, Love]



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

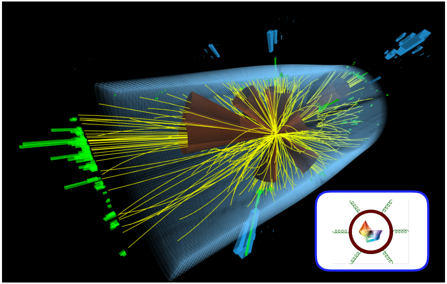
$$\langle\Psi|\mathcal{E}(\hat{n}_1)\cdots\mathcal{E}(\hat{n}_k)|\Psi\rangle$$

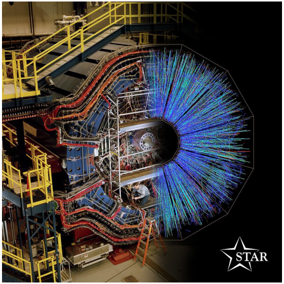


- From the perspective of QFT, jet substructure is the study of correlation functions of energy flow operators.

Towards the World of Hadron Colliders

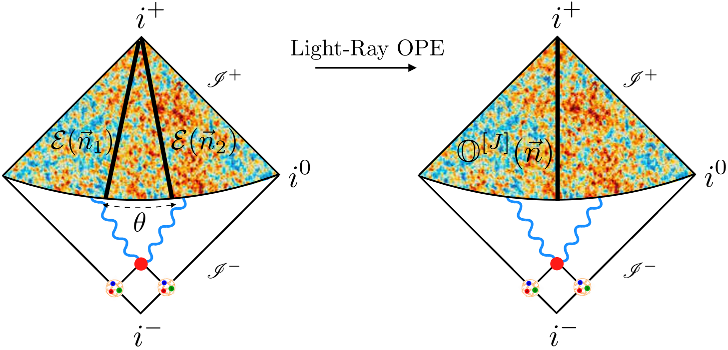
- Can this theoretical idealization possibly work in the messy world of hadron colliders?





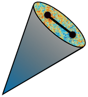
- Can it provide new ways of understanding these complex collisions?

Scaling Behavior of Quarks and Gluons



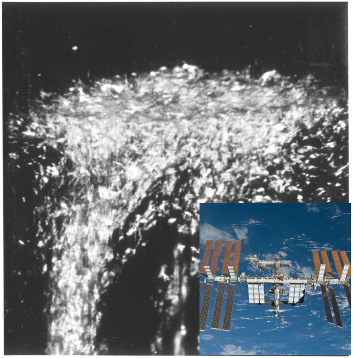
Scaling Behavior in QFT

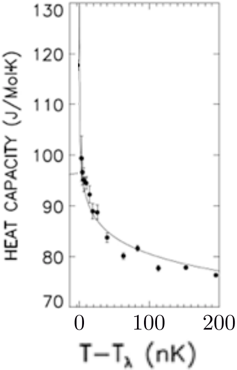
- Why is jet substructure theoretically interesting?



- QFTs exhibit universal behavior as operators are brought together.

λ-point of Helium

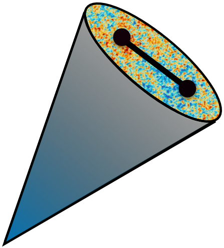


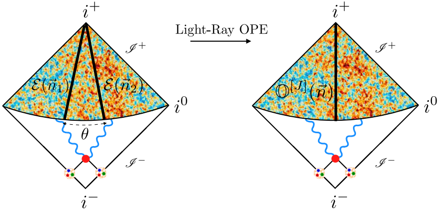


$$\boxed{\mathcal{O}(x)\mathcal{O}(0) = \sum x^{\gamma_i} c_i \mathcal{O}_i}$$

The OPE Limit of Lightray Operators

- Energy flow operators admit an OPE!
- Jet Substructure is the study of the OPE limit of lightray operators.





