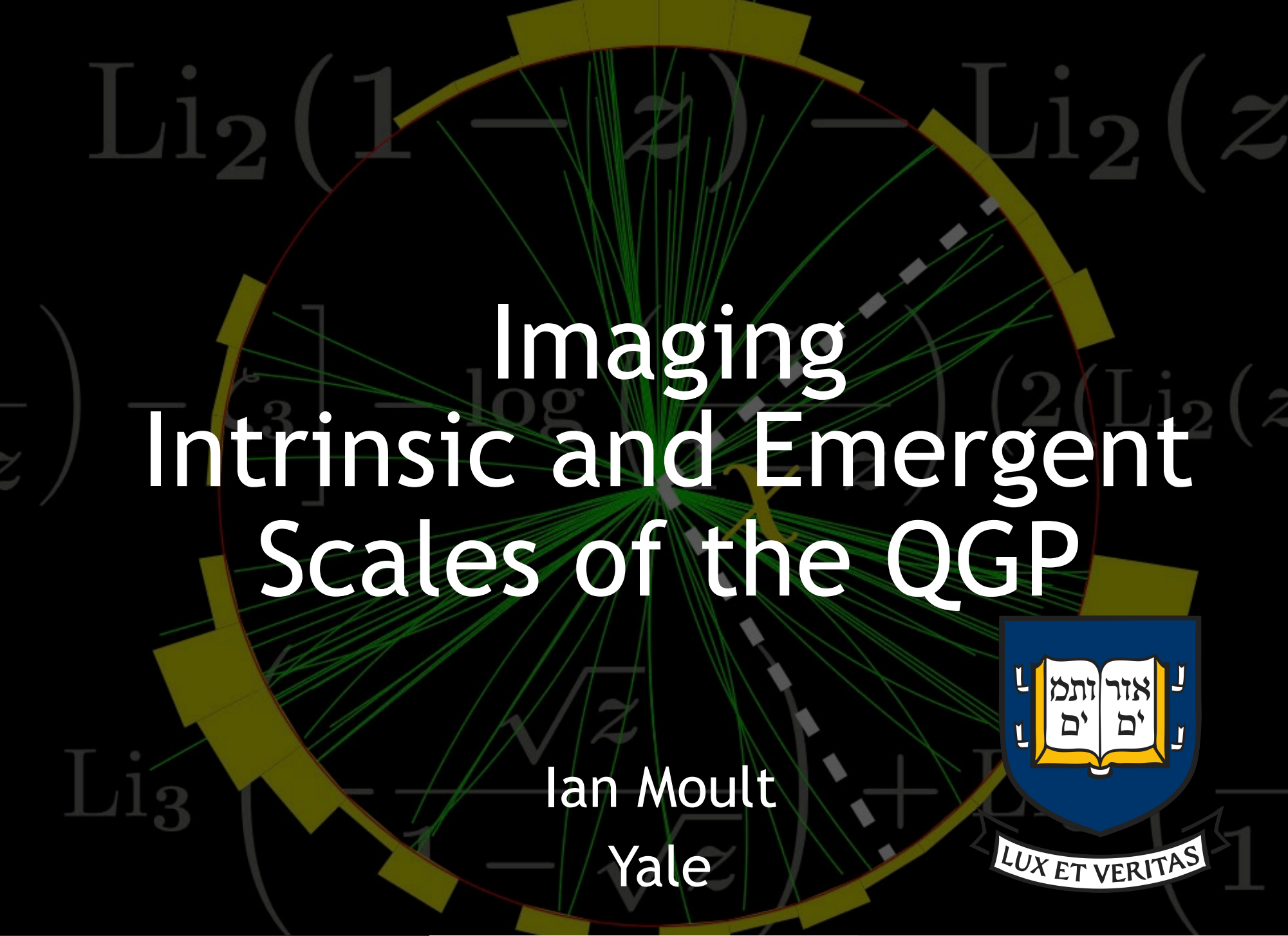
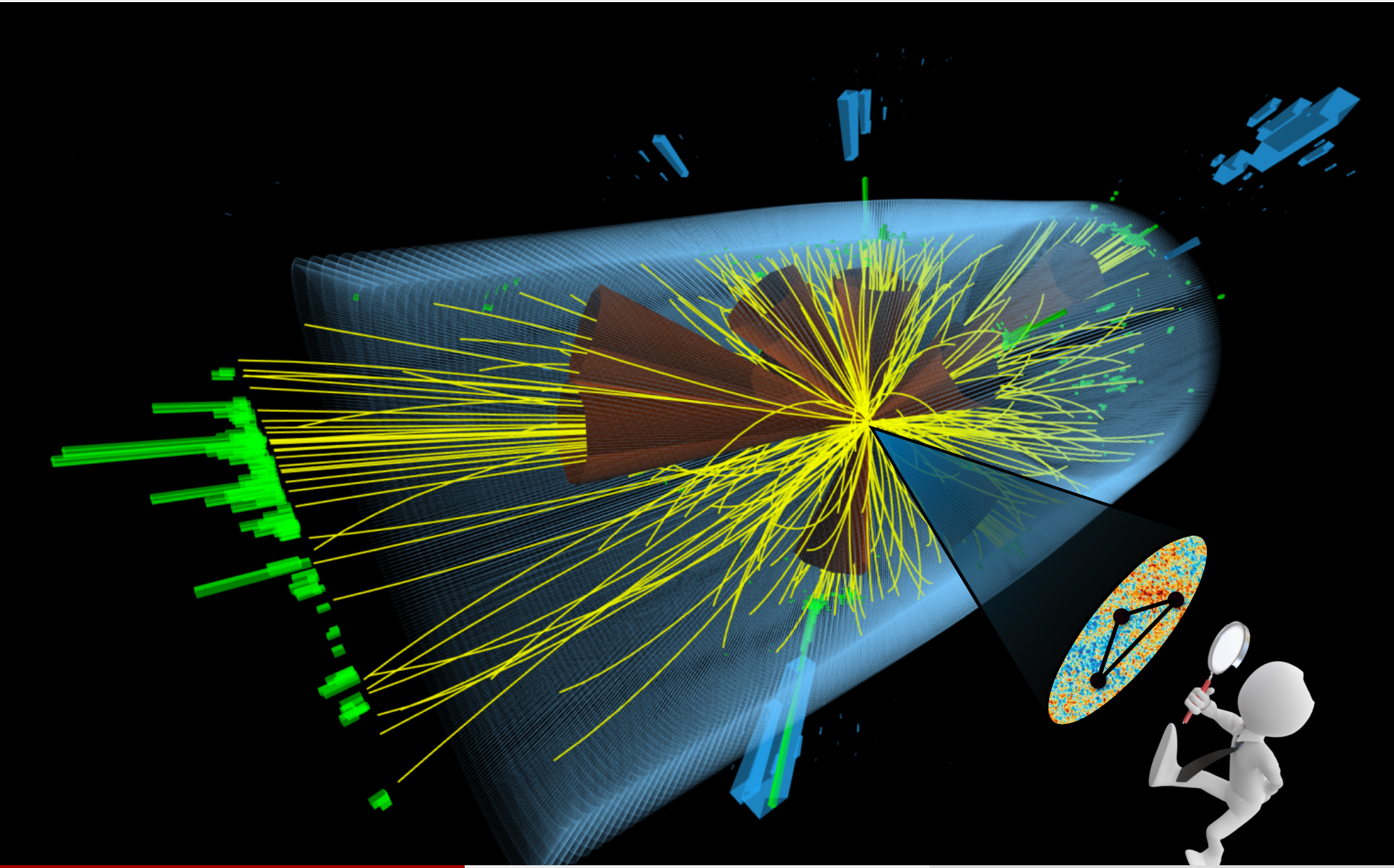


Imaging Intrinsic and Emergent Scales of the QGP

Ian Moult
Yale

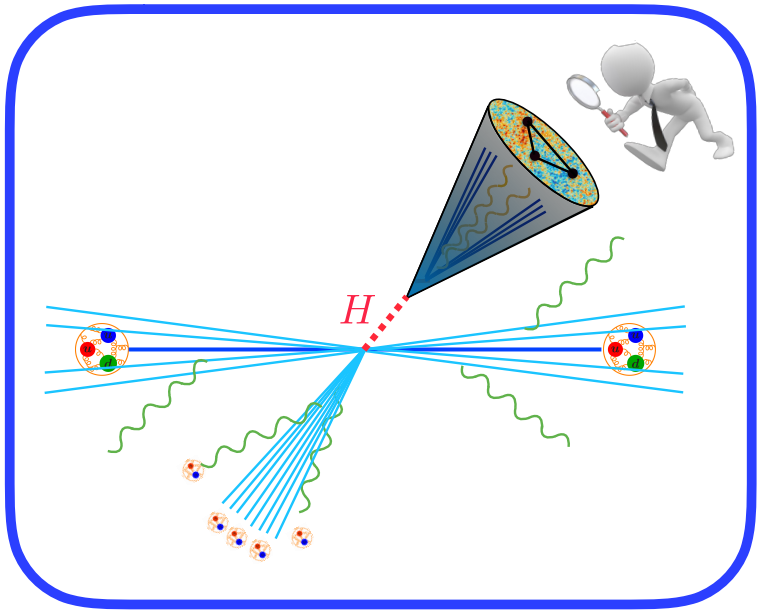
Jet Substructure!



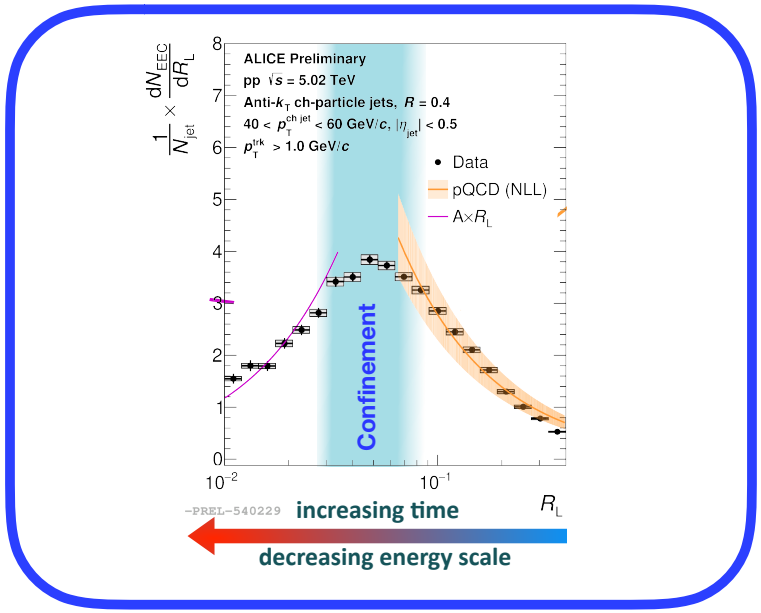
Jet Substructure

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

Innovative Search Techniques



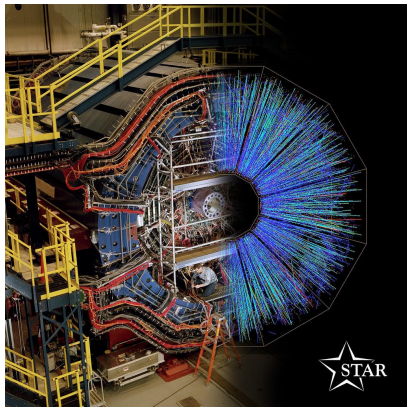
Novel Probes of QCD Dynamics

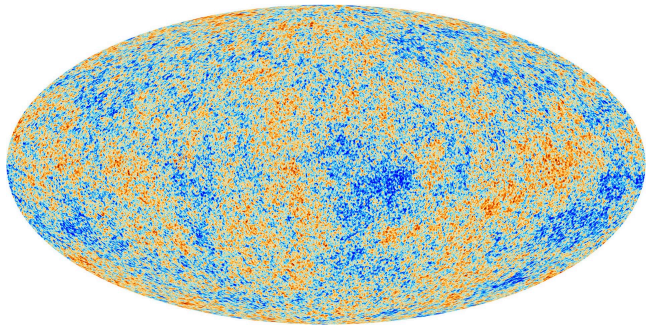


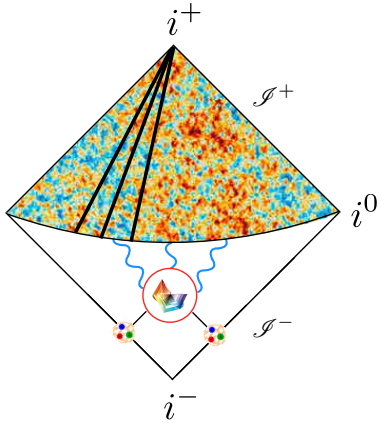
- Has evolved well beyond its origin to have a large impact on BSM, SM, high energy QCD and nuclear physics.

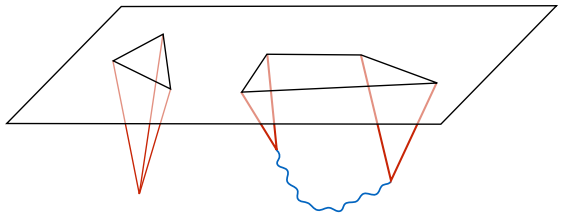
Decoding Energy Flux: QGP

- Subtle questions about the QGP are imprinted in collider energy flux:





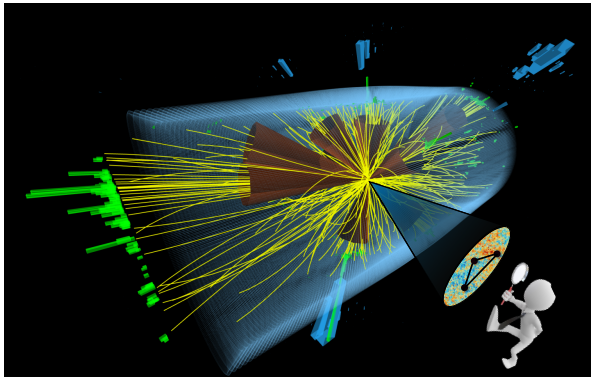


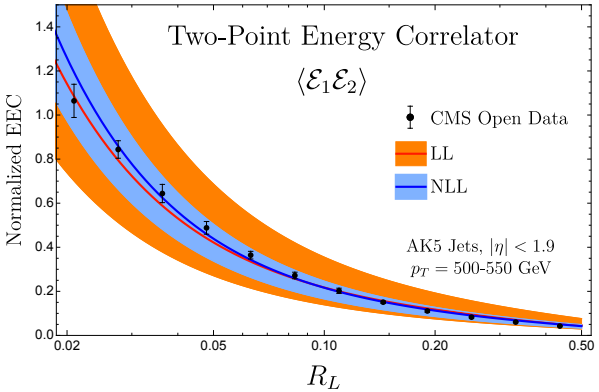


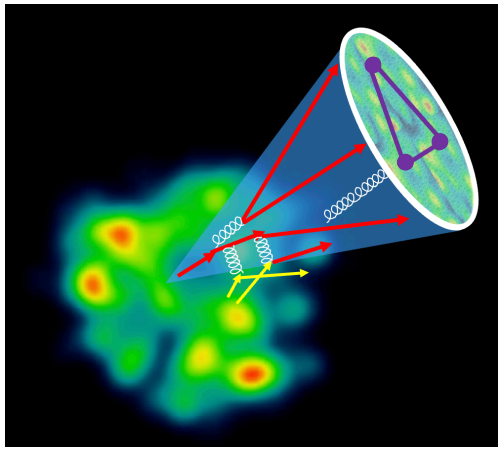
- Requires development of field theoretic techniques to interpret correlations in terms of the dynamics of the underlying field theory.

