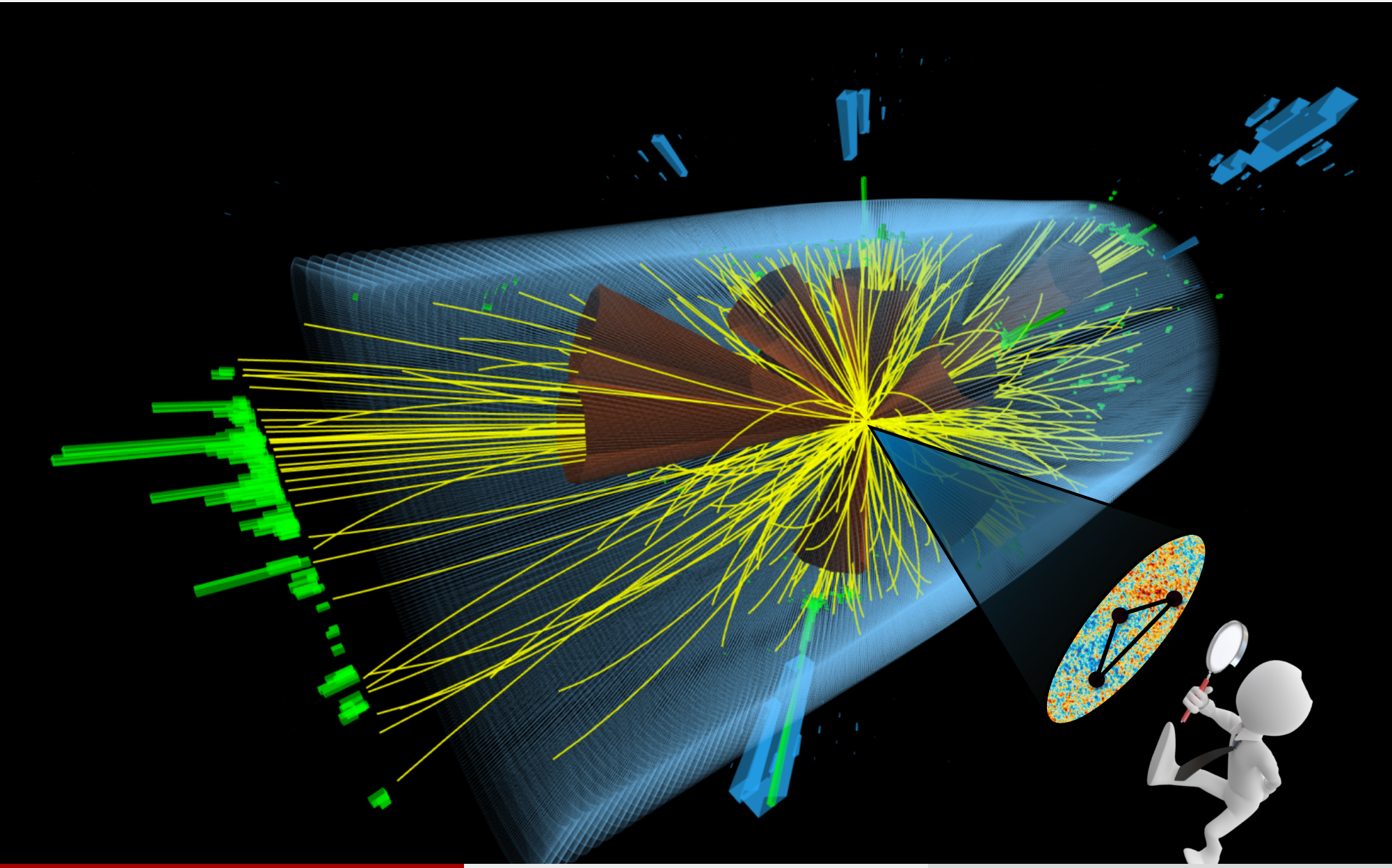
Imaging Intrinsic and Emergent Scales of the QGP

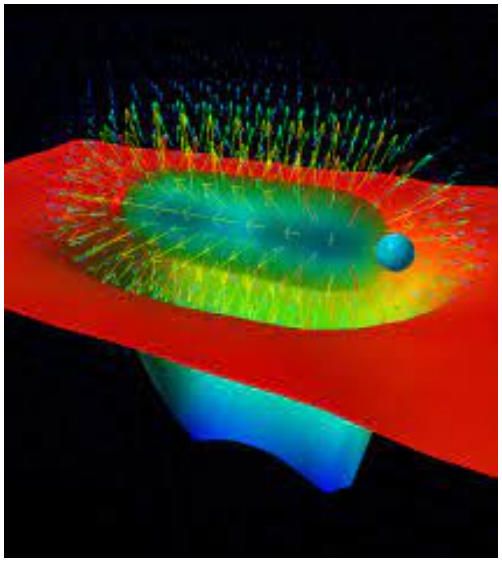
Ian Moult
Yale

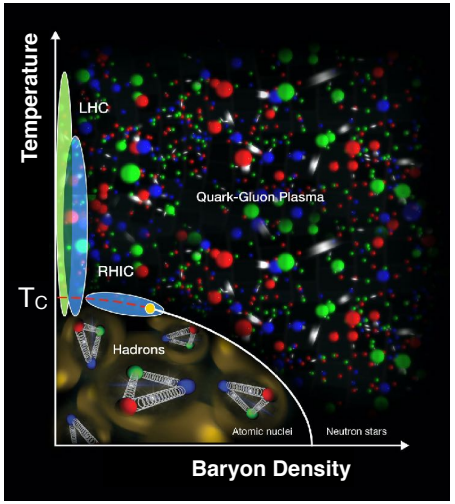
Jet Substructure!

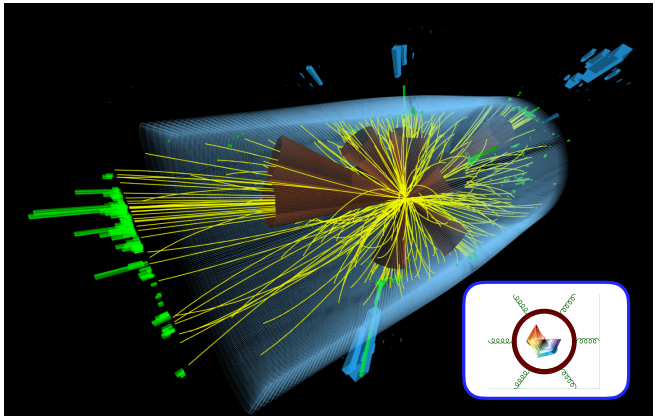


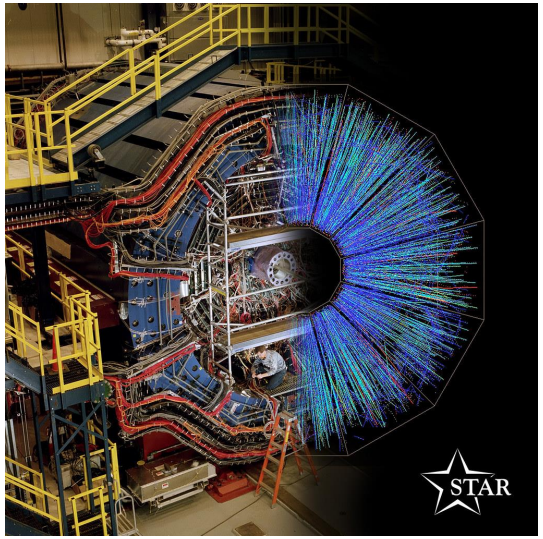
A Laboratory for QCD

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



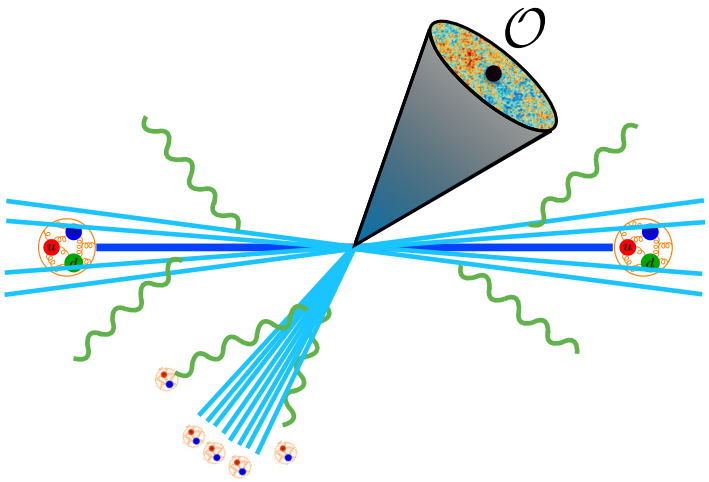




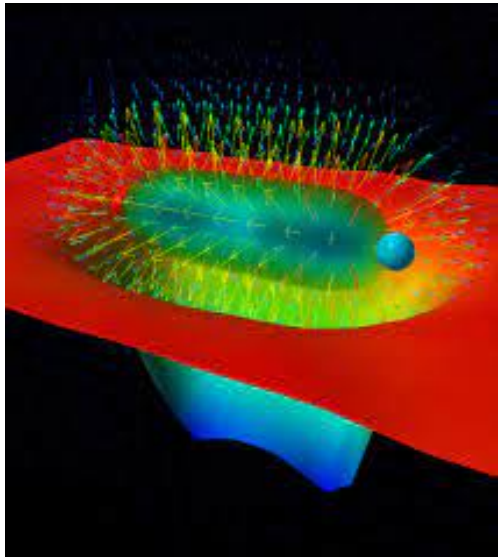


Observables

- Observables are the link between theory and experiment: We want to make this link as direct as possible.



