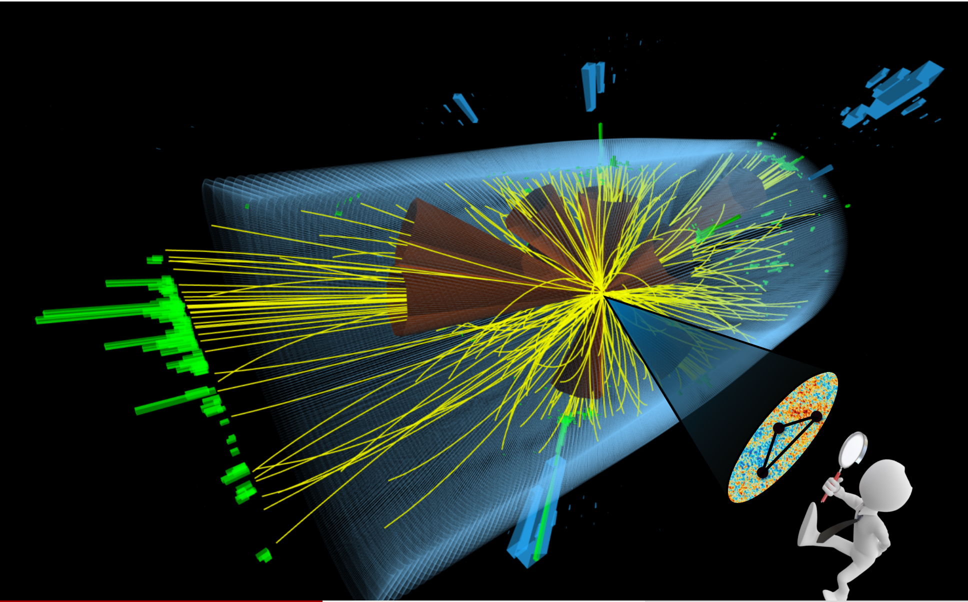
Imaging QCD Dynamics with Jet Substructure

Ian Moult
Yale

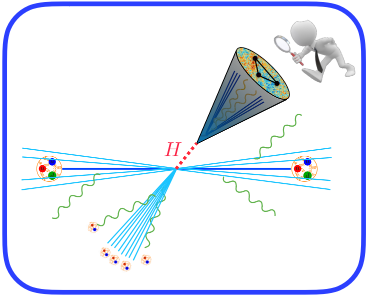
Jet Substructure!

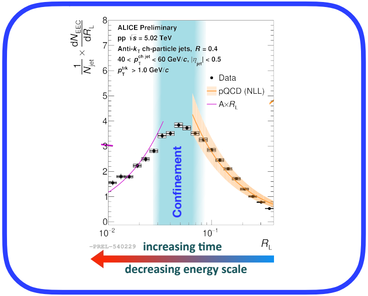


Jet Substructure

- Jet substructure has emerged as a central new technique at colliders:

Innovative Search Techniques | **Novel Probes of QCD Dynamics**

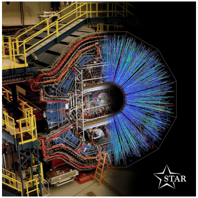


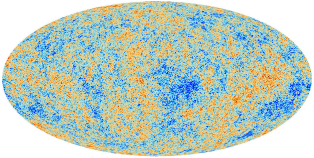


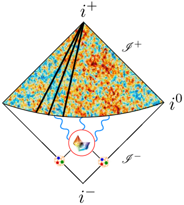
- Has evolved well beyond its origin to have a large impact on BSM, SM, high energy QCD and nuclear physics.

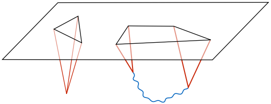
Decoding Energy Flux

- Subtle questions about QCD are imprinted in collider energy flux:





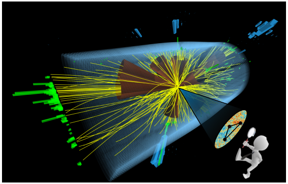




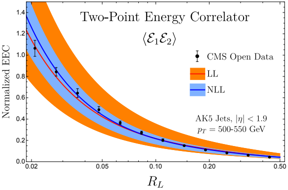
- Requires development of field theoretic techniques to interpret correlations in terms of the dynamics of the underlying field theory.

