Energy-Energy Correlation Functions at the LHC

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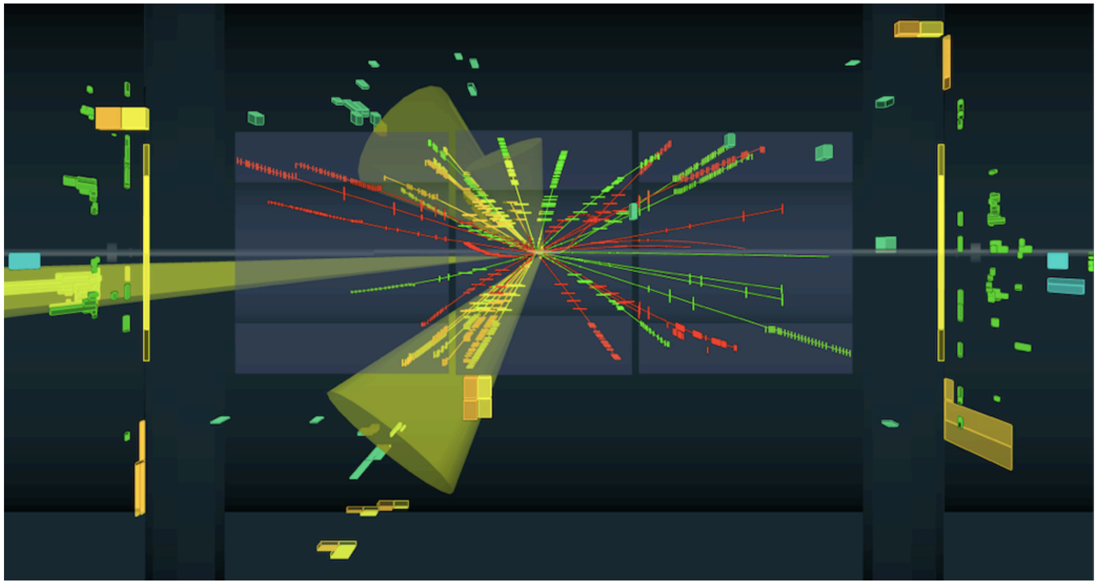
Standard Model at the LHC 2023
Fermilab

Based on 2205.03414 and 2210.09311

QCD at the LHC

- **Jets are emergent phenomena in QCD**

⇒ QCD precision studies and New Physics searches



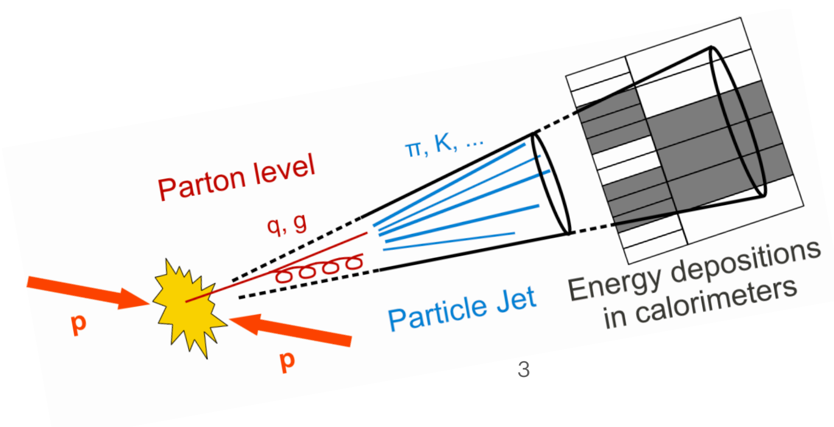
QCD at the LHC

- **Jets are emergent phenomena in QCD**

⇒ QCD precision studies and New Physics searches

⇒ Internal kinematic properties are clean probes of QCD dynamics

Robust Jet Substructure Observables!



Energy Flow Inside the Jet

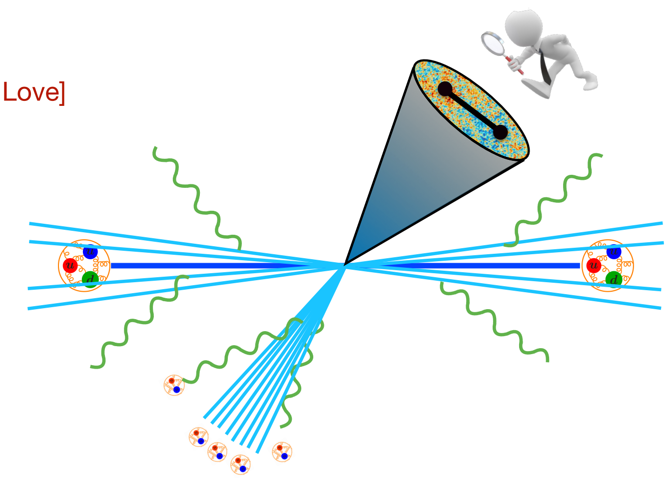
- Distribution of energy inside the jet is described by correlation functions of the energy flow operators ⇒ Energy Correlators.

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

[Basham, Brown, Ellis, Love]

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

Defined from first principles in QFT!

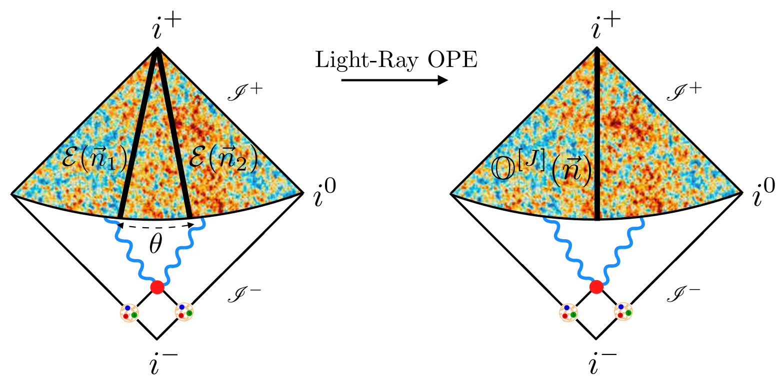


Any physics dynamics will be imprinted in the energy distributions inside the jet.

