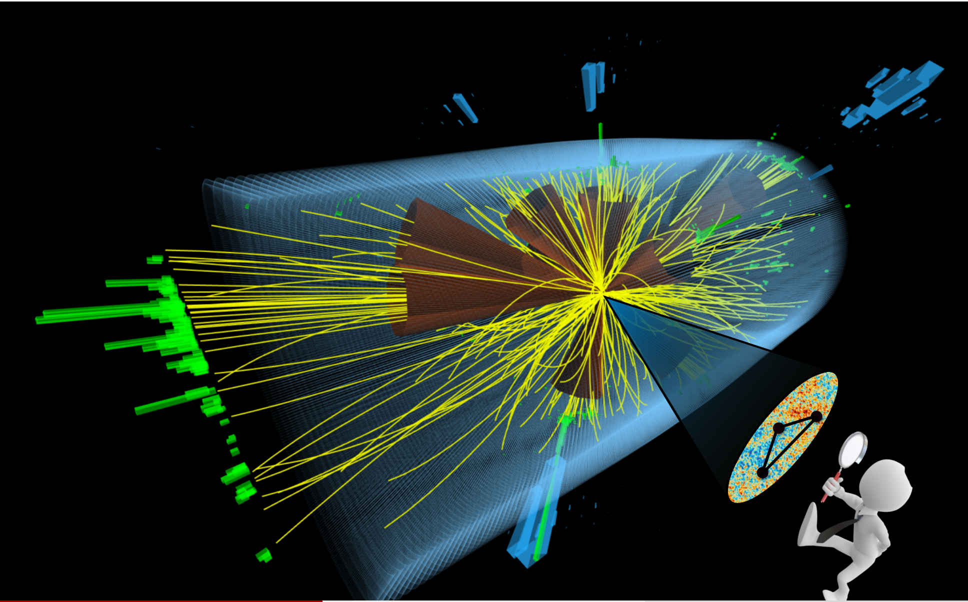
Imaging QCD Dynamics with Jet Substructure

Ian Moult

Yale

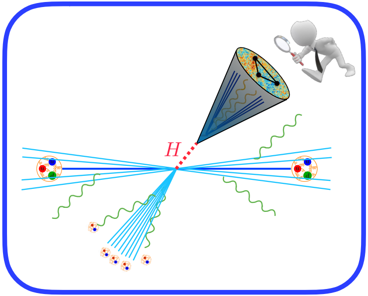
Jet Substructure!



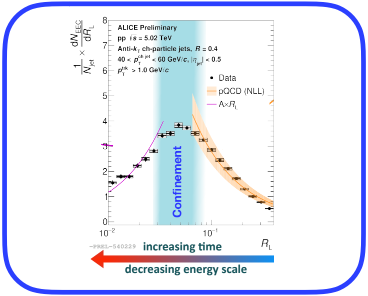
Jet Substructure

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

Innovative Search Techniques



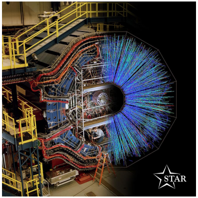
Novel Probes of QCD Dynamics

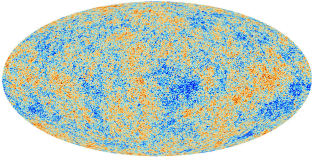


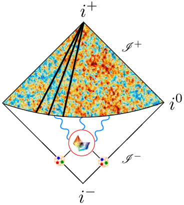
- Has evolved well beyond its origin to have a large impact on BSM, SM, high energy QCD and nuclear physics.

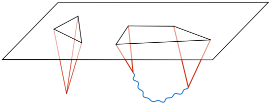
Decoding Energy Flux

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





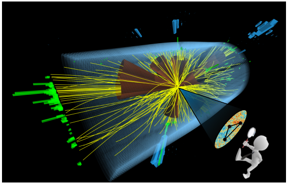




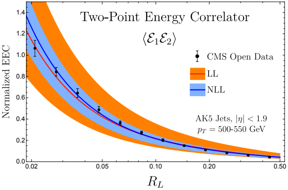
- Requires development of field theoretic techniques to interpret correlations in terms of the dynamics of the underlying field theory.