Outline

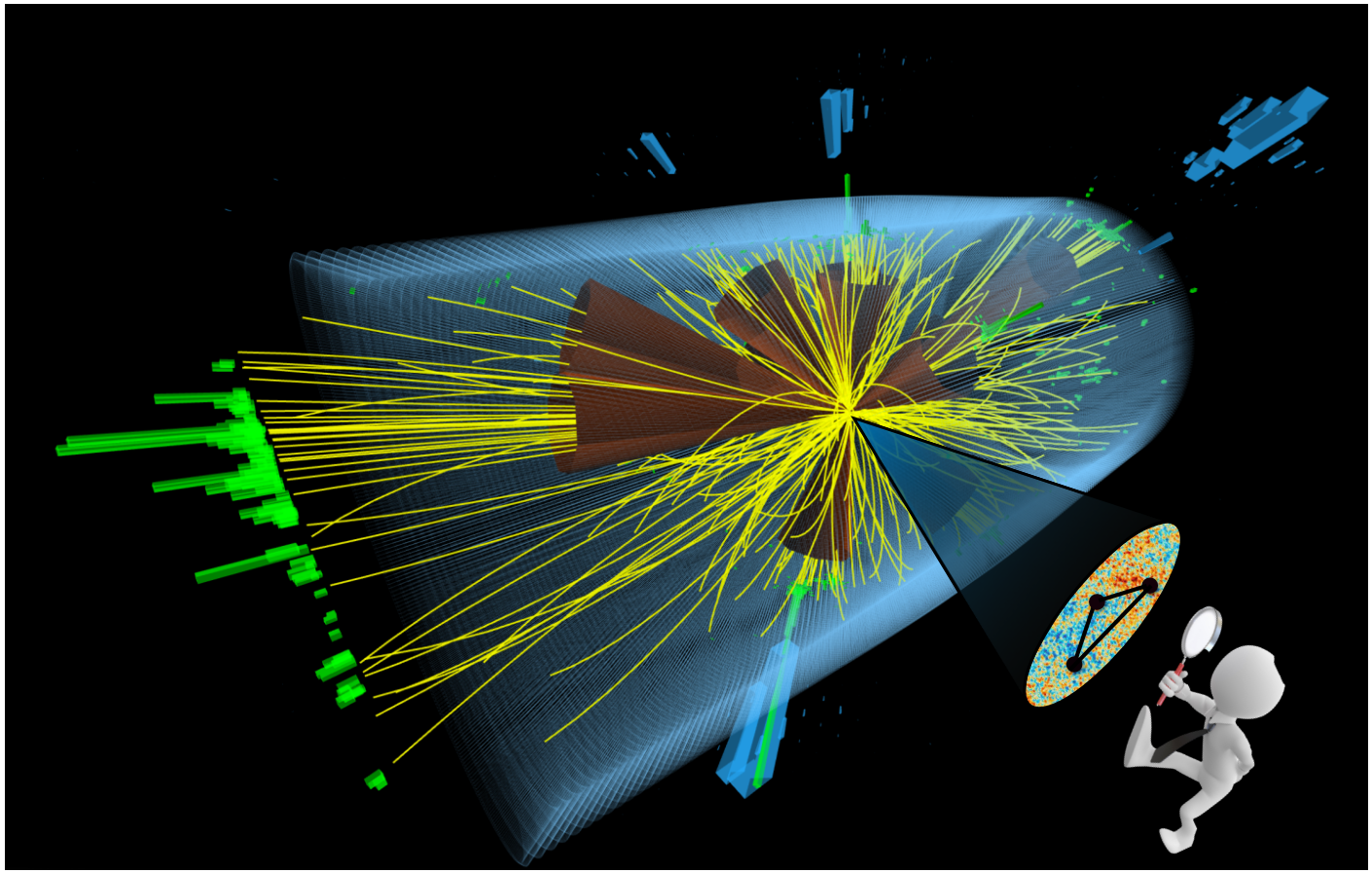
- Decoding Energy Flux
- Scaling Behavior of Quarks and Gluons
- Imaging Intrinsic and Emergent Scales of the QGP





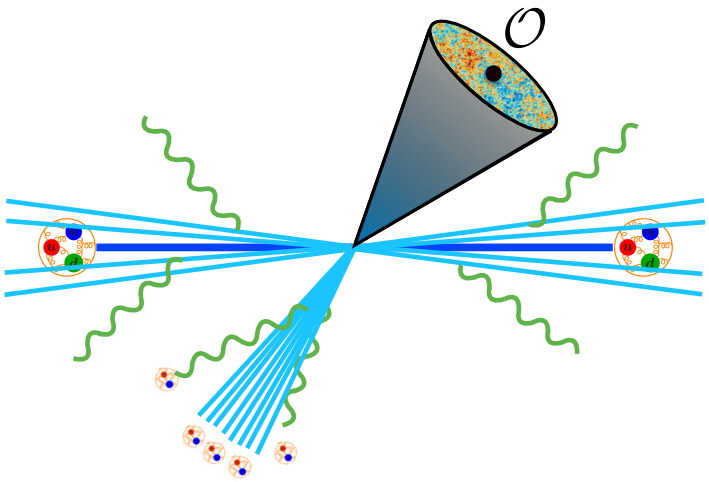


Decoding Energy Flux



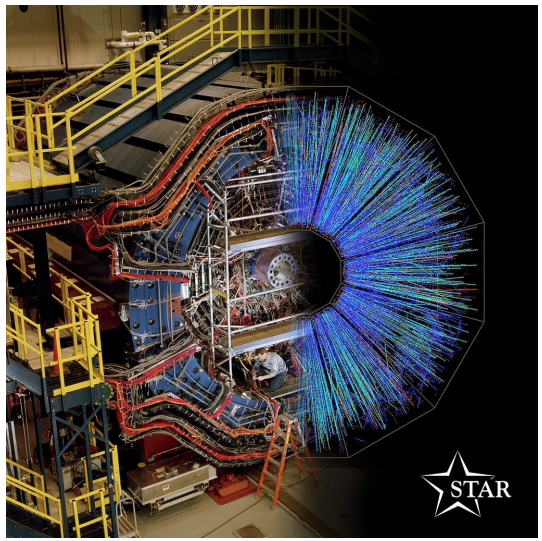
Observables

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



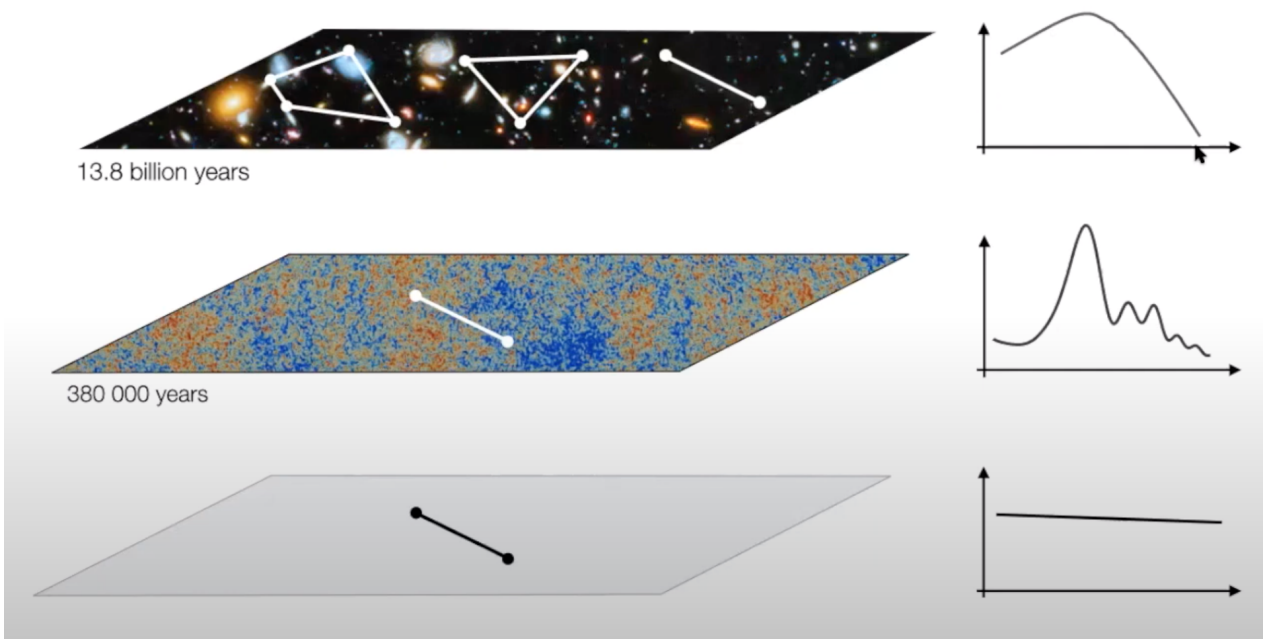
$$\langle \mathcal{O} \rangle = \langle \Psi | \mathcal{O} | \Psi \rangle$$

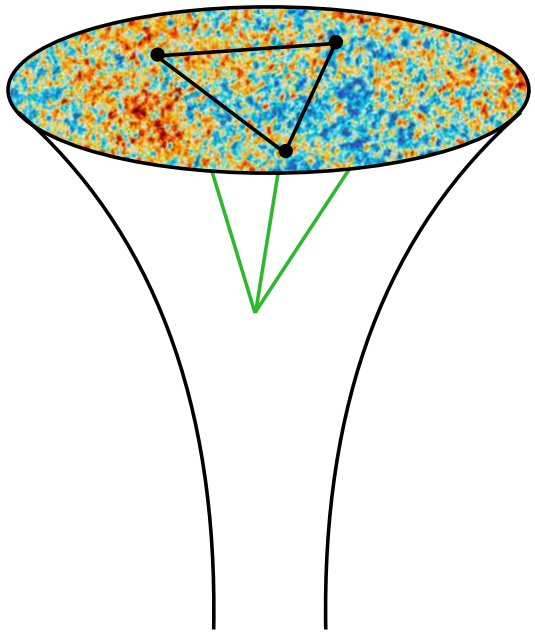
- As we move to studying more subtle features, we need to sharpen this link.
- Correctly choosing observables facilitates the experiment $\leftrightarrow$ theory link.

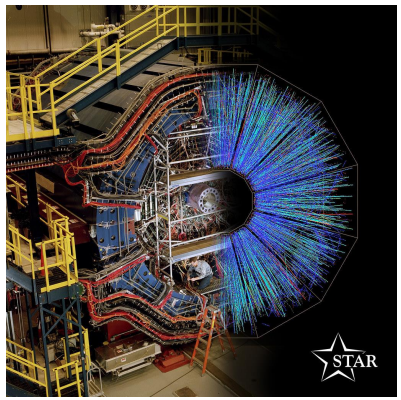


Decoding Energy Flux

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







- What is the analog for collider physics?

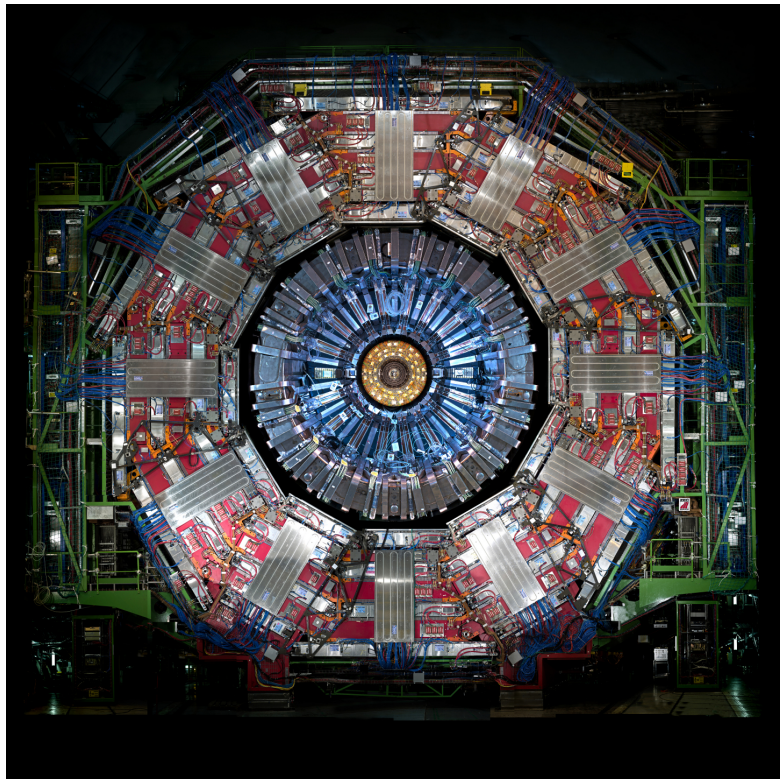
Defining the Problem

- What is a detector?

