Energy Correlators, Heavy Flavor, & Precision QCD

Evan Craft — Yale University

MITP

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

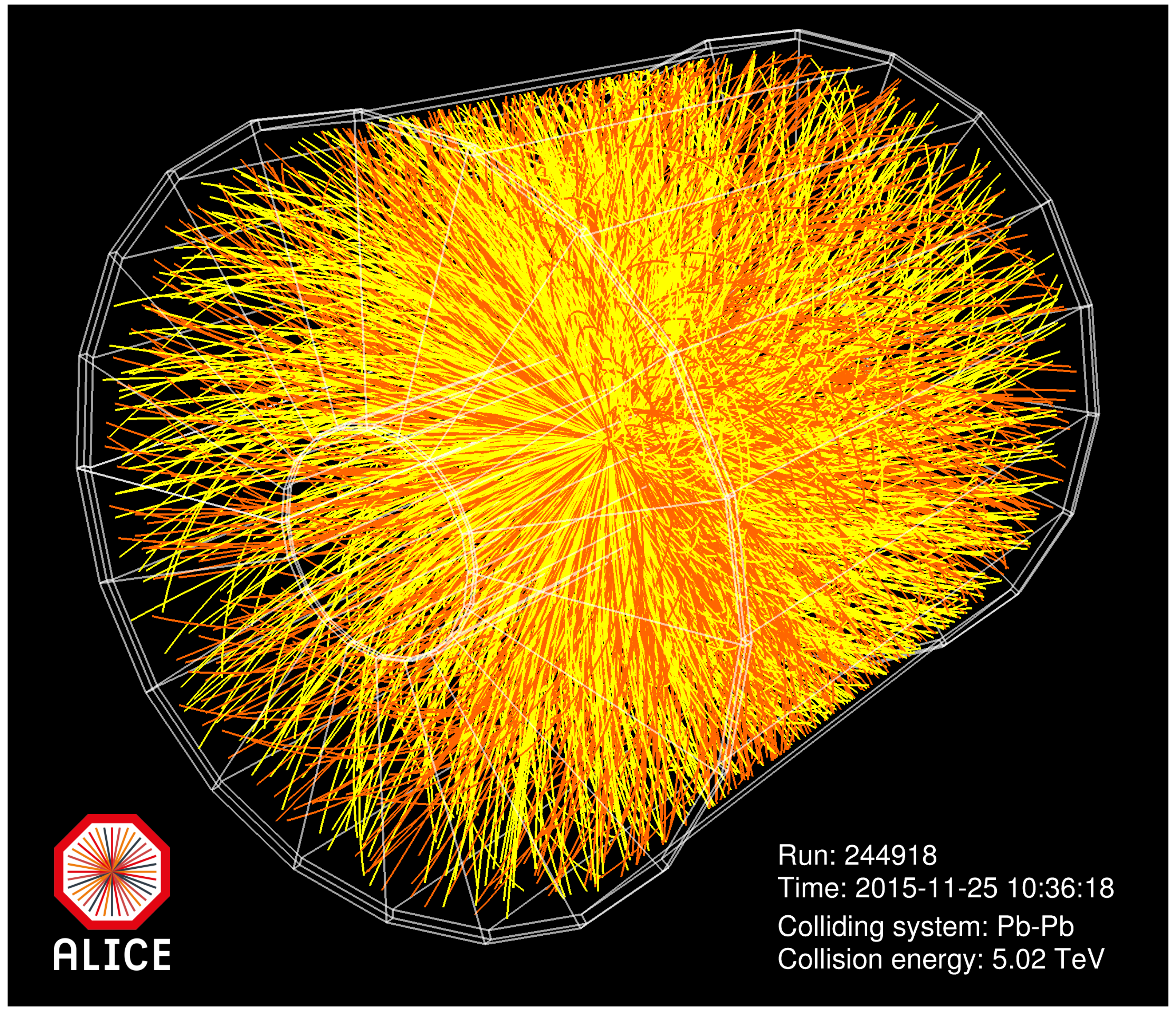
Yale University

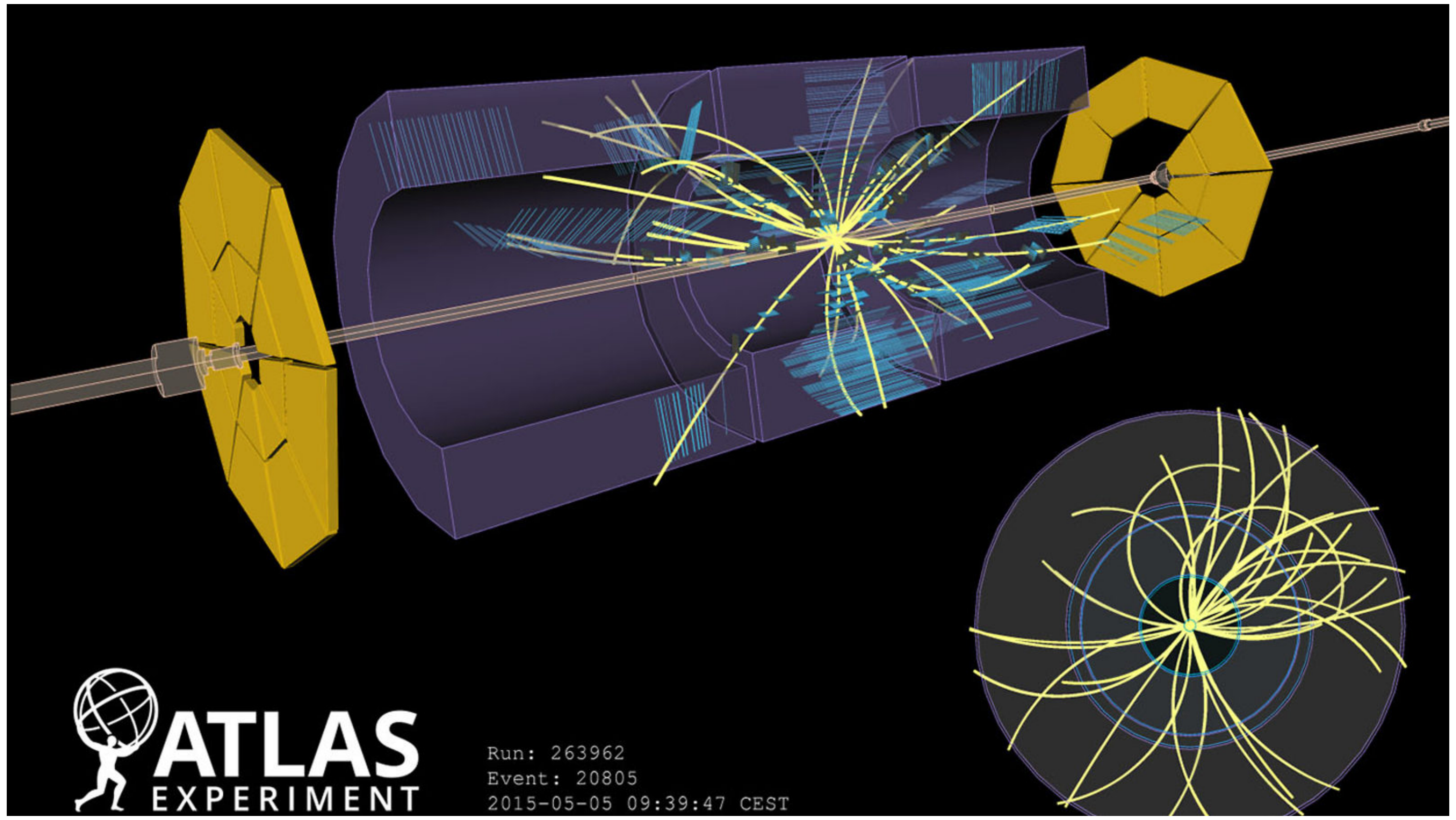
MIT

Collider Experiments

Many important questions have been addressed at collider experiments

→ Great historical success in verifying properties of the standard model





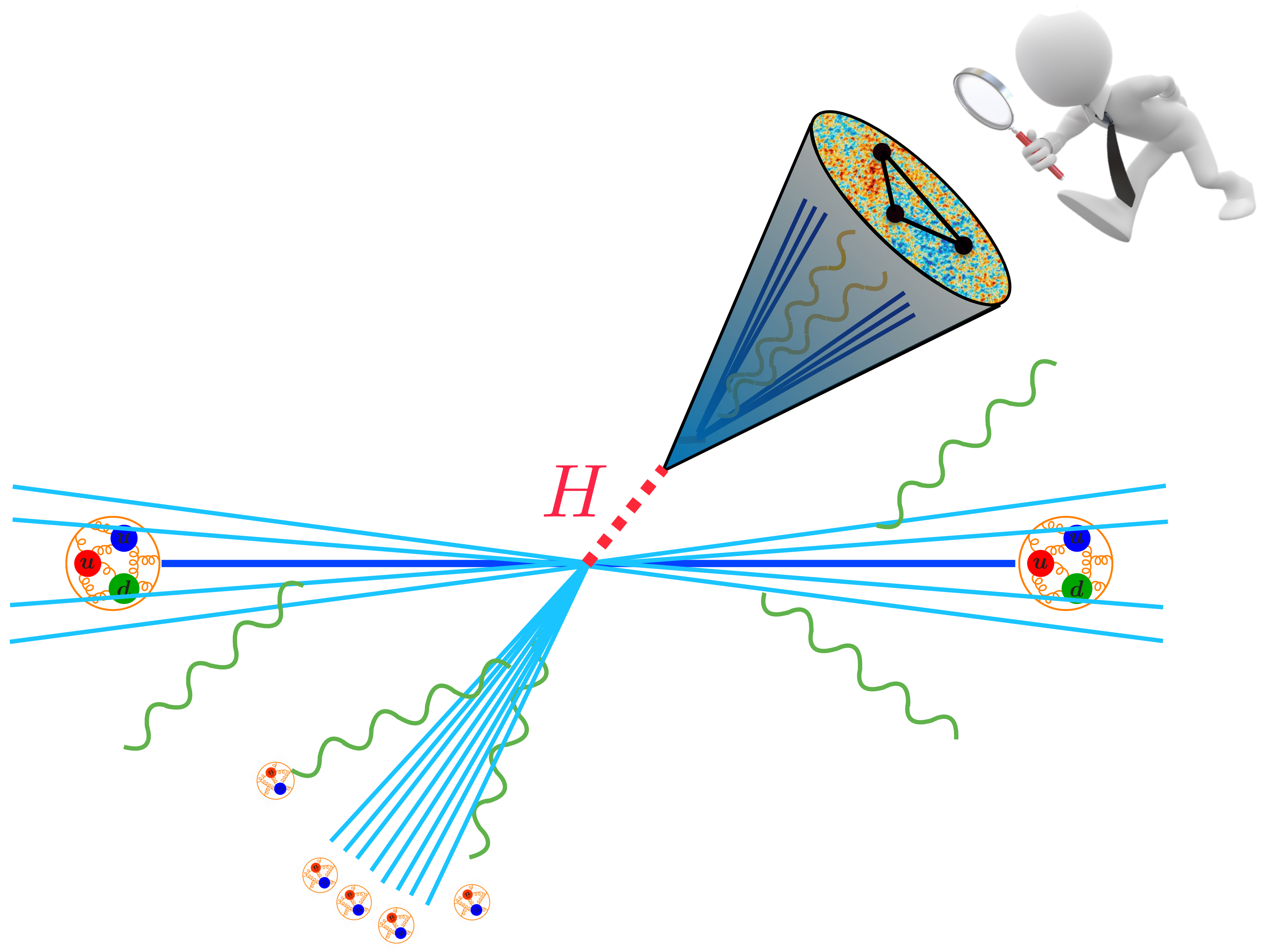
→ But the detailed structure of QCD produces immensely complicated datasets.

→ Need new tools for future success

A unique frontier for novel collaborations between both theory and experiment

Jet Substructure

In recent years, strong success in high energy physics has been driven by remarkable progress in jet substructure.



→ Uses the internal structure of jets to provide qualitatively new ways to study physics at colliders

→ Has impacted multiple collider experiments ranging from proton colliders all the way up to heavy ions.

Jet substructure as a new Higgs search channel at the LHC

Jonathan M. Butterworth (University Coll. London), Adam R. Davison (University Coll. London), Mathieu Rubin (Paris, LPTHE), Gavin P. Salam (Paris, LPTHE)

Sep, 2008

3 pages

Part of Proceedings, 16th International Conference on Supersymmetry and the Unification of Fundamental Interactions (SUSY08) : Seoul, Korea, June 16-21, 2008, 189-191

Published in: *AIP Conf.Proc.* 1078 (2009) 1, 189-191

Proceedings of: 16th International Conference on Supersymmetry and the Unification of Fundamental Interactions (SUSY08), 189-191

Published: Jan 26, 2009

e-Print: 0809.2530 [hep-ph]

DOI: 10.1063/1.3051904

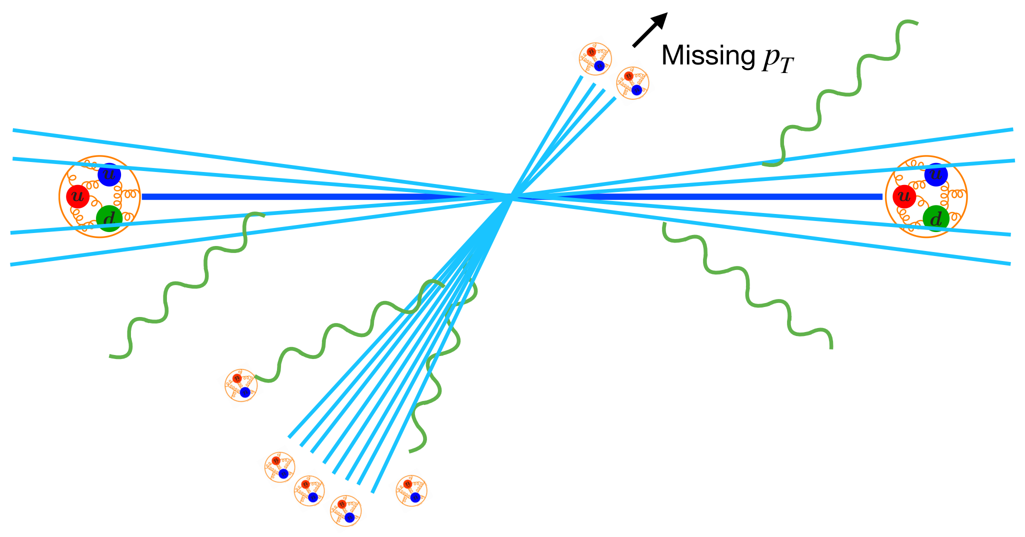
View in: HAL Archives Ouvertes, ADS Abstract Service, CERN Document Server

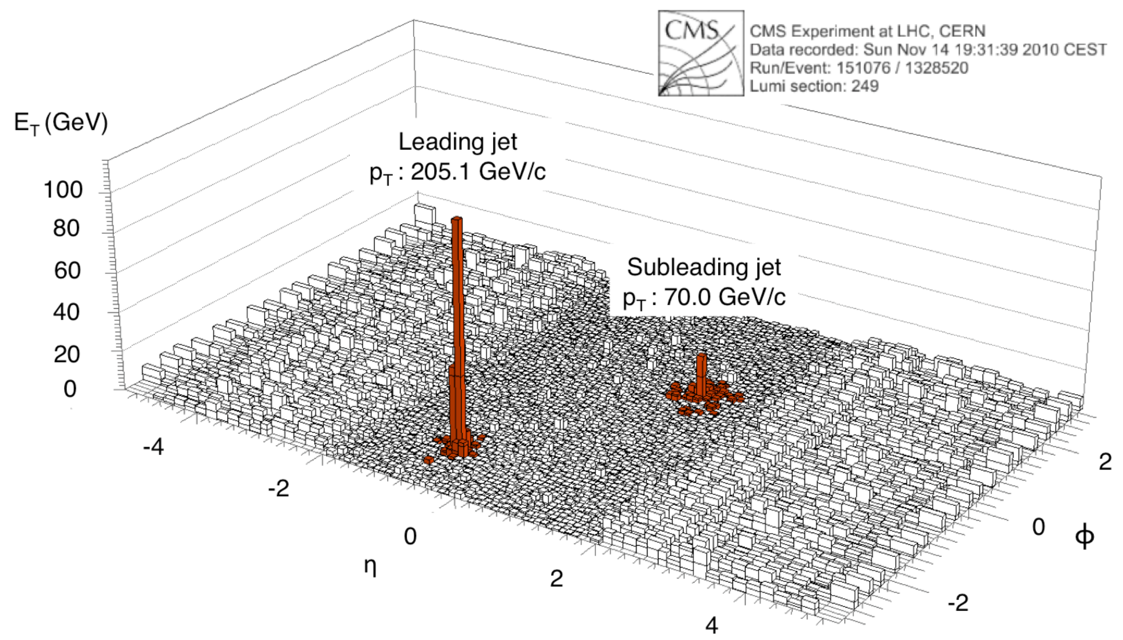
How do we study collisions?

Along with **many** more exciting observations!

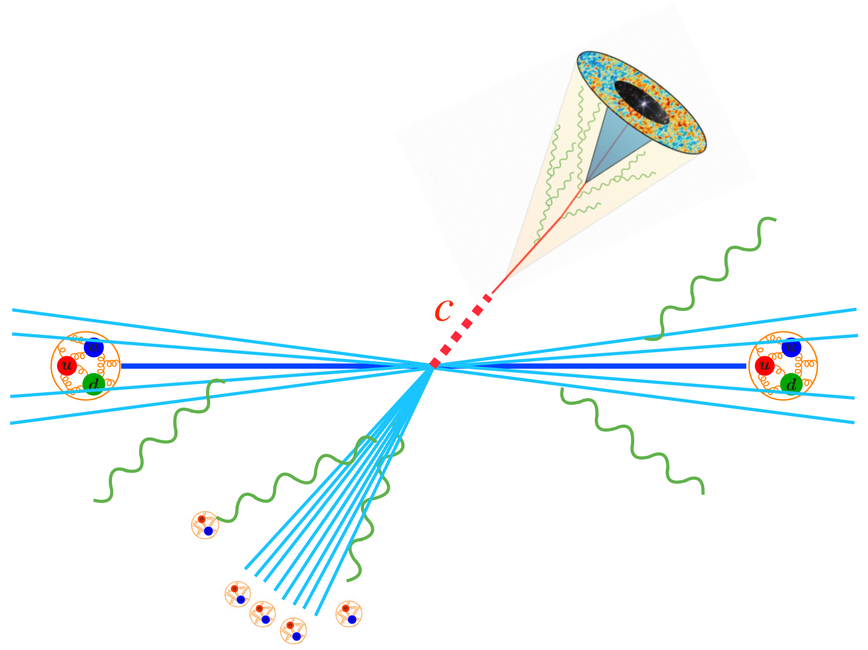
Several remarkable observations made by studying **jets**

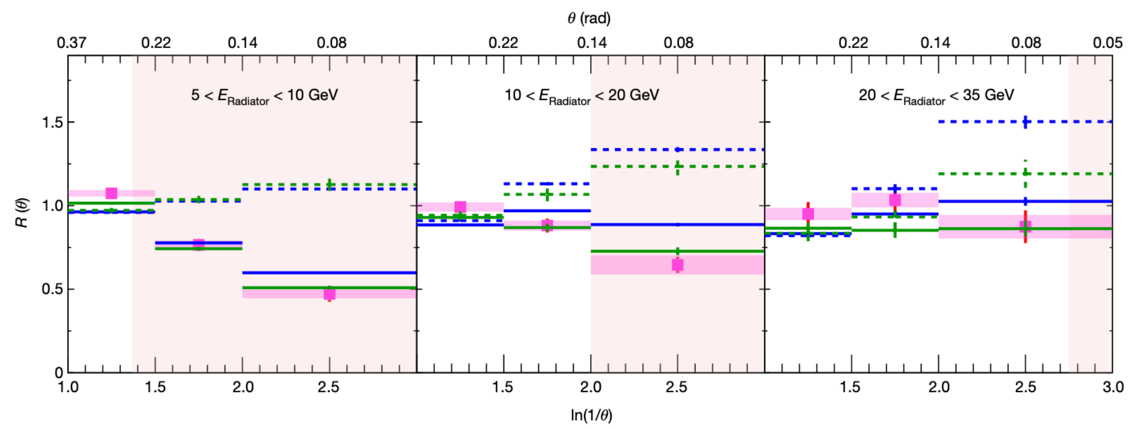
→ provided initial evidence for the **existence** of the Quark Gluon Plasma



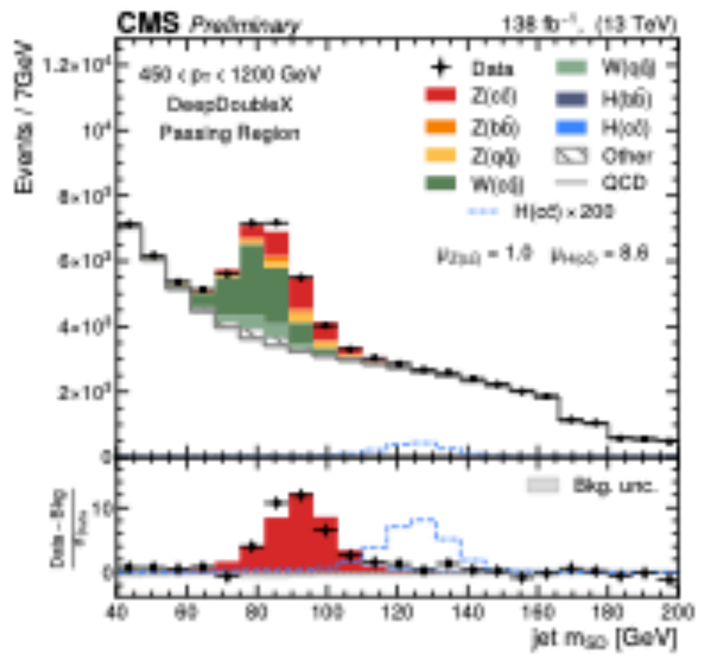


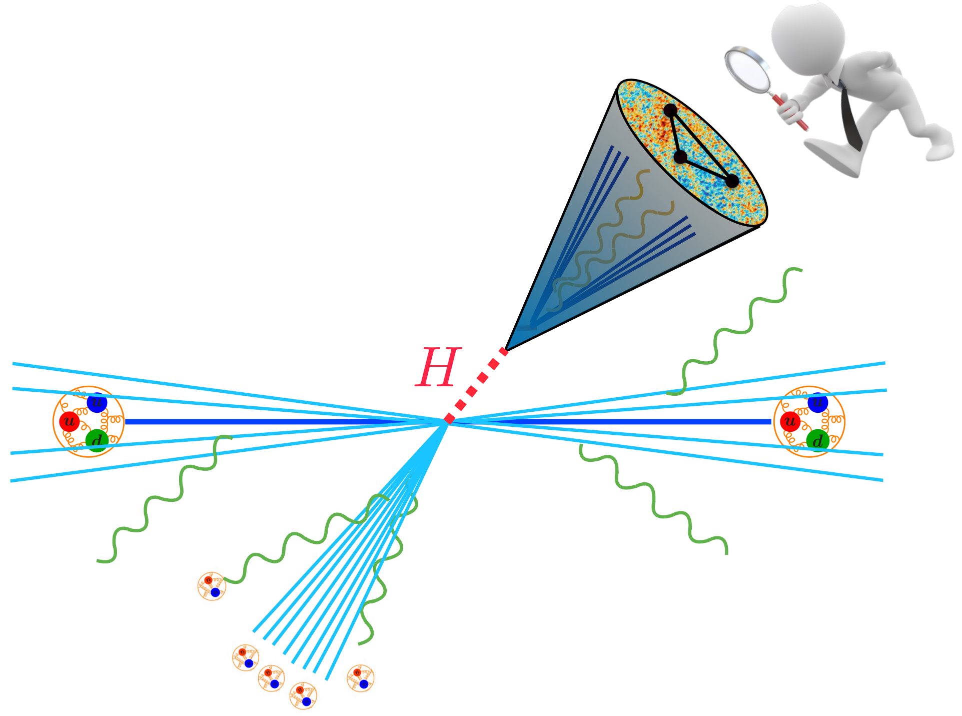
→ allowed first ever observation of the **“dead cone”** effect of QCD





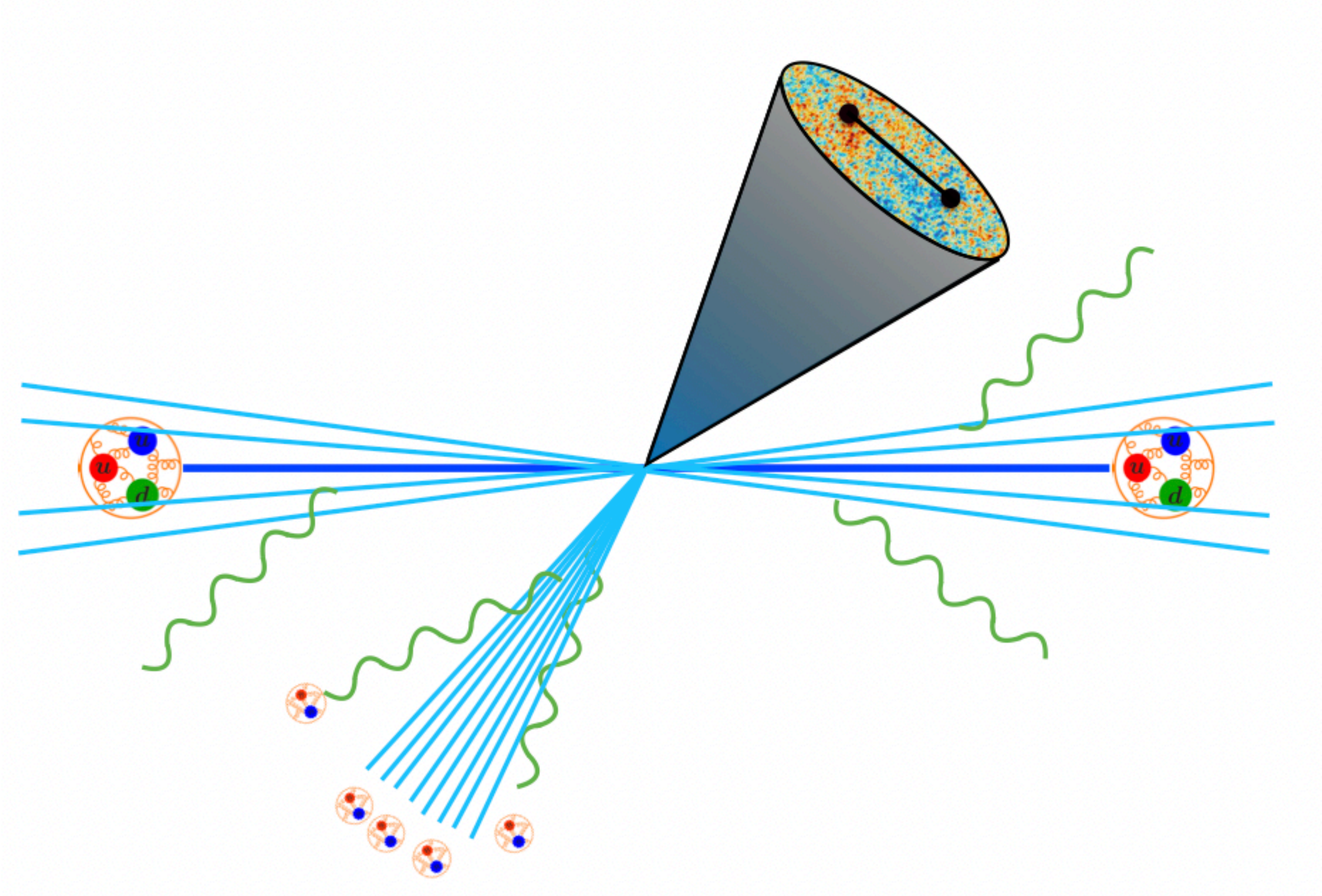
→ provides the most stringent bounds on **charm** Yukawa couplings