Outline

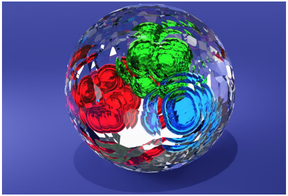
- Decoding Energy Flux



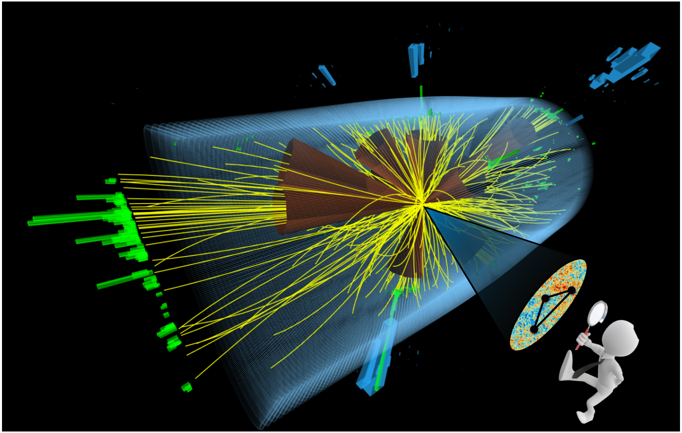
- Scaling Behavior of Quarks and Gluons



- Imaging Intrinsic and
  Emergent Scales of QCD

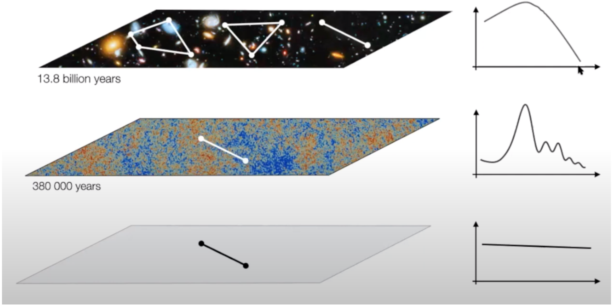


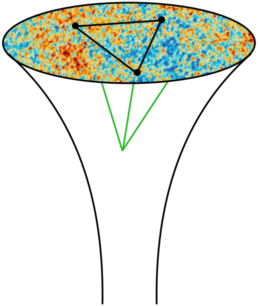
Decoding Energy Flux

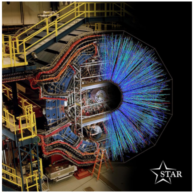


Decoding Energy Flux

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







- What is the analog for collider physics?

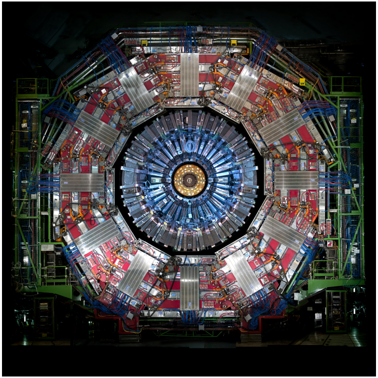
Defining the Problem

- What is a detector?

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

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

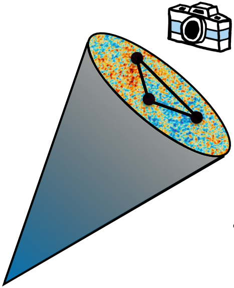
[Caron Huot, Kologlu, Kravchuk, Meltzer, Simmons Duffin]



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

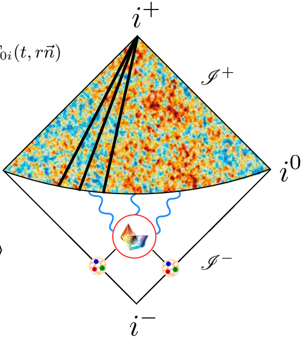
Calorimeter Cells in Field Theory

- 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]



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

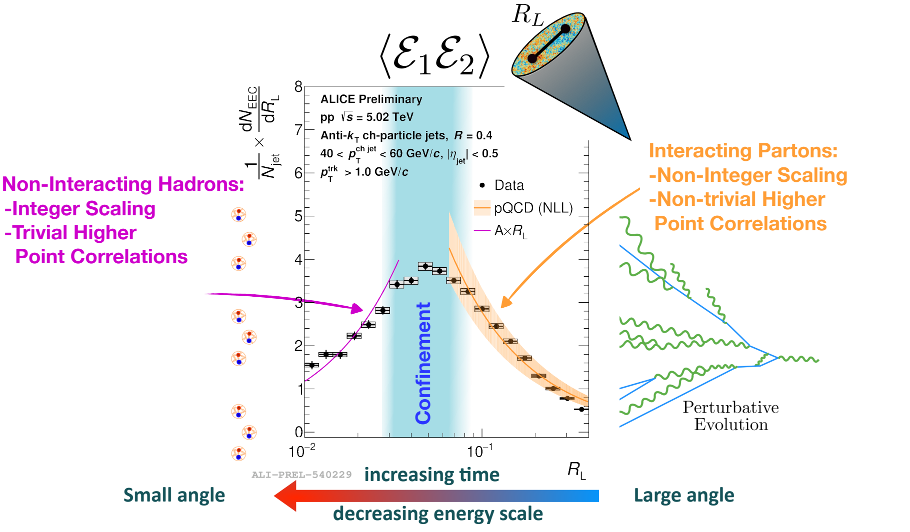
$$\langle\Psi|\mathcal{E}(\hat{n}_1)\cdots\mathcal{E}(\hat{n}_k)|\Psi\rangle$$



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

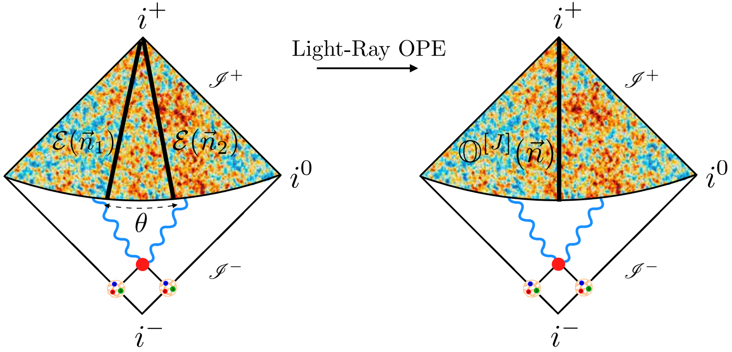
Energy Correlators: Reality

Figure: Wenqing Fan



- Imaging the confinement transition with Jet Substructure!

