Beautiful and Charming Energy Correlators

Loopfest 2023 - SLAC

Bianka Meçaj - Yale University

Based on 2210.09311 and ongoing work

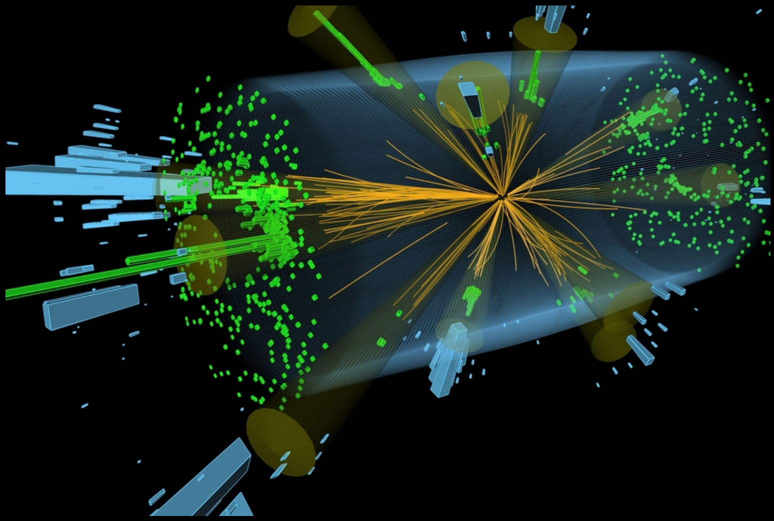

Evan Craft


Kyle Lee


Ian Moult

QCD at Hadron Colliders

Almost every LHC event contains jets



Jets are reconstructed using jet algorithms (anti-k_T)

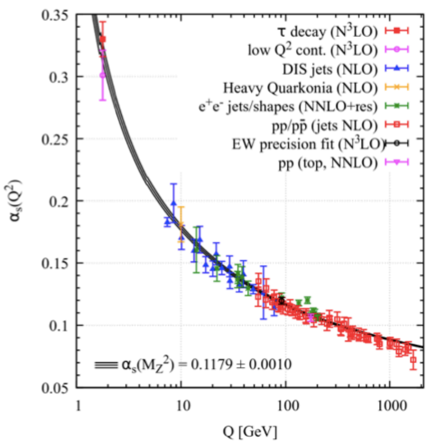
Cacciari, Salam 2006
Salam, Soyez 2007

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

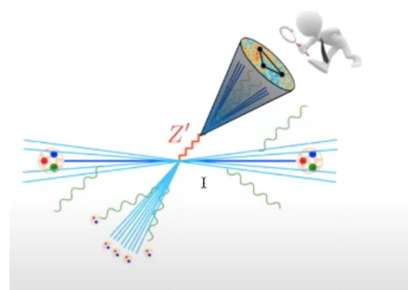
Jets at the LHC

Jet substructure

QCD precision tests



New Physics

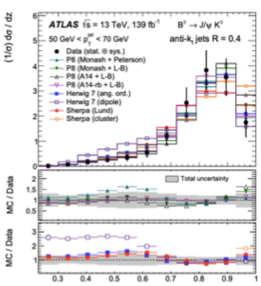


Both precision measurements and New Physics searches require precise description of jet cross sections.