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

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

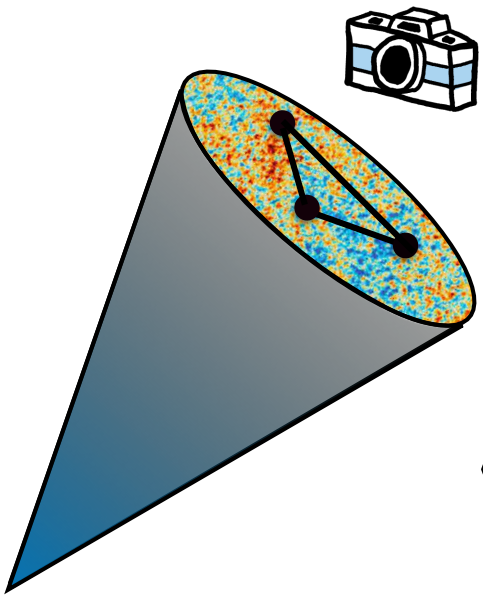
[Caron Huot, Kologlu, Kravchuk, Meltzer, Simmons Duffin]



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

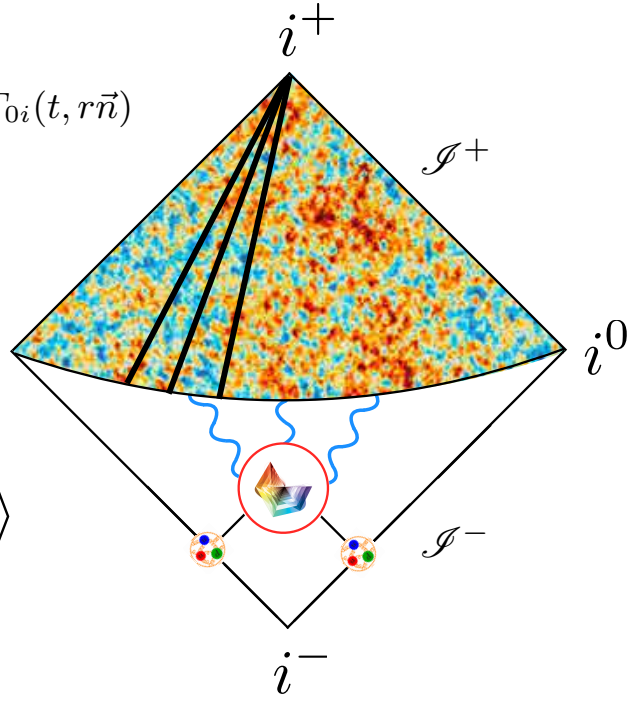
Calorimeter Cells in Field Theory

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



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

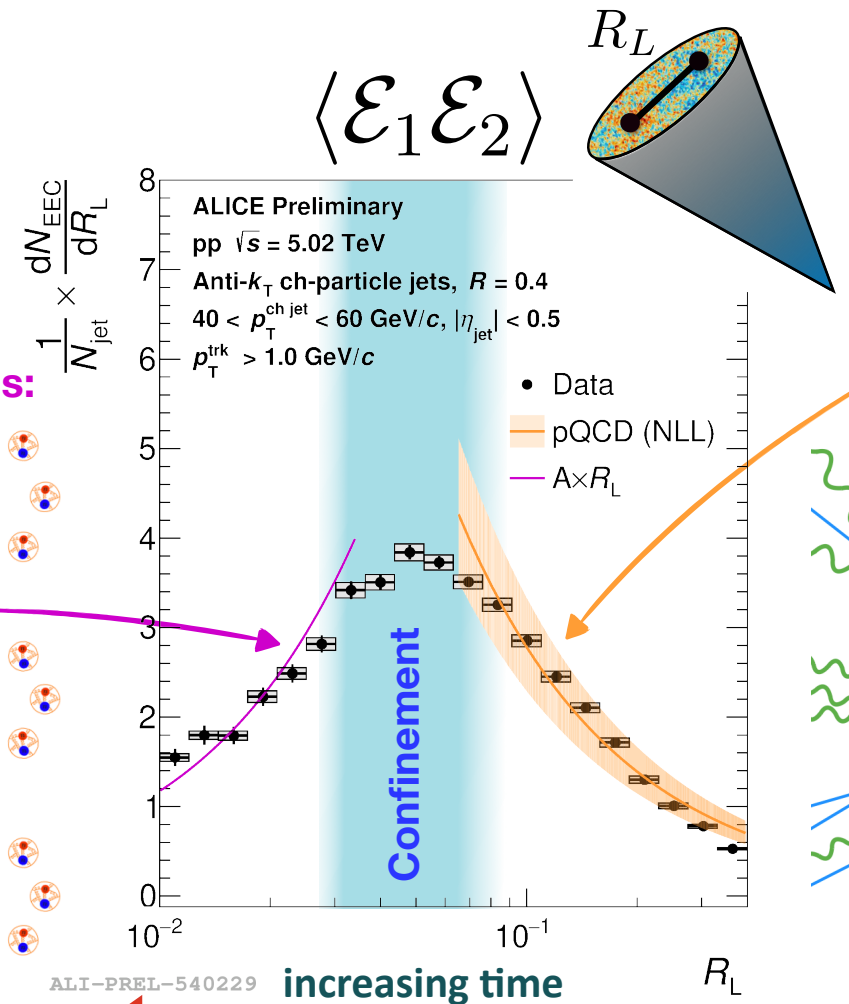
$$\langle\Psi|\mathcal{E}(\hat{n}_1)\cdots\mathcal{E}(\hat{n}_k)|\Psi\rangle$$



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

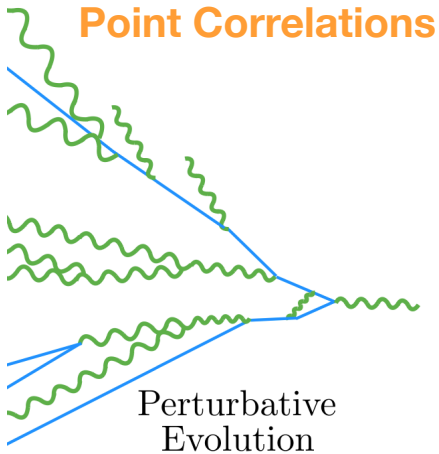
Energy Correlators: Reality

Figure: Wenqing Fan



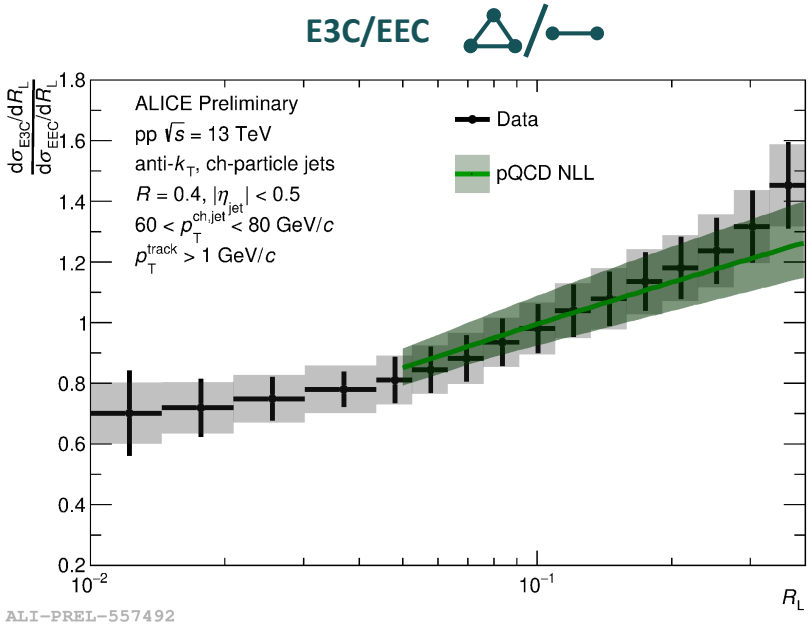
Non-Interacting Hadrons:
-Integer Scaling
-Trivial Higher Point Correlations

Interacting Partons:
-Non-Integer Scaling
-Non-trivial Higher Point Correlations



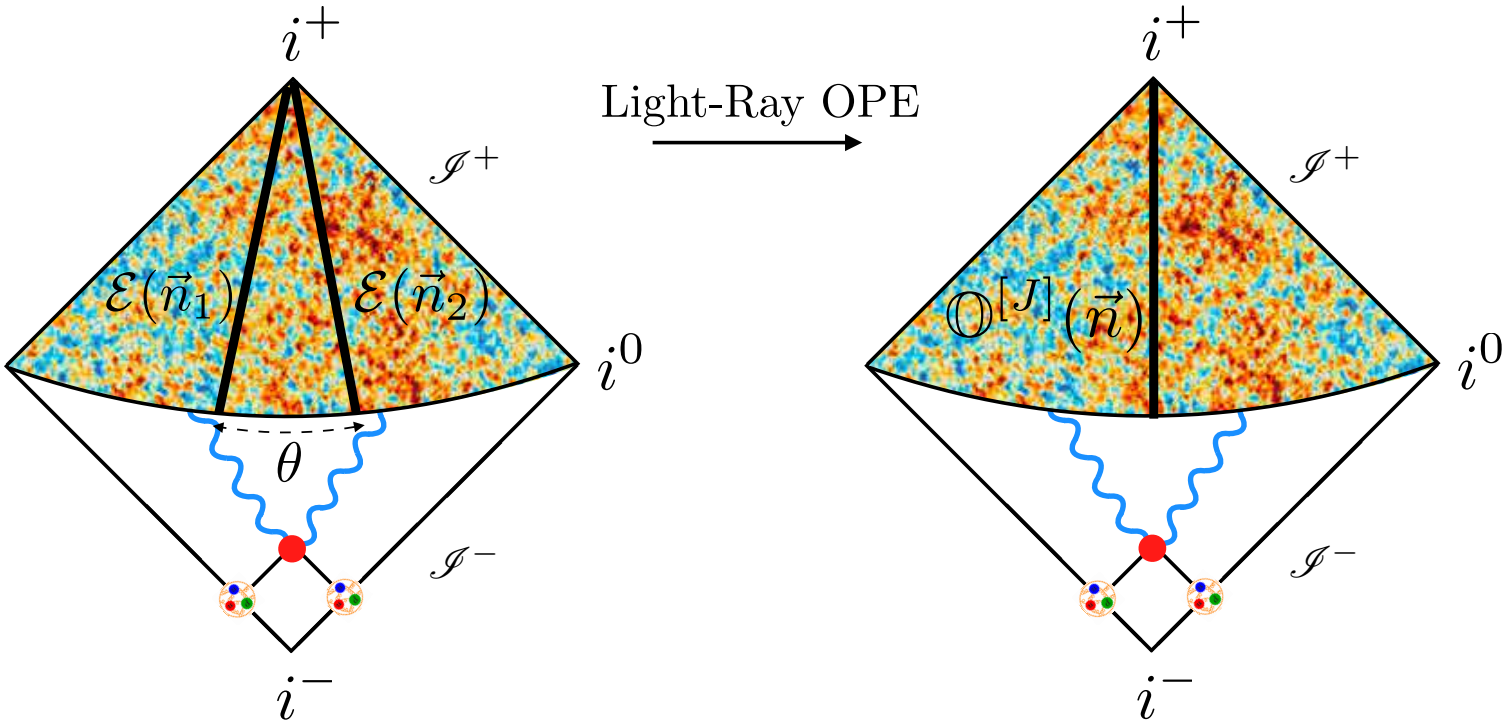
Energy Correlators: Reality

- See talk by Ananya Rai on realities of vacuum measurement.



- See talk by Jussi Viinikainen on realities of heavy ion measurement.

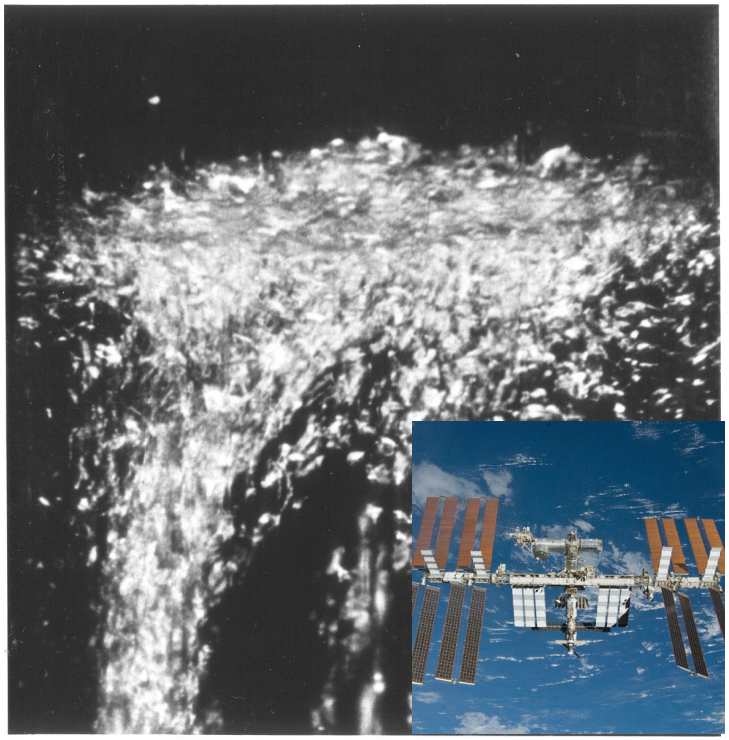
Scaling Behavior of Quarks and Gluons

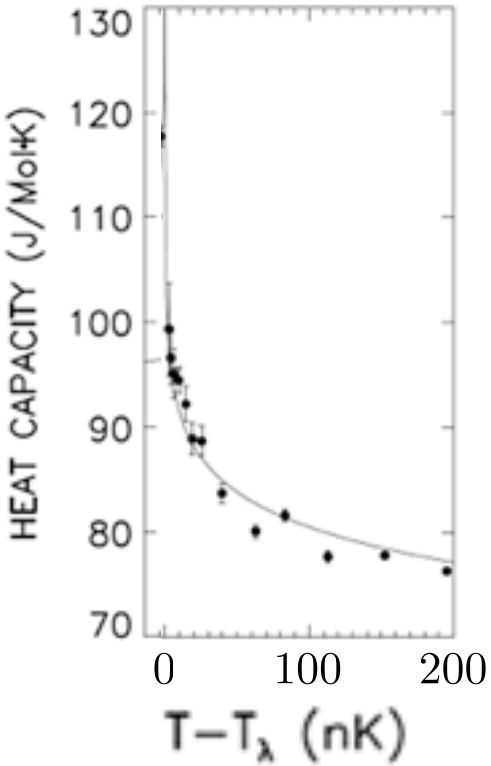


Scaling Behavior in QFT

- Scaling behavior in Euclidean regime well understood.