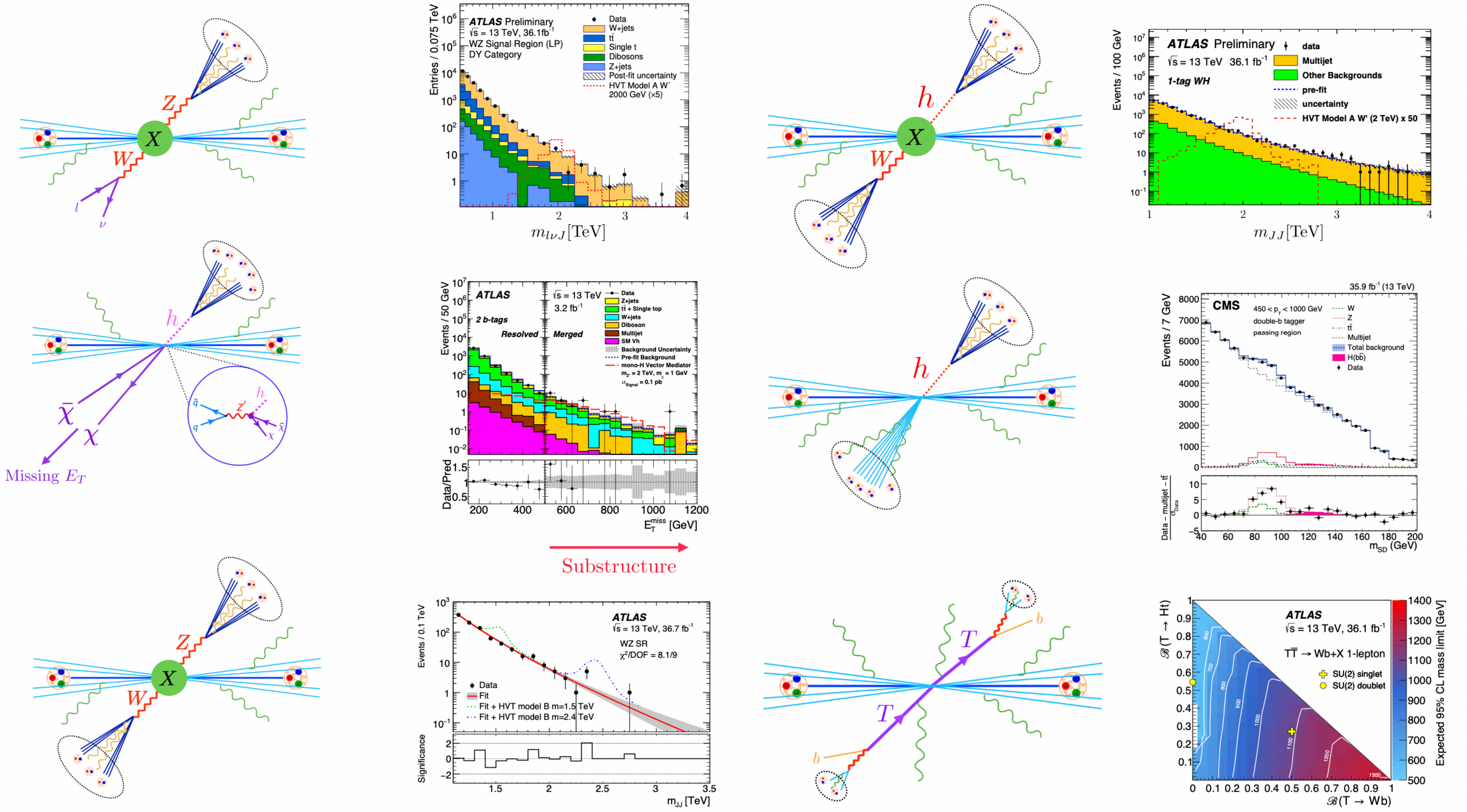


Looking Forward

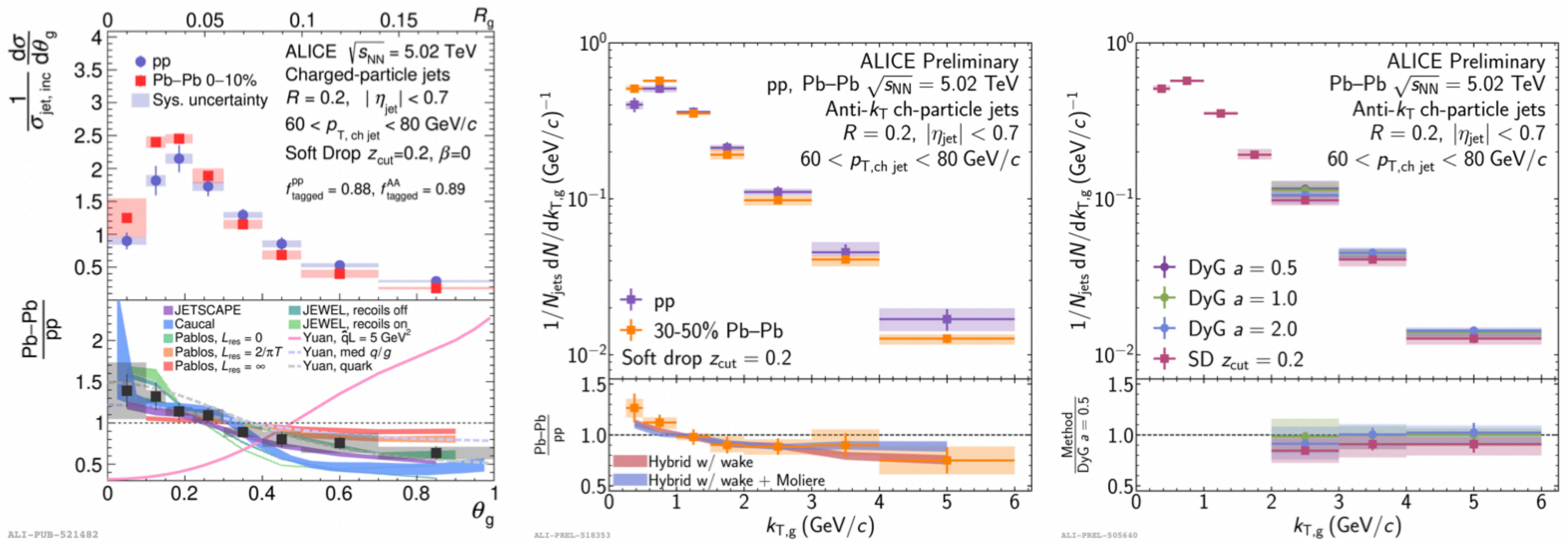
Large impact on **future** searches and probes across nuclear/particle physics



→ ***Jet Substructure** is intrinsically tied to the future of collider studies*



→ ***(B)SM** searches at the ATLAS and CMS*



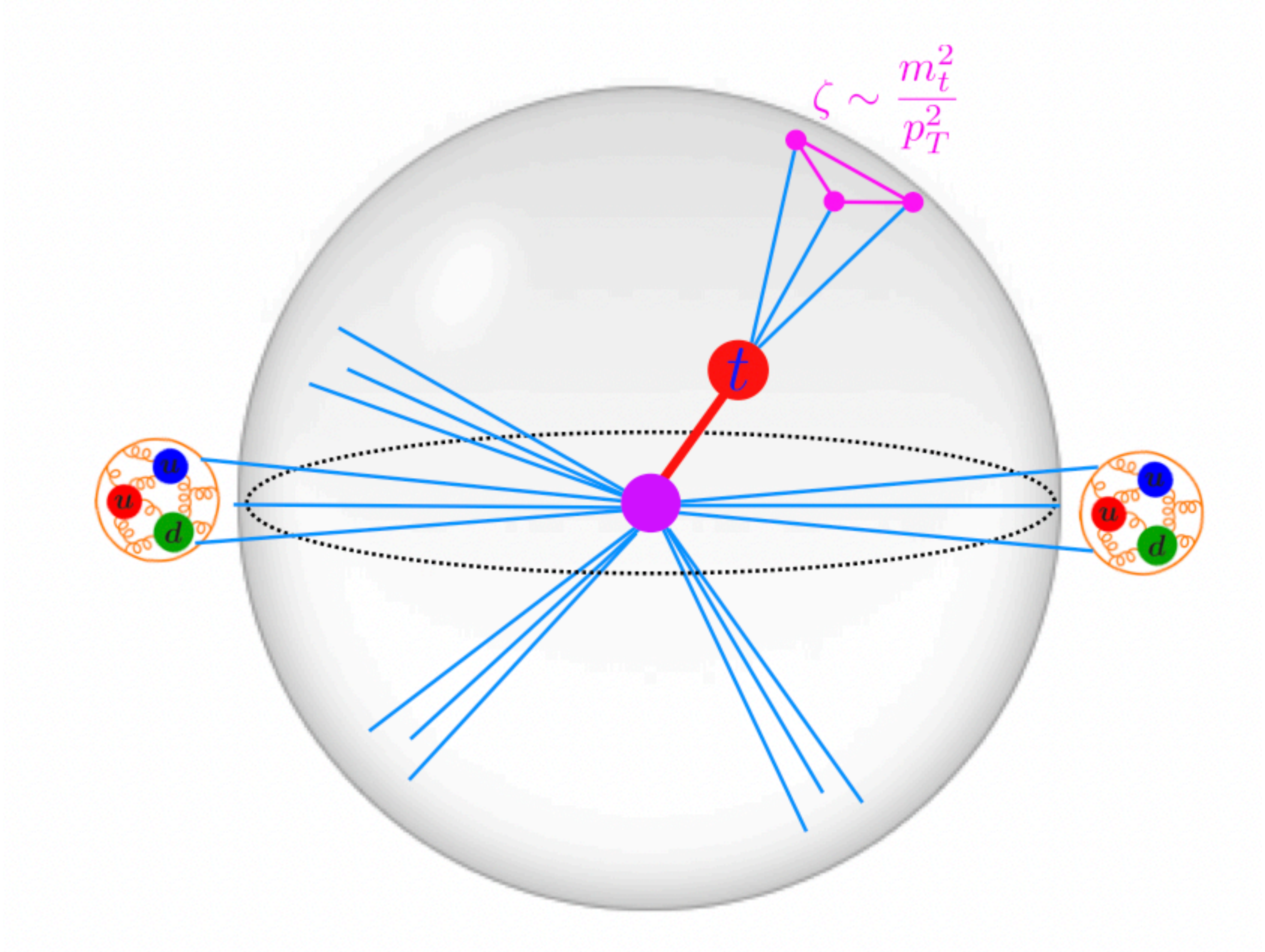
[H. Bossi]

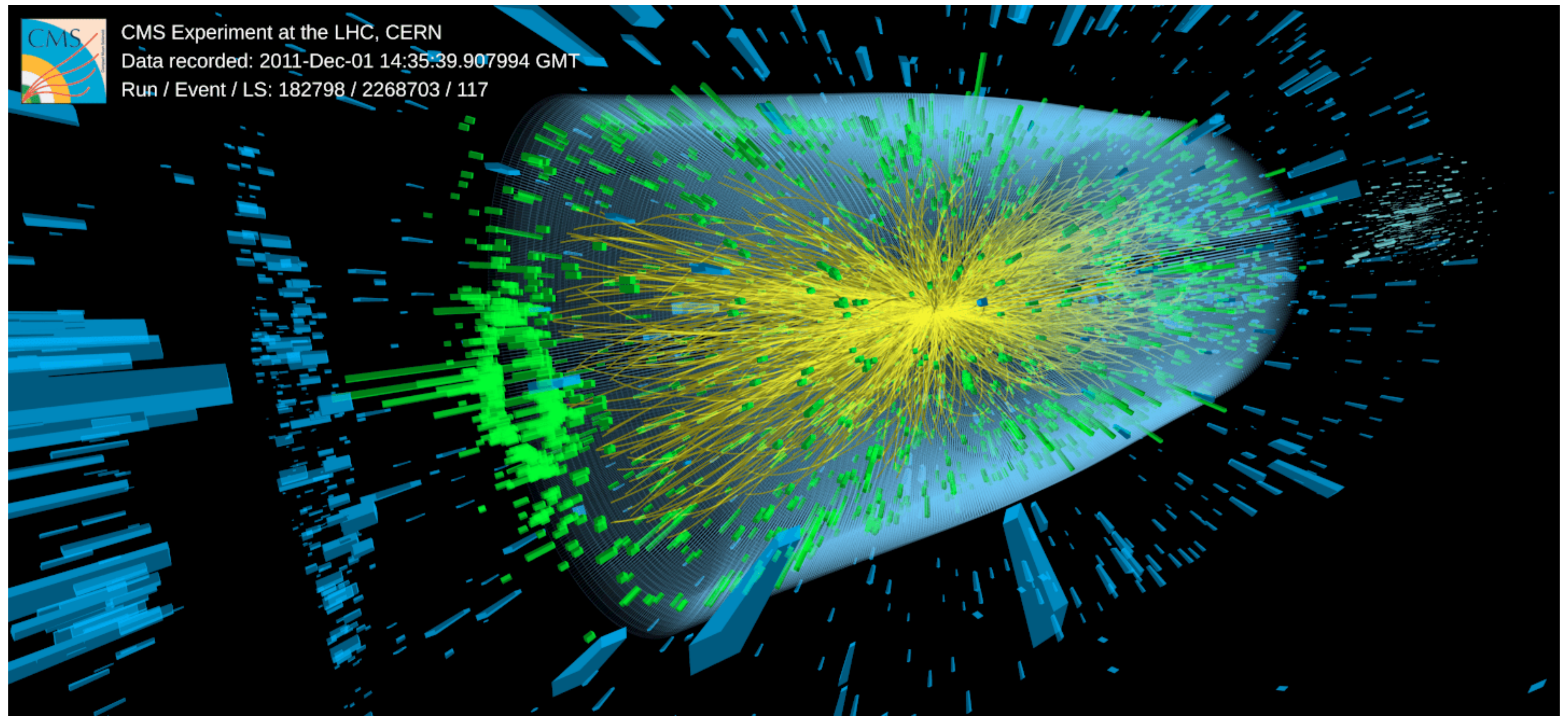
→ ***Quark Gluon Plasma** studies at ALICE*

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, …



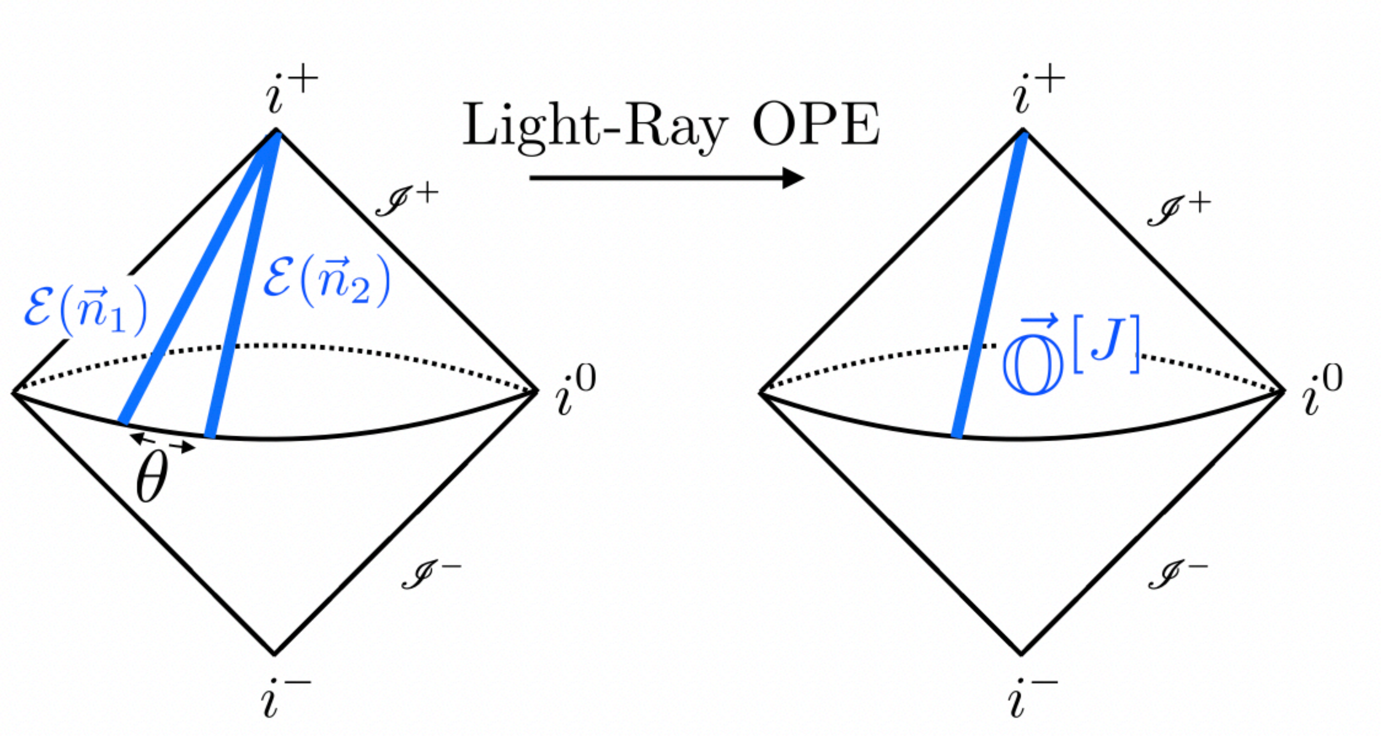


Requires the development of a new set of theoretical tools

Outline

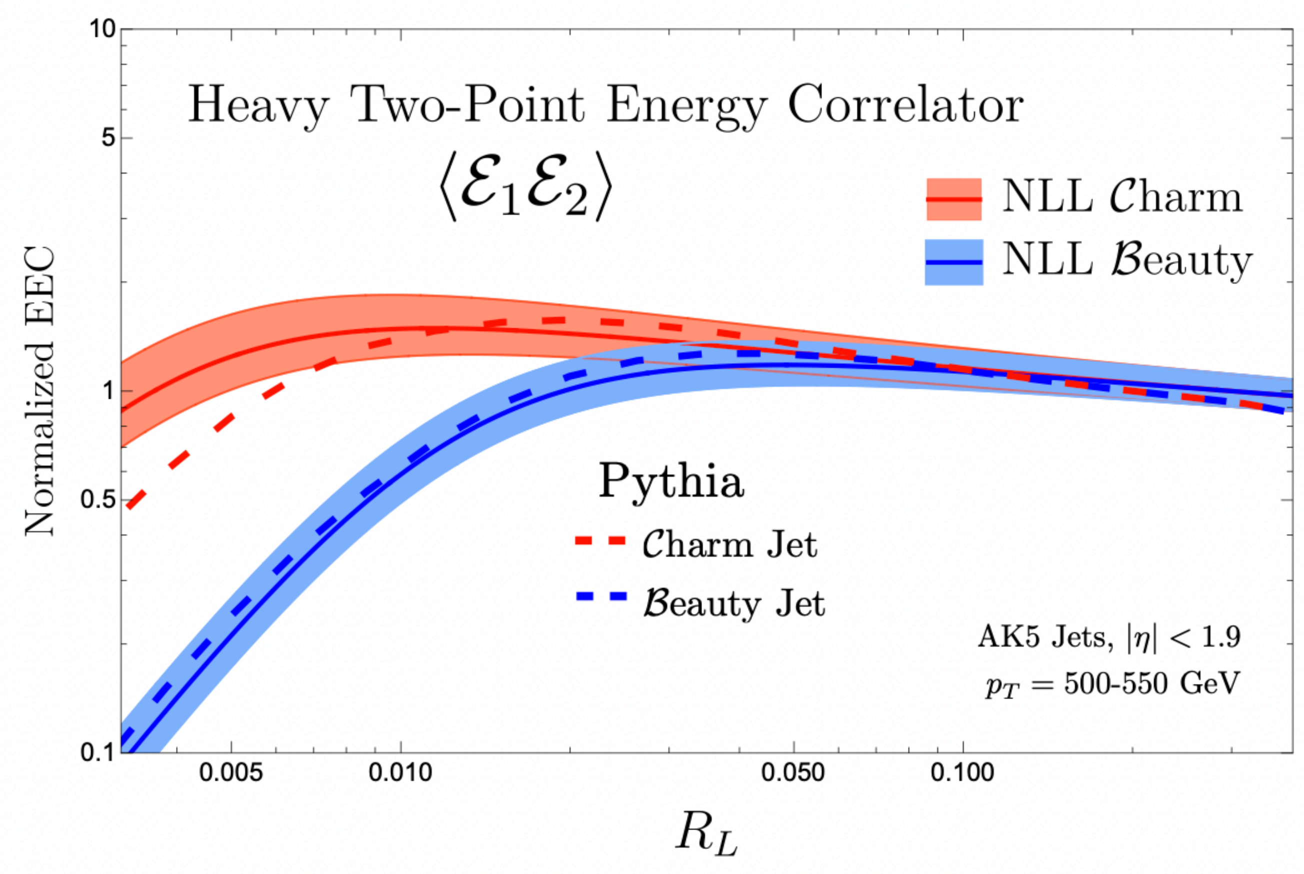
1. Energy Flow Operators

→ General Overview



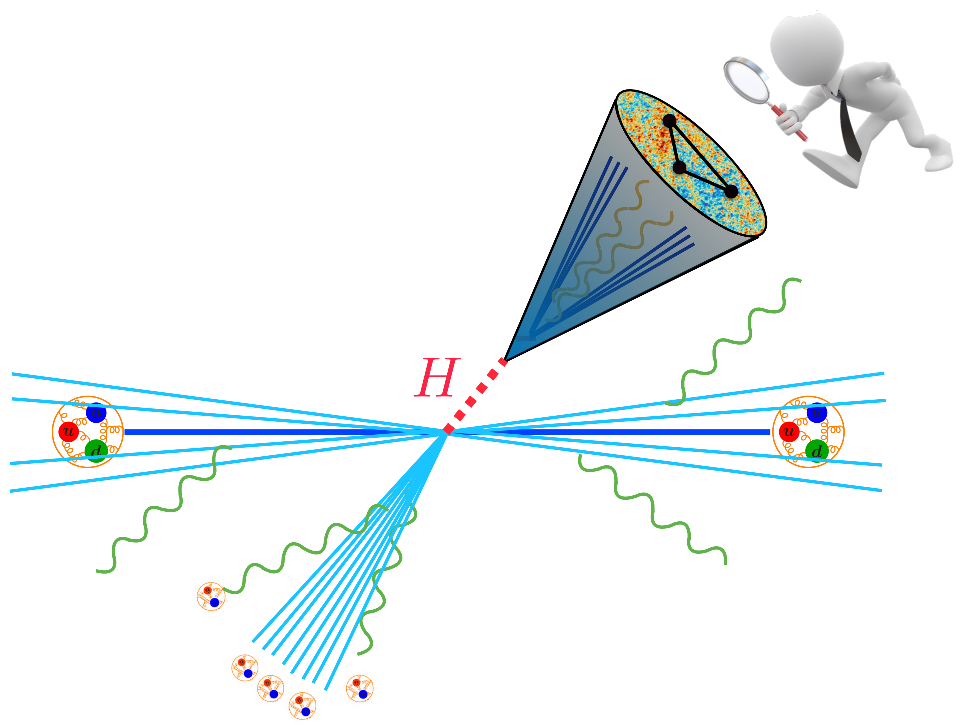
2. Applications to Heavy Flavor

→ Two Point Heavy Collinear EEC



3. The Frontiers of Jet Physics

→ Higher Point Correlators

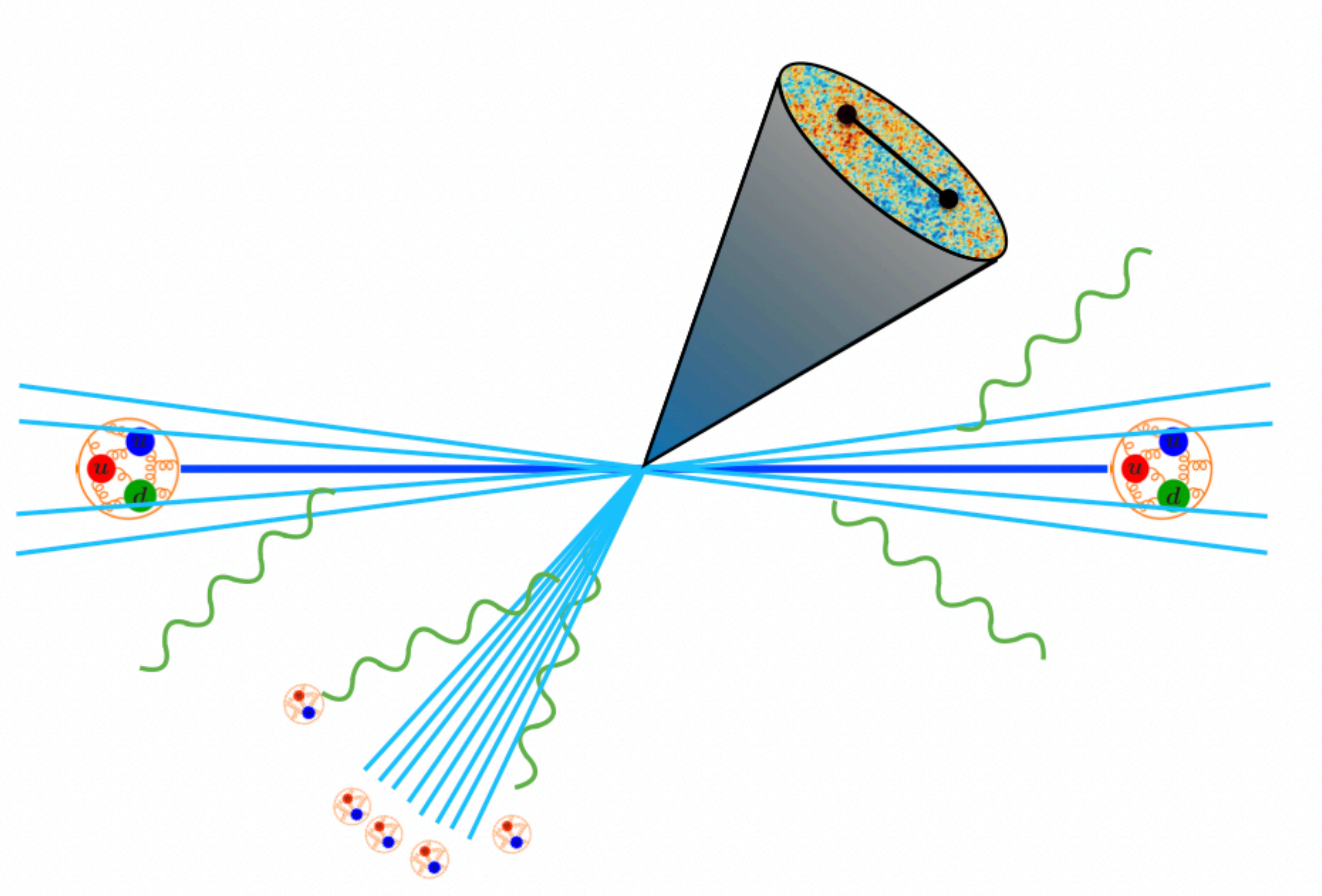


Energy Flow Operators

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"*

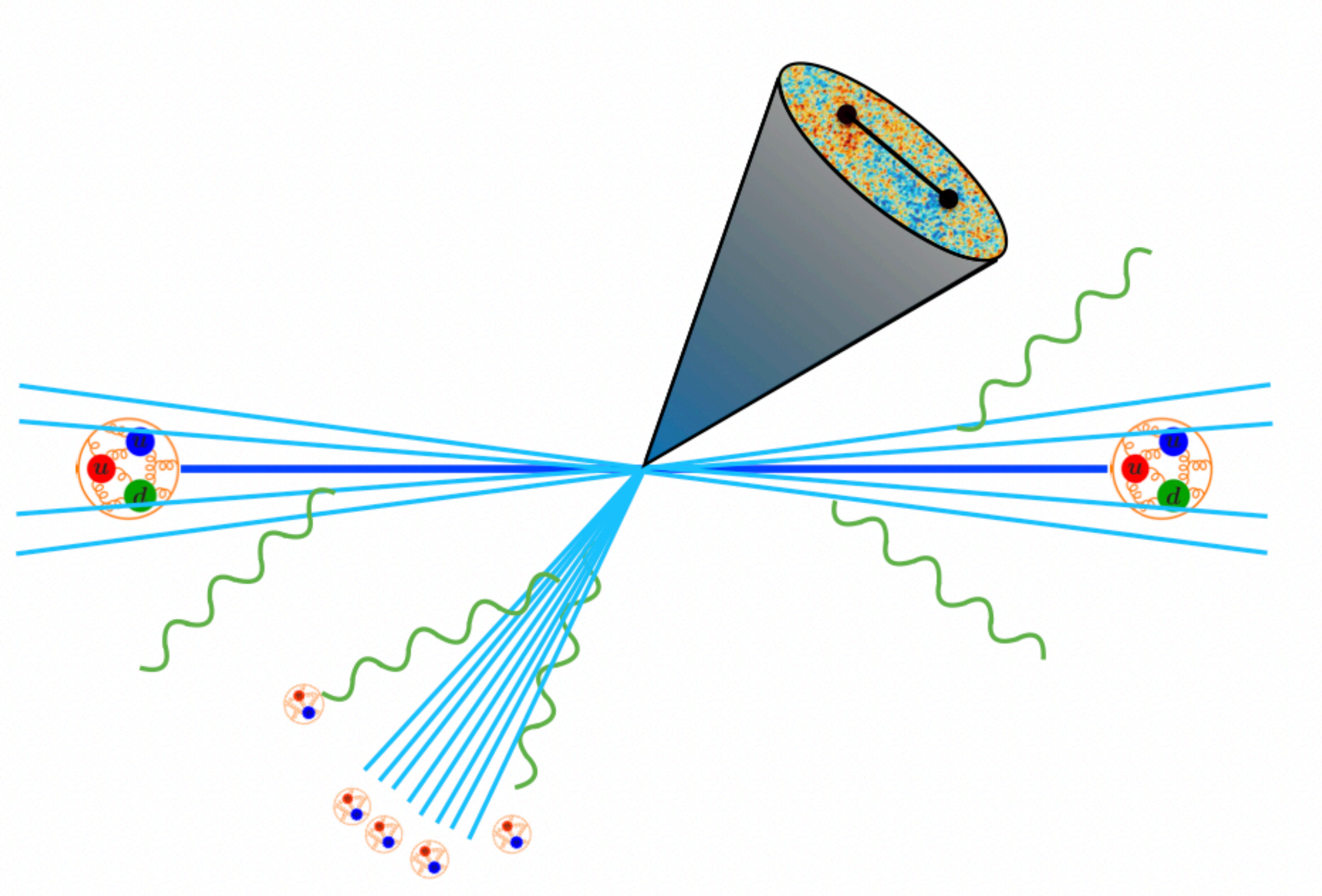
$$\langle \Psi \,|\, \mathcal{E}(\hat{n}_1)\ldots\mathcal{E}(\hat{n}_k) \,|\, \Psi \rangle$$