Jets at the LHC

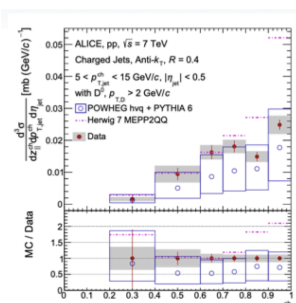
Jet substructure and heavy quarks

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



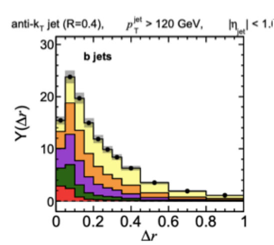
ATLAS Collaboration `21

ATLAS



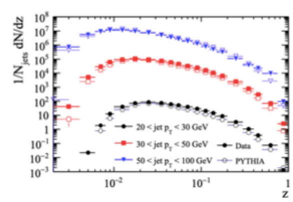
ALICE Collaboration `19

ALICE



CMS Collaboration `00

CMS



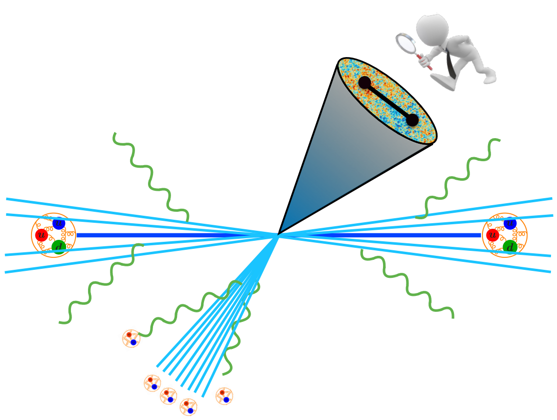
Kara Mattioli's Thesis `22

LHCb

Can we probe intrinsic mass effects with jet substructure?

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.

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

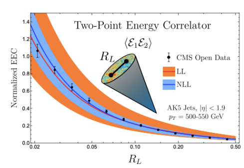
[Basham, Brown, Ellis, Love]

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

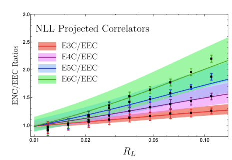
Energy correlators for jet substructure at LHC

Outline

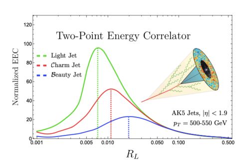
- **Scaling behavior**



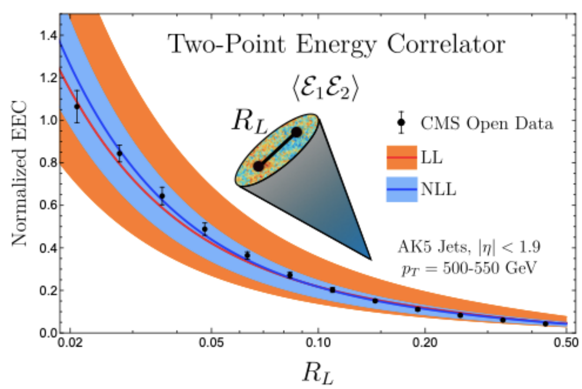
- **Spectrum of the jet**



- **Heavy quark jets**



Scaling behavior

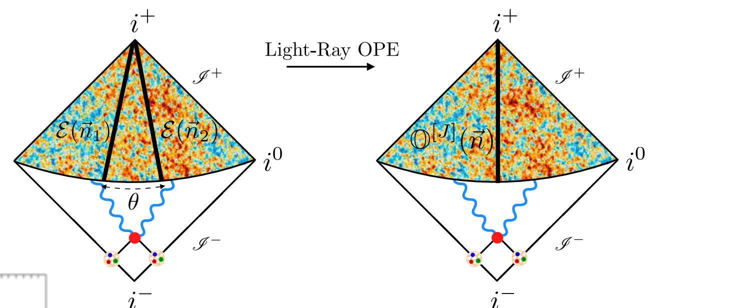


Scaling behavior

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

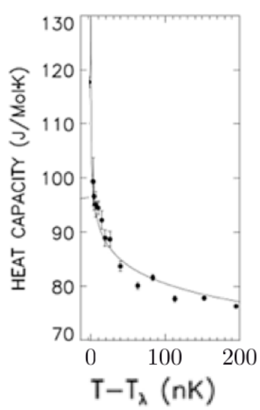
- Energy correlators admit an OPE

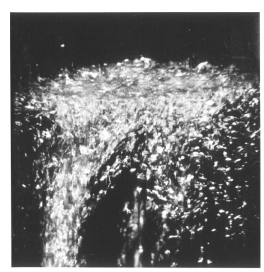
$\langle\Psi \mid \varepsilon(\vec{n}_1)\varepsilon(\vec{n}_2) \mid \Psi\rangle \sim \sum \theta^{\gamma_i}\mathcal{O}_i(\vec{n}_1)$



