Conformal Colliders meet the LHC

Boost-Hamburg 2022

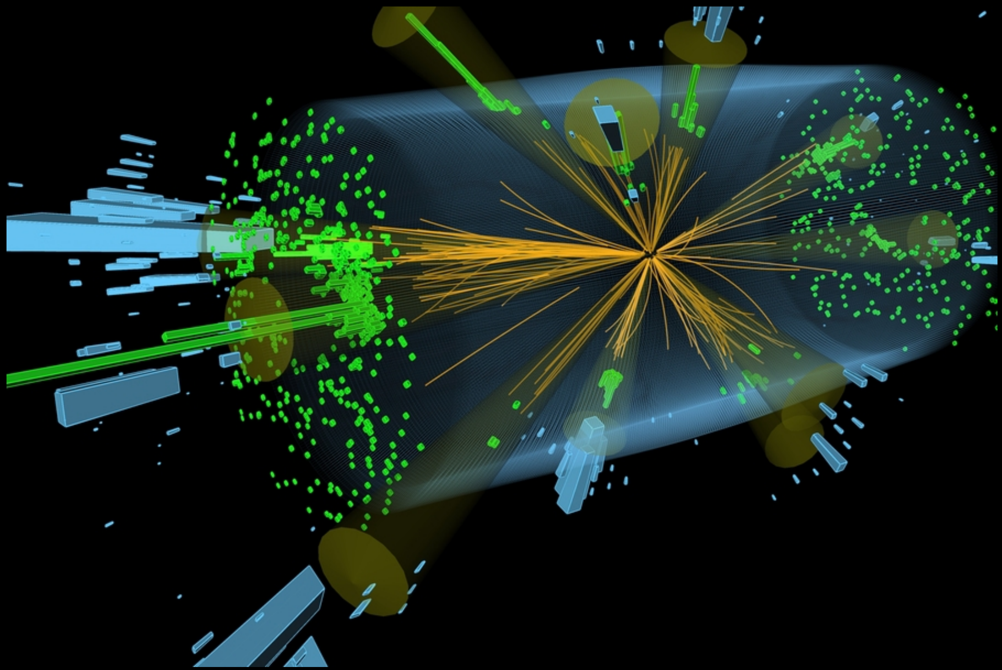
Bianka Meçaj - Yale University

Based on work with Ian Moult and Kyle Lee

arXiv:2205.03414

QCD at Hadron Colliders

Almost every LHC event contains jets



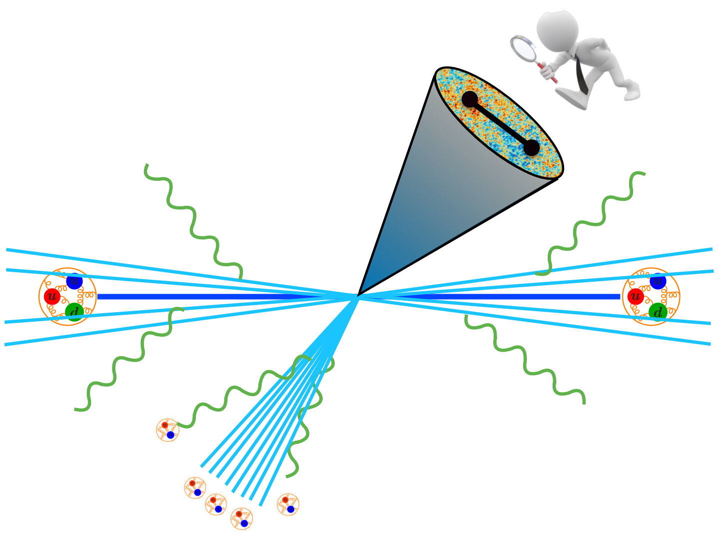
Cacciari, Salam 2006
Salam, Soyez 2007

Jets are reconstructed using jet algorithms (anti-k_T)

How can we learn the most about underlying physics from the reconstructed jets?

Jet substructure

Study the internal structure of a jet



Any physics dynamics will be imprinted in the energy distributions inside the jet.

Well-defined in QFT!

- Distribution of energy inside the jet is described by correlation functions of the energy flow operators ⇒energy correlators.