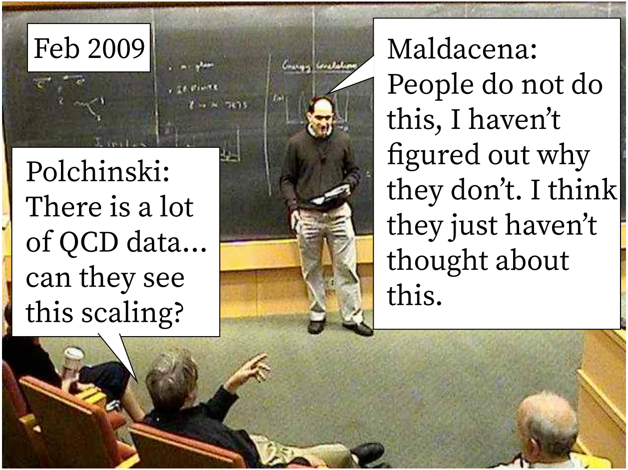
$$\mathcal{E}(\hat{n}_1)\mathcal{E}(\hat{n}_2) \sim \sum \theta^{\tau_i - 4}\mathbb{O}_i(\hat{n}_1)$$

[Hofman, Maldacena]
[Chang, Kologlu, Kravchuk, Simmons Duffin, Zhiboedov]

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

Theory-Experiment Gap

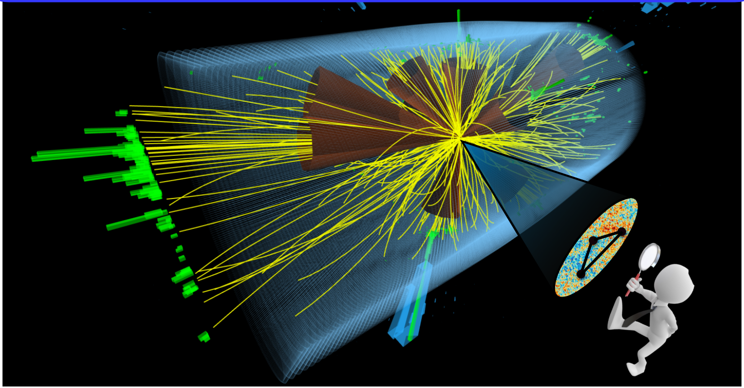
- OPE scaling is the most basic prediction of QFT for jet substructure.



[Basham, Brown, Ellis, Love]

- Shockingly, still true as of 2022...

Open Data at the LHC



The Leading Twist Lightray OPE

[Hofman, Maldacena]
[Chen, IM, Zhu]

- The twist-2 operators in QCD are characterized by a spin-J and a transverse spin $j = 0, 2$.
- These can be light-transformed to obtain a vector of twist-2 lightray operators parametrized by spin-J:

Local Operators

[Kravchuk, Simmons Duffin]

transverse spin-0

$$\begin{cases} \mathcal{O}_q^{[J]} = \frac{1}{2^J} \bar{\psi} \gamma^+ (iD^+)^{J-1} \psi \\ \mathcal{O}_g^{[J]} = -\frac{1}{2^J} F_a^{\mu+} (iD^+)^{J-2} F_a^{\mu+} \end{cases}$$

transverse spin-2

$$\mathcal{O}_{\tilde{g}\textcircled{\lambda}}^{[J]} = -\frac{1}{2^J} F_a^{\mu+} (iD^+)^{J-2} F_a^{\nu+} \epsilon_{\lambda,\mu} \epsilon_{\lambda,\nu}$$

helicity ±

$$\xrightarrow{\lim_{r\to\infty} r^2 \int_0^\infty dt} \quad \vec{\mathbb{O}}^{[J]}(\vec{n}) = \begin{array}{c|l} \begin{bmatrix} \mathbb{O}_q^{[J]}(\vec{n}) \\ \mathbb{O}_g^{[J]}(\vec{n}) \\ \mathbb{O}_{\tilde{g},+}^{[J]}(\vec{n}) \\ \mathbb{O}_{\tilde{g},-}^{[J]}(\vec{n}) \end{bmatrix} & \begin{array}{l} \textbf{unpolarized} \\ \\ \textbf{polarized} \end{array} \end{array}$$

- The anomalous dimensions of these operators,

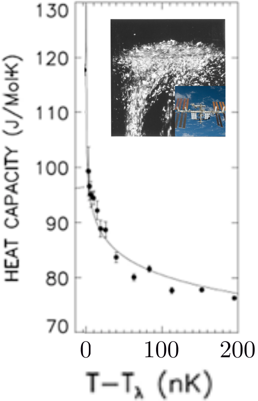
$$\frac{d}{d\ln\mu^2} \vec{\mathbb{O}}^{[J]}(\hat{n}_1) = \hat{\gamma}(J) \vec{\mathbb{O}}^{[J]}(\hat{n}_1)$$