Outline

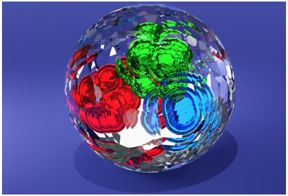
- Decoding Energy Flux



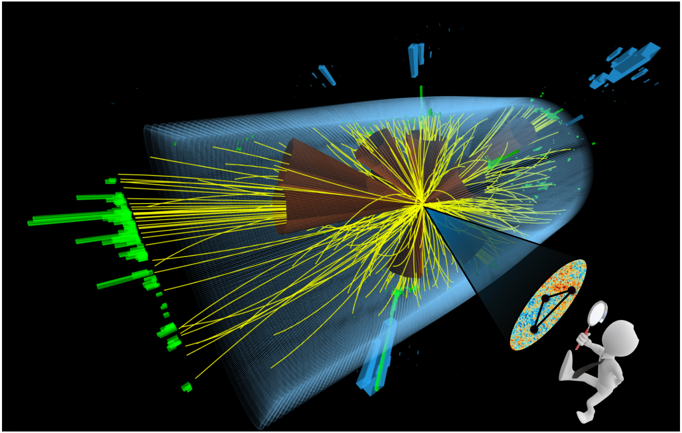
- Scaling Behavior of Quarks and Gluons



- Imaging Intrinsic and Emergent Scales of QCD

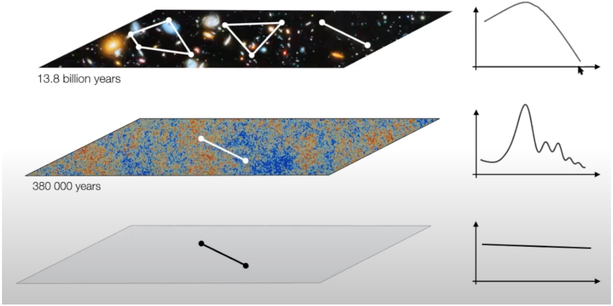


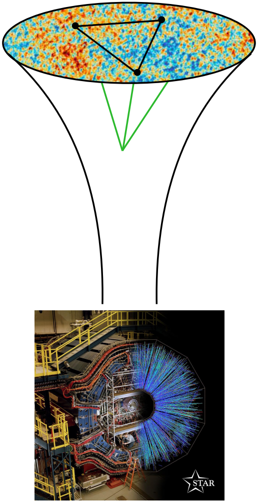
Decoding Energy Flux



Decoding Energy Flux

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

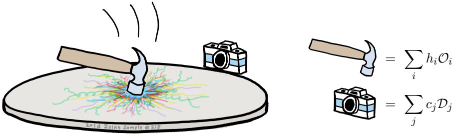




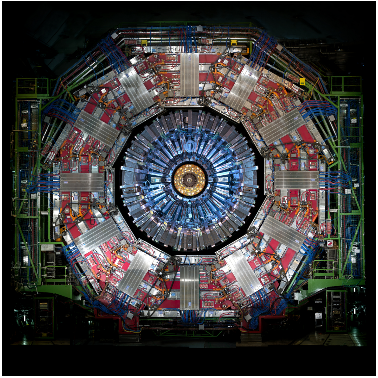
- What is the analog for collider physics?

Defining the Problem

- What is a detector?



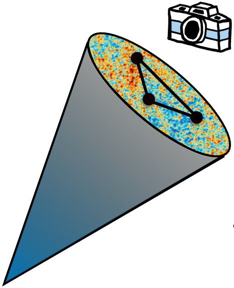
[Caron Huot, Kologlu, Kravchuk, Meltzer, Simmons Duffin]



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

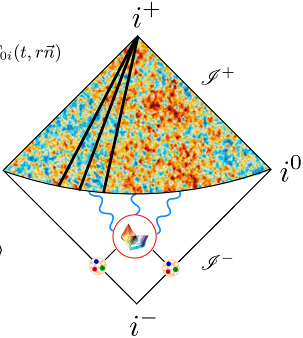
Calorimeter Cells in Field Theory

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



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

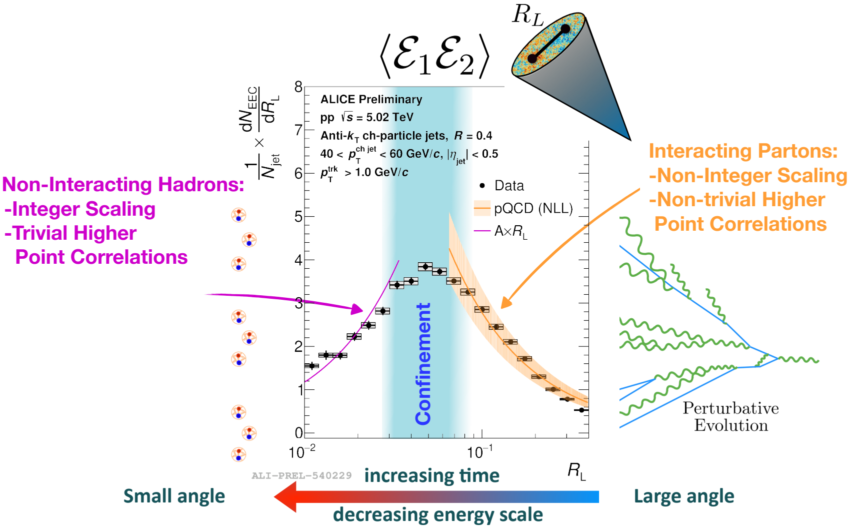
$$\langle \Psi | \mathcal{E}(\hat{n}_1) \cdots \mathcal{E}(\hat{n}_k) | \Psi \rangle$$



- Provides a sharp link between experimentally measurable observables and the underlying QFT.