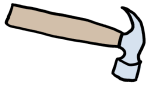
$$\langle \mathcal{O} \rangle = \langle \Psi | \mathcal{O} | \Psi \rangle$$



- As we move to studying more subtle features, we need to sharpen this link.
- Correctly choosing observables facilitates the experiment $\leftrightarrow$ theory link.

Correlators=Experiment

- Typically one views the set of correlation functions as what one would like to calculate/ extract from a system. If you know all the correlators you have solved the system.
- Two levels of belief:
  1. "We will view the correlation functions as our experimental results. We will treat the correlation functions as the physical properties of a system."
  2. "What is reality? All that we can measure in our world appears to be correlation functions. Thus, it is tempting to define the physical theory of our world as a theory of correlation functions, and correlation functions may represent the reality of our world."



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

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

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

Defining the Problem

- What correlation functions can we measure at colliders?
- What is a detector?

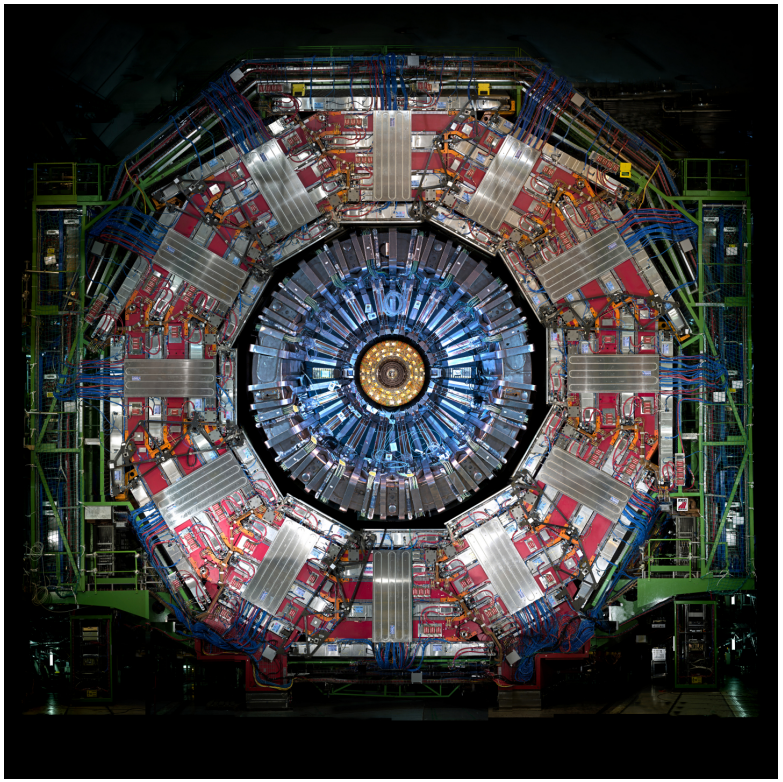
$$= \sum_i h_i \mathcal{O}_i$$

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

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

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

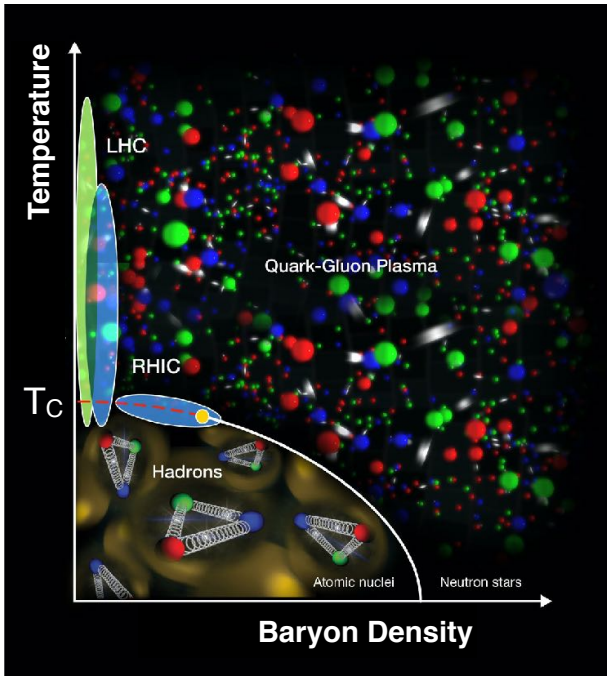
$$\langle \Psi | \mathcal{E}(\hat{n}_1) \cdots \mathcal{E}(\hat{n}_k) | \Psi \rangle$$

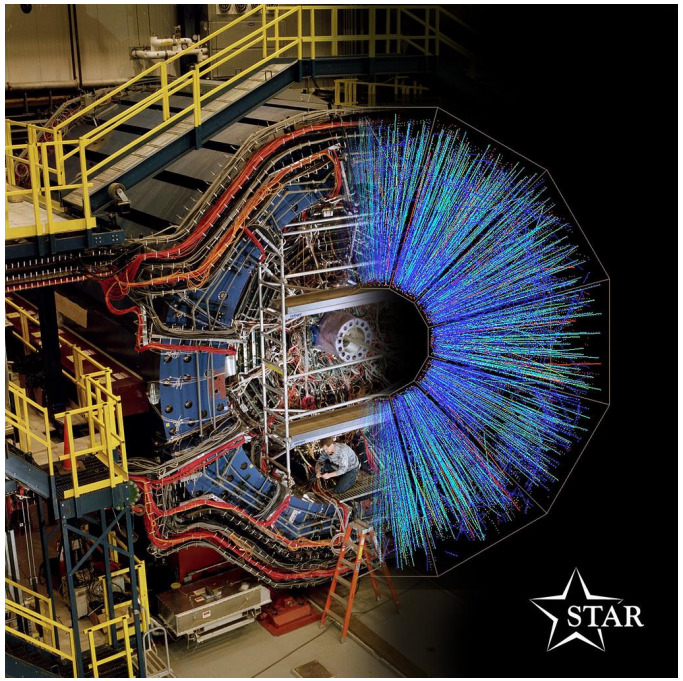


- Provide a sharp link between experimentally measurable observables and the underlying QFT.

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.

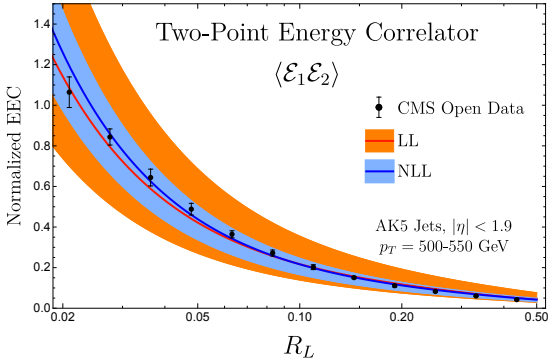




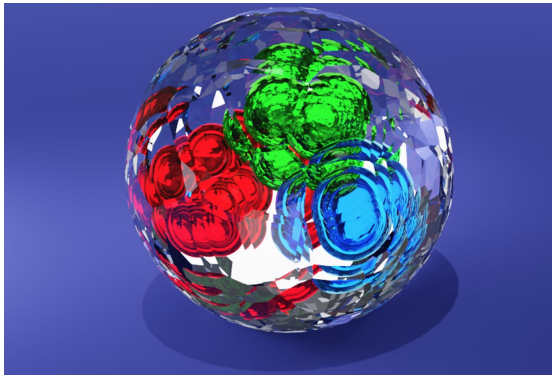
- Extracting subtle signals in an extremely complicated environment provides a primary target for new jet substructure techniques.

