



# Beautiful and Charming Energy Correlators

**DIS 2023-Michigan State University**

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Based on [2205.03414](#) and [2210.09311](#)



Evan Craft



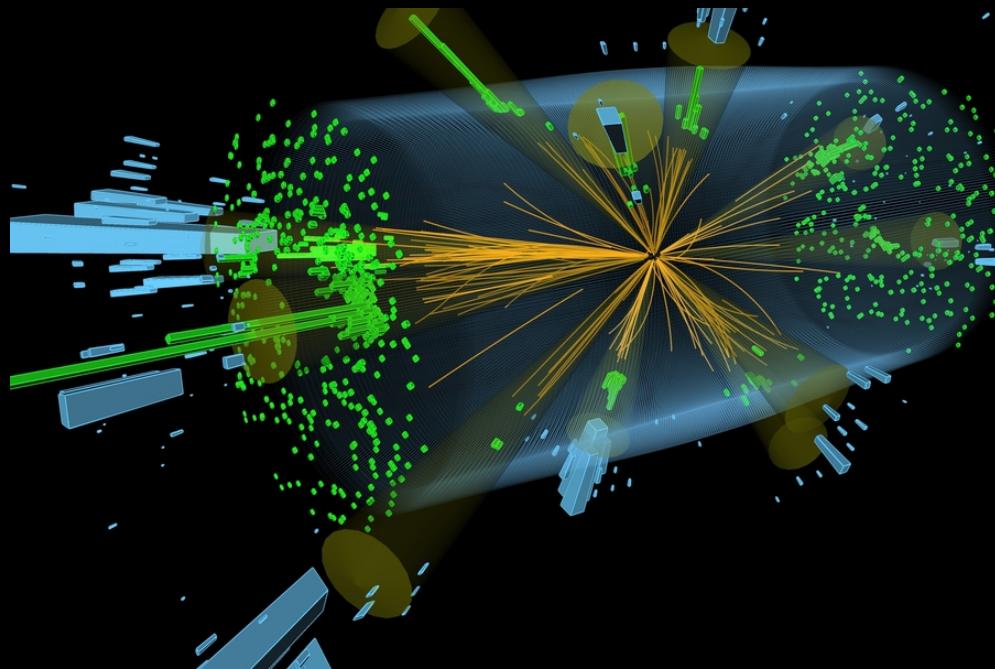
Kyle Lee



Ian Moulton

# QCD at Hadron Colliders

Almost every LHC event contains jets



Jets are reconstructed using jet algorithms ( $\text{anti-}k_T$ )

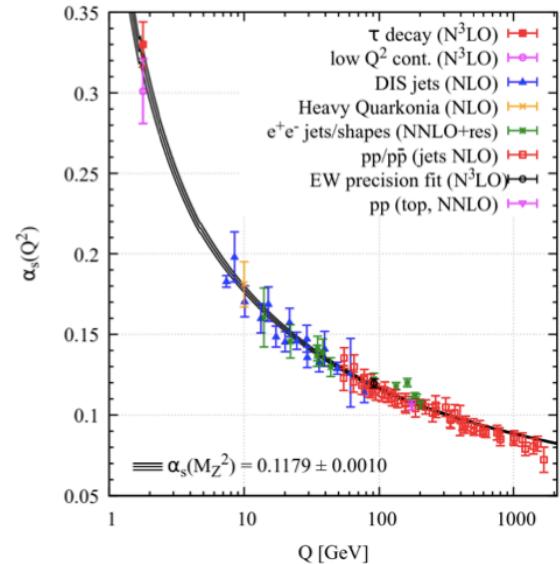
Cacciari, Salam 2006  
Salam, Soyez 2007

