Harnessing intricacies of Jets for Breakthroughs in QCD at the Collider Frontier

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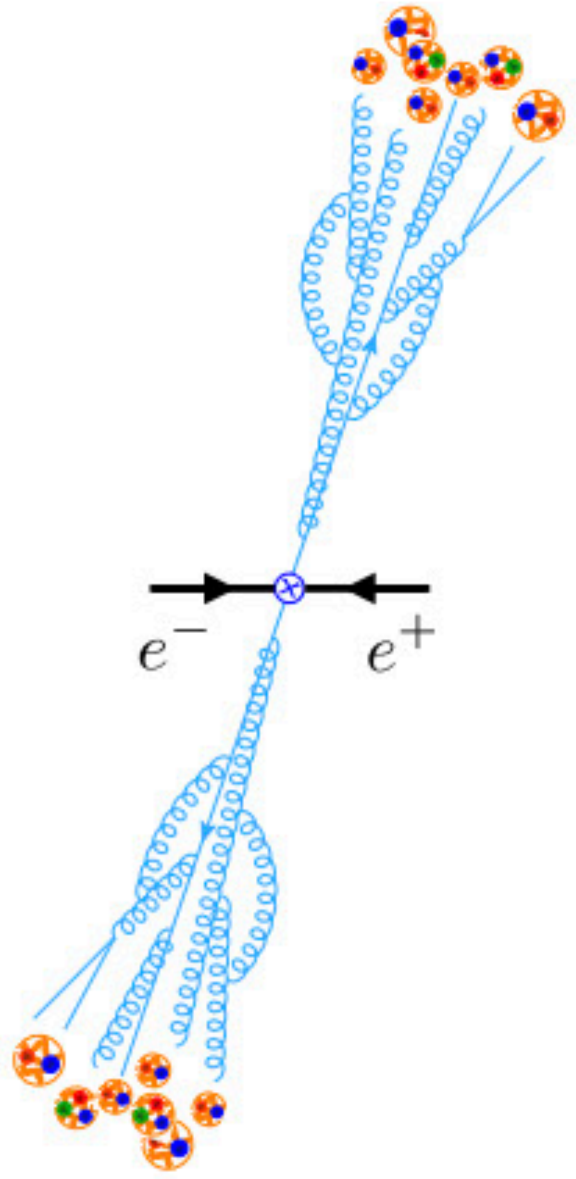
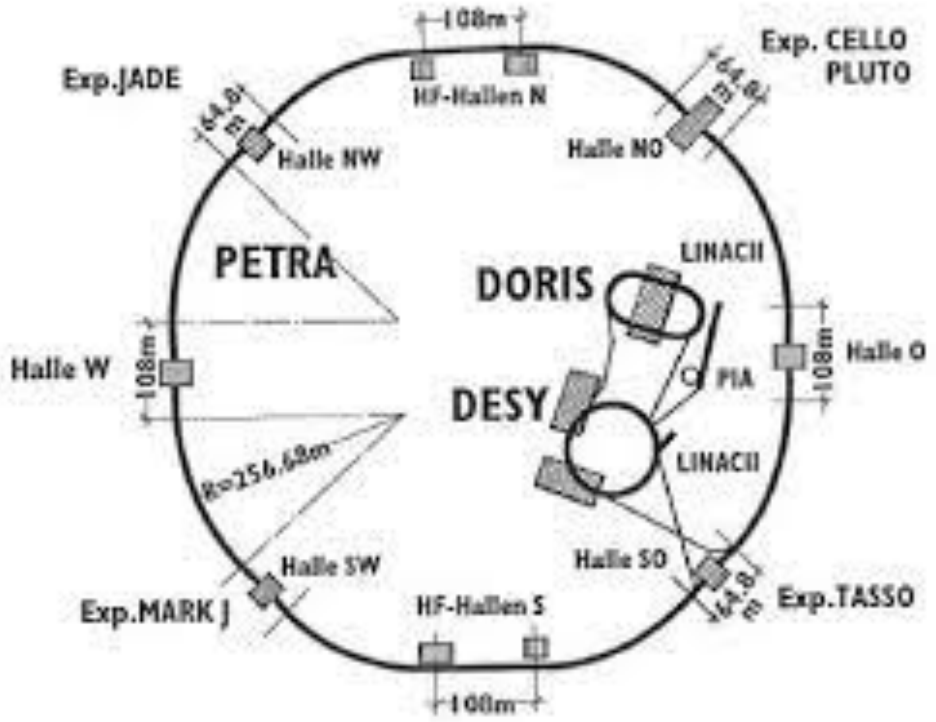
CTP, MIT

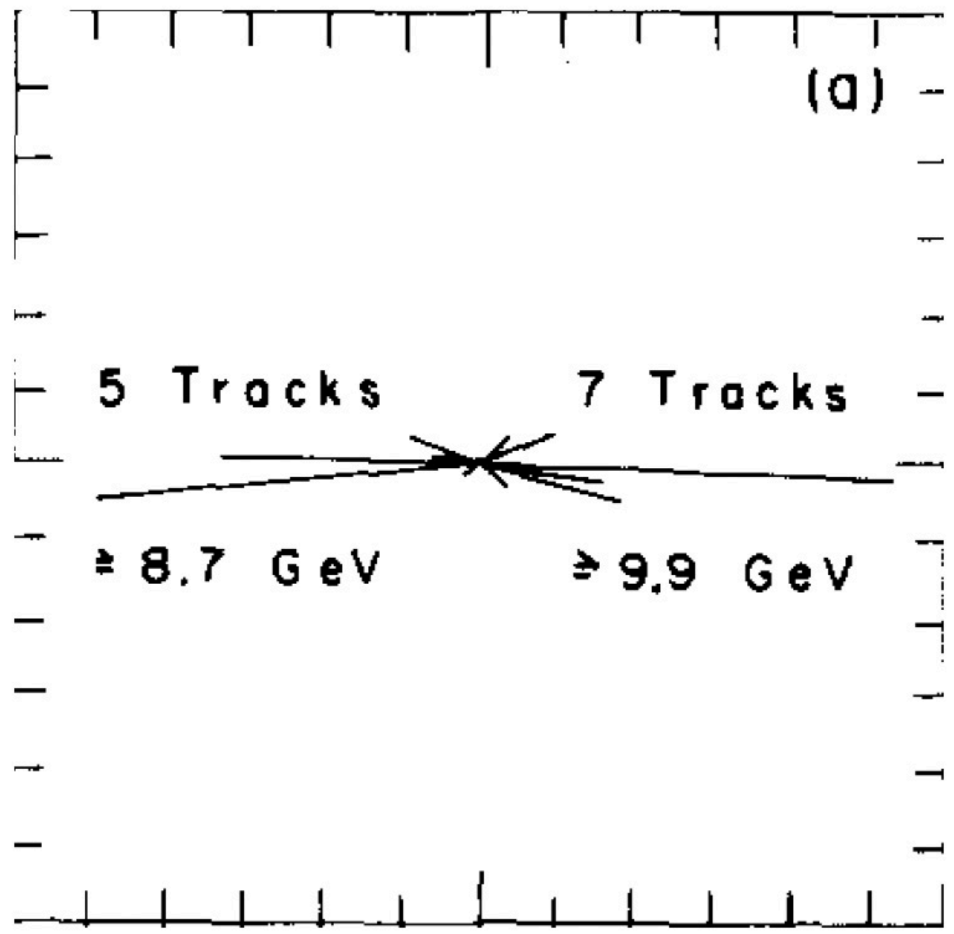
Universität Wien
November 2024

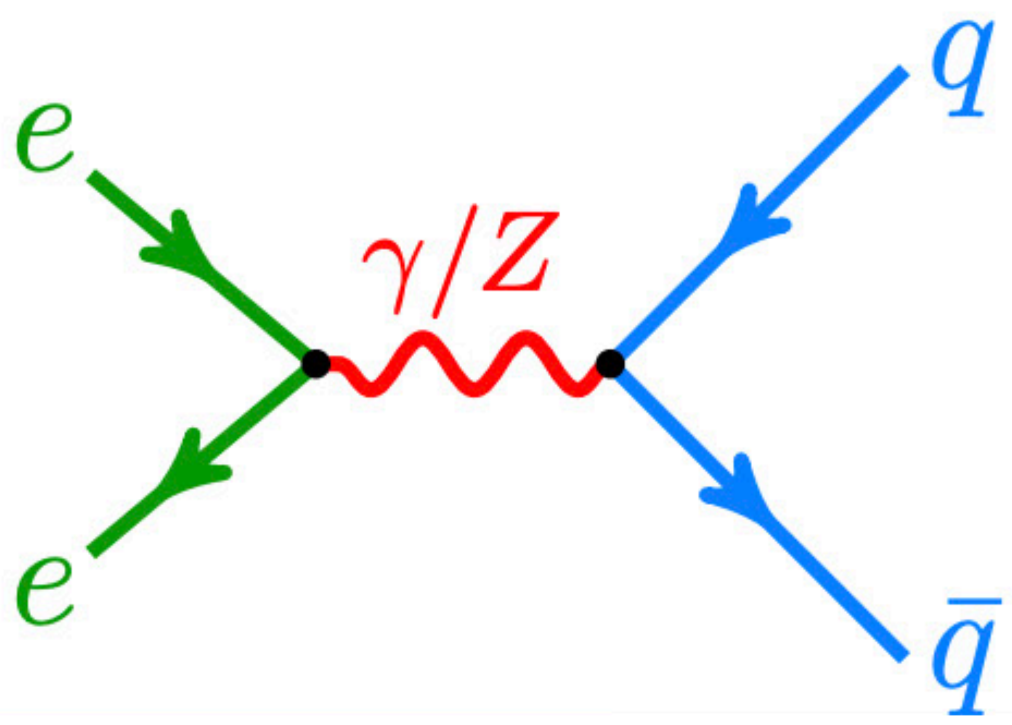
THE DAWN OF QCD: FROM PARTONS TO JETS



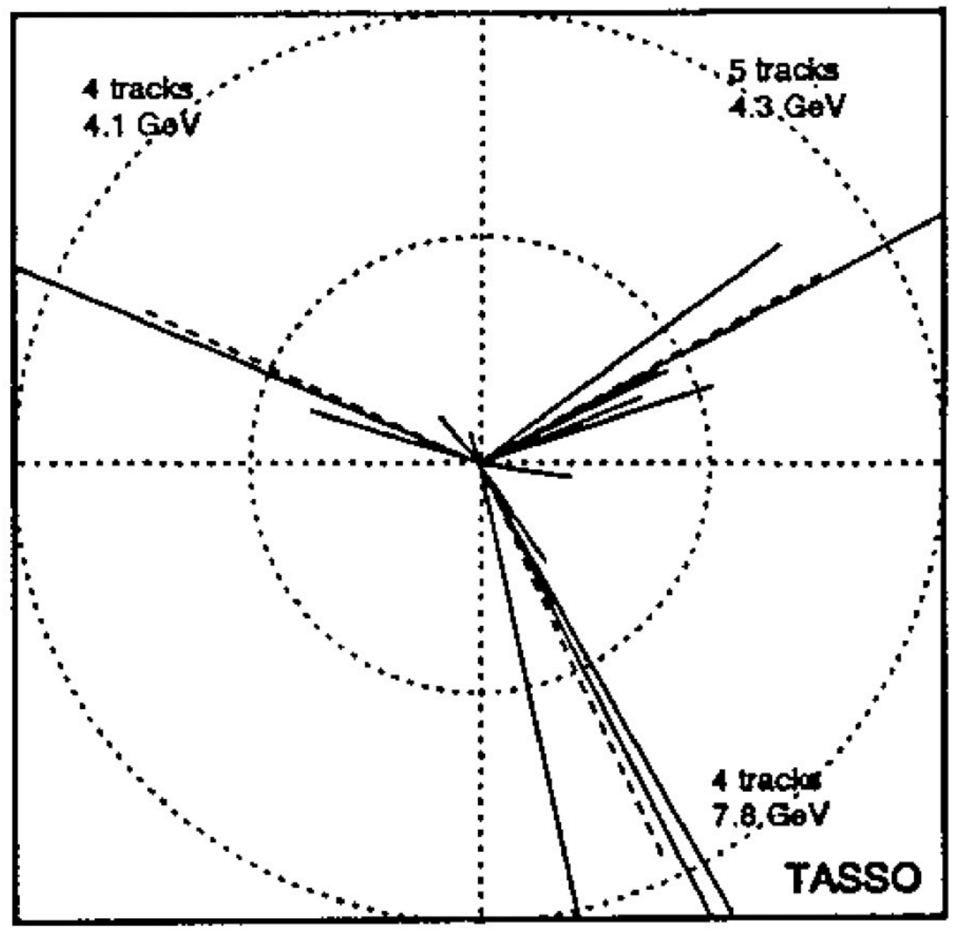


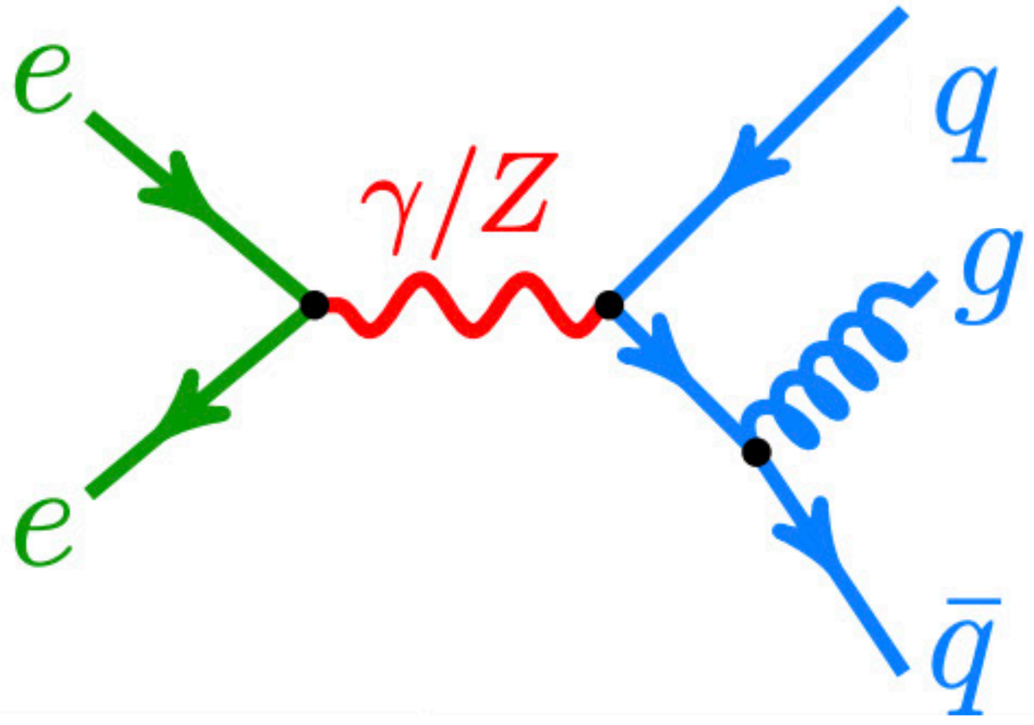
2-jet event

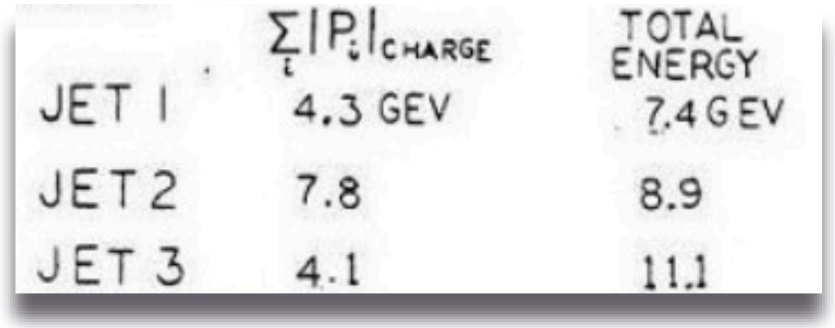




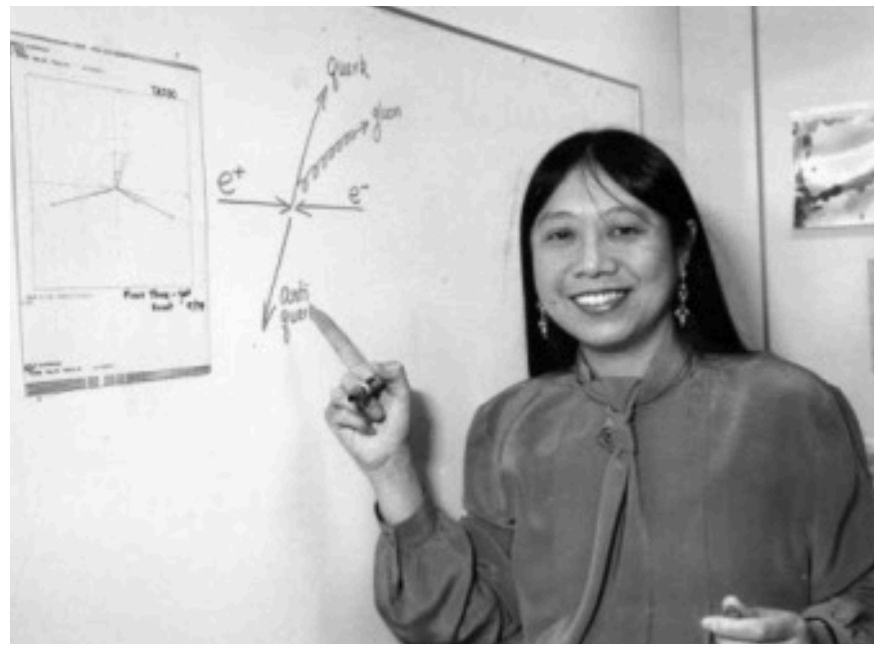
3-jet event







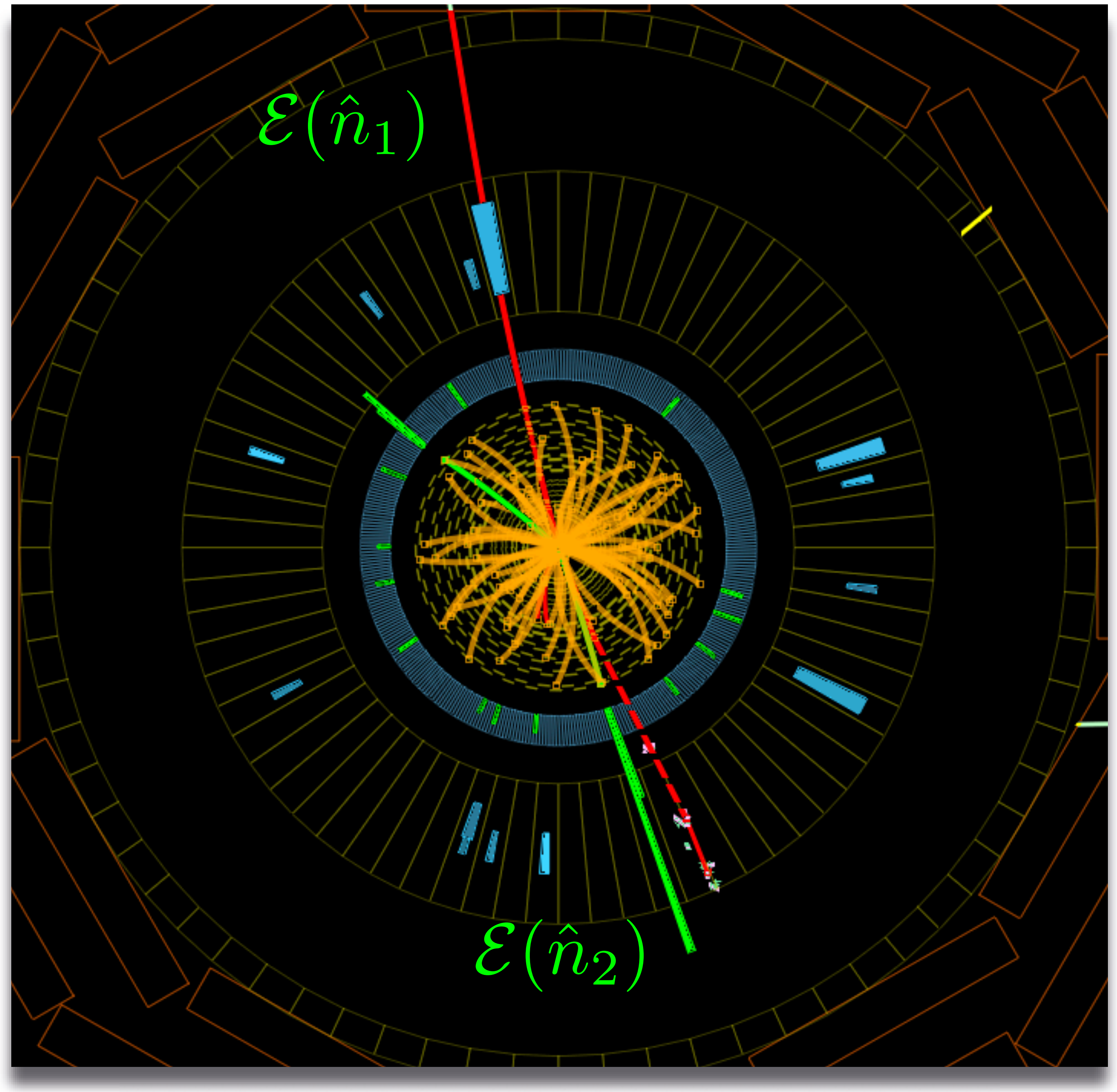
	$\sum_i \lvert P_i \rvert_{CHARGE}$	TOTAL ENERGY
JET 1	4.3 GEV	7.4 GEV
JET 2	7.8	8.9
JET 3	4.1	11.1



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!

JETS AND ENERGY FLOW

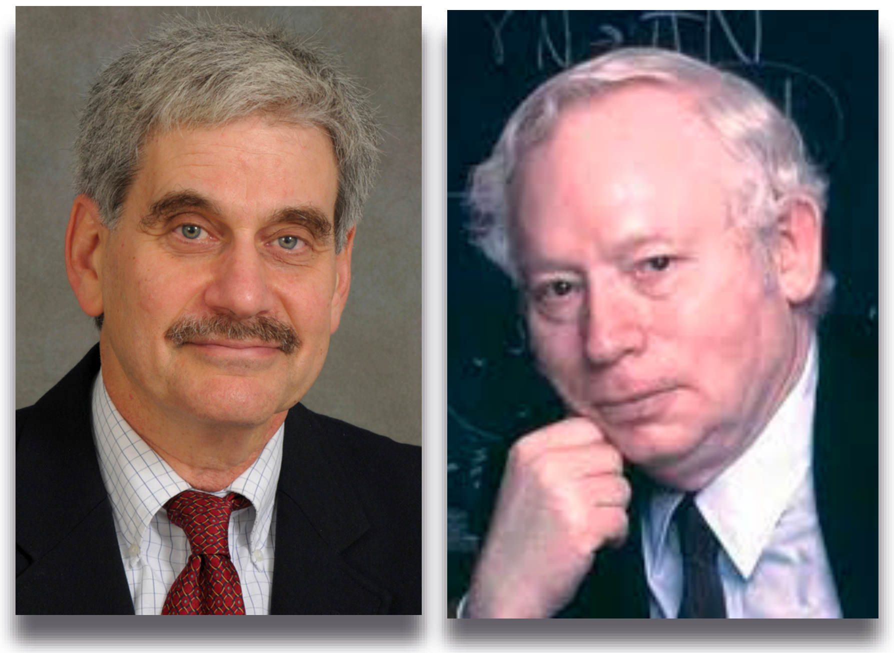


Energy Flow Operators

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

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

Basham, Brown, Ellis, Love, `78-79
Sveshnikov, Tkachov, `95
Korchemsky, Sterman, `01
Bauer, Fleming, Lee, Sterman `08



Sterman `75
Sterman, Weinberg `77

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

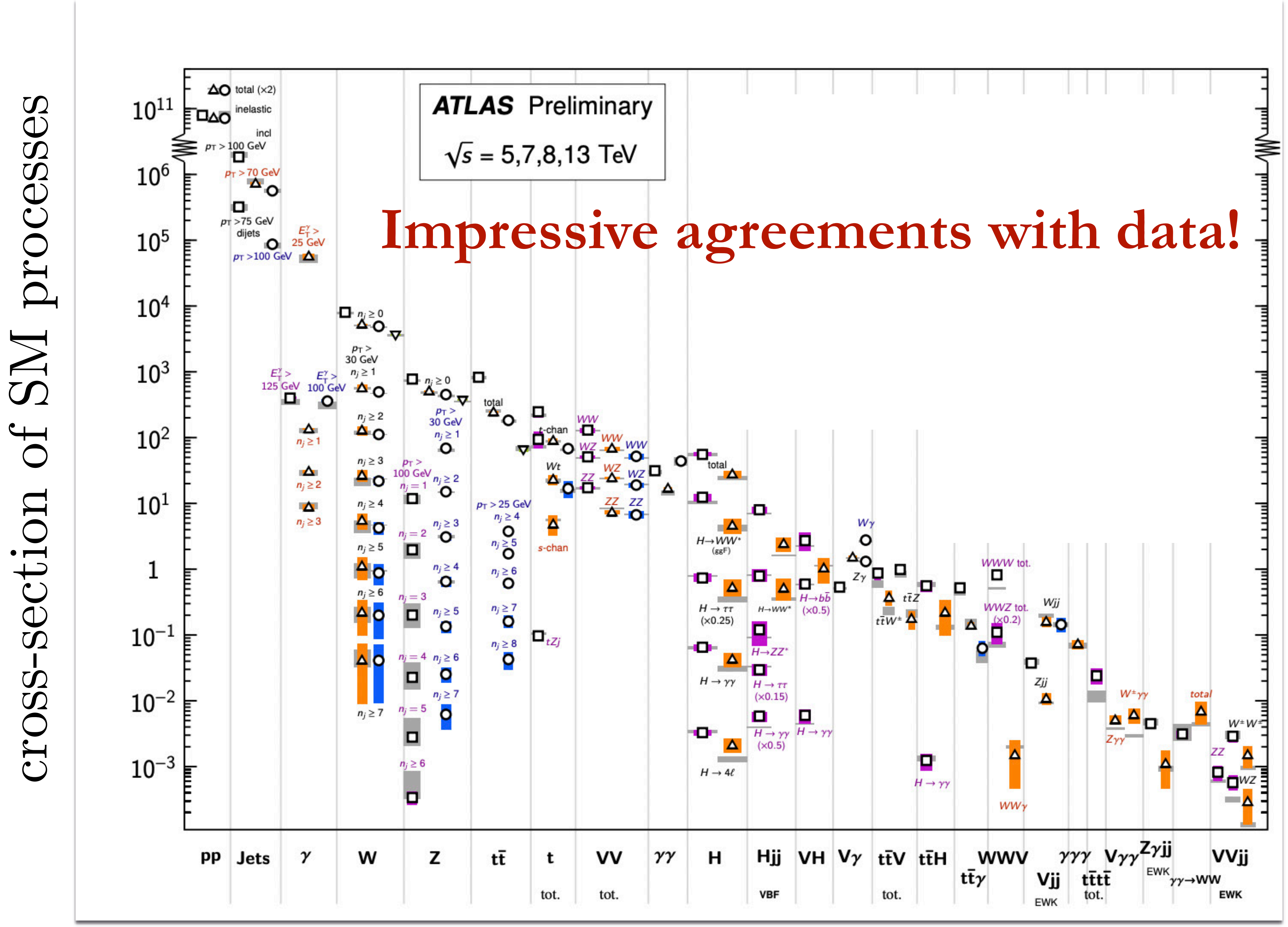
⟹

"Energy flow becomes the focus of computability"

