Energy Correlators at the Collider Frontier

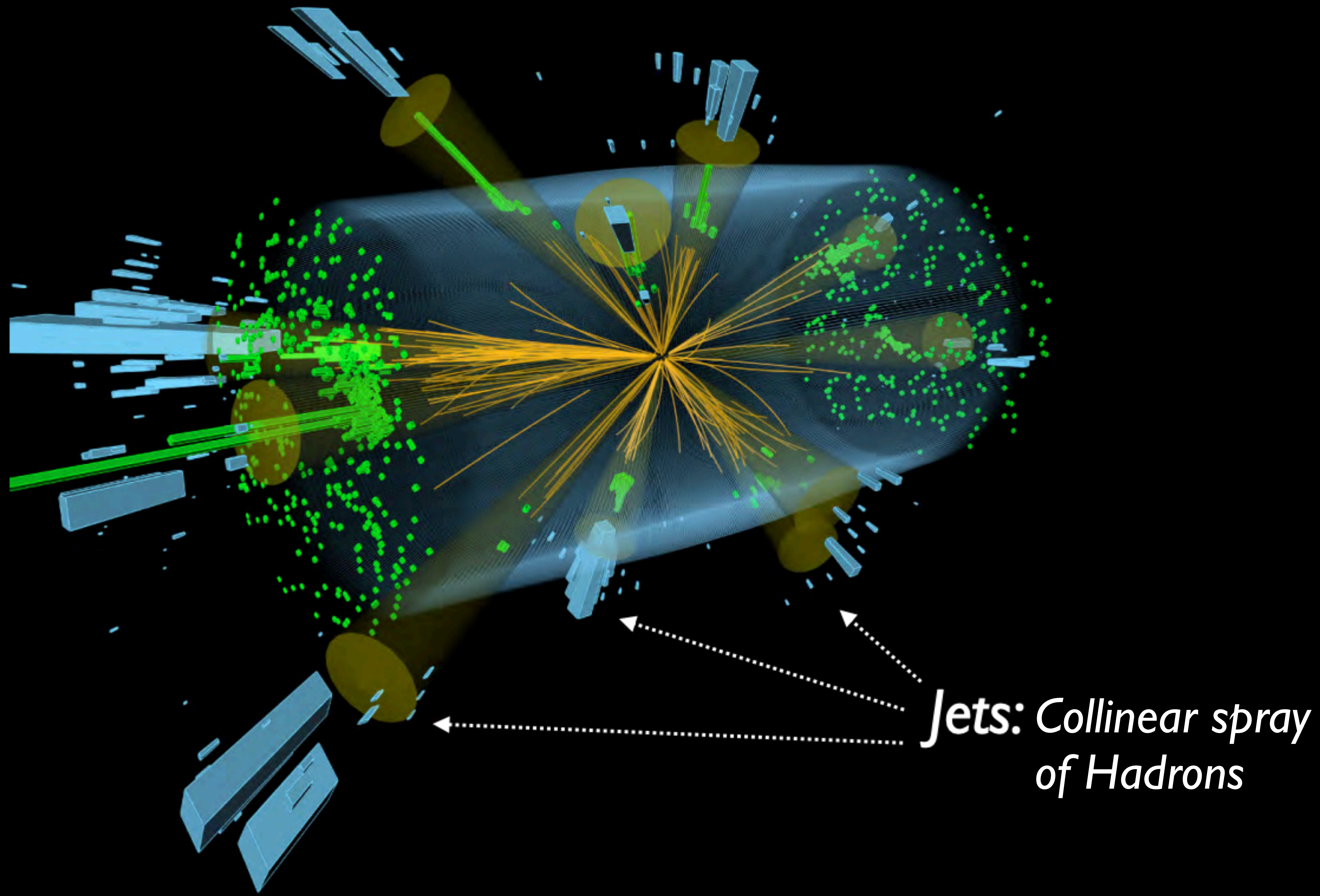
Kyle Lee

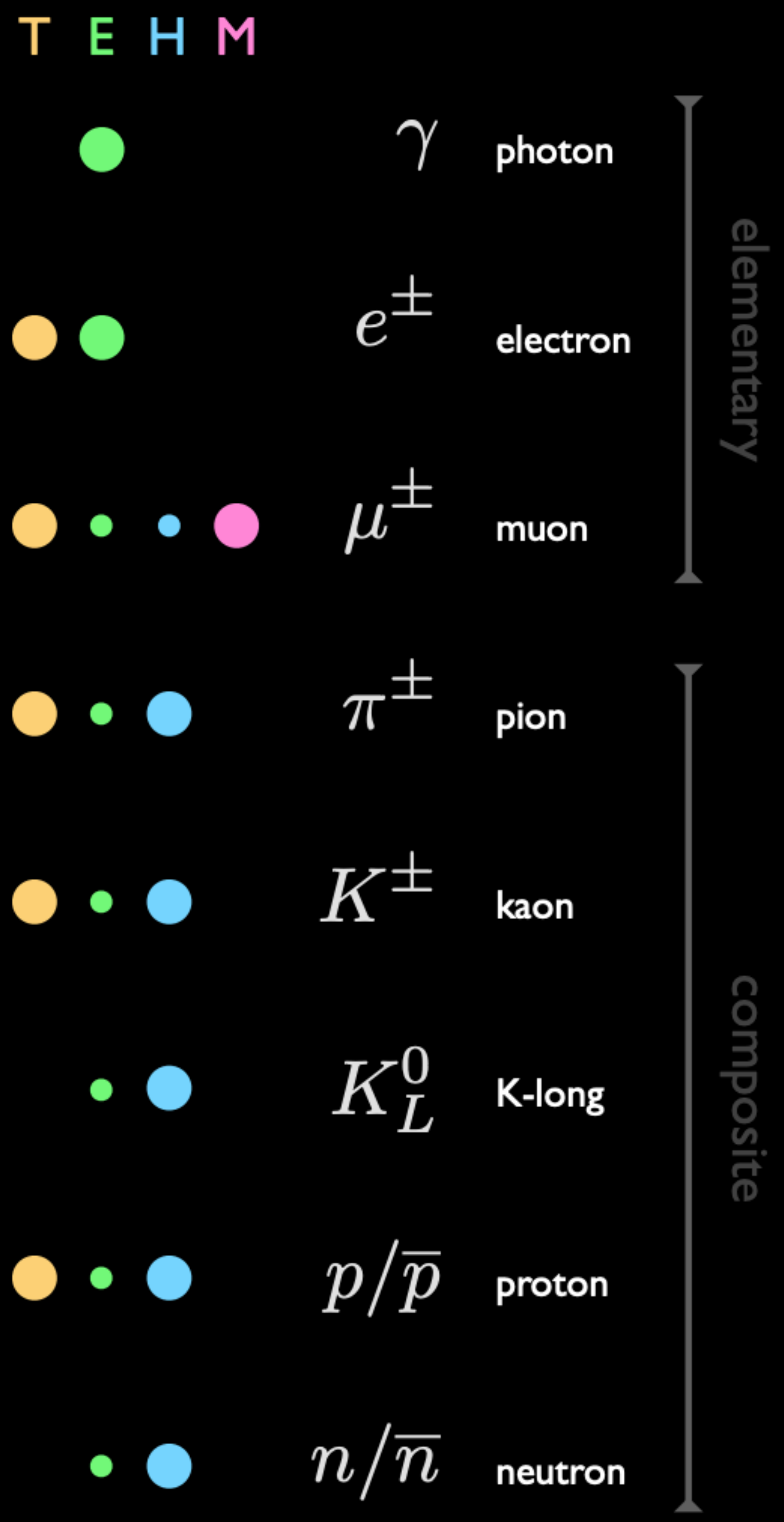
University of Minnesota

03.06.2026

Argonne

Collider Event



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EXPERIMENT
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t at the LHC, CERN
2016-May-29 22:35:55.226560 GMT
: 274199 / 548714092 / 285
CMS Experiment at the LHC, CERN
Data recorded: 2016-Oct-11 10:44:24.059904 GMT
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EXPERIMENT
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ATLAS
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http://atlas.ch
ATLAS
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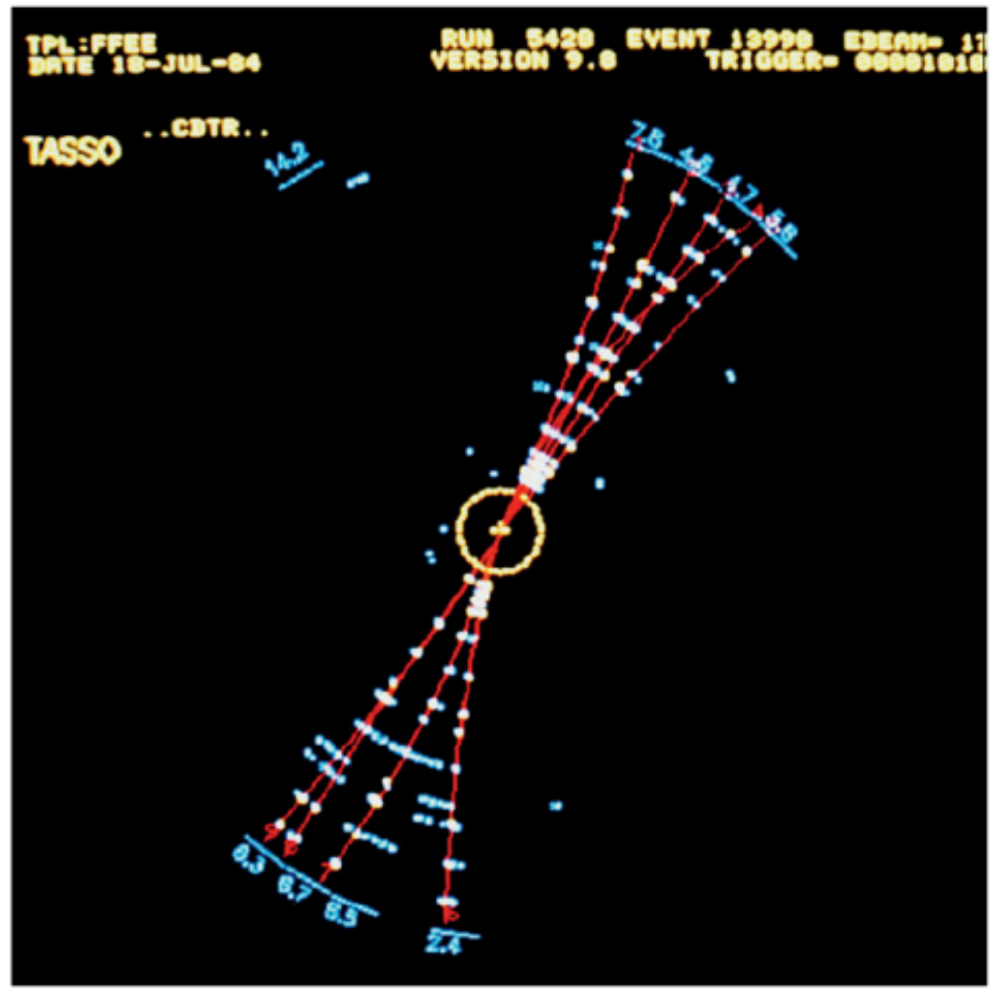
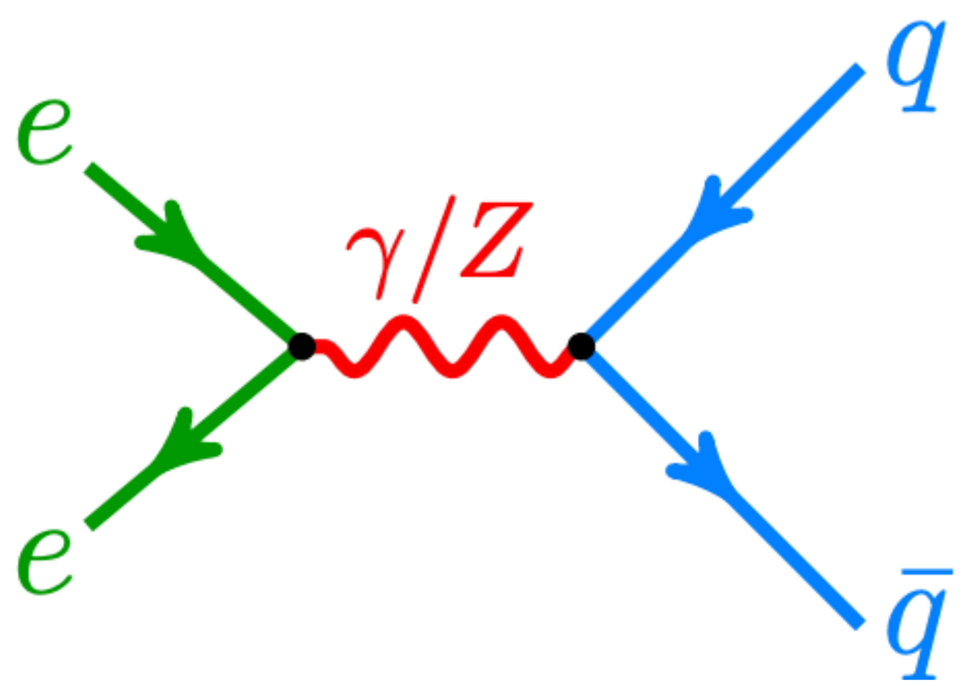
THE DAWN OF QCD: FROM PARTONS TO JETS

2-jet event





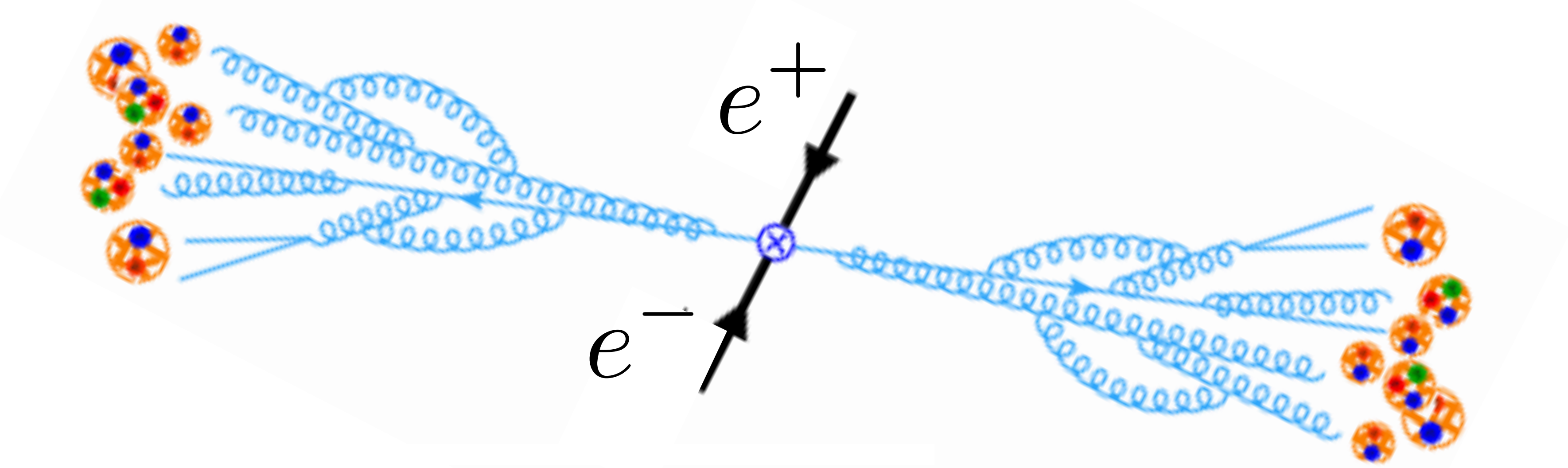
Evidence for Jet Structure in Hadron Production by e^+e^- Annihilation*

G. Hanson, G. S. Abrams, A. M. Boyarski, M. Breidenbach, F. Bulos, W. Chinowsky, G. J. Feldman, C. E. Friedberg, D. Fryberger, G. Goldhaber, D. L. Hartill,† B. Jean-Marie, J. A. Kadyk, R. R. Larsen, A. M. Litke, D. Lüke,‡ B. A. Lulu, V. Lüth, H. L. Lynch, C. C. Morehouse, J. M. Paterson, M. L. Perl, F. M. Pierre,§ T. P. Pun, P. A. Rapidis, B. Richter, B. Sadoulet, R. F. Schwitters, W. Tanenbaum, G. H. Trilling, F. Vannucci,‖ J. S. Whitaker, F. C. Winkelmann, and J. E. Wiss

e Berkeley Laboratory and Department of Physics, University of California, Berkeley, Califo and Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

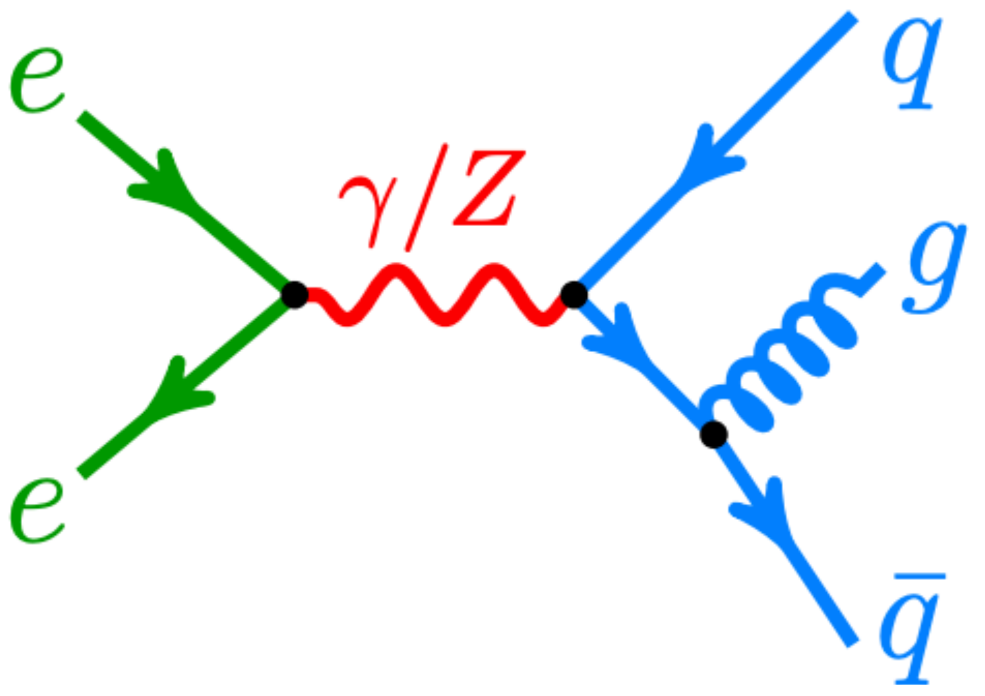
(Received 8 October 1975)

We have found evidence for jet structure in $e^+e^- \to$ hadrons at center-of-mass energies of 6.2 and 7.4 GeV. At 7.4 GeV the jet-axis angular distribution integrated over azimuthal angle was determined to be proportional to $1+(0.78\pm0.12)\cos^2\theta$.



3-jet event

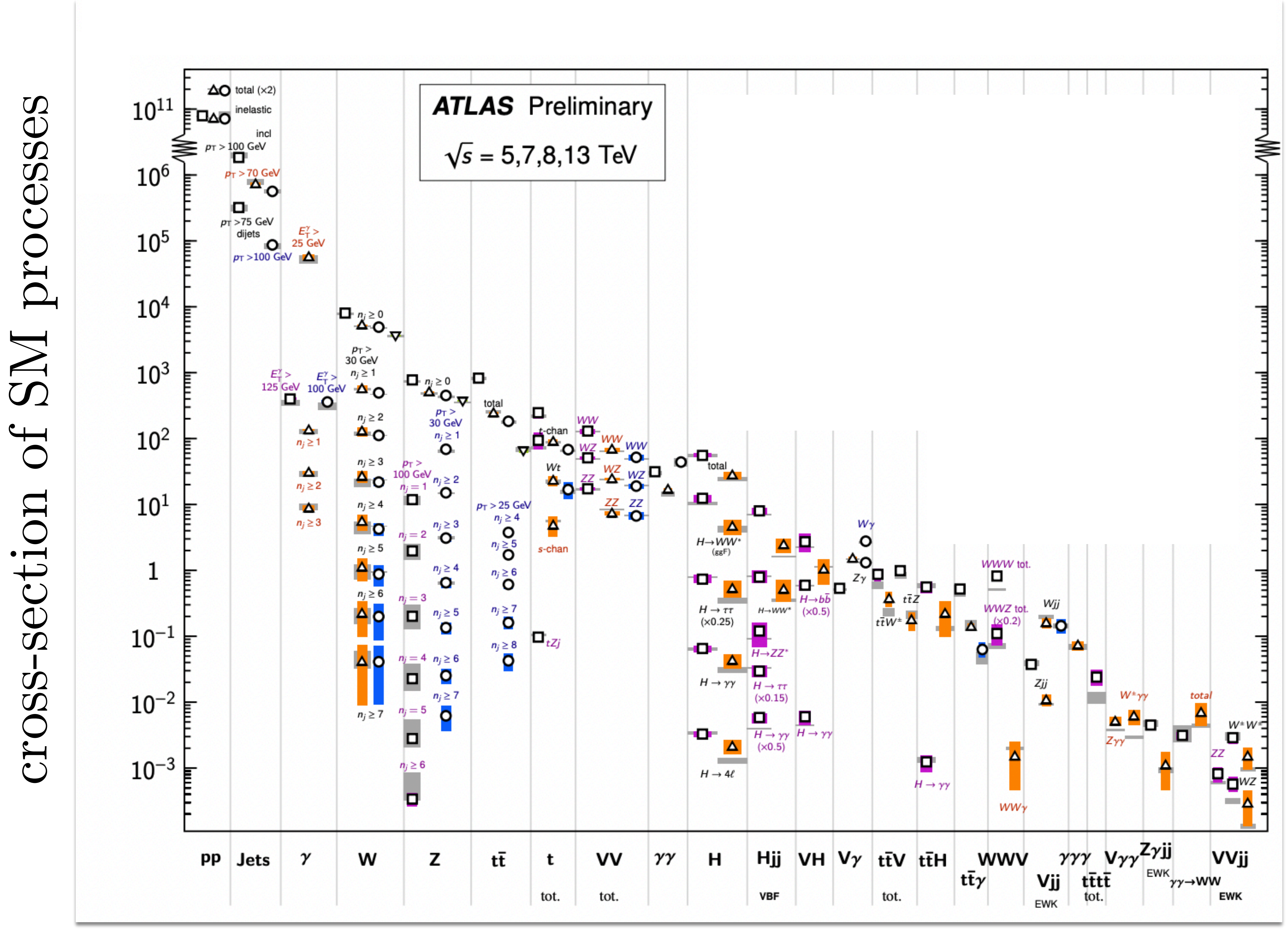
Wu, Zobernig `79

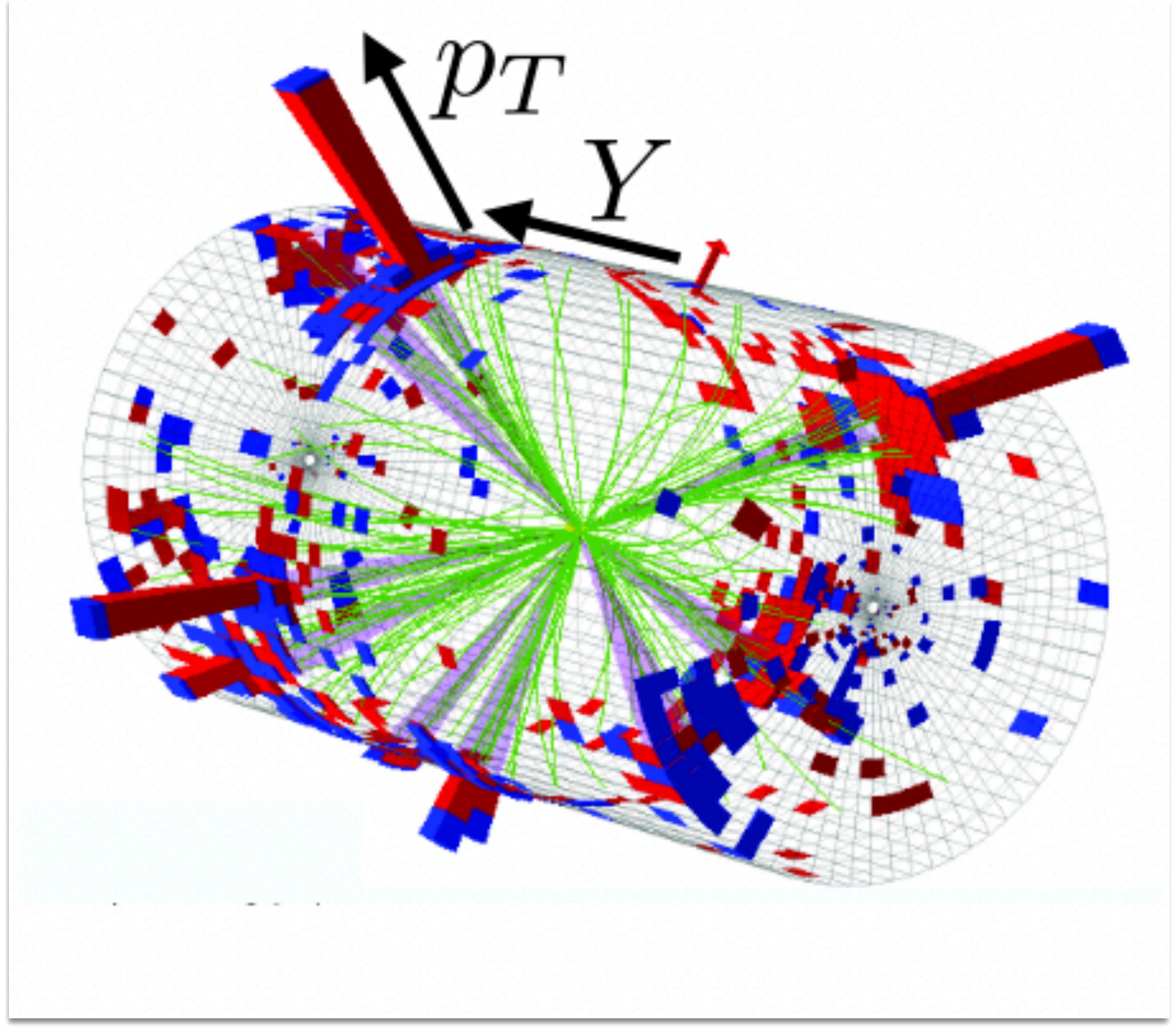


Jets unveiled the partonic nature of QCD, playing an important role in the confirmation of QCD as the theory of strong interactions!

HIGH-MULTIPLICITY JETS AT COLLIDERS

- **The effort to achieve precise predictions of jet cross sections has driven important theoretical developments in Quantum Field Theory**



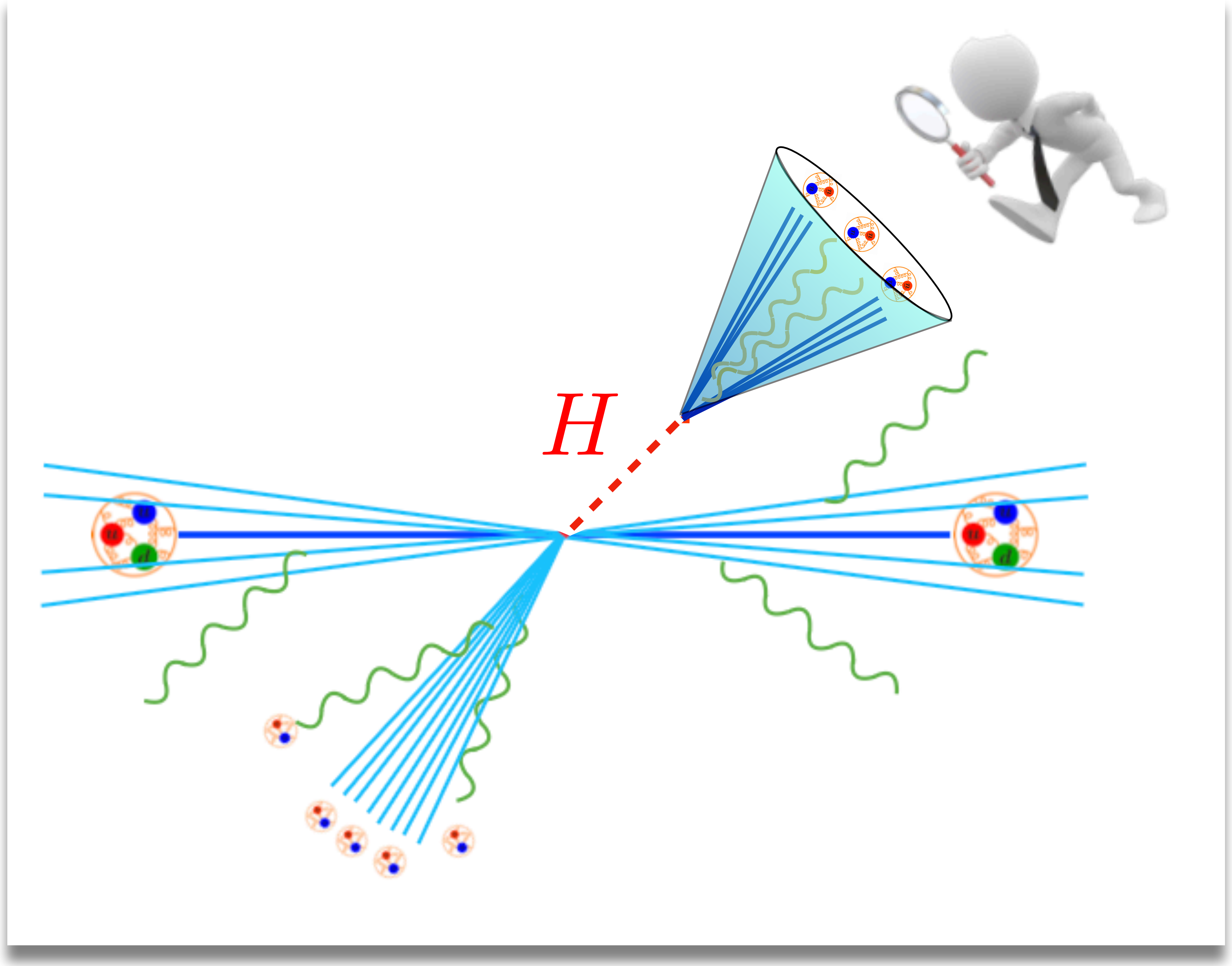


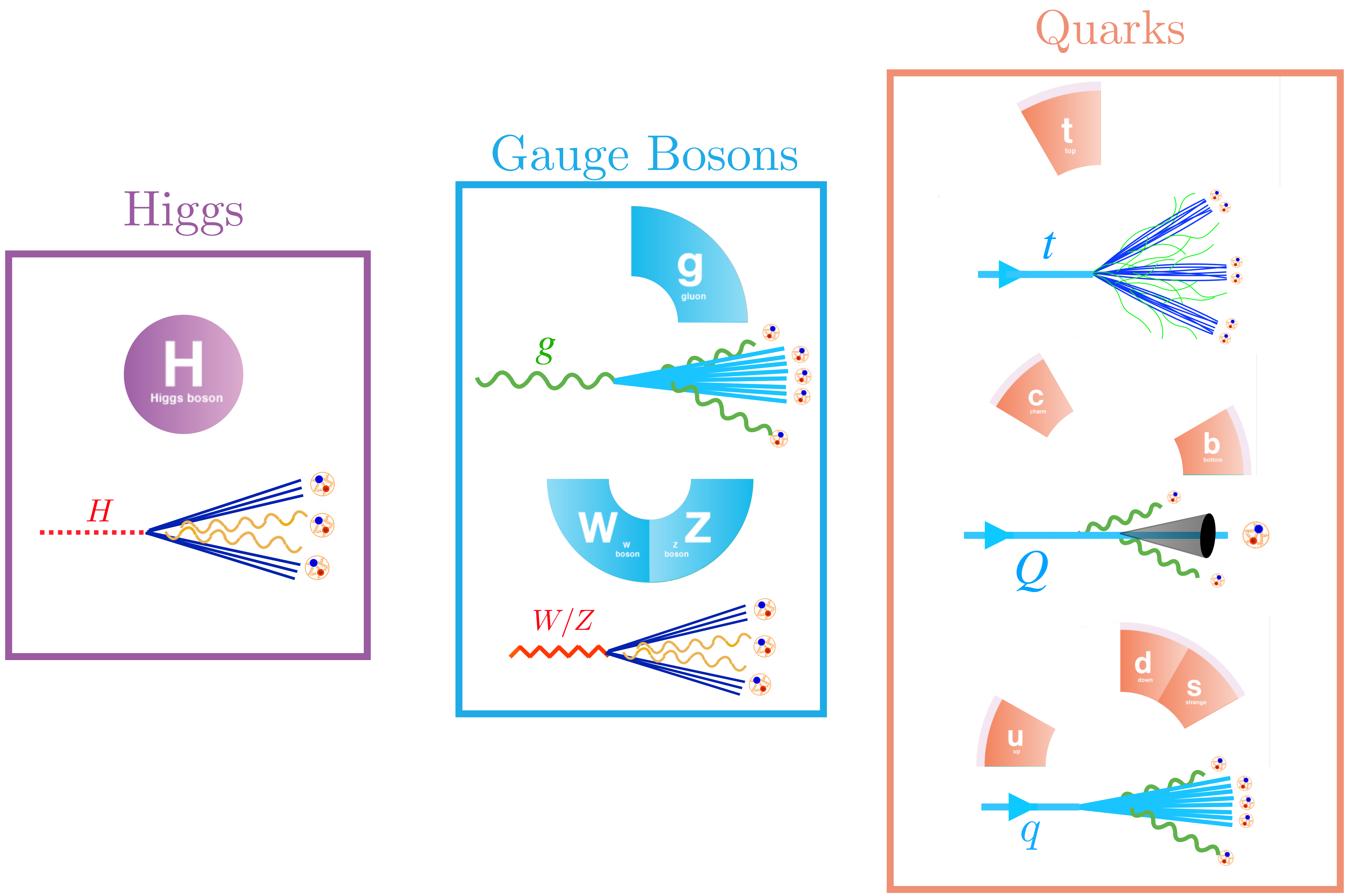
9-jet event at the LHC

- **Field of jet physics have always been intricately connected to the success of the collider physics program!**

JET SUBSTRUCTURE: STUDYING ENERGY FLOW INSIDE JETS

- Beyond massless QCD jets, highly energetic colliders (the LHC and proposed future colliders) produce boosted H/W/Z bosons and top quarks whose multi-body decays appear as jets.

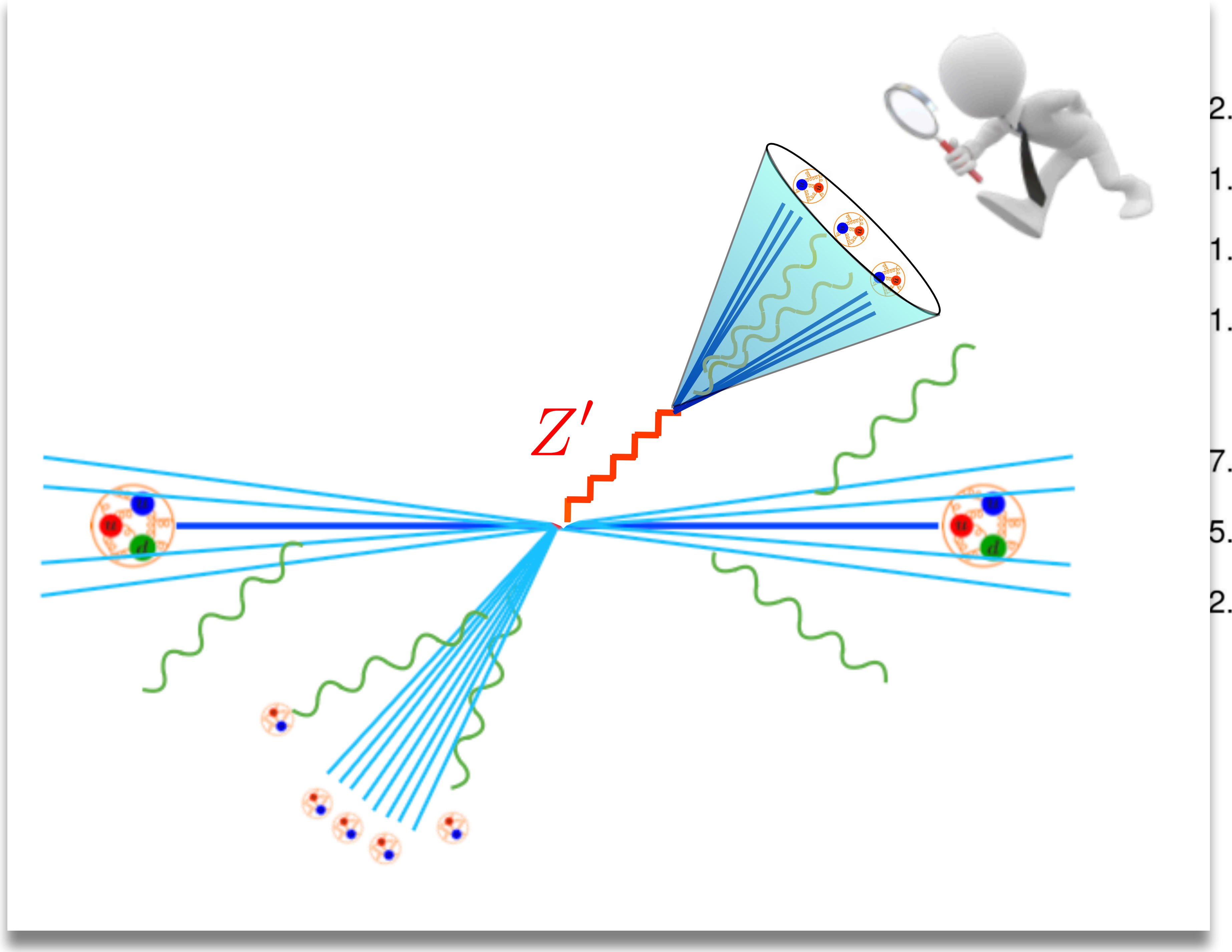


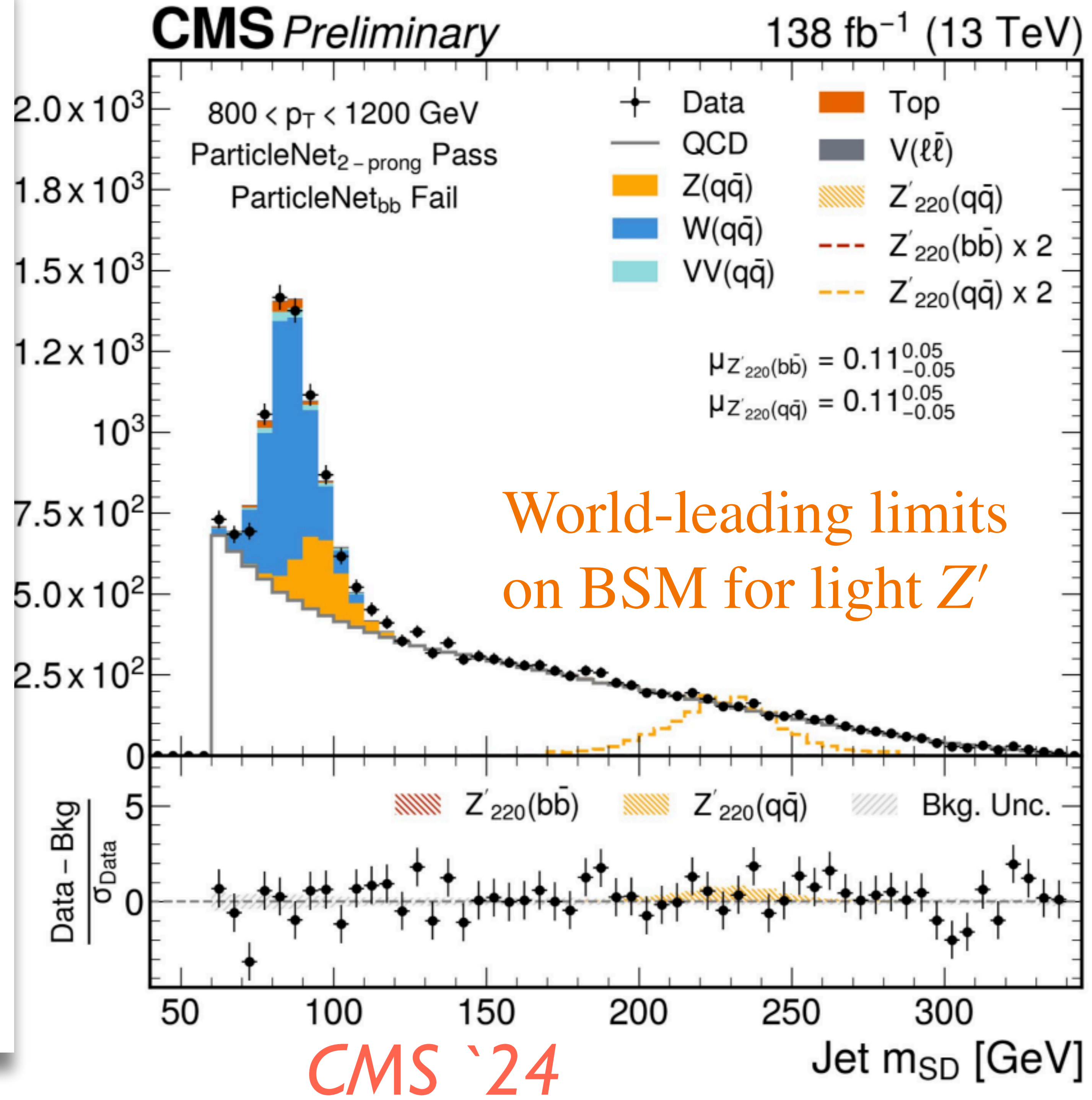


- Since its introduction in 2008 by Butterworth, Davison, Rubin, and Salam for Higgs reconstruction, jet substructure has provided a novel way to probe the vast LHC jet data by analyzing energy patterns within jets.

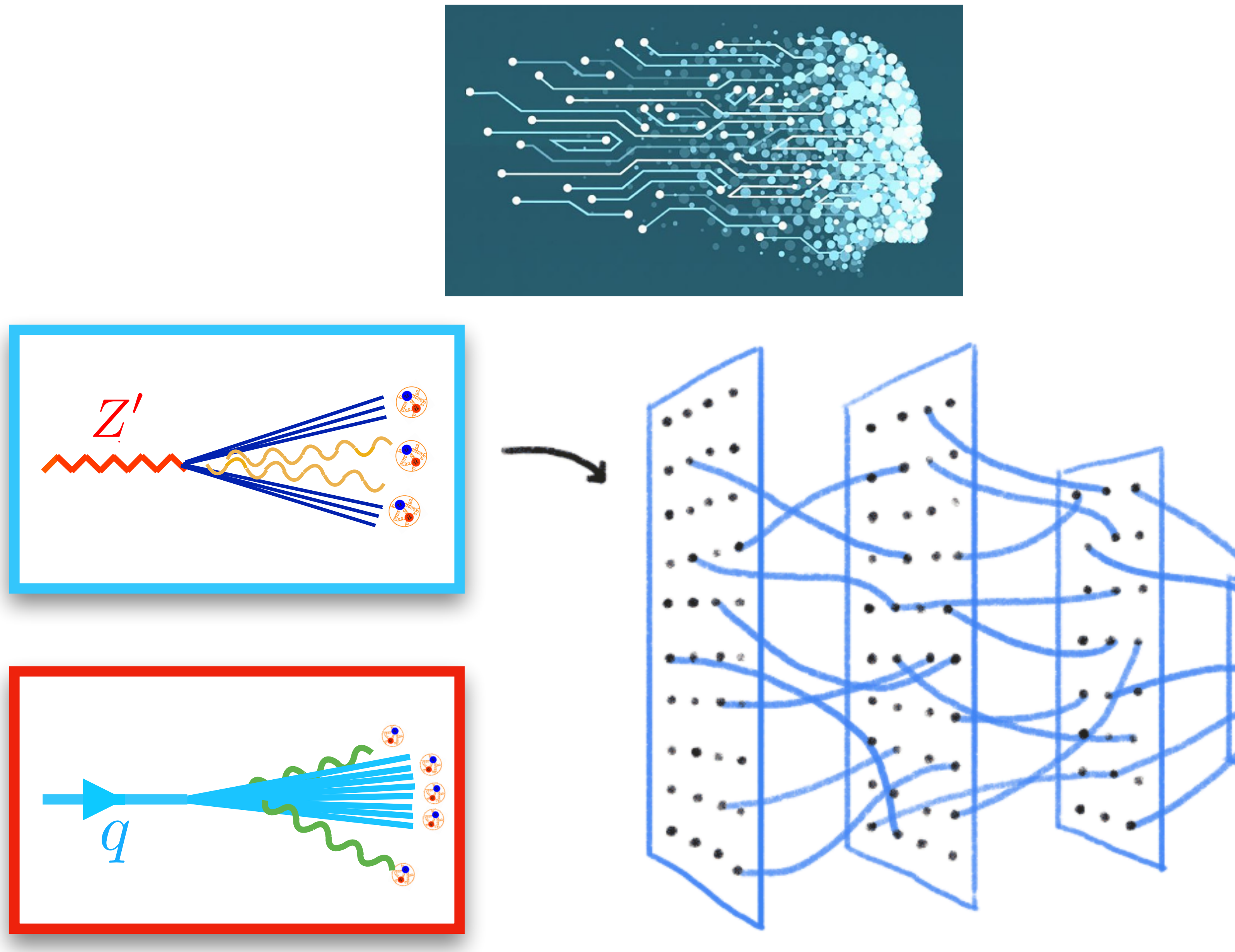
JET SUBSTRUCTURE: STUDYING ENERGY FLOW INSIDE JETS

- **This has had a tremendous impact on carrying out new physics searches and the need to study energy flux in QCD.**





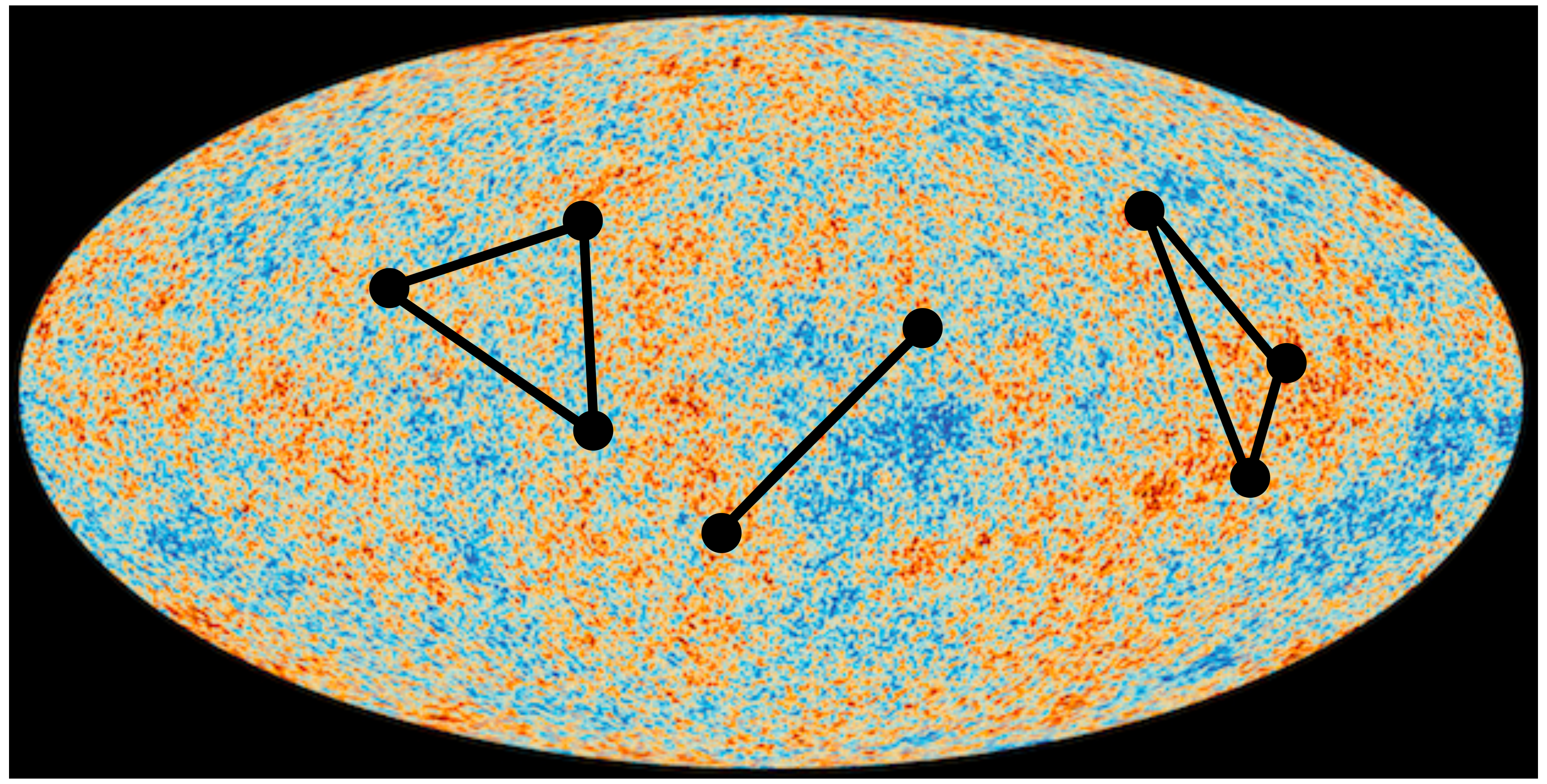
CMS `24

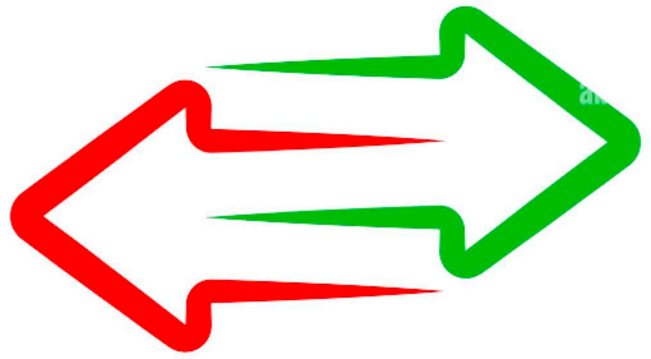


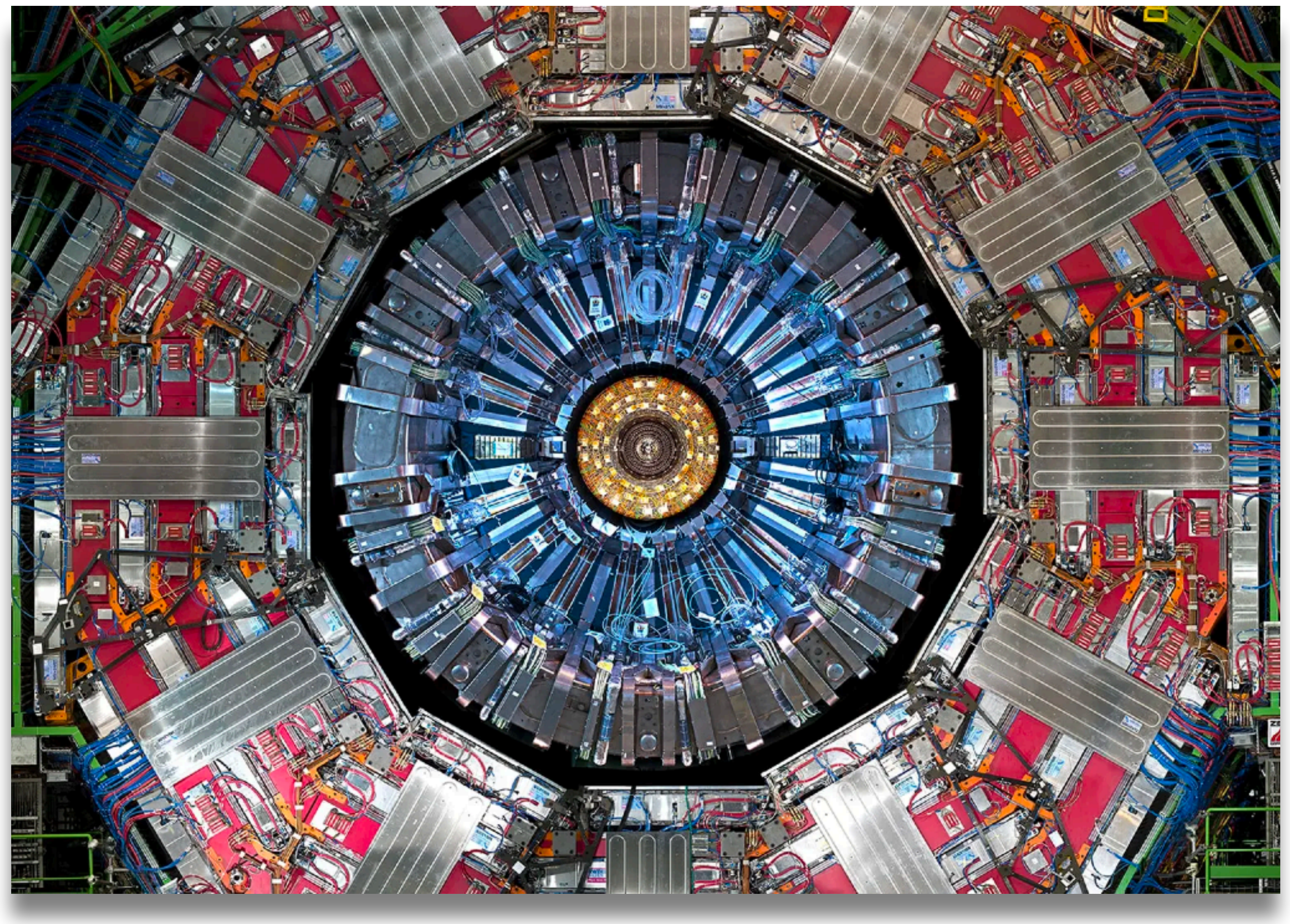
- **Therefore, important Standard Model and BSM questions are also encoded in the energy flow inside jets. This motivates a dedicated, precision theoretical program and tools to decode the energy flow inside jets.**

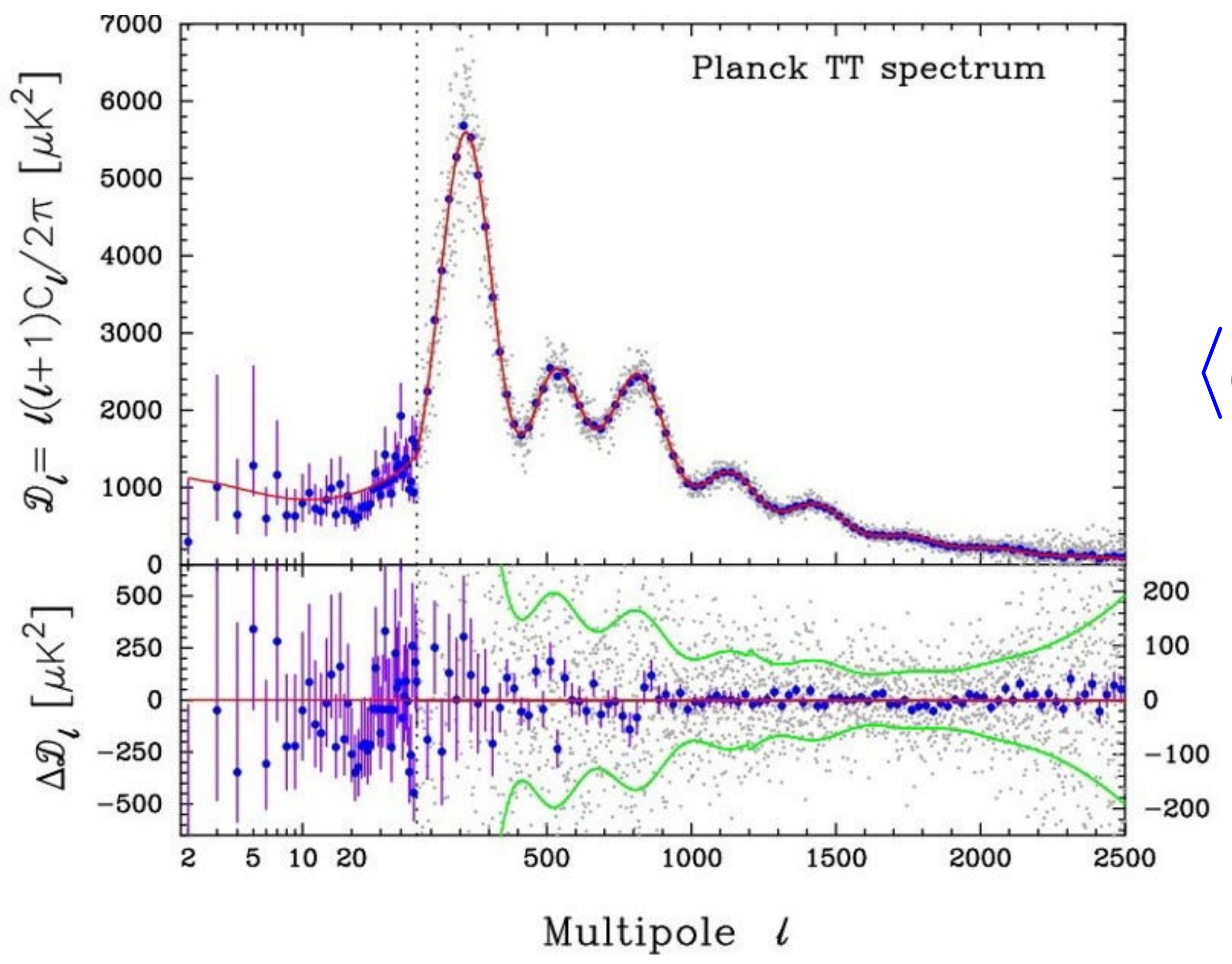
new theory insight needed!

DECODING ASYMPTOTIC ENERGY FLUX IN COLLIDERS









$\langle \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \cdots \zeta_{\vec{k}_n} \rangle$

We probe primordial perturbations by analyzing correlations in the CMB

Much like cosmology, we infer microscopic (early time) physics from asymptotic (late time) **energy flux**

From **QFT** point of view, **what field theoretic observables** describe this patterns of **energy flux**?

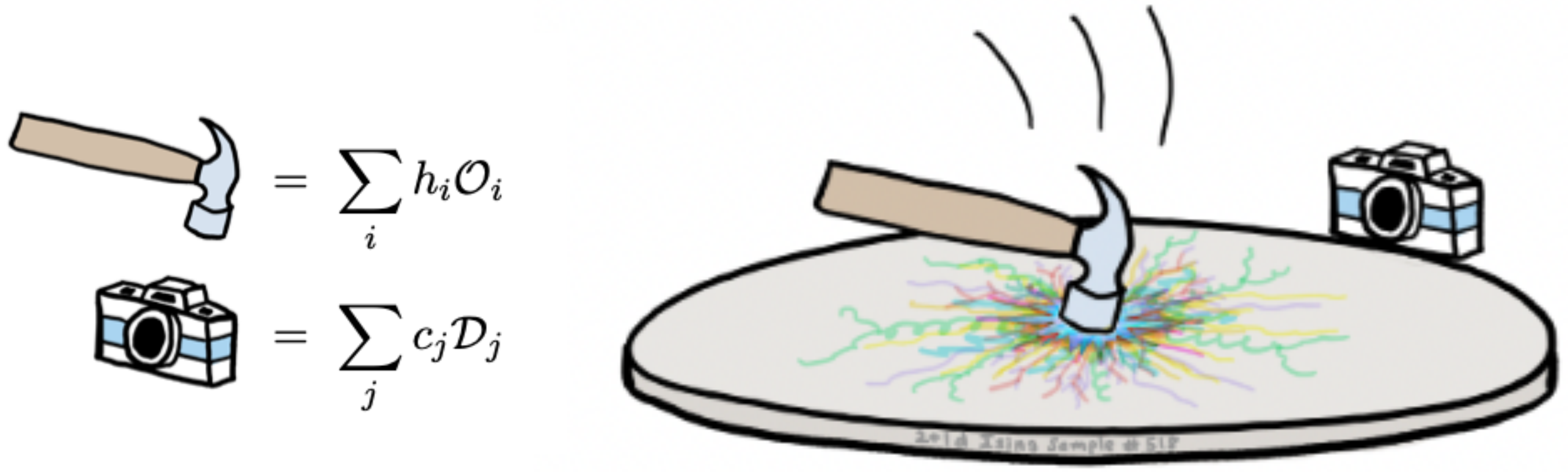
DETECTORS IN QFT

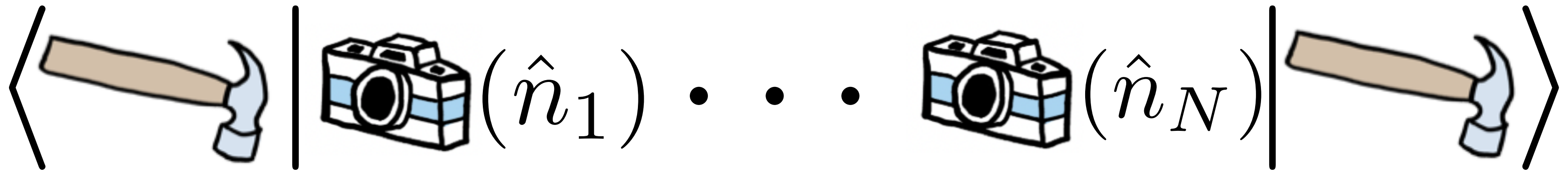
From QFT point of view, what is a detector?

Energy Flow Operators

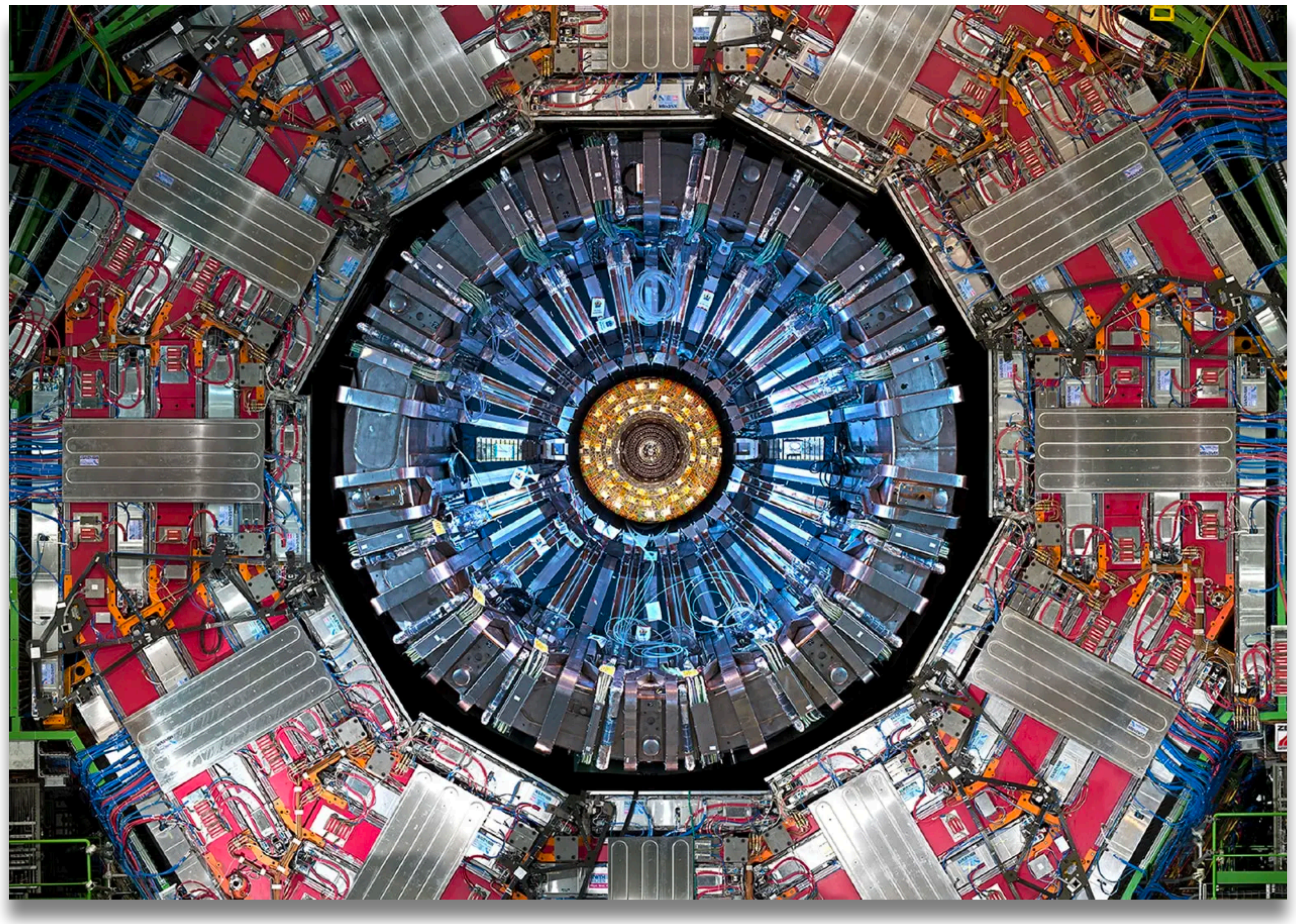
$$= \mathcal{E}(\hat{n}) = \int_0^\infty dt \lim_{r\to\infty} r^2 n^i T_{0i}(t, r\hat{n})$$

$$\mathcal{E}(\hat{n})|X\rangle = \sum_a E_a \delta^{(2)}\left(\Omega_{\vec{p}_a} - \Omega_{\hat{n}}\right)|X\rangle$$





Caron-Huot, Kologlu, Kravchuk, Meltzer, Simmons-Duffin`22



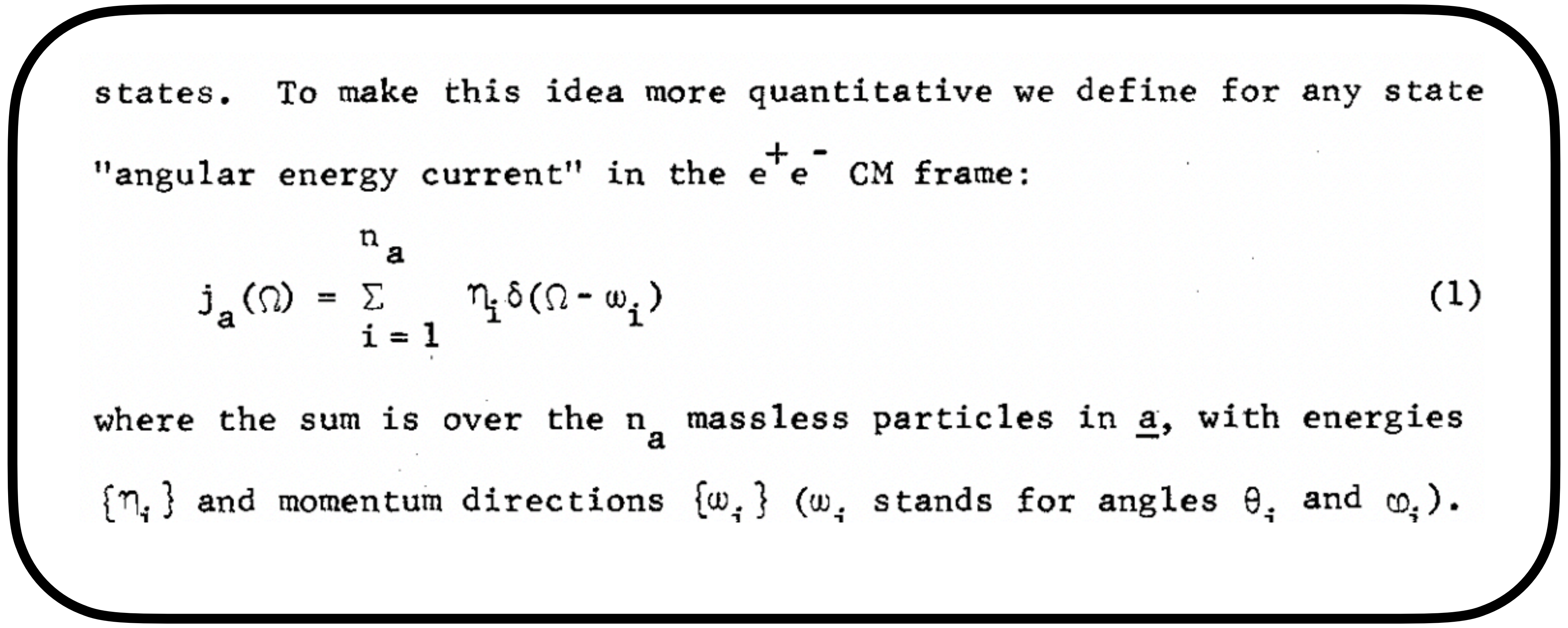
From the perspective of QFT, jet substructure is the study of correlation functions of energy flow operators.