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

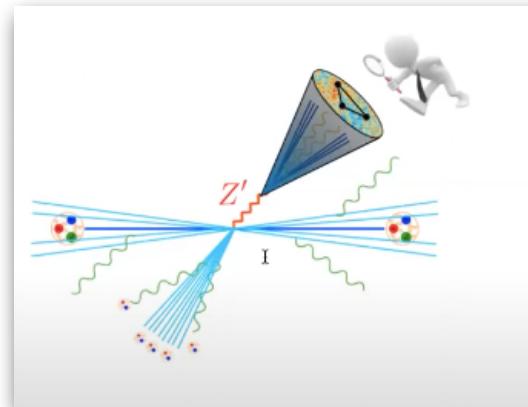
# Jets at the LHC

## Jet substructure

### QCD precision tests



### New Physics

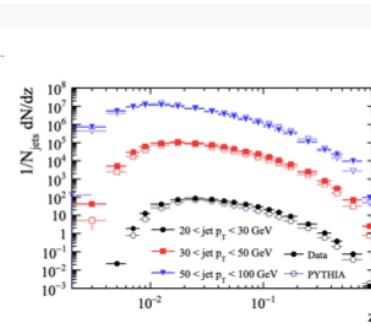
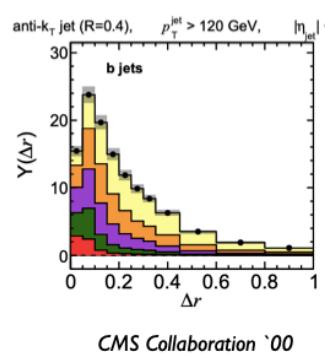
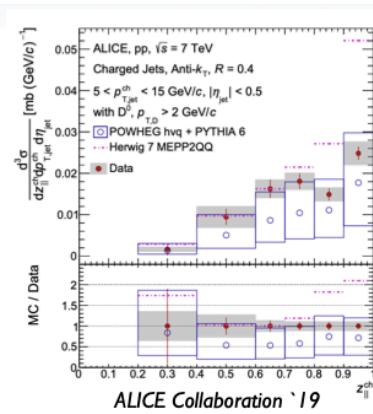
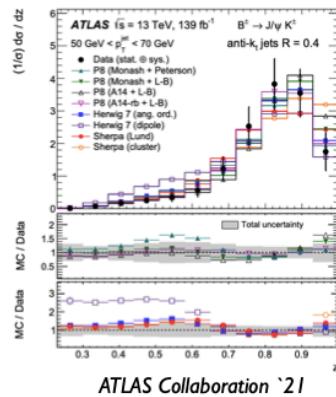


Both precision measurements and New Physics searches require precise description of jet cross sections.

# Jets at the LHC

## Jet substructure and heavy quarks

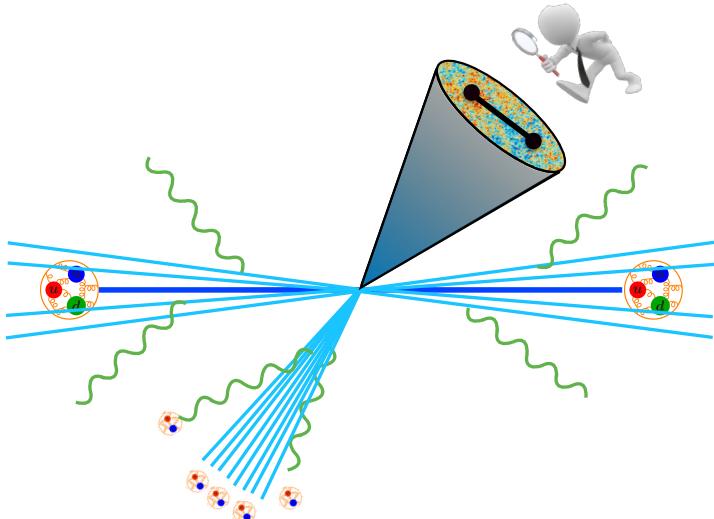
Many interesting processes include heavy quark effects:  $h \rightarrow b\bar{b}$ ,  $h \rightarrow c\bar{c}$



Kara Mattioli's Thesis '22

# 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  $\Rightarrow$  energy correlators.

$$\langle \Psi | \varepsilon(\vec{n}_1) \varepsilon(\vec{n}_2) \dots \varepsilon(\vec{n}_n) | \Psi \rangle$$

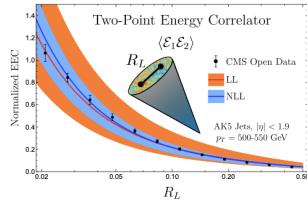
[Basham, Brown, Ellis, Love]

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

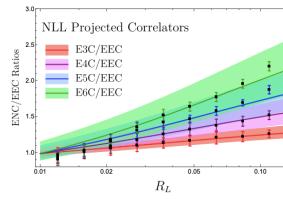
# Energy correlators for jet substructure at LHC

