Energy Correlators, Heavy Flavor, & Precision QCD

Evan Craft — Yale University

BOOST 2023




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

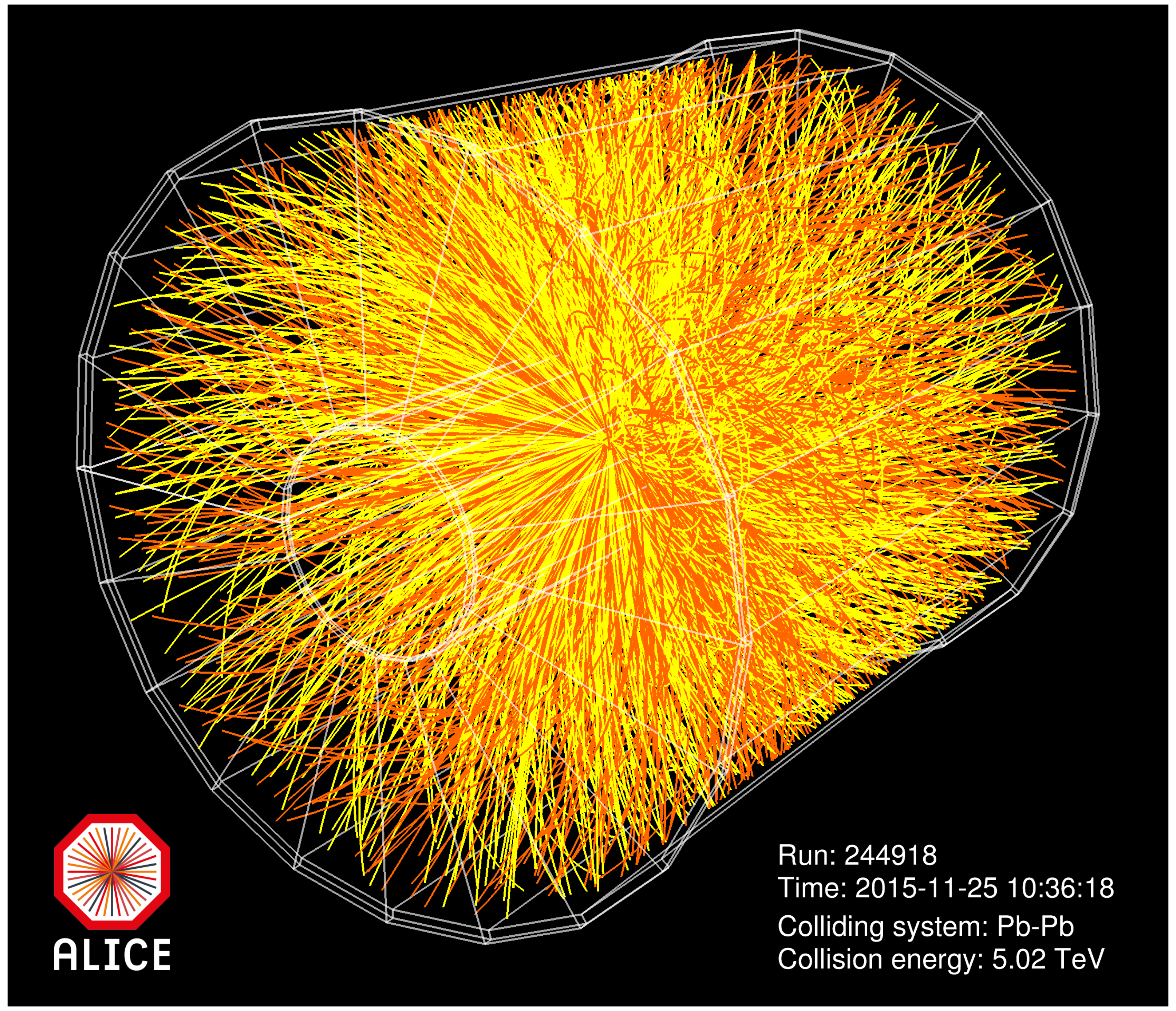
Yale University

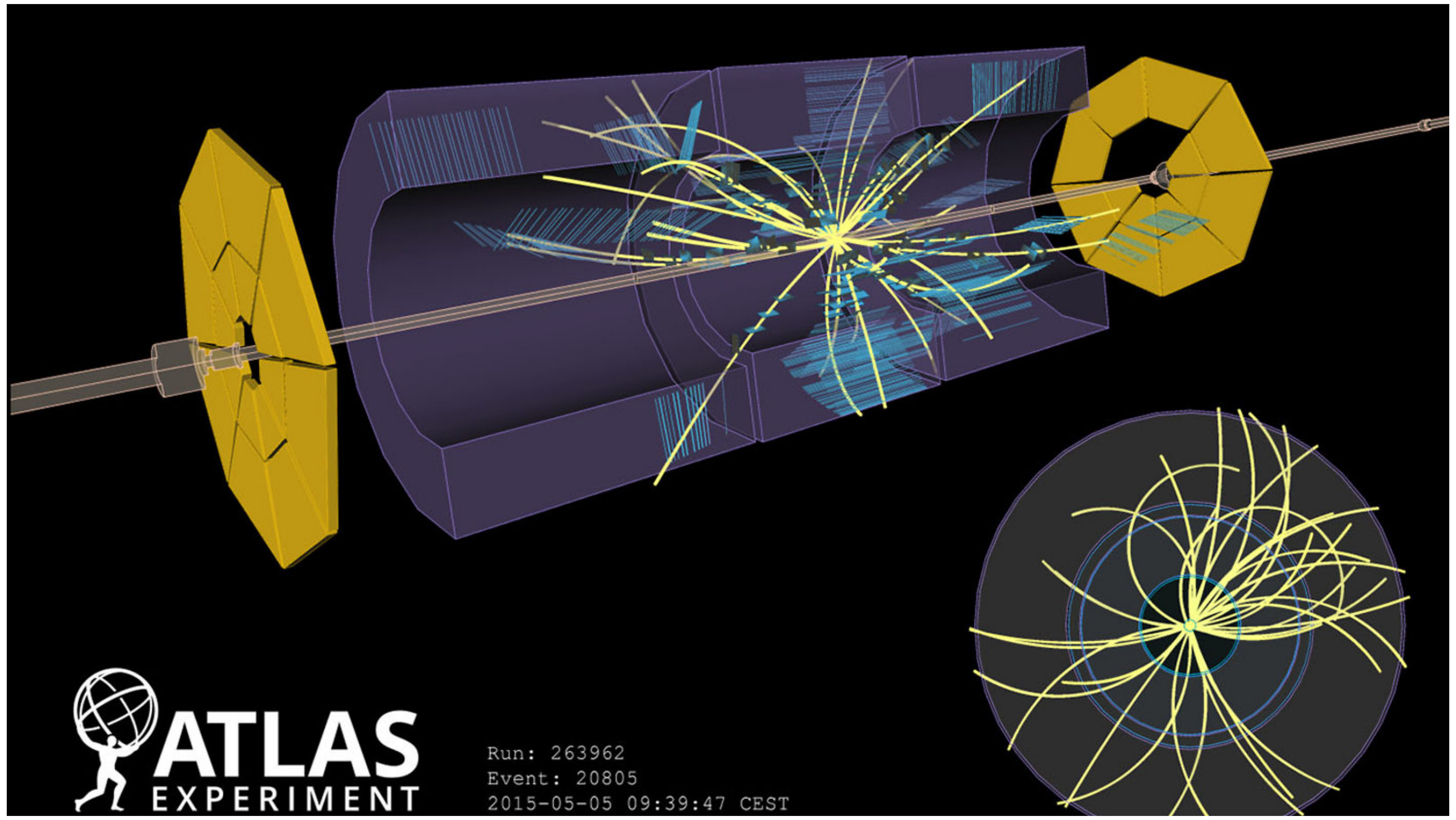
MIT

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.

