“What else can we learn from **energy correlators?**”


# The Beauty and Charm Of *Quantum Chromodynamics*

**Evan Craft — Yale University**

**Graduate Fellow, KITP @ Santa Barbara**

# This talk

"A *perspective* on jet substructure that works extremely well"

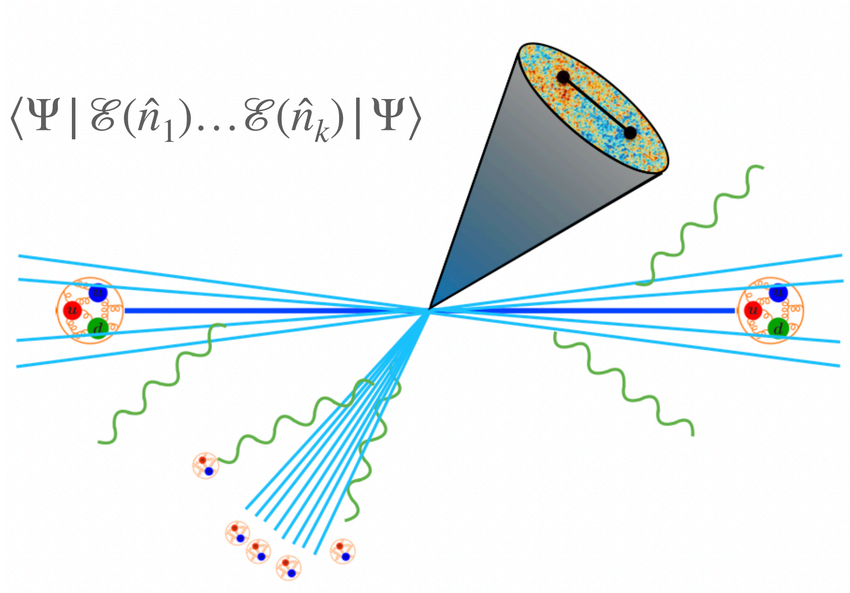
***Goal:***

1. ***What can we do with it?***
2. ***And how we can push it further?***

# Energy Flow Operators

**Jet substructure can be given a *rigorous* and *formal* definition in terms of energy flow operators**

$$\mathscr{E}(\vec{n}) = \lim_{r\to\infty} r^2 \int_0^\infty dt \left[ n^i T_i^0(tr, r\vec{n}) \right]$$




→ **theoretical definition of a calorimeter cell**

→ **can define and measure correlation functions**

**Detailed radiation pattern of a jet completely controlled by n-point correlation functions of energy flow**

- ***scet factorization***

$$\langle \mathscr{E}(\hat{n}_1)\mathscr{E}(\hat{n}_2) \rangle \sim H \otimes J \otimes S$$

- ***operator product expansion***

$$\langle \mathscr{E}(\hat{n}_1)\mathscr{E}(\hat{n}_2) \rangle \sim \sum C_i \, \mathbb{O}_i$$

# Energy Flow Operators

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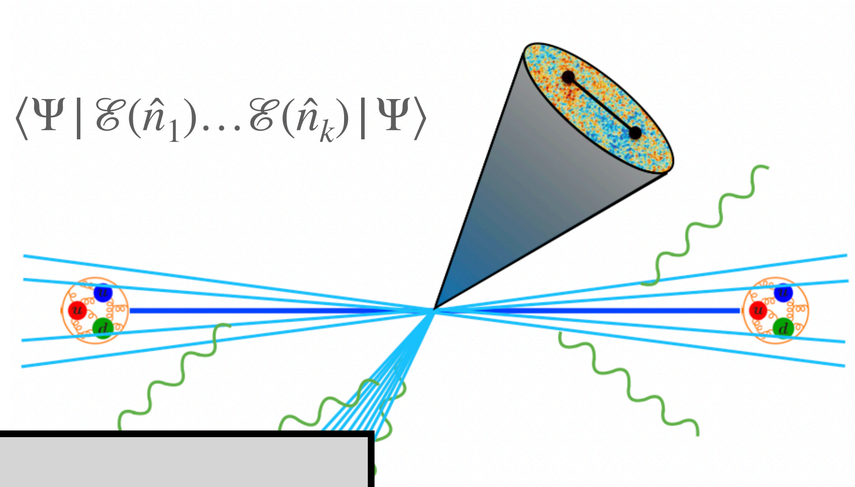


$$\mathcal{E}(\vec{n}) = \lim_{r \to \infty} \int_0^r dt\, t^2\, n^i T_{0i}(t, t\vec{n})$$