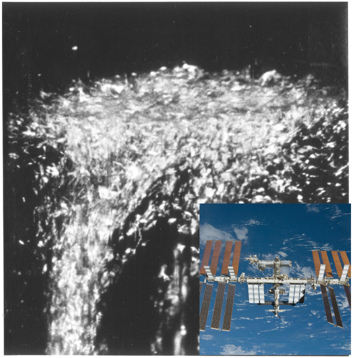
Scaling Behavior of Quarks and Gluons

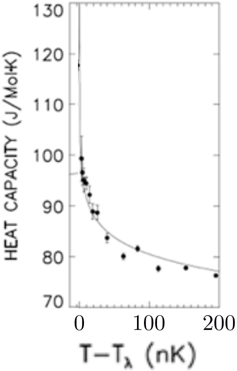


Scaling Behavior in QFT

- Scaling behavior in Euclidean regime well understood.

λ-point of Helium

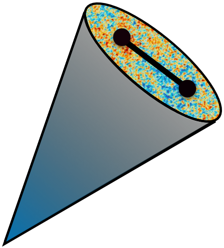


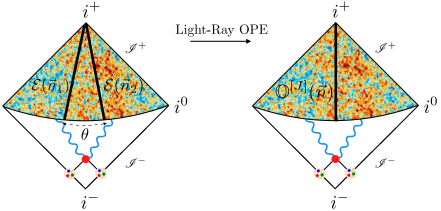


$$\boxed{\mathcal{O}(x)\mathcal{O}(0) = \sum x^{\gamma_i} c_i \mathcal{O}_i}$$

The OPE Limit of Lightray Operators

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





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

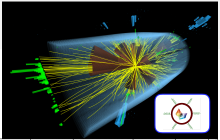
[Hofman, Maldacena]
[Chang, Kologlu, Kravchuk, Simmons Duffin, Zhiboedov]
QCD: [Dixon, Moult, Zhu]

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

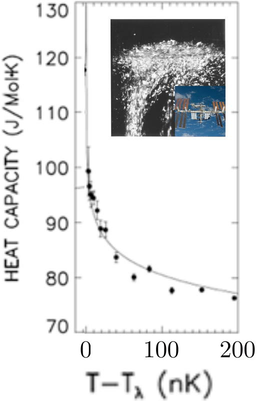
See early work by [Konishi, Ukawa, Veneziano]

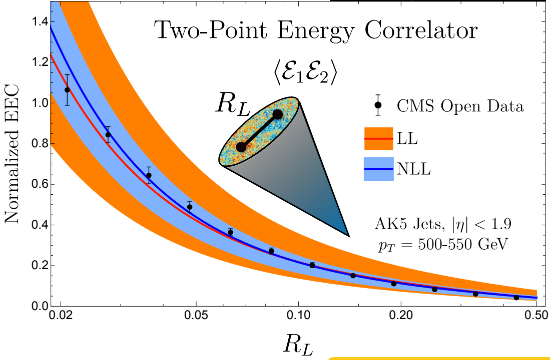
Scaling Behavior in Jets

[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!





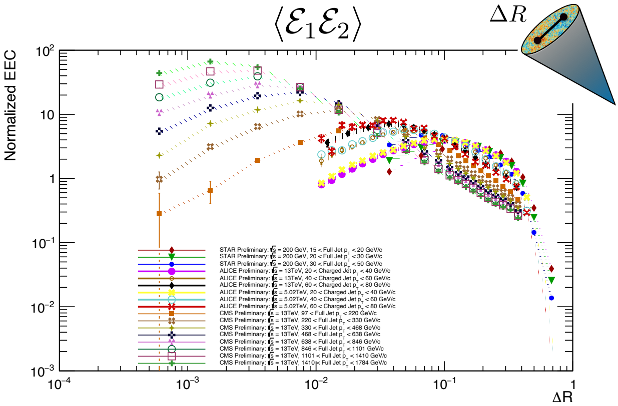
$$\mathcal{E}(\hat{n}_1)\mathcal{E}(\hat{n}_2) \sim \sum \theta^{\tau_i - 4}\mathbb{O}_i(\hat{n}_1)$$

- 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.

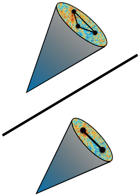
- Measurements from ALICE, CMS and STAR from 15 GeV to 1784 GeV recently released!



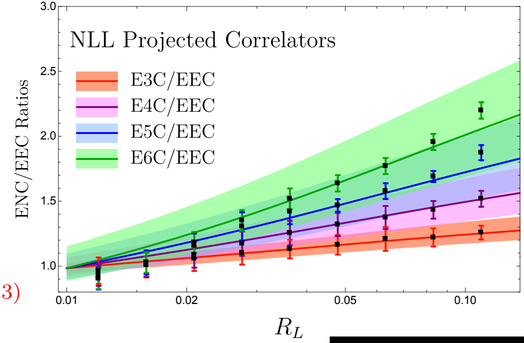
- Dominated by classical scaling. Can we accurately measure anomalous scaling?

The Spectrum of a Jet

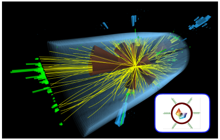
- The light-ray OPE predicts that the N-point correlators develop an anomalous scaling that depends on N.



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



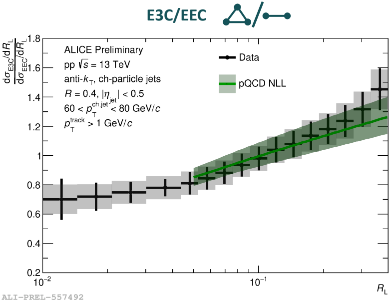
- Directly probes the spectrum of (twist-2) lightray operators from asymptotic energy flux.