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

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

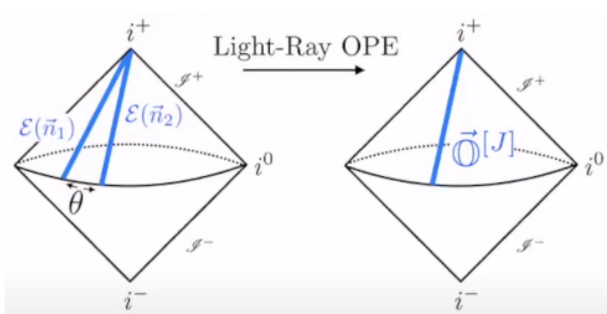




The light-ray OPE

- The leading scaling behavior at the LHC is described by the leading terms in the OPE: **twist two light-ray operators.**
- Light-ray OPE is a rigorous and convergent expansion in CFT.

$$\varepsilon\left(\vec{n}_1\right)\varepsilon\left(\vec{n}_2\right)=\sum c_i\theta^{\tau_i-4}\mathbb{O}_i\left(\vec{n}_1\right)$$



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

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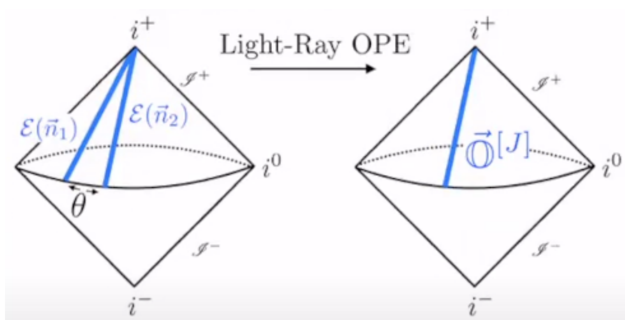
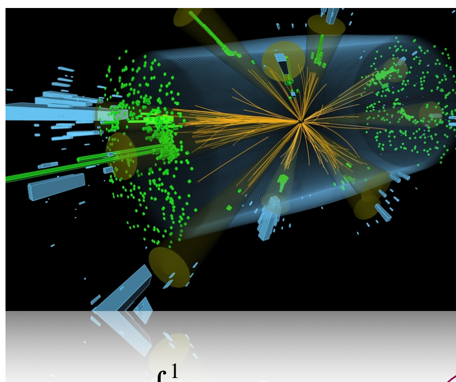
Have to understand the structure of these operators in QCD!



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

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

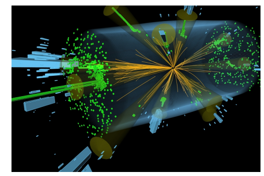
Hard function: includes pdfs

Matching coefficient, jet algorithm

Energy correlator jet function

Two-point energy correlator

The simplest jet substructure observable

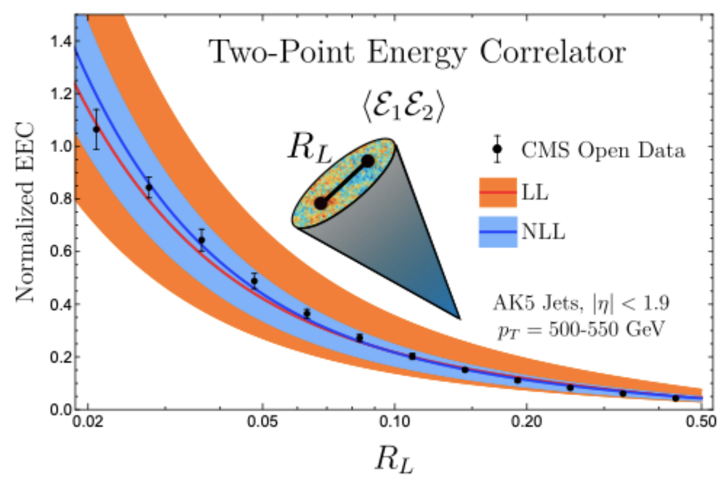


- The complicated LHC environment is described by a simple observable!