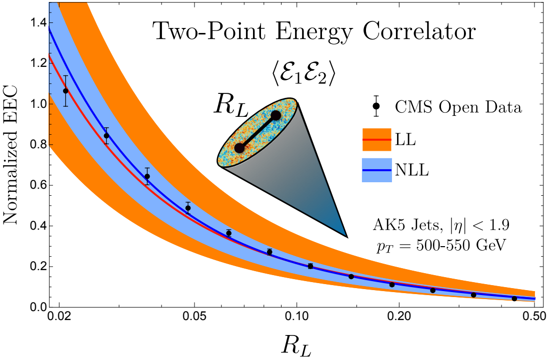
determines the leading behavior of jet substructure.

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!



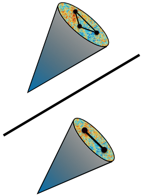


$$\mathcal{E}(\hat{n}_1)\mathcal{E}(\hat{n}_2) \sim \sum \theta^{\tau_i - 4} \mathbb{O}_i(\hat{n}_1)$$

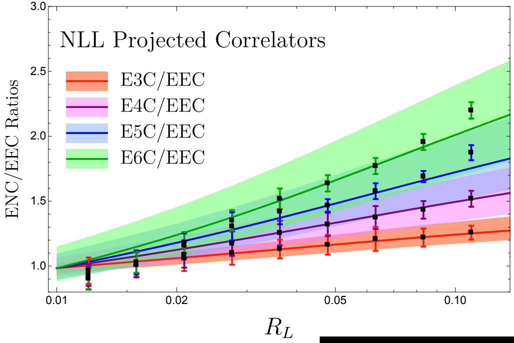
- Beautiful scaling behavior in energy flux, provides a common language from superfluid helium to jet substructure!

The Spectrum of a Jet

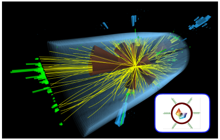
- The light-ray OPE predicts that the N-point correlators develop an anomalous scaling that depends on N.



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

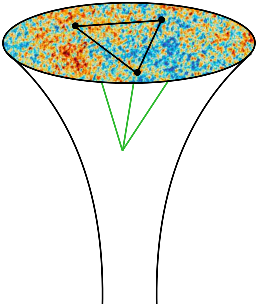


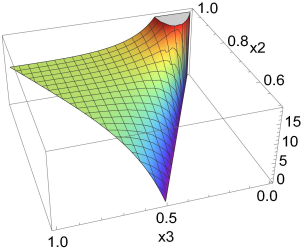
- Directly probes the spectrum of (twist-2) lightray operators from asymptotic energy flux.



Non-Gaussianities

- Higher-point correlators probe more detailed aspects of interactions.
- e.g. Non-Gaussianities allow one to distinguish models of inflation.
- Three-point function, $\langle \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \zeta_{\vec{k}_3} \rangle$, first computed by Maldacena.



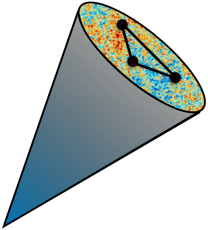


[Cabass, Pajer, Stefanysyzn, Supel]

- Can we compute shapes of higher-point functions of energy flux?

Multi-point Correlators at Weak Coupling

- Turn out to have an elegant perturbative structure. e.g. in $\mathcal{N} = 4$



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

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

- Here Φ and D_2^+ are polylogarithmic functions

$$\Phi(z) = \frac{2}{z-\bar{z}}\left(\mathrm{Li}_2(z) - \mathrm{Li}_2(\bar{z}) + \frac{1}{2}\left(\log(1-z) - \log(1-\bar{z})\right)\log(z\bar{z})\right)$$

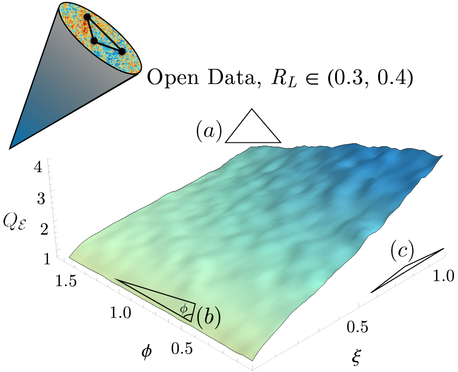
$$D_2^+(z) = \mathrm{Li}_2(1-|z|^2) + \frac{1}{2}\log(|1-z|^2)\log(|z|^2)$$

- Real world QCD involves more complicated polynomials, but is otherwise similar.