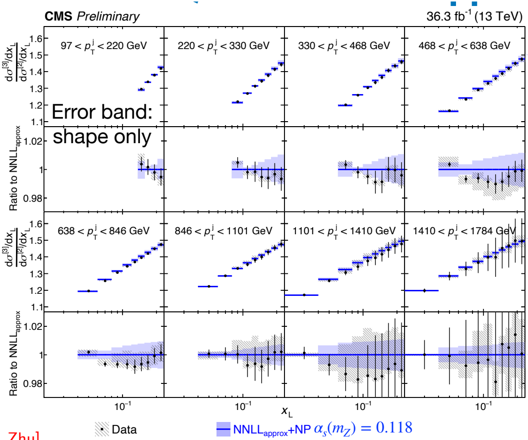


Anomalous Scaling of $3/2$ Ratio

- Anomalous scaling measured from 15 GeV to 1784 GeV!

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

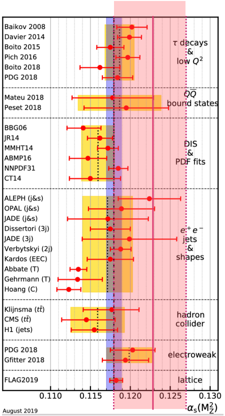


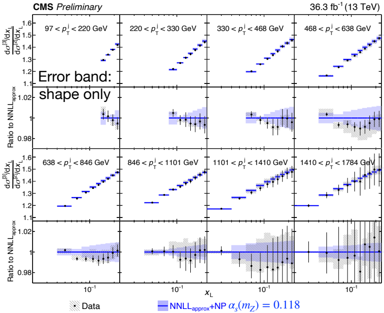


Using [Lee, Mecaj, Moult], [Chen, Gao, Li, Xu, Zhang, Zhu]

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.

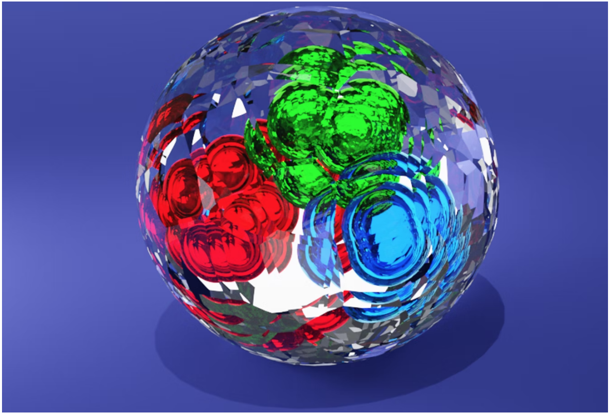




$$\alpha_s(m_Z) = 0.1229^{+0.0040}_{-0.0050}$$

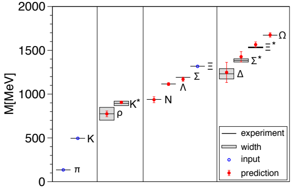
$$= 0.1229^{+0.0014(stat.)+0.0030(theo.)+0.0023(exp.)}_{-0.0012(stat.)-0.0033(theo.)-0.0036(exp.)}$$

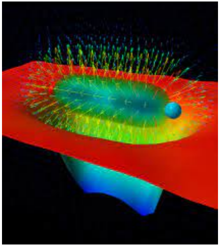
The Confinement Transition

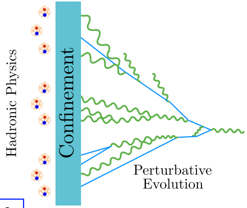


Dynamics of Hadronization

- What are the dynamics of the hadronization process?



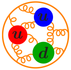


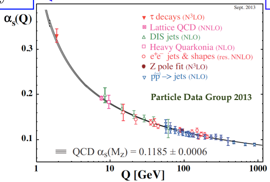


Long Time Scale
Low Energy

$\alpha_s(Q)$

Short Time Scale
High Energy

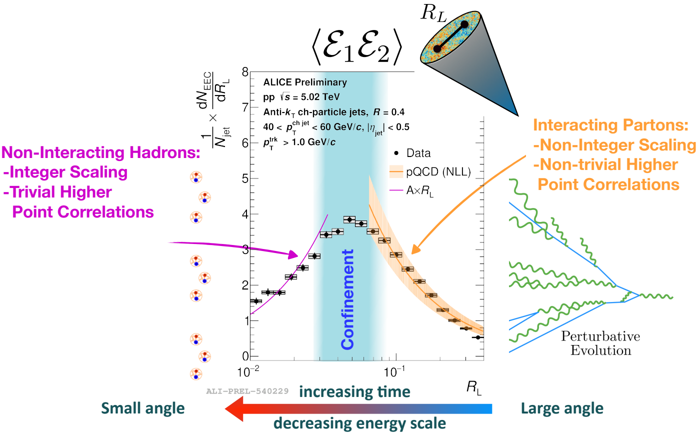




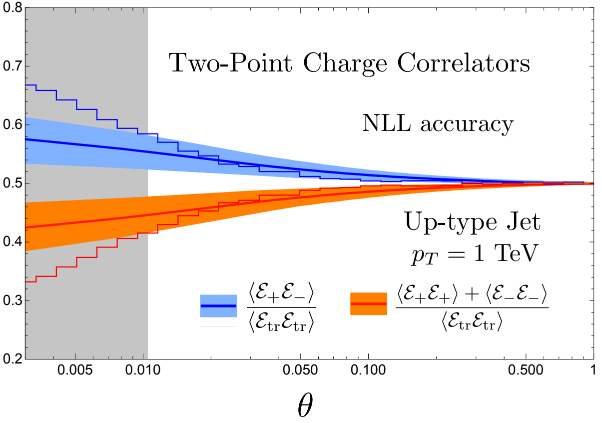
$\hat{O} = \alpha_s + \alpha_s^2 + \cdots$

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!