Energy Correlators: Reality

Figure: Wenqing Fan



- Imaging the confinement transition with Jet Substructure!

Energy Correlators: Reality

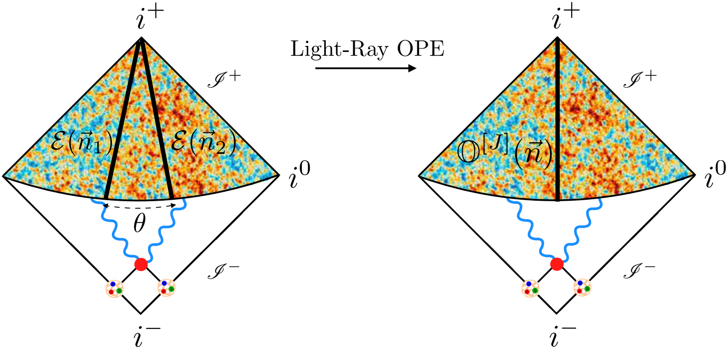
- For more detailed talks on aspects of energy correlators, see:
  - Andrew Tamis

  - Wenqing Fan

  - Ananya Rai

  - Jack Holguin

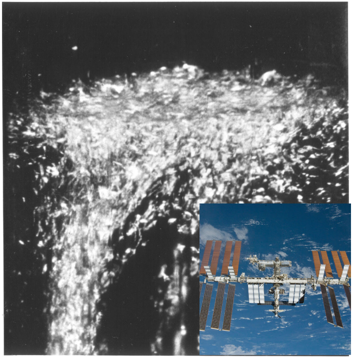
Scaling Behavior of Quarks and Gluons

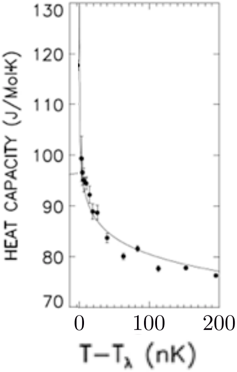


Scaling Behavior in QFT

- Scaling behavior in Euclidean regime well understood.

λ-point of Helium

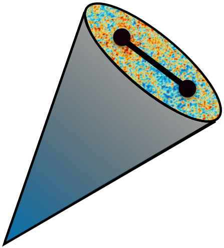


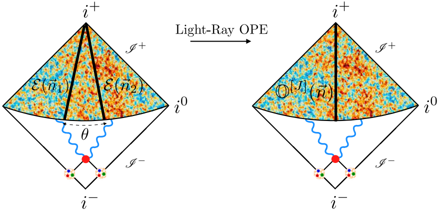


$$\mathcal{O}(x)\mathcal{O}(0) = \sum x^{\gamma_i} c_i \mathcal{O}_i$$

The OPE Limit of Lightray Operators

- Energy flow operators admit a Lorentzian OPE: "the lightray OPE"





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

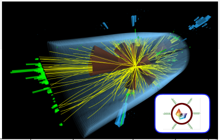
[Hofman, Maldacena]
[Chang, Kologlu, Kravchuk, Simmons Duffin, Zhiboedov]
QCD: [Dixon, Moult, Zhu]

- Predicts universal scaling behavior in correlations of energy flux at energies $E \gg \Lambda_{\text{QCD}}$.

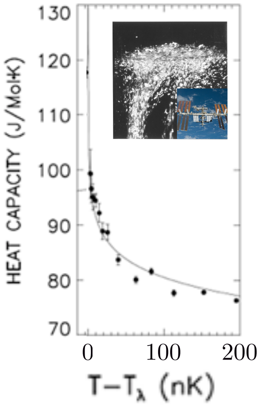
See early work by [Konishi, Ukawa, Veneziano]

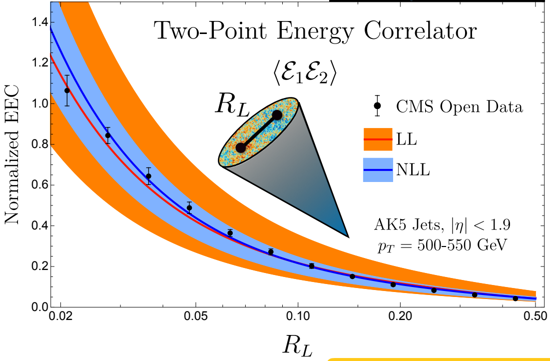
Scaling Behavior in Jets

[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!