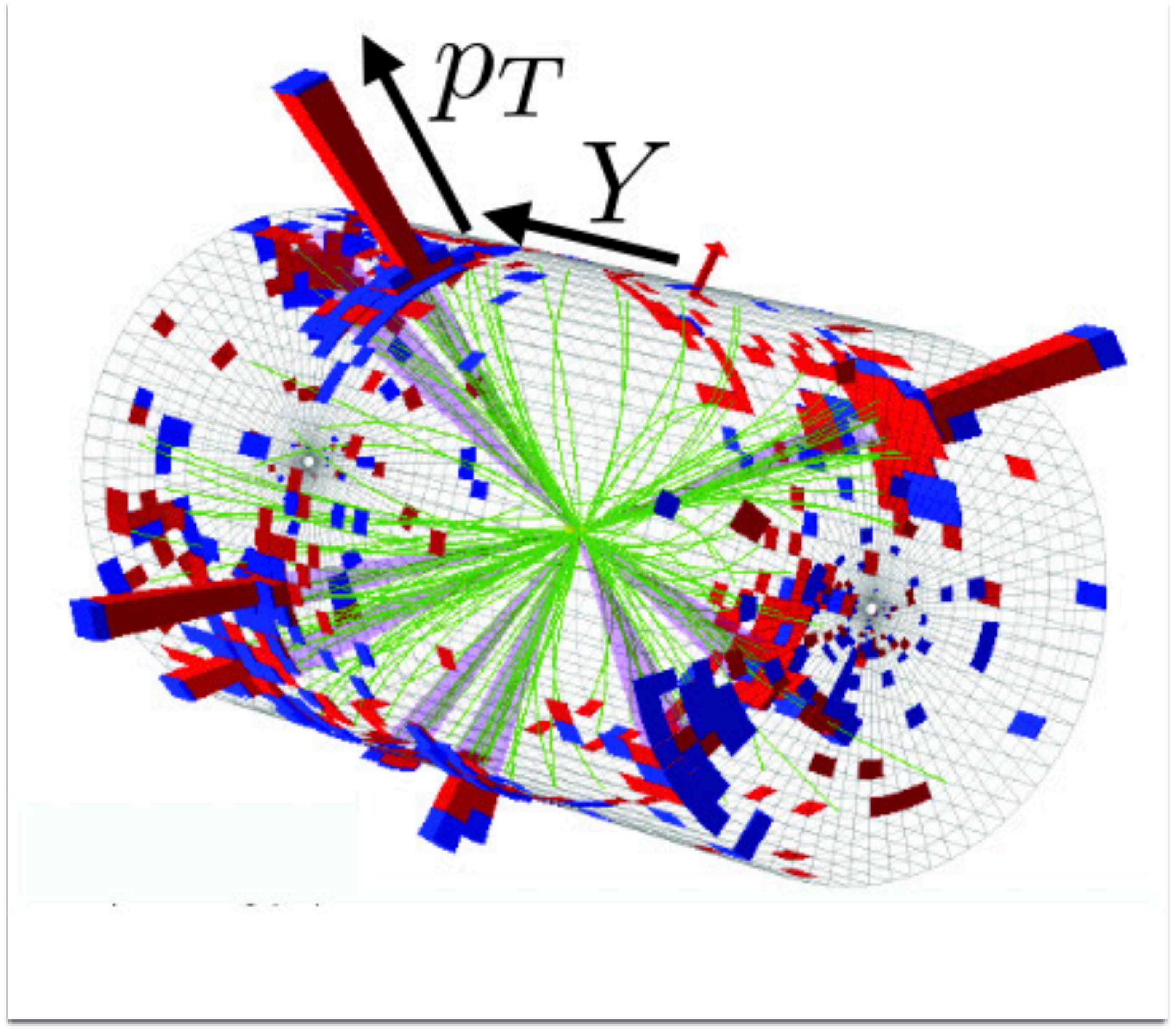
Sterman-Weinberg jets played a crucial role in formulating the first IRC definition to study energy flow, or jets

JETS AT COLLIDERS

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



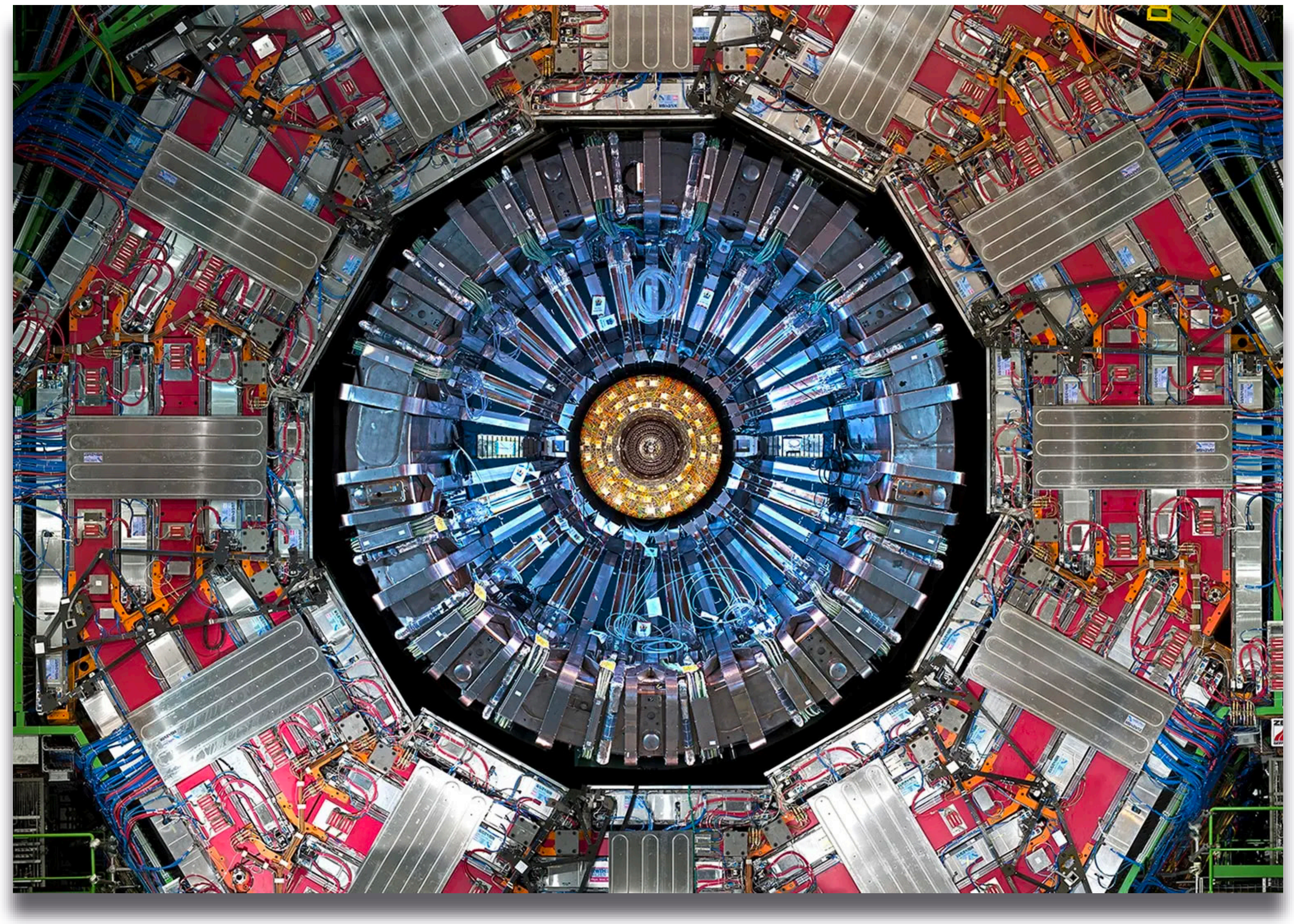
Impressive agreements with data!



9-jet at the LHC

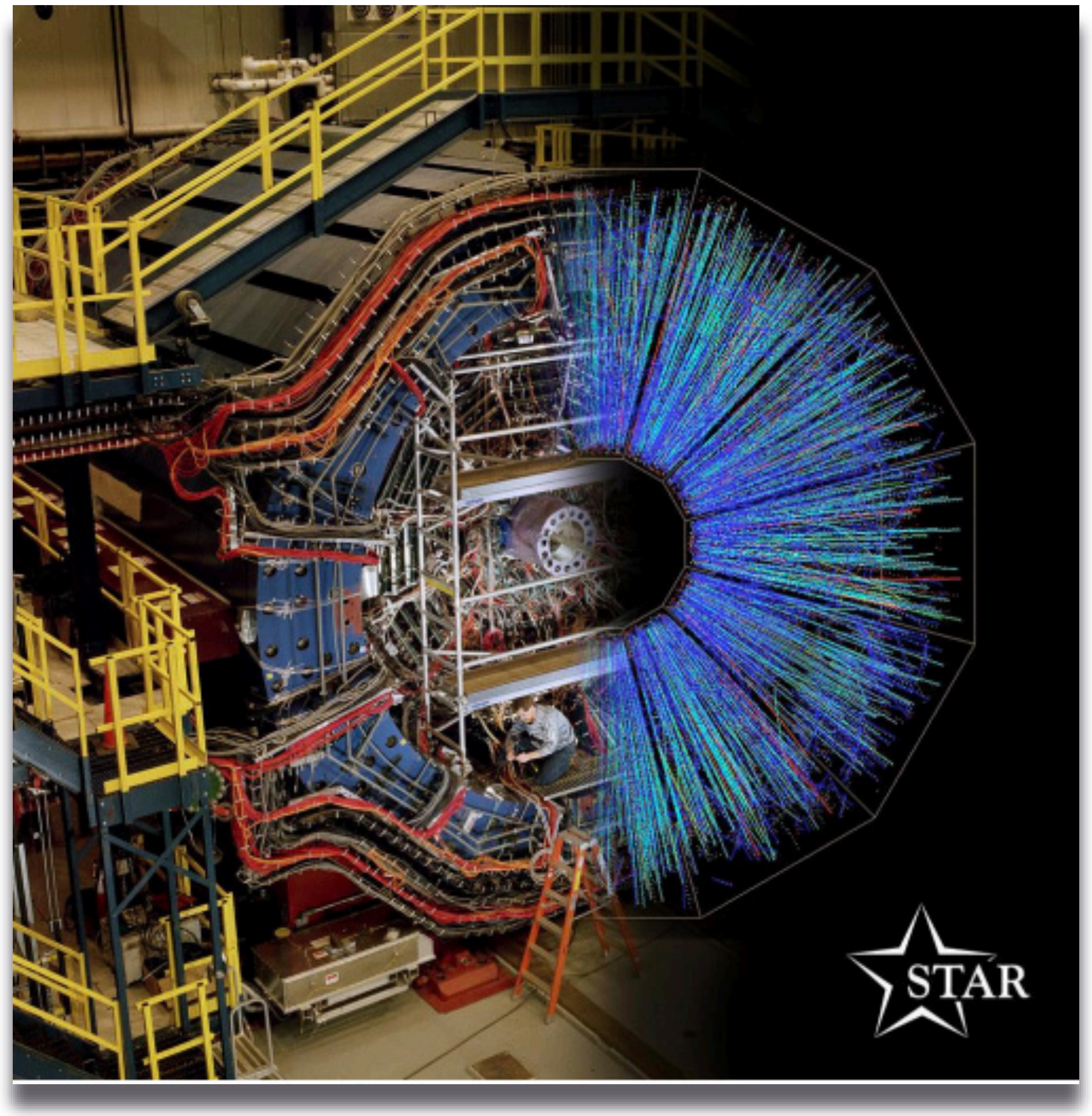
- **Field of jet physics (energy flow) have always been intricately connected to the success of the collider physics program!**

EXCITING COLLIDER PHYSICS ERA



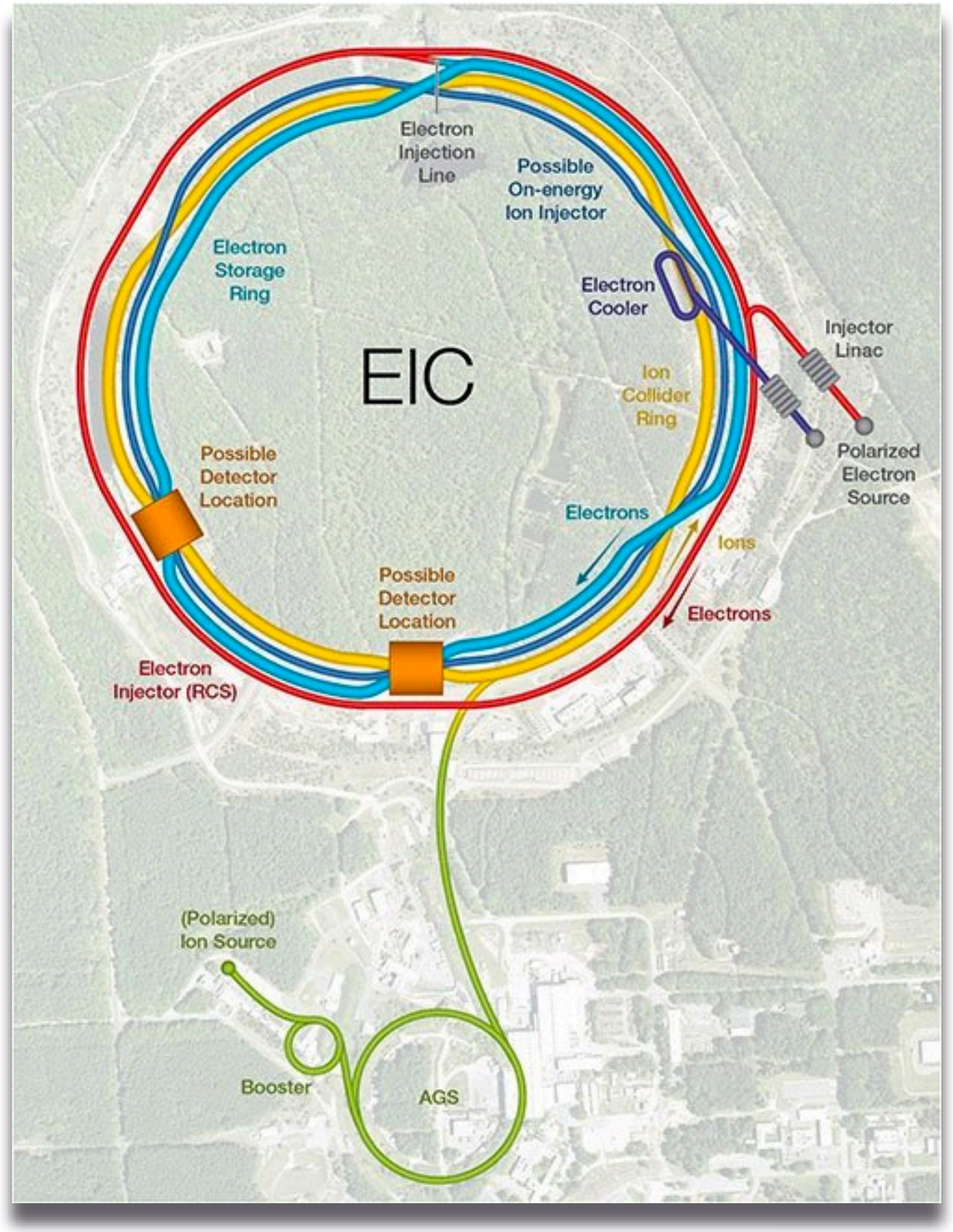
LHC, 2008 - Present

Run 3 running!



RHIC, 2000 - Present

sPHENIX: 2024-



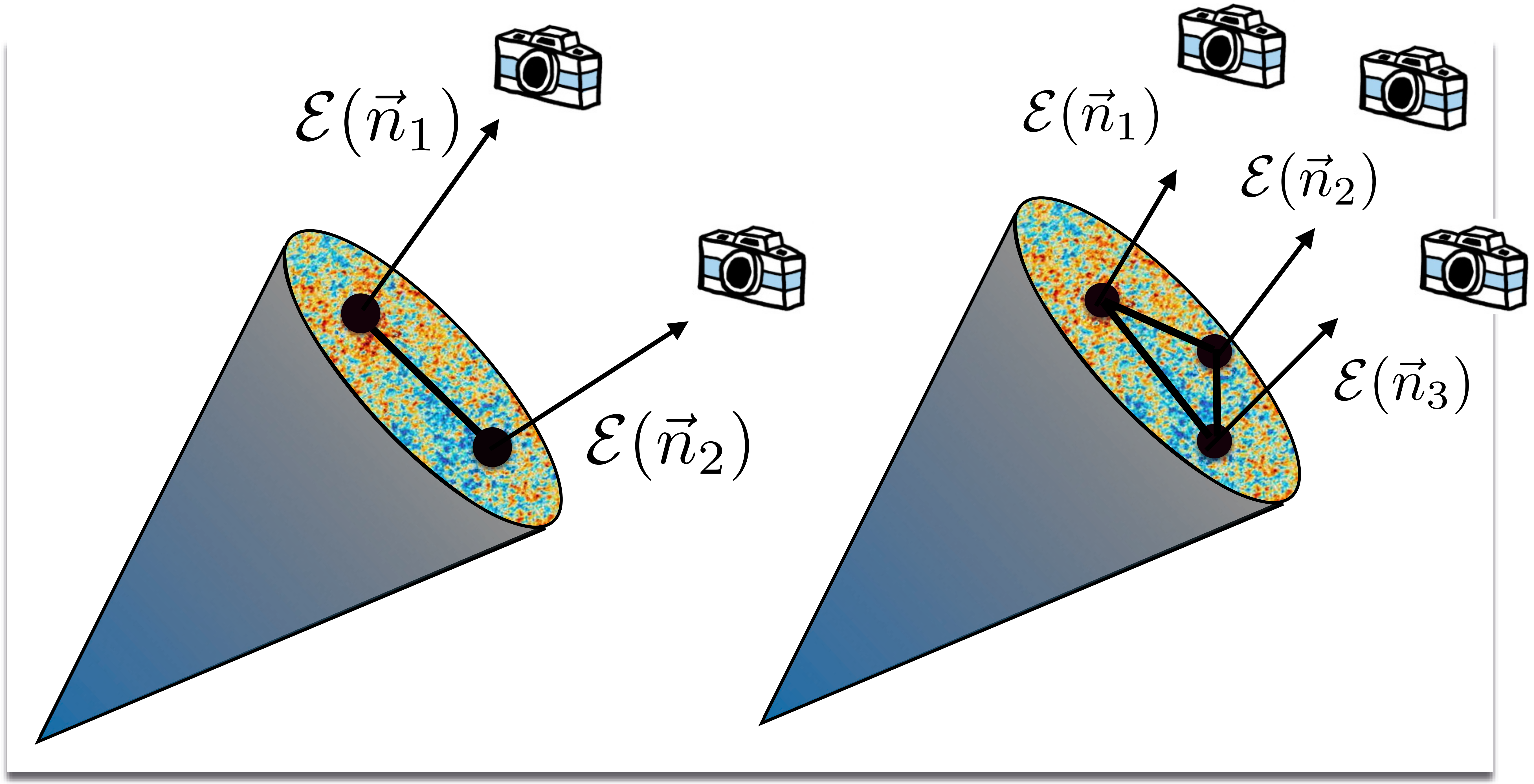
EIC, 2030s-

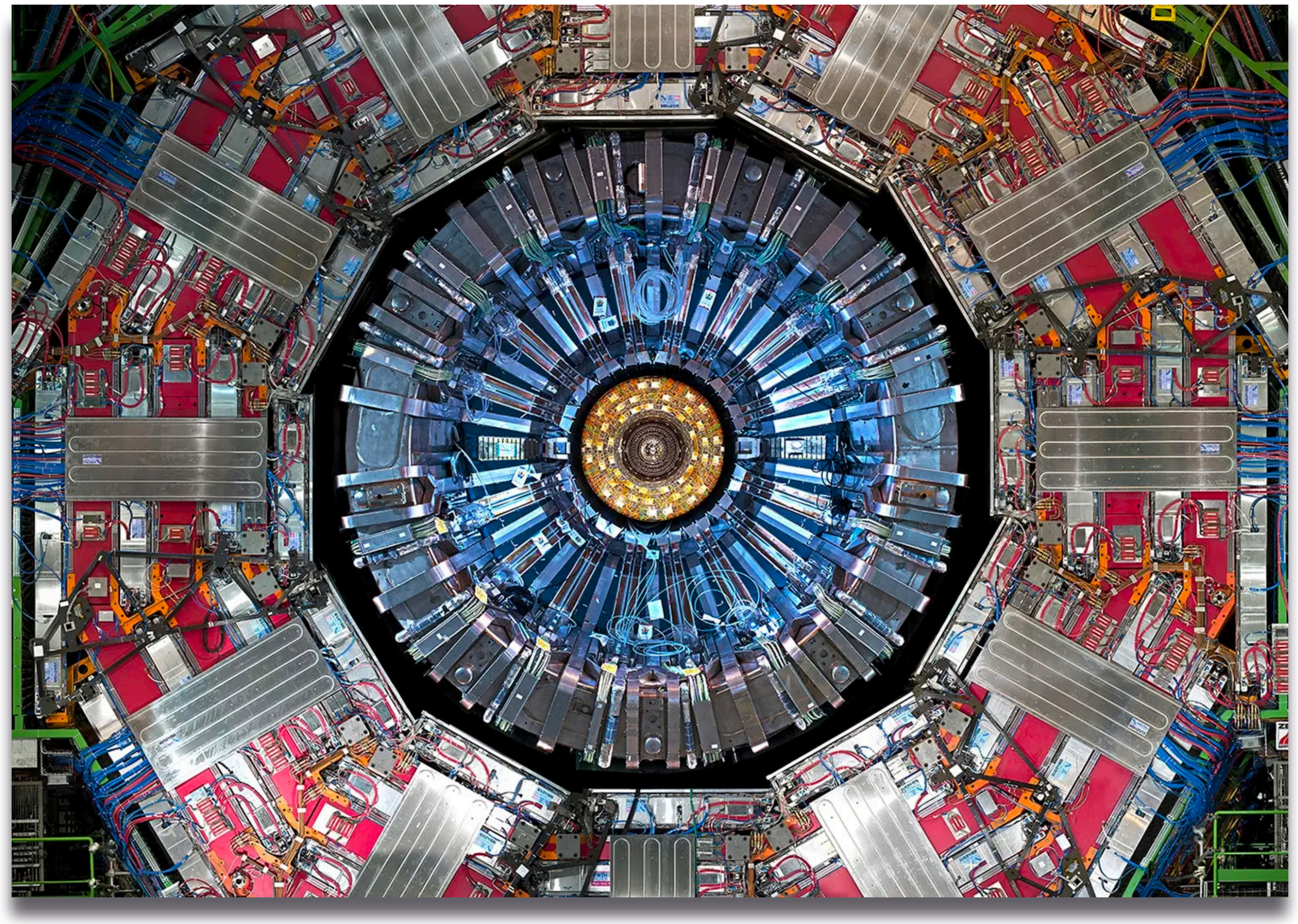
- **Jets at colliders give us the means to probe field theory in data!**

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

JET SUBSTRUCTURE: STUDYING ENERGY FLOW WITHIN JETS

- Modern detectors with spectacular angular resolution gives us an unprecedented opportunity to peer into the energy flow within jets





- Relative to inclusive jet cross-section, or one-point energy correlation, jet substructure gives us opportunity to study multi-point correlations of energy within jets