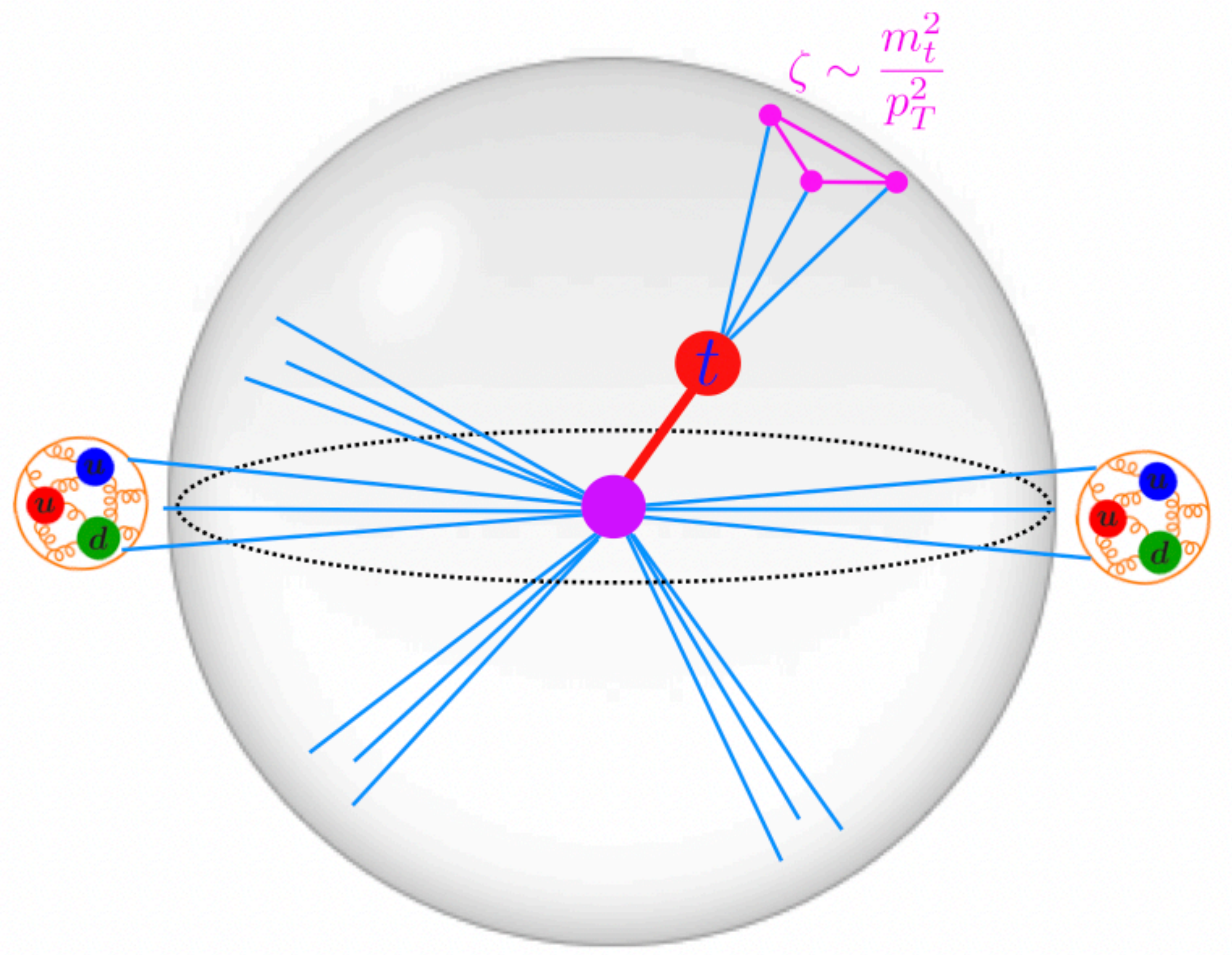
→ Need new tools for future success

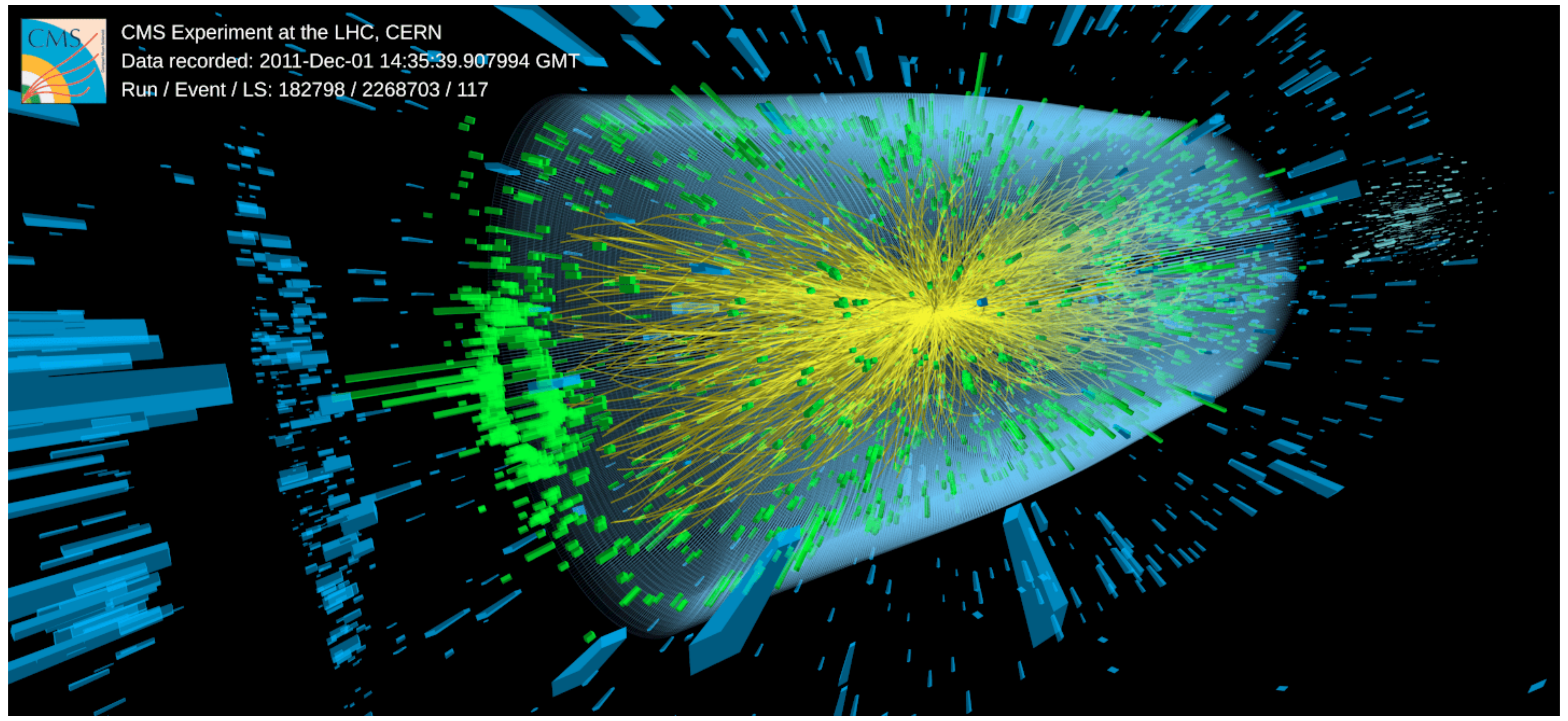
A unique frontier for novel collaborations between both theory and experiment

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 ...**





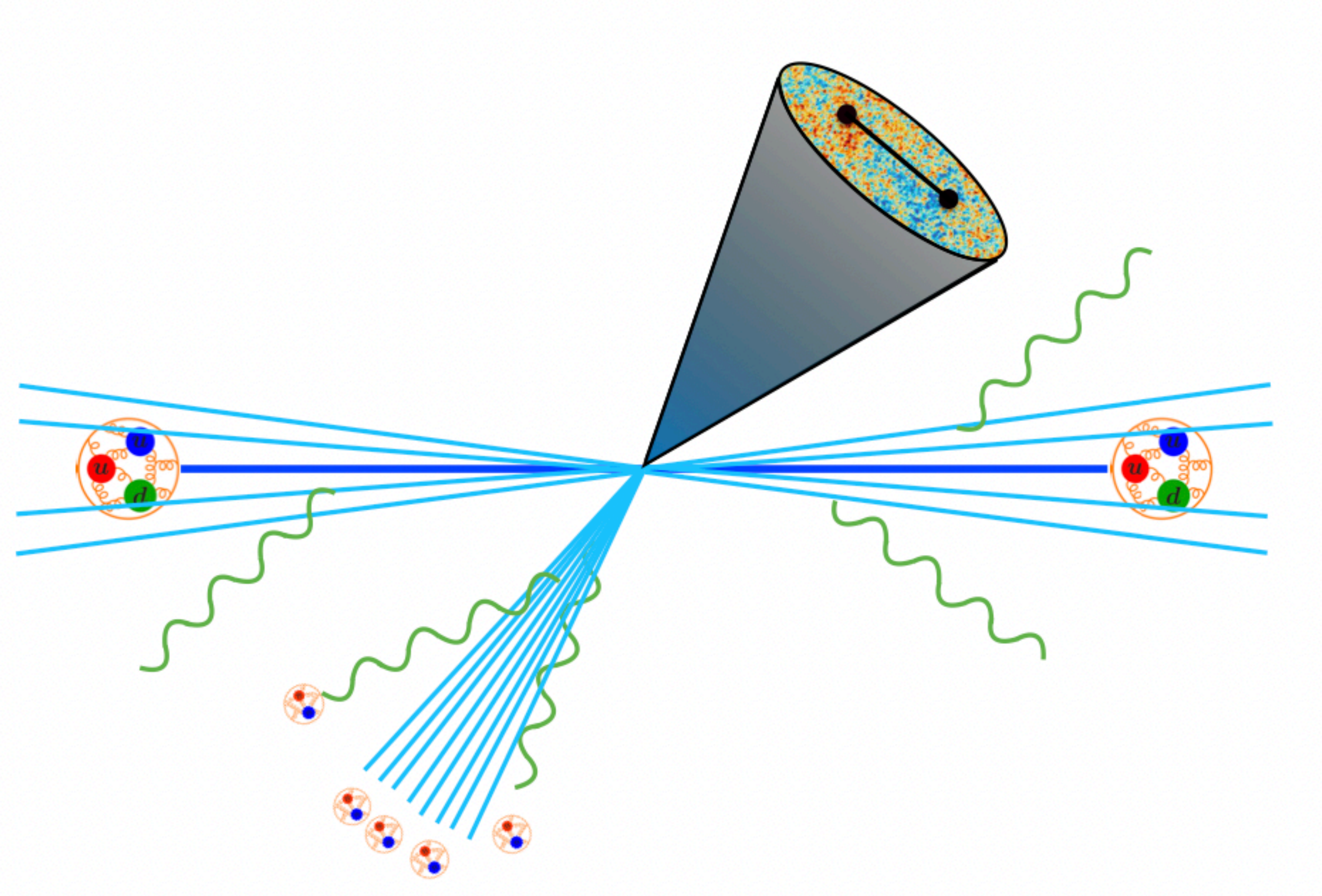
Requires the development of a new set of theoretical tools

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



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

→ ***"ANEC/Lightray/Calorimeter Cell"***

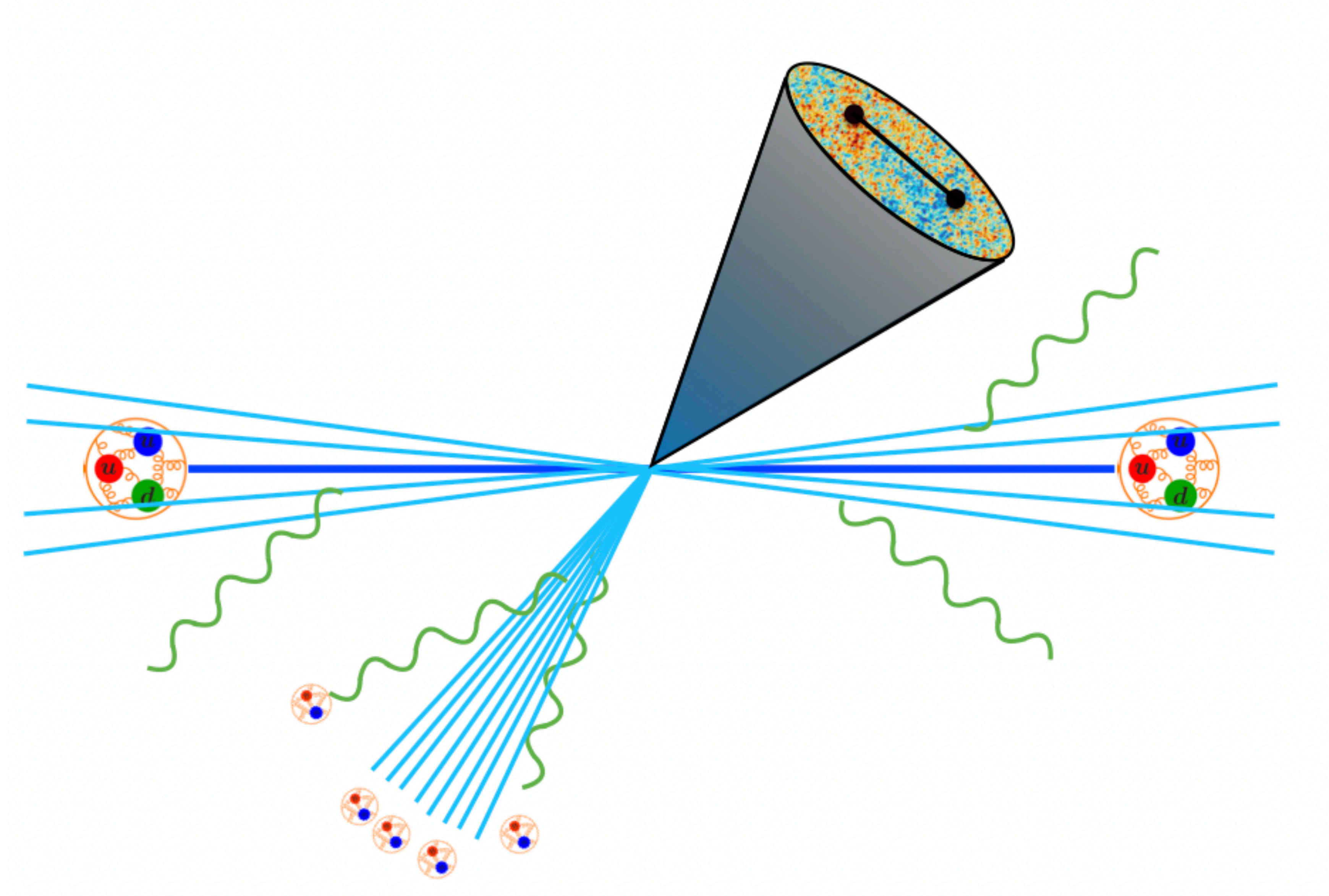
$$\langle \Psi \,|\, \mathcal{E}(\hat{n}_1)\ldots\mathcal{E}(\hat{n}_k) \,|\, \Psi \rangle$$