Goal: calculate and measure correlations of energy flow

→ theoretical def

→ can define and measure correlation functions

$$\langle \mathcal{E}(\hat{n}_1)\mathcal{E}(\hat{n}_2) \rangle \sim H \otimes J \otimes S$$

**Detailed radiation pattern of a jet completely controlled by n-point correlation functions of energy flow**

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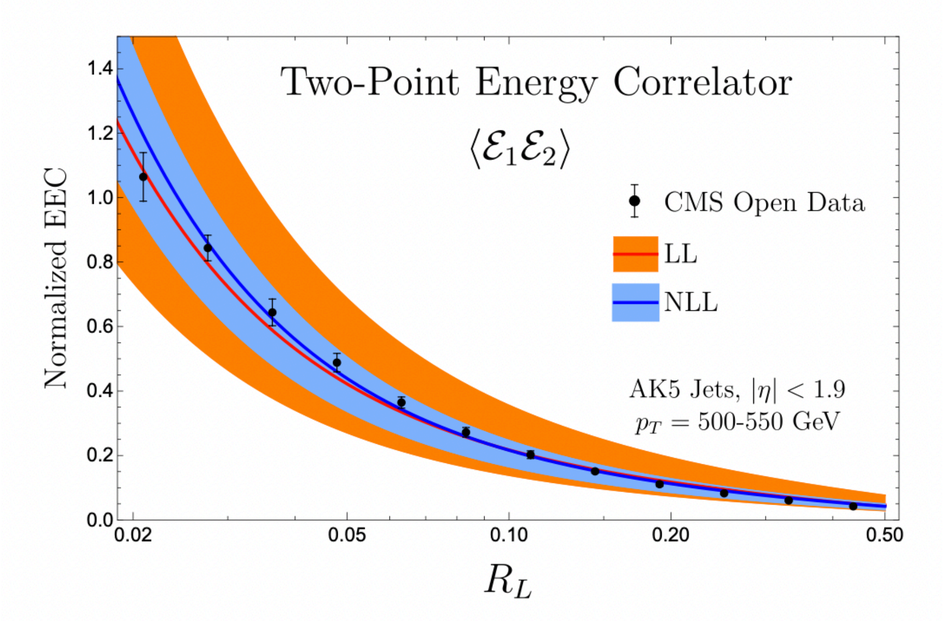
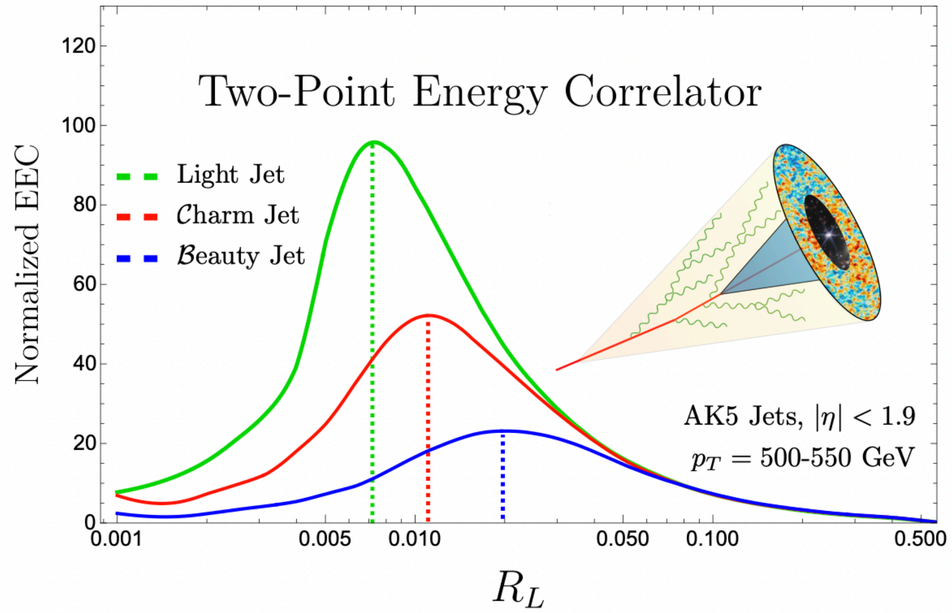
# What can we do with energy correlators?