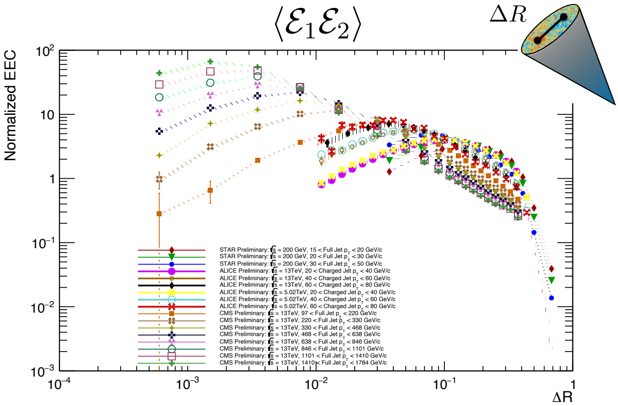
$$\mathcal{E}(\hat{n}_1)\mathcal{E}(\hat{n}_2) \sim \sum \theta^{\tau_i - 4} \mathbb{O}_i(\hat{n}_1)$$

- Beautiful scaling behavior in energy flux, even in complicated hadronic environment!

Scaling Behavior in Jets

Thanks to Helen Caines, Meng Xiao, ChenFeng Lu, Andrew Tamis, Ananya Rai.

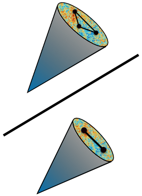
- Measurements from ALICE, CMS and STAR from 15 GeV to 1784 GeV recentlv released!

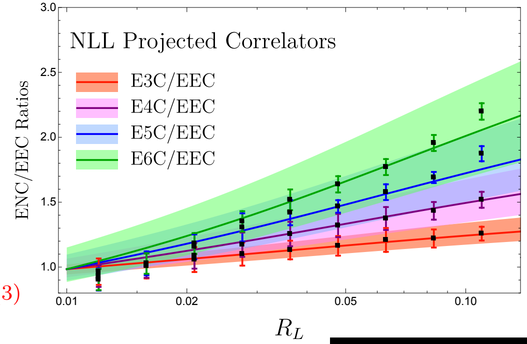


- Dominated by classical scaling. Can we accurately measure anomalous scaling?

The Spectrum of a Jet

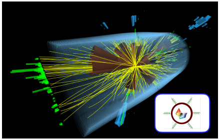
- The light-ray OPE predicts that the N-point correlators develop an anomalous scaling that depends on N.





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

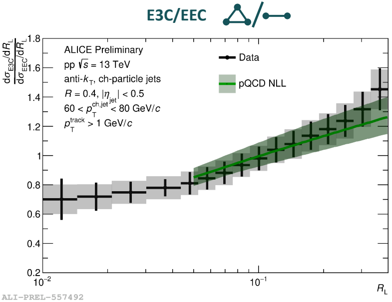
- Directly probes the spectrum of (twist-2) lightray operators from asymptotic energy flux.

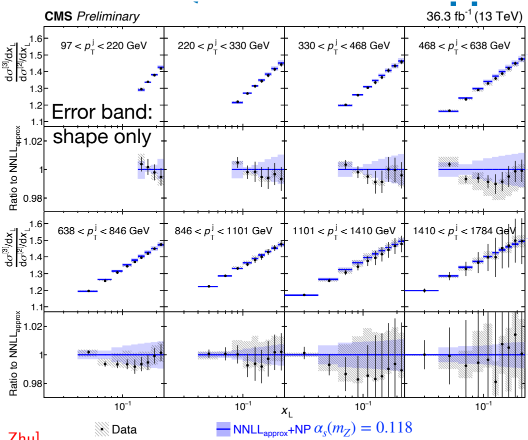


Anomalous Scaling of 3/2 Ratio

- Anomalous scaling measured from 15 GeV to 1784 GeV!

$$\frac{\langle \mathcal{E}_1\mathcal{E}_2\mathcal{E}_3\rangle}{\langle \mathcal{E}_1\mathcal{E}_2\rangle} \sim \frac{\langle \mathbb{O}^{[3]}\rangle}{\langle \mathbb{O}^{[3]}\rangle} \sim R_L^{\gamma(4)-\gamma(3)}$$