Outline

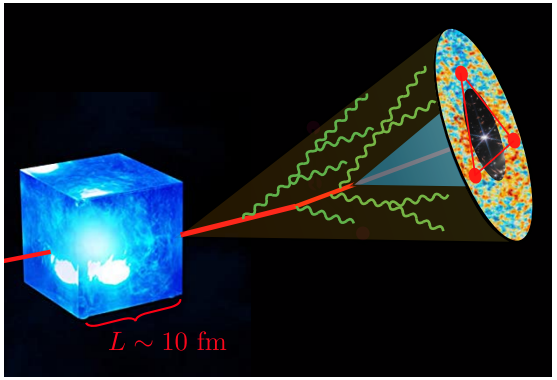
- Scaling Behavior of Quarks and Gluons



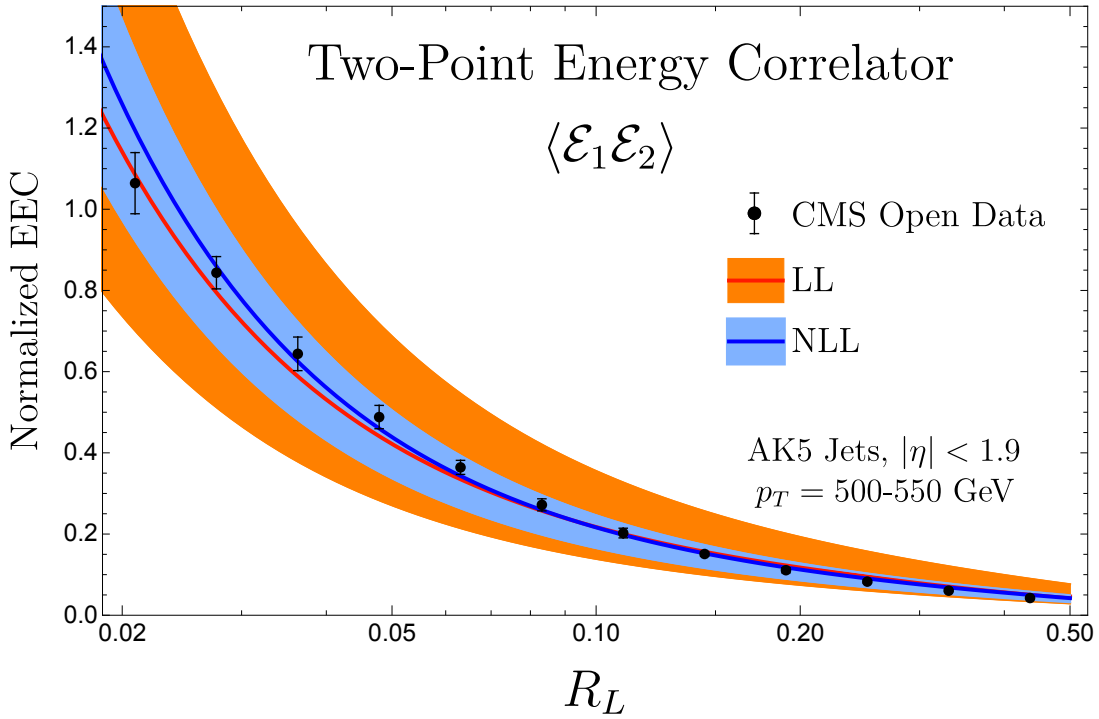
- Resolving the Scales of the QGP



- Seeing Beauty in the QGP

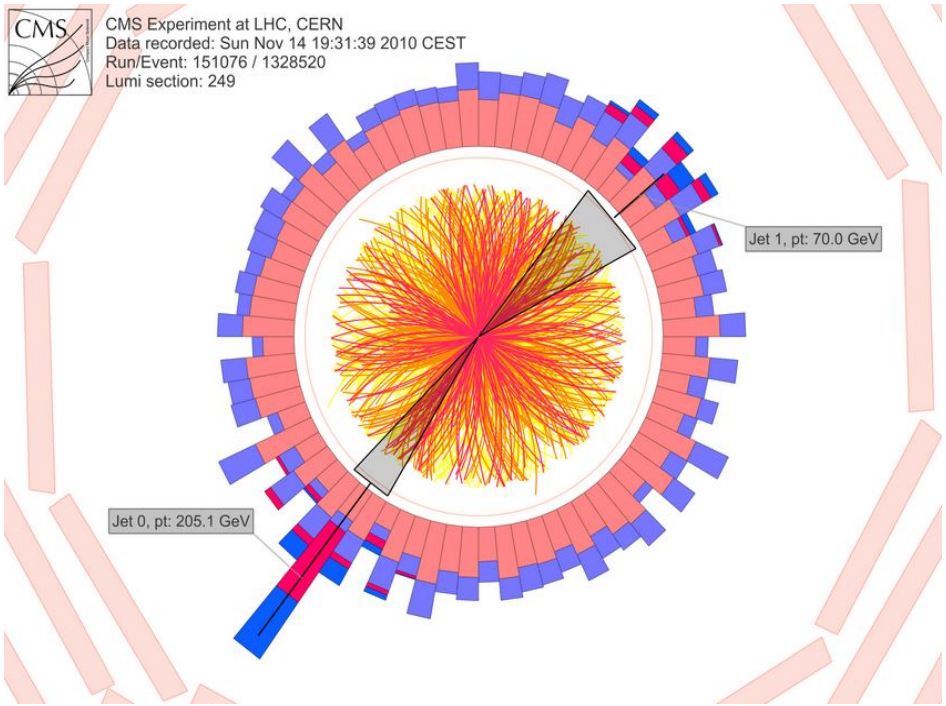


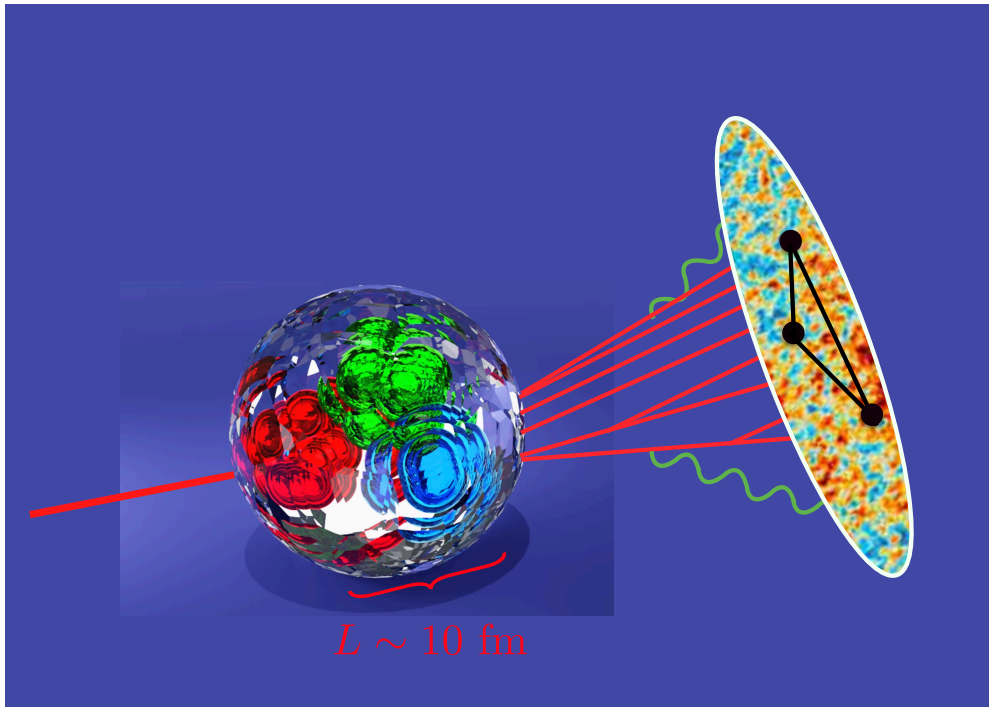
Scaling Behavior of Quarks and Gluons



Imaging the Plasma

- Energetic quarks and gluons produced in the collisions shoot through the plasma, much like the classic Rutherford experiment.

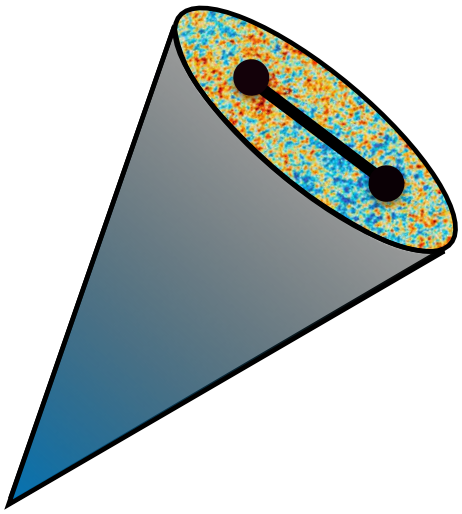


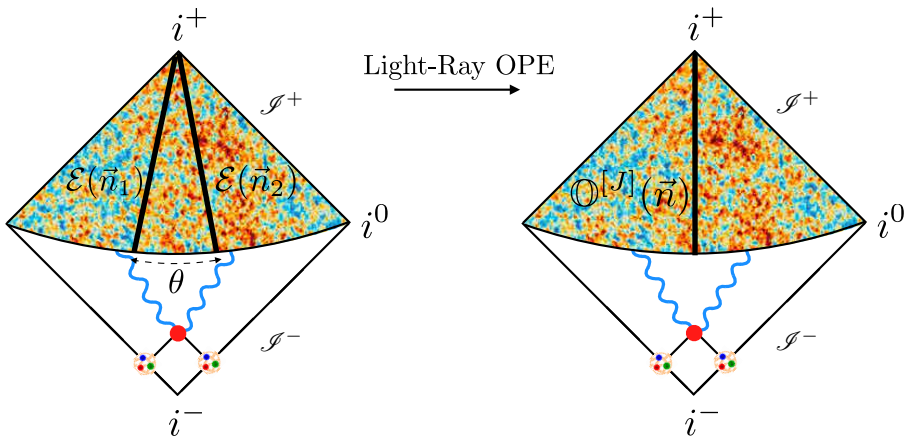


- How can we see there was a 10^{-14}m ball of plasma at the center?
- We must first understand the case where there is no plasma.

The OPE Limit of Lightray Operators

- Energy flow operators admit an OPE
  $\Longrightarrow$ power law scaling in the absence of other scales.