**The two point correlator exhibits a polynomial scaling on massless jets**

**Lightray OPE must be violated by the quark mass**

**This scaling is softly broken by the mass at $\theta \sim m_q/p_{T,jet}$**

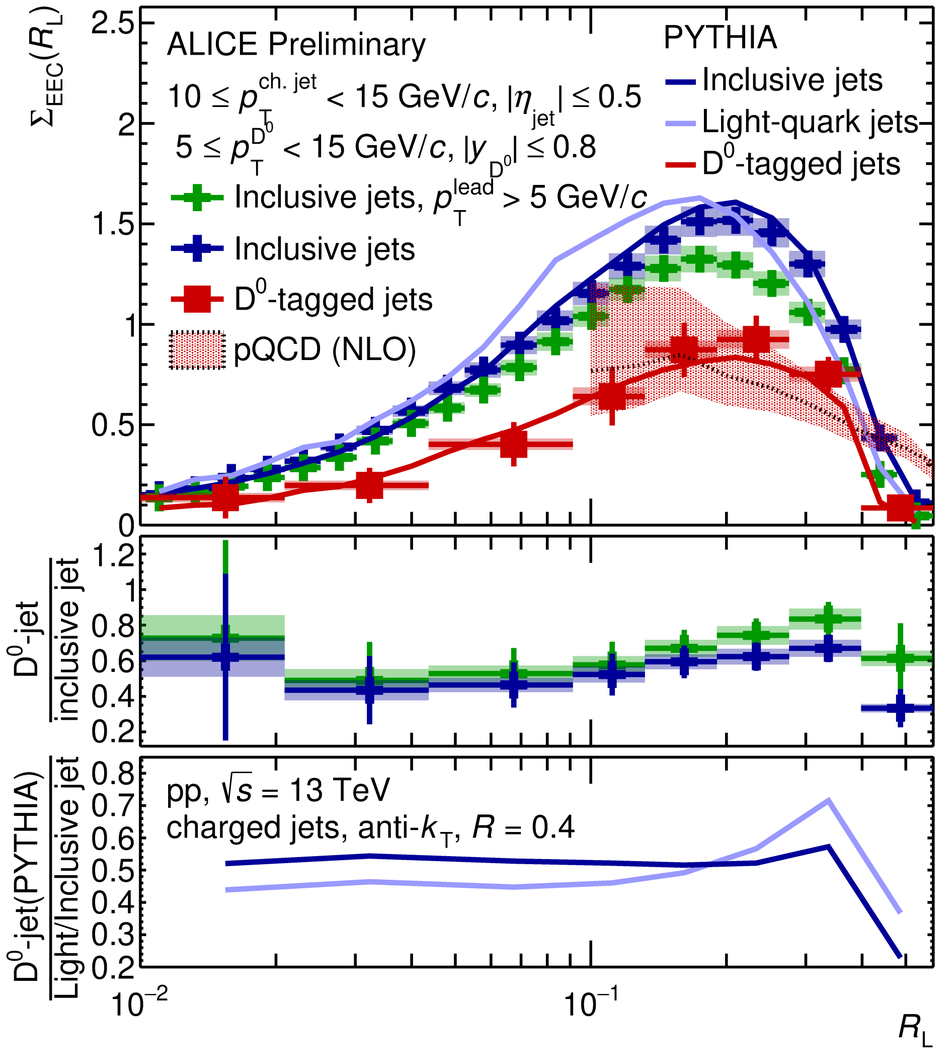
**Exact prefactor is 1.6**

# Fresh Data!