Scaling Behavior

Energy correlators inside high energy jets at the LHC

⇒small angle limit



- **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]

Scaling Behavior

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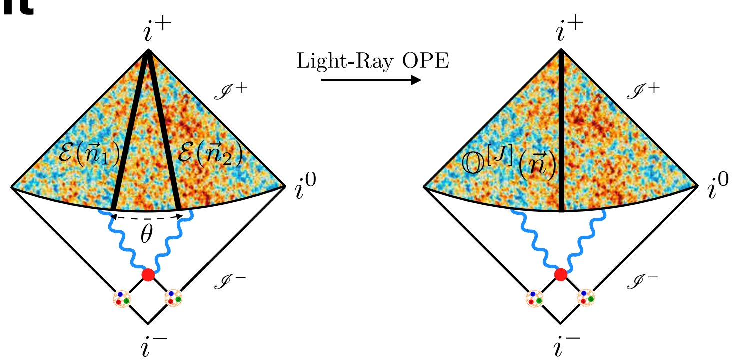

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$$\langle \Psi \mid \varepsilon(\vec{n}_1)\varepsilon(\vec{n}_2) \mid \Psi \rangle \sim \sum \theta^{\gamma_i} \mathcal{O}_i(\vec{n}_1)$$

⇒ Use LHC jets to test the leading QCD operators in this expansion

Scaling Behavior

Energy correlators inside high energy jets at the LHC

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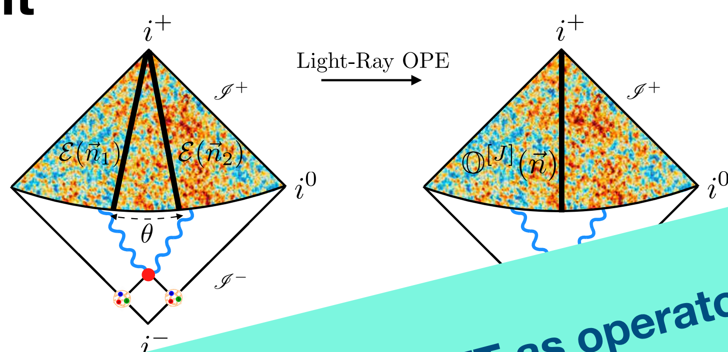


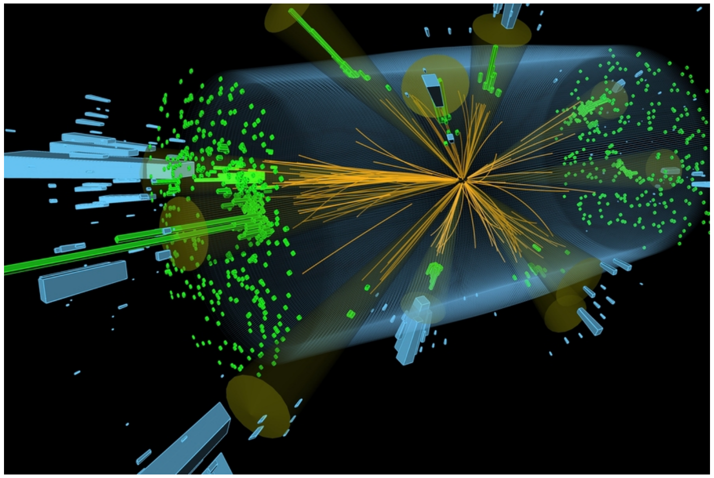
- **Energy corr**

Universal scaling behavior in QFT as operators are brought together!

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

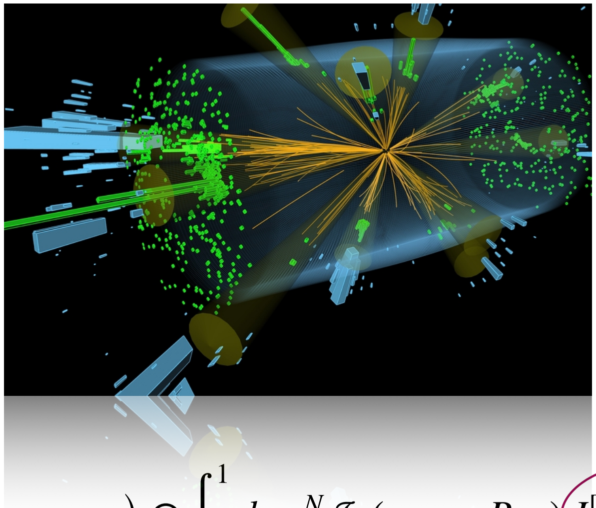
⇒ Use LHC jets to test the leading QCD operators in this expansion

Energy Correlators at the LHC



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, BM, Moult]

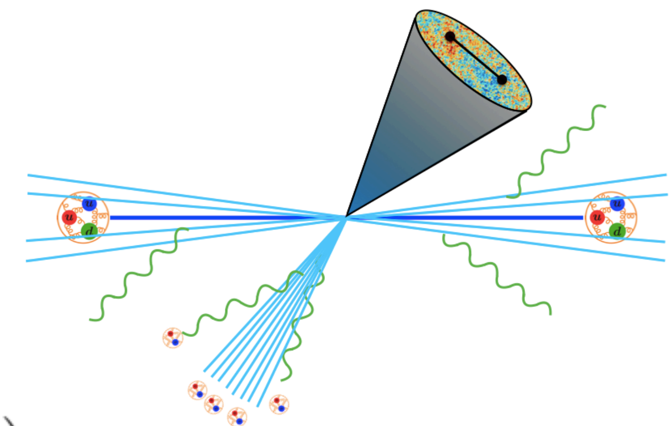
Can calculate any higher point correlator at the LHC