## Outline

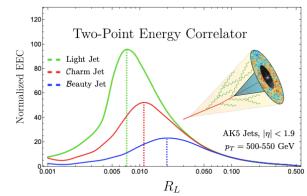
- Scaling behavior



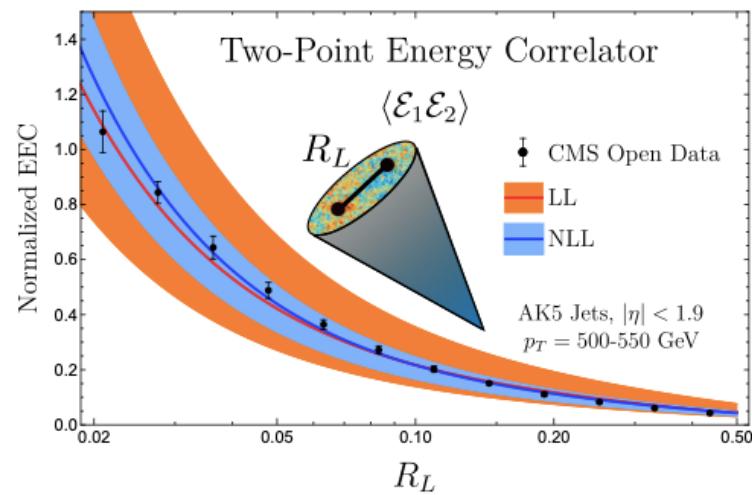
- Spectrum of the jet



- Heavy quark jets



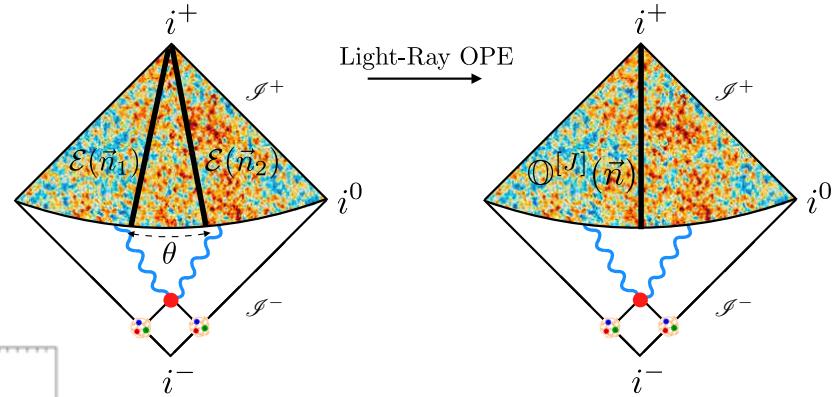
# Scaling behavior



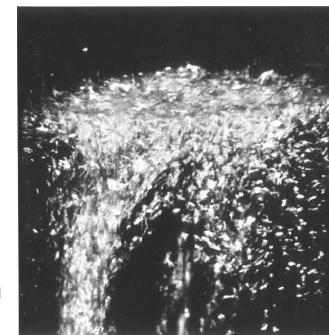
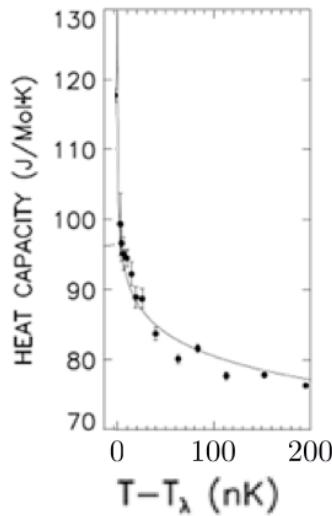
# Scaling behavior

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

- Energy correlators admit an OPE
$$\langle \Psi | \epsilon(\vec{n}_1) \epsilon(\vec{n}_2) | \Psi \rangle \sim \sum \theta^{\gamma_i} \mathcal{O}_i(\vec{n}_1)$$
- Universal scaling behavior in QFT as operators are brought together!

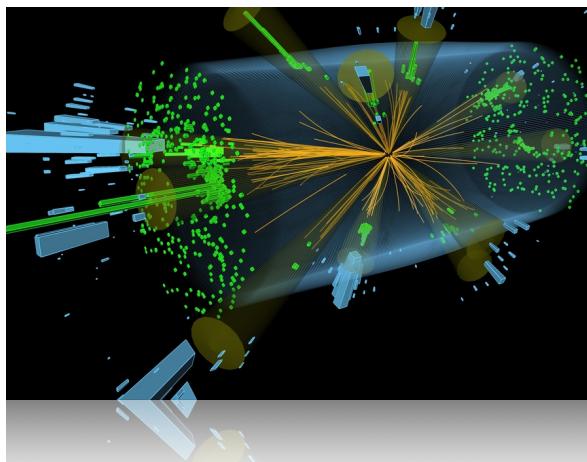


[Hofman, Maldacena]  
[Chang, Kologlu, Kravchuk, Simmons Duffin, Zhiboedov]



# Energy Correlators at the LHC

## Factorization Formula



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

Hard function: includes pdfs

Matching coefficient, jet algorithm

Can calculate any higher point correlator at the LHC

[Lee, Mecaj, Moult]

Energy correlator jet function

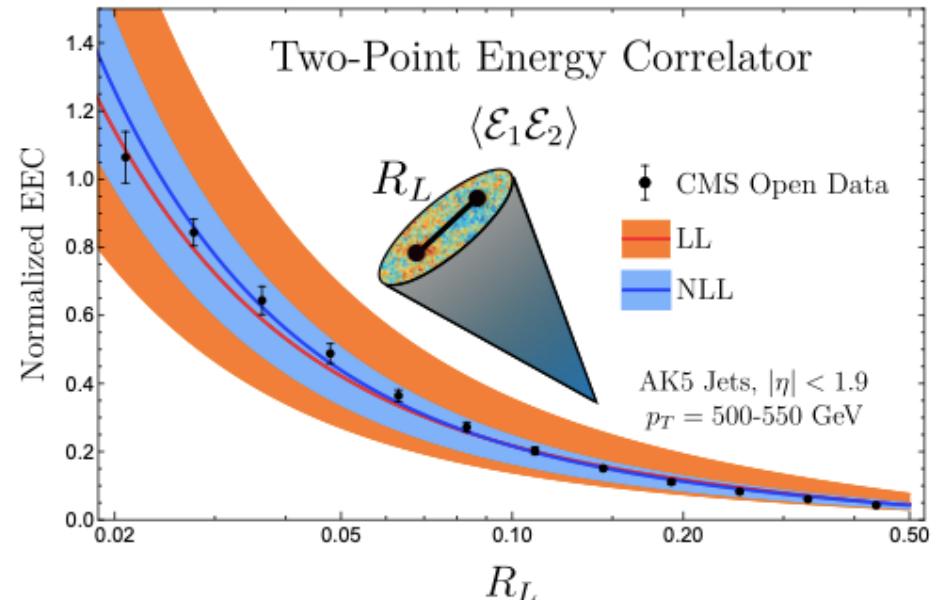
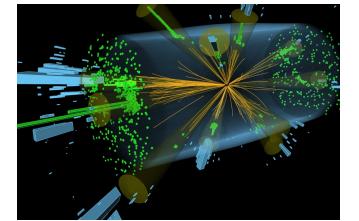
# Two-point energy correlator