**New Measurement from ALICE (Preeti Dhanker, Berkeley)**

**1. Dead Cone Effect clearly seen in the heavy to inclusive ratio**

**2. Excellent confirmation of QCD factorization and OPE**

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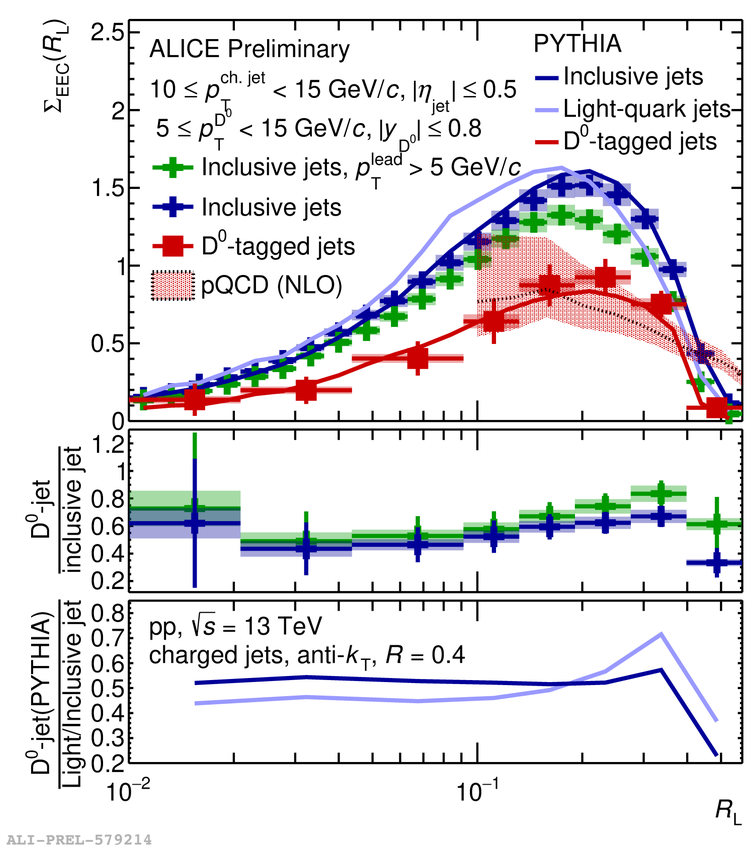
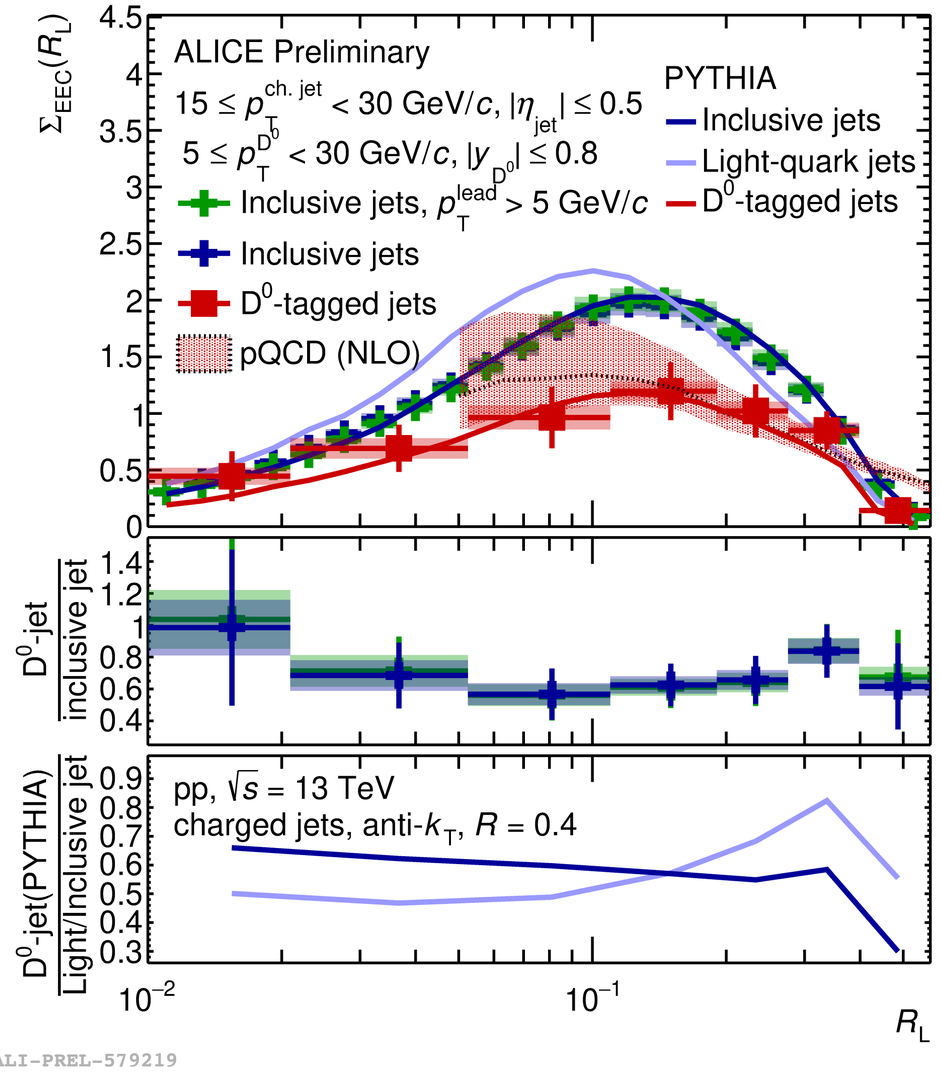
# Fresh Data!