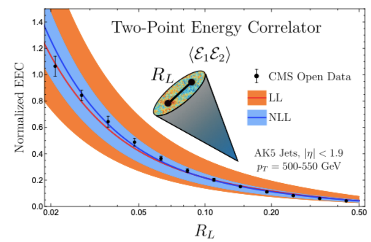
$$\langle \Psi \mid \varepsilon(\vec{n}_1)\varepsilon(\vec{n}_2)\ldots\varepsilon(\vec{n}_n) \mid \Psi \rangle$$

[Basham, Brown, Ellis, Love]

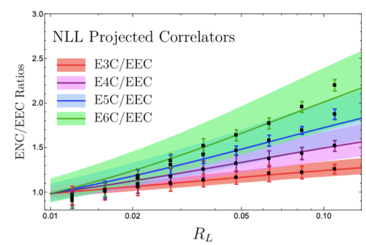
$$\mathcal{E}(\vec{n}) = \lim_{r\to\infty} \int_0^\infty dt\; r^2 n^i T_{0i}(t, r\vec{n})$$

Energy correlators for jet substructure at LHC

Outline



- **Scaling behavior**



- **Spectrum of the jet**

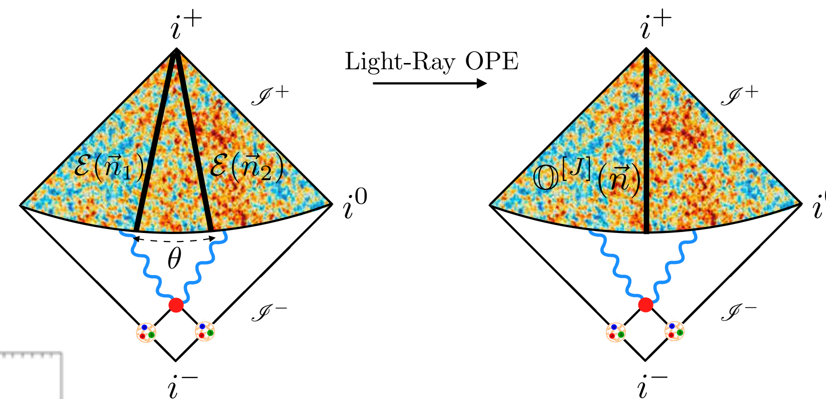
- **Applications of the Results**

Scaling behavior

We will study energy correlators inside high energy jets at the LHC: small angle behavior

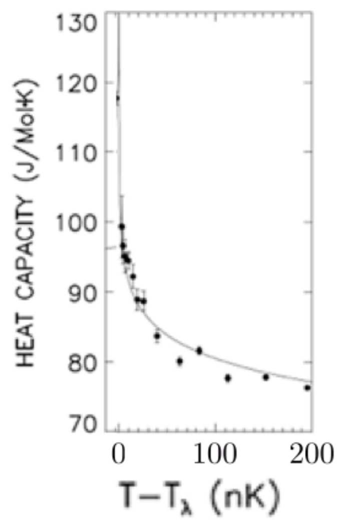
- Energy correlators admit an OPE

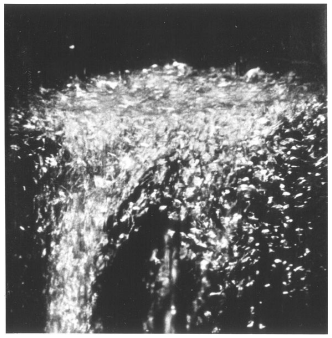
$$\langle \Psi \mid \varepsilon(\overrightarrow{n}_1)\varepsilon(\overrightarrow{n}_2) \mid \Psi \rangle \sim \sum \theta^{\gamma_i} \mathcal{O}_i(\overrightarrow{n}_1)$$



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

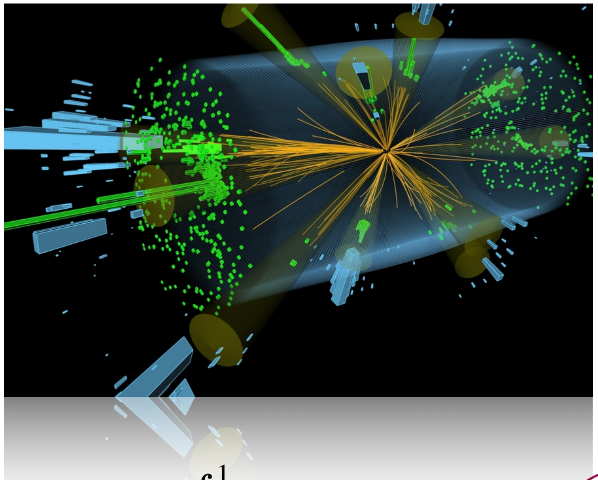
- Universal scaling behavior in QFT as operators are brought together!