## The simplest jet substructure observable

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

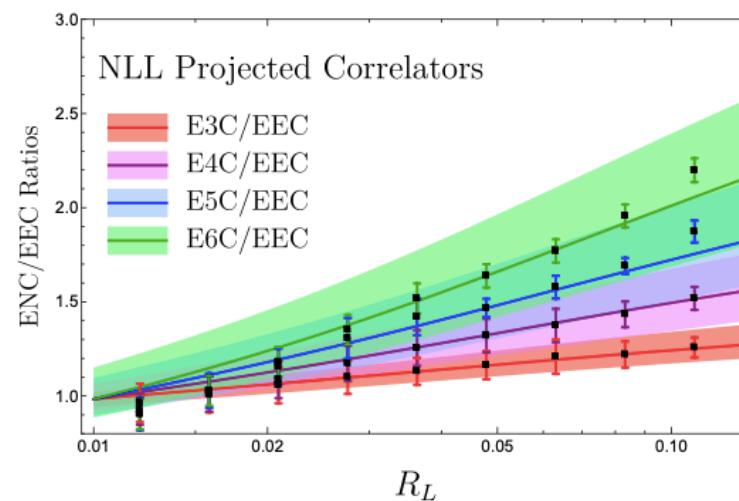
$$\langle \Psi | \epsilon(\vec{n}_1) \epsilon(\vec{n}_2) | \Psi \rangle \sim \sum \theta^{\gamma_i} \mathcal{O}_i(\vec{n}_1)$$

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



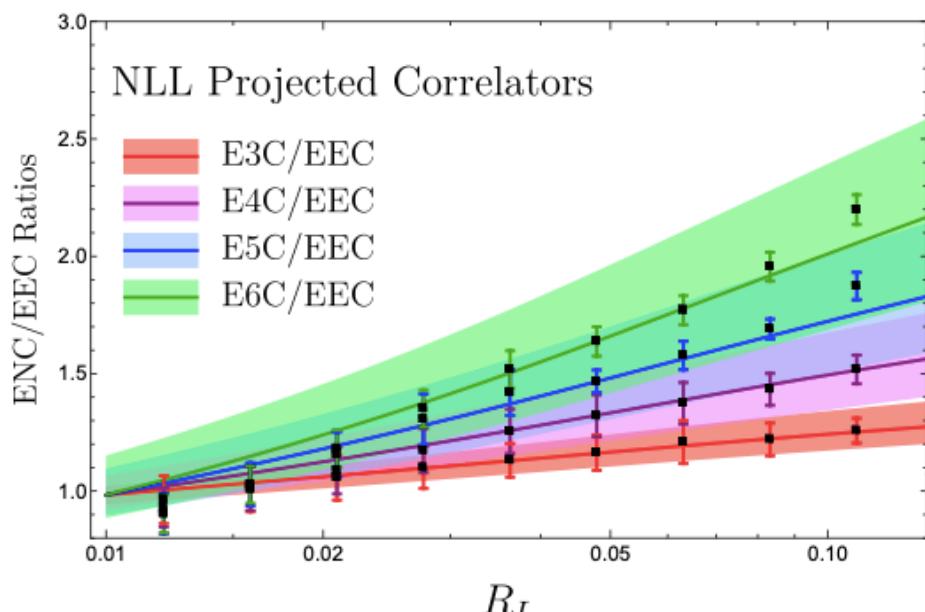
[Lee, Mecaj, Moult]