= energy correlators!

$$\langle \mathcal{E}(\hat{n}_1)\cdots\mathcal{E}(\hat{n}_N)\rangle \equiv \langle\Psi|\mathcal{E}(\hat{n}_1)\cdots\mathcal{E}(\hat{n}_N)|\Psi\rangle$$

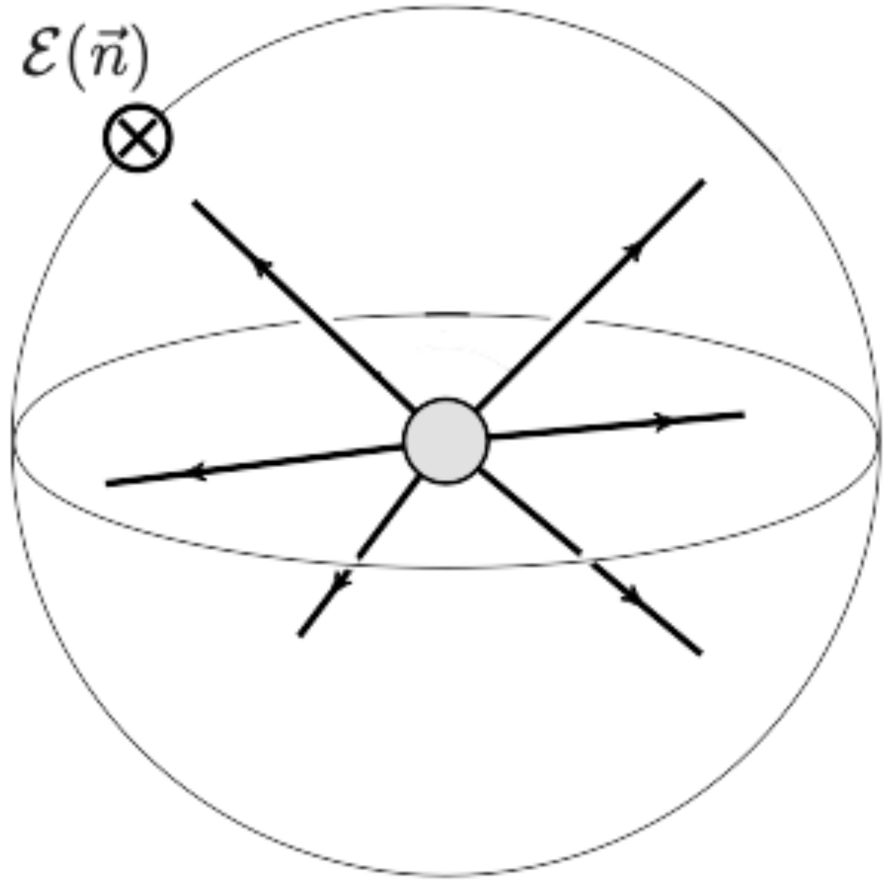
ENERGY CORRELATORS

Discussion of a perturbative computation of 1-point correlation $\langle \mathcal{E}(n) \rangle$


states. To make this idea more quantitative we define for any state "angular energy current" in the e^+e^- CM frame:

$$j_a(\Omega) = \sum_{i=1}^{n_a} \eta_i \delta(\Omega - \omega_i) \quad (1)$$

where the sum is over the n_a massless particles in a, with energies $\{\eta_i\}$ and momentum directions $\{\omega_i\}$ (ω_i stands for angles θ_i and φ_i).

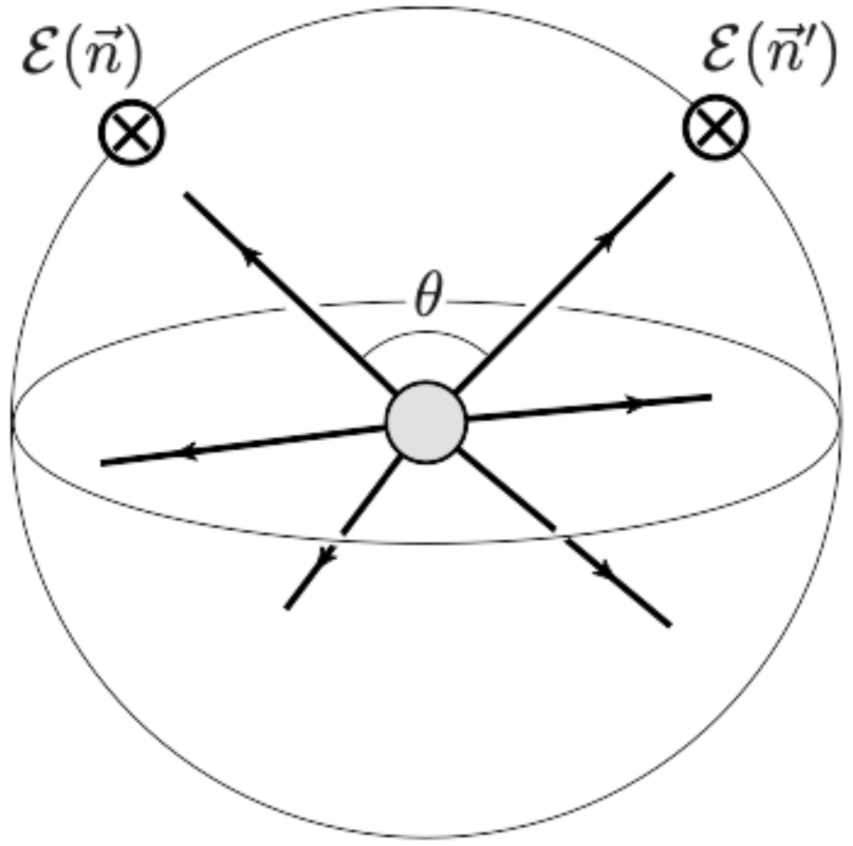


Sterman `75

"Energy flow becomes the focus of computability"

Calculations of two-point correlation $\langle \mathcal{E}(n_1)\mathcal{E}(n_2) \rangle$ to characterize collider events

Basham, Brown, Ellis, Love, `78



Stephen Ellis

ENERGY CORRELATORS INSIDE JETS

CERN COURIER

STRONG INTERACTIONS | NEWS

Measuring energy correlators inside jets

3 November 2023

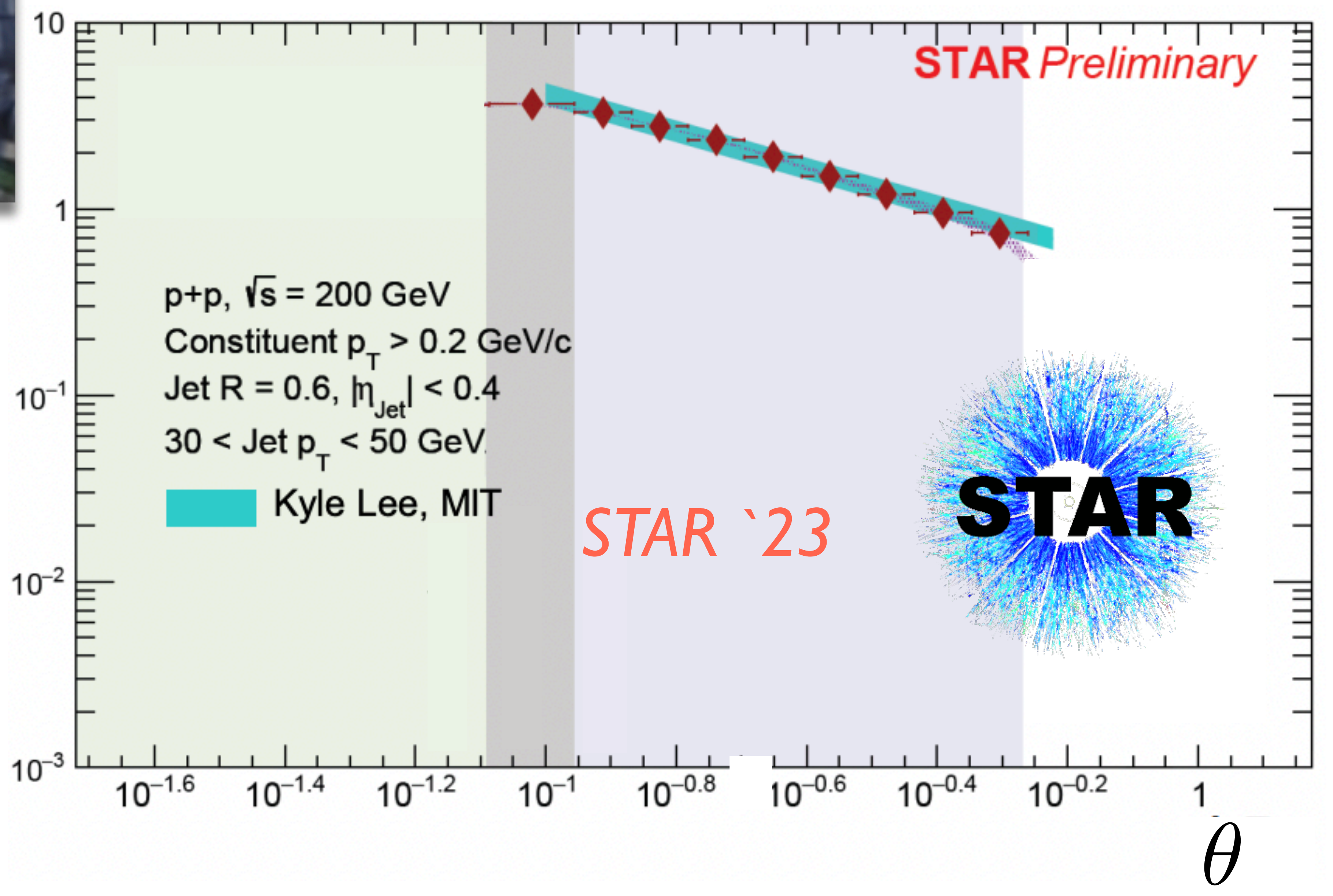
CERN COURIER

STRONG INTERACTIONS | NEWS

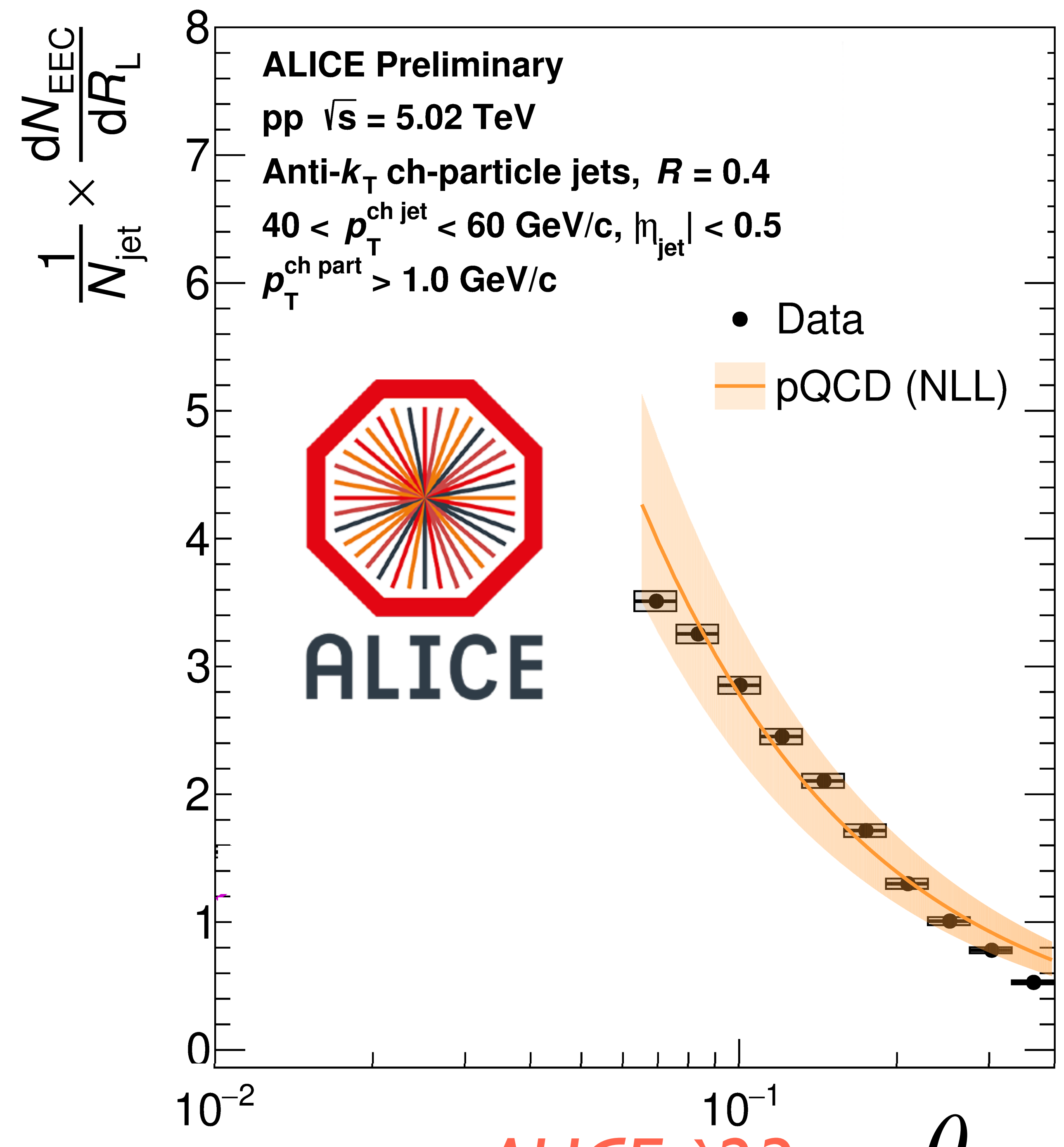
Charming energy–energy correlators

9 September 2025

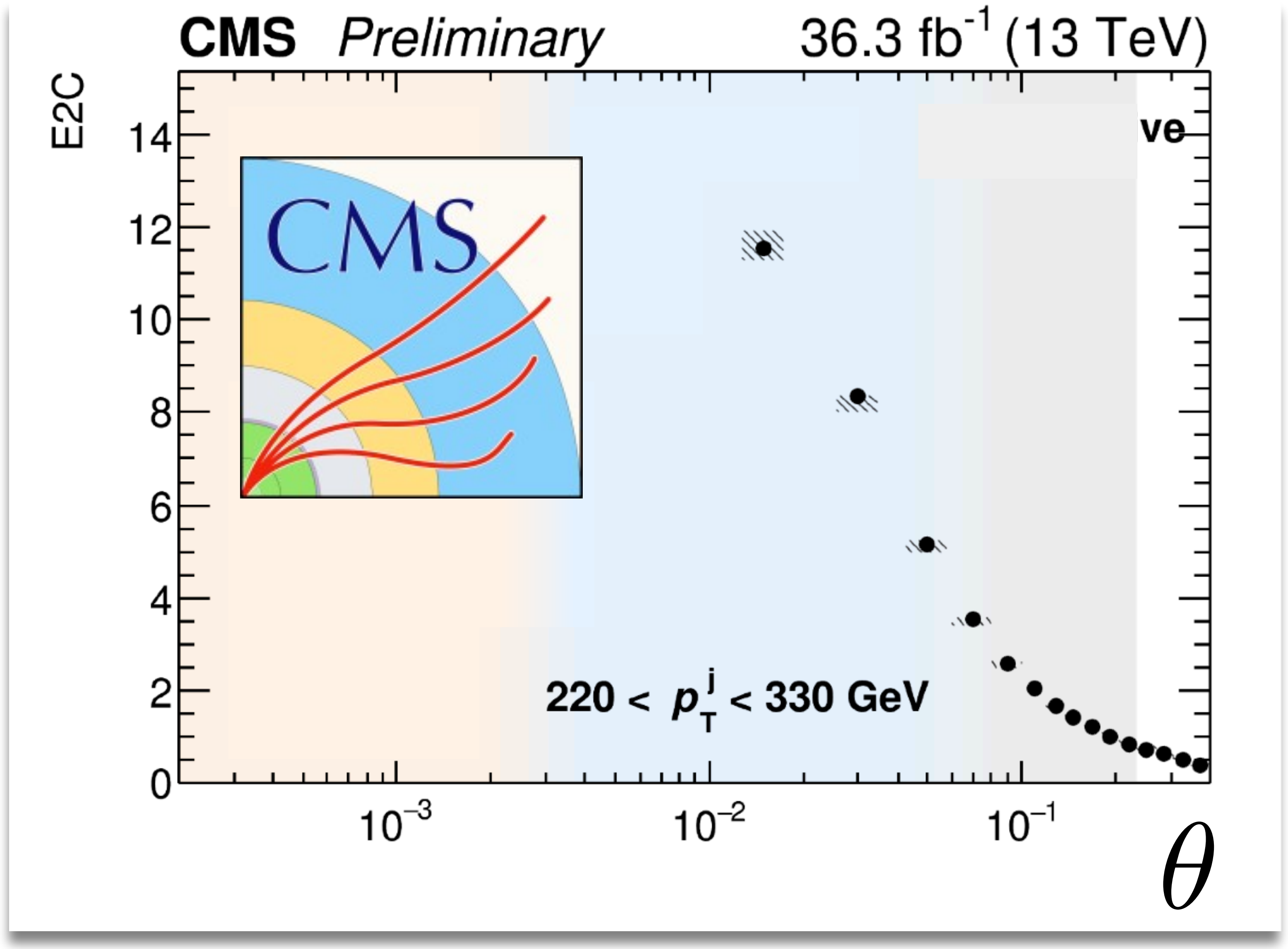
ALICE `25



STAR `23



ALICE `23

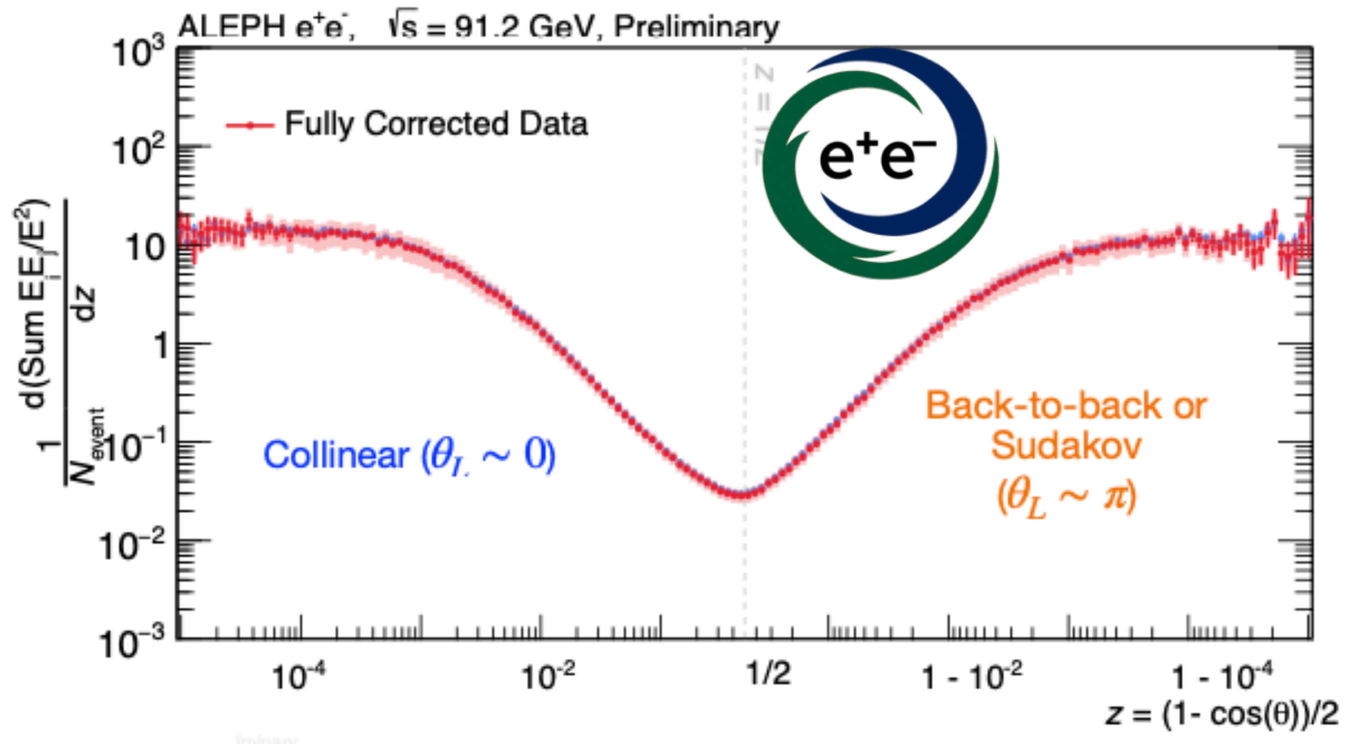


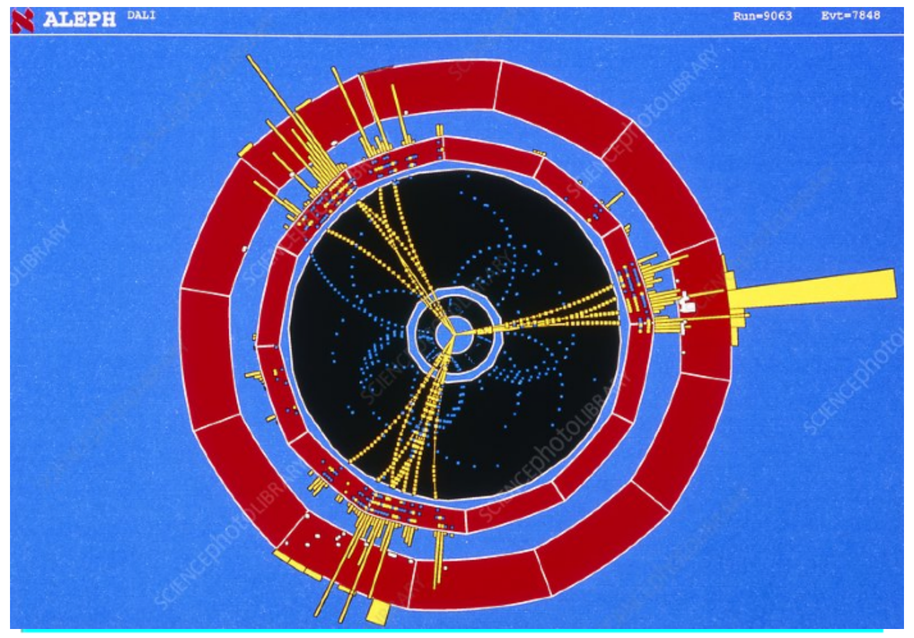
CMS `23

MANY COLLIDER “COSMOLOGIES”

- LEP reanalyses

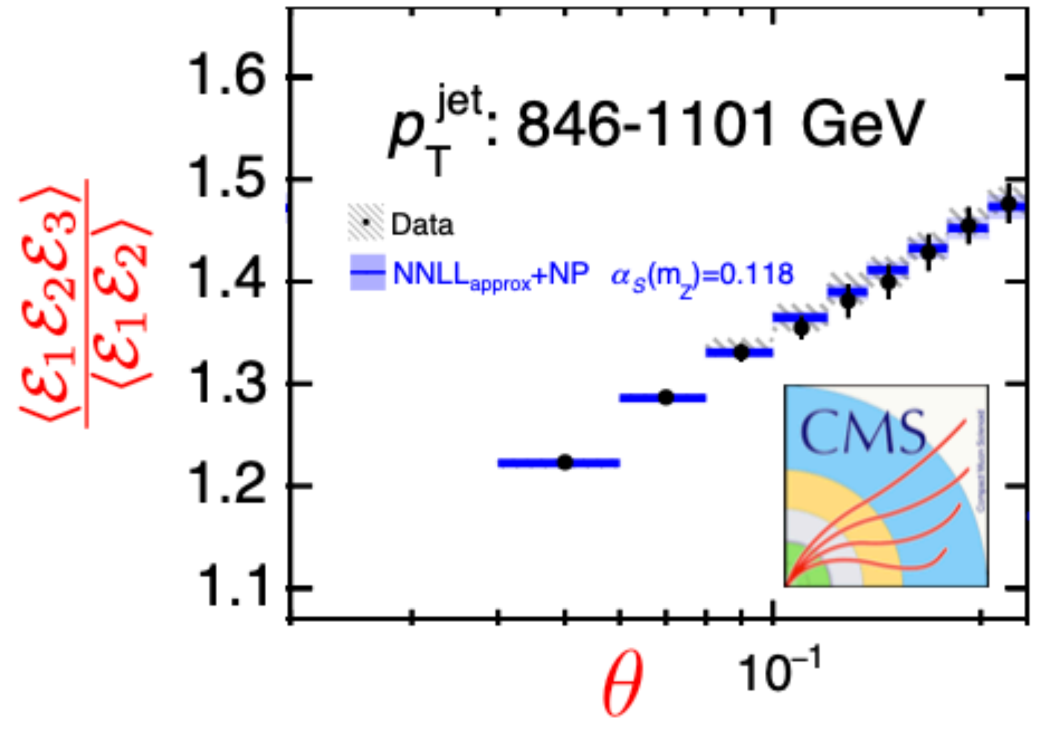
e^+e^-

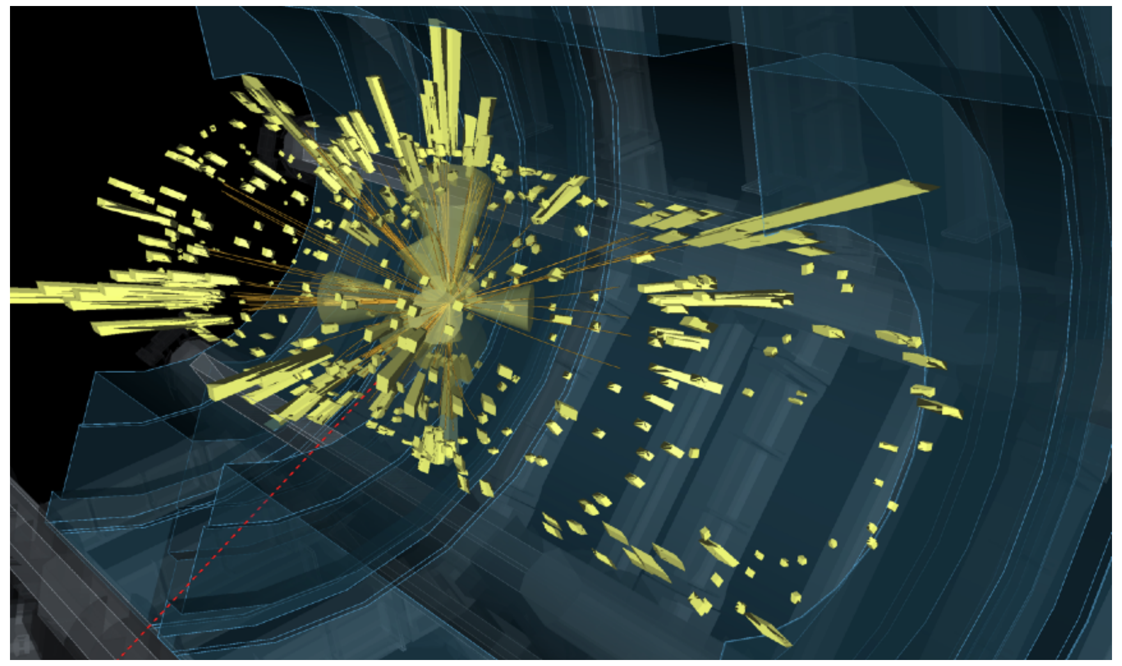




- LHC and RHIC measurements

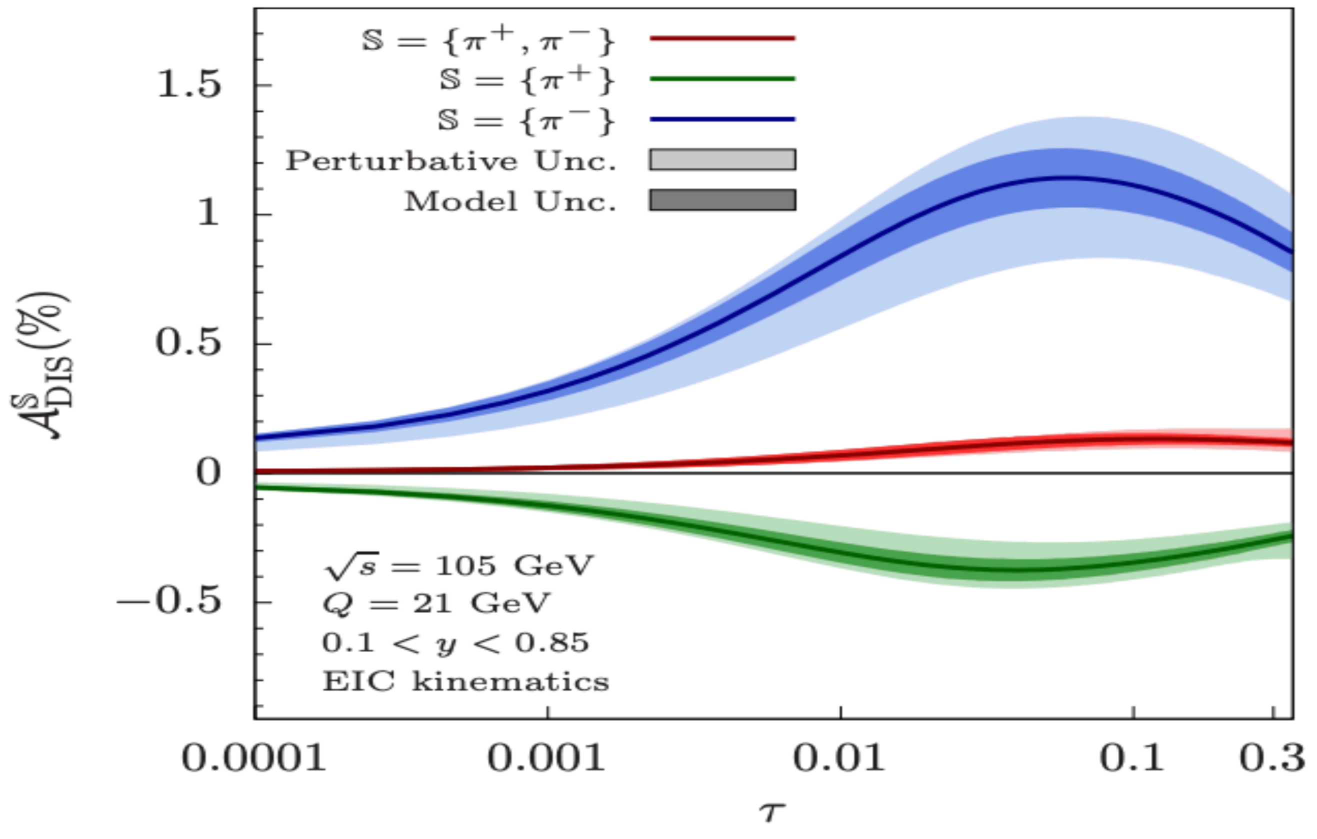
pp

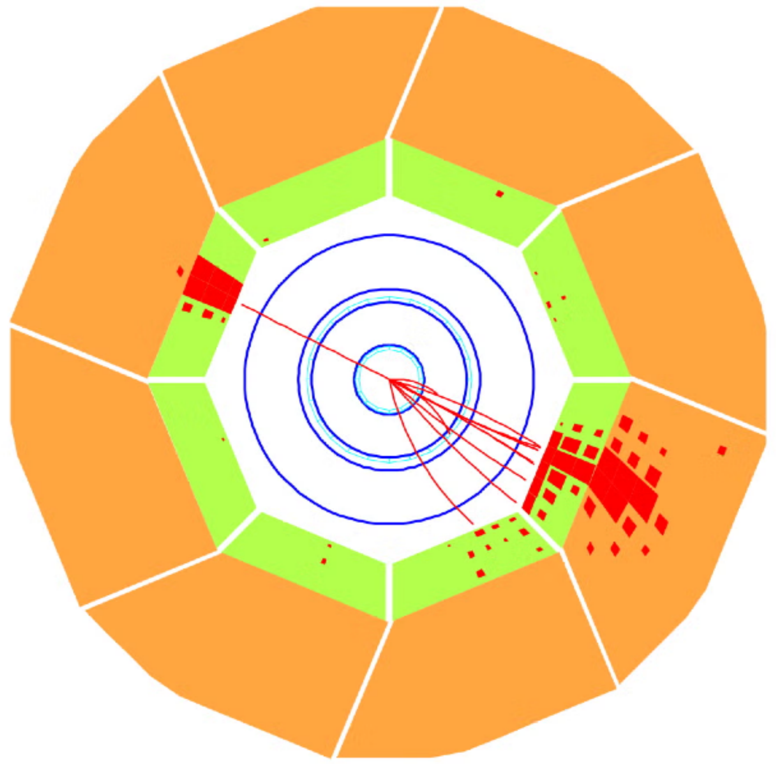




- HERA reanalyses (ongoing)
- EIC simulation studies

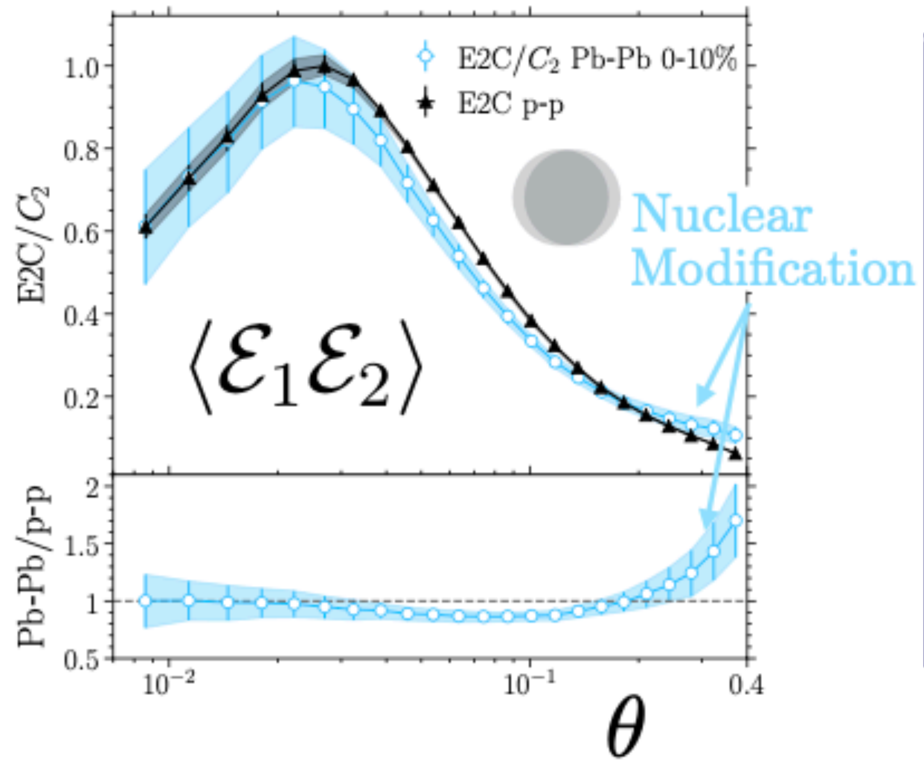
ep

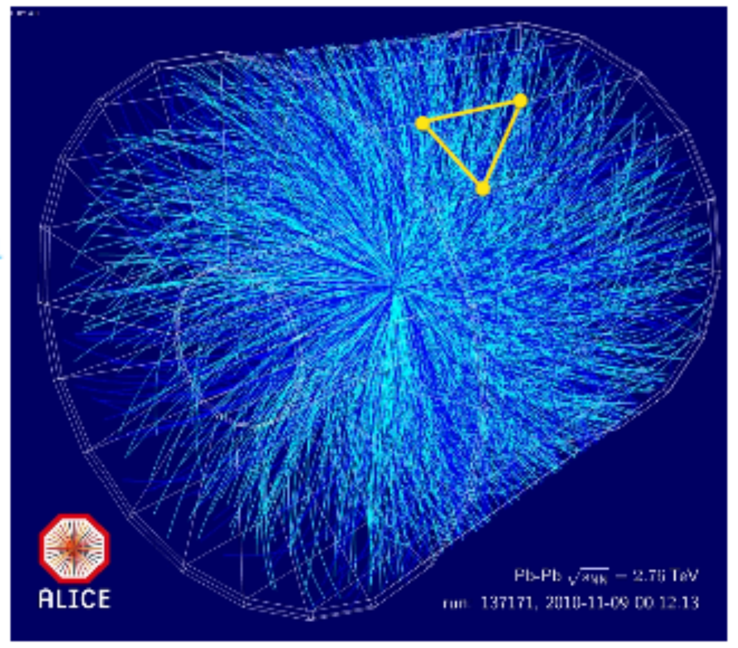




- LHC measurements
- RHIC (ongoing)

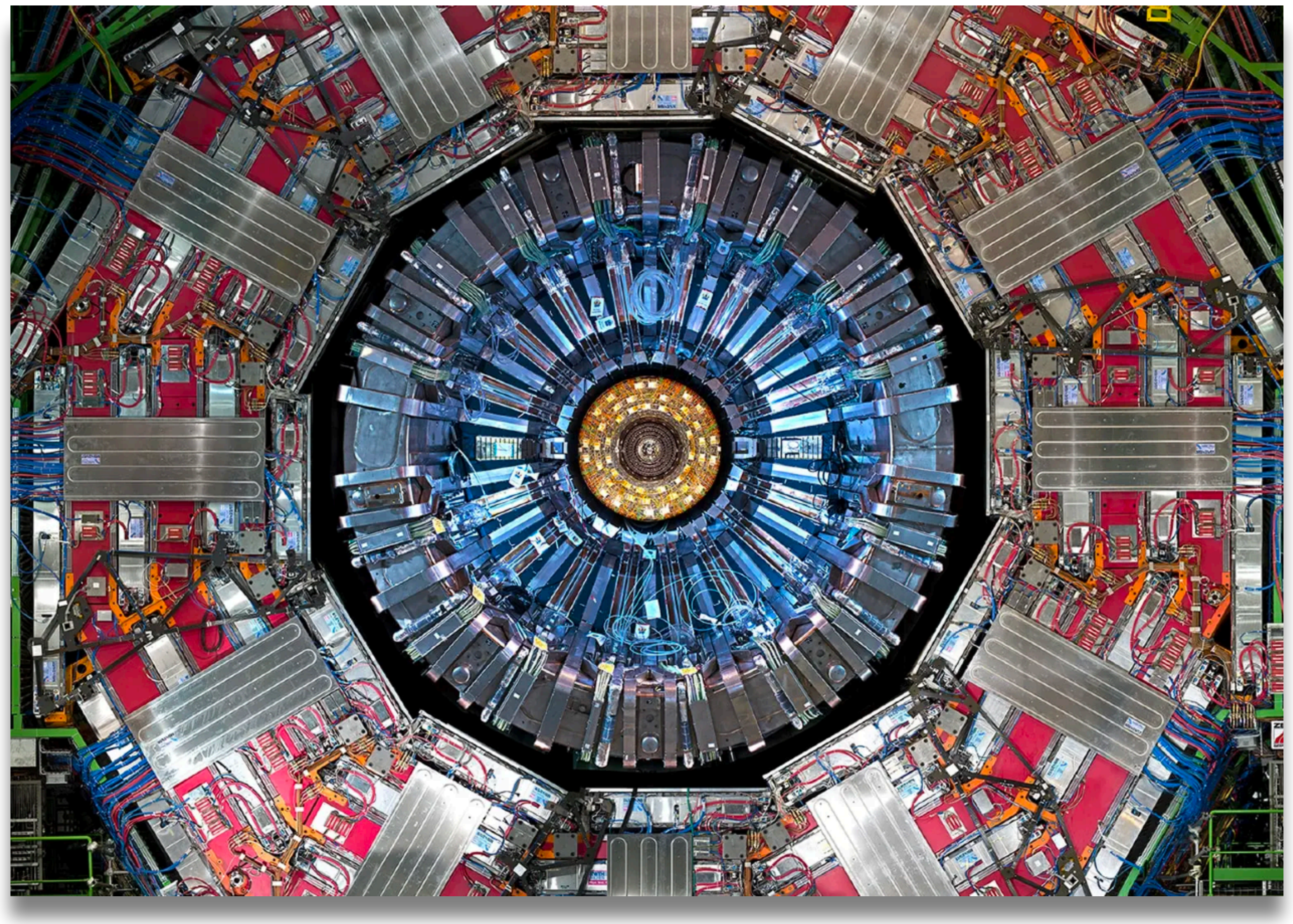
Pb-Pb





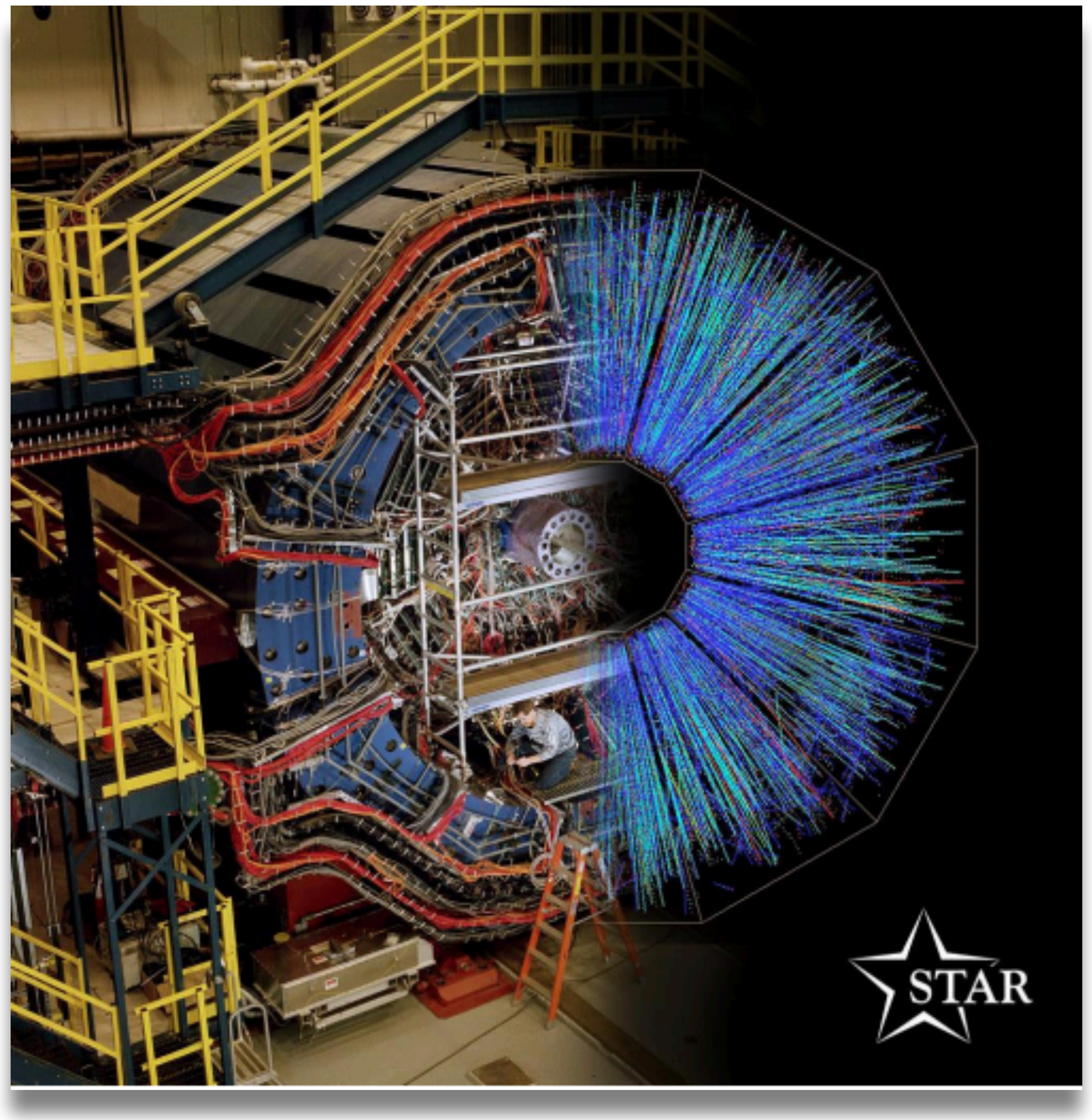
Many different collider experiments with correlations of energy flow

EXCITING COLLIDER PHYSICS ERA



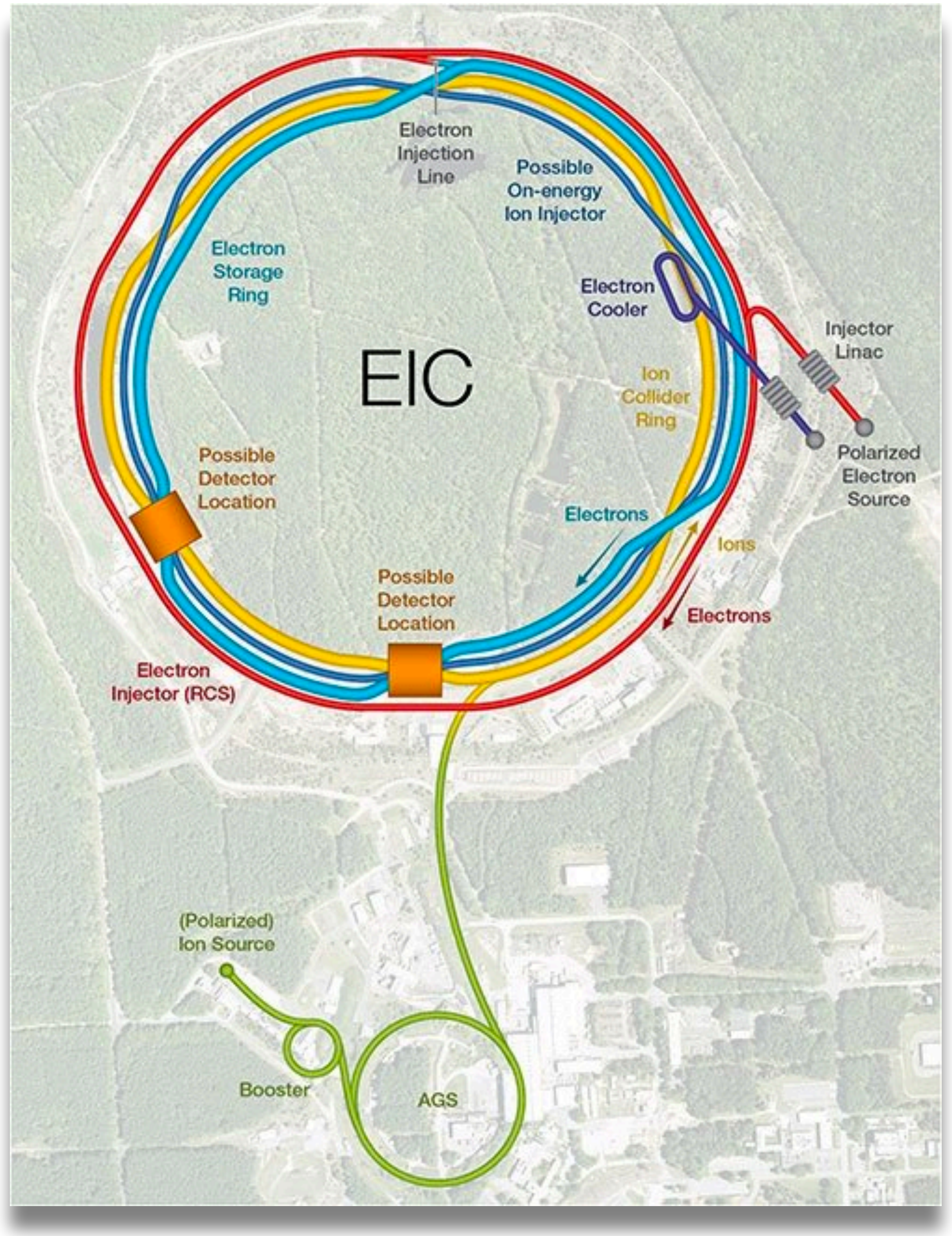
LHC, 2008 - Present

Run 3 running!



RHIC, 2000 - Present

sPHENIX: 2024-



EIC, 2030s-

+ More Future Colliders

How can we harness energy correlators to continue making breakthroughs in collider frontier?

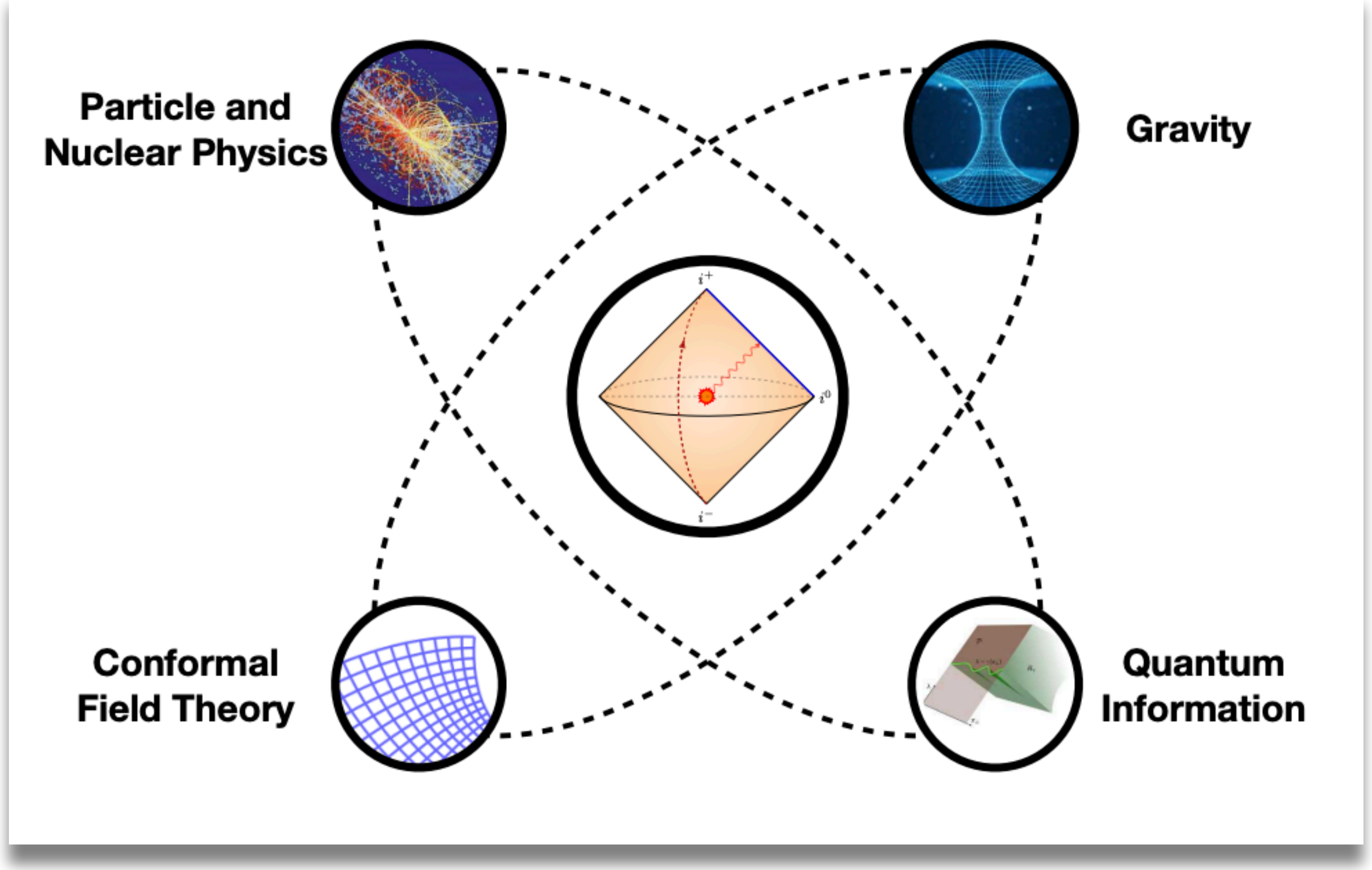
BRINGING IDEAS FROM FORMAL THEORY, PHENOMENOLOGY, AND EXPERIMENTALISTS

UC SANTA BARBARA
Kavli Institute for
Theoretical Physics

Energy Correlators: From Theory to Experiment

Coordinators: Kyle Lee, Ian Moult, and David Simmons-Duffin

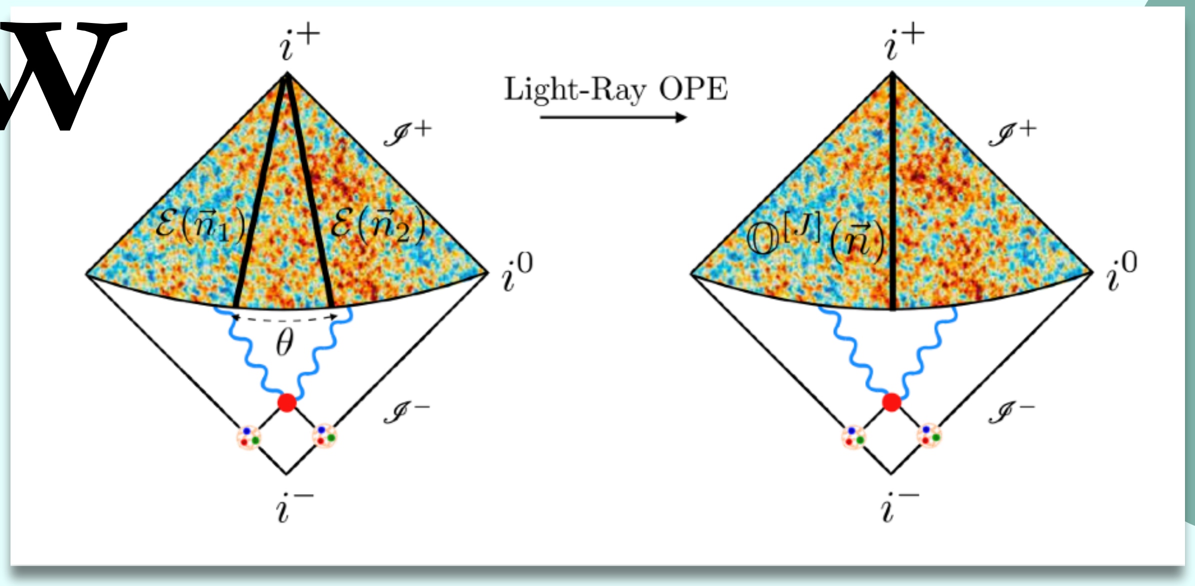
Feb 1, 2027 - Feb 4, 2027



Asymptotic Detectors are fundamental objects of Lorentzian Field Theories!

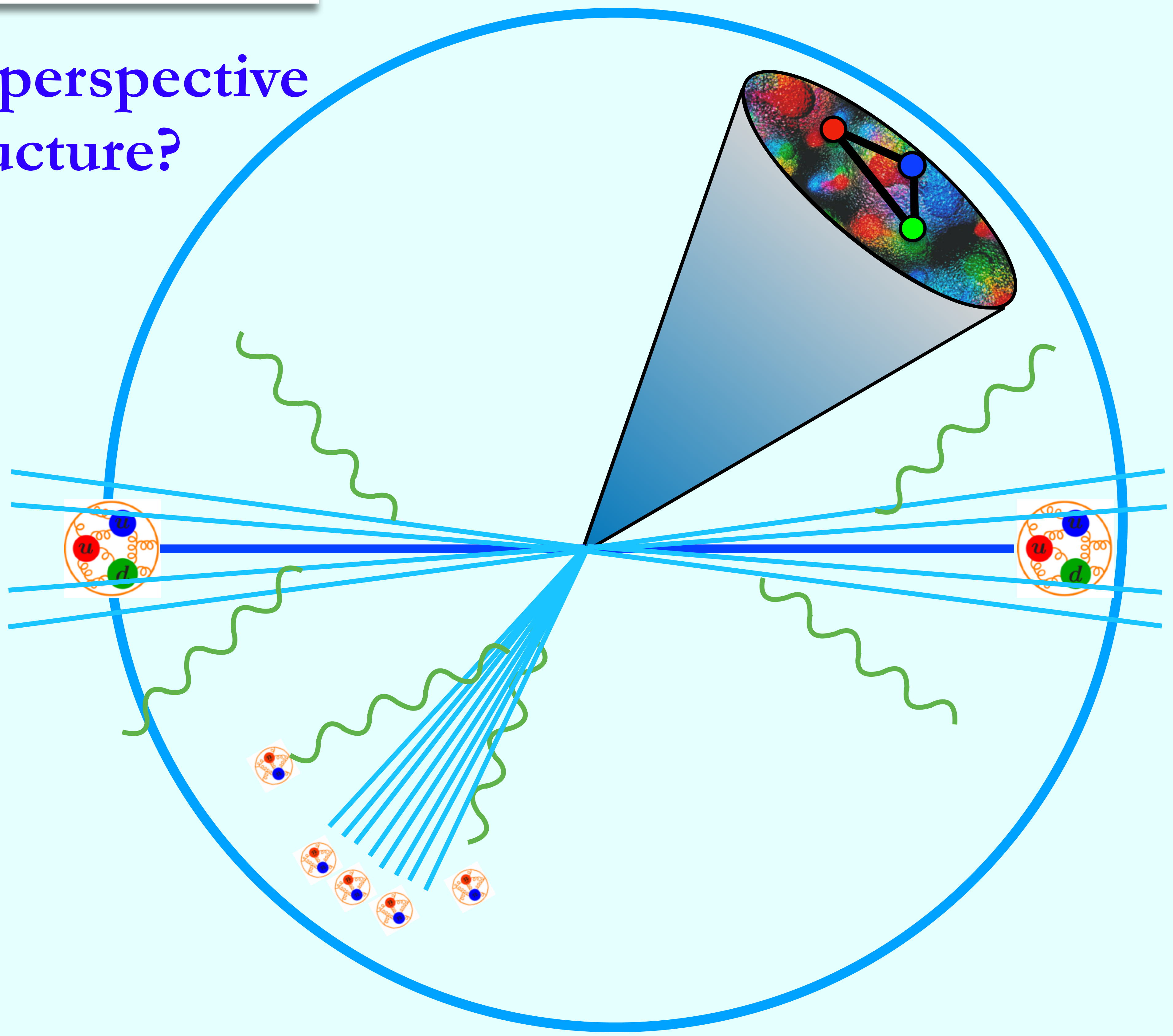
…***This conference will bring together formal theorists, phenomenologists, and experimentalists to advance the use of energy flow observables across collider physics and formal quantum field theory.***

Overview



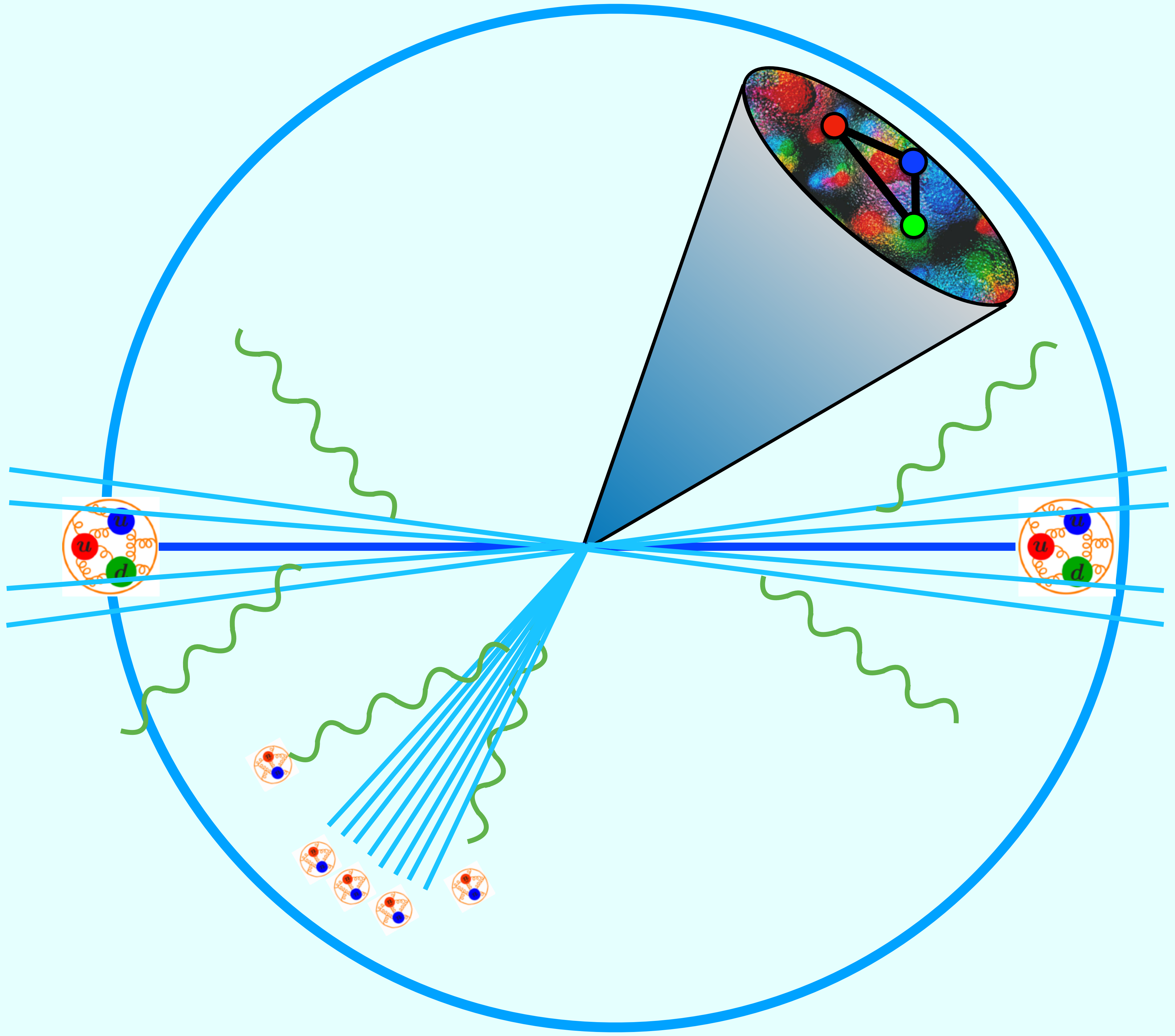
I. Universal Scaling

What is the QFT perspective of jet substructure?