Hard function: includes pdfs

Matching coefficient, jet algorithm

Energy correlator jet function

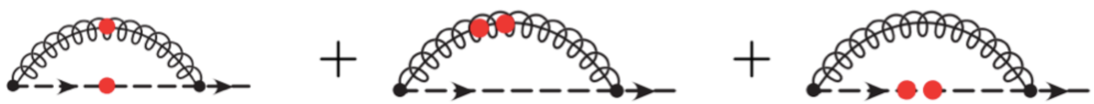
Energy correlator jet function



- EEC jet function definition:

$$J(z) = \sum_{i,j} \mathrm{Tr}\langle 0 \mid \frac{\bar{\not{n}}}{2} \xi_n(x) \delta(\omega - \bar{n} \cdot \mathcal{P}) \bar{\xi}_n(0) \mid 0 \rangle \frac{E_i E_j}{(Q/2)^2} \delta\left(z - \frac{1 - \cos\chi_{ij}}{2}\right)$$

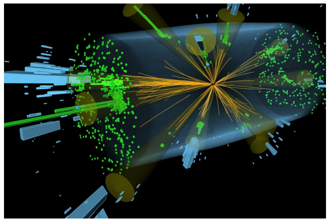
- There are three type of diagrams that contribute at one-loop



$\ni x(1-x)\delta(z - \frac{1-\cos\chi_{12}}{2})$ $\ni (1-x)^2\delta(z)$ $\ni x^2\delta(z)$

Two-point energy correlator

The simplest jet substructure observable

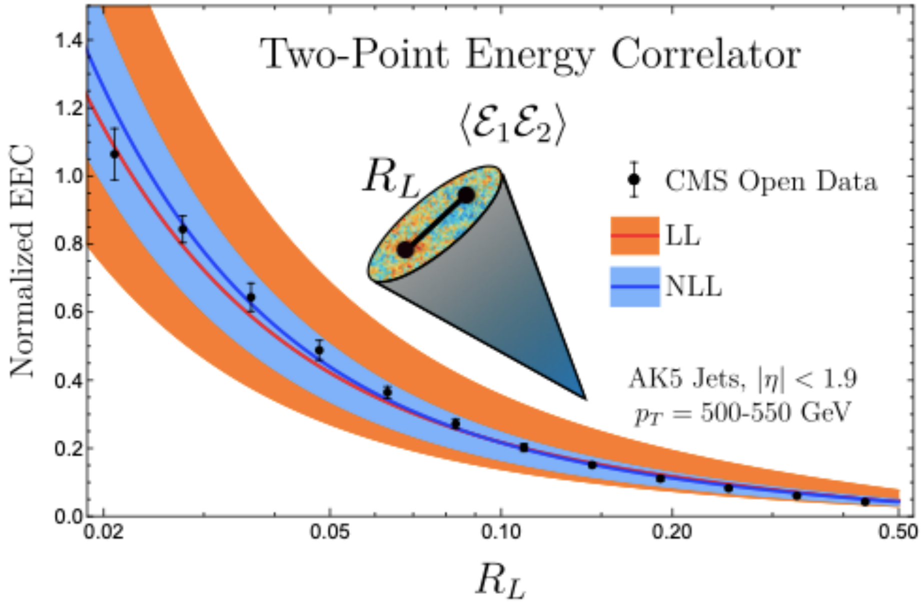


- The complicated LHC environment is described by a simple observable!

- 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.

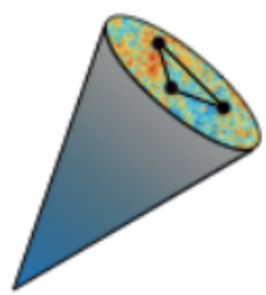


[Lee, BM, Moult]

Higher point correlators

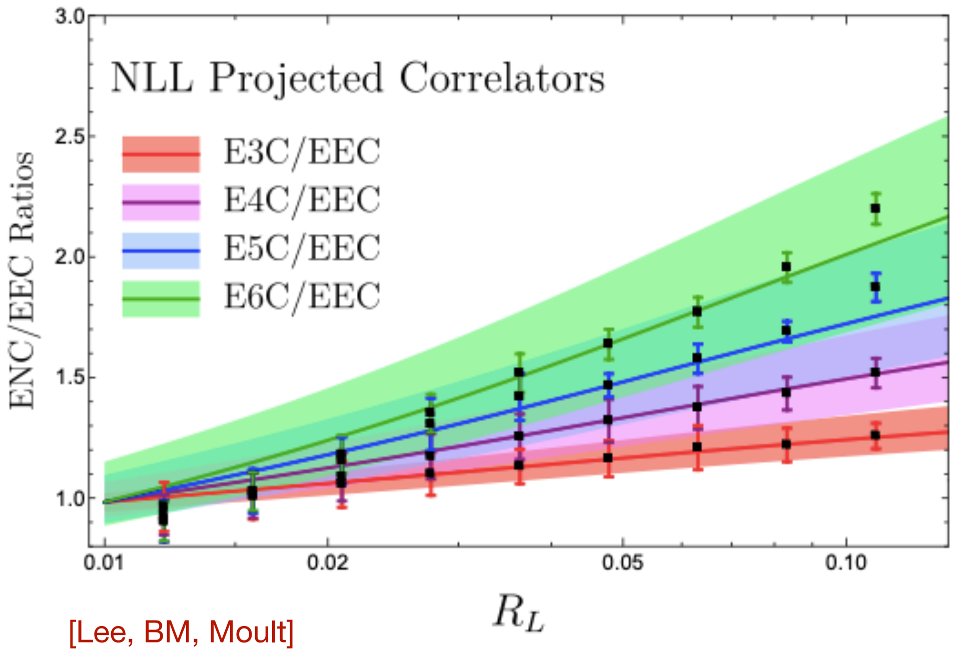
Scaling behavior

- The high energies at the LHC are a suitable environment to test higher point correlation functions of the energy flow operator.



