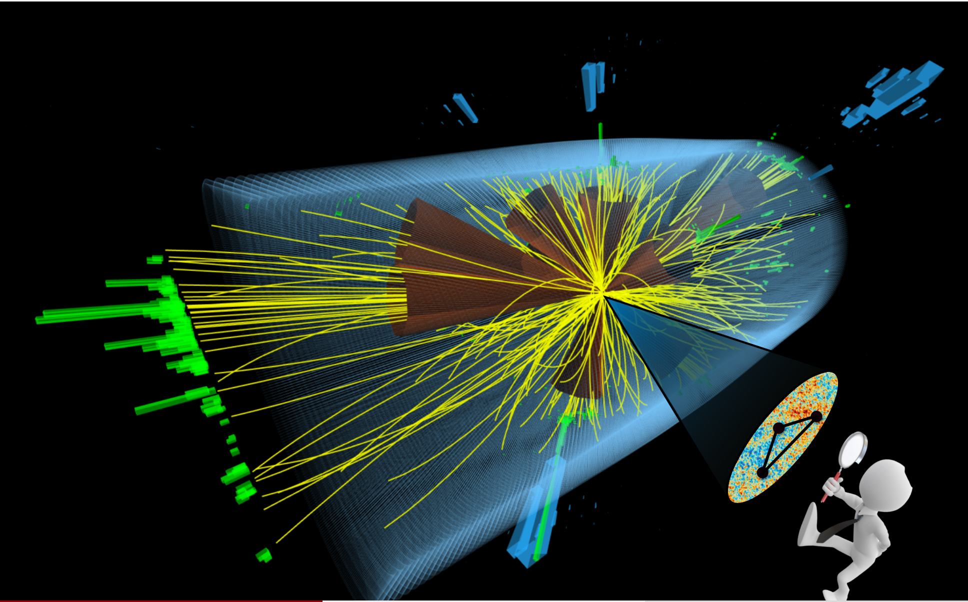
Imaging the Intrinsic and Emergent Scales of QCD with Colliders

Ian Moult

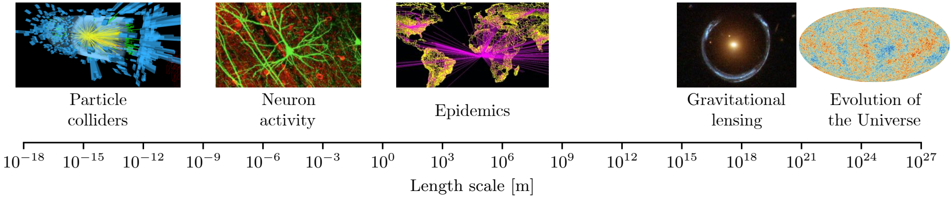
Yale

Colliders

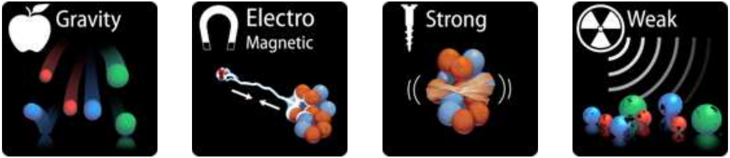


Length Scales

- Colliders allow us to probe the shortest distance scales:



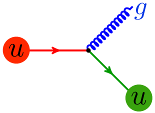
- Dominated by the physics of the Strong Nuclear Force: Quantum Chromodynamics (QCD)



Emergent Behavior of QCD

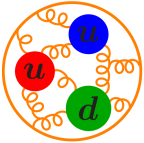
- Microscopic degrees of freedom of QCD are quarks and gluons:

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

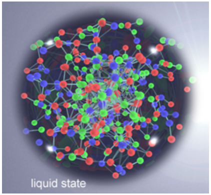


- QCD exhibits a variety of complicated emergent behavior:

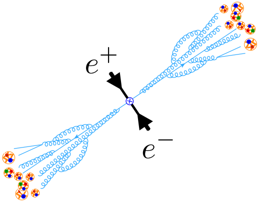
Hadrons



Quark Gluon Plasma

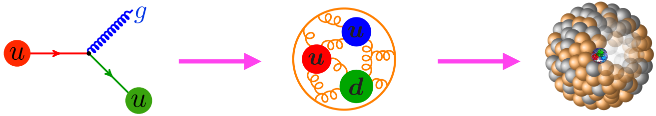


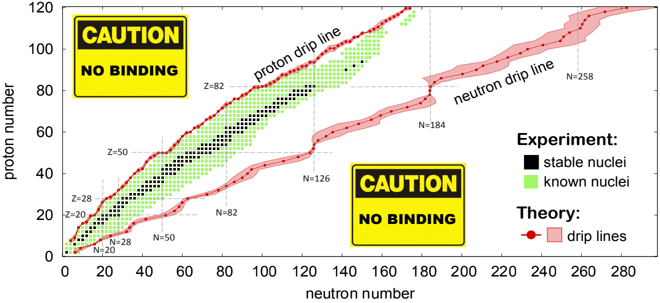
Jets

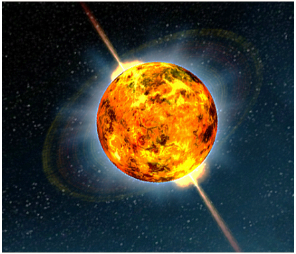


Doubly Emergent Behavior

- All of nuclear physics emerges from this simple Lagrangian.



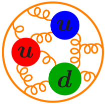


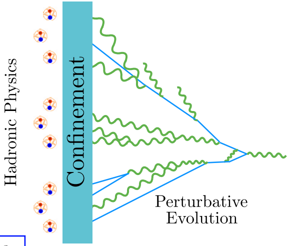


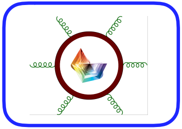
- An extremely rich theory at the forefront of current research.

The Complexity of QCD

- The degrees of freedom of QCD depend on the energy scale:



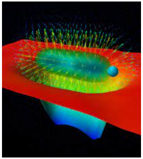


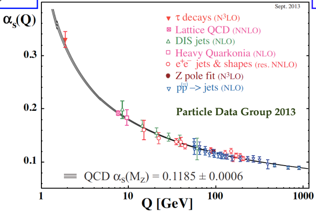


Long Time Scale
Low Energy

$\alpha_s(Q)$ ←

Short Time Scale
High Energy

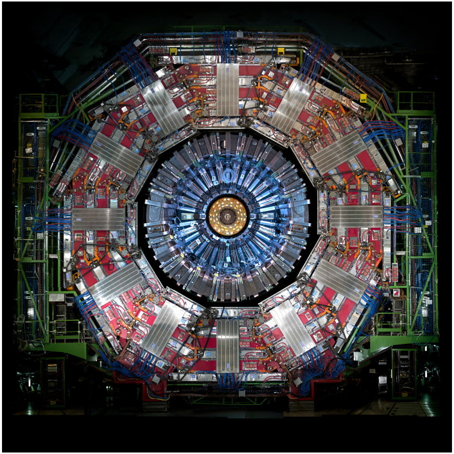




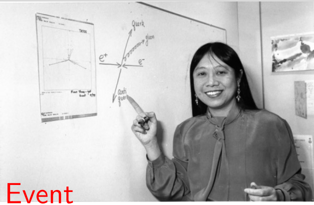
$$\hat{O} = \alpha_s + \alpha_s^2 + \cdots$$

- To see quarks and gluons, we need a powerful microscope!