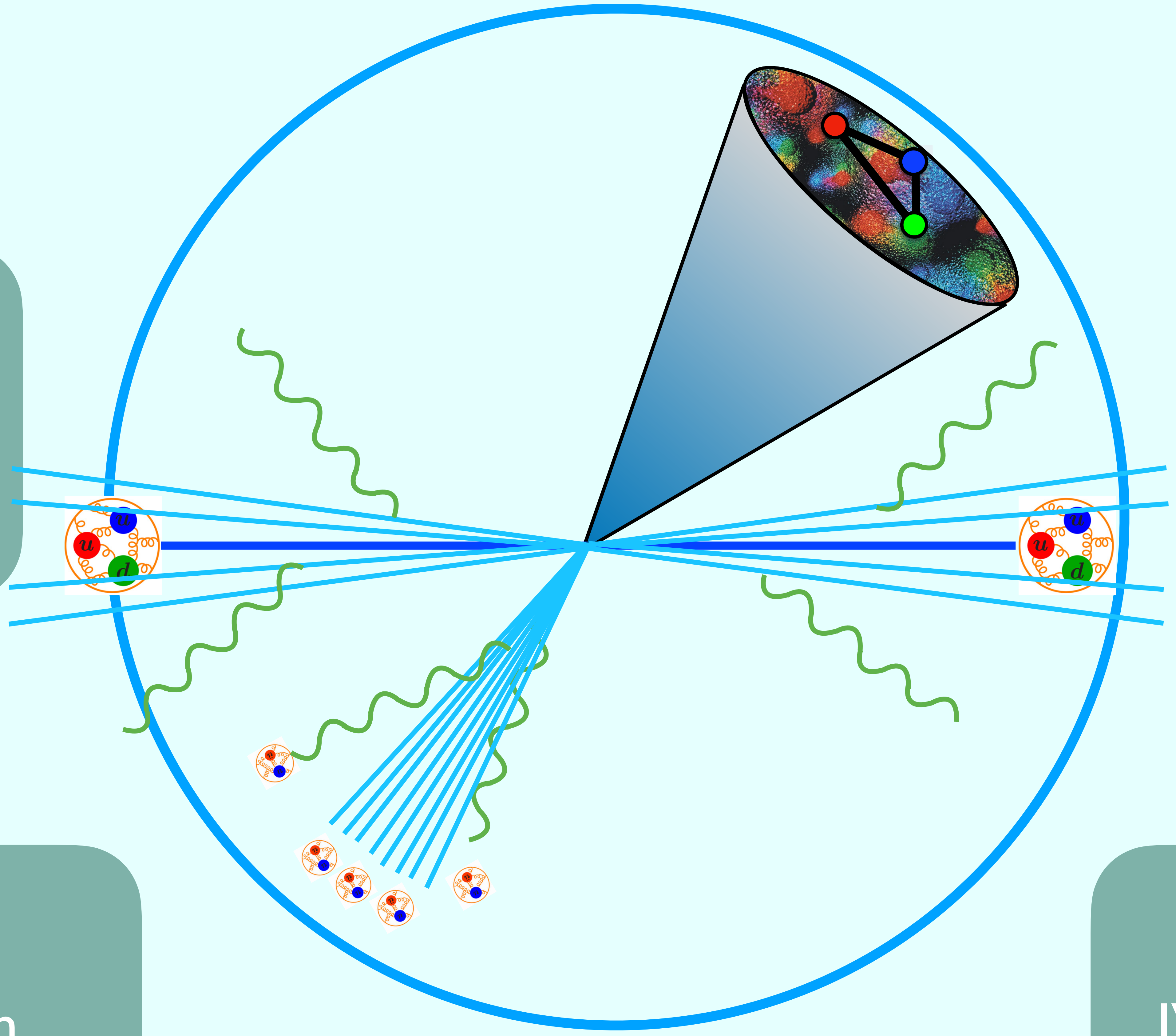
Overview

I. Universal Scaling

II. Precision QCD

VI. Real-time Simulations

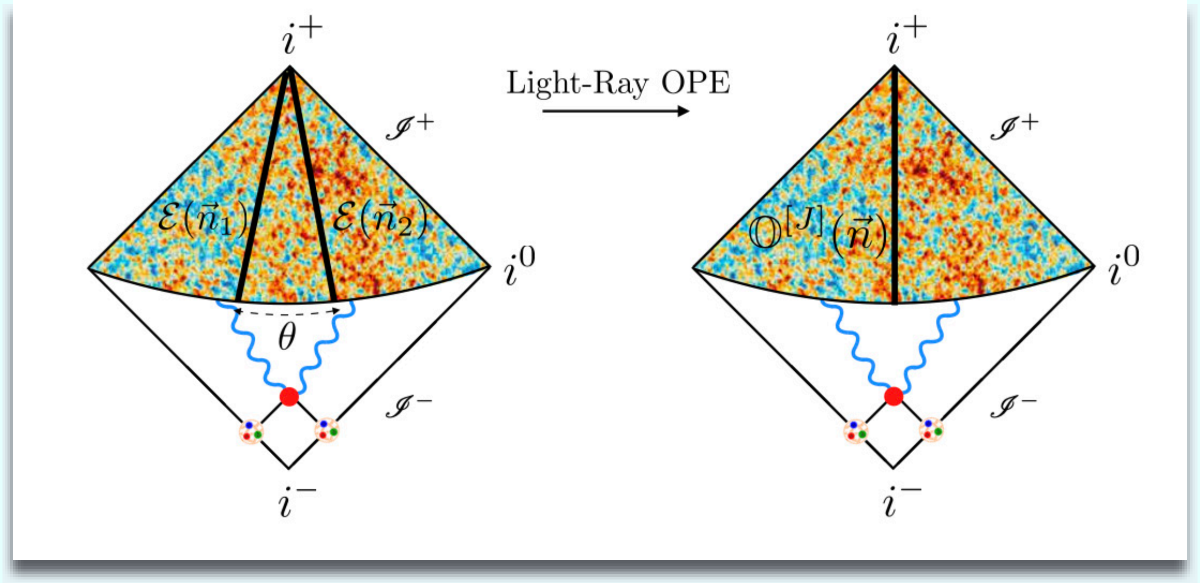
III. Heavy Flavor Physics



V. Hadronization

IV. Medium Dynamics

Overview



QFT perspective of jet substructure

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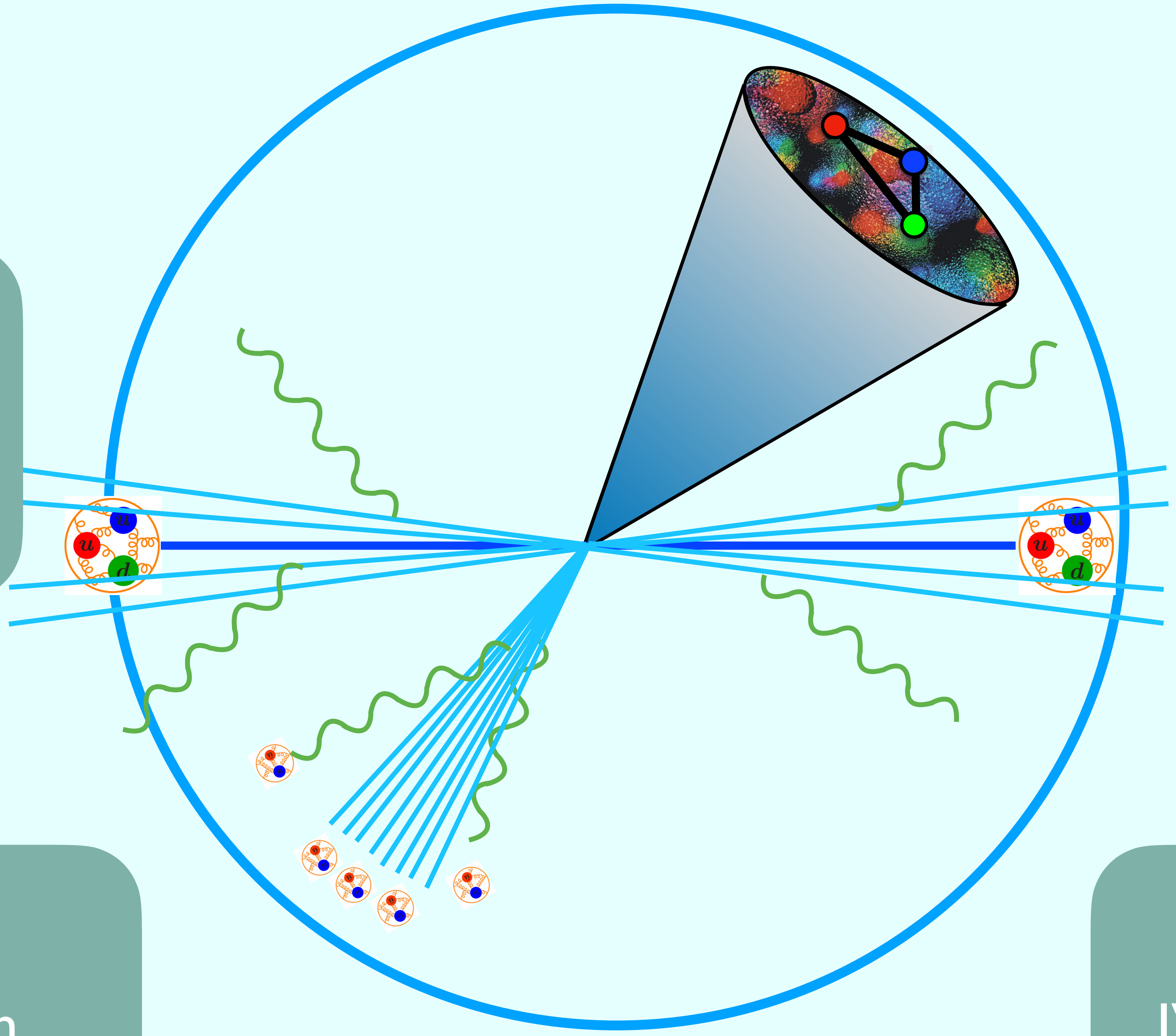

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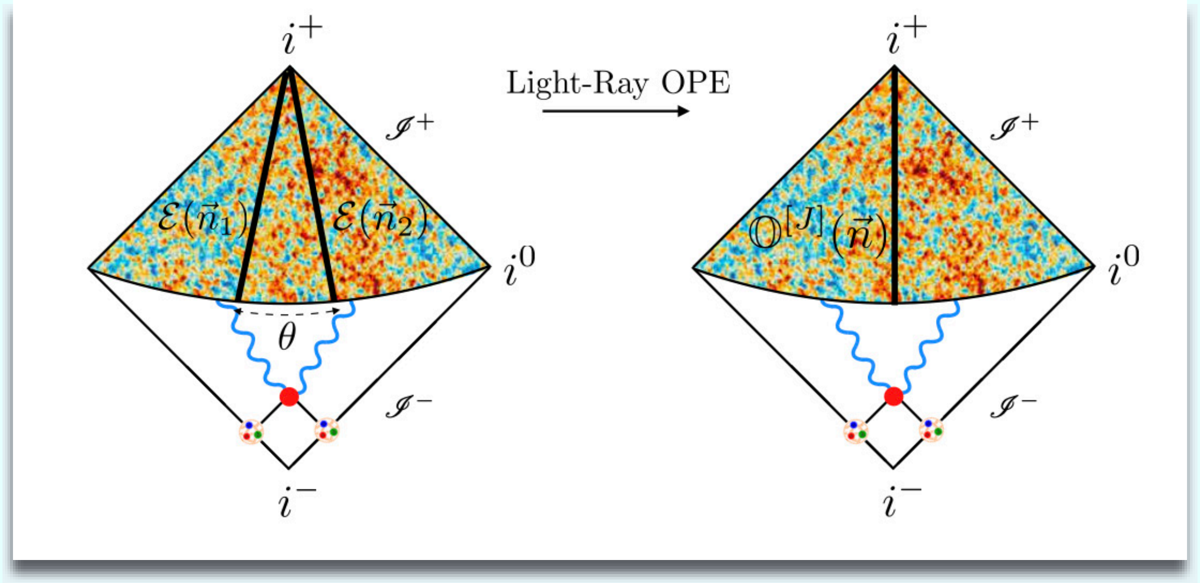

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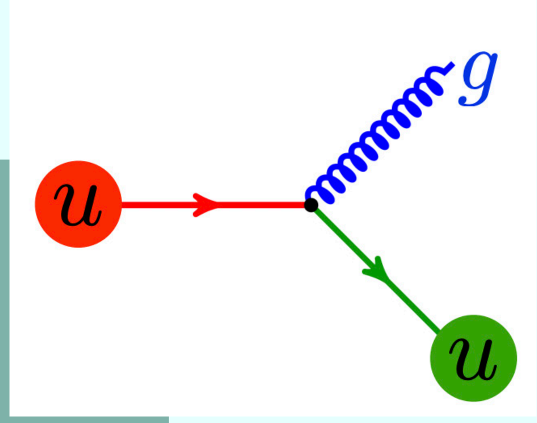
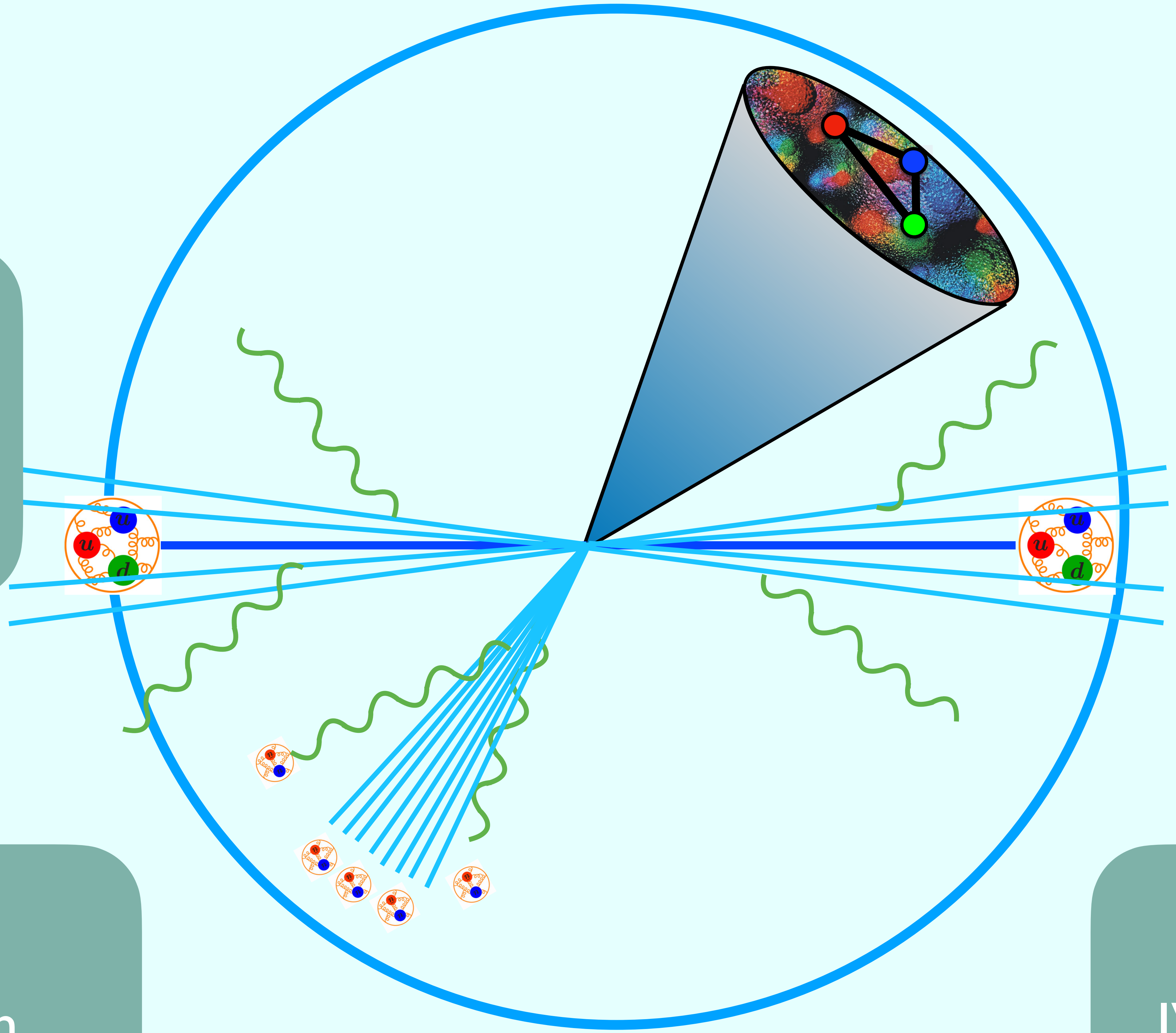


Precise determination of α_s



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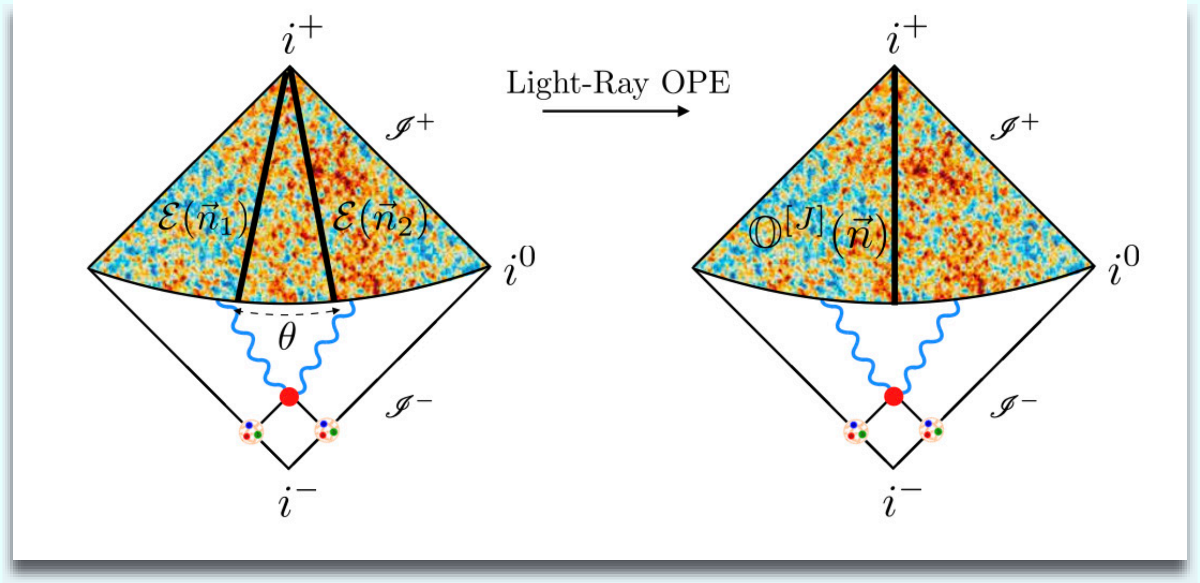

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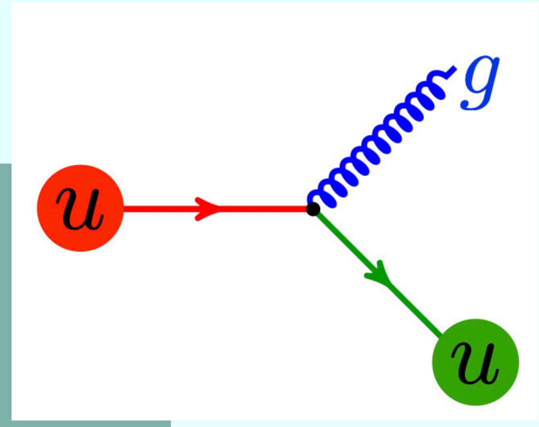

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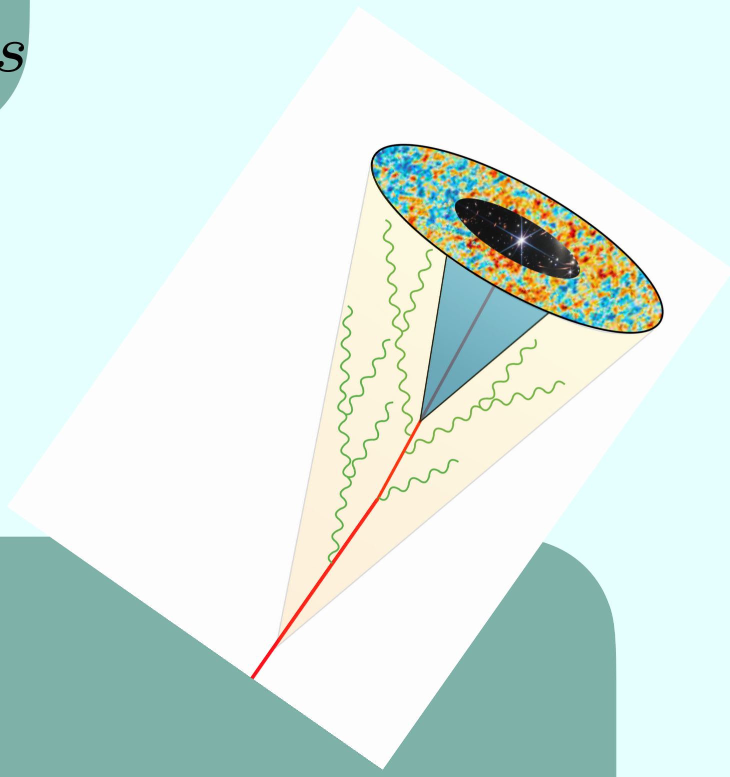

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Revealing dead-cone

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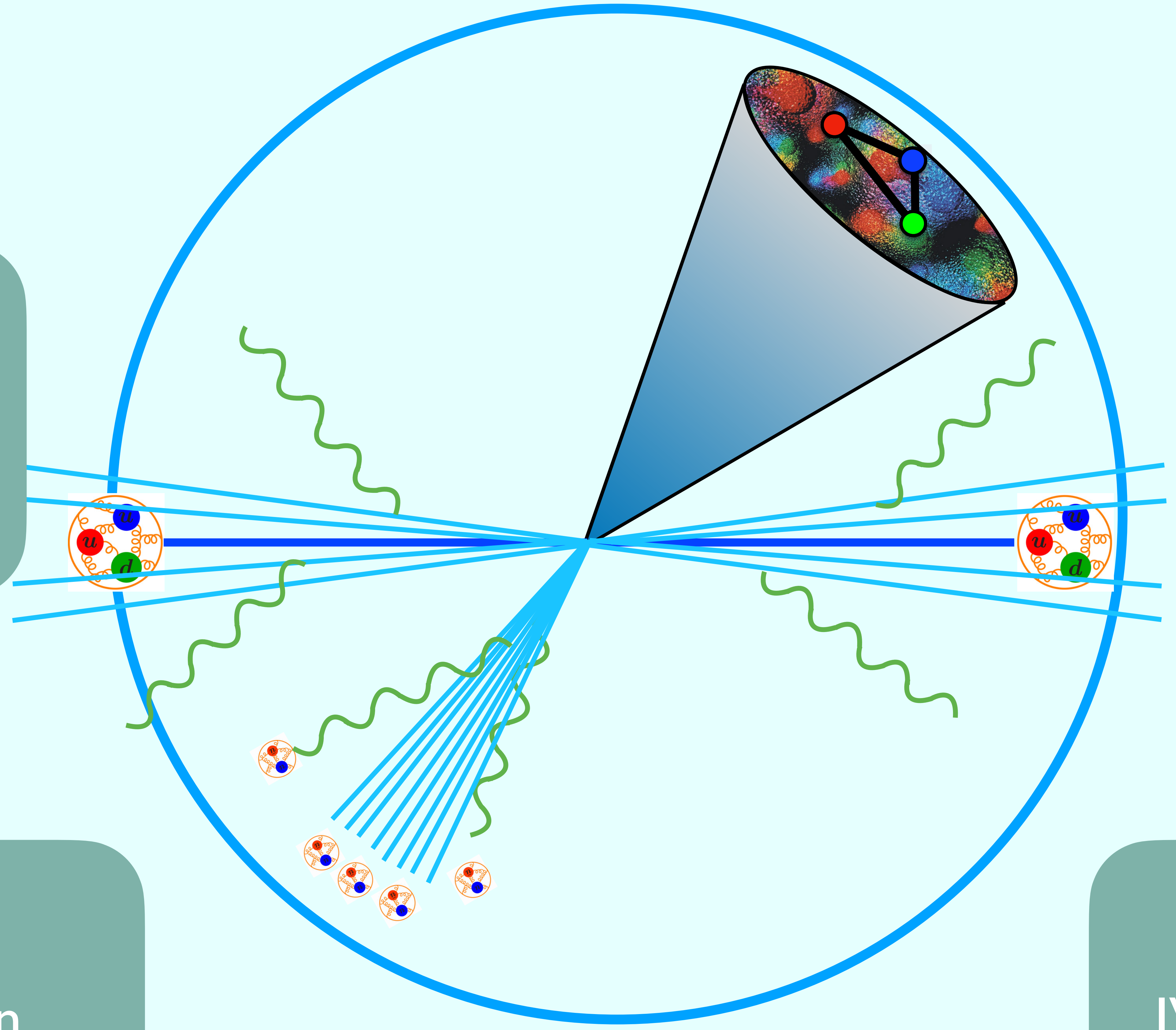

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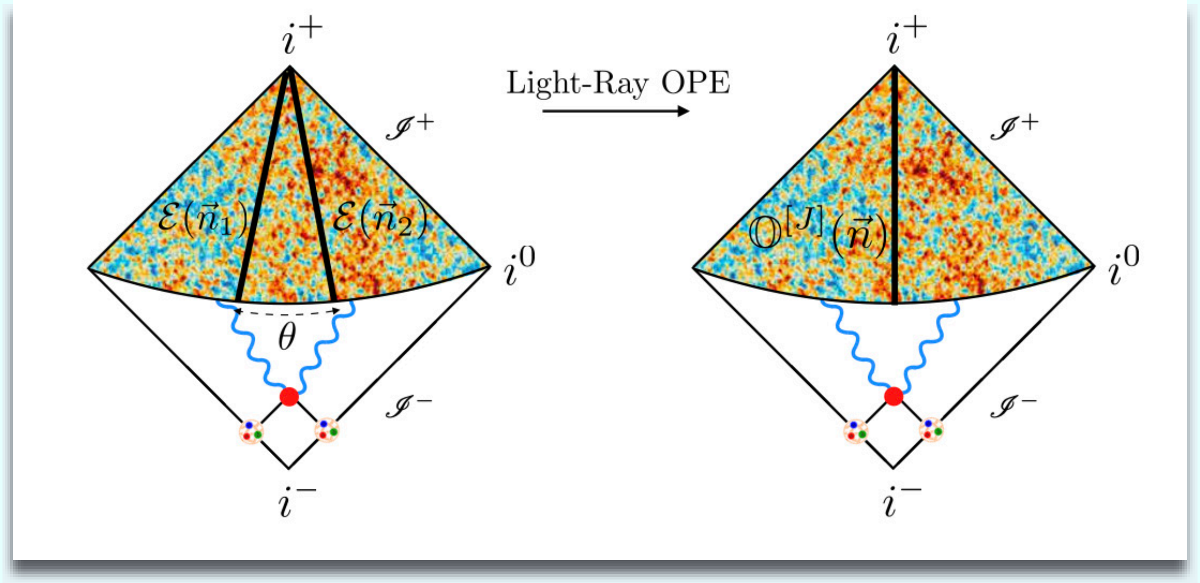

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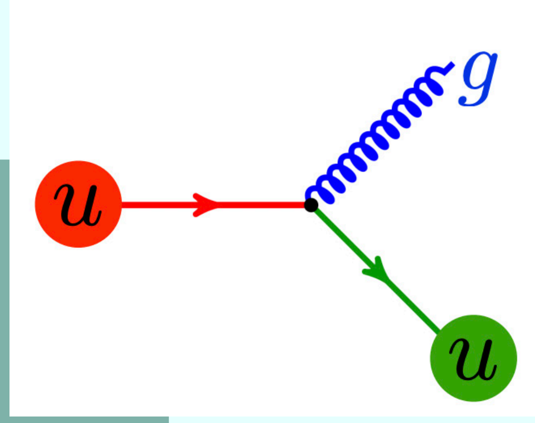