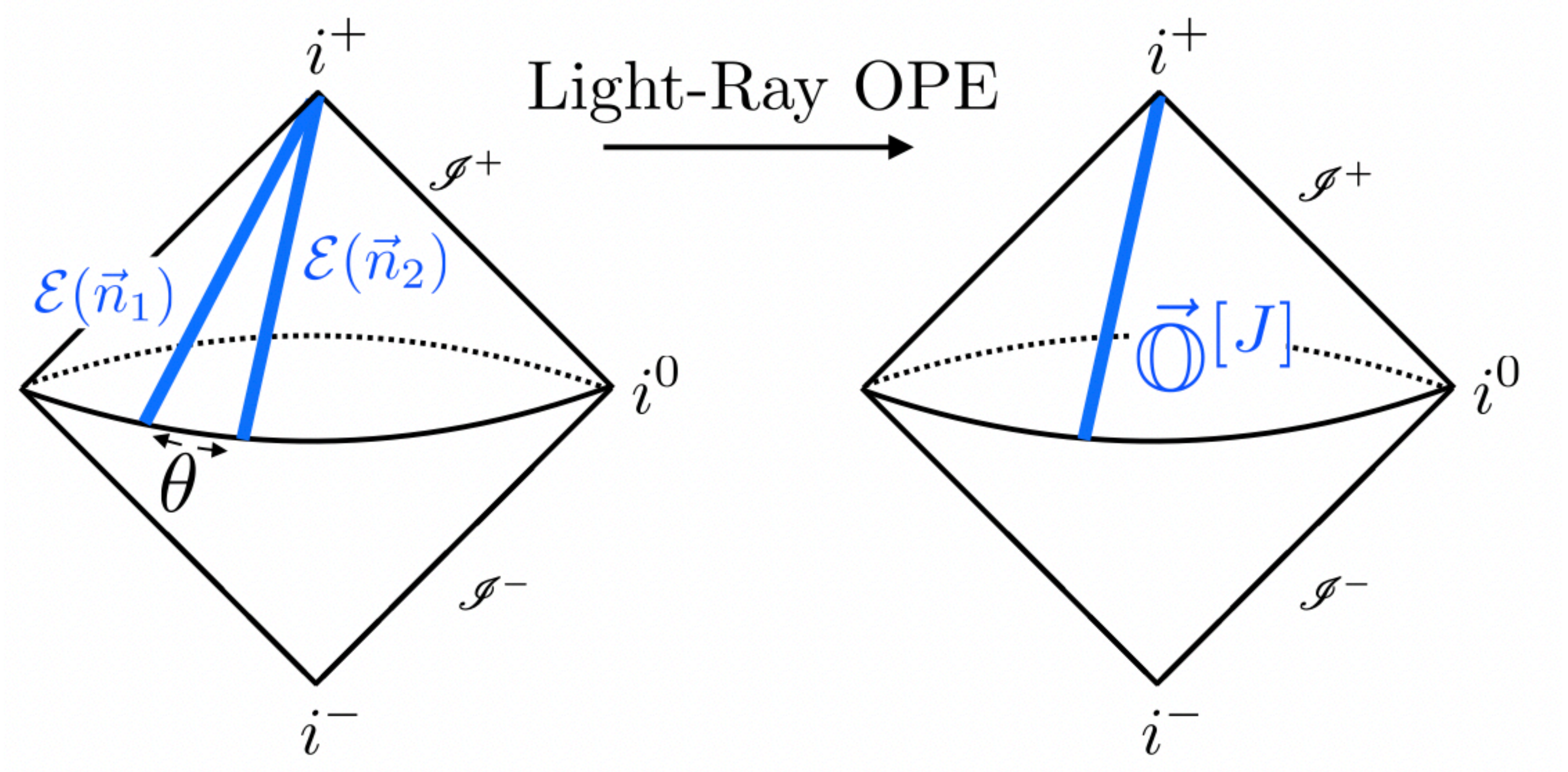
→ *"Statistical Correlations"*

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.





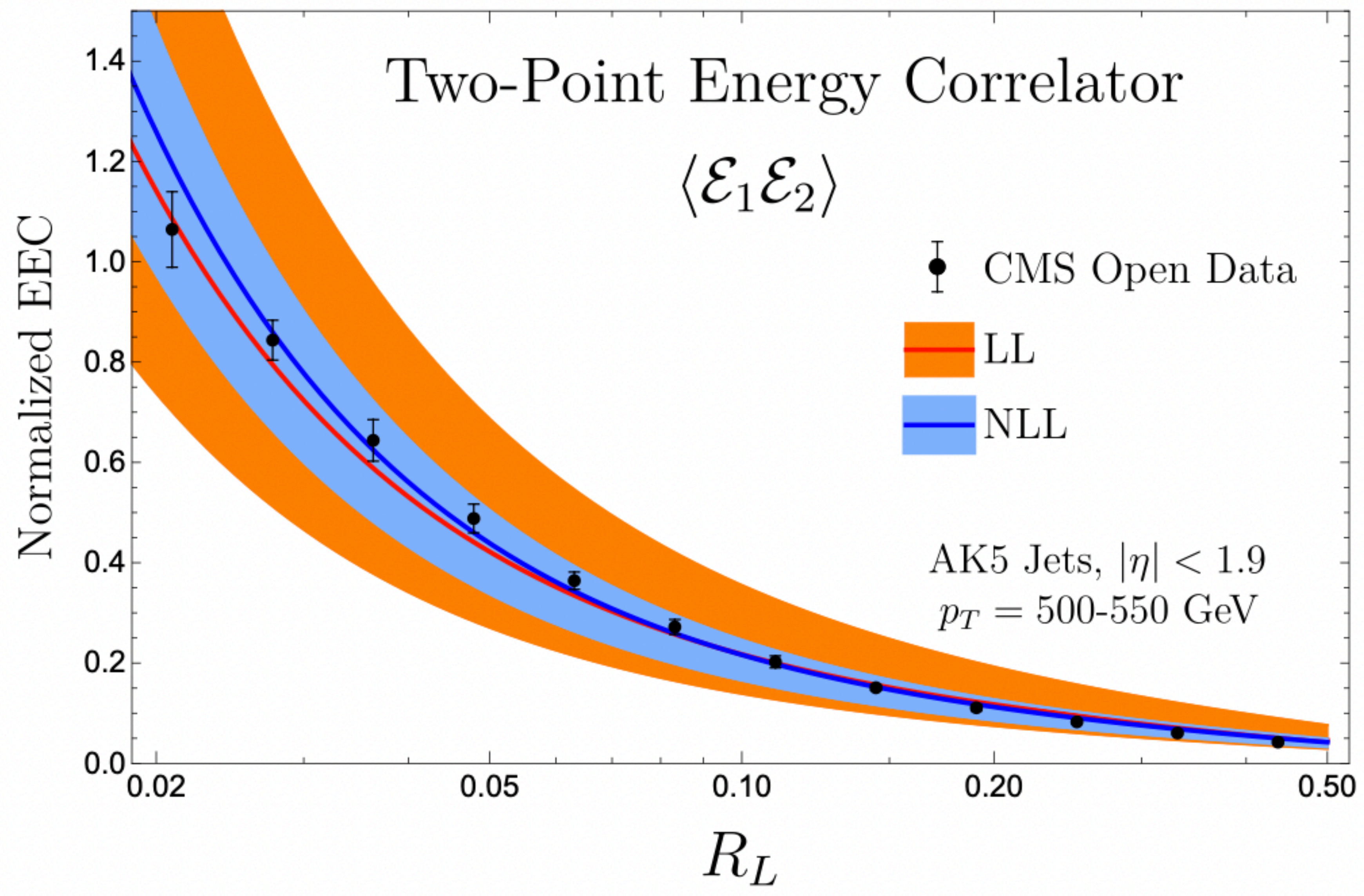
$$\mathscr{E}(\hat{n}_1)\mathscr{E}(\hat{n}_2) \sim \sum_i \theta^{\tau_i - 4}\, \mathbb{O}_i(\hat{n}_1)$$

[Hofman, Maldacena]

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

Universal Behavior of QCD

[Lee, Mecaj, Moult]



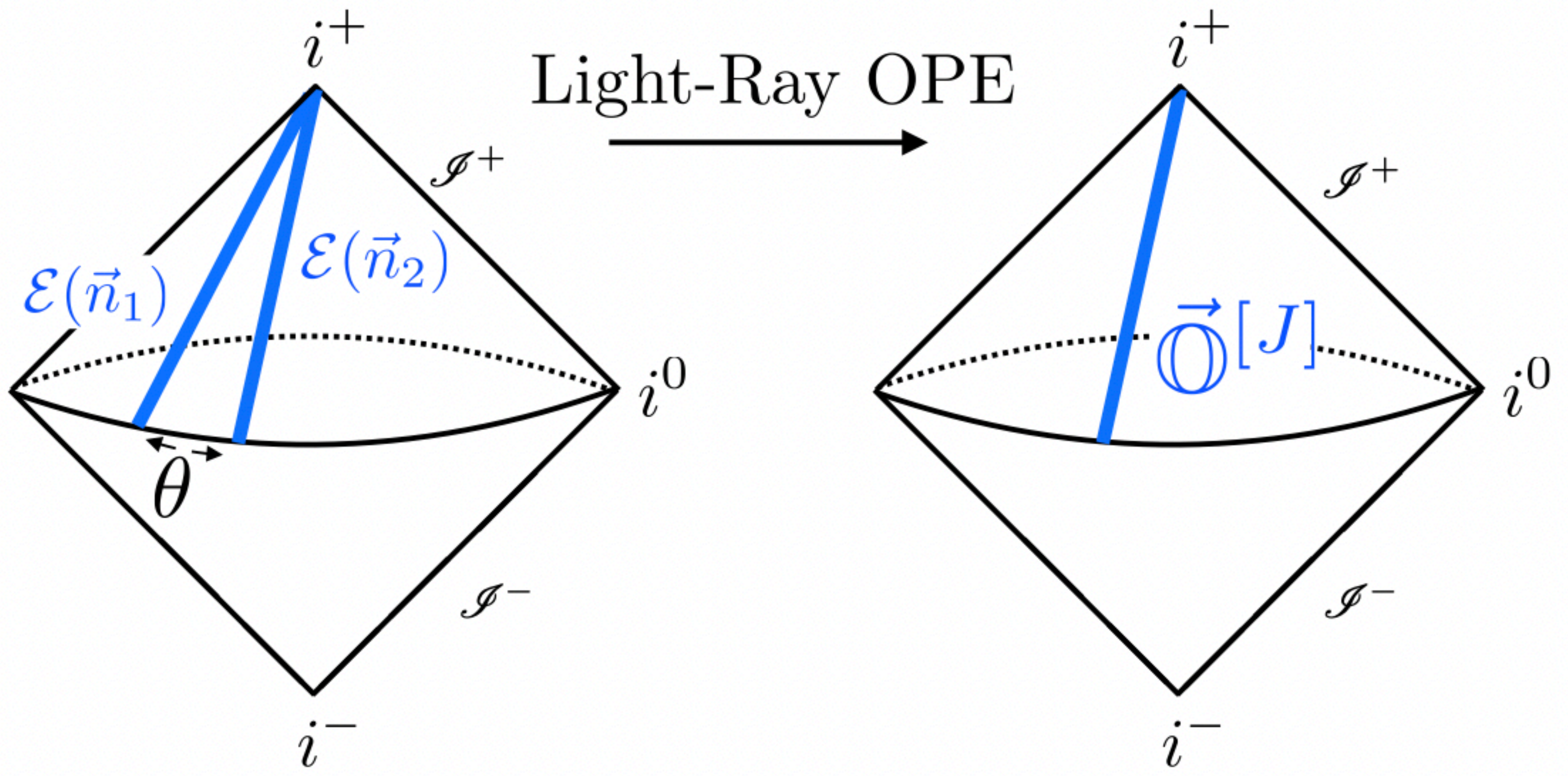
Energy flow operators exhibit universal scaling

→ The substructure of jets is completely determined by the OPE structure of light-ray operators

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

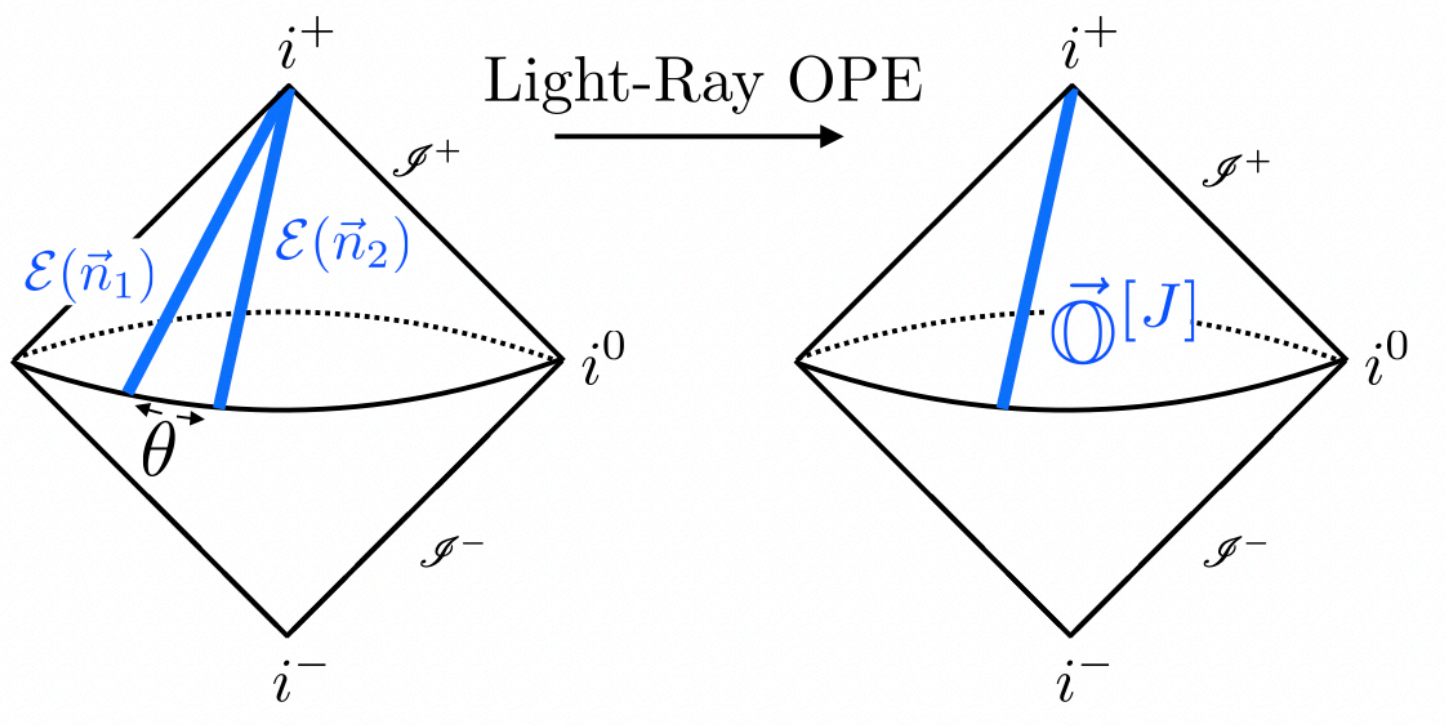
[Hofman, Maldacena]
[Moult, Zhu]

Reformulation of jet substructure using a broader language such that it can draw from diverse areas of physics



Universal Behavior of QCD

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

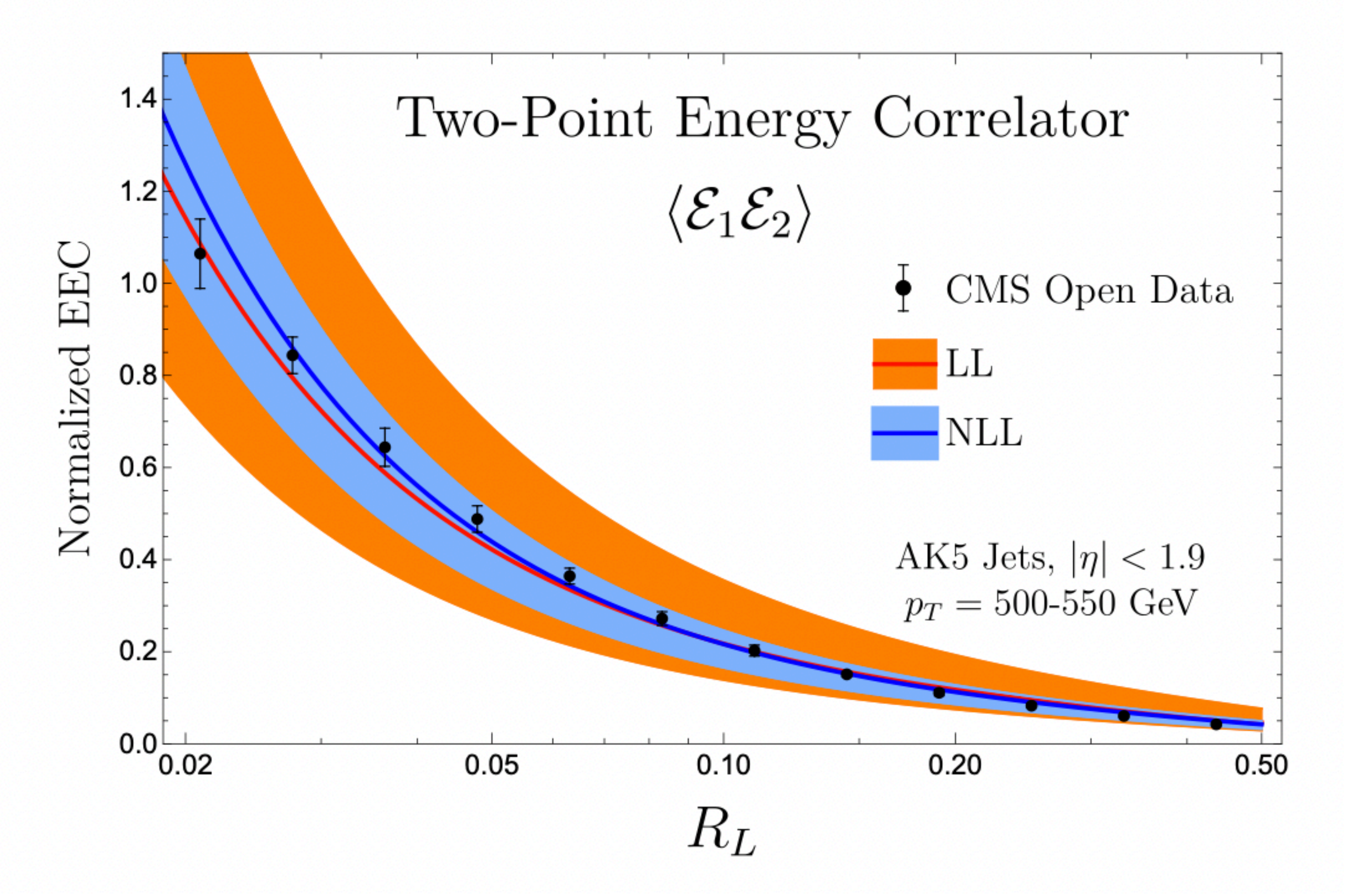


In the UV regime, we can explicitly do the OPE and obtain the exact scaling

$$\mathscr{E}(\hat{n}_1)\mathscr{E}(\hat{n}_2) = -\frac{1}{2\pi}\frac{2}{\theta_S^2}\hat{\mathscr{J}}\left[\hat{C}_{\phi_S}(2) - \hat{C}_{\phi_S}(3)\right]\vec{\mathbb{O}}^{[3]}(\hat{n}) + \ldots$$

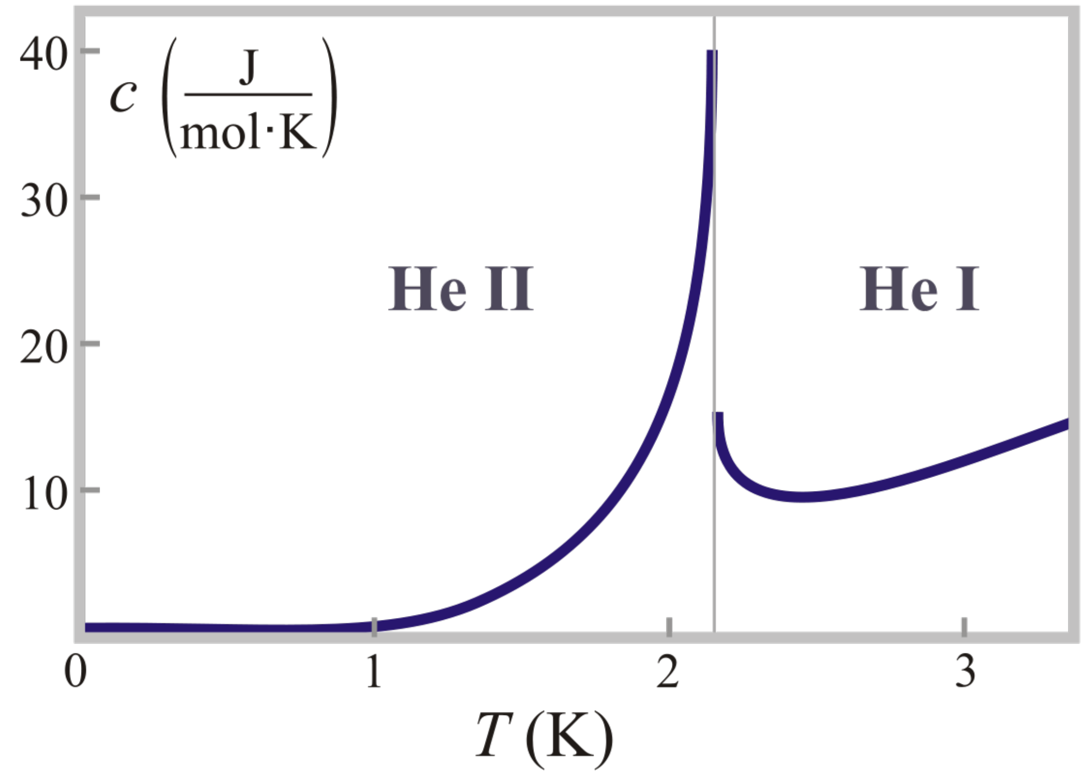
[Moult, Zhu]

$$\mathscr{E}(\hat{n}_1)\mathscr{E}(\hat{n}_2)\mathscr{E}(\hat{n}_3) = -\frac{1}{2\pi}\frac{2}{\theta_S^2}\frac{2}{\theta_L^2}\hat{\mathscr{J}}\left[\hat{C}_{\phi_S}(2) - \hat{C}_{\phi_S}(3)\right]\left[\hat{C}_{\phi_L}(3) - \hat{C}_{\phi_L}(4)\right]\vec{\mathbb{O}}^{[4]}(\hat{n}) + \ldots$$



[Lee, Mecaj, Moult]

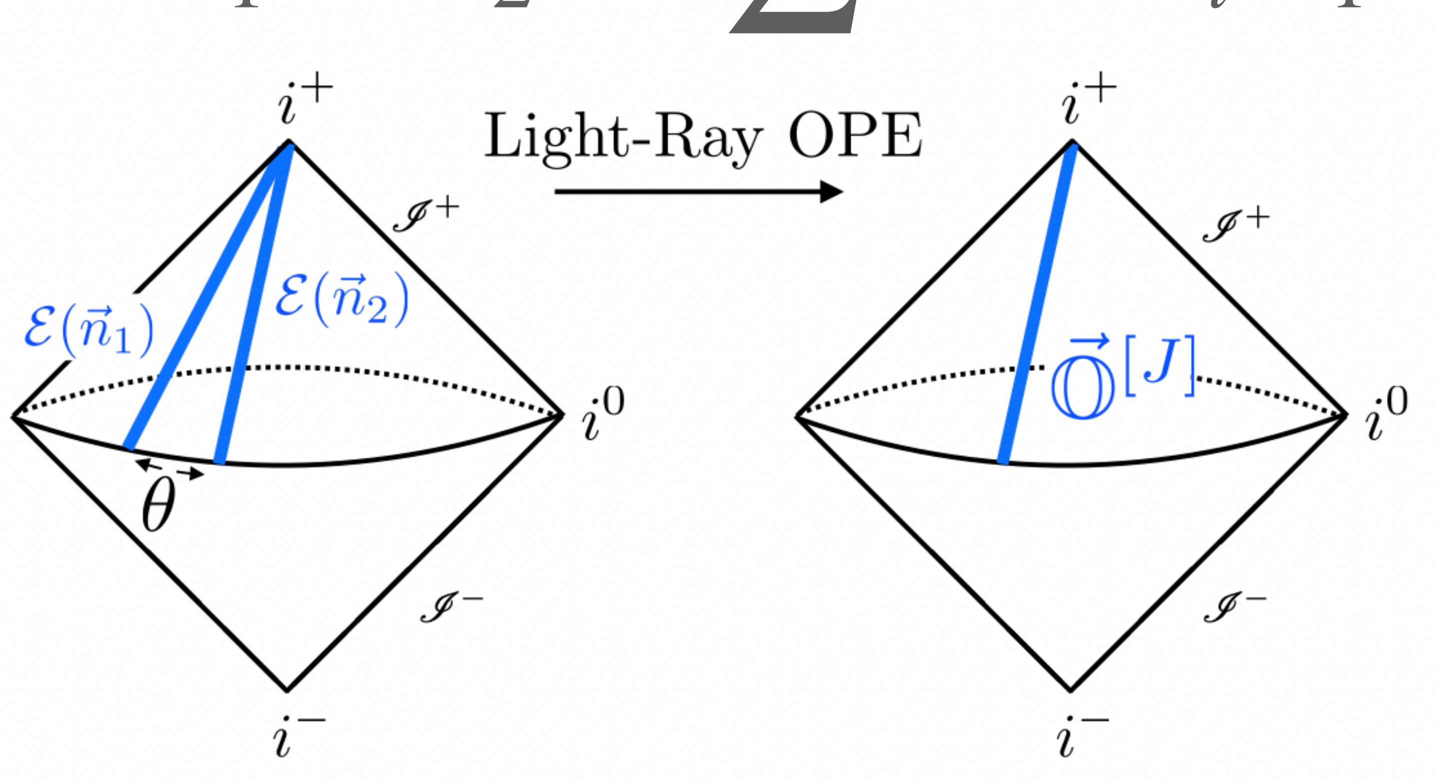
The scaling behavior of the twist-2 light ray operators completely control the leading behavior of jet substructure