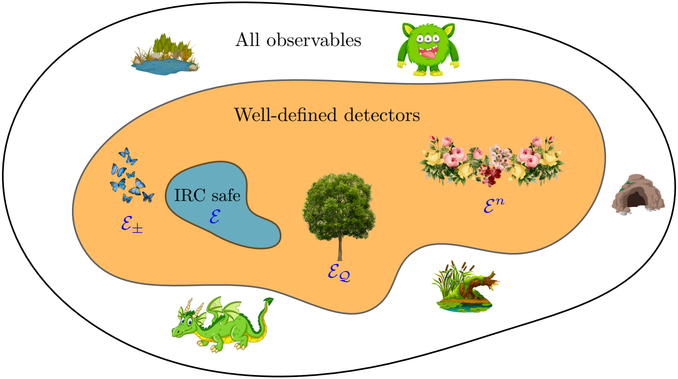
Beyond Energy Flux



[Lee, Moult]

The Space of Detectors

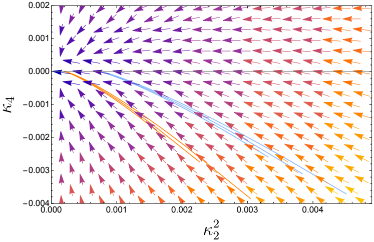
- Details of the hadronization process are encoded in the quantum numbers (charge, flavor, ...): By definition, energy flux is insensitive!
- What is the space of detectors over which we can gain theoretical control?

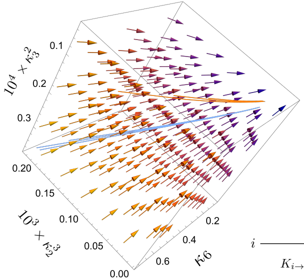


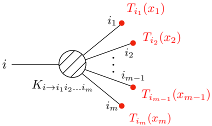
Factorization

[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).



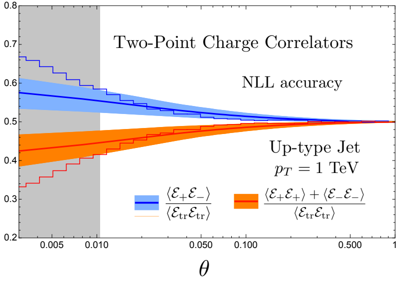


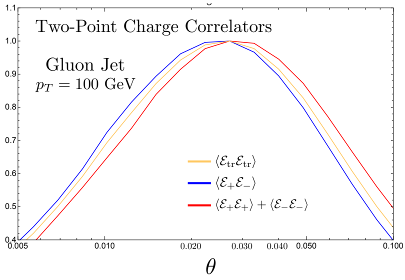


- Enables the calculation of correlations on energy flux carried by hadrons of specific quantum numbers: e.g. $\langle\Psi|\mathcal{E}_+(\hat{n}_1)\cdots\mathcal{E}_-(\hat{n}_k)|\Psi\rangle$

Charged Energy Flux

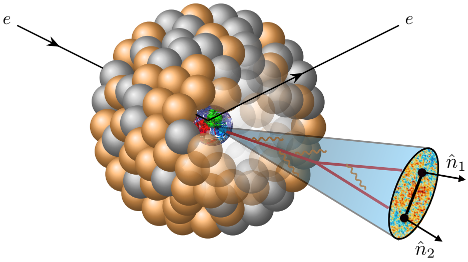
- Opposite sign hadrons exhibit enhanced small angle correlations relative to like sign hadrons.
- Not electromagnetic in nature: generated by hadronization!





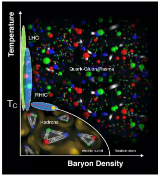
- How far can we push into the confinement transition? Experimental measurements will be crucial.

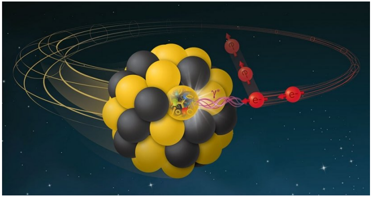
Identifying Intrinsic and Emergent Scales of QCD

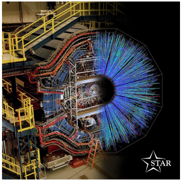


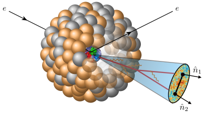
Imaging Emergent and Intrinsic Scales of QCD

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

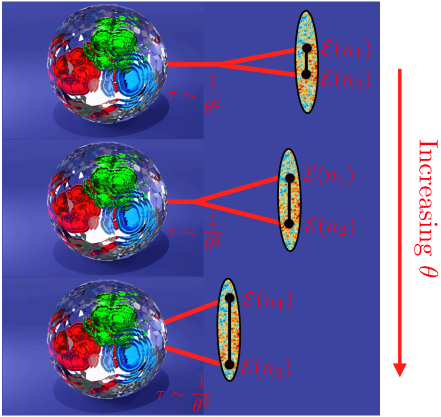








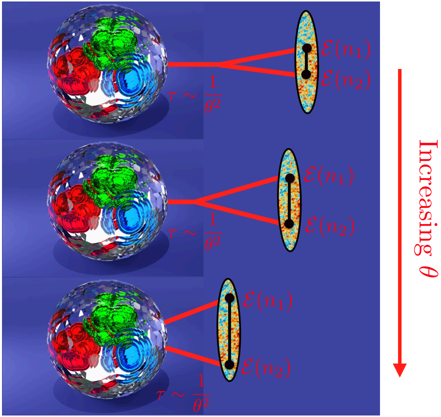
Application I: Resolving the Scales of the QGP