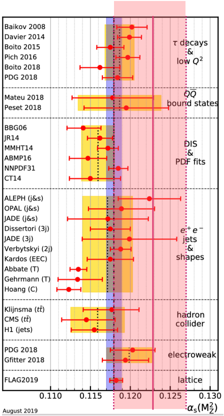


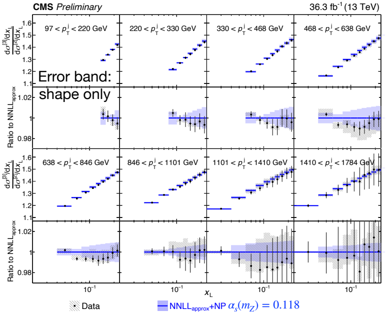


Using [Lee, Mecaj, Moult], [Chen, Gao, Li, Xu, Zhang, Zhu]

The Strong Coupling

- Proof of principle α_s can be extracted from jet substructure in complicated hadron collider environment: 4% accuracy.
- Hope to use high energies of the LHC to resolve previous tensions in α_s extractions.

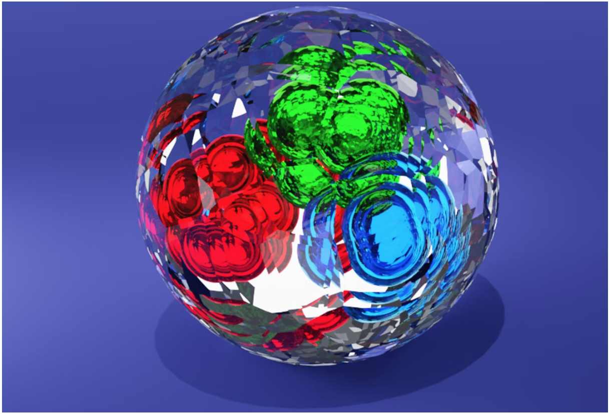




$$\alpha_s(m_Z) = 0.1229^{+0.0040}_{-0.0050}$$

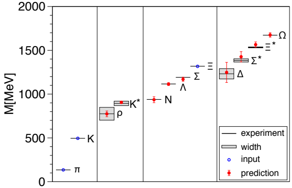
$$= 0.1229^{+0.0014(stat.)+0.0030(theo.)+0.0023(exp.)}_{-0.0012(stat.)-0.0033(theo.)-0.0036(exp.)}$$

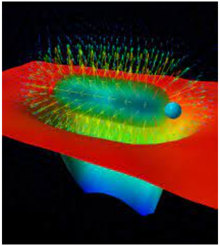
The Confinement Transition

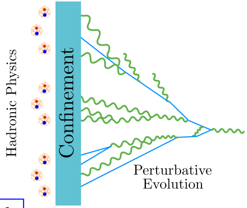


Dynamics of Hadronization

- What are the dynamics of the hadronization process?



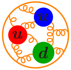


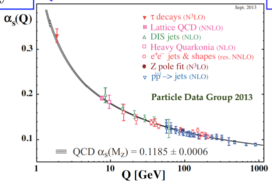


Long Time Scale
Low Energy

$\alpha_s(Q)$ ←

Short Time Scale
High Energy

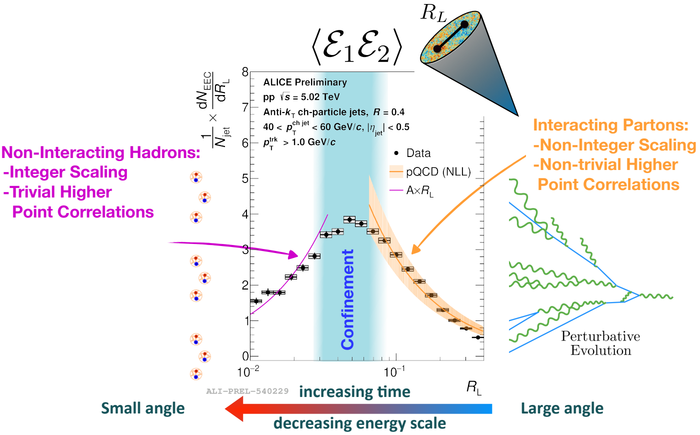




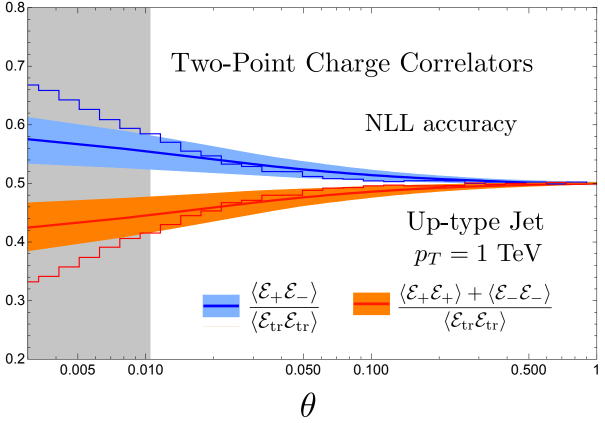
$$\hat{O} = \alpha_s + \alpha_s^2 + \cdots$$

The Confinement Transition

- 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!