**Low vs. High $p_T$**




**Better convergence at higher energies, as expected.**

# Computational Details

***Simplicity*** **allows us to understand complexity: theoretically and experimentally**

→ **astounding theoretical control**

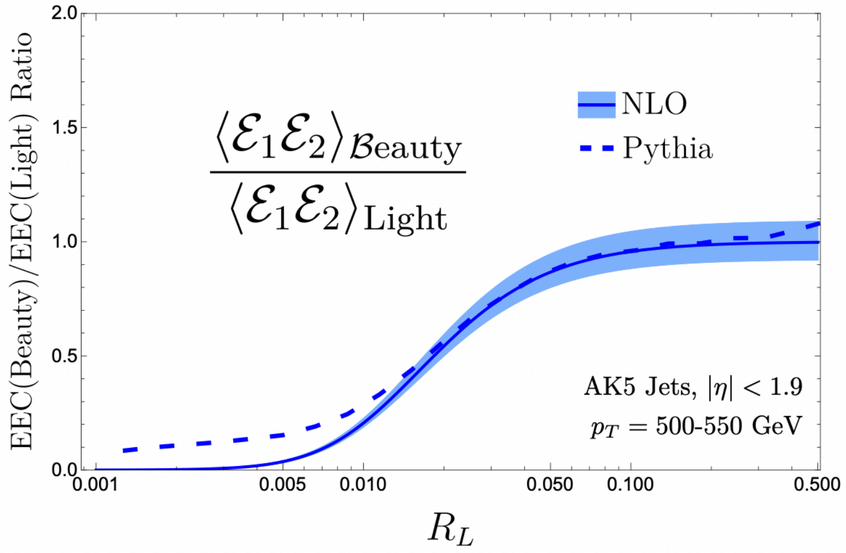
→ **can be directly measured at colliders**

$$\langle \mathscr{E}\,\mathscr{E}\rangle(\theta) = \int_0^1 dx\, x^2\, \vec{J}(\log\frac{zx^2Q^2}{\mu^2}, m, \mu)\cdot\vec{H}(x, \frac{Q^2}{\mu^2}, \mu)$$

- $$\frac{d\vec{H}(x,\frac{Q^2}{\mu^2},\mu)}{d\log\mu^2} = -\sum_j \int_x^1 P_{ij}(x/z,\alpha_s(\mu))\,\vec{H}(\frac{x}{y},\frac{Q^2}{\mu^2},\mu)\frac{dy}{y}$$

- $$\frac{d\,\vec{J}(\log\frac{zQ^2}{\mu^2},\mu)}{d\log\mu^2} = \sum_j \int_0^1 P_{ij}(y,\alpha_s(\mu))\,\vec{J}(\log\frac{zy^2Q^2}{\mu^2},\mu)\,y^2dy$$