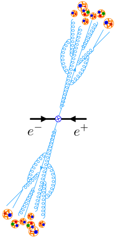
The Evolution of Collider Physics



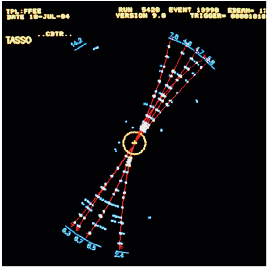
Jets for Discovering the Gluon



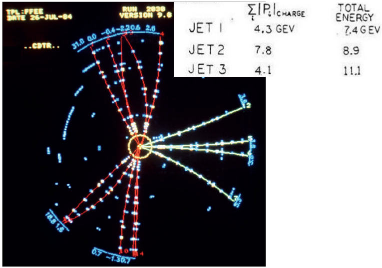
- Jets used to discover the gluon.

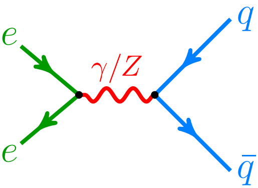


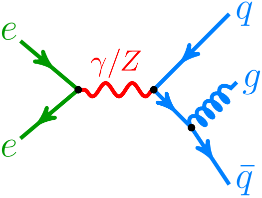
2-Jet Event



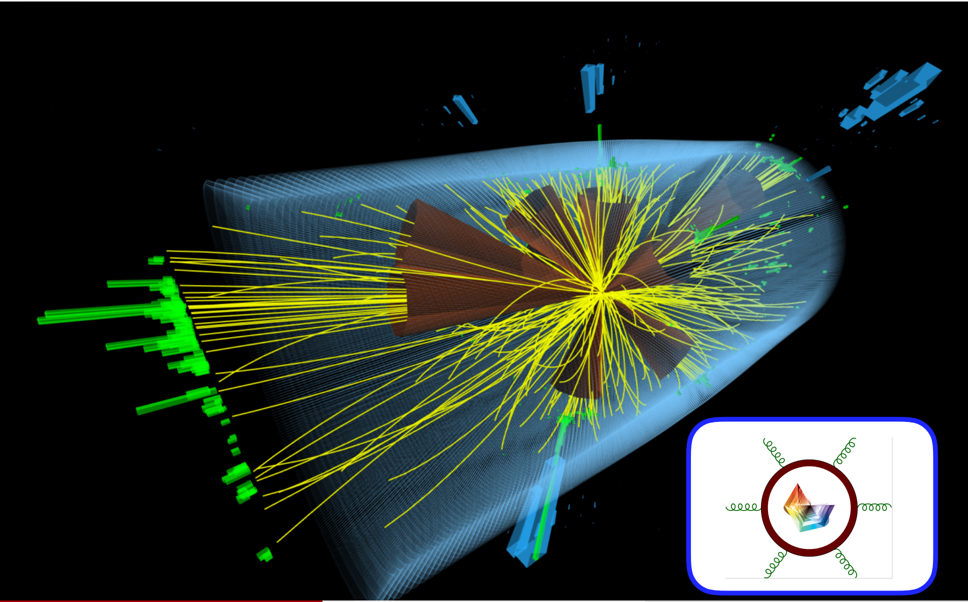
3-Jet Event







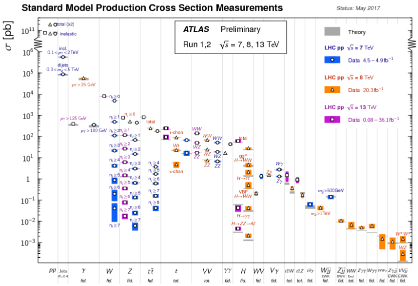
The Modern Era

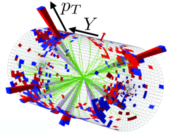


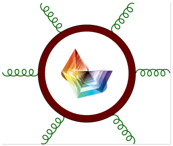
Jets at the LHC

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

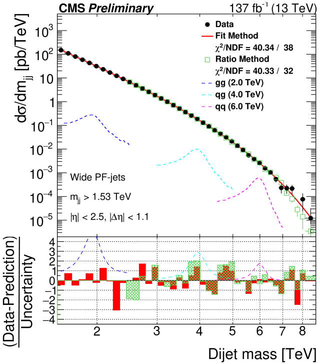
Jet Kinematic Distributions





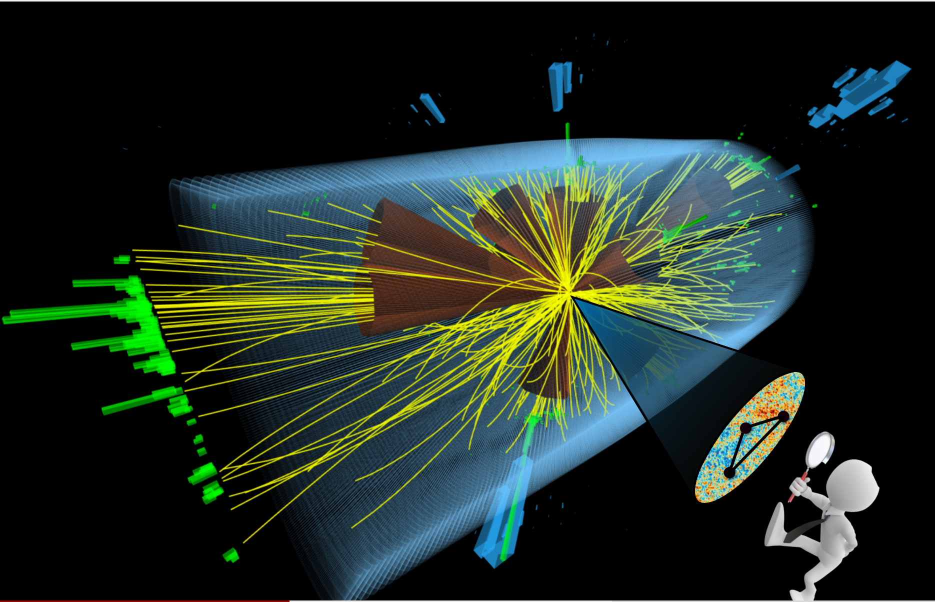


Dijet Mass



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

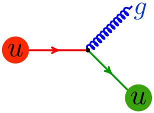
Jet Substructure!

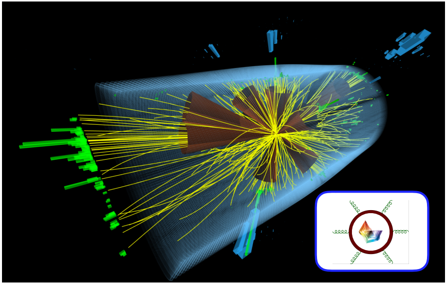


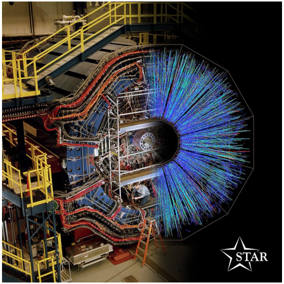
Particle Colliders

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

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

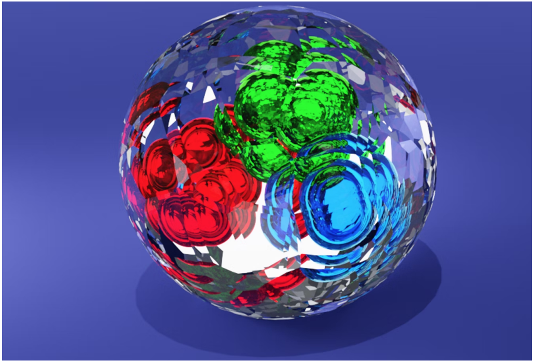






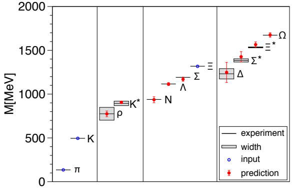
- Microscopic dynamics encoded in Macroscopic energy flux.