Energy Correlators at the LHC

Factorization Formula



$$\frac{\mathrm{d}\Sigma}{\mathrm{d}p_T\mathrm{d}\eta\mathrm{d}z} = \sum_i \mathscr{H}_i\left(p_T z, \eta, \mu\right) \otimes \int_0^1 dx\, x^N \mathscr{J}_{ij}(z, x, p_T R, \mu) J_j^{[N]}(z, x, \mu)$$

[Lee, Mecaj, Moult]

Can calculate any higher point correlator at the LHC

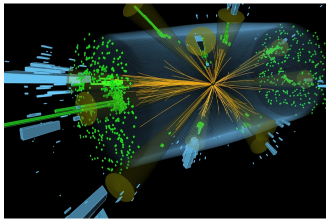
Hard function: includes pdfs

Matching coefficient, jet algorithm

Energy correlator jet function

Two-point energy correlator

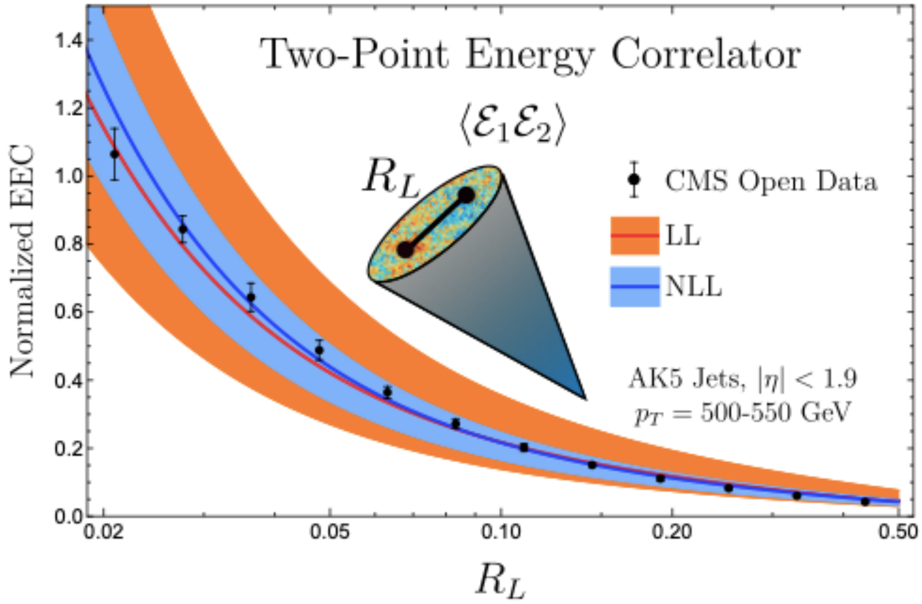
The simplest jet substructure observable



- The complicated LHC environment is described by a simple observable!
- Probe the OPE structure of $\langle \varepsilon(\vec{n}_1)\varepsilon(\vec{n}_2)\rangle$

$$\langle \Psi \mid \varepsilon(\vec{n}_1)\varepsilon(\vec{n}_2) \mid \Psi\rangle \sim \sum \theta^{\gamma_i}\mathcal{O}_i(\vec{n}_1)$$