- Probe the OPE structure of $\langle \varepsilon(\vec{n}_1)\varepsilon(\vec{n}_2)\rangle$

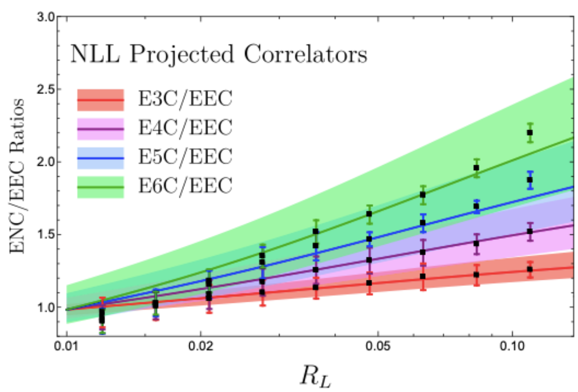
$$\langle \Psi \mid \varepsilon(\vec{n}_1)\varepsilon(\vec{n}_2) \mid \Psi \rangle \sim \sum \theta^{\gamma_i}\mathcal{O}_i(\vec{n}_1)$$

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



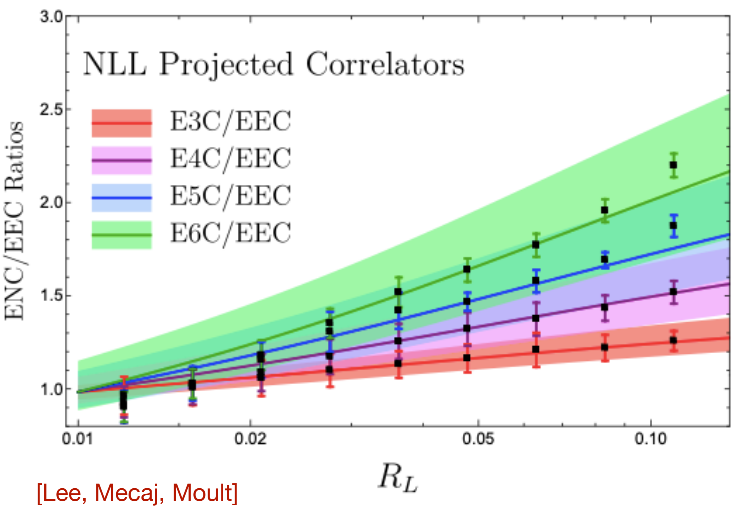
[Lee, Mecaj, Moult]

Jet Spectrum



The jet spectrum

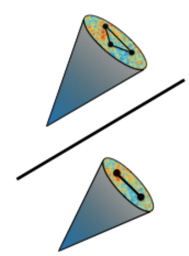
Higher-point correlators



[Lee, Mecaj, Moult]

[Chen, Moult, Zhang, Zhu]