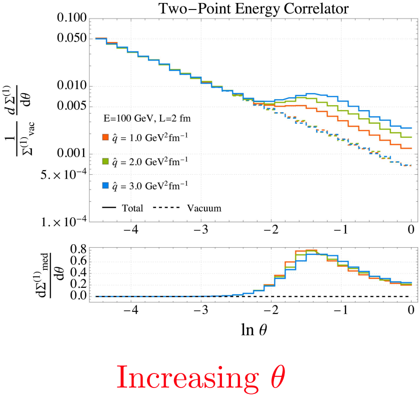


- The QGP introduces a number of new scales into the problem.
- Here we will consider the simplest case of a static medium.
- We will focus on one scale, $\theta_L \sim \frac{1}{\sqrt{LE}}$, which determines the angle at which splittings resolve the medium

Application I: Resolving the Scales of the QGP

- QGP scales cleanly imprinted in two-point correlation.

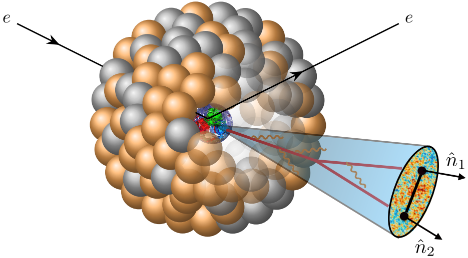


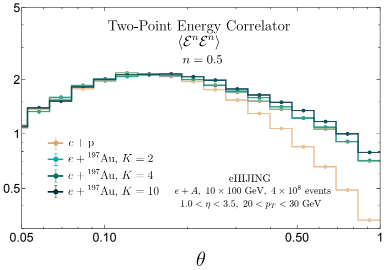


[Andres, Dominguez, Holguin, Kunnawalkam Elayavalli, Marquet, Moult]

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.



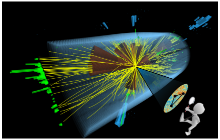


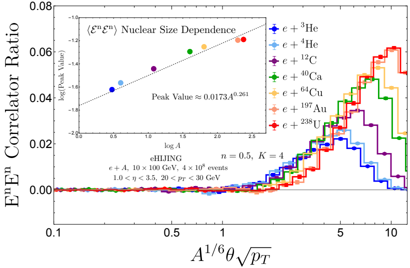
[Devereaux, Fan, Ke, Lee, Moult]

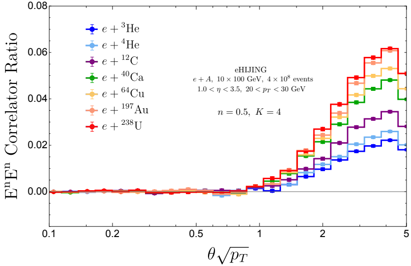
- The size of the nucleus represents a clear physical scale that will be imprinted in the angular structure of the correlator.

Application II: Imaging Cold Nuclear Matter

- Nuclear sizes cleanly imprinted into correlators.







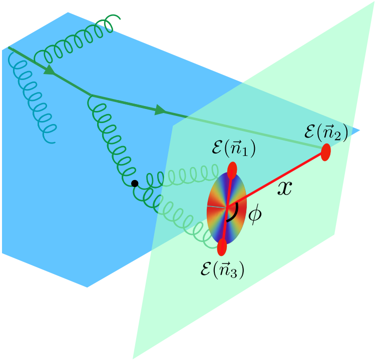
- Achieve femtometer resolution from asymptotic energy flux!
- Provides a common language from hot to cold QCD.

Jet Substructure

- Significant recent progress in our ability to study QCD using jet substructure.
- Energy correlators provide a precise mapping between asymptotic energy flux, and properties of the underlying field theory.
- We can track different quantum numbers through the confinement transition.
- We can identify scales in complicated QCD systems: hot and cold nuclear matter.

- Can this provide new ways of studying spin?

Spin Physics with Jet Substructure

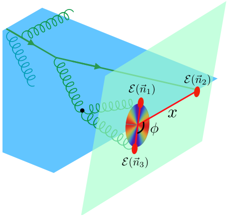


Spin in Jet Substructure

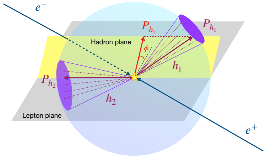
- Much less work incorporating spin into this story
  $\implies$ deserves more investigation.