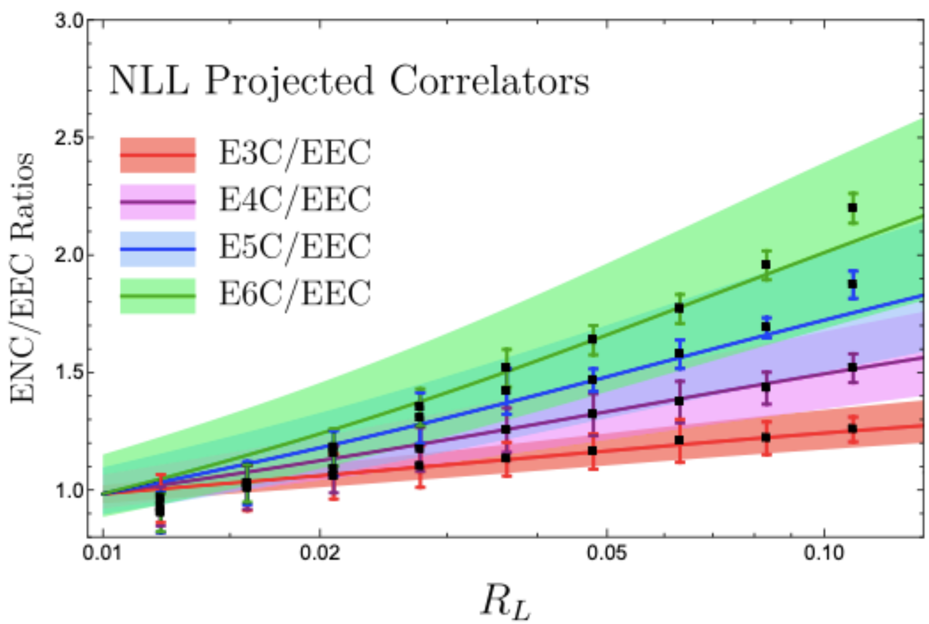
- A jet substructure observable that can test quantum scaling behavior of operators.



[Lee, Mecaj, Moult]

The jet spectrum

Higher-point correlators



[Lee, Mecaj, Moult]

[Chen, Moult, Zhang, Zhu]

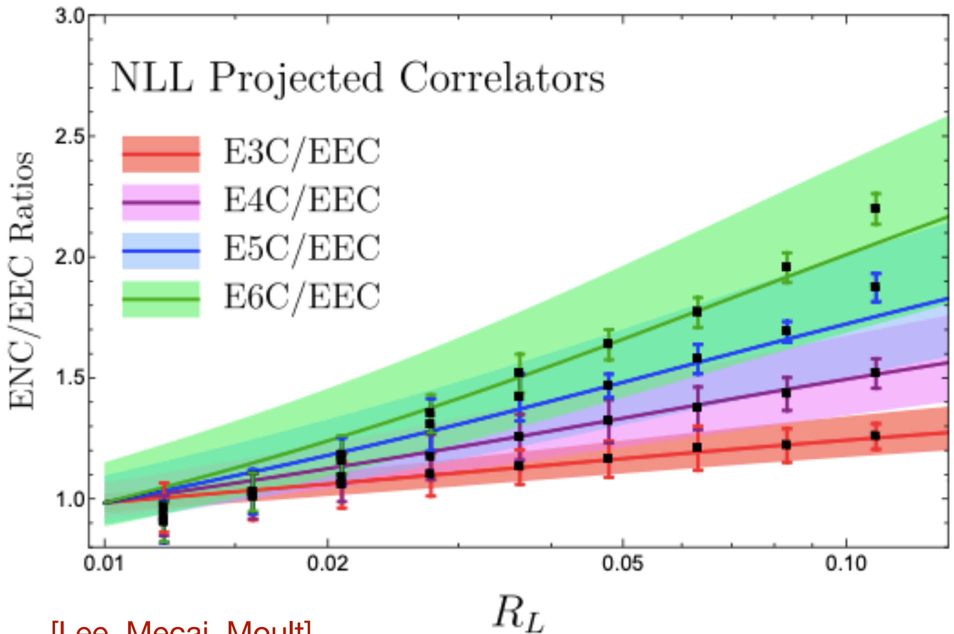
- Can be observed at the high energies at the LHC at high precision
- Ratio of the higher-point correlators with the two-point isolates anomalous scaling!
- The anomalous scaling behavior depends on N (slope increases with N)

$\Downarrow$

- First hand probe of the anomalous dimensions of QCD operators.
- Non-perturbative effects cancel in the ratio