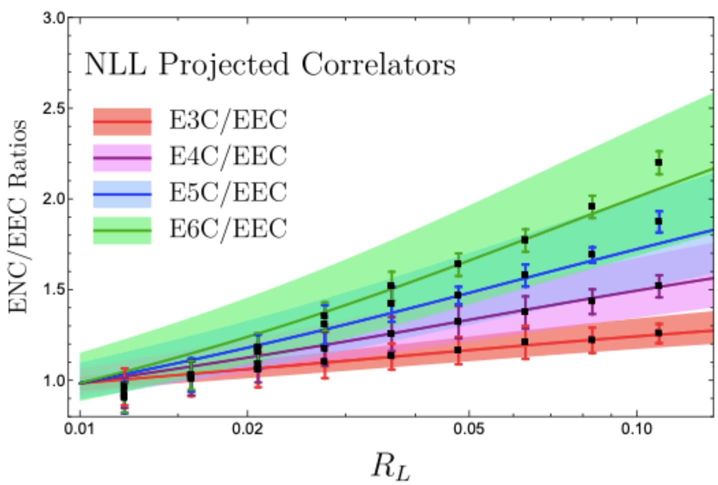
Asymptotic energy flux directly probes the spectrum of (twist-2) lightray operators at the quantum level!



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

The jet spectrum

Higher-point correlators



[Lee, Mecaj, Moult]

[Chen, Moult, Zhang, Zhu]

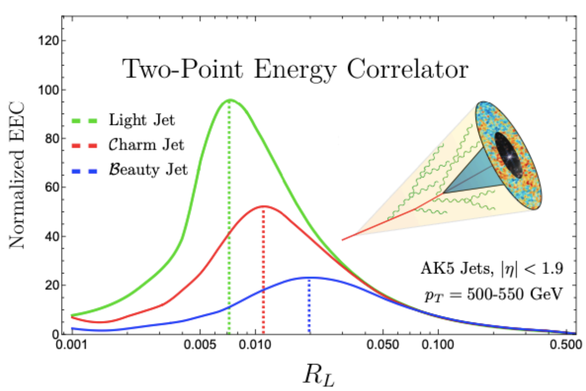
$$\theta^\gamma \to \exp\left(\frac{\hat{\gamma}}{2\beta_0} \ln \frac{\alpha_s(\theta Q)}{\alpha_s(Q)}\right)$$

- 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

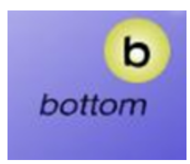
Heavy quark jets



Energy Correlators on heavy jets

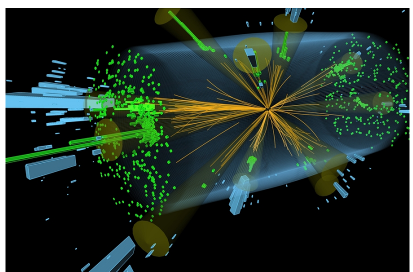
Introduce an additional scale

- 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)

[Czakon, Generet, Mitov, Poncelet; 2021]

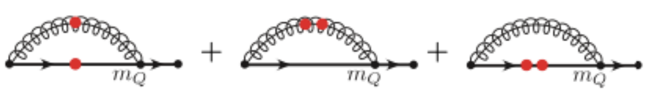
$$\Sigma^{[N]}\left(R_L, p_T^2, m_Q, \mu\right) = \int_0^1 dx x^N \vec{J}^{[N]}\left(R_L, x, m_Q, \mu\right) \cdot \overrightarrow{H}\left(x, p_T^2, \mu\right)$$

$\mu_H \sim p_T$

$\mu_J \sim p_T R$

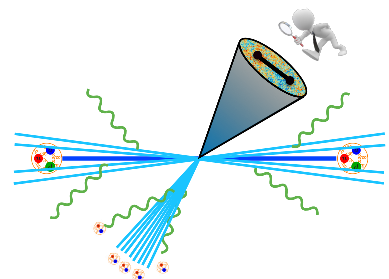
Massive Energy Correlator Jet Function (NLO)

[Craft, Lee, BM, Moult]