The jet spectrum

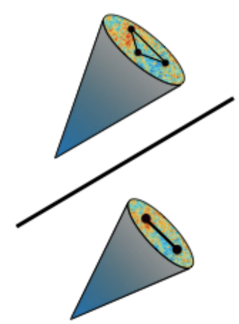
Higher-point correlators



[Lee, BM, Moult]

[Chen, Moult, Zhang, Zhu]

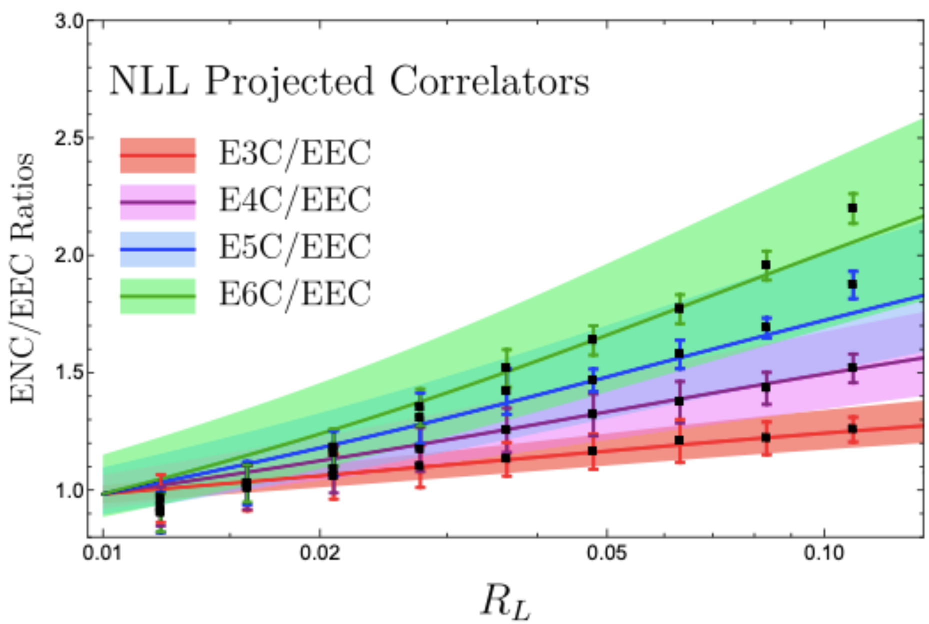
Asymptotic energy flux directly probes the spectrum of (twist-2) lightray operators at the quantum level!



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

The jet spectrum

Higher-point correlators



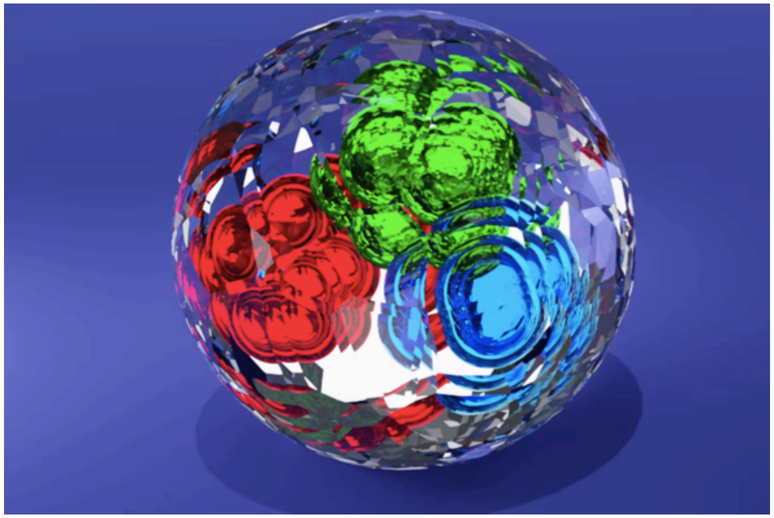
[Lee, BM, Moult]

[Chen, Moult, Zhang, Zhu]

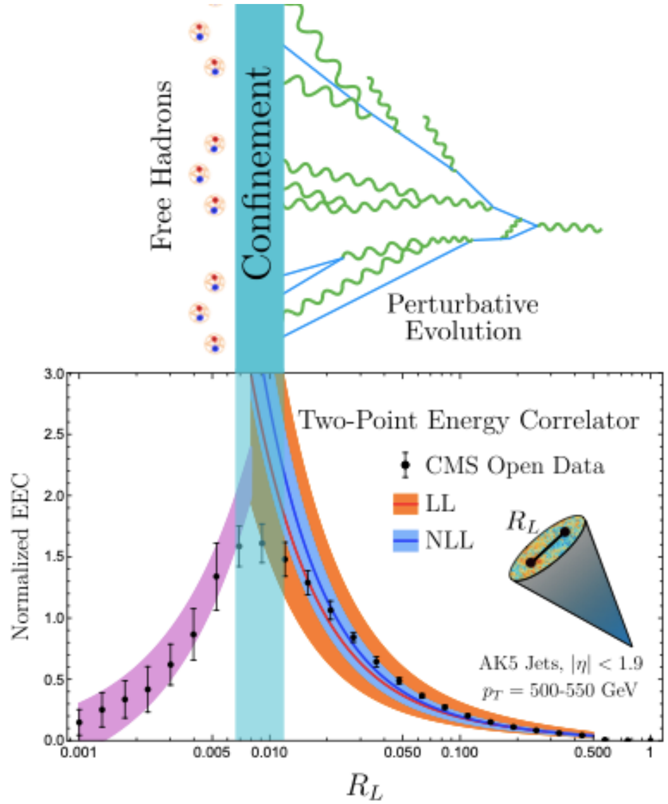
- Can be observed at the high energies at the LHC at high precision
- Ratio of the higher-point correlators with the two-point isolates anomalous scaling!
- The anomalous scaling behavior depends on N (slope increases with N)

$\Downarrow$

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



Confinement transition in jet substructure?

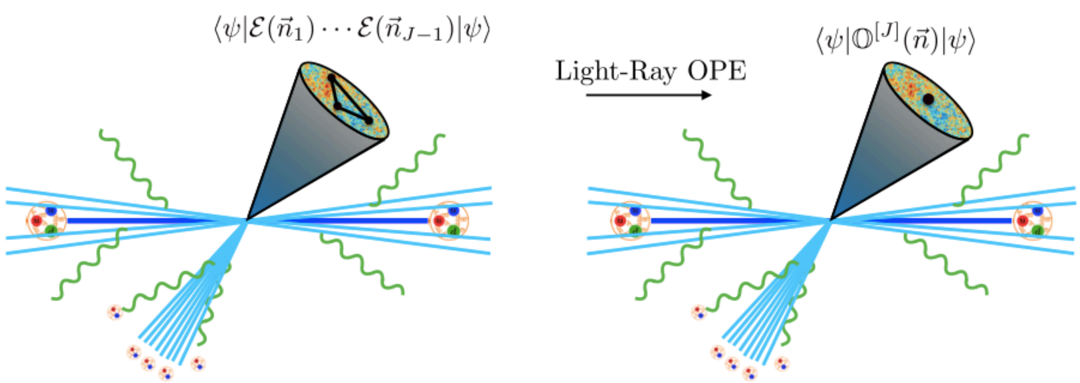


Any underlying dynamics will be imprinted in the energy correlators, including hadronization transition.