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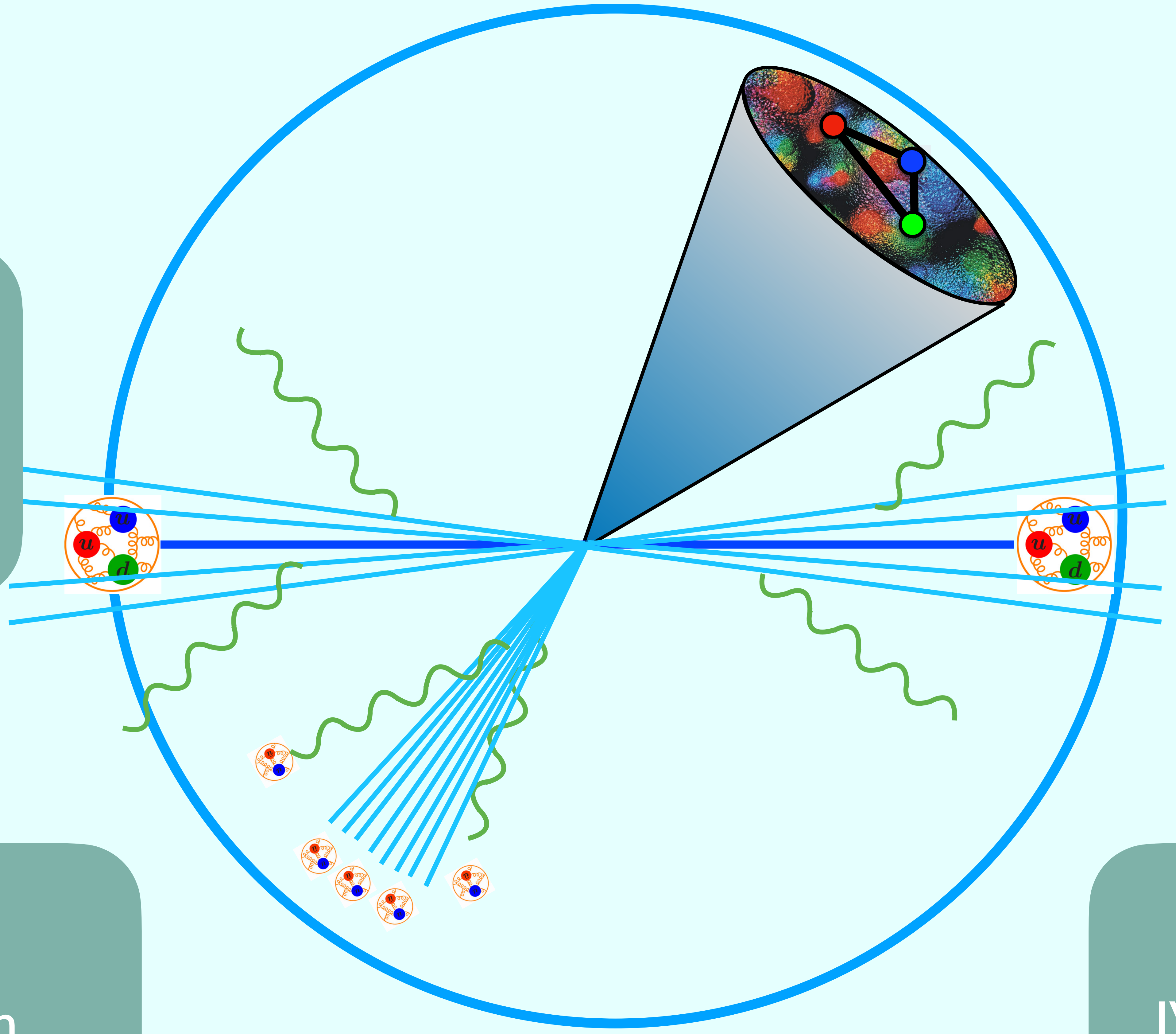

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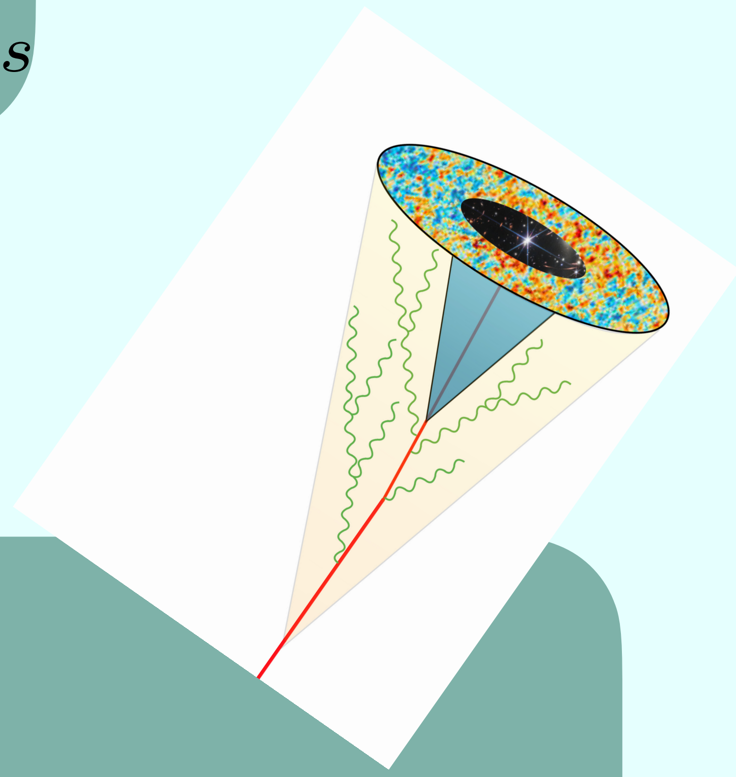

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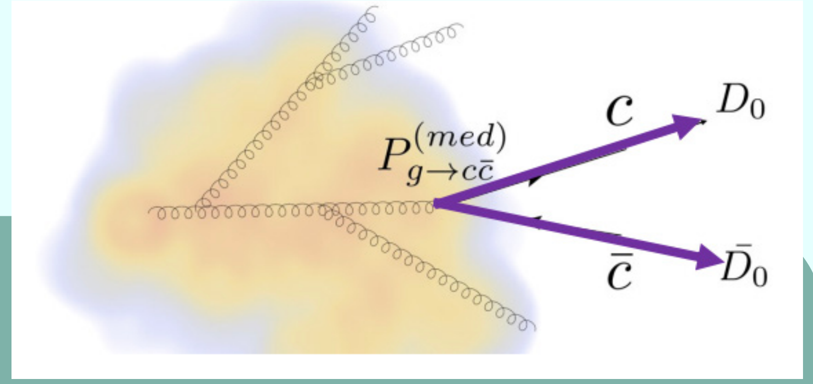
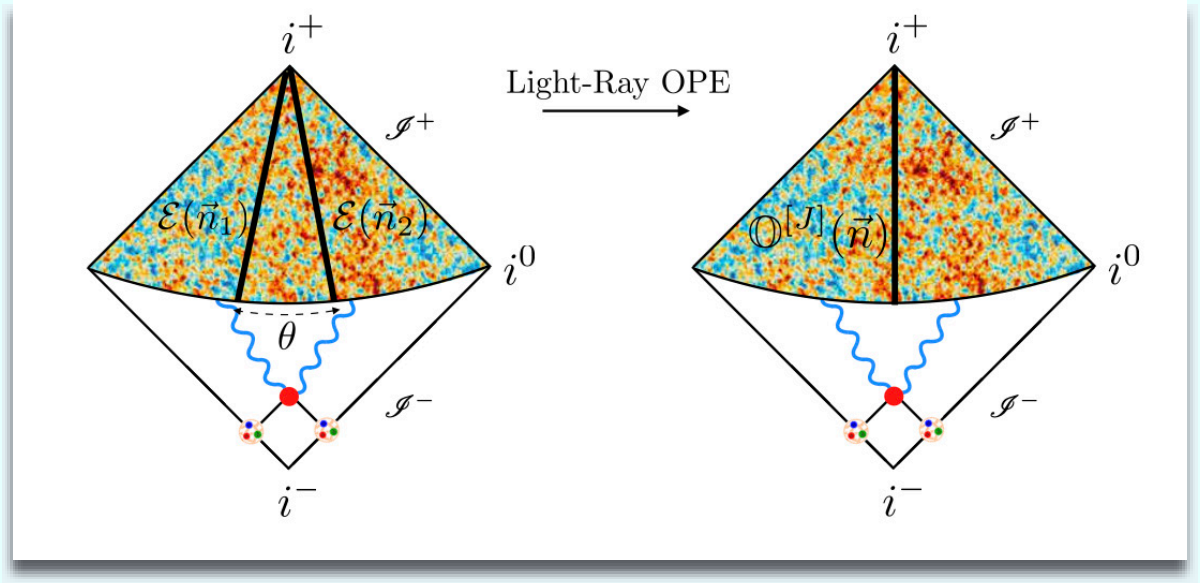


IV. Medium Dynamics

Revealing medium scale and modifications

Overview



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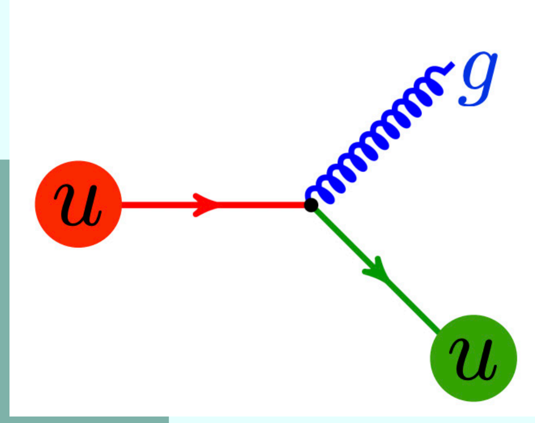

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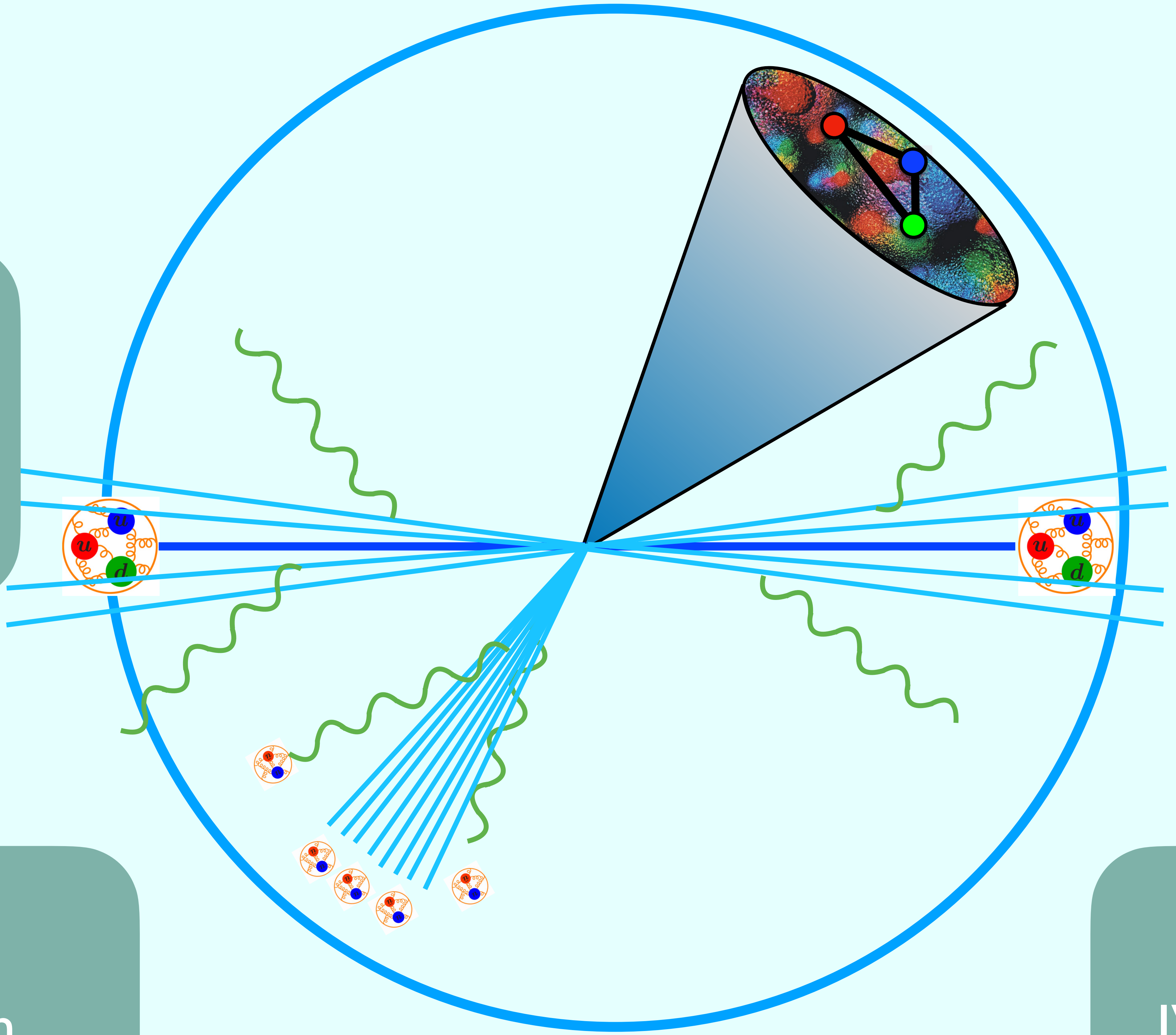

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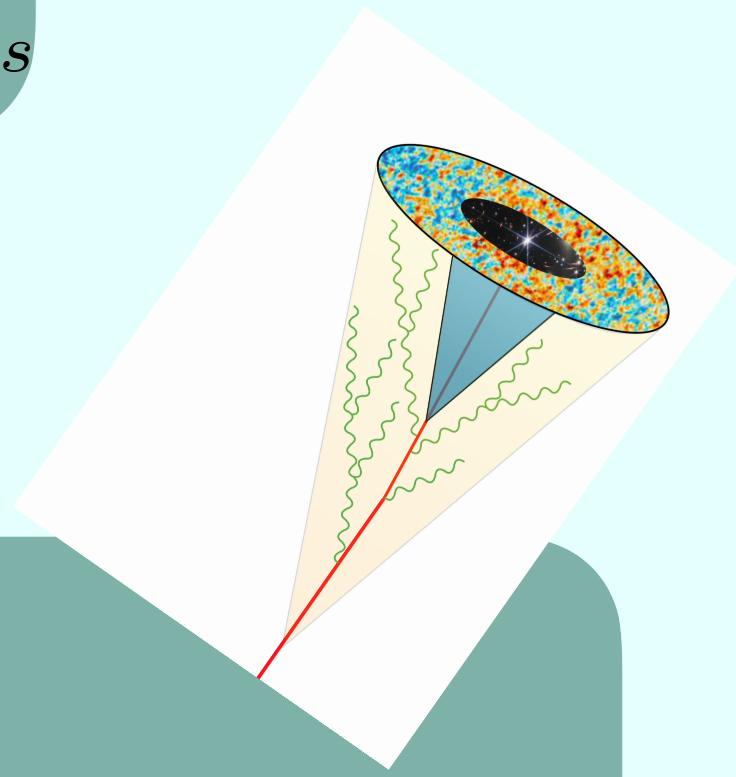

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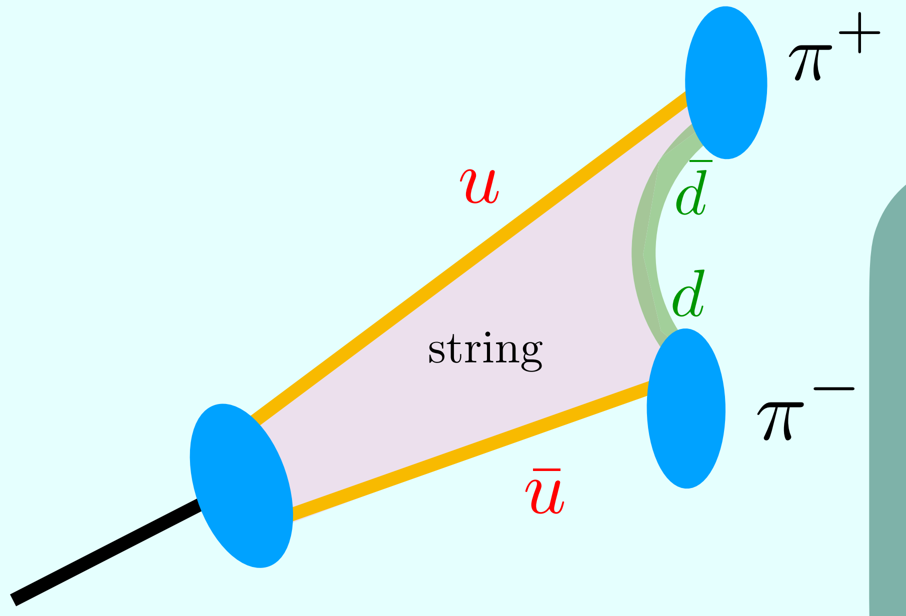

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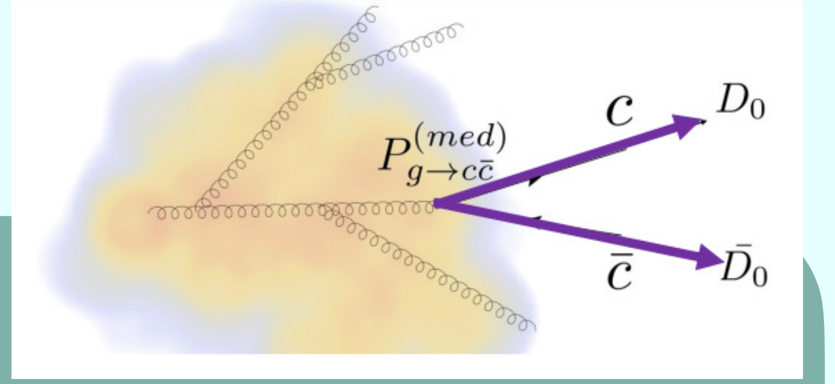
Discrimination between hadronization mechanisms



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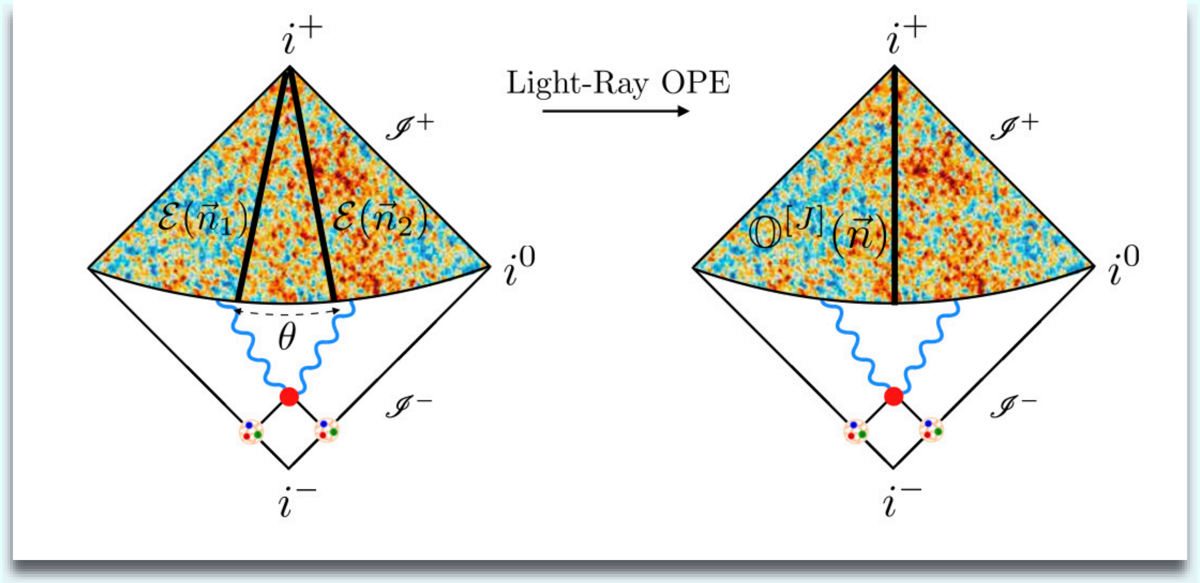

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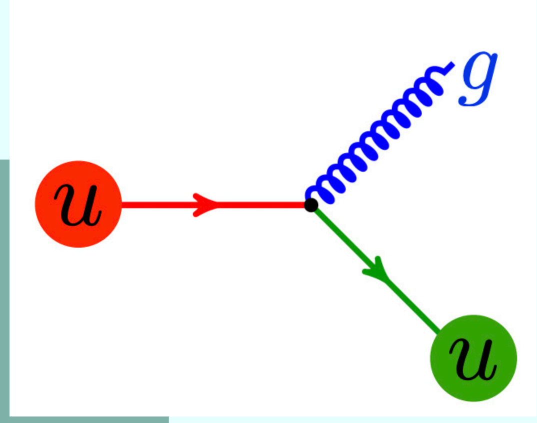

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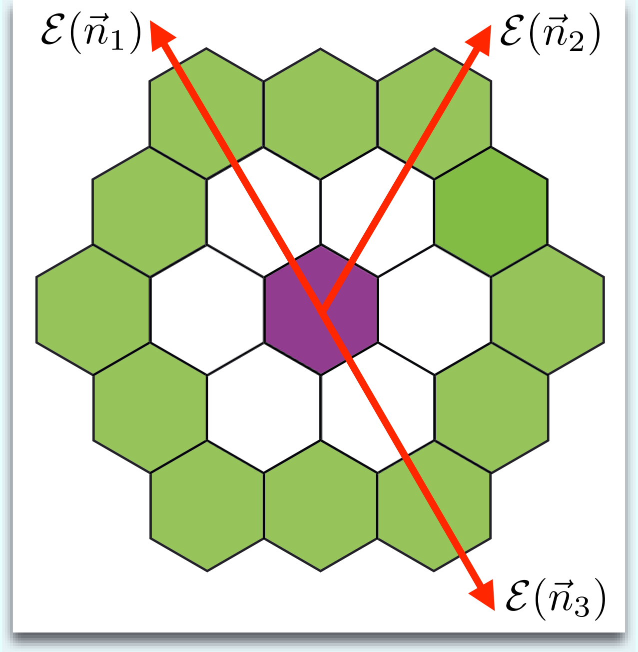
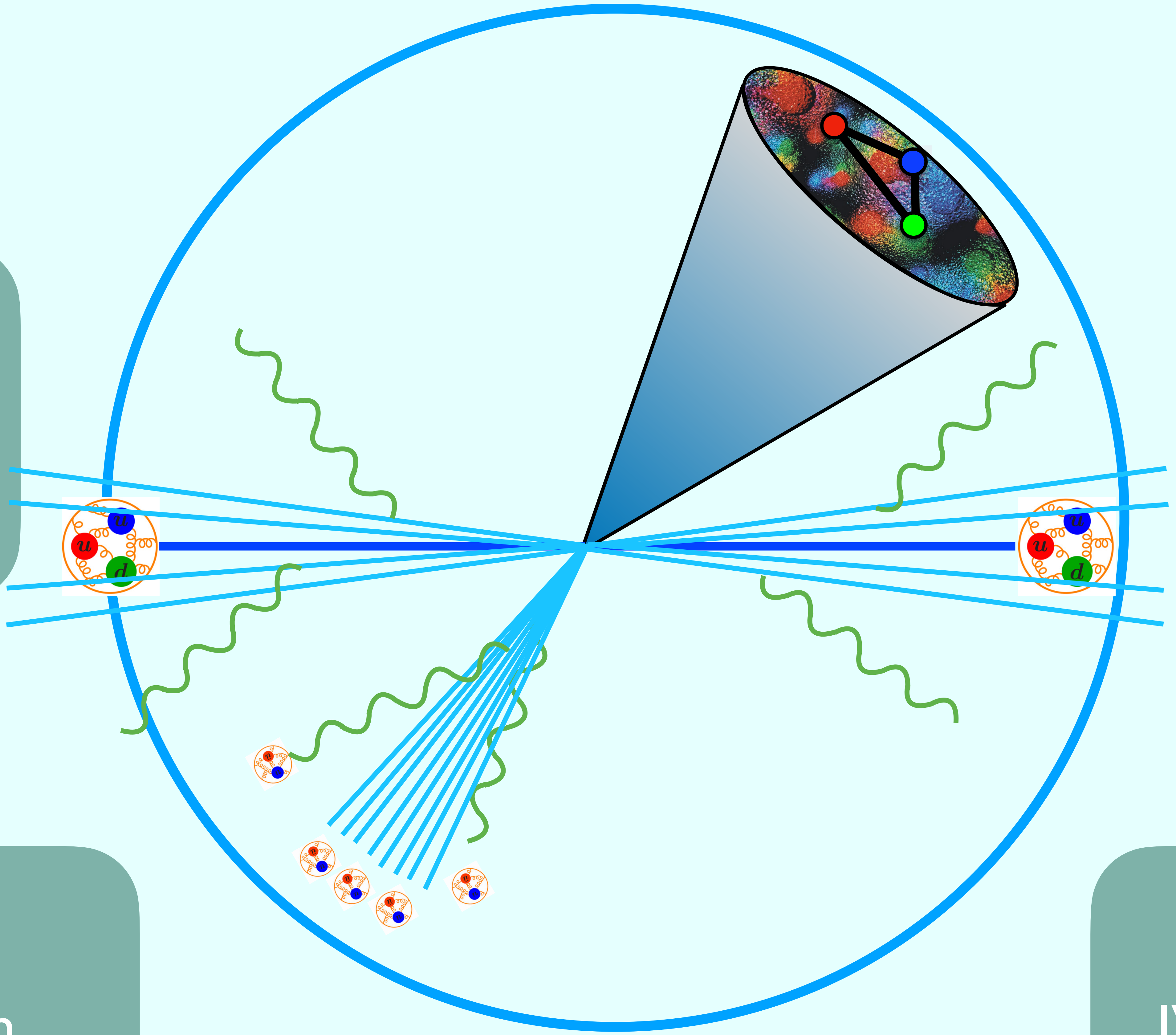
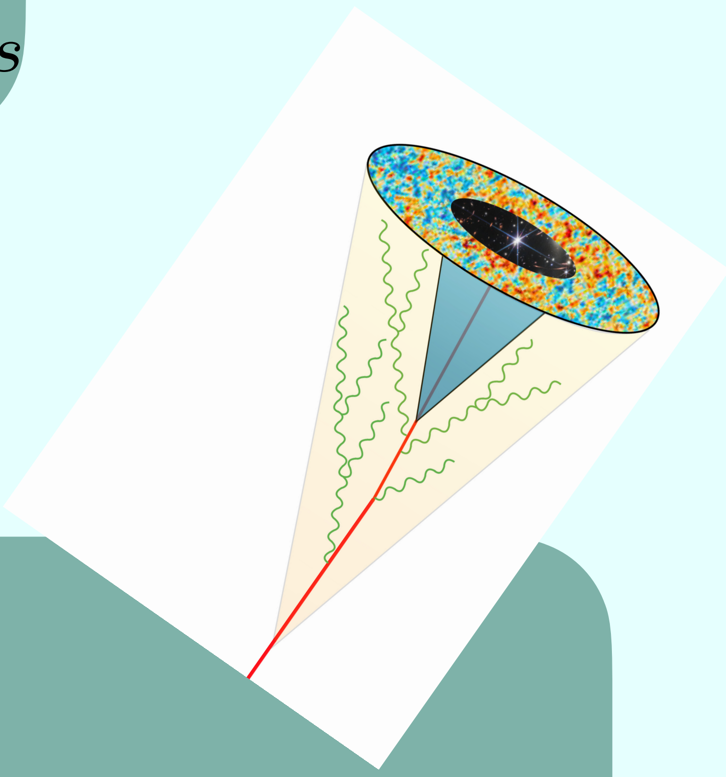


