Energy Correlators, Heavy Flavor, & Precision QCD

Evan Craft — Yale University

DPF-Pheno 2024




Based on work with K. Lee, B. Mecaj, I. Moult, & M. Gonzalez

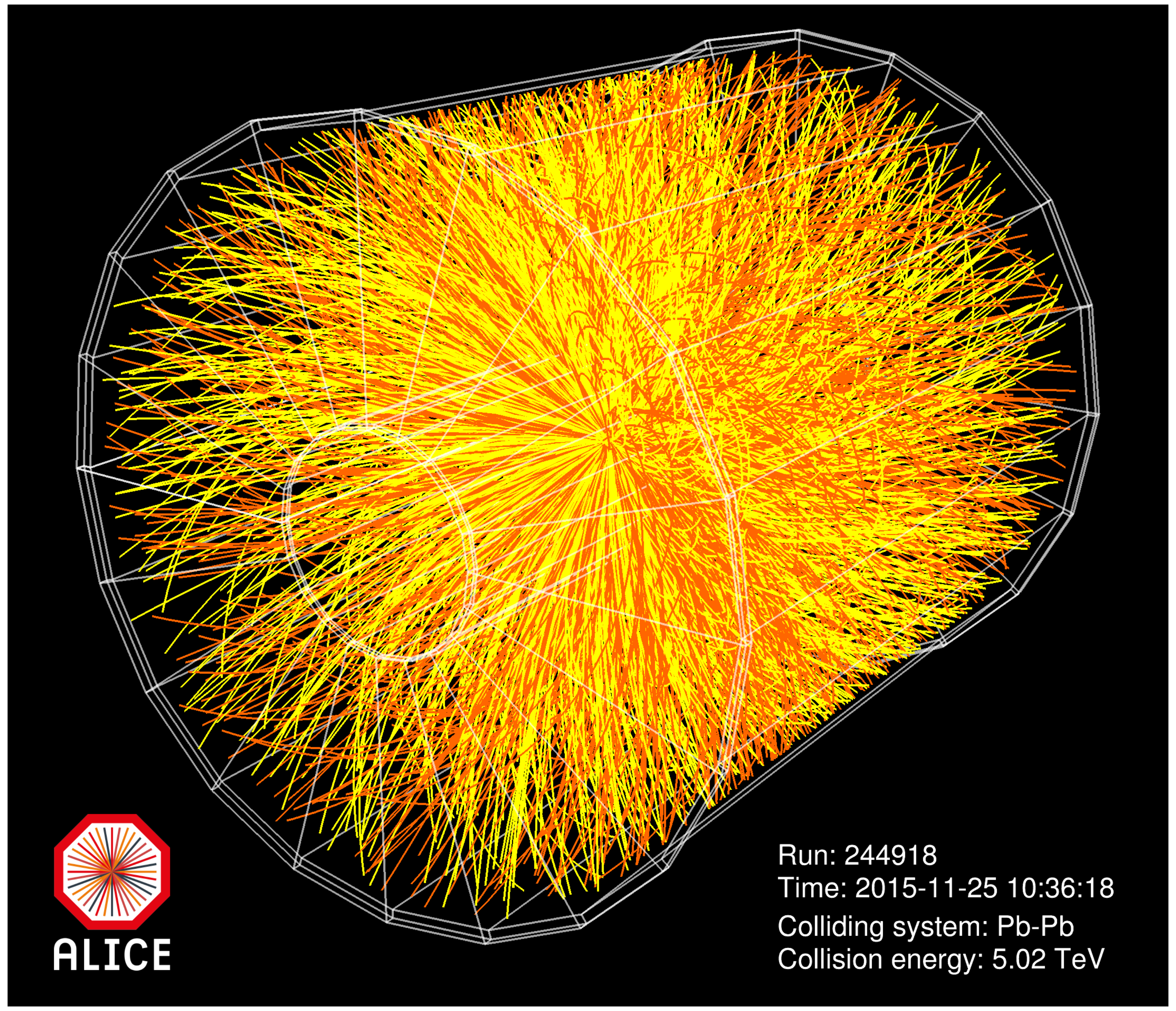
Yale University

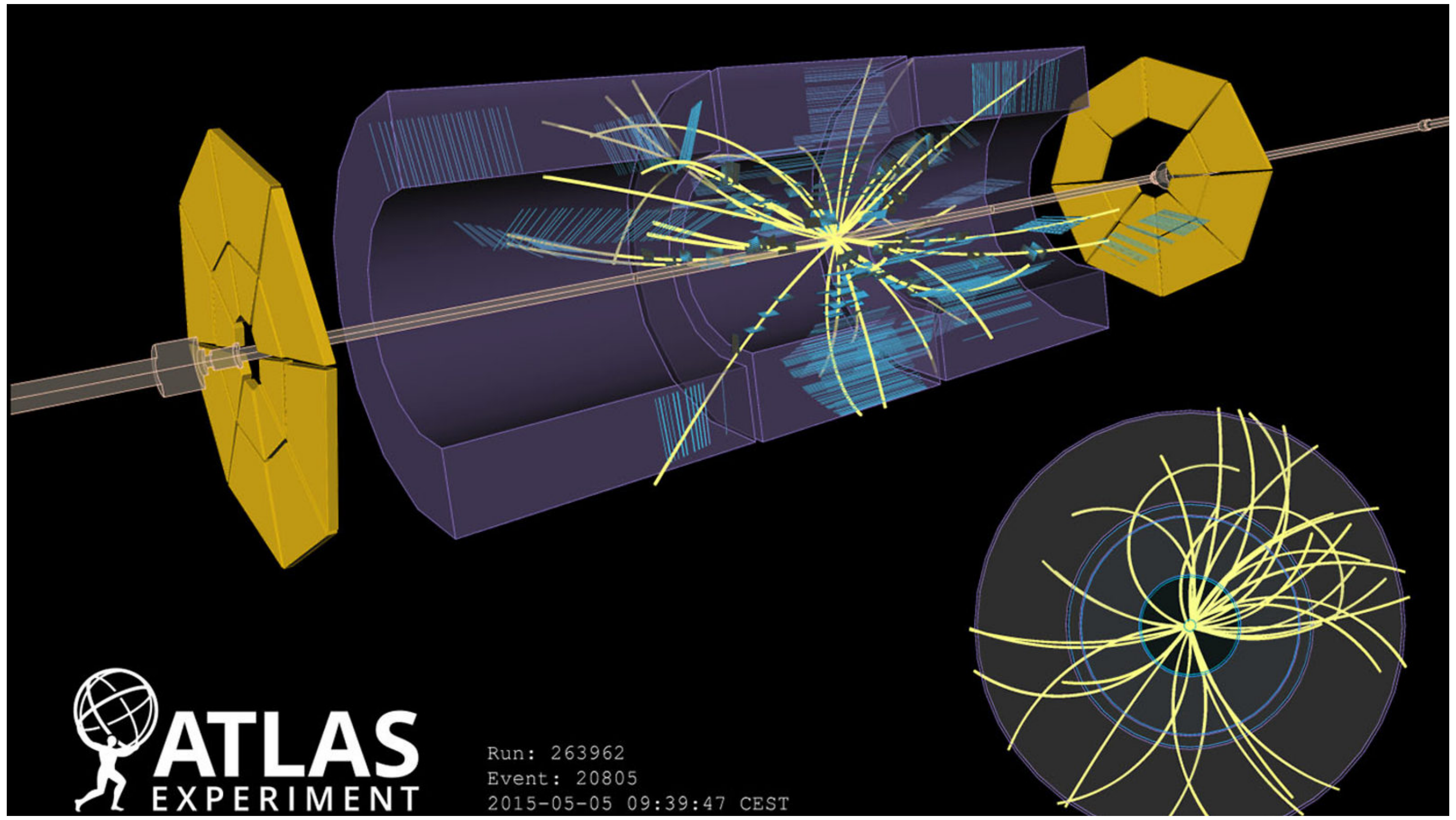
MIT

Collider Experiments

Many important questions have been addressed at collider experiments

→ Great historical success in verifying properties of the standard model





→ But the detailed structure of QCD produces immensely complicated datasets.

→ Need new tools for future success

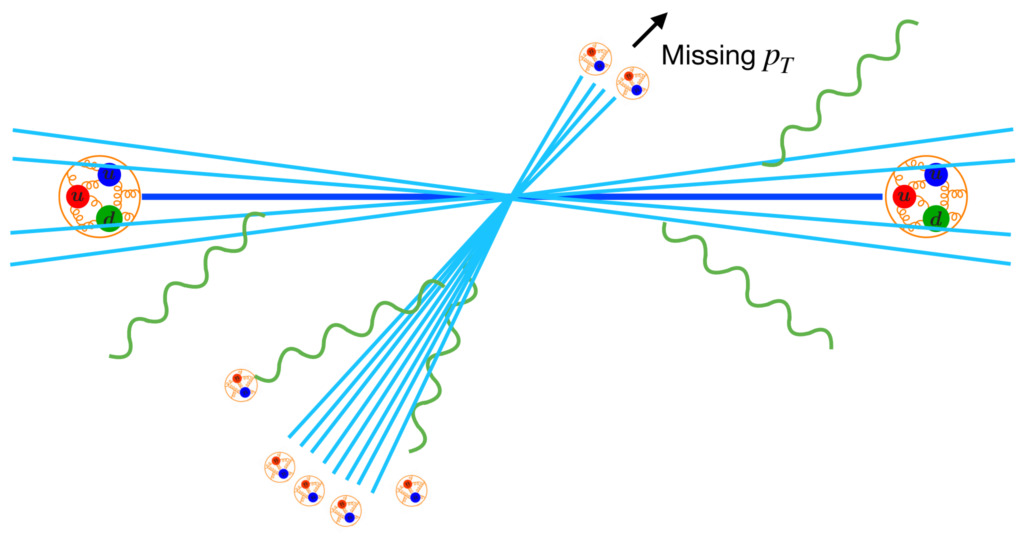
A unique frontier for novel collaborations between both theory and experiment

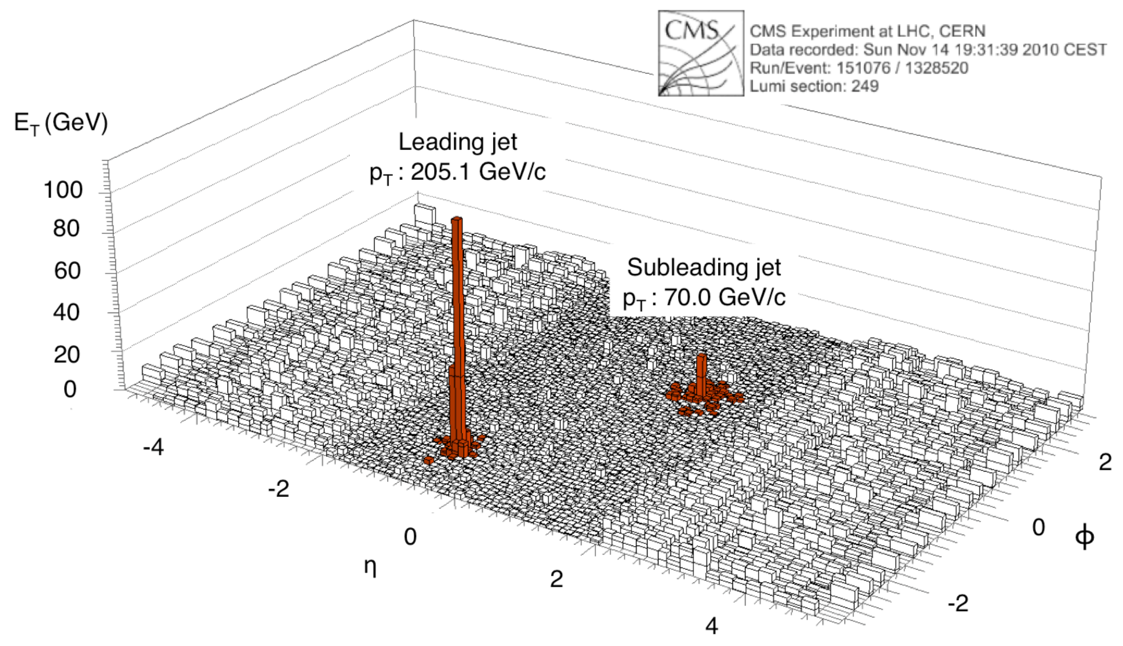
How do we study collisions?

Along with **many** more exciting observations!

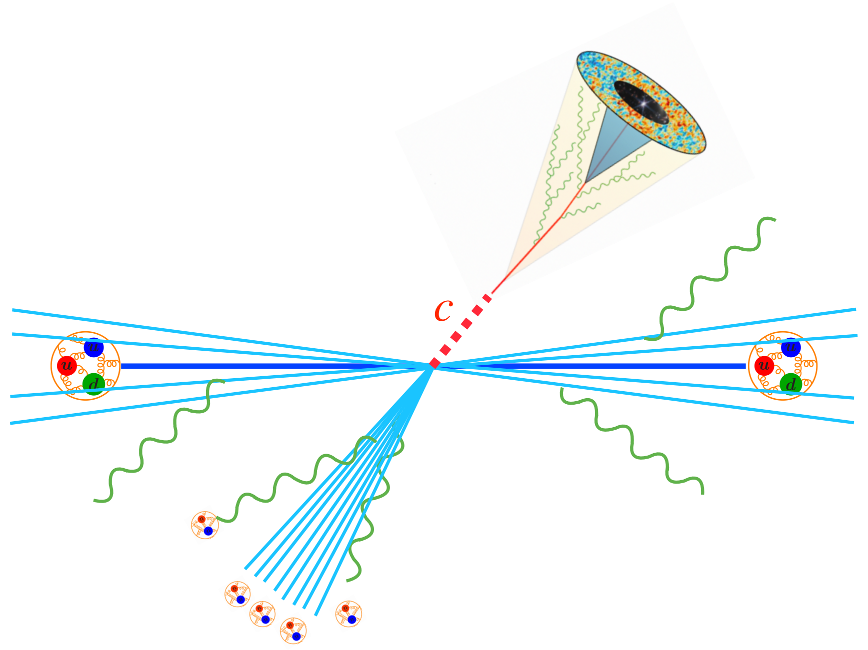
Several remarkable observations made by studying **jets**

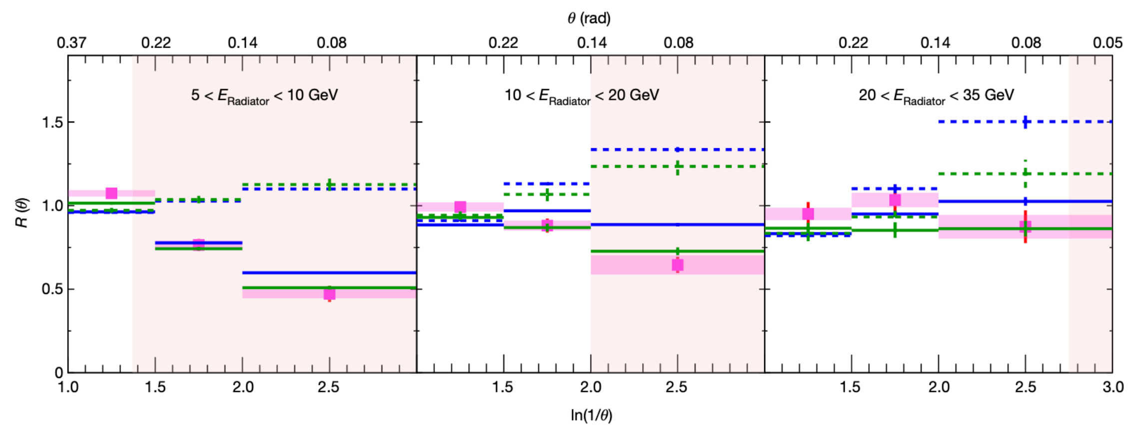
→ provided initial evidence for the **existence** of the Quark Gluon Plasma