In superfluid helium, most precise measurements suggest $C \sim |T - T_c|^{.009}$

Universal Behavior of QCD

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



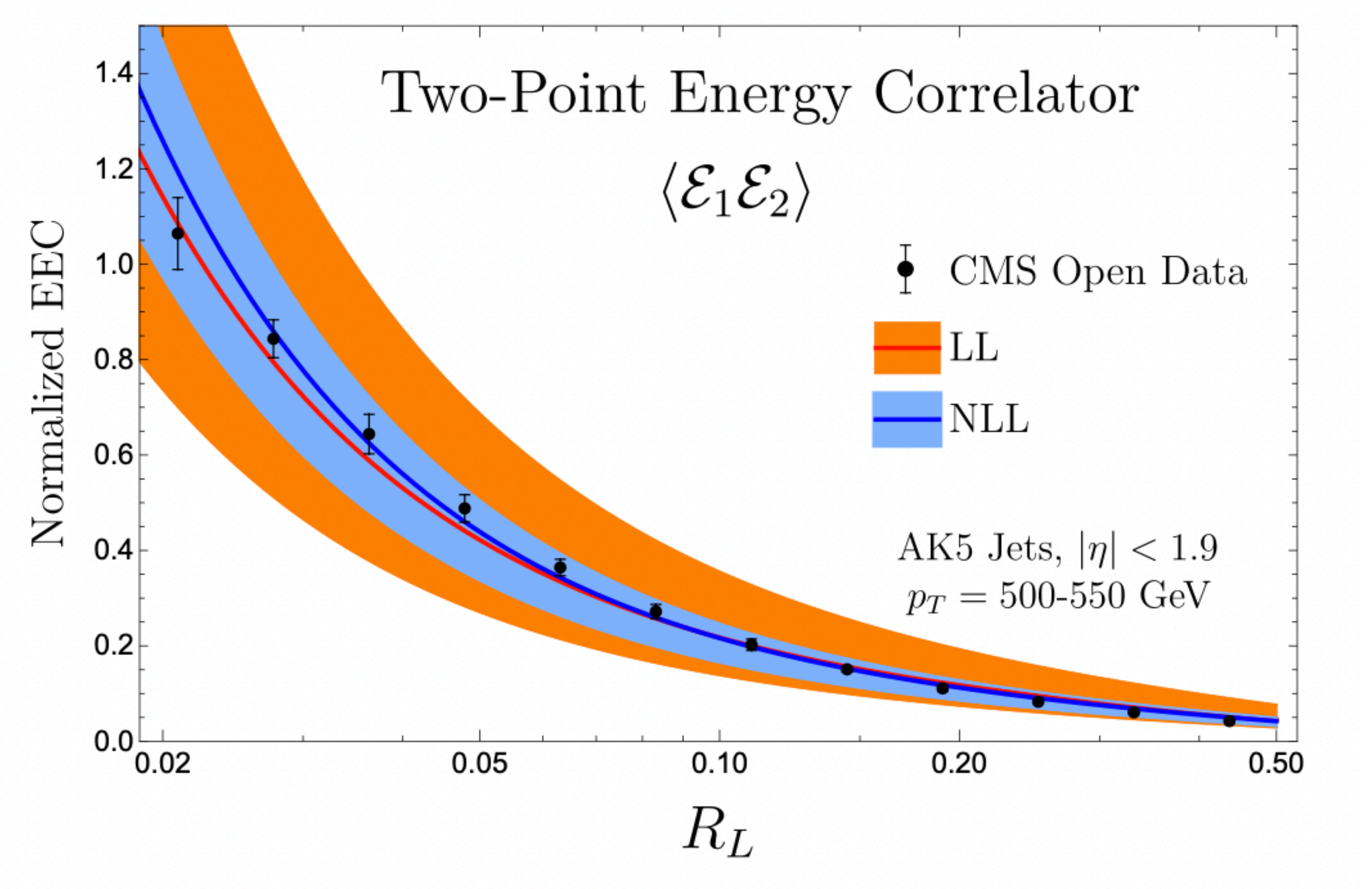
In the **UV regime**, we can explicitly do the OPE and obtain the exact scaling

$$\mathscr{E}(\hat{n}_1)\mathscr{E}(\hat{n}_2) = -\frac{1}{2\pi}\frac{2}{\theta_S^2}\hat{\mathscr{J}}\left[\hat{C}_{\phi_S}(2) - \hat{C}_{\phi_S}(3)\right]\vec{\mathbb{O}}^{[3]}(\hat{n}) + \ldots$$

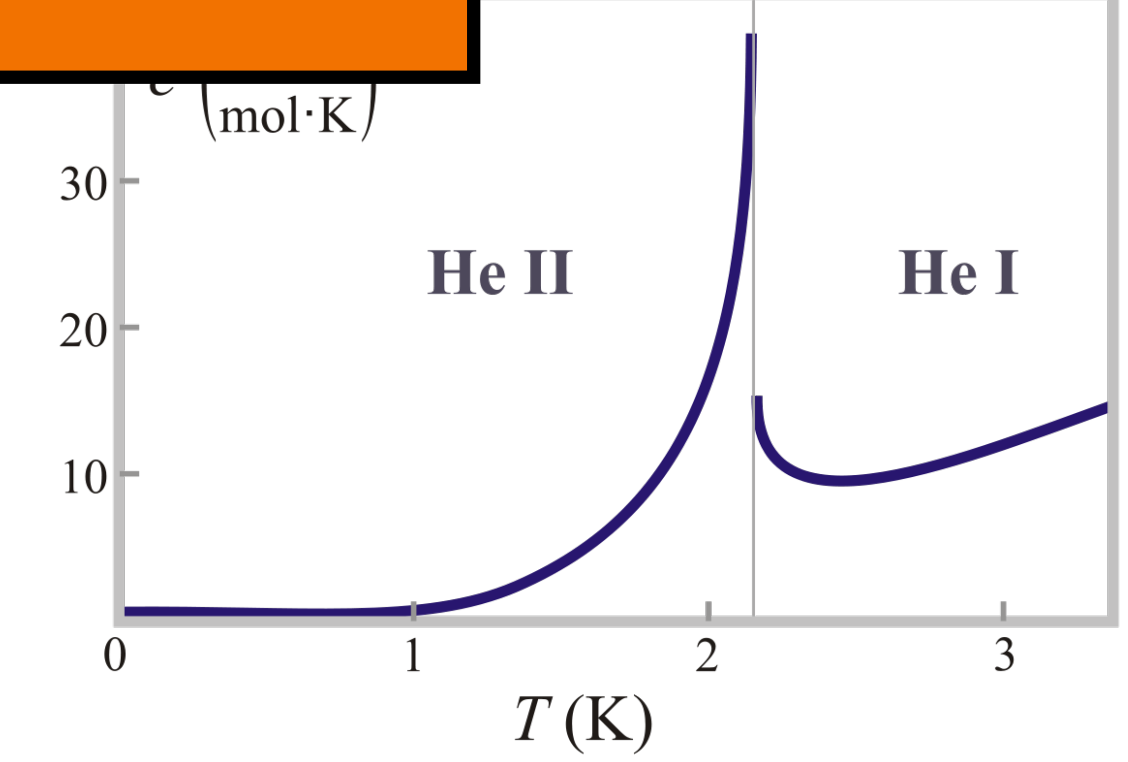
[Moult, Zhu]

$$\mathscr{E}(\hat{n}_1)\mathscr{E}(\hat{n}_2)\mathscr{E}(\hat{n}_3) = -\frac{1}{2\pi}$$

All explained nicely in Hao Chen's talk



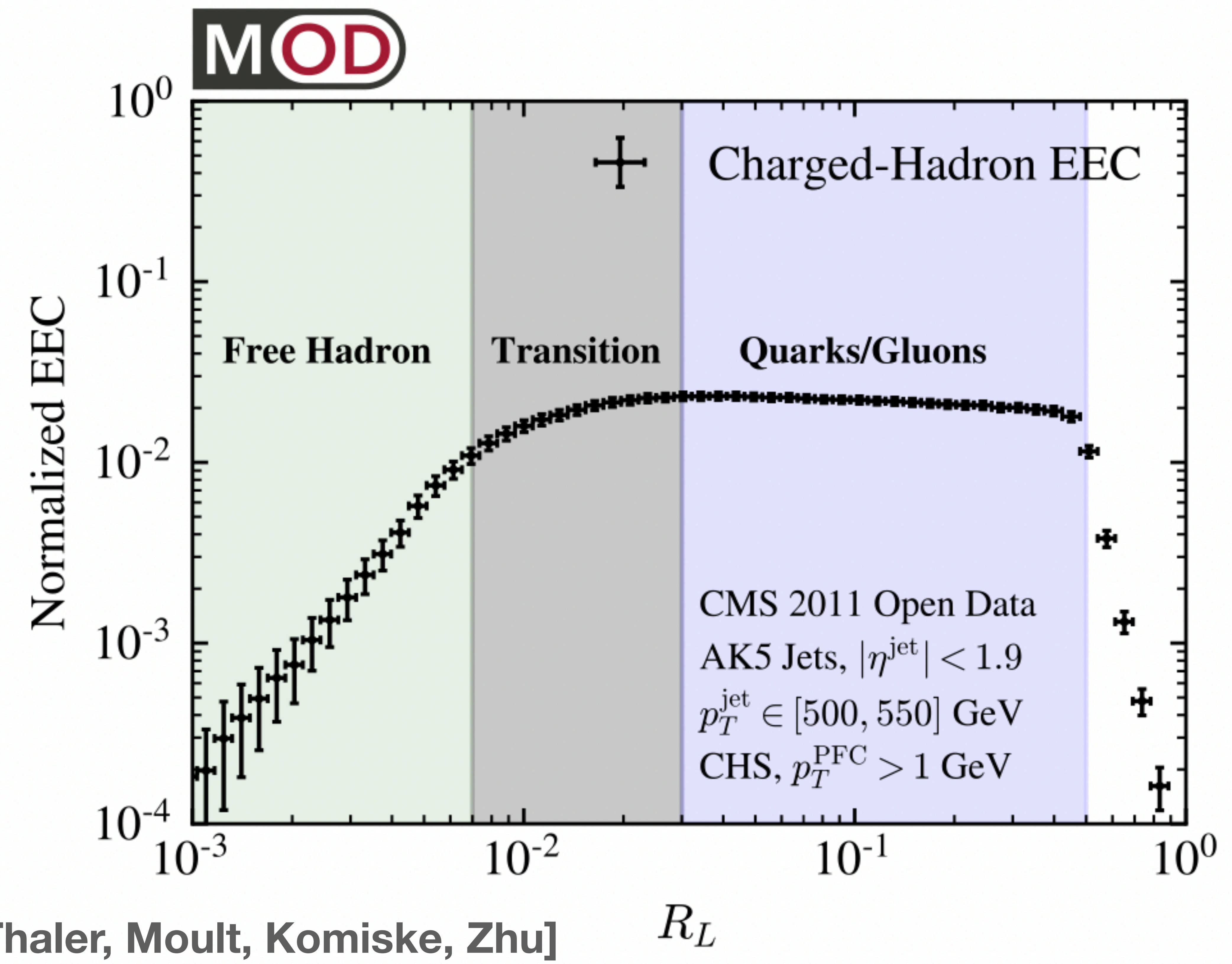
The scaling behavior of the twist-2 light ray operators completely control the leading behavior of **jet substructure**



In **superfluid helium**, most precise measurements suggest $C \sim |T - T_c|^{.009}$

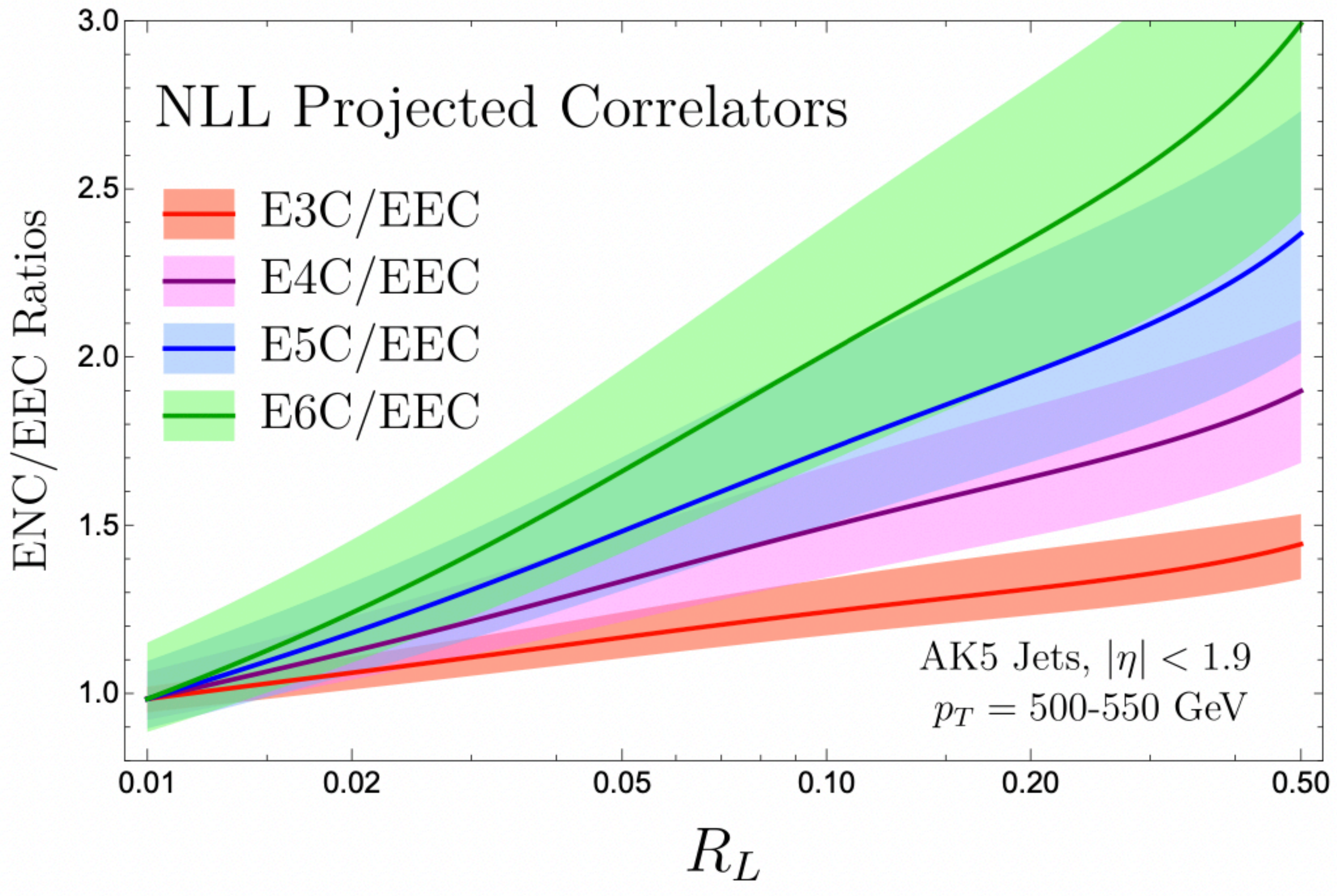
[Lee, Mecaj, Moult]

What can you do with this?



[Thaler, Moult, Komiske, Zhu]

[Moult, Mecaj, Lee]

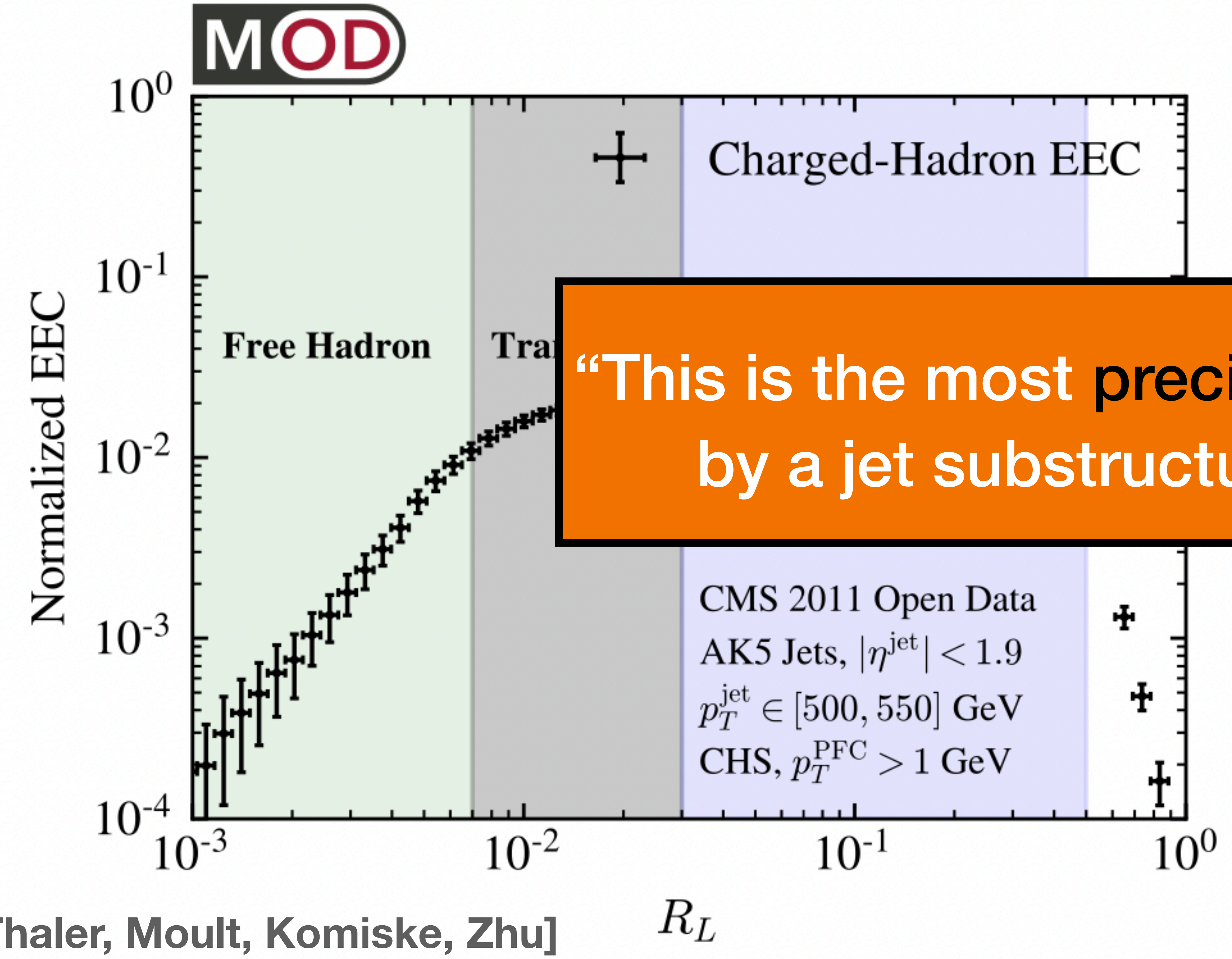


$$\mathcal{E}(\hat{n}_1)\mathcal{E}(\hat{n}_2) \sim \sum_i \theta^{\tau_i - 4}\, \mathbb{O}_i(\hat{n}_1)$$

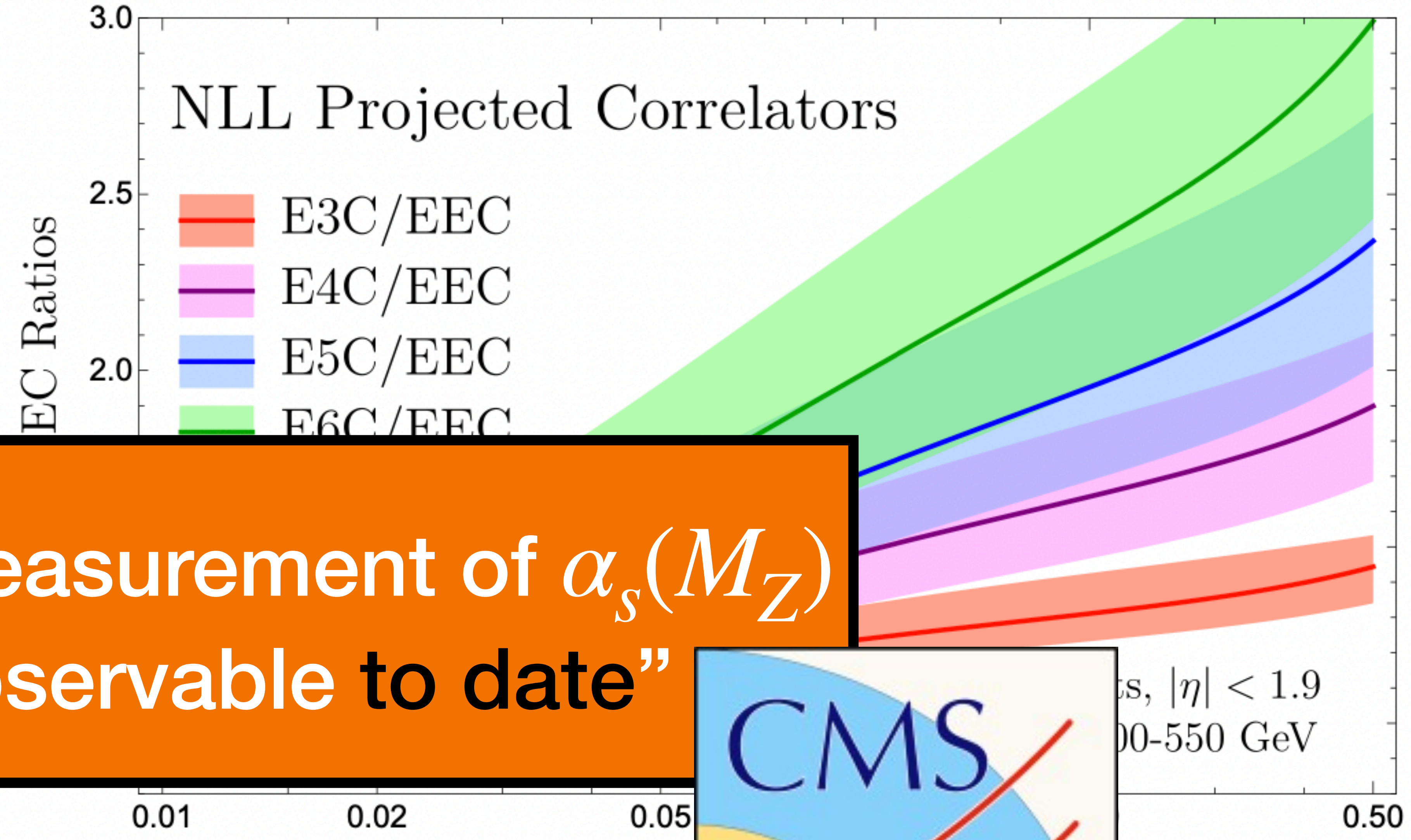
Access to anomalous dimensions of QCD twist-2 operators directly at the LHC

What can you do with this?

[Moult, Mecaj, Lee]



[Thaler, Moult, Komiske, Zhu]



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

$$\mathscr{E}(\hat{n}_1)\mathscr{E}(\hat{n}_2) \sim \sum_i \ldots \mathbb{O}_i(\hat{n}_1)$$

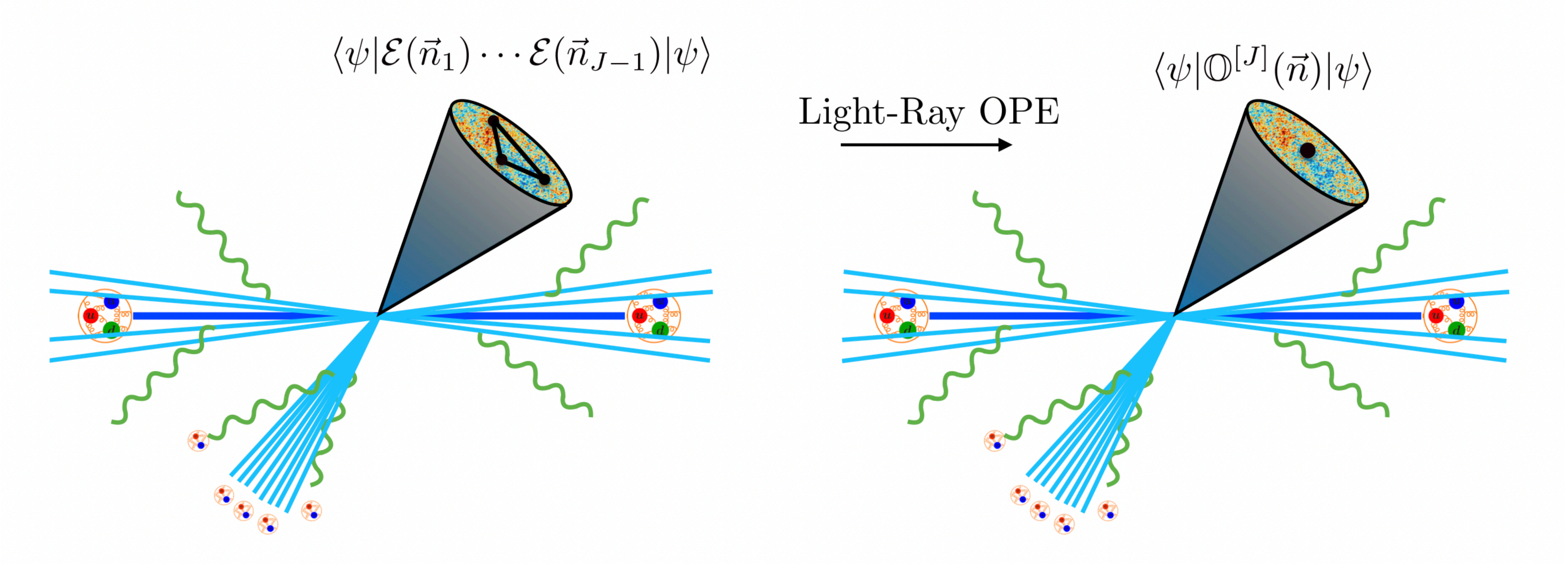
Access to anomalous dimensions of QCD twist-2 operators directly at the LHC

Can we ask other questions?