λ-point of Helium

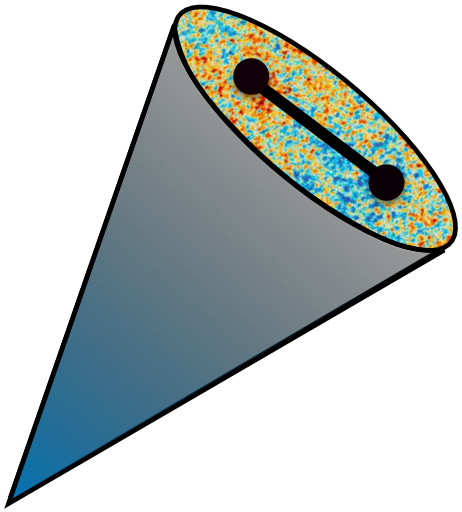


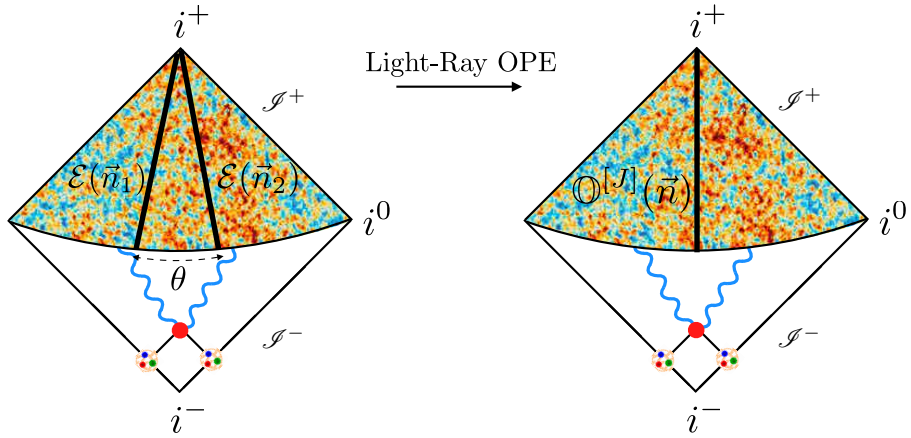


$$\mathcal{O}(x)\mathcal{O}(0) = \sum x^{\gamma_i} c_i \mathcal{O}_i$$

The OPE Limit of Lightray Operators

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





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

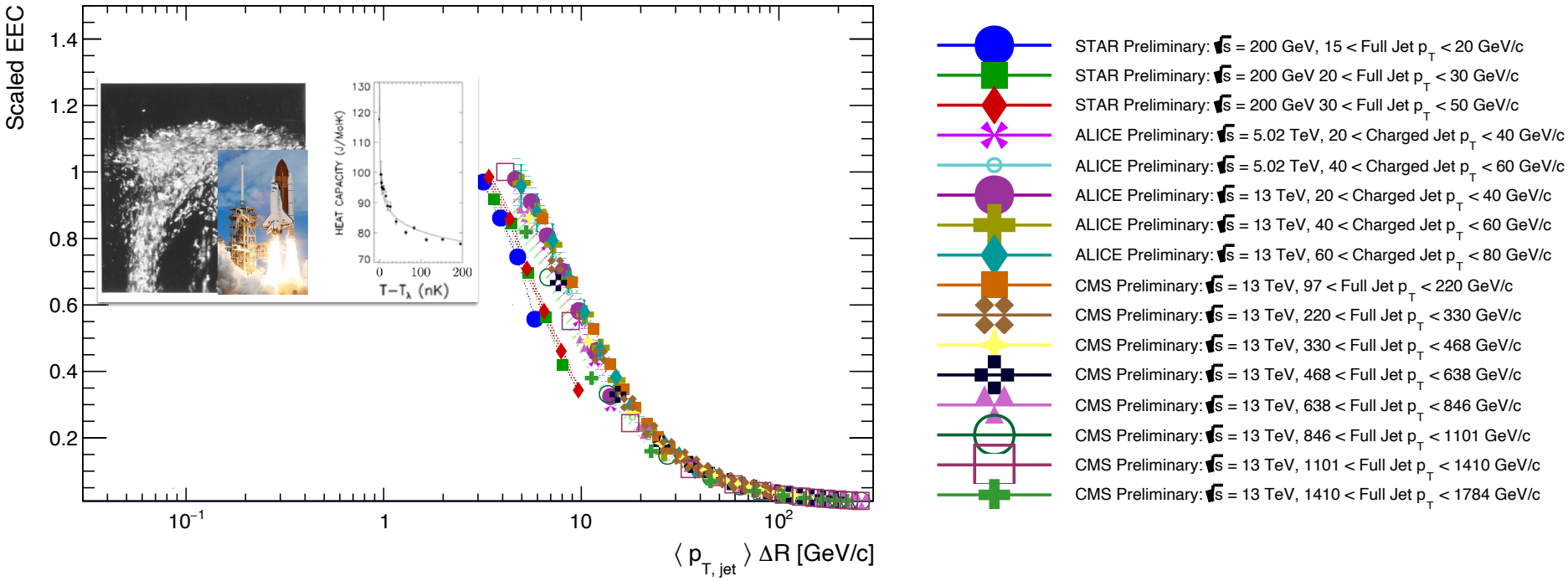
[Hofman, Maldacena]
[Chang, Kologlu, Kravchuk, Simmons Duffin, Zhiboedov]

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

Scaling Behavior in Jets

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

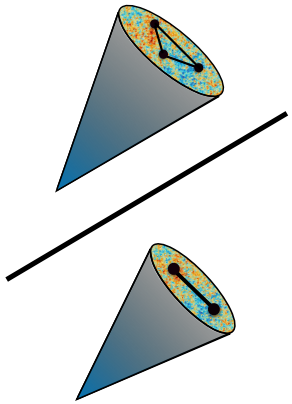
- The $\mathcal{E}(\hat{n}_1)\mathcal{E}(\hat{n}_2)$ OPE inside high-energy jets!

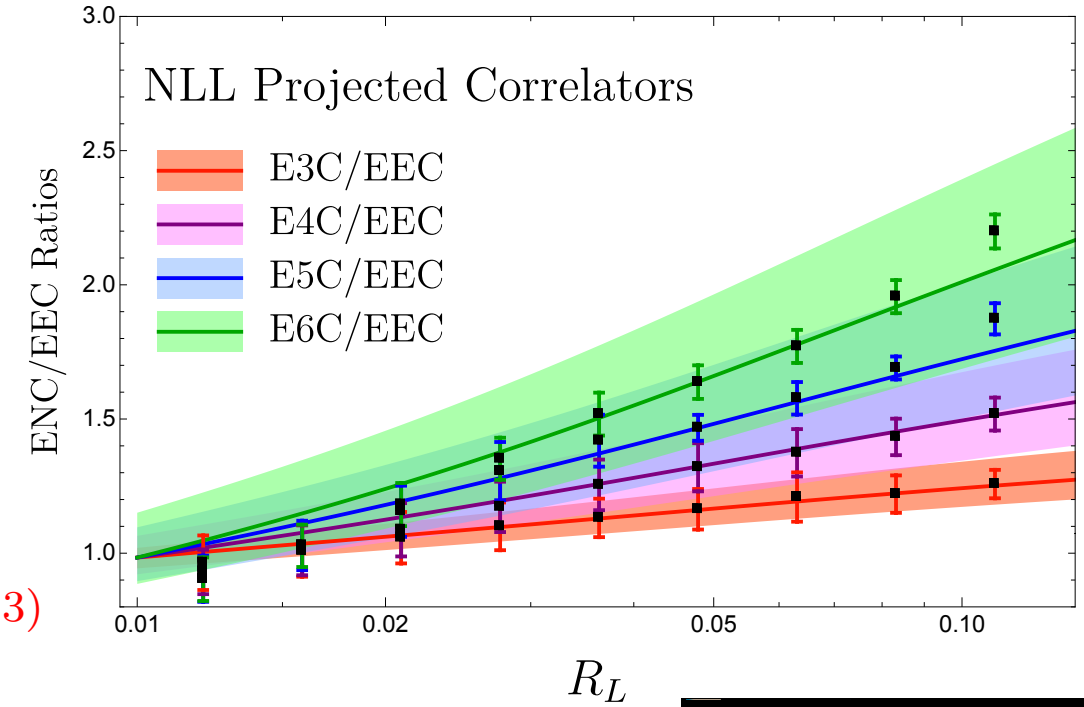


- Dominated by classical scaling. Can we accurately measure anomalous scaling?

The Spectrum of a Jet

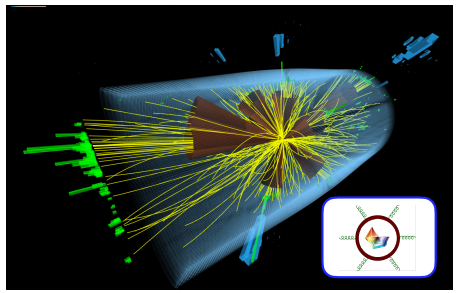
- The light-ray OPE predicts that the N-point correlators develop an anomalous scaling that depends on N.





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

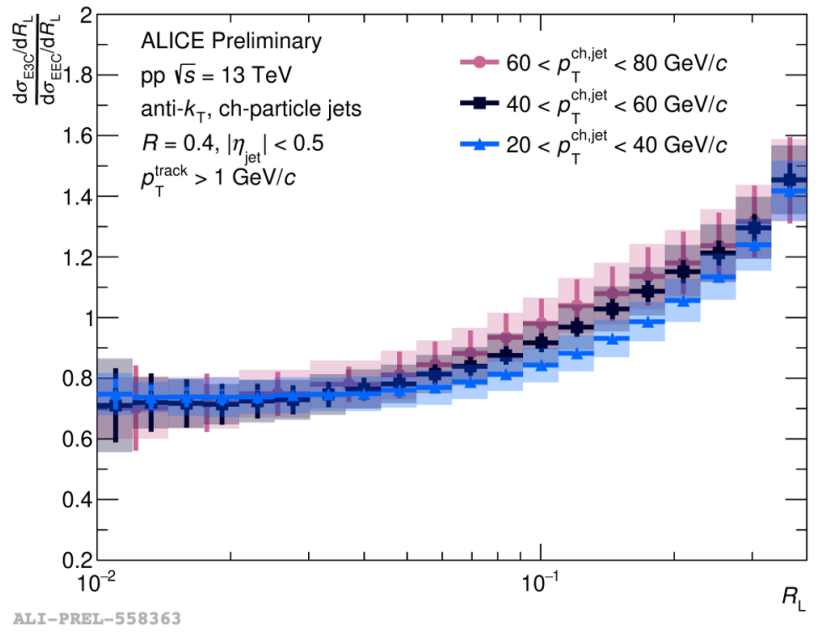
- Directly probes the spectrum of (twist-2) lightray operators from asymptotic energy flux.

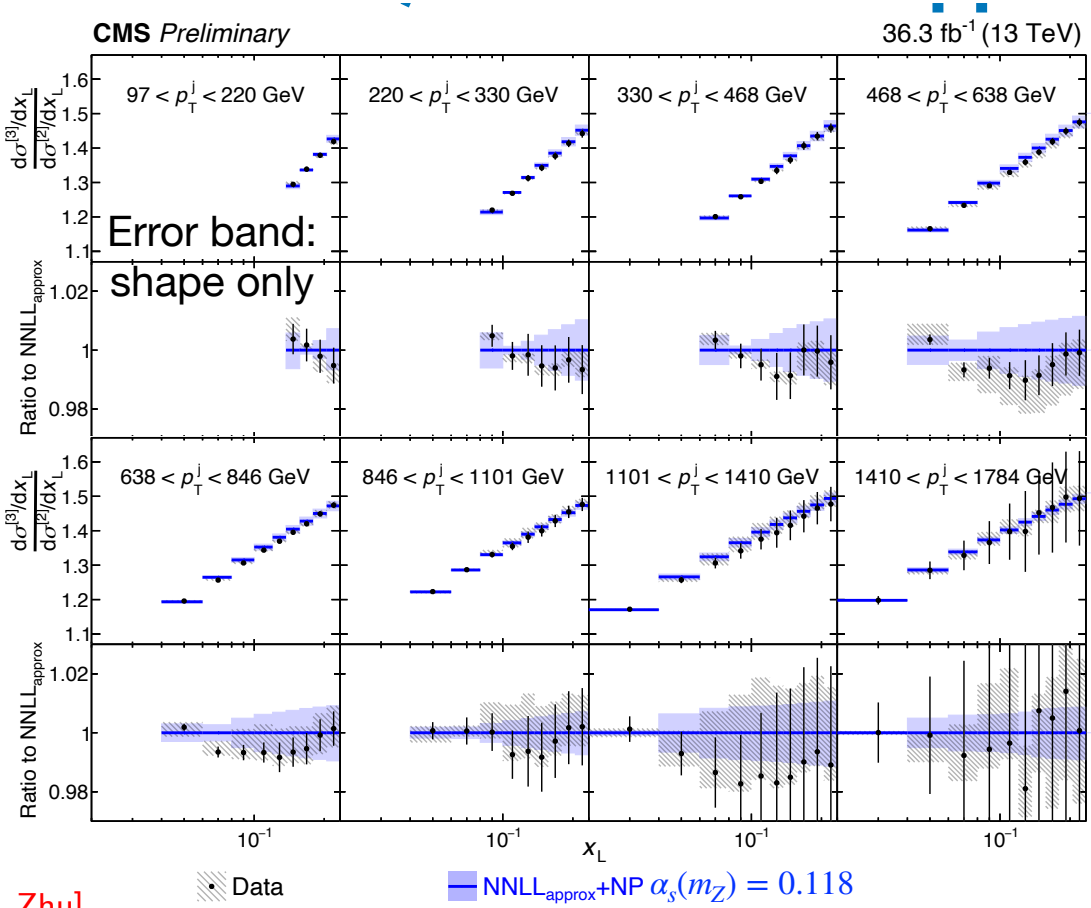


Anomalous Scaling of $3/2$ Ratio

- Anomalous scaling measured from 15 GeV to 1784 GeV!