The jet spectrum

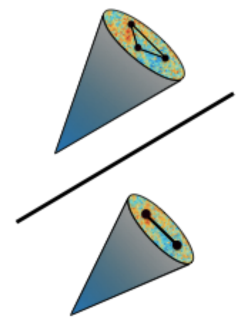
Higher-point correlators



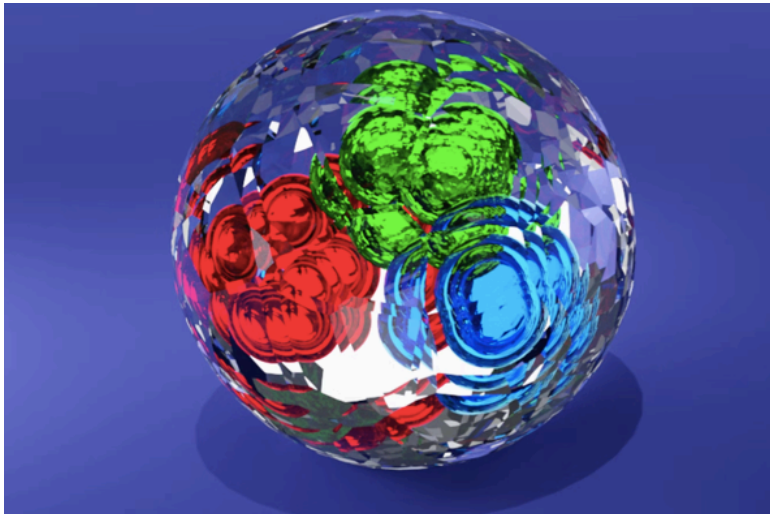
[Lee, Mecaj, Moult]

[Chen, Moult, Zhang, Zhu]

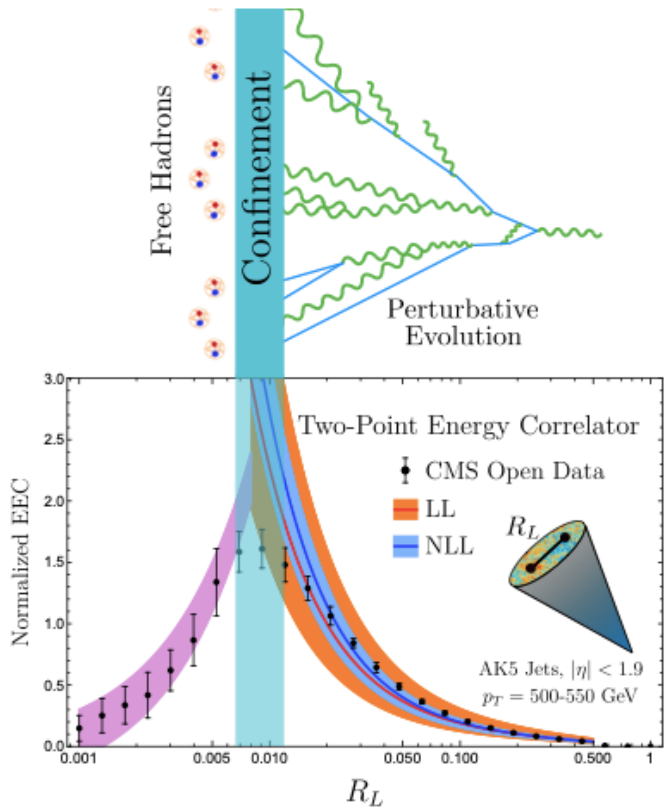
Asymptotic energy flux directly probes the spectrum of (twist-2) lightray operators at the quantum level!



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



Confinement transition in jet substructure?