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

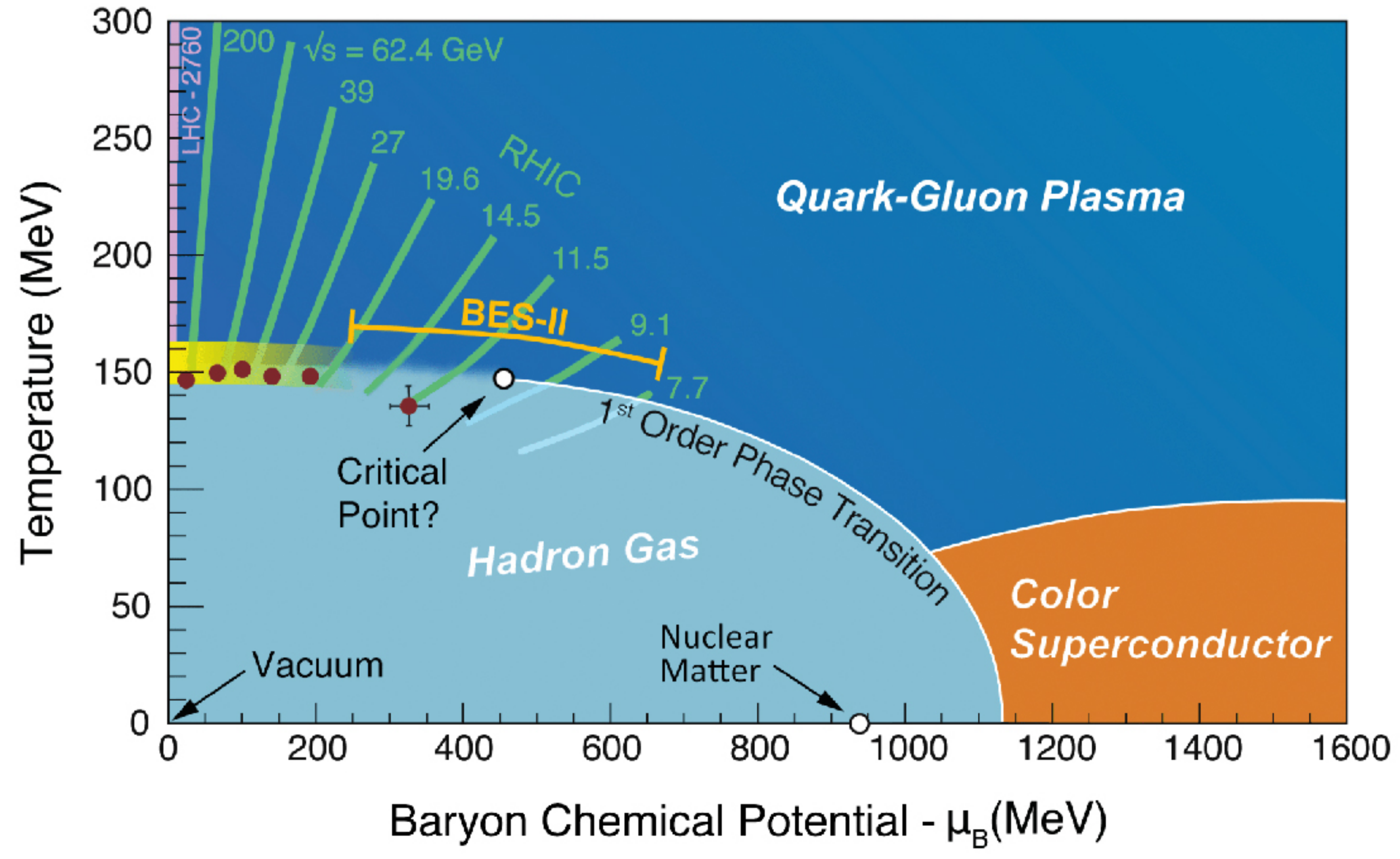
Evan Craft — Yale University
arXiv: 2210.09311

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

Yale University

MIT

Many Puzzles in QCD



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

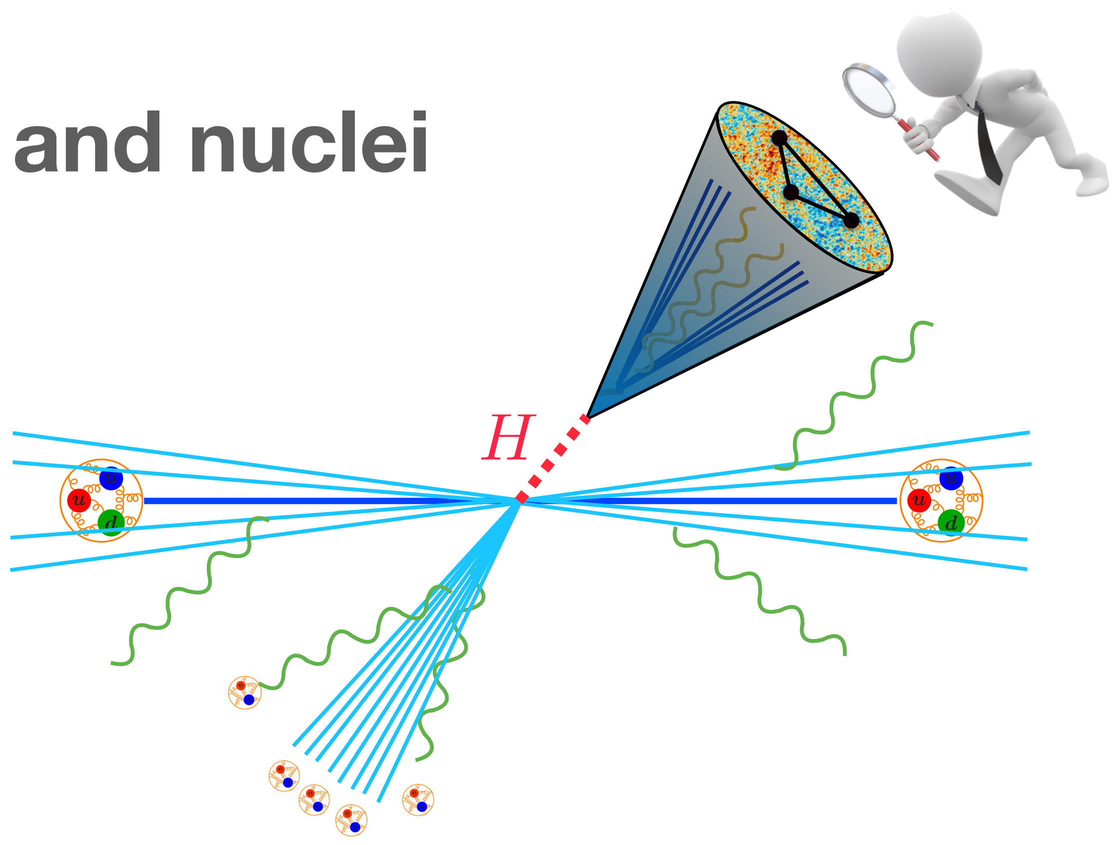
→ Confinement

Cold QCD

→ Gluon Saturation

→ Proton Spin and Radius Puzzle

→ 3D Structure of protons and nuclei

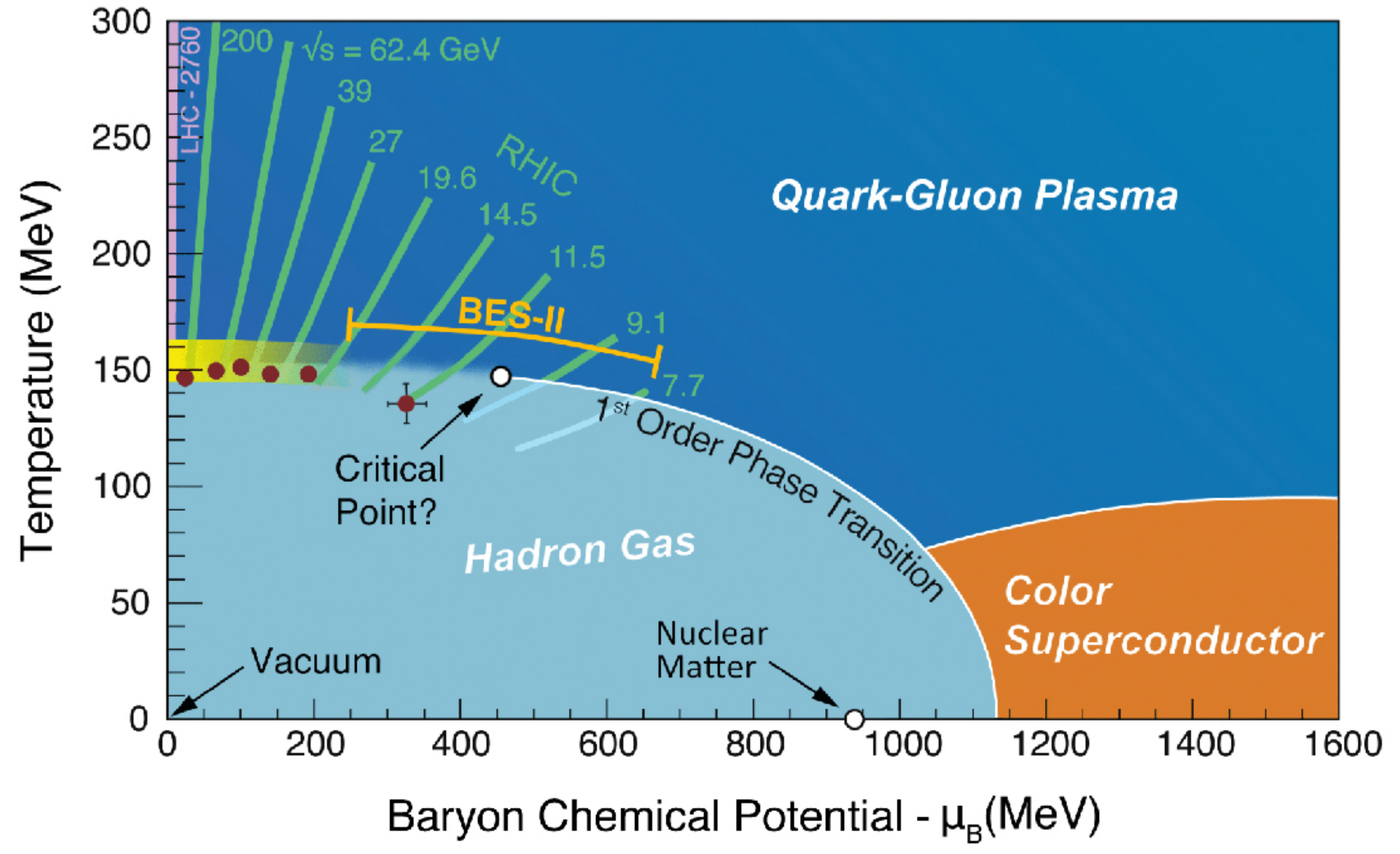


Numerous collider experiments spanning several continents working to resolve these fundamental questions

Many Puzzles in QCD

Several open questions remain across both Particle and Nuclear Physics

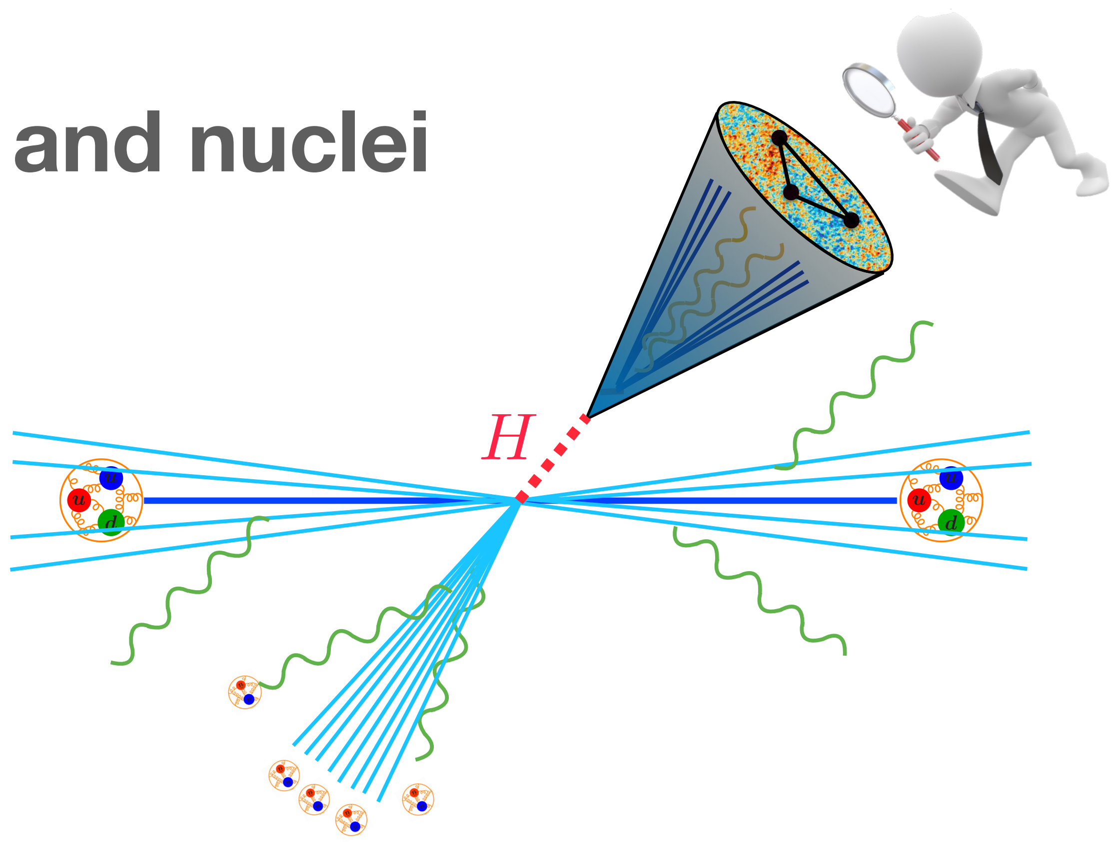
→ Many of these open problems are deeply connected to Quantum Chromodynamics



→ Why is color charge so complicated?

Hot QCD	Medium QCD	Cold QCD
→ Quark Gluon Plasma	→ Strong CP	→ Gluon Saturation
→ Hadronization	→ Rare Higgs Decays	→ Proton Spin and Radius Puzzle
→ Quarkonia	→ Confinement	→ 3D Structure of protons and nuclei

Flavor Dead Cone Effect (Nature Physics, 2021)



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

Application: Confinement

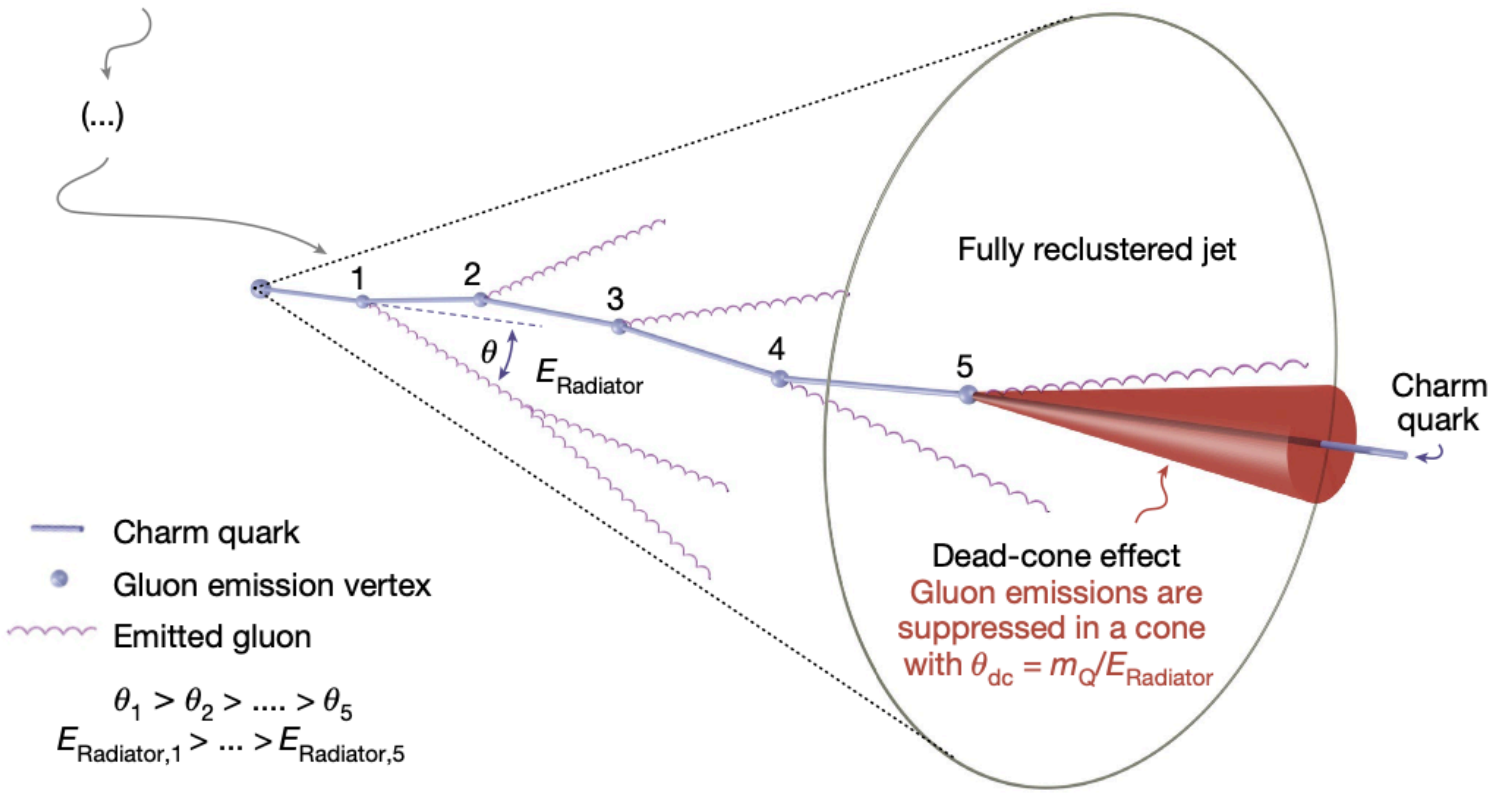
[ALICE Collaboration, Nature Physics]

Dokshitzer, Khoze, Troyan (1991)

Heavy quark radiation of gluons must be ***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.

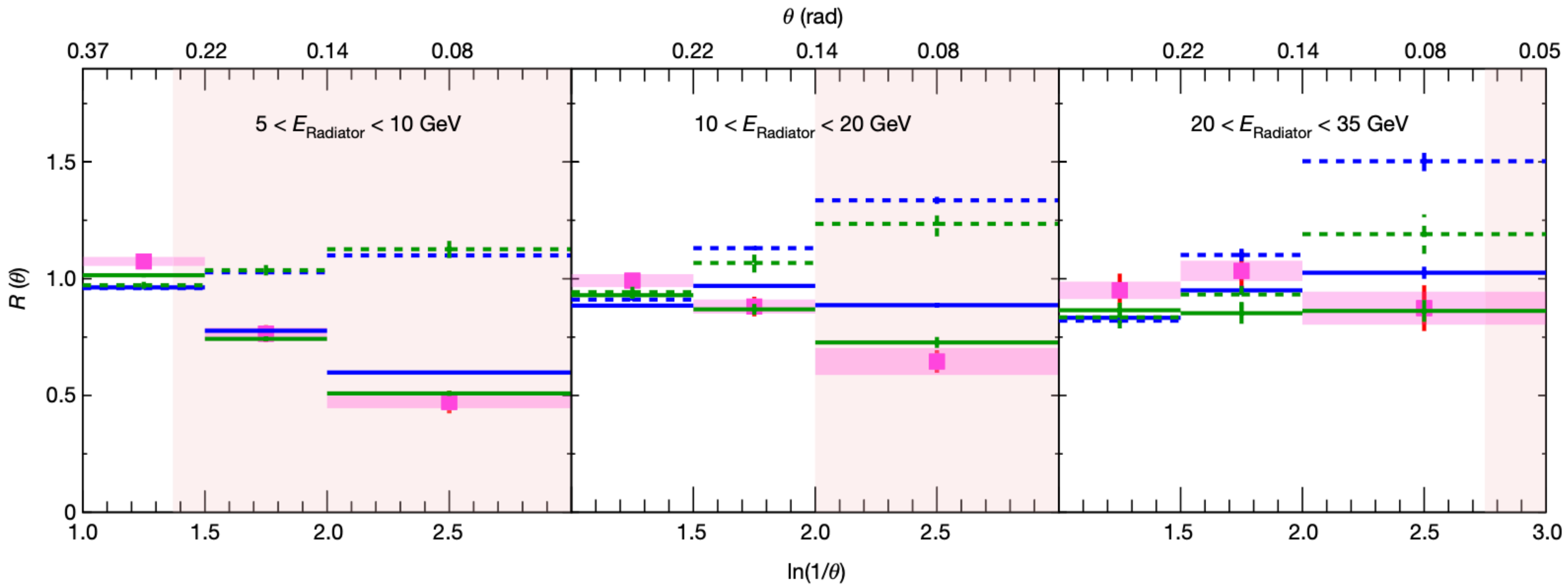
Measured this year by ALICE using a complex **iterative declustering** technique

→ Inferred all gluon emissions *directly*

→ State of the art analysis techniques

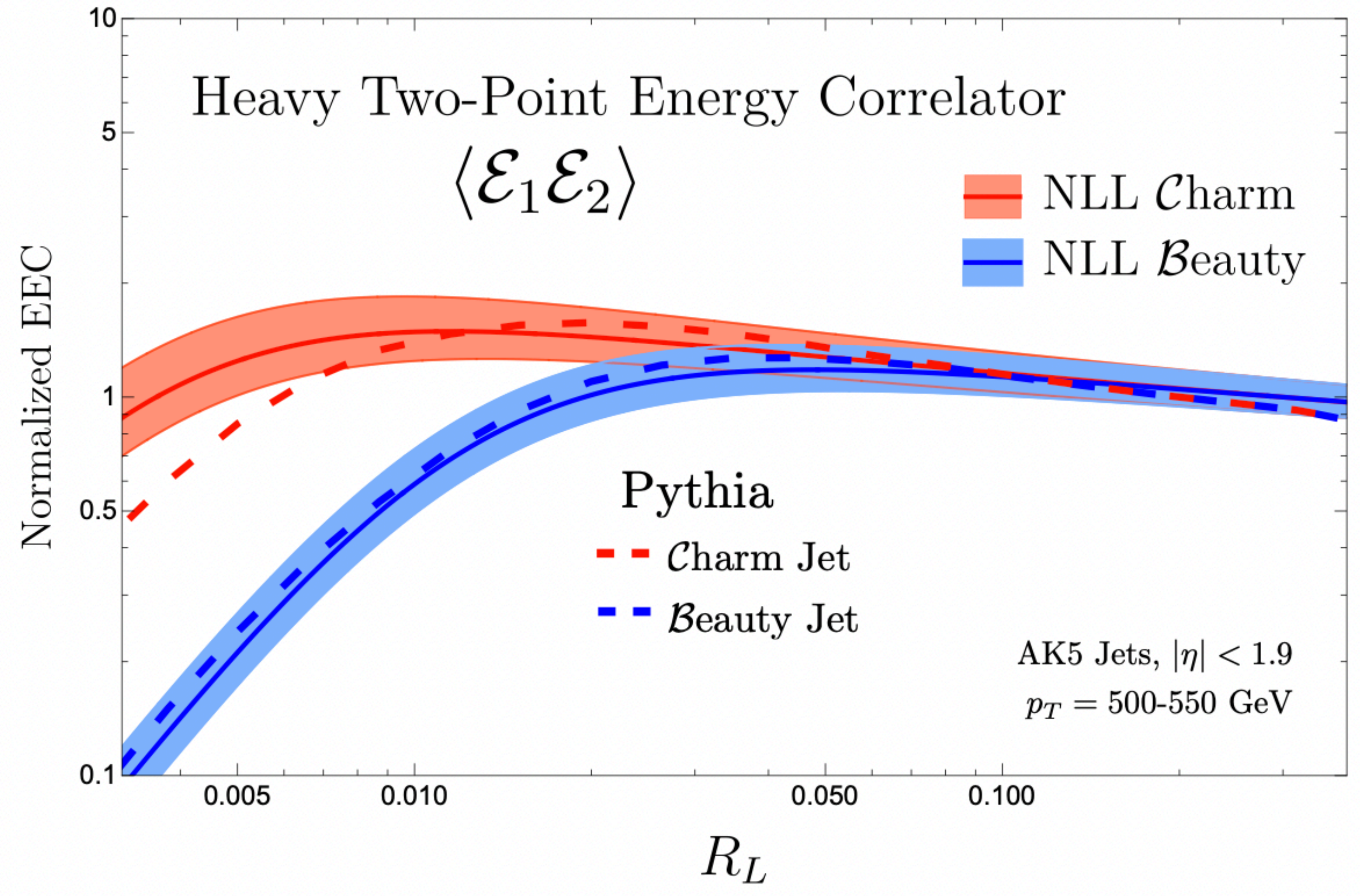
Application: Confinement

ALICE measured this effect using an iterative declustering algorithm and the Lund Plane



[ALICE Collaboration, Nature Physics]

[EC, Lee, Mecaj, Moult]



→ EECs can be **systematically computed** in perturbation theory

→ Dead cone effect is visible **by eye** using light-ray operators

→ Can easily be **extended** to other heavy flavor based analyses

Application: Confinement

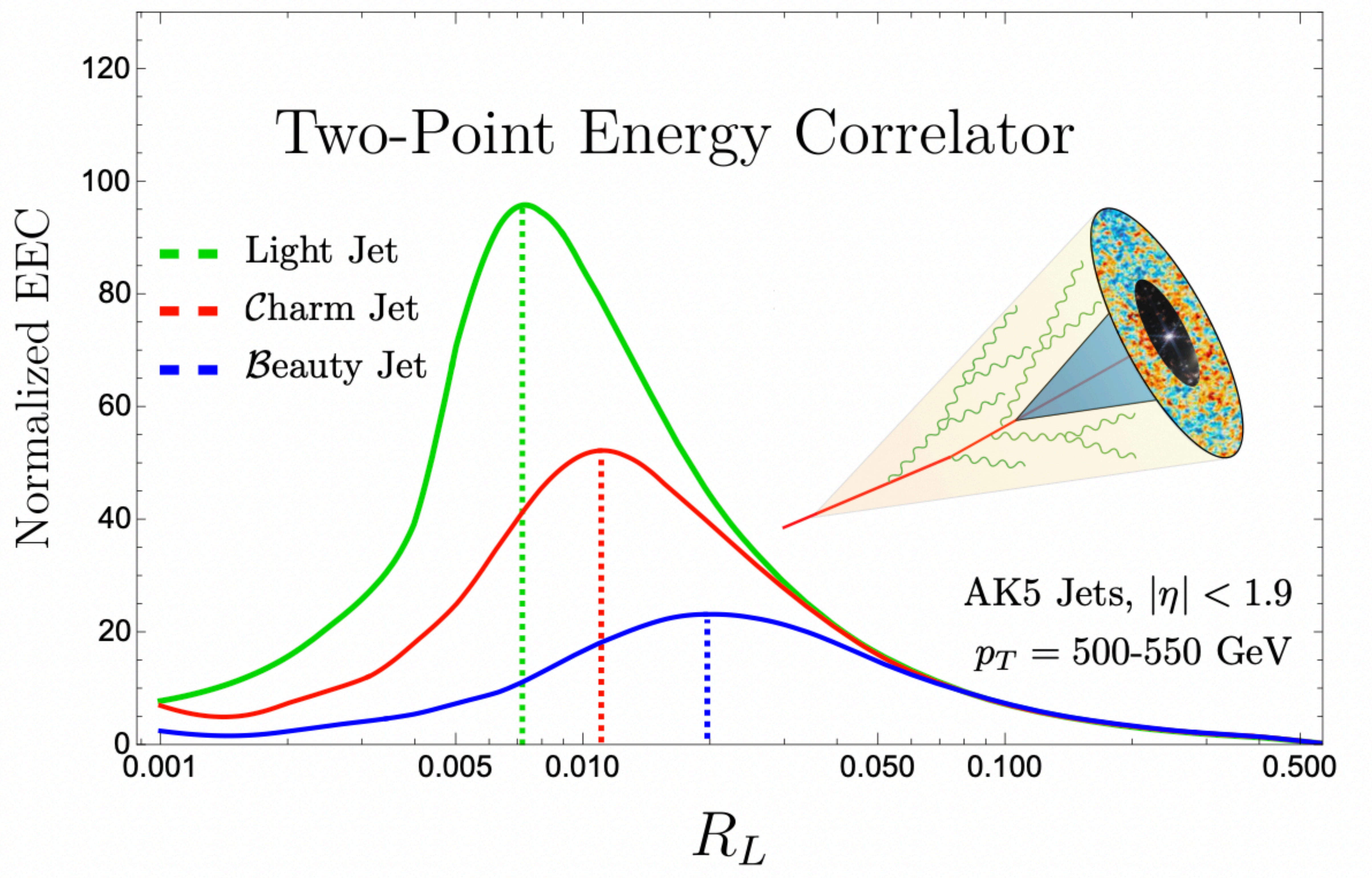
In the **UV regime**, scaling should be independent of mass