# Jet Spectrum



# The jet spectrum

## Higher-point correlators



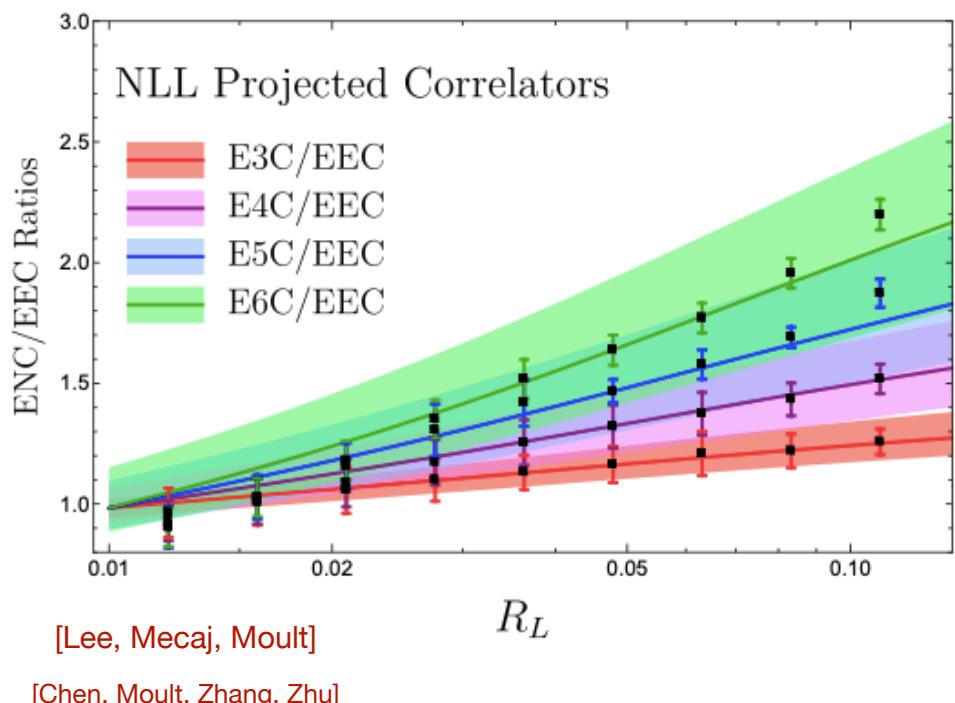
[Lee, Mecaj, Moult]

[Chen, Moult, Zhang, Zhu]

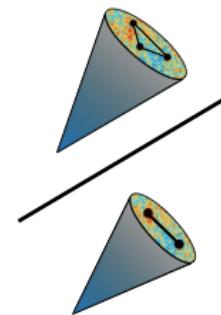
- Can be observed at the high energies at the LHC at high precision
- Ratio of the higher-point correlators with the two-point isolates anomalous scaling!
- The anomalous scaling behavior depends on  $N$  (slope increases with  $N$ )  
    ↓
- First hand probe of the anomalous dimensions of QCD operators.
- Non-perturbative effects cancel in the ratio

# The jet spectrum

## Higher-point correlators

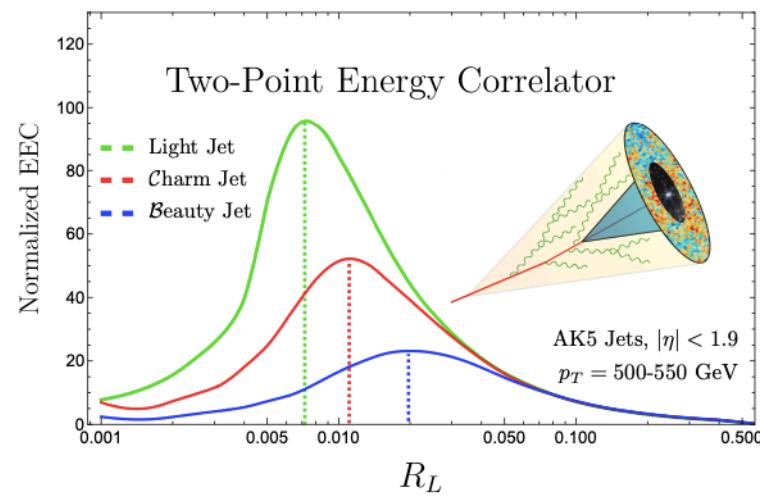


Asymptotic energy flux directly probes the spectrum of (twist-2) lightray operators at the quantum level!



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

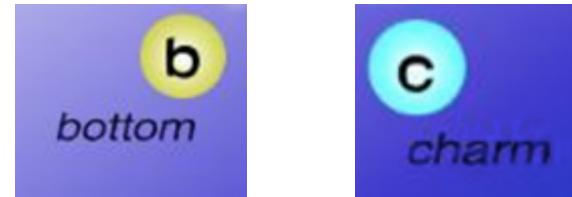
# Heavy quark jets



# Energy Correlators on heavy jets

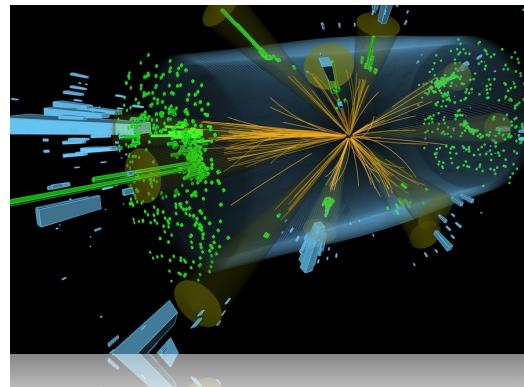
Introduce an additional scale

- At the LHC energies there is access to the transition phase from massless to massive behaviour  $\Rightarrow$  more complexity
- Also very interesting!
  - Can probe intrinsic mass effects of quarks before confinement into hadrons