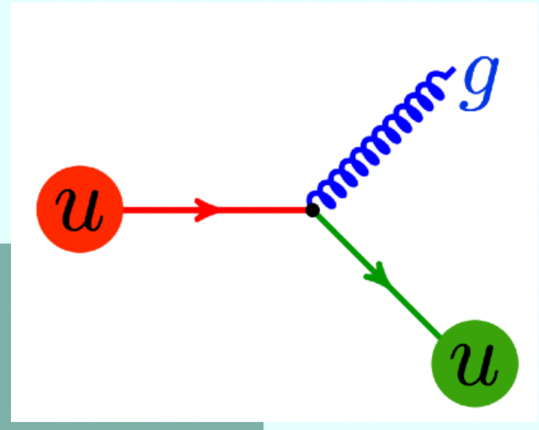


Overview

I. Universal Scaling



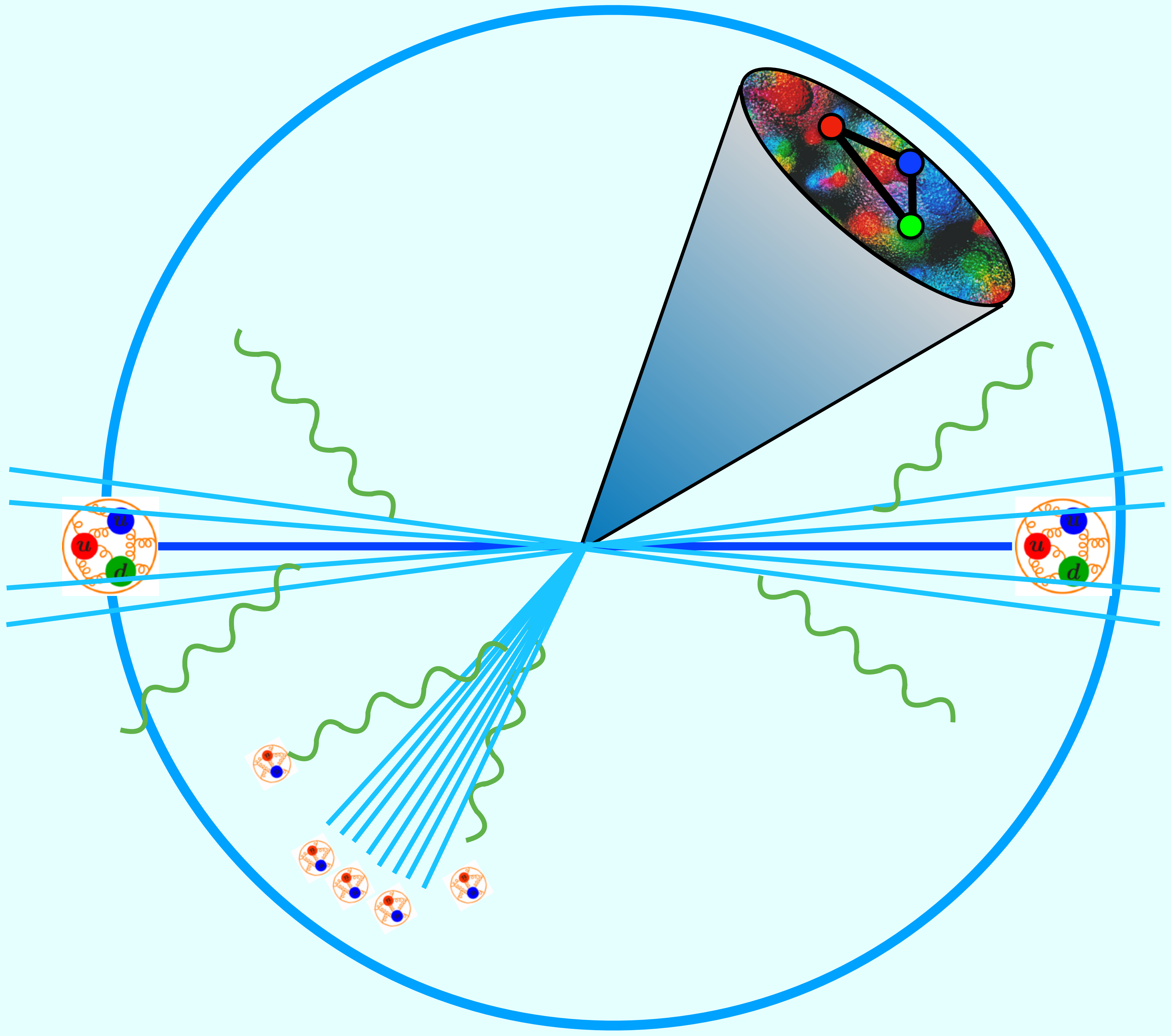
II. Precision SM



Can we carry out precision study of the Standard Model? (For example, α_s extraction)

Overview

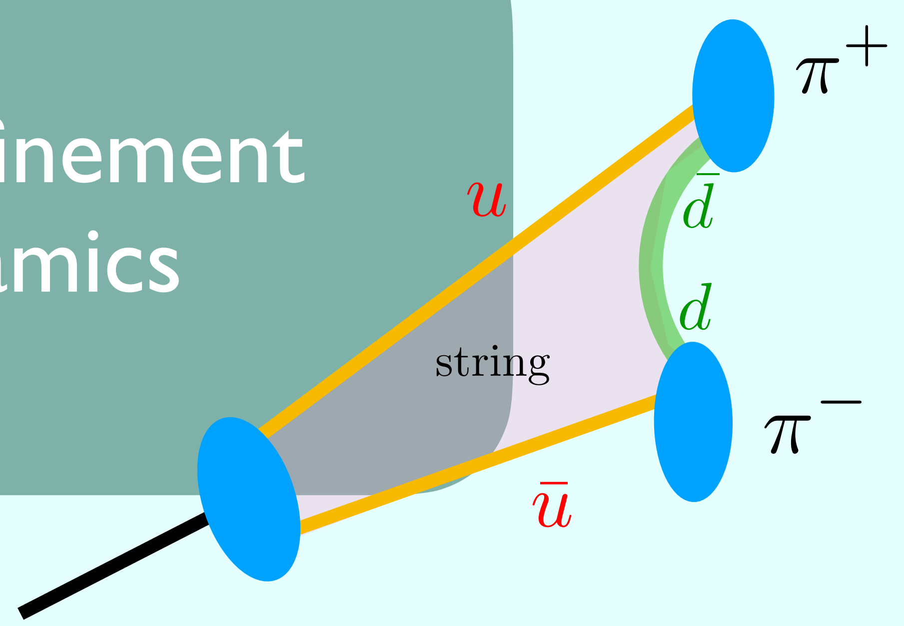
I. Universal Scaling



II. Precision SM

Can we understand confinement mechanism?

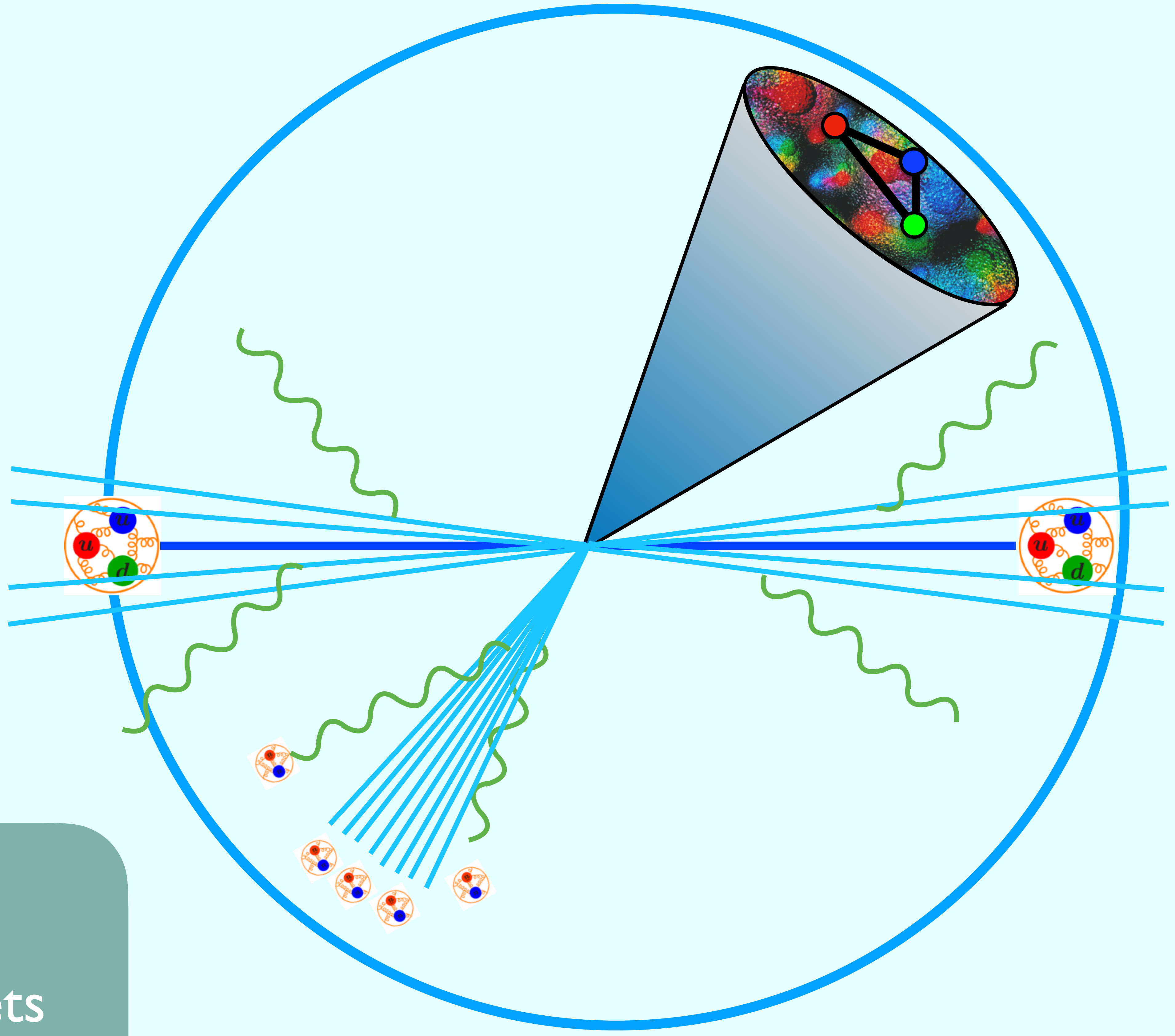
III. Confinement Dynamics

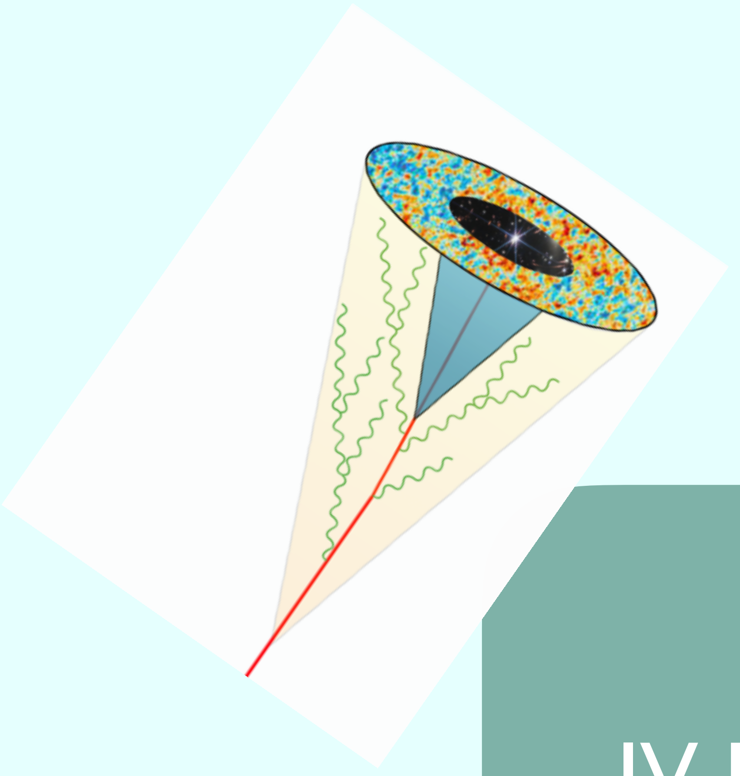


Overview

I. Universal Scaling

II. Precision SM





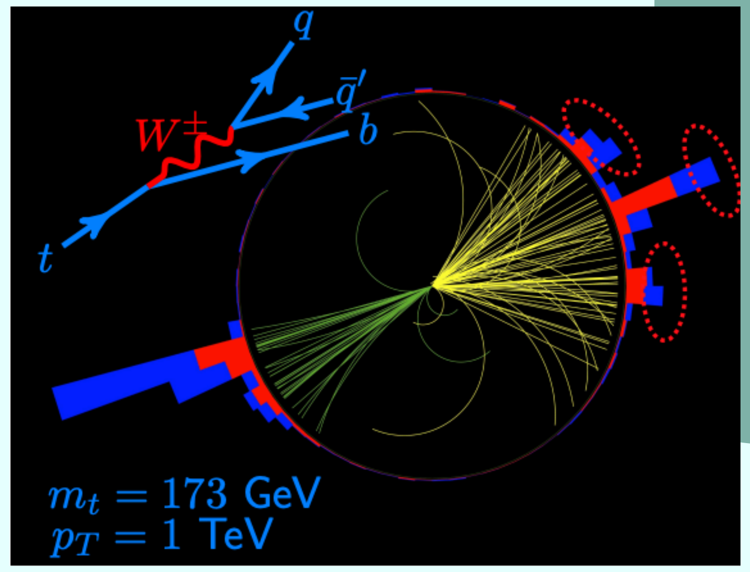
IV. Heavy Flavor Jets

III. Confinement Dynamics

Can we improve our understanding of the heavy flavor scale in jets?

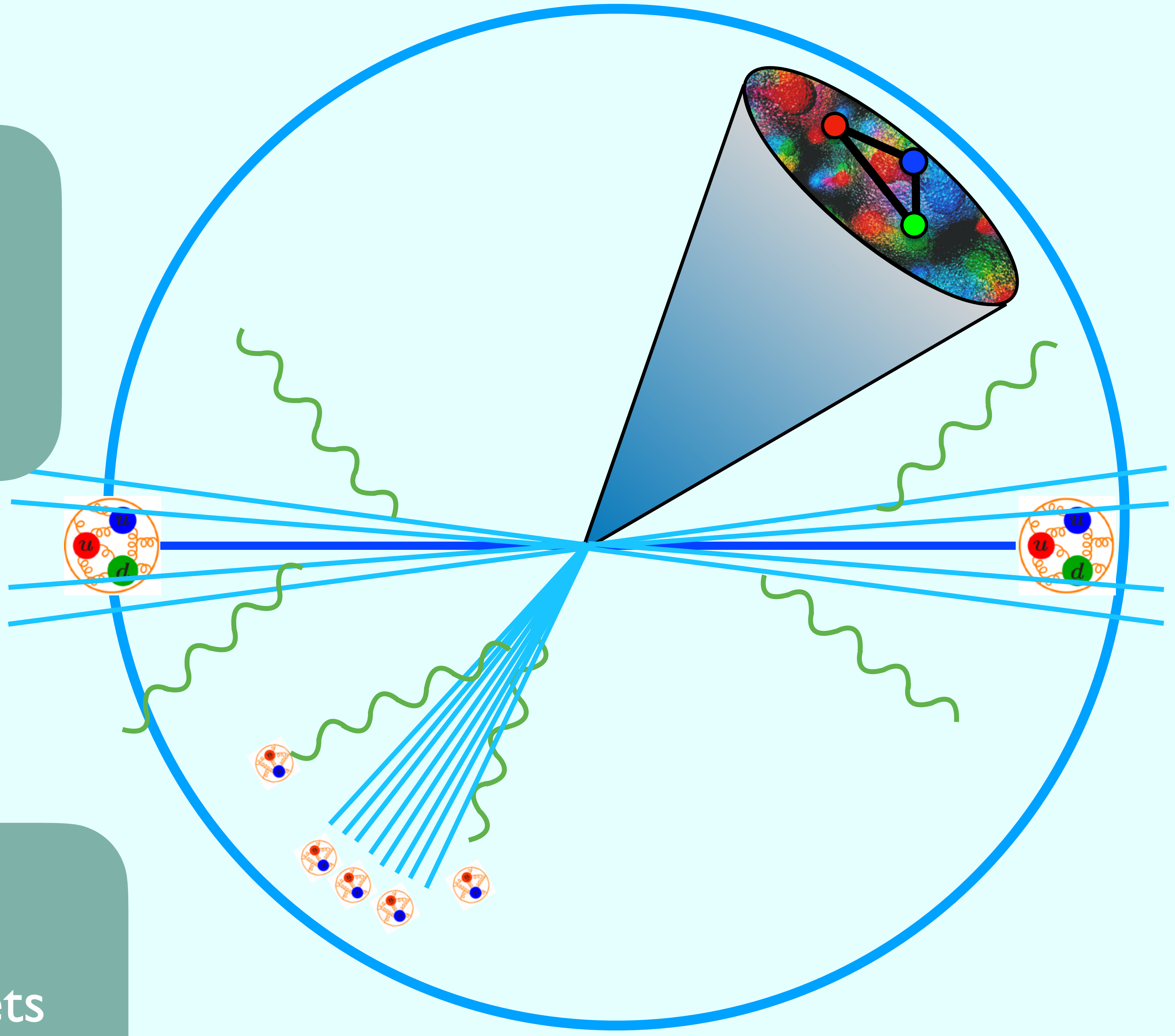
Overview

Can we do precision electroweak studies and constrain new physics?



V. Electroweak and New physics

I. Universal Scaling



II. Precision SM

III. Confinement Dynamics

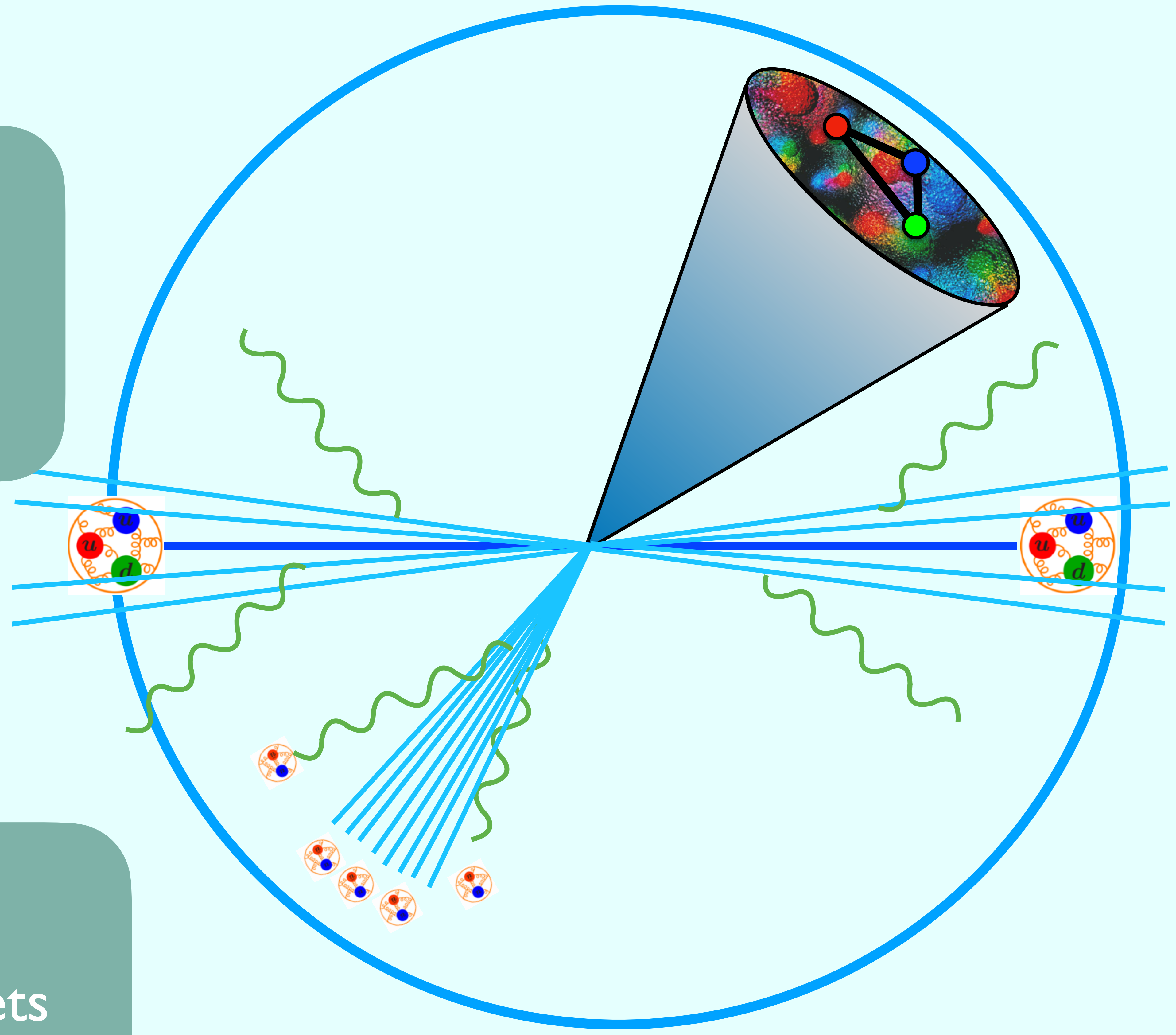
IV. Heavy Flavor Jets

Overview

What is the QFT perspective of jet substructure?

I. Universal Scaling

V. Electroweak and New physics



II. Precision SM

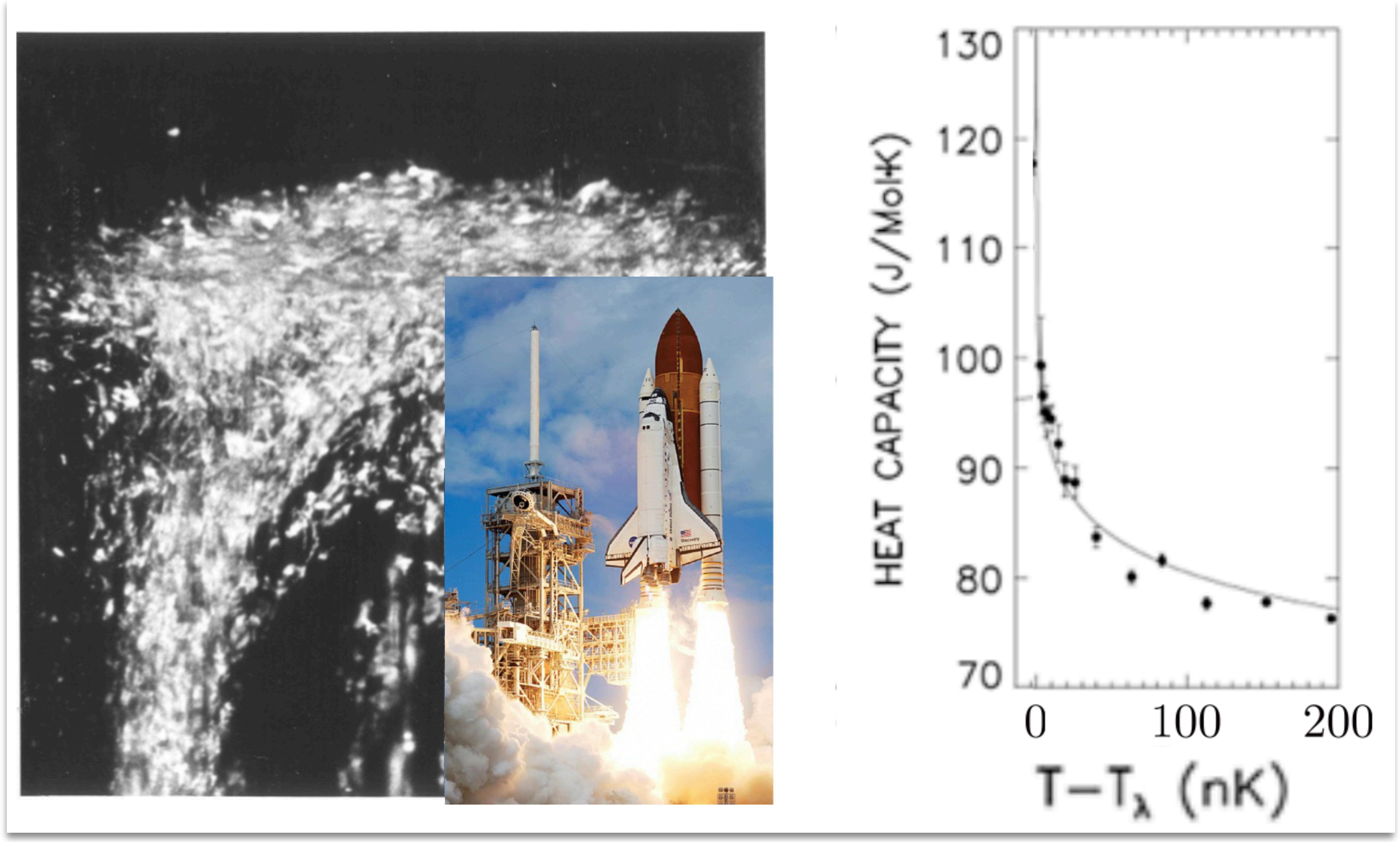
IV. Heavy Flavor Jets

III. Confinement Dynamics

SCALING BEHAVIOR IN QFT

- **Why is the study of jet substructure of interest in QFT?**
- **QFTs display universal scaling behaviors when operators approach one another**

Wilson `70



Euclidean Operator Product Expansion

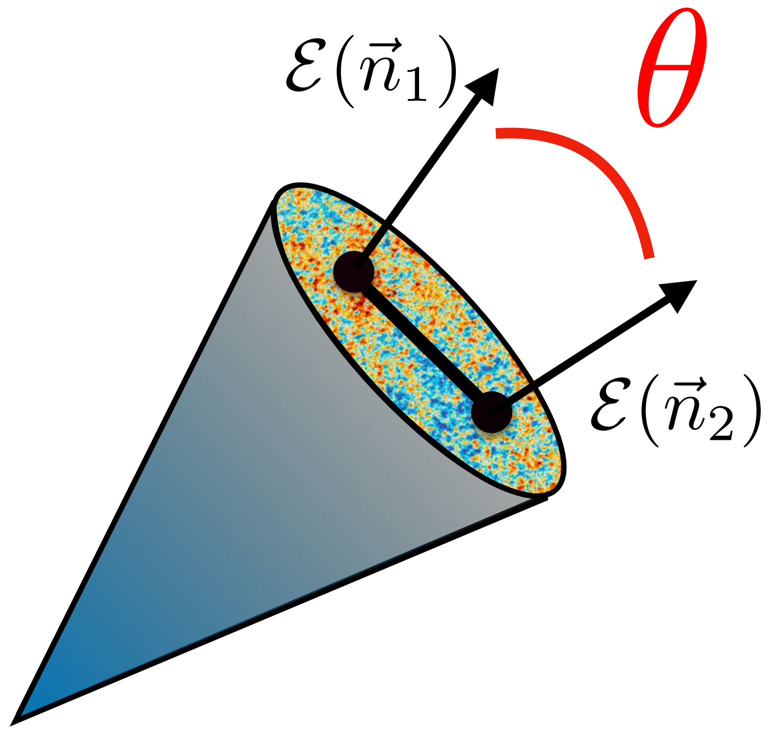
$$\mathcal{O}(x)\mathcal{O}(0) = \sum x^{\gamma_i} c_i \mathcal{O}_i$$

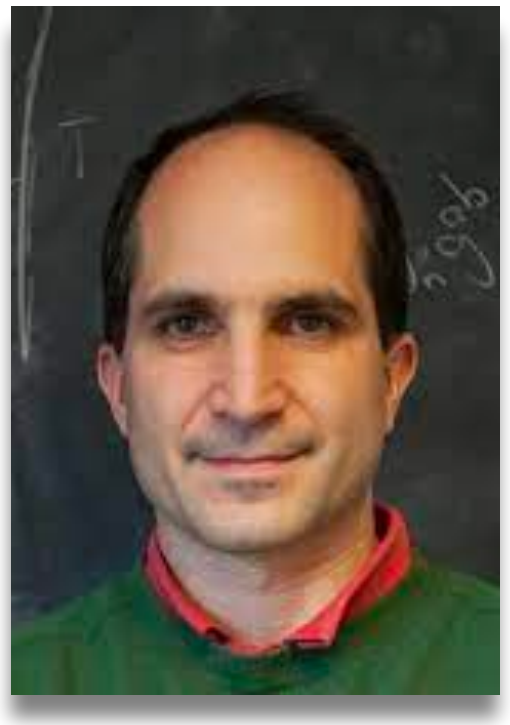
- **Critical phenomena give us access to universal scaling behavior as Euclidean operators are brought together**

UNIVERSAL LORENTZIAN SCALING WITHIN JETS

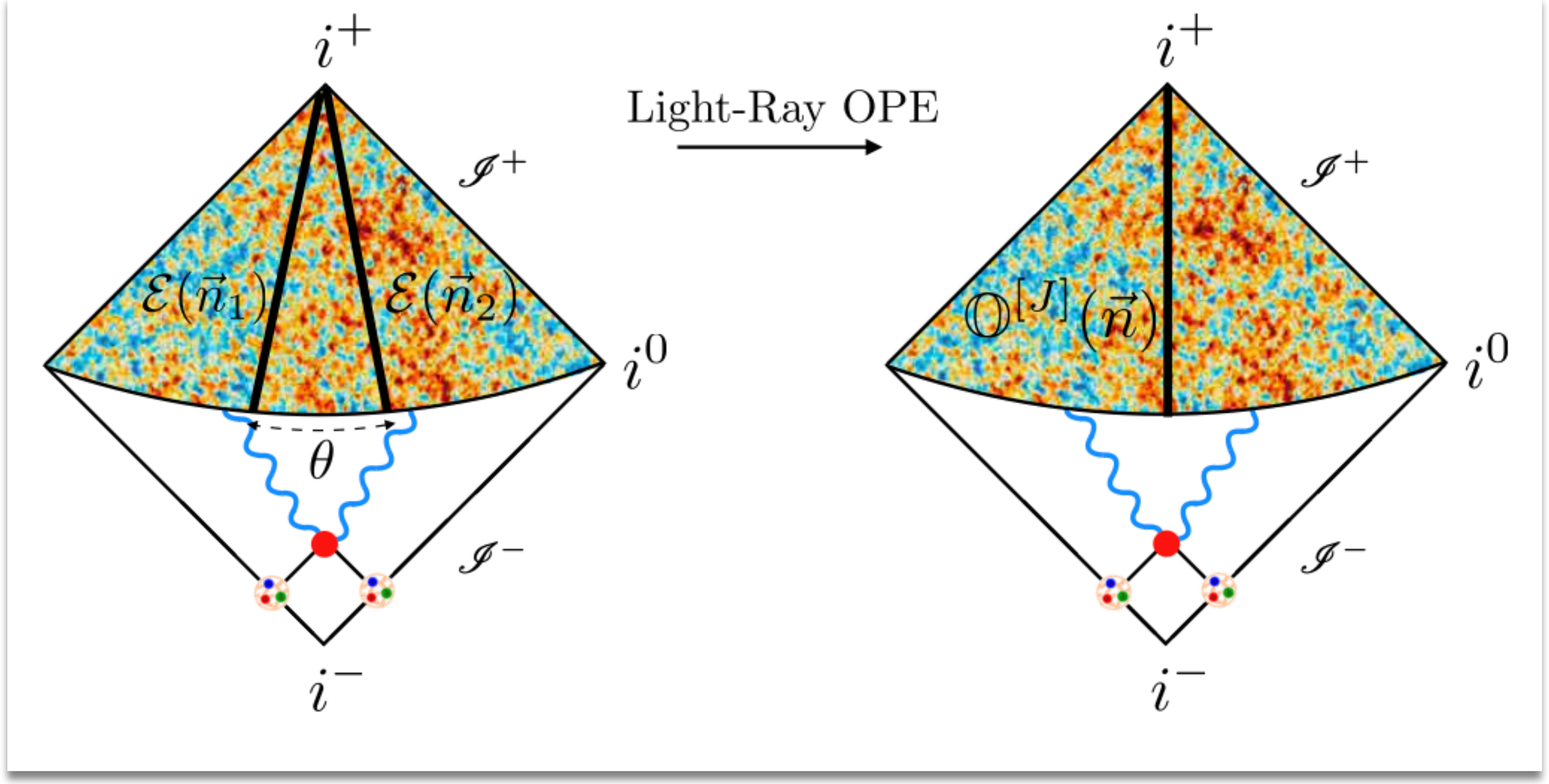
- **Jet substructure describes the limit where energy flow operators are brought together, thus probing the OPE limit of Lorentzian operators**

$\Longrightarrow$ **Profound field theory predictions within jets!**





Hofman, Maldacena `08



Light-ray Operator Product Expansion

$$\mathcal{E}\left(\hat{n}_1\right)\mathcal{E}\left(\hat{n}_2\right) \sim \sum \theta^{\gamma(3)-2}\mathbb{O}_i\left(\hat{n}_1\right)$$

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

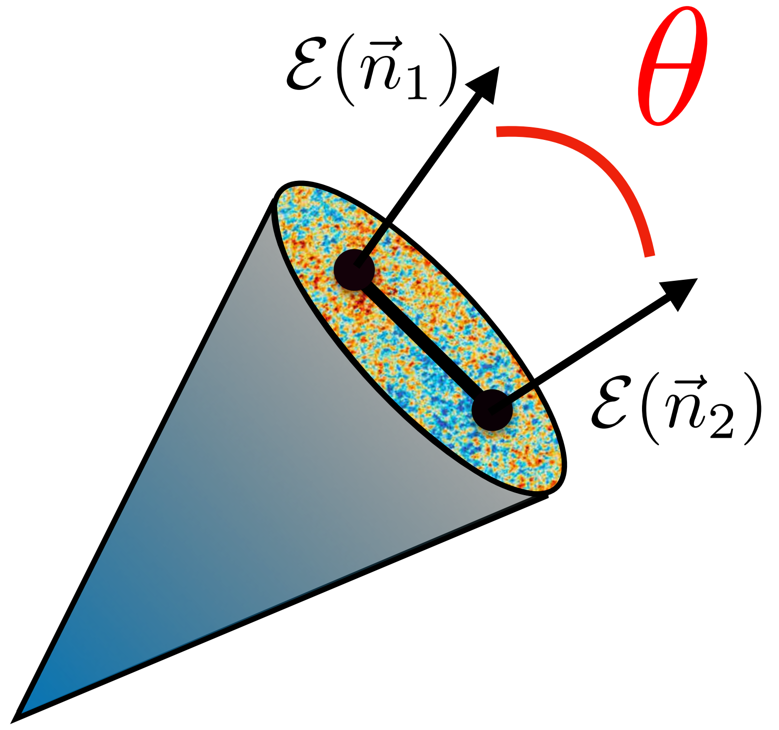
$$\mathcal{E}(\hat{n})|X\rangle = \sum_a E_a \delta^{(2)}\left(\Omega_{\vec{p}_a} - \Omega_{\hat{n}}\right)|X\rangle$$

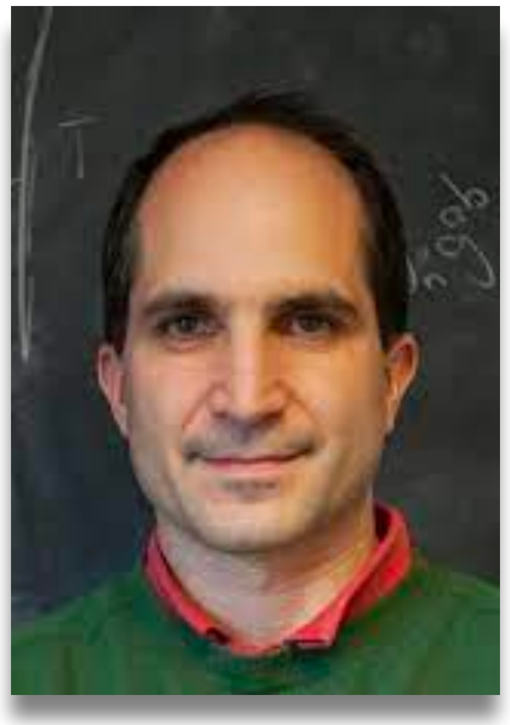
- **Light-ray Operator Product Expansion predicted universal scaling within jets within the context of conformal field theory**

UNIVERSAL LORENTZIAN SCALING WITHIN JETS

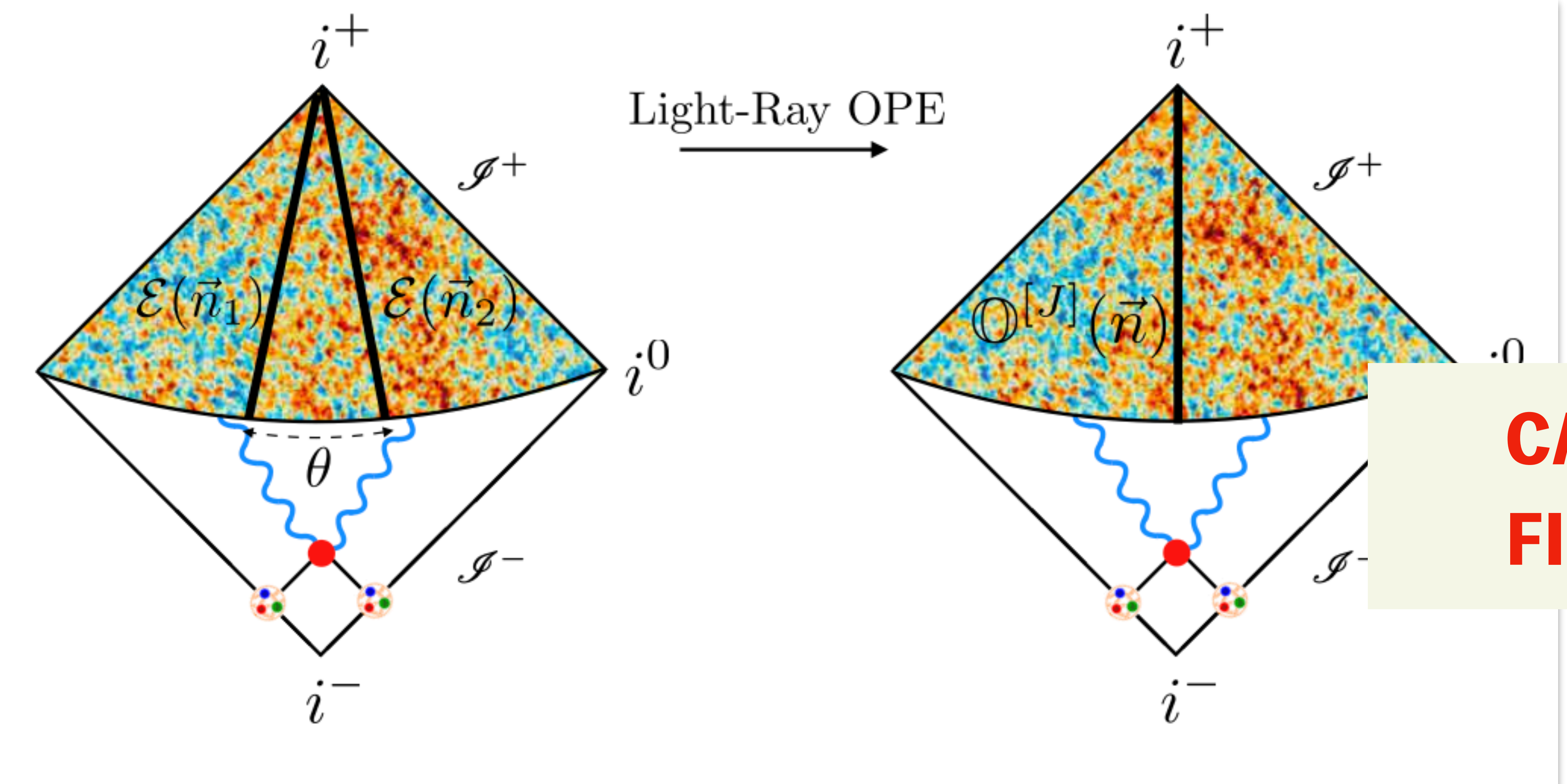
- **Jet substructure describes the limit where energy flow operators are brought together, thus probing the OPE limit of Lorentzian operators**

$\Longrightarrow$ **Profound field theory predictions within jets!**





Hofman, Maldacena `08



Light-ray Operator Product Expansion

$$\mathcal{E}(\hat{n}_1)\,\mathcal{E}(\hat{n}_2) \sim \sum \theta^{\gamma(3)-2}\mathbb{O}_i(\hat{n}_1)$$

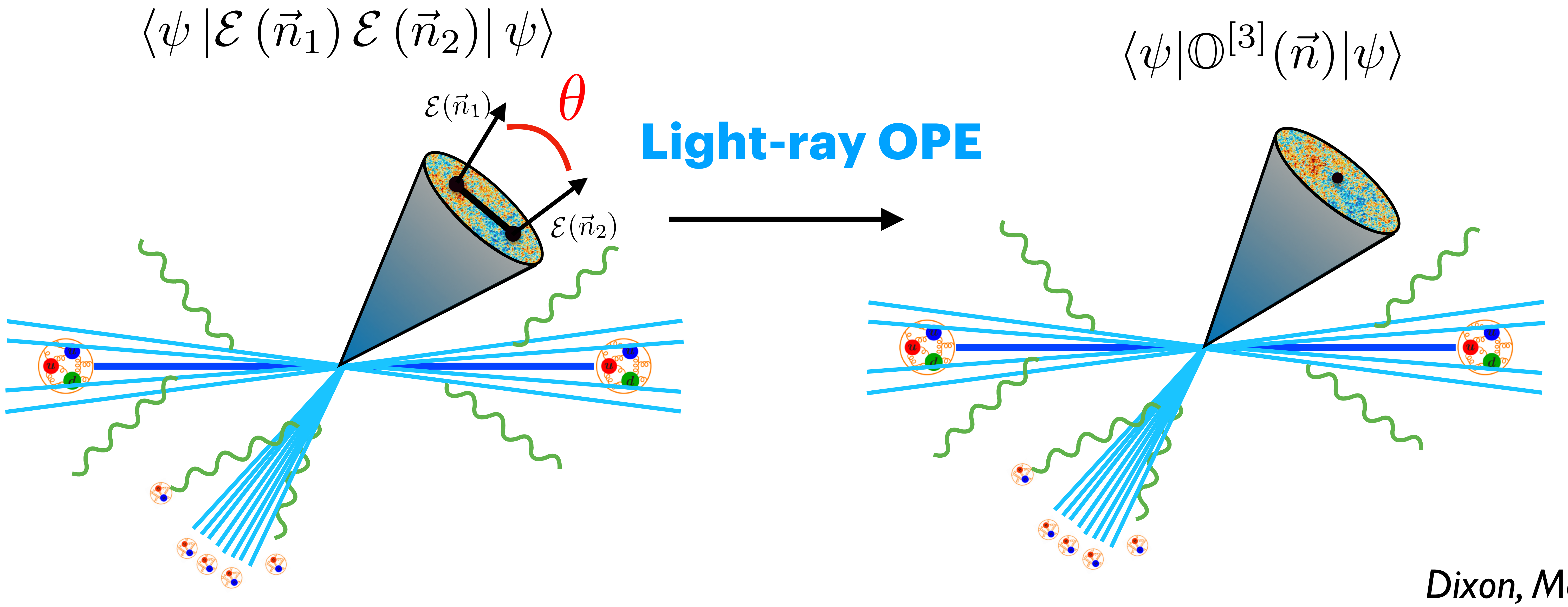
CAN THIS UNIVERSAL SCALING OF THE FIELD THEORY BE OBSERVED IN JETS???

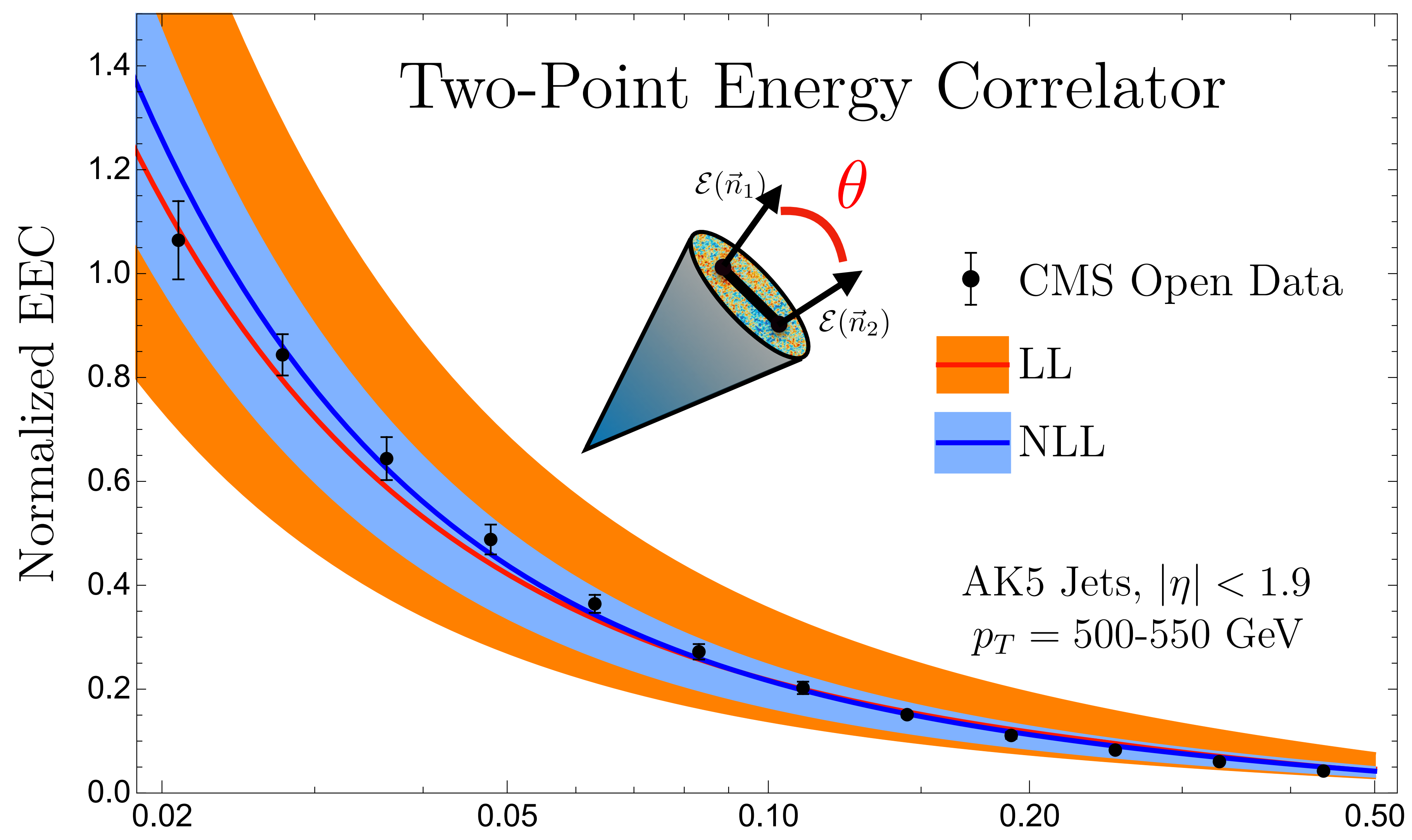
$$\mathcal{E}(\hat{n})|X\rangle = \sum_a E_a \delta^{(2)}\left(\Omega_{\vec{p}_a} - \Omega_{\hat{n}}\right)|X\rangle$$

- **Light-ray Operator Product Expansion predicted universal scaling within jets within the context of conformal field theory**

UNIVERSAL SCALING BEHAVIOR IN JETS!

- **In QCD, we developed the proper framework to observe the universal scaling behavior within jets!**



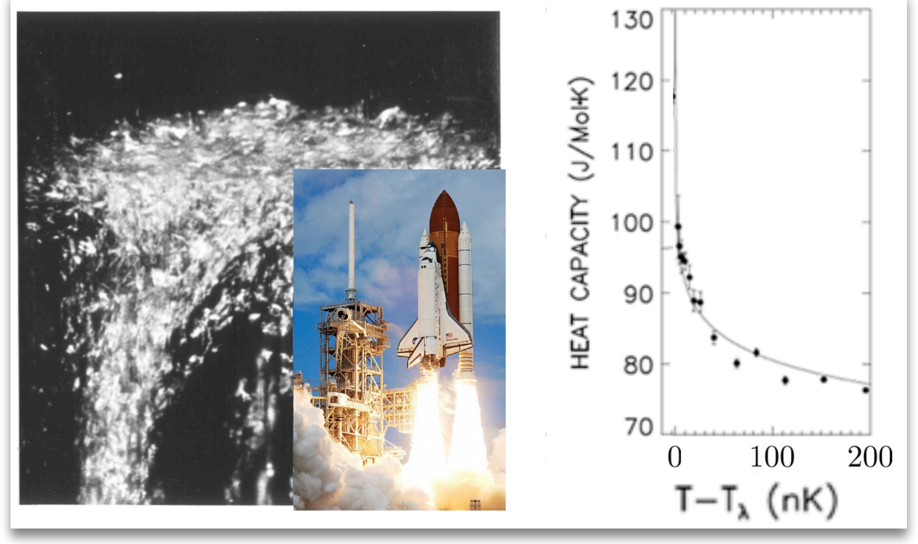


Dixon, Moult, Zhu `19
KL, Meçaj, Moult `22 Chen `23
KL, Moult, Zhang `24 KL, Stewart `25

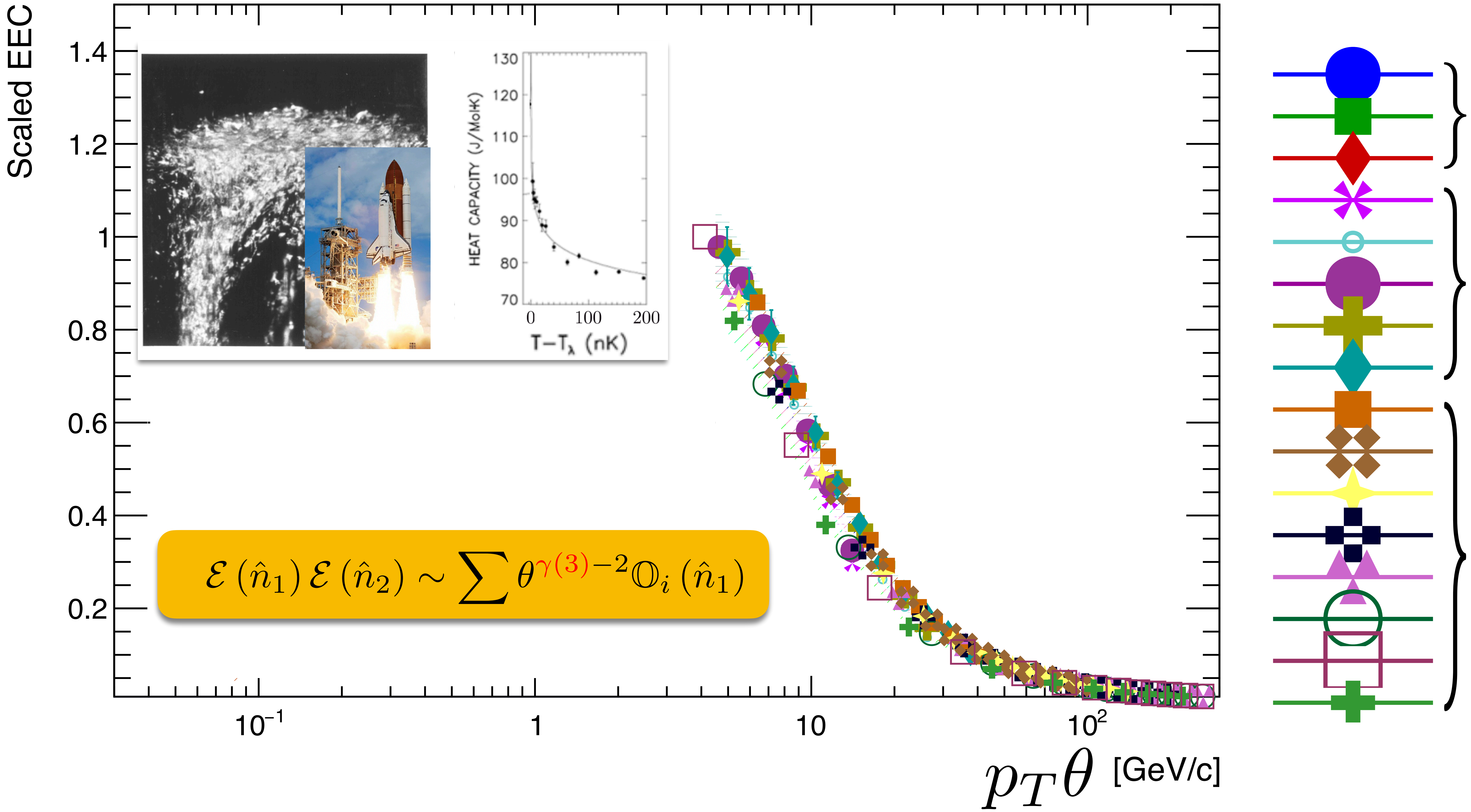
QCD factorization:

$$\frac{d\sigma^{pp\to \text{jet}(\mathcal{E}\mathcal{E})X}}{dp_T\,d\eta\,d\theta} = \sum_{a,b,c} f_{a/A} \otimes f_{b/B} \otimes H^c_{ab} \otimes \mathcal{G}^{\text{EEC}}_c(\theta)$$

Λ_{QCD} p_T $p_T R$ $p_T\theta$



SCALING FROM 15 GEV TO 2 TEV IN DATA!



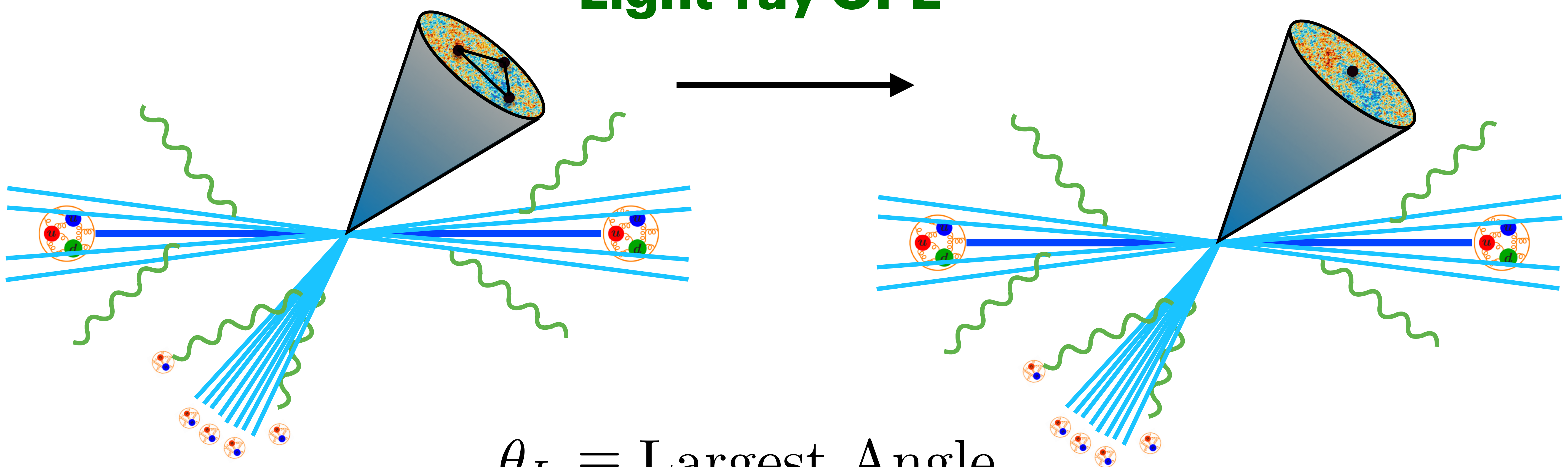
- **Universal scaling of QCD operators revealed in data from STAR, ALICE, and CMS, from 15 GeV to 1784 GeV!**

THE SPECTRUM OF A JET

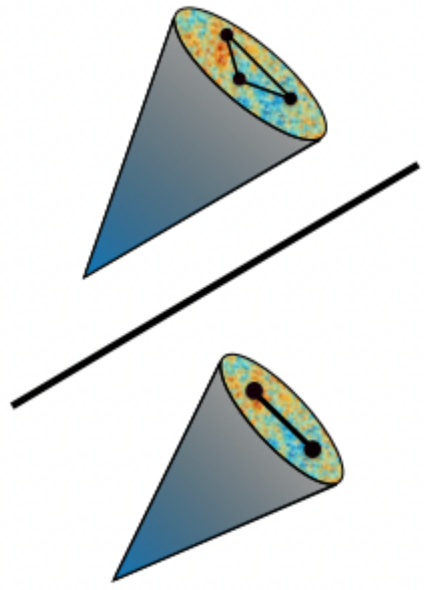
- **The light-ray OPE can be iteratively applied to N-point correlators, predicting their anomalous scaling behavior with N**

Chen, Moult, Zhang, Zhu `20
KL, Meçaj, Moult `22
Chen, Gao, Li, Xu, Zhang, Zhu `23

$\langle\psi|\mathcal{E}(\vec{n}_1)\cdots\mathcal{E}(\vec{n}_N)|\psi\rangle$ **Light-ray OPE** $\langle\psi|\mathbb{O}^{[J]}(\vec{n})|\psi\rangle$

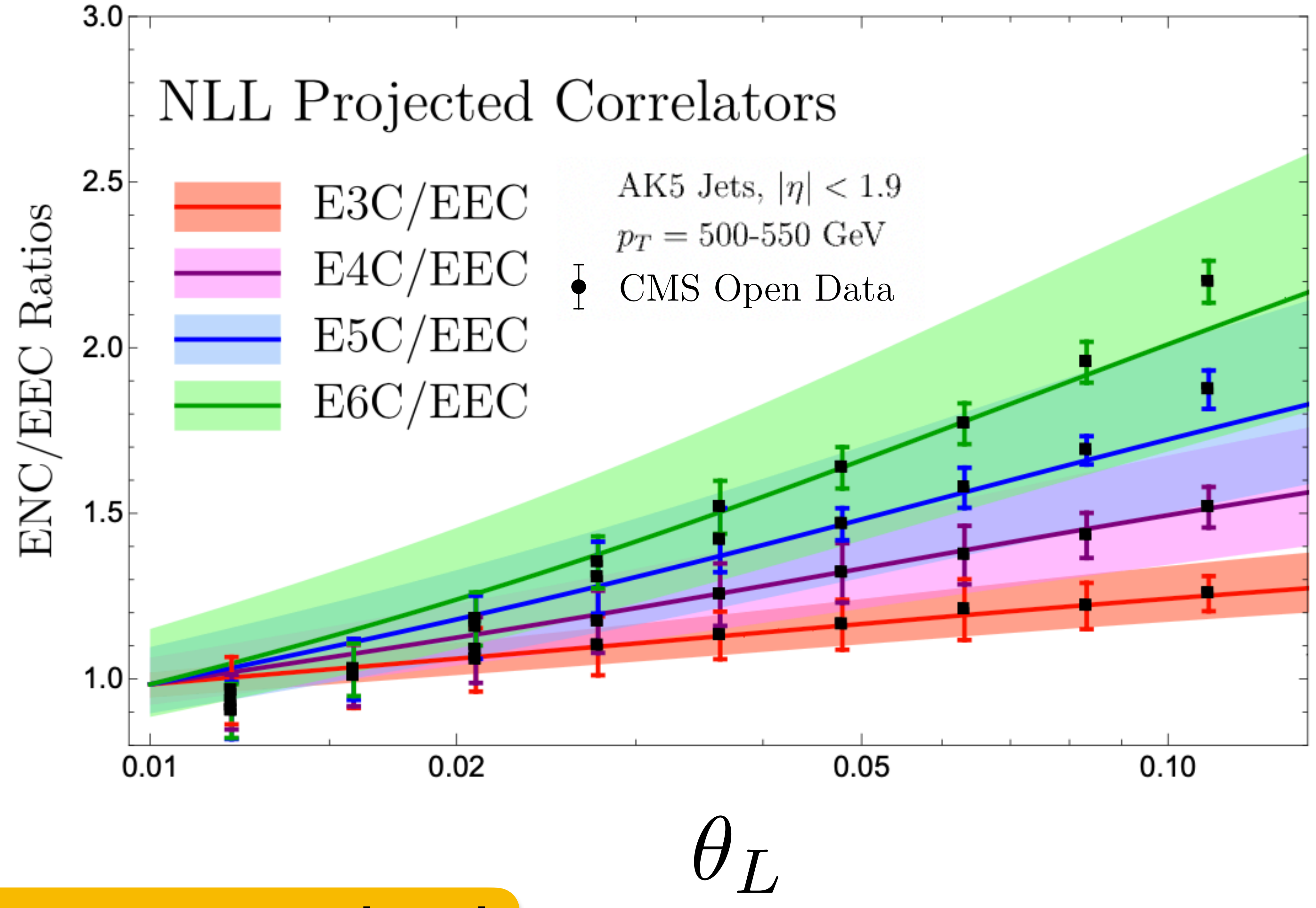


$\theta_L \equiv \text{Largest Angle}$



$$\frac{\langle\mathcal{E}_1\mathcal{E}_2\cdots\mathcal{E}_N\rangle}{\langle\mathcal{E}_1\mathcal{E}_2\rangle} \sim \frac{\langle\mathbb{O}^{[N+1]}\rangle}{\langle\mathbb{O}^{[3]}\rangle} \sim \theta_L^{\gamma(N+1)-\gamma(3)}$$

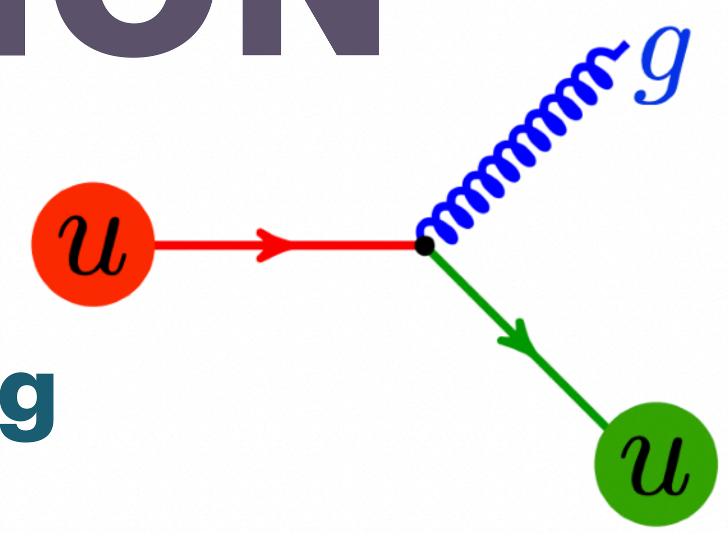
$$\gamma(N) \propto \alpha_s$$



$$\mathcal{E}_1\cdots\mathcal{E}_N \sim \theta^{\gamma(N+1)-2}\mathbb{O}_i^{[N+1]}$$

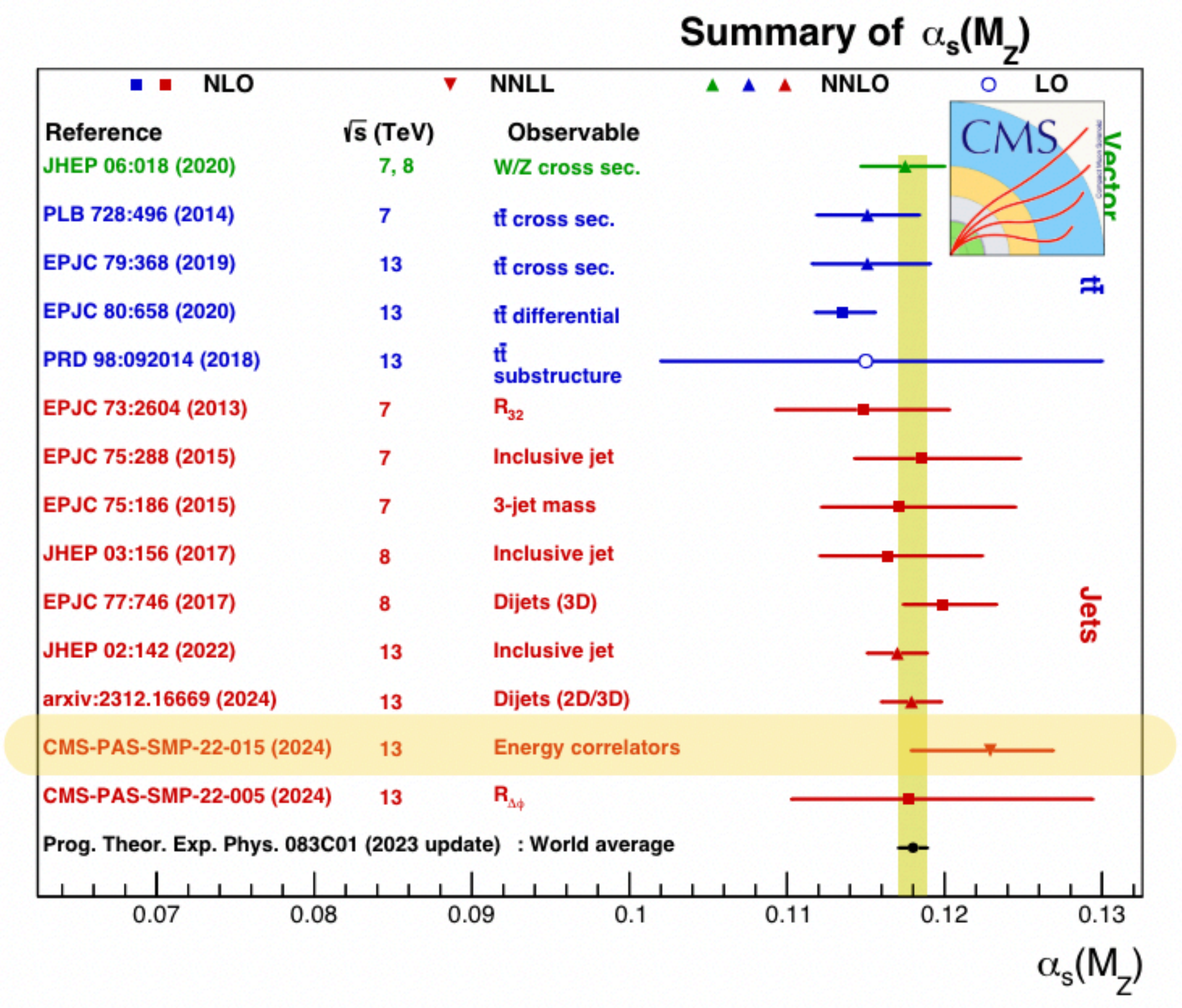
quantum classical

STRONG COUPLING DETERMINATION



- **How strong is the Strong Force?** In comparison, EM coupling: $\alpha_e = 0.0072973525693(11)$