Shape Dependence of Non-Gaussianities

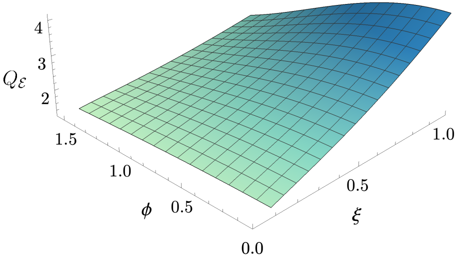
- Can directly study non-gaussianities inside high energy jets.

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



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

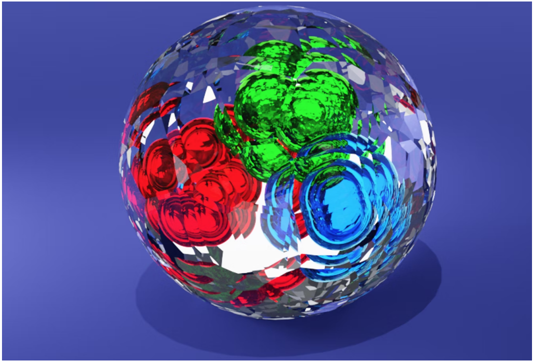
LL + LO prediction, $R_L = 0.35$



[Chen, Moult, Thaler, Zhu]

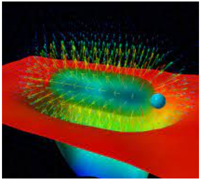
- Illustrates theoretical control over multi-point correlations!

Identifying Intrinsic and Emergent Scales of QCD

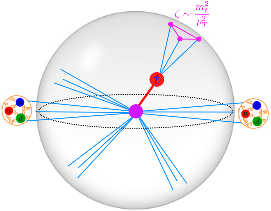


Three Examples

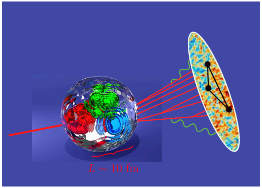
- The Confinement Transition



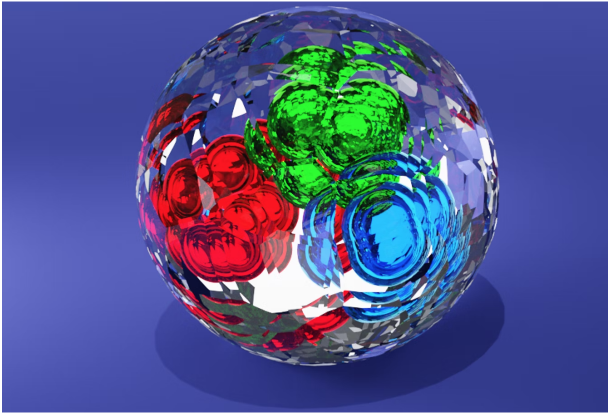
- Weighing the Top Quark



- Resolving the Scales of the Quark Gluon Plasma

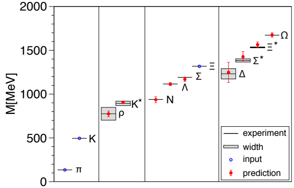


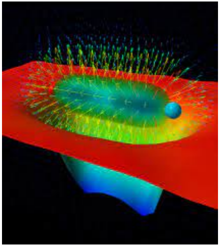
The Confinement Transition

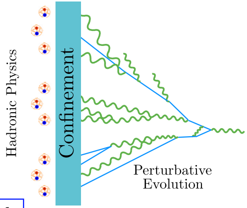


Dynamics of Hadronization

- What are the dynamics of the hadronization process?