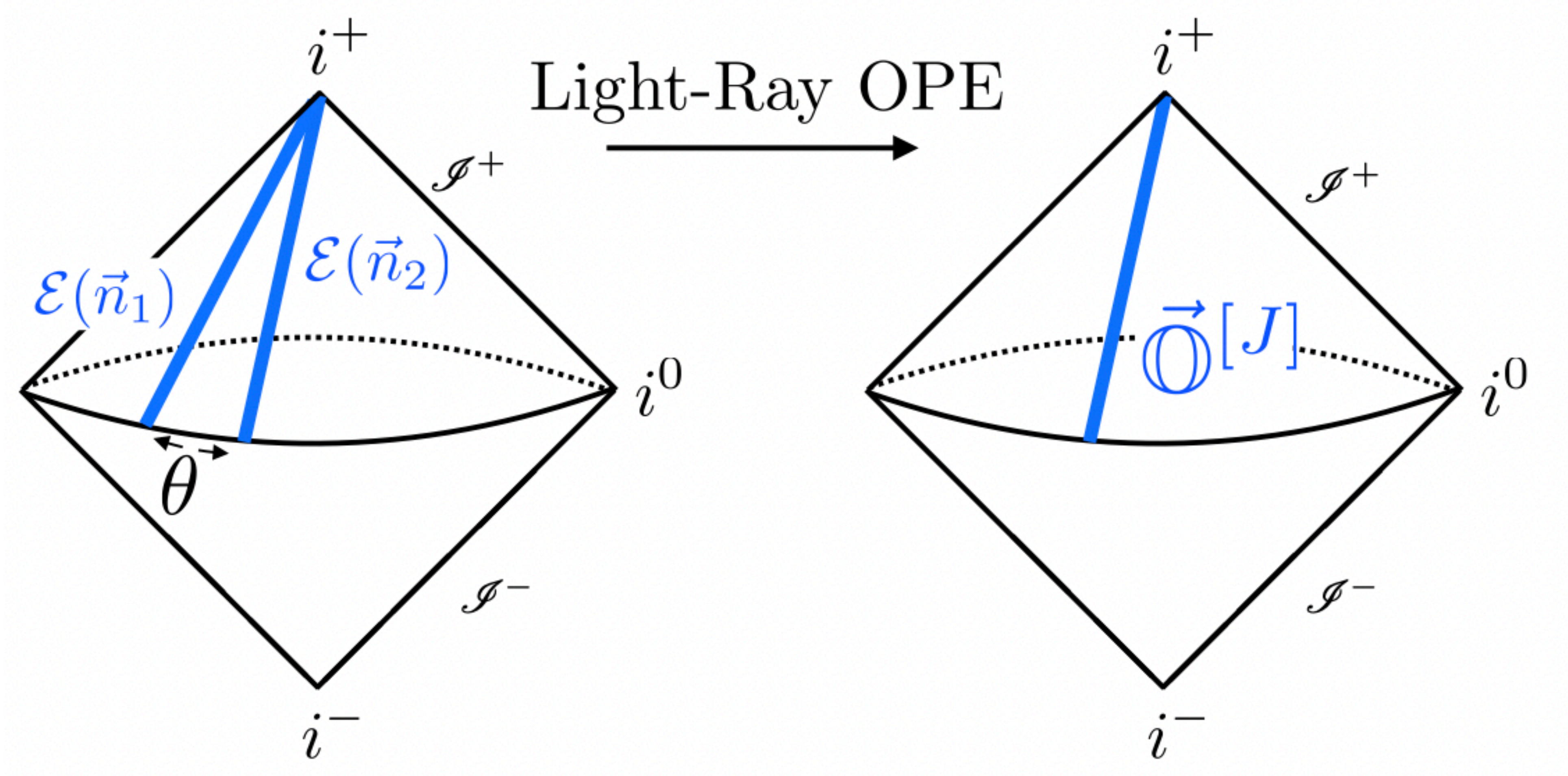
→ ***"Statistical Correlations"***

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]

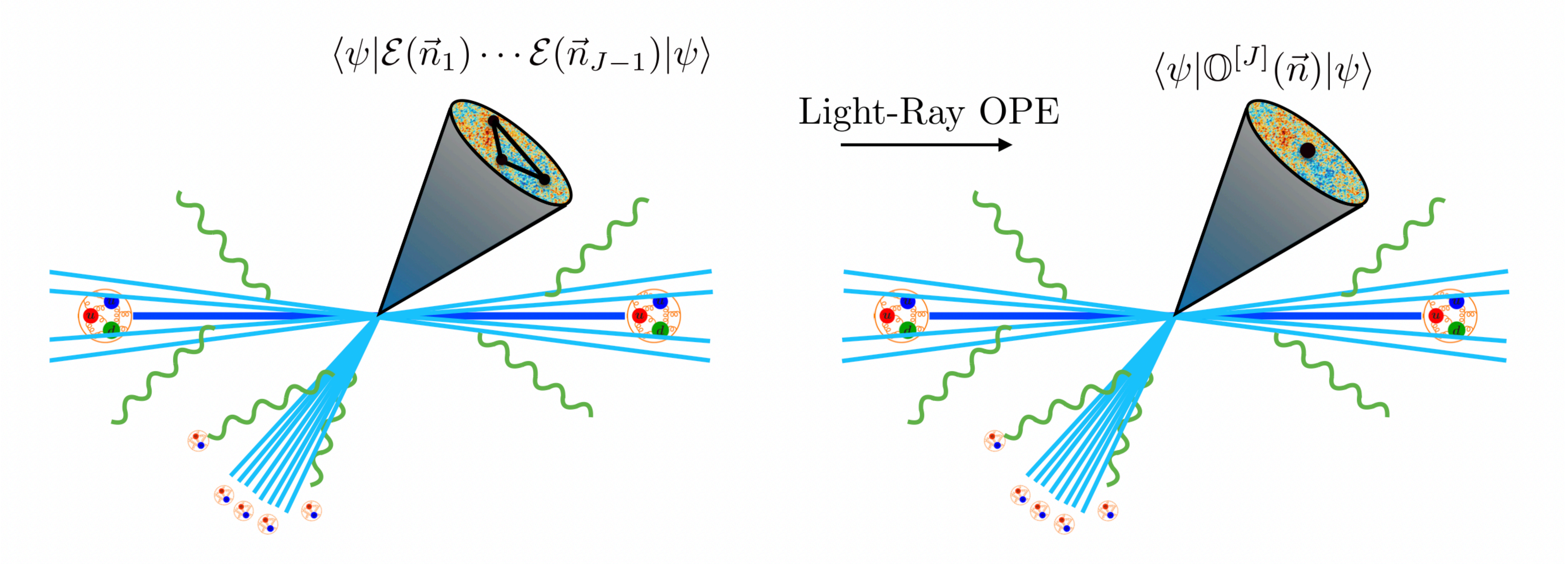
In the small angle limit, these lightray operators should exhibit the universal behavior of QCD

Universal Behavior of QCD

Allows us to **replace heuristic jet shapes** with **field theoretic objects** controlling the underlying theory

→ Can directly relate **observations** to **field theoretic quantities**

→ Able to exploit new, **formal theory developments** to understand collider experiments