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

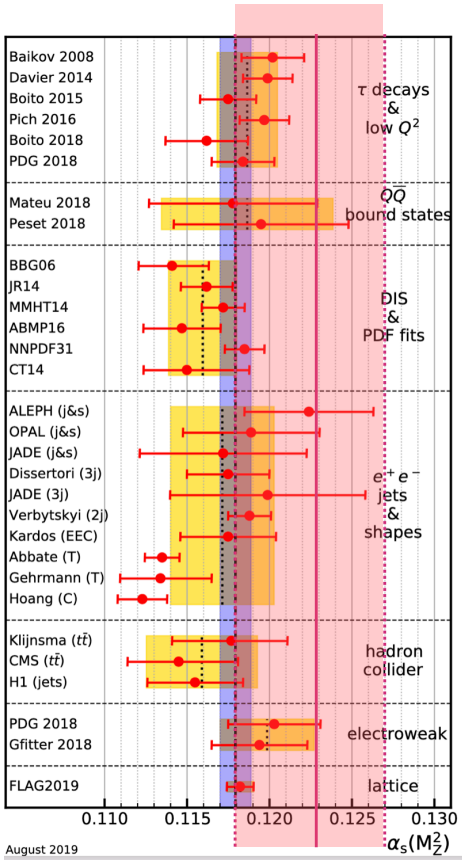


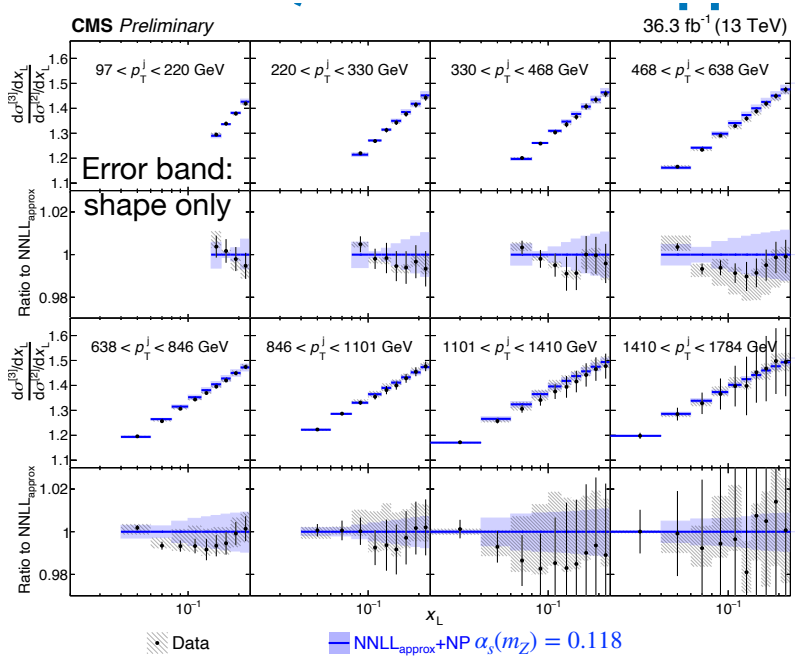


Using [Lee, Mecaj, Moult], [Chen, Gao, Li, Xu, Zhang, Zhu]

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.



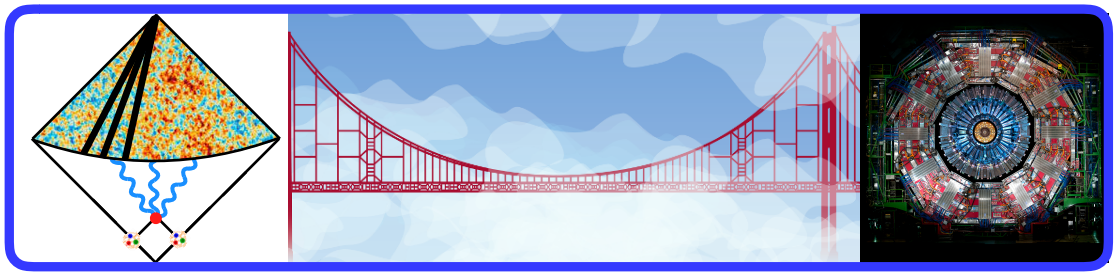


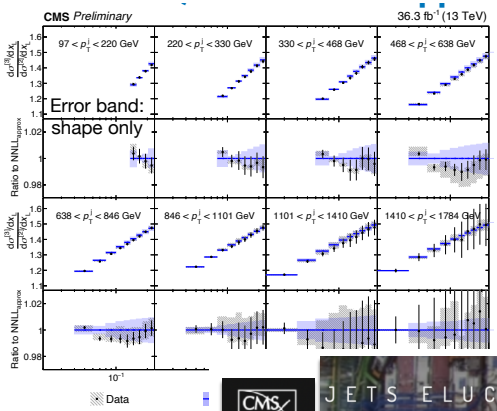
$$\alpha_s(m_Z) = 0.1229^{+0.0040}_{-0.0050}$$

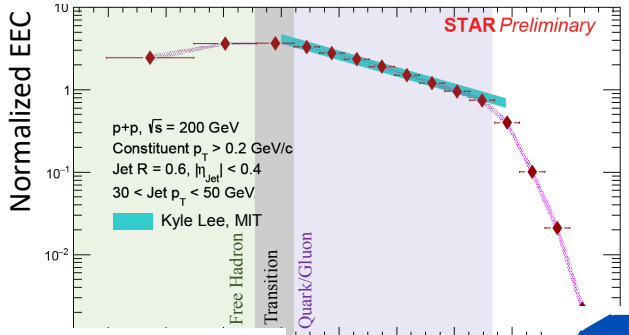
$$= 0.1229^{+0.0014(stat.)+0.0030(theo.)+0.0023(exp.)}_{-0.0012(stat.)-0.0033(theo.)-0.0036(exp.)}$$

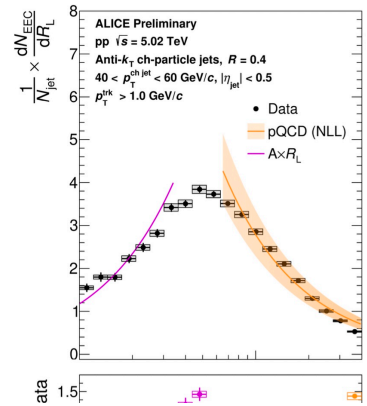
Energy Correlators in Data

- A milestone in connecting jet substructure with QFT!









CERN COURIER

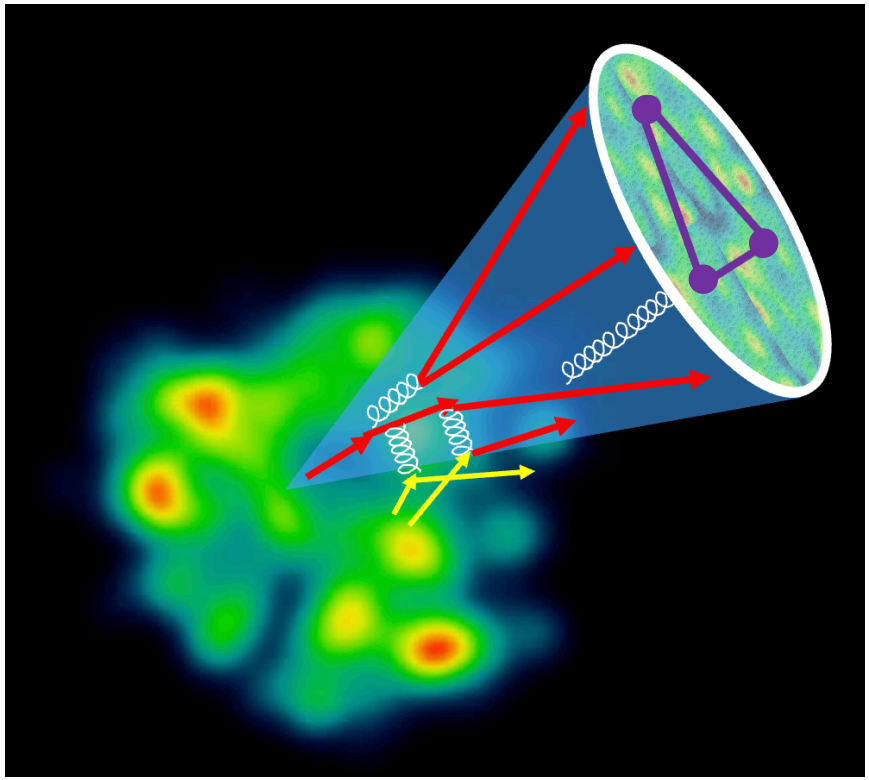
STRONG INTERACTIONS | NEWS

Measuring energy correlators inside jets

3 November 2023

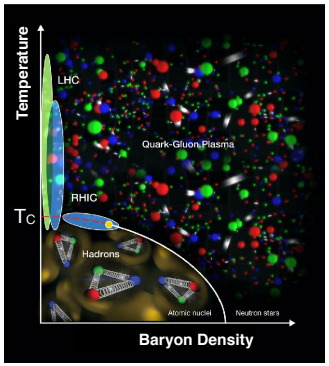
- Can we image how the QGP modifies the correlators?

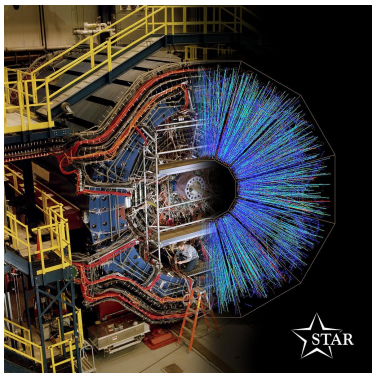
Resolving the Scales of the QGP

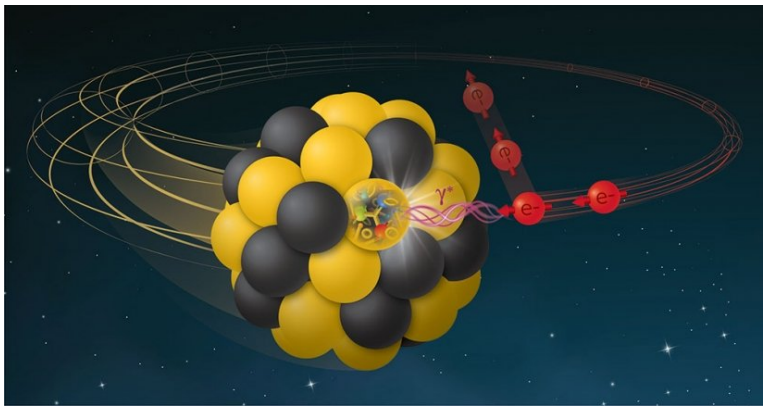


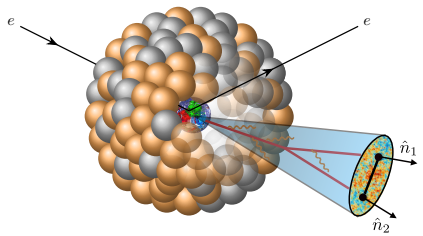
Imaging Emergent and Intrinsic Scales of QCD

- Upshot: Massless QCD above the confinement scale exhibits powerlaw scaling in energy flux $\Longrightarrow$ 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.

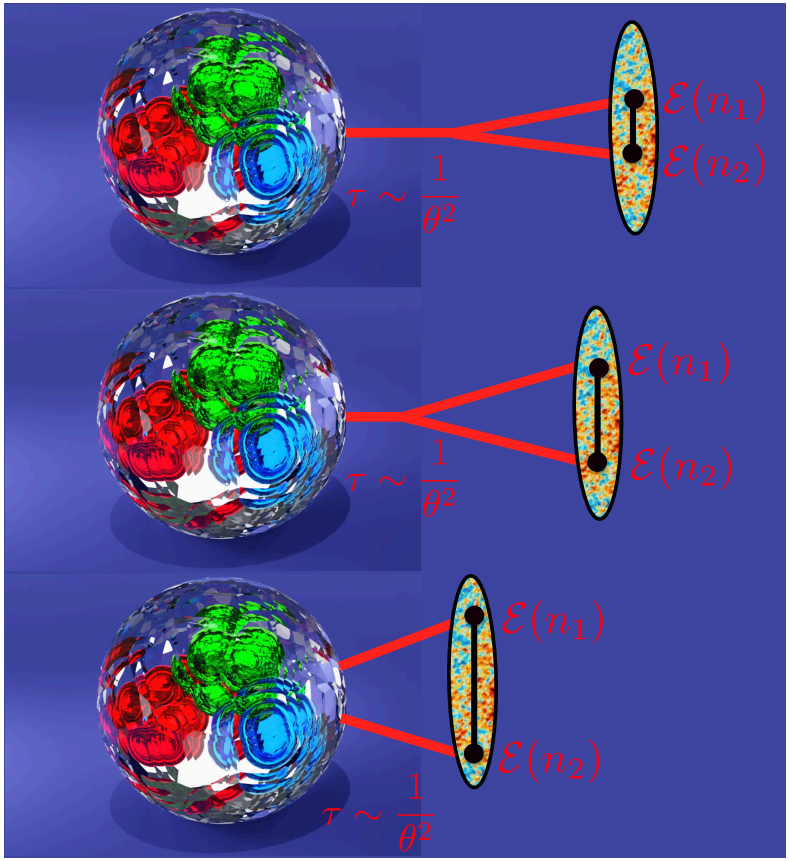








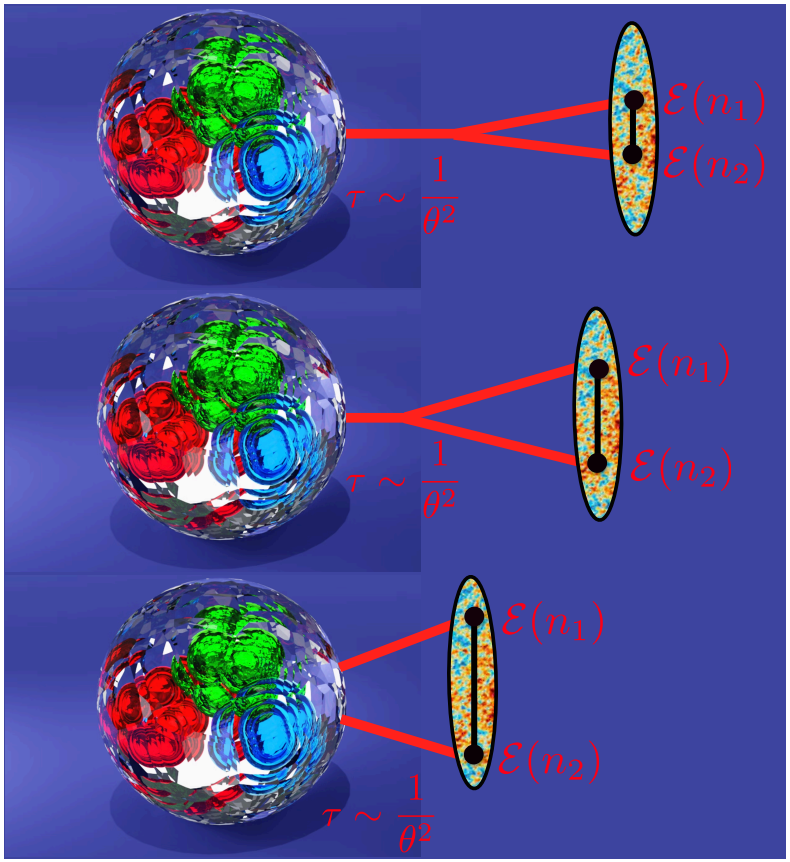
Resolving the Scales of the QGP: Static Medium