EC, Moult, Lee, Mecaj




***dead cone*** ***effect in QCD***

**Explicit tests of QCD**

→ **SCET factorization**

→ **Renormalization Group Evolution**

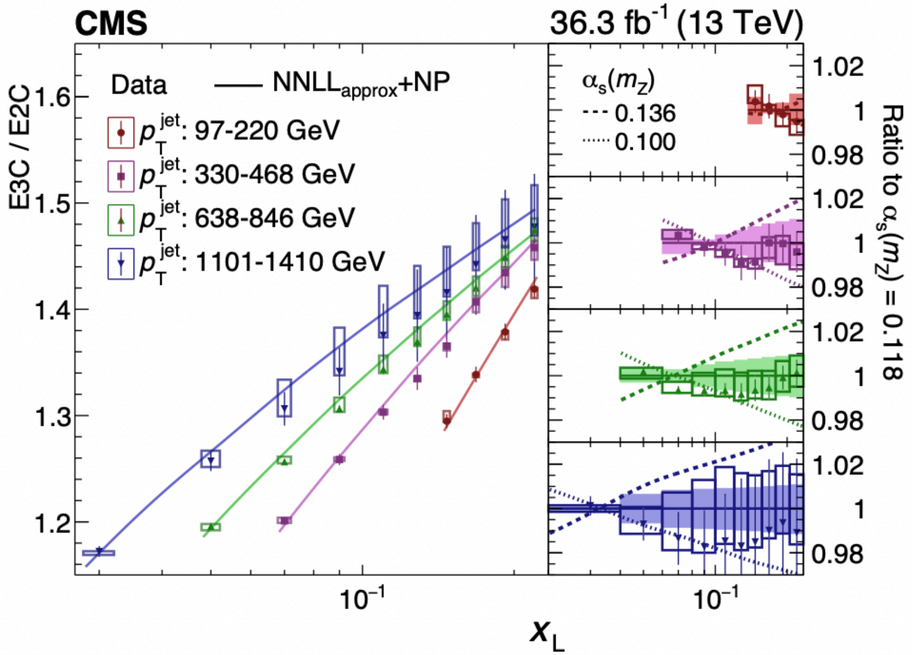
→ **Fragmentation**

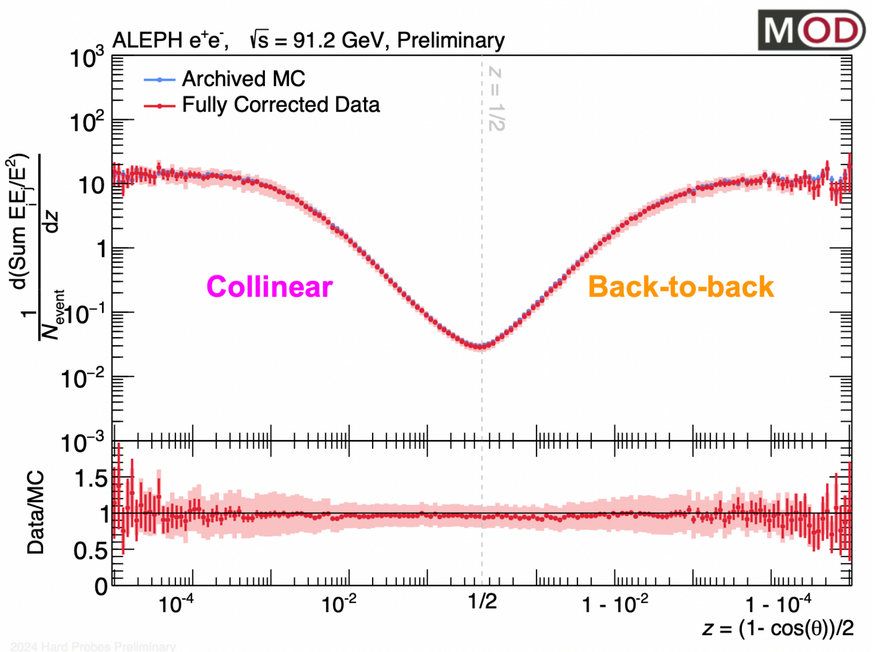

# Increasing the Precision and Accuracy of $\alpha_s$ extraction

## Among other things

"This is the ***most precise*** measurement of $\alpha_s(M_Z)$ by a jet substructure observable **to date**"

# New Data, New Opportunities




## CMS Measurement

**2022**

- **Massless Jets**
- **Collinear Regime**

## ALEPH Measurement

**Oct.**

- **Includes Heavy Hadrons**
- **Full Angular Resolution**

**H. Bossi, et. al**

# New Data, New Opportunities

***Collinear***

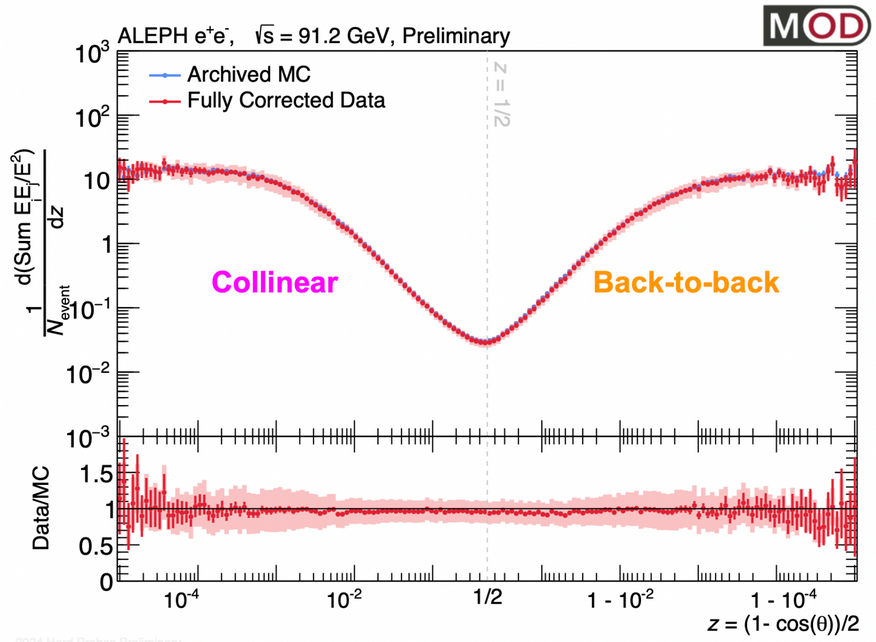
Increasing **precision** and **accuracy** of $\alpha_s$ extraction