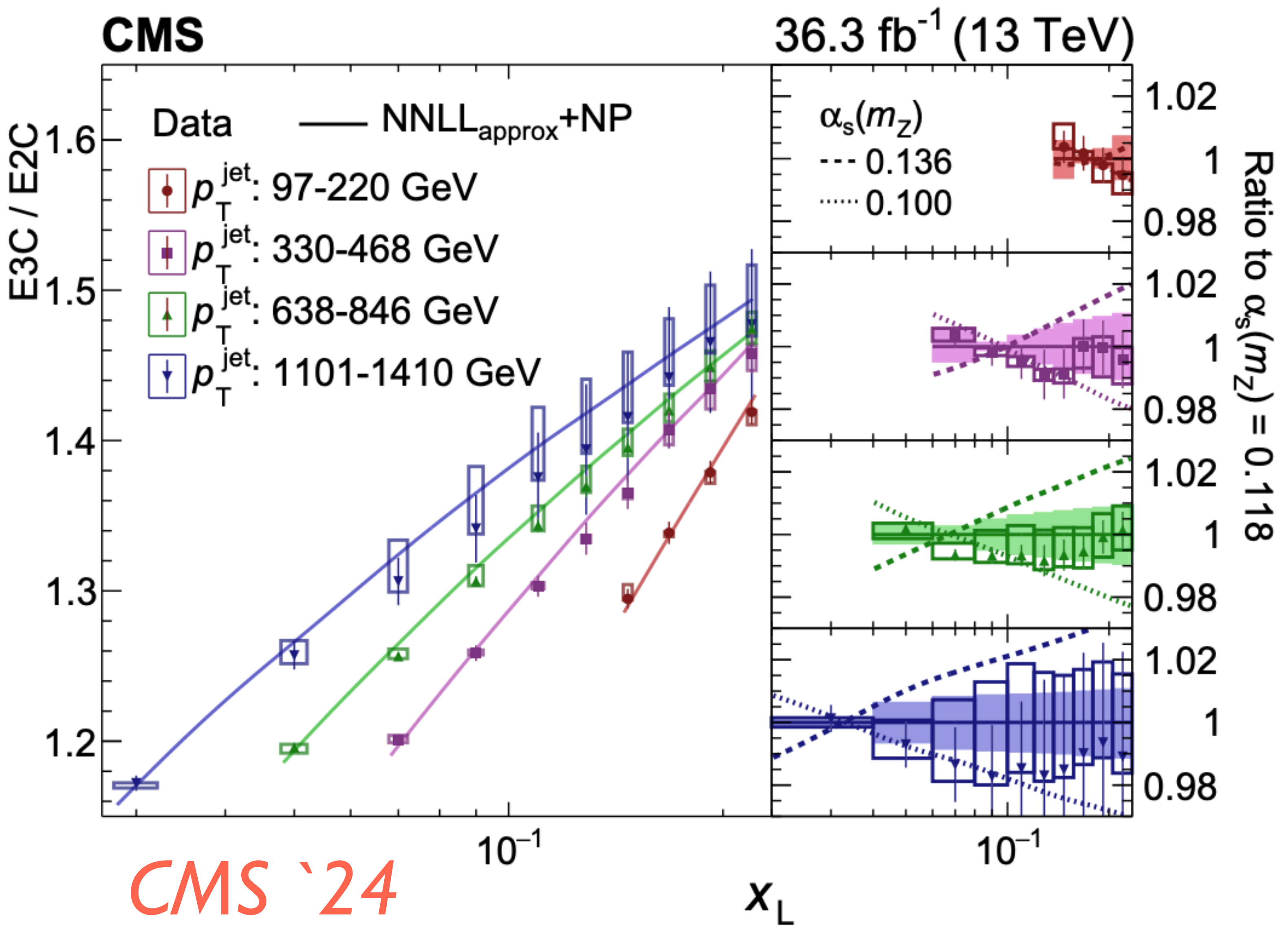
Quarks are never free, and thus it is very hard to measure their coupling



CMS collaboration carried out most precise determination of the strong coupling constant for jet substructure

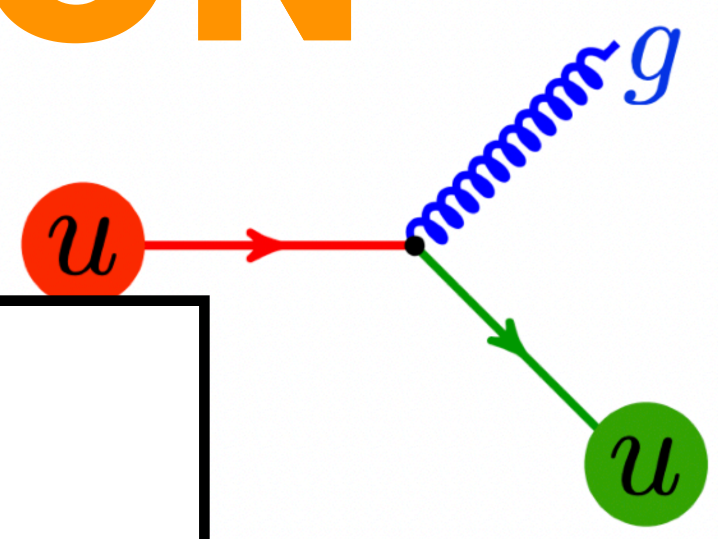
$$\alpha_s(m_Z) = 0.1229^{+0.0040}_{-0.0050} \Longrightarrow \text{4\% uncertainty}$$

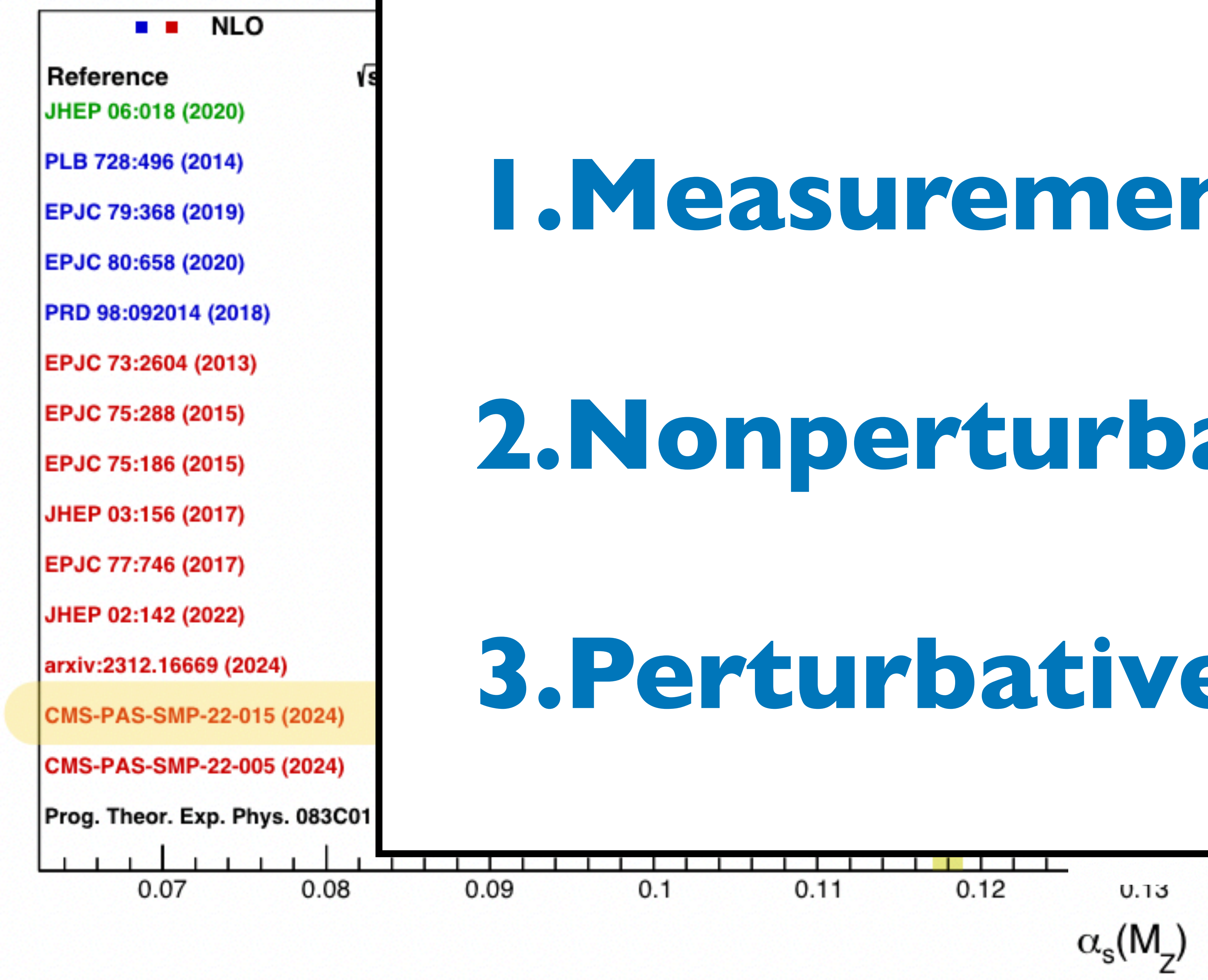
Energy Correlators in Jet



CMS `24

ROAD TO IMPROVED PRECISION





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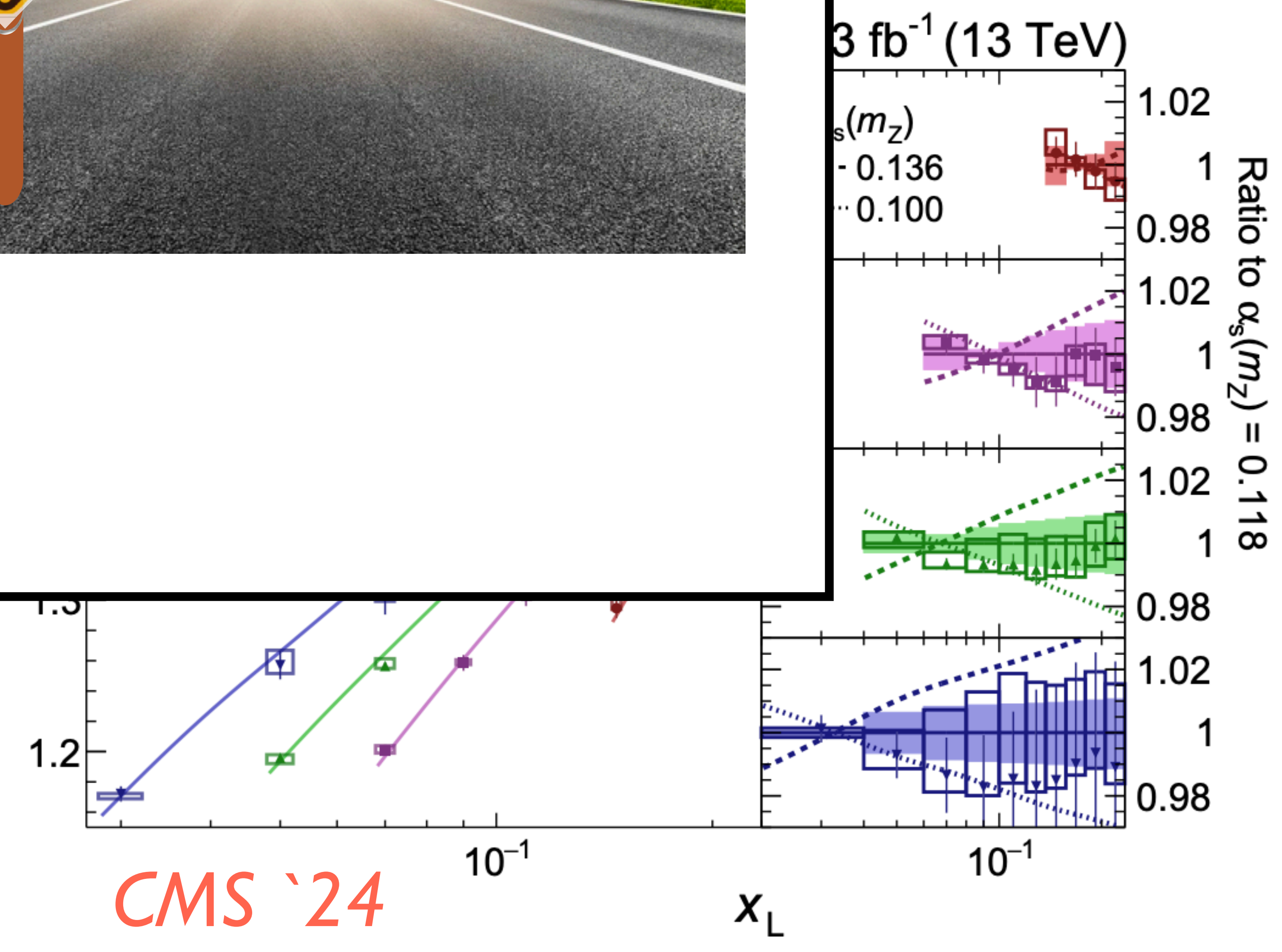
Road to precision

1. **Measurements on Tracks**
2. **Nonperturbative corrections**
3. **Perturbative corrections**



CMS `24

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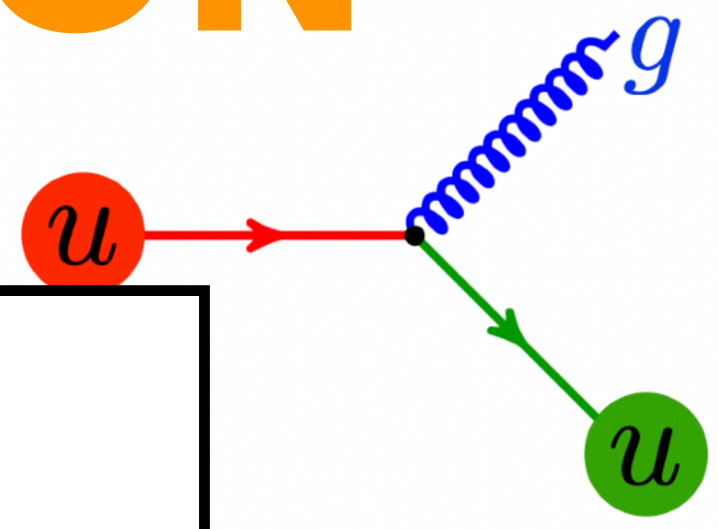

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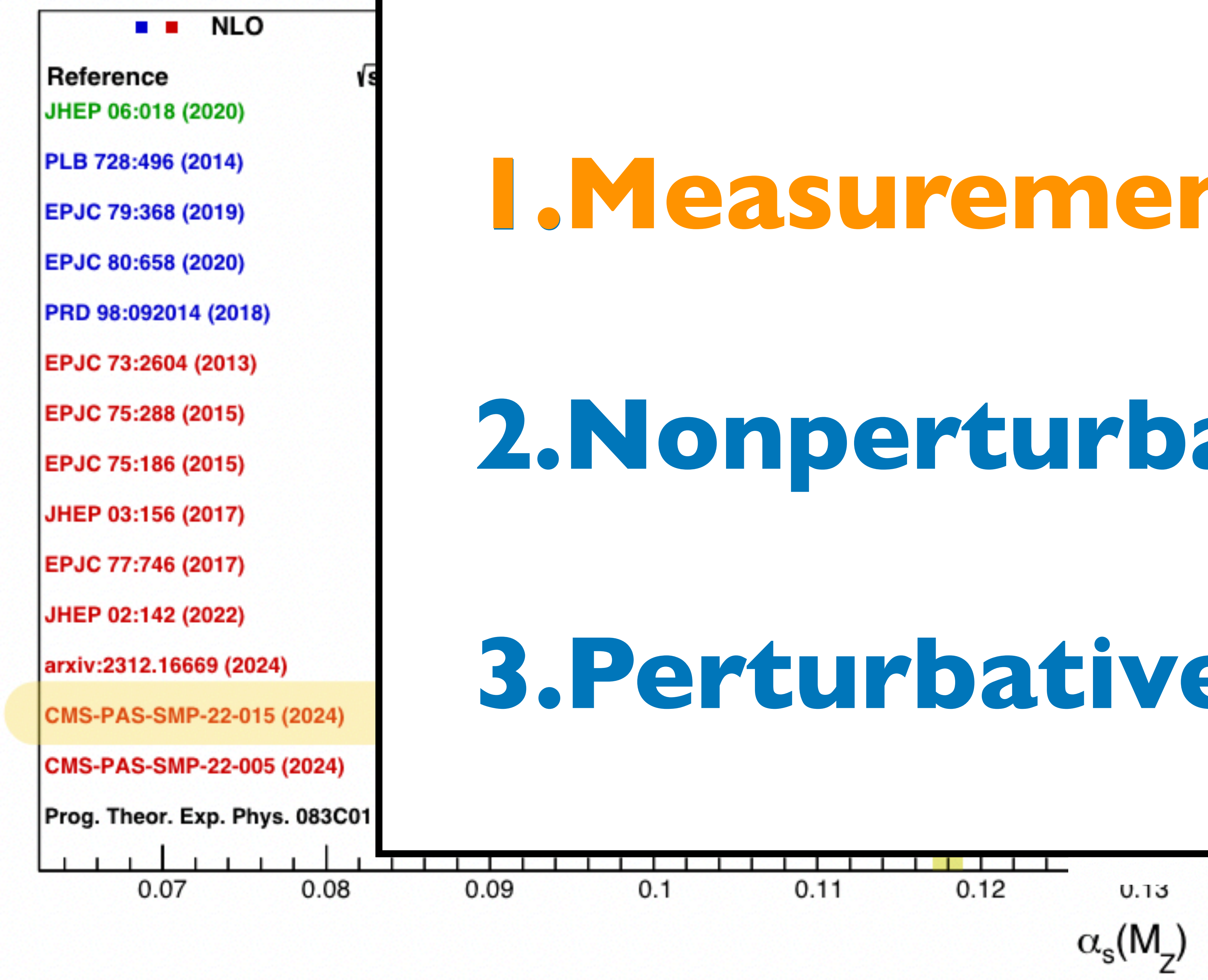
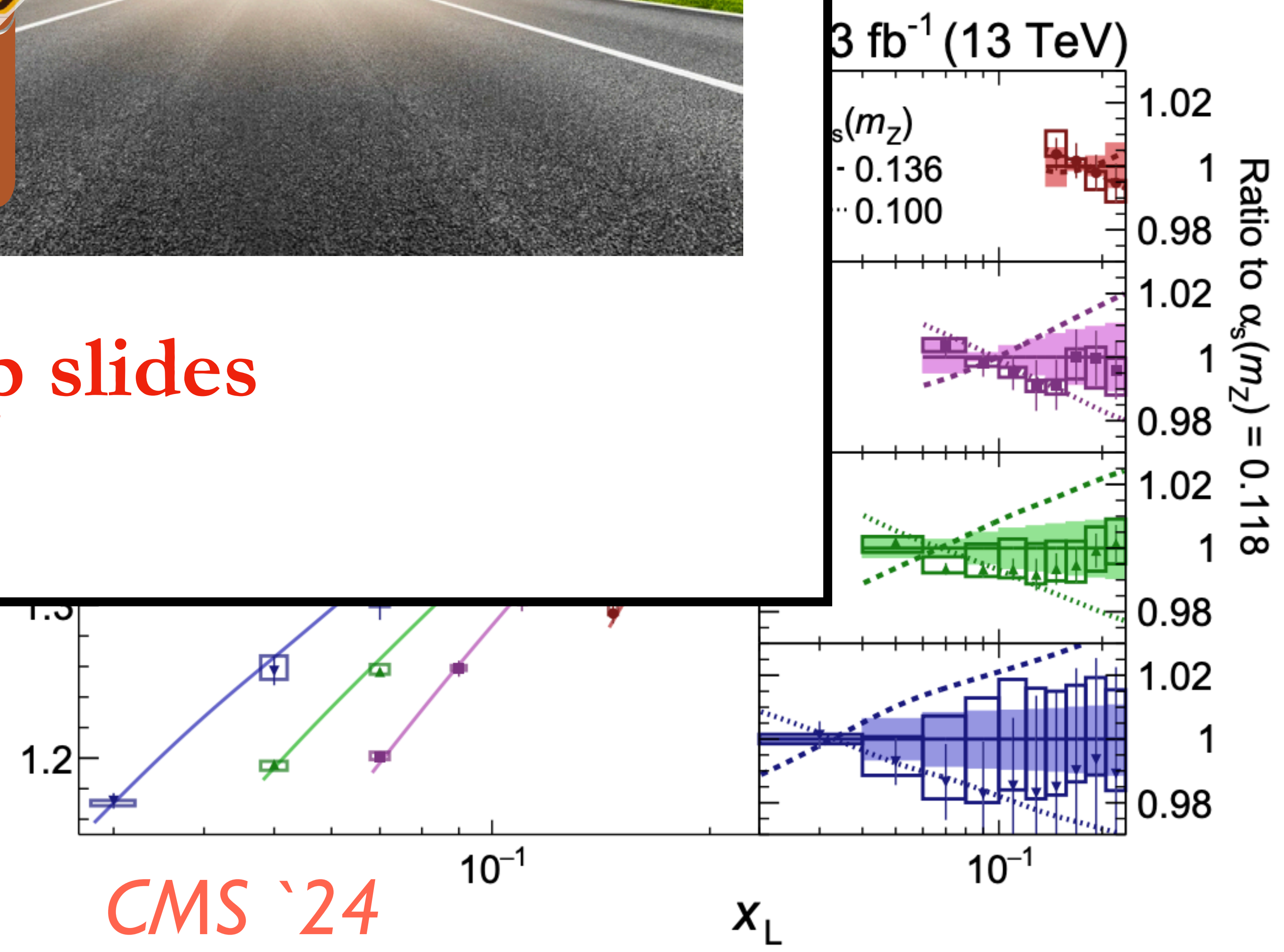


Road to precision

1. **Measurements on Tracks**

   Backup slides

2. **Nonperturbative corrections**
3. **Perturbative corrections** ← Backup slides

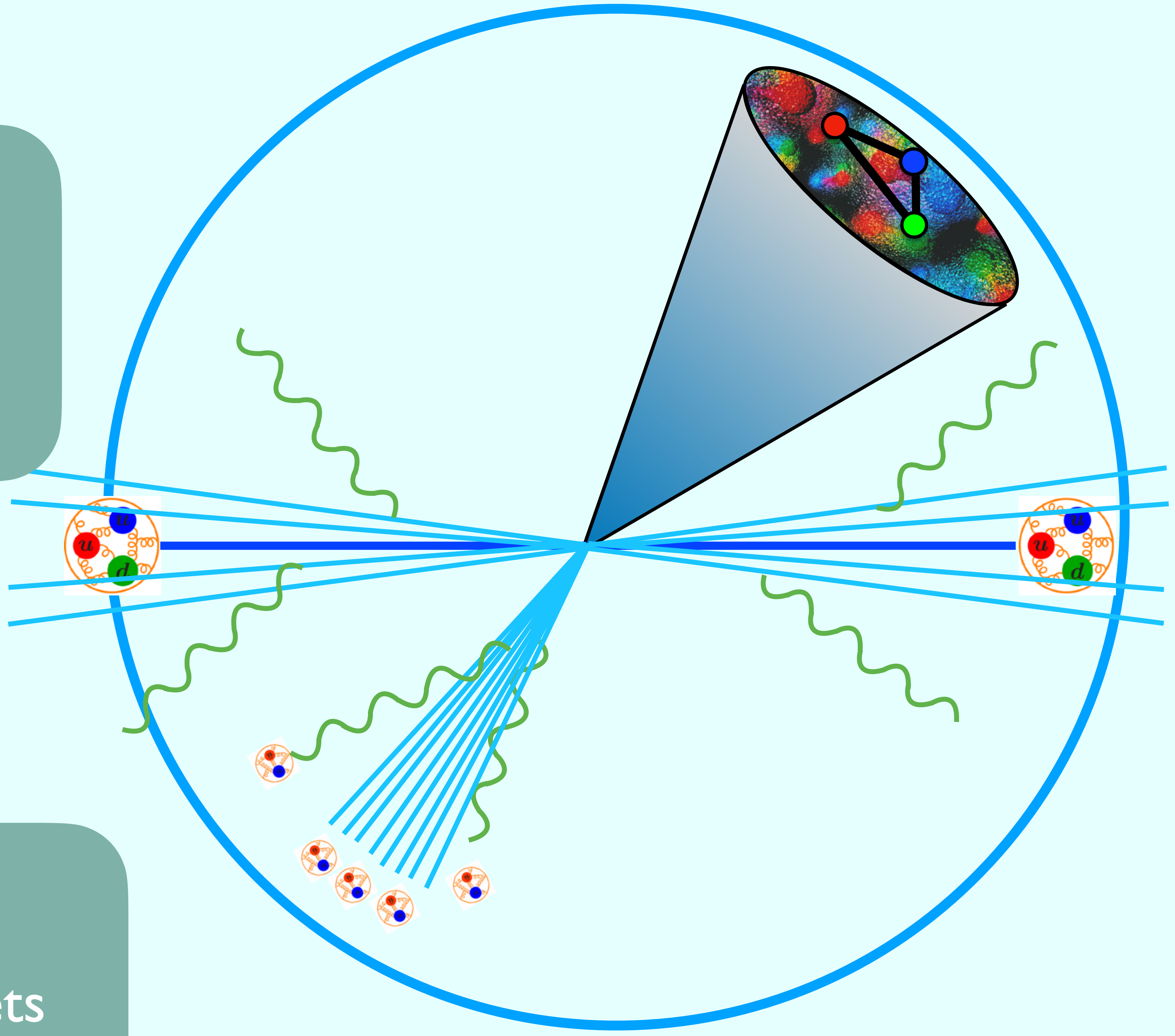


Overview

I. Universal Scaling

Can we carry out precision study of the Standard Model?

V. Electroweak and New physics



II. Precision SM

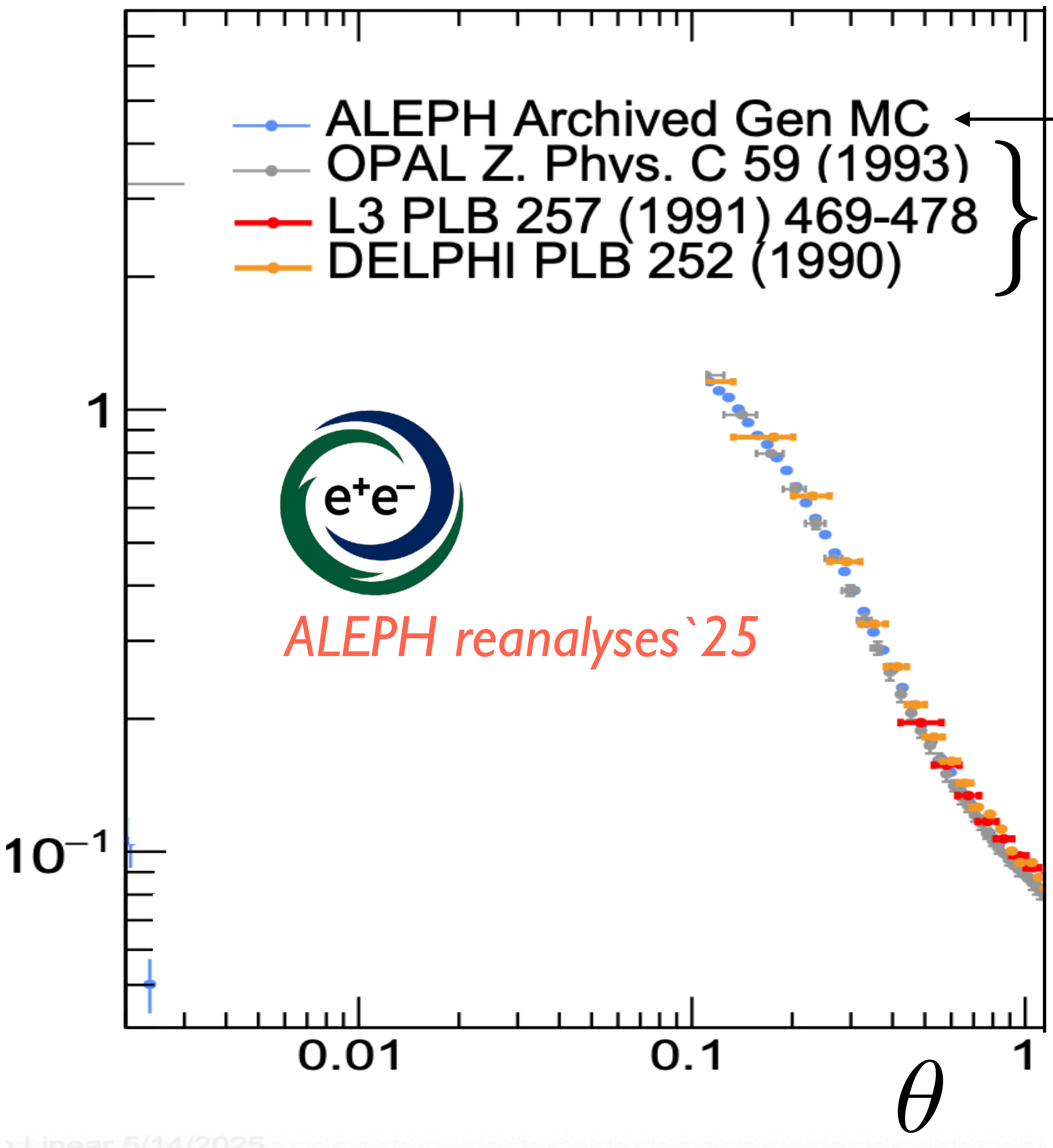
IV. Heavy Flavor Jets

III. Confinement Dynamics

MEASURING TRACKS

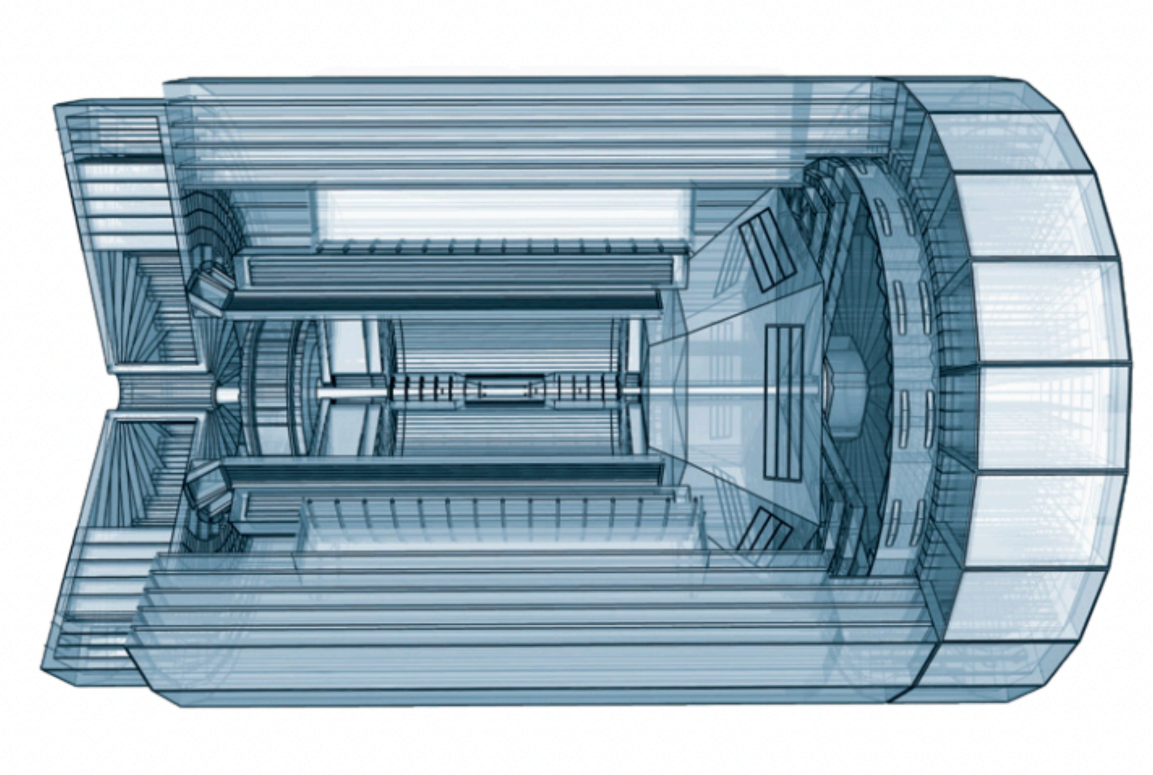
- **Measuring tracks (i.e. EM charged particles) provides much more precise experimental results**

Two-Point Energy Correlators



Tracks $\mathcal{E}_{\rm tr}(\hat{n})$

All particles $\mathcal{E}(\hat{n})$



Modern detectors have state-of-the-art tracking systems!

Track Energy Flow Operator

$$\mathcal{E}_{\rm tr}(\hat{n})|X\rangle = \sum_{h\in\{+,-\}} E_h \delta^{(2)}\left(\Omega_{\vec{p}_h} - \Omega_{\hat{n}}\right)|X\rangle$$

- **Depend on quantum numbers of final state hadrons other than energy**

$\Longrightarrow$ **not computable purely from perturbation theory**

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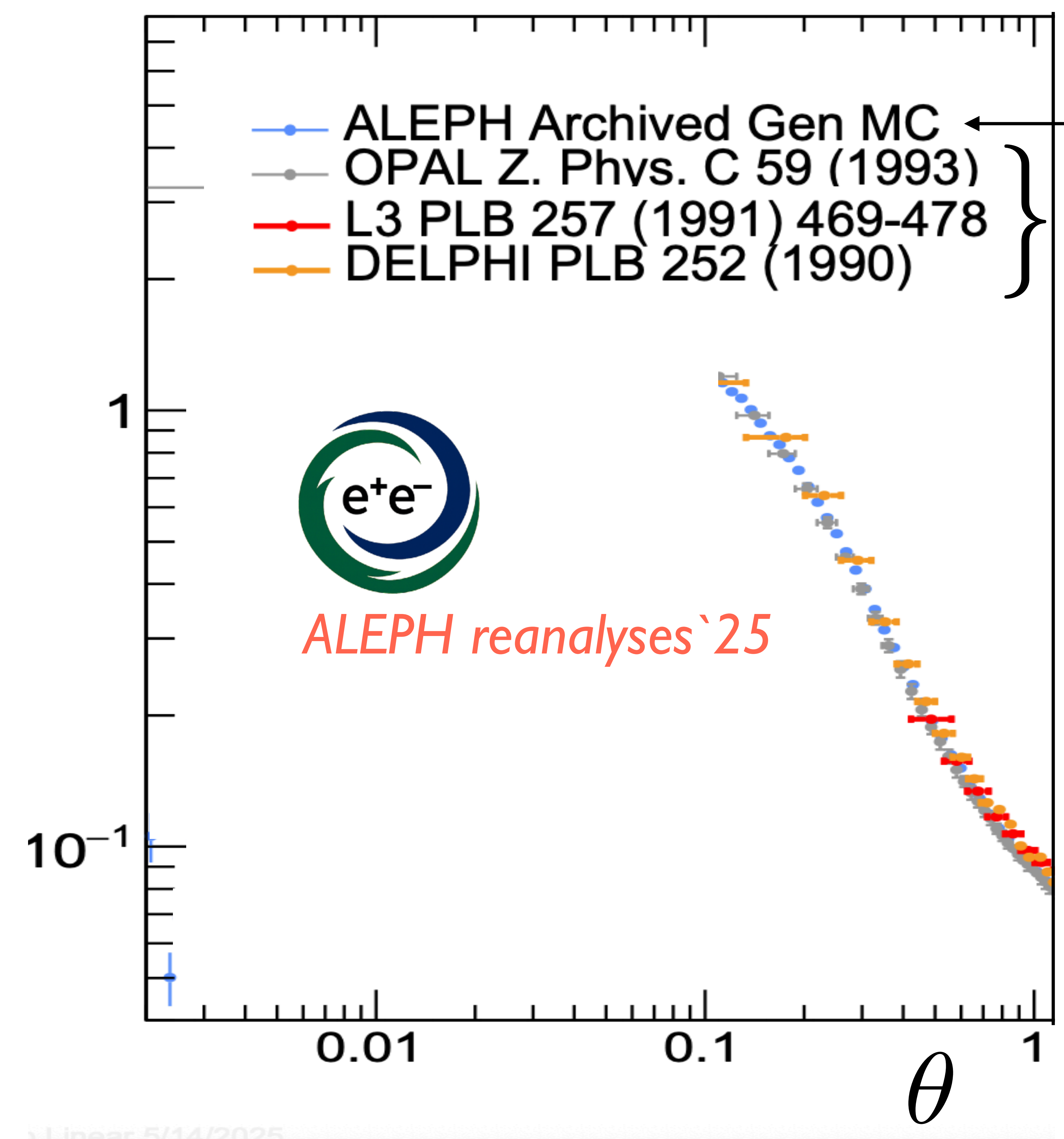
Two-Point Energy Correlators



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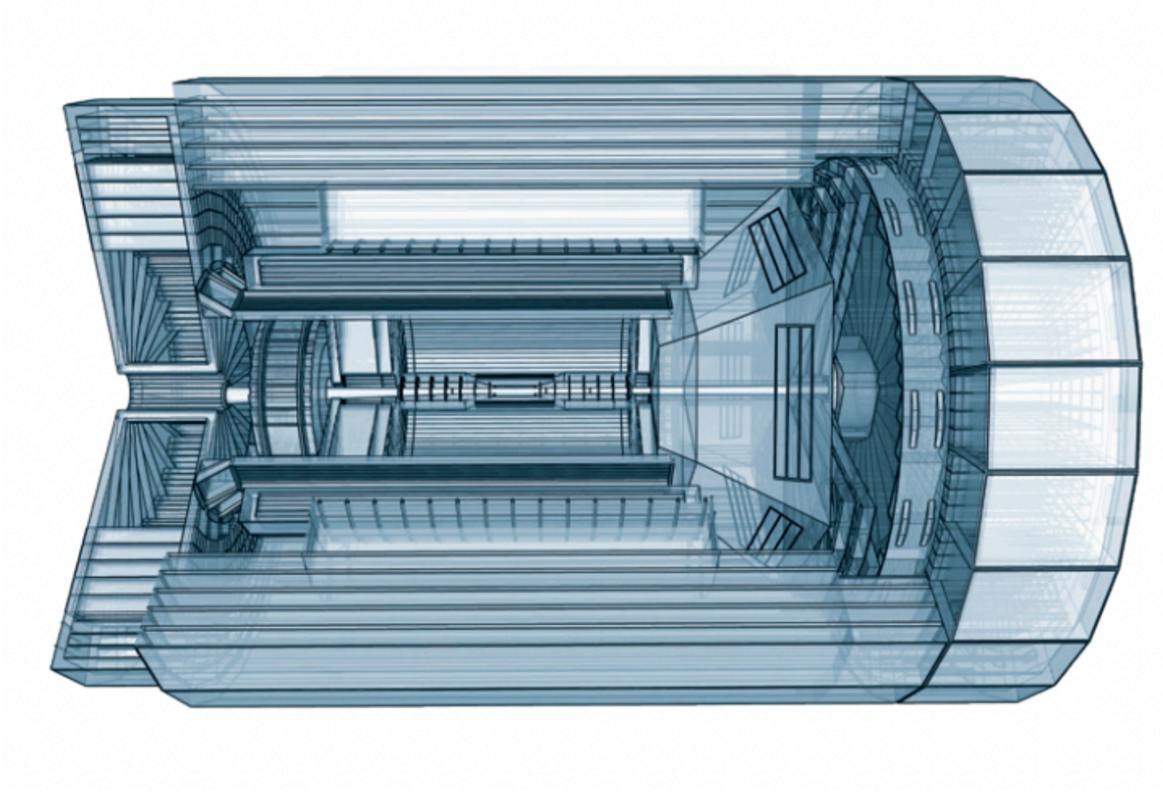

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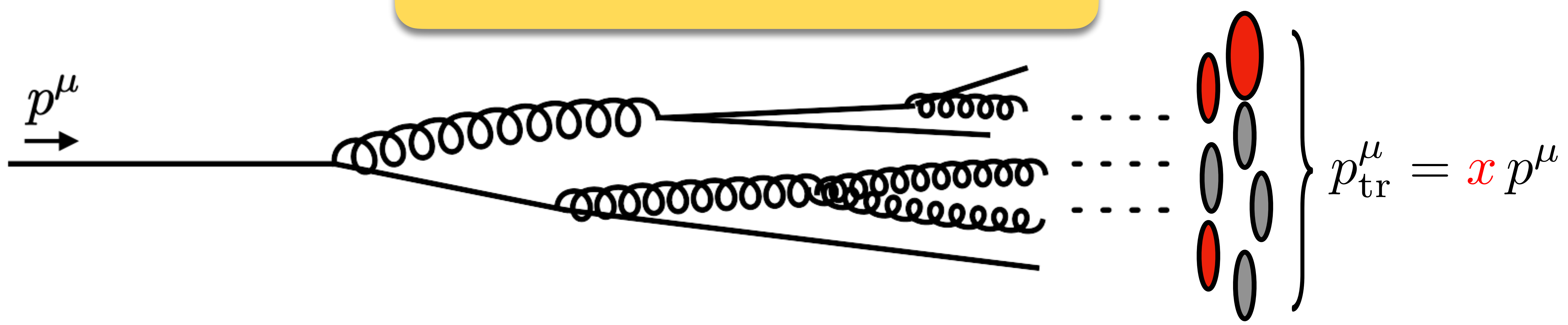
We need QCD factorization :

separate calculable perturbative from universal nonperturbative dynamics

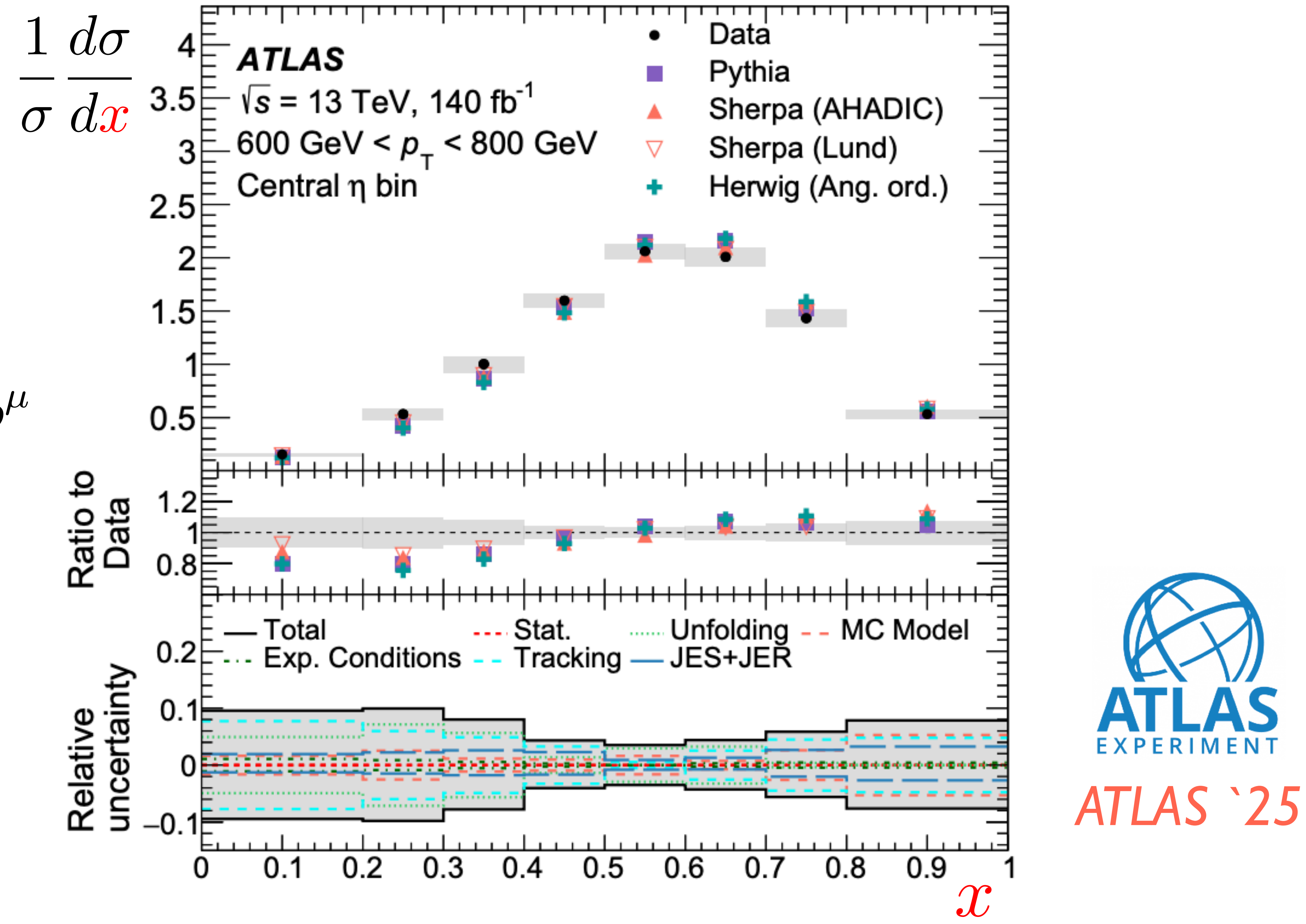
TRACK FUNCTIONS

- **Track functions are non-perturbative functions describing the momentum fraction of initial parton converted to tracks (charged hadrons).**

$T_q(x)$ **Track Functions**



Chang, Procura, Thaler, Waalewijn `13
Jaarsma, Li, Moult, Waalewijn, Zhu et al `21, 22,23
KL, Moult `23,23



ATLAS `25

- **Track function formalism provides the essential matching between partonic and hadronic detectors**

$$\mathcal{E}(\vec{n}) \longleftrightarrow \mathcal{E}_{\rm tr}(\vec{n})$$
$$T_i(x)$$

ENERGY CORRELATORS ON TRACK

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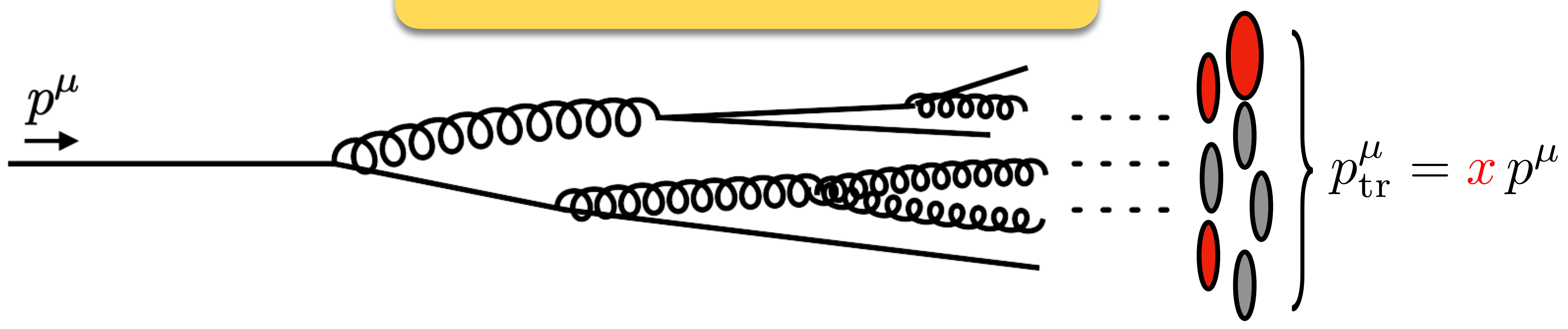
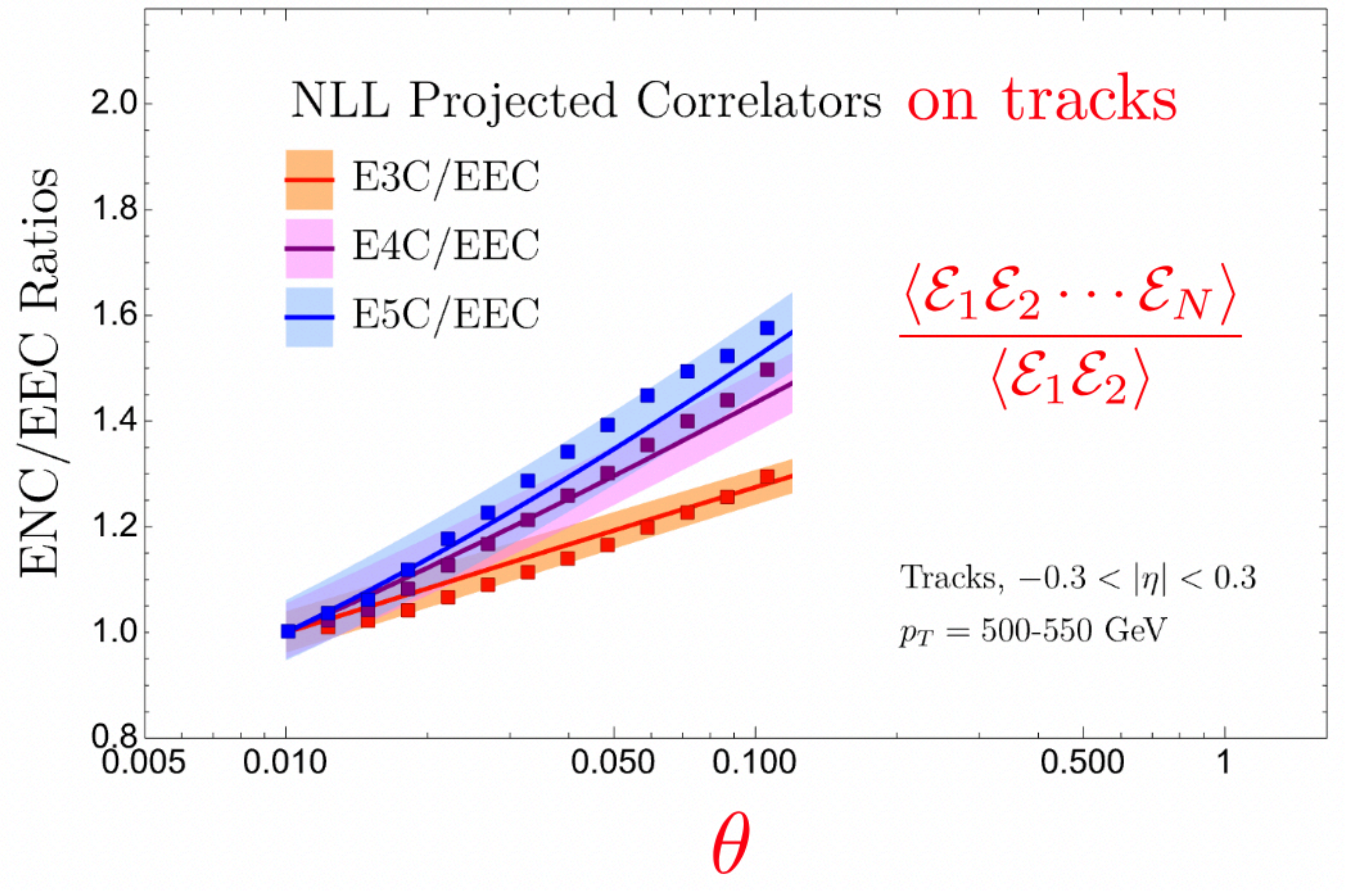
$T_q(x)$ **Track Functions**



Chang, Procura, Thaler, Waalewijn `13
Jaarsma, Li, Moult, Waalewijn, Zhu et al `21, 22,23
KL, Moult `23,23

Predictions for Track Energy Correlators



KL, Li, Moult, Waalewijn `In Progress
Jaarsma, Li, Moult, Waalewijn, Zhu et al `23

- **We can use such track-level theoretical predictions to exploit precision track-level experimental measurements!**

ENERGY CORRELATORS ON TRACK

- Track functions are non-perturbative functions describing the momentum fraction of initial parton converte

p^μ

Road to precision

1. **Measurements on Tracks**
2. **Nonperturbative corrections** ← Backup slides

   KL, Pathak, Stewart, Sun `24
3. **Perturbative corrections** ← Backup slides

   Czakon, Generet, Mitov, Poncelet `21
   Bonino, Gehrmann, Stagnitto `24
   Poncelet, KL, Moult, Terry, Zhang `25
   KL, Moult, Zhang `24, `24

orrelators

cks

$\cdot \mathcal{E}_N\rangle$

$< |\eta| < 0.3$

GeV

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rogress]

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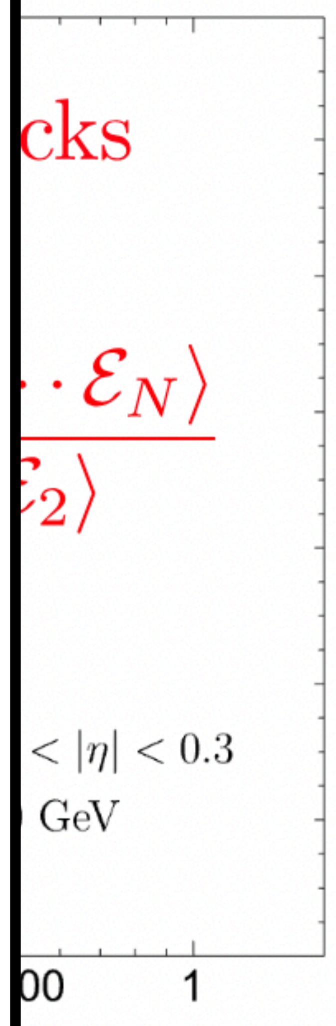

Will bring unprecedented precision calculation of jet substructure

KL, Li, Moult, Waalewijn [in Progress]

- We can use such track-level theoretical predictions to exploit precision track-level experimental measurements!

Overview

I. Universal Scaling

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V. Electroweak and
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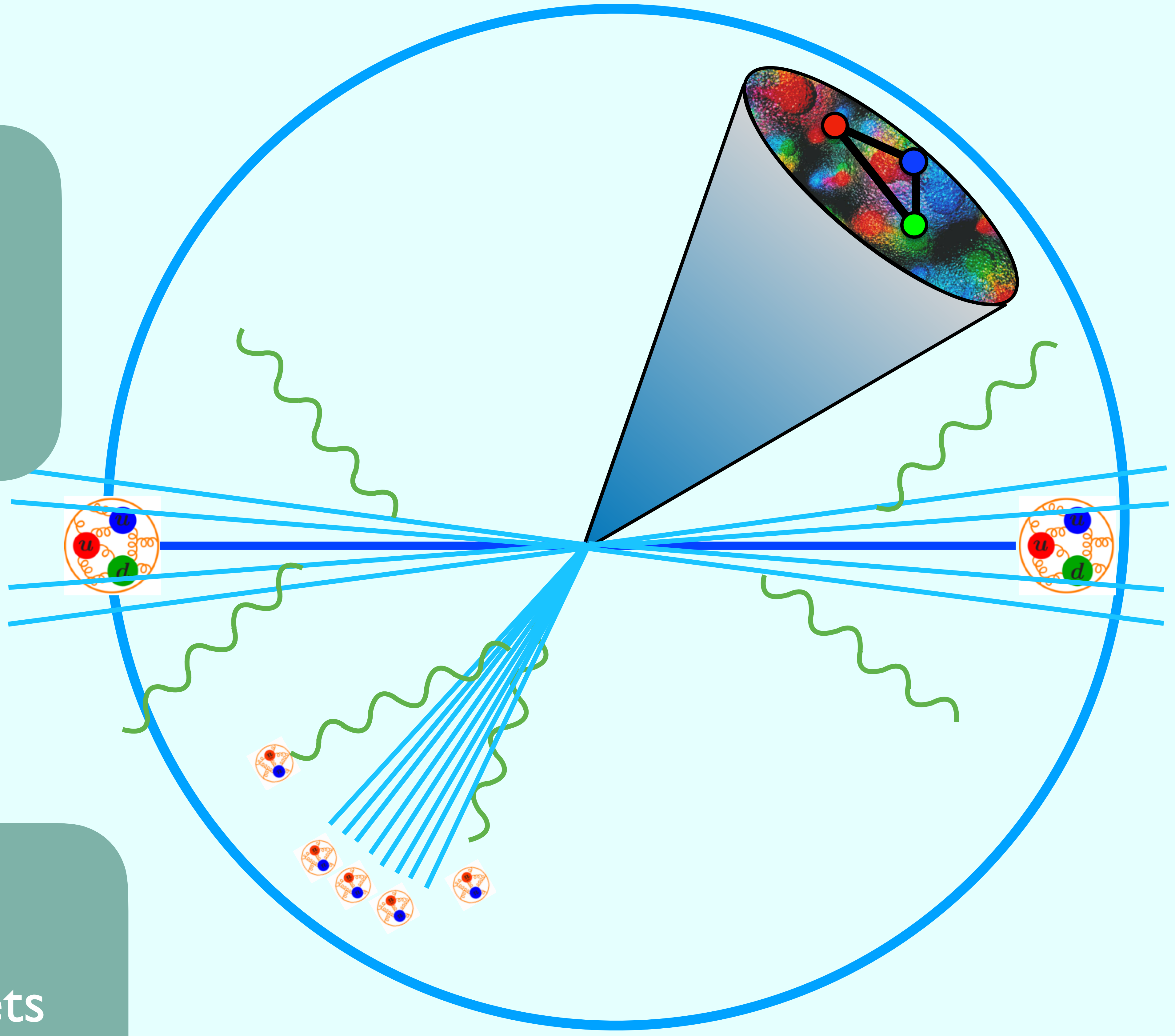


Can we understand confinement mechanism?