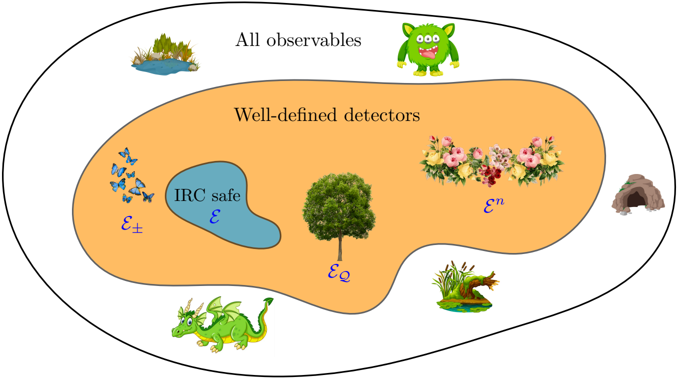
Beyond Energy Flux



[Lee, Moult]

The Space of Detectors

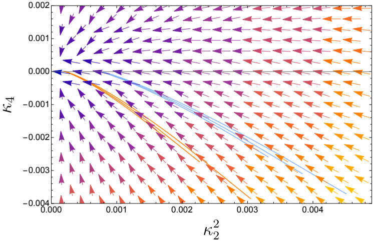
- Details of the hadronization process are encoded in the quantum numbers (charge, flavor, ...): By definition, energy flux is insensitive!
- What is the space of detectors over which we can gain theoretical control?

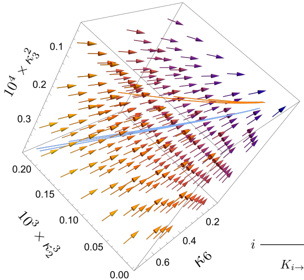


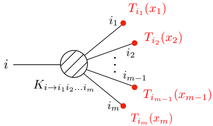
Factorization

[Chen, Jaarsma, Li, Moult, Waalewijn, Zhu]

- More general observables can be calculated by combining factorization into universal matrix elements, with the Renormalization Group.
- Tremendous recent progress in understanding renormalization group evolution of functions characterizing correlations in the hadronization process (beyond DGLAP).





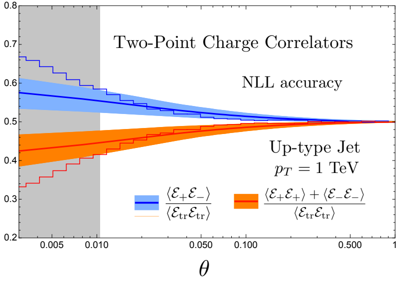


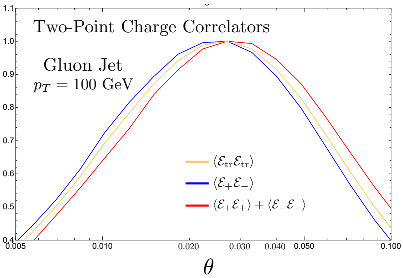
- Enables the calculation of correlations on energy flux carried by hadrons of specific quantum numbers: e.g. $\langle \Psi | \mathcal{E}_+(\hat{n}_1) \cdots \mathcal{E}_-(\hat{n}_k) | \Psi \rangle$

Charged Energy Flux

[Lee, Moult]

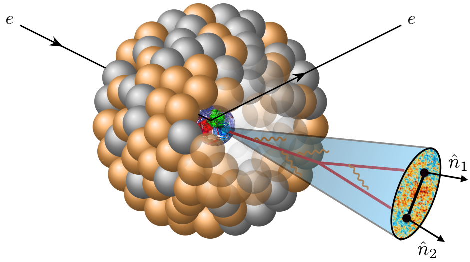
- Opposite sign hadrons exhibit enhanced small angle correlations relative to like sign hadrons.
- Not electromagnetic in nature: generated by hadronization!





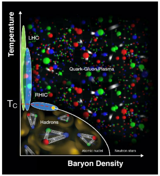
- How far can we push into the confinement transition? Experimental measurements will be crucial.