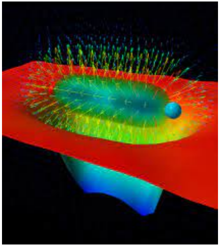
The Frontiers of Quantum Chromodynamics: 5 Open Questions

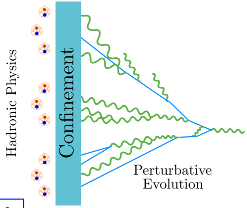


Dynamics of Hadronization

- What are the dynamics of the hadronization process?







Long Time Scale
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$\alpha_s(Q)$

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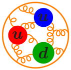
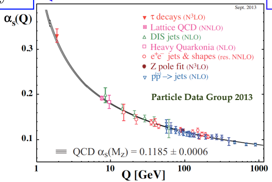


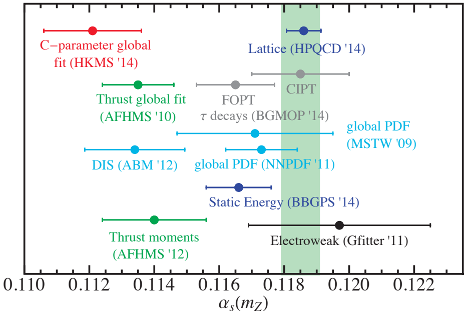


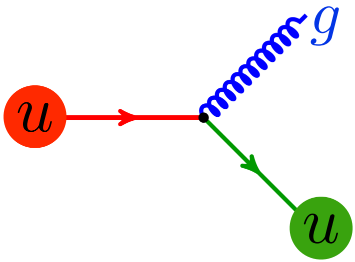
$$\hat{O} = \alpha_s + \alpha_s^2 + \cdots$$

- Clay Millenium Prize: Prove Confinement

How Strong is the Strong Force?

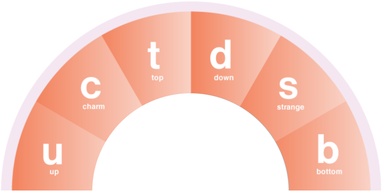
- What is the value of the strong coupling constant?
- The electromagnetic coupling is one of the best known natural quantities $\alpha_e = 0.0072973525693(11)$.
- There are currently large discrepancies in different extractions of the strong coupling.

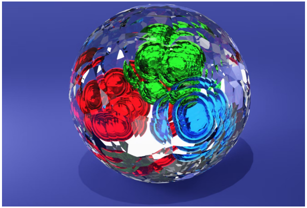


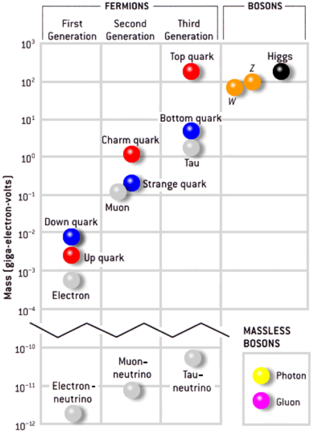


How Heavy are the Quarks?

- What are the masses of the quarks?
- Electron mass well measured, $m_e = 0.51099895000(15)$ MeV.
- Quarks are never free $\Longrightarrow$ very hard to measure their masses!

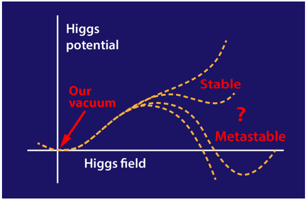


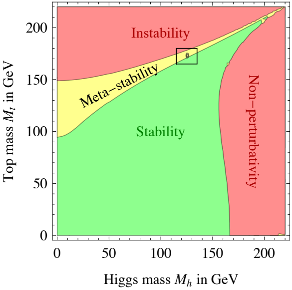


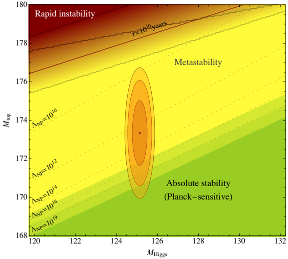


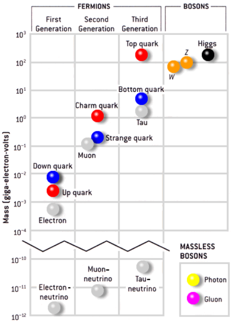
How Heavy are the Quarks?

- The mass of the heaviest quark, the top quark, provides the leading uncertainty on the stability of the universe!





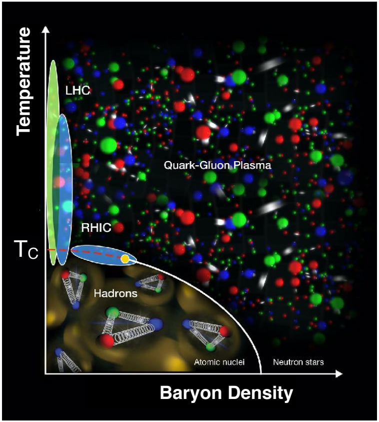


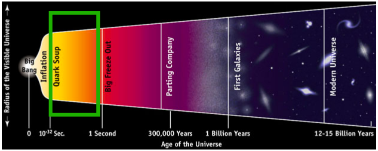


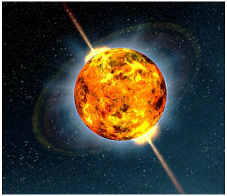
- Can only be produced and studied in colliders.

Extreme States of QCD Matter

- What are the phases of QCD matter?



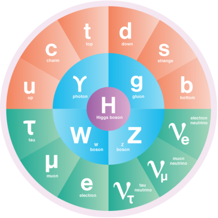


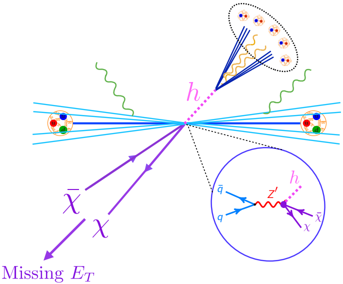


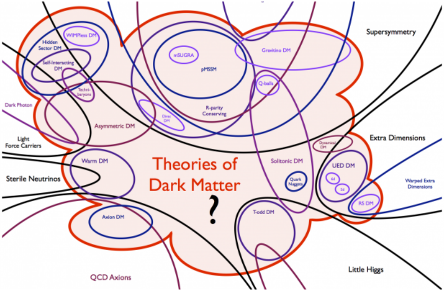
- Required to understand the dynamics of the early universe and the collisions of neutron stars.