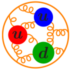


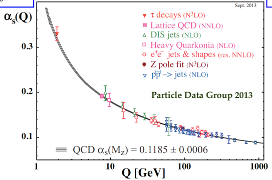


Long Time Scale
Low Energy

$\alpha_s(Q)$

Short Time Scale
High Energy





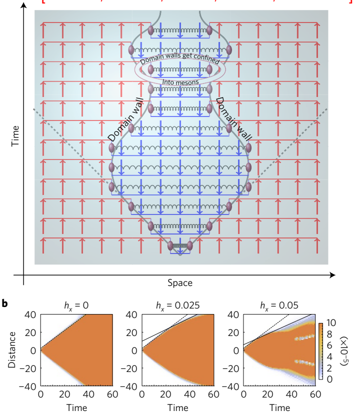
$$\hat{O} = \alpha_s + \alpha_s^2 + \cdots$$

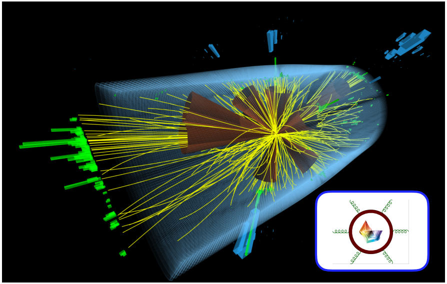
The Confinement Transition

- Occurs on a timescale of 10^{-23}s

  $\implies$ hard to directly measure as a function of time.

[Kormos, Collura, Salam, Takacs, Calabrese]

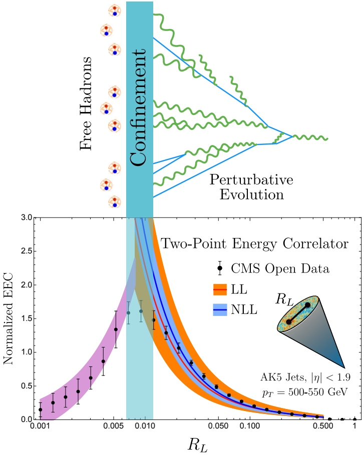




- Can it be directly imaged in asymptotic energy flux?

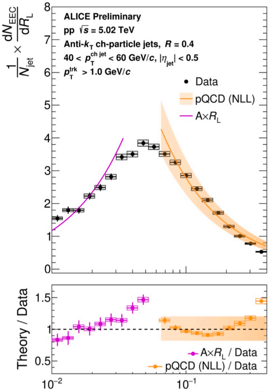
The Confinement Transition

- 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!

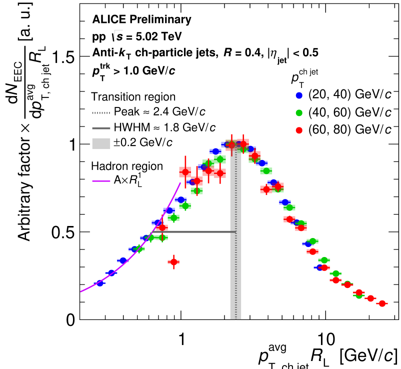


The Confinement Transition

- Beautiful measurement by ALICE confirms this picture:



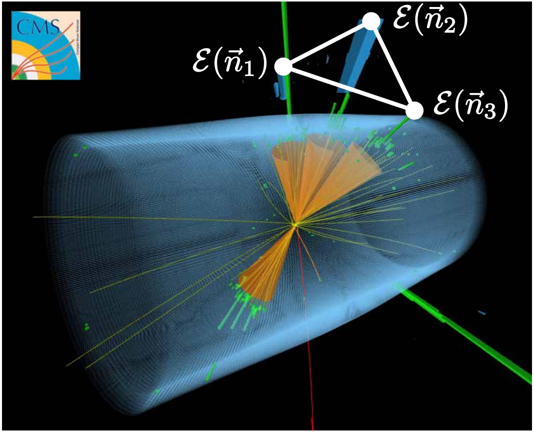
ALI-PREL-540229



ALI-PREL-540185

- Illustrates universality of the hadronization transition.