# Factorization theorem

Can compute any higher point correlators on massive quarks at LHC at NLL



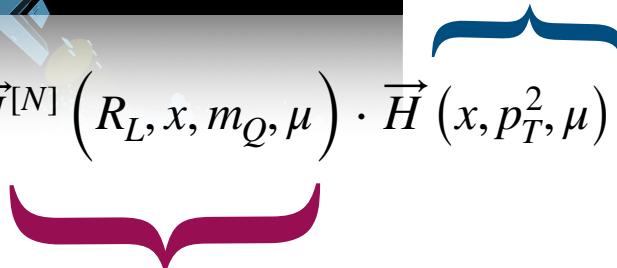
Hard function (NNLO)

$$\Sigma^{[N]}(R_L, p_T^2, m_Q, \mu) = \int_0^1 dx x^N \vec{J}^{[N]}(R_L, x, m_Q, \mu) \cdot \vec{H}(x, p_T^2, \mu)$$

[Czakon, Generet, Mitov, Poncelet; 2021]

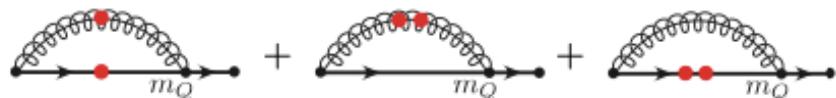
$$\mu_H \sim p_T$$

$$\mu_J \sim p_T R$$



Massive Energy Correlator Jet Function (NLO)

[Craft, Lee, BM, Moult]

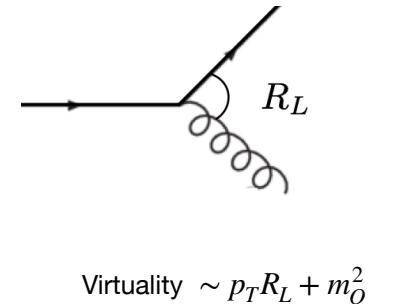


# Massive jets

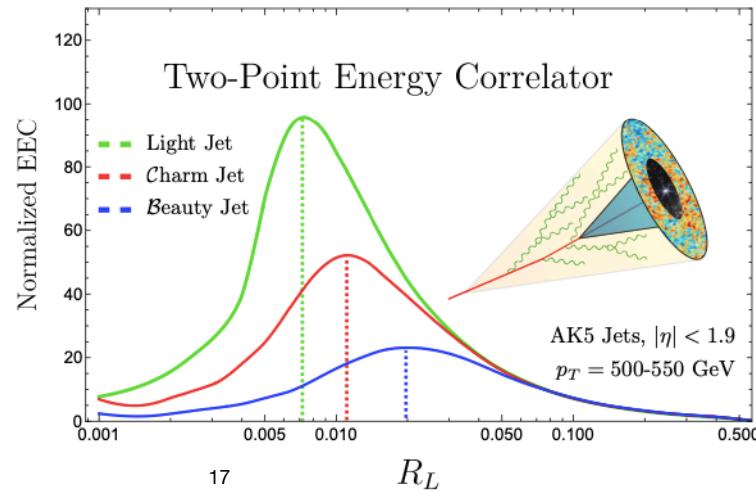
$$\Sigma^{[N]}(R_L, p_T^2, m_Q, \mu) = \int_0^1 dx x^N \vec{J}^{[N]}(R_L, x, m_Q, \mu) \cdot \vec{H}(x, p_T^2, \mu)$$

Massive Energy Correlator Jet Function

Hard function



- Formation time changes with the mass of the quark.
- Can clearly see this from the two-point EEC.

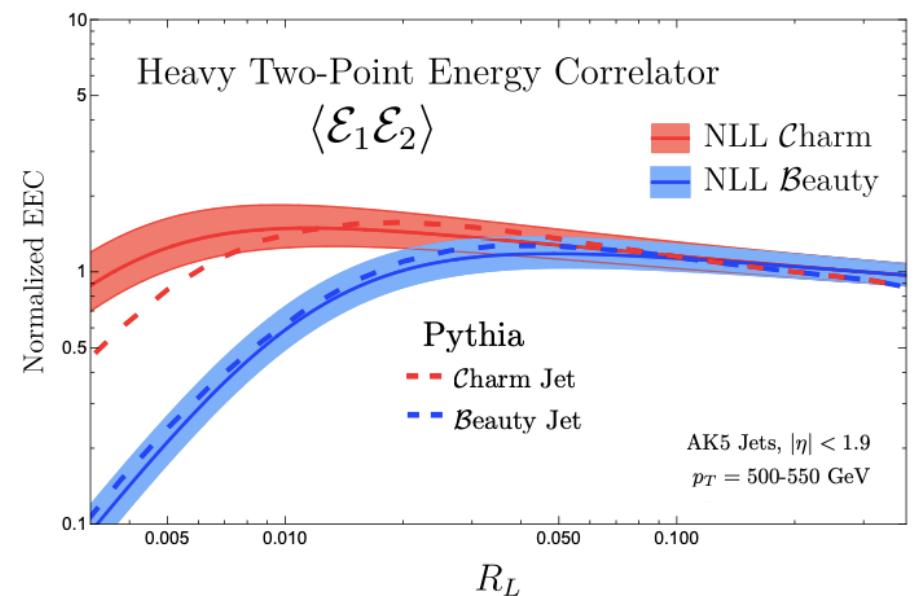


[Craft, Lee, BM, Moult]