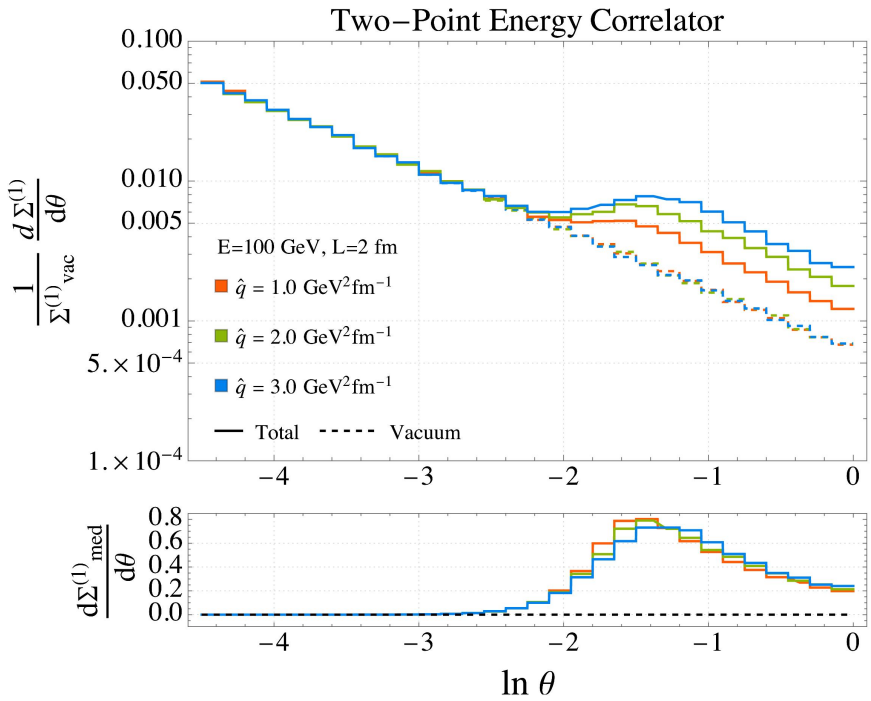
- The QGP introduces a number of new scales into the problem.
- Consider first a static medium.
- We will focus on one scale, $\theta_L \sim \frac{1}{\sqrt{LE}}$, which determines the angle at which splittings resolve the medium

Resolving the Scales of the QGP: Static Medium

- QGP scales cleanly imprinted in two-point correlation.



Increasing θ

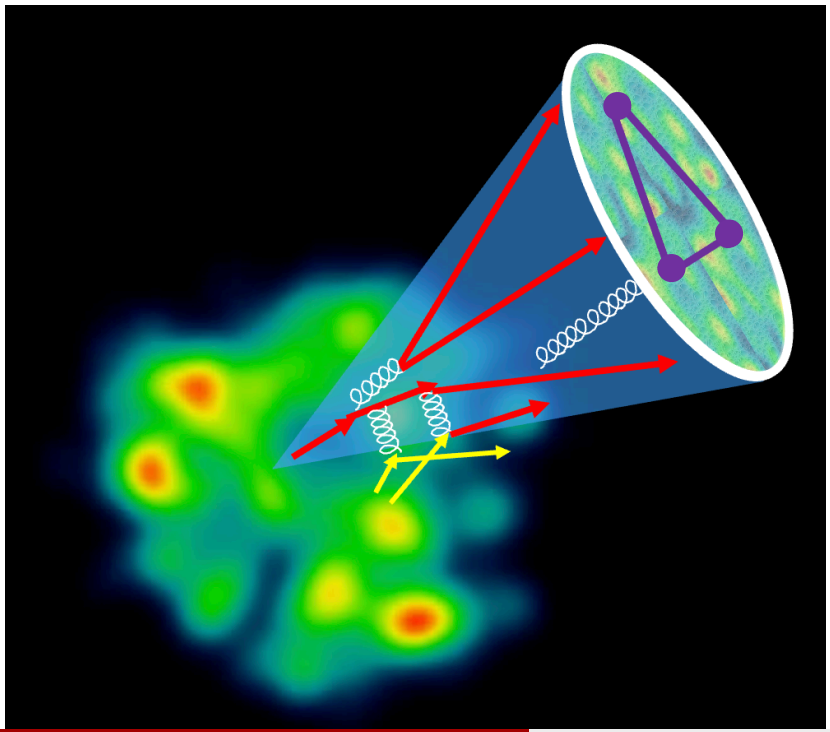


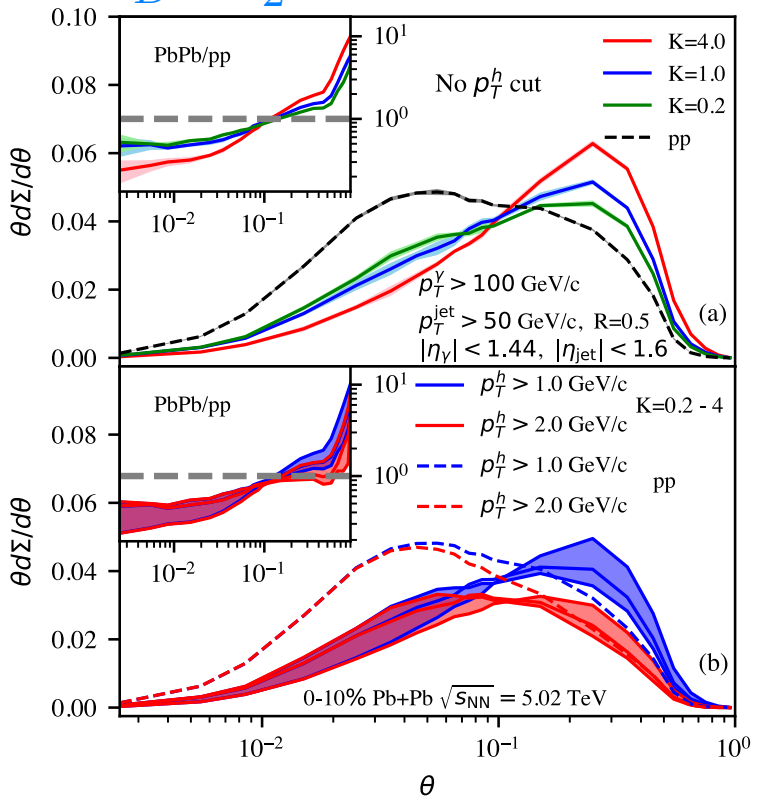
Increasing θ

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

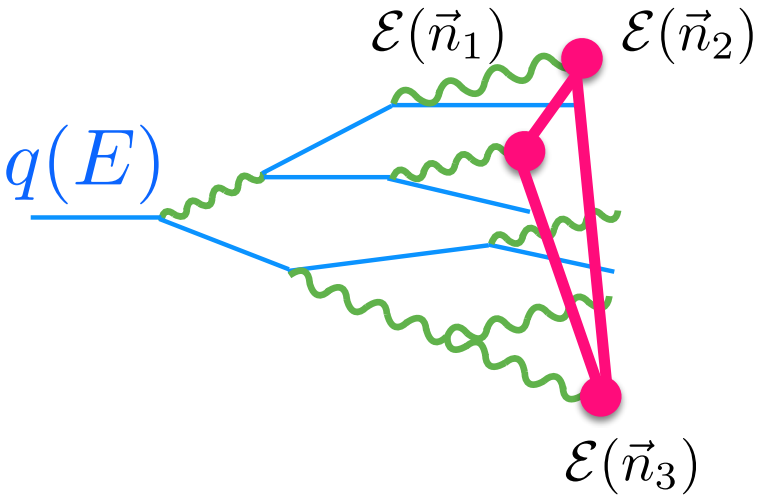
Resolving the Scales of the QGP: Full Simulation

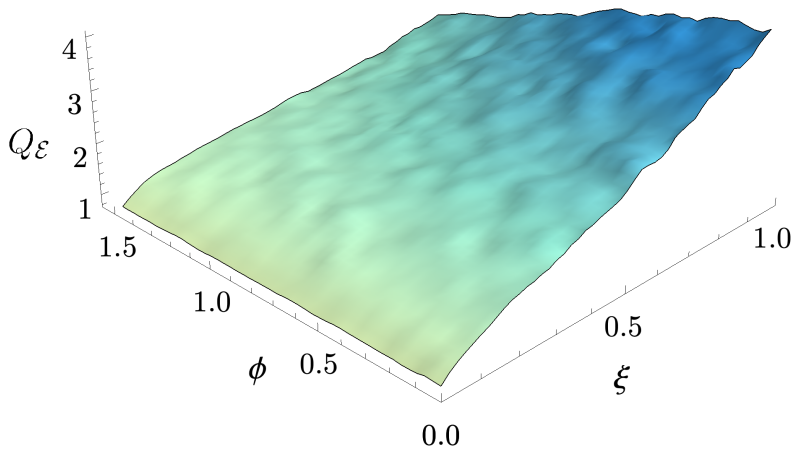
- Perform full simulation in CoLBT. [X.N. Wang et al.]
- Enhanced at large angles from both medium response and bremstrahlung. Suppressed at small angles by energy loss and momentum broadening. [Yang, He, Moult, Wang]
- Sensitivity to the Debye screening mass $\mu_D^2 = \frac{3}{2} K g^2 T^2$: Probe short distance structure of the QGP.





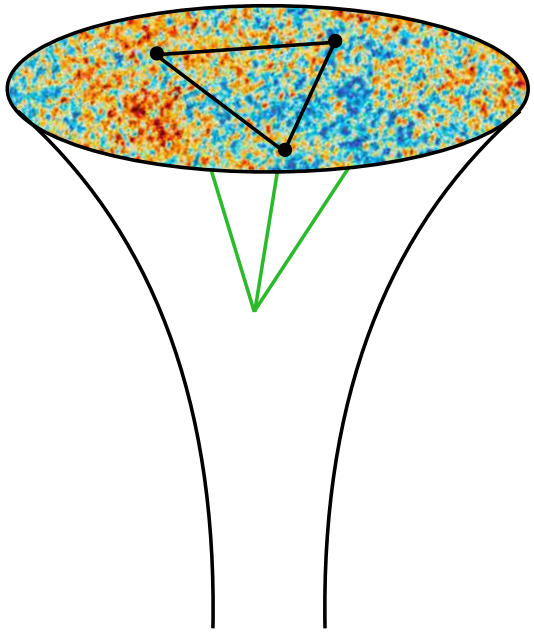
Non-Gaussianities in Energy Flux

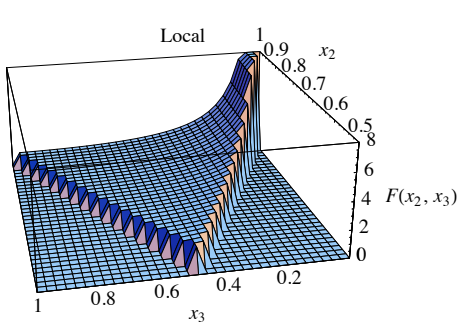


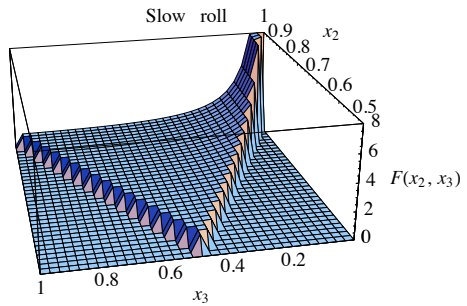


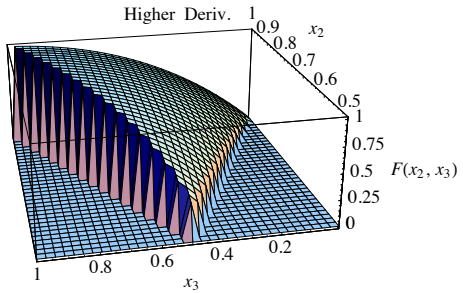
Non-Gaussianities

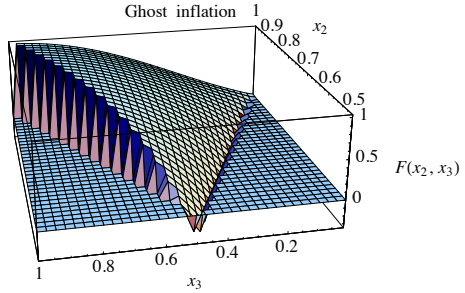
- Higher-point correlators probe more detailed aspects of interactions.
- e.g. Non-Gaussianities allow one to distinguish models of inflation.







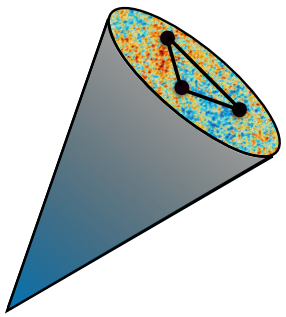




- What is the structure of higher-point functions of energy flux?