Beautiful and Charming Energy Correlators

Evan Craft — Yale University

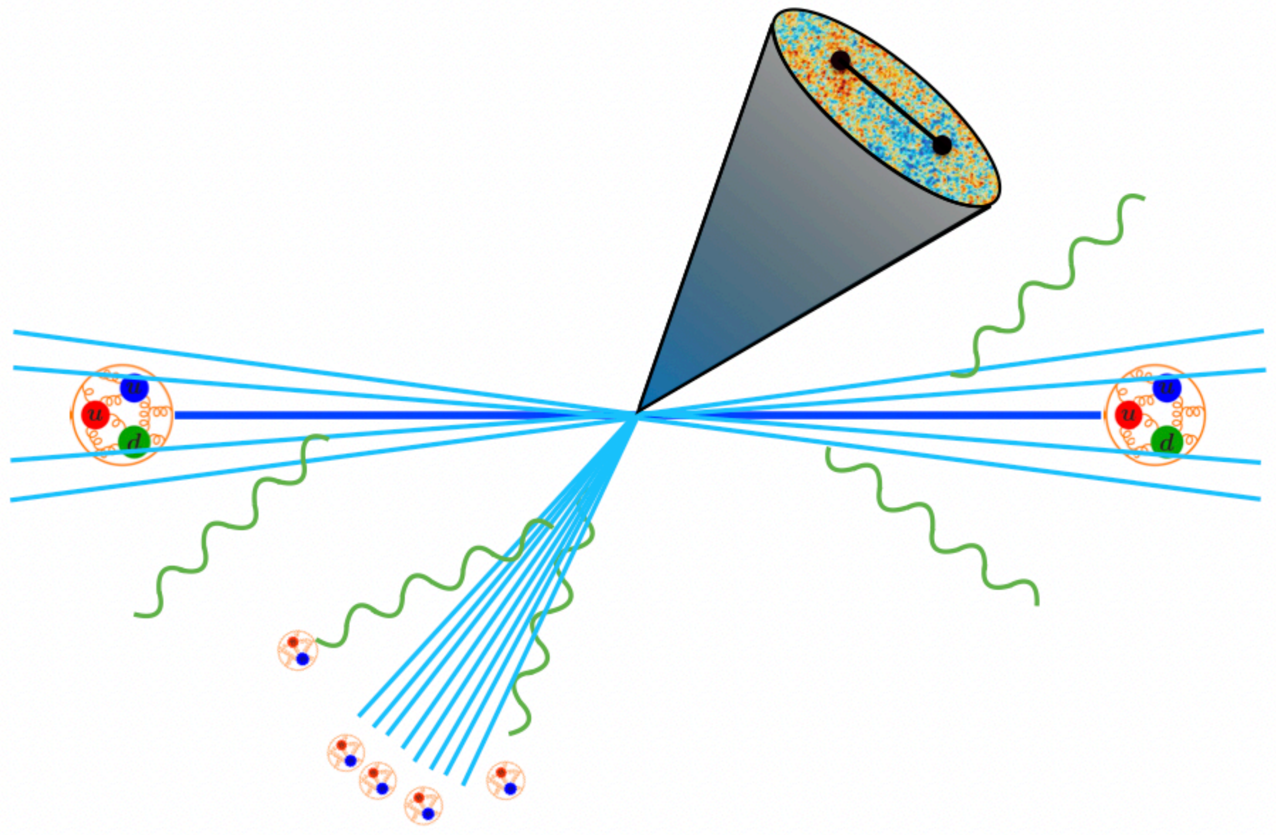
arXiv: 2210.09311

Yale University

MIT

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

Application: Intrinsic Mass



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

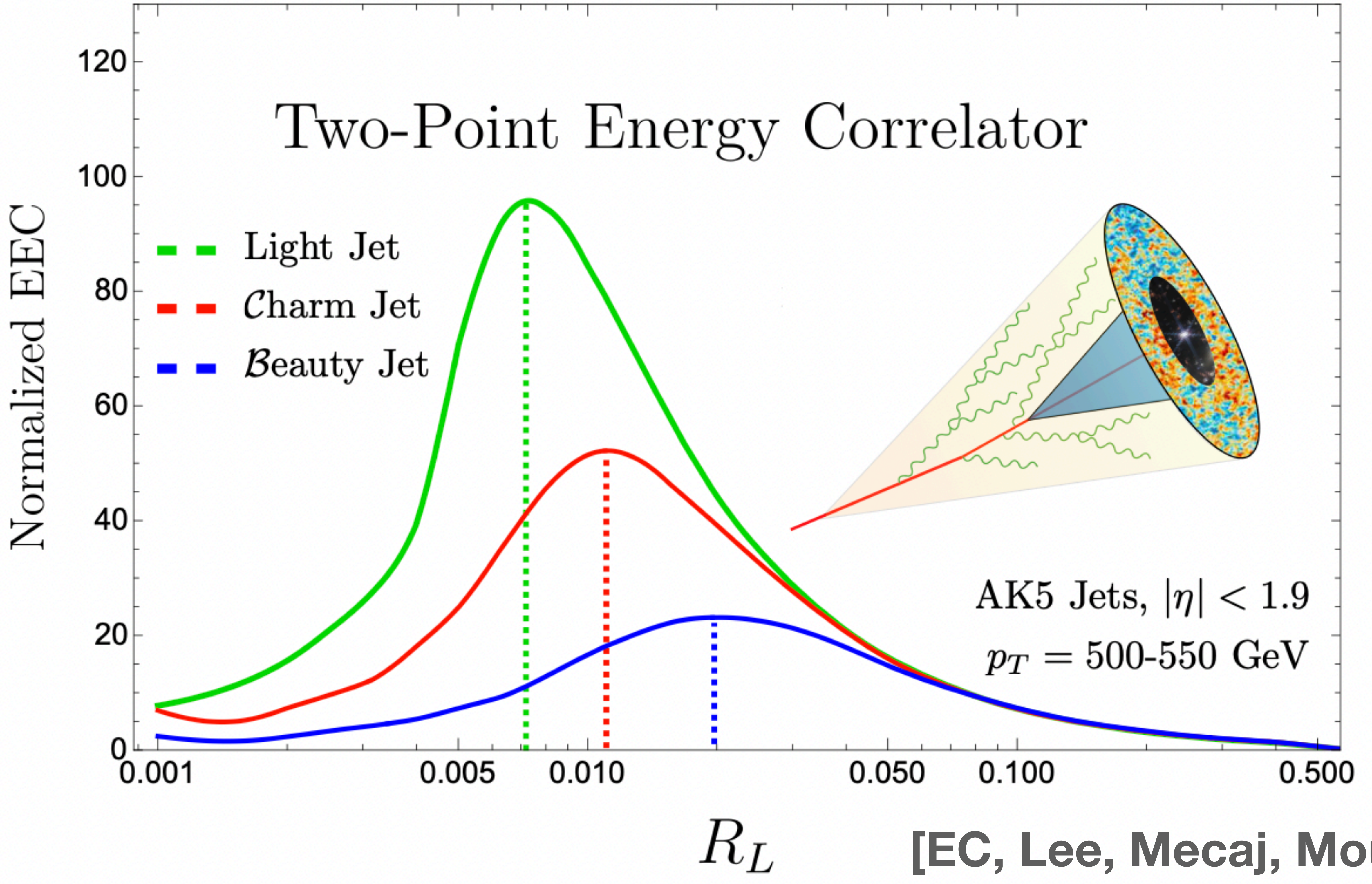
→ allows for an unprecedented window into hadronization effects

→ 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

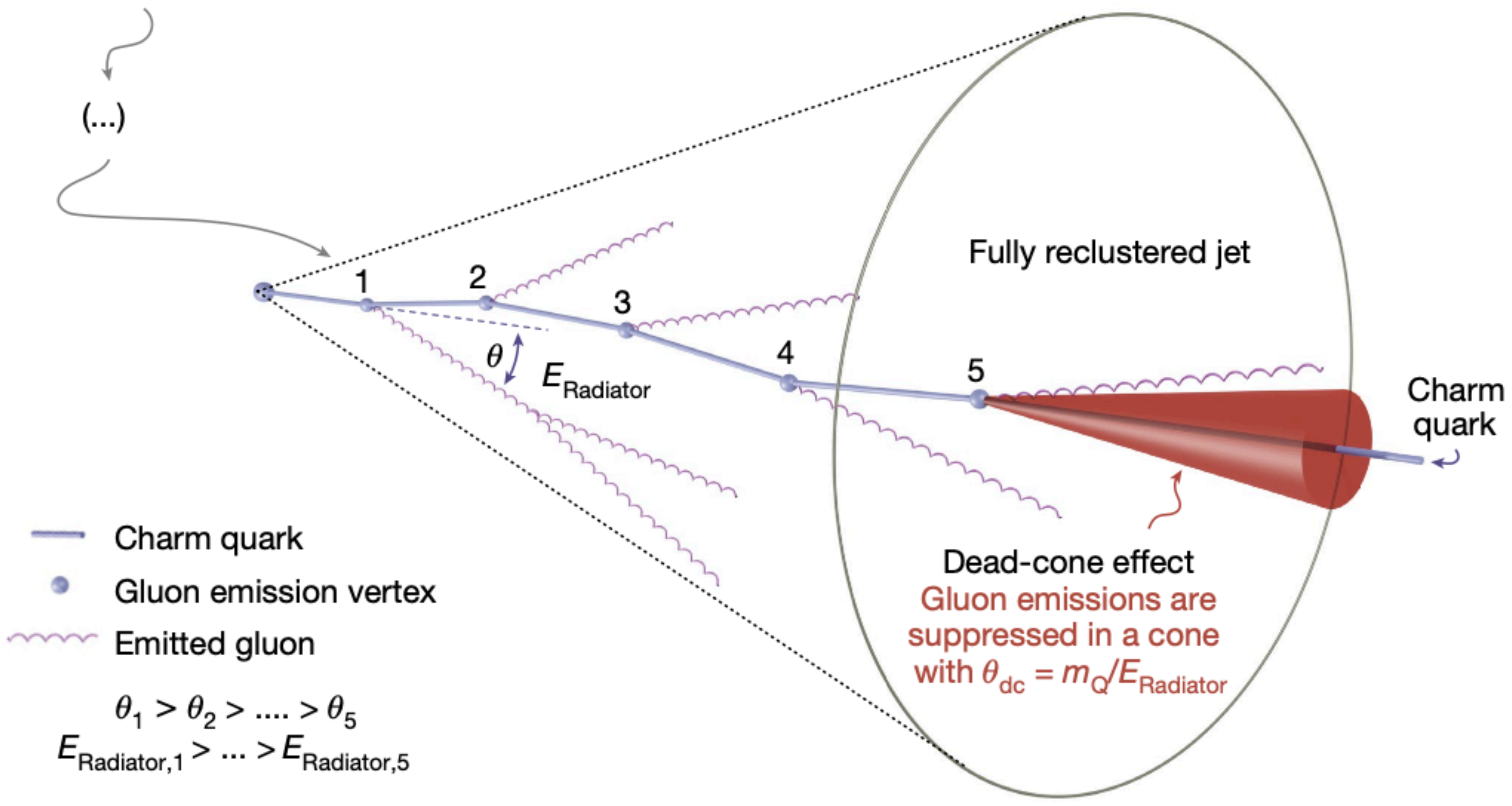
[ALICE Collaboration, Nature Physics]

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.

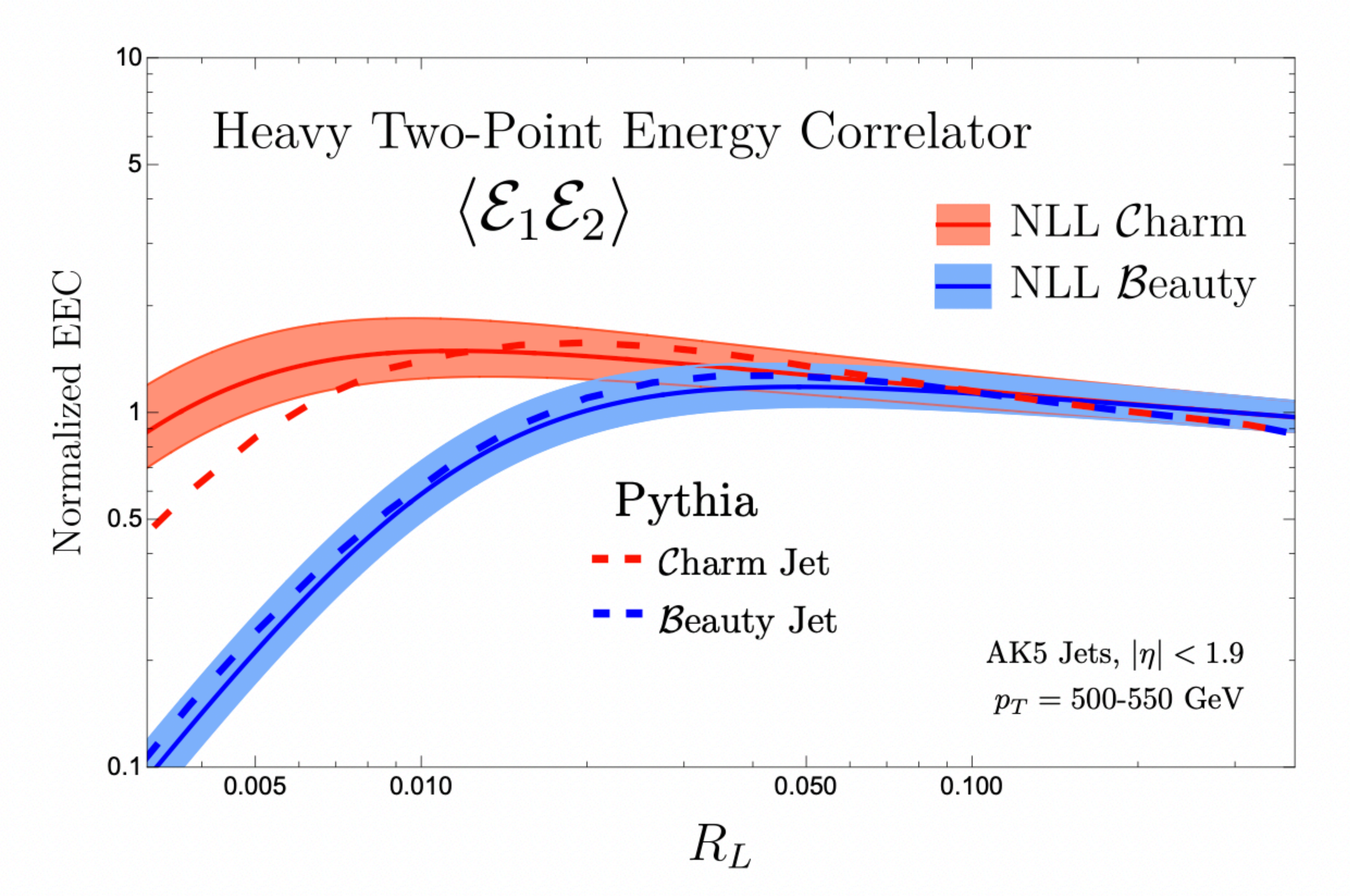
Measured this year by ALICE using a complex iterative declustering technique

→ 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

Application: Intrinsic Mass

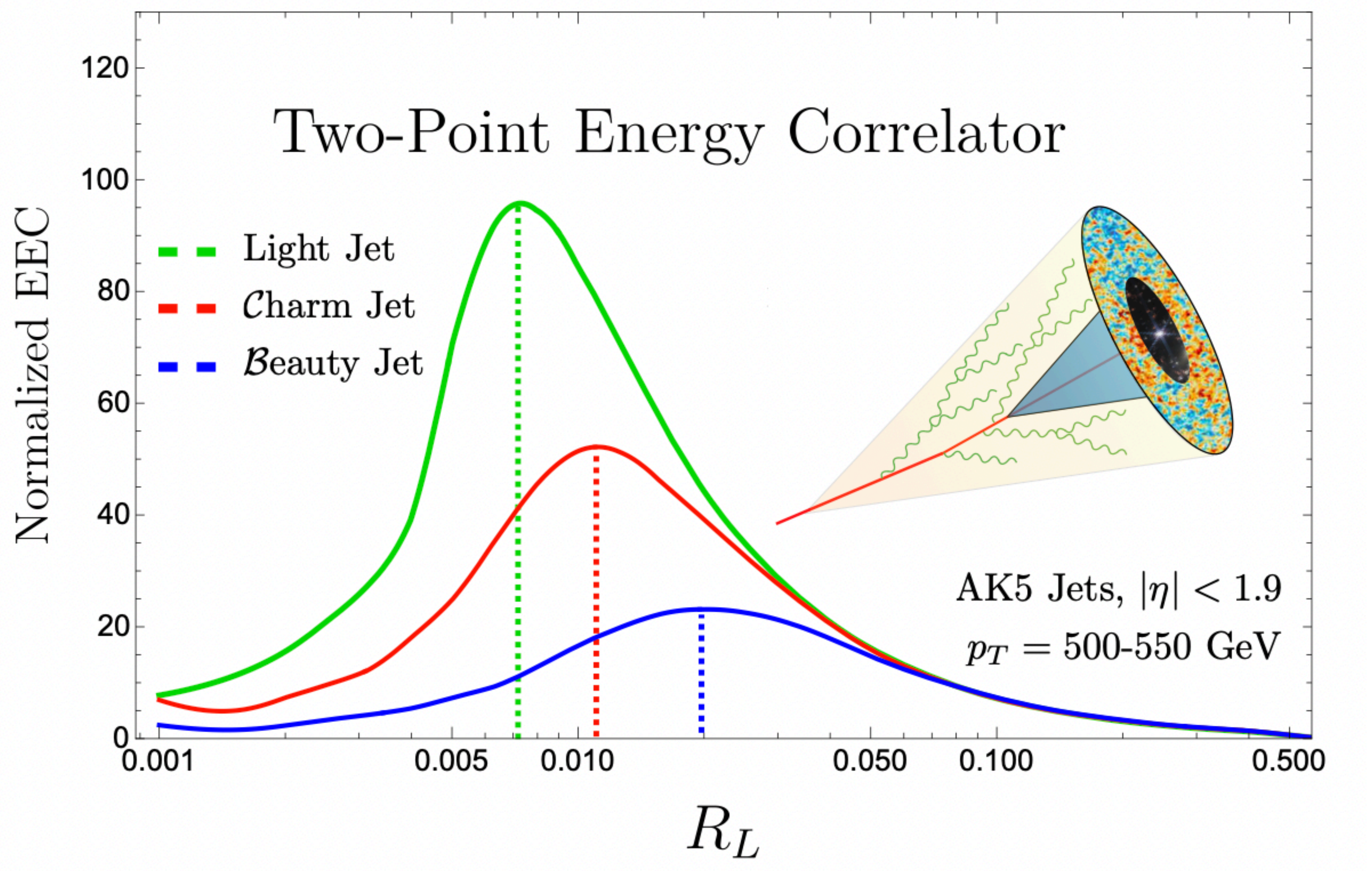
In the UV regime, scaling should be independent of mass