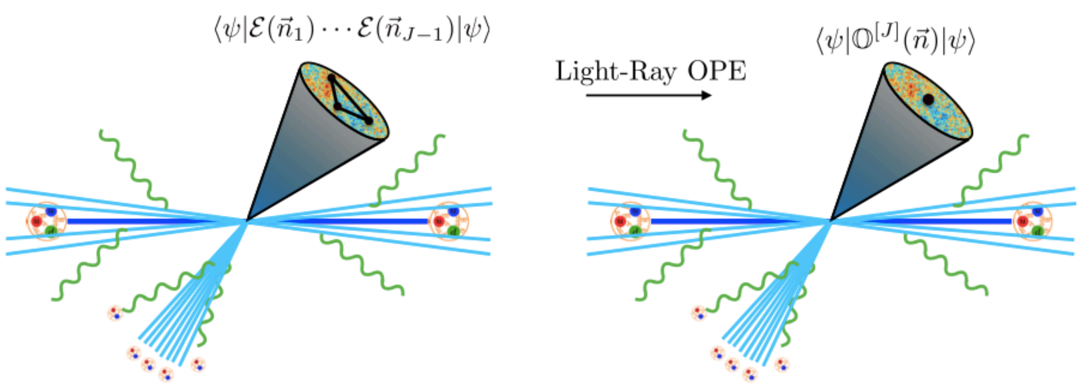


Any underlying dynamics will be imprinted in the energy correlators, including hadronization transition.

Jet substructure from first principles!

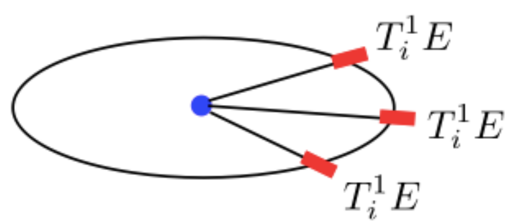
- Energy correlator is a jet substructure observable defined from first principles in QFT

$\Rightarrow$ No room for ambiguity what it's being measured in theory.



- Formalism we have presented can be applied for any conserved charge for LHC processes.
- No jet grooming or pruning is needed to extract the final results, pure QFT calculation!
- Not sensitive to soft and wide angle radiations.

Implementation on tracks



$$E_i \rightarrow \int dx_i \, x_i T_i(x_i) E_i = T_i^{(1)} E_i$$

Multiply by the first moment of the track function

- Incorporate information not only from the calorimeter but also from the tracks.

[Li, Moult, van Velzen, Waalewijn, Zhu]

- Possible using track functions.

See Yibei's talk

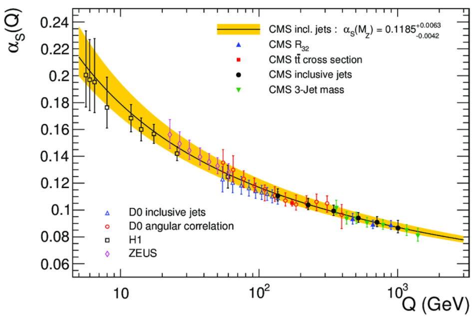
- Better precision

The anomalous dimension can also be measured from these first moments!

Extensions of these results

- Precision measurements,

example: strong coupling, since the anomalous dimensions are proportional to α_s.



- Extend these results to massive quark jets:

Intrinsic dynamics from non-zero mass effect

- Better jet modeling in MC simulations, especially for heavy quarks

See Kyle's talk on Thursday!

- Higher order NLL are important for better precision in parton showers:

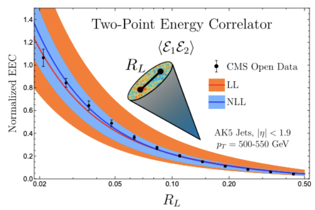
"reference resummation" for testing DGLAP finite moments

Conclusions

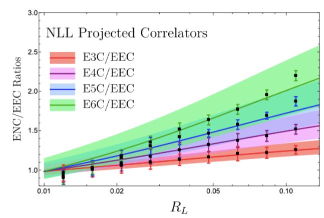
- Factorization formula for calculating energy correlators study jet substructure at the LHC.

$$\frac{d\Sigma}{dp_T d\eta dz} = \sum_i \mathscr{H}_i\left(p_T z, \eta, \mu\right) \otimes \int_0^1 dx\, x^N \mathscr{J}_{ij}(z, x, p_T R, \mu)\, J_j^{[N]}(z, x, \mu)$$

- Can probe a universal scaling behavior of QFT in the complicated LHC environment.



- Higher-point correlators can be calculated for LHC and probe anomalous scaling dimension of operators.



- There is a myriad of future applications of such jet observables that can be applied to both QCD in the vacuum and heavy ions

Thank you!