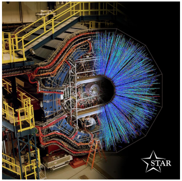
Identifying Intrinsic and Emergent Scales of QCD

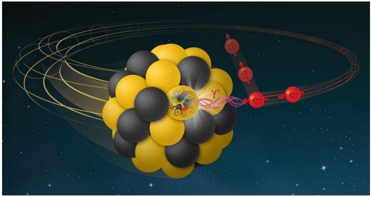


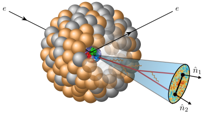
Imaging Emergent and Intrinsic Scales of QCD

- Upshot: Massless QCD above the confinement scale exhibits powerlaw scaling in energy flux $\implies$ any new scale introduced into the system will imprint itself at a characteristic scale.
- Understanding of jets in vacuum allows them to be used as well calibrated probes in more complicated systems: hot and cold nuclear matter.

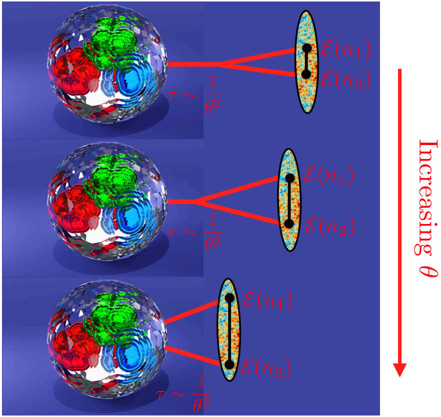








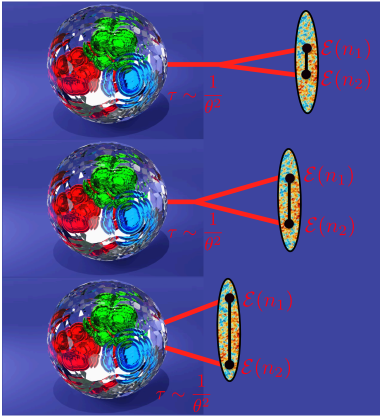
Application I: Resolving the Scales of the QGP



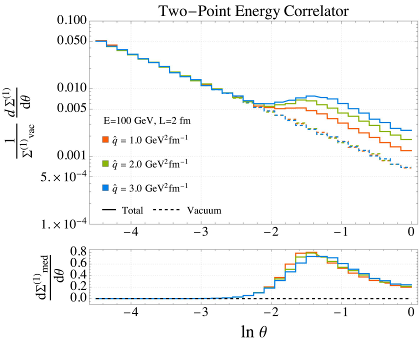
- The QGP introduces a number of new scales into the problem.
- Here we will consider the simplest case of a static medium.
- We will focus on one scale, $\theta_L \sim \frac{1}{\sqrt{LE}}$, which determines the angle at which splittings resolve the medium

Application I: Resolving the Scales of the QGP

- QGP scales cleanly imprinted in two-point correlation.



Increasing θ

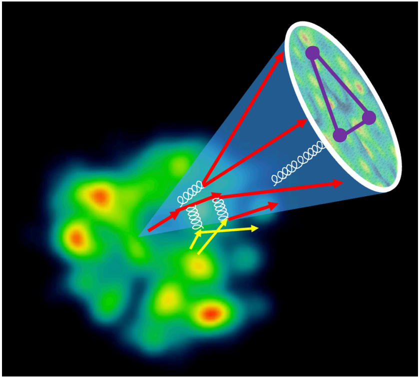


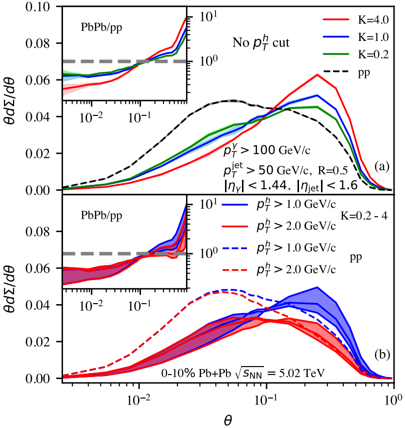
Increasing θ

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

Application I: Resolving the Scales of the QGP

- Modifications persist in realistic simulation with dynamic medium. Provides sensitivity to Debye mass.





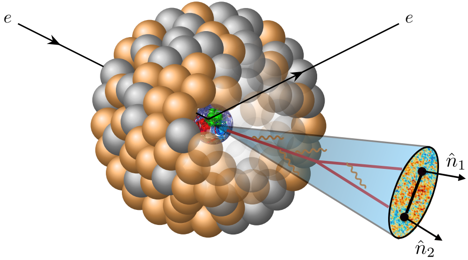
[Yang, He, Moult, Wang]

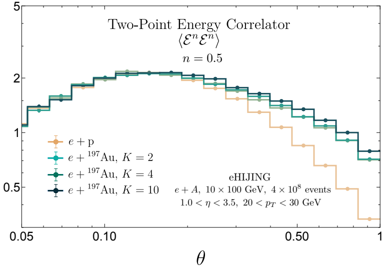
Application I: Resolving the Scales of the QGP

- What does it look like in data?