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

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

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

Application: Confinement

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

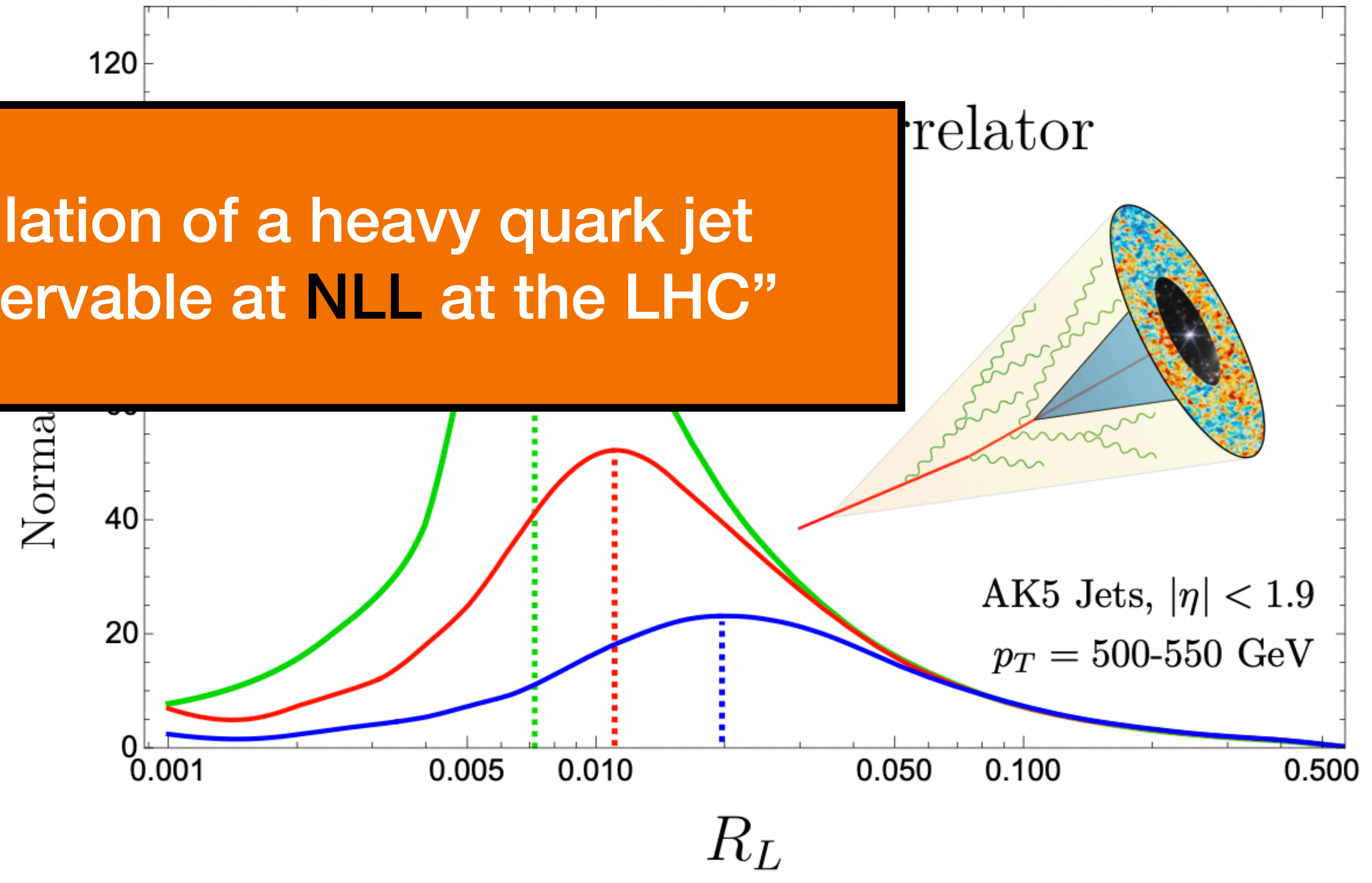
$$\mathscr{E}(\hat{n}_1)\mathscr{E}(\hat{n}_2) \sim$$

"First **ever** calculation of a heavy quark jet substructure observable at **NLL** at the LHC"

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

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

Application: Confinement

Formally, the EEC is defined in terms of **correlation functions**

$$\frac{d\Sigma}{dz} \sim \int d^4x\, e^{iQx} \langle 0 | \mathcal{O}(x)\mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\mathcal{O}^\dagger(0)|0\rangle$$

Source Term

Energy Flow

$$z \equiv \frac{1-\cos\theta}{2}$$

In the collinear limit, satisfies a **factorization theorem**

$$\frac{d\Sigma}{dz} \sim \vec{J} \otimes \vec{H}$$

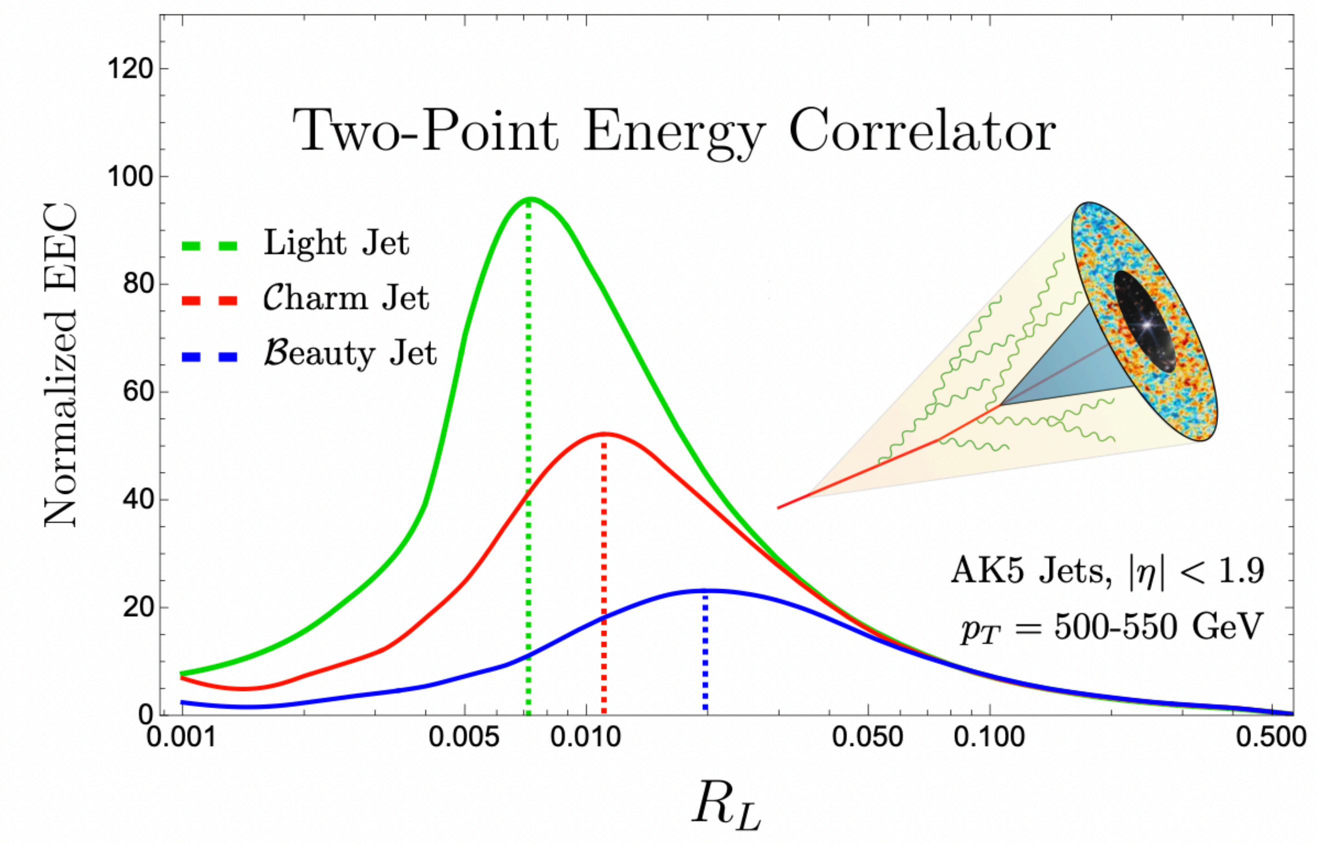
Jet Function: "quark evolution"

Hard Function: "initiates process"

Quark Jet Function

$$J_{qg\leftarrow q} \sim \frac{1}{z}\left(\frac{3}{4} - \frac{5}{2}\delta^2 - \frac{\delta^4}{1+\delta^2} + 3\delta^3\tan^{-1}\left[\frac{1}{\delta}\right] + \frac{1}{2}\delta^2\left[1-\delta^2\right]\log\left[\frac{\delta^2}{1+\delta^2}\right]\right)$$

Depends only on the **ratio:** $\delta = \frac{m}{Q\sqrt{z}}$

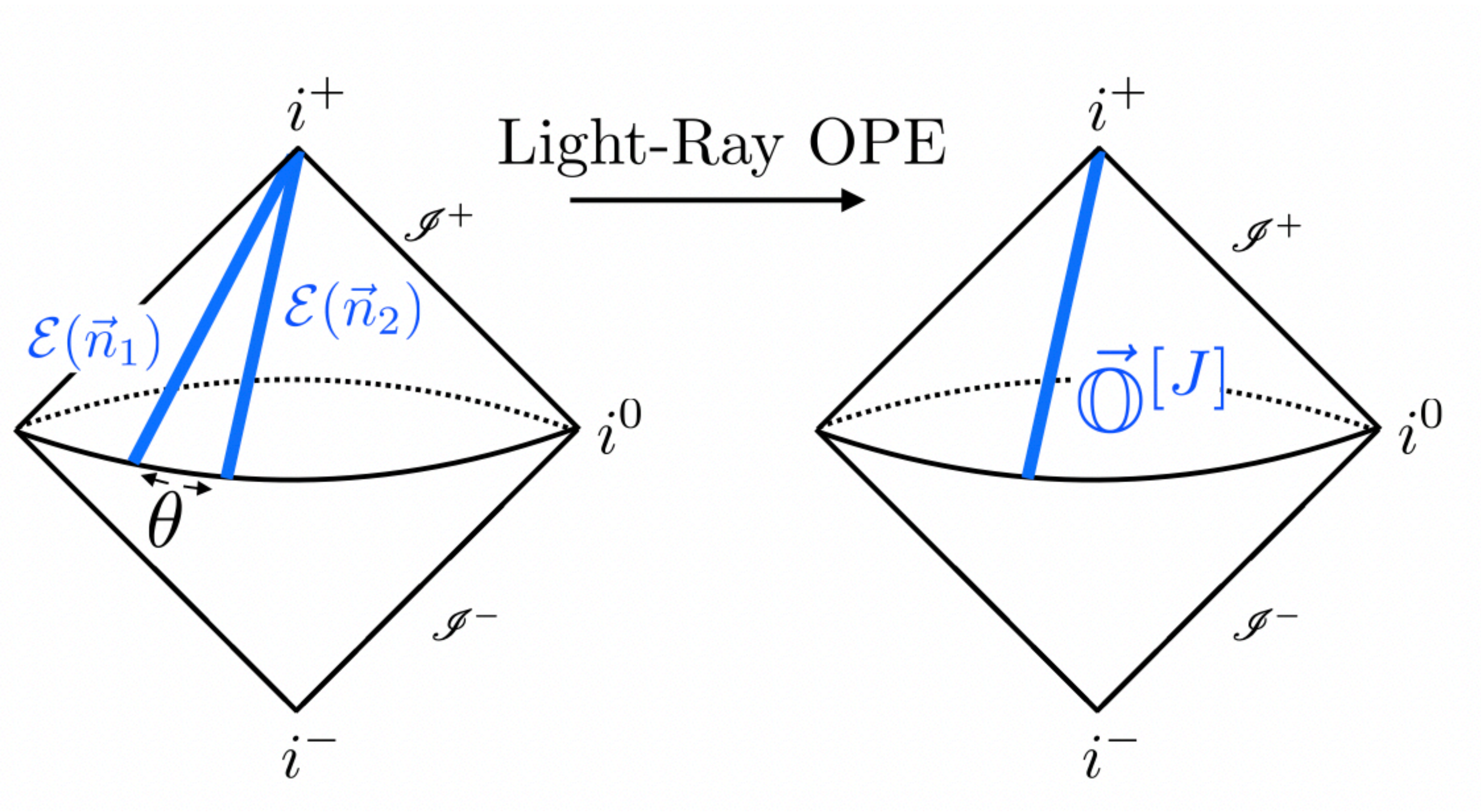


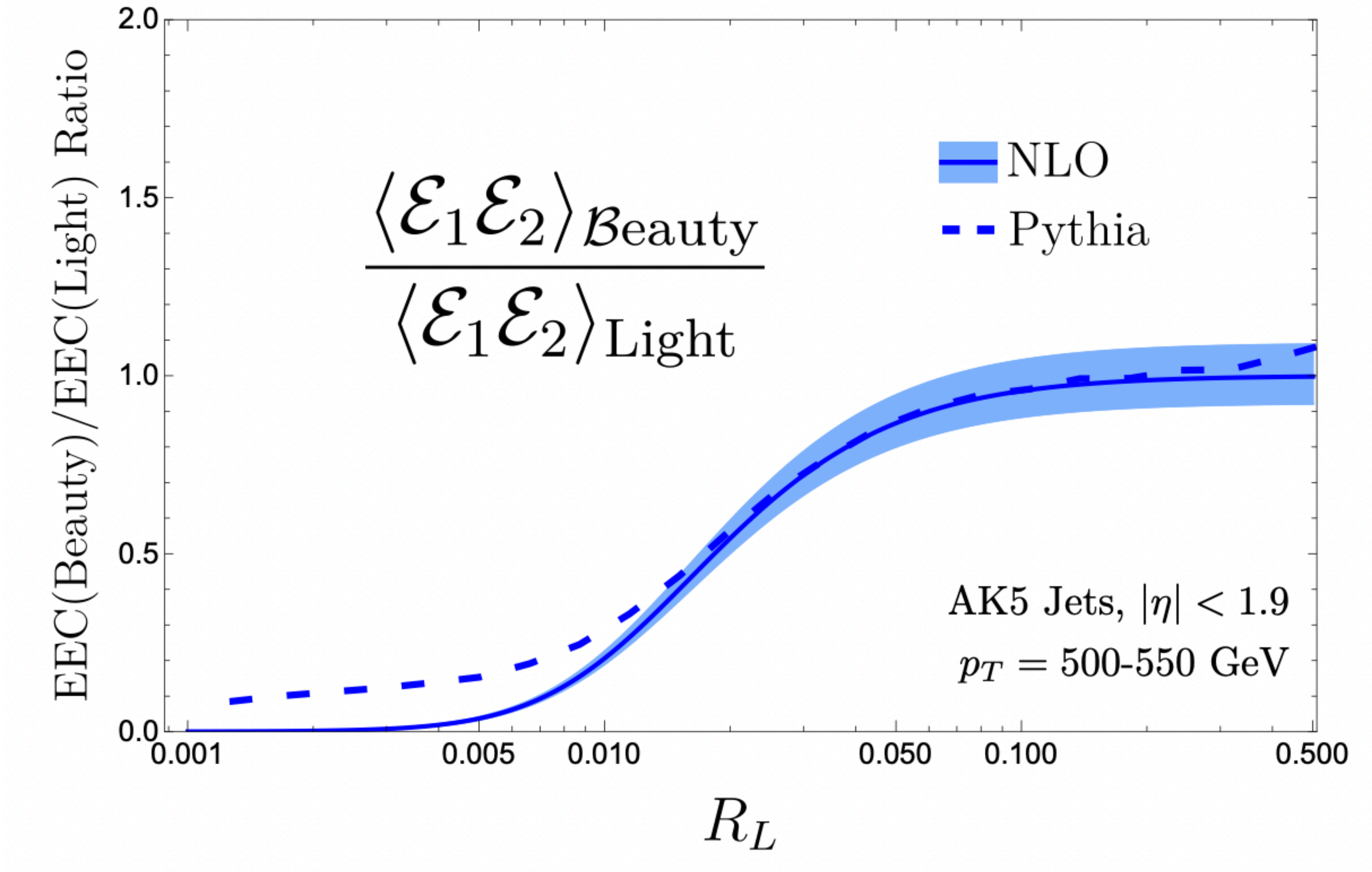
Application: Confinement

[EC, Lee, Mecaj, Moult]

No need for jet grooming to see this suppression!

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





→ **Highlights the role of formal theory in identifying the correct field theoretic observables for experiments**

Pushing the Boundaries of Jet Substructure

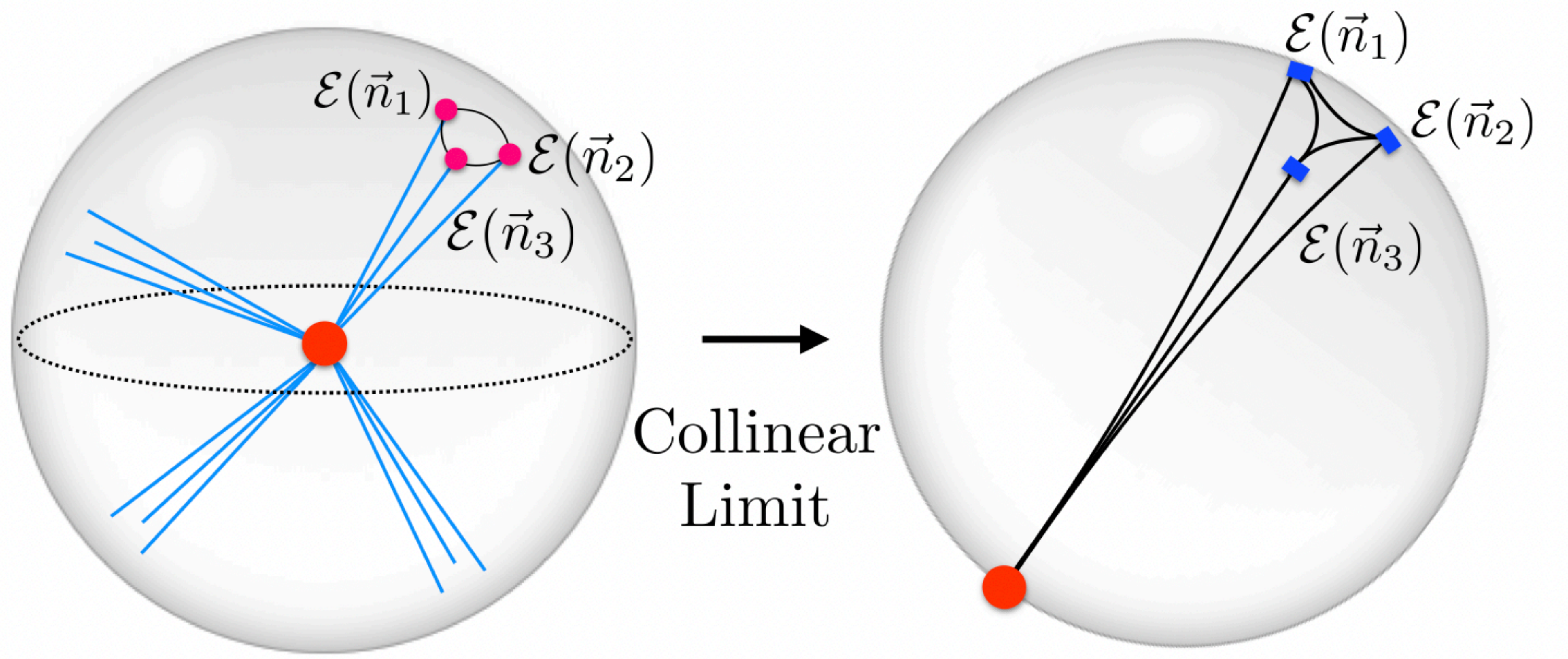
Evan Craft — Yale University

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

Yale University

MIT

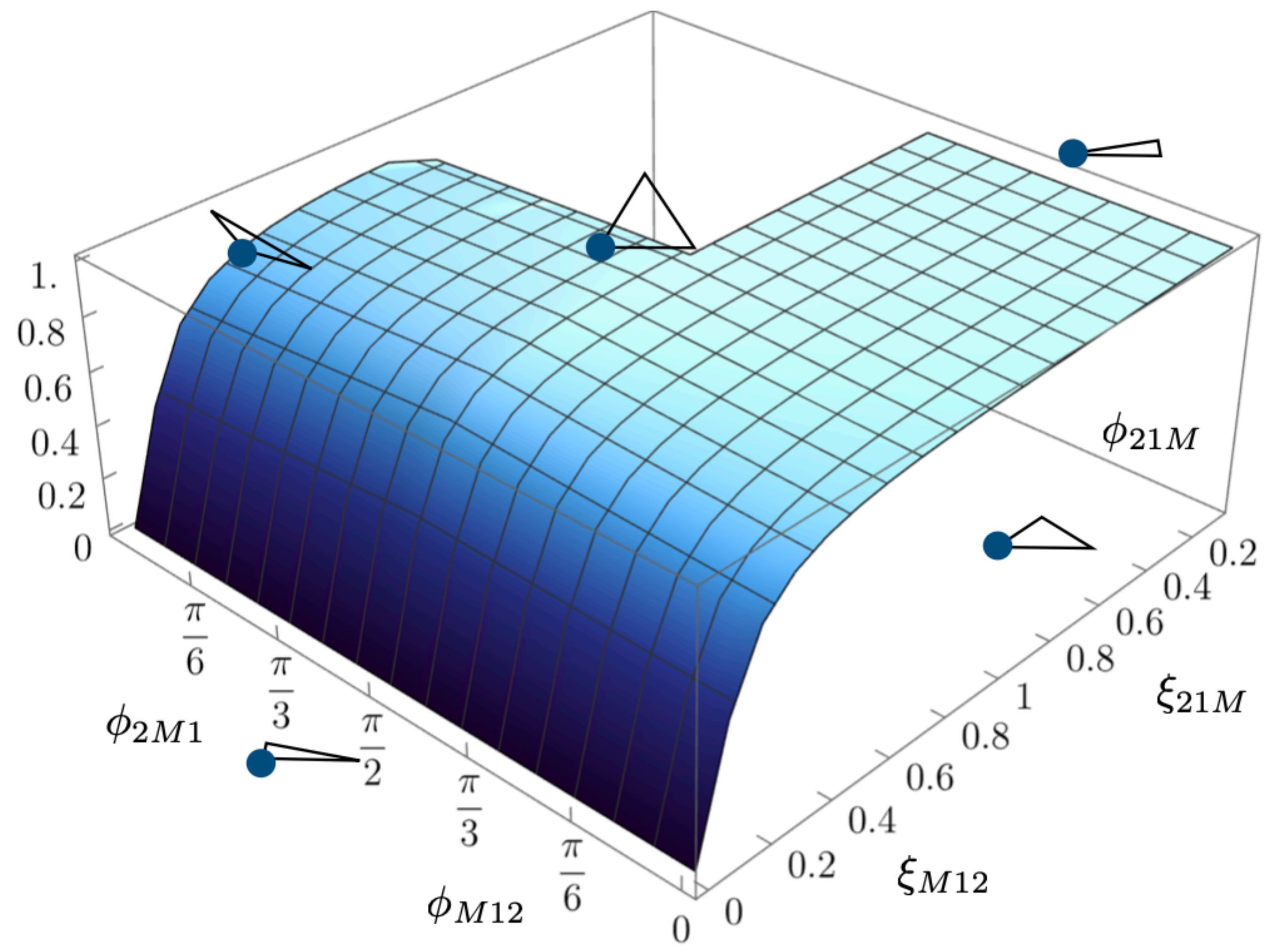
Extension: Higher Points



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

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

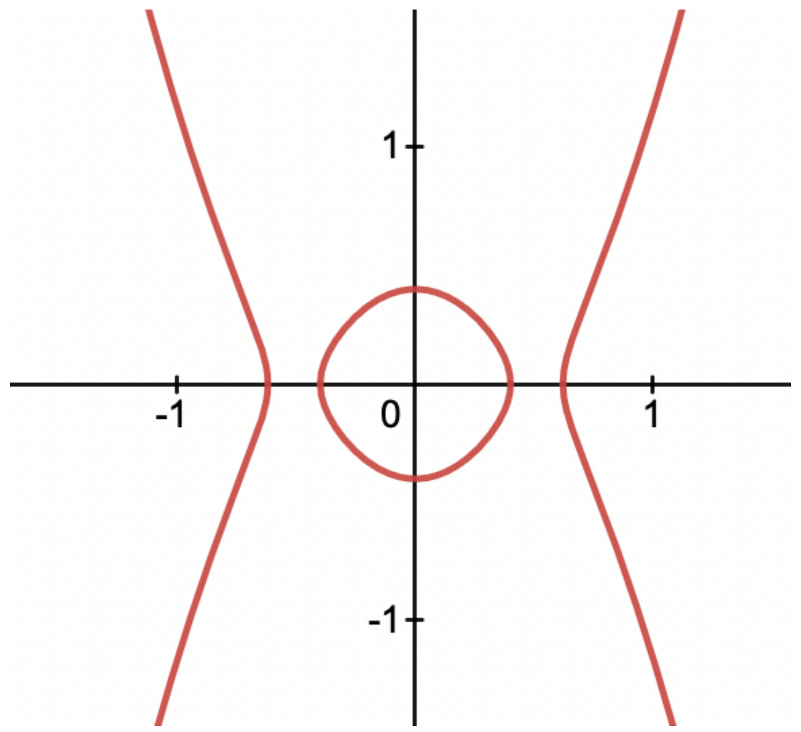
→ **Probe fundamental operators of QCD**

Elliptic Polylogarithms

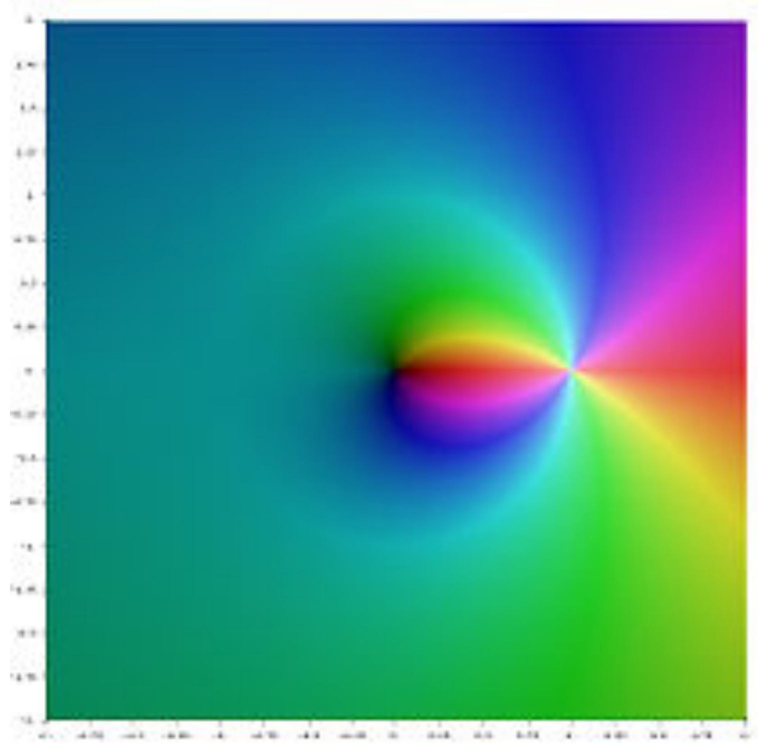
In addition to elliptic integrals, one encounters further complex structures with the EEEC

→ Multiple Elliptic Polylogarithms (MPLs)

→ Elliptic Curve + Iterated Logarithm



+



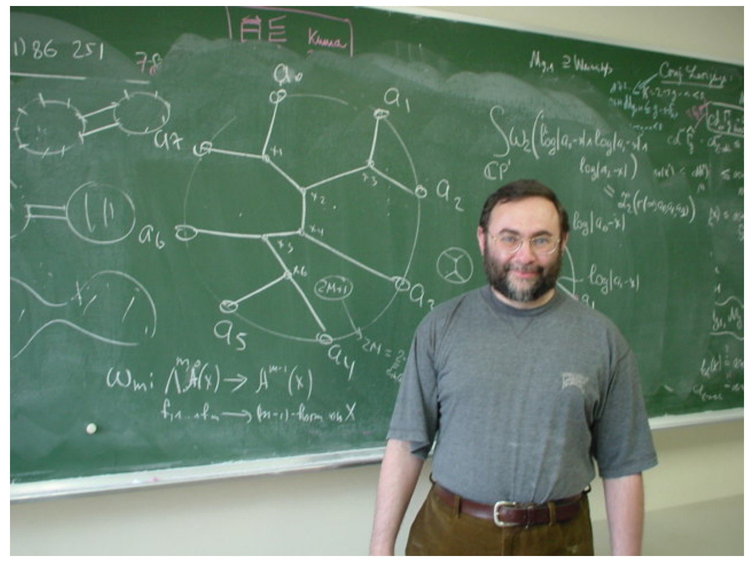
elliptic structure

polylogarithmic structure

→ Only understood within the last 5 years

→ EEC at the frontiers of math and physics

C. Duhr



A. Goncharov

↓ Elliptic Polylogarithms

tools for massive EEEC

↓ Generalized Polylogarithms

tools for massless EEEC

Elliptic polylogarithms and iterated integrals on elliptic curves. Part I: general formalism

Johannes Broedel (Humboldt U., Berlin, Inst. Math. and Humboldt U., Berlin), Claude Duhr (CERN and Louvain U., CP3), Falko Dulat (SLAC), Lorenzo Tancredi (CERN)

Dec 19, 2017

54 pages

Published in: *JHEP* 05 (2018) 093

Published: May 15, 2018

e-Print: 1712.07089 [hep-th]

DOI: 10.1007/JHEP05(2018)093

Report number: CERN-TH-2017-273, CP3-17-57, HU-EP-17-29, HU-Mathematik-2017-09, SLAC-PUB-17194