Jet substructure from first principles!

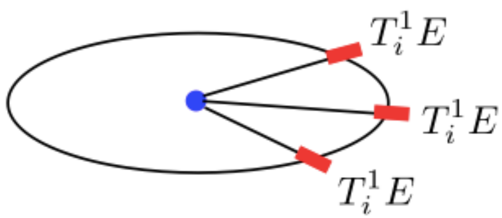
- Energy correlator is a jet substructure observable defined from first principles in QFT

⇒ 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



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

Multiply by the first moment of the track function

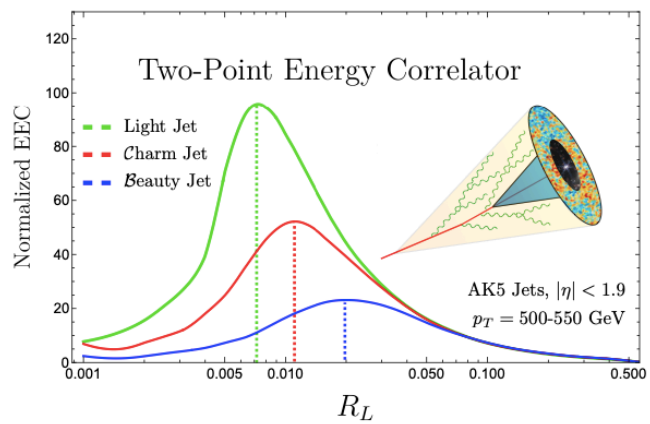
- Incorporate information not only from the calorimeter but also from the tracks.

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

- Possible using track functions.
- Better precision

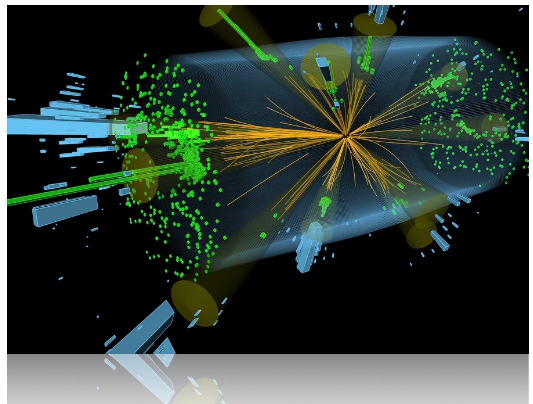
The anomalous dimension can also be measured from these first moments!

Energy Correlators on Heavy Jets



Factorization theorem

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



Hard function (NNLO)

[Czakon, Generet, Mitov, Poncelet; 2021]

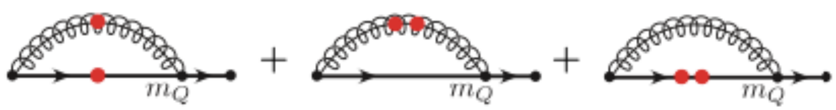
$$\Sigma^{[N]}\left(R_L, p_T^2, m_Q, \mu\right) = \int_0^1 dx x^N \vec{J}^{[N]}\left(R_L, x, m_Q, \mu\right) \cdot \vec{H}\left(x, p_T^2, \mu\right)$$

$\mu_H \sim p_T$

$\mu_J \sim p_T R$

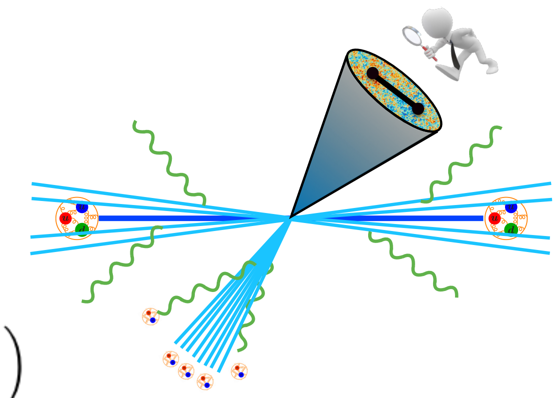
Massive Energy Correlator Jet Function (NLO)

[Craft, Lee, BM, Moult]



Heavy quark jet function

Result



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

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.

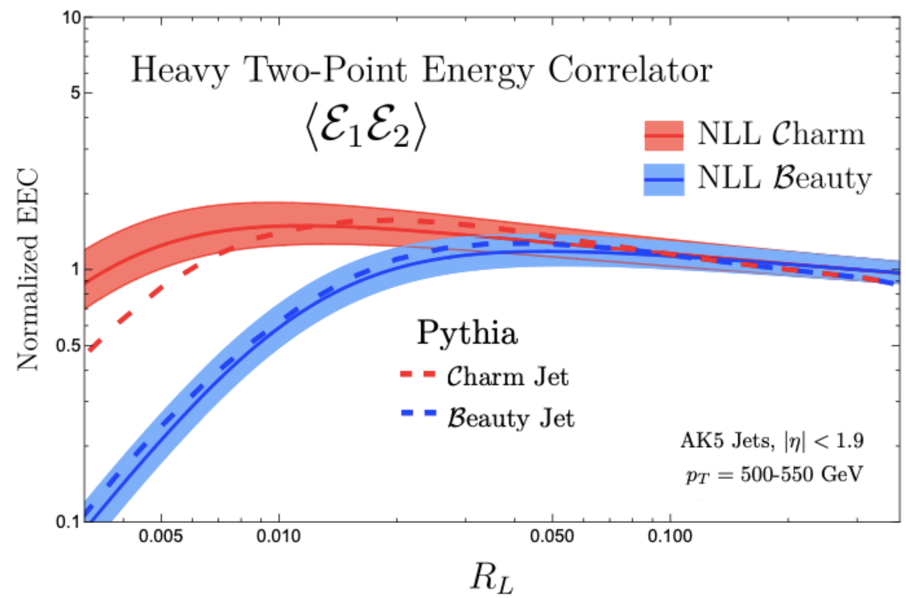
$$J_q^{\mathrm{bare}}(z, \mu) = \delta(z) + \frac{\alpha_s C_F}{4\pi}\left[\delta(z)\left(-\frac{3}{\epsilon_{\mathrm{UV}}} - \frac{37}{3}\right) + 3\frac{Q^2}{\mu^2}\mathcal{L}_0\left(\frac{Q^2}{\mu^2}z\right)\right]$$
$$= \delta(z) + \frac{\alpha_s C_F}{4\pi}\left[\delta(z)\left(-\left(\gamma_{qq}^{(0)}(3)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

[Craft, Lee, BM, Moult]

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.