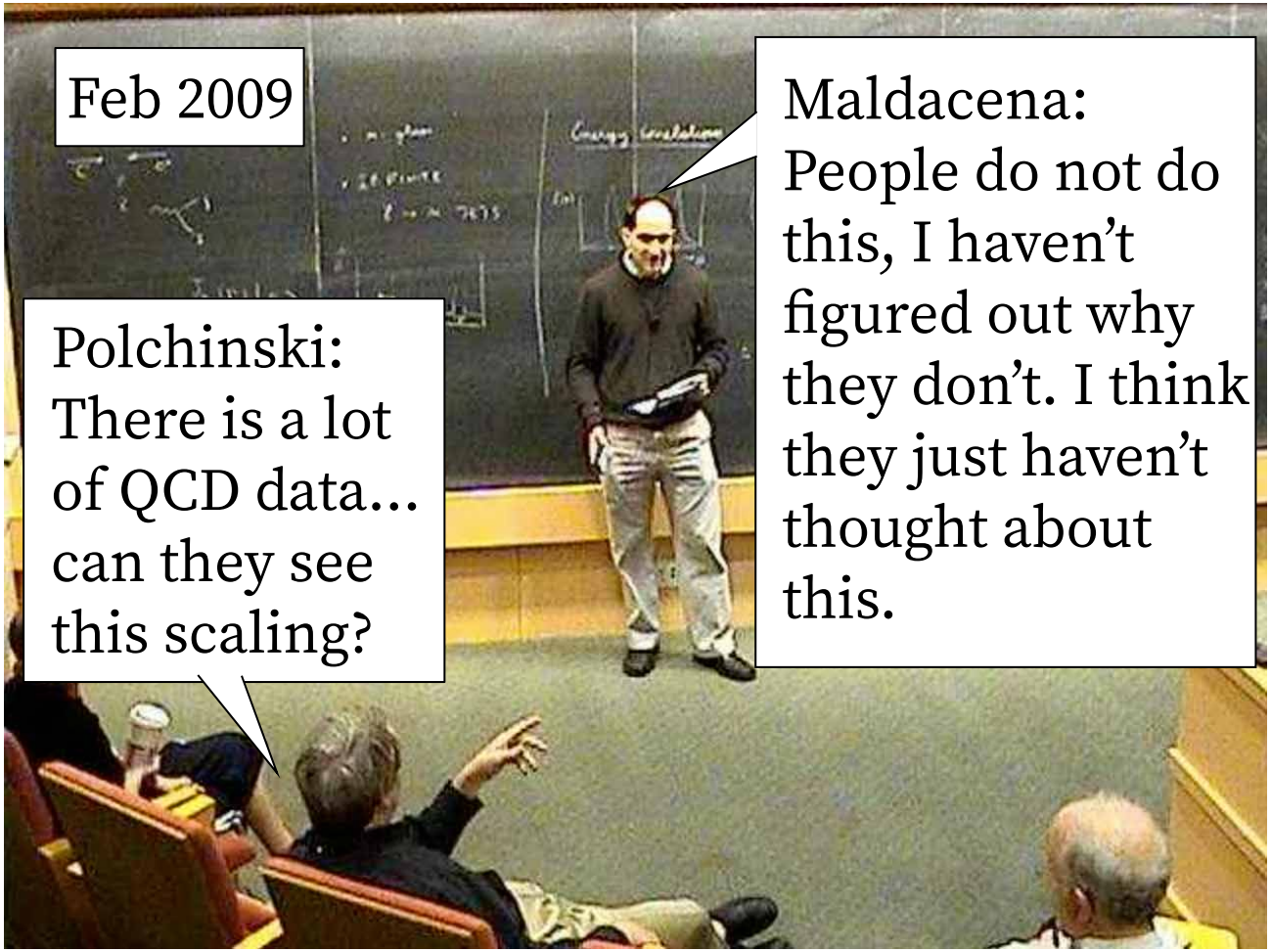
$$\mathcal{E}(\hat{n}_1)\mathcal{E}(\hat{n}_2) \sim \sum \theta^{\tau_i - 4}\mathbb{O}_i(\hat{n}_1)$$

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

- Predicts universal scaling behaviors for correlations in energy flux: A general phenomenon in QFT. Can it be tested?

Theory-Experiment Gap I

- Maldacena has been waiting 15 years:



Theory-Experiment Gap II

- Steve Ellis has been waiting 45 years:

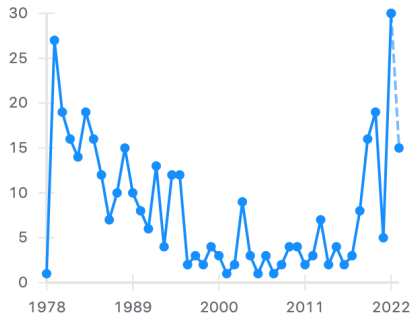
Energy Correlations in electron - Positron Annihilation: Testing QCD

C.Louis Basham (Washington U., Seattle), Lowell S. Brown (Washington U., Seattle), Stephen D. Ellis (Washington U., Seattle), Sherwin T. Love (Washington U., Seattle)
Aug, 1978

13 pages
Published in: *Phys.Rev.Lett.* 41 (1978) 1585
DOI: 10.1103/PhysRevLett.41.1585
Report number: RLO-1388-759
View in: OSTI Information Bridge Server, ADS Abstract Service

cite claim reference search 381 citations

Citations per year



Abstract: (APS)
An experimental measure is presented for a precise test of quantum chromodynamics. This measure involves the asymmetry in the energy-weighted opening angles of the jets of hadrons produced in the process e+e−→hadrons at energy W. It is special for several reasons: It is reliably calculable in asymptotically free perturbation theory; it has rapidly vanishing (order 1W2) corrections due to nonperturbative confinement effects; and it is straightforward to determine experimentally.

SUCCESSIVE COMBINATION JET ALGORITHM FOR HADRON COLLISIONS

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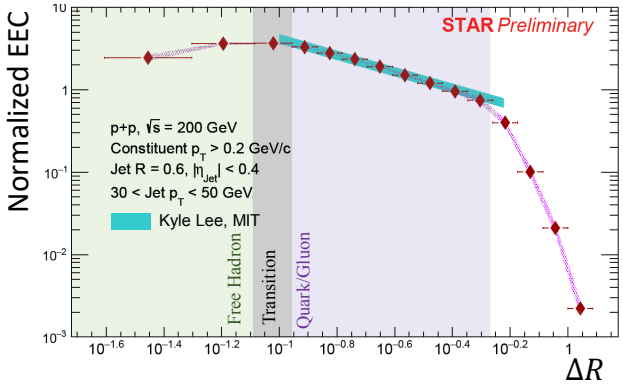
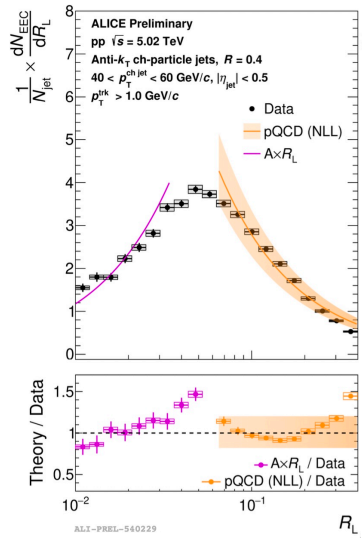
Abstract

Jet finding algorithms, as they are used in e^+e^- and hadron collisions, are reviewed and compared. It is suggested that a successive combination style algorithm, similar to that used in e^+e^- physics, might be useful also in hadron collisions, where cone style algorithms have been used previously.

Finally....

- A milestone in connecting jet substructure with QFT.
- Observation of new field theory phenomenon never tested in other systems.