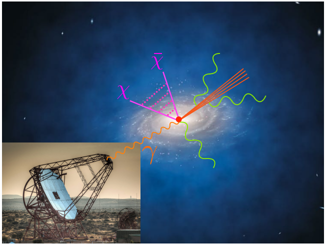
Beyond the Standard Model

- What is the nature of physics beyond the Standard Model?



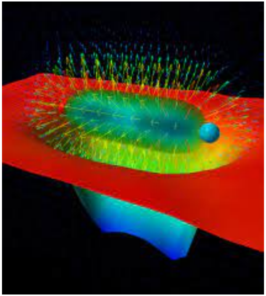


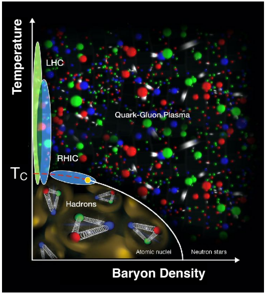


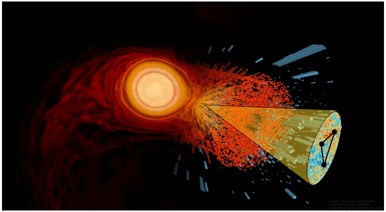


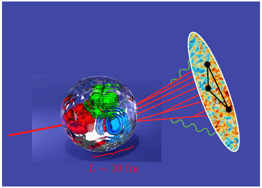
Extracting the Answers from Colliders

- The answers are all encoded in collider energy flux!

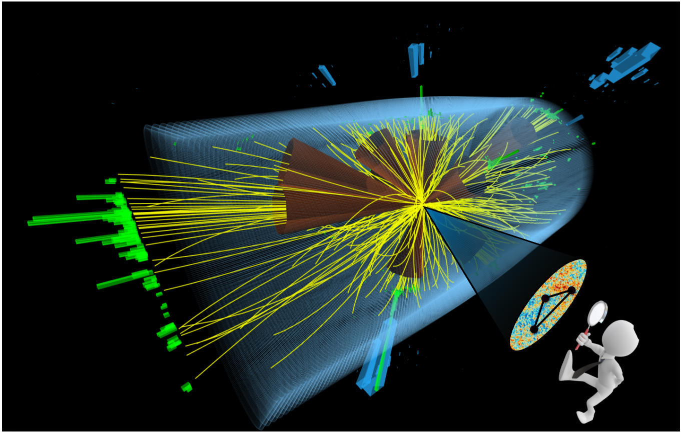






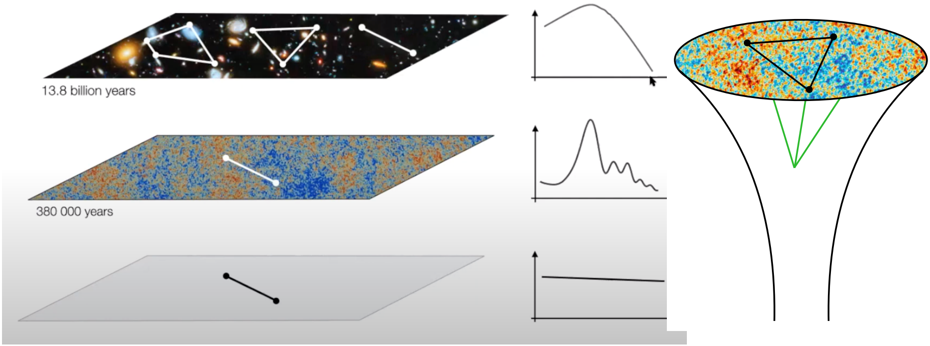


Decoding Energy Flux



Correlation Functions

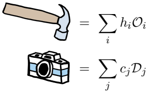
- In condensed matter physics or cosmology we decode the underlying dynamics using correlation functions.



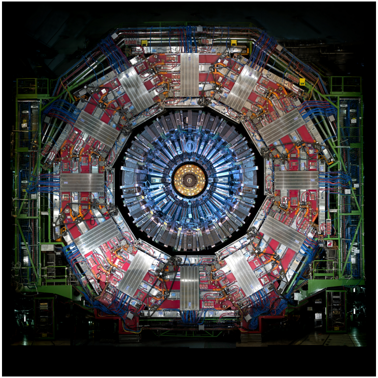
- Can we achieve a similarly coherent picture of collider physics?

Defining the Problem

- What is a detector?



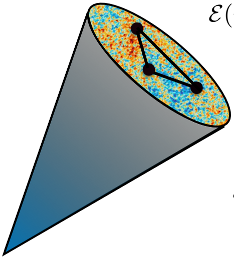
[Caron Huot, Kologlu, Kravchuk, Meltzer, Simmons Duffin]



- To be able to understand colliders, we must understand what a detector is in the language of Quantum Field Theory.

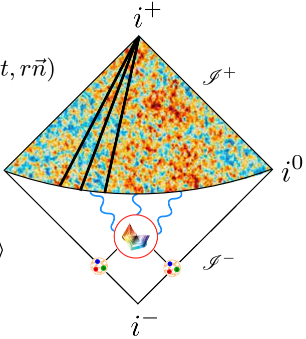
Calorimeter Cells in Field Theory

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



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

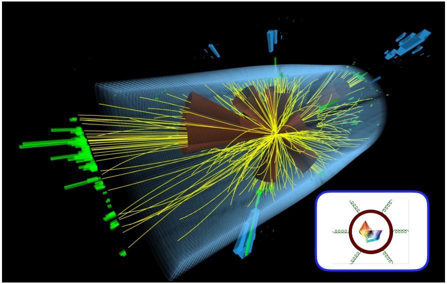
$$\langle \Psi | \mathcal{E}(\hat{n}_1) \cdots \mathcal{E}(\hat{n}_k) | \Psi \rangle$$

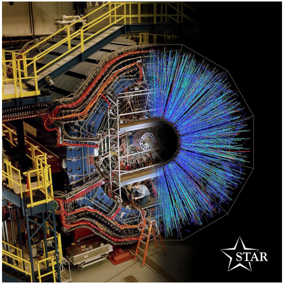


- From the perspective of QFT, jet substructure is the study of correlation functions of energy flow operators.

Towards the Real World

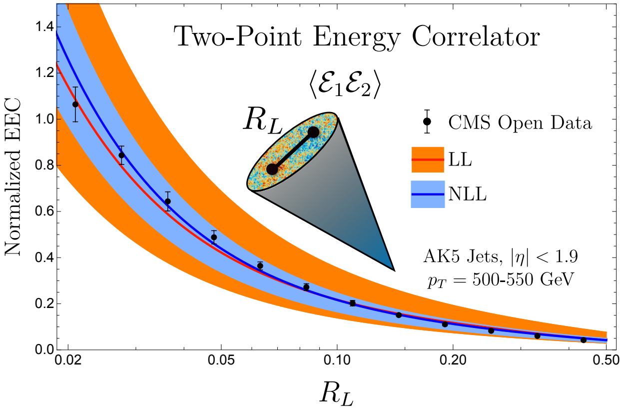
- Can this theoretical idealization possibly work in the messy real world?





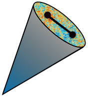
- Can it provide new ways of understanding complex collisions?