View in: ADS Abstract Service, CERN Document Server

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.)**

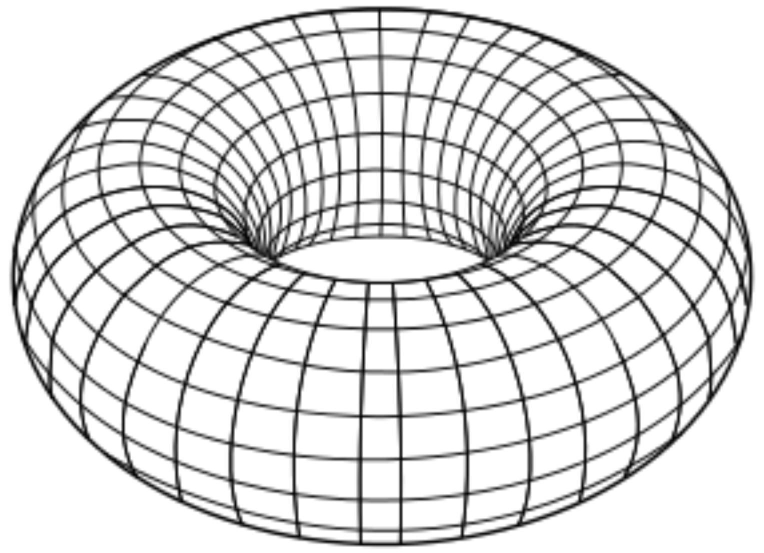
Two Point $\int \frac{1}{y}, \int \frac{x^2}{y}, \int \frac{1}{(x^2-p^2)\,y}$

→ **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.**

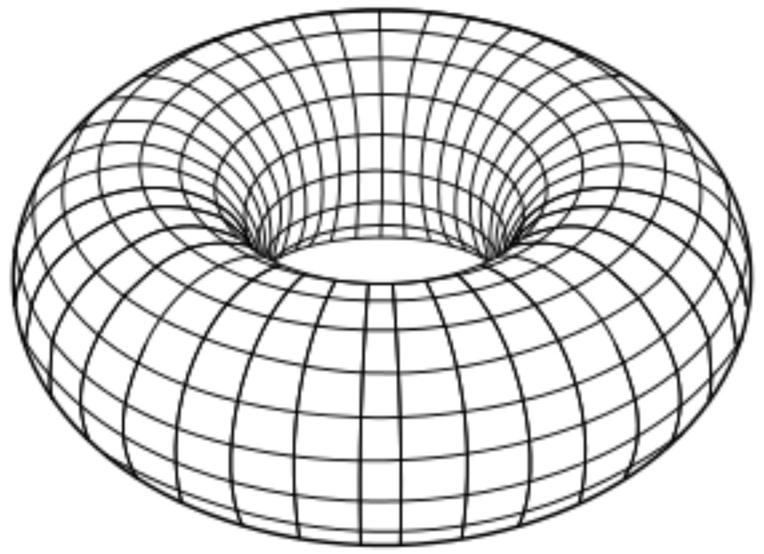
→ **analytic isomorphism to a torus**



Topological Aspects

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

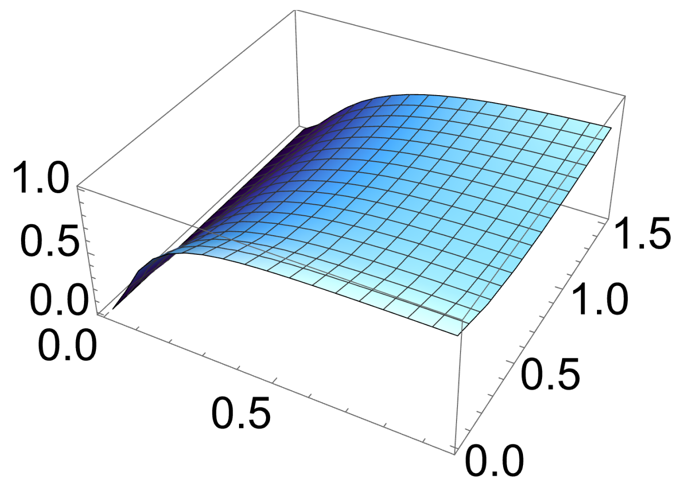
$$y^2 = 4x^3 - g_1 x - g_3 \longrightarrow$$



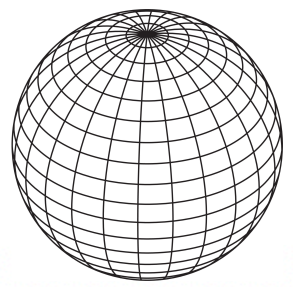
$$\omega_1 \sim {}_2F_1(1/2\,,1/2\,,1\,;\lambda)$$

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

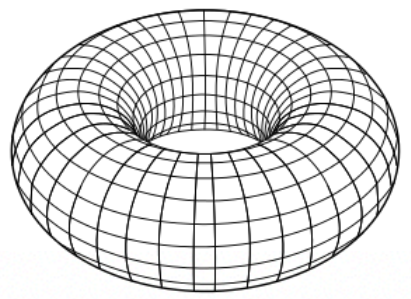
periods deformed by kinematics

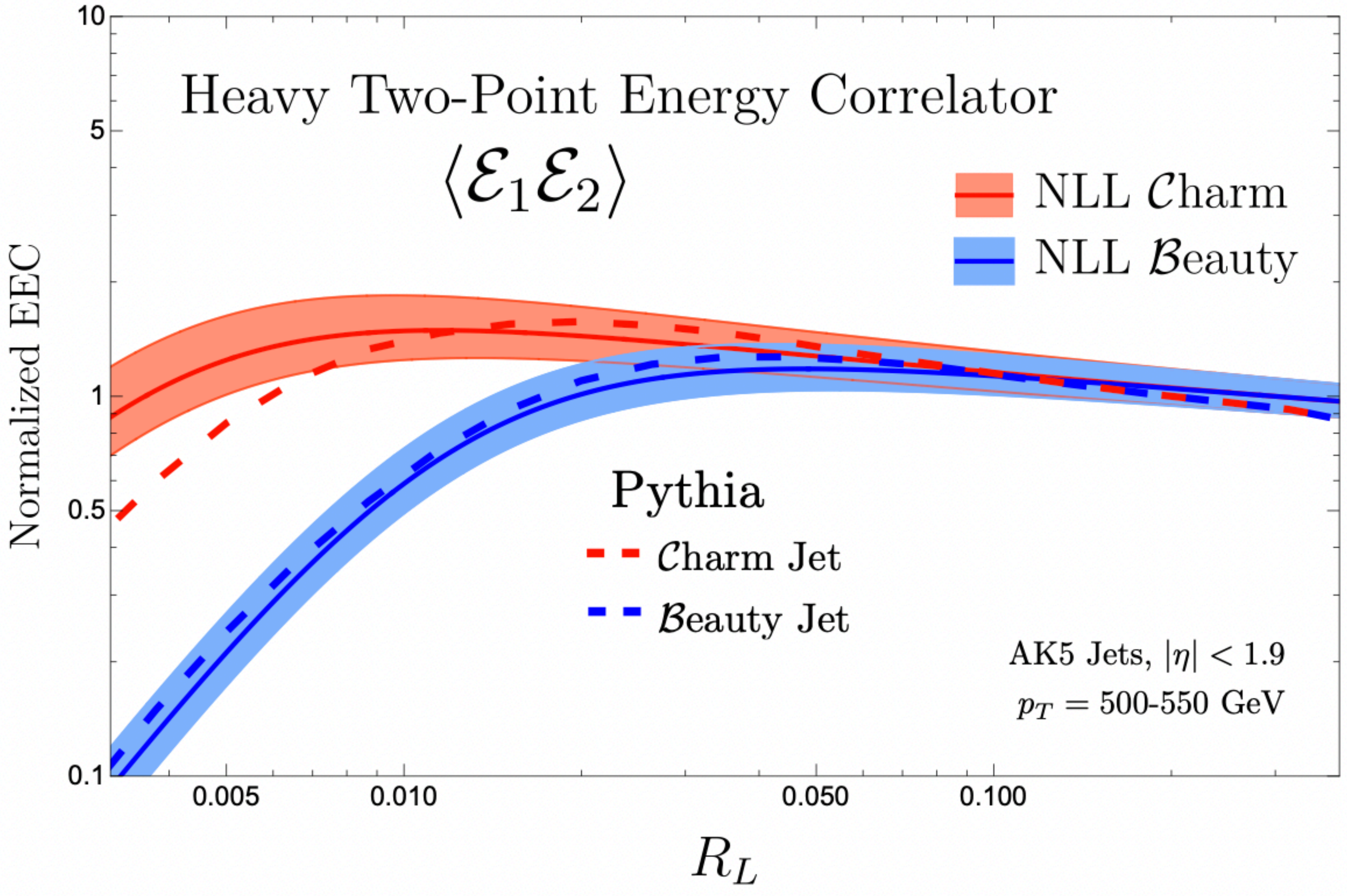


Similar degeneration for the three point!



topology **degenerates** in the collinear limit

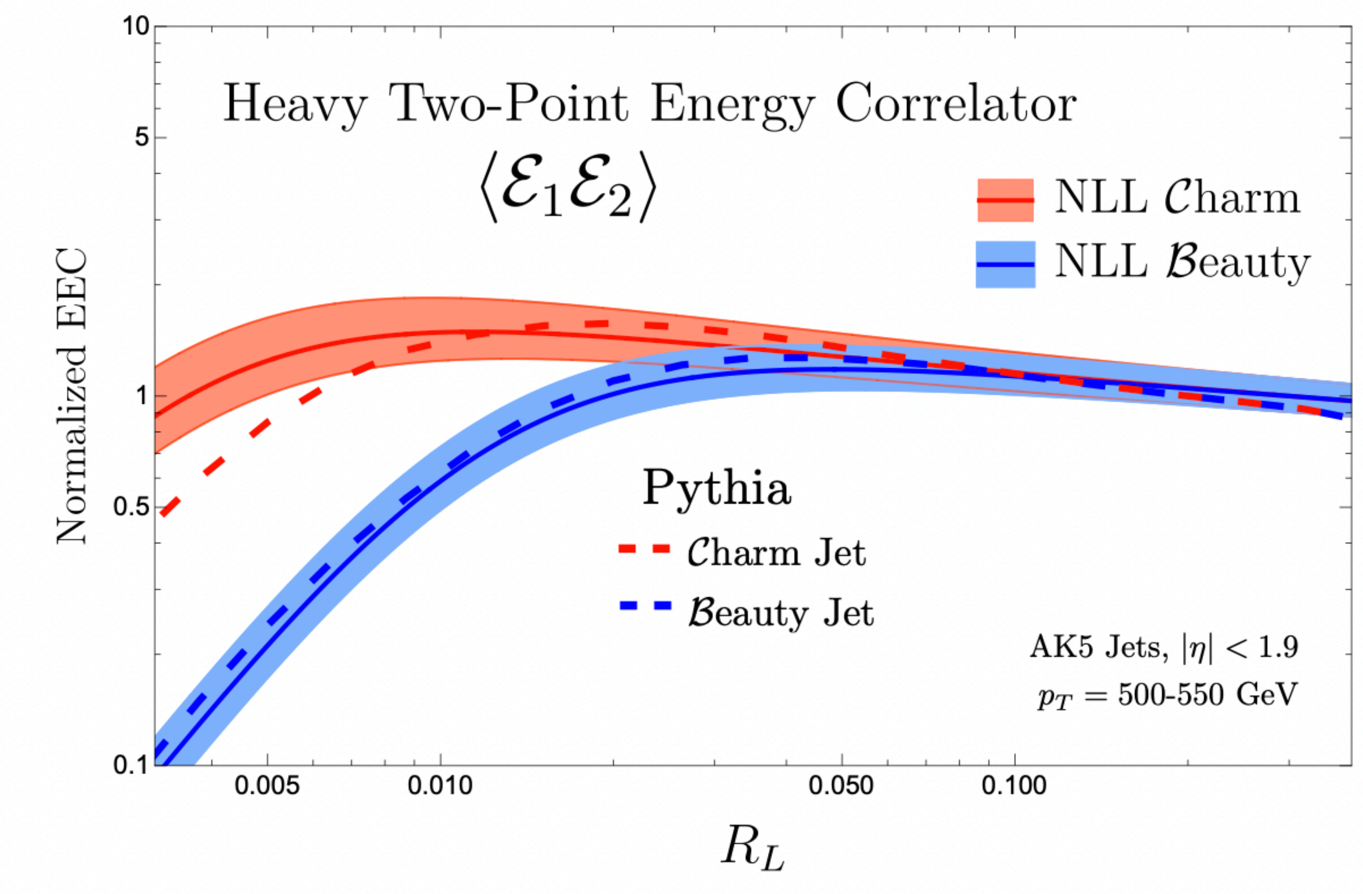




[EC, Lee, Mecaj, Moult]

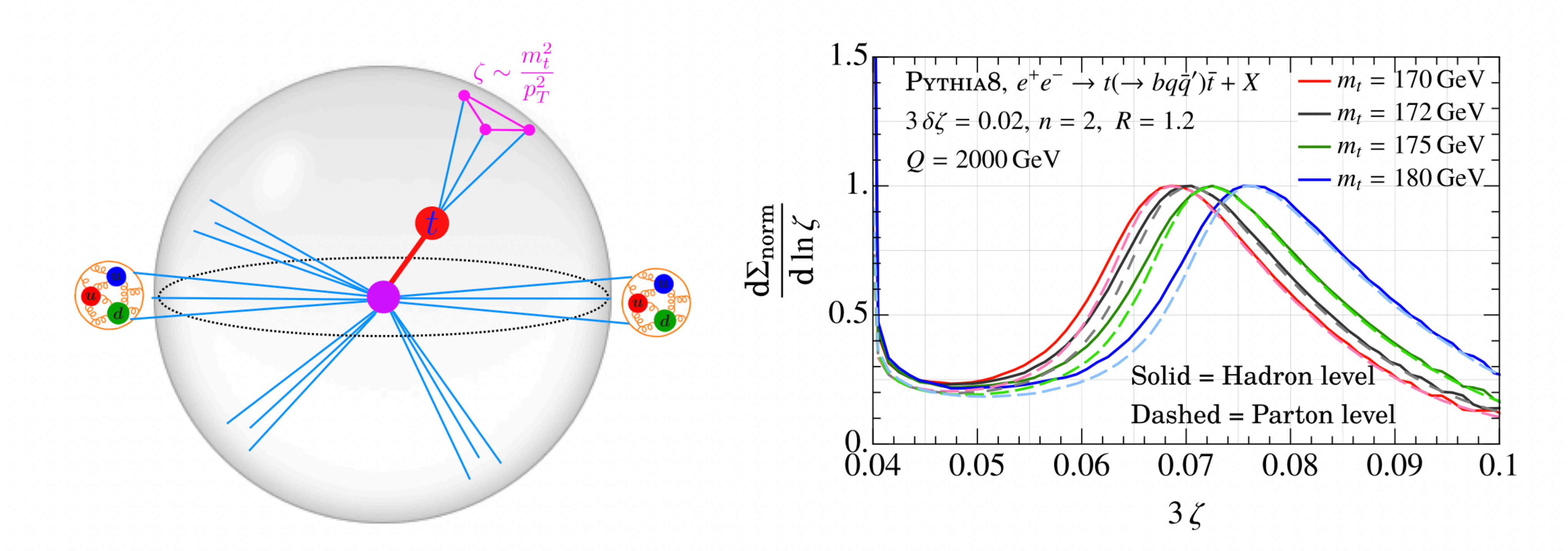
Interesting to study the **topological** aspects of the observable

What can you do with this?

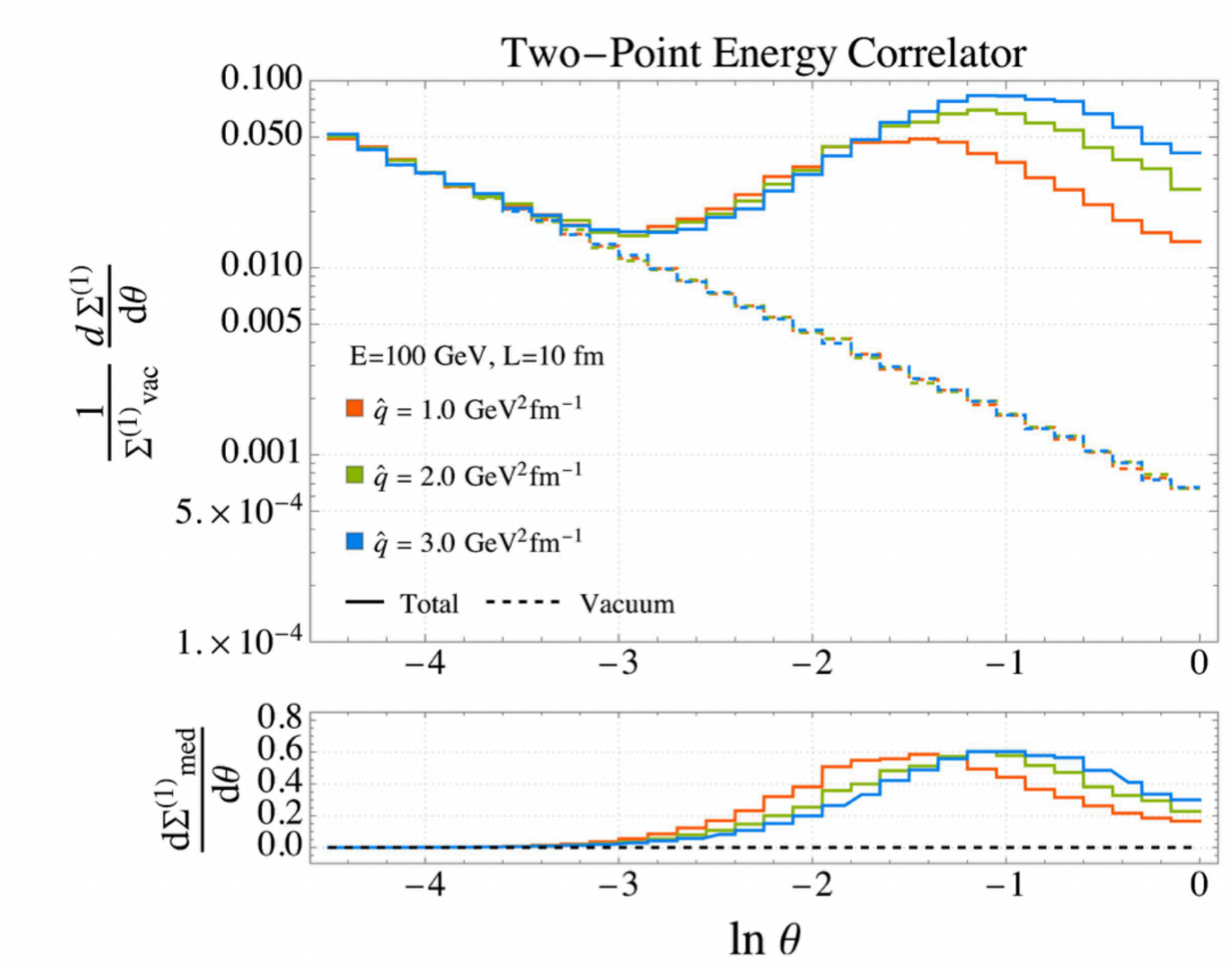


Hadronization and Confinement

Precision Measurements of the Top Mass



[Holguin, Moult, Pathak, Procura]



Because of its dual description, the EEC has been applied to a **diverse range of fundamental questions**

→ **Energy Correlators** present a promising avenue for bolstering our collider studies

Understanding the Quark Gluon Plasma

[Andres, Holguin, Moult, …]

What about the Heavy E3C?

Formal

1. Understanding the space of functions generated by correlations of heavy energy flow

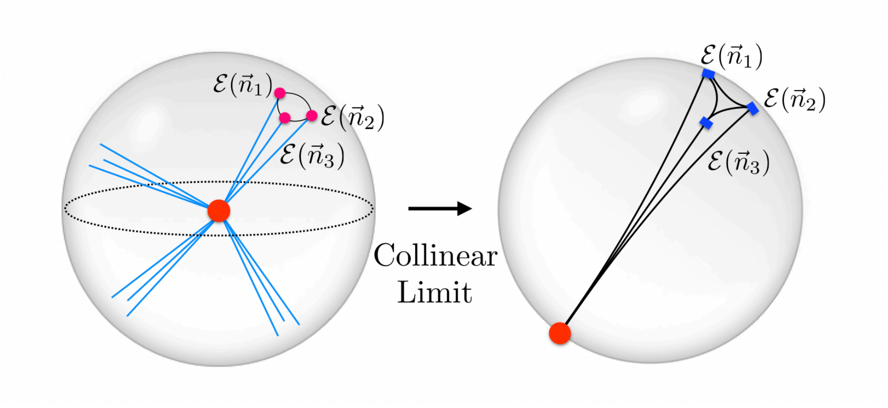
$$\int \frac{1}{y}\{E,F,\Pi\},\quad \int \frac{x^2}{y}\{E,F,\Pi\},\ldots \subset \text{ E3C}$$

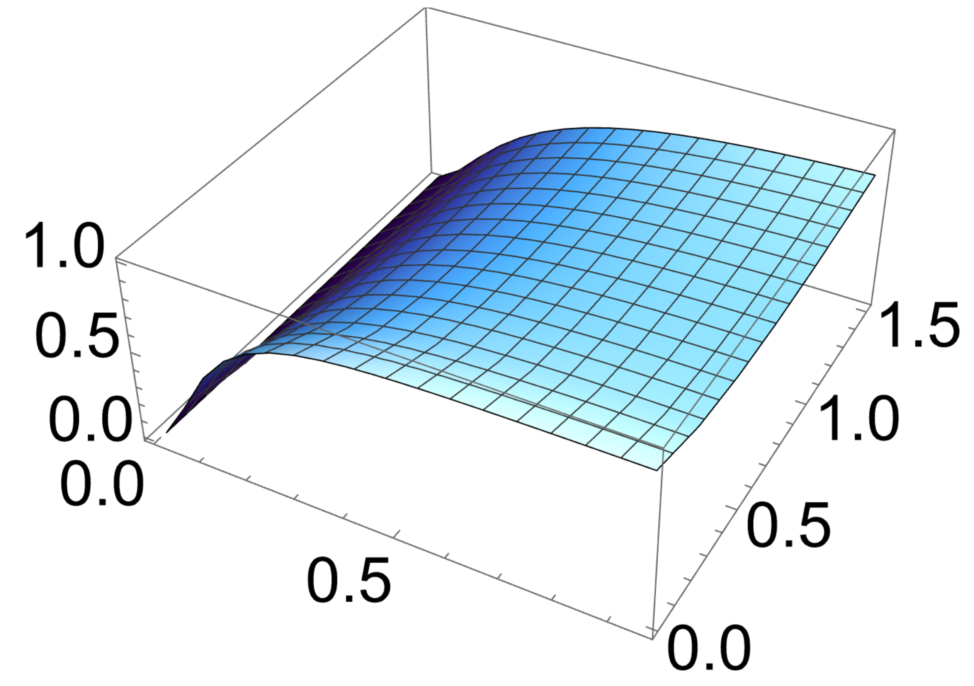
2. Playground for heavy SCET factorization with clear applications to collider physics

$$\frac{d\Sigma}{d\psi_1 d\psi_2 d\psi_3} \sim \vec{J} \otimes \vec{H} \otimes \vec{S}$$

Phenomenological

1. Access to the shape of the deadcone with applications to precision tests of QCD





2. An example of a 3 parameter, heavy event shape observable

→ Useful for tuning event generators

→ Playground for testing ML techniques

What about the Heavy E3C?

Formal

1. Understanding the space of functions generated by correlations of heavy energy flow

2. Playground for heavy SCET factorization with clear applications to collider physics

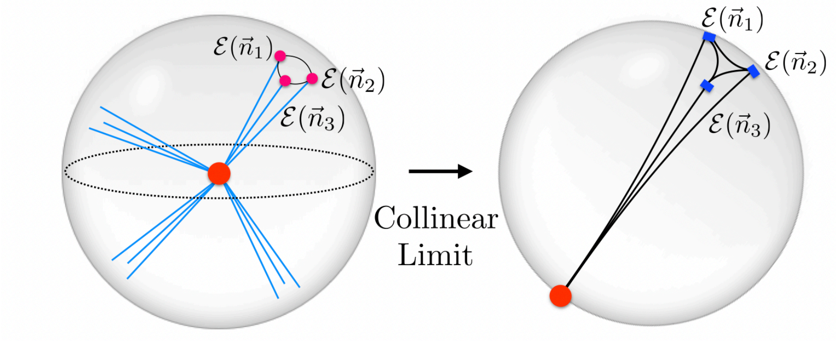
$$\int \frac{1}{y}\{E, F, \Pi\}, \quad \int \frac{x^2}{y}\{E \ldots$$

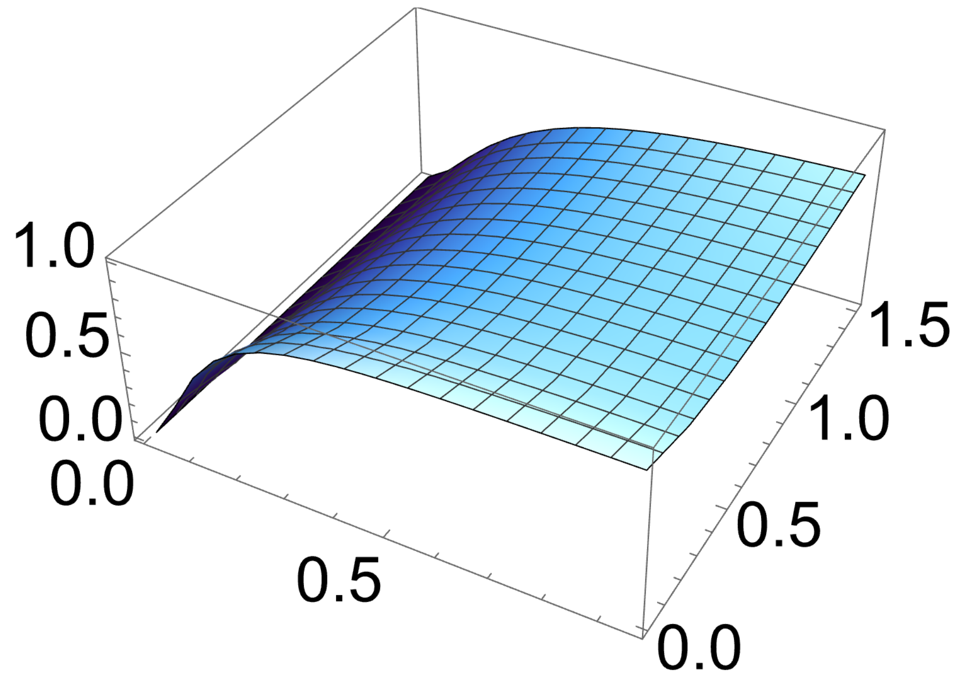
$$\ldots \vec{J} \otimes \vec{H} \otimes \vec{S}$$