# Massive two point correlator

First massive jet substructure observable at NLL

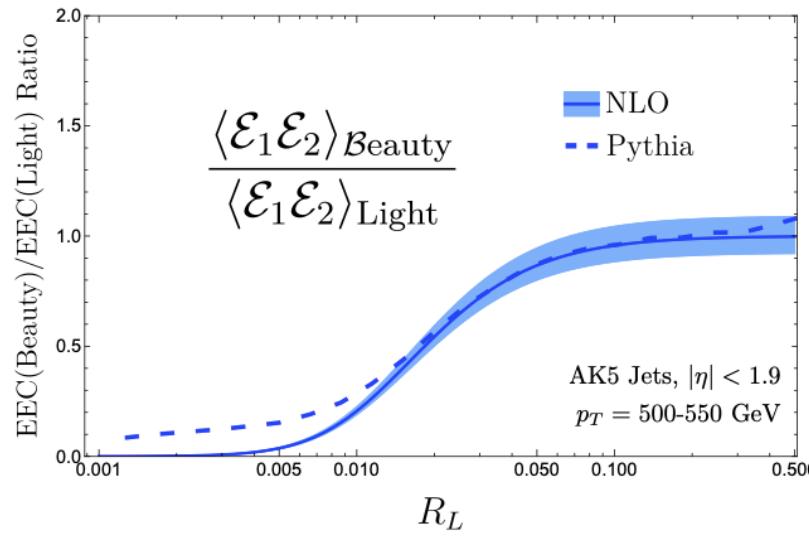
- Scaling behaviour identical to massless case for larger scales.
- A turn-over for  $R_L \rightarrow m_Q/p_T$
- The change in the slope is perturbative effect contrary to massless jets:  $R_L \rightarrow \Lambda_{QCD}/p_T$
- The turn-over region is of interest for improving heavy quark description in parton shower.



[Craft, Lee, BM, Moult]

# Intrinsic mass effects

## Dead-cone effect

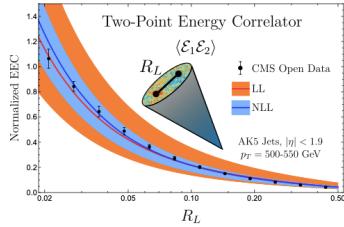


[Craft, Lee, BM, Moult]

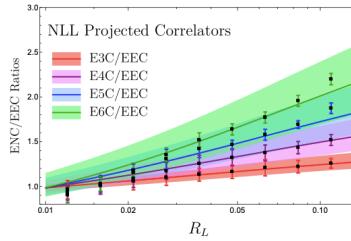
- Ratios of the massive and massless EEC isolate mass (IR) effects.
- A transition region related to the quark mass, which is perturbatively calculable.
- Excellent agreement with MC.
- Small angle suppression can be interpreted as a dead-cone effect.

# Conclusions

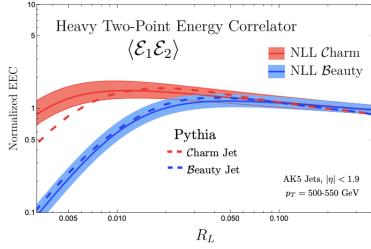
- Can probe a universal scaling behavior of QFT in the complicated LHC environment.



- Higher-point correlators are calculated for LHC and are a direct probe of anomalous scaling dimension of QCD operators.



- Energy Correlators for heavy quark jets probe intrinsic mass effects of elementary particles.



# **What is next?**

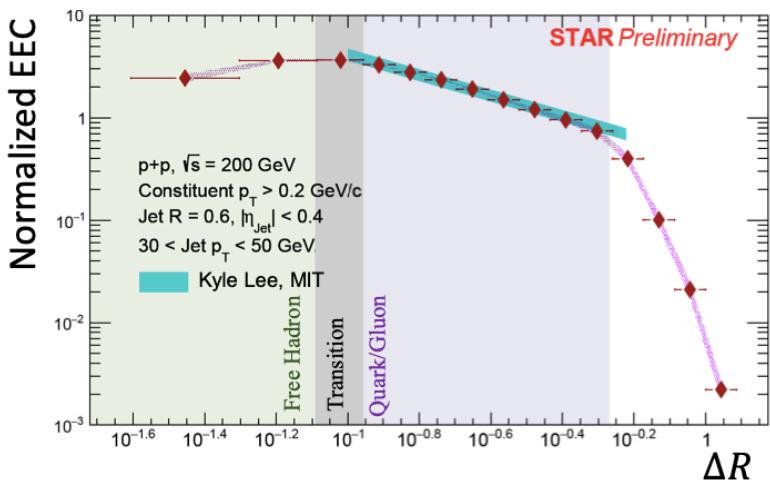
**Experimental Measurements for both light and heavy quark energy correlators.**