Scaling Behavior of Quarks and Gluons



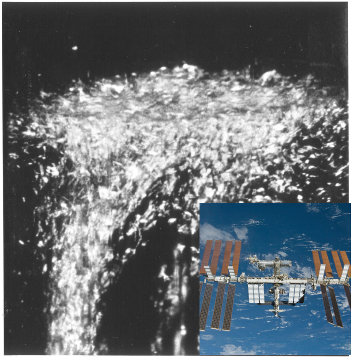
Scaling Behavior in QFT

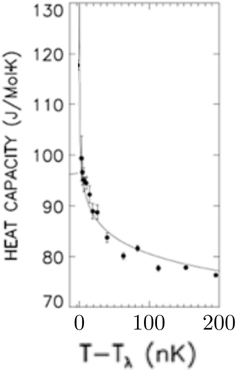
- Why is jet substructure theoretically interesting?



- QFTs exhibit universal behavior as operators are brought together.

λ-point of Helium

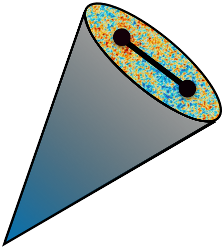


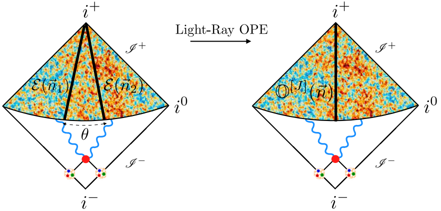


$$\mathcal{O}(x)\mathcal{O}(0) = \sum x^{\gamma_i} c_i \mathcal{O}_i$$

The OPE Limit of Lightray Operators

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





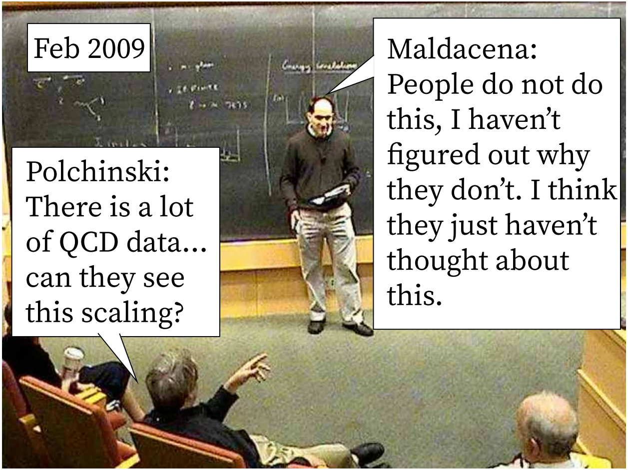
$$\mathcal{E}(\hat{n}_1)\mathcal{E}(\hat{n}_2) \sim \sum \theta^{\tau_i - 4}\mathbb{O}_i(\hat{n}_1)$$

[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.

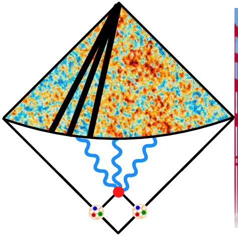
Theory-Experiment Gap

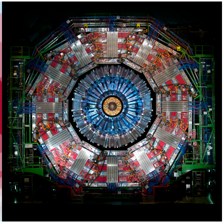
- OPE scaling is the most basic prediction of QFT for jet substructure.



- Shockingly, still true as of 2022...

Open Data as the Bridge Between Theory and Experiment





[Komiske, Moult, Thaler, Zhu]

Open Data

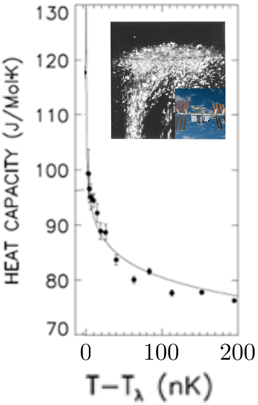
- A primary driver of recent progress in jet substructure has been the availability of Open Data.

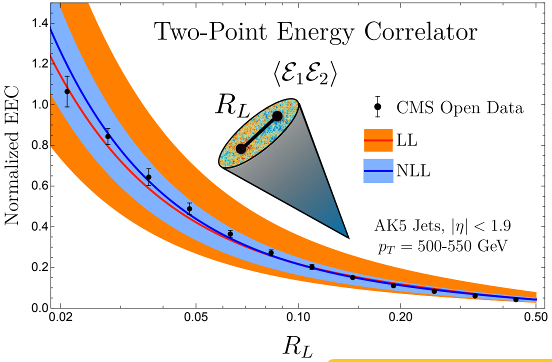
- Short-circuits the traditional path from formal theory development to collider physics applications:
  - Enables rapid transport of ideas from “theory world” to ”real world”.
  - Can illustrate that new approaches are phenomenologically viable.
  - Provides tests on real data for observables where standard simulations can’t be trusted $\Longrightarrow$ learn new features of QCD.

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!





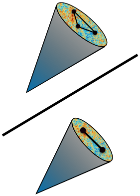
$$\mathcal{E}(\hat{n}_1)\mathcal{E}(\hat{n}_2) \sim \sum \theta^{\tau_i - 4} \mathbb{O}_i(\hat{n}_1)$$

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

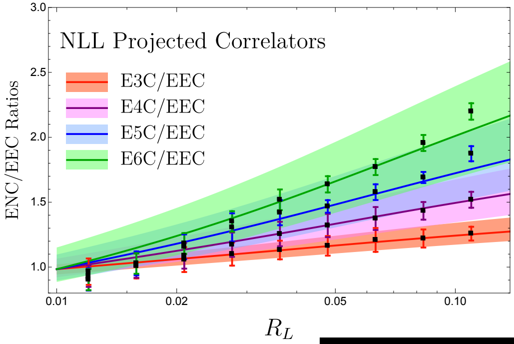
The Spectrum of a Jet

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

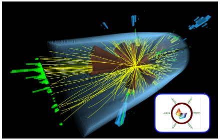
- Different correlation functions should have different quantum mechanical scalings:



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

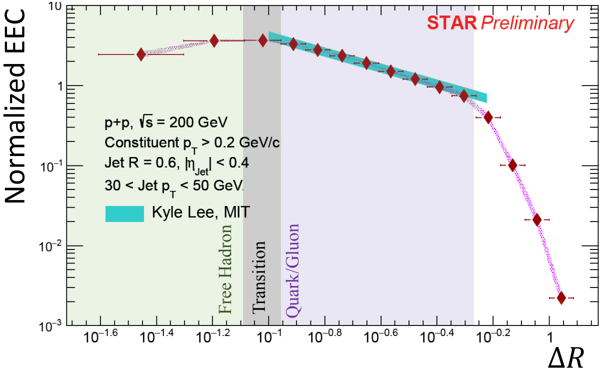


- Beautiful simplicity from complex collisions!