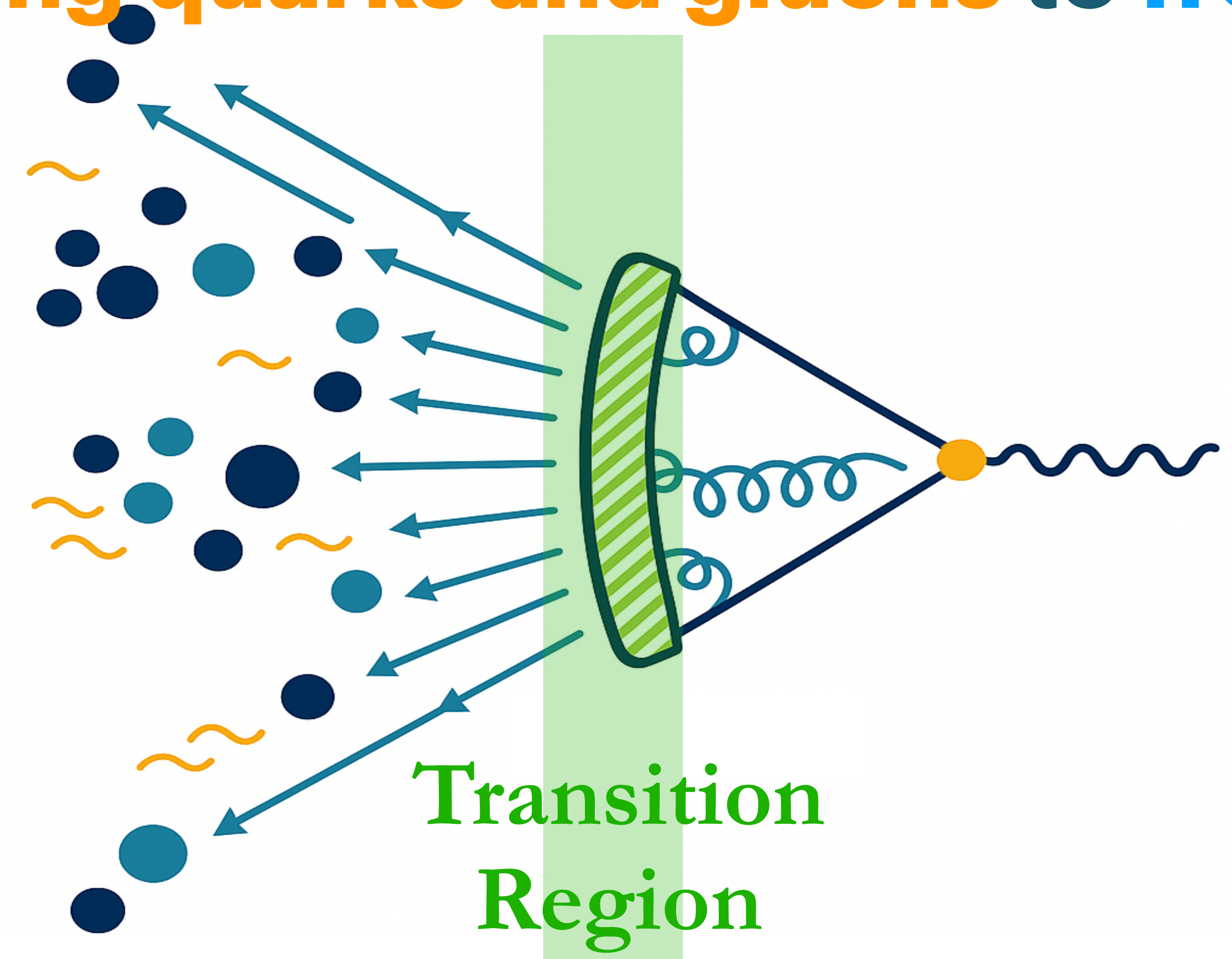
III. Confinement
Dynamics

IV. Heavy Flavor Jets

QUARK GLUON SCALING AND HADRONIZATION

- **Energy correlators allow the hadronization process to be directly imaged inside high energy jets: transition from interacting quarks and gluons to free hadrons is clearly visible!**

$$\theta \sim \frac{\Lambda_{\mathrm{QCD}}}{p_T}$$



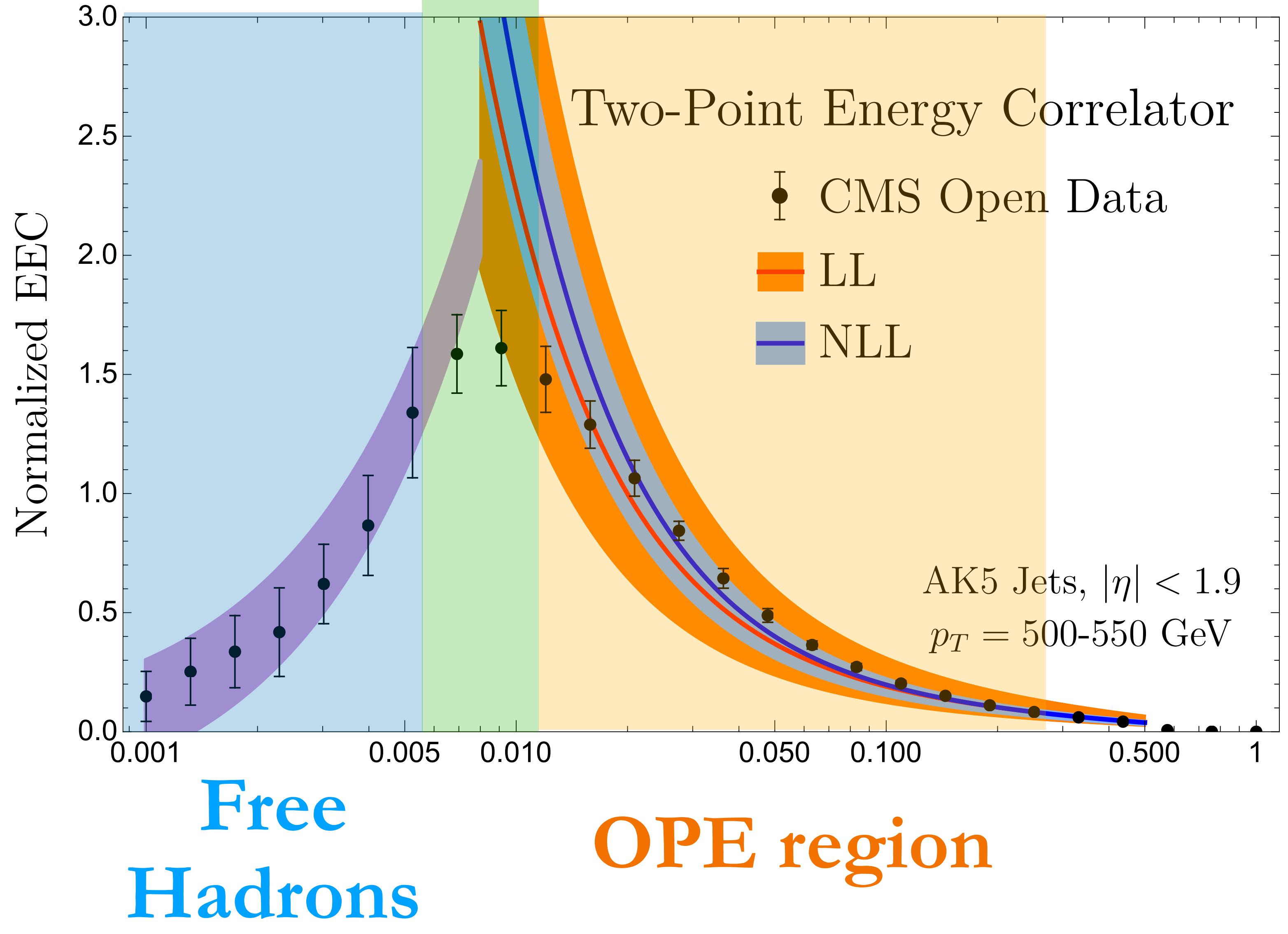
EEC gives angular scale

$$\mu \sim p_T \theta_{ij}$$

Sensitivity to scales of QCD $\Longrightarrow \Lambda_{\mathrm{QCD}}$

Free hadrons

$$\langle \mathcal{E}(\vec{n}_1)\,\mathcal{E}(\vec{n}_2)\cdots\mathcal{E}(\vec{n}_N)\rangle \approx \langle\mathcal{E}\rangle^N = \left(\frac{Q}{\Omega_d}\right)^N$$



OPE region

$$\mathcal{E}(\hat{n}_1)\,\mathcal{E}(\hat{n}_2) \sim \sum \theta^{\gamma(3)-2}\mathbb{O}_i(\hat{n}_1)$$

describes collinear splittings of quarks and gluons

KL, Meçaj, Moult `22
Komiske, Moult, Thaler, Zhu `22

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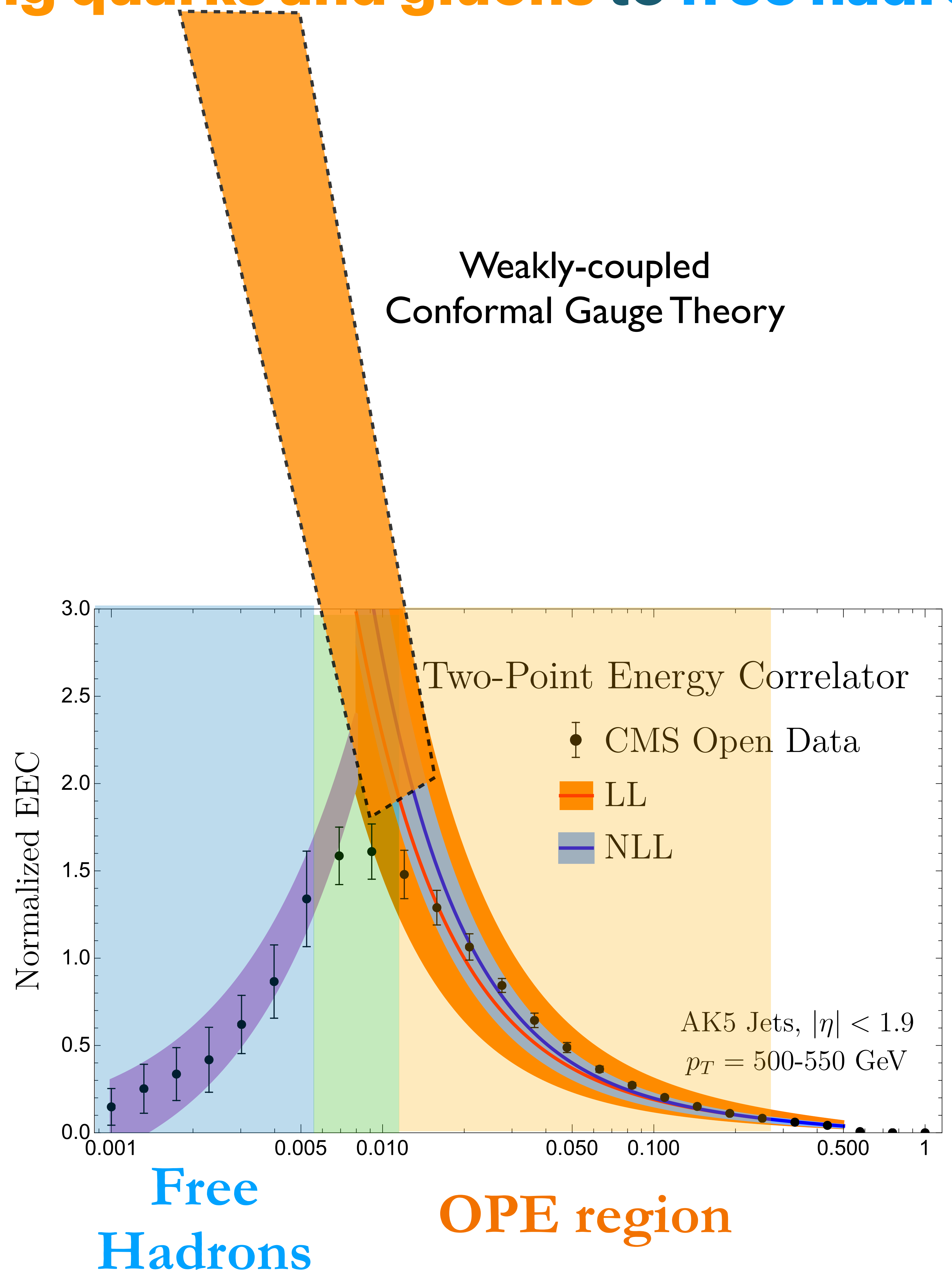

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QUARK GLUON SCALING AND HADRONIZATION

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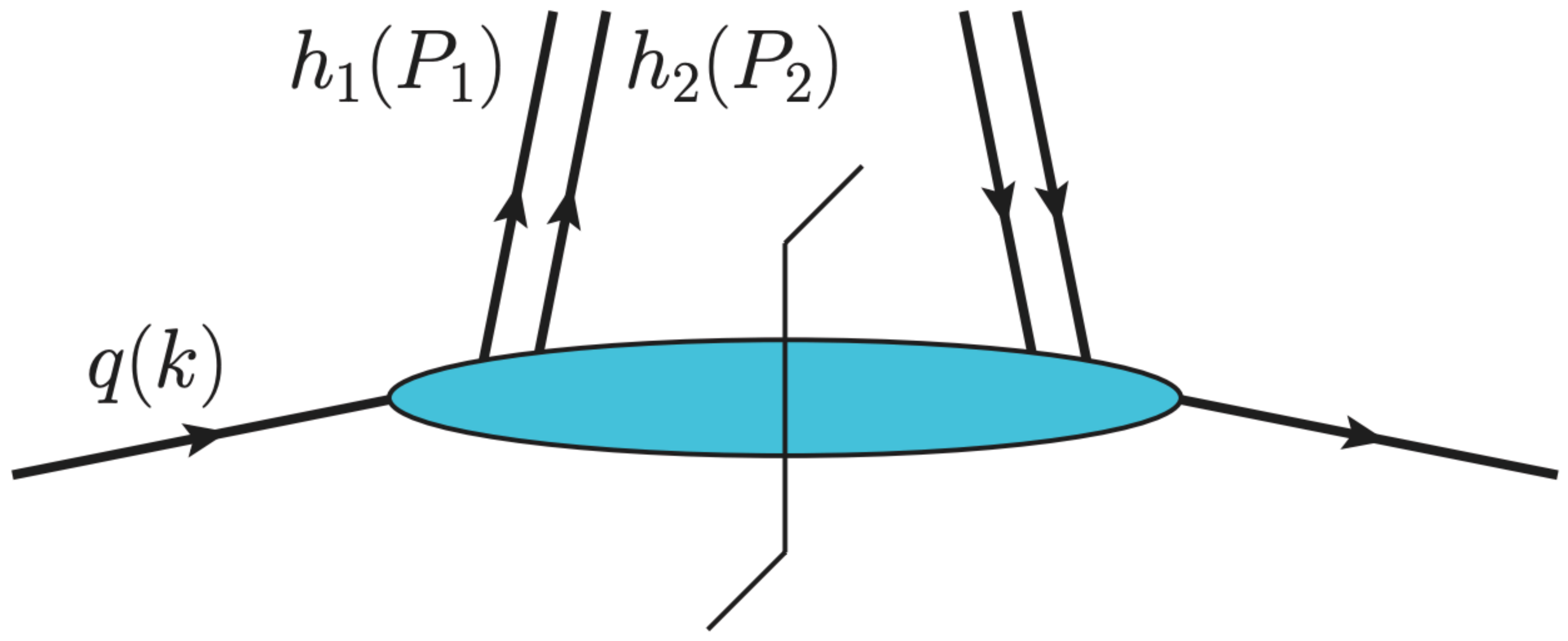
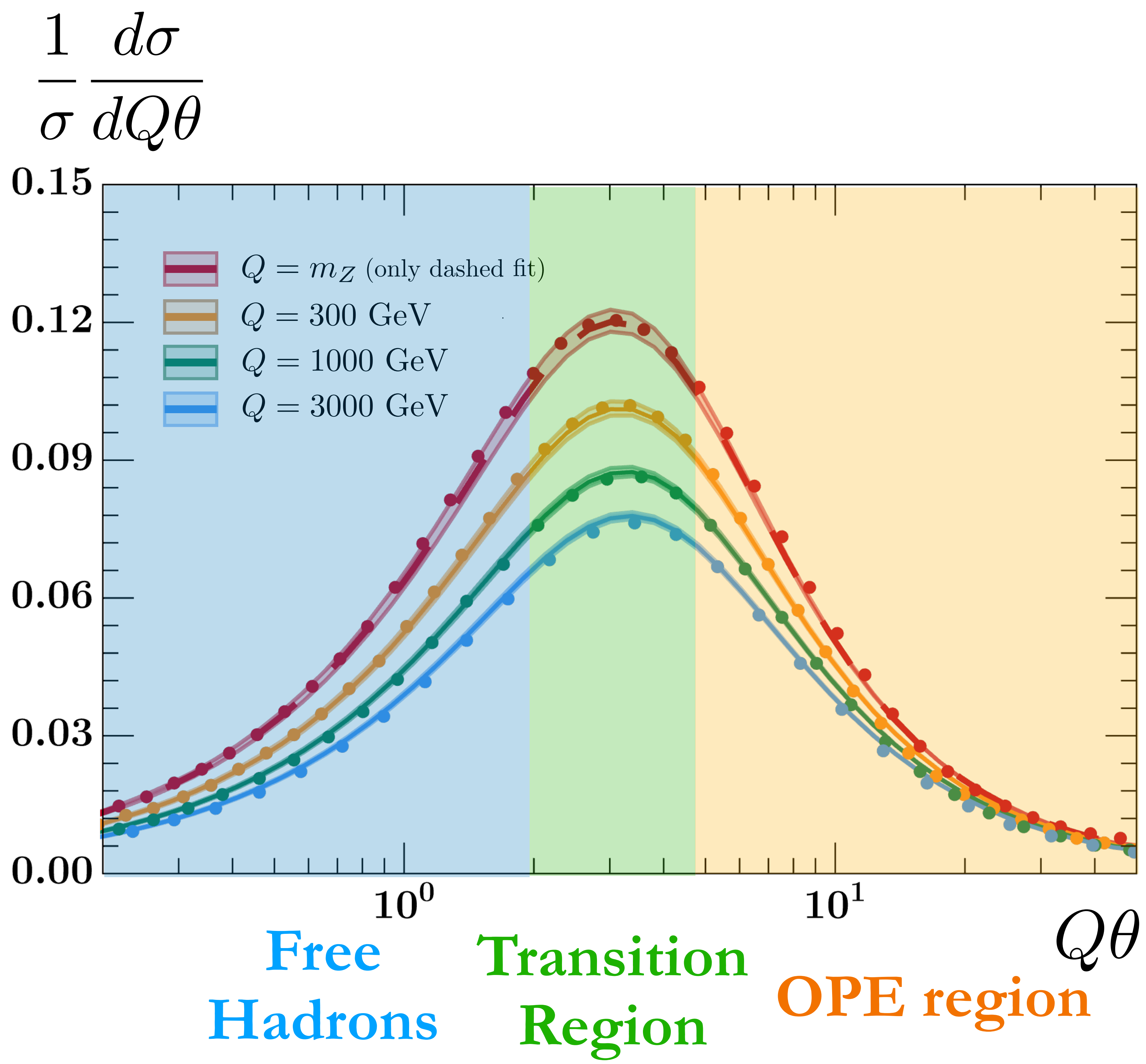
Dihadron fragmentation functions give universal behaviors that describe the transition behavior



KL, Stewart `25
Chang, Chen, Liu, Simmons-Duffin, Yuan, Zhu `25



CONFINEMENT MAGIC AND DETECTORS

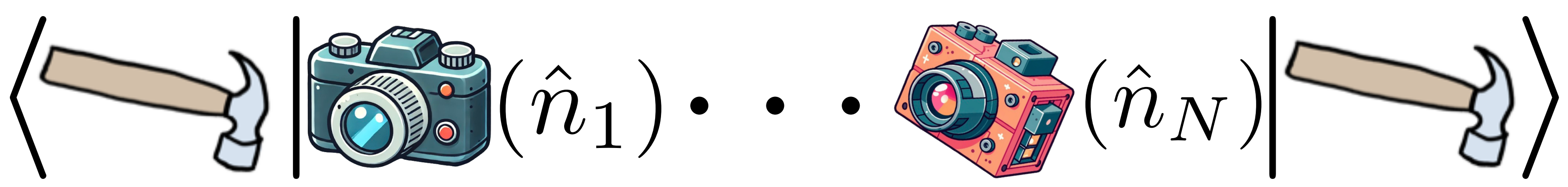
From QFT point of view, what is an ***asymptotic detectors***?

Energy Flow Operators

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

$$\mathcal{E}_{\text{tr}}(\hat{n}), \cdots,$$

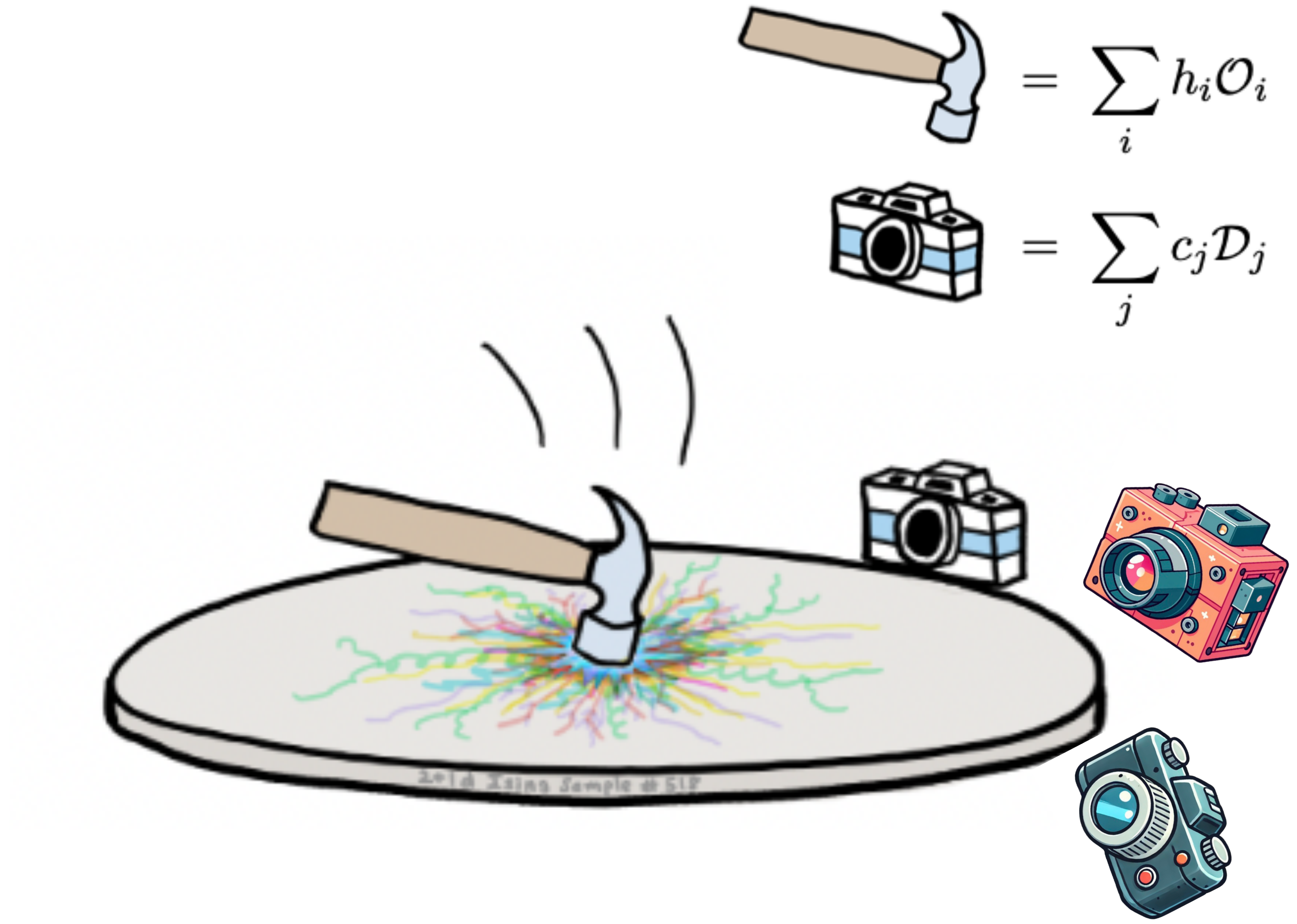
Correlations of general asymptotic detectors



Much interests from various QFTs:

Caron-Huot, Kologlu, Kravchuk, Meltzer, Simmons-Duffin `22
Henriksson, Kravchuk, Oertel `23
Herrmann, Kologlu, Moult `24
Homrich, Simmons-Duffin, Vieira `24
Li, Simmons-Duffin `25
Chang, Chen, Simmons-Duffin, Zhu `25

Critical O(N), Wilson-Fisher, Fishnet CFTs, QCD, …



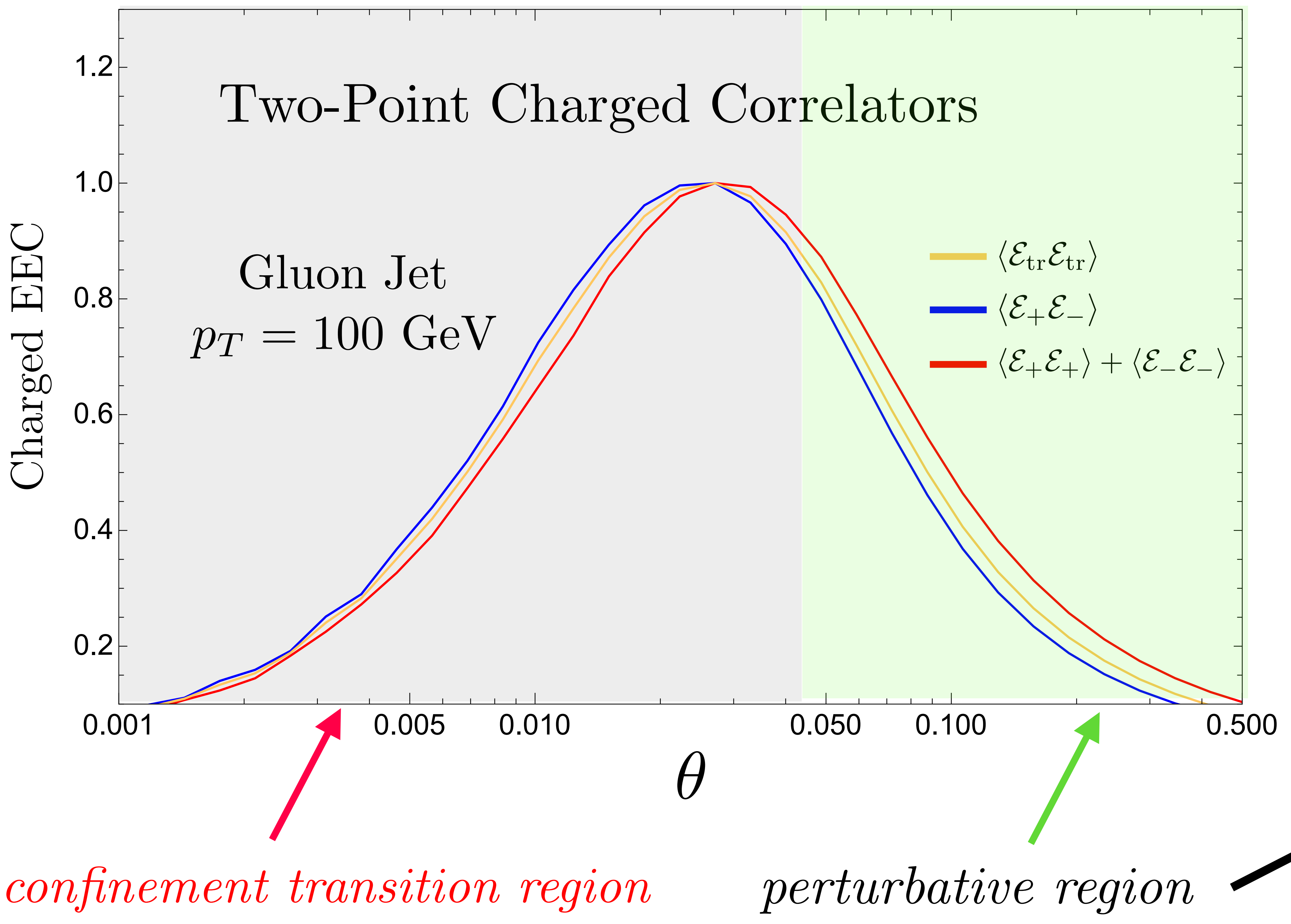
CORRELATION BETWEEN CHARGED HADRONS

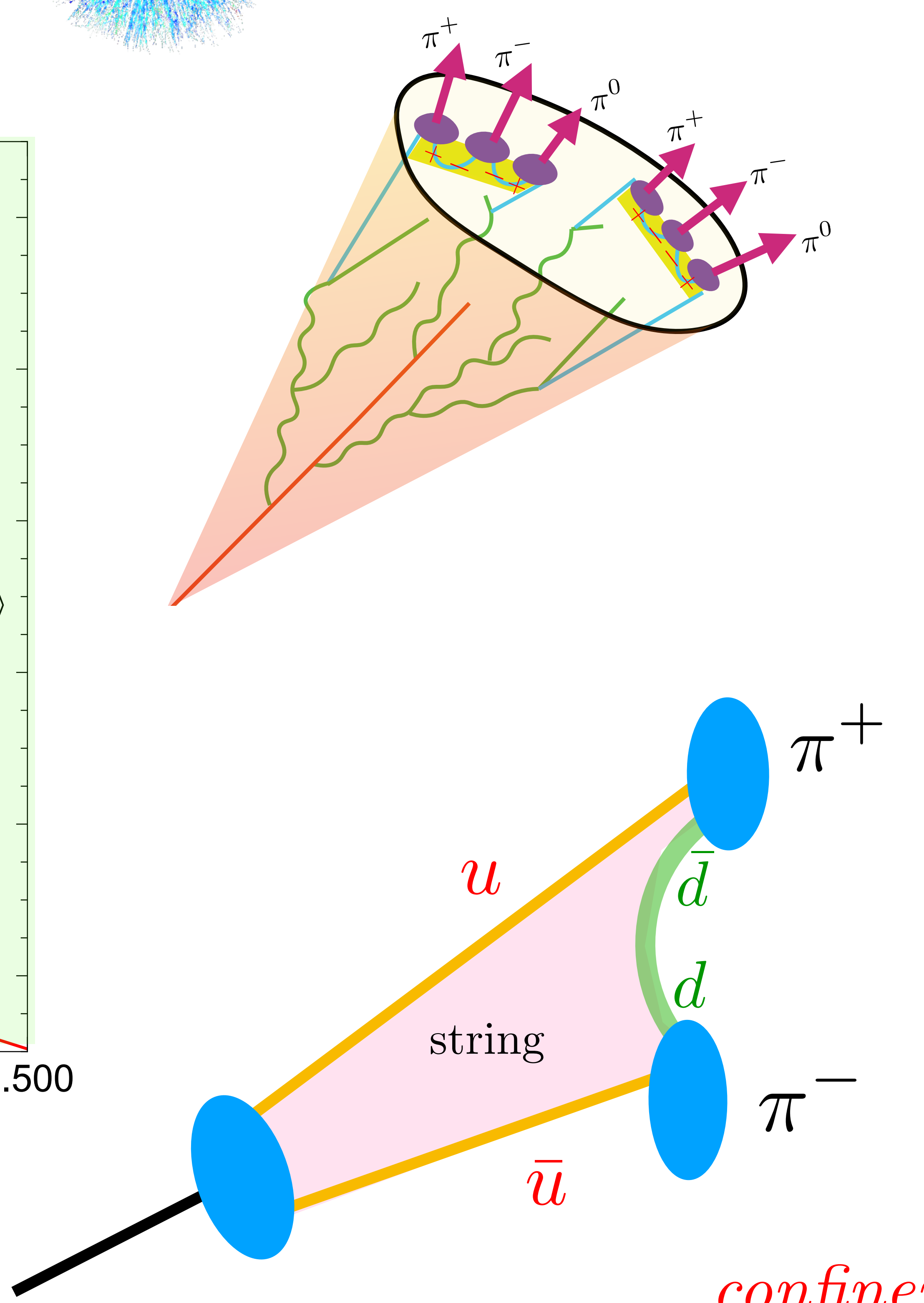
- Unlike-signed charged correlators are correlated more as the angle becomes smaller!

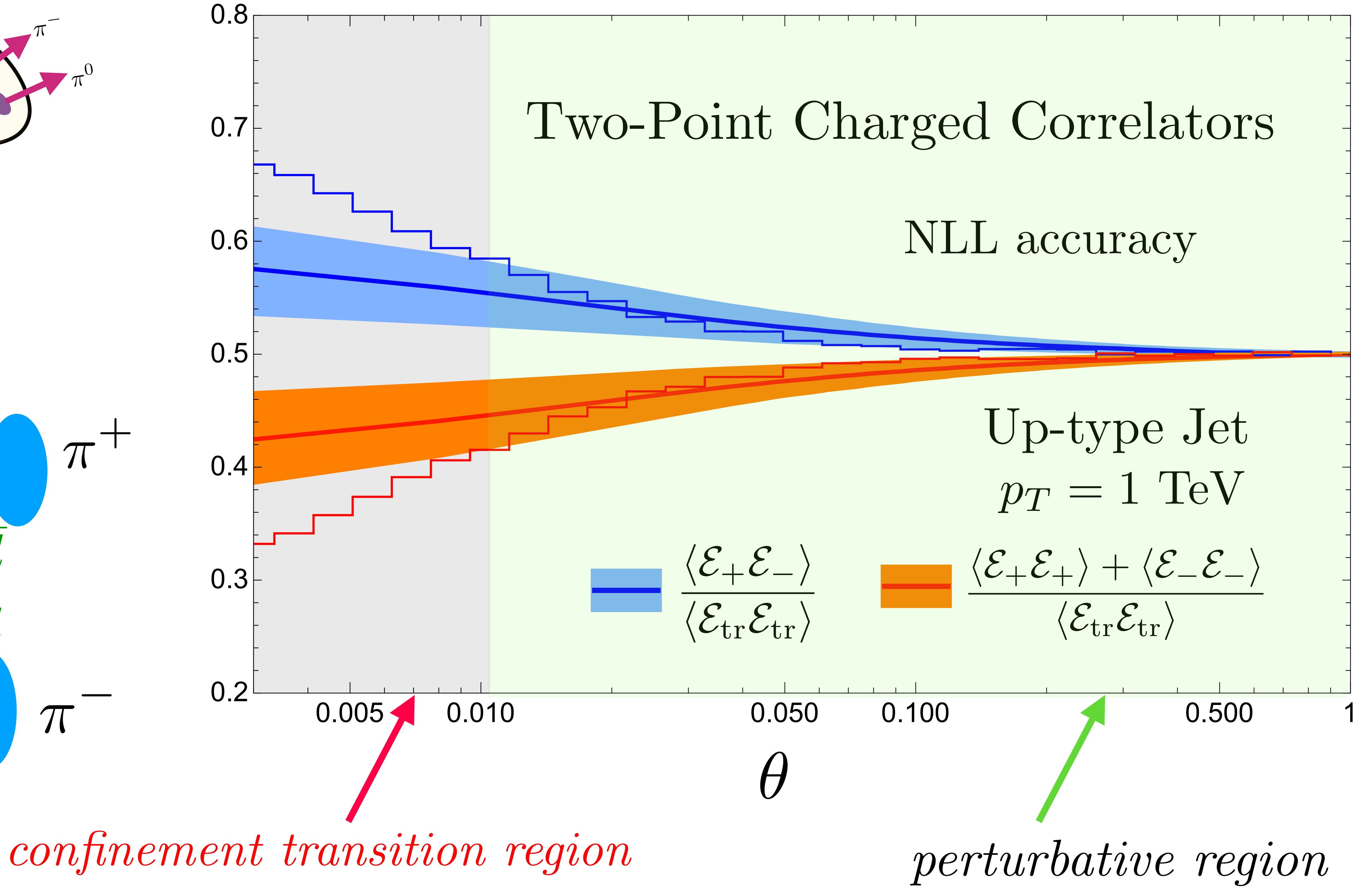
(Recently also measured *STAR `25*) STAR

KL, Moult `23

$$\langle \mathcal{E}_+\mathcal{E}_-\rangle, \langle \mathcal{E}_+\mathcal{E}_+\rangle, \langle \mathcal{E}_-\mathcal{E}_-\rangle$$







- The correlation between unlike-signed hadron pair is expected to grow in string-like hadronization

CORRELATION BETWEEN CHARGED HADRONS

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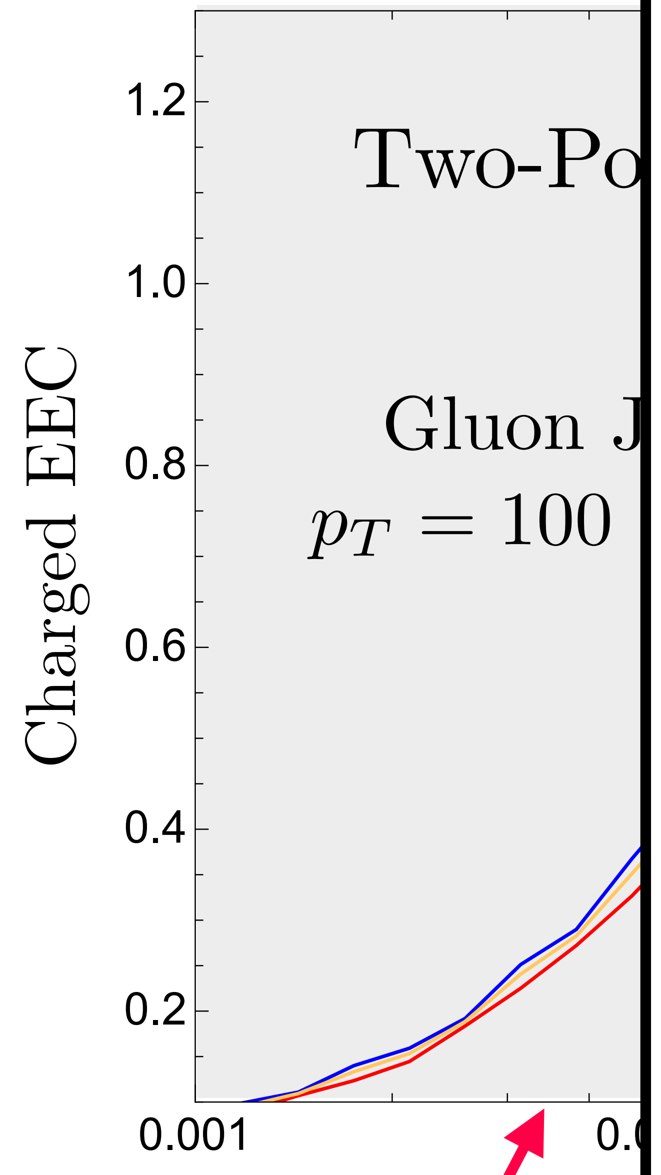
(Recen

`23

$\mathcal{E}_-\mathcal{E}_-\rangle$



Probing Confinement with energy correlators

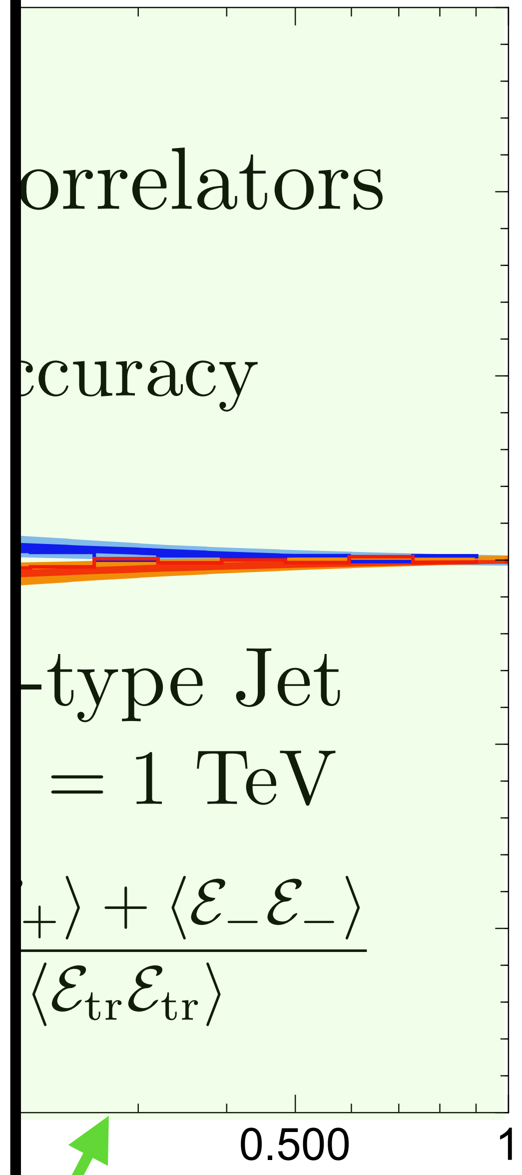
(Backup slides)

I. Measuring flavor correlations $\langle \mathcal{E}_{K^+}(\vec{n}_1)\mathcal{E}_{\pi^-}(\vec{n}_2)\rangle$

KL, Moult, Song, Sterman [In Progress]

II. Measuring spin correlations $\langle \mathcal{E}_{\uparrow}(\vec{n}_1)\mathcal{E}_{\uparrow}(\vec{n}_2)\rangle$

Kuk, KL, Michel, Sun `25



θ $\bar{u}$ θ

confinement transition region *perturbative region* *confinement transition region* *perturbative region*

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(Recen `23

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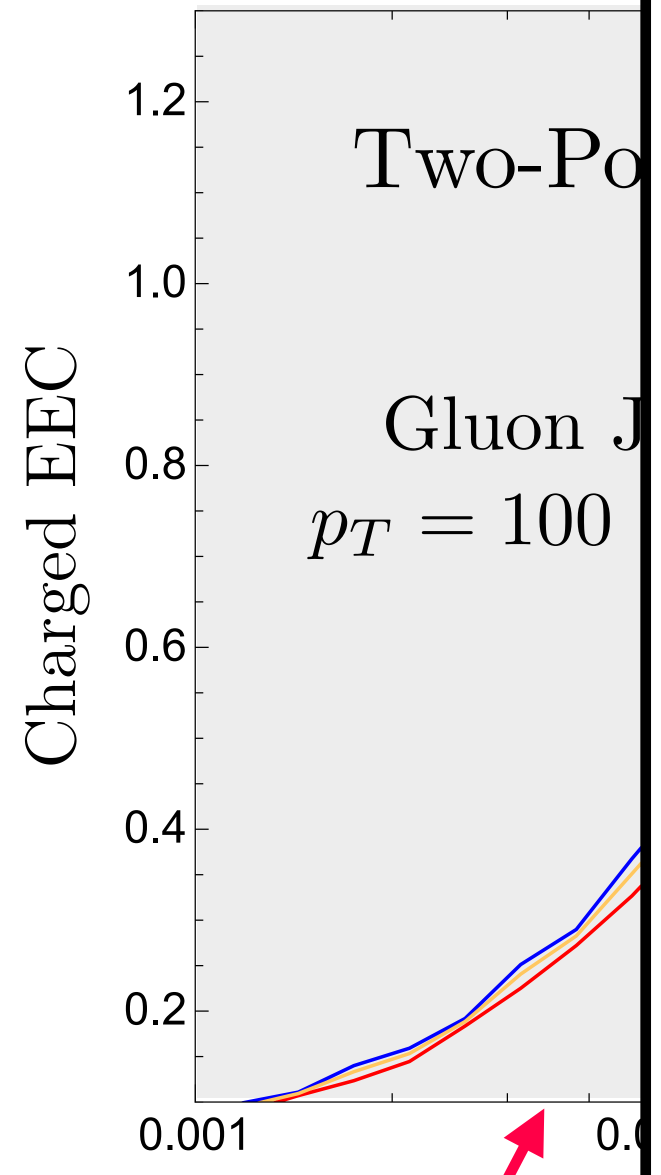

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KL, Moult, Song, Sterman [In Progress]

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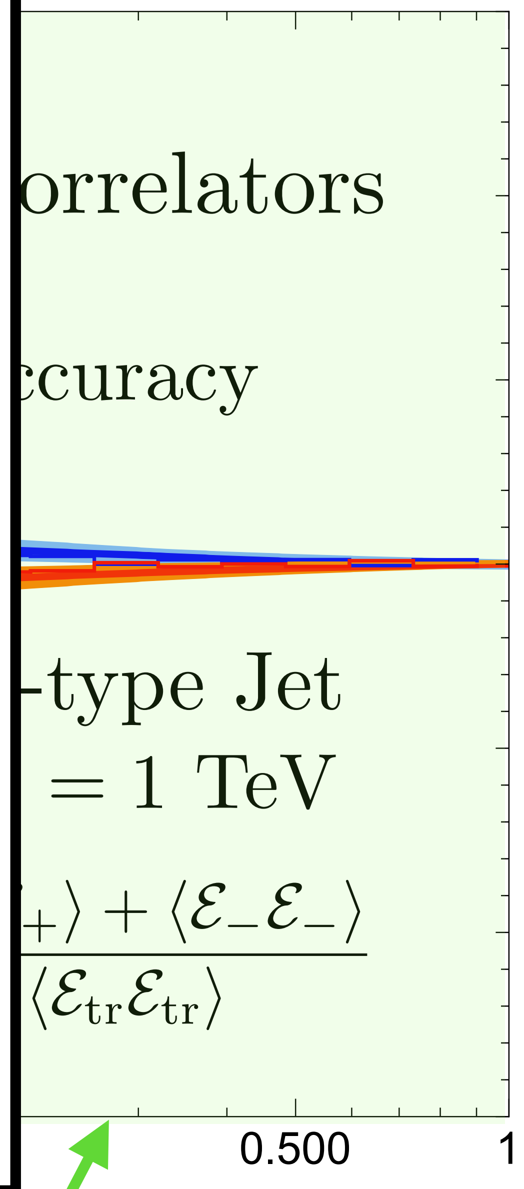
Kuk, KL, Michel, Sun `25

Explore different correlations to unlock confinement!



θ $\bar{u}$ θ

confinement transition region *perturbative region* *confinement transition region* *perturbative region*

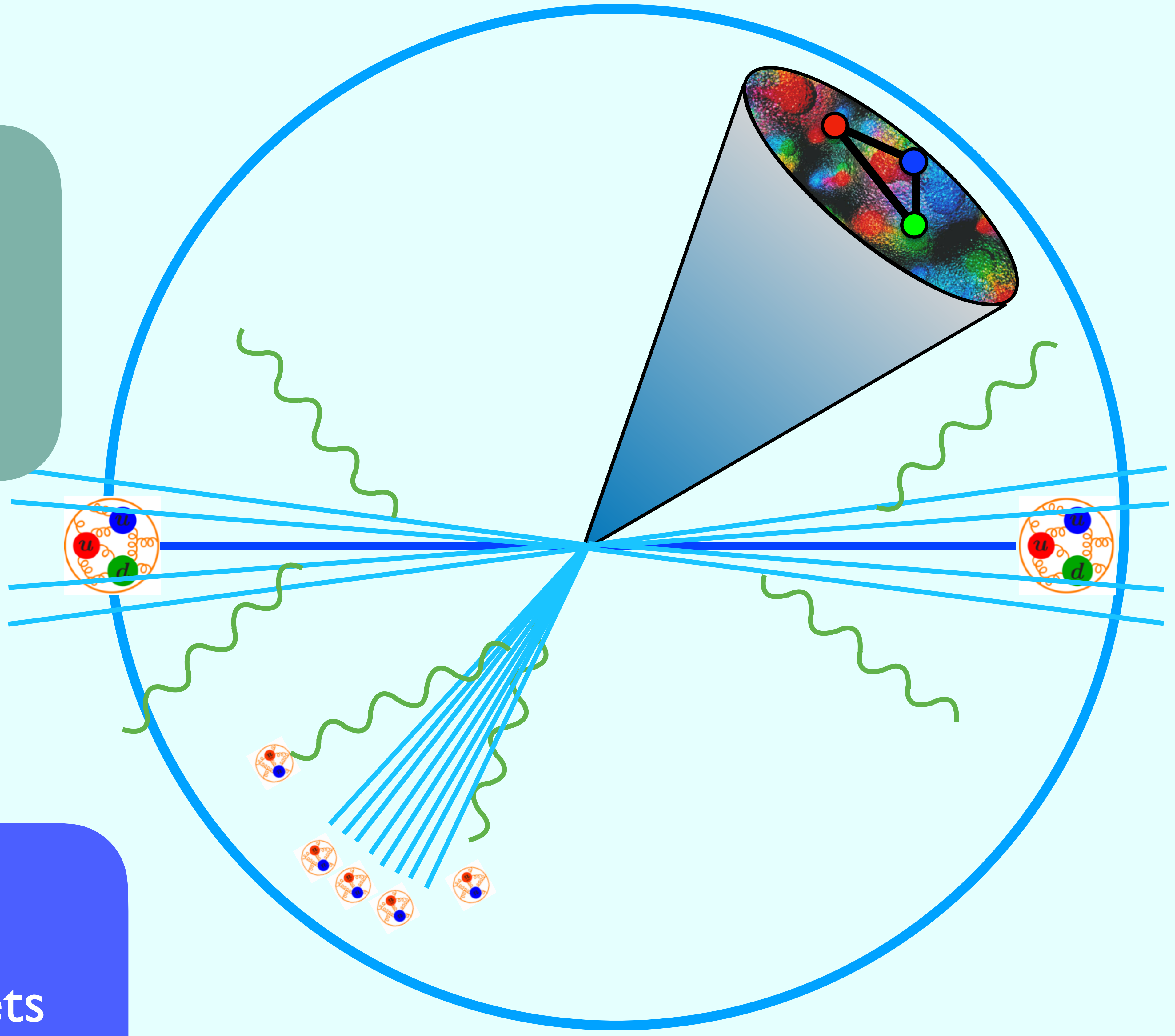
- **The correlation between unlike-signed hadron pair is expected to grow in string-like hadronization**

Overview

I. Universal Scaling

II. Precision SM

V. Electroweak and New physics



III. Confinement Dynamics

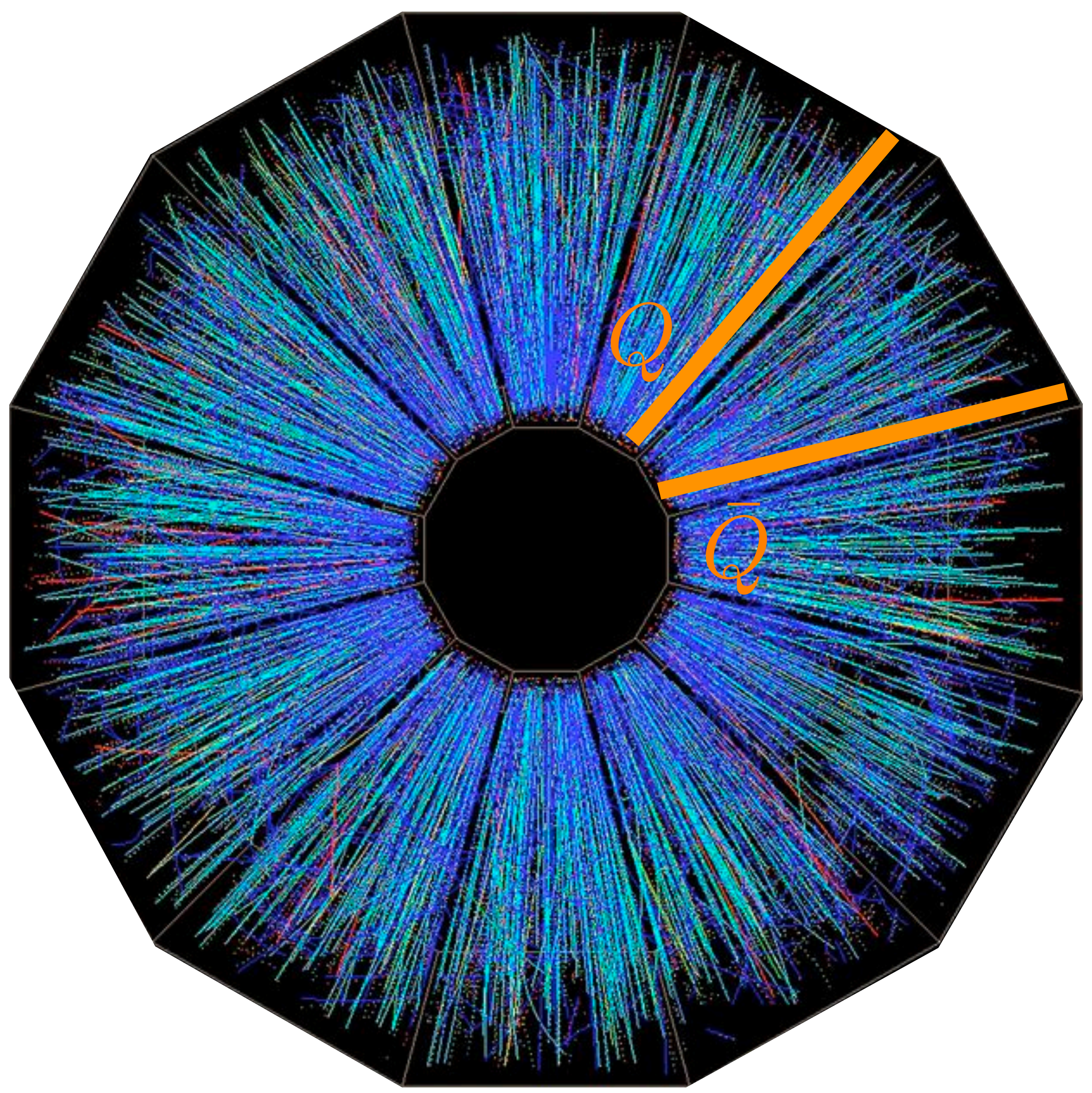
IV. Heavy Flavor Jets

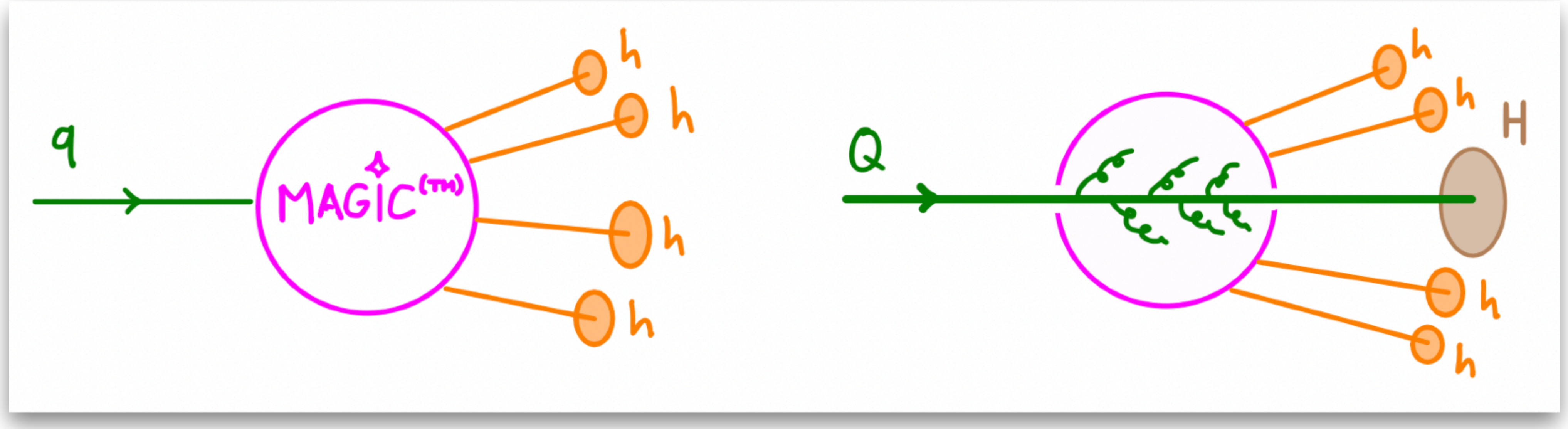
Can we improve our understanding of the heavy flavor scale in jets?

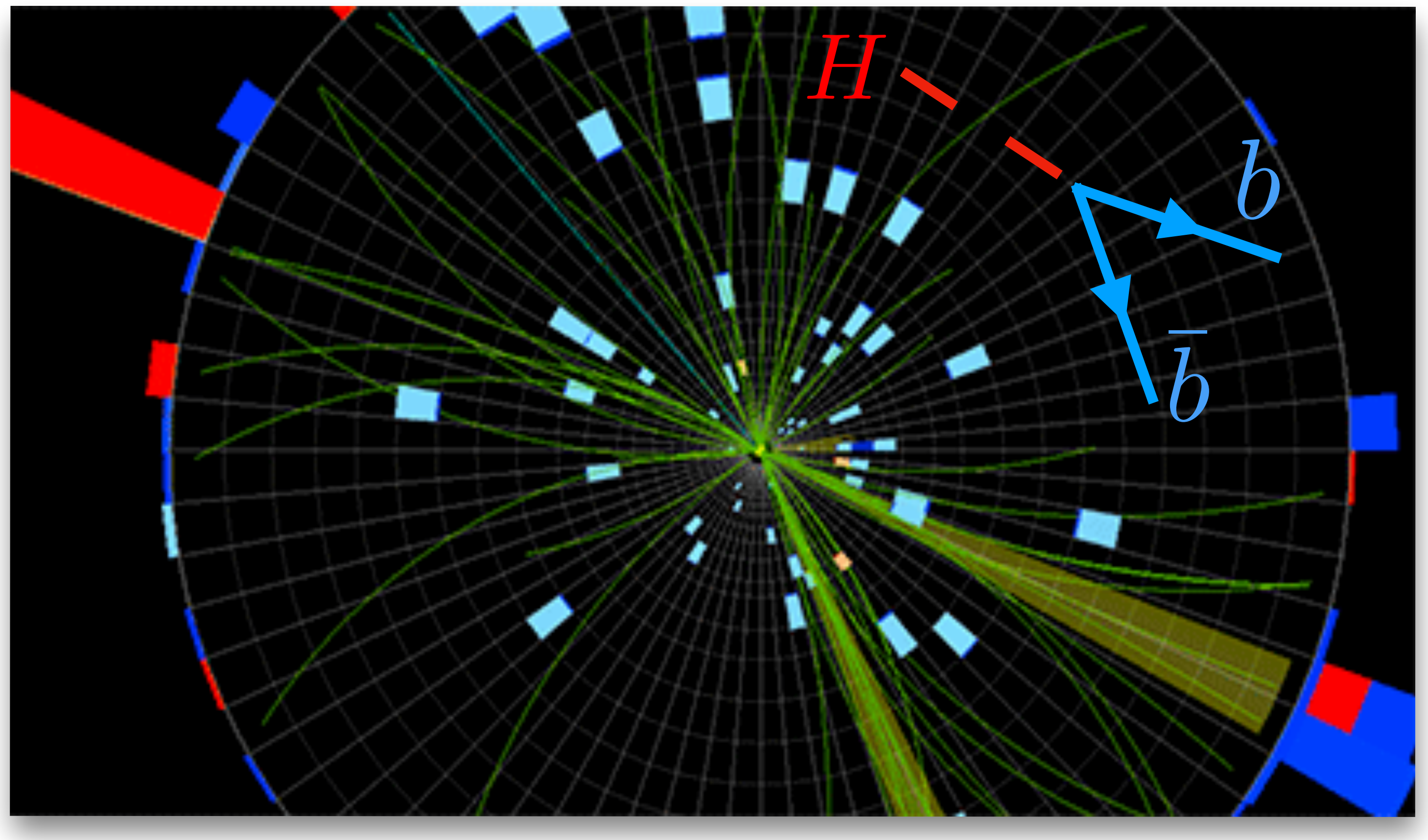
UNRAVELING HEAVY FLAVOR DYNAMICS

- **Heavy quark dynamics** are important for understanding **medium, hadronization, Higgs, BSM searches, flavor tagging, gluon structure, etc.**

Fickinger, Fleming, Kim, Mereghetti `16
Kang, Ringer, Vitev `17
Li, Vitev `18
Lee, Shrivastava, Vaidya `19
Attems, Brewer, et al `22
von Kuk, Michel, Sun `23
…







- **Two-point correlators give access to an angular scale** $\mu \sim p_T \theta_{ij}$

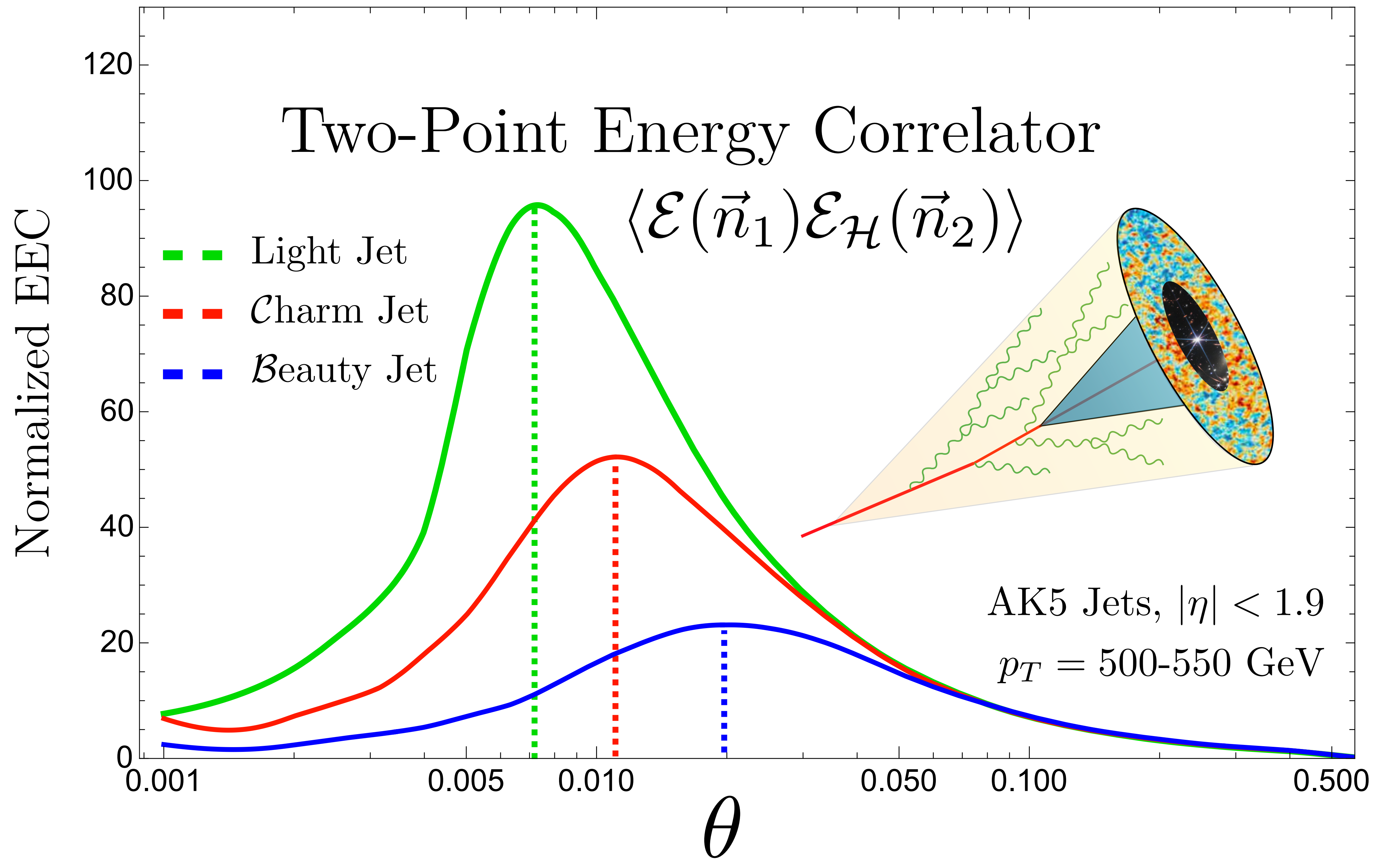
This gives sensitivity to scales of QCD $\Longrightarrow \Lambda_{\rm QCD}, m_Q, \cdots$

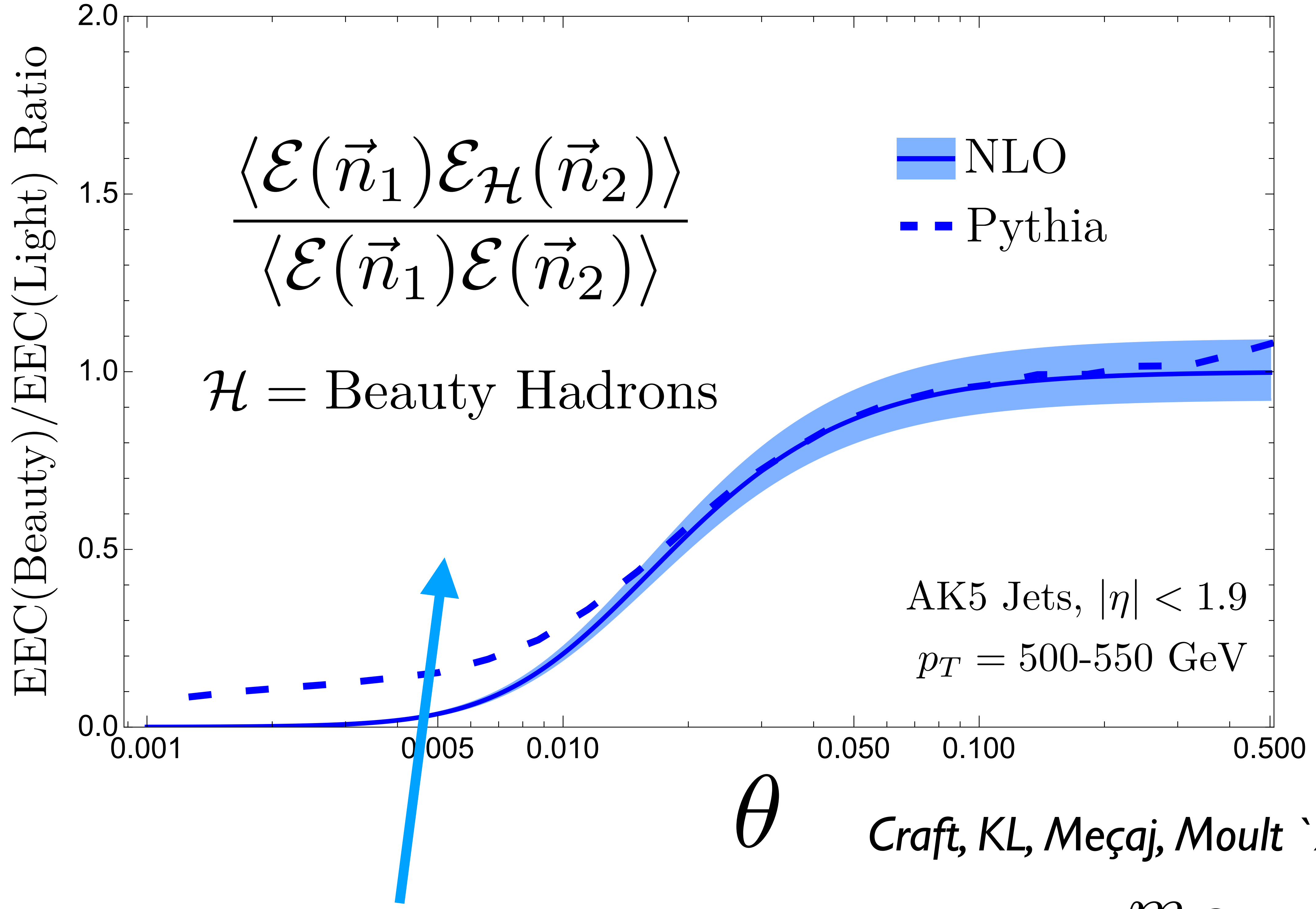
BEAUTIFUL AND CHARMING CORRELATORS

- **Two-point correlators capture the effects of intrinsic mass of heavy quarks**

Heavy Flavor Energy Flow Operator :

$$\mathcal{E}_{\mathcal{H}}(\hat{n})|X\rangle = \sum_{h\in H,\bar{H}} E_h \delta^2(\Omega_{\vec{p}_h} - \Omega_{\hat{n}})|X\rangle$$



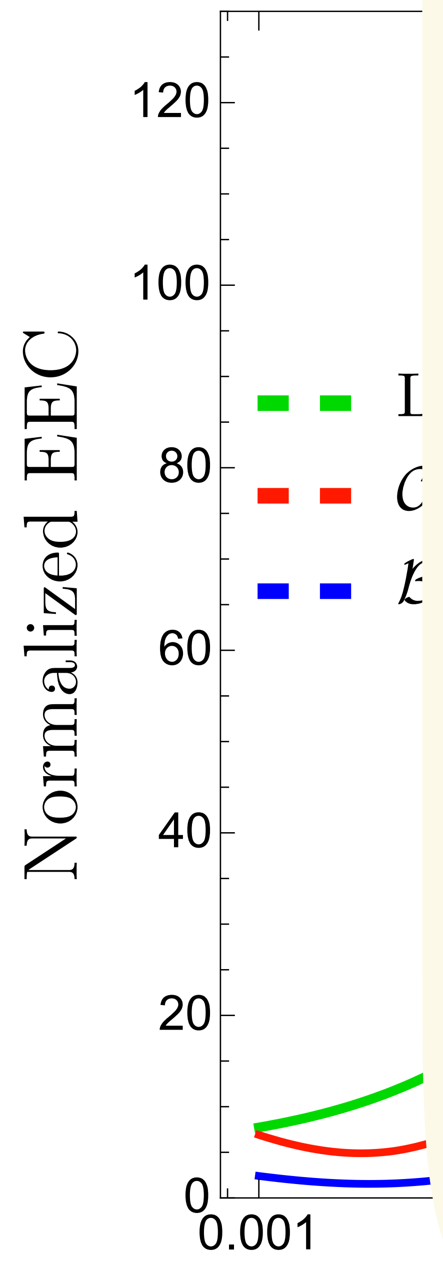


Craft, KL, Meçaj, Moult `22

- **Ratio of the two-point correlators clearly shows the dead-cone region around** $\theta \lesssim \frac{m_Q}{E}$

BEAU… …ORS

- **Two-poi…**

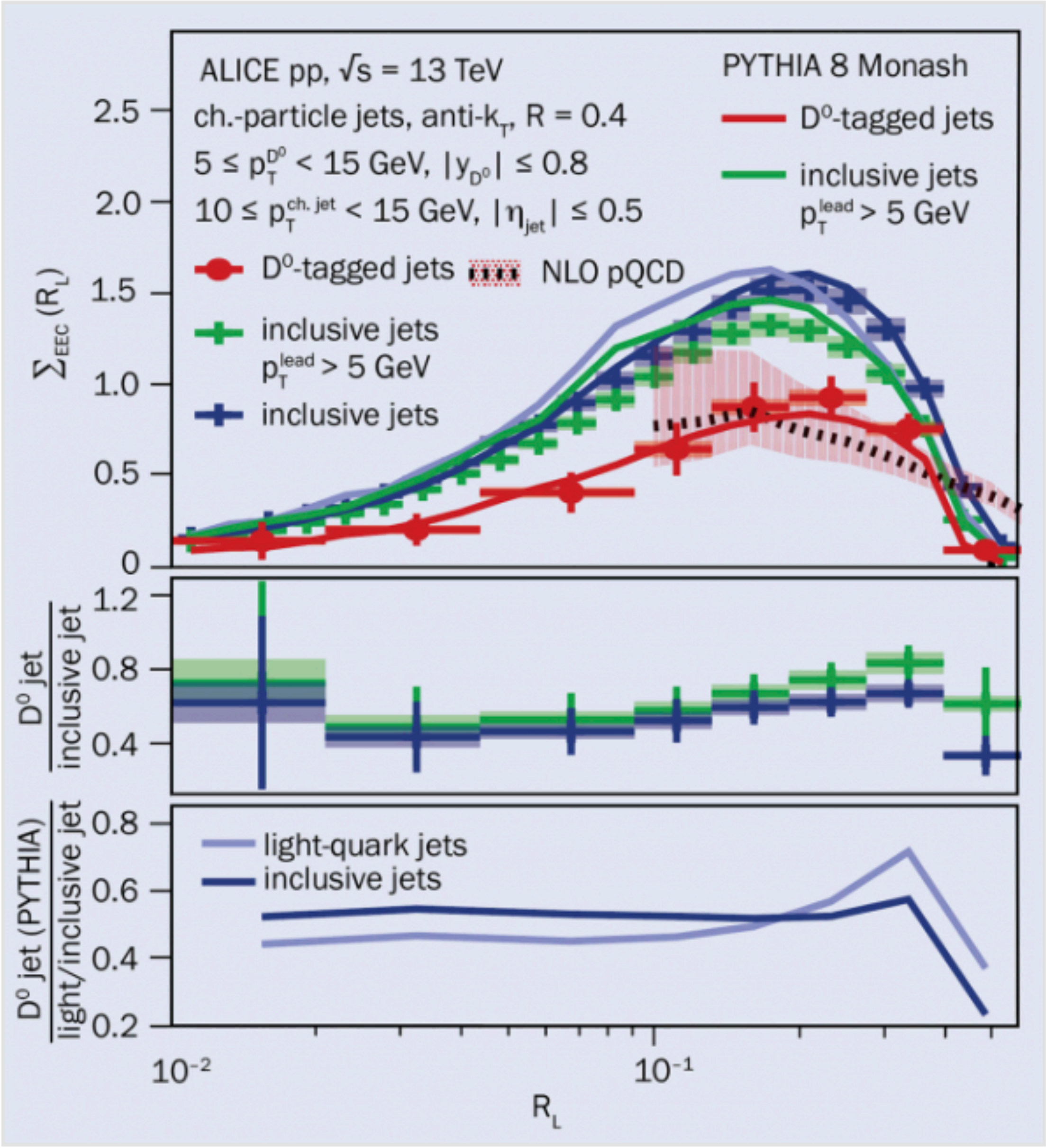


STRONG INTERACTIONS | NEWS

Charming energy–energy correlators

9 September 2025

A report from the ALICE experiment.