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

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

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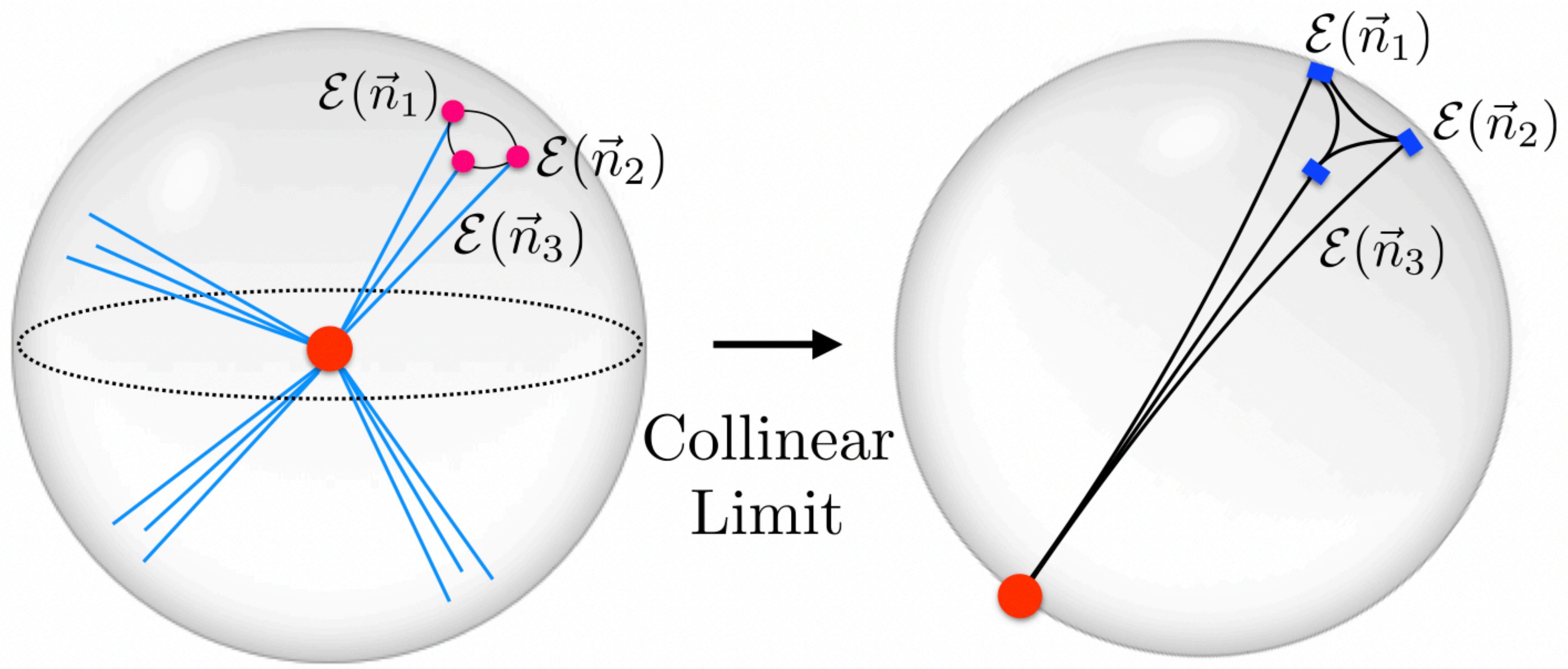
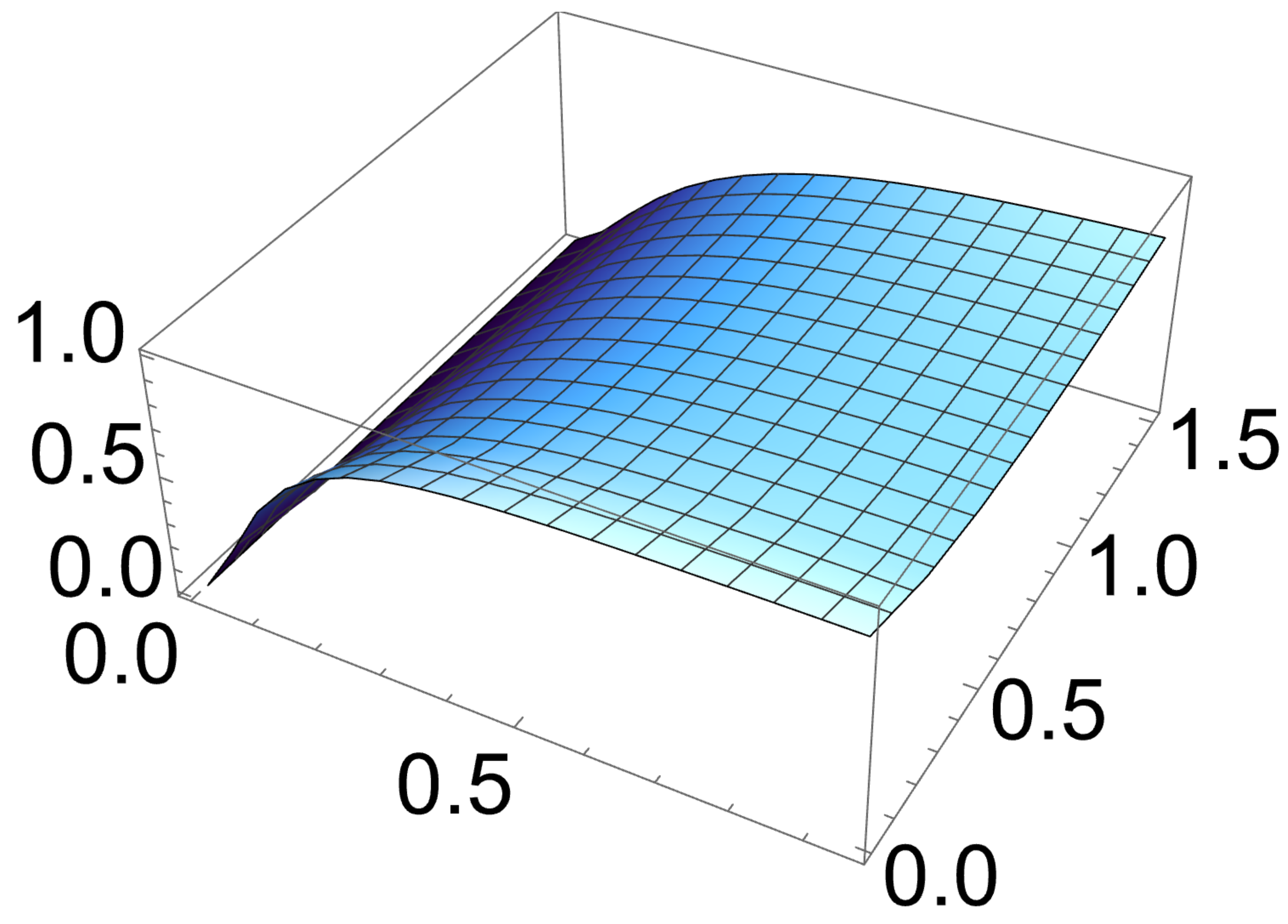
Extension: Higher Points

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

Fixes the structures which appear in the result

Beautiful Structures: Elliptic Functions

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

Kinematic constraint gives rise to an elliptic curve

$$y^2 = 4x^3 - g_1 x - g_3$$

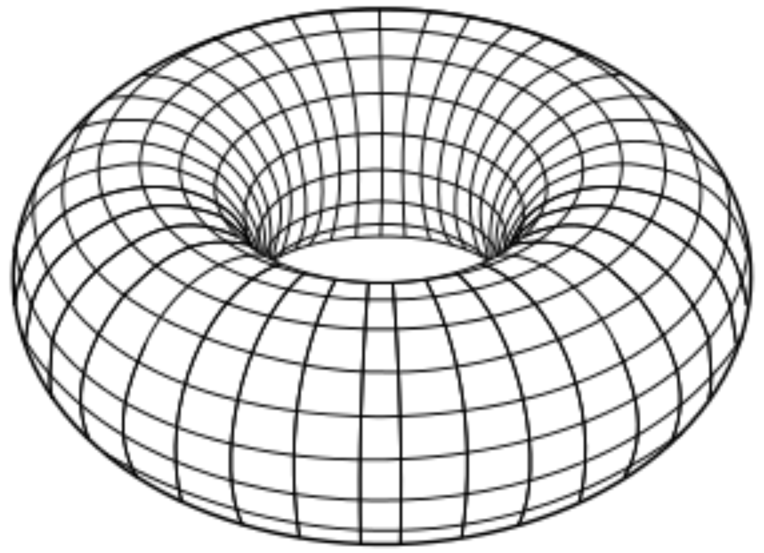
g_1, g_3 **depend on the kinematic configuration (mass, angle, etc.)**

Two Point $\int \frac{1}{y}, \int \frac{x^2}{y}, \int \frac{1}{(x^2 - p^2)\, y}$

→ **Elliptic Integrals:** E, F, Π

Three Point $\int \frac{1}{y}\{E, F, \Pi\}, \int \frac{x^2}{y}\{E, F, \Pi\}, \ldots$