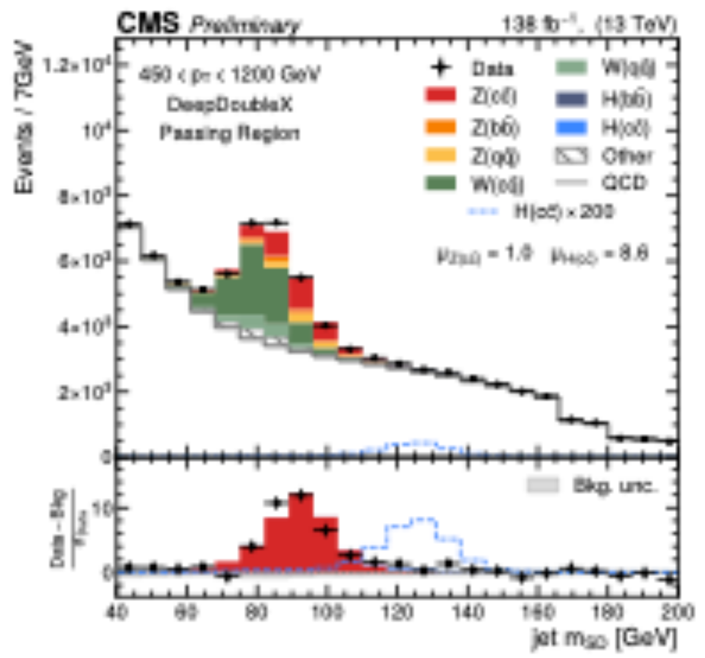


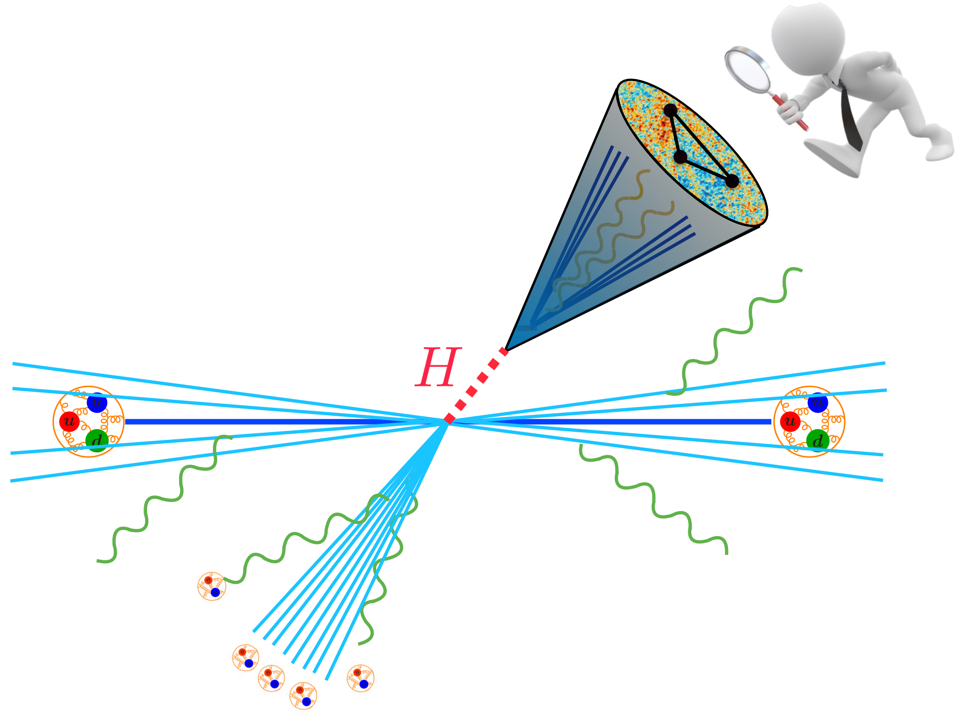
→ allowed first ever observation of the **"dead cone"** effect of QCD





→ provides the most stringent bounds on **charm** Yukawa couplings

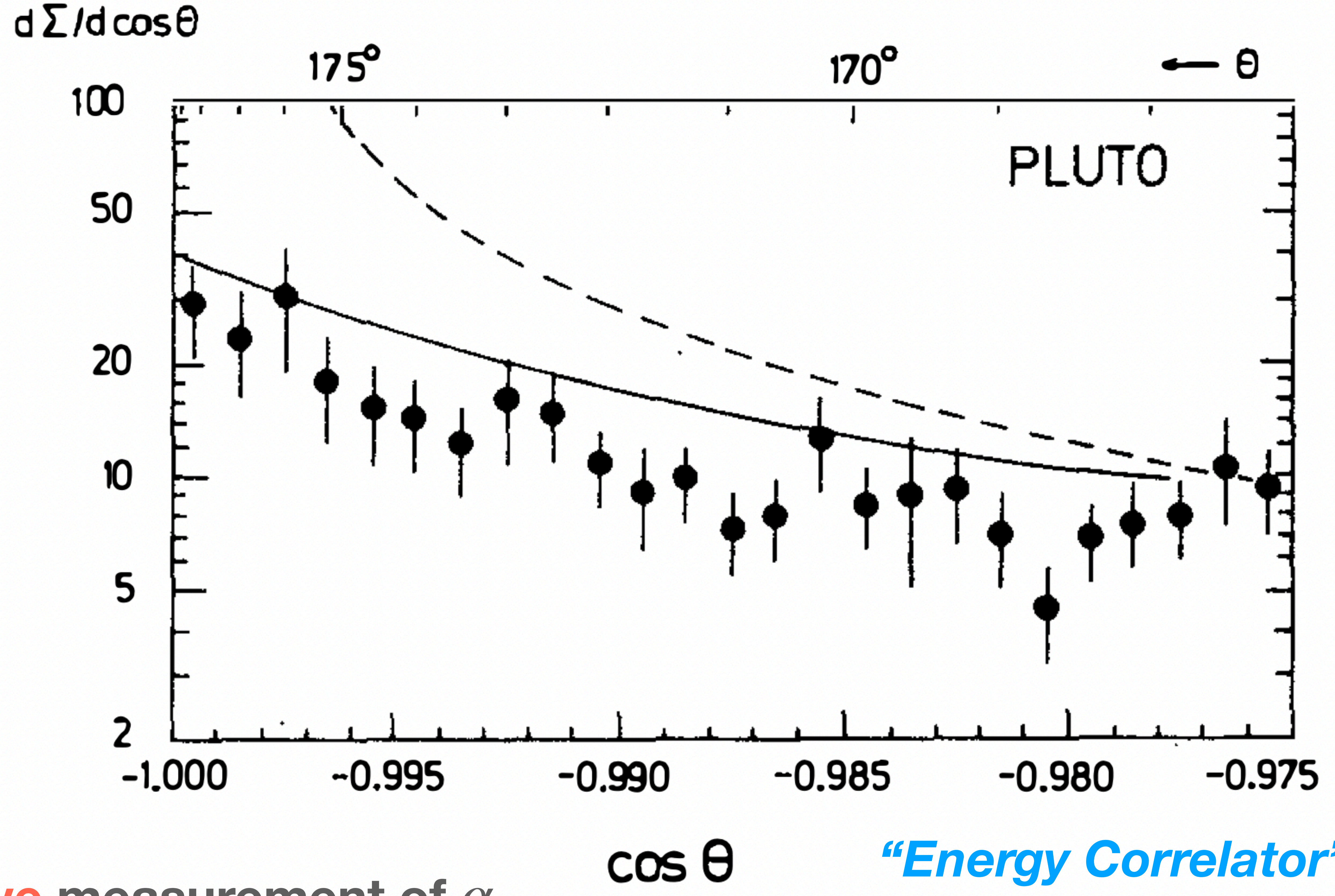




How do we study collisions?

[Basham, Ellis, Love, Brown]

$$\mathrm{EEC}(\chi) = \frac{1}{\Delta\chi\, N} \int_{\chi-\Delta\chi/2}^{\chi+\Delta\chi/2} \sum_{\text{events}}^{N} \sum_{i,j} \frac{E_i E_j}{E_{\text{vis}}^2}\, \delta(\chi' - \chi_{ij})\, d\chi'$$



→ First introduced **EEC** as experimental observable **sensitive** to α_s (1978)

→ Measured in e^+e^- by **PLUTO** (1978)

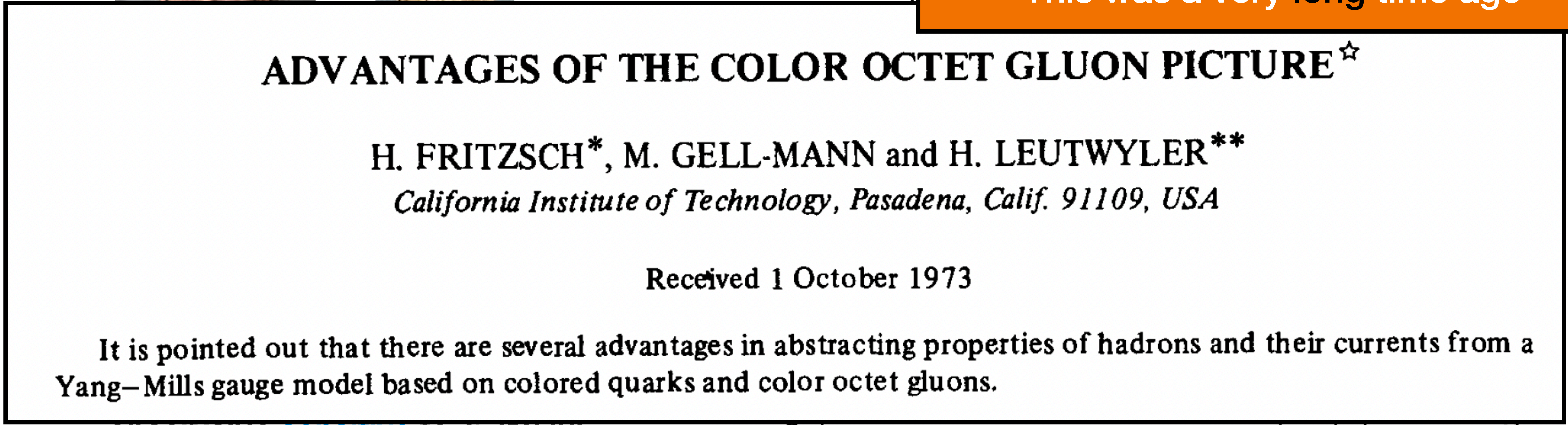
"Energy Correlator" (EEC)

Provided an **impressive** measurement of α_s

How do we study collisions?

$$\mathrm{EEC}(\chi) = \ldots$$

"This was a very long time ago"



ADVANTAGES OF THE COLOR OCTET GLUON PICTURE ☆

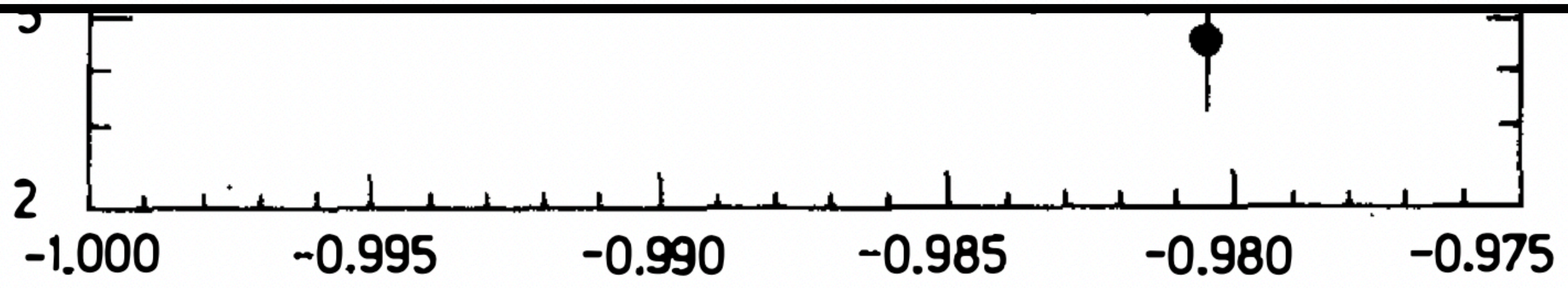
H. FRITZSCH*, M. GELL-MANN and H. LEUTWYLER**
California Institute of Technology, Pasadena, Calif. 91109, USA

Received 1 October 1973

It is pointed out that there are several advantages in abstracting properties of hadrons and their currents from a Yang–Mills gauge model based on colored quarks and color octet gluons.

observable **sensitive** to α_s (1978)

→ Measured in e^+e^- by **PLUTO** (1978)



"Energy Correlator" (EEC)

Provided an **impressive** measurement of α_s

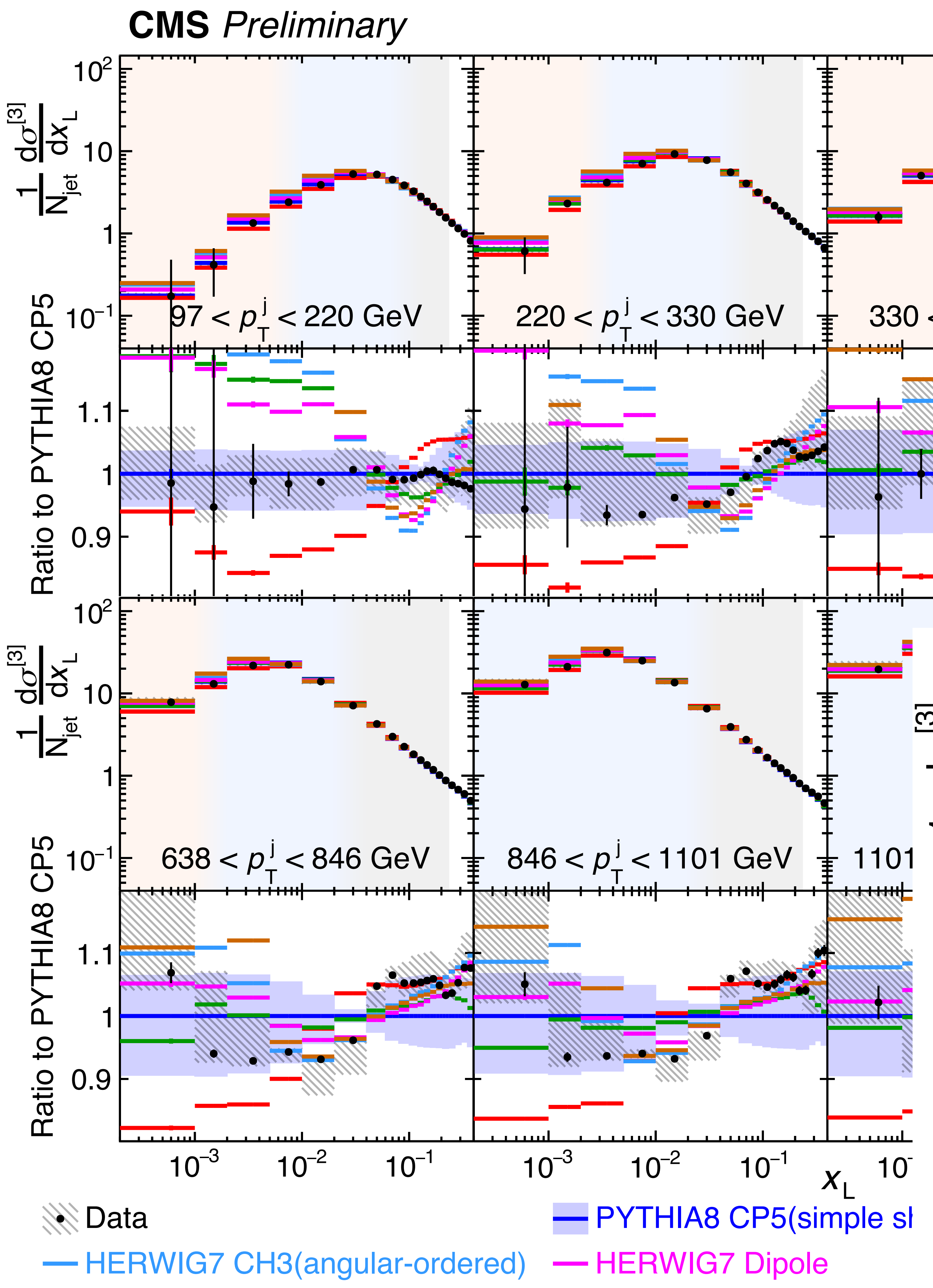
The EEC in 2024

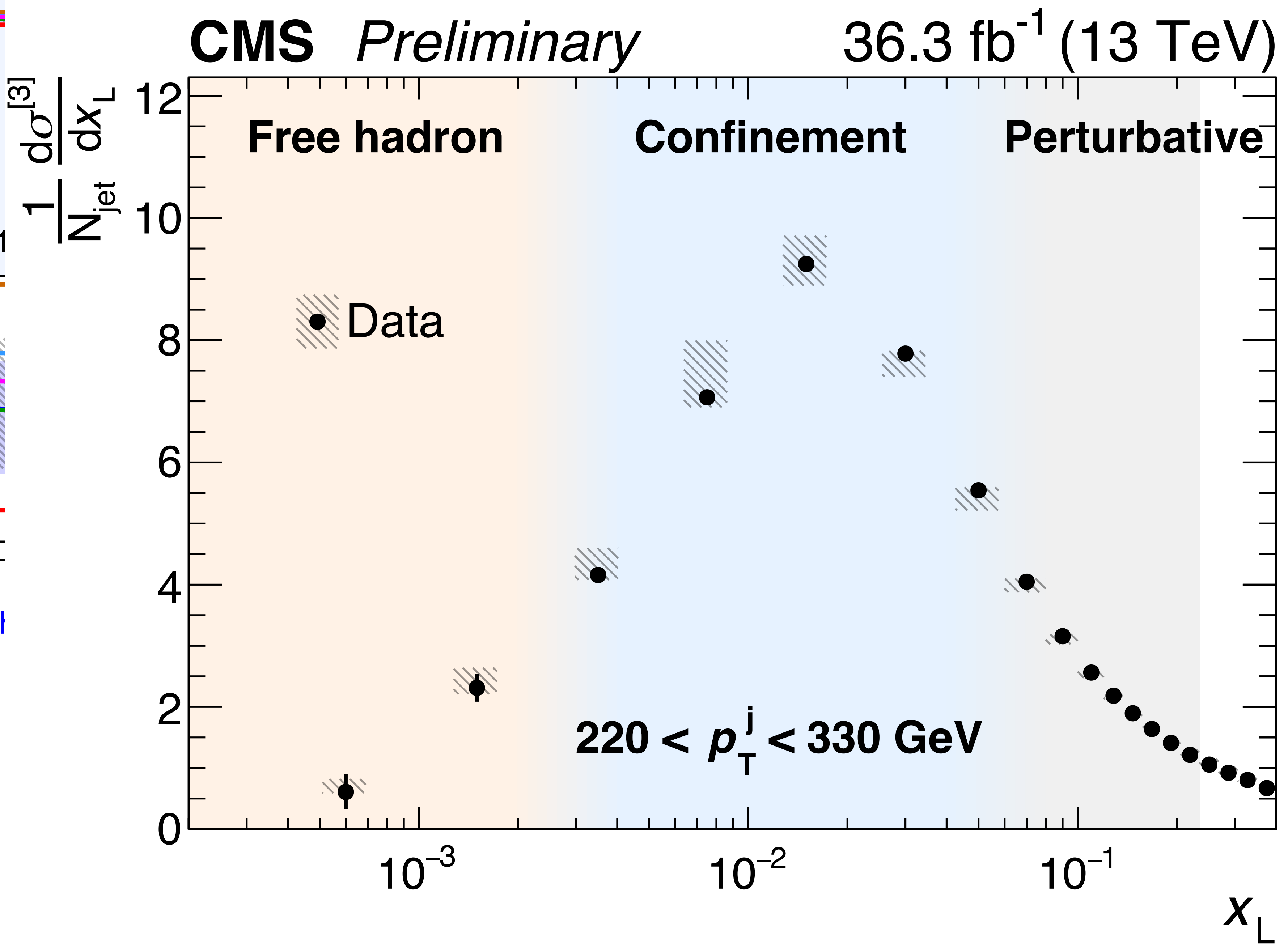
"Energy Correlator" (EEC)