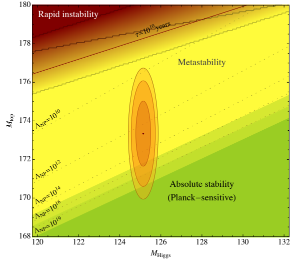
Weighing the Top Quark

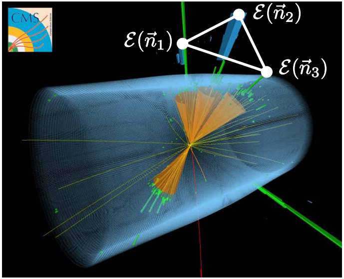


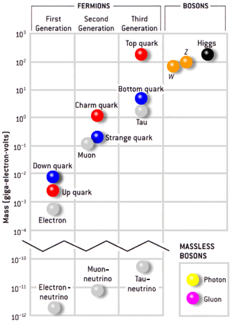
[Holguin, Moult, Pathak, Procura]

Top Quark Mass

- The top quark mass is one of the most important parameters of the SM. e.g. electroweak vacuum stability/criticality, electroweak fits, etc.
- Need simple observables with top mass sensitivity that can be computed from first principles field theory.

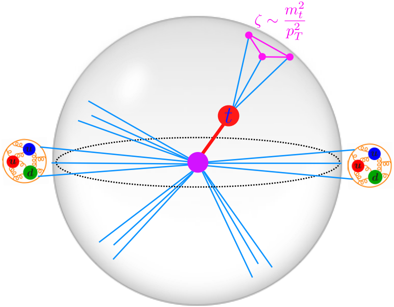


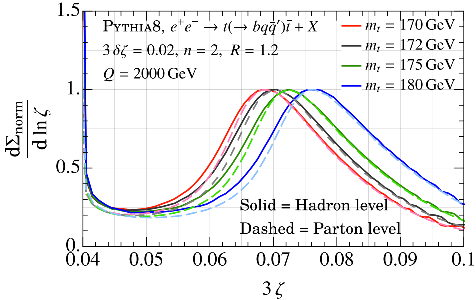




Top Quark Mass Measurement

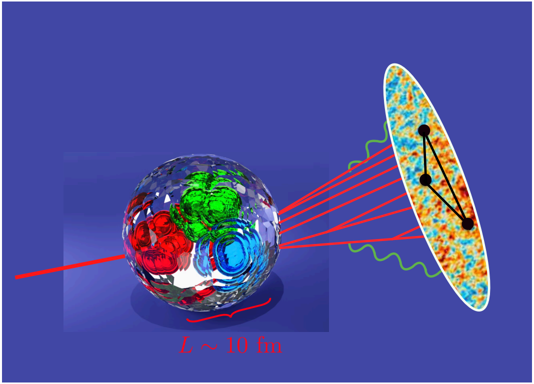
- Massive particles imprint their existence at a characteristic angular scale $\zeta \sim m^2/Q^2$.





- Optimistic for a precision top mass extraction at the LHC!

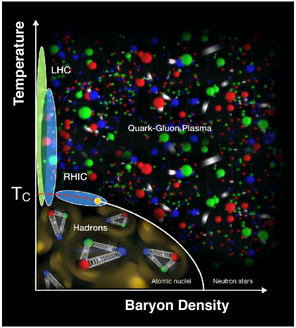
Resolving the Scales of the Quark Gluon Plasma

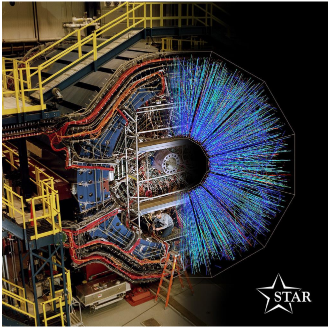


[Andres, Dominguez, Holguin, Kunnawalkam Elayavalli, Marquet, Moult]

The Quark Gluon Plasma

- Resolving the mystery of how asymptotically free quarks and gluons conspire to form a strongly coupled fluid is a primary goal of the nuclear physics program.