***Central***

Fundamental tests of QCD and SCET **factorization**

***Back to Back***

Increasing **precision** and **accuracy** of $\alpha_s$ extraction




ALEPH Measurement

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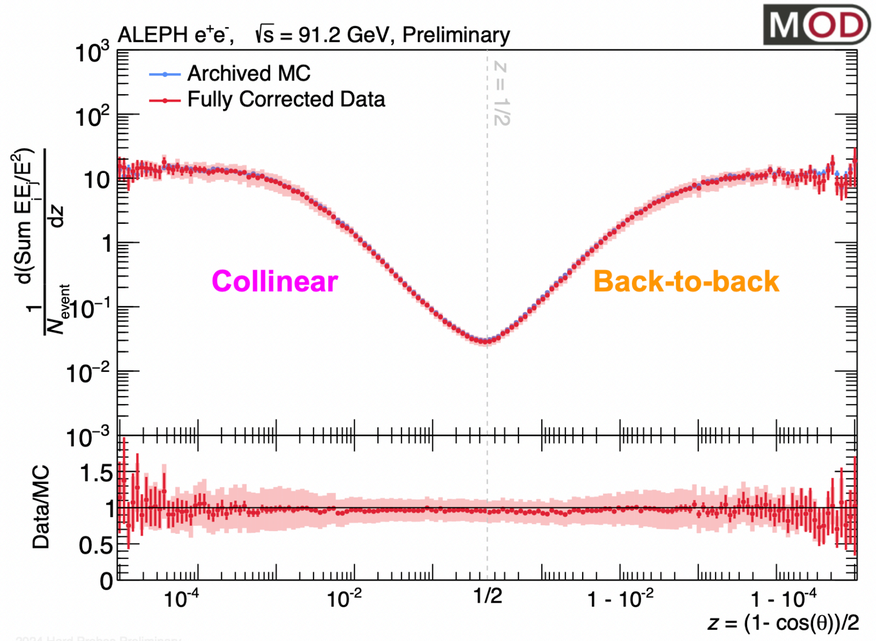


ALEPH Measurement

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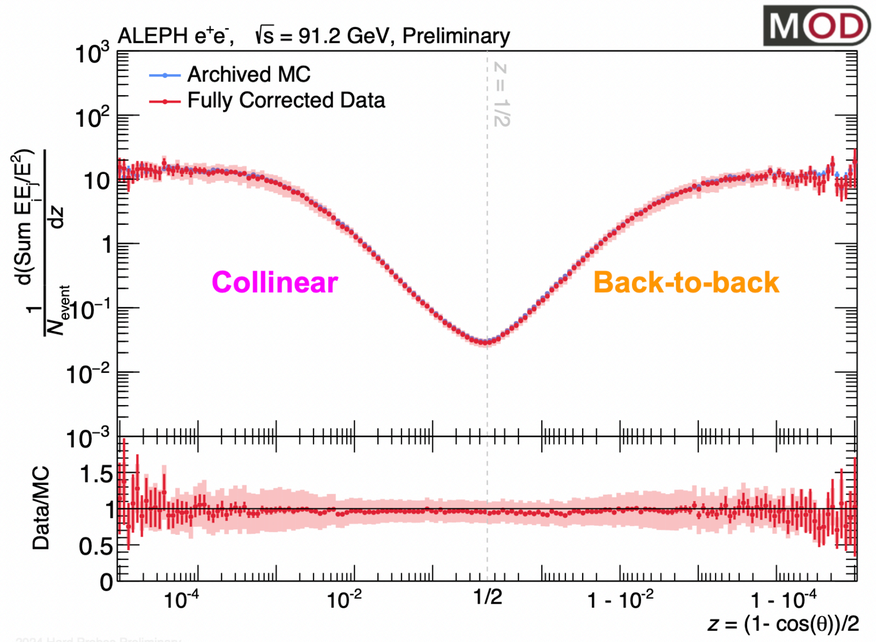



ALEPH Measurement

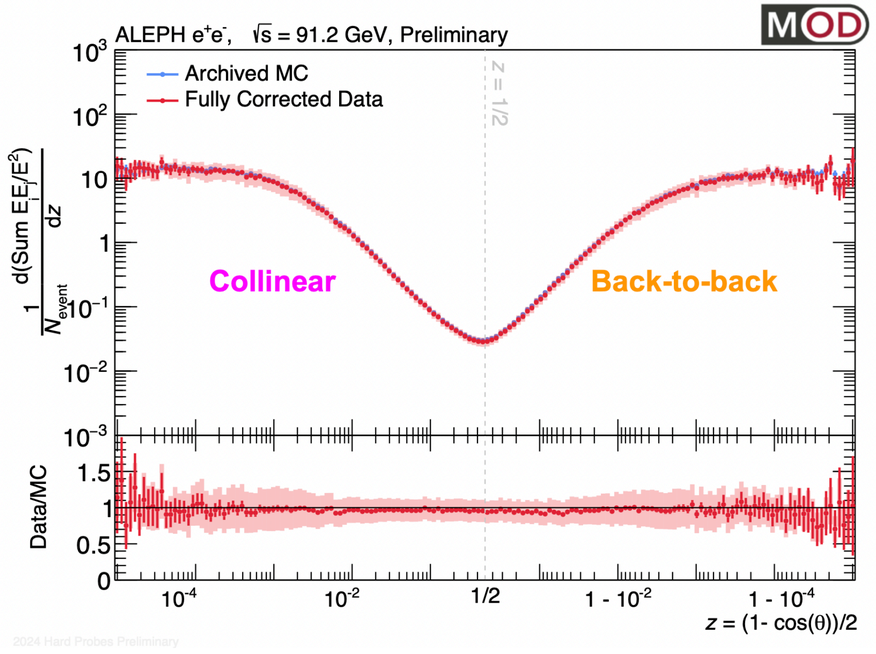
We have already focused on the collinear regime, so instead I move attention to the central and back to back.