Shape Dependence of Non-Gaussianities: Vacuum

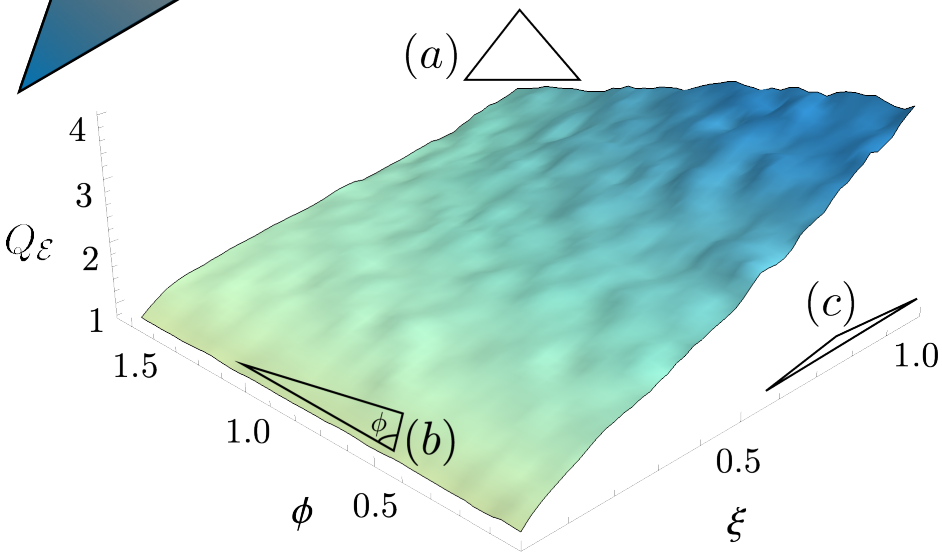
- Can directly study non-gaussianities inside high energy jets.

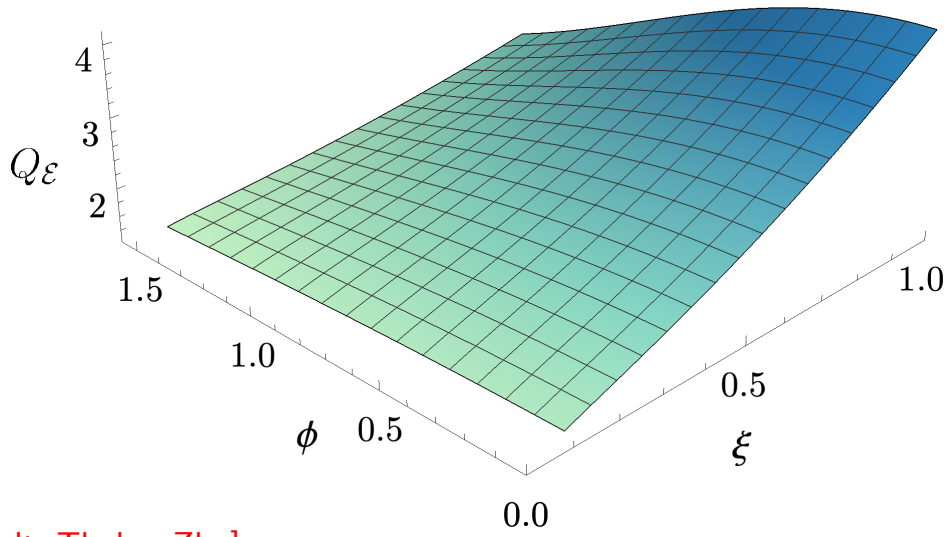


Open Data, $R_L \in (0.3, 0.4)$

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

LL + LO prediction, $R_L = 0.35$





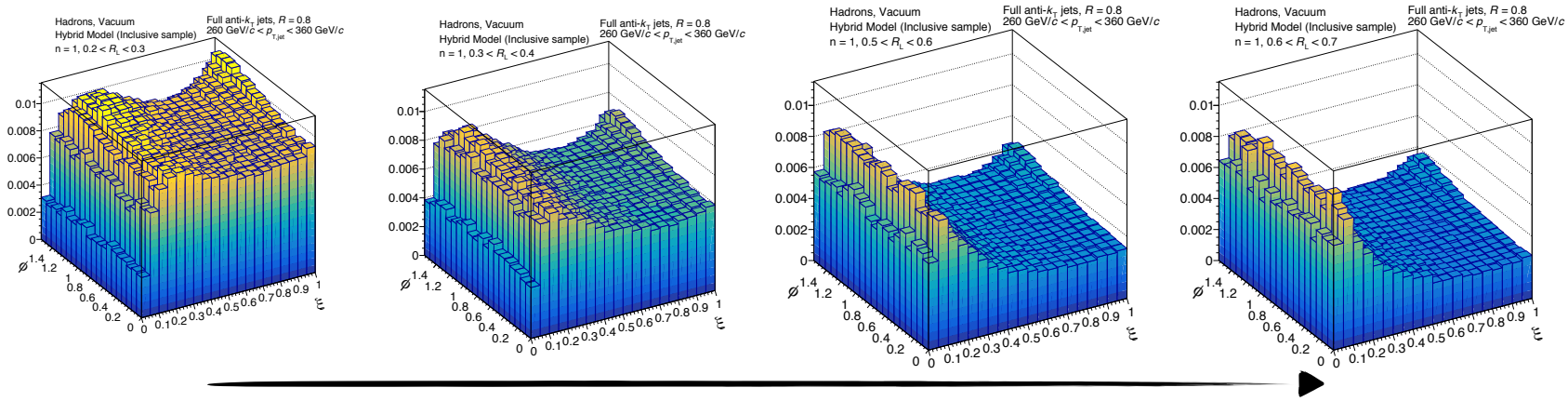
[Chen, Moult, Thaler, Zhu]

- Illustrates theoretical control over multi-point correlations!

Resolving the Scales of the QGP

- Higher point correlators allow us to probe the "shape" of modifications from the QGP: unravel different physical effects
- Illustrate by imaging the wake in the hybrid model.

Vacuum



[Bossi, He, Kudinoor, Moult, Pablos, Rai, Rajagopal]

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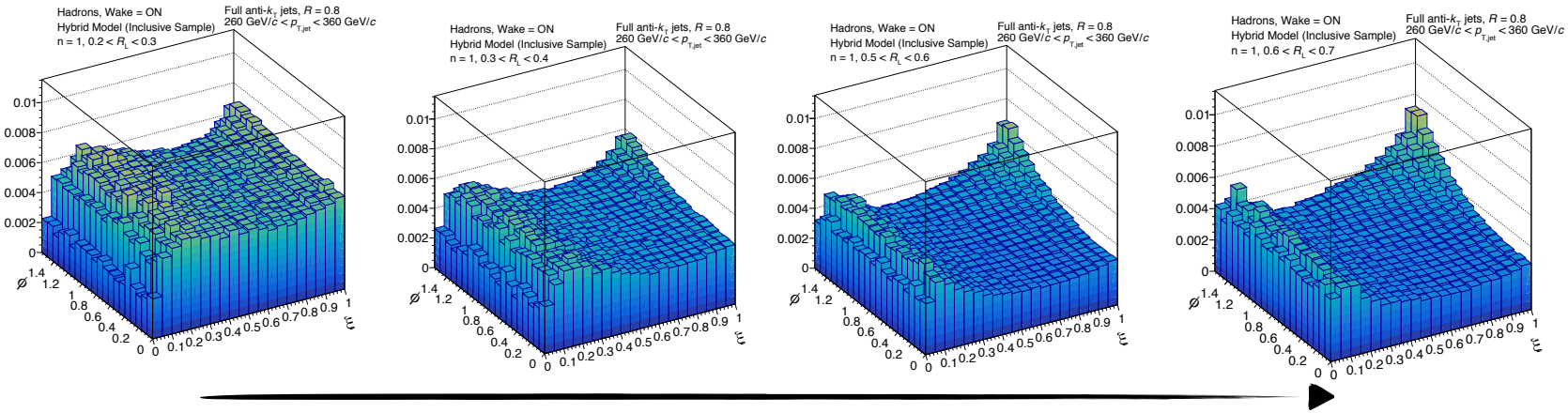
Wake



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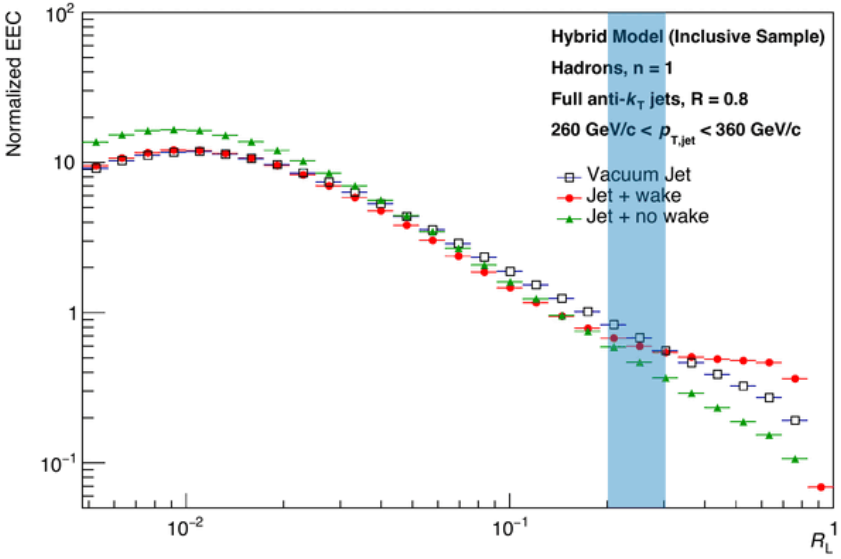

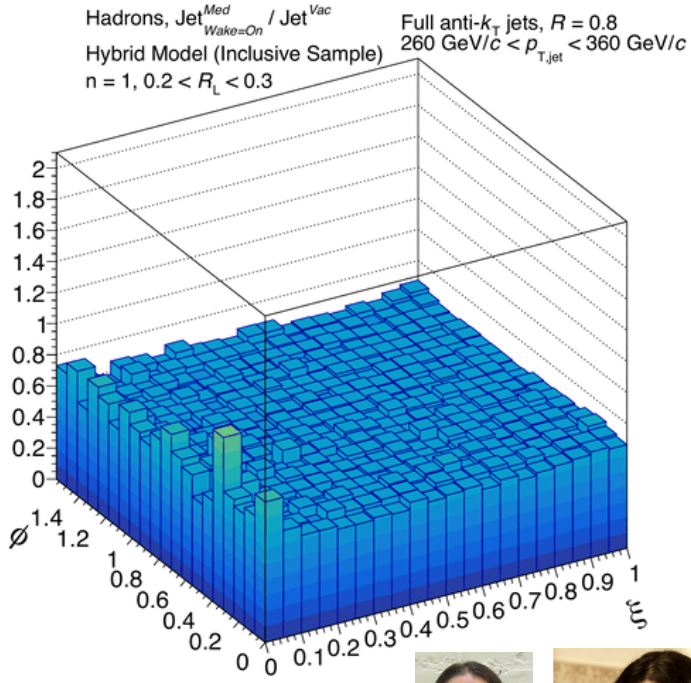

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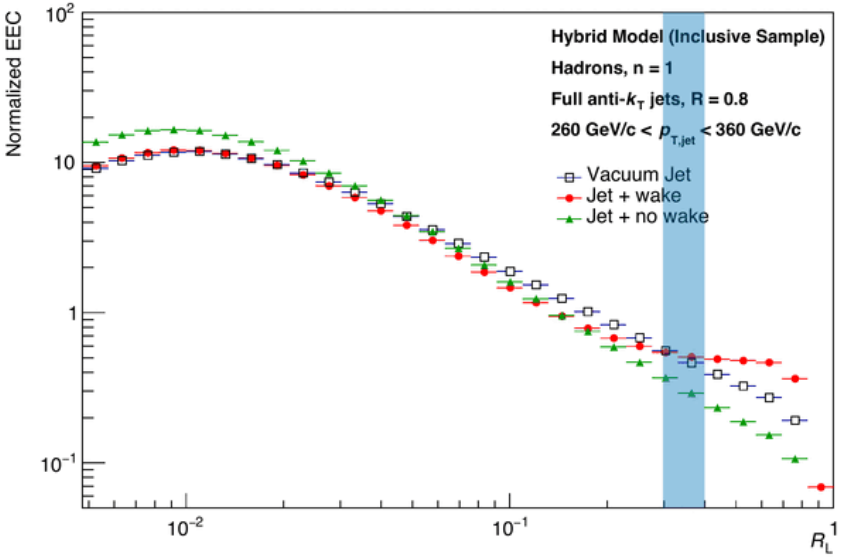

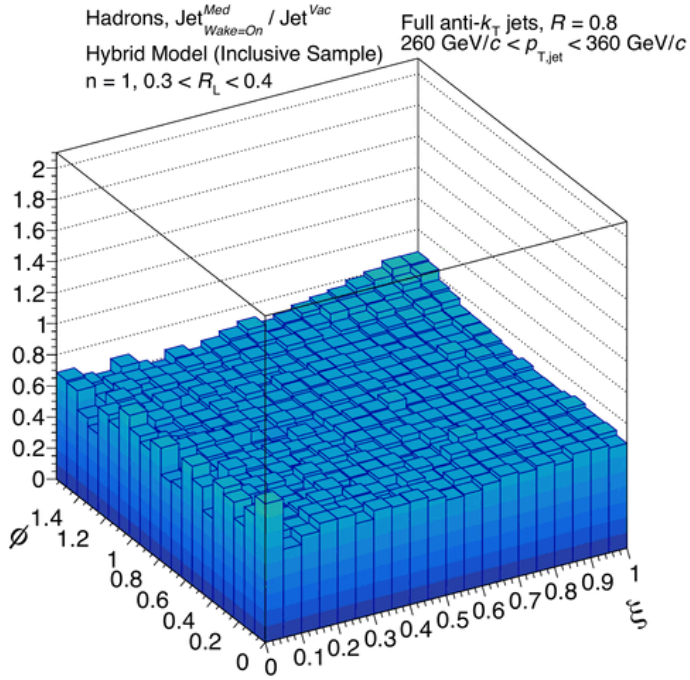

[Bossi, He, Kudinoor, Moult, Pablos, Rai, Rajagopal]