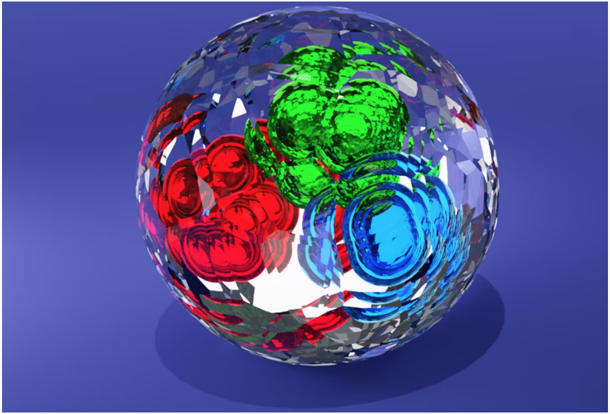
Experimental Verification

- Recent measurement by the STAR collaboration:



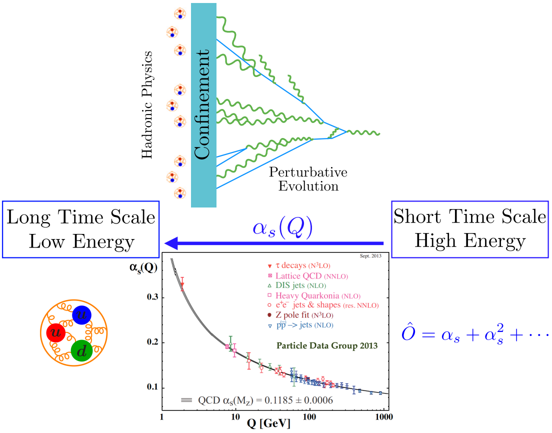
- Beautiful validation of universal scaling across energies!

The Confinement Transition



The Confinement Transition

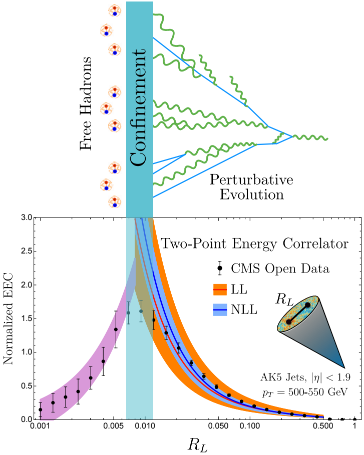
- Jets exhibit a transition from weakly coupled quarks and gluons to freely propagating hadrons: Occurs on a timescale of 10^{-23}s.



- Can it be directly imaged in asymptotic energy flux?

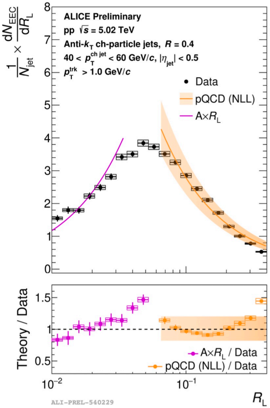
The Confinement Transition

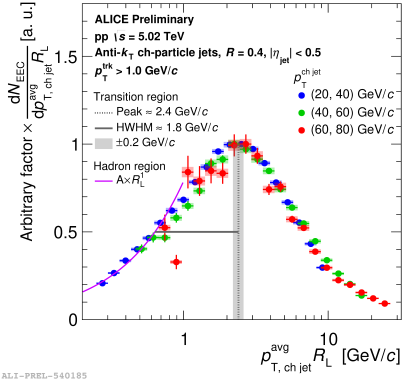
- Energy correlators allow the hadronization process to be directly imaged inside high energy jets: transition from interacting quarks and gluons and free hadrons clearly visible!



The Confinement Transition

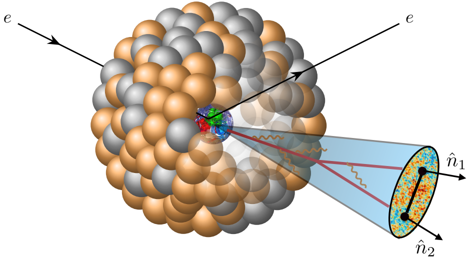
- Beautiful measurement by ALICE confirms this picture:





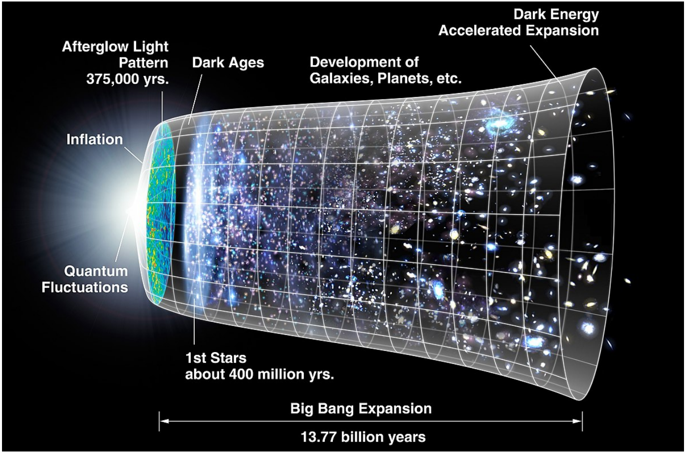
- Illustrates universality of the hadronization transition.

Imaging the Intrinsic and Emergent Scales of QCD with Jet Substructure



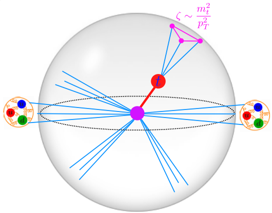
Unravelling the Initial Conditions

- Use jets as a calibrated probe of the initial condition.

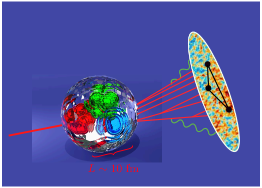


Three Examples

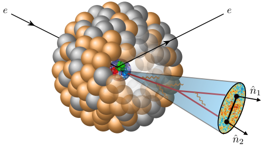
- Weighing the Heaviest Quark



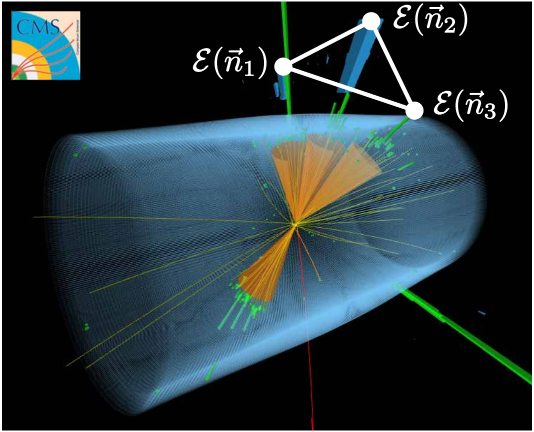
- Resolving the Scales of the Most Perfect Fluid



- Imaging Cold Nuclear Matter



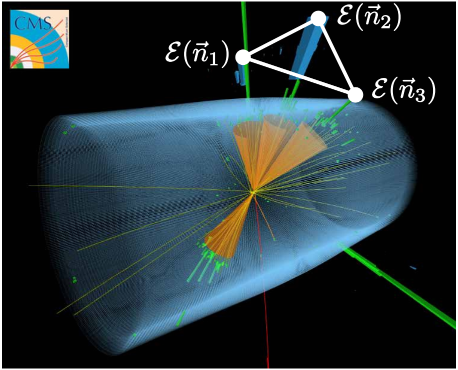
Weighing the Heaviest Quark

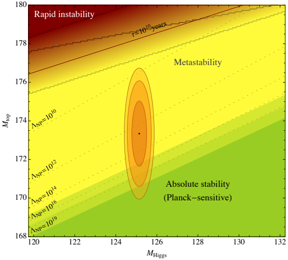


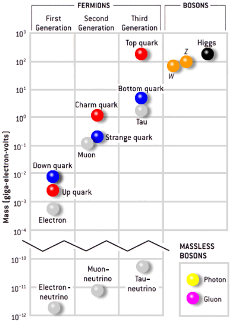
[Holguin, Moult, Pathak, Procura]

Top Quark Mass

- The top quark mass determines the stability of the universe.
- Due to its large mass it can only be produced in collider experiments, and lives for $\sim 10^{-25}$s, making it hard to measure.