Both halves of this slide are in *symbiosis*

Phenomenological

1. Access to the shape of the deadcone with applications to precision tests of QCD





2. An example of a 3 parameter, heavy event shape observable

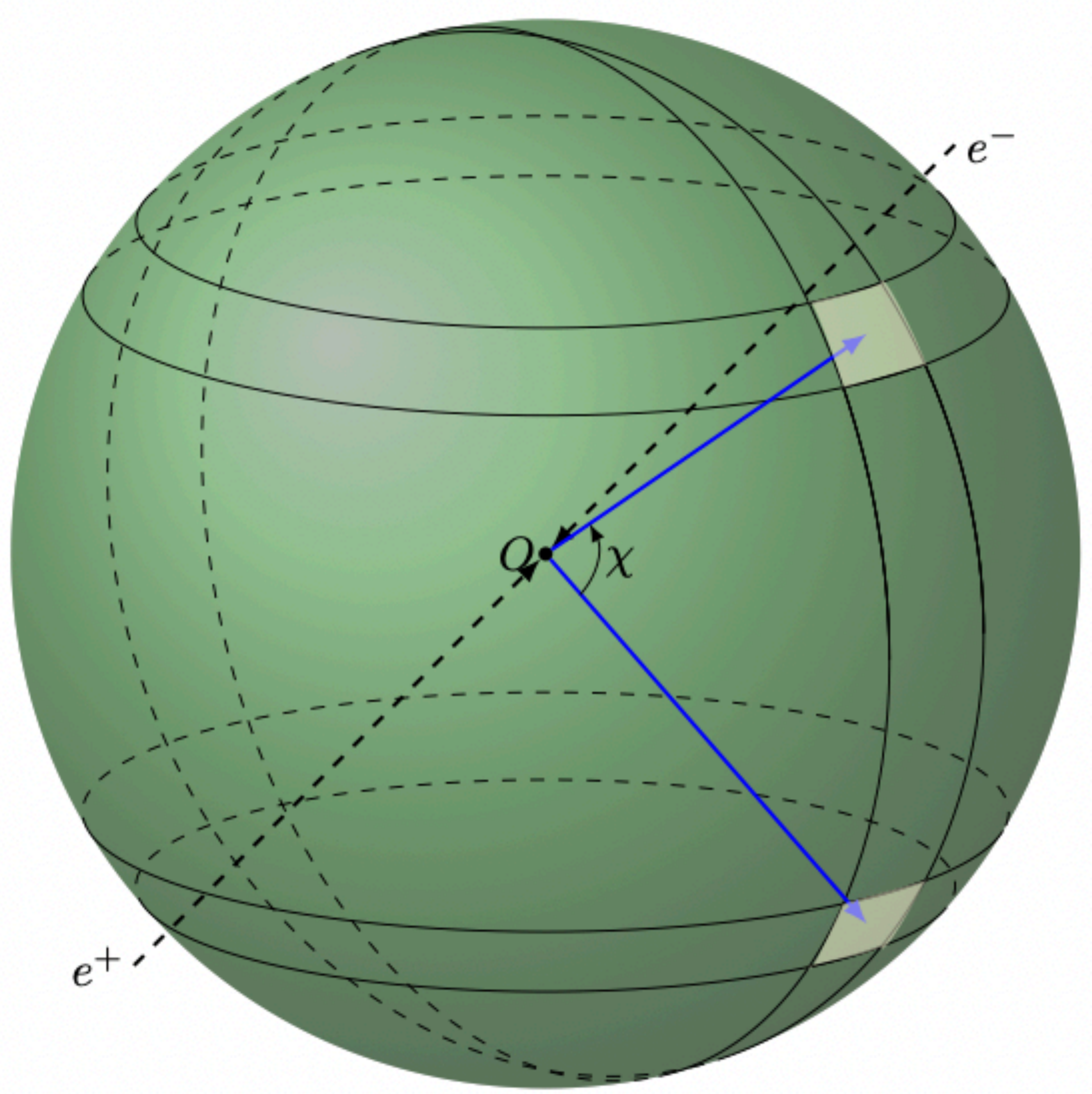
→ Useful for tuning event generators

→ Playground for testing ML techniques

Two Symbiotic Perspectives

Experimental View

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



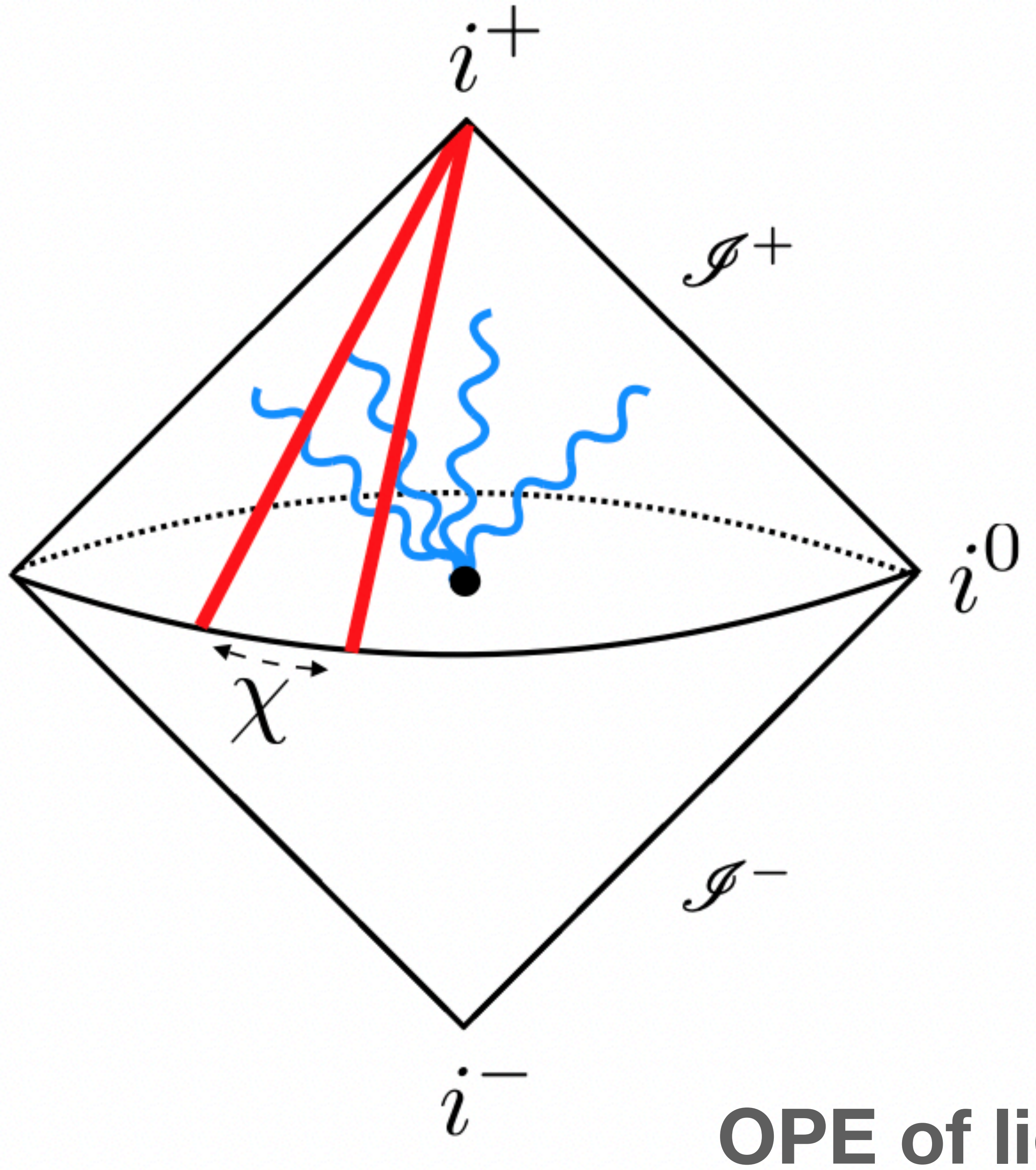
Calorimeter cells at null infinity

Theoretical Foundation

$$\frac{d\sigma}{d\cos\chi} = \frac{\int d^4x\, e^{iq\cdot x} \langle \mathcal{O}(x) \mathcal{E}(\vec{n}_1) \mathcal{E}(\vec{n}_2) \mathcal{O}^\dagger(0) \rangle}{\int d^4x\, e^{iq\cdot x} \langle \mathcal{O}(x) \mathcal{O}^\dagger(0) \rangle}$$

Beautiful Correspondence

$\longleftrightarrow$



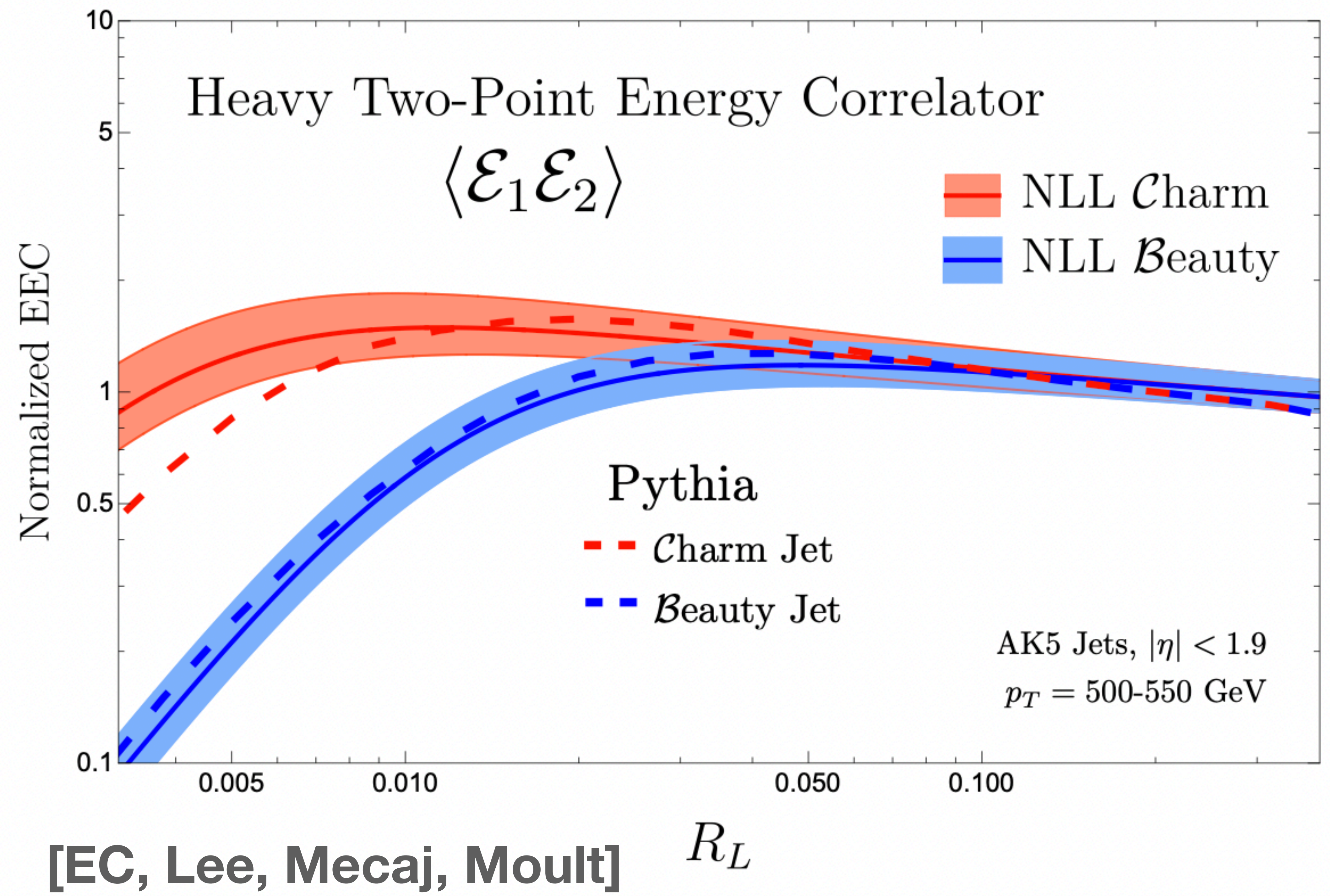
OPE of lightray operators

Concluding Remarks

Unifying Theory and Experiment

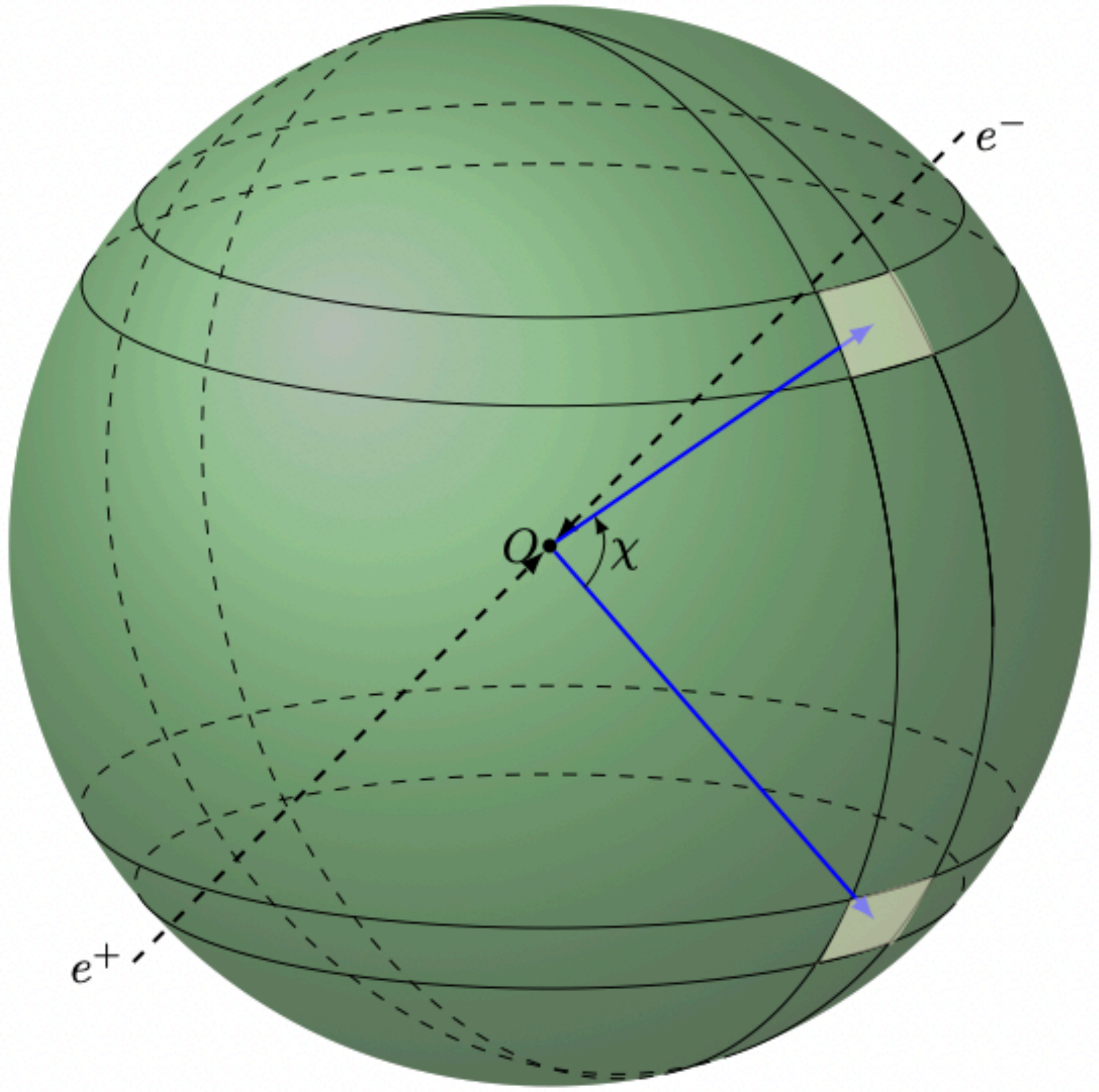
Two Symbiotic Perspectives

Beautiful and Charming Interplay!



[EC, Lee, Mecaj, Moult]

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

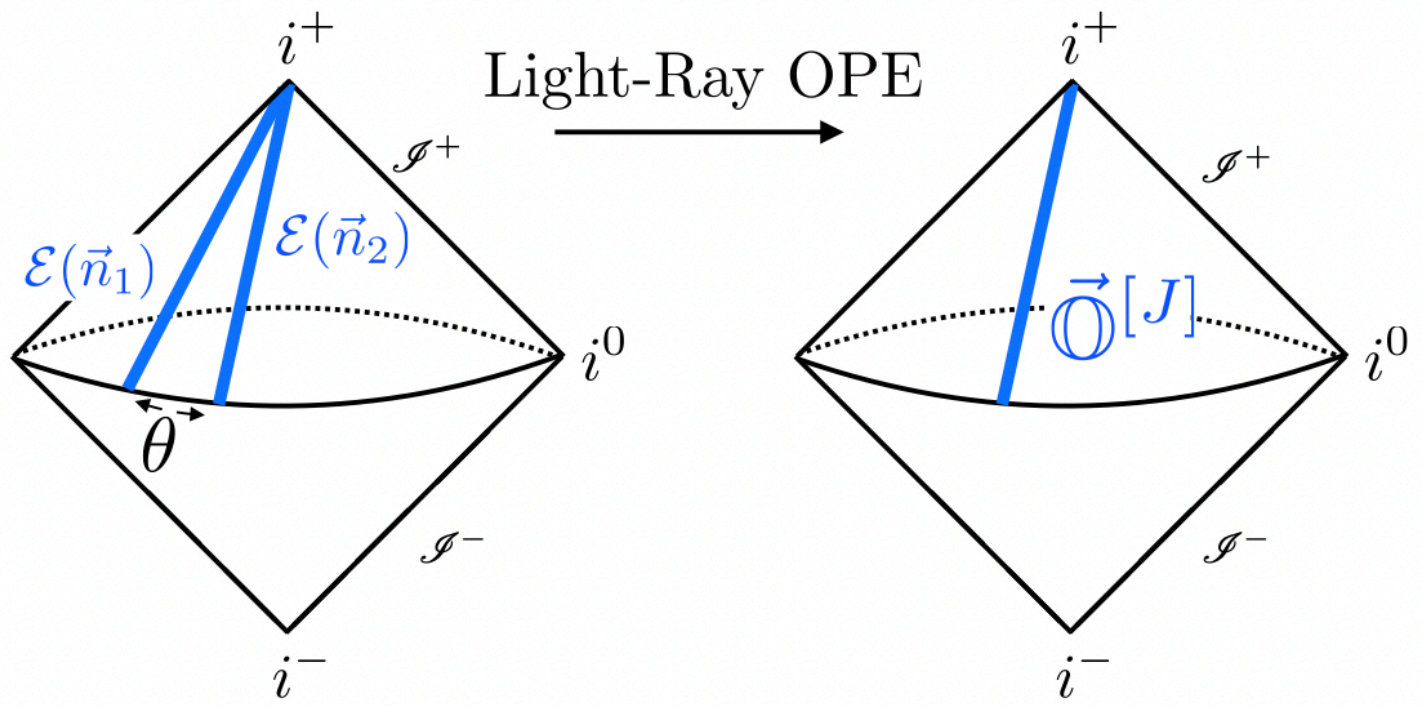


Experiment

New Observables

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

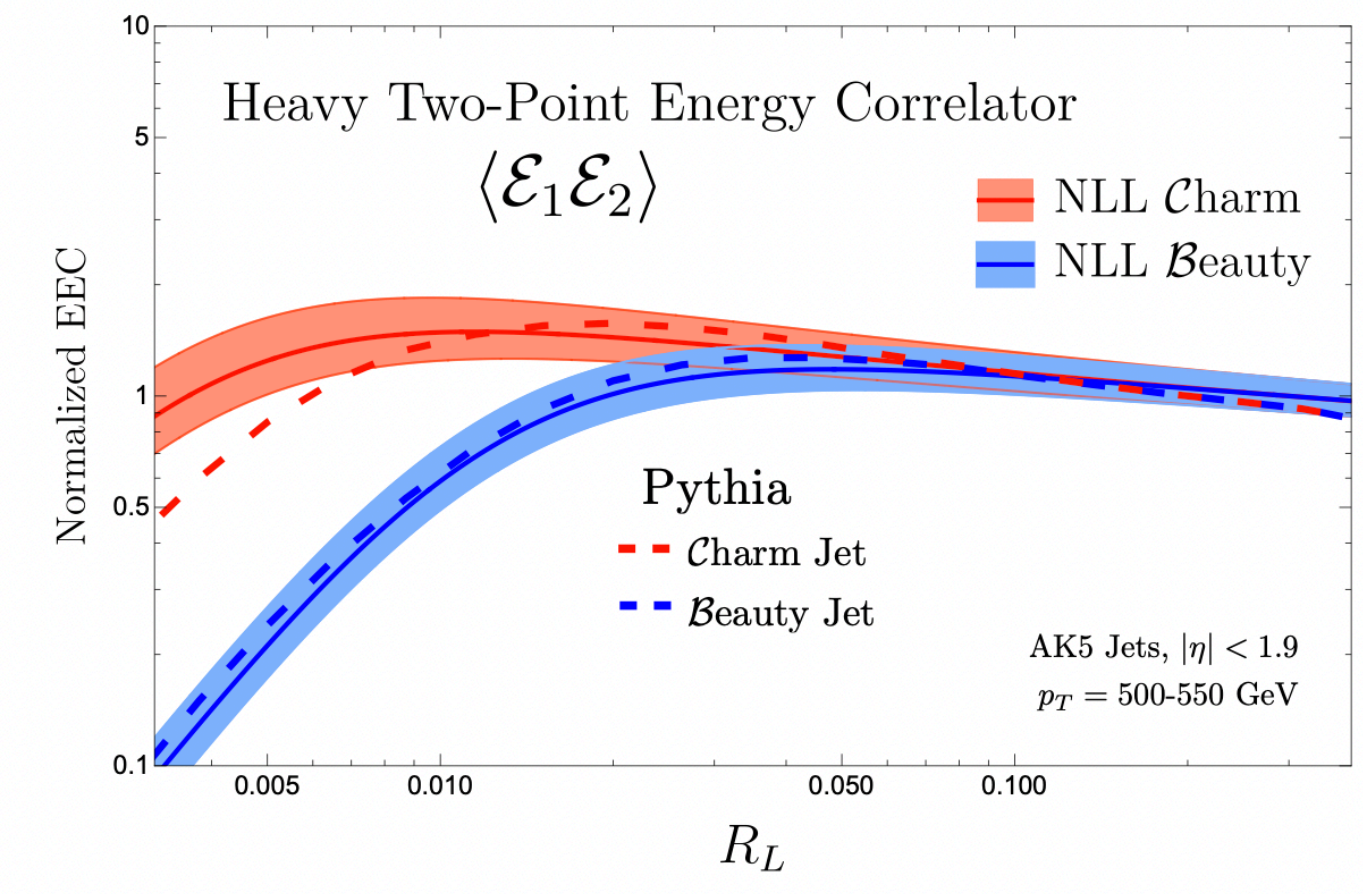
Theory



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

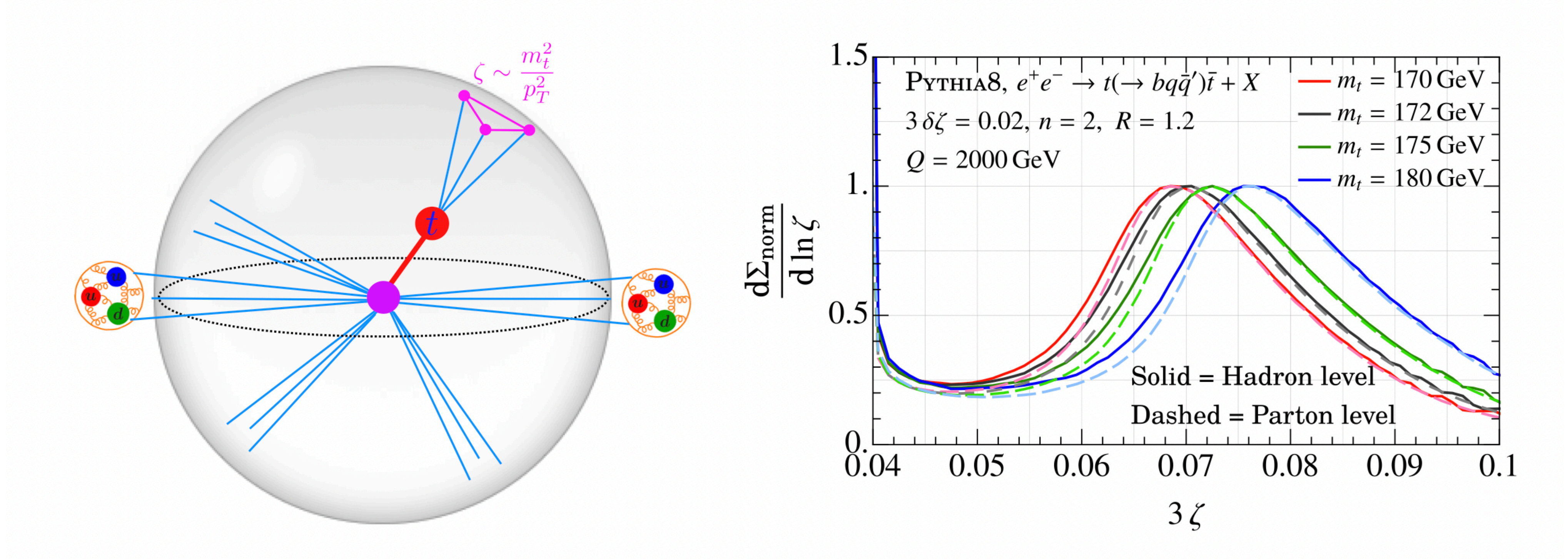
Symbiosis in Action

[EC, Lee, Mecaj, Moult]



Hadronization and Confinement

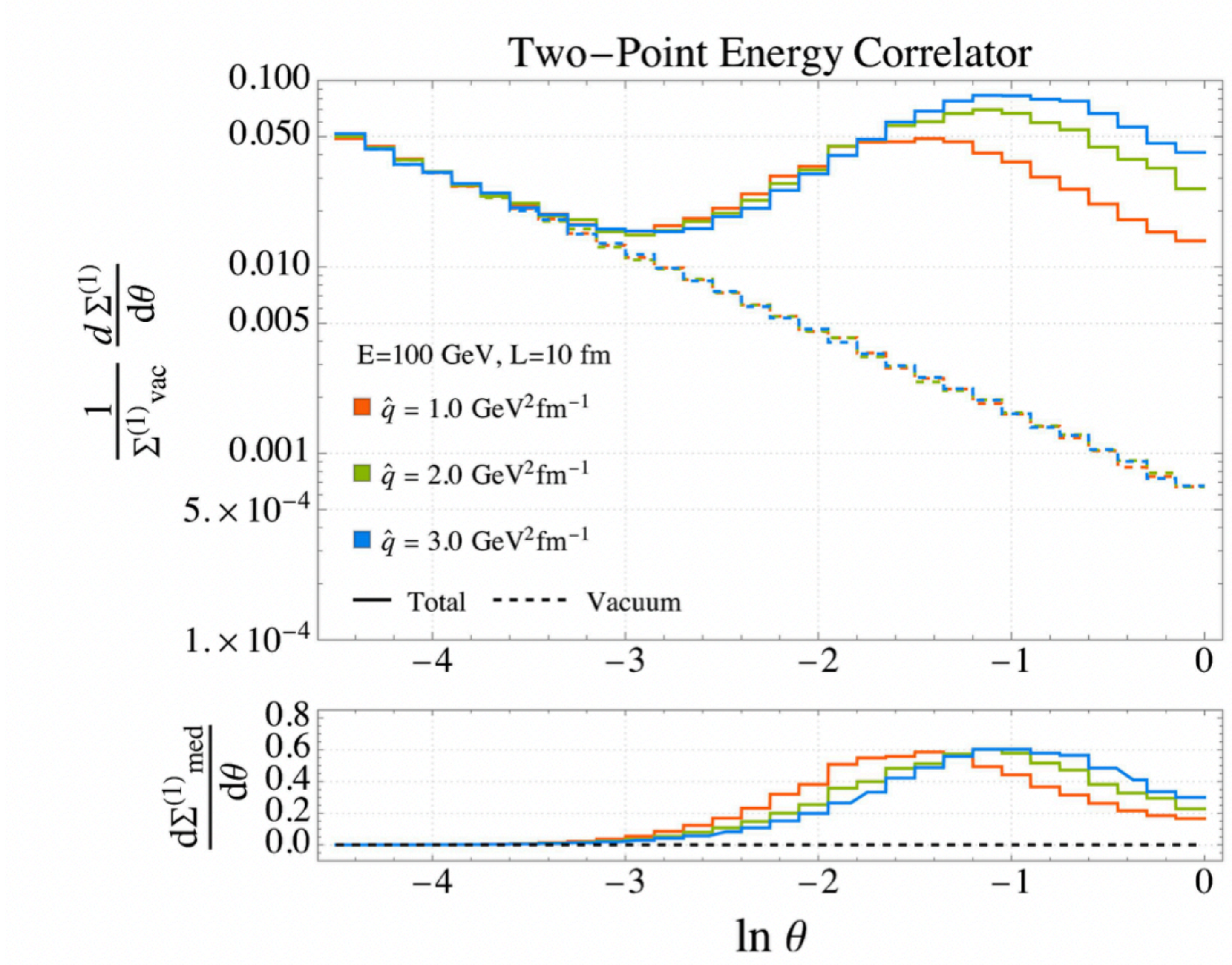
Precision Measurements of the Top Mass



[Holguin, Moult, Pathak, Procura]

Because of it's dual description, the EEC has been applied to a diverse range of fundamental questions

→ **Energy Correlators present a promising avenue for bolstering our collider studies**



Understanding the Quark Gluon Plasma

[Andres, Holguin, Moult, …]

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