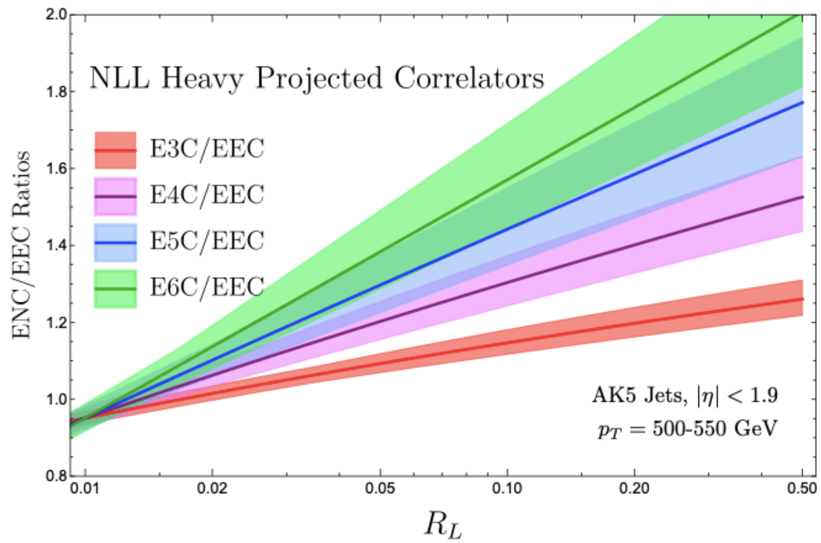


[Craft, Lee, BM, Moult]

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 behaviour 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]

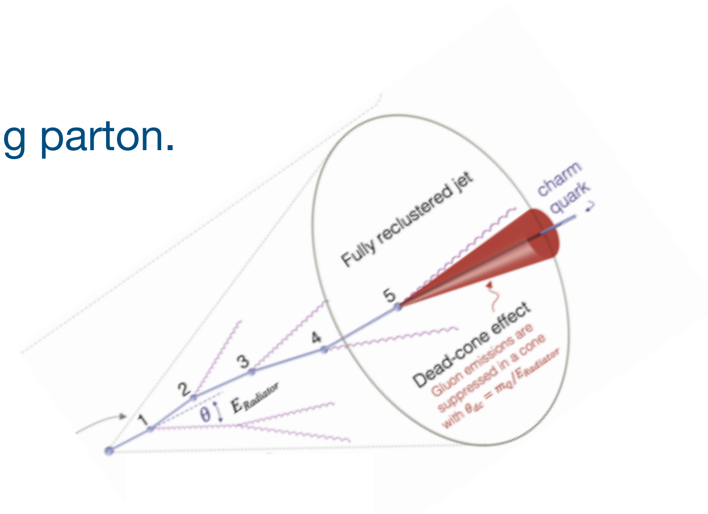
Dead-cone effect in QCD

Fundamental phenomena

- Parton-shower pattern depends on the mass of the emitting parton.
- Angular suppression $\propto \frac{M}{E}$.

Observable used for the observation of the dead-cone effect in LHC data

$$R(\theta) = \frac{1}{N^{\mathrm{D^0\,jets}}} \frac{\mathrm{d}n^{\mathrm{D^0\,jets}}}{\mathrm{d}\ln(1/\theta)} \Bigg/ \frac{1}{N^{\mathrm{inclusive\,jets}}} \frac{\mathrm{d}n^{\mathrm{inclusive\,jets}}}{\mathrm{d}\ln(1/\theta)} \Bigg|_{k_{\mathrm{T}}, E_{\mathrm{Radiator}}}$$

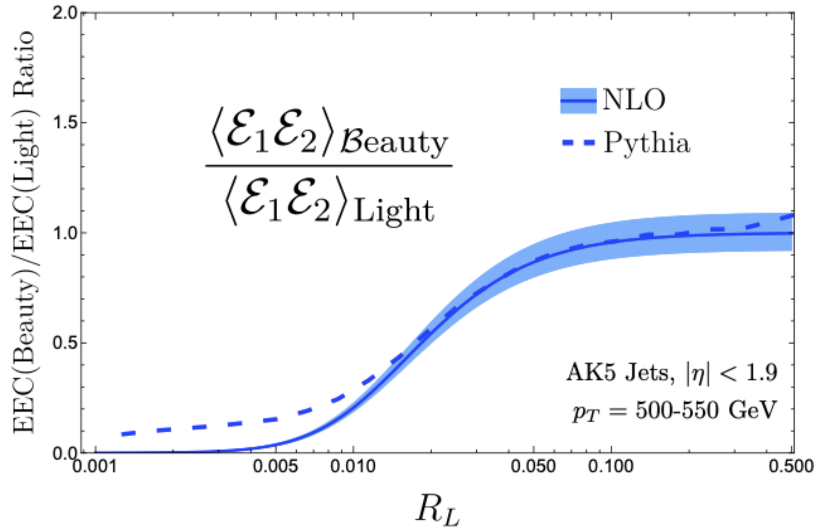


First observation for QCD by ALICE collab in [2106.05713]

- Calculate it from first principles in QFT?