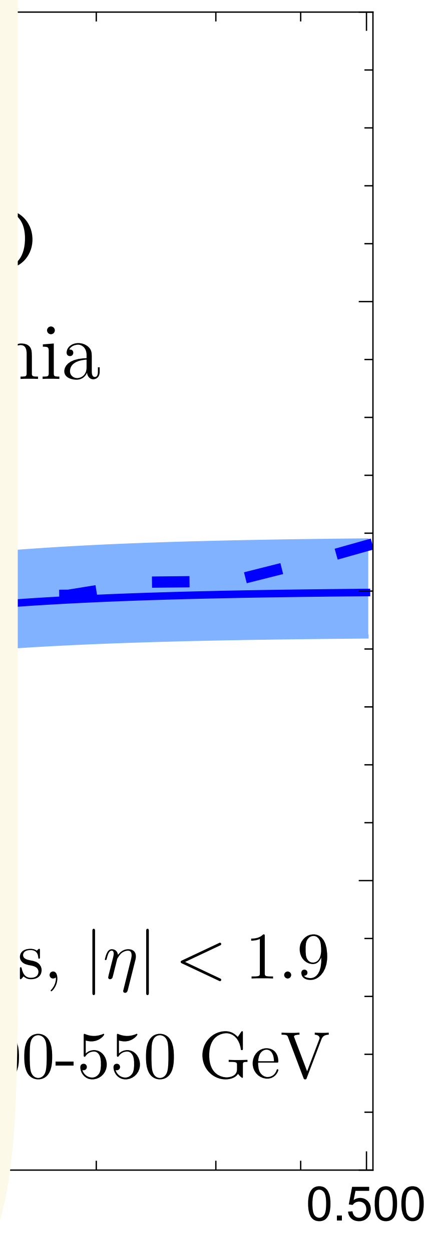


ALICE

Narrow sprays of particles called jets erupt from high-energy quarks and gluons. The ALICE collaboration has now measured so-called energy–energy correlators (EECs) of charm-quark jets for the first time – revealing new details of the elusive "dead cone" effect.

Unlike in quantum electrodynamics, the quantum chromodynamics (QCD) coupling constant gets weaker at higher energies – a feature known as asymptotic freedom. This

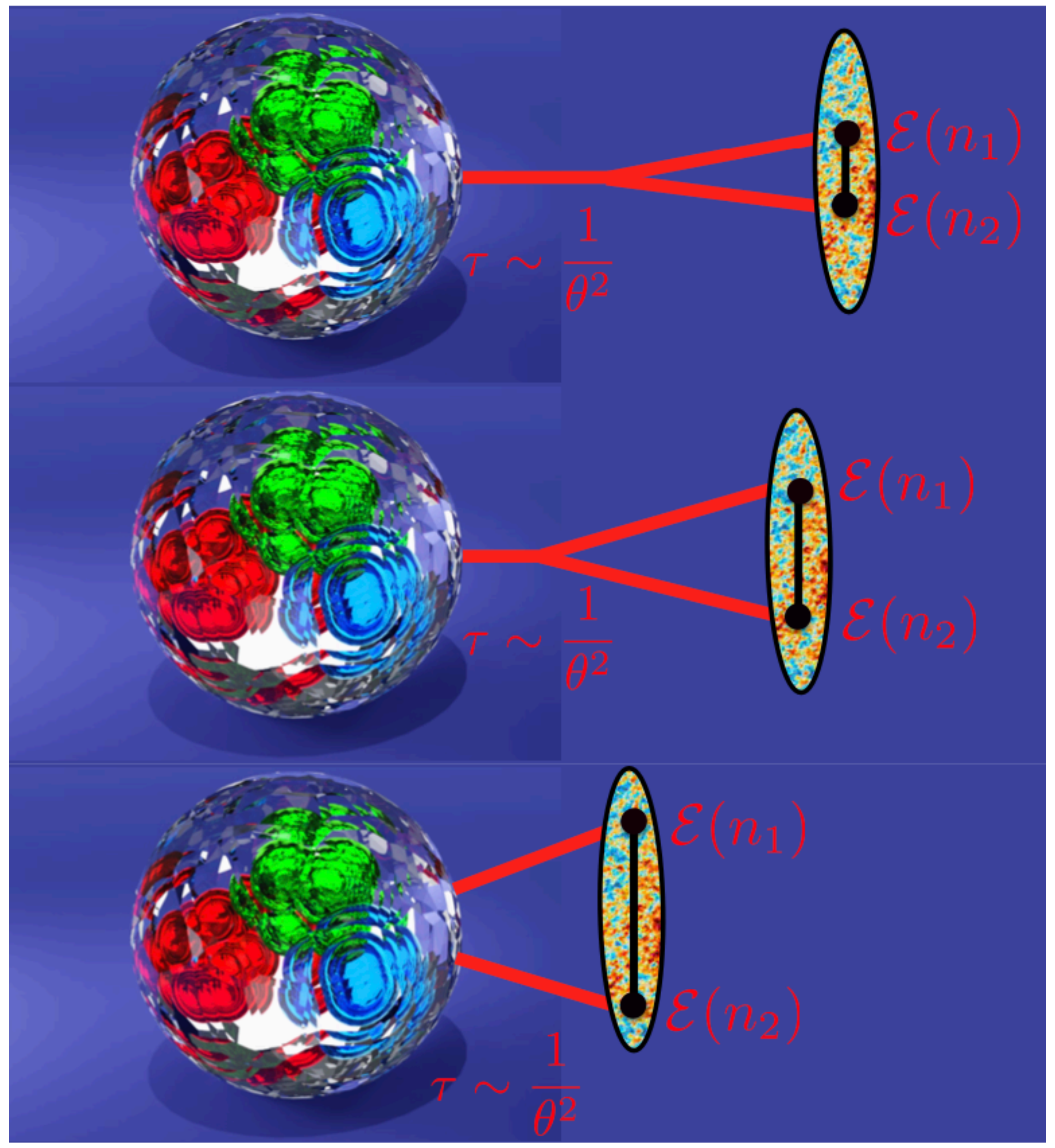
ALICE `25

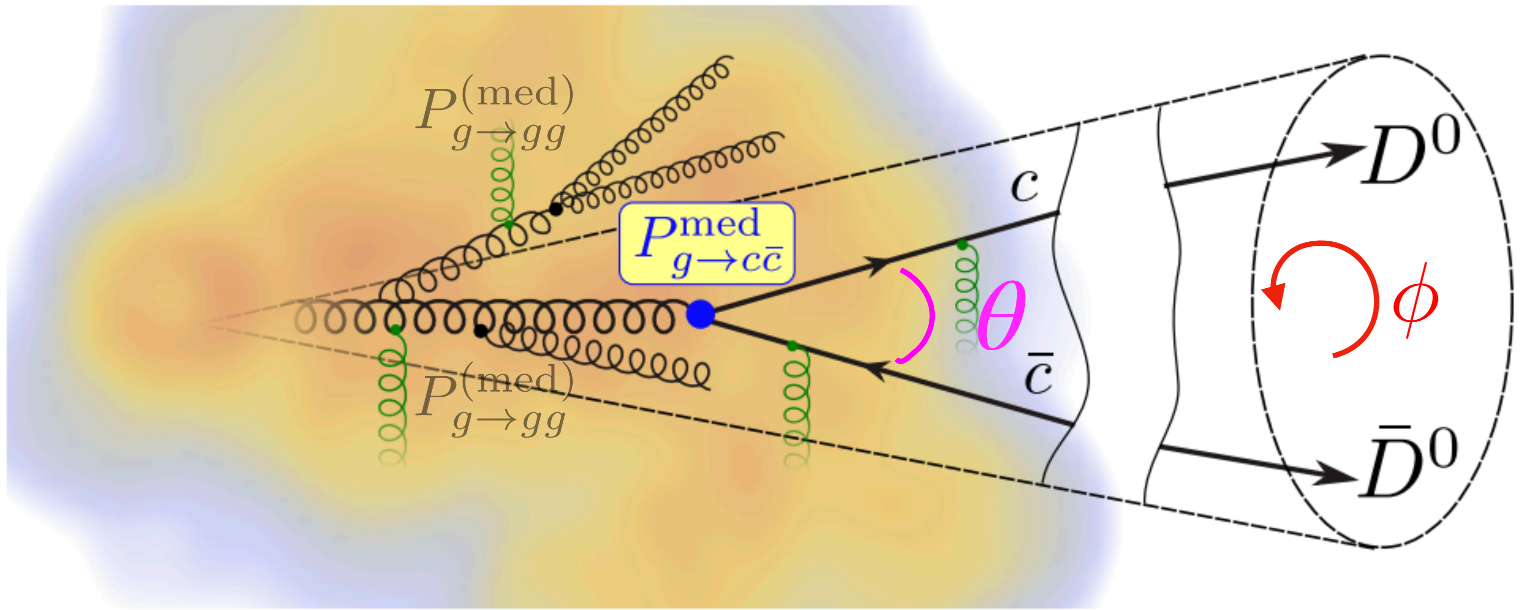


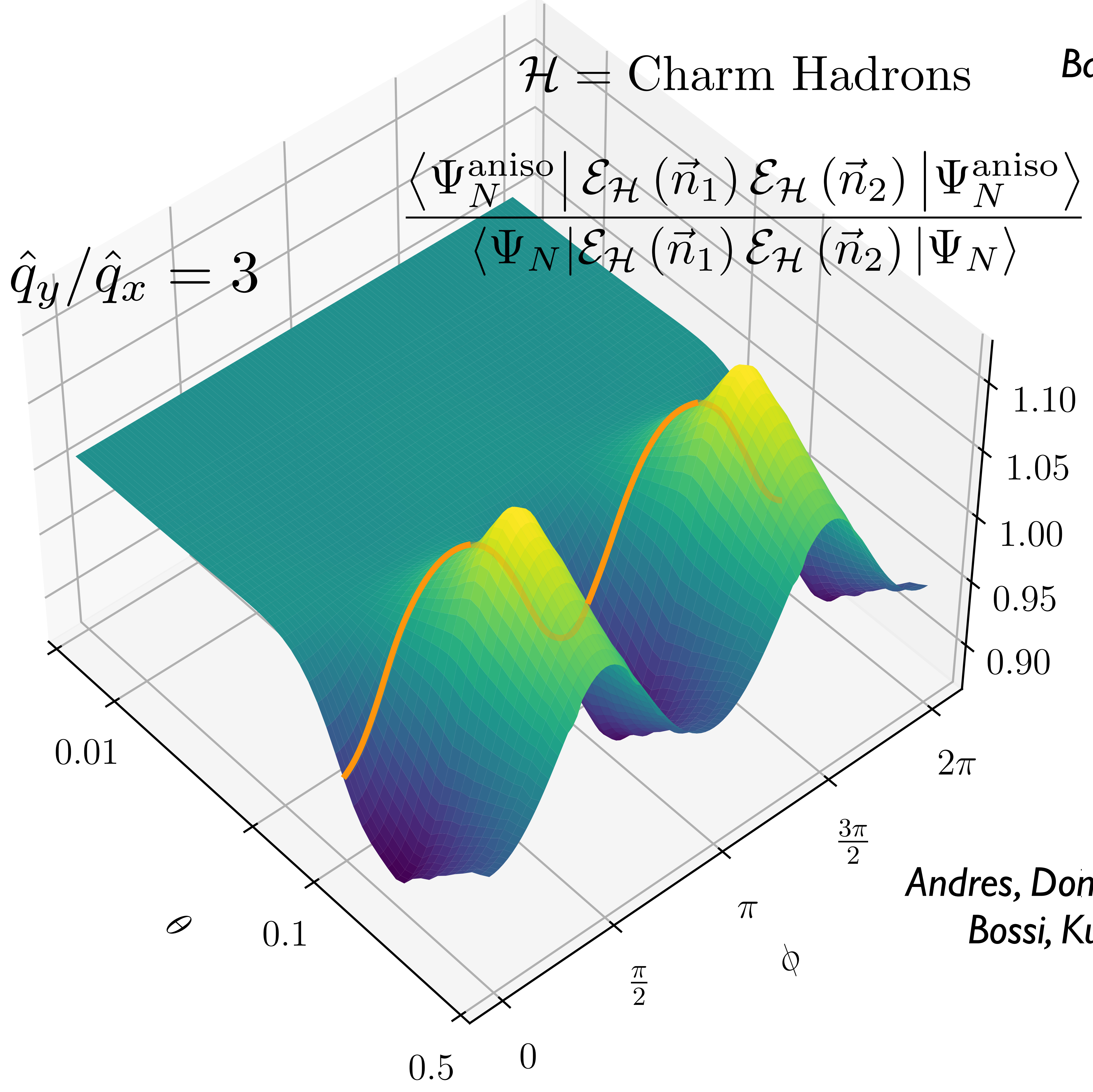
L, Meçaj, Moult `22

- **Ratio of the two-point correlators clearly shows the dead-cone region around** $\theta \lesssim \frac{m_Q}{E}$

BONUS: RESOLVING THE QGP USING HEAVY FLAVOR ENERGY CORRELATORS







Barata, Brewer, KL, Silva `25

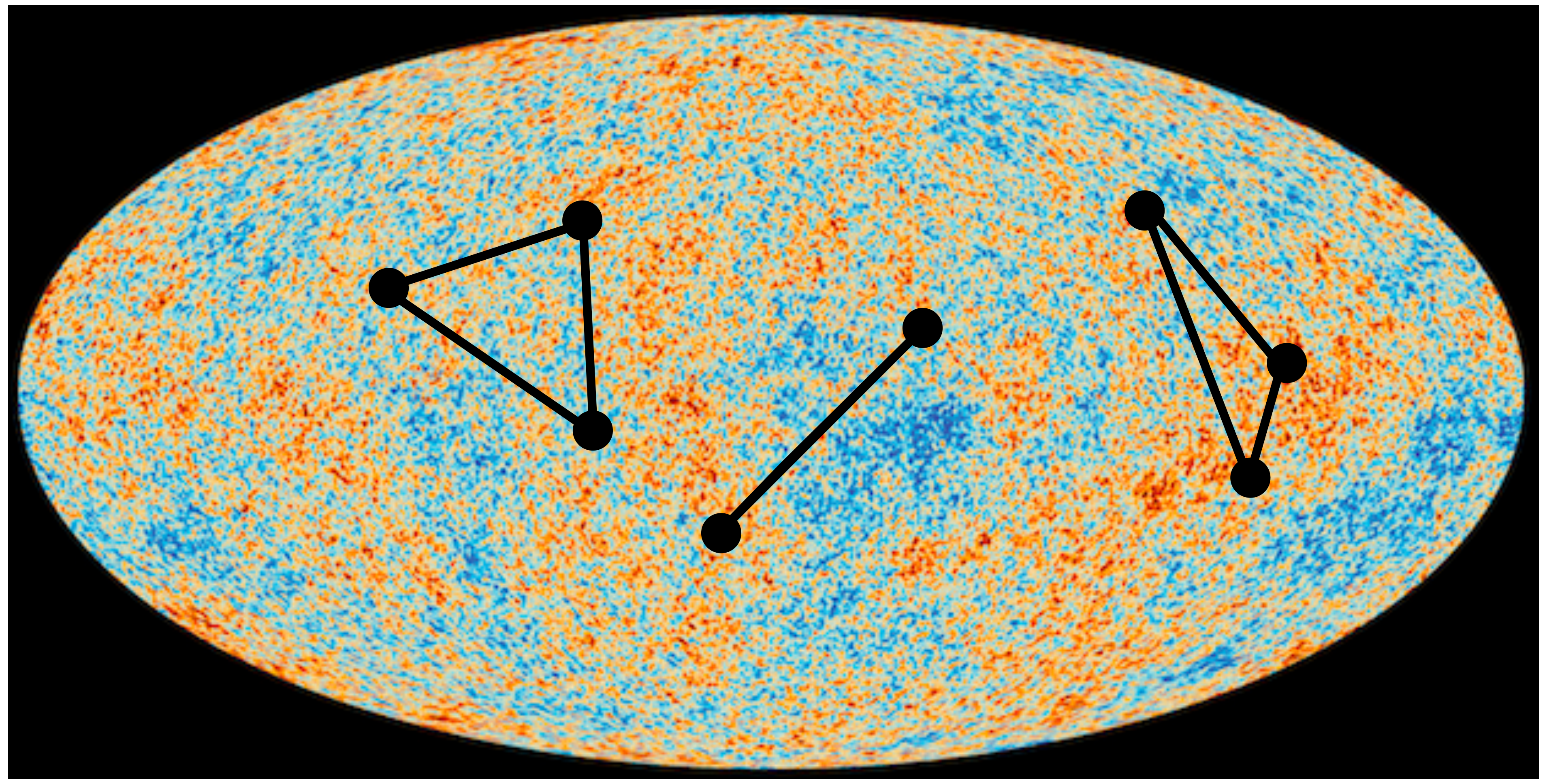
See also

Andres, Dominguez, Holguin, Marquet, Moult `23,24
Bossi, Kudinoor, Moult, Pablos, Rai, Rajagopal `24
Barata, Kang, Mayo, Penttala `24
...
CMS `25

- **Heavy flavor EEC allow gluon to heavy flavor splitting to be isolated**

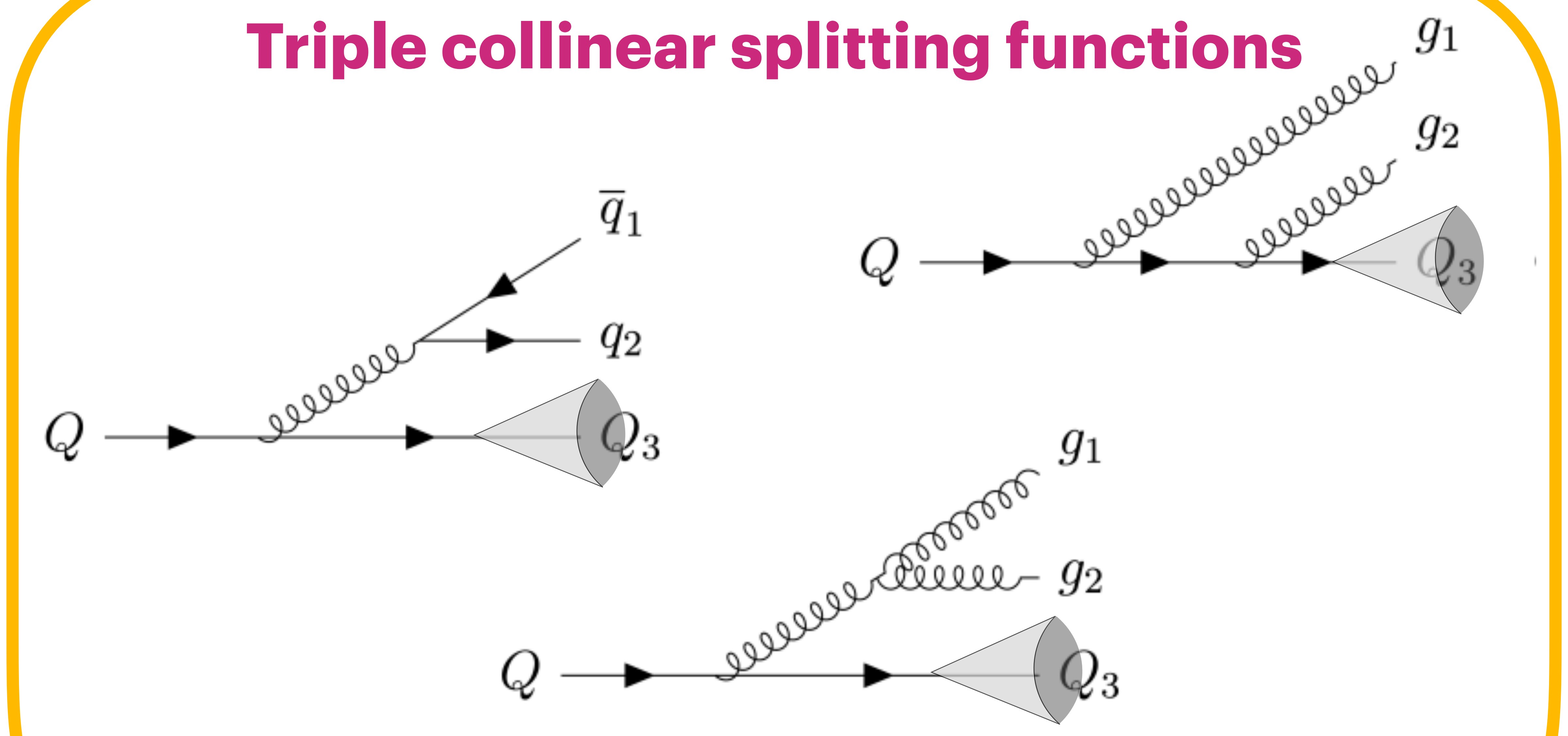
HIGHER POINT CORRELATORS

- **Higher-point correlators probe more detailed aspects of interactions**



Maldacena `02

Triple collinear splitting functions



$\Longrightarrow$ ***Can now compute 3-point correlations!***

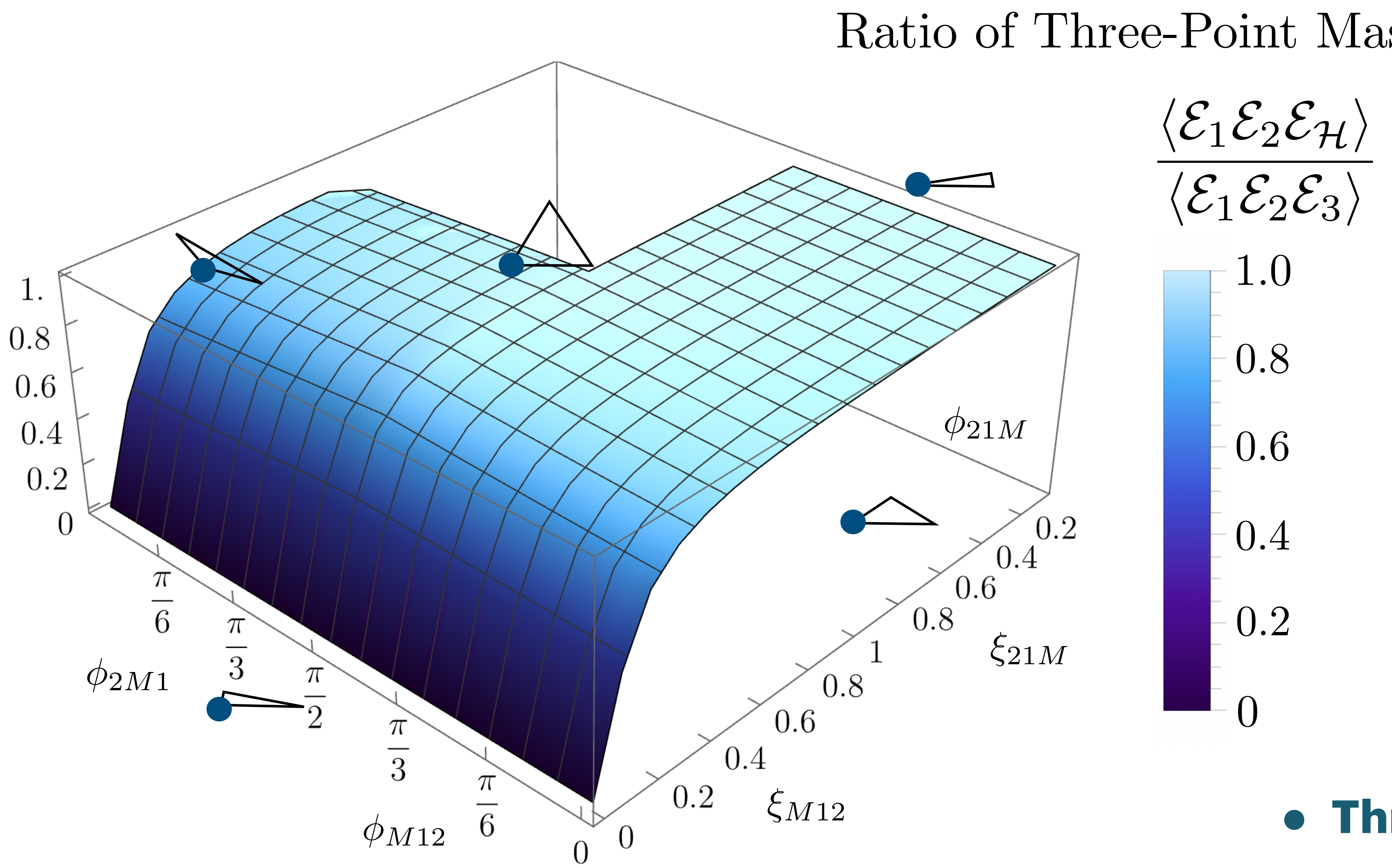
Craft, Gonzalez, KL, Meçaj, Moult `23
Dhani, Rodrigo, Sborlini `23

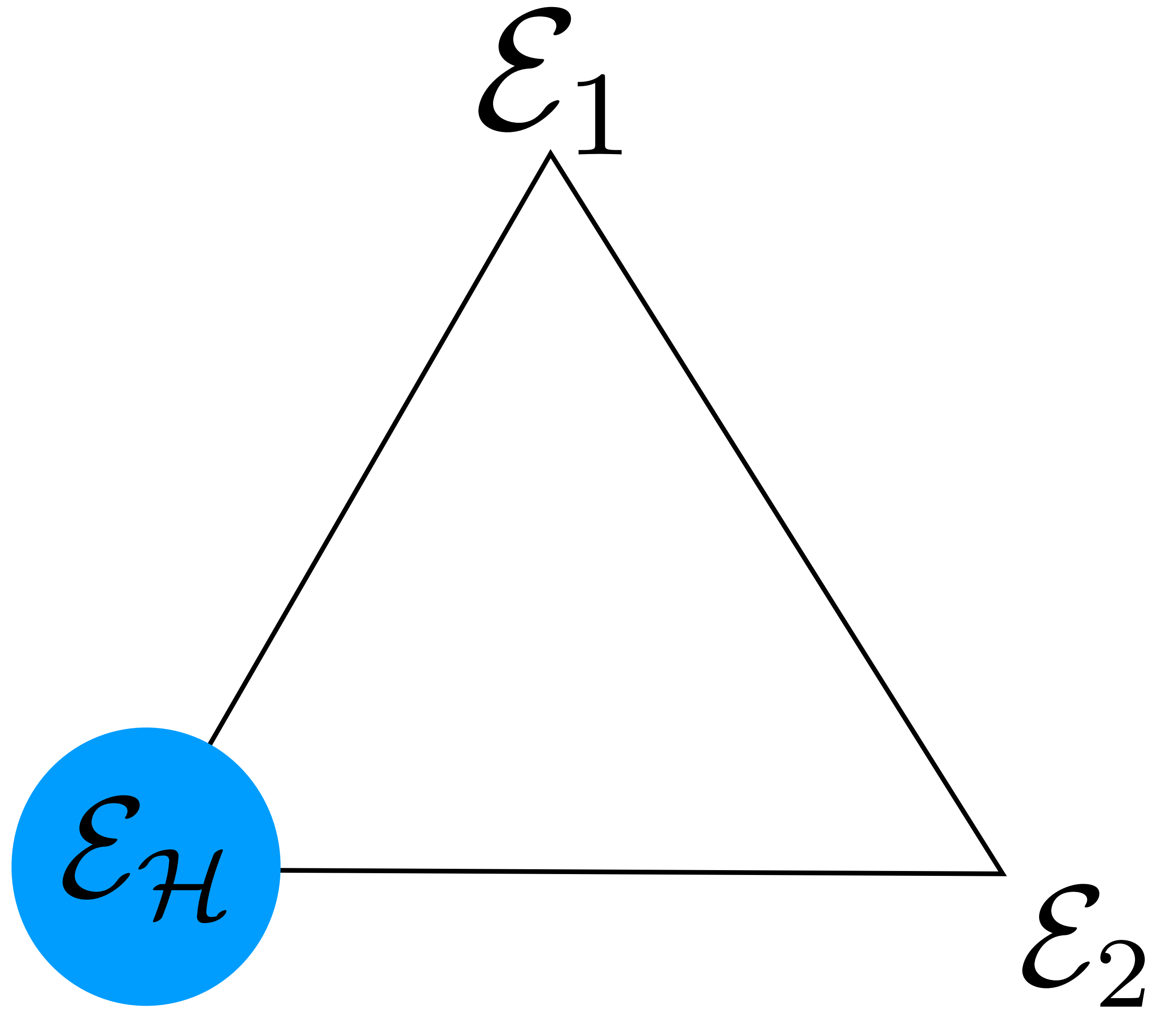
- **Cosmologists are hunting for non-gaussianities (genuine 3-pt correlation) in CMB to distinguish models of inflation**

PROBING THE DYNAMICS OF THE DEAD-CONE

- **Application: three-point correlations probe the non-trivial dynamics of the dead-cone**

Craft, Gonzalez, KL, Meçaj, Moult [In Progress]





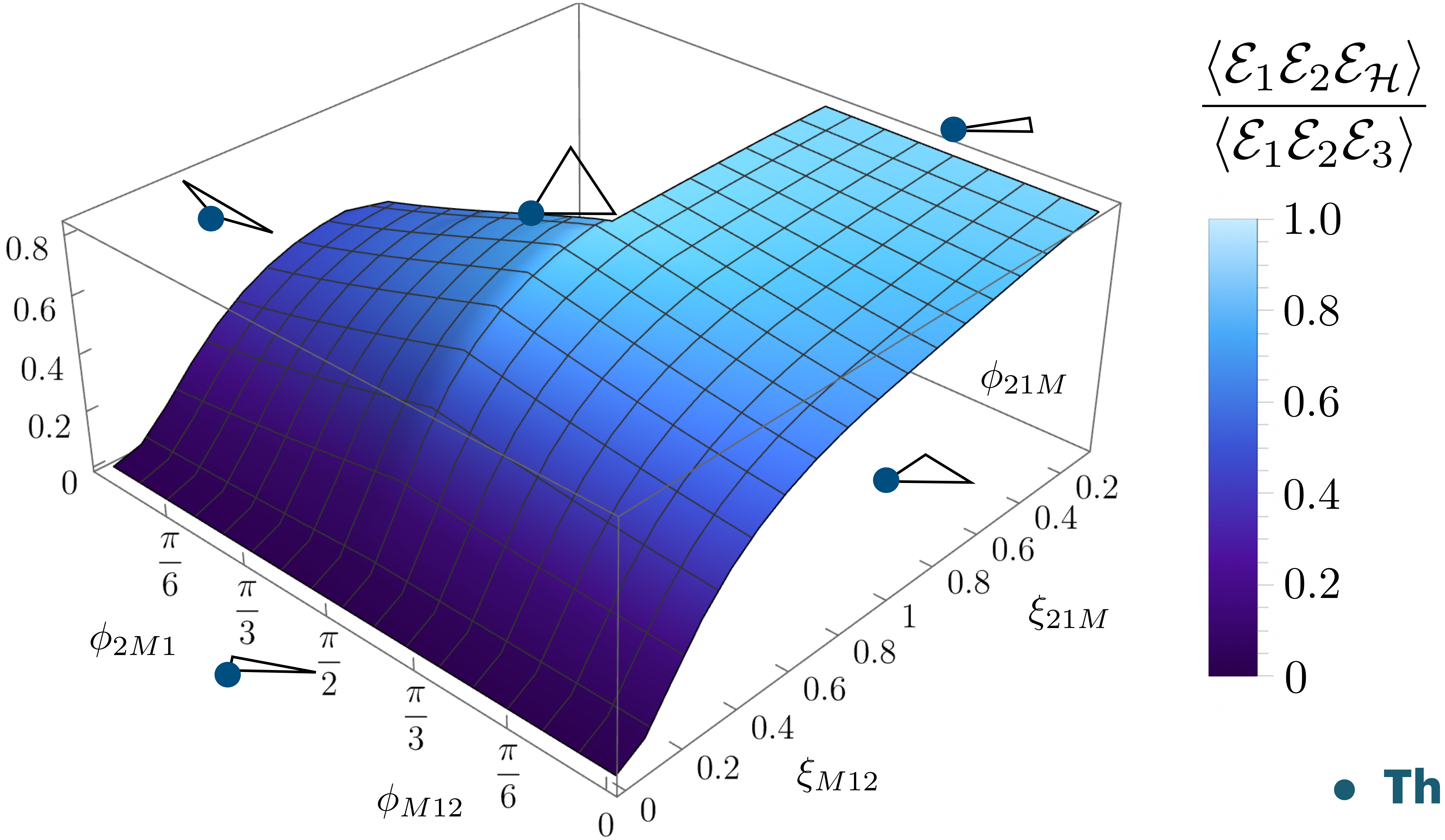
- **Three-point structure allows us to probe the nontrivial shape of the dead-cone**

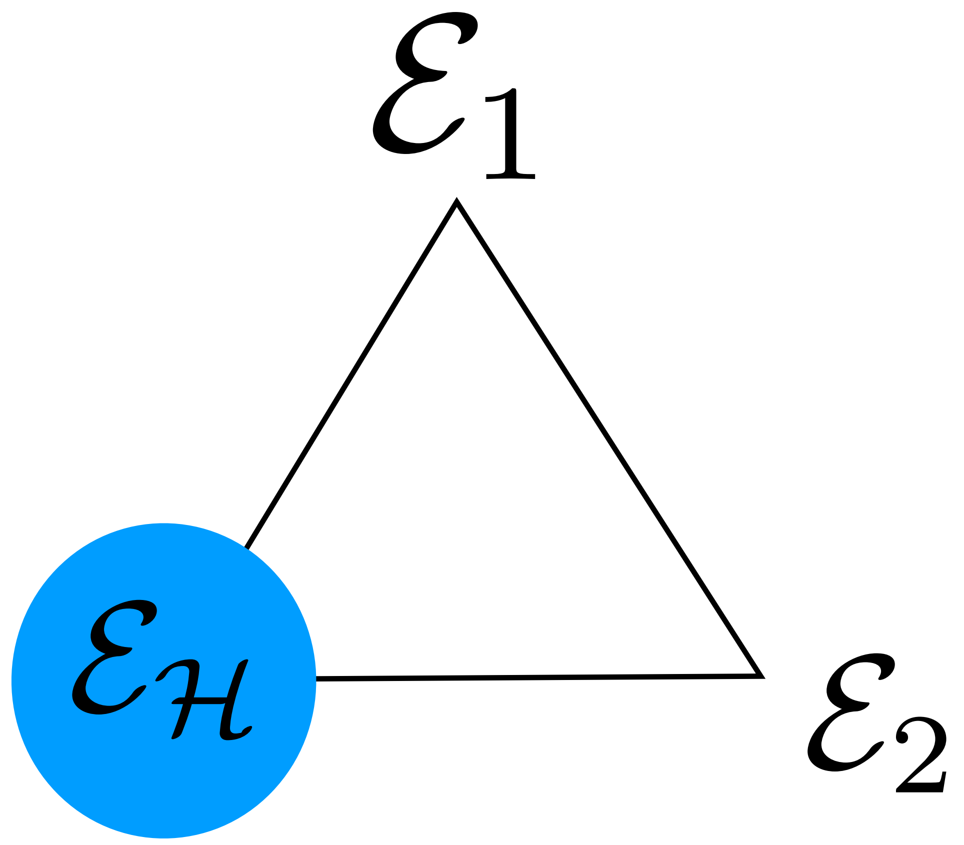
PROBING THE DYNAMICS OF THE DEAD-CONE

- **Application: three-point correlations probe the non-trivial dynamics of the dead-cone**

Craft, Gonzalez, KL, Meçaj, Moult [In Progress]

Ratio of Three-Point Massive Correlators





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PROBING THE DYNAMICS OF THE DEAD-CONE

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Craft, Gonzalez, KL, Meçaj, Moult [In Progress]

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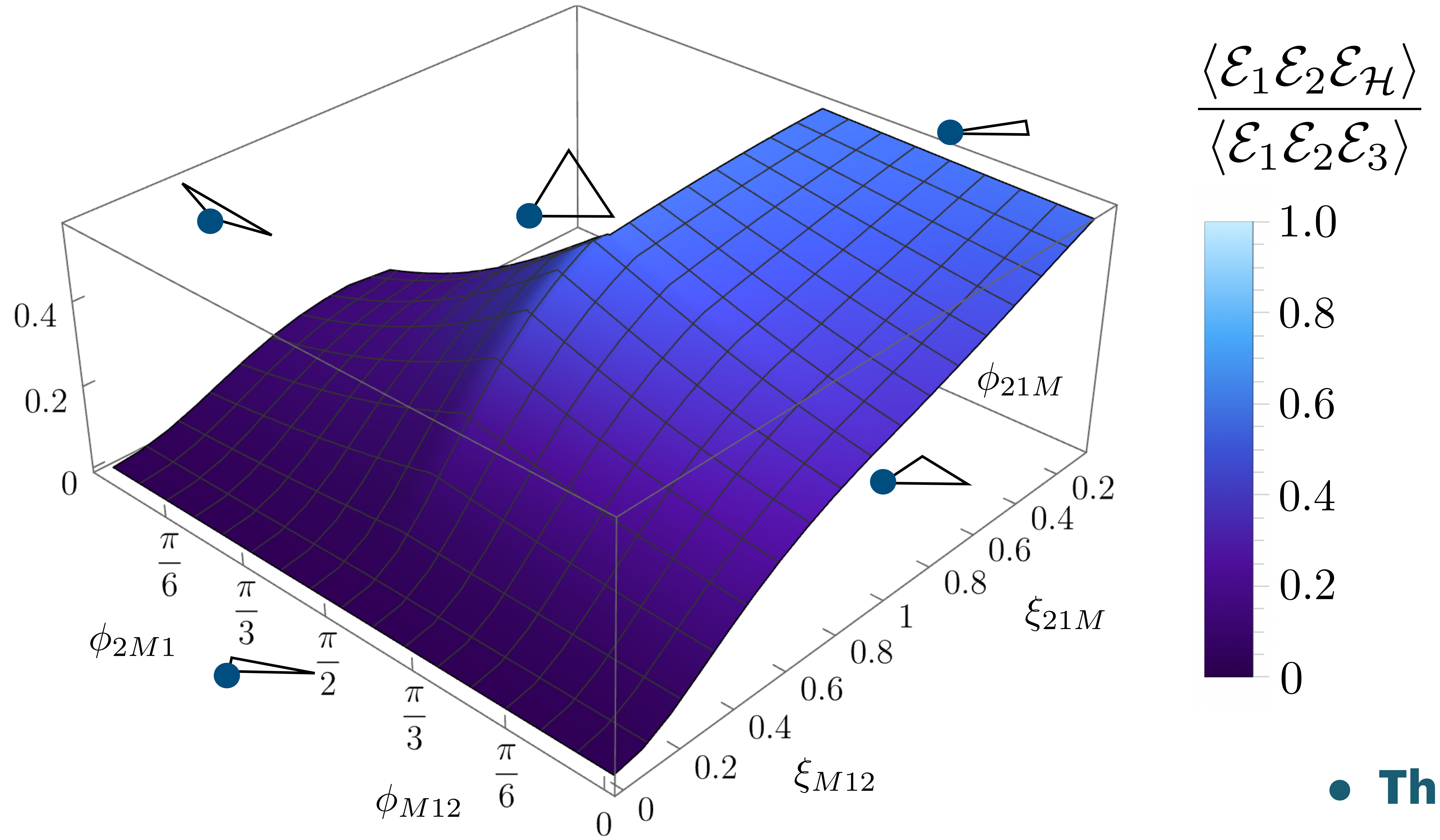
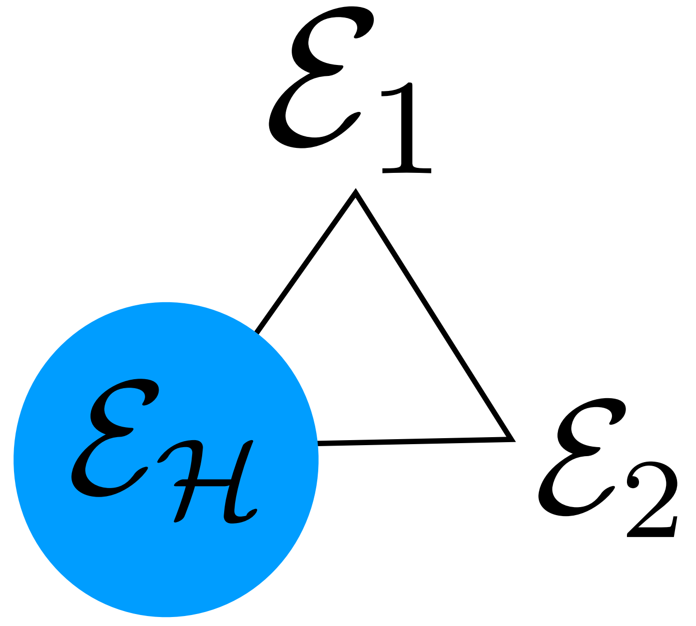
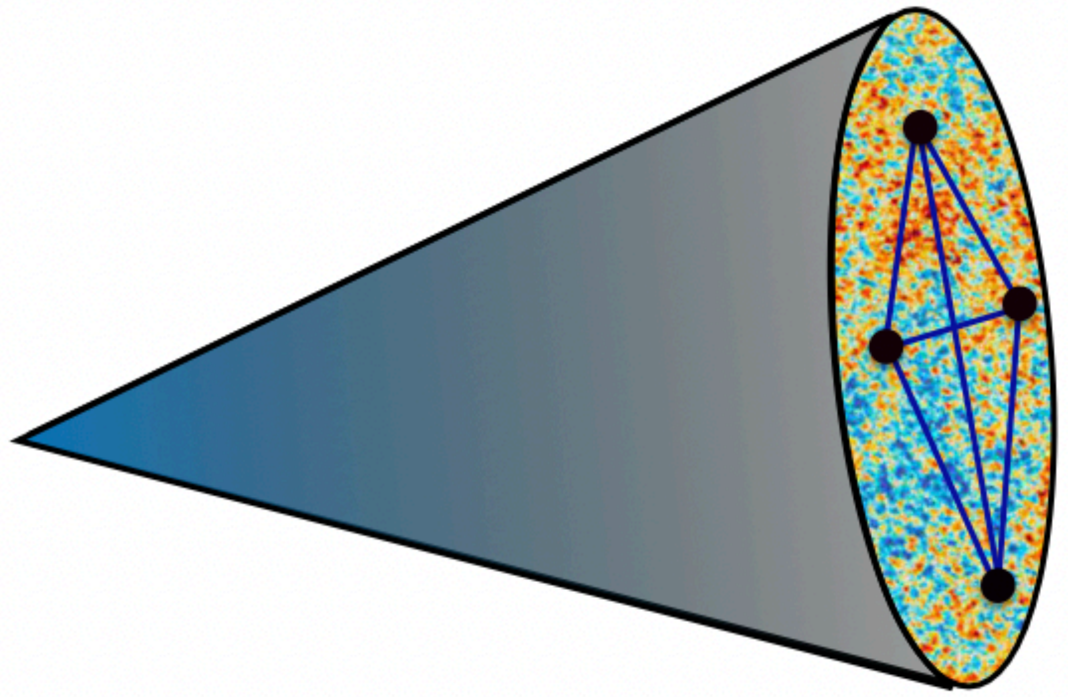




- **Three-point structure allows us to probe the nontrivial shape of the dead-cone**

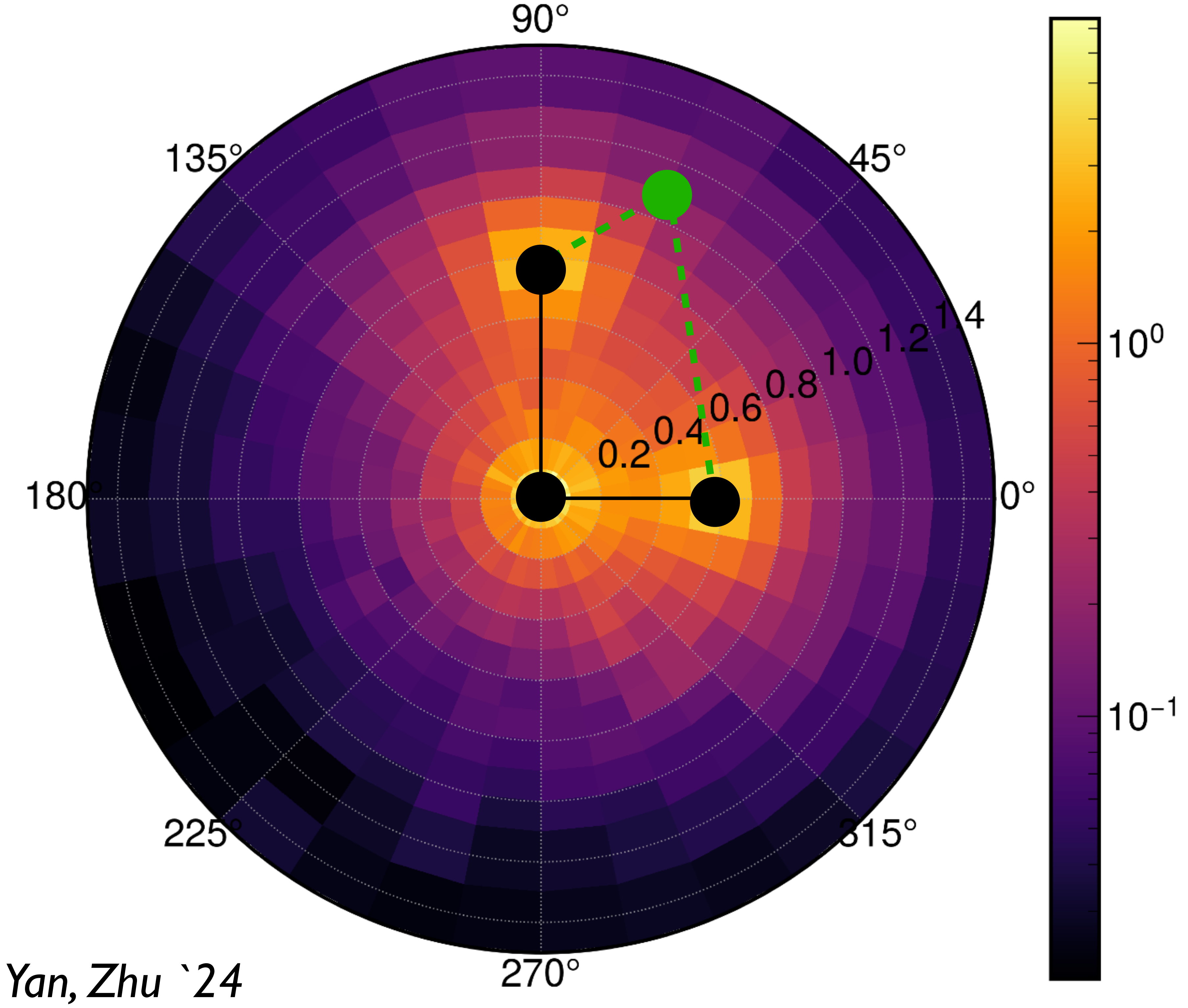
BONUS: PUSHING THE LIMIT OF HIGHER POINTS

- **Phenomenologically interesting to probe OPE and spinning operators**



$$\mathrm{E^N C} \overset{\text{coll.}}{=} \int_0^1 dx_1 \cdots dx_N \, \delta(1 - \sum_i x_i) \, (x_1 \cdots x_N)^2 \, \mathcal{P}^{(0)}_{1 \to N} \,,$$

Gonzalez, Harris, KL, Moult, Rothman [In Progress]



- **Analytic computation for $\mathcal{N} = 4$** *Chicherin, Moult, Sokatchev, Yan, Zhu `24*
  He, Jiang, Yang, Zhang `24

Push the precision of higher-point correlators to probe dynamics nontrivially!

Overview

Can we do precision electroweak studies and constrain new physics?

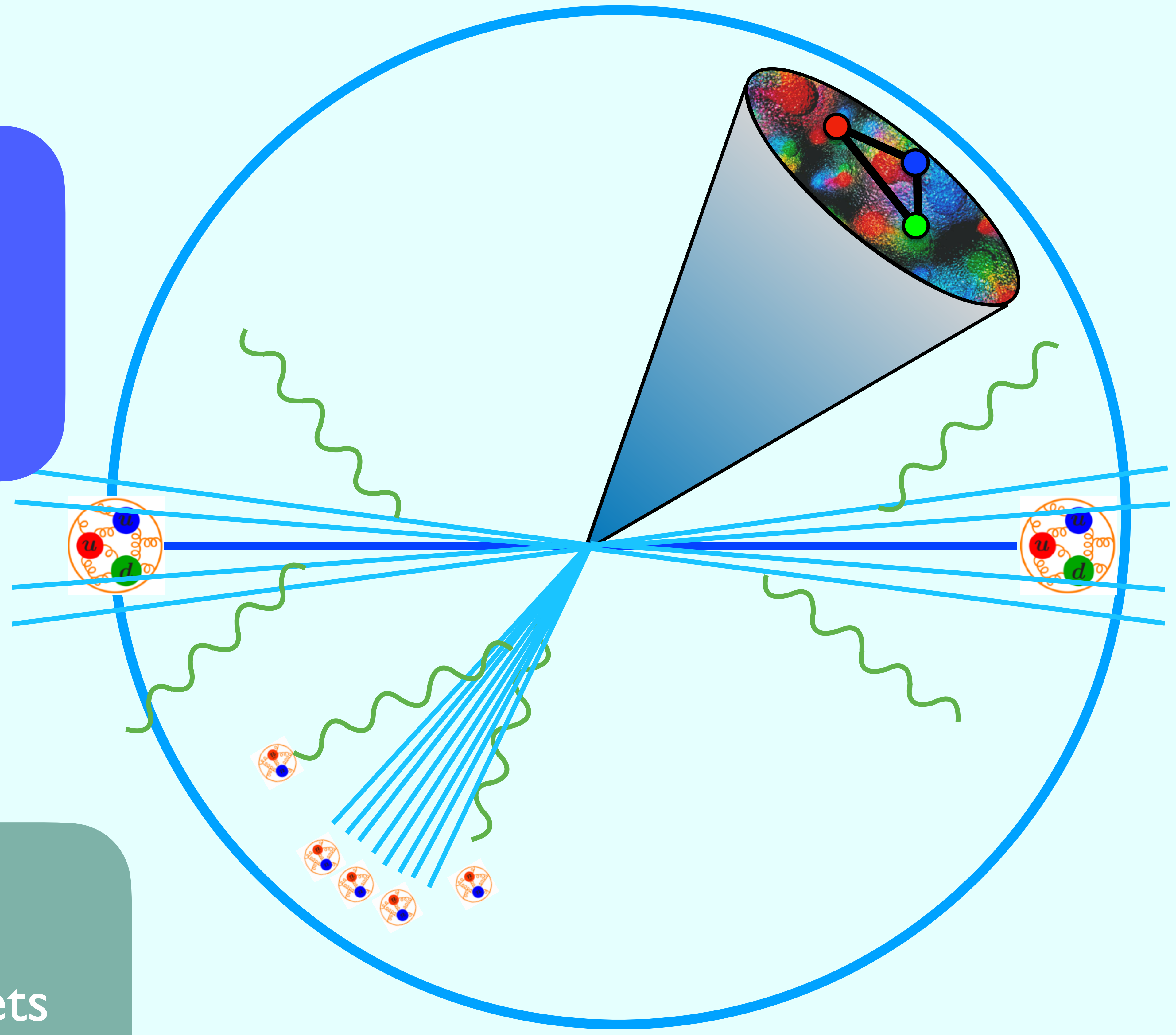
I. Universal Scaling

II. Precision SM

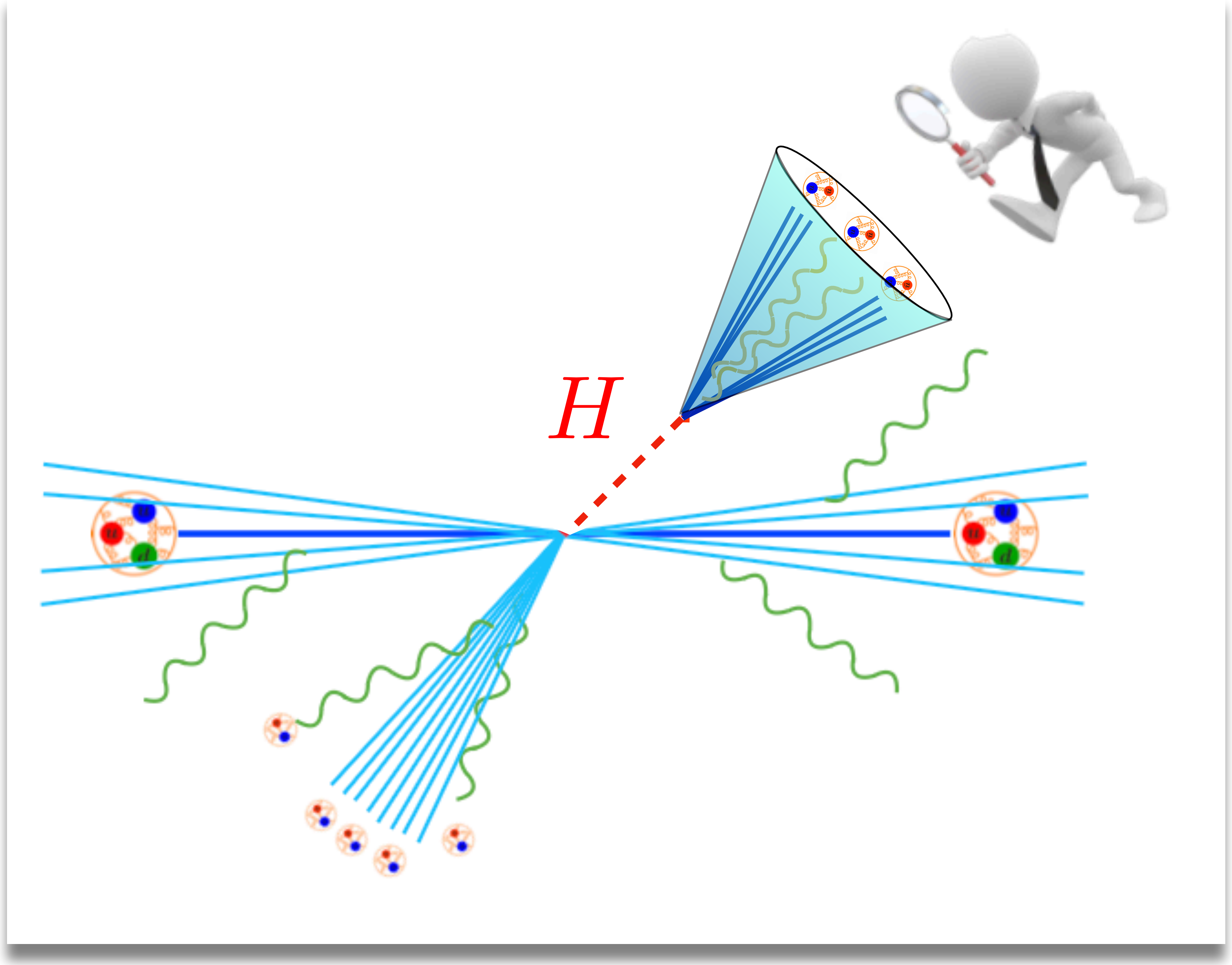
III. Confinement Dynamics

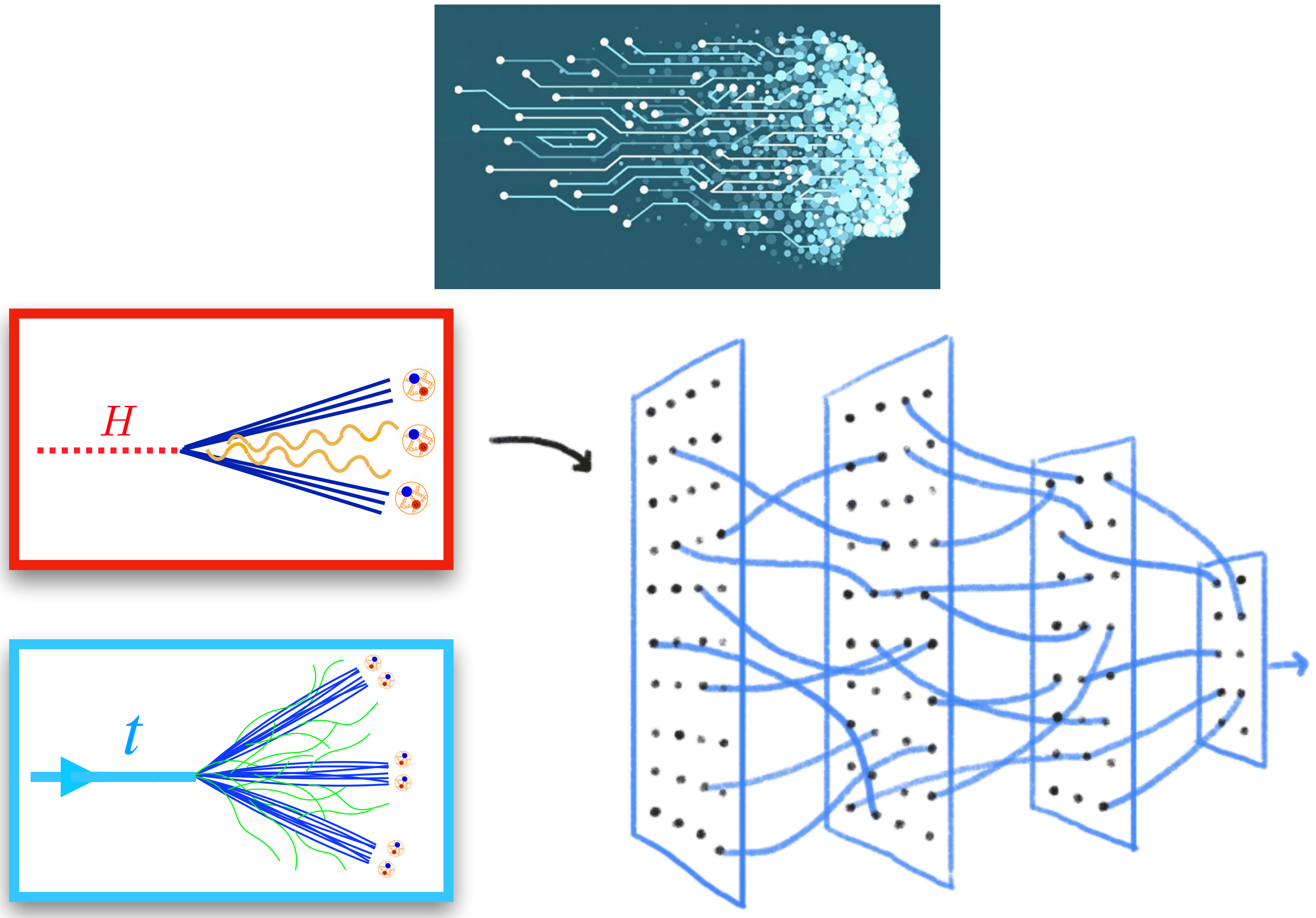
IV. Heavy Flavor Jets

V. Electroweak and New physics



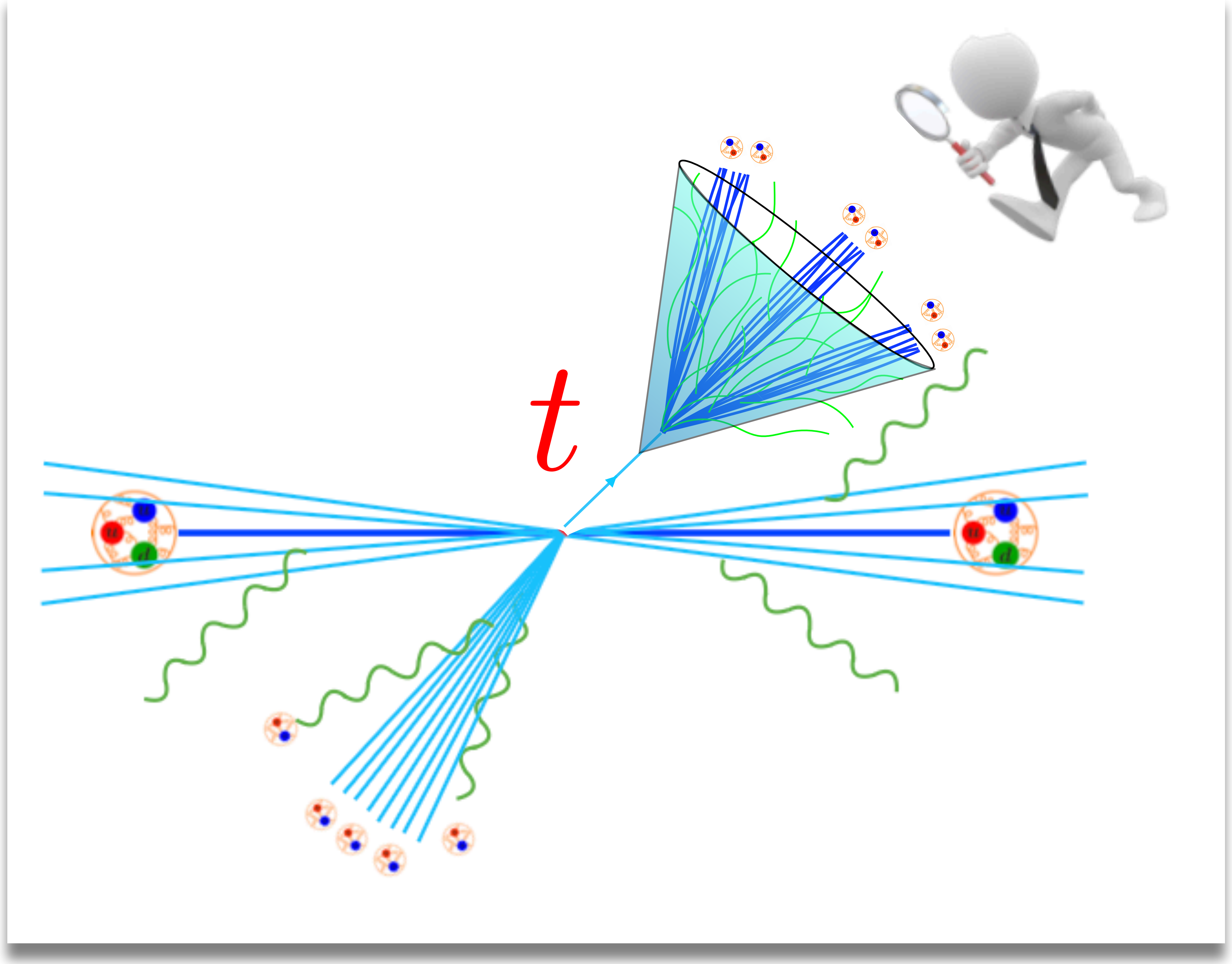
JET SUBSTRUCTURE : ELECTROWEAK SCALE AND NEW PHYSICS

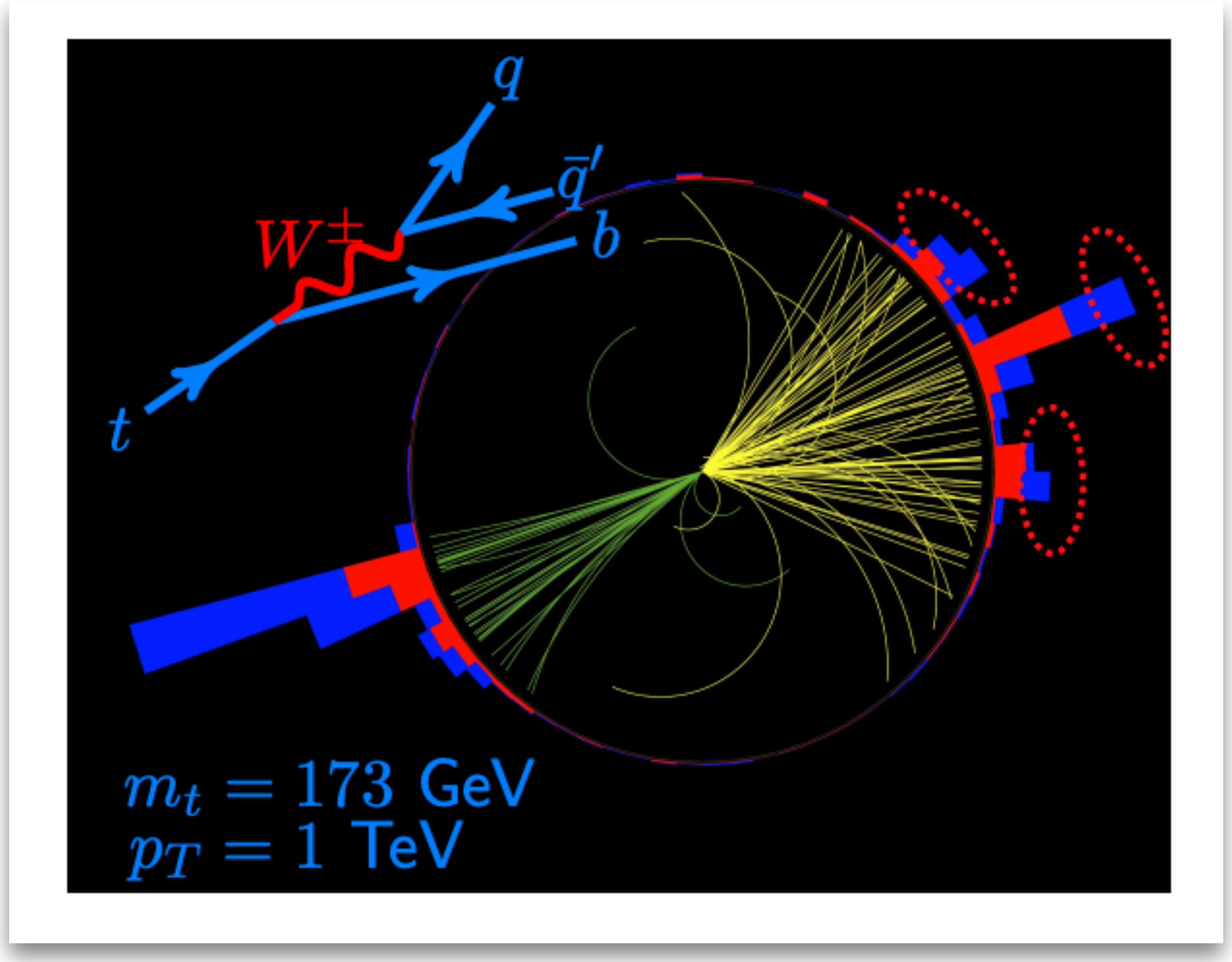


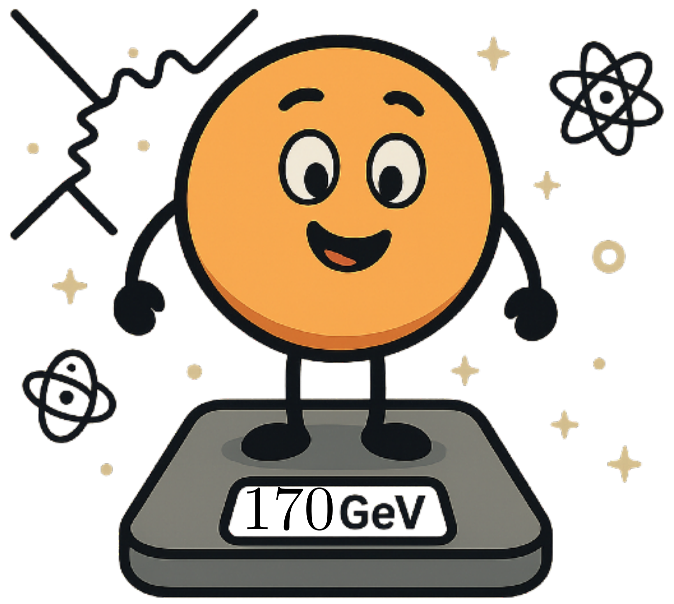


- Since its first introduction in 2008 by Butterworth, Davison, Rubin and Salam to reconstruct Higgs, modern jet substructure studies have been widely used for electroweak and new heavy resonances.
- In parallel, a surge of ML techniques now enables more efficient tagging of these objects.