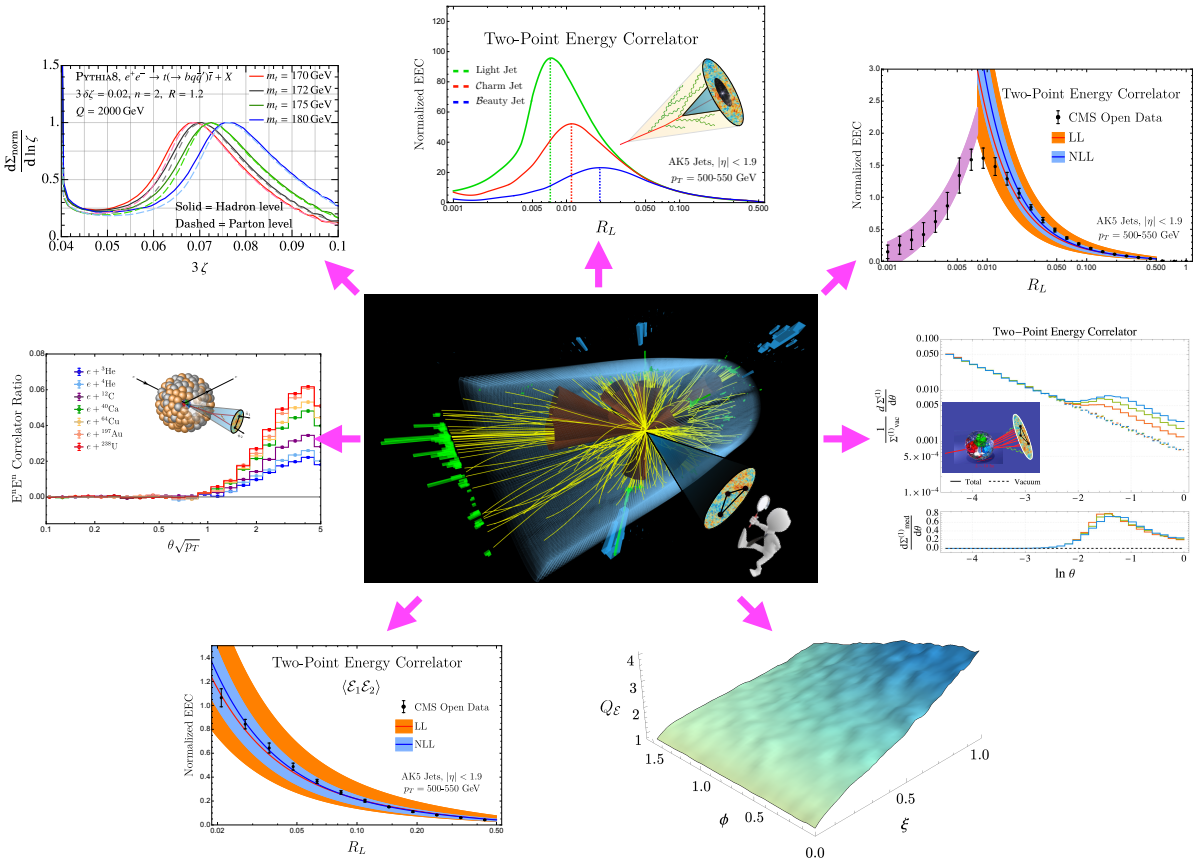




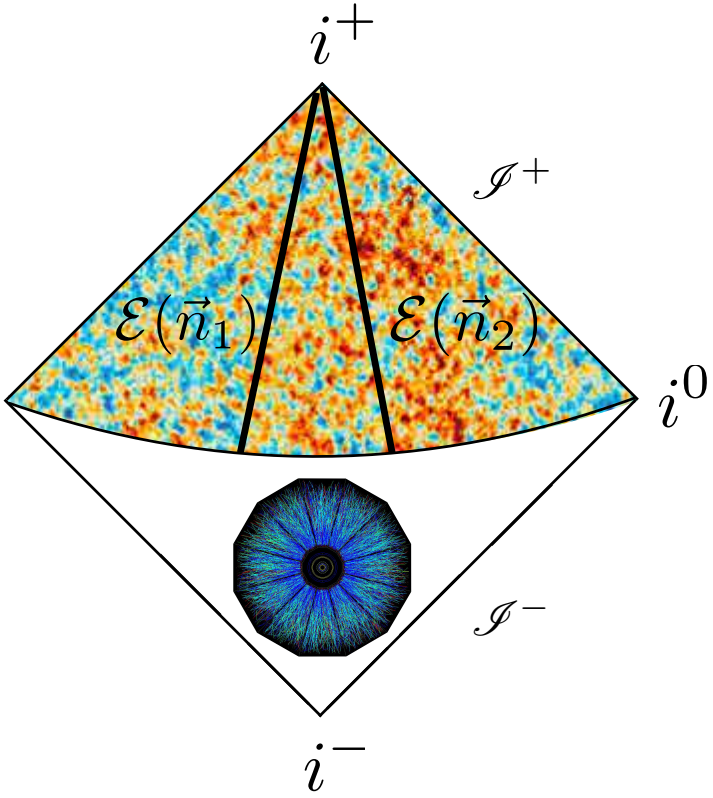
"This is the first time I ever found the LHC interesting"
-Anonymous Field Theorist

Imaging Emergent and Intrinsic Scales

- 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.

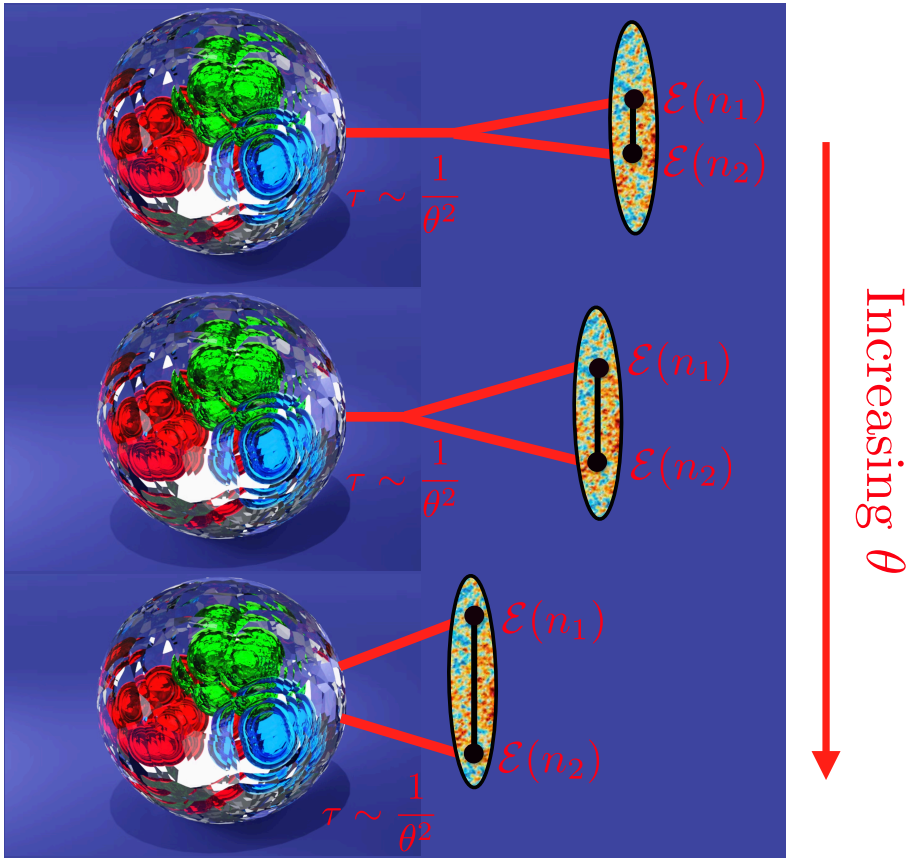


Resolving the Scales of the QGP



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

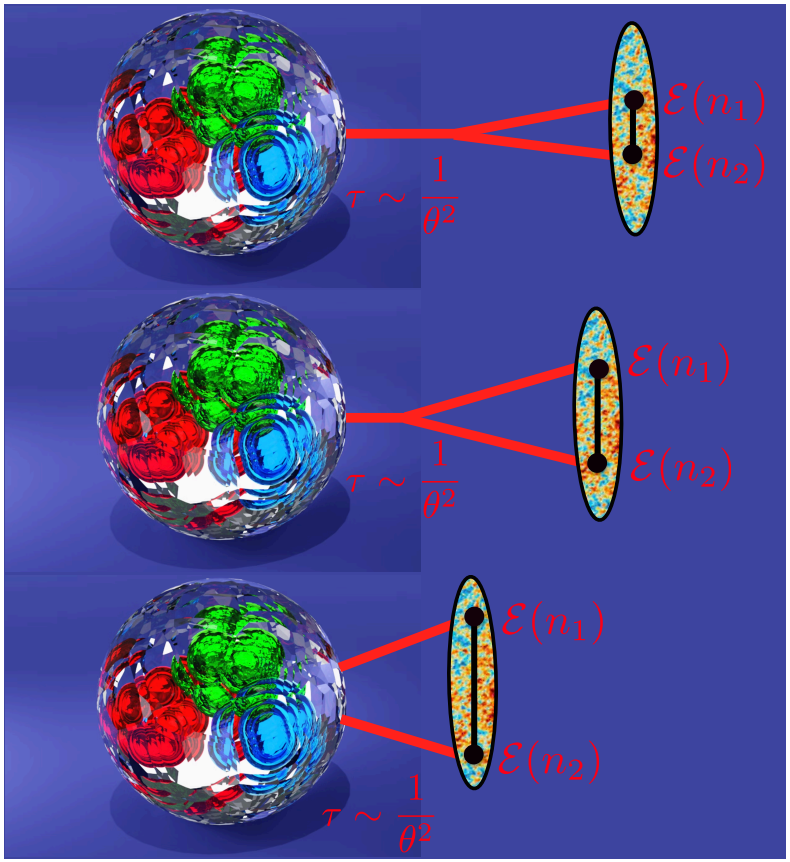
Resolving the Scales of the QGP



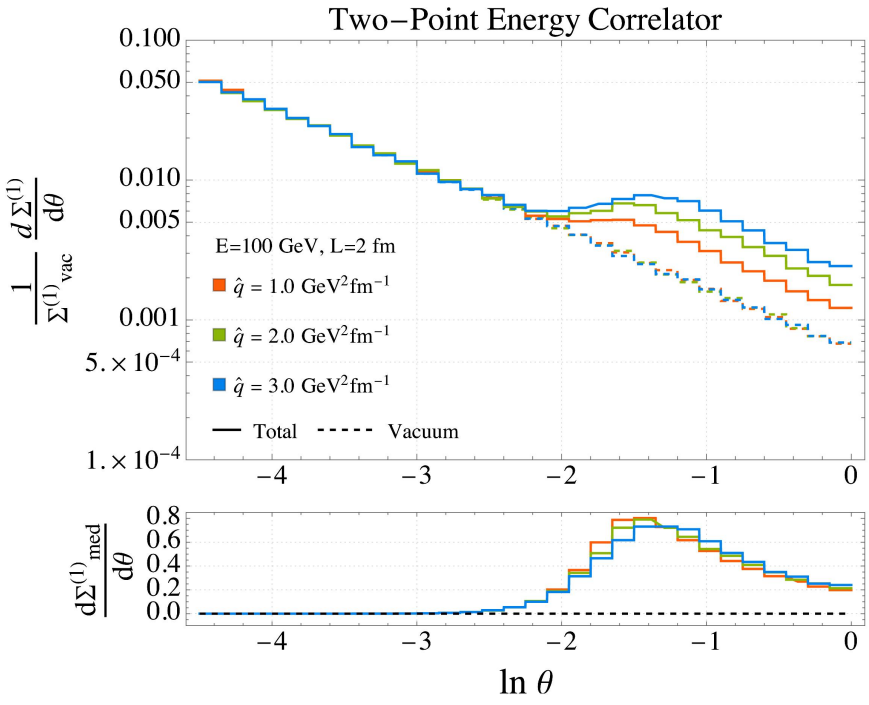
- The QGP introduces a number of new scales into the problem.
- Here we will consider the simplest case of a static medium.
- We will focus on one scale, $\theta_L \sim \frac{1}{\sqrt{LE}}$, which determines the angle at which splittings resolve the medium

Resolving the Scales of the QGP

- QGP scales cleanly imprinted in two-point correlation.