Application II: Imaging Cold Nuclear Matter

- EIC will provide high energy collisions on a variety of nuclei.
- Allows for the study of medium modification in a simplified setting.

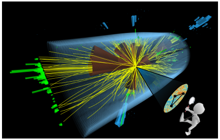




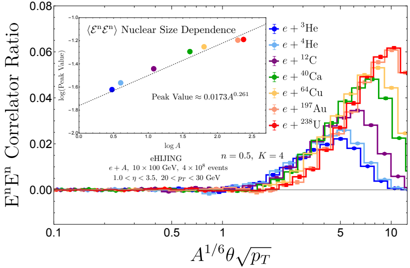
[Devereaux, Fan, Ke, Lee, Moult]

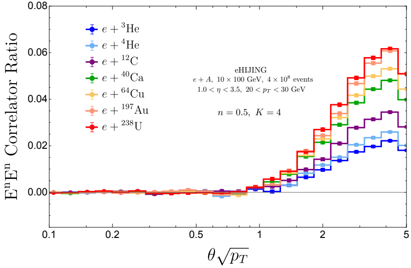
- The size of the nucleus represents a clear physical scale that will be imprinted in the angular structure of the correlator.

Application II: Imaging Cold Nuclear Matter



- Nuclear sizes cleanly imprinted into correlators.

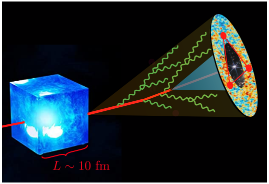


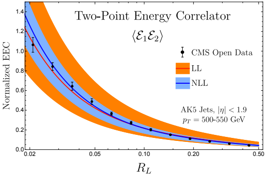


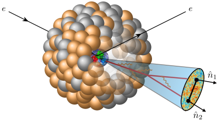
- Achieve femtometer resolution from asymptotic energy flux!
- Provides a common language from hot to cold QCD.

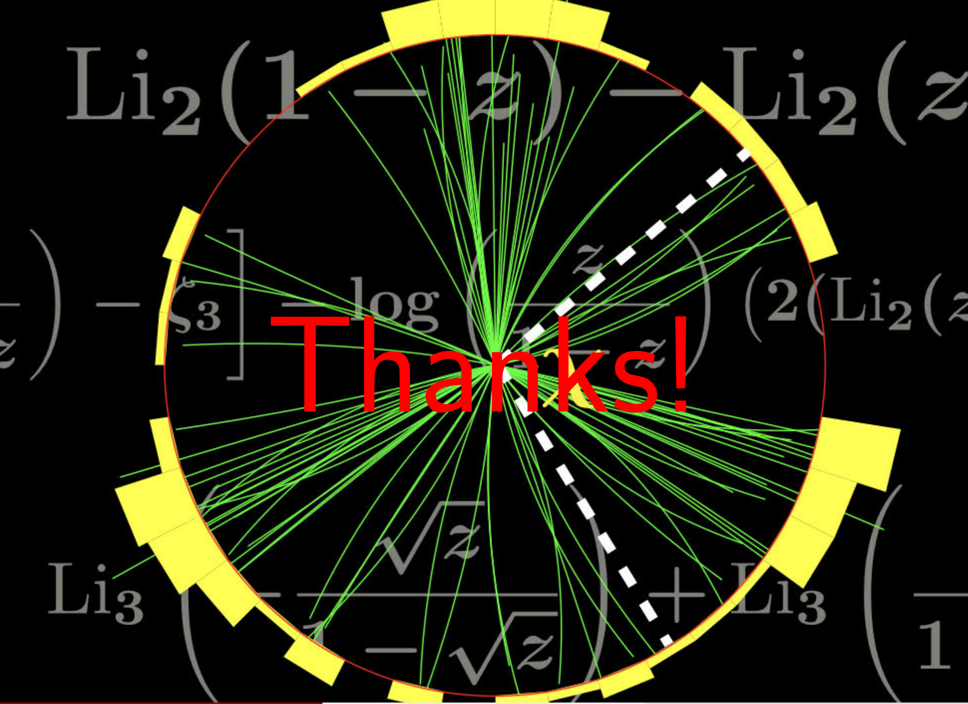
Summary

- Jet Substructure provides new ways to study the dynamics of QCD.
- Correlation functions, $\langle \mathcal{E}(n_1) \cdots \mathcal{E}(n_k) \rangle$, provide a sharp link between theory and experiment.
- A variety of recent measurements shed new light on energy flux in QCD!









Thanks!