VI. Real-time Simulations

Quantum Computing





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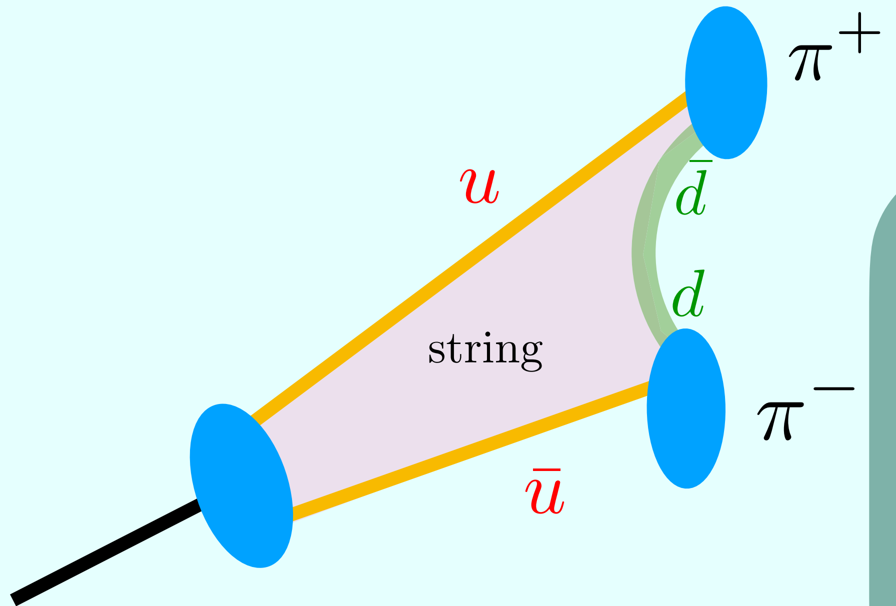

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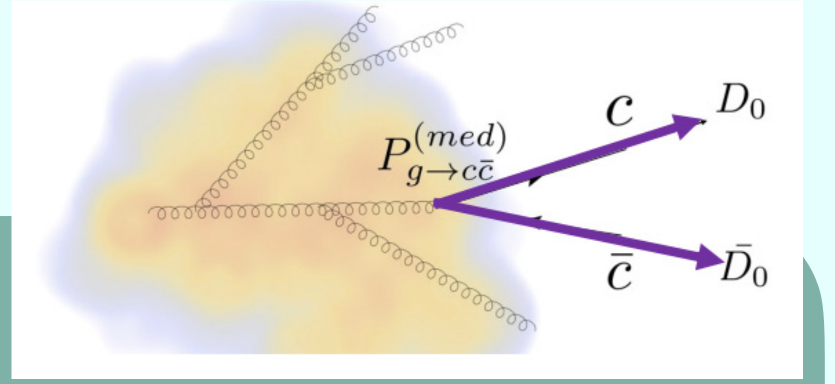

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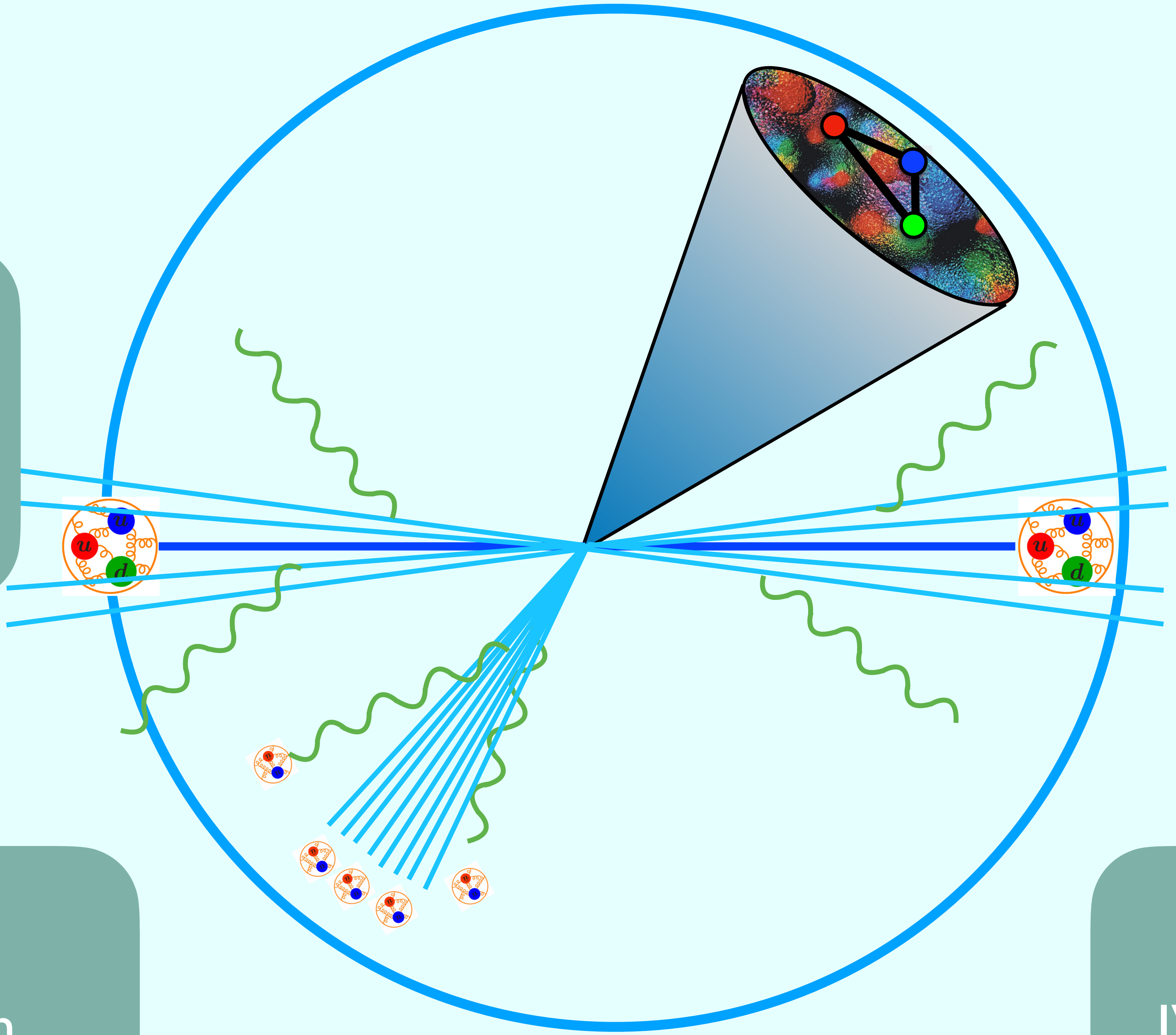
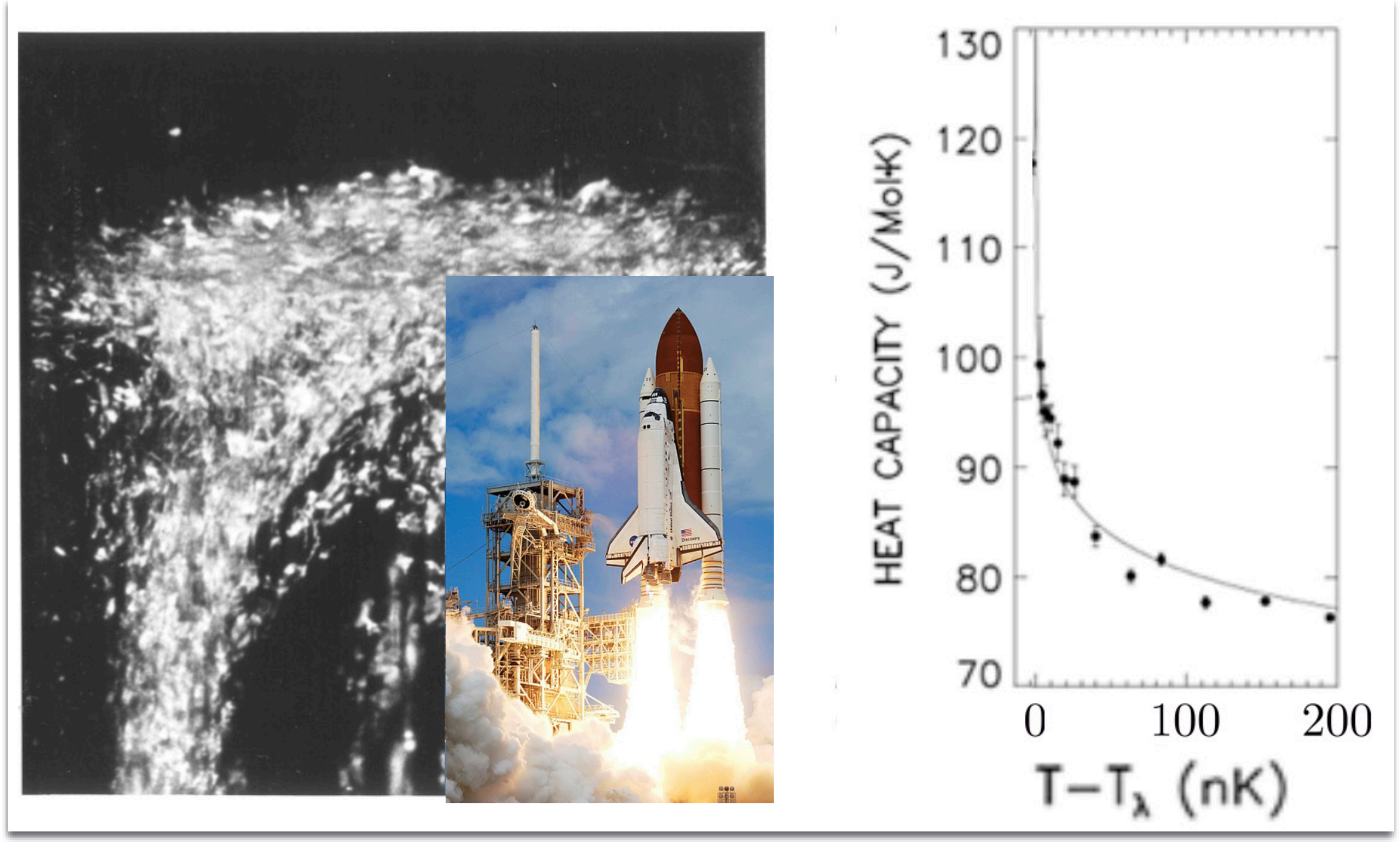


SCALING BEHAVIOR IN QFT

- **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

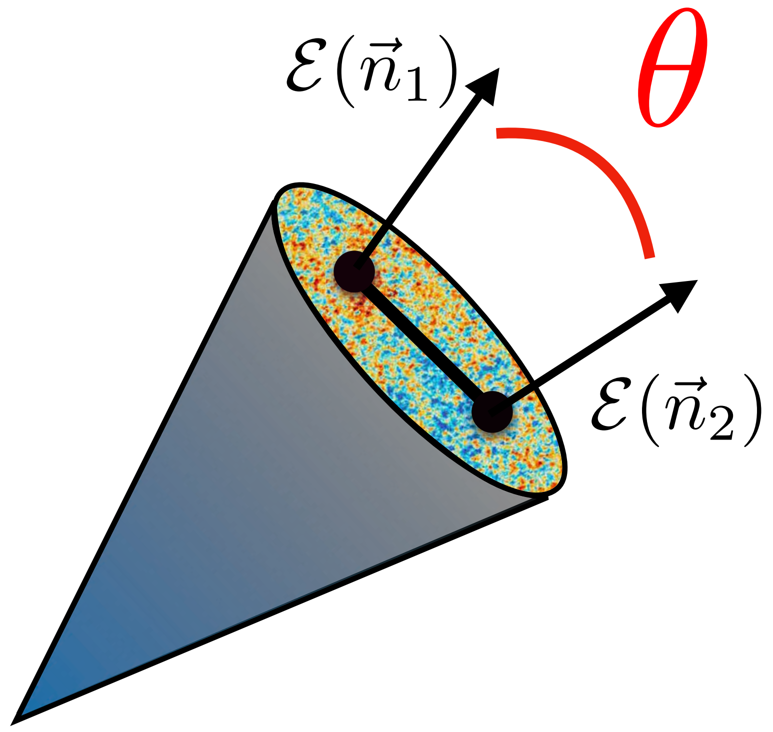
$$\mathcal{O}(x)\mathcal{O}(0) = \sum x^{\gamma_i} c_i \mathcal{O}_i$$

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

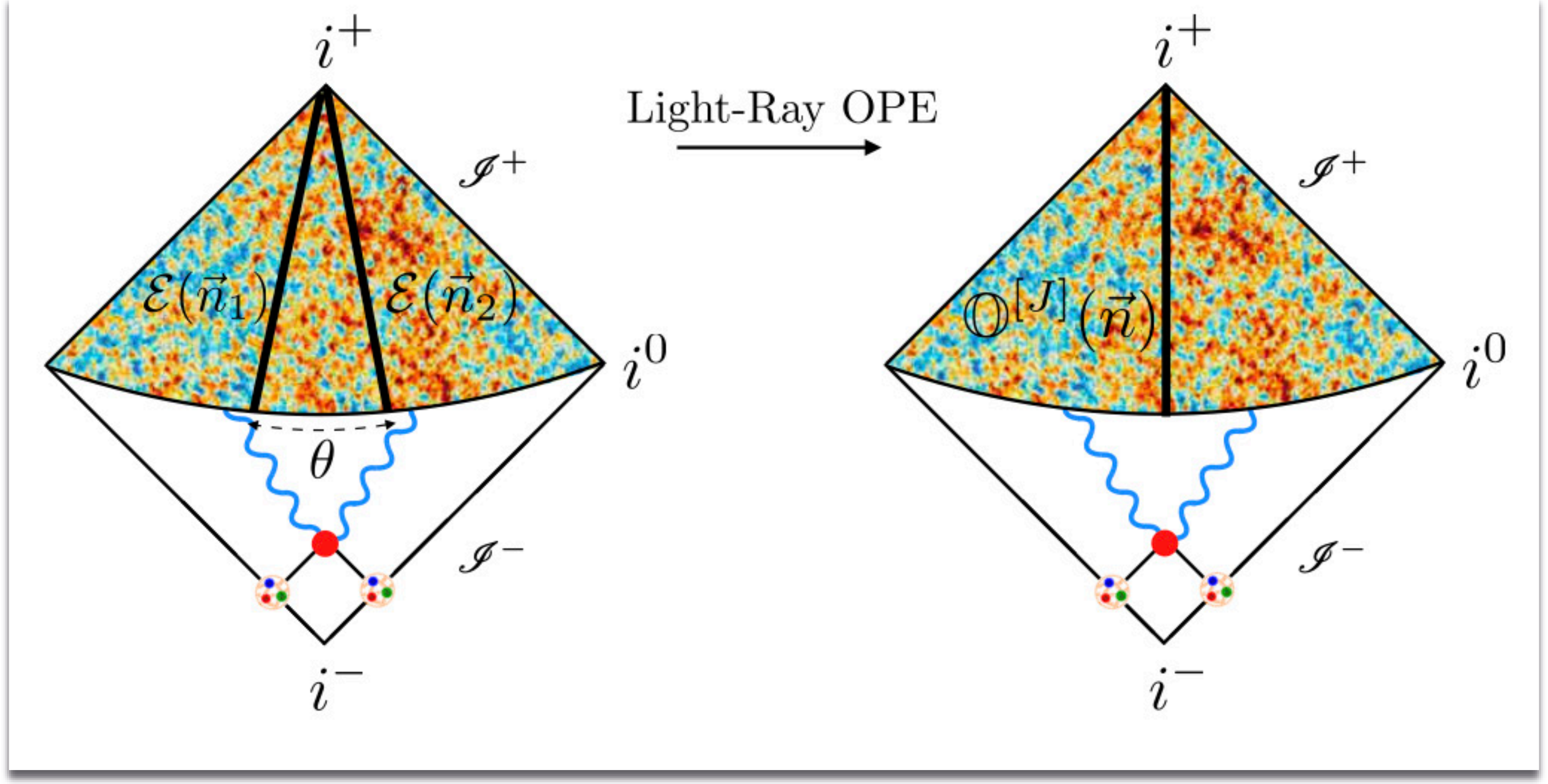
UNIVERSAL LORENTZIAN SCALING WITHIN JETS

- **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

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

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

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Much interests from the formal theory:

Kravchuk, Simmons Duffin, `18
Henn, Sokatchev, Yan, Zhiboedov, `19
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Belitsky, Hohenegger, Korchemsky, Sokatchev, Zhiboedov, `13
Kologlu, Kravchuk, Simmons Duffin, Zhiboedov, `19
Chang, Kologlu, Kravchuk, Simmons-Duffin, `20
Caron-Huot, Kologlu, Kravchuk, Meltzer, Simmons-Duffin, `22
…

Firat, Monin, Rattazzi, Walters `23
Gonzo, Ilderton `23
Hartman, Mathys `24
Chen, Karlsson, Zhiboedov `24
Chicherin, Moult, Sokatchev, Yan, Zhu `24

- **Light-ray Operator Product Expansion predicted universal scaling within jets within the context of CFT**

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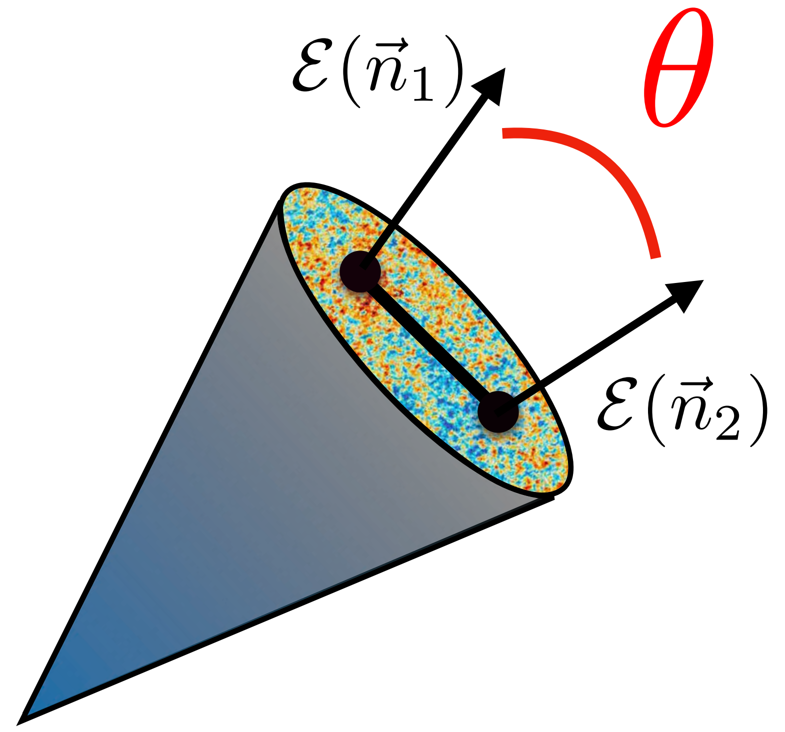

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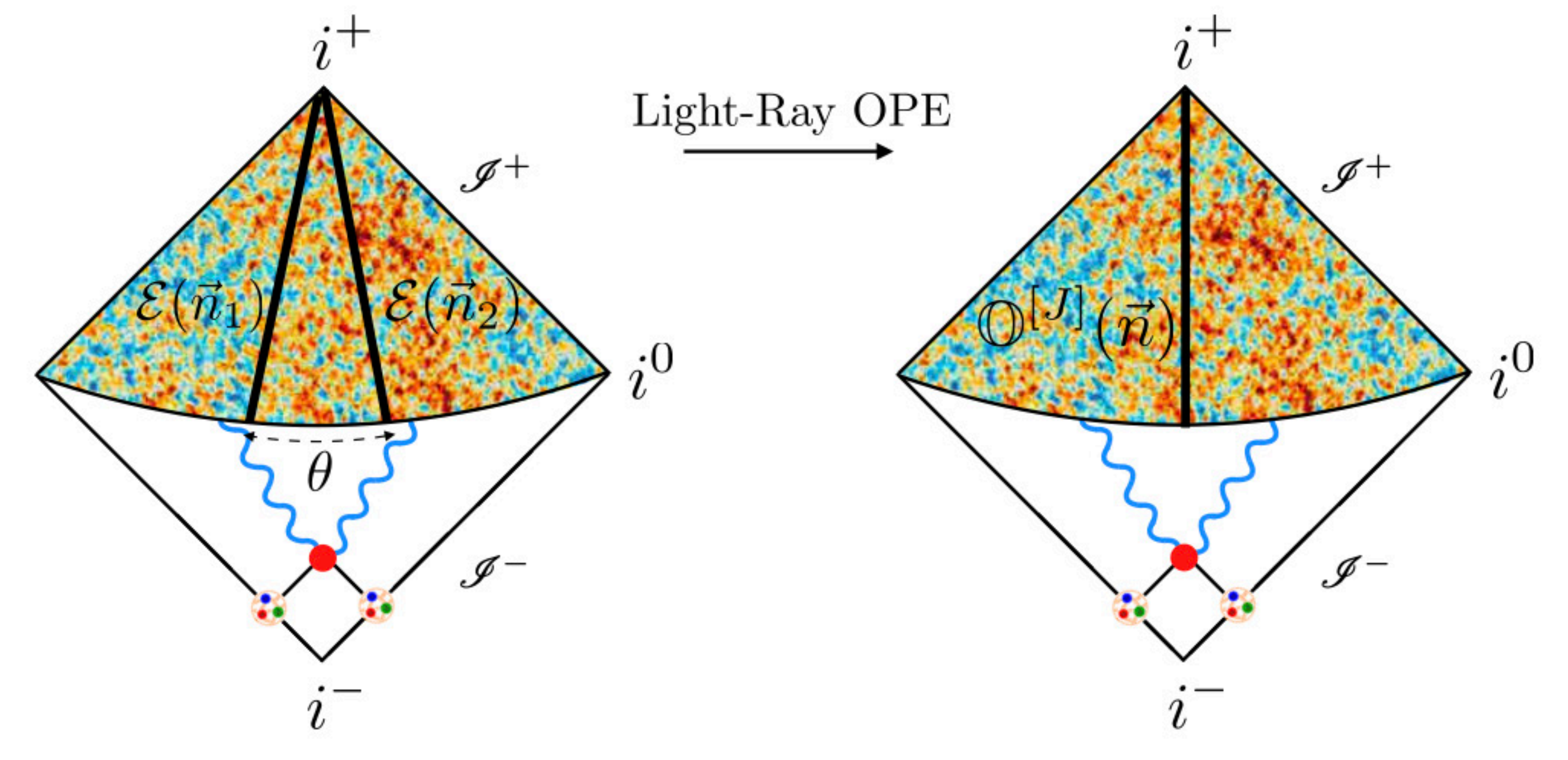

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…
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CAN THIS UNIVERSAL SCALING OF THE FIELD THEORY BE OBSERVED IN JETS???

- **Light-ray Operator Product Expansion predicted universal scaling within jets within the context of CFT**

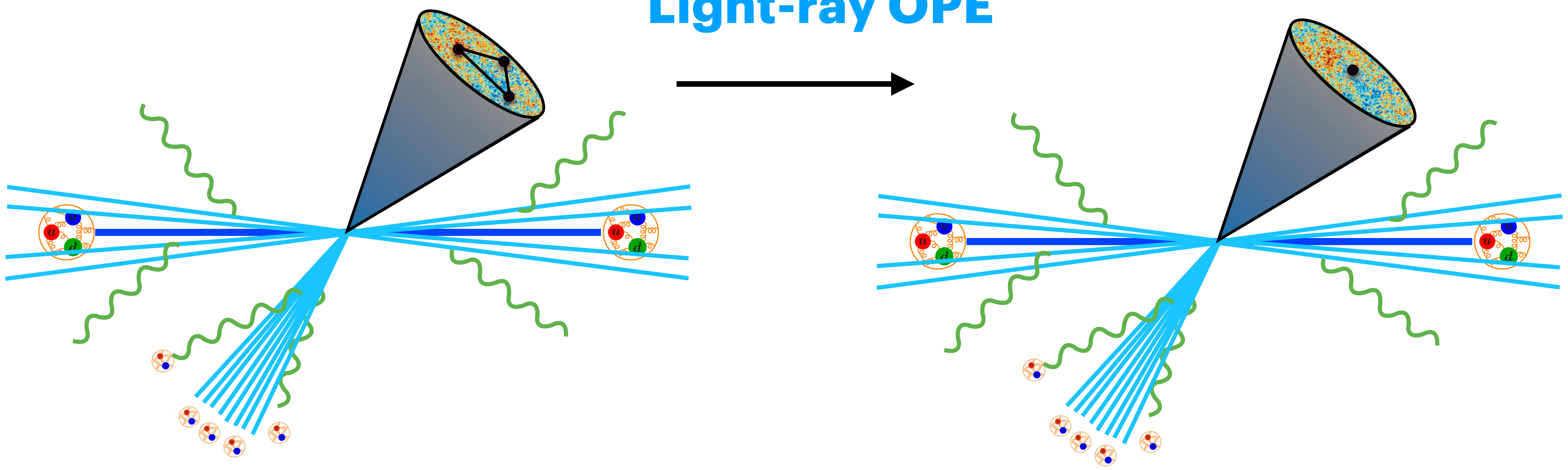
UNIVERSAL SCALING BEHAVIOR IN JETS!