Heavy quark jet function

Result



$$J_Q^{\rm bare}(z,M,\mu) = \delta(z)\left(1+\frac{\alpha_s C_F}{4\pi}\left[-\left(\gamma_{qq}^{(0)}(3)+\gamma_{gq}^{(0)}(3)\right)\left(\frac{1}{\epsilon_{\rm UV}}+\ln\frac{\mu^2}{M^2}\right)-\frac{19}{6}\right]\right)$$
$$+\frac{\alpha_s C_F}{\pi}\frac{1}{z}\left[\frac{3}{4}-\frac{5}{2}\delta^2-\frac{\delta^4}{1+\delta^2}+3\delta^3\arctan\left(\frac{1}{\delta}\right)+\frac{1}{2}\delta^2(1-\delta^2)\ln\frac{\delta^2}{1+\delta^2}\right]$$

The mass should not affect the UV behavior of the jet function.
This can be seen from comparing the UV poles with the light quark jet function.

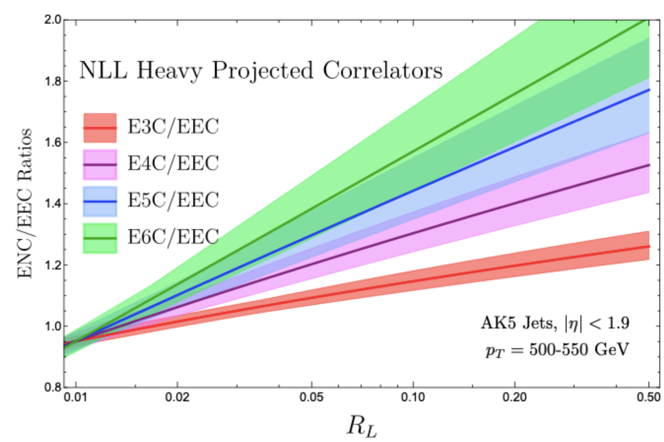
$$J_q^{\rm bare}(z,\mu) = \delta(z)+\frac{\alpha_s C_F}{4\pi}\left[\delta(z)\left(-\frac{3}{\epsilon_{\rm UV}}-\frac{37}{3}\right)+3\frac{Q^2}{\mu^2}\mathcal{L}_0\left(\frac{Q^2}{\mu^2}z\right)\right]$$
$$= \delta(z)+\frac{\alpha_s C_F}{4\pi}\left[\delta(z)\left(-\left(\gamma_{qq}^{(0)}(3)+\gamma_{gq}^{(0)}(3)\right)\frac{1}{\epsilon_{\rm UV}}-\frac{37}{3}\right)+3\frac{Q^2}{\mu^2}\mathcal{L}_0\left(\frac{Q^2}{\mu^2}z\right)\right]$$

[Craft, Lee, BM, Moult]

Projected energy correlators

Resolve the UV scaling behaviour

- Ratios of higher point correlators with the two point EEC are independent of IR effects, including quark mass.
- The exact behavior as the massless case.
- Non-trivial cross check of the factorization theorem!
- Anomalous dimensions should not be affected by the IR physics.



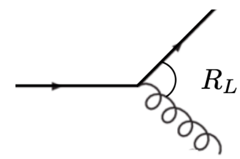
[Craft, Lee, BM, Moult]

Massive jets

Massive Energy Correlator Jet Function

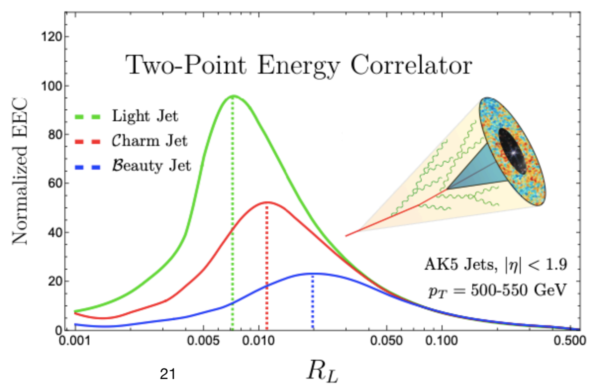
$$\Sigma^{[N]}\left(R_L, p_T^2, m_Q, \mu\right) = \int_0^1 dx x^N \vec{J}^{[N]}\left(R_L, x, m_Q, \mu\right) \cdot \vec{H}\left(x, p_T^2, \mu\right)$$