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

Quote taken *directly* from:

CMS Collaboration, 2024





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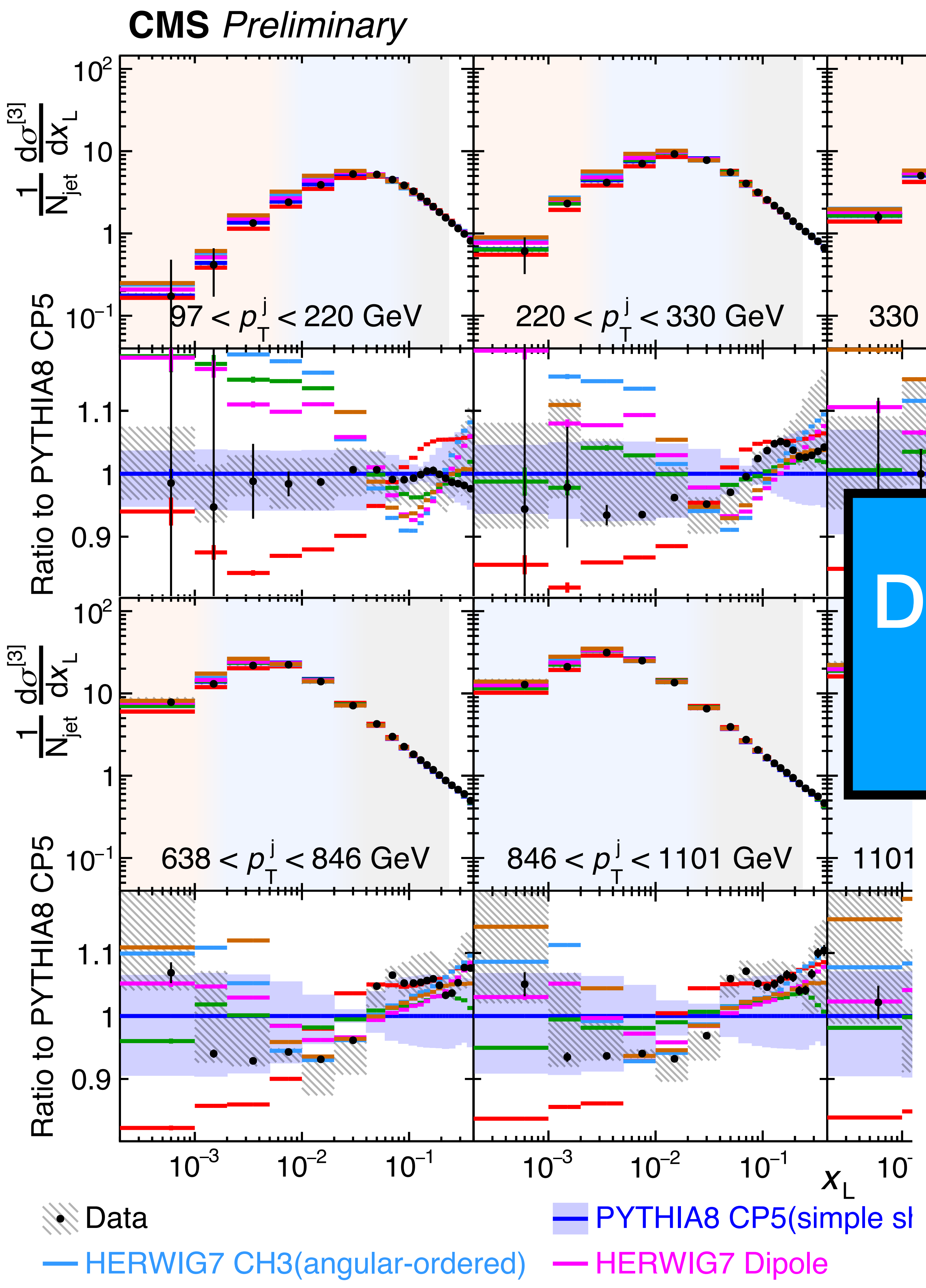
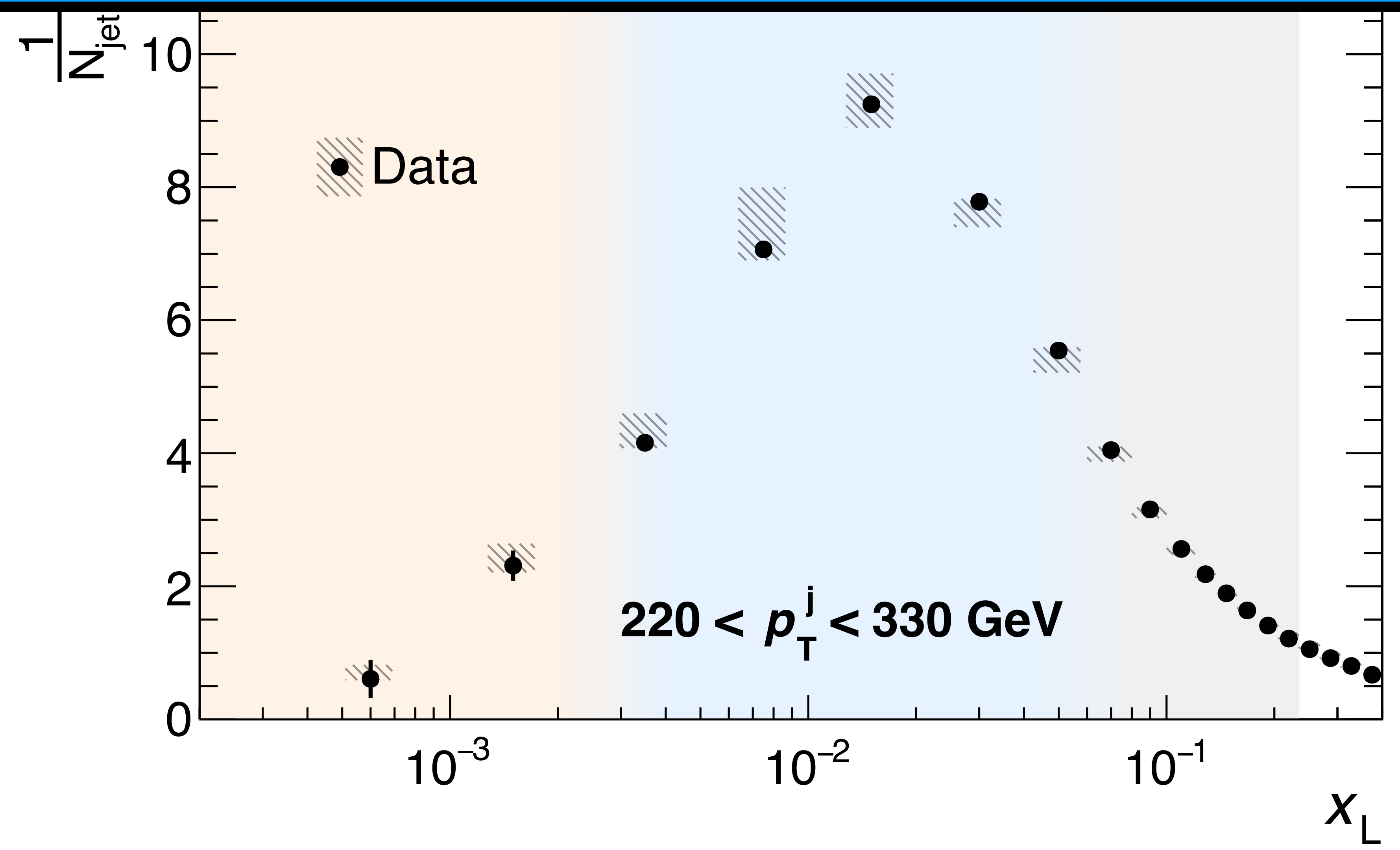


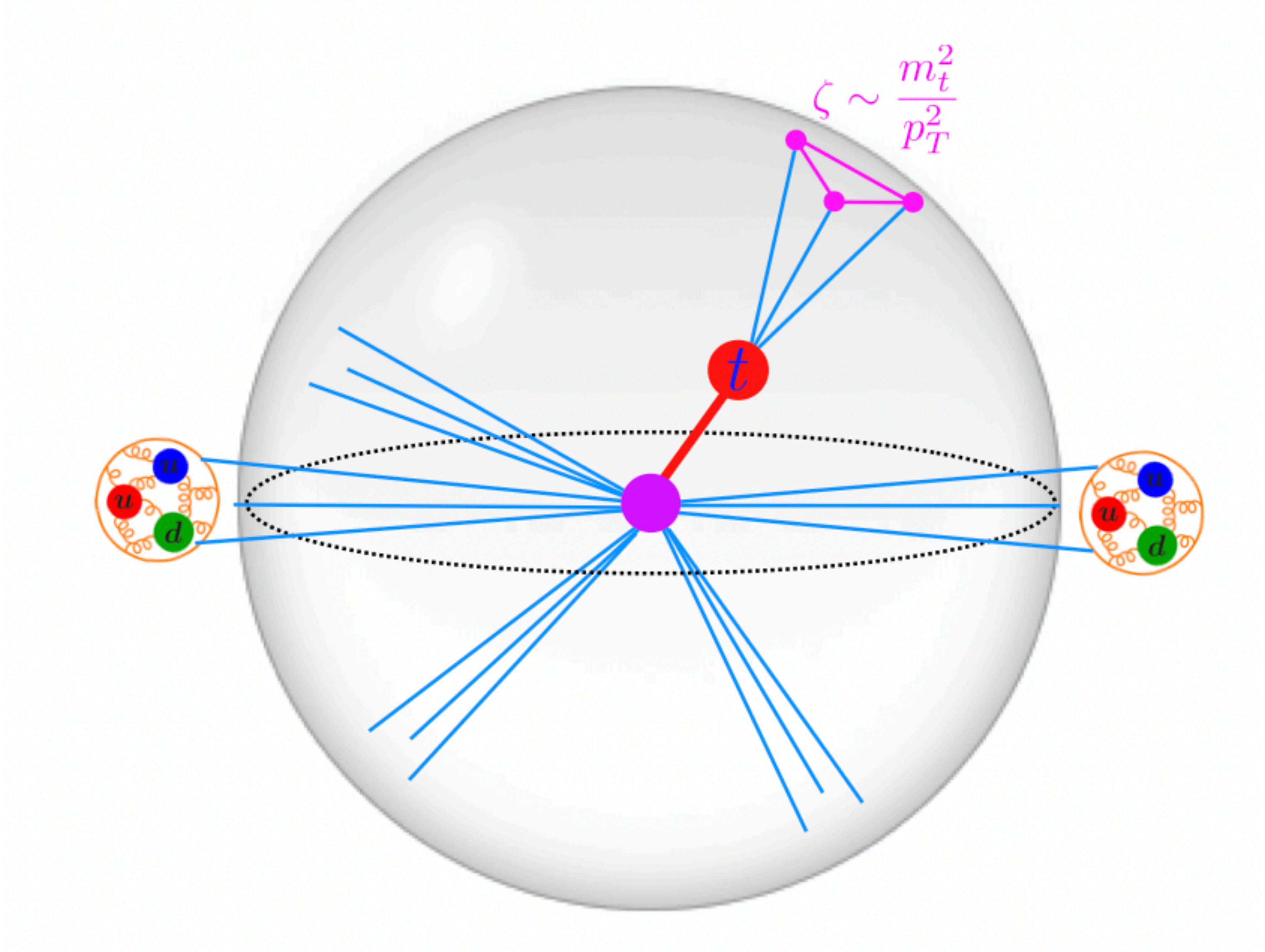
Direct result of **powerful** advances in both **theory** and **experiment** (unfolding, SCET, etc.)

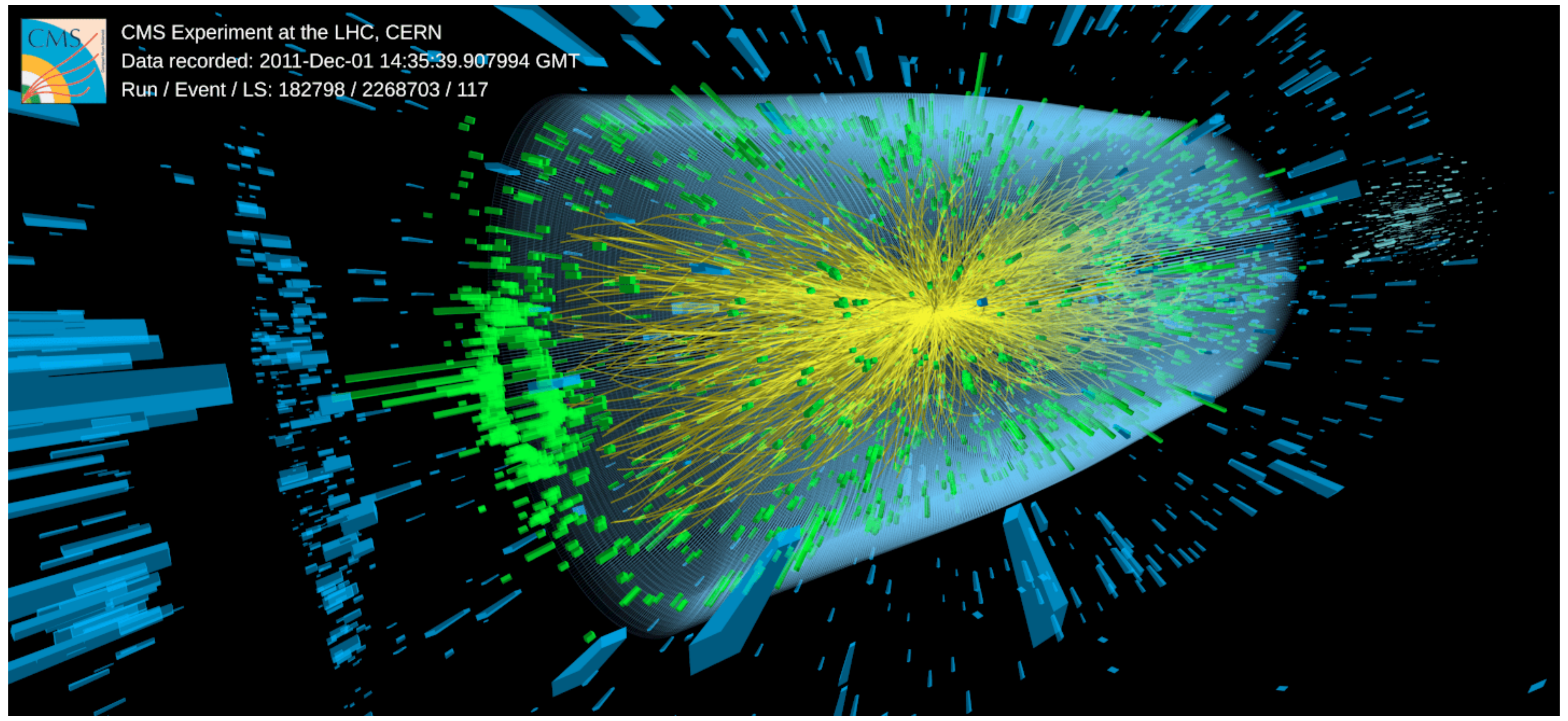


From Searches to Measurements

To fully take advantage of the LHC, it is necessary to bolster our current physics searches with first principles theory calculations

→ Many interesting opportunities to study QCD at high energies: understanding confinement, precision measurements, α_s, m_t ...