# Exciting experimental results!



Talk by N.Sahoo and A.Tamis at  
HARD PROBES-March 2023

- STAR collaboration  $\sqrt{s} = 200\text{GeV}$



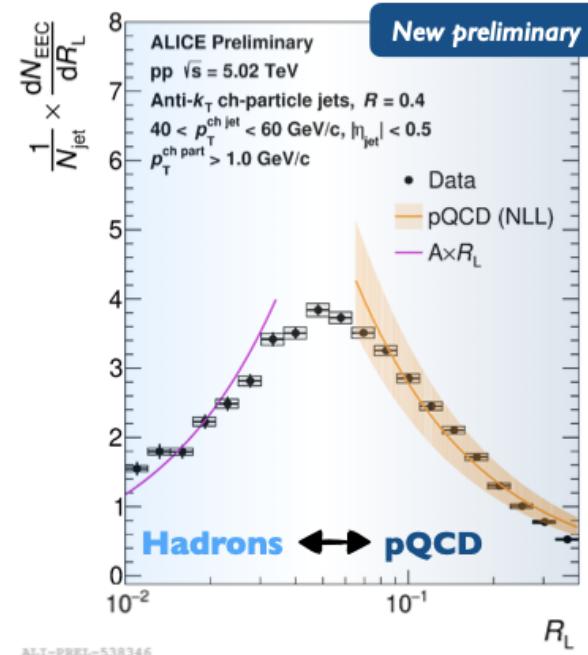
$$\text{Normalized EEC} = \frac{1}{\sum_{\text{jets}} \sum_{i \neq j} \frac{E_i E_j}{p_{T,jet}^2}} \frac{d(\sum_{\text{jets}} \sum_{i \neq j} \frac{E_i E_j}{p_{T,jet}^2})}{d(\Delta R)}$$

Direct observation of the transition from free hadrons to quarks/gluons at a universal scaling!



Talk by J.Mulligan and R.Cruz-Torres  
at HARD PROBES-March 2023

- ALICE collaboration  $\sqrt{s} = 5\text{TeV}$



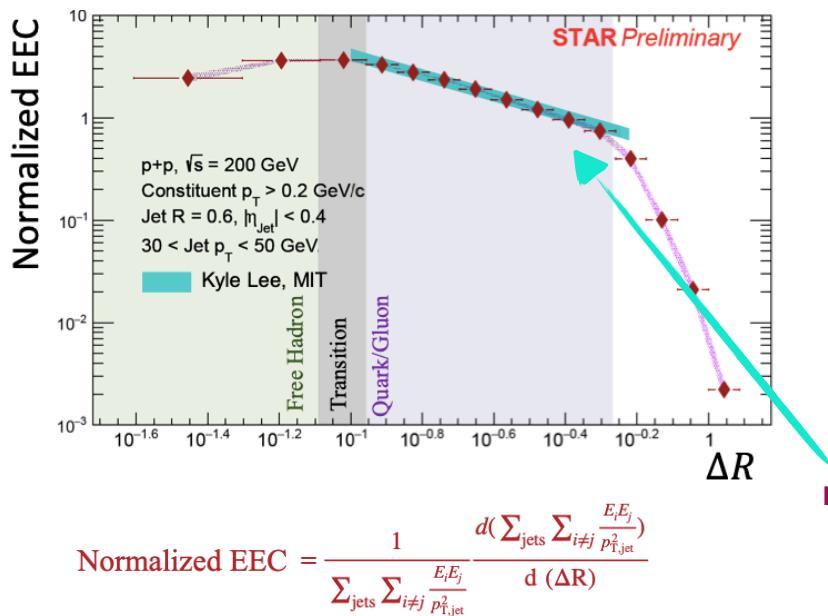
Universal behavior of the transition region.

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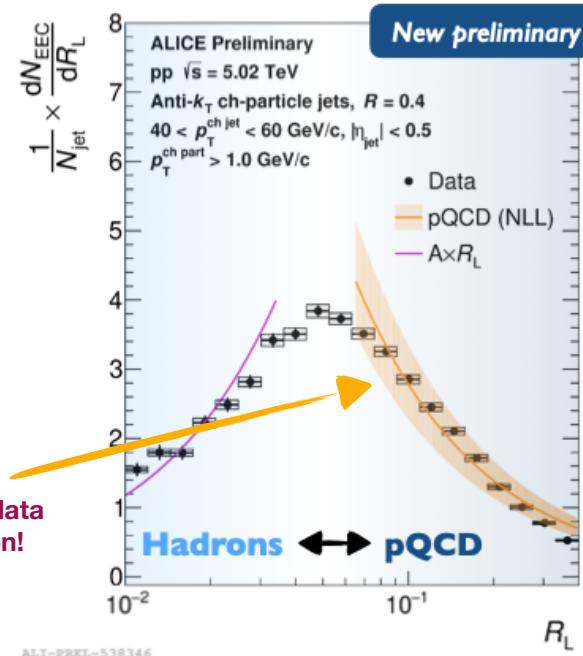


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Universal behavior of the transition region.

**Thank you!**