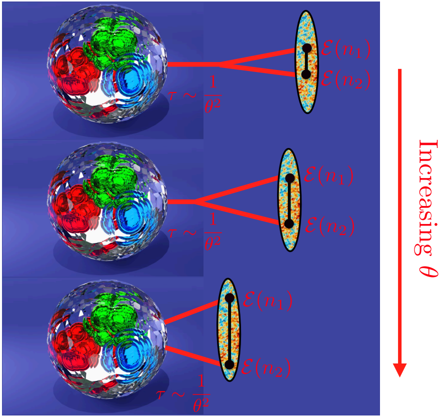


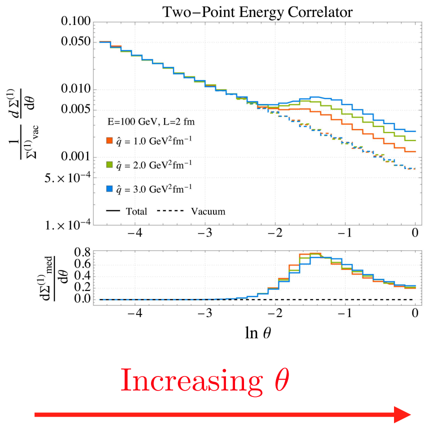


- This extreme state of matter can be produced in high energy colliders.

Resolving the Scales of the QGP

- QGP scales cleanly imprinted in two-point correlation!

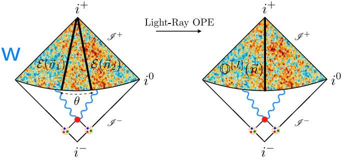




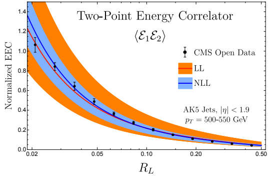
- Resolve Femtometer scales from asymptotic energy flux!

Summary

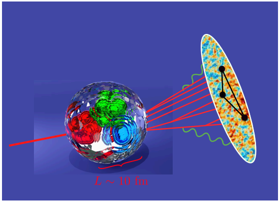
- Insights from formal theory are providing new ways to think about jet substructure.

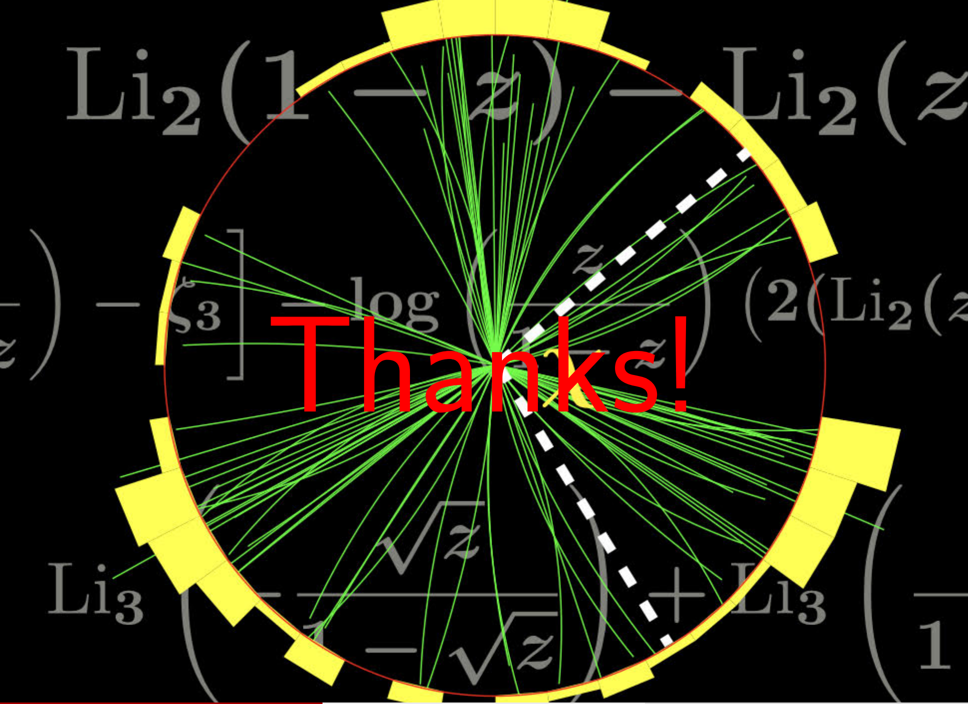


- Jet Substructure provides a physical realization of the OPE limit of lightray operators $\Longrightarrow$ direct bridge between recent field theory developments and QCD phenomenology.



- Energy correlators allow asymptotic energy flux to be decoded in terms of the underlying field theory.





Thanks!