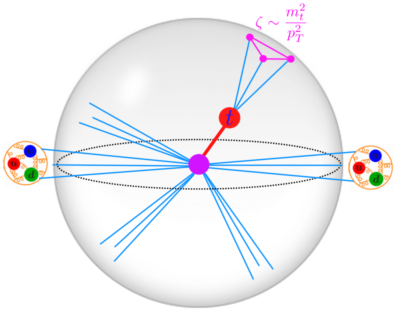


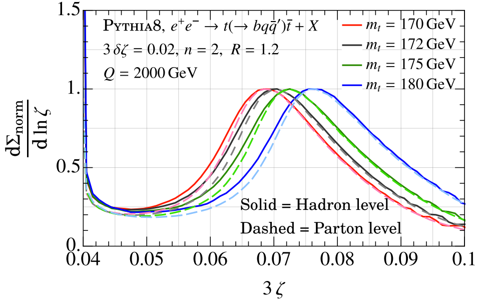




Top Quark Mass Measurement

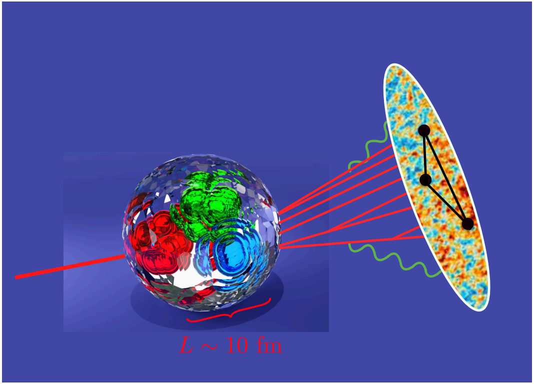
- Massive particles imprint their existence at a characteristic angular scale $\zeta \sim m^2/Q^2$.





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

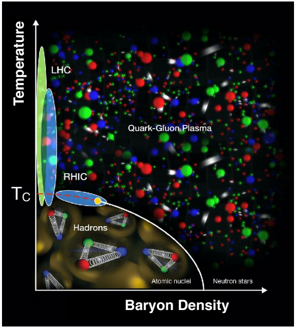
Imaging the Most Perfect Fluid

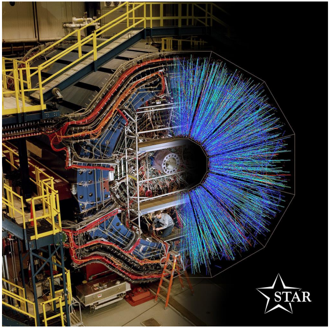


[Andres, Dominguez, Holguin, Kunnawalkam Elayavalli, Marquet, Moult]

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.

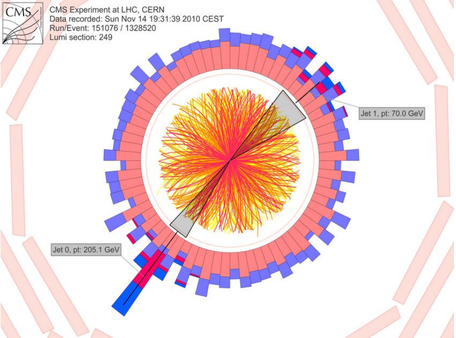


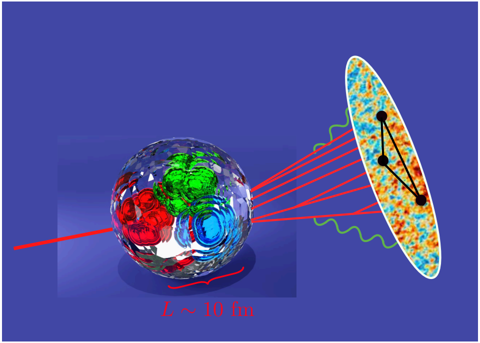


- This extreme state of matter can be produced in high energy colliders.

Imaging the Plasma

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

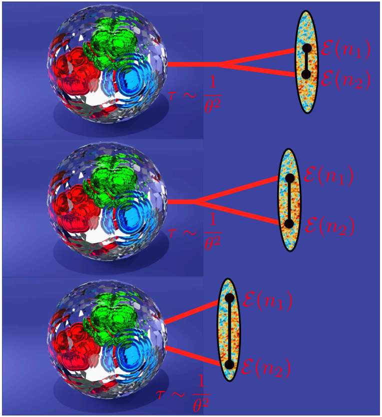




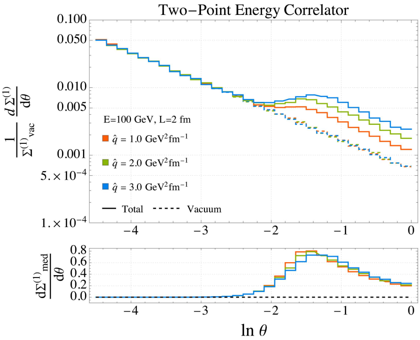
- How can we see there was a 10^{-14}m ball of plasma at the center?

Resolving the Scales of the QGP

- QGP scales cleanly imprinted in two-point correlation!



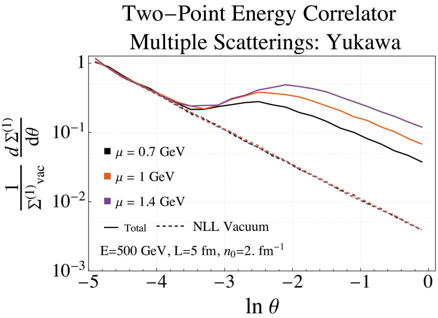
Increasing θ

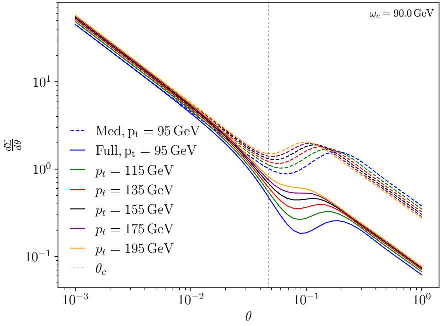


Increasing θ

- Resolve Femtometer scales from asymptotic energy flux!

- Detailed shape of the transition probes medium interaction and transport coefficients:



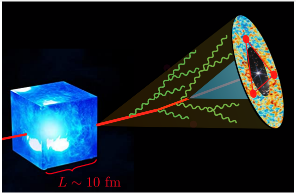


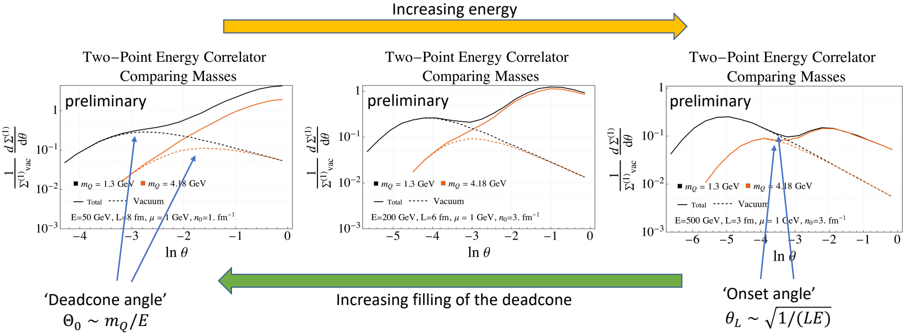
[Barata, Mehtar-Tani]

- Optimistic for significant progress with forthcoming measurements.