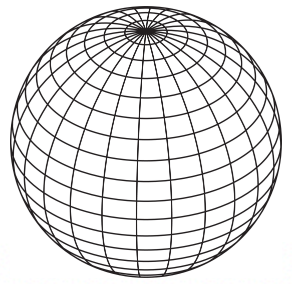
→ **eMPL's, Dilogarithms, etc.**

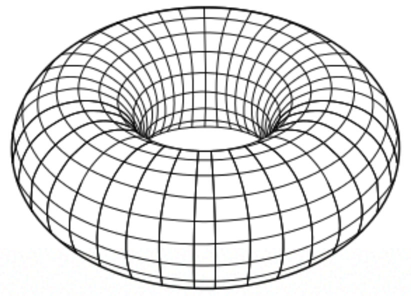


analytic isomorphism to a torus

Topological Aspects

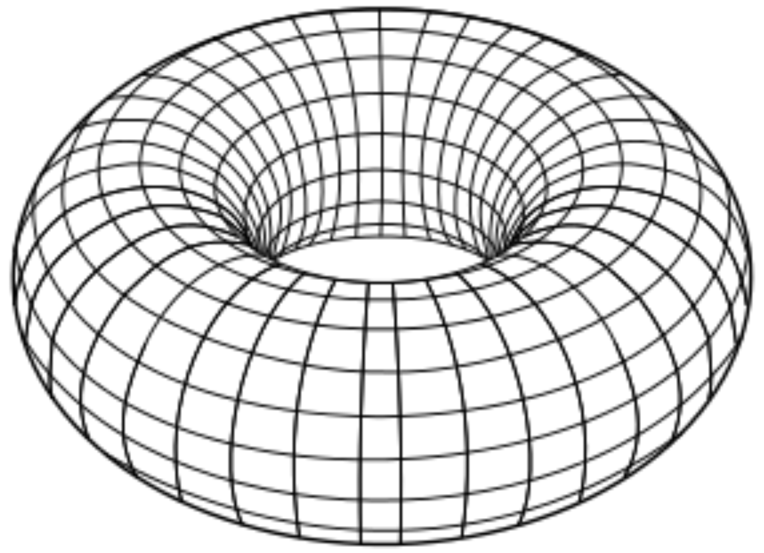
topology **degenerates** in the collinear limit





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

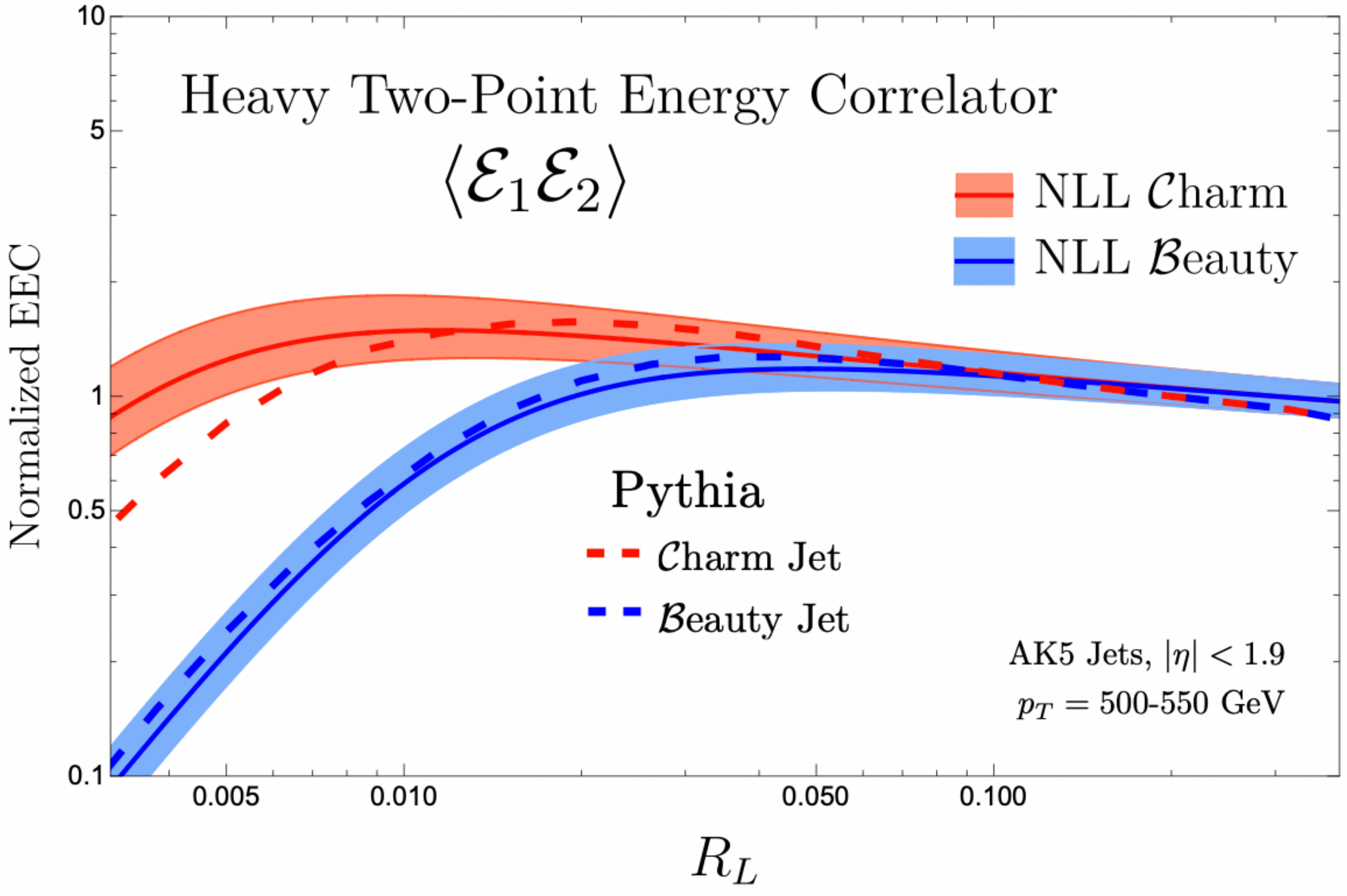
$$y^2 = 4x^3 - g_1 x - g_3 \longrightarrow$$



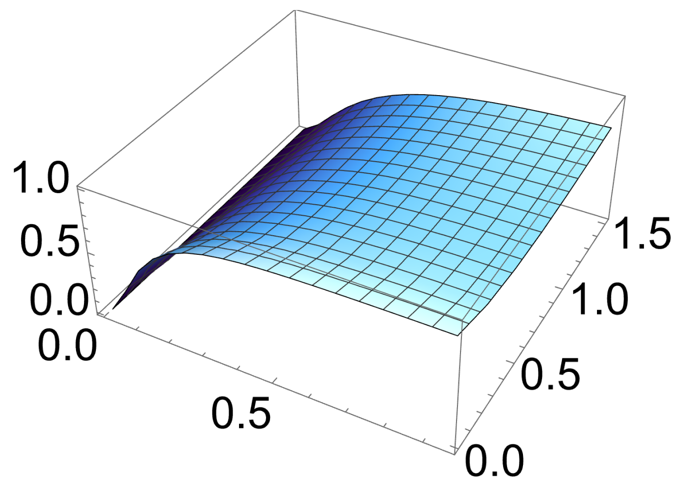
$$\omega_1 \sim {}_2F_1(1/2\,, 1/2\,,1\,; \lambda)$$

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

periods deformed by kinematics



[EC, Lee, Mecaj, Moult]

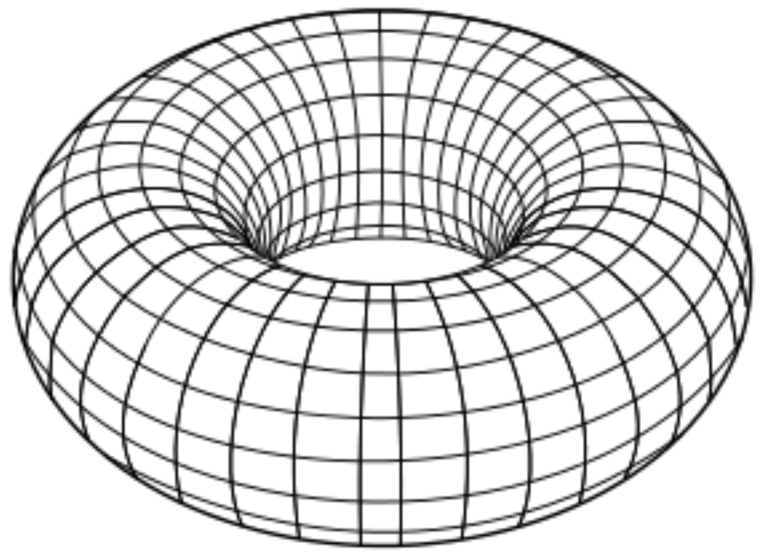


Similar degeneration for the three point!