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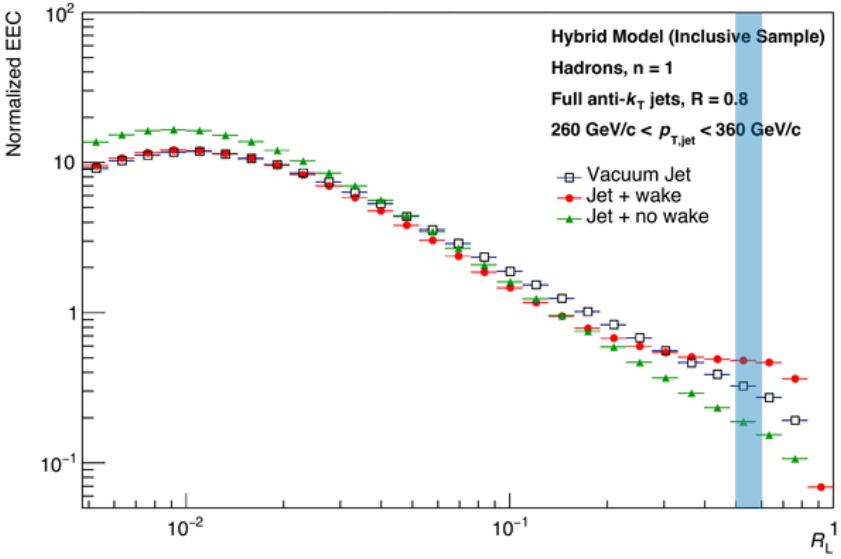

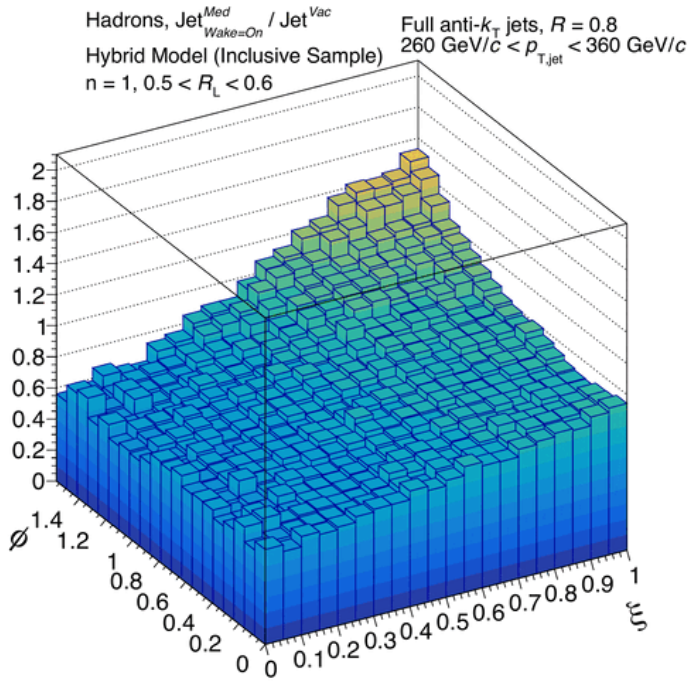

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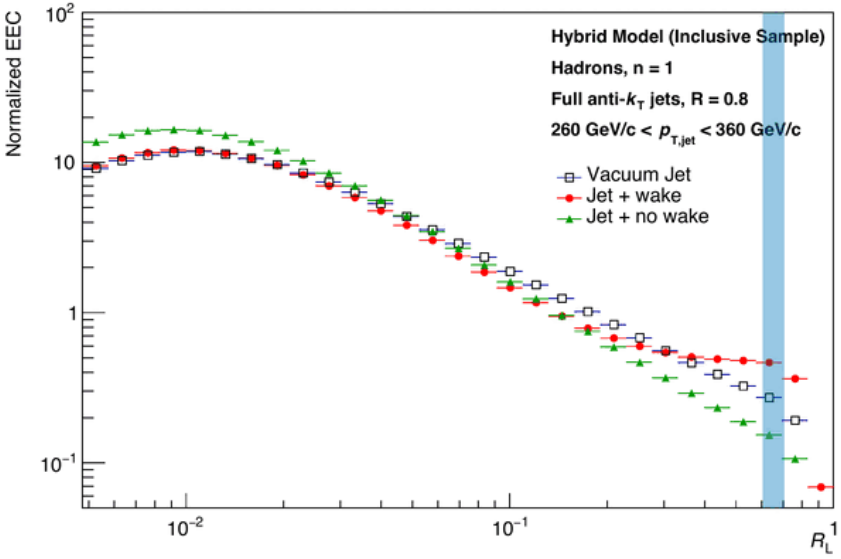
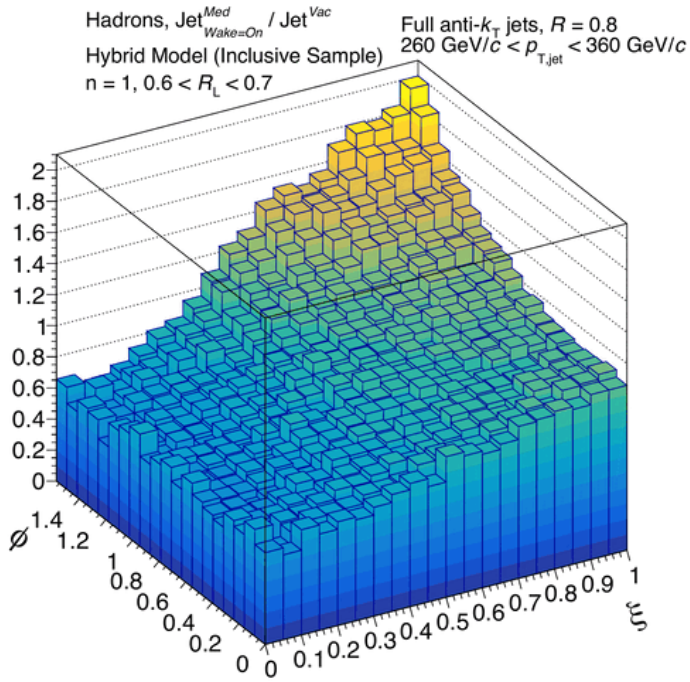
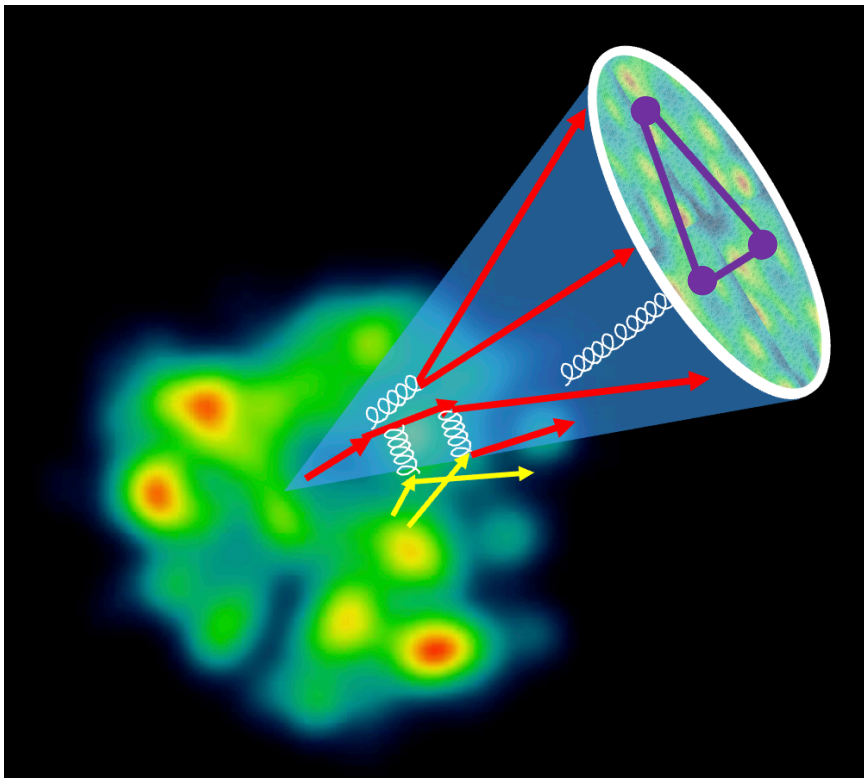




[Bossi, He, Kudinoor, Moult, Pablos, Rai, Rajagopal]

Energy Correlators in Data

- Measurement of energy correlators in heavy ion will be a milestone in bridging collider measurements with the underlying QFT description of the QGP!



DATA?

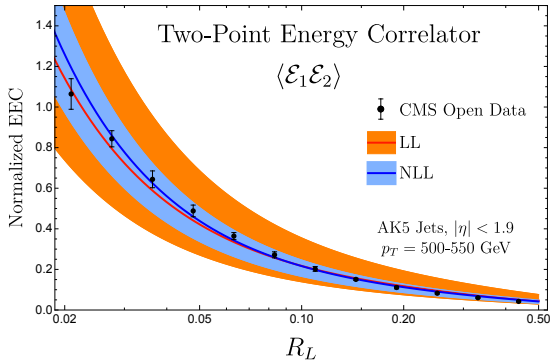
- Will provide a direct measurement of this fundamental quantity in a finite temperature non-abelian gauge theory!

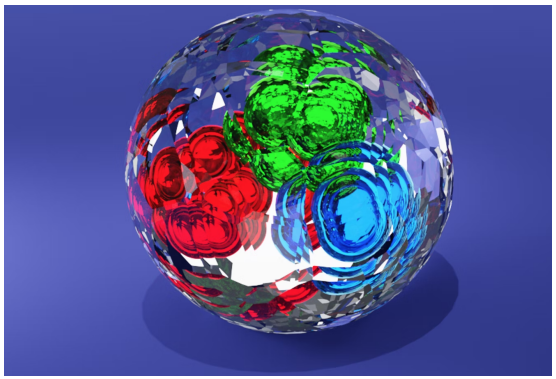
Summary

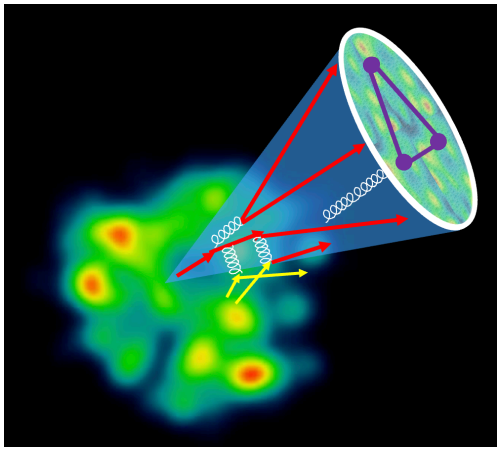
- Correlation functions, $\langle \mathcal{E}(n_1) \cdots \mathcal{E}(n_k) \rangle$, provide a sharp link between theory and experiment. And can now be directly measured.

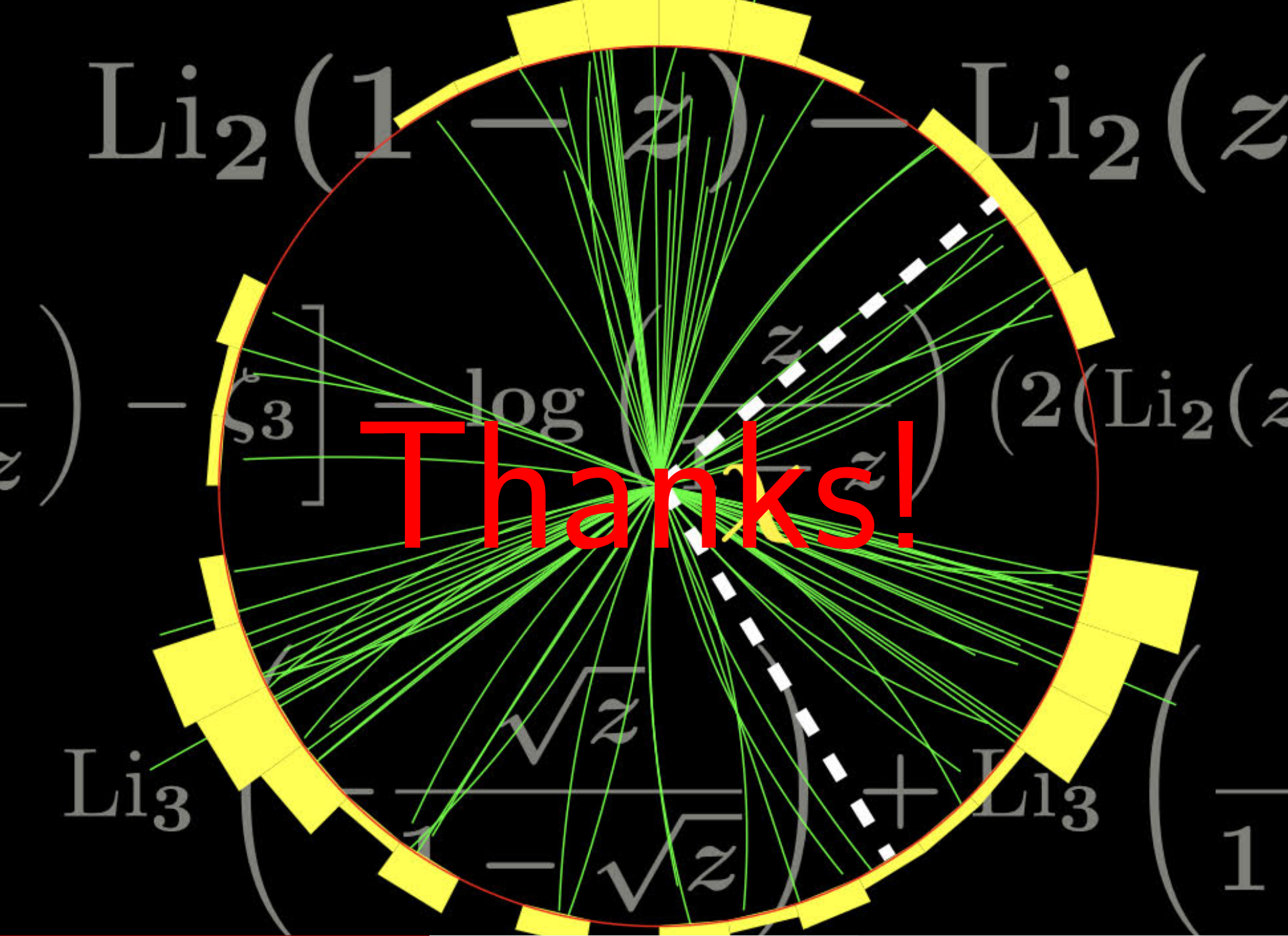
- Intrinsic and emergent scales imprint themselves in correlation functions at characteristic scales.

- Energy correlators provide a unique new tool to unravel the microscopic structure of the QGP.








Thanks!