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.**

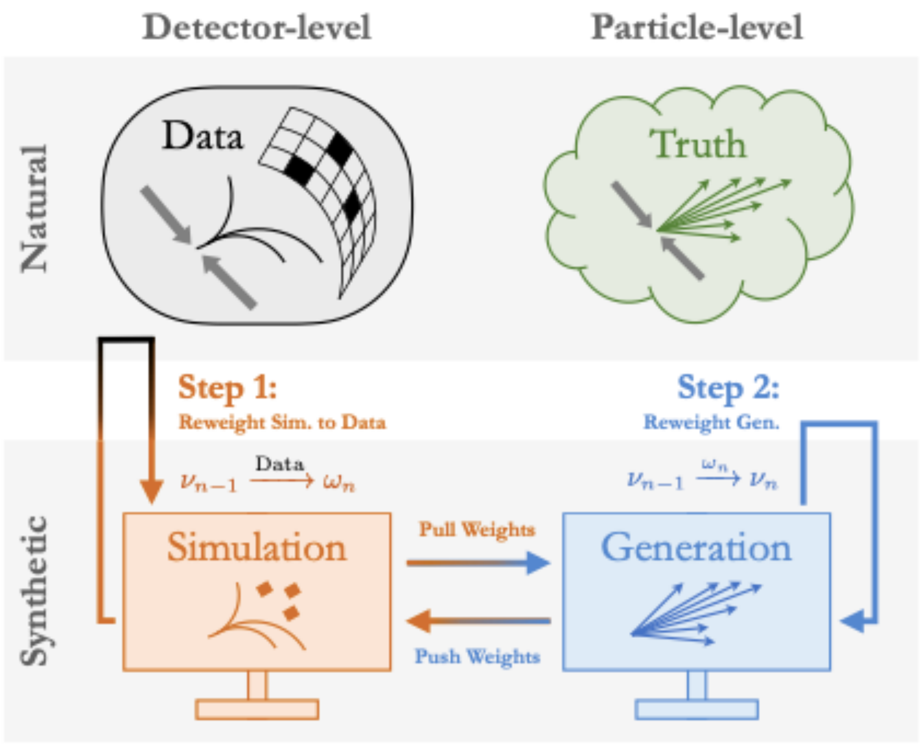
Applications of these results

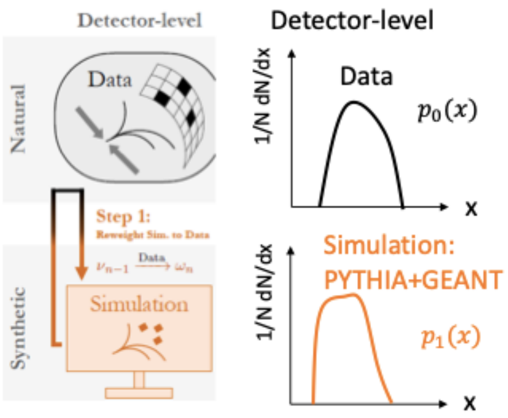
- **Precision measurements: α_s measurement**
- **Jet modeling in MC simulations: heavy flavours**
- Precision in parton showers: "reference resummation" for testing DGLAP finite moments.
- **Understand properties of the QGP: multi-scale problem too, global properties of plasma.**

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

Energy Correlators and Machine Learning

Unfolding for detector effects

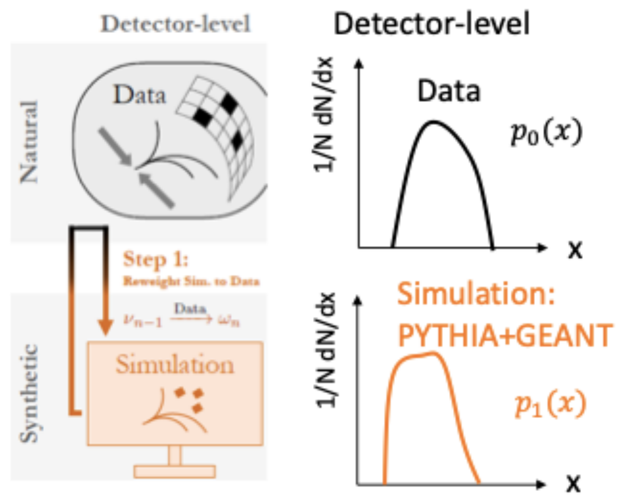




Energy Correlators and Machine Learning

Omnifold

- Simultaneously unfold for multiple observables; suitable for energy correlators
- **Correlation information is preserved**
- Unbinned method



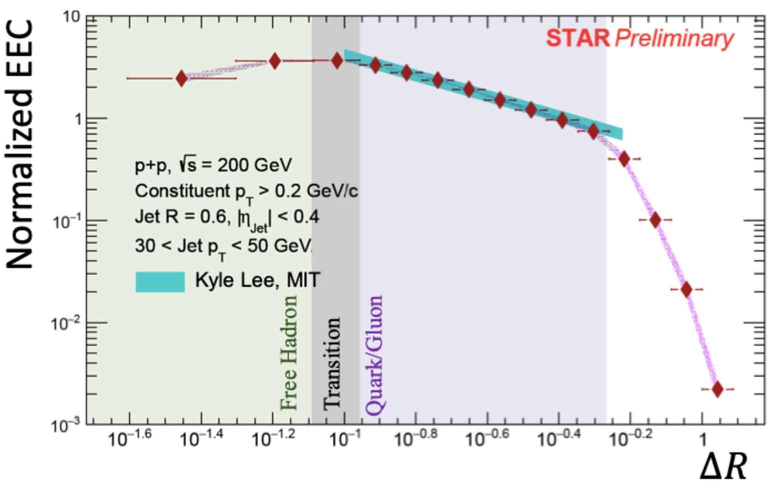
What is next?