Increasing θ

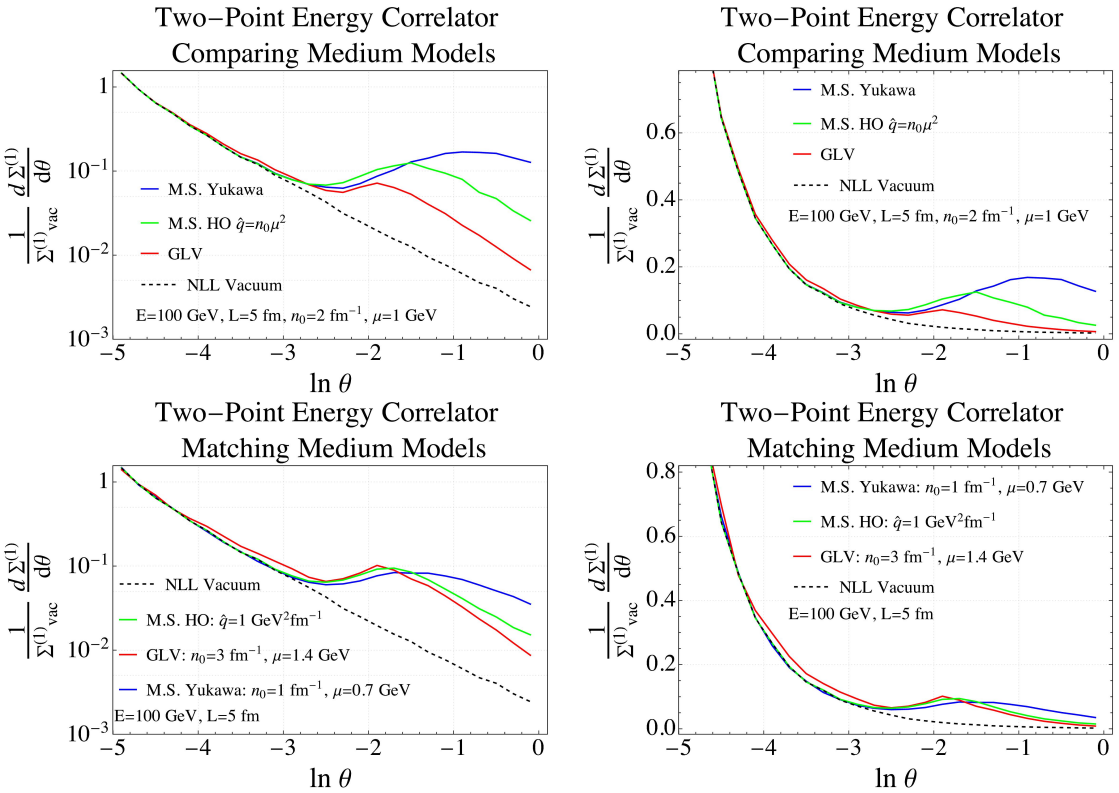


Increasing θ

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

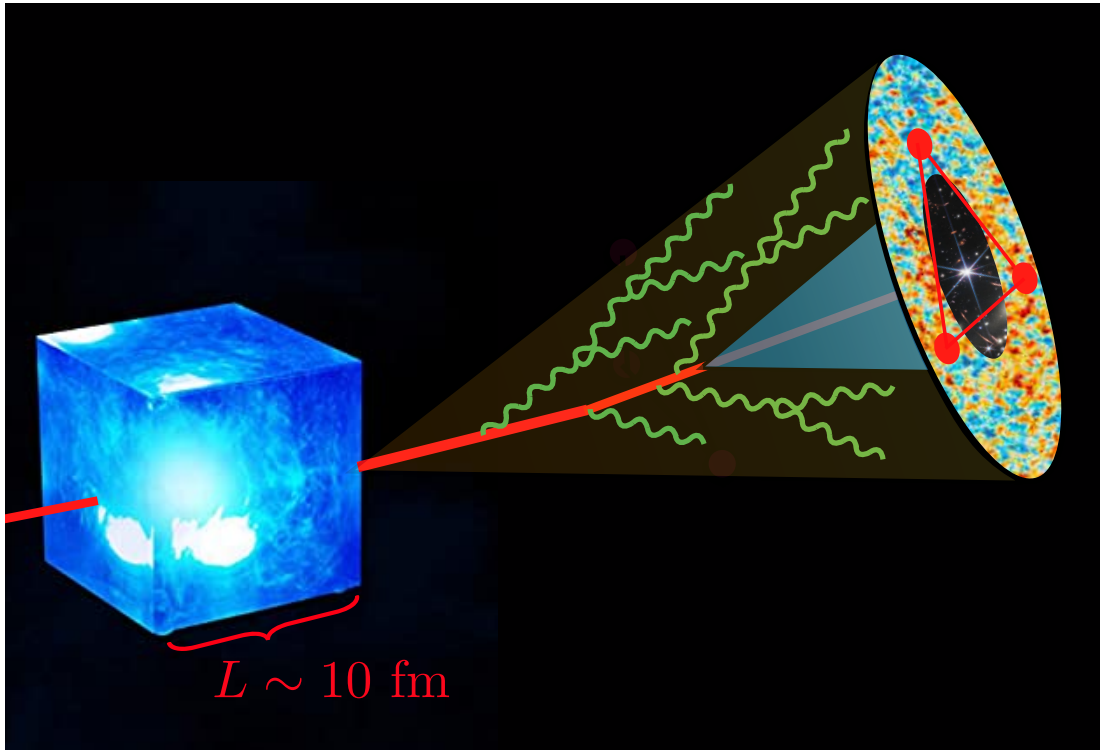
Resolving the Scales of the QGP

- Presence of sharp transition is a robust prediction.



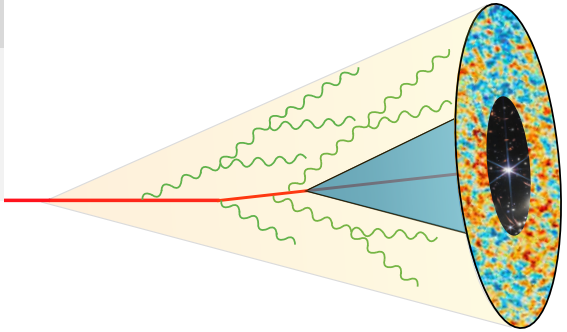
- Detailed behavior of the transition is sensitive to parameters of the underlying physical model $\Longrightarrow$ Measurements will be exciting!