# Full Angle Calculation

**Heavy flavor effects require new functions**

**Total Energy Correlator**

**Heavy and light effects mixed in**




$$\langle \mathcal{E}\,\mathcal{E}\rangle(\theta) = \int d^4x\, e^{iQx} \int d\Omega_{\hat{n}_1} \int d\Omega_{\hat{n}_2}\; \delta(\cos\theta - \cos\theta_{ij})$$
$$L_{\mu\nu} \times \langle 0\,|\,J^\mu(x)\,\mathcal{E}_{\hat{n}_1}\mathcal{E}_{\hat{n}_2}\,J^\nu(0)\,|\,0\rangle$$

**From a calculational perspective we get elliptic integrals**

$$\langle \mathcal{E}\,\mathcal{E}\rangle(\theta) \sim E(k) + F(k) + \sum_i \Pi(n_i, k)$$

**This class of functions does not appear in the massless case!**


# The Beauty and Charm Of *Summary Slides*

## The Bigger Picture

“What else can we learn from **energy correlators?**”

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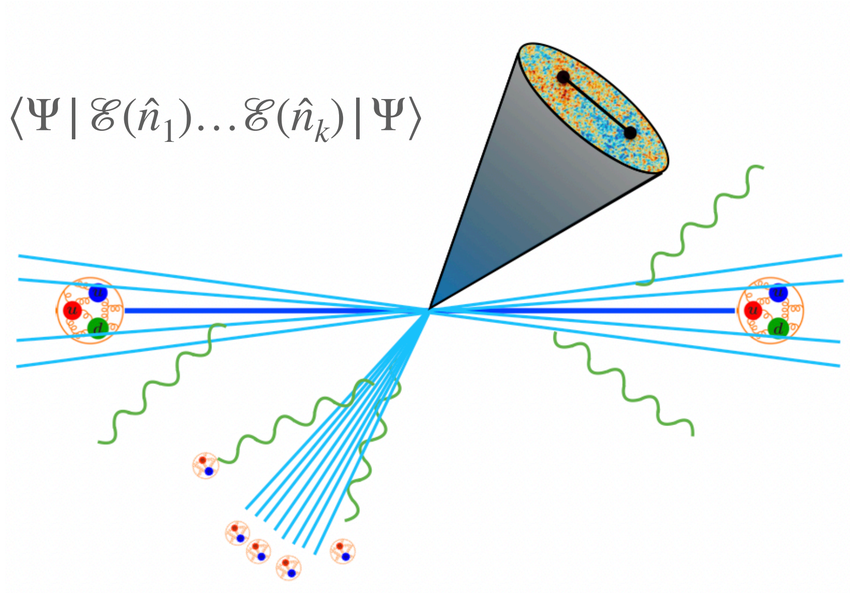


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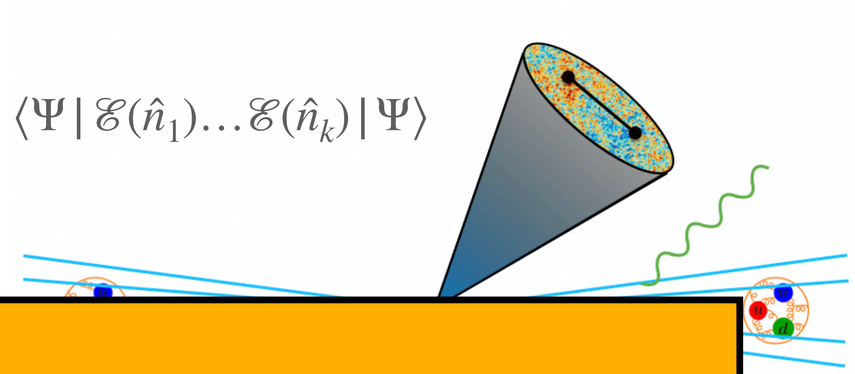


**Jet substructure can be given a *rigorous* and *formal* definition in terms of energy flow operators**

$$\mathcal{E}(\vec{n}) =$$

**Excellent *test* of SCET factorization**

→ theoretic

→ can define and measure correlation functions

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