Hard function



Virtuality $\sim p_T R_L + m_Q^2$

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

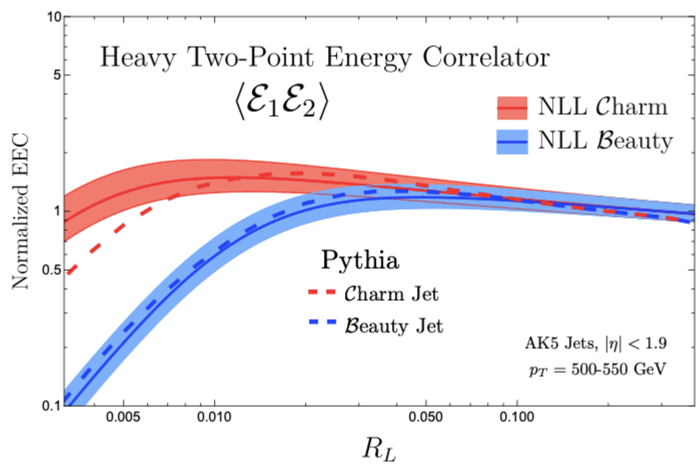


[Craft, Lee, BM, Moult]

Massive two point correlator

First massive jet substructure observable at NLL

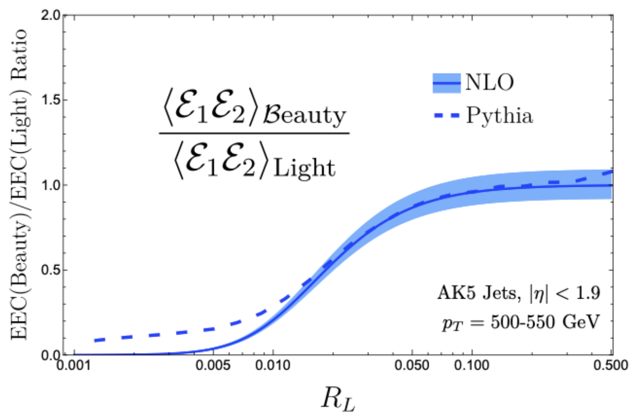
- Scaling behaviour identical to massless case for larger scales.
- A turn-over for $R_L \to m_Q/p_T$
- The change in the slope is perturbative effect contrary to massless jets: $R_L \to \Lambda_{QCD}/p_T$
- The turn-over region is of interest for improving heavy quark description is parton shower.



[Craft, Lee, BM, Moult]

Intrinsic mass effects

Dead-cone effect

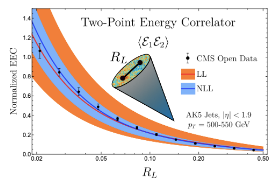


[Craft, Lee, BM, Moult]

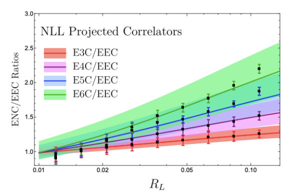
- **Ratios of the massive and massless EEC isolate mass (IR) effects.**
- **A transition region related to the quark mass, which is perturbatively calculable.**
- **Excellent agreement with MC.**
- **Small angle suppression can be interpreted as a dead-cone effect.**

Conclusions

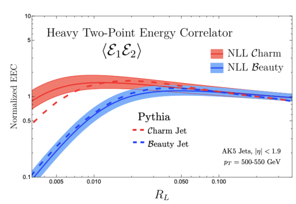
- Can probe a universal scaling behavior of QFT in the complicated LHC environment.



- 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.