Seeing Beauty in the QGP with Energy Correlators

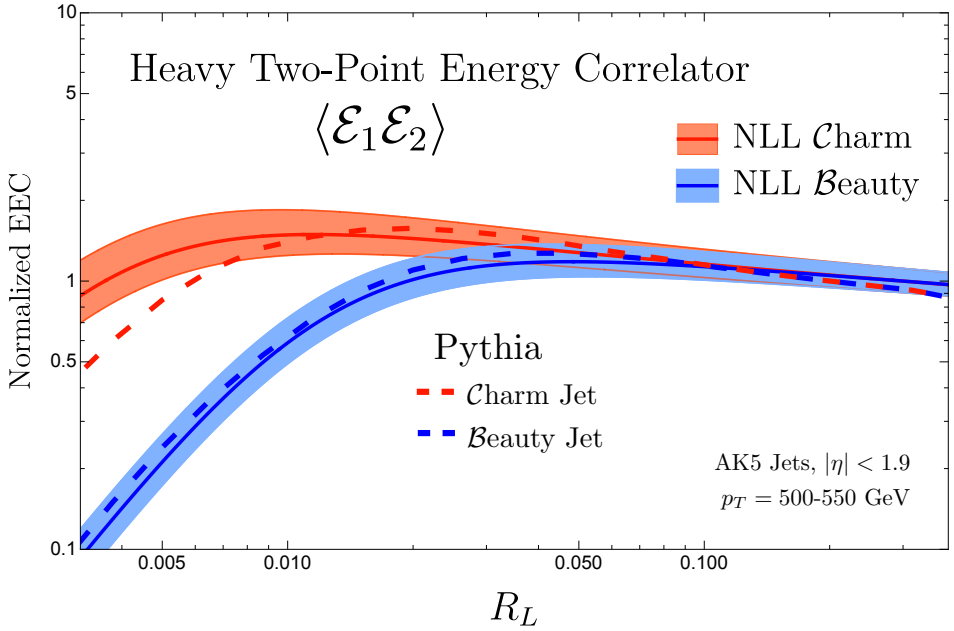


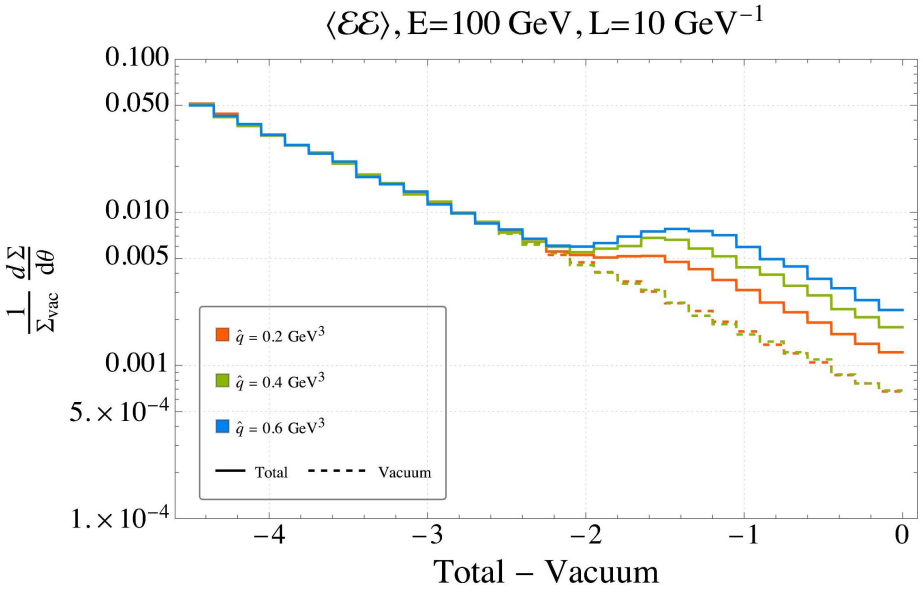
[Andres, Dominguez, Holguin, Marquet, Moult]

Heavy Quarks in the QGP



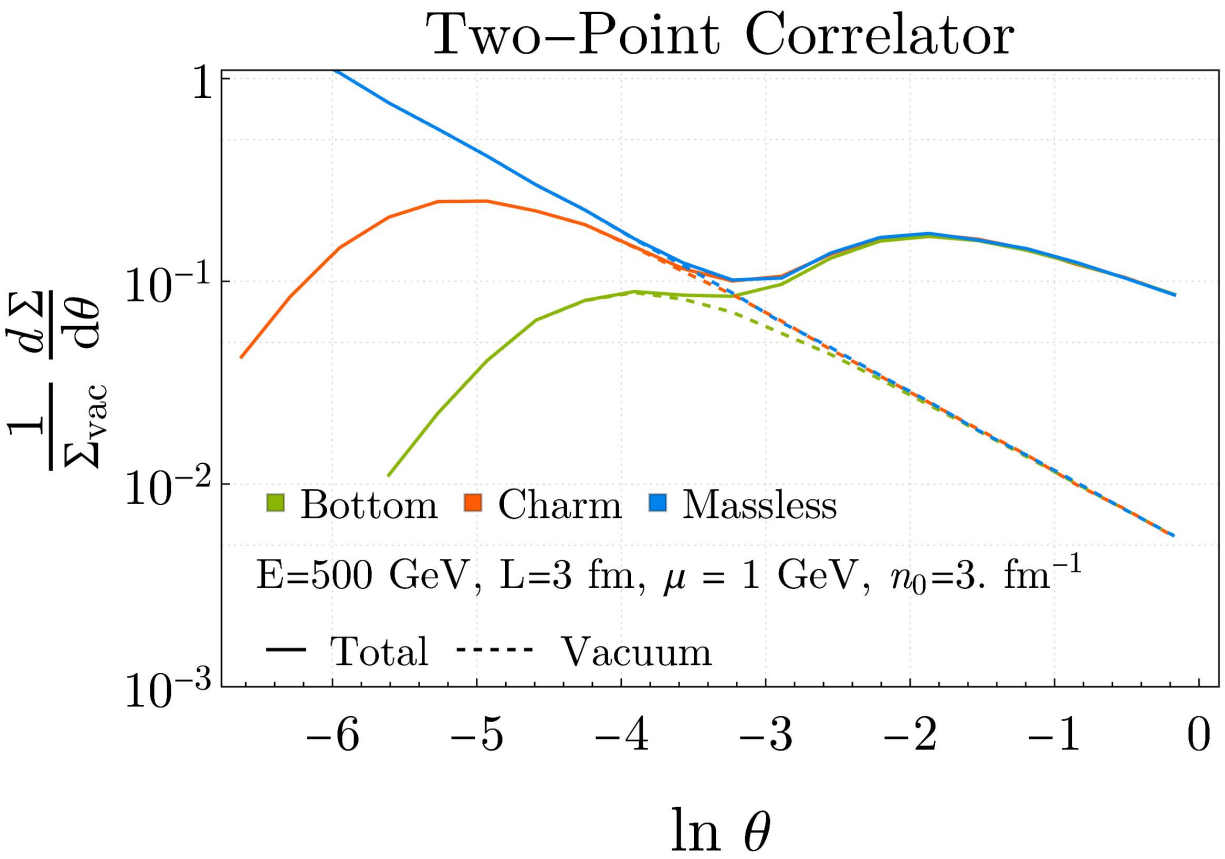
- Heavy quarks provide an ideal probe of the QGP since they cannot be thermally produced.
- Large samples of b,c quarks will produced in next heavy ion runs.
- Rich system due to the presence of two scales $\theta_L \sim \frac{1}{\sqrt{LE}}$, $\theta_0 \sim \frac{m}{E}$
- Deadcone is a feature of vacuum, its modification due to medium induced radiation provides a sensitive probe of the QGP.





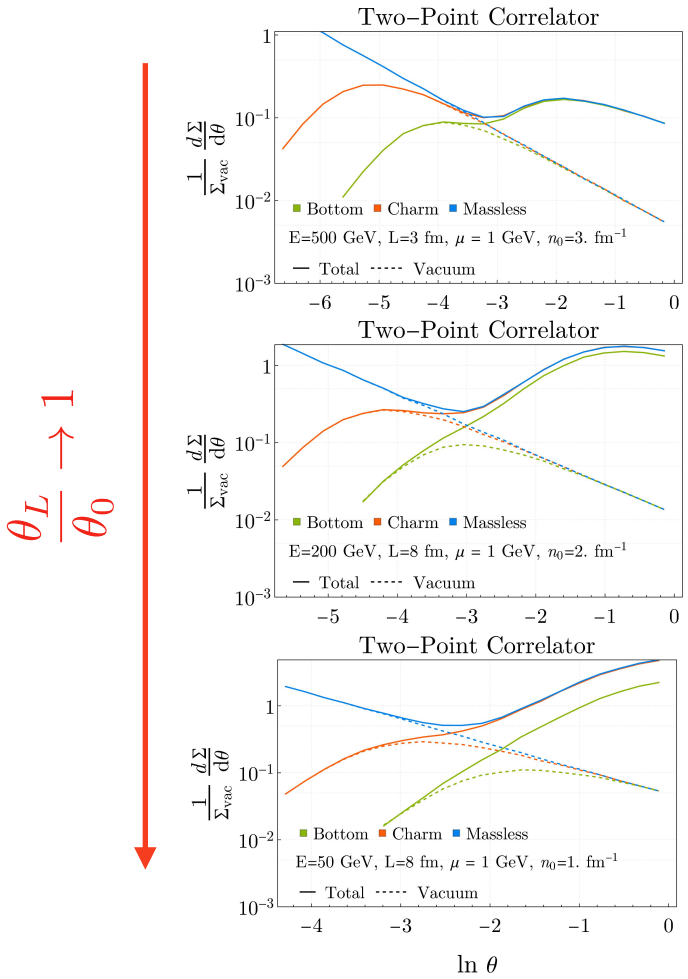
Resolving Two Scales

- If $\theta_L \gg \theta_0$, the dynamics of the two scales are separated.

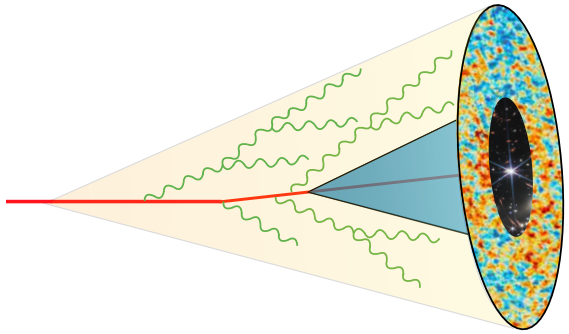


- We can now bring $\theta_L \to \theta_0$ and see if we can fill the "dead cone" with medium induced radiation.