- I will briefly highlight two approaches:

  - Perturbative spin correlations

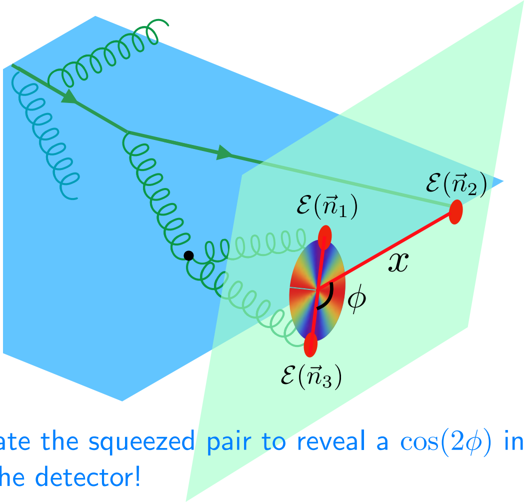


  - Correlations between hadrons



Perturbative Spin Correlations [Chen, Moult, Zhu]

- Higher point correlators in unpolarized jets are sensitive to perturbative spin effects.



- We can rotate the squeezed pair to reveal a $\cos(2\phi)$ interference pattern in the detector!

Perturbative Spin Correlations

- Energy correlators probe operators with definite quantum numbers: twist-2 spin-3 transverse spin 2.

$$\langle \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\mathcal{E}(\vec{n}_3)\rangle \sim C_1(\theta_S,\mu)\left\langle \mathcal{E}(\vec{n}_1)\mathbb{O}^{[3]}(\vec{n}_2)\right\rangle_\mu \sim C_1(\theta_S,\mu)C_2(\theta_L,\mu)\left\langle \mathbb{O}^{[4]}(\vec{n}_1)\right\rangle_\mu$$

$\theta_S Q$ $\theta_L Q$ Q **Energy Scale**

transverse spin-0

$$\mathcal{O}_q^{[J]} = \frac{1}{2^J}\bar{\psi}\gamma^+(iD^+)^{J-1}\psi$$

$$\mathcal{O}_g^{[J]} = -\frac{1}{2^J}F_a^{\mu+}(iD^+)^{J-2}F_a^{\mu+}$$

transverse spin-2

$$\mathcal{O}_{\tilde{g},ij}^{[J]} = -\frac{1}{2^J}F_a^{(i+}(iD^+)^{J-2}F_a^{j)+}$$

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

CANNOT MIX

RG equation:

$$\frac{d}{d\ln\mu^2}\vec{\mathcal{O}}^{[J]} = -\widehat{\gamma}(J)\cdot\vec{\mathcal{O}}^{[J]}$$

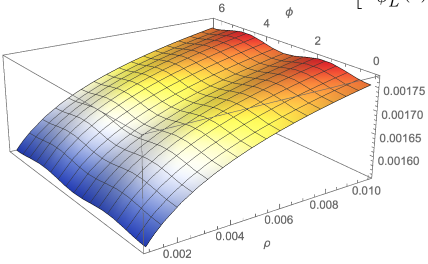
$$\widehat{\gamma}(J) = \begin{pmatrix} \gamma_{qq}(J) & 2n_f\gamma_{qg}(J) & 0 \\ \gamma_{gq}(J) & \gamma_{gg}(J) & 0 \\ 0 & 0 & \gamma_{\tilde{g}\tilde{g}}(J)\mathbf{1} \end{pmatrix}$$

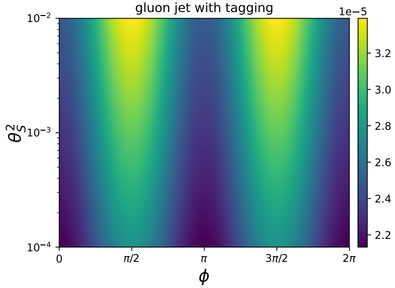
Perturbative Spin Correlations

- Full result exhibits an angular "ripple" on top of a power law.

$$\mathcal{E}(\hat{n}_1)\mathcal{E}(\hat{n}_2)\mathcal{E}(\hat{n}_3) = \frac{1}{(2\pi)^2}\frac{2}{\theta_S^2}\frac{2}{\theta_L^2}\vec{\mathcal{J}}\left[\widehat{C}_{\phi_S}(2) - \widehat{C}_{\phi_S}(3)\right]\left[\frac{\alpha_s(\theta_L Q)}{\alpha_s(\theta_S Q)}\right]^{\frac{\widehat{\gamma}^{(0)}(3)}{\beta_0}}$$

$$\cdot\left[\widehat{C}_{\phi_L}(3) - \widehat{C}_{\phi_L}(4)\right]\left[\frac{\alpha_s(Q)}{\alpha_s(\theta_L Q)}\right]^{\frac{\widehat{\gamma}^{(0)}(4)}{\beta_0}}\vec{\mathbb{O}}^{[4]}(\hat{n}_1) + \cdots$$

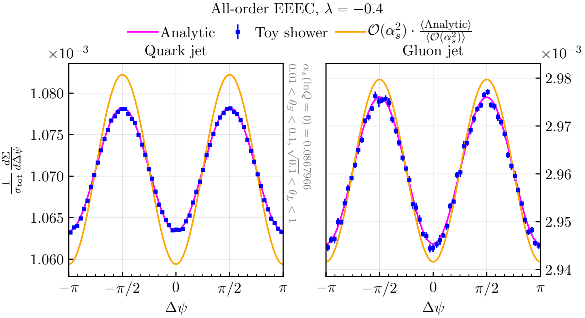




- Hope to observe in LHC data!

Perturbative Spin Correlations

- First analytic resummation incorporating spin interference effects in jet substructure.
- Allows for validation of recent implementations of spin correlations in parton showers.



- Nice interplay between analytic calculations and parton shower development.

Spin Correlations: Nucleons

[Li, Liu, Yuan, Zhu]

- Extended using the Nucleon-Energy-Correlator to DIS.
- Probes linearly polarized gluons inside the nucleus.