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

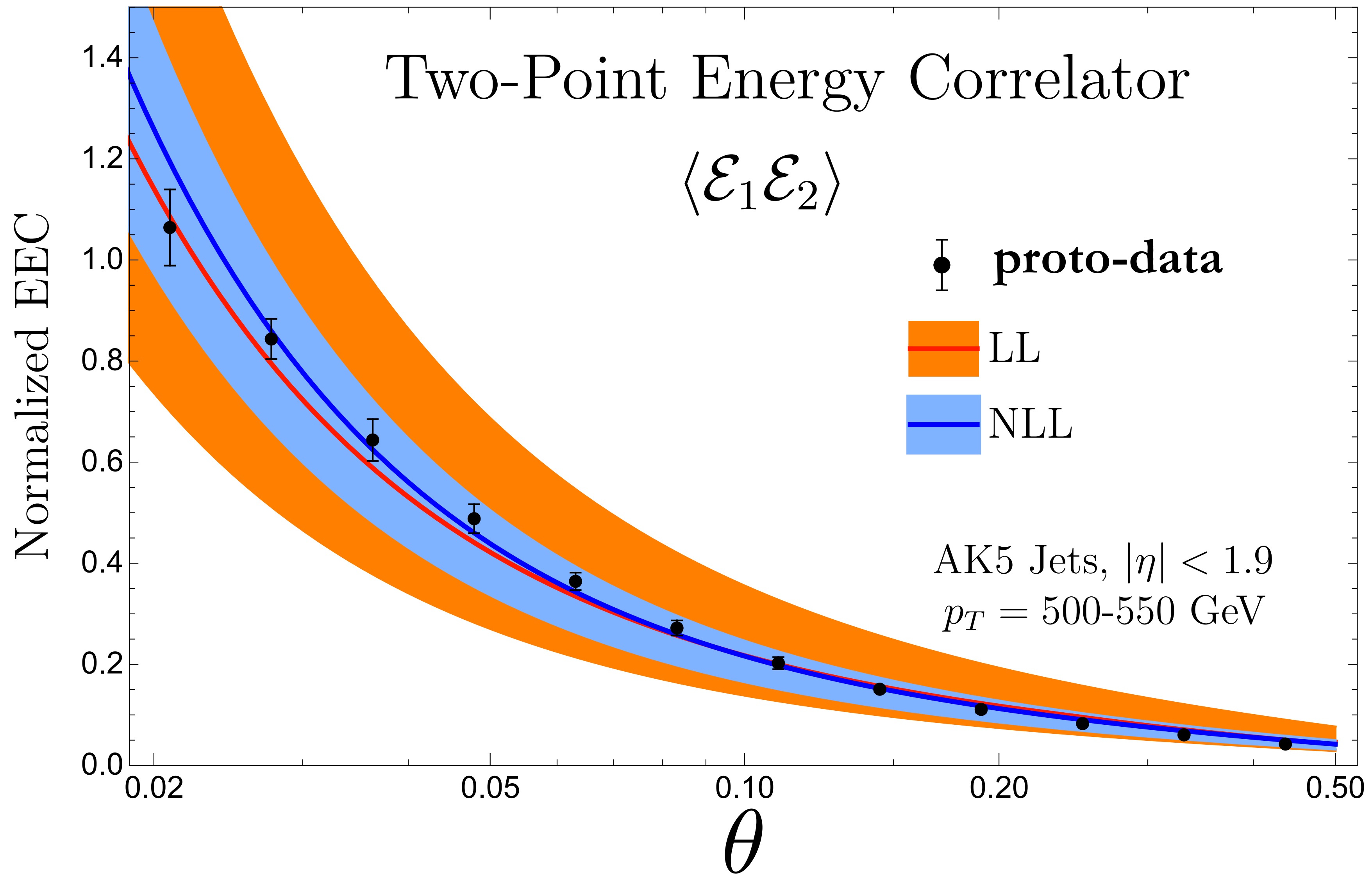
$\langle\psi\,|\mathcal{E}\left(\vec{n}_1\right)\mathcal{E}\left(\vec{n}_2\right)|\,\psi\rangle$

Light-ray OPE

$\langle\psi|\mathbb{O}^{[3]}(\vec{n})|\psi\rangle$



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

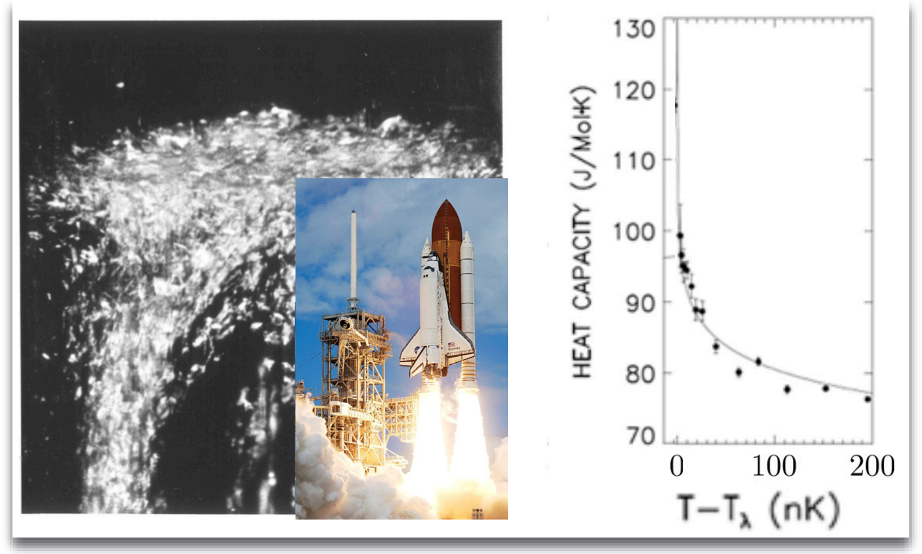


QCD factorization:

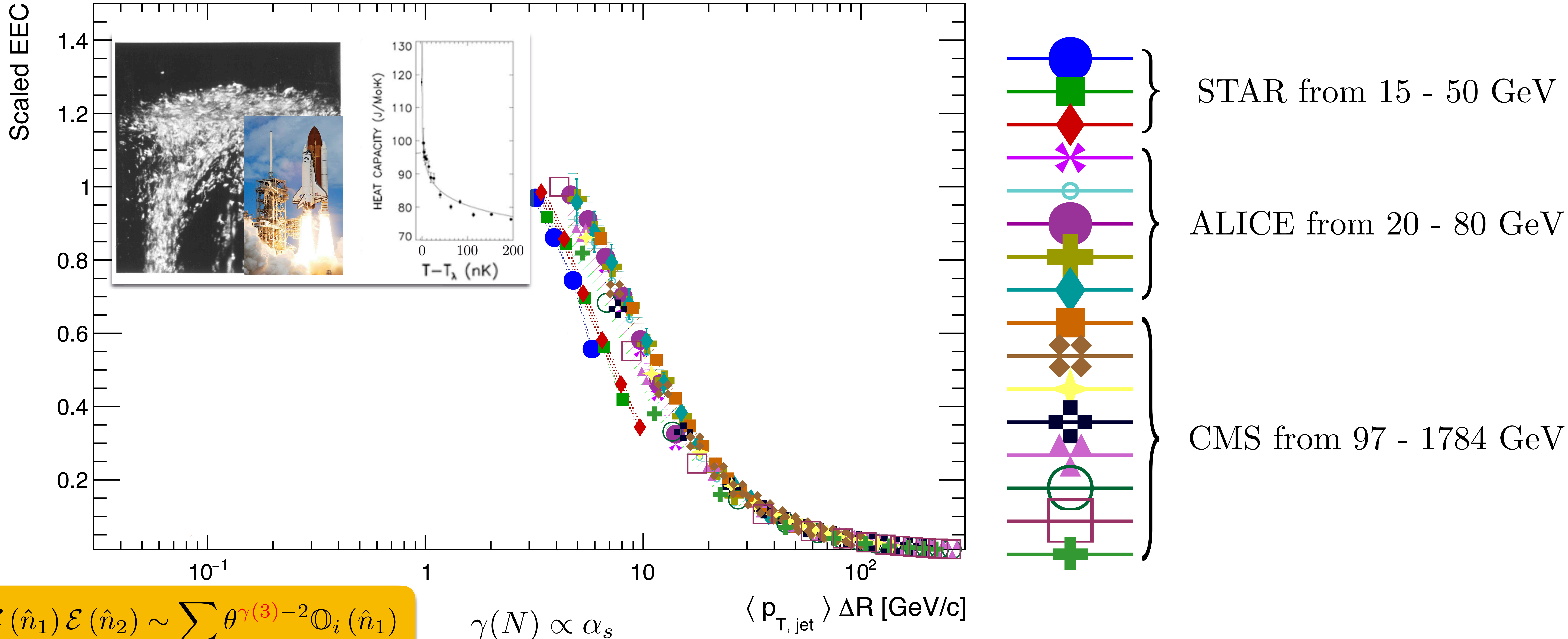
$$\frac{d\sigma^{pp\to\text{jet}(\mathcal{E}\mathcal{E})X}}{dp_T\,d\eta\,d\theta} = \sum_{a,b,c} f_{a/A}\otimes f_{b/B}\otimes H^c_{ab}\otimes\mathcal{G}^{\text{EEC}}_c(\theta)$$

Λ_{QCD} $\quad p_T \quad p_T R$

$p_T\theta$



SCALING FROM 15 GEV TO 2 TEV IN DATA!



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

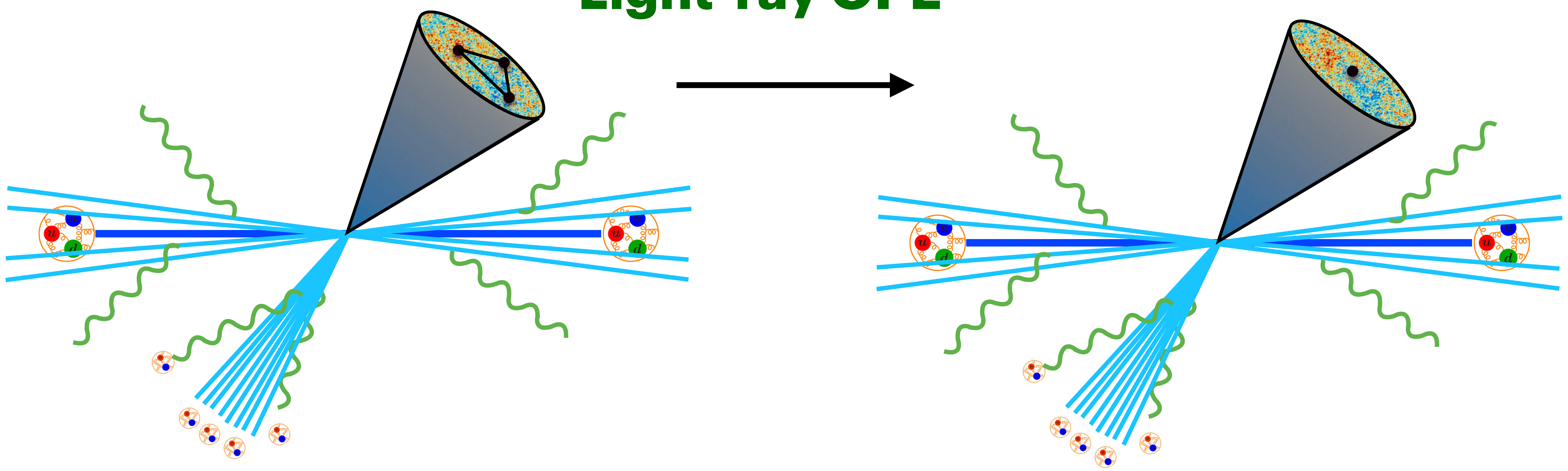
$$\gamma(N) \propto \alpha_s$$

- **Universal scaling of QCD operators revealed in data from ALICE, CMS, and STAR, 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**

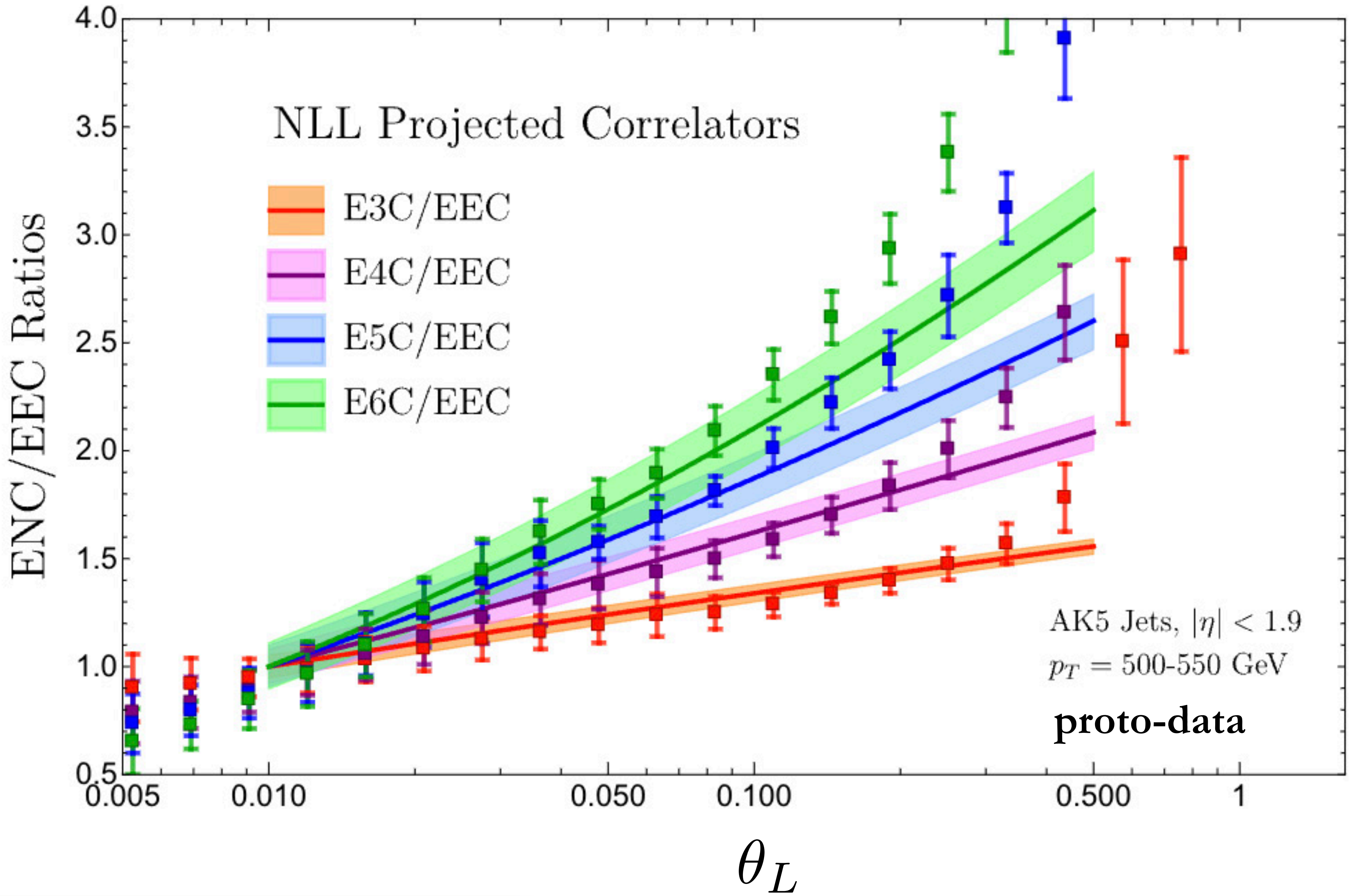
Chen, Moult, Zhang, Zhu `20
KL, Meçaj, Moult `22
Chen, Gao, Li, Xu, Zhang, Zhu `23

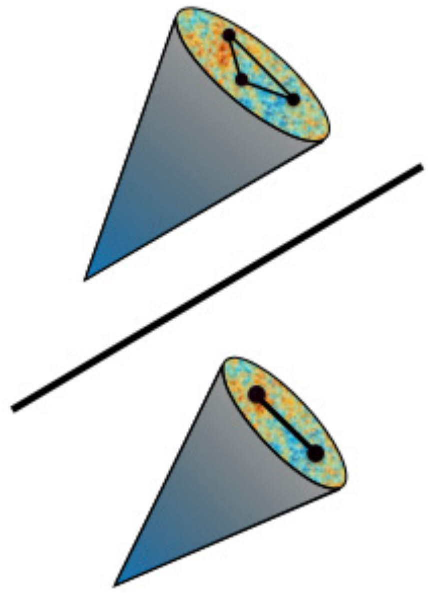


$\langle\psi\,|\mathcal{E}\,(\vec{n}_1)\cdots\mathcal{E}\,(\vec{n}_N)|\,\psi\rangle$

Light-ray OPE

$\langle\psi|\mathbb{O}^{[J]}(\vec{n})|\psi\rangle$





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

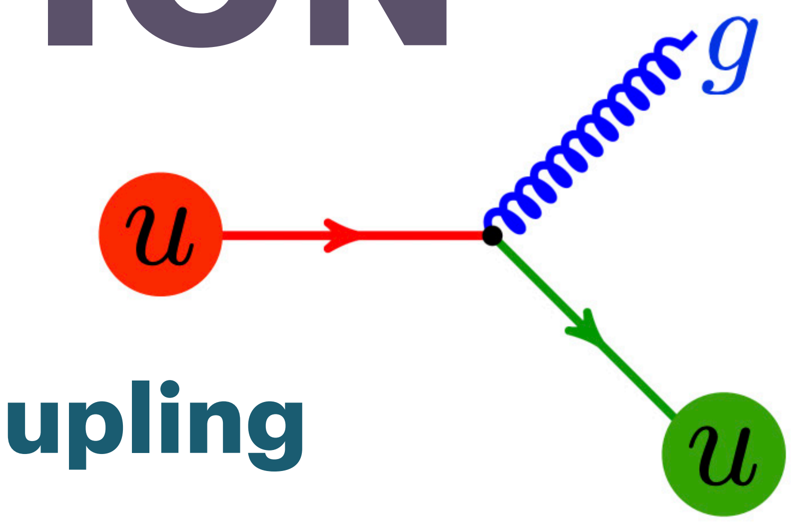
$$\gamma(N)\propto\alpha_s$$

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

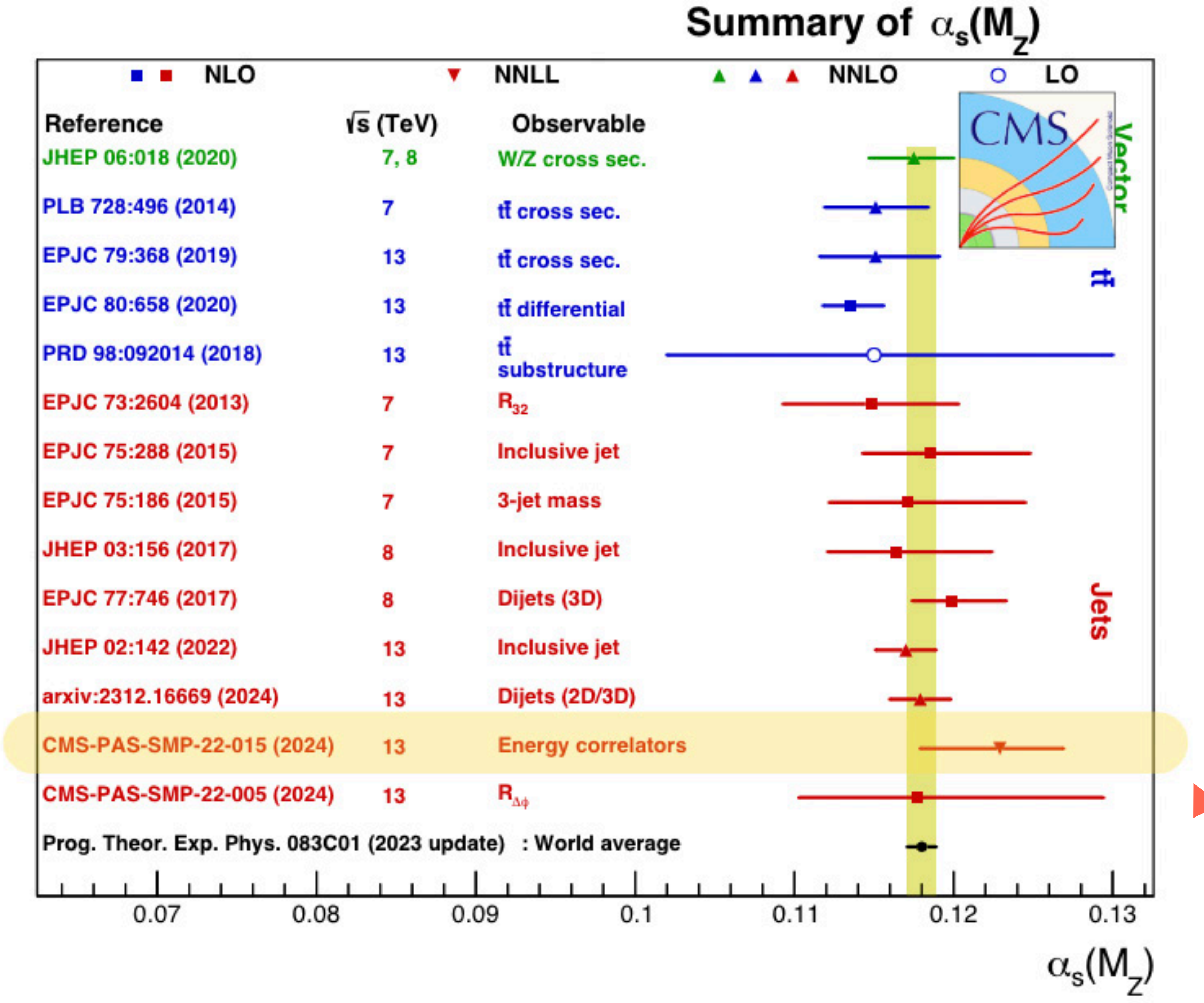
quantum classical

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



This yielded the worlds most precise α_S measurement from jet substructure: $\alpha_S = 0.1229^{+0.0040}_{-0.0050}$.

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

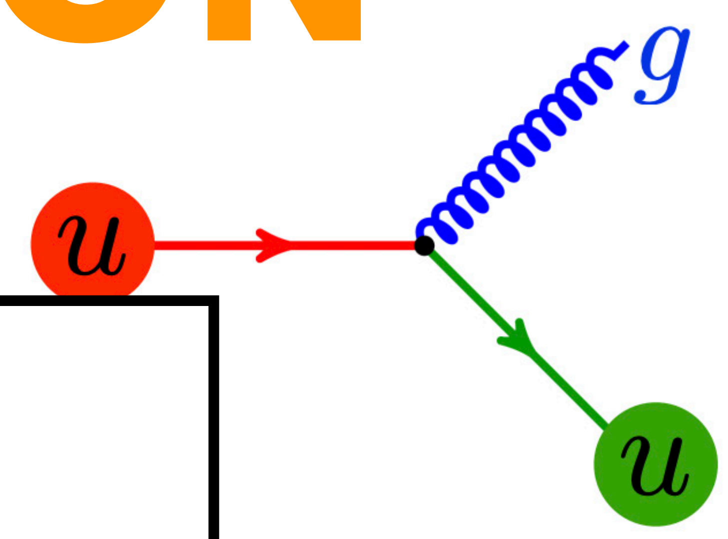
$$\alpha_s(m_Z) = 0.1229^{+0.0040}_{-0.0050}$$

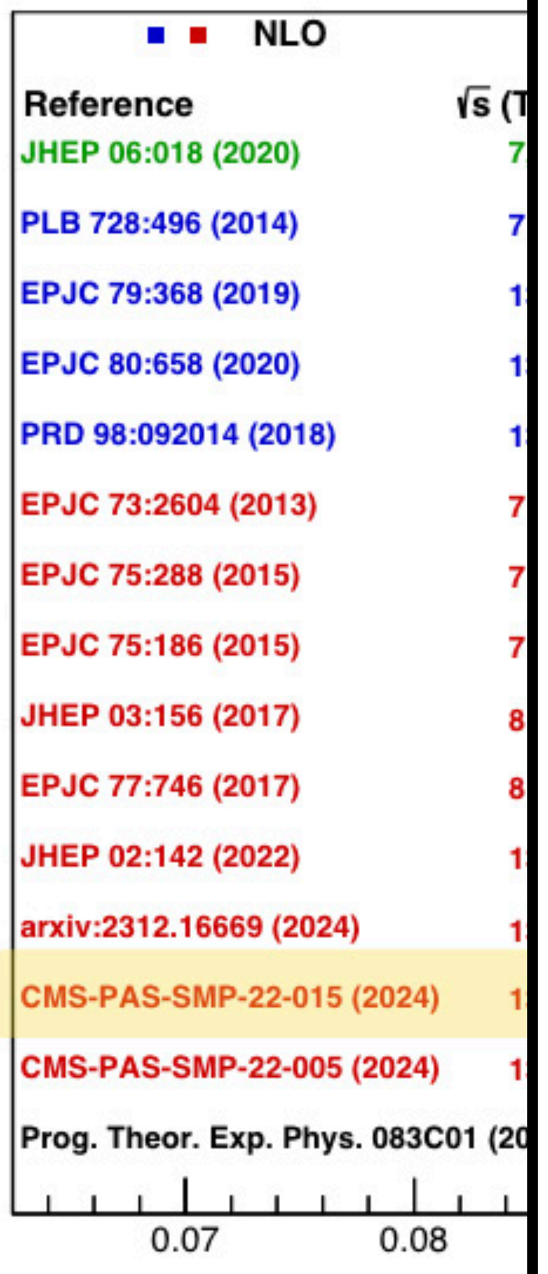
CMS Collaboration `23

$$\Longrightarrow \boxed{4\%\ \text{uncertainty}}$$

Energy Correlators in Jet

ROAD TO IMPROVED PRECISION





Road to precision

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

tion

3

This yielded the worlds most precise α_S measurement from jet substructure: $\alpha_S = 0.1229^{+0.0040}_{-0.0050}$.