Zombie Cones

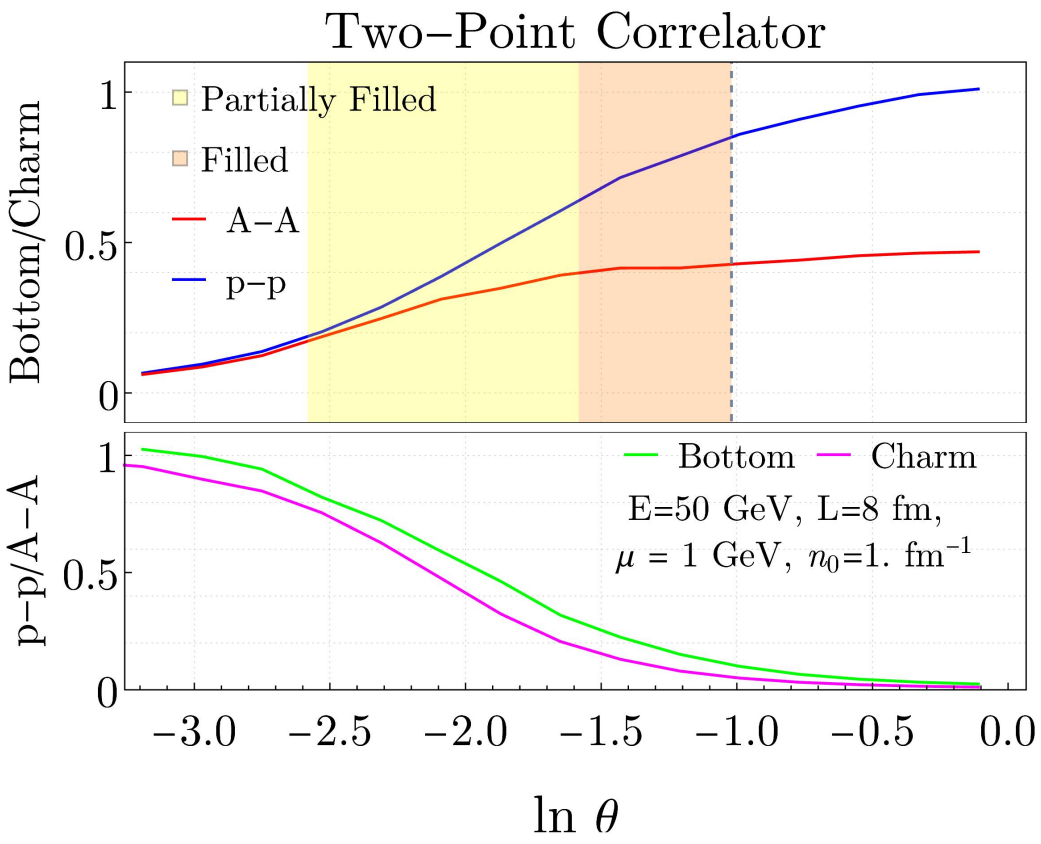


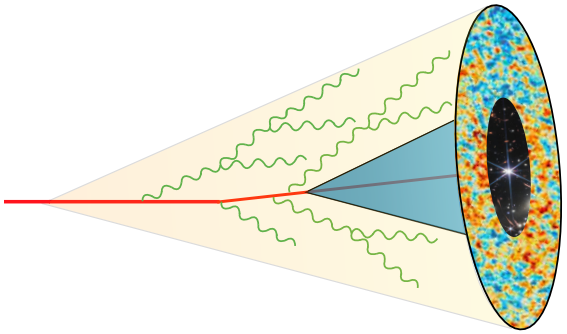
- As $\theta_L/\theta_0 \to 1$ medium induced radiation increasingly fills the deadcone.
- Dynamics when $\theta_L \sim \theta_0$ requires explicit in medium calculation.



Resolving the Scales of the QGP

- A particularly clean target for experiment will be the b/c ratio: Both can be traced through the plasma, and the dynamics between m_c and m_b is perturbatively calculable.



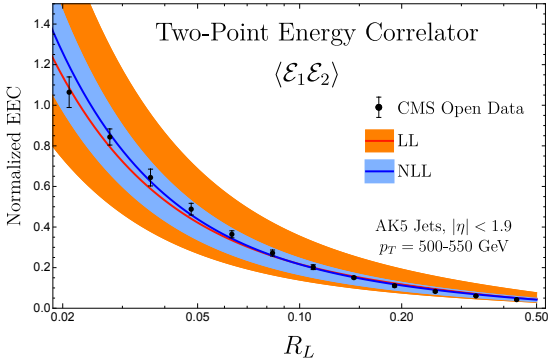


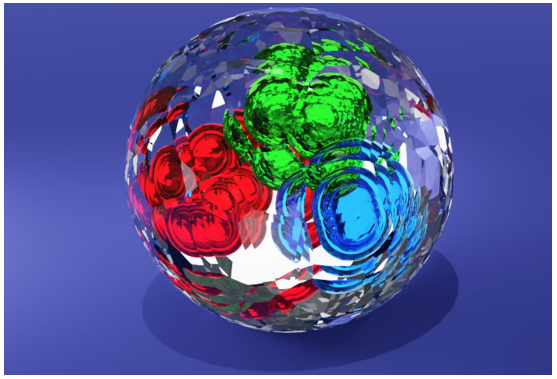
Summary

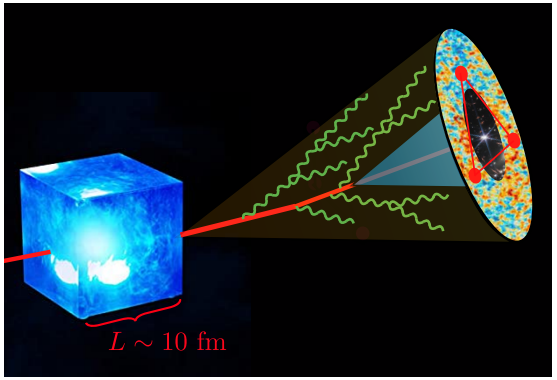
- Correlation functions, $\langle \mathcal{E}(n_1) \cdots \mathcal{E}(n_k) \rangle$, provide a sharp link between theory and experiment. And can now be directly measured :)

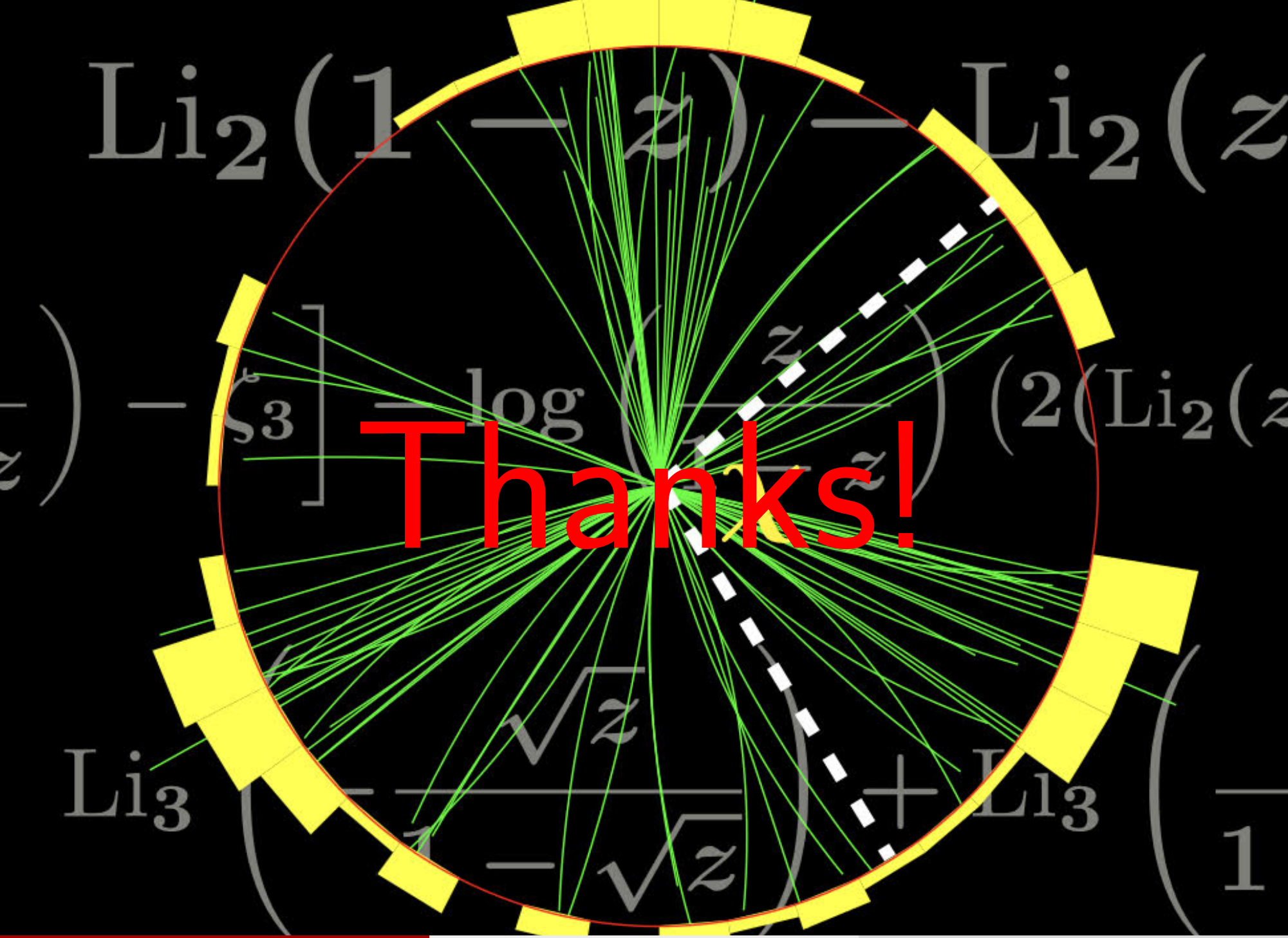
- Intrinsic and emergent scales imprint themselves in correlation functions at characteristic scales.

- Heavy quarks in the QGP provide a rich multi-scale system which is sure to provide new insights into its microscopic dynamics.








Thanks!