Interesting to study the **topological** aspects of the observable

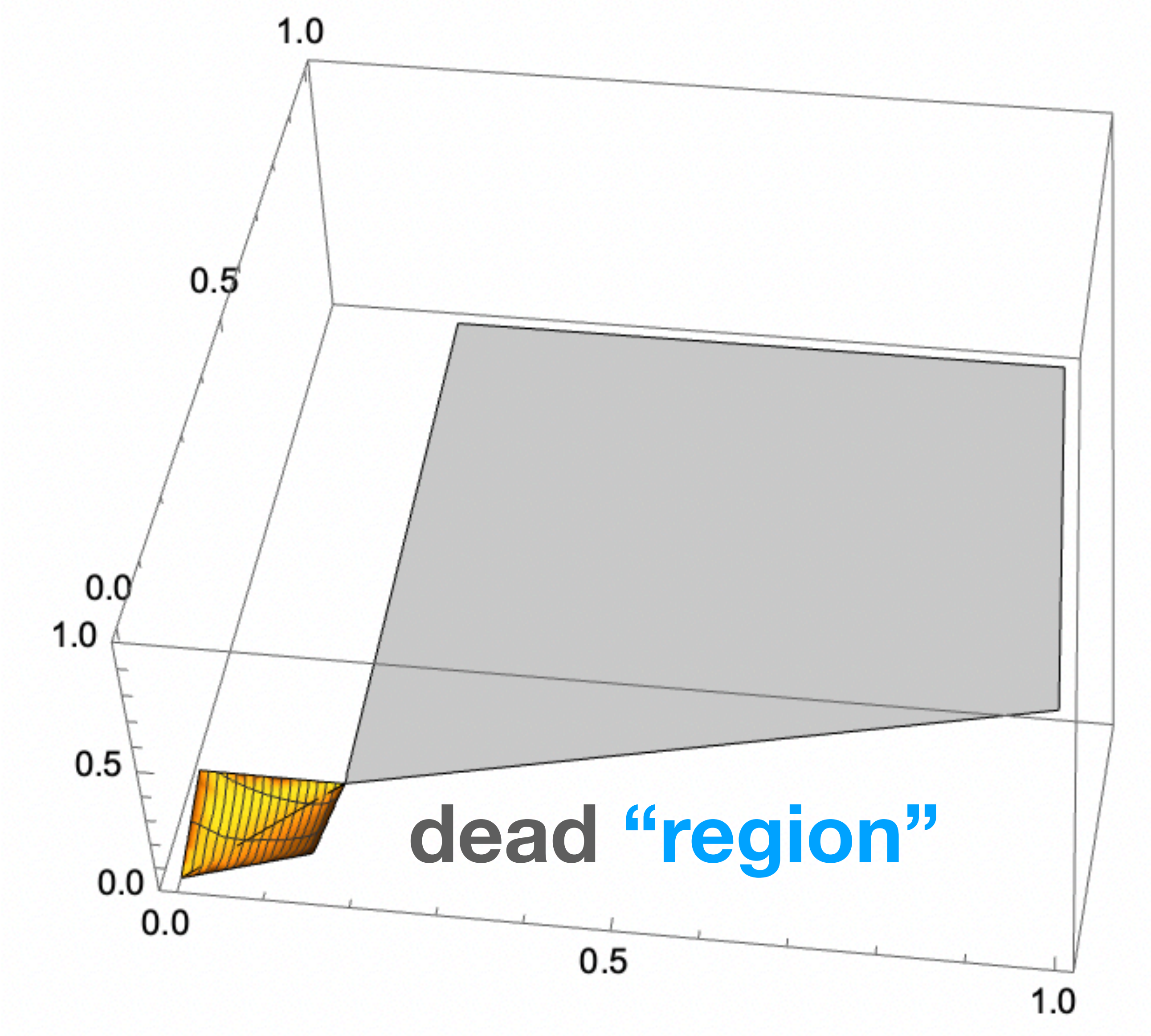
Topological Aspects

degeneration of **functional complexity** in kinematic limits

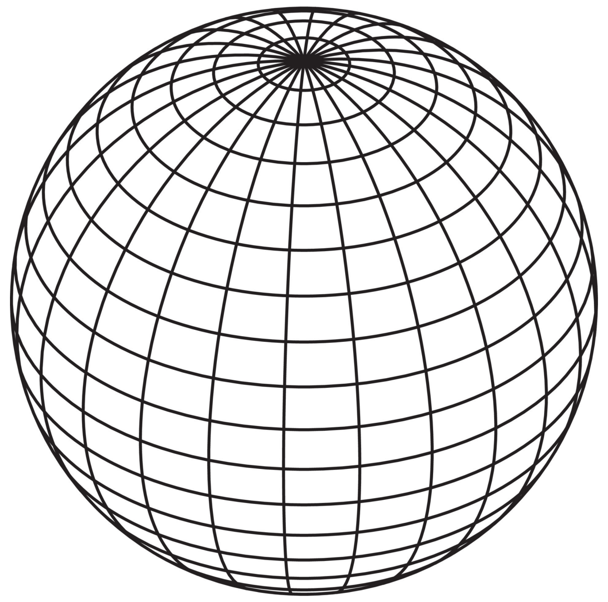


$$\int \frac{1}{y}\{E, F, \Pi\}, \quad \int \frac{x^2}{y}\{E, F, \Pi\}, \ldots$$

eMPL's, iterated integrals over elliptic functions



change kinematics →

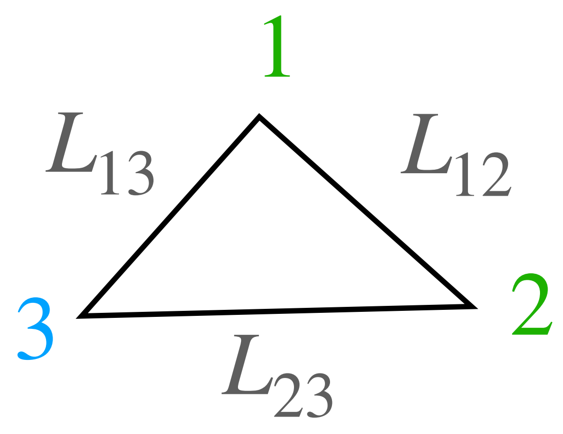


$$\text{Li}_2 = \int \frac{dt}{t} \ln(1-t)$$

dilogarithms, completely classical functions

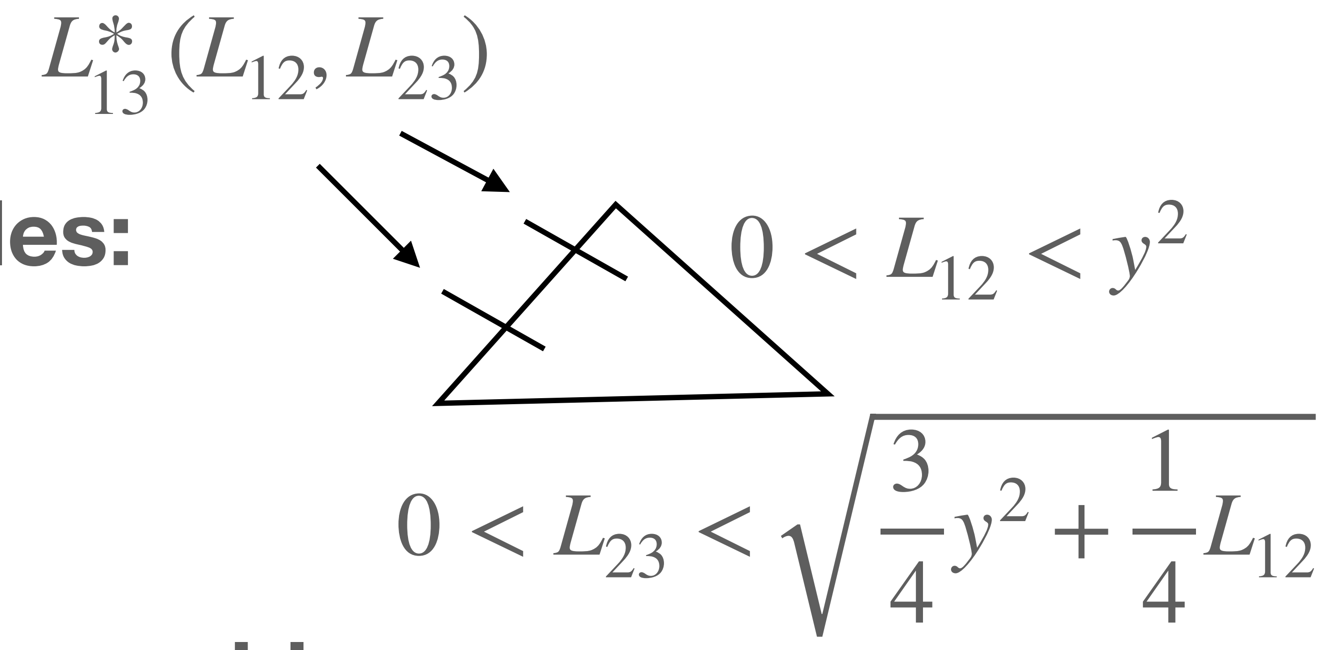
Three Point Triangle:

3 is heavy, 1&2 are light



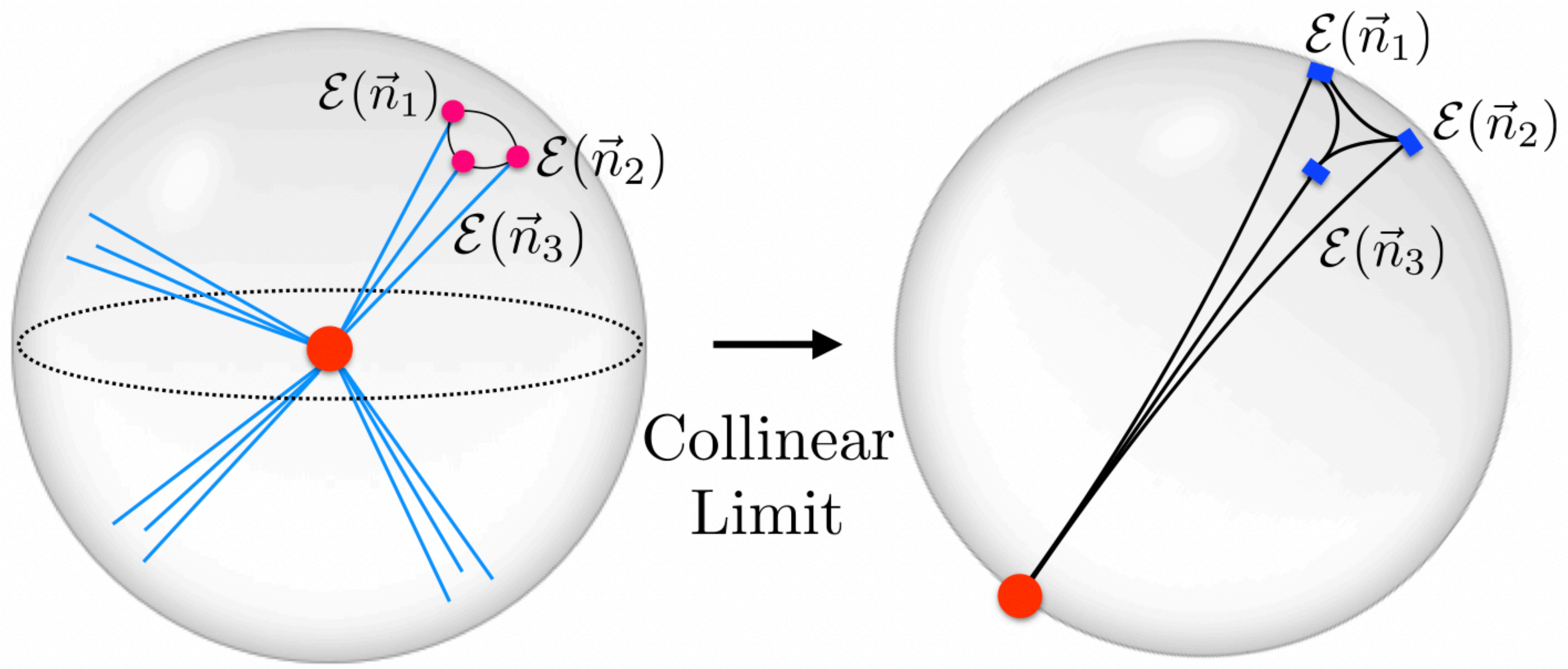
"Dead"-Cone Triangles:

$y = 2m/Q$



Interesting to study the topological aspects of the observable

Extension: Higher Points



Natural to also consider **higher point** correlators

Experimental Side

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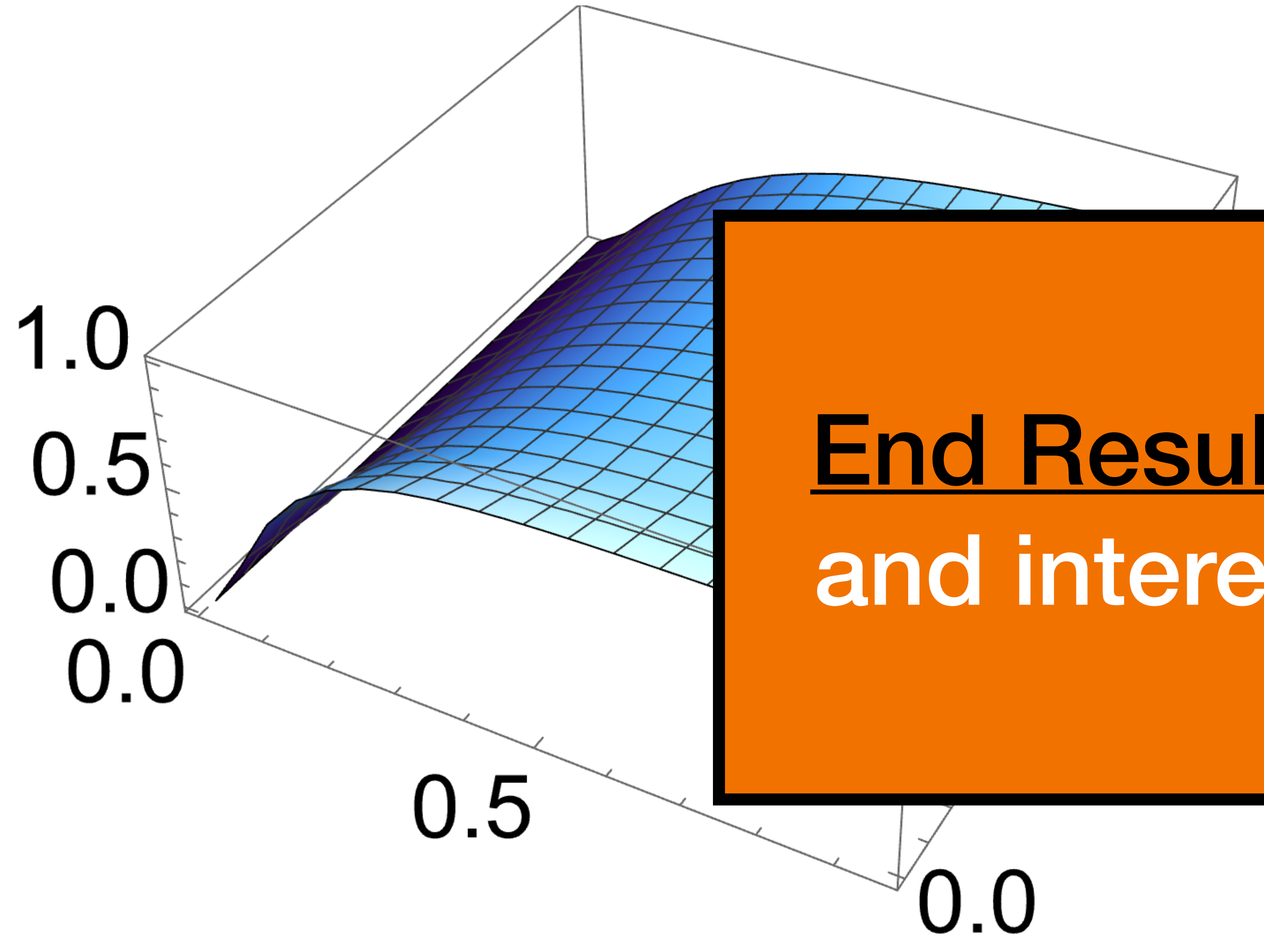