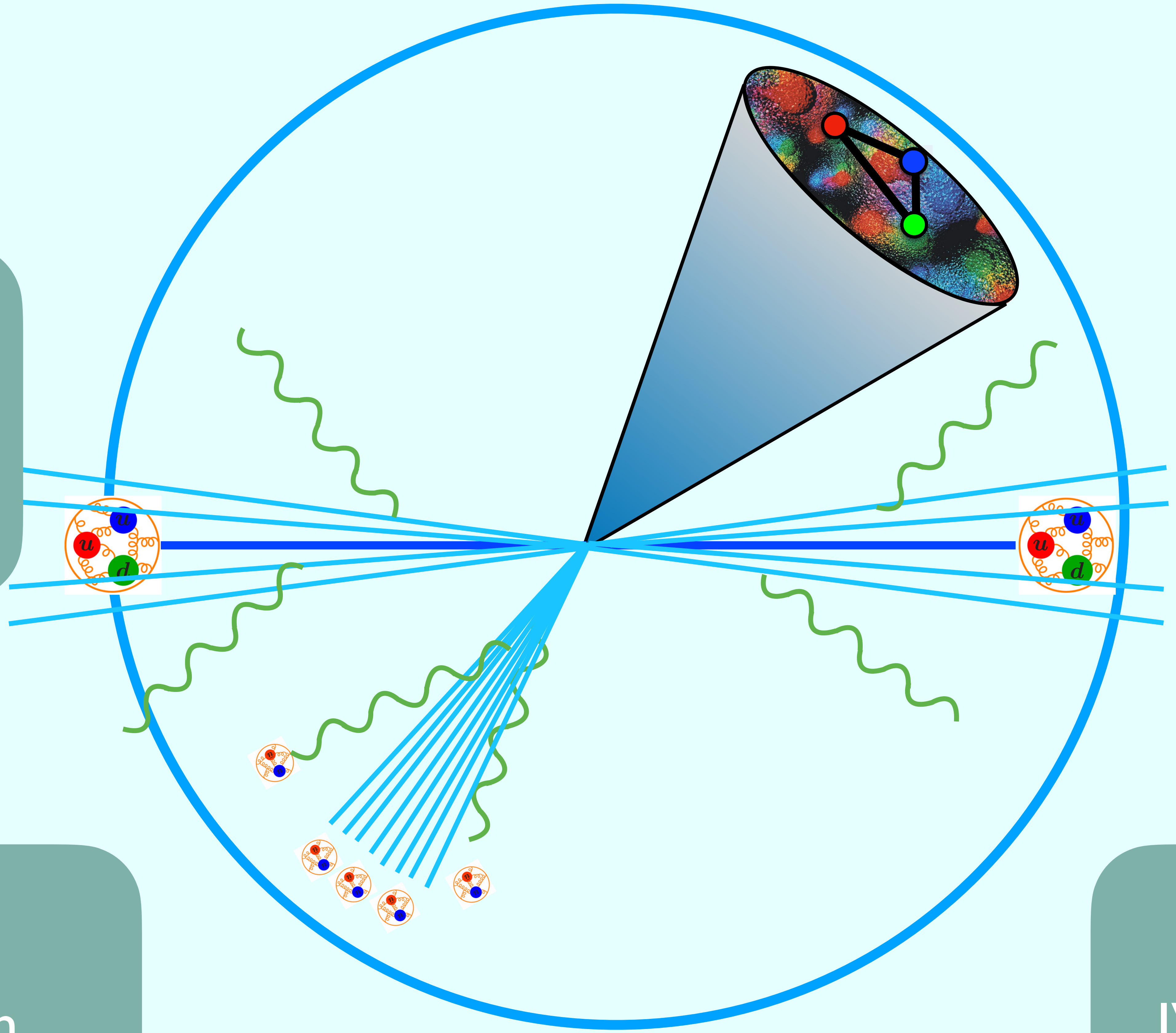
Overview

I. Universal Scaling

II. Precision QCD

VI. Real-time Simulations

III. Heavy Flavor Physics



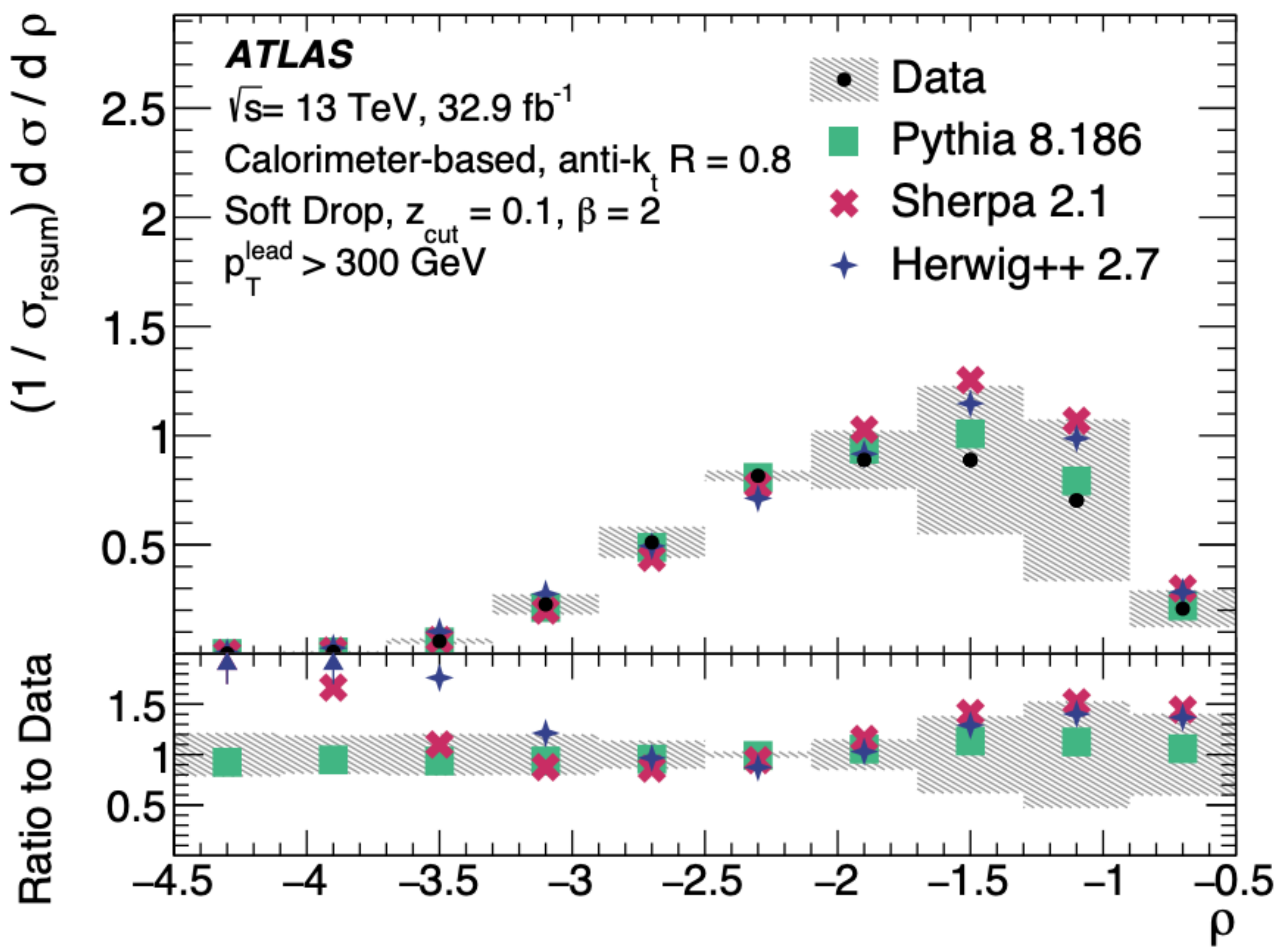
V. Hadronization

IV. Medium Dynamics

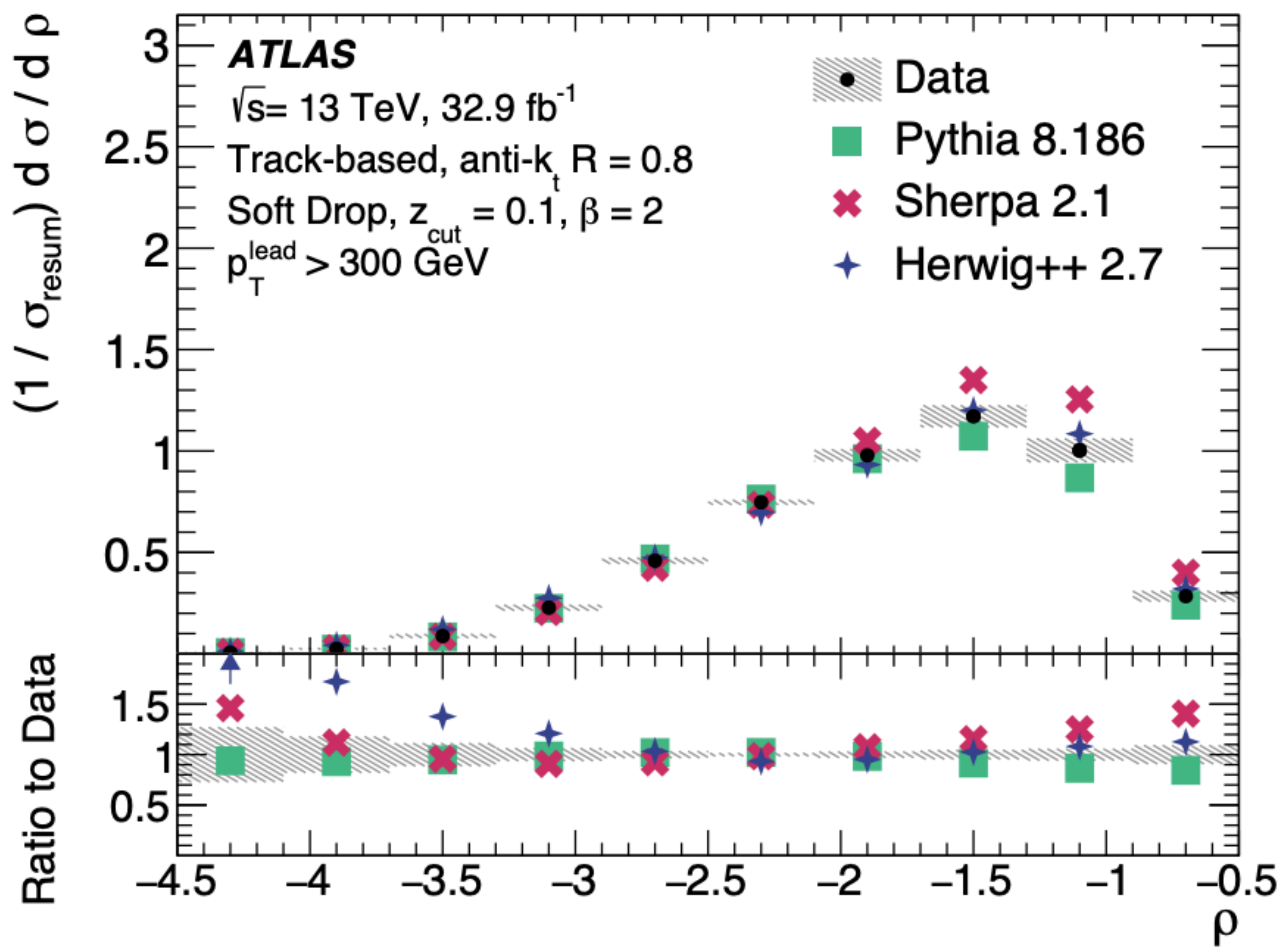
MEASURING TRACKS

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

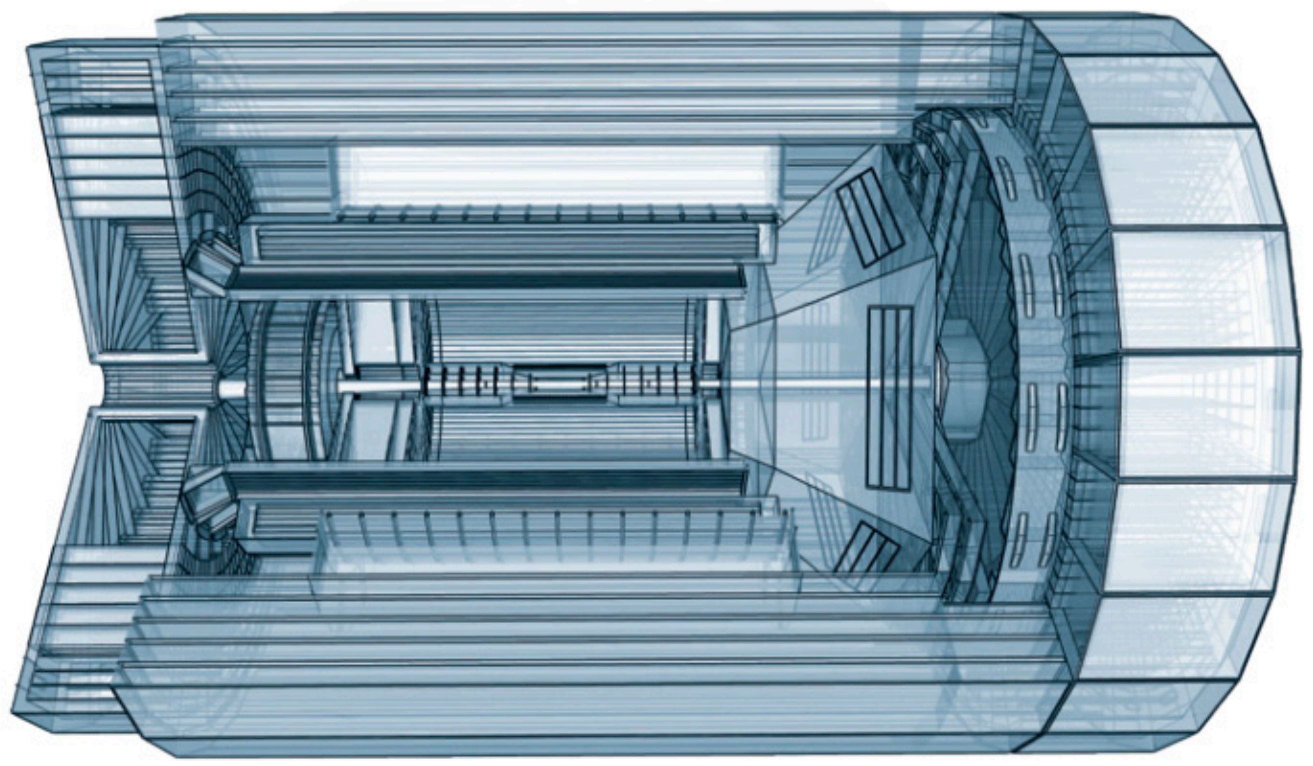
- **Measuring tracks provides much more precise experimental results**



All particles



Tracks

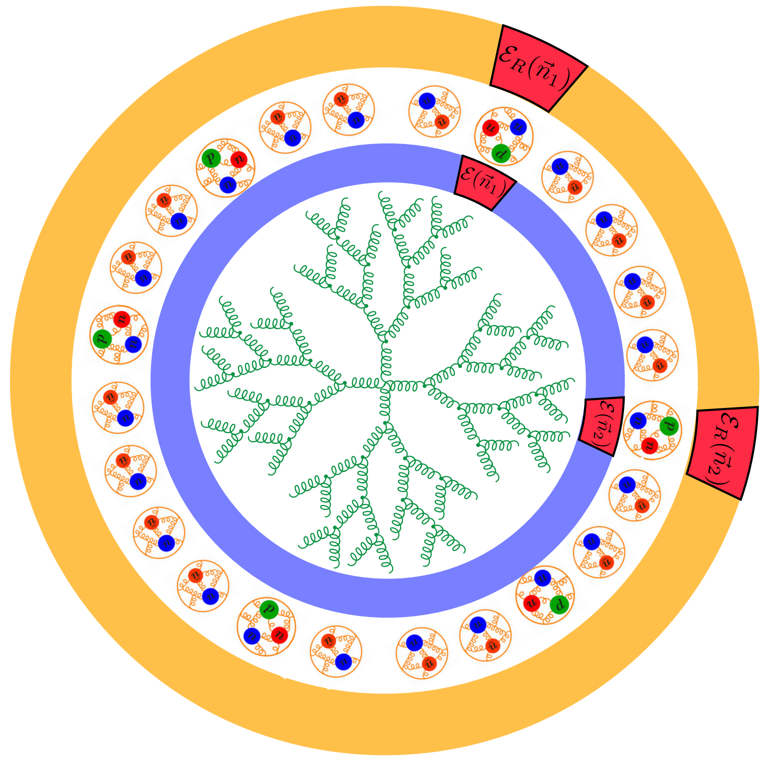


Modern detectors have state-of-the-art tracking systems!

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

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

We need QCD factorization



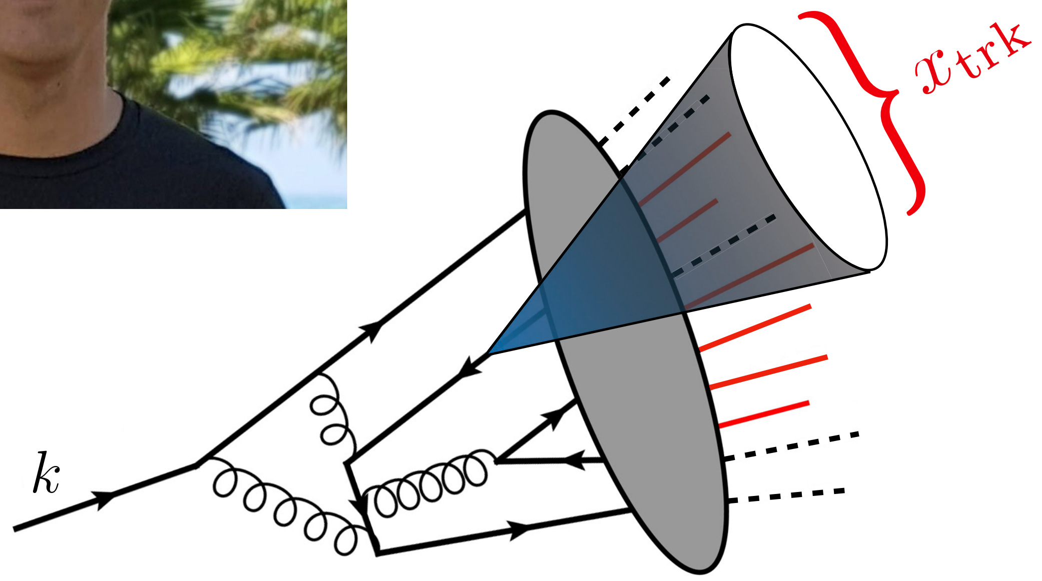
TRACK INSIDE JETS

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

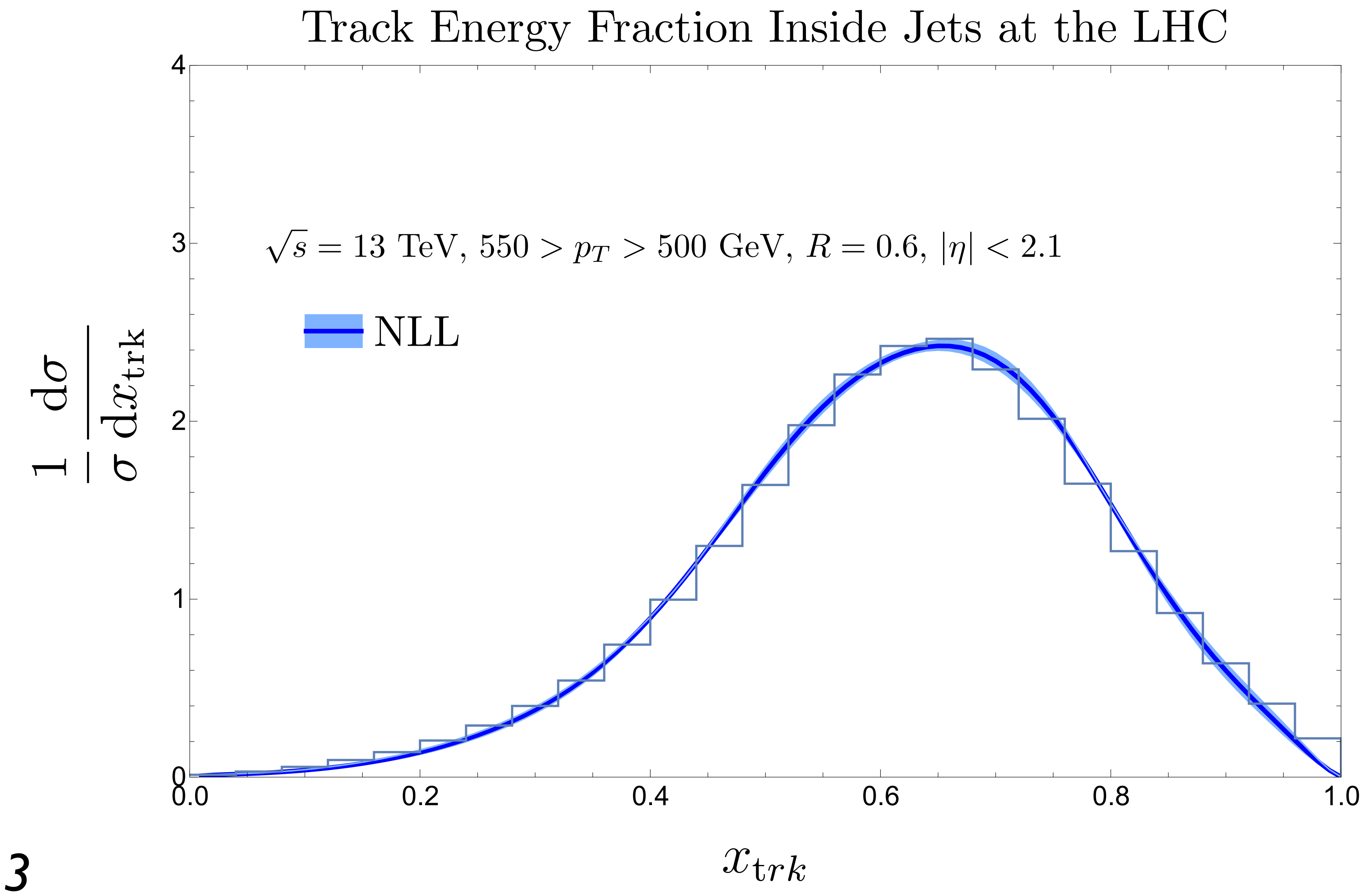
QCD factorization:

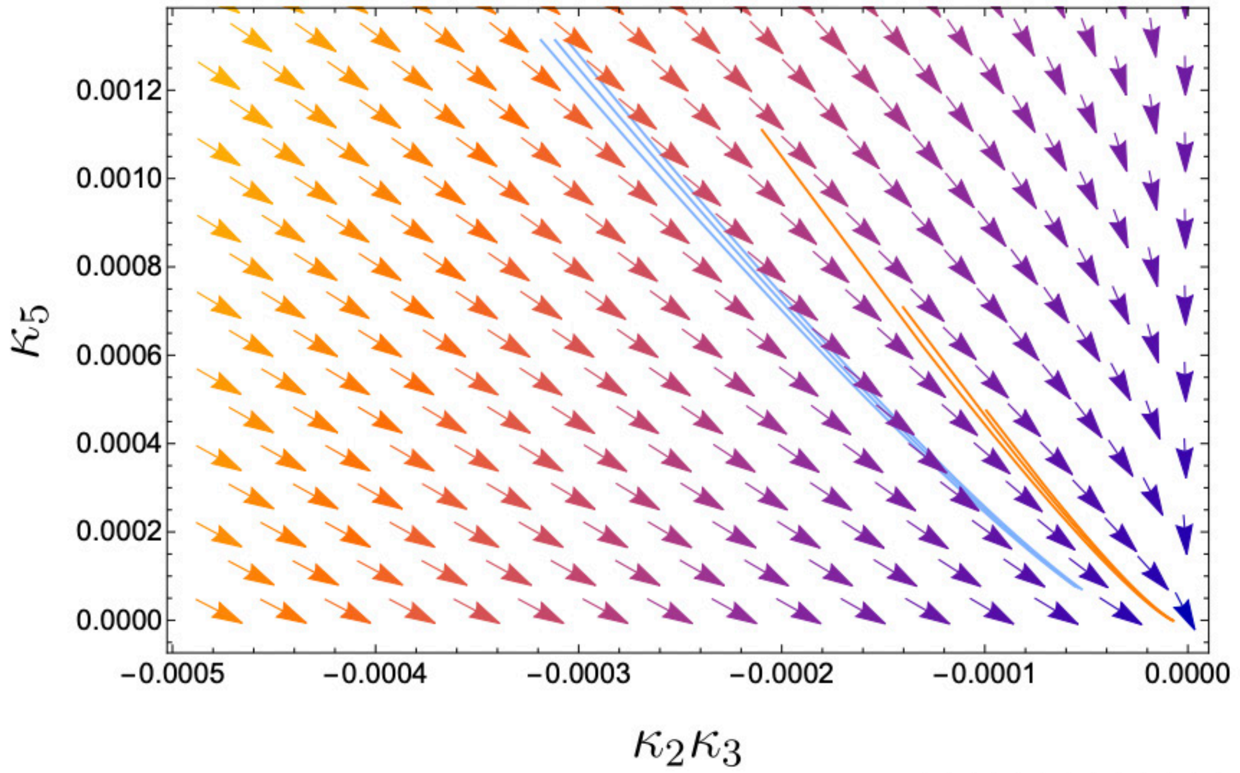
Requires separation of parts that are perturbative from universal non-perturbative functions