JET SUBSTRUCTURE : ELECTROWEAK SCALE AND NEW PHYSICS

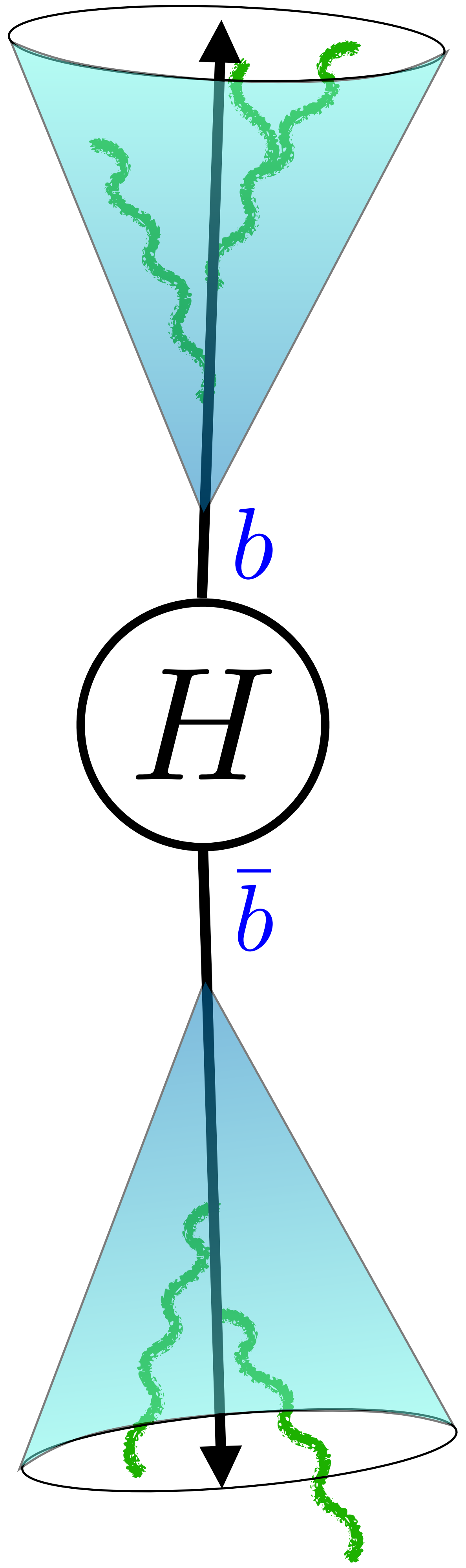






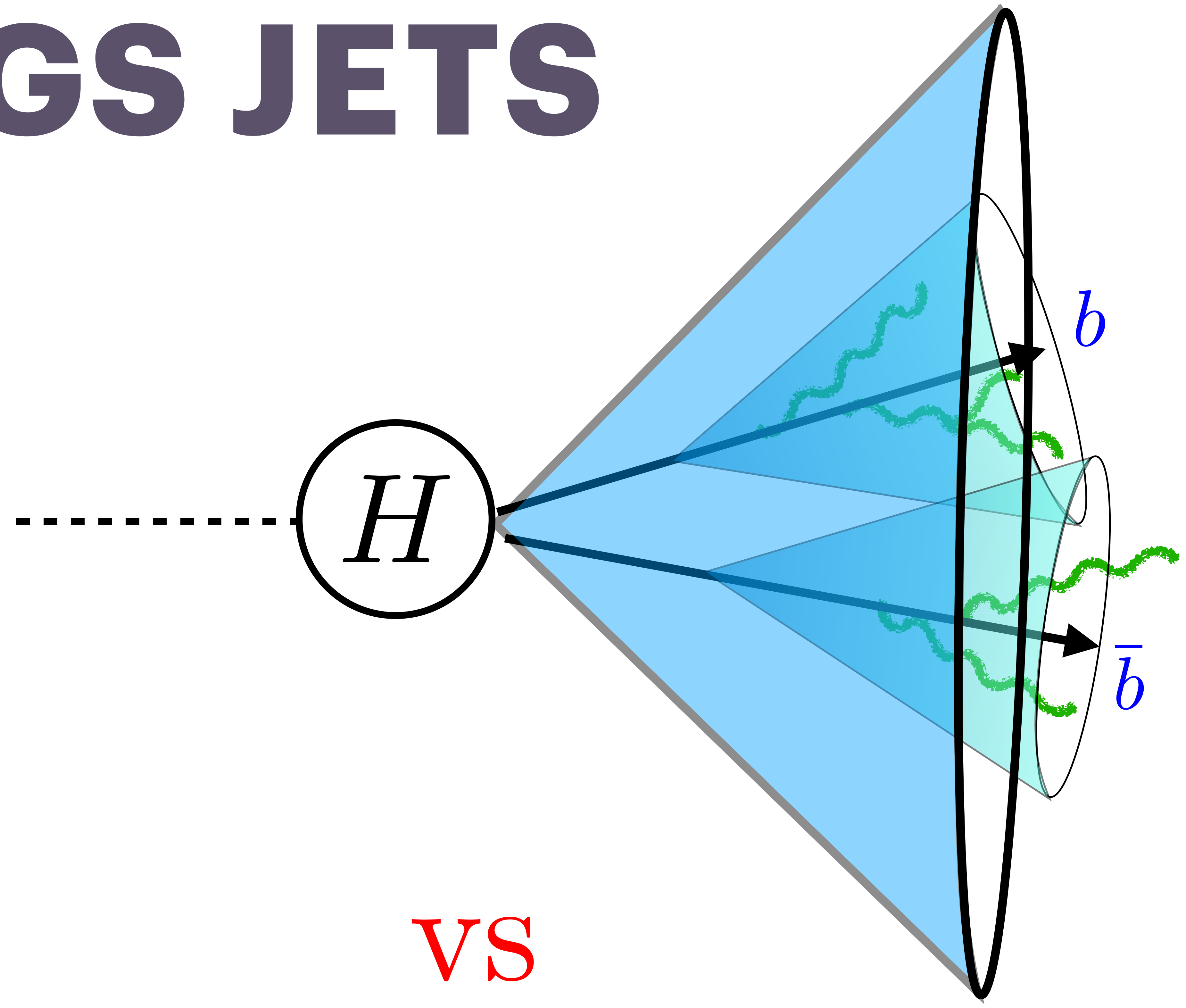
- **Concretely, can advancements in energy correlator calculations give precision extraction of top quark mass? Need to improve understanding of multi-prong structure and boost**

BOOSTED HIGGS JETS

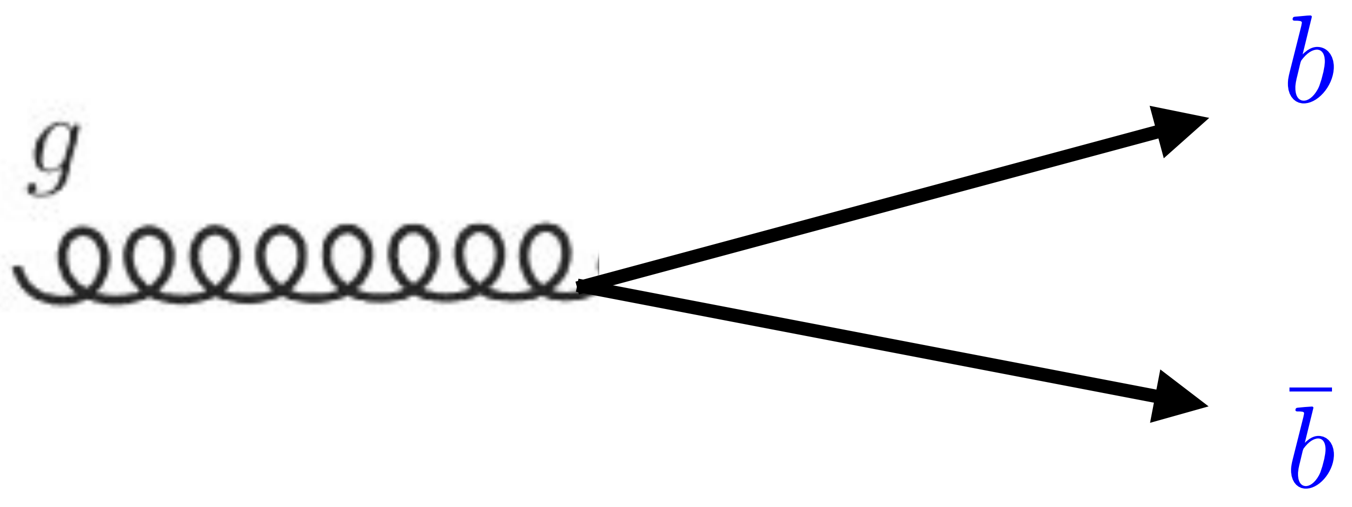


Large Boost

$E \gg m_H$



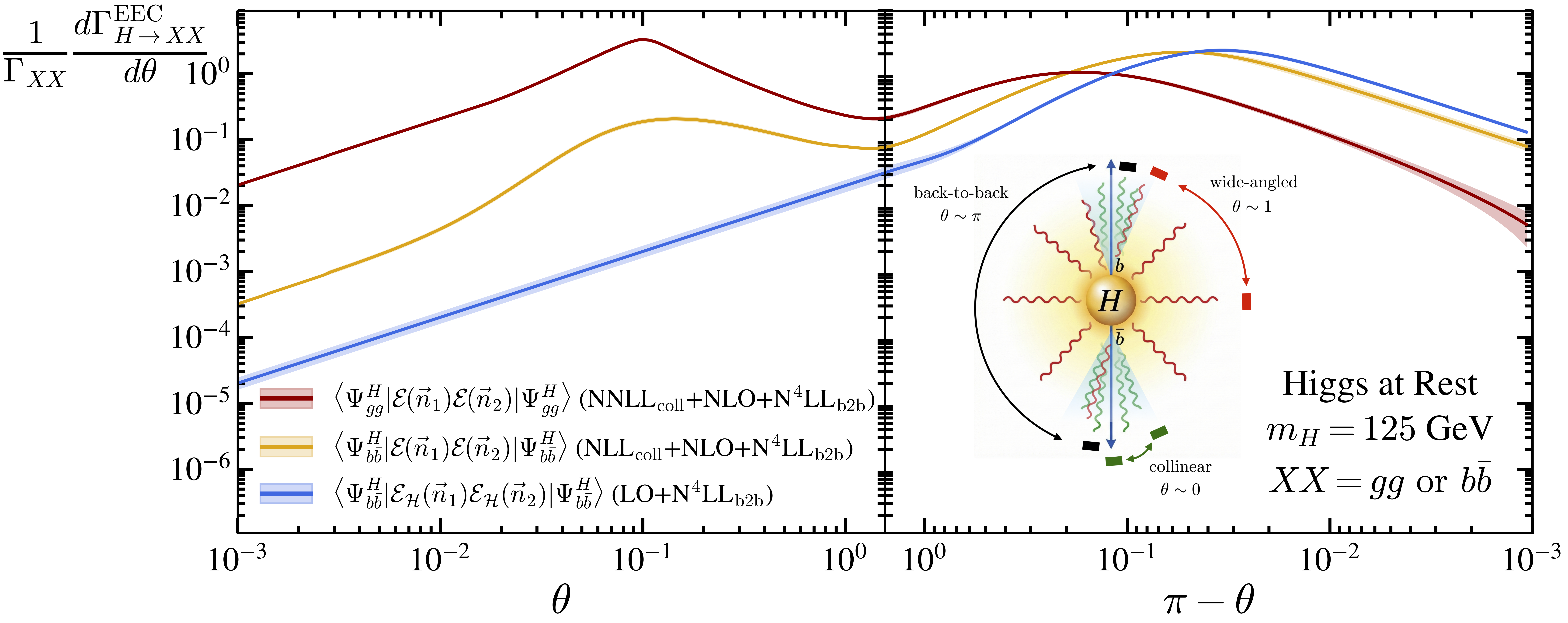
VS



- **Can we discriminate scalar (Higgs) vs color octet vector (gluons) sourcing heavy quark pairs?**

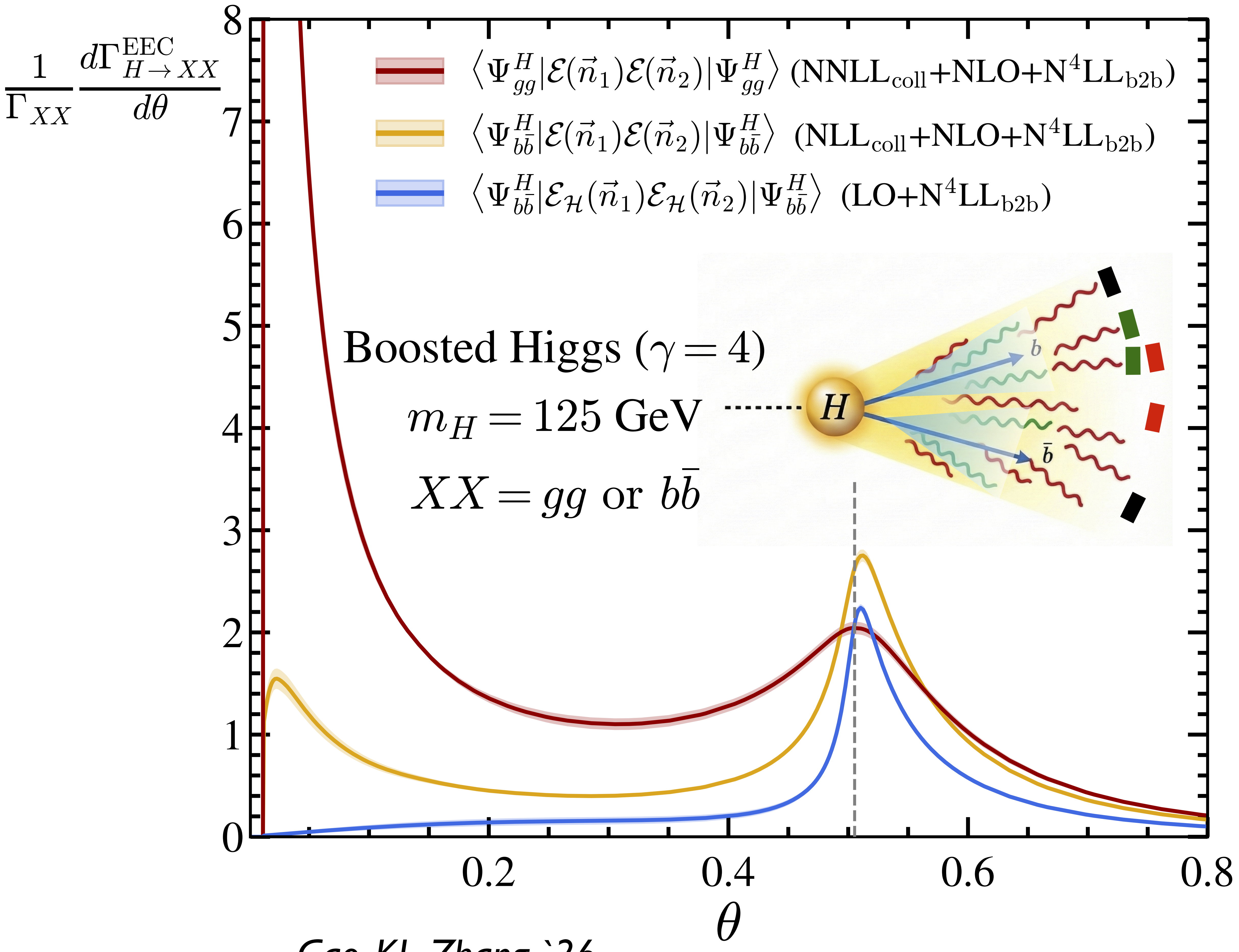
HIGGS AT REST

Gao, KL, Zhang `26



- **Using "heavy flavor detector" vs "inclusive energy detector" clearly discriminates back-to-back region vs collinear emissions within b-jets.**

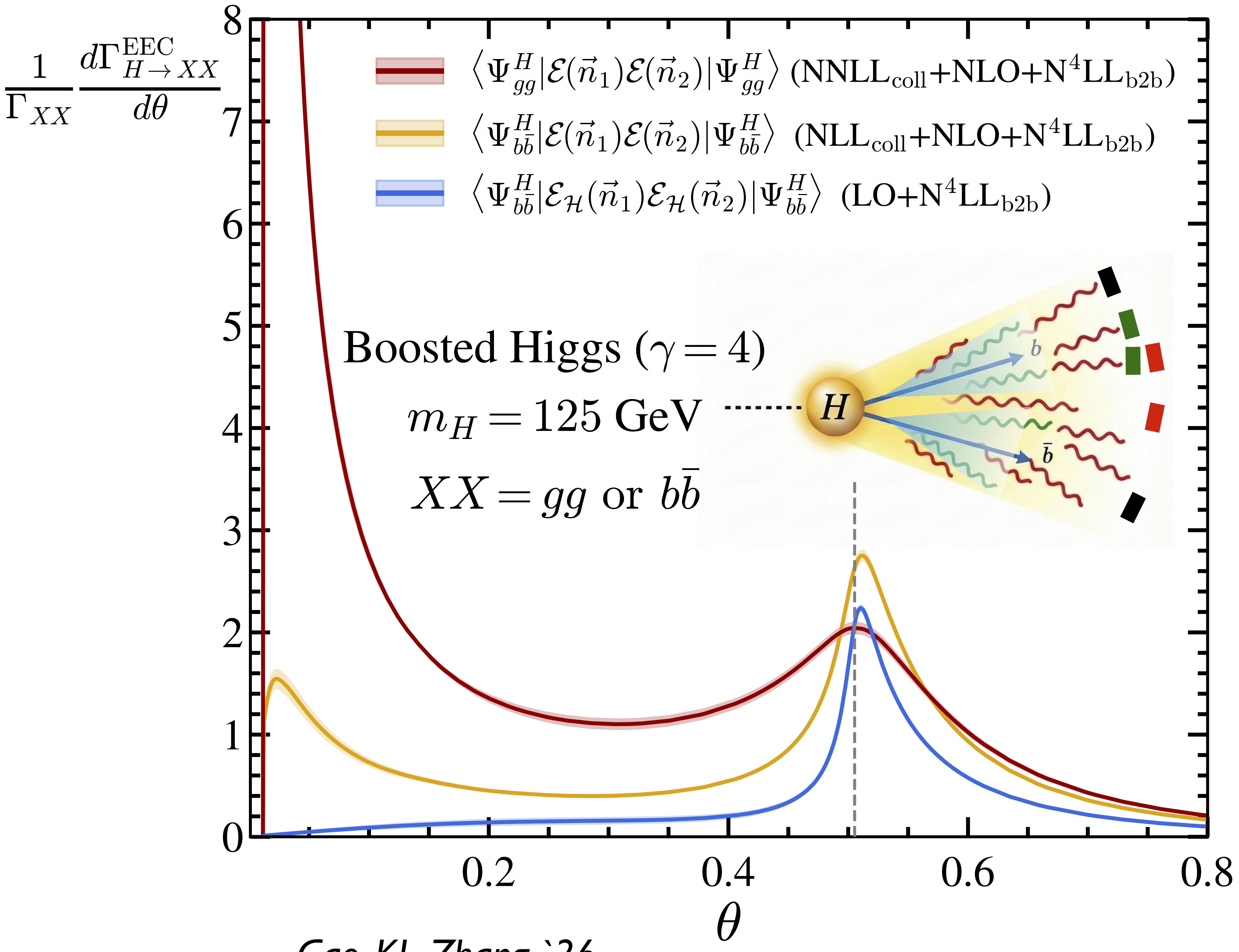
BOOSTED HIGGS JETS

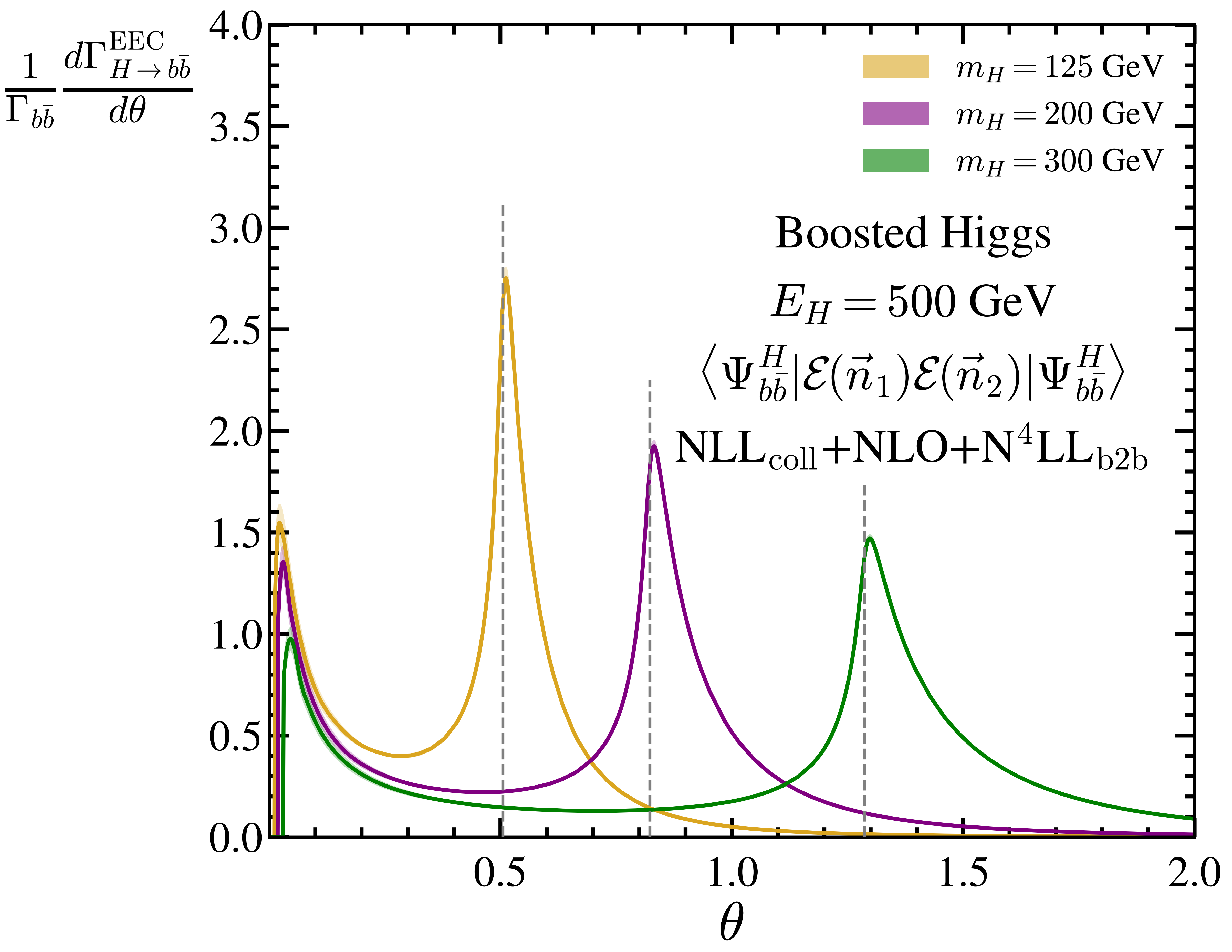


Gao, KL, Zhang `26

- **Within boosted jets with two b quarks, radiation patterns are clearly distinguished depending on the source**

BOOSTED HIGGS JETS





Gao, KL, Zhang `26

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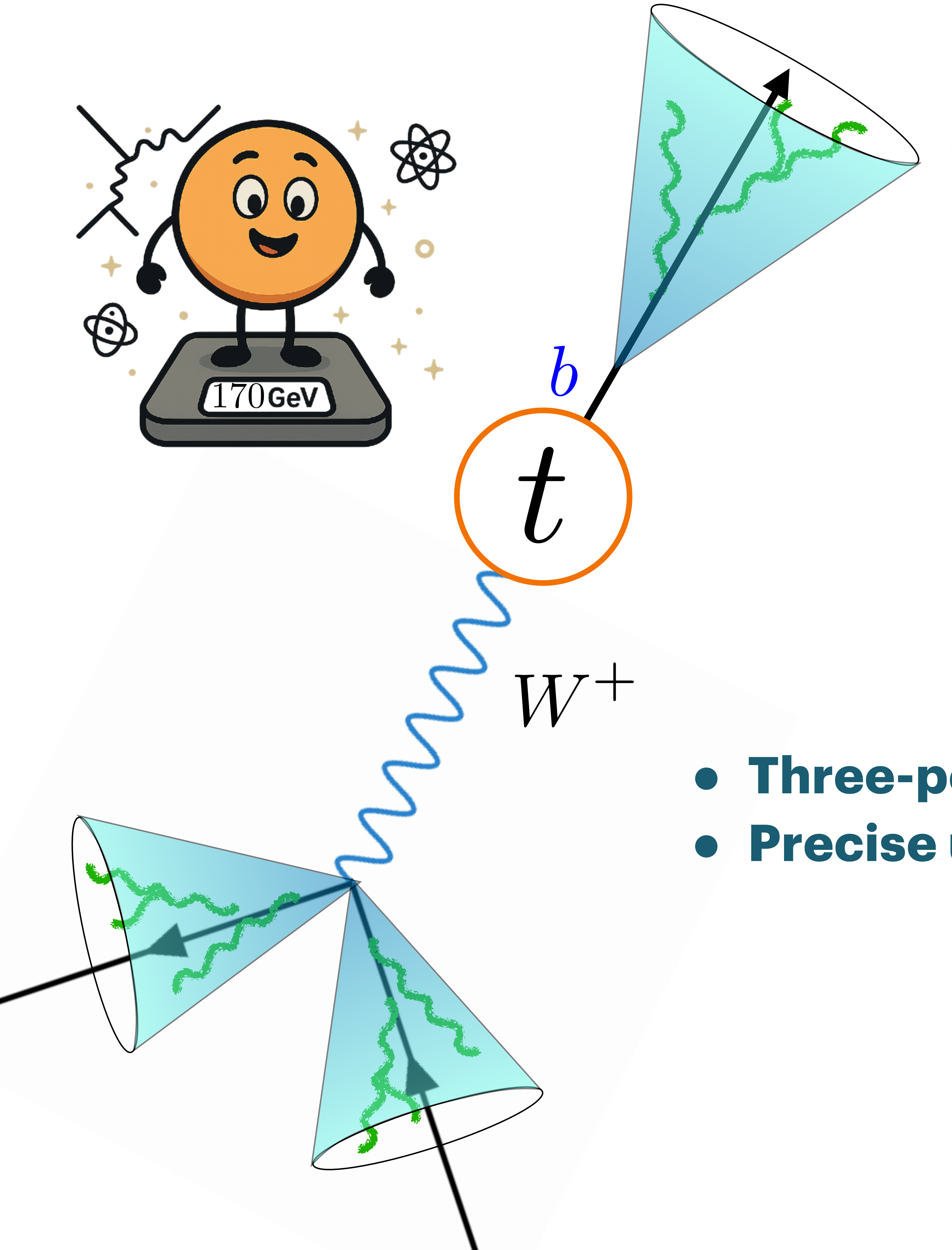
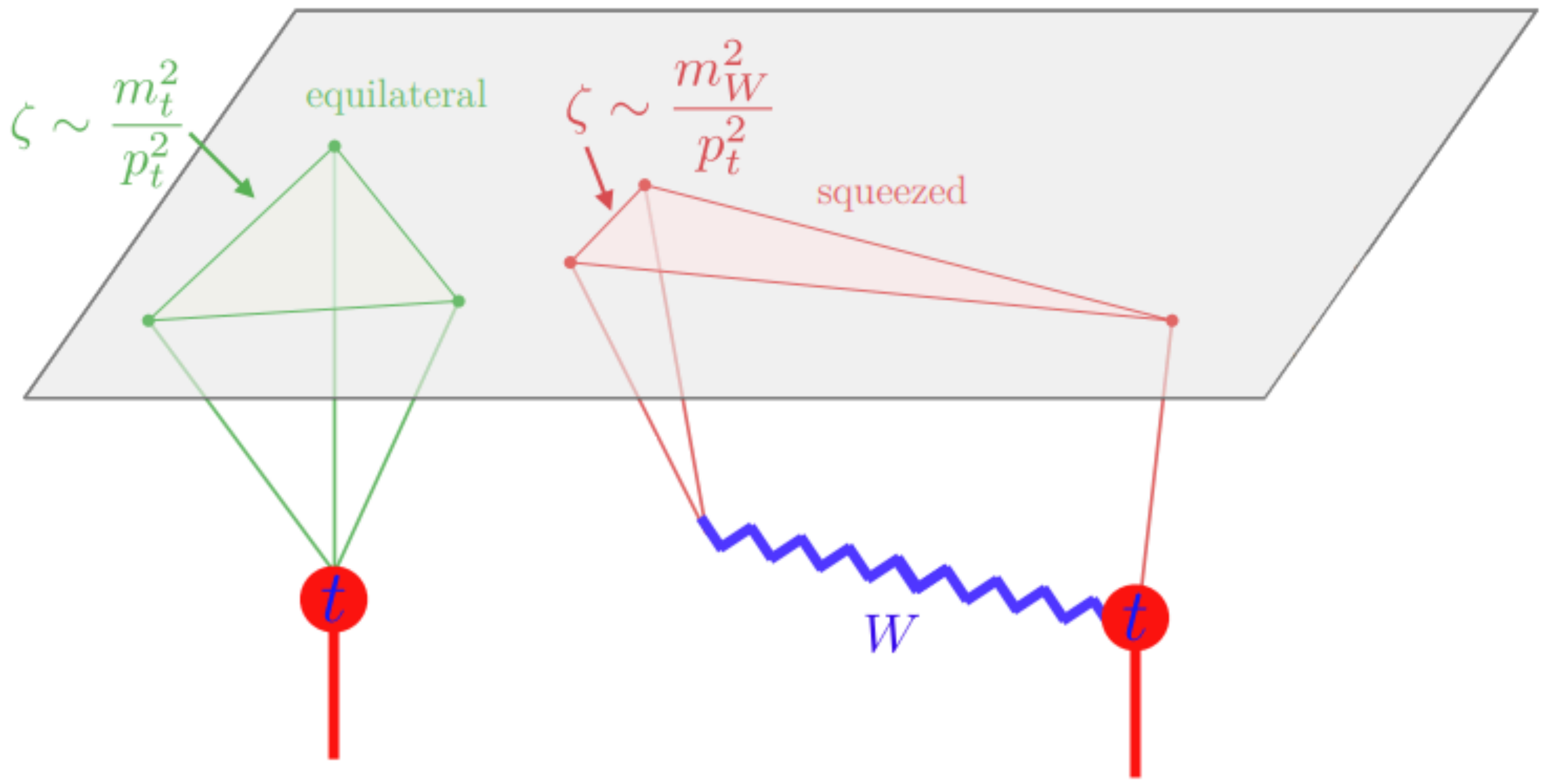
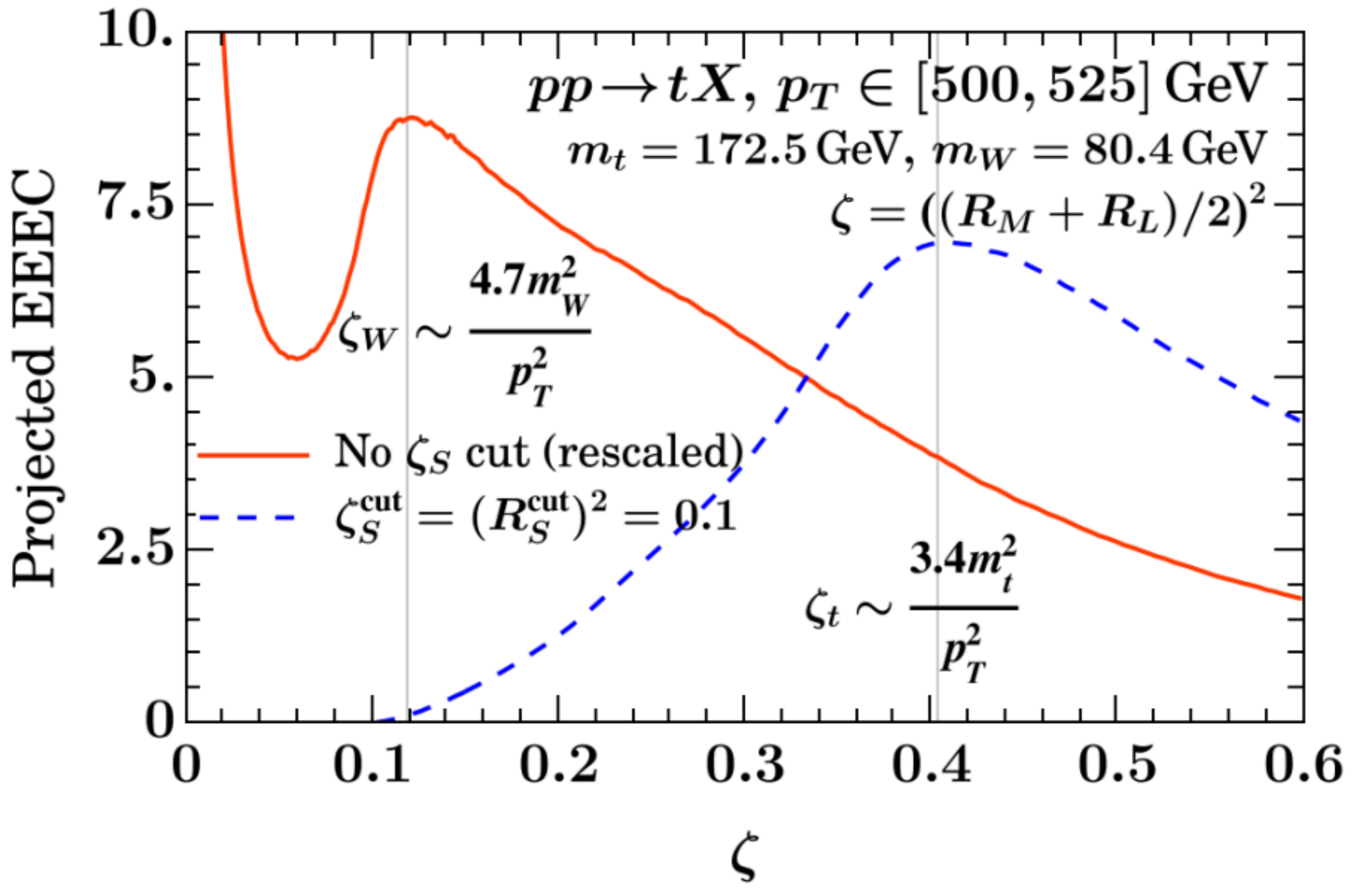
WEIGHING TOP QUARK WITH ENERGY CORRELATORS





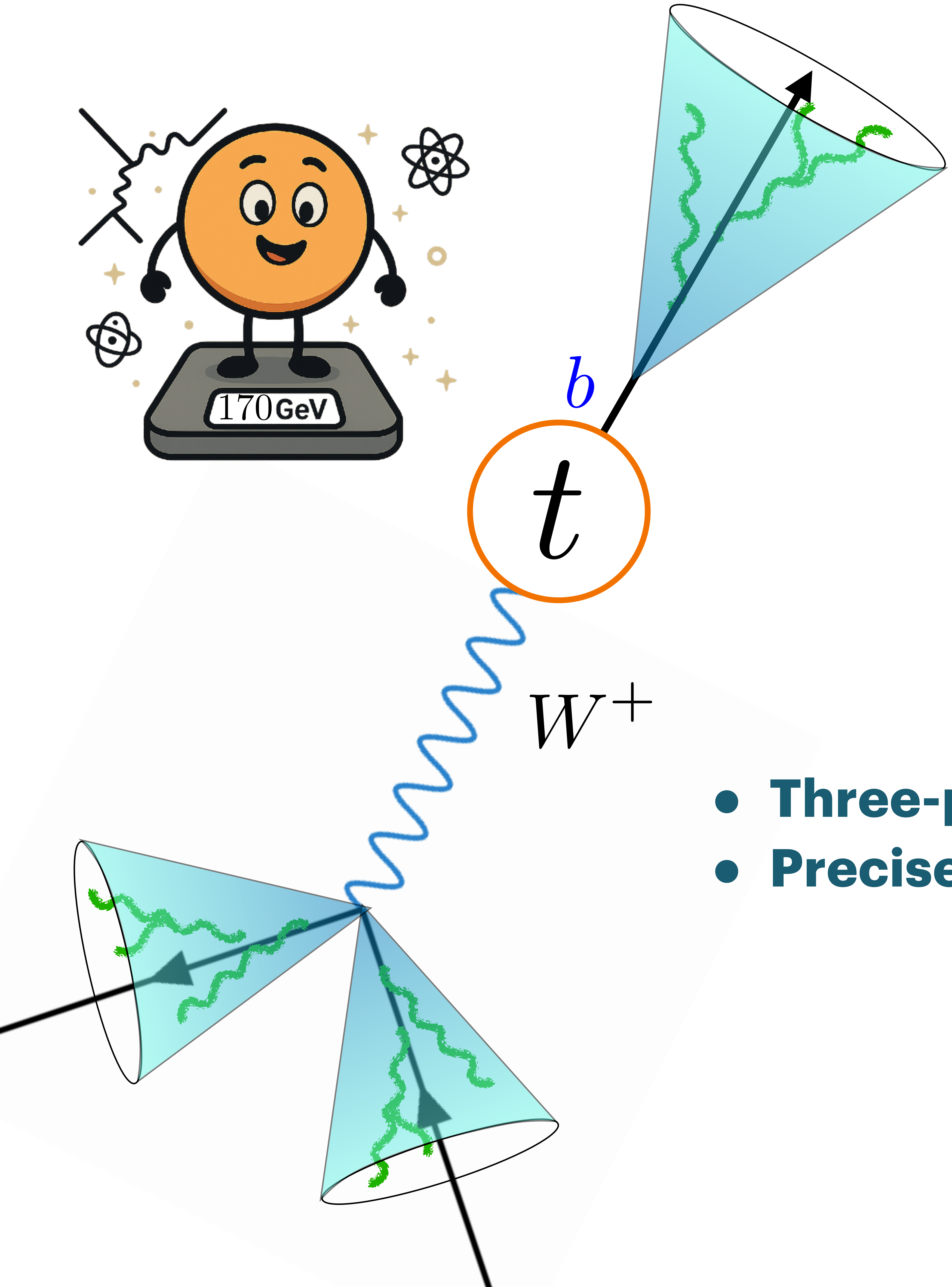


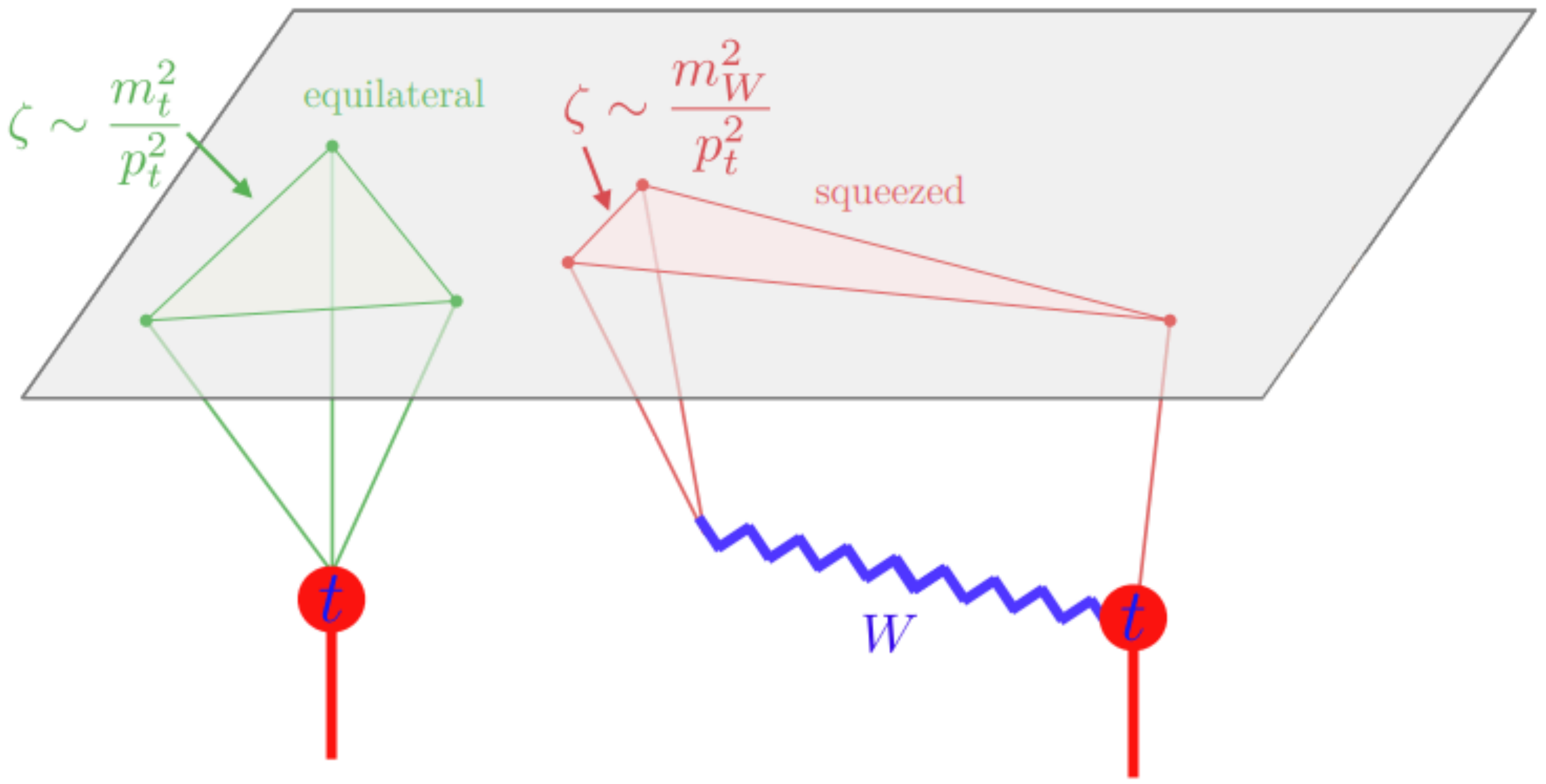
Holguin, Moult, Pathak, Procura, Schöfbeck `24
Holguin, KL, Moult, Pathak [In Progress]

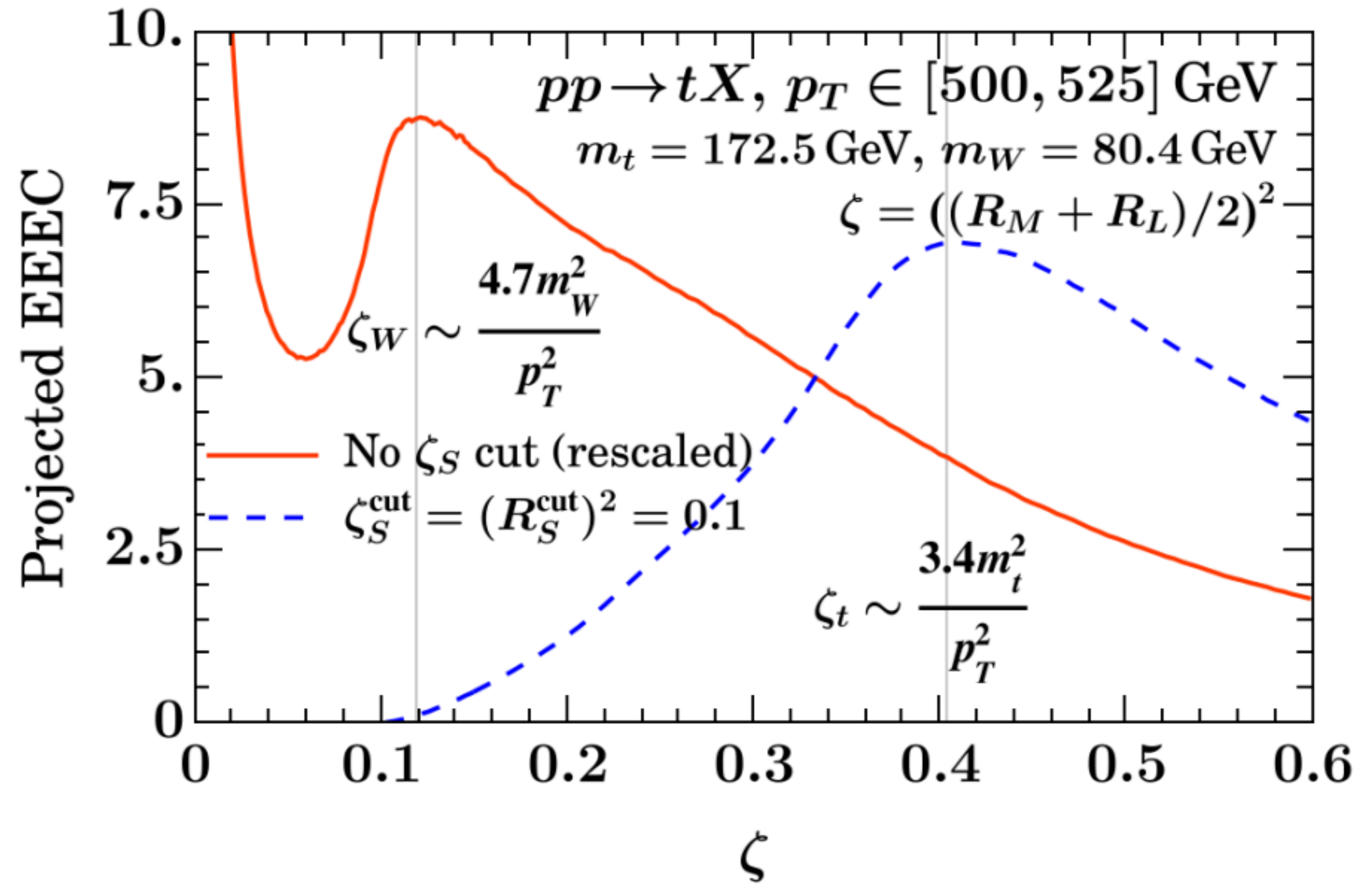
- **Three-point energy correlators can give measurements of top quark mass**
- **Precise understanding of squeezed configuration important to understand**

$$\frac{d\sigma}{dx_{12}dz} \sim H(Q,\mu) \int d^2b e^{-ibQ\sqrt{1-z}} J_q^{[2]}(b, x_{12}, \mu)\, J_q(b,\mu) S(b,\mu)$$

WEIGHING TOP QUARK WITH ENERGY CORRELATORS







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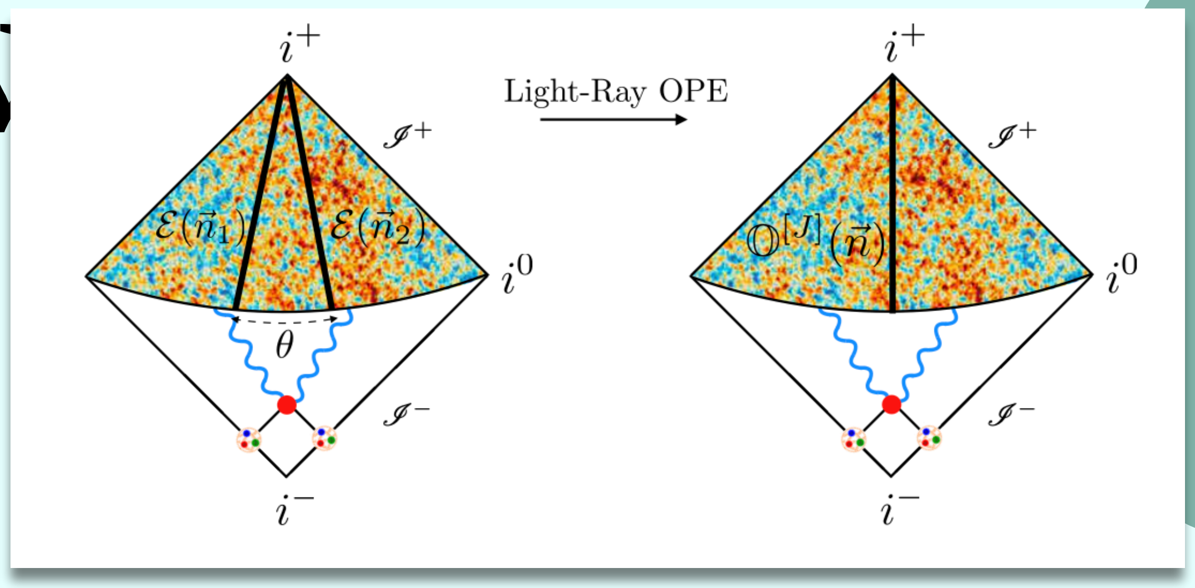
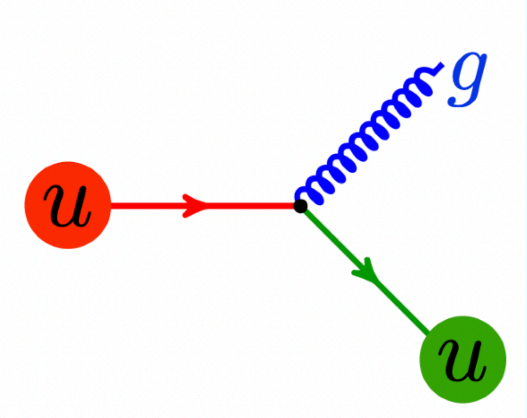
Carry out precision electroweak studies and explore applications to BSM searches using energy correlators!

Overview

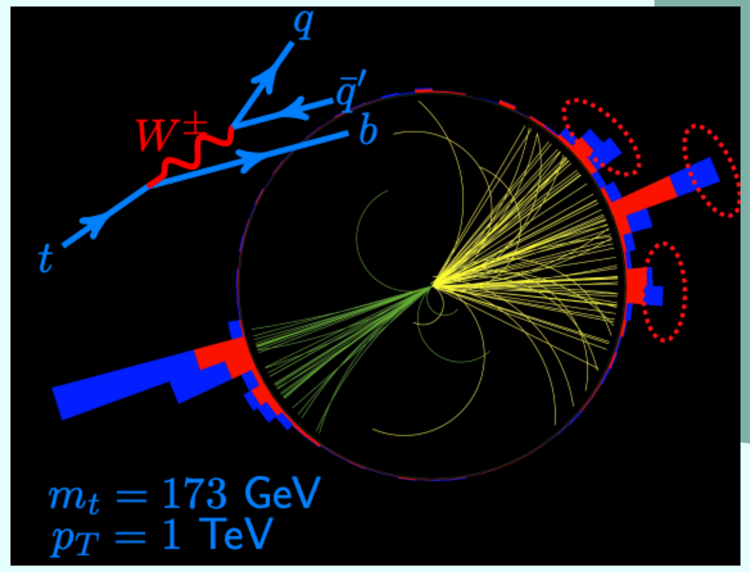


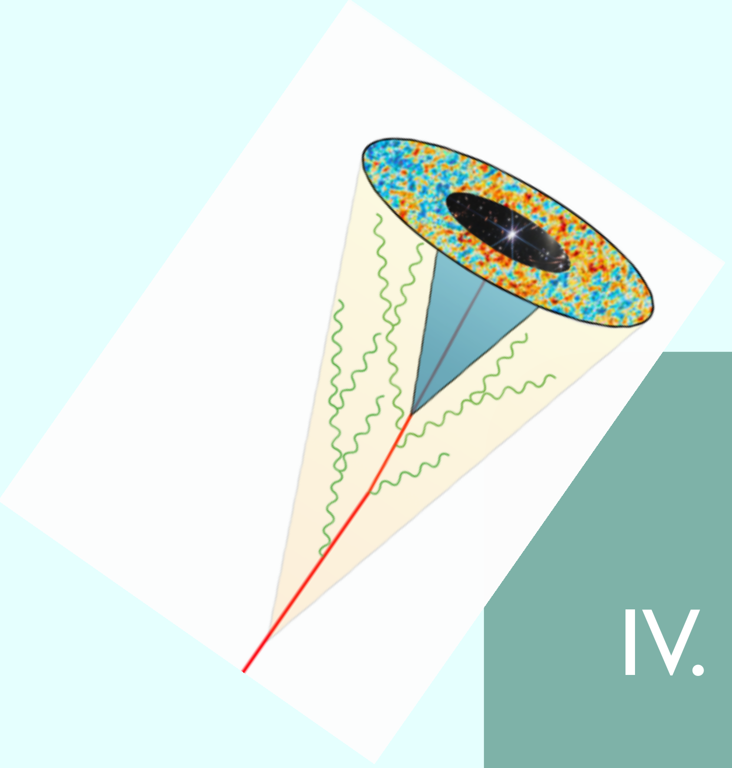
I. Universal Scaling

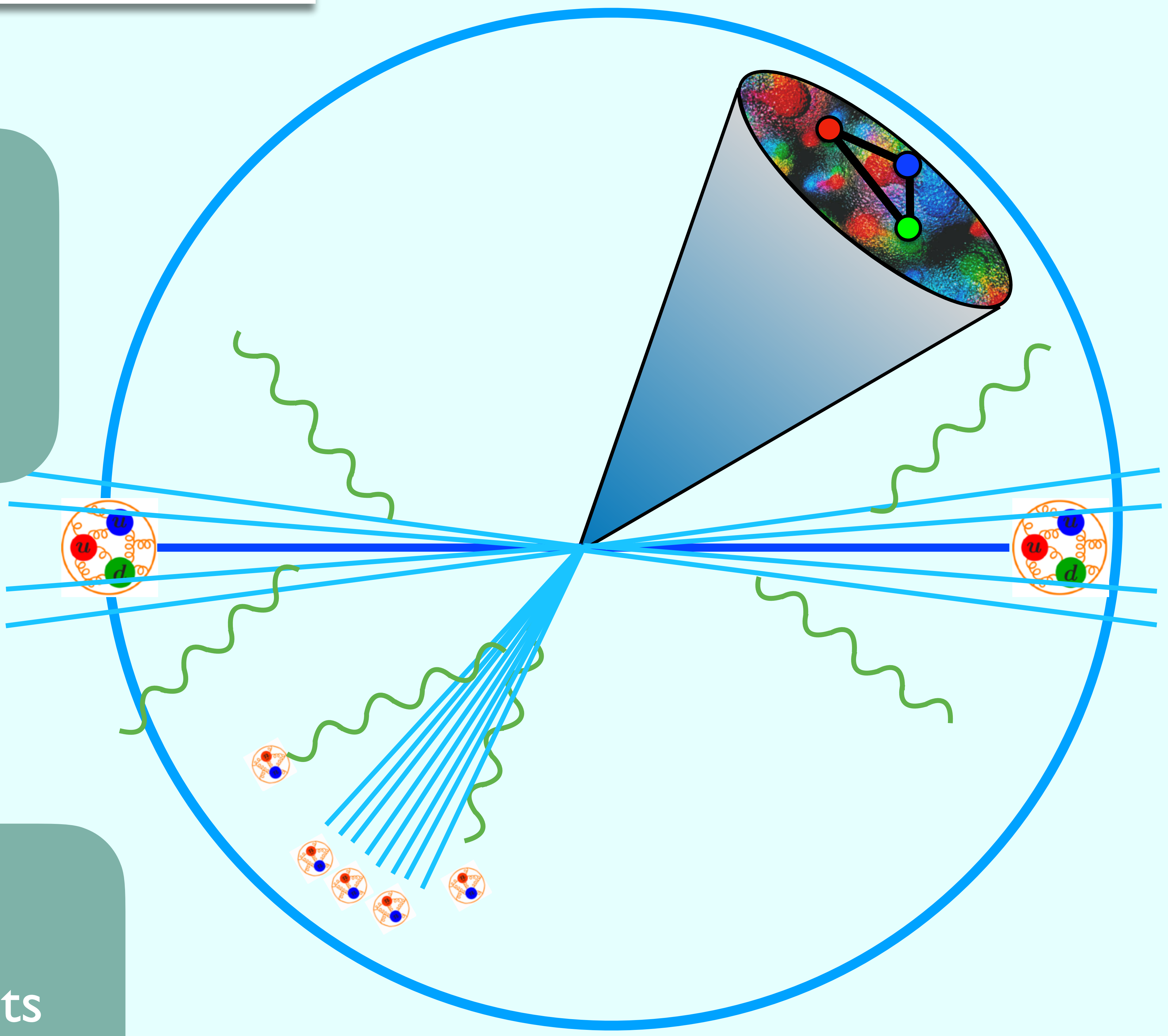


II. Precision SM

V. Electroweak and New physics

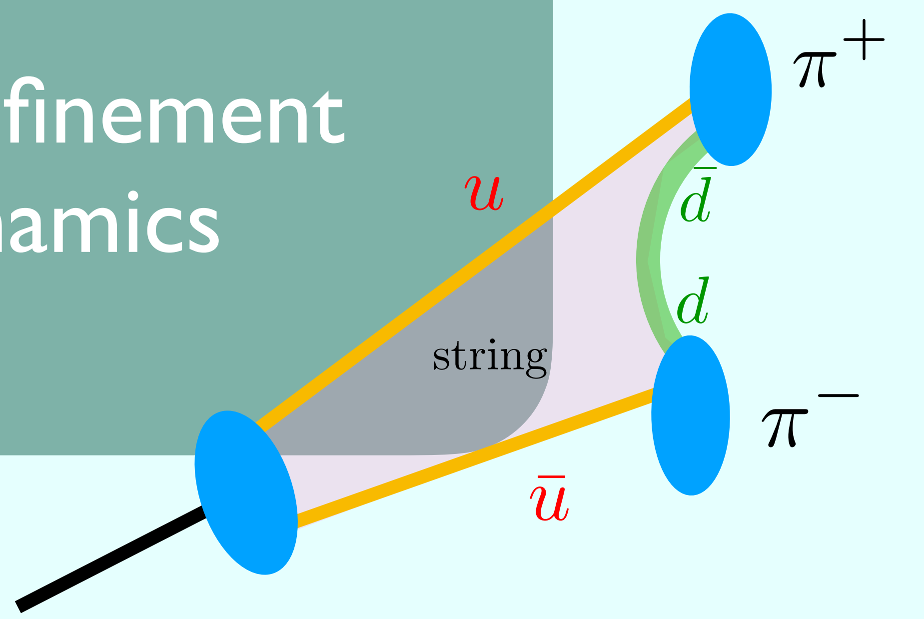


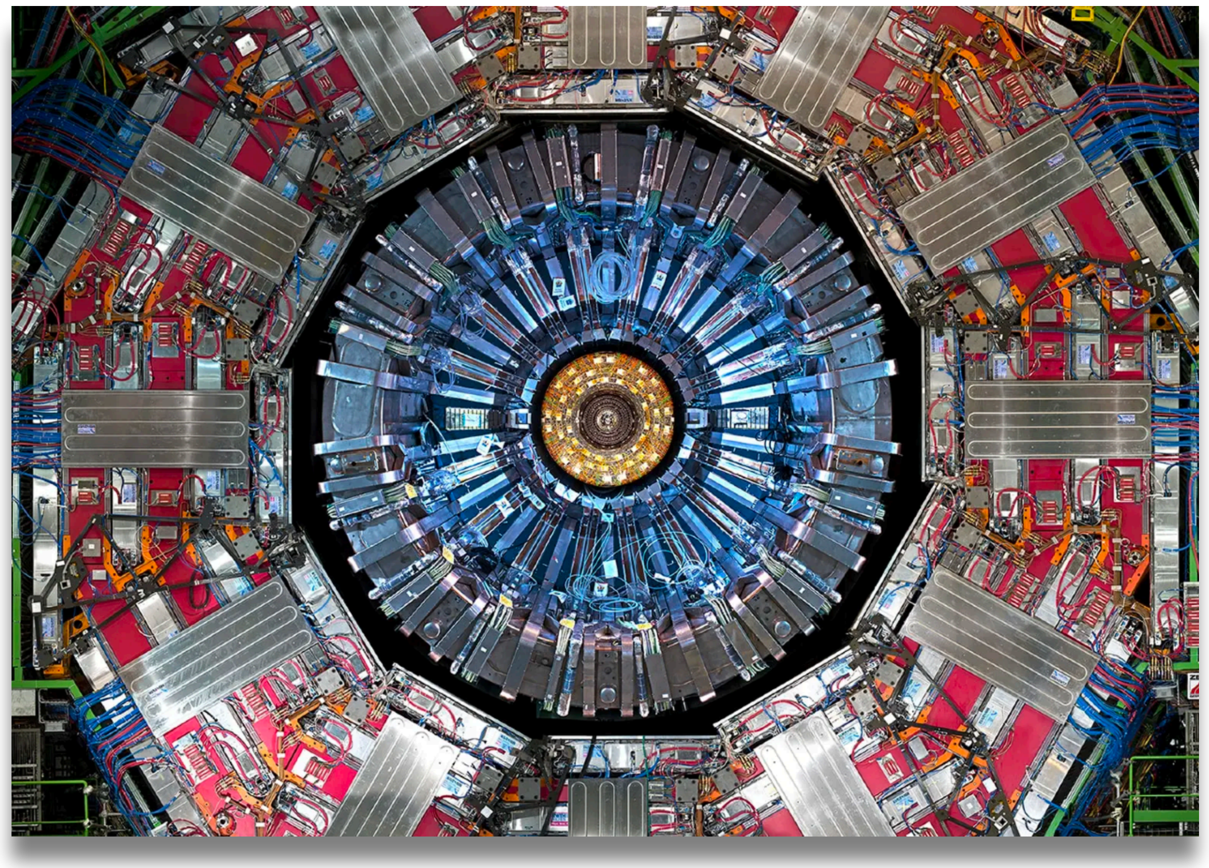




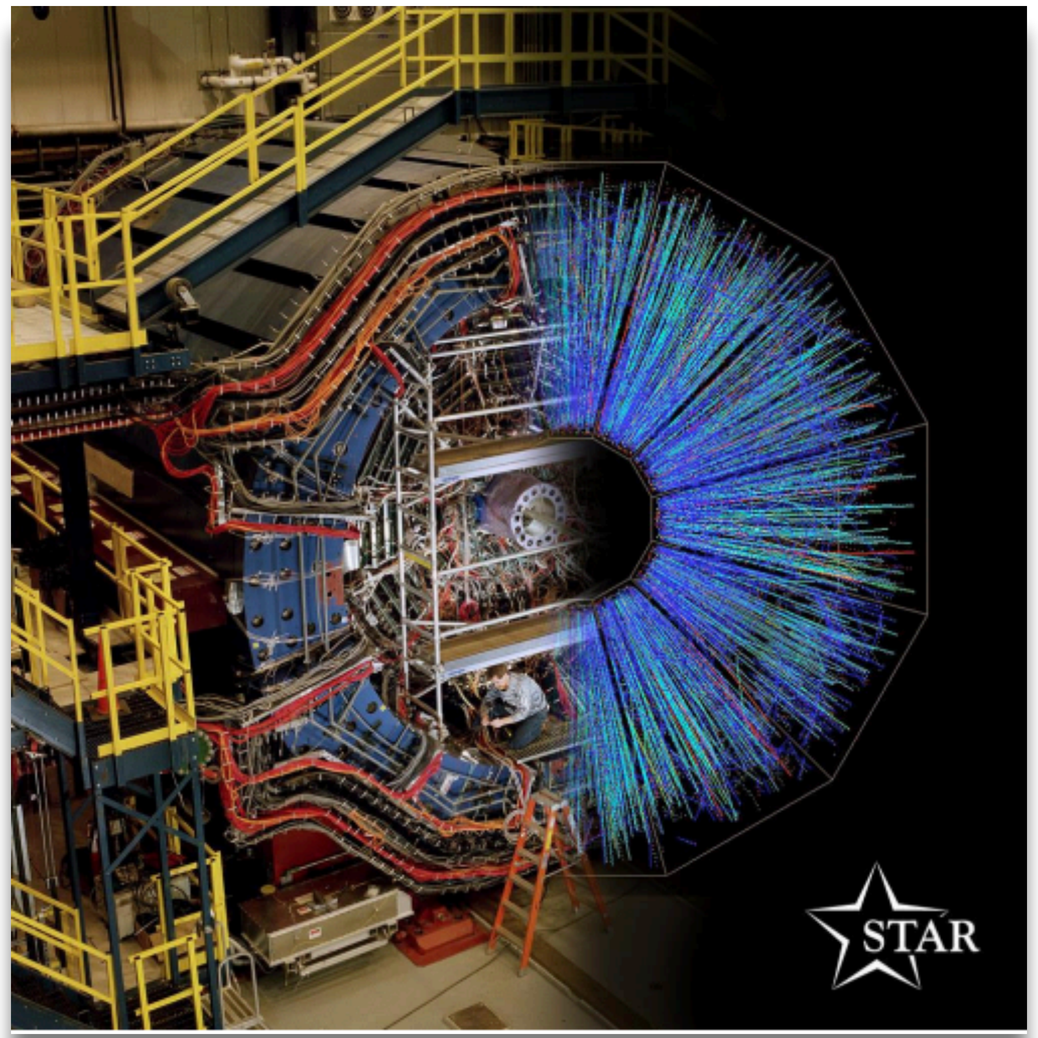
IV. Heavy Flavor Jets

III. Confinement Dynamics

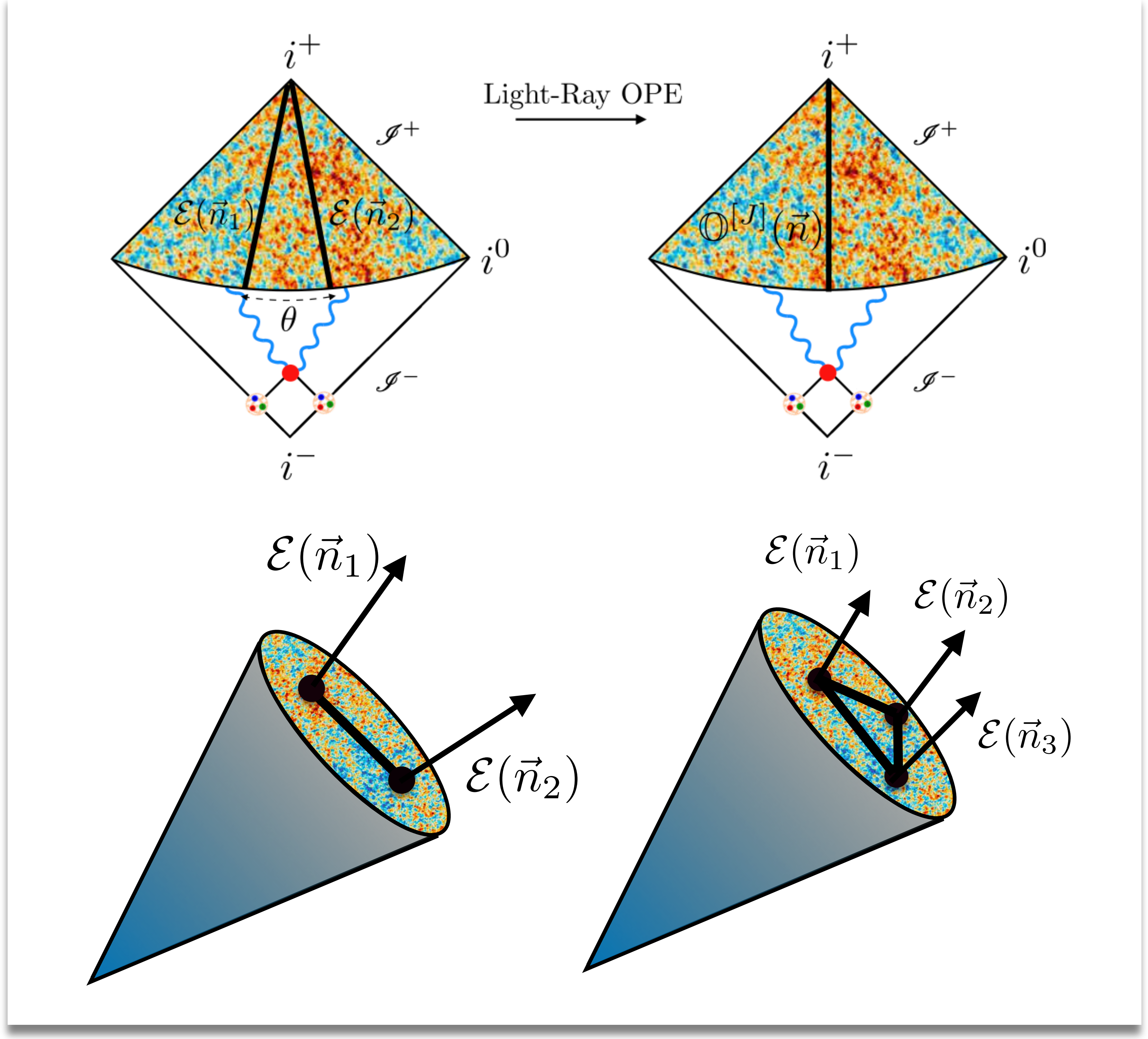




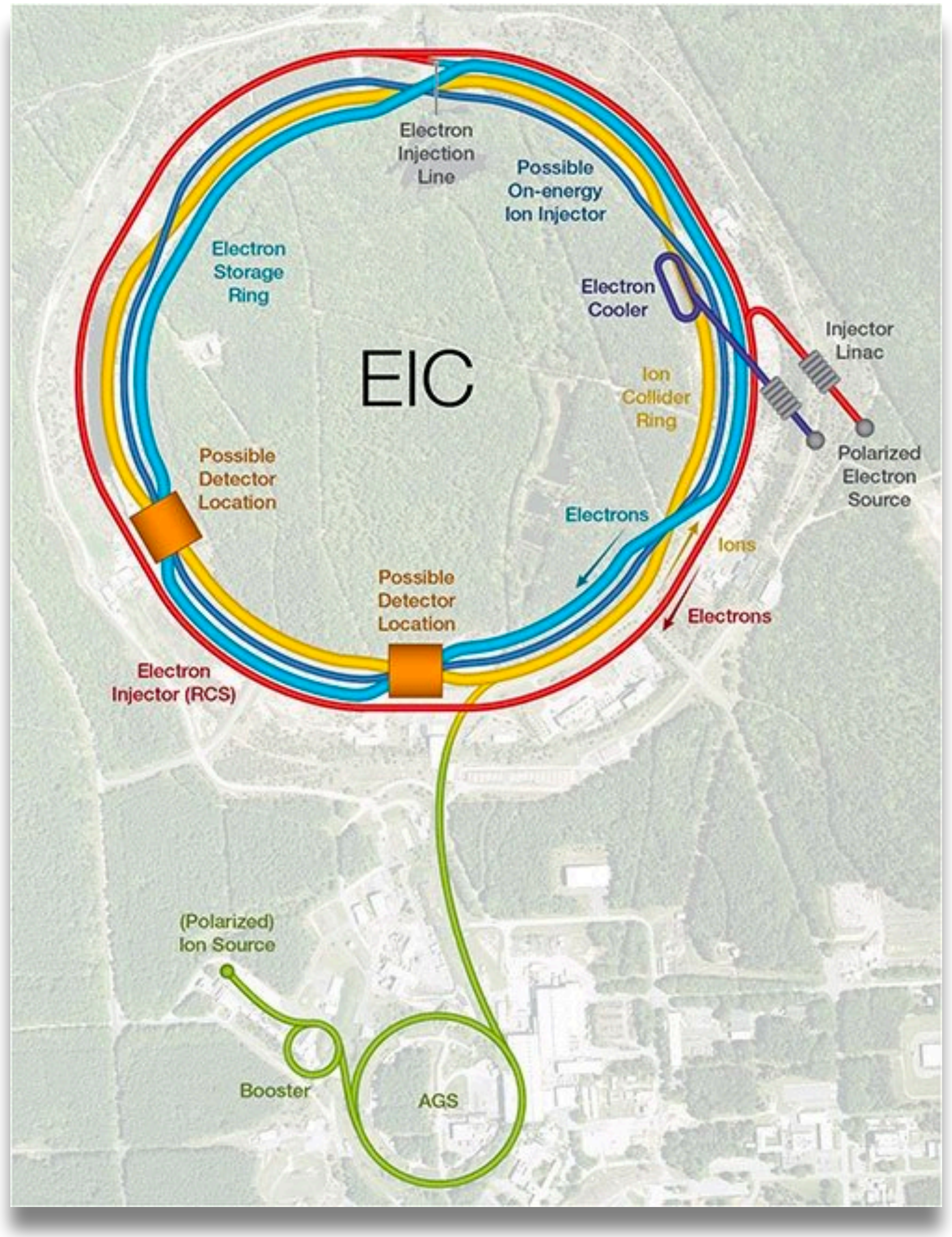
LHC



RHIC



Energy correlators provide sharp link between underlying field theory and real world!