Heavy Quarks in the Medium

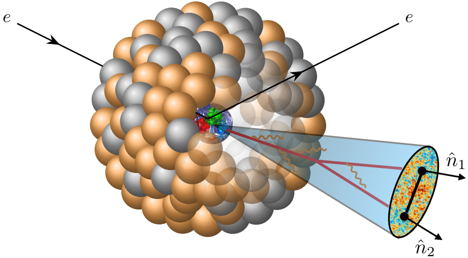
- Heavy quarks provide a theoretically clean probe of the medium.





- Correlators separately resolve medium and heavy quark mass scales.

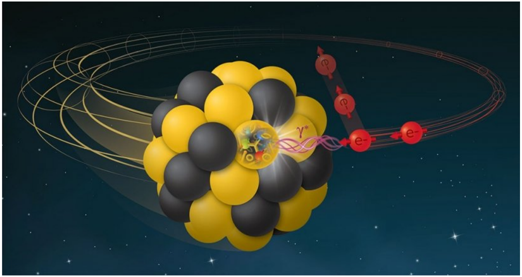
Imaging Cold Nuclear Matter

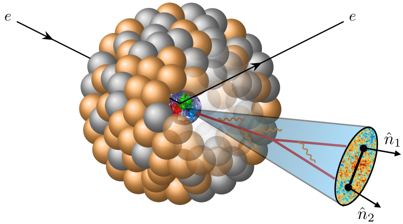


[Devereaux, Fan, Ke, Lee, Moult]

The Future Electron Ion Collider

- The EIC will provide the first high energy collisions on large nuclei.
- Jets will play a key role in unravelling nuclear dynamics from asymptotic energy flux.

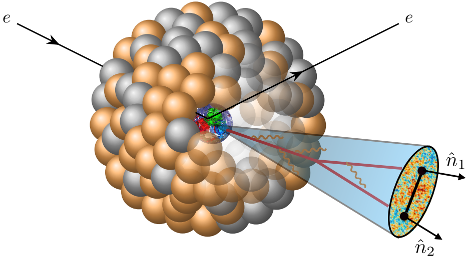


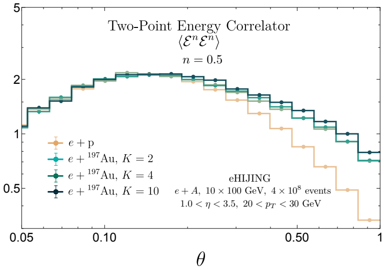


- A beautifully clean environment to apply all the developments of the past decade!

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.

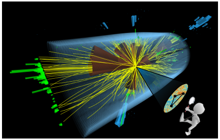


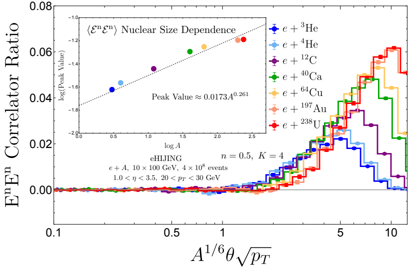


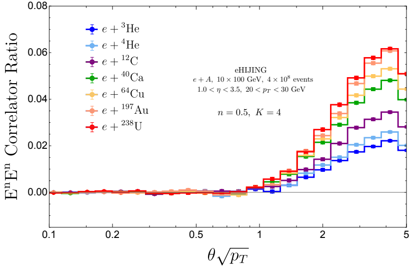
- The size of the nucleus represents a clear physical scale that will be imprinted in the angular structure of the correlator.

Imaging Cold Nuclear Matter

- Nuclear sizes cleanly imprinted into correlators.



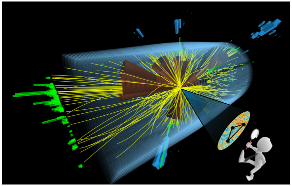


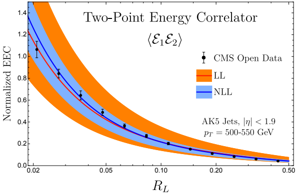


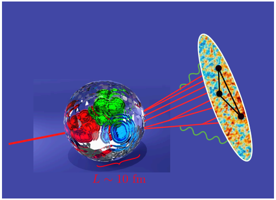
- Achieve femtometer resolution from asymptotic energy flux!
- Provides a common language from hot to cold QCD.

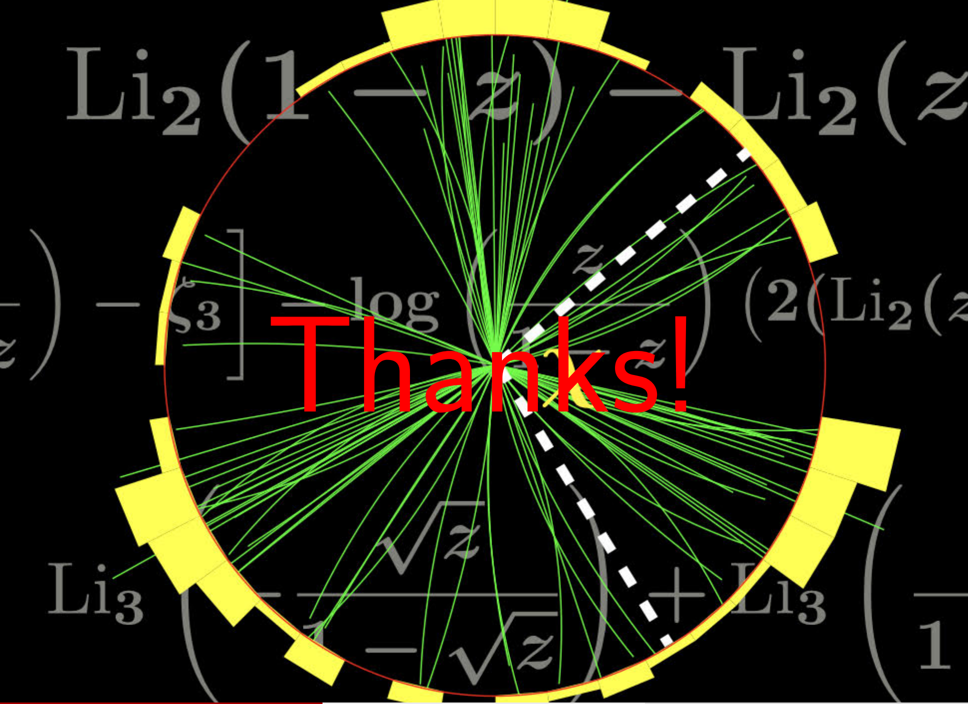
Summary

- Colliders allow us to access a wealth of exciting phenomena.
- Significant recent progress in decoding collider energy flux.
- Understanding the rich dynamics of the strong force remains a vibrant topic driving collider physics.









Thanks!