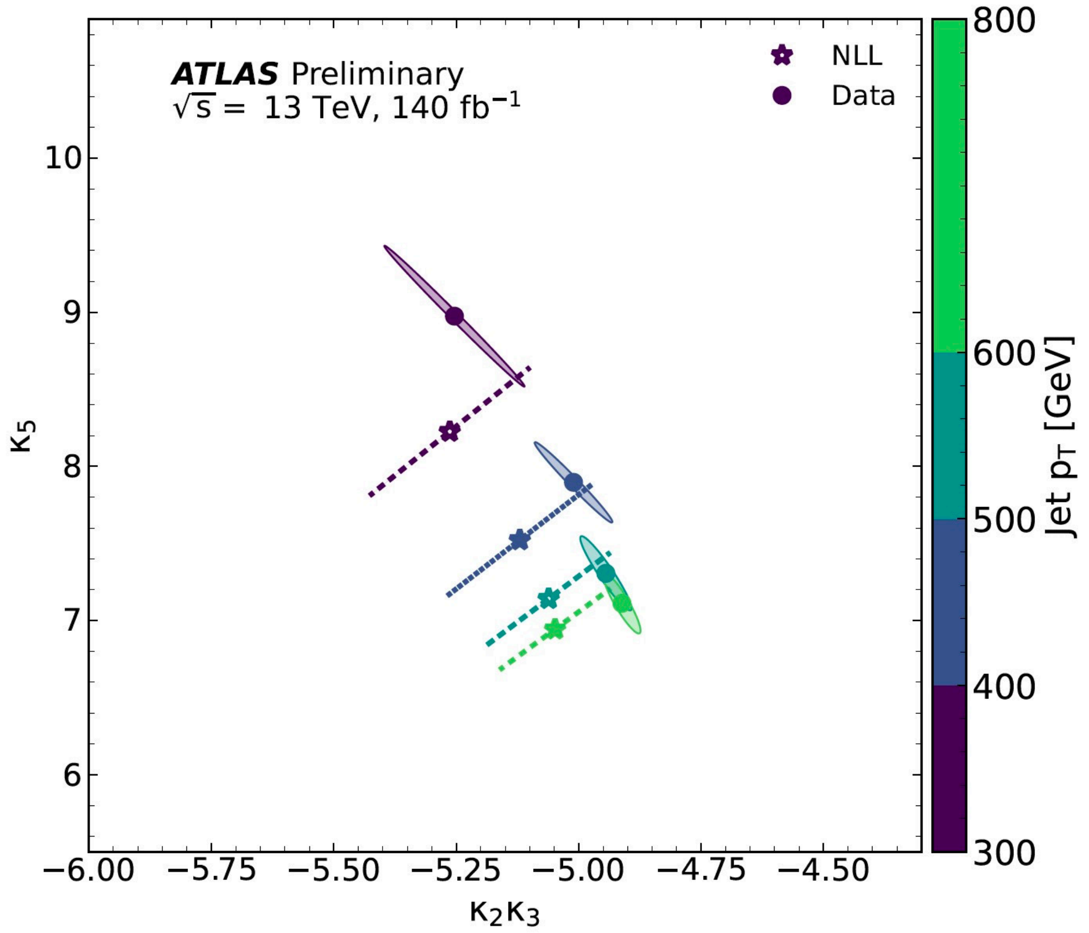
- **Non-perturbative Track functions describe the total energy fraction of charged hadrons from a fragmenting quark or a gluon state**



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





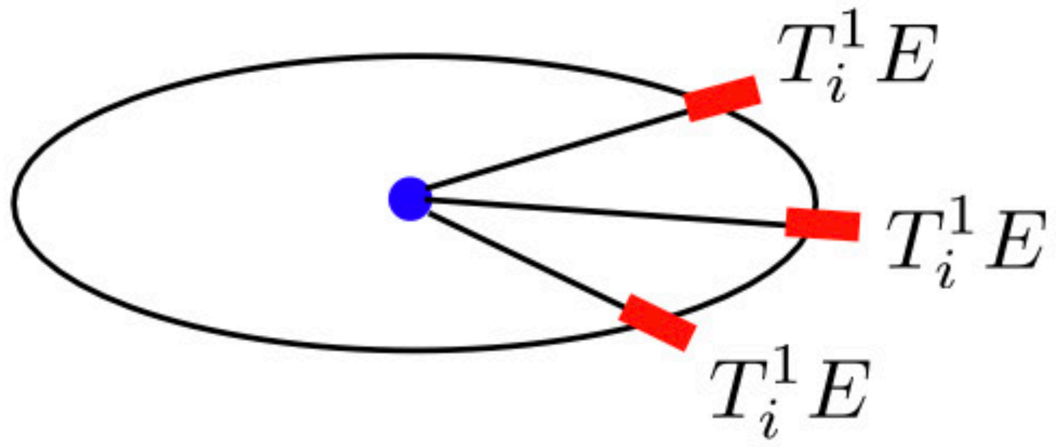


ATLAS preliminary

ENERGY CORRELATORS ON TRACK

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

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



$$\langle \mathcal{E}_R(\vec{n}_1)\,\mathcal{E}_R(\vec{n}_2)\cdots\mathcal{E}_R(\vec{n}_k)\rangle = \sum_{i_1,i_2,\cdots i_k} T_{i_1}(1)\cdots T_{i_k}(1)\,\langle \mathcal{E}_{i_1}(\vec{n}_1)\,\mathcal{E}_{i_2}(\vec{n}_2)\cdots\mathcal{E}_{i_k}(\vec{n}_k)\rangle$$

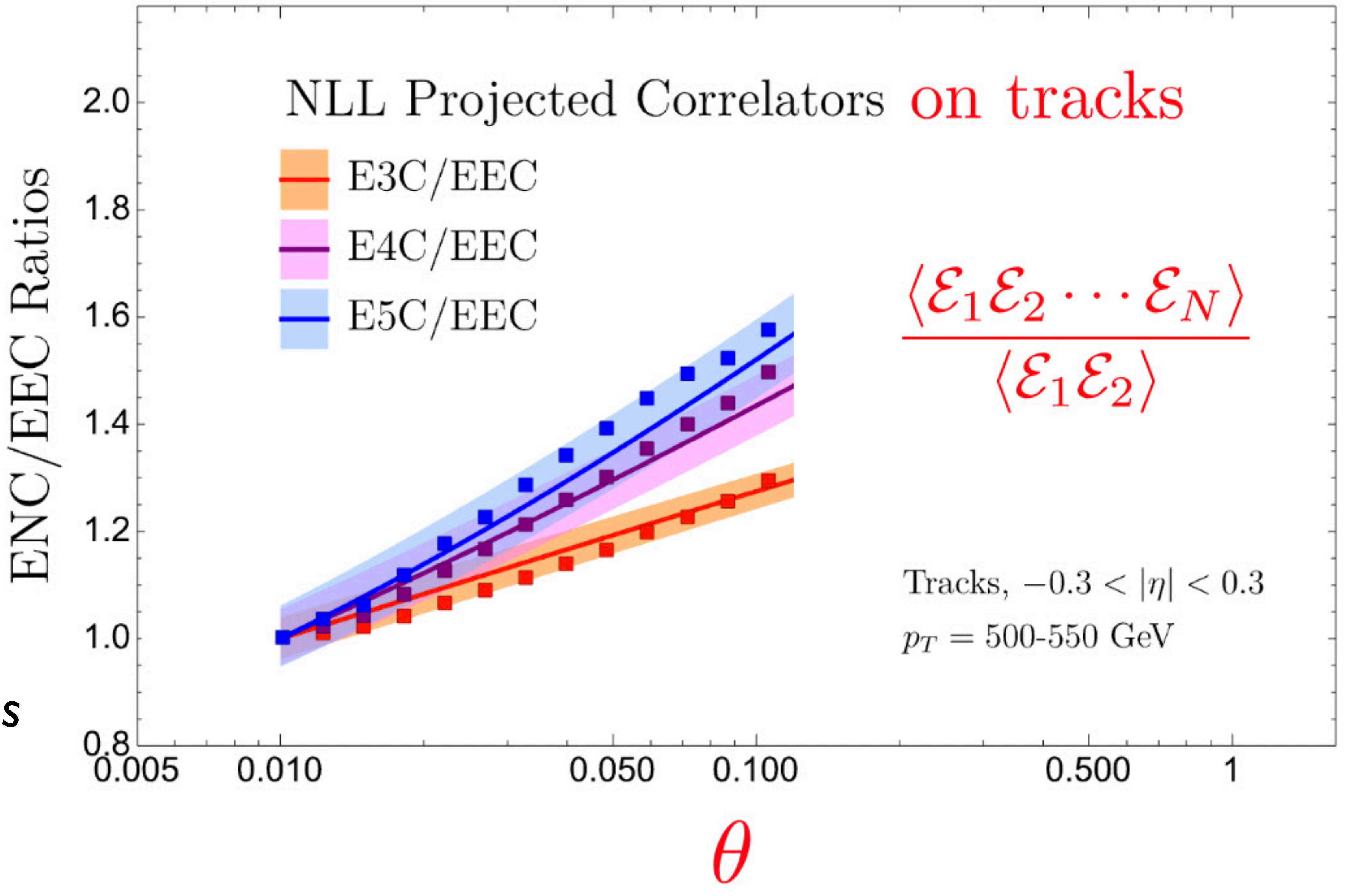
$$+\text{contact terms}$$

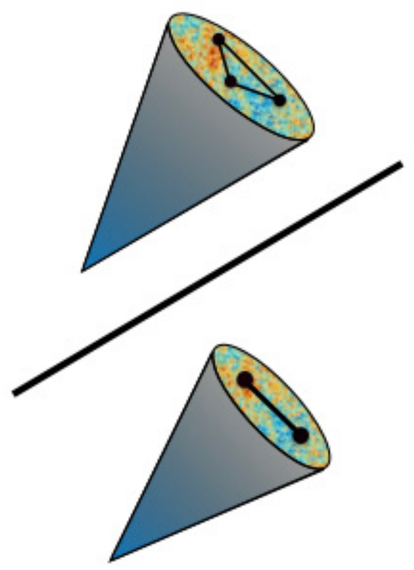
- **Only depends on the "moments" of track functions** $\Longrightarrow$ **Only involves NP *numbers*, not functions**

Predictions for tracks in Energy Correlators

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

KL, Li, Moult, Waalewijn `In Progress



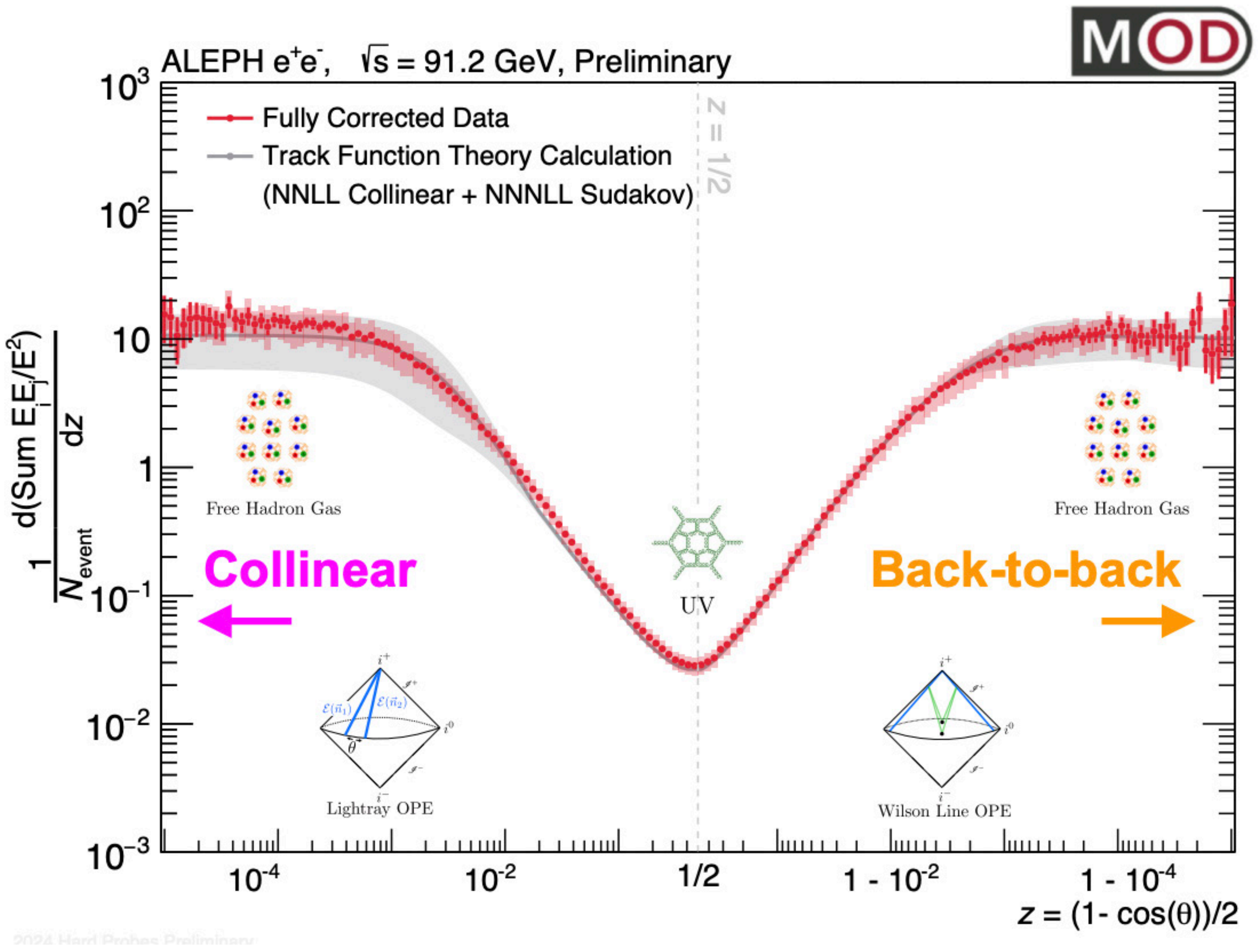


$$\frac{\langle \mathcal{E}_1\mathcal{E}_2\cdots\mathcal{E}_N\rangle}{\langle \mathcal{E}_1\mathcal{E}_2\rangle} \sim \frac{\langle \mathbb{O}^{[N+1]}\rangle}{\langle \mathbb{O}^{[3]}\rangle} \sim \theta_L^{\gamma(N+1)-\gamma(3)}$$

ENERGY CORRELATORS ON TRACK

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

Slide from Yu-Chen Chen, Hard Probe 2024



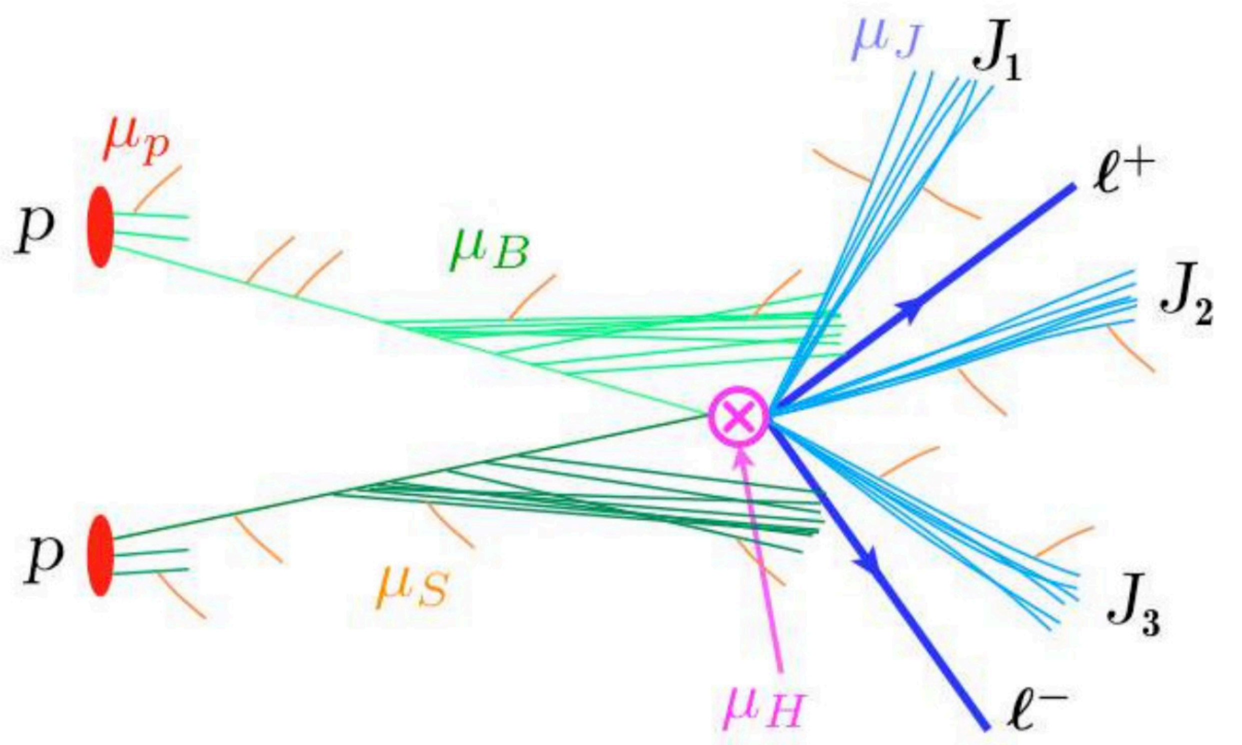
Reanalysis of ALEPH data on tracks

Jaarsma, Li, Moult, Waalewijn, Zhu `In Progress

Collinear Limit:
-NNLL Collinear Resummation
(Three Loop DGLAP Evolution)
Non-Perturbative Parameter Ω
extracted from thrust

Back-to-Back Limit:
-NNNLL Sudakov Resummation
- **Non-Perturbative Parameter Ω**
- **extracted from thrust**
- **Collins-Soper Kernel extracted from lattice QCD**

Effective Field Theory methods at the heart of the theoretical analysis!

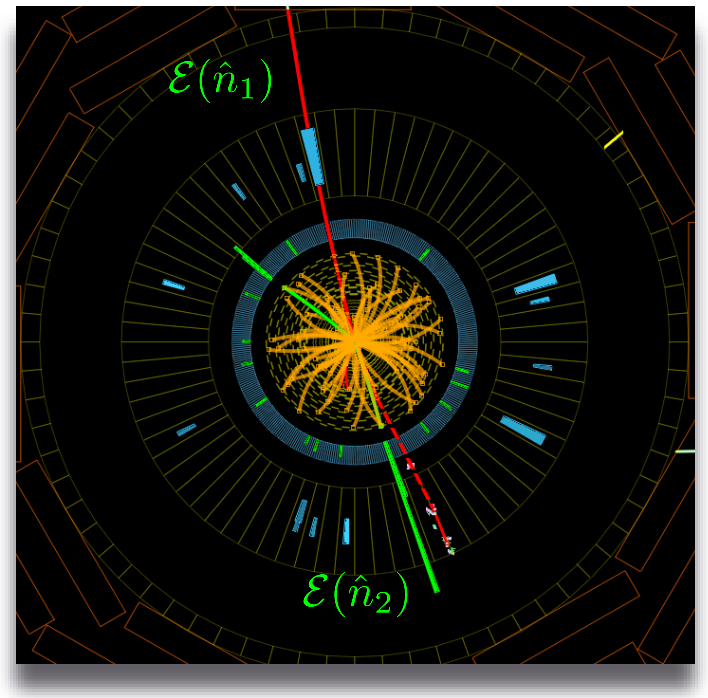


Bauer, Fleming, Luke, Pirjol, Stewart `00-01

EEC on track for e^+e^- allows one to study event-wide correlations very precisely!

POWER CORRECTIONS

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



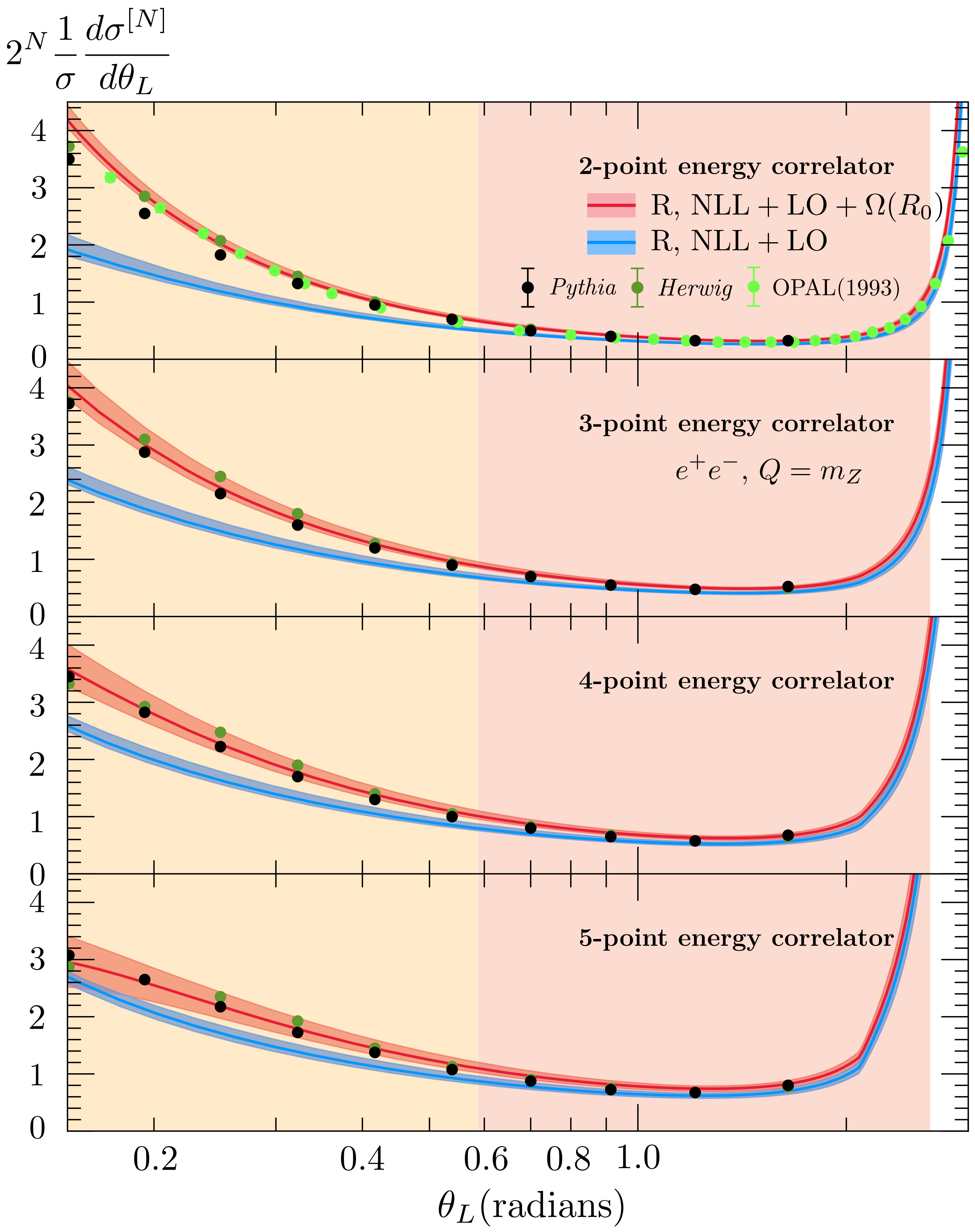
e^+e^- in the collinear limit exhibits same universal behavior as hadron jets

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

Universal Power Corrections

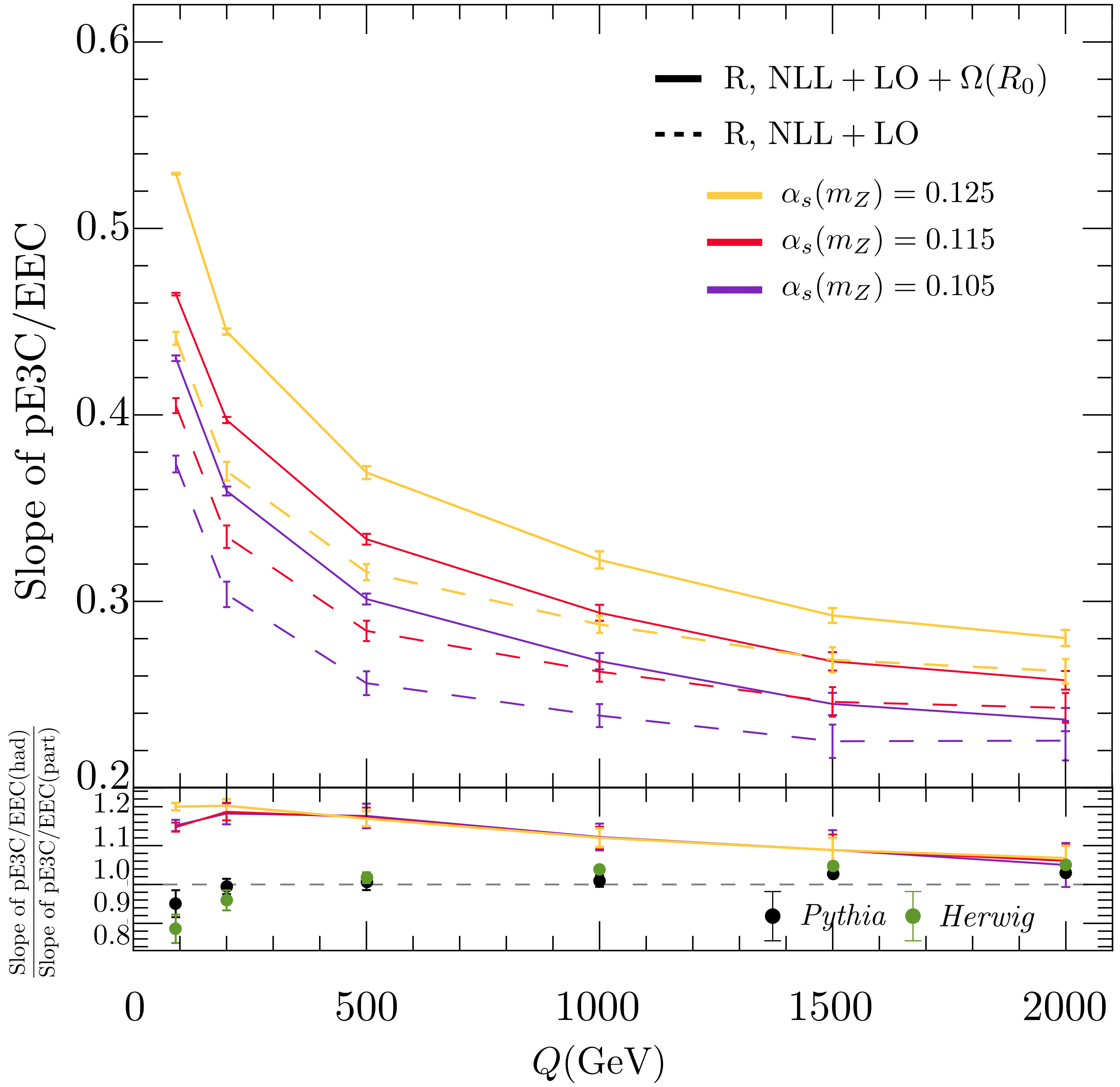
Renormalon subtractions

Hoang, Kluth `08
Hoang, Stewart, et al `07, 09,14,20
Hoang et al`23



Lee, Sterman `06

Schindler, Stewart, Sun `23
KL, Pathak, Stewart, Sun `24
Chen, Monni, Xu, Zhu `24



At Q=1000, 10% impact of power correction