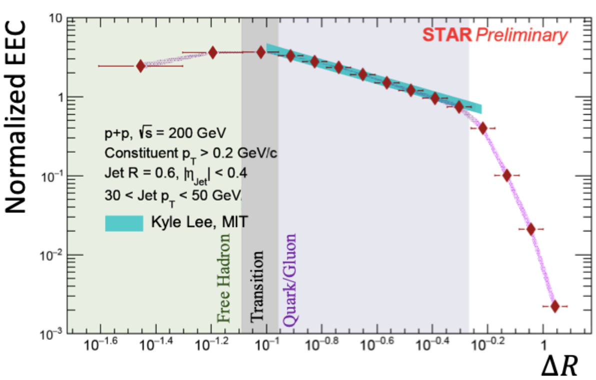
What is next?

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 $\sqrt{s} = 200GeV$

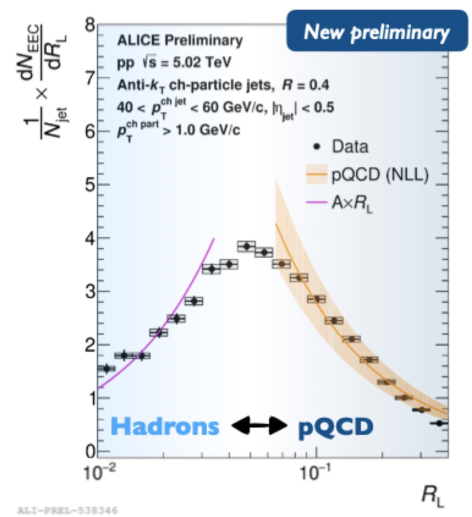


$$\text{Normalized EEC} = \frac{1}{\sum_{\text{jets}} \sum_{i \neq j} \frac{E_i E_j}{p_{T,\text{jet}}^2}} \frac{d\left(\sum_{\text{jets}} \sum_{i \neq j} \frac{E_i E_j}{p_{T,\text{jet}}^2}\right)}{d\,(\Delta R)}$$

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 $\sqrt{s} = 5TeV$



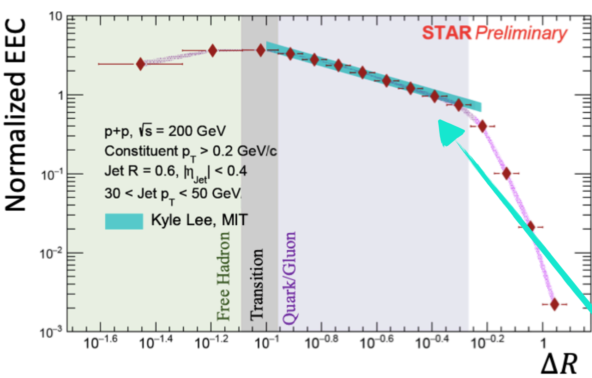
Universal behavior of the transition region.

Exciting experimental results!

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

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

- STAR collaboration $\sqrt{s} = 200 GeV$
- ALICE collaboration $\sqrt{s} = 5 TeV$



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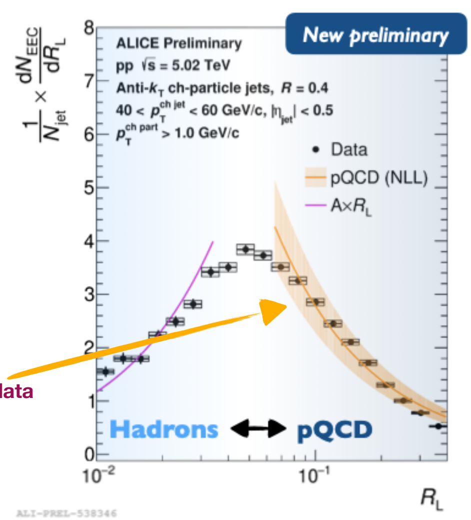
Direct observation of the transition from free hadrons to quarks/gluons at a universal scaling!

Excellent agreement of data with the theory NLL calculation



Universal behavior of the transition region.

Thank you!