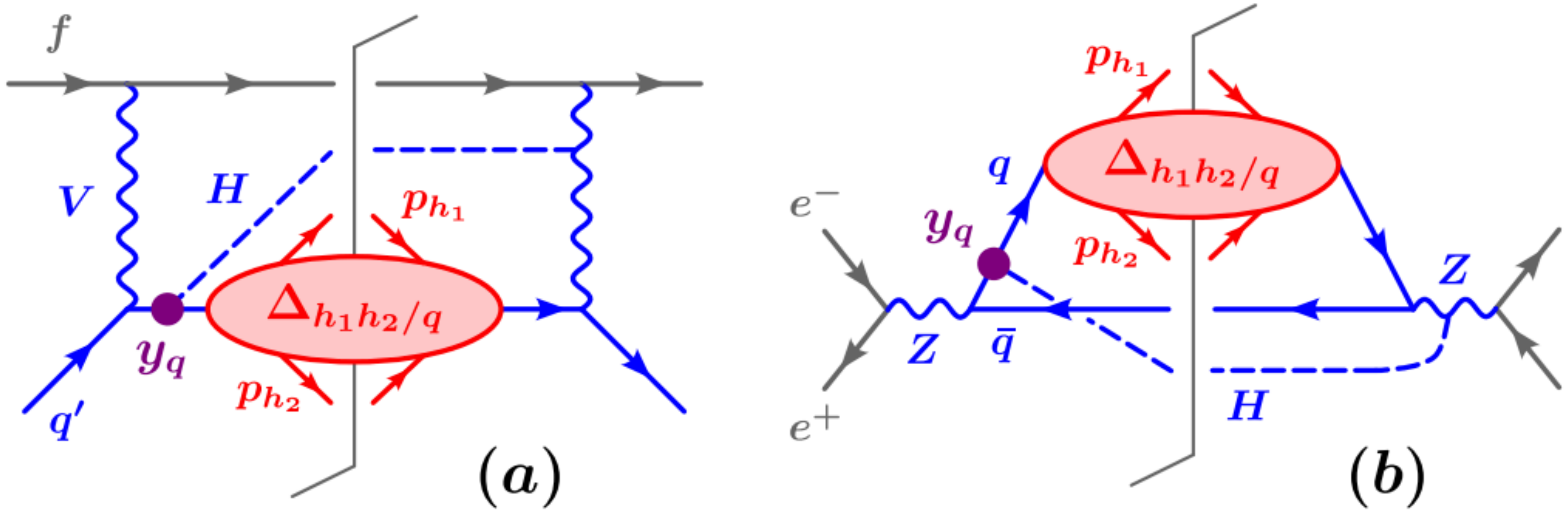


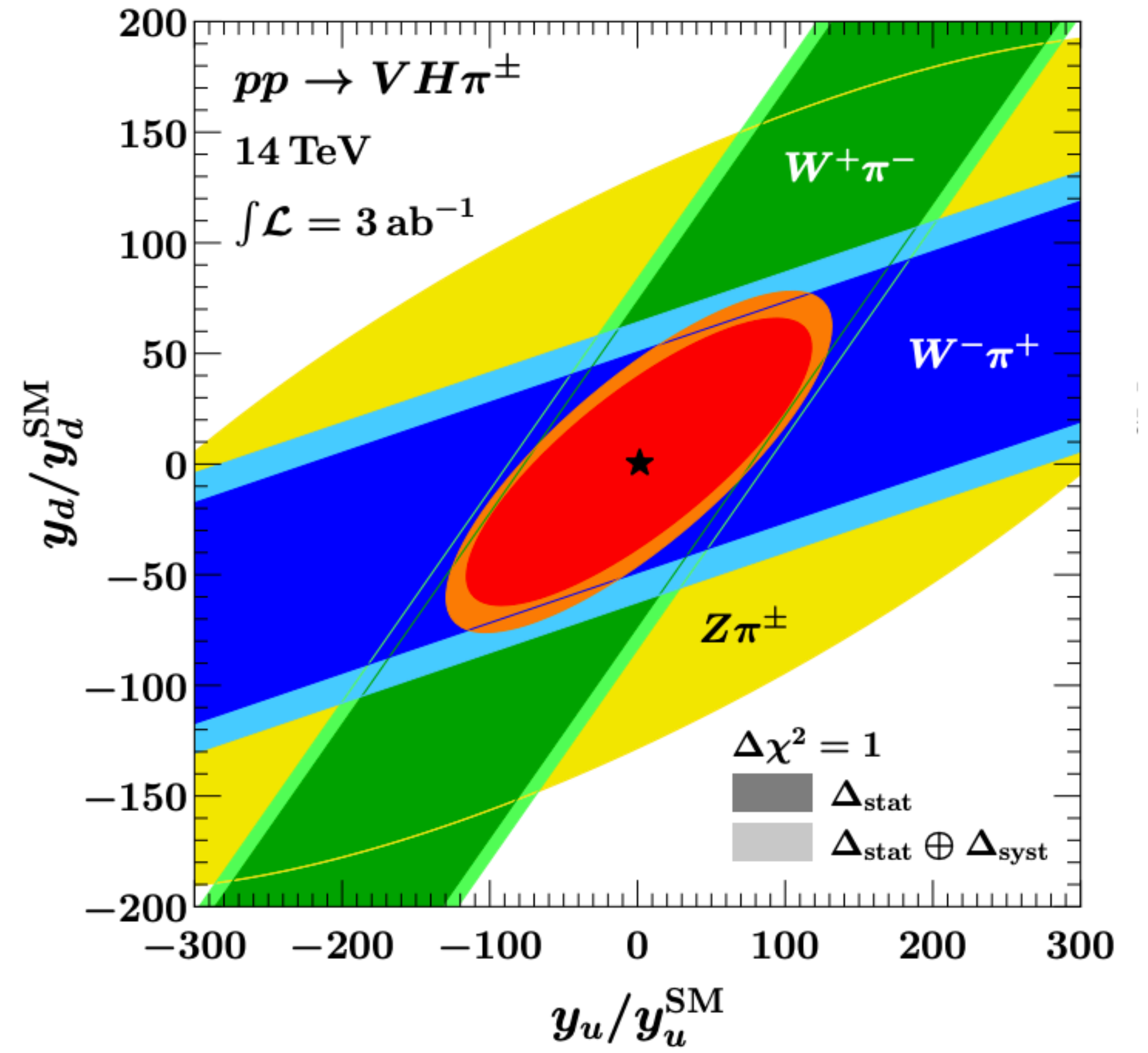
EIC

Backup slides

MANY MORE EXCITING PROPOSALS…

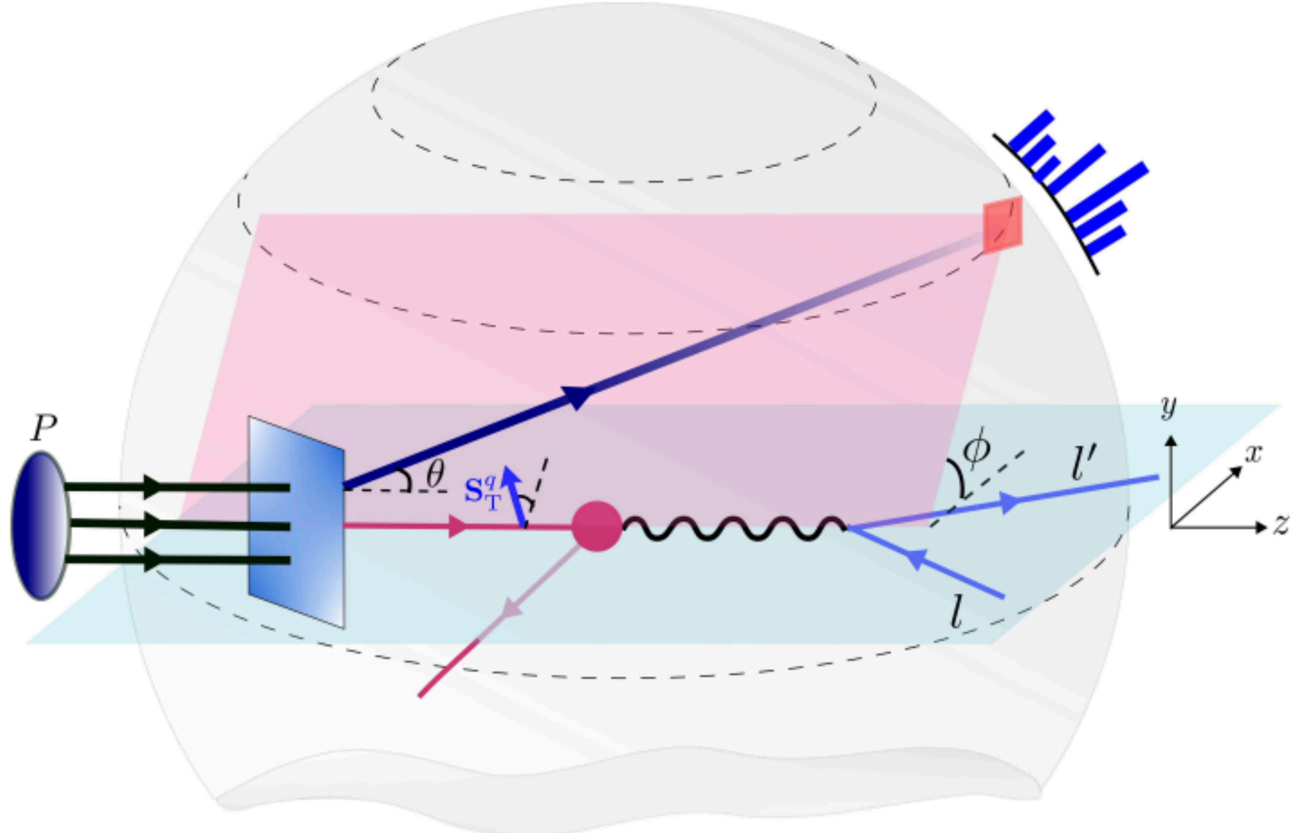
- **Using di-hadron correlations, improve light-quark Yukawa coupling determinations**

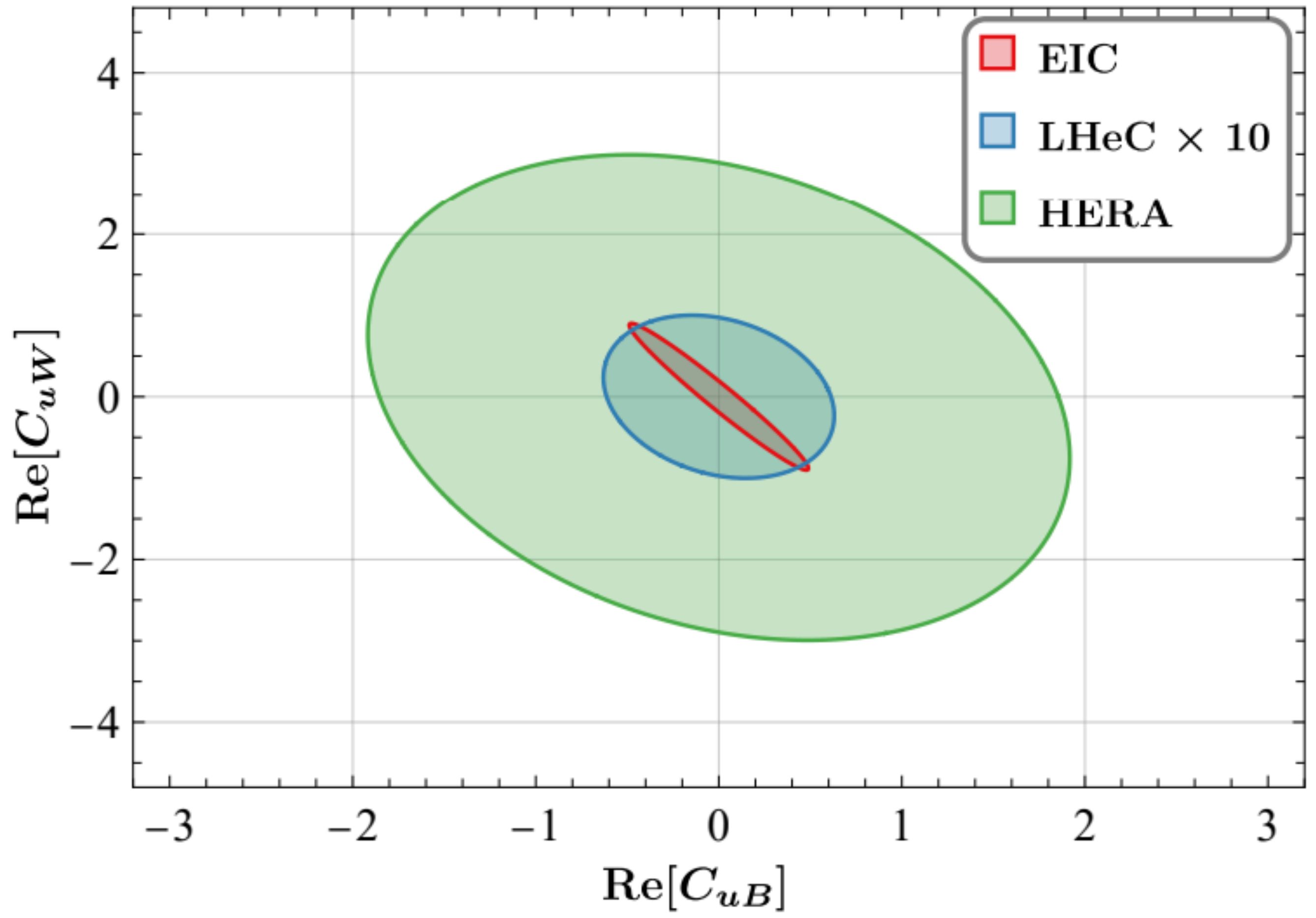




Michel `25

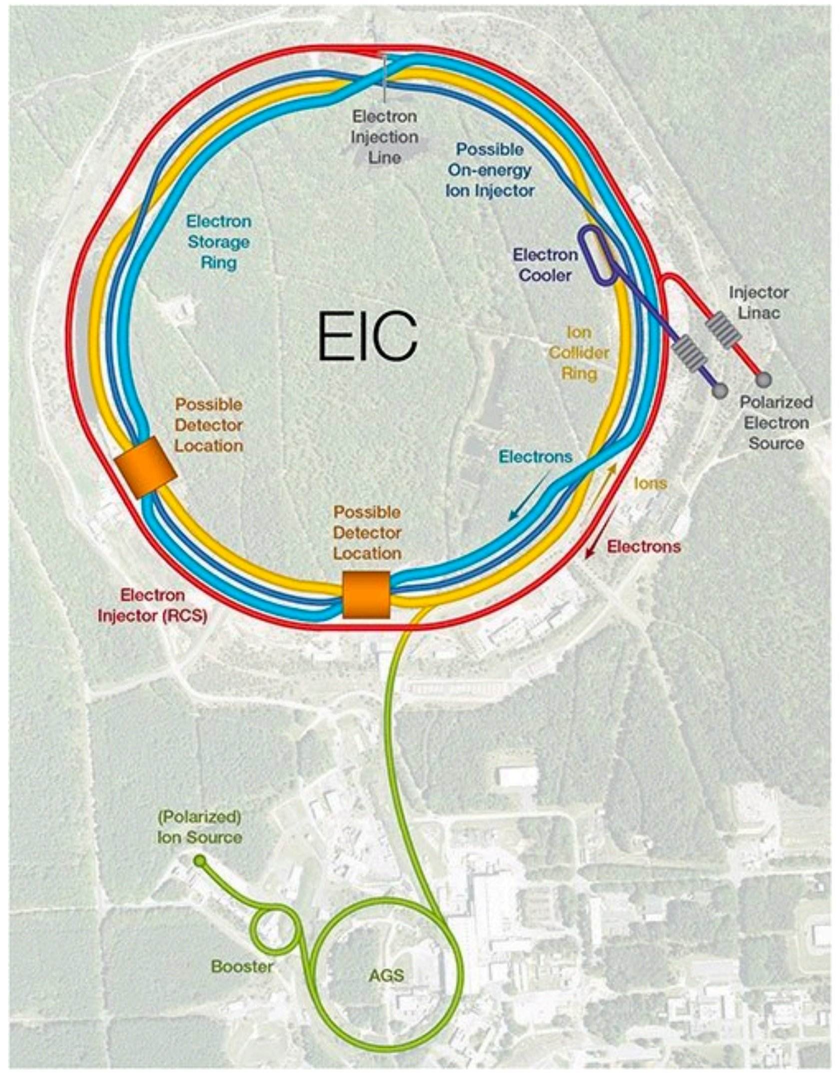
- **Using nucleon-energy correlators, enable constraints on the light-quark dipole operators**



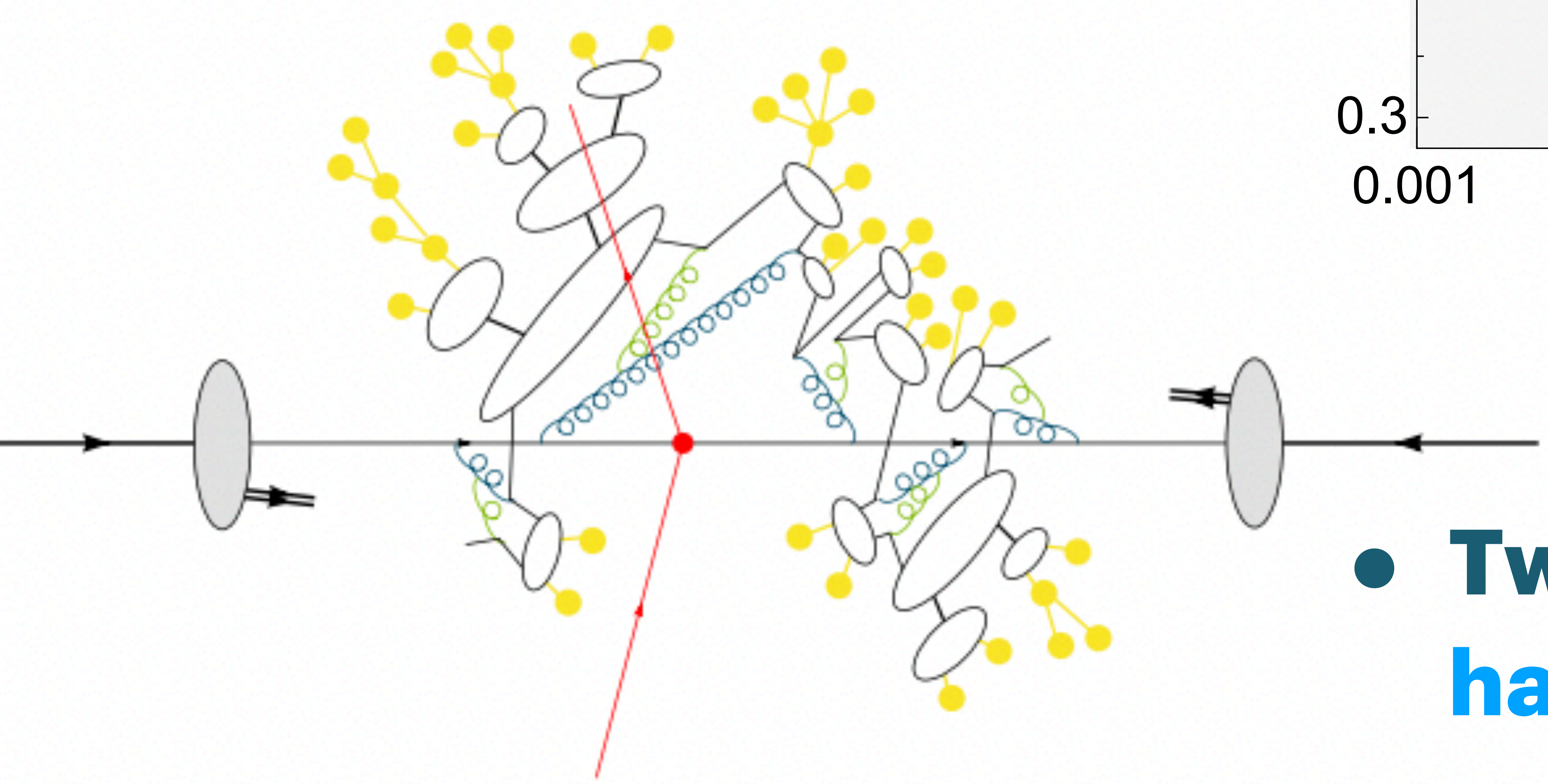


Huang, Tong, Wang `25

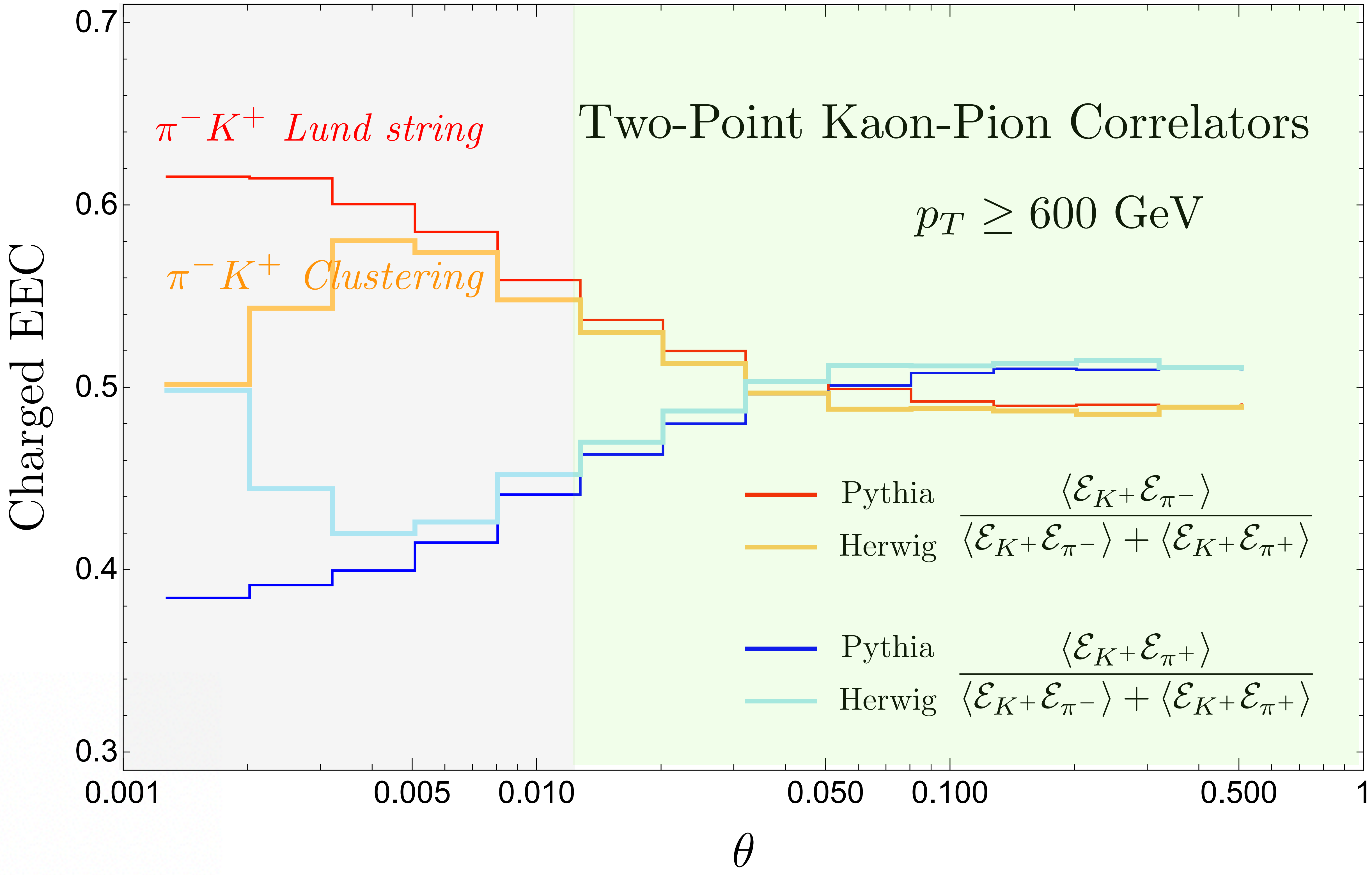
DISCRIMINATING HADRONIZATION MECHANISMS

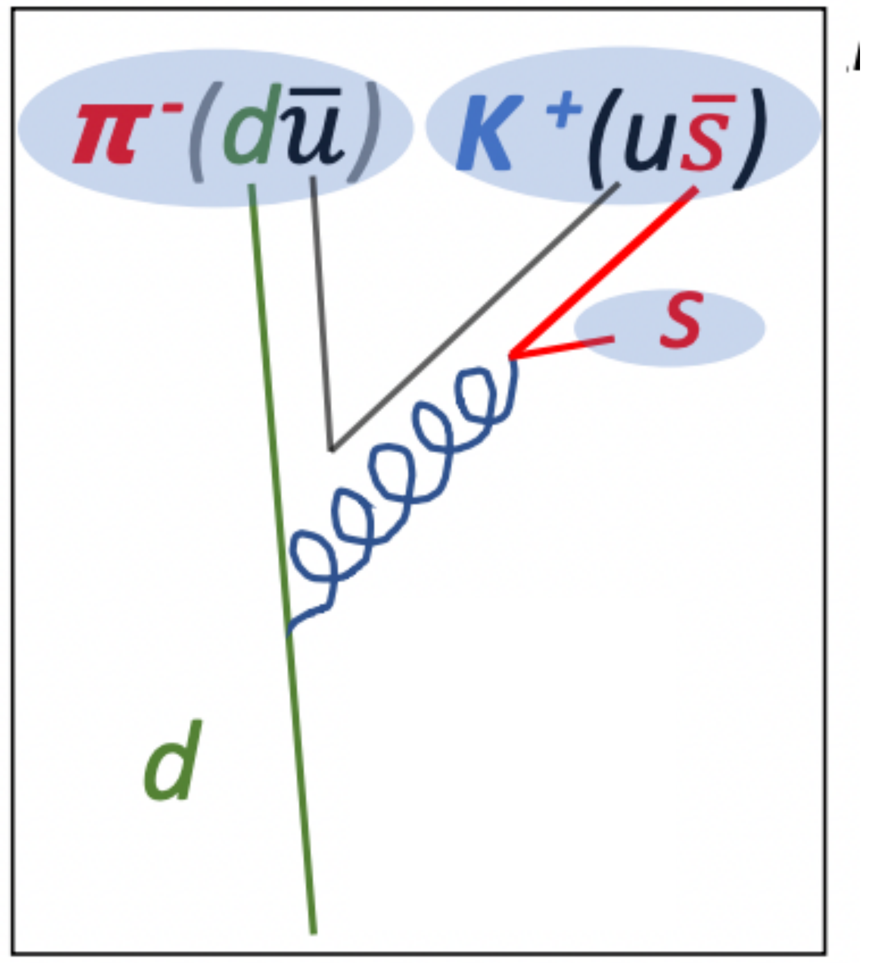


Clustering model (Herwig)



EIC can discriminate this! **KL**, *Moult, Song, Sterman [In Progress]*



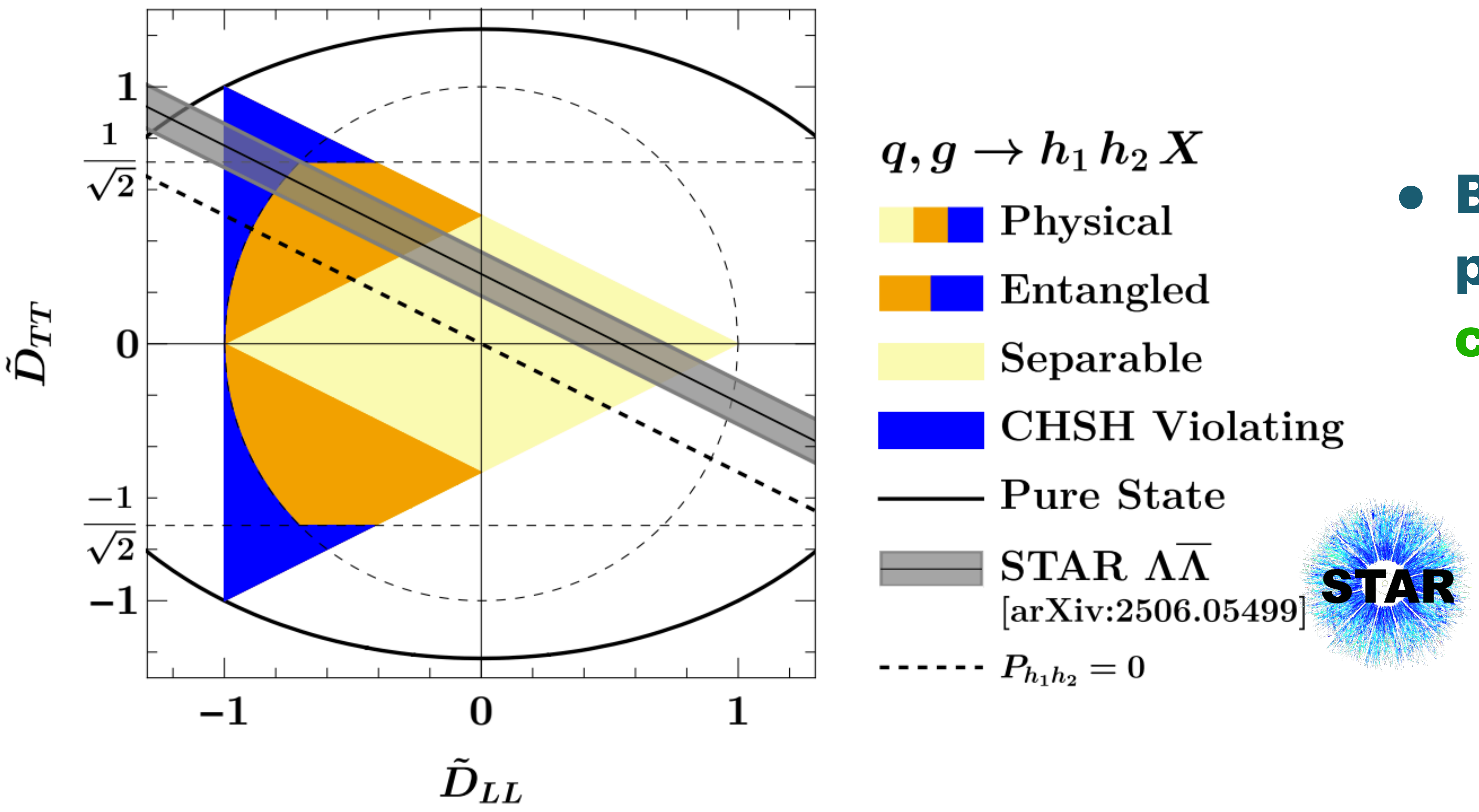


Lund string model (Pythia)

- **Two-point charged correlators already nontrivially probe the two hadronization mechanisms by eye, and pave the path to go even beyond!**

$\langle \mathcal{E}_{\uparrow}(\vec{n}_1)\mathcal{E}_{\uparrow}(\vec{n}_2)\rangle$ TESTING THE QUANTUMNESS OF CONFINEMENT PROCESS

*Kuk, **KL**, Michel, Sun `25*
*Casi, **KL**, Moult [In Progress]*

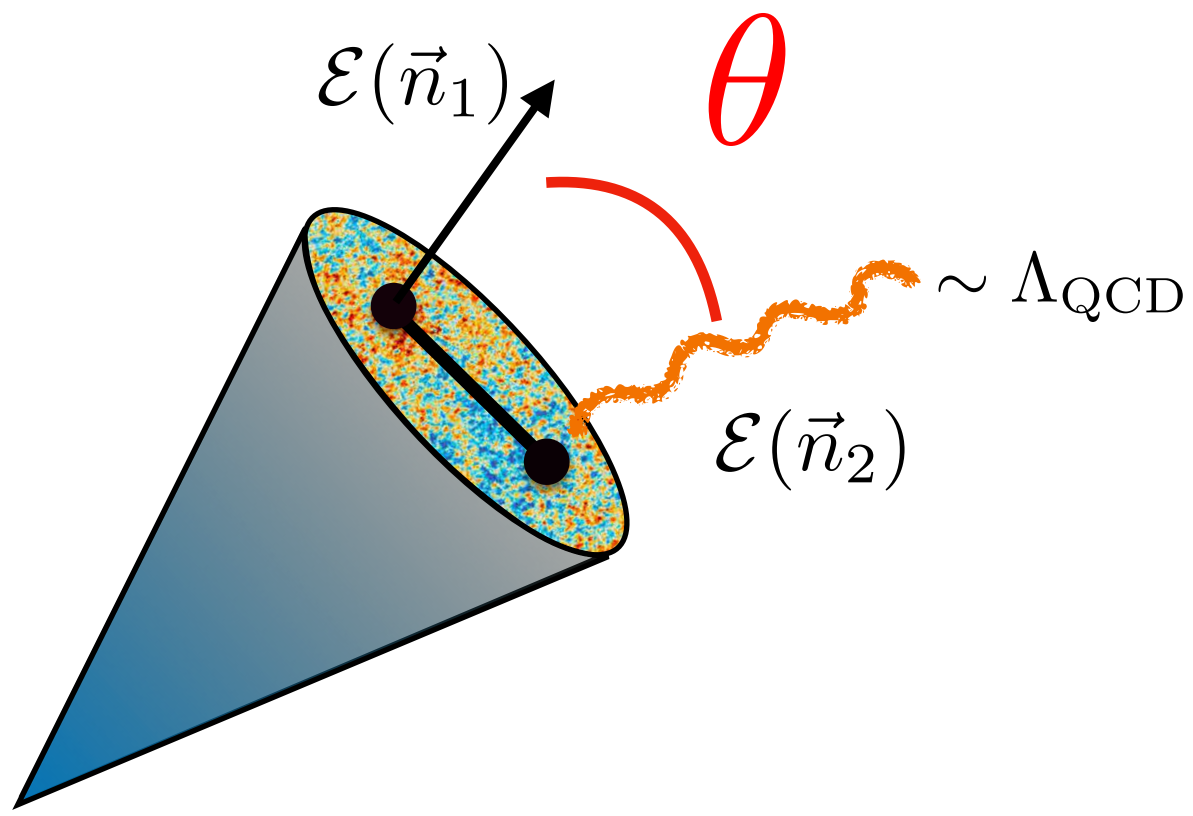


- By additionally probing spins of outgoing hadron pairs, we are able to determine whether the confinement process is quantum.

POWER CORRECTIONS

1. Measurements on Tracks
2. Power corrections
3. Improved perturbative accuracy

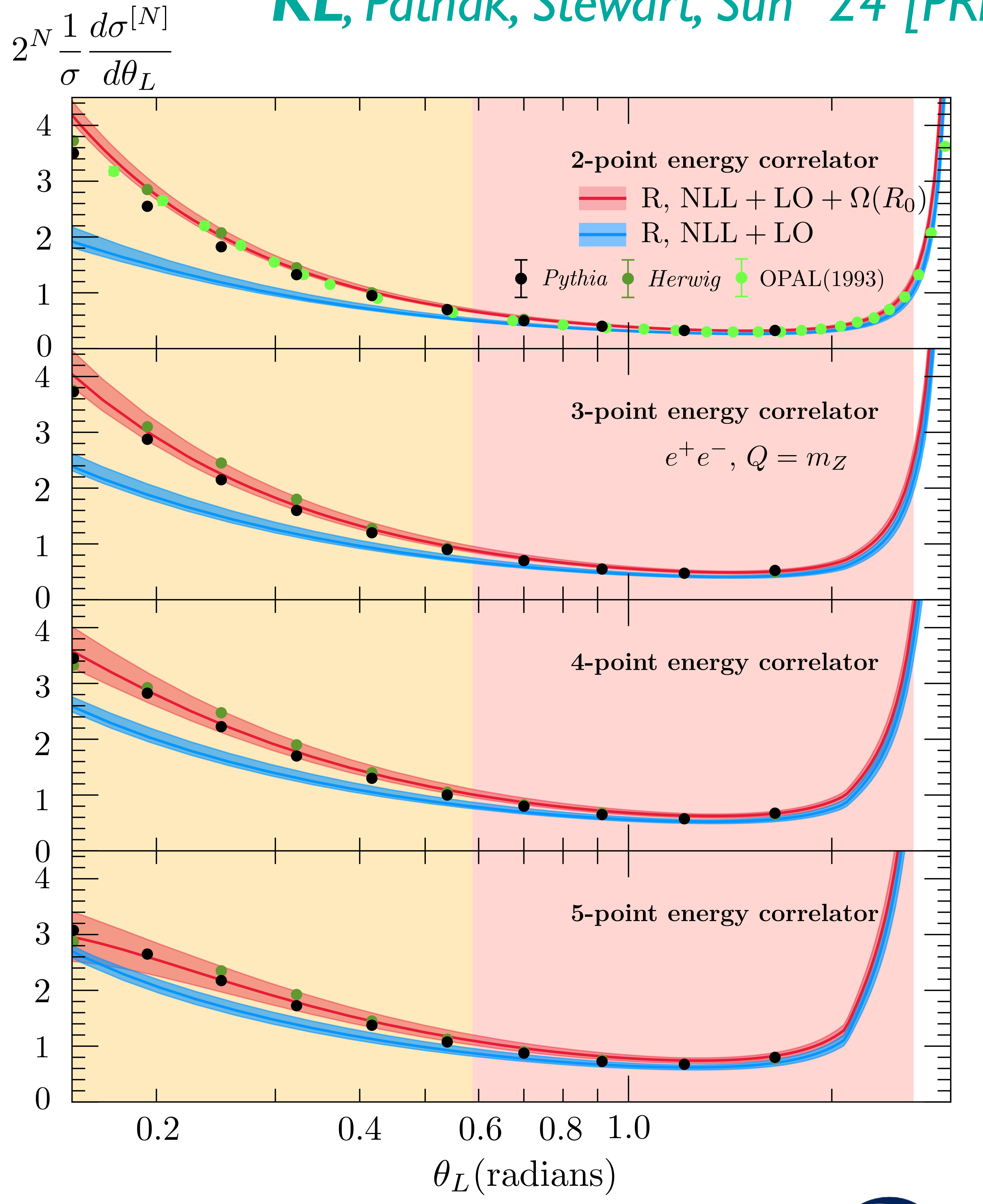
KL, Pathak, Stewart, Sun `24 [PRL]

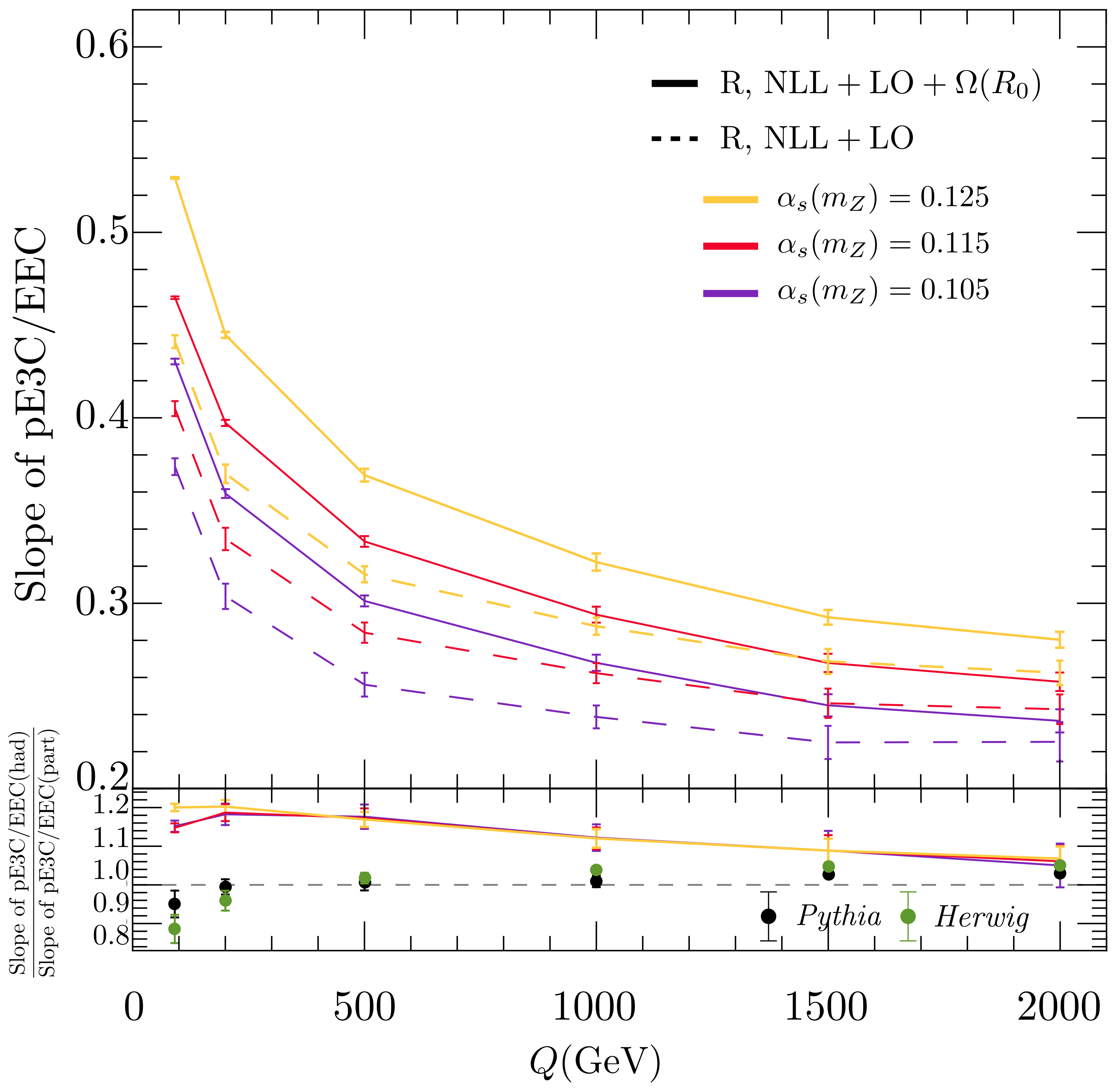


e^+e^- in the collinear limit exhibits same universal behavior as hadron jets

$$\frac{1}{\sigma}\frac{d\sigma^{[N]}}{dx_L} = \frac{1}{\sigma}\frac{d\hat{\sigma}^{[N]}}{dx_L} + \boxed{\frac{N}{2^N}\frac{\bar{\Omega}_{1q}}{Q\left(x_L\left(1-x_L\right)\right)^{3/2}}}$$

Universal Power Corrections





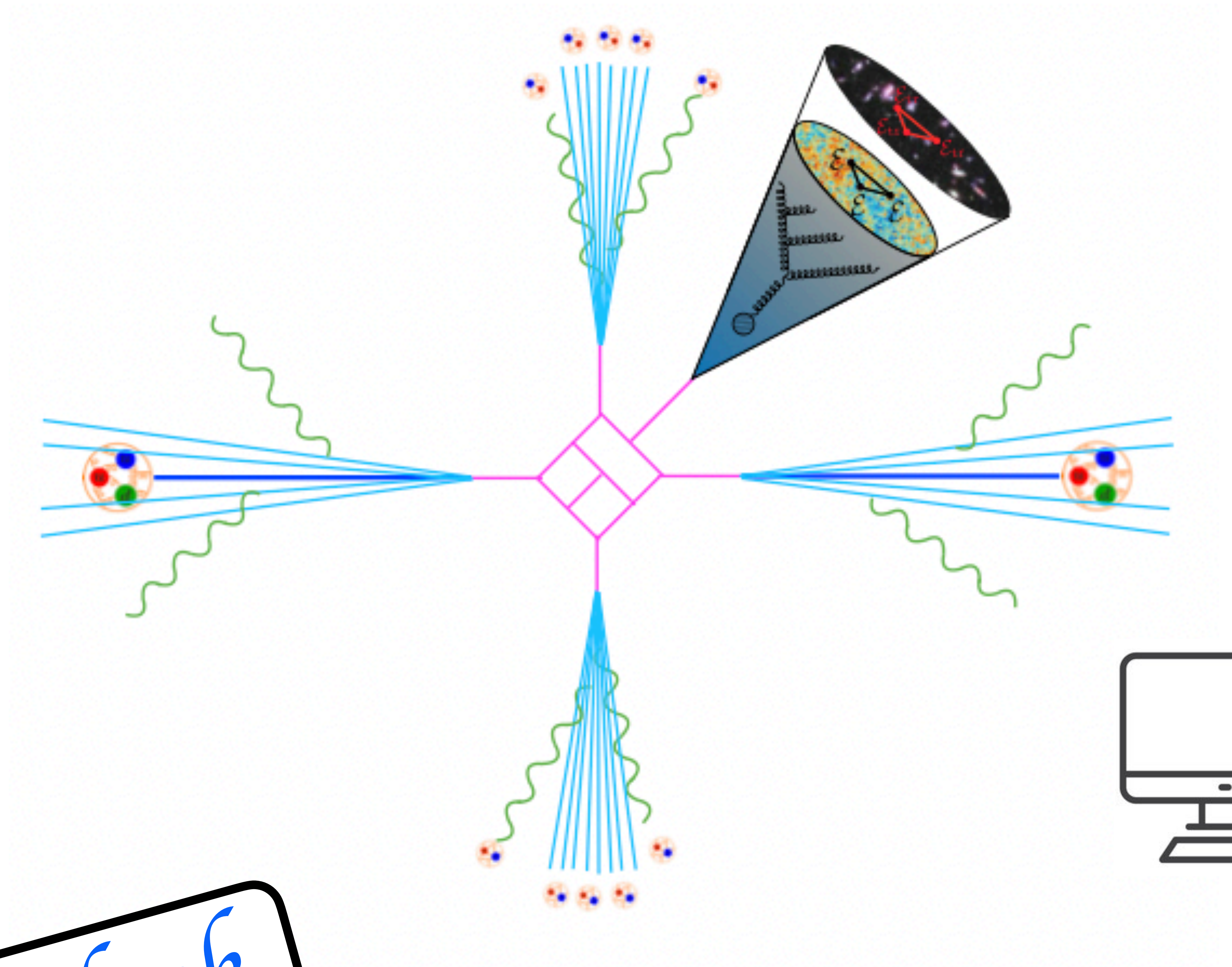
At Q=1000, 10% impact of power correction

LEP analyses revitalized! Bossi et al `25

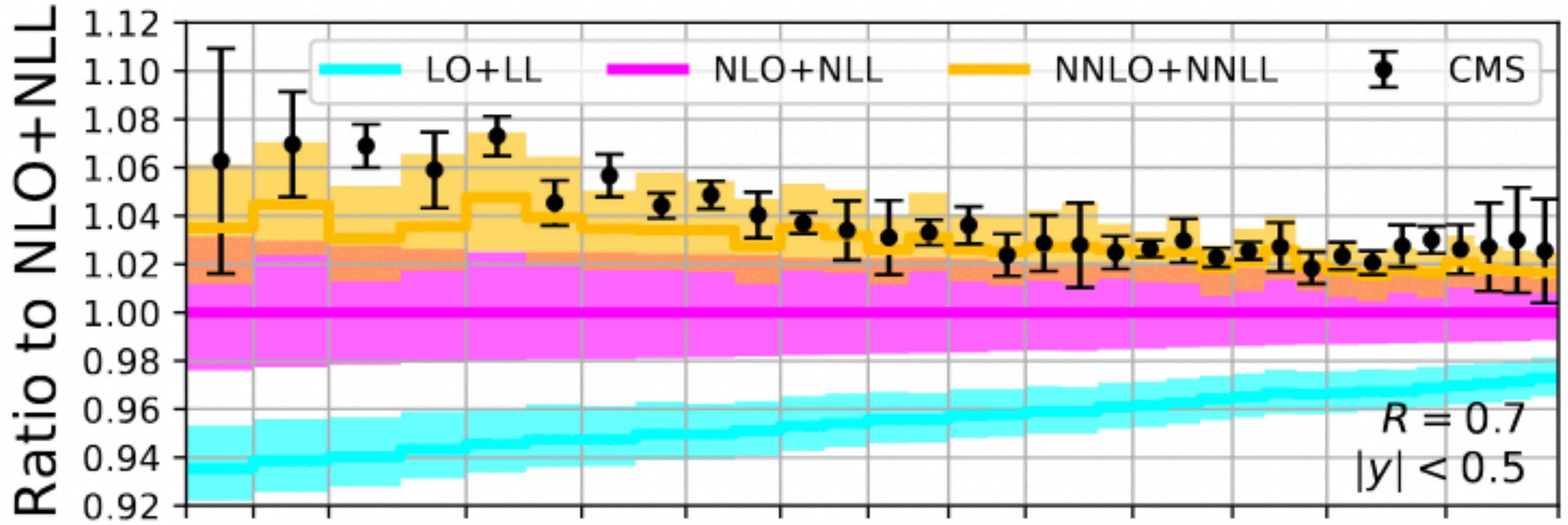
IMPROVING PERTURBATIVE ACCURACY

1. Measurements on Tracks
2. Power corrections
3. Improved perturbative accuracy

$$\langle\psi\left|\mathcal{E}\left(\vec{n}_1\right)\cdots\mathcal{E}\left(\vec{n}_{J-1}\right)\right|\psi\rangle$$



- Dominant uncertainty was from the calculation of the single jet state.



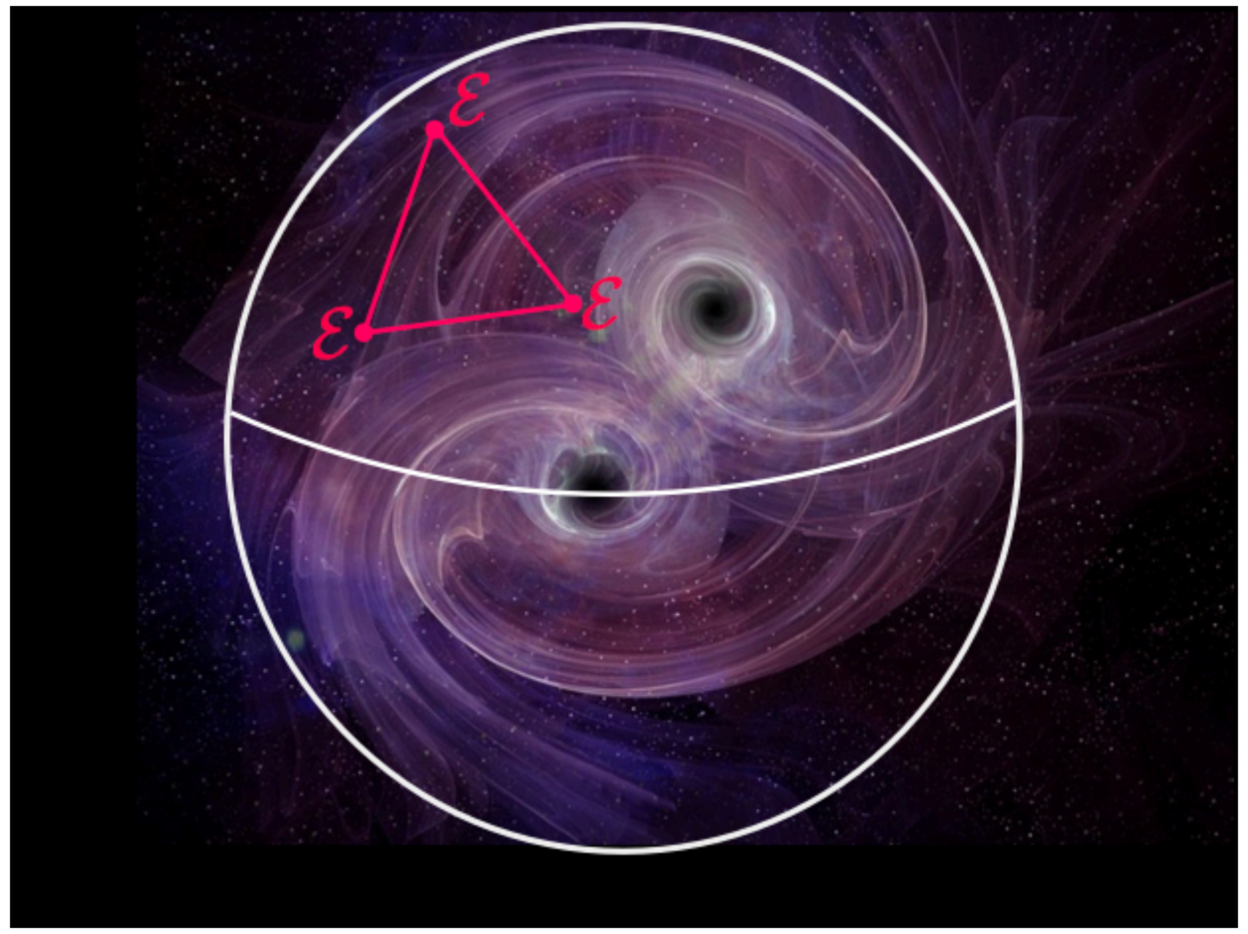
~1 mil CPU hours

*Poncelet, **KL**, Moult, Terry, Zhang `25*
***KL**, Moult, Zhang `24, `24*

- Our factorization theorem is able to interface with state-of-the-art perturbative calculations to import into jet substructure studies

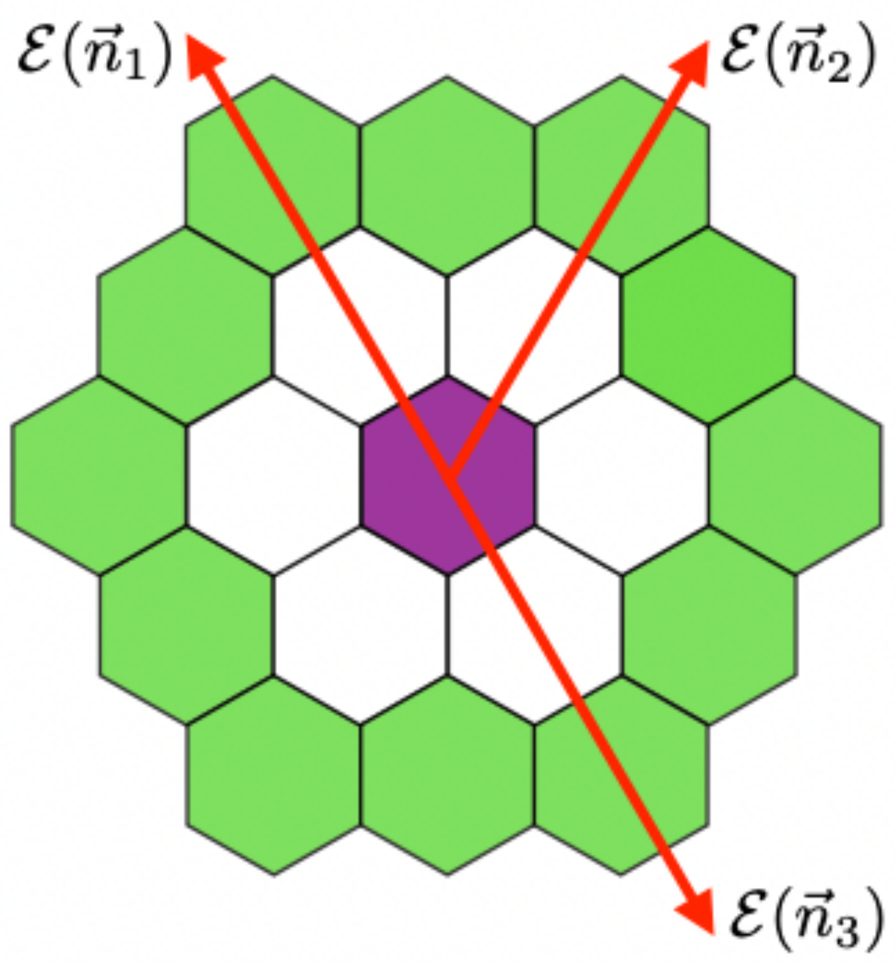
LORENTZIAN FIELD THEORETIC OBJECT: ASYMPTOTIC DETECTORS APPLIED TO DIFFERENT SYSTEM

Gravity



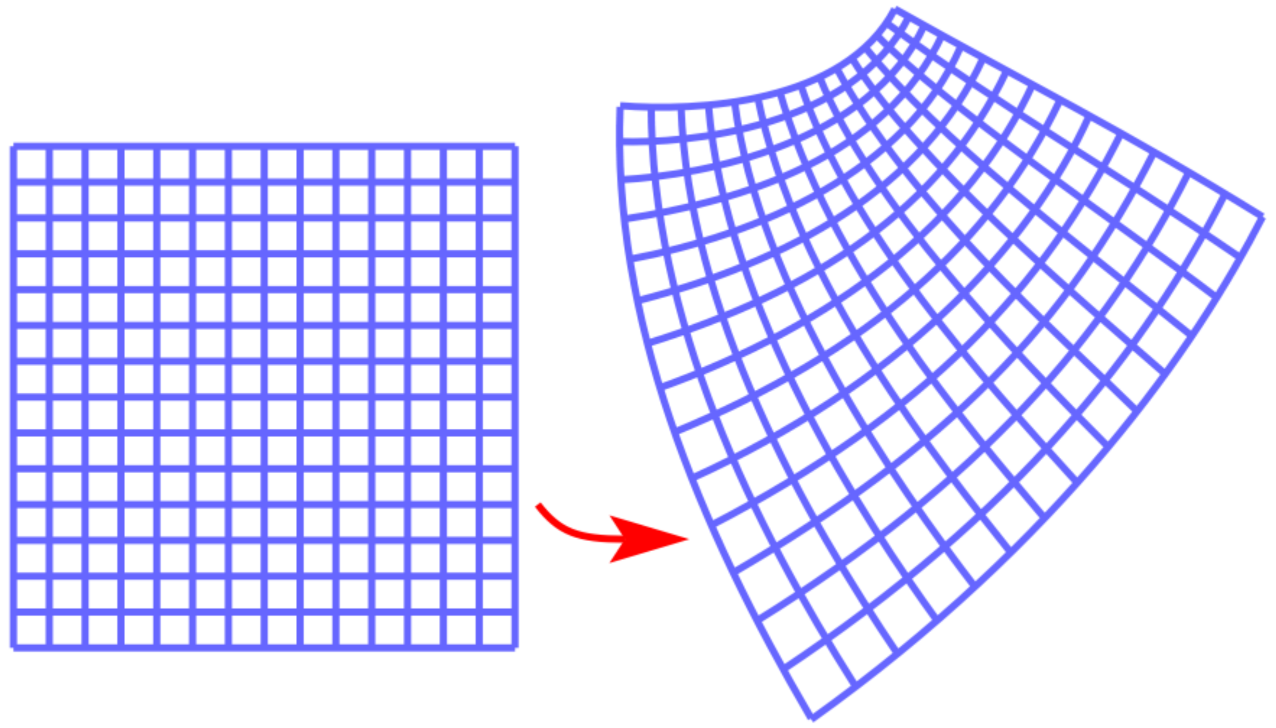
Herrmann, Kologlu, Moult, Parra-Martinez, Yan `25

2+1 Quantum Computing



***KL**, Turro, Yao `24*
*Herrmann, Kang, **KL**, Moran, Zhou [In Progress]*

Conformal Field Theories



Hofman, Maldacena `08

Importantly, energy correlators can be explored in general Lorentzian field theories.
QFT connections allow cross-pollination of ideas from different systems / field theories