End Result: We can calculate and measure new and interesting observables for jet substructure

Theoretical Side

transverse spin 2

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

helicity ± 1

excited by **2-point**

excited by **3-point**

→ Access to **non-Gaussianities**

→ Full **Shape** Dependence

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

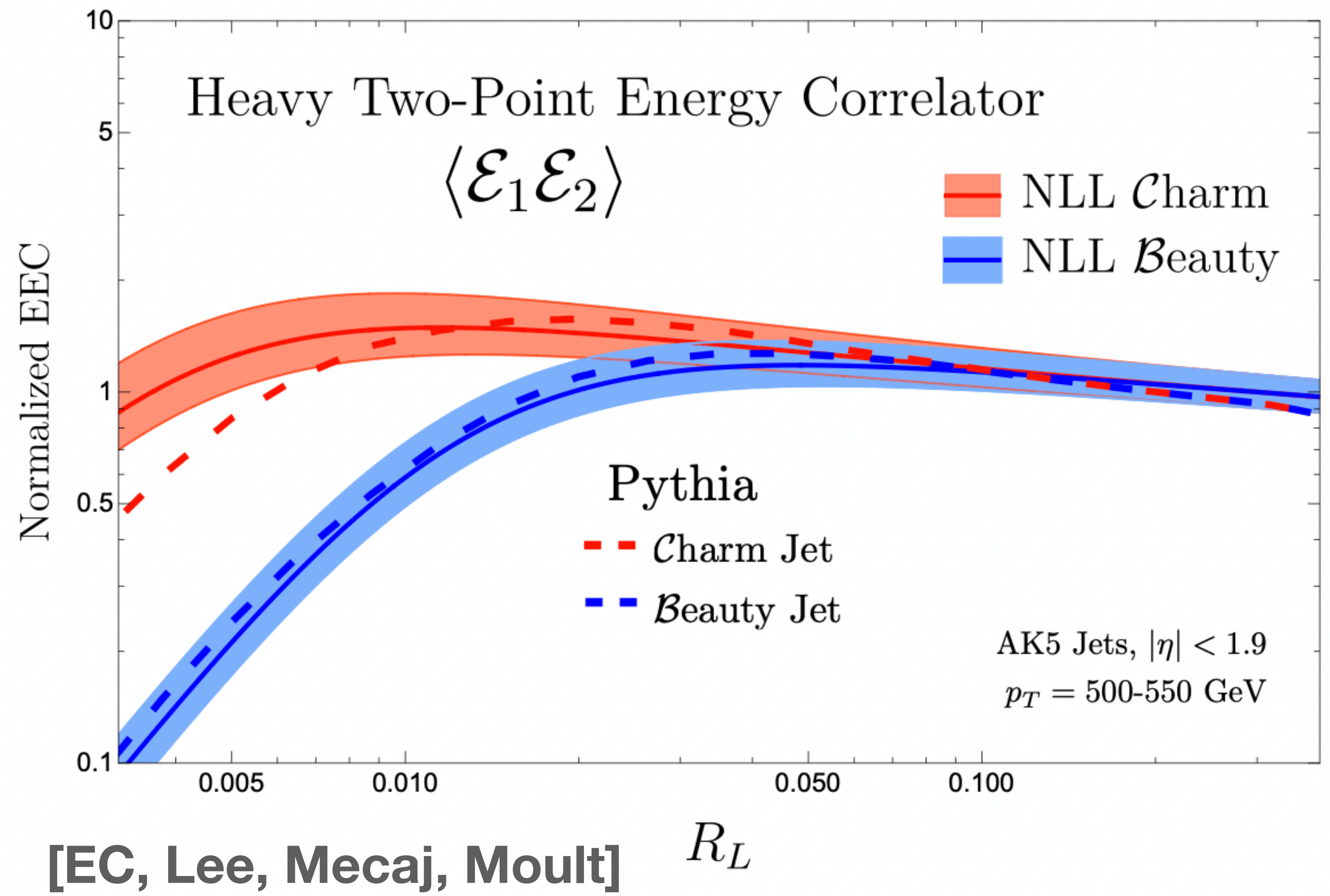
→ Probe fundamental operators of **QCD**

Concluding Remarks

Unifying Theory and Experiment

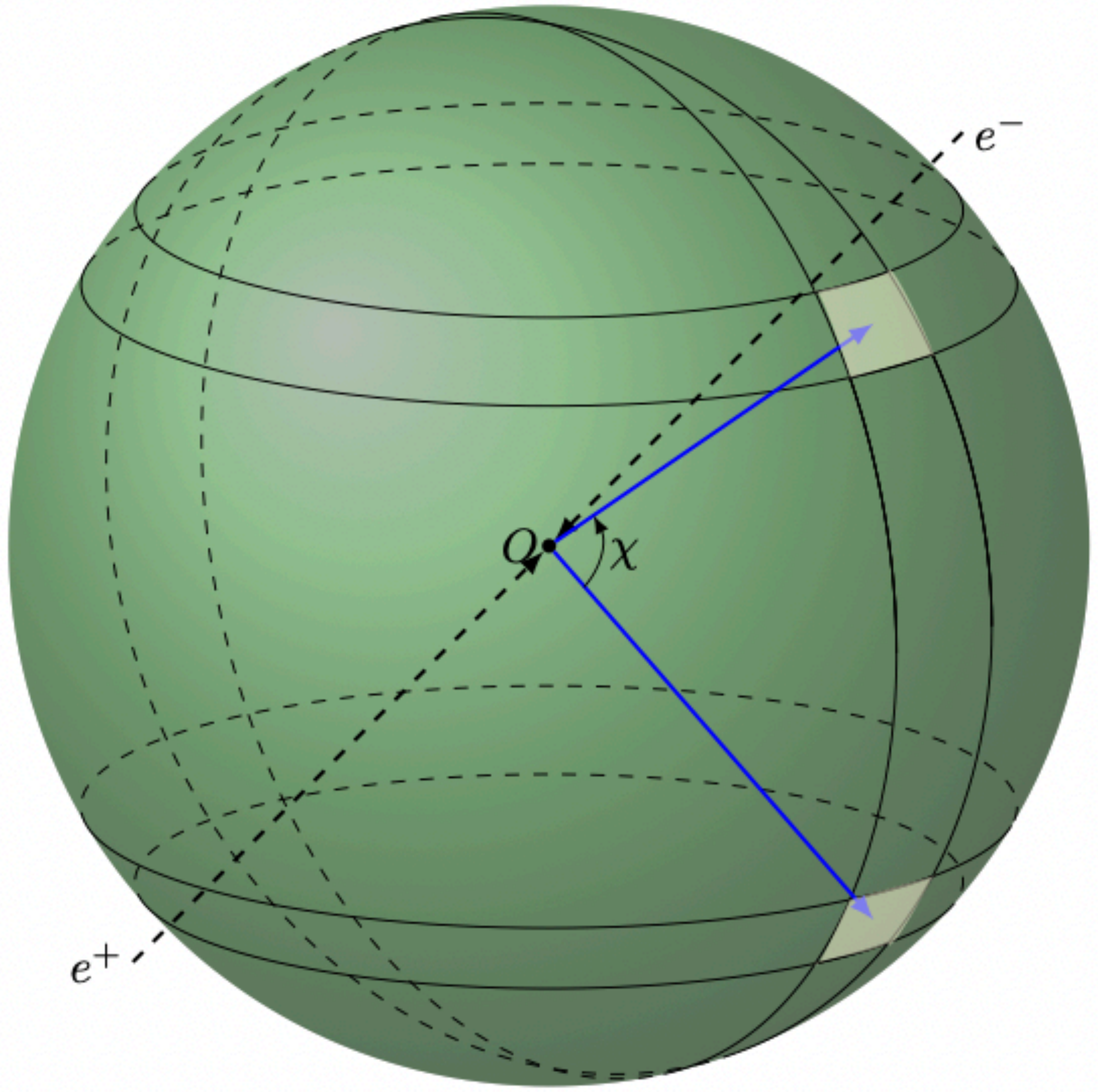
Two Symbiotic Perspectives

Beautiful and Charming Interplay!



[EC, Lee, Mecaj, Moult]

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

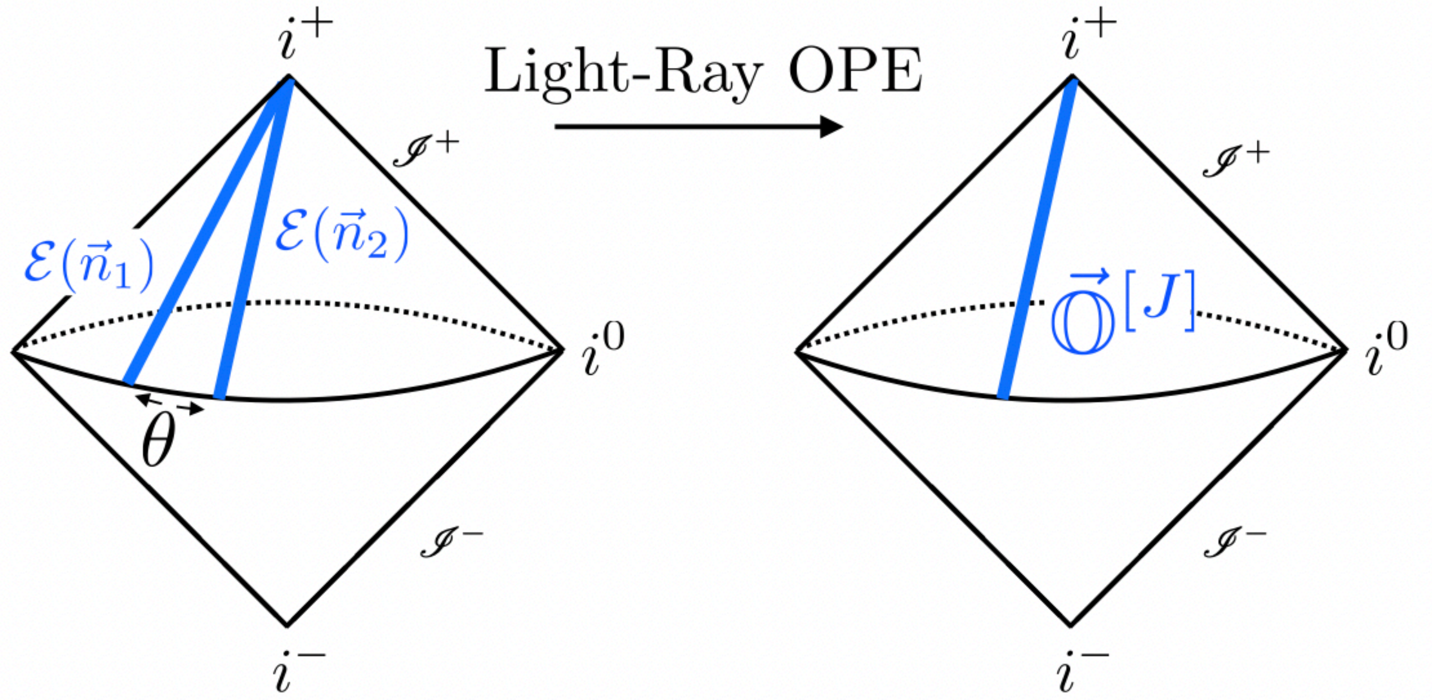


Experiment

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