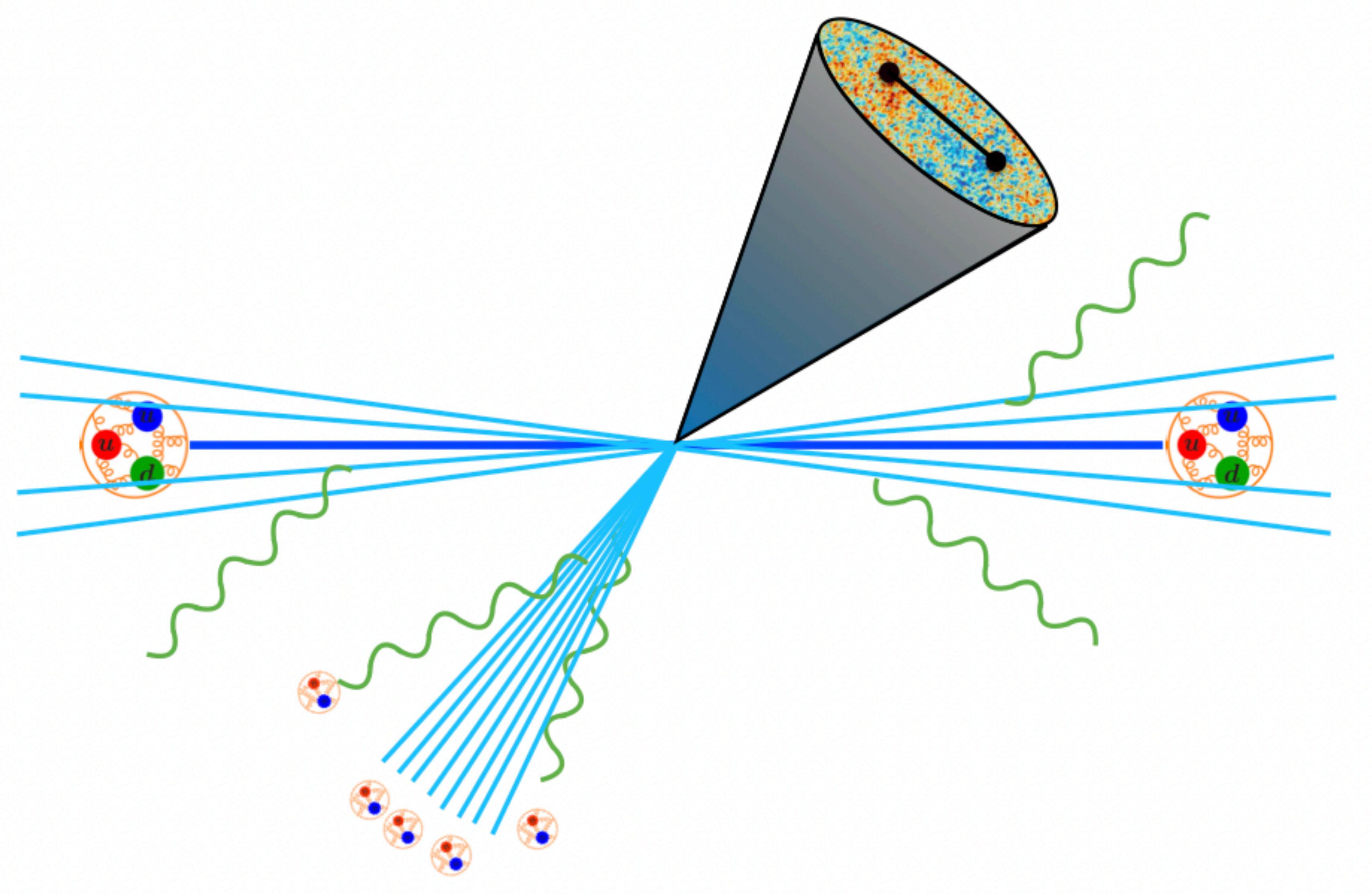
Requires the development of a new set of theoretical tools

Reformulating Jet Substructure

Field Theoretic Foundations

Energy Flow Operators

From the perspective of QFT, jet substructure is the study of correlation functions of energy flow operators



$$\mathcal{E}(\vec{n}) = \lim_{t\to\infty} t^3 \int_0^1 dv\, v^2 \left[n^i T_i^0(t, tv\,\vec{n}) \right]$$

Sveshnikov, Tkachov (1995)

→ ***"Energy Flow Operator"***

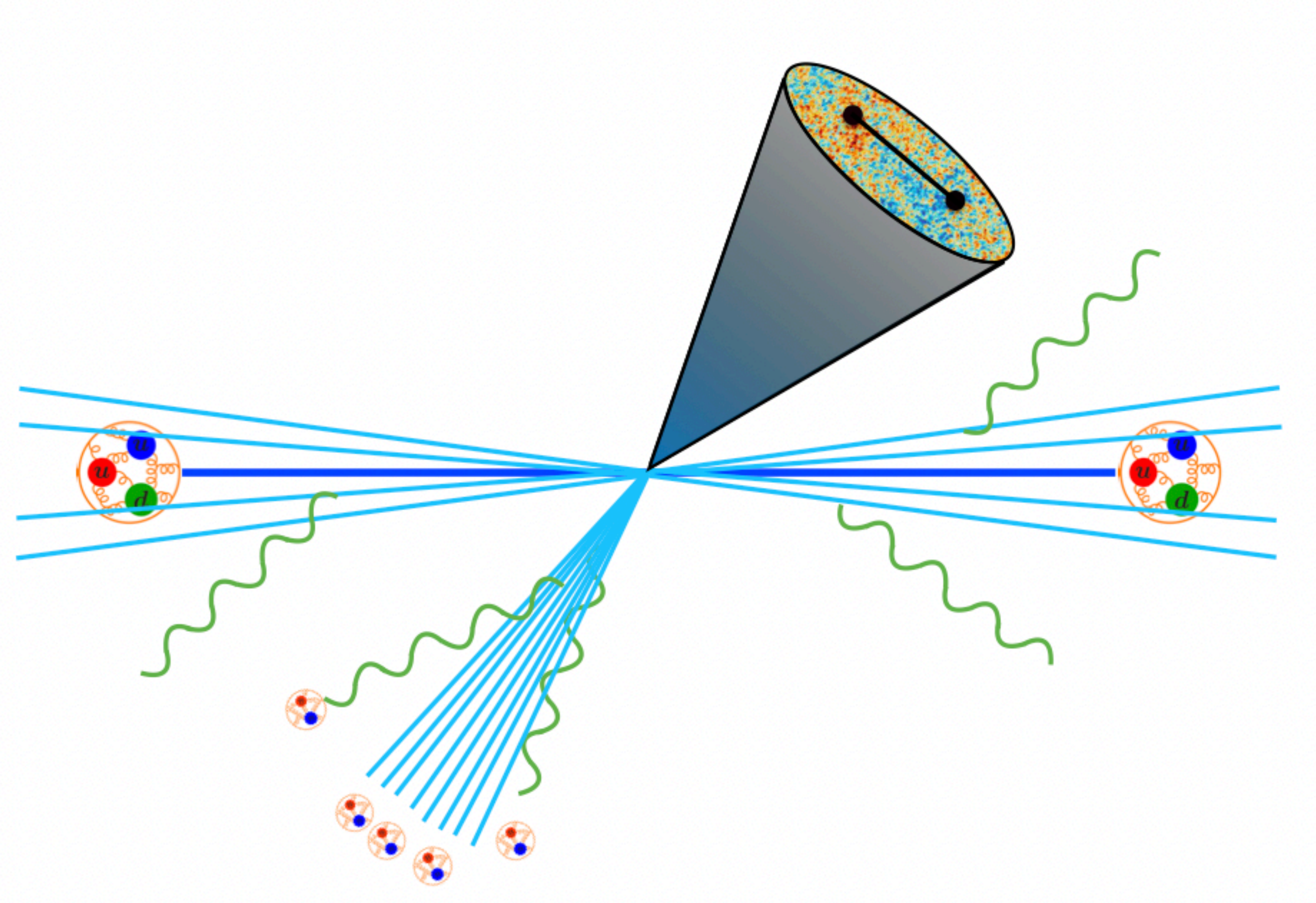
$$\langle \Psi \,|\, \mathcal{E}(\hat{n}_1) \ldots \mathcal{E}(\hat{n}_k) \,|\, \Psi \rangle$$

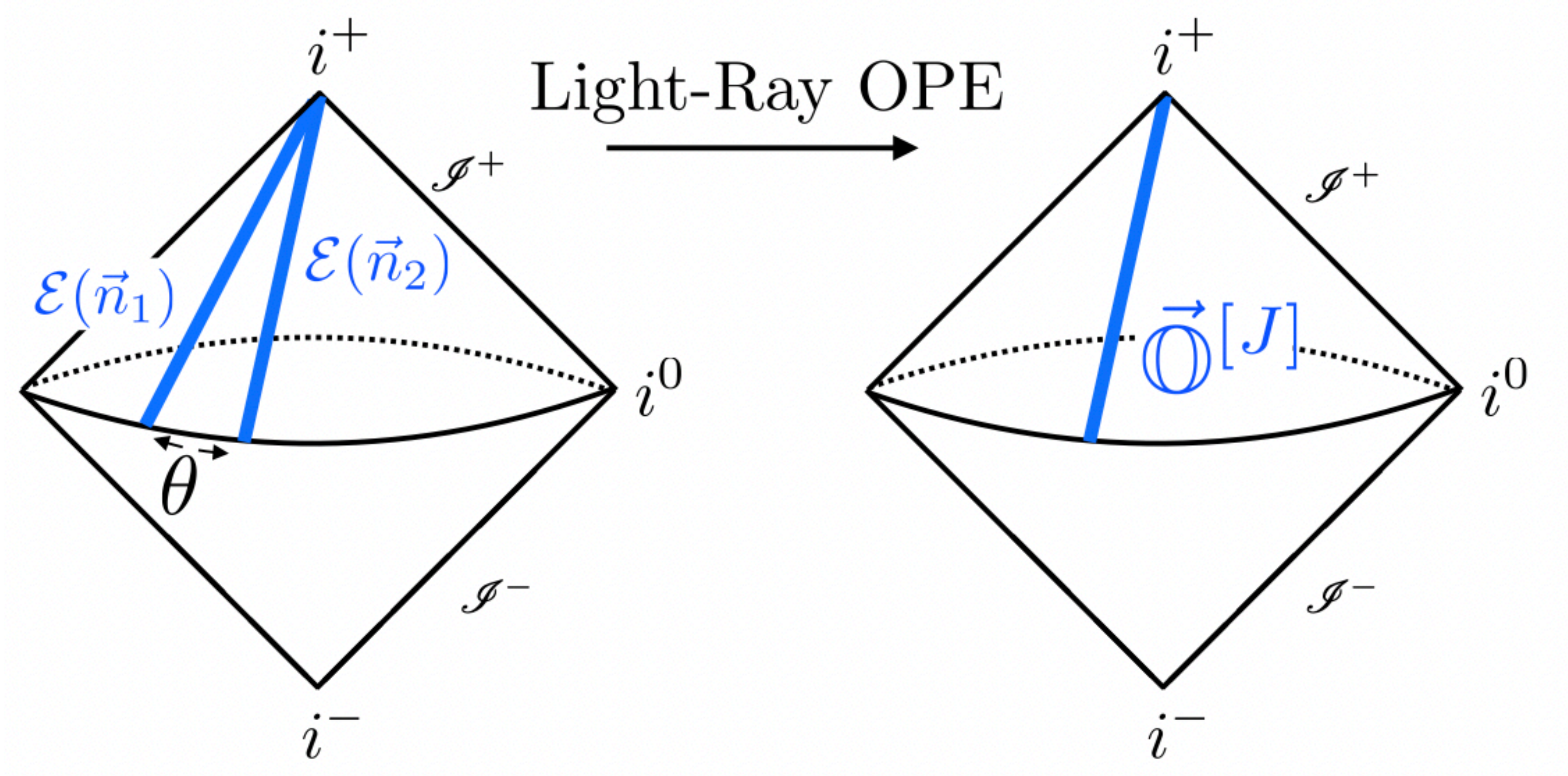
→ ***"Statistical Correlations"***

These correlation functions measure the flow of energy at infinity.

Energy Flow Operators

Situations of interest at the LHC involve non-generic configurations of lightray operators: interested in the small angle (OPE) limit.



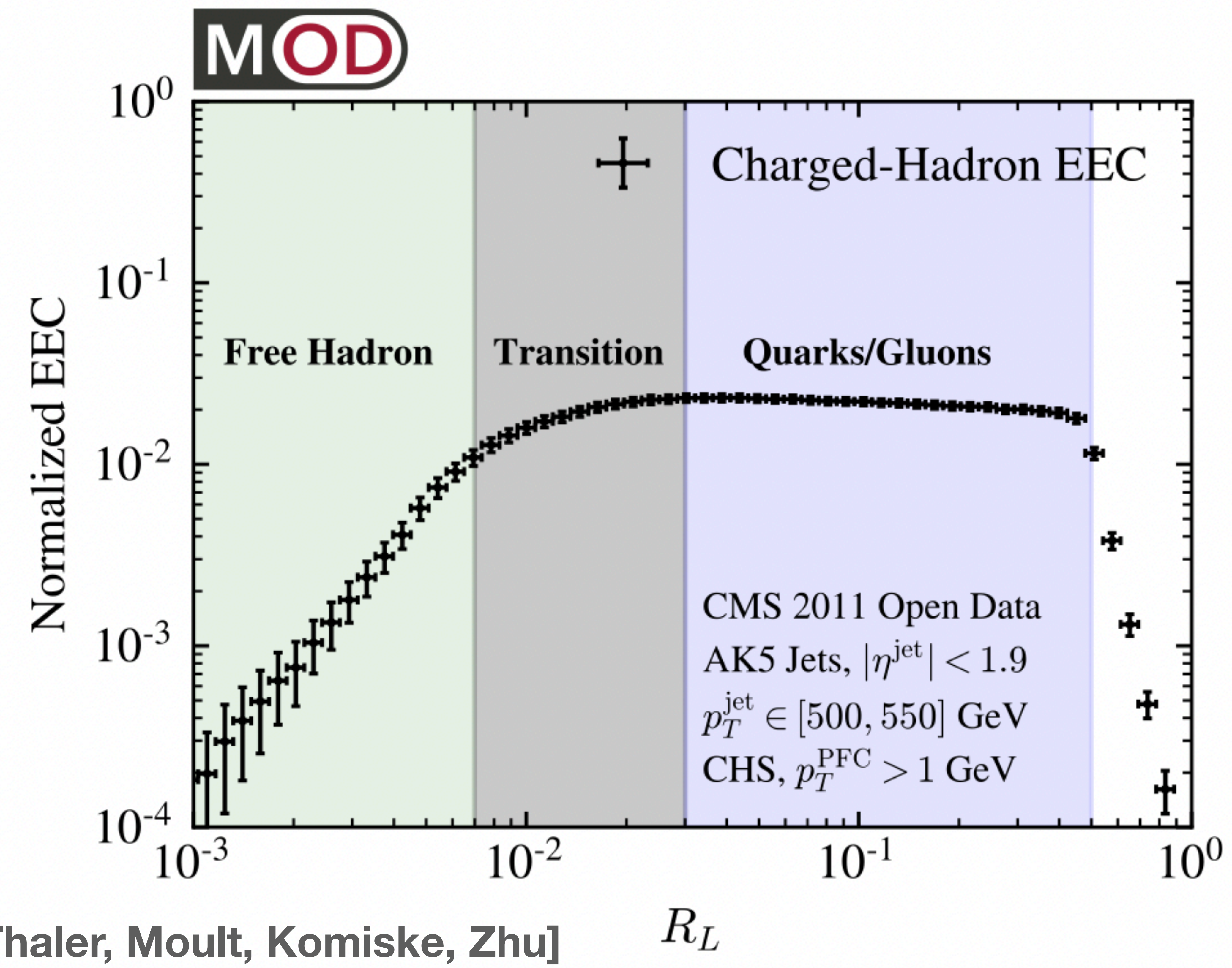


$$\mathscr{E}(\hat{n}_1)\mathscr{E}(\hat{n}_2) \sim \sum_i \theta^{\tau_i - 4}\, \mathbb{O}_i(\hat{n}_1)$$

[Hofman, Maldacena]

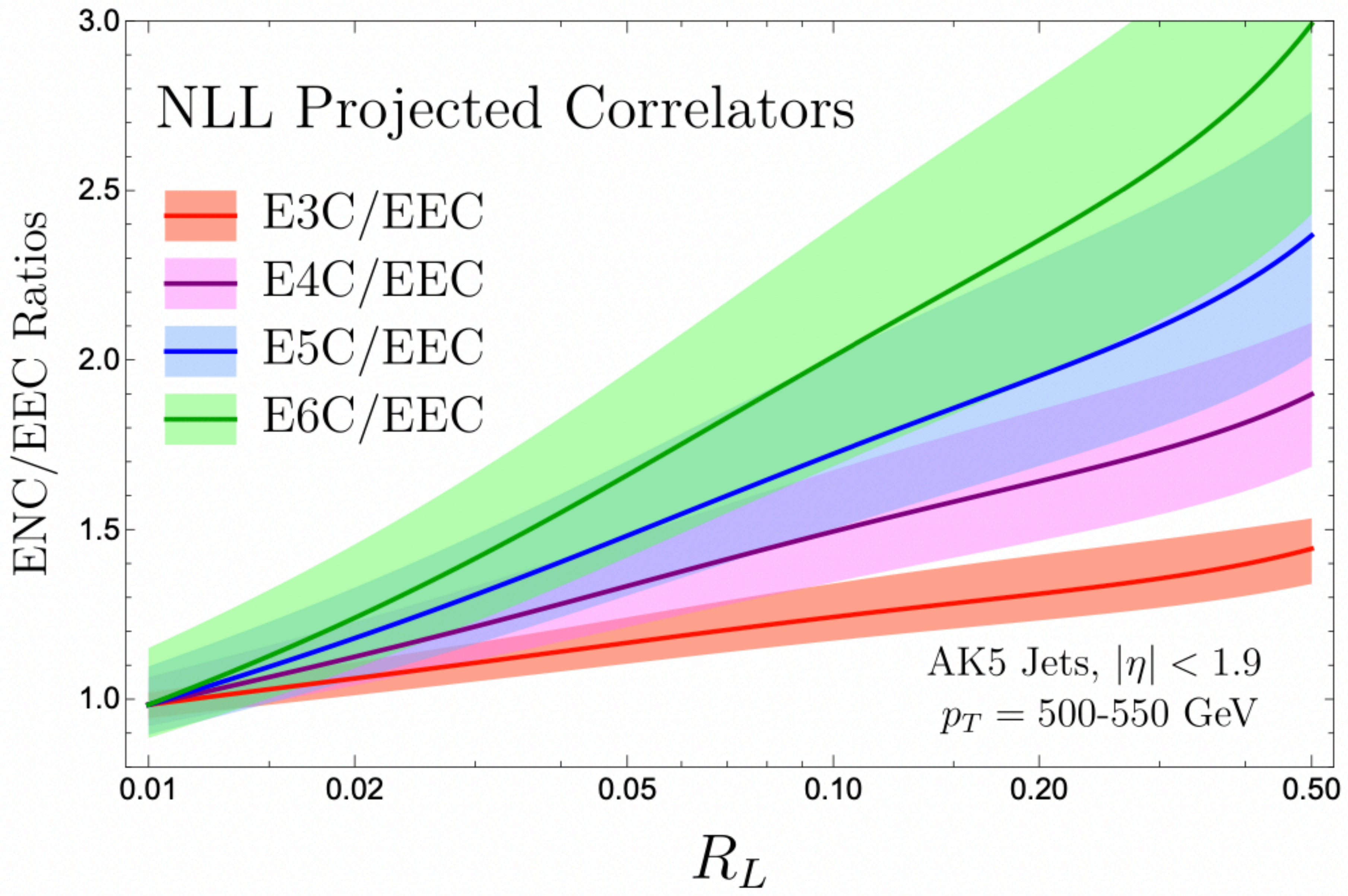
In the small angle limit, these lightray operators should exhibit the universal behavior of QCD

Energy Flow Operators



[Thaler, Moult, Komiske, Zhu]

[Moult, Mecaj, Lee]



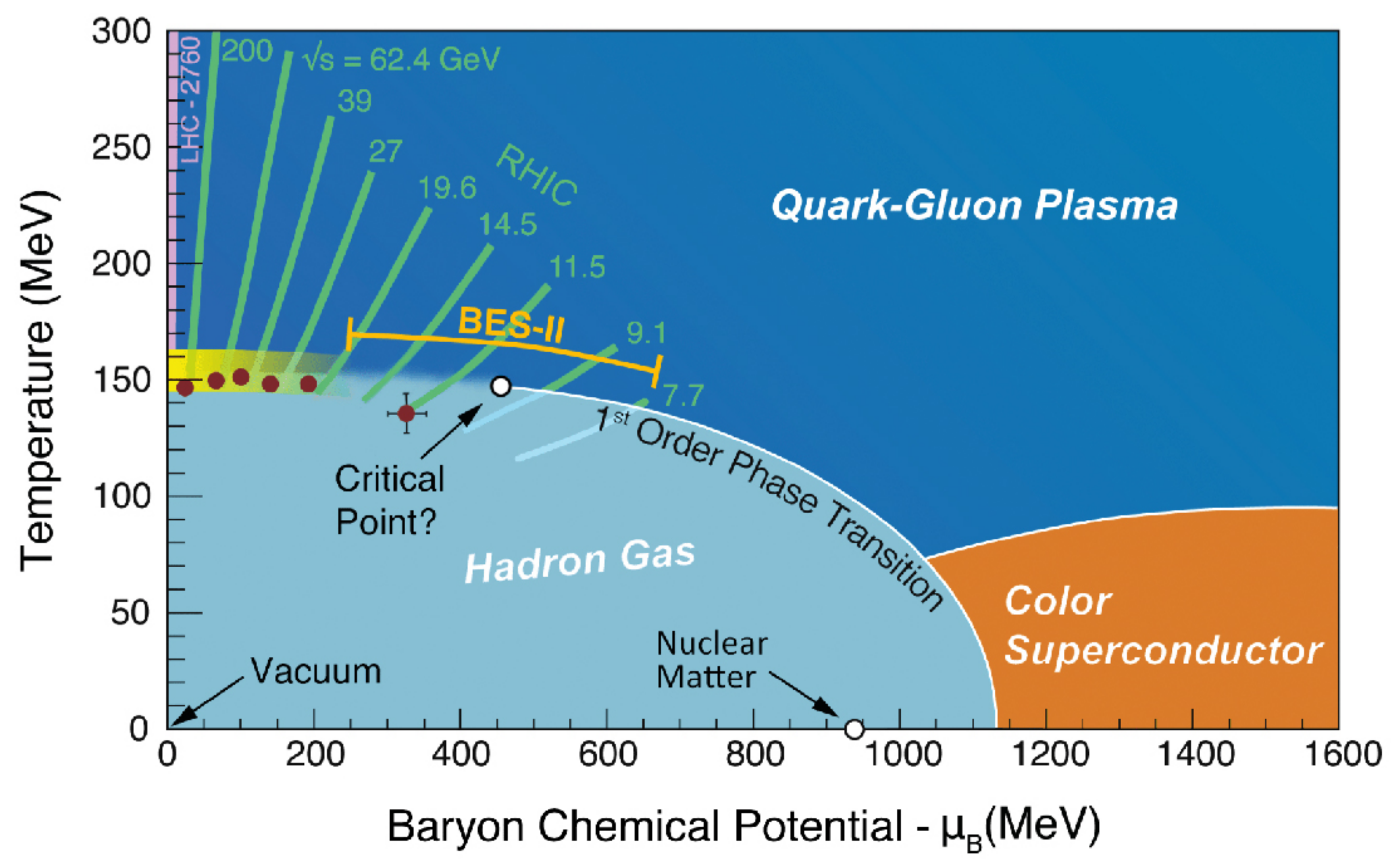
$$\mathscr{E}(\hat{n}_1)\mathscr{E}(\hat{n}_2) \sim \sum_i \theta^{\tau_i - 4}\, \mathbb{O}_i(\hat{n}_1)$$

It is precisely this scaling behaviour which allows for such precise measurements of $\alpha_s(M_Z)$

Going Beyond $\alpha_s(M_Z)$

Several open questions remain across both Particle and Nuclear Physics

→ Many of these open problems are deeply connected to Quantum Chromodynamics



→ Why is color charge so complicated?

Hot QCD

→ Quark Gluon Plasma

→ Hadronization

→ Quarkonia

Medium QCD

→ Strong CP

→ Rare Higgs Decays

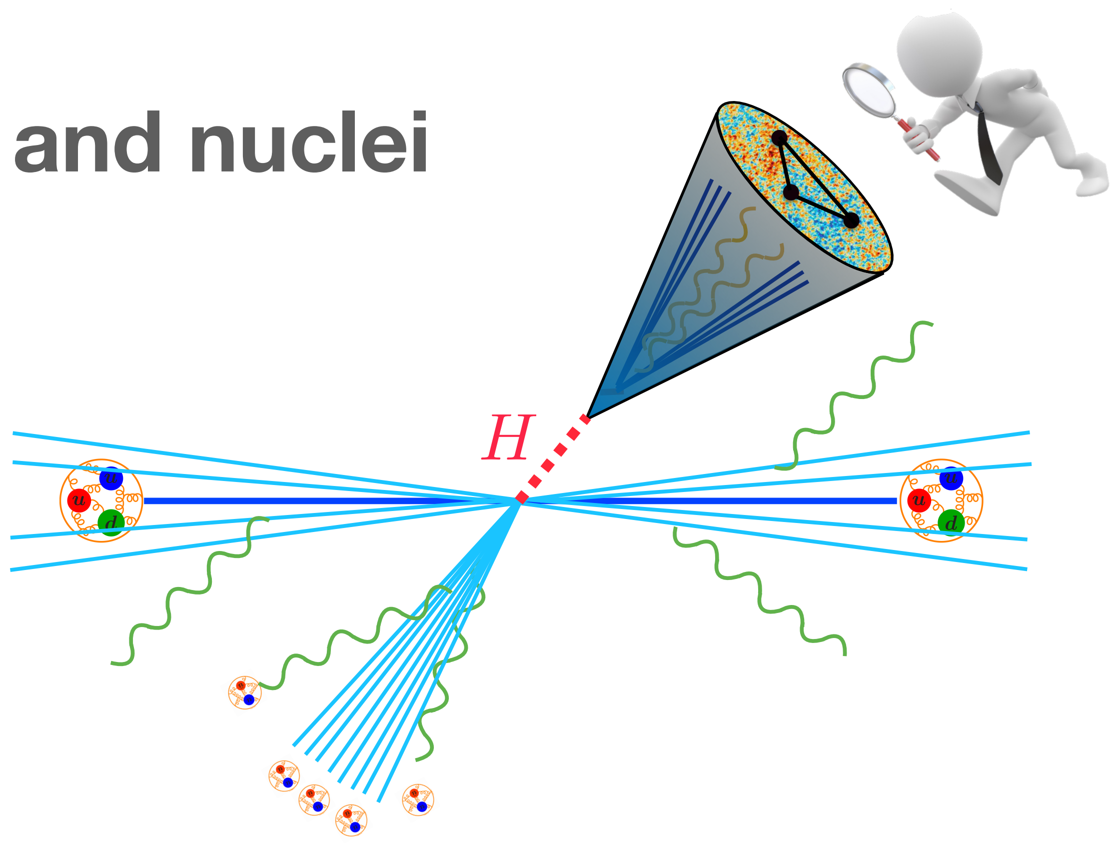
→ Confinement

Cold QCD

→ Gluon Saturation

→ Proton Spin and Radius Puzzle

→ 3D Structure of protons and nuclei



Numerous collider experiments spanning several continents working to resolve these fundamental questions

Beautiful and Charming Energy Correlators

Evan Craft — Yale University

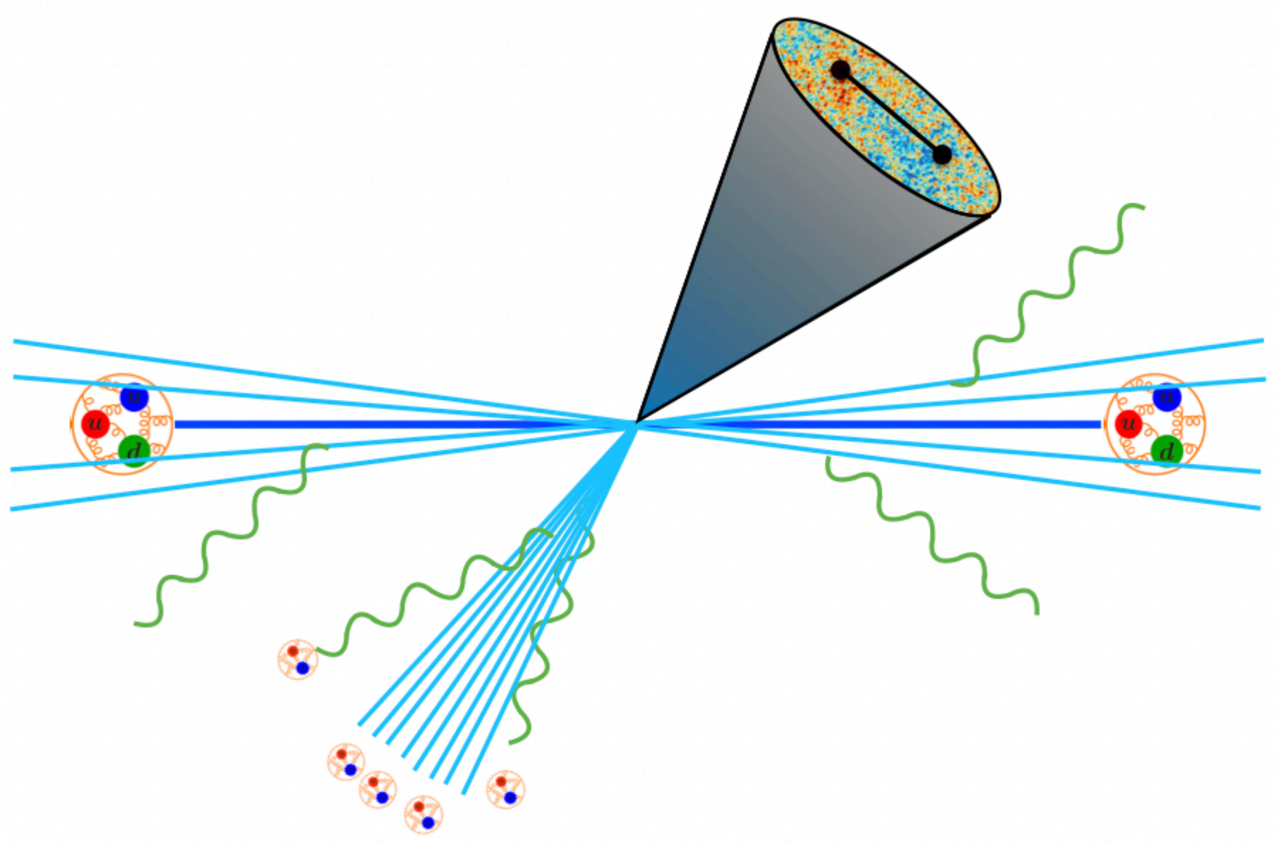
arXiv: 2210.09311

Based on work with K. Lee, B. Mecaj, I. Moult

Yale University

MIT

Application: Intrinsic Mass



Intrinsic masses of QCD imprinted onto **energy correlators**

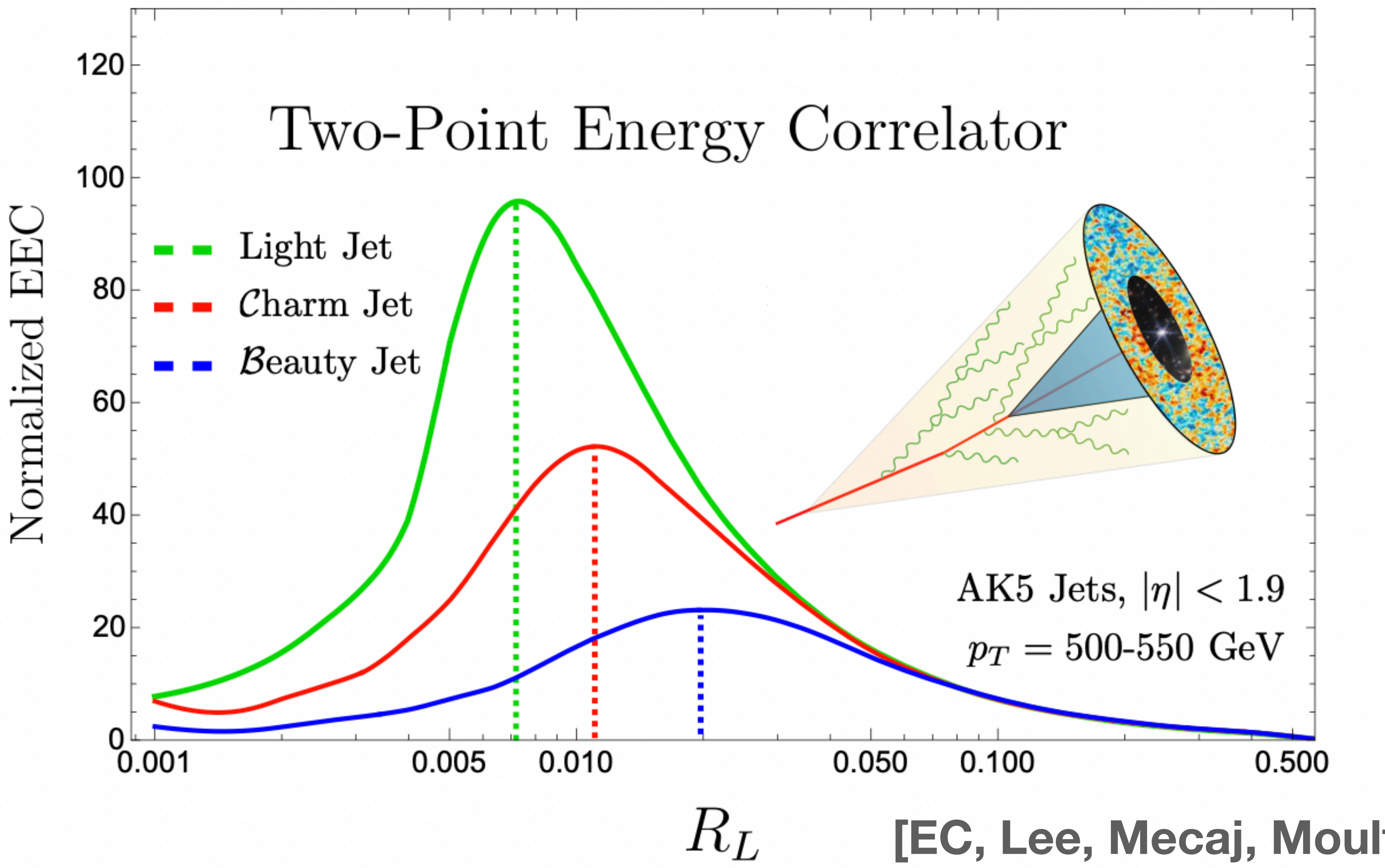
→ allows for an unprecedented window into hadronization effects

→ provides a powerful perspective for probing jet substructure

→ provides a new, unifying technique for understanding intrinsic mass

$$\langle \Psi \,|\, \mathcal{E}(\hat{n}_1) \ldots \mathcal{E}(\hat{n}_k) \,|\, \Psi \rangle$$

the **"perfect"** observable



[EC, Lee, Mecaj, Moult]

Application: Intrinsic Mass

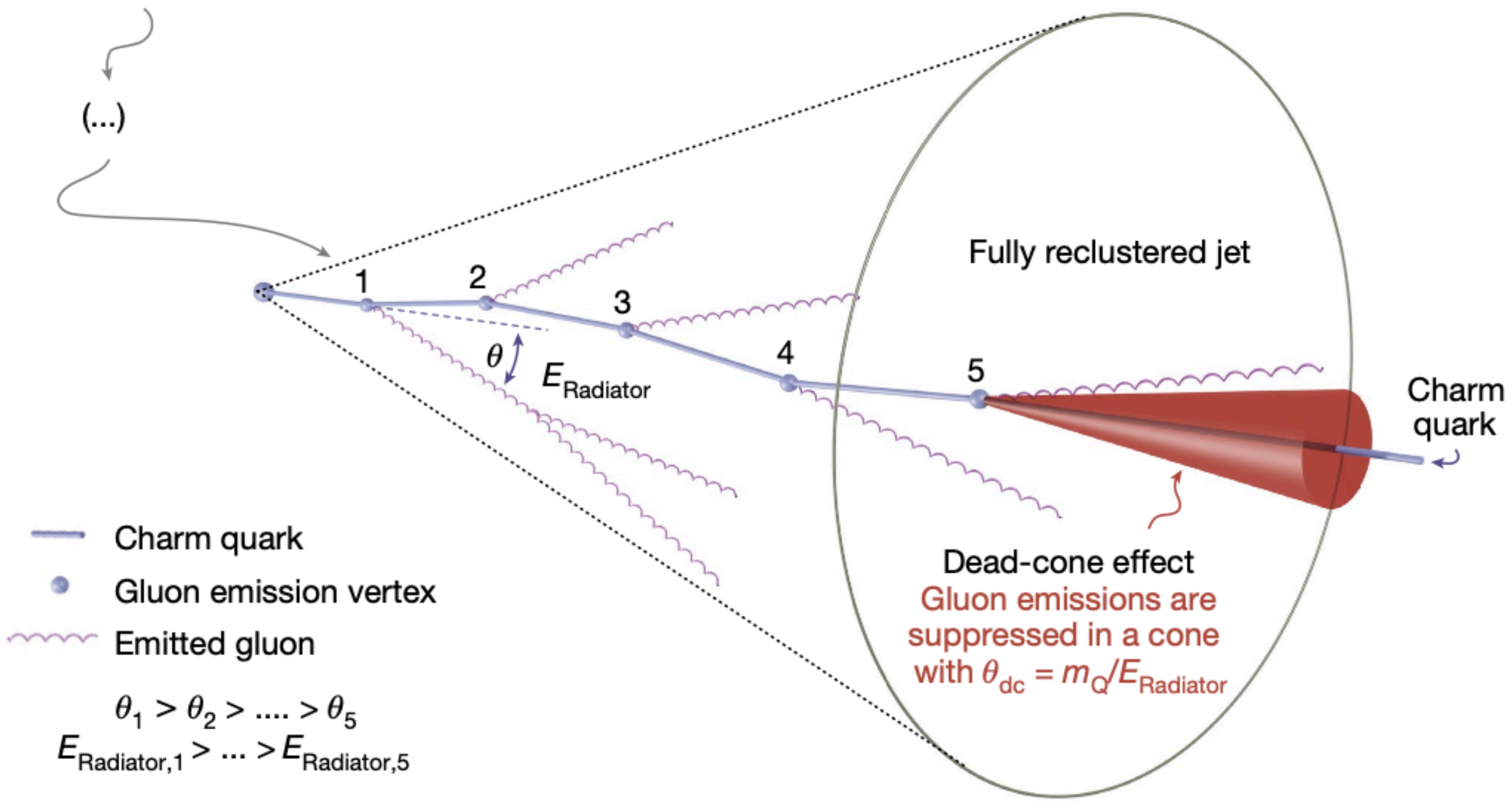
[ALICE Collaboration, Nature Physics]

Dokshitzer, Khoze, Troyan (1991)

Heavy quark radiation of gluons is *suppressed* within a cone of radius m_q/E_q around its center.

→ Fundamental property of all gauge field theories

→ Direct signature of intrinsic mass before confinement



We can access this effect simply with statistical correlations (light-ray operators) — providing a precise, field theoretic description of the dead cone.

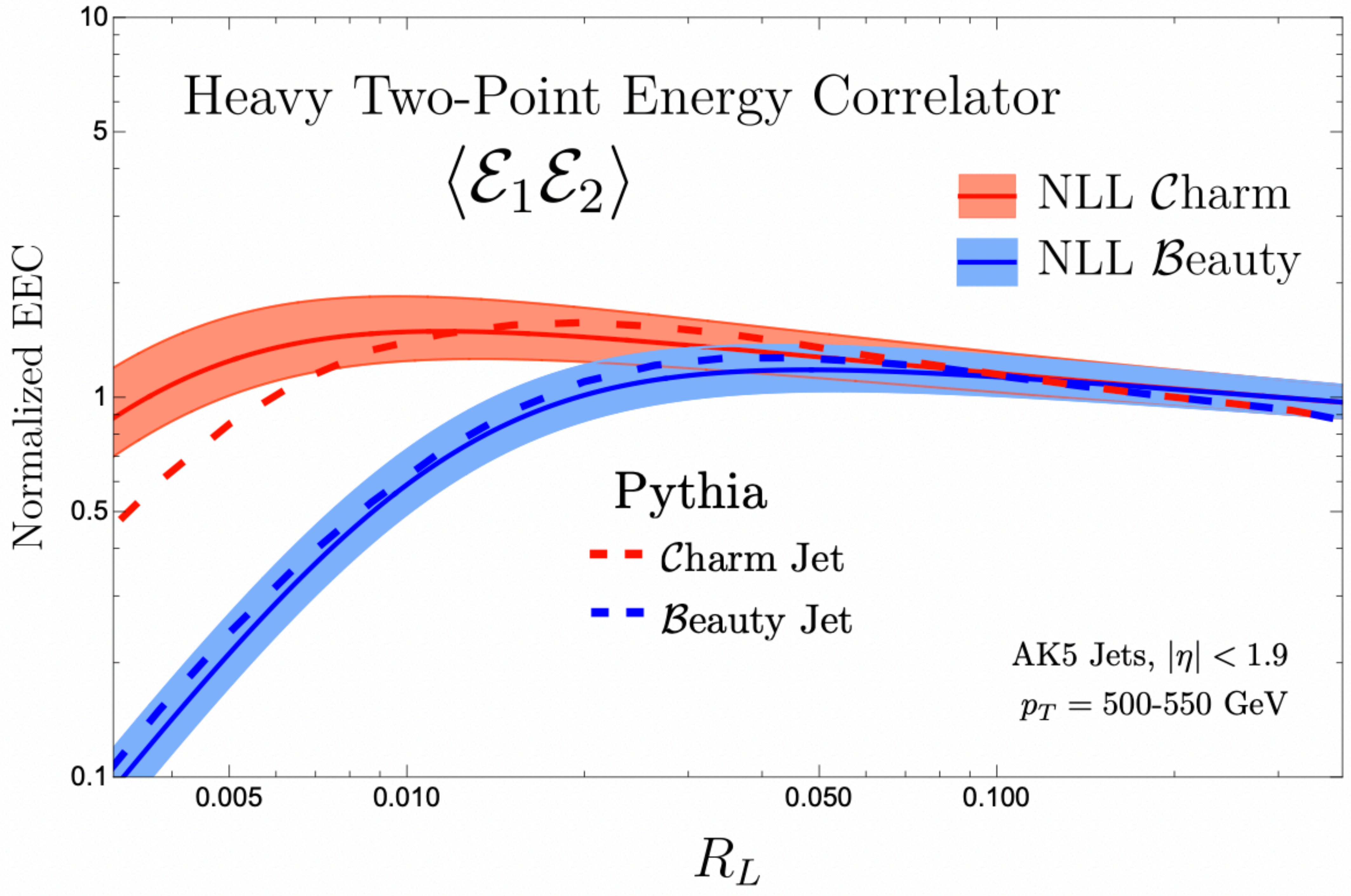
Measured this year by ALICE using a complex iterative declustering technique

→ Inferred all gluon emissions *directly*

→ State of the art analysis techniques

Application: Intrinsic Mass

Heavy quark radiation of gluons is *suppressed* within a cone $\theta_q \sim m_q/E_q$ and this suppression is visibly imprinted on energy correlators



[EC, Lee, Mecaj, Moult]

Exposes the "dead-cone" effect of fundamental QCD, using correlations of light-ray operators

→ first collinear NLL calculation of a heavy quark jet substructure observable at the LHC

$$EEC = H \times J \times S$$

→ fundamental test of SCET factorization at the LHC

Application: Intrinsic Mass

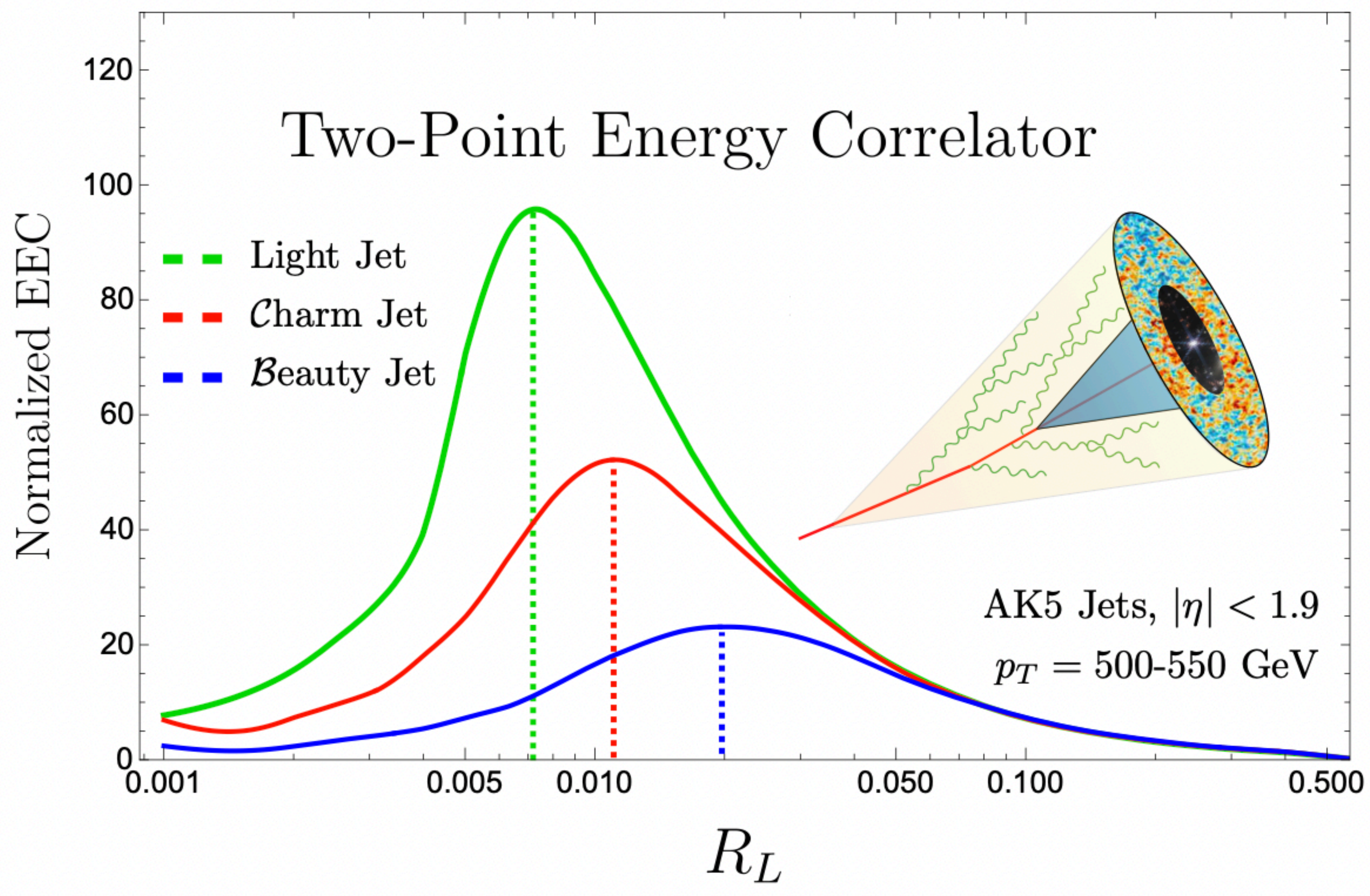
In the **UV regime**, scaling should be independent of mass

$$\mathscr{E}(\hat{n}_1)\mathscr{E}(\hat{n}_2) \sim \sum_i \theta^{\tau_i - 4}\, \mathbb{O}_i(\hat{n}_1)$$

In the **IR regime**, mass is an intrinsic scale, and should be imprinted on the correlator

$$\langle \Psi | \mathscr{E}(\hat{n}_1) \ldots \mathscr{E}(\hat{n}_k) | \Psi \rangle$$

[EC, Lee, Mecaj, Moult]



EECs provide a precise, **field-theoretic description** of the dead-cone effect

Transition Scale $\sim \dfrac{m_q}{p_{T,jet}}$

Pushing the Boundaries of Jet Substructure

Evan Craft — Yale University

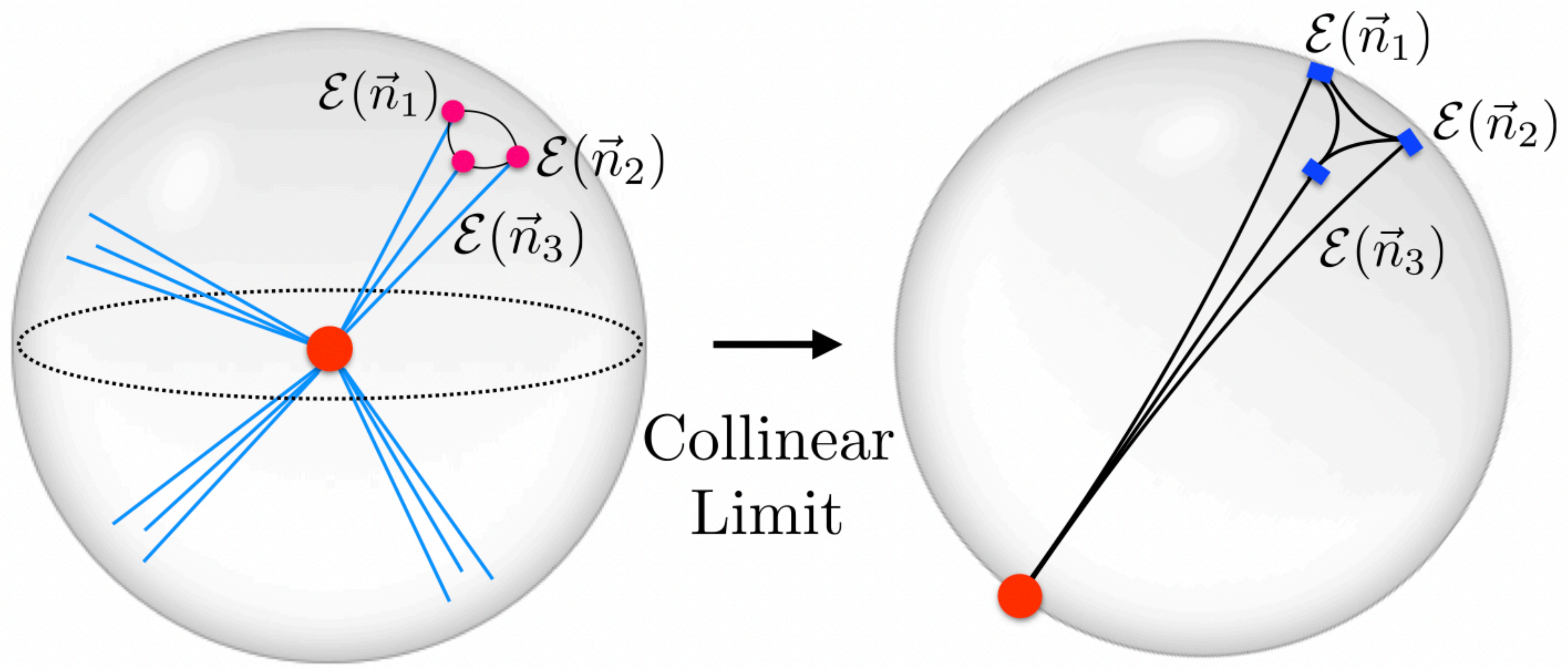



Work in prep. with K. Lee, B. Mecaj, I. Moult, & M. Gonzalez

Yale University

MIT

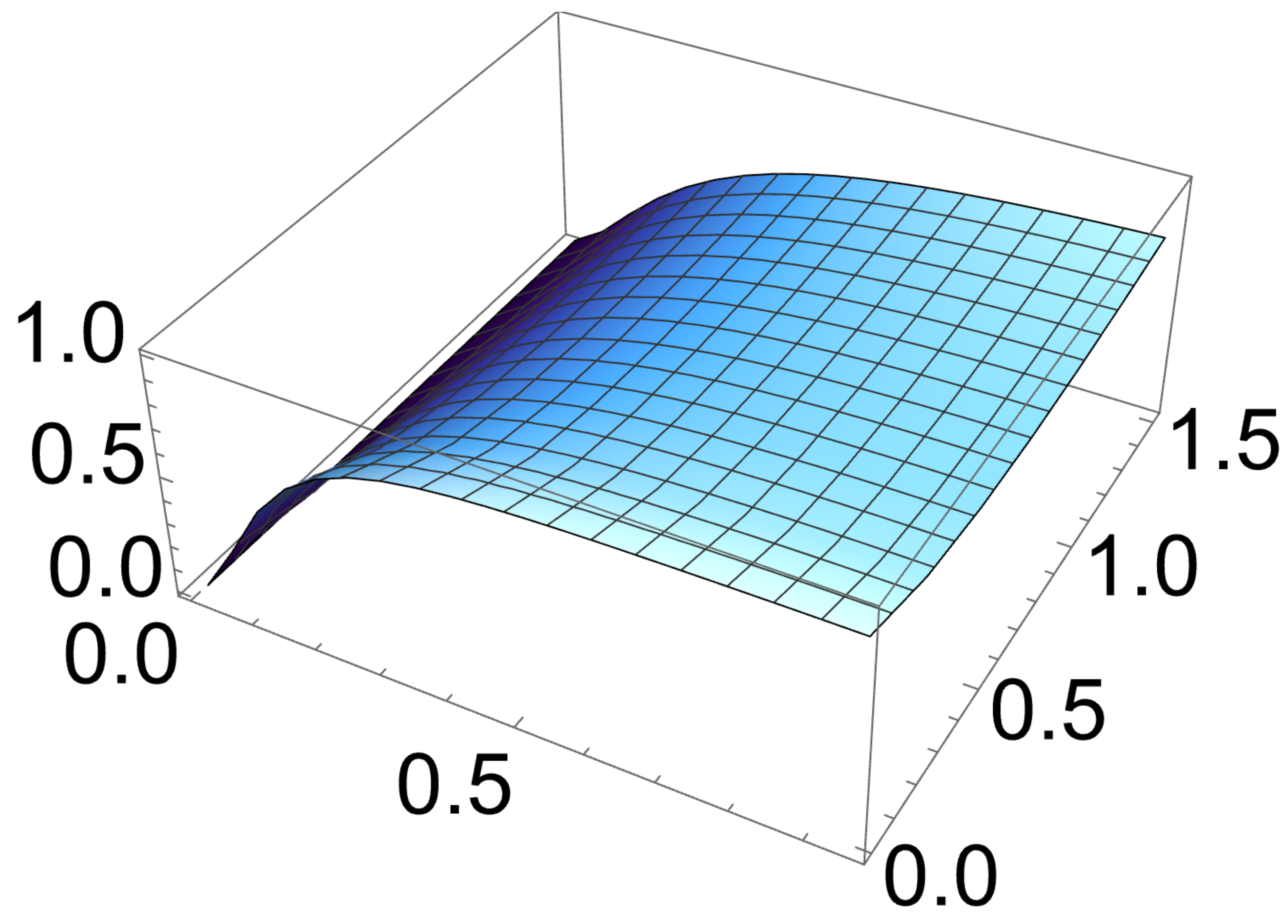
Extension: Higher Points



Natural to also consider higher point correlators

Experimental Side

3-point EEC allows access to the shape of the dead-cone!



→ **Access to non-Gaussianities**

→ **Full Shape Dependence**

Theoretical Side

transverse spin 0

$$\mathcal{O}_q^{[J]} = \frac{1}{2^J}\bar{\psi}\gamma^+(iD^+)^{J-1}\psi$$

$$\mathcal{O}_g^{[J]} = -\frac{1}{2^J}F_a^{\mu+}\gamma^+(iD^+)^{J-2}F_a^{\mu+}$$

excited by 2-point

transverse spin 2

$$\mathcal{O}_{\tilde{g}\lambda}^{[J]} = -\frac{1}{2^J}F_a^{\mu+}\gamma^+(iD^+)^{J-2}F_a^{\nu+}\epsilon_{\lambda\mu}\epsilon_{\lambda\nu}$$

helicity ± 1

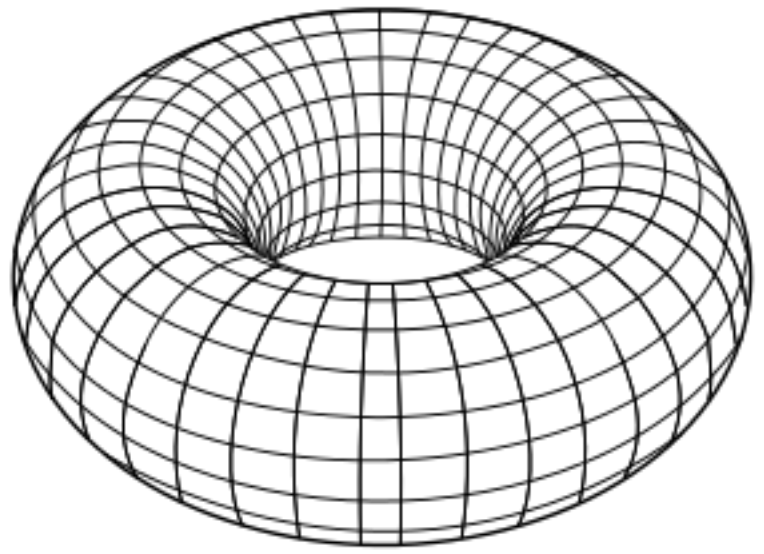
excited by 3-point

$$\mathscr{E}(\hat{n}_1)\ldots\mathscr{E}(\hat{n}_k) \sim \sum_i \theta^{\tau_i - 4}\,\mathbb{O}_i(\hat{n}_1)$$

→ **Probe fundamental operators of QCD**

Topological Aspects

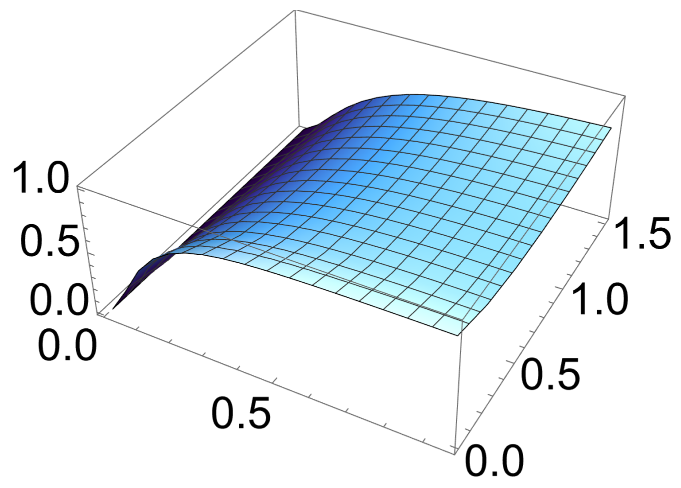
There is a direct mapping from the kinematic configuration of the EEC, to the torus

$y^2 = 4x^3 - g_1 x - g_3$ ⟶ 

$$\omega_1 \sim {}_2F_1(1/2\,,1/2\,,1\,;\lambda)$$

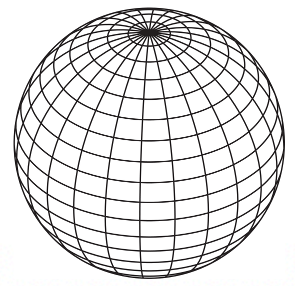
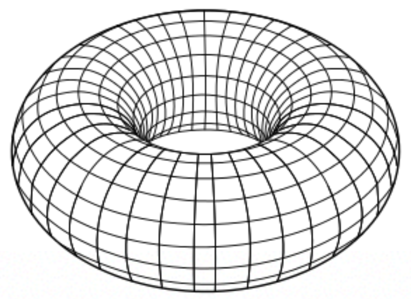
$$\omega_2 \sim {}_2F_1(1/2\,,1/2\,,1\,;1-\lambda)$$

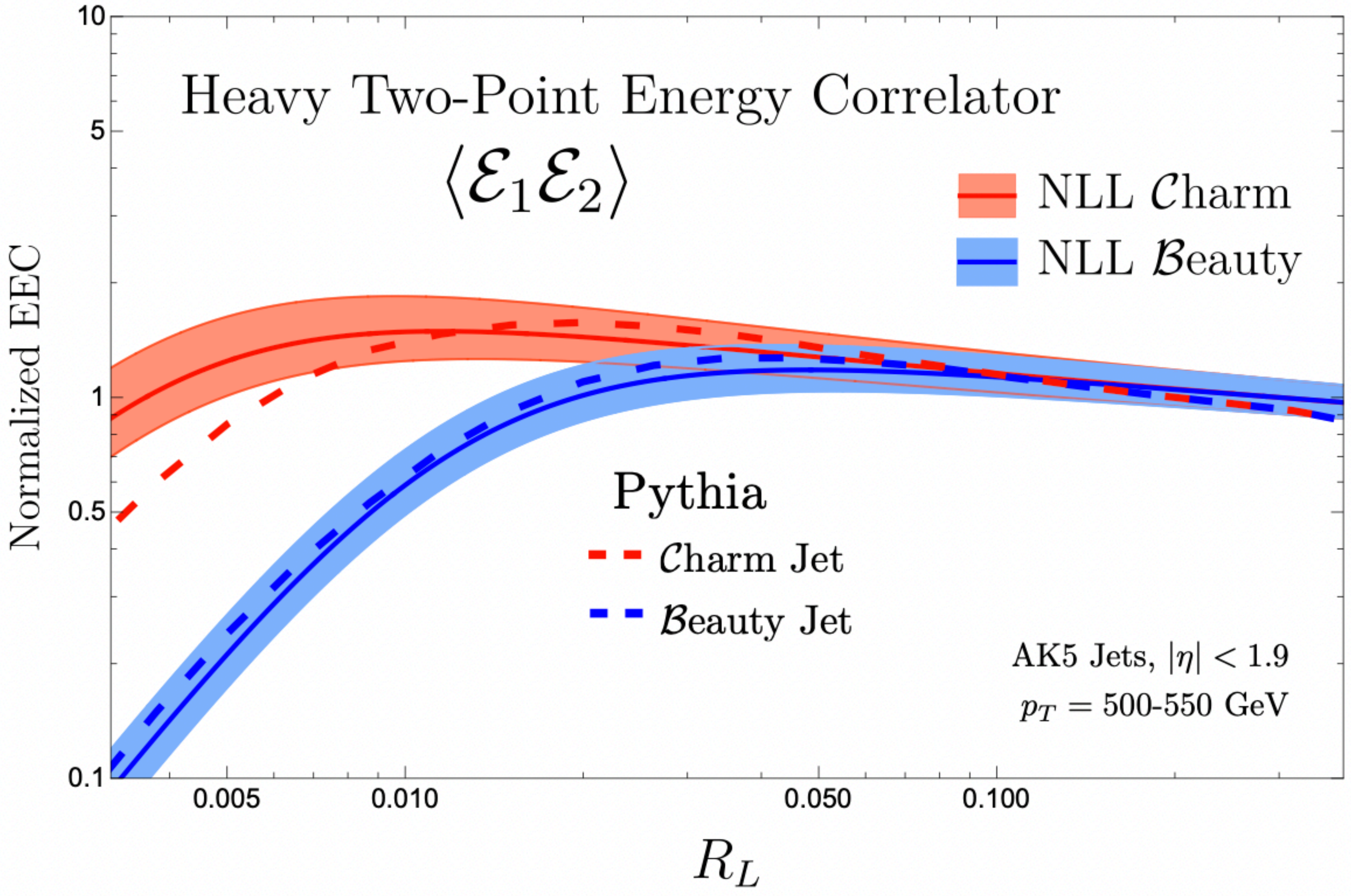
periods deformed by kinematics



Similar degeneration for the three point!

topology degenerates in the collinear limit

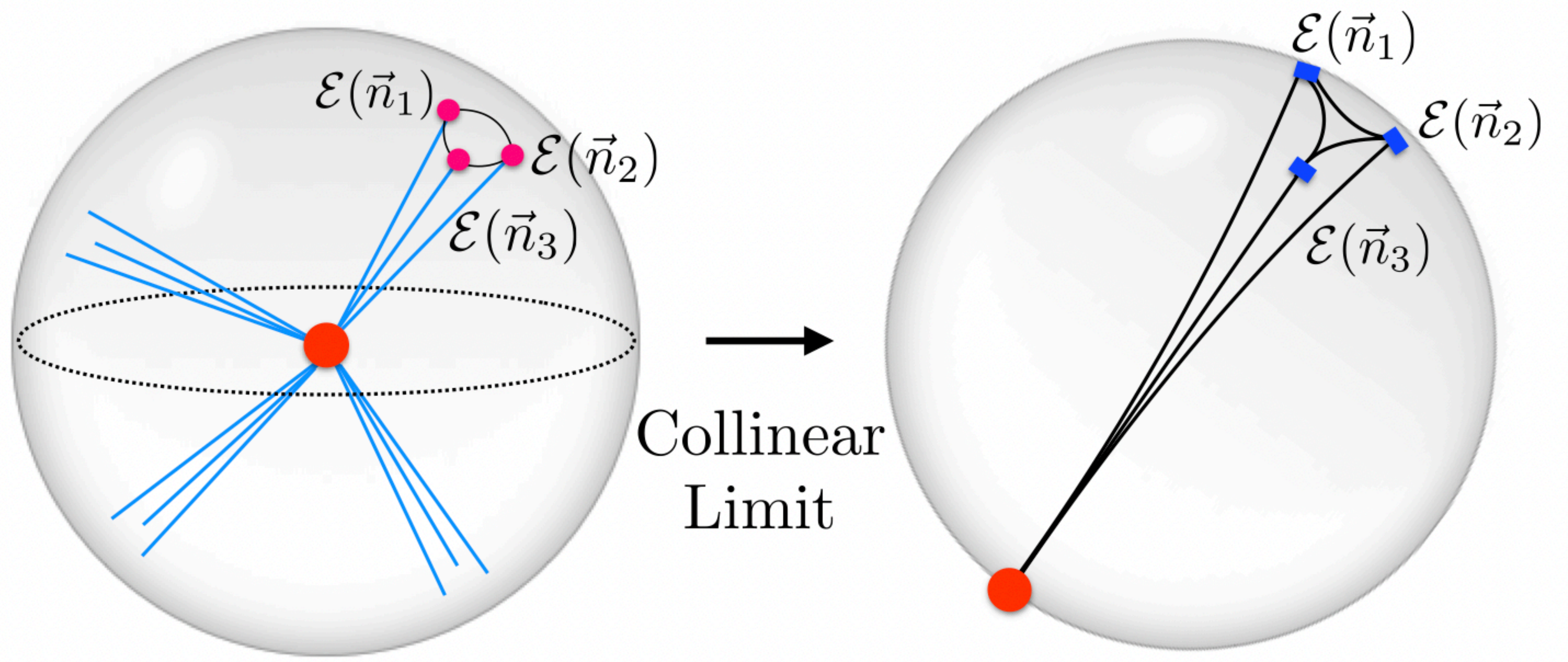
 ⟵ 



[EC, Lee, Mecaj, Moult]

Interesting to study the topological aspects of the observable

Extension: Higher Points



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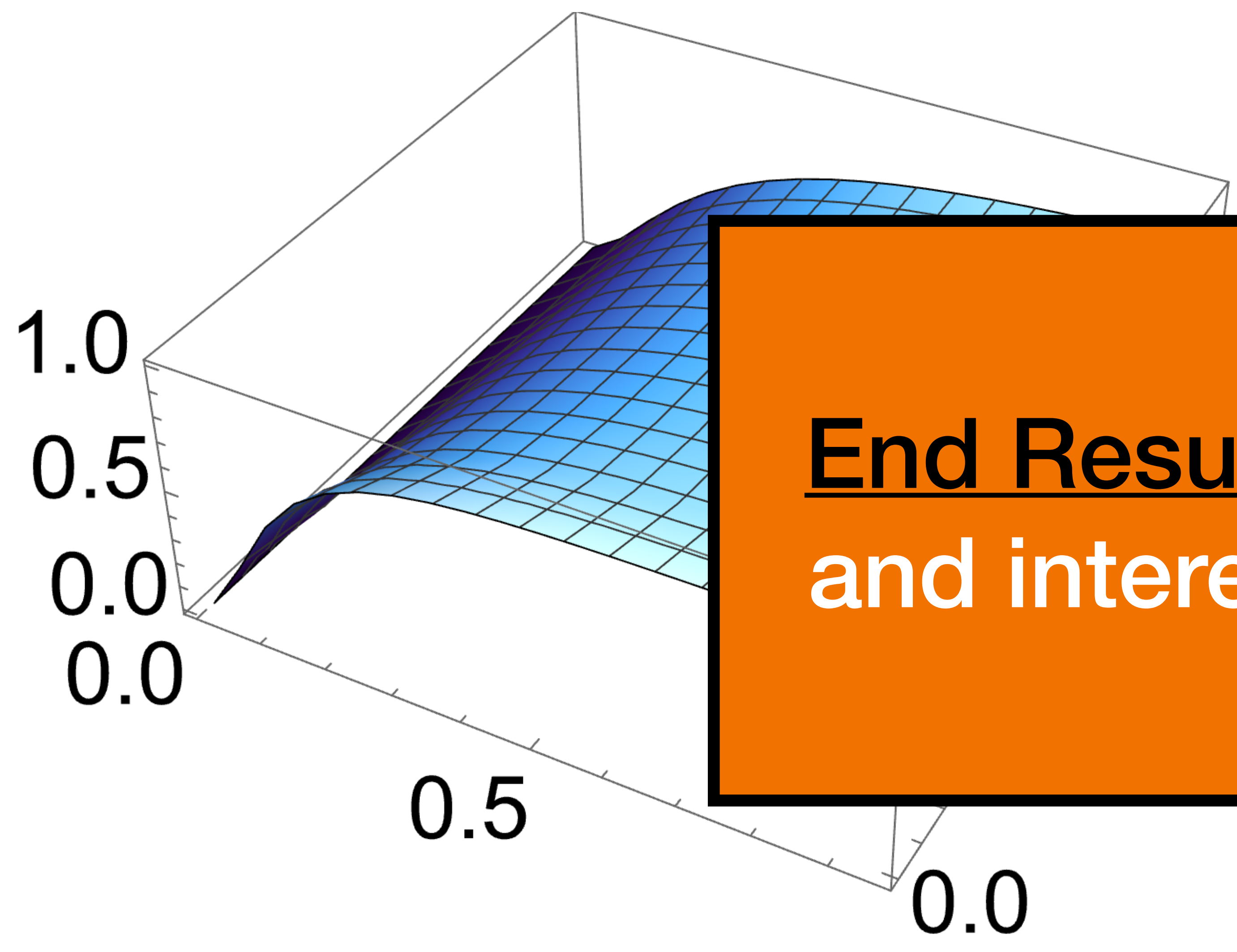


Theoretical Side

transverse spin 2

$$= -\frac{1}{2^J} F_a^{\mu+}\gamma^+(iD^+)^{J-2}F_a^{\nu+}\epsilon_{\lambda\mu}\epsilon_{\lambda\nu}$$

End Result: We can calculate and measure new and interesting observables for jet substructure

helicity ± 1

excited by **2-point**

excited by **3-point**

→ Access to **non-Gaussianities**

→ Full **Shape** Dependence

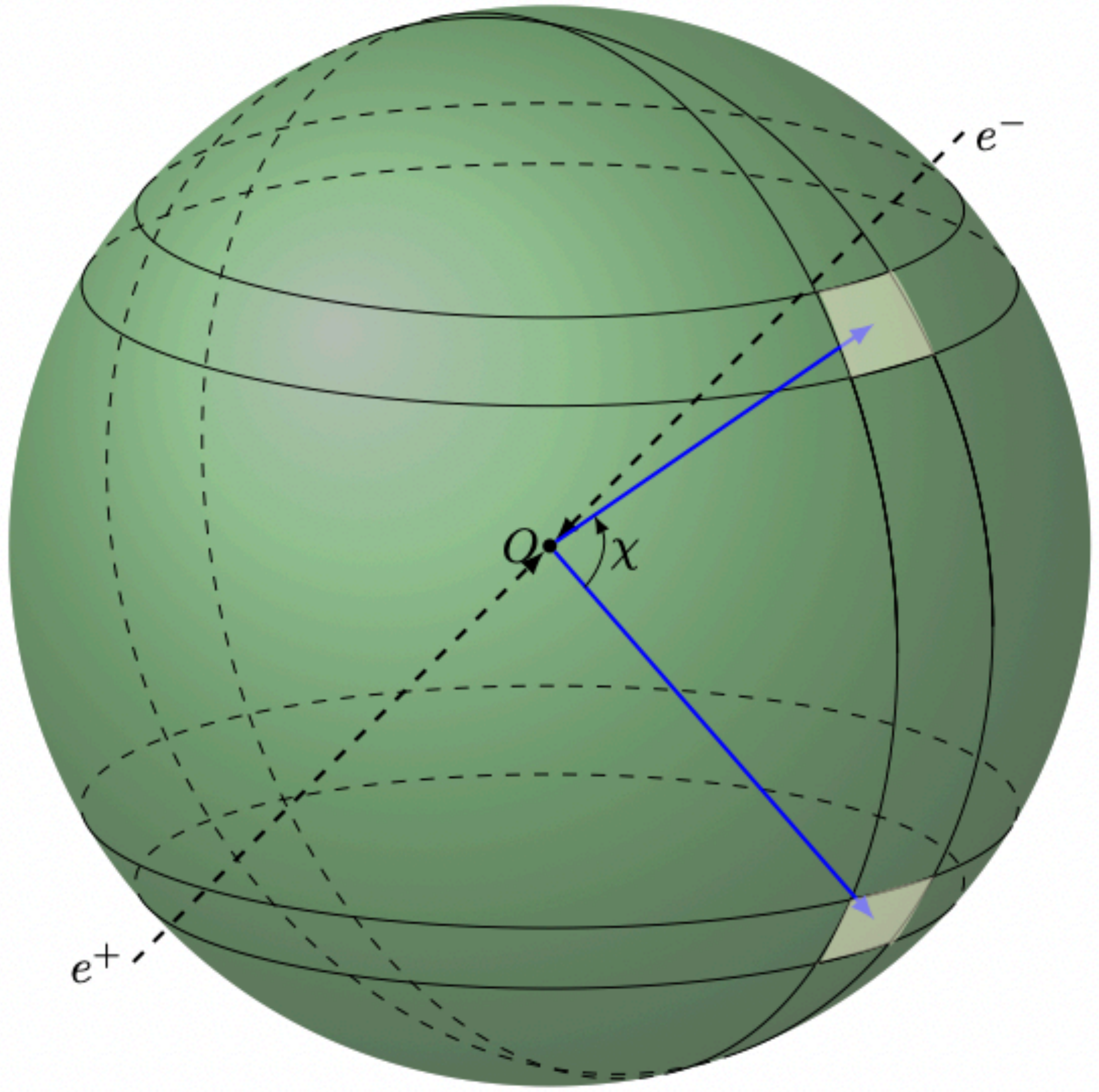
$$\mathcal{E}(\hat{n}_1)\ldots\mathcal{E}(\hat{n}_k) \sim \sum_i \theta^{\tau_i - 4}\mathbb{O}_i(\hat{n}_1)$$

→ Probe fundamental operators of **QCD**

Concluding Remarks

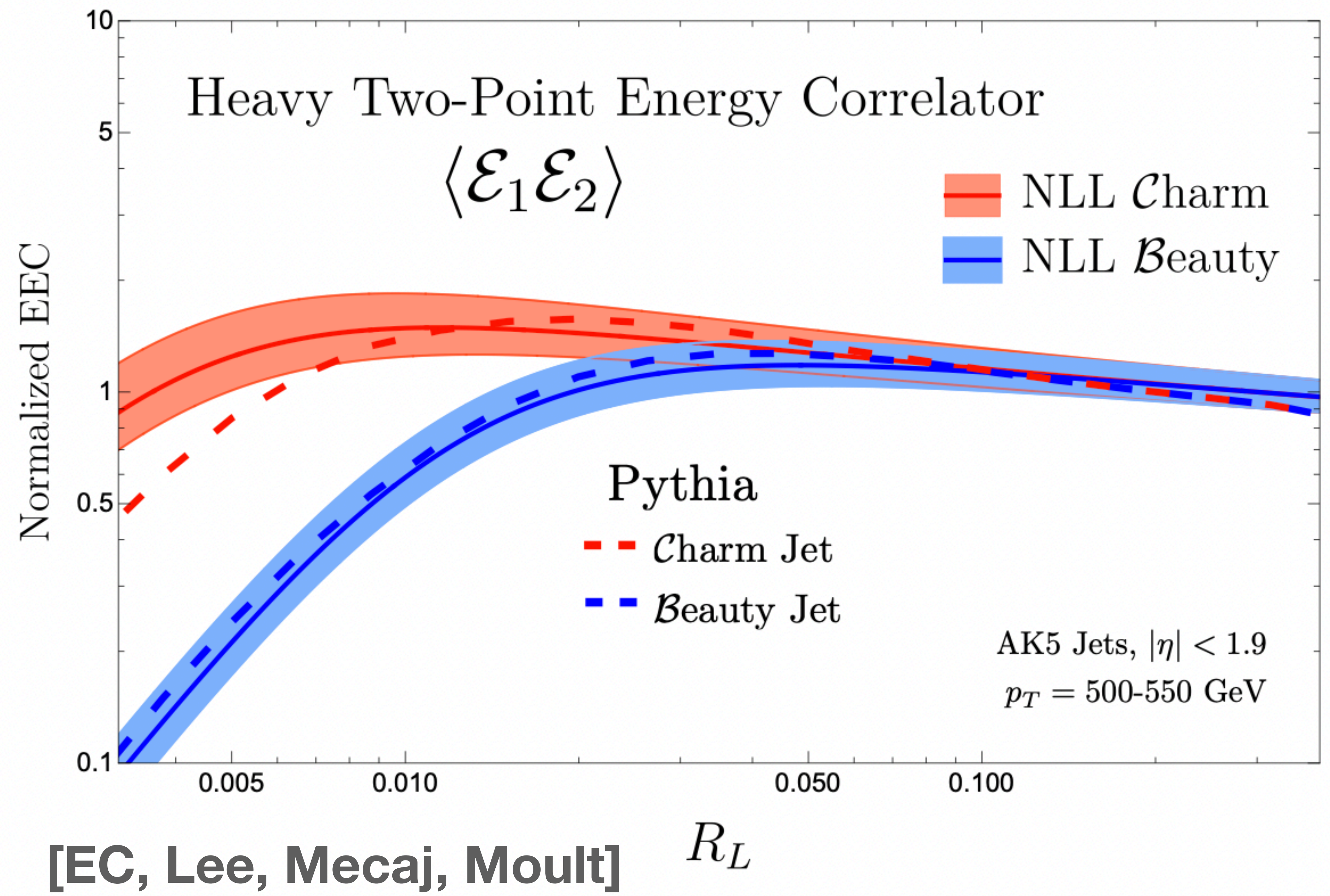
Unifying Theory and Experiment

Two Symbiotic Perspectives



Beautiful and Charming Interplay!

$$\frac{d\sigma}{d\cos\chi} = \sum_{i<j} \int d\sigma \frac{E_i E_j}{Q^2} \delta\left(\vec{n}_i \cdot \vec{n}_j - \cos\chi\right)$$



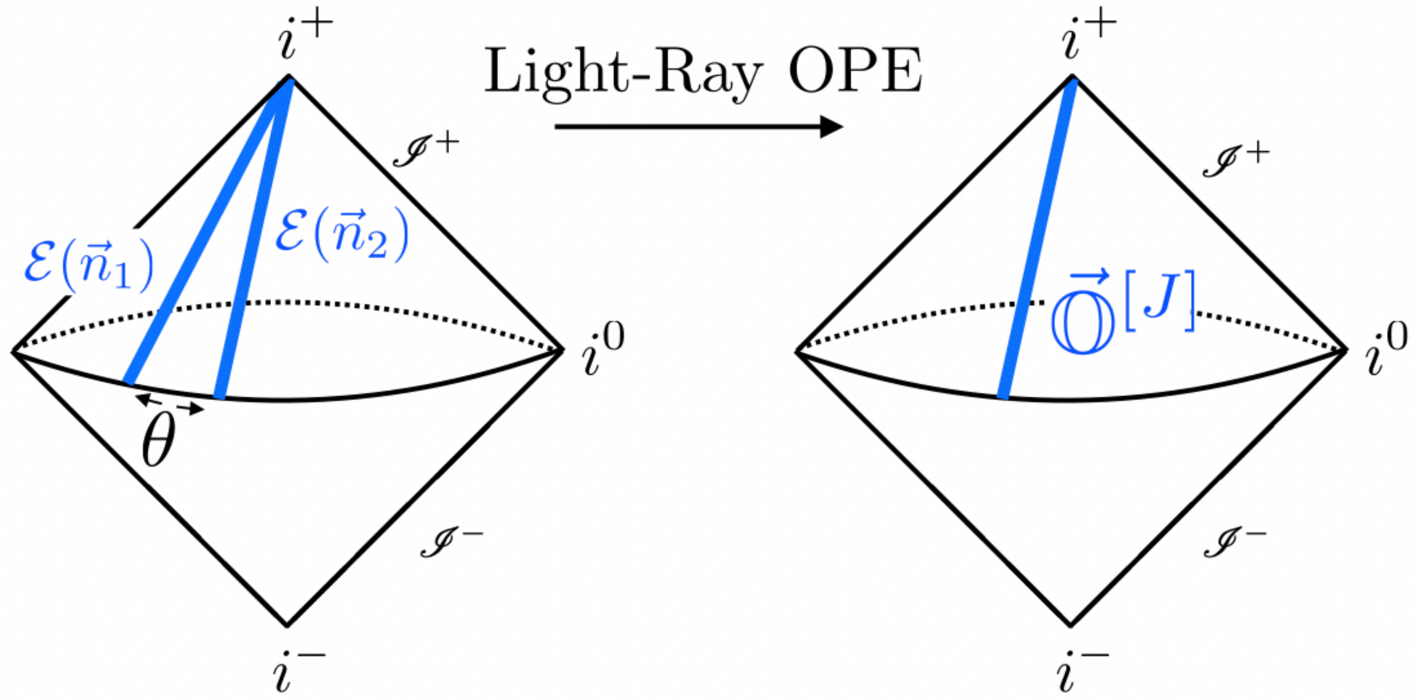
[EC, Lee, Mecaj, Moult]

Experiment

New Observables

$$\mathscr{E}(\hat{n}_1)\mathscr{E}(\hat{n}_2) \sim \sum_i \theta^{\tau_i - 4}\, \mathbb{O}_i(\hat{n}_1)$$

Theory



This sort of collaboration is crucial for the success of future collider studies

Summary

Jet substructure provides a physical realization of the OPE limit of light-ray operators

→ Direct bridge between recent theoretical advancements and QCD Phenomenology

Creates an unprecedented symbiosis between theory and experiment

→ Allowing for sharp probes of interesting physics, new and old