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 $\sqrt{s} = 200GeV$

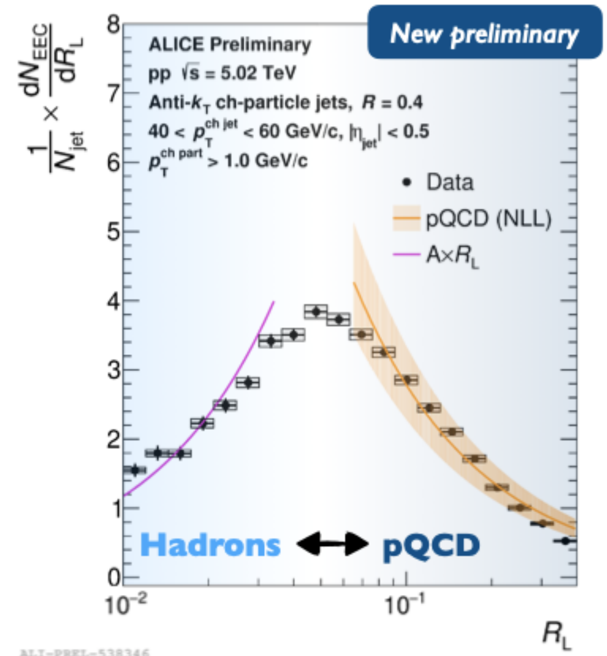


$$\text{Normalized EEC} = \frac{1}{\sum_{\text{jets}} \sum_{i\neq j} \frac{E_i E_j}{p_{T,\text{jet}}^2}} \frac{d\left(\sum_{\text{jets}} \sum_{i\neq j} \frac{E_i E_j}{p_{T,\text{jet}}^2}\right)}{d\,(\Delta R)}$$

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

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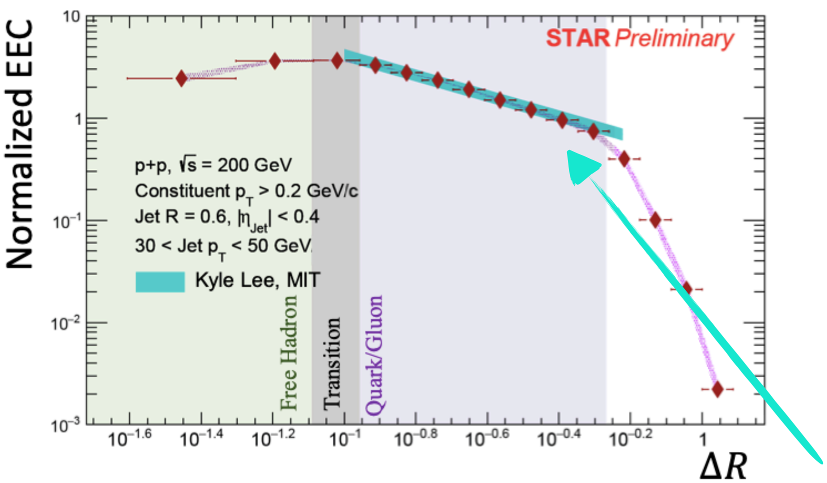

$$\text{Normalized EEC} = \frac{1}{\sum_{\text{jets}} \sum_{i \neq j} \frac{E_i E_j}{p_{T,\text{jet}}^2}} \frac{d\left(\sum_{\text{jets}} \sum_{i \neq j} \frac{E_i E_j}{p_{T,\text{jet}}^2}\right)}{d\,(\Delta R)}$$

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

Excellent agreement of data with our NLL calculation!

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

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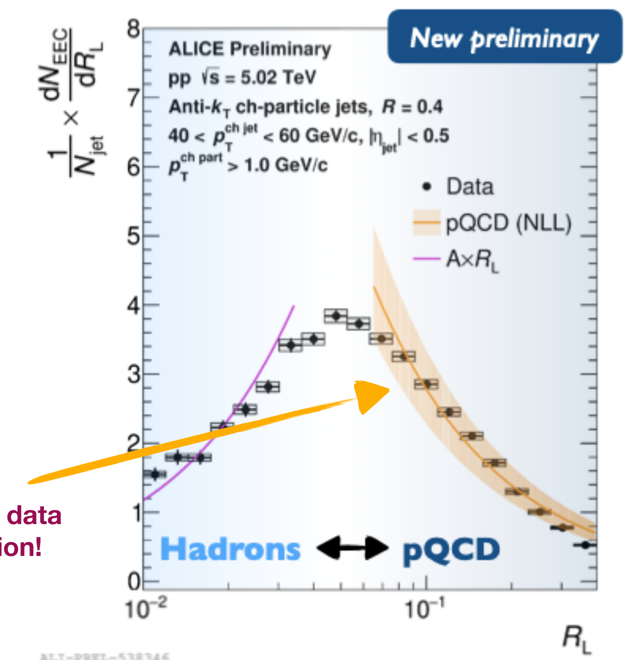


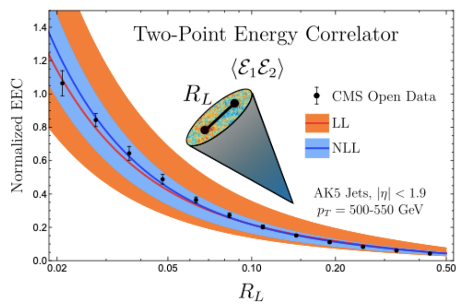
Universal behavior of the transition region.

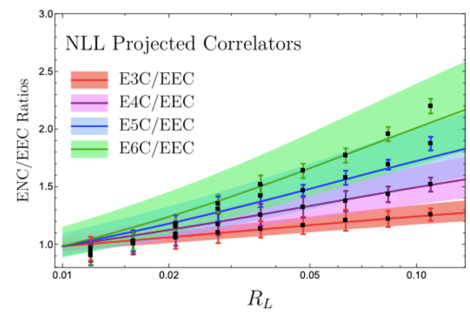
Conclusions

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

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

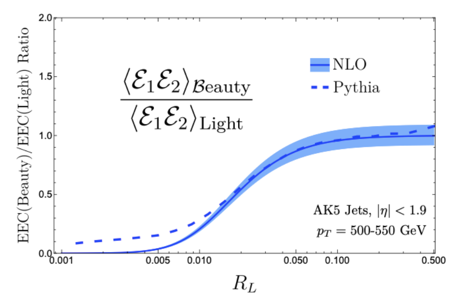
- Probe a universal scaling in QFT and anomalous scaling dimensions in the complicated LHC environment.





- A simple factorization formula for massive quark jets: probe bare quark mass effects

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



A myriad of applications of energy correlators for QCD in the vacuum and heavy ions for precision physics.

Thank You!