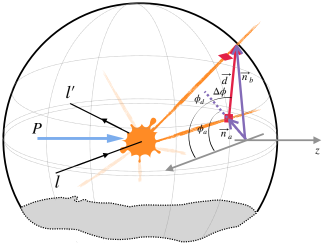


FIG. 2. The measurement proposed as a probe of the gluon polarization in the DIS process. The energy flow into different pixels (in red blocks) at $\vec{n}_a$ and $\vec{n}_b$ are recorded, for $\theta_a \ll \theta_b$. ϕ angles are measured from the plane where lies the leptons. The measurement of $E_i(\vec{n}_a)$ induces the NEEC.

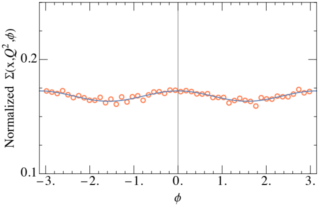
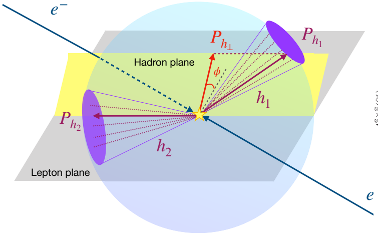


FIG. 4. $\cos(2\phi)$ asymmetry at $\mathcal{O}(\alpha_s^2+\alpha_s^3)$ in the Breit frame.

- Very interesting for EIC.

Spin Correlations: Hadrons

- Alternatively, one can study correlations on subsets of hadrons.
- Recent proposal (Kang, Lee, Shao, Zhao): azimuthally dependent two-point correlator on pions.



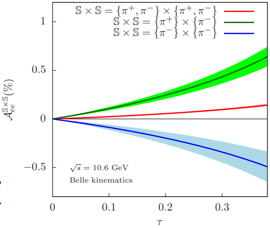
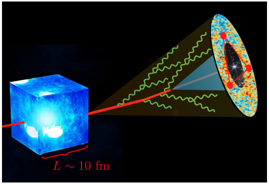


Figure 2: $A_{ee}^{\mathbb{S}\times\mathbb{S}}(\tau)$ for $\mathbb{S}\times\mathbb{S} = \{\pi^+, \pi^-\}\times\{\pi^+, \pi^-\}, \{\pi^+\}\times\{\pi^-\}$ and $\{\pi^-\}\times\{\pi^-\}$ at $\sqrt{s} = 10.6$ GeV with Collins functions fitted in [14].

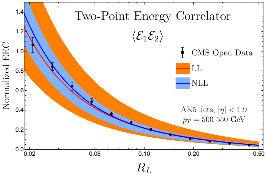
- Provides direct sensitivity to the Collins function.

Summary

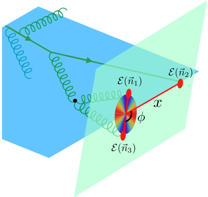
- Jet Substructure provides new ways to study the dynamics of QCD.

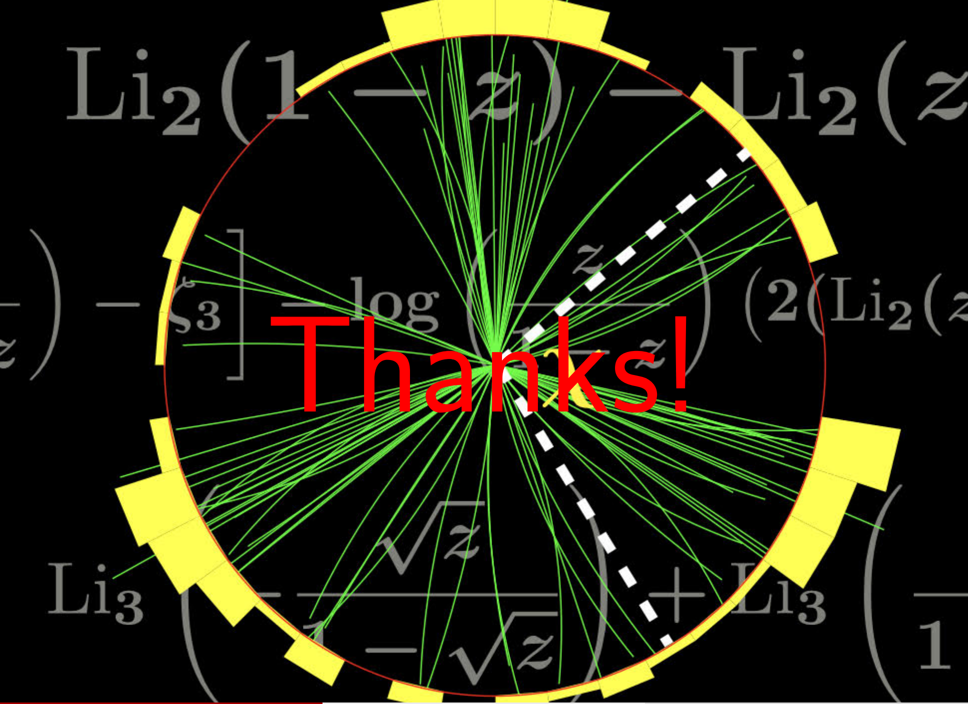


- Correlation functions, $\langle \mathcal{E}(n_1) \cdots \mathcal{E}(n_k) \rangle$, provide a sharp link between theory and experiment.



- Look forward to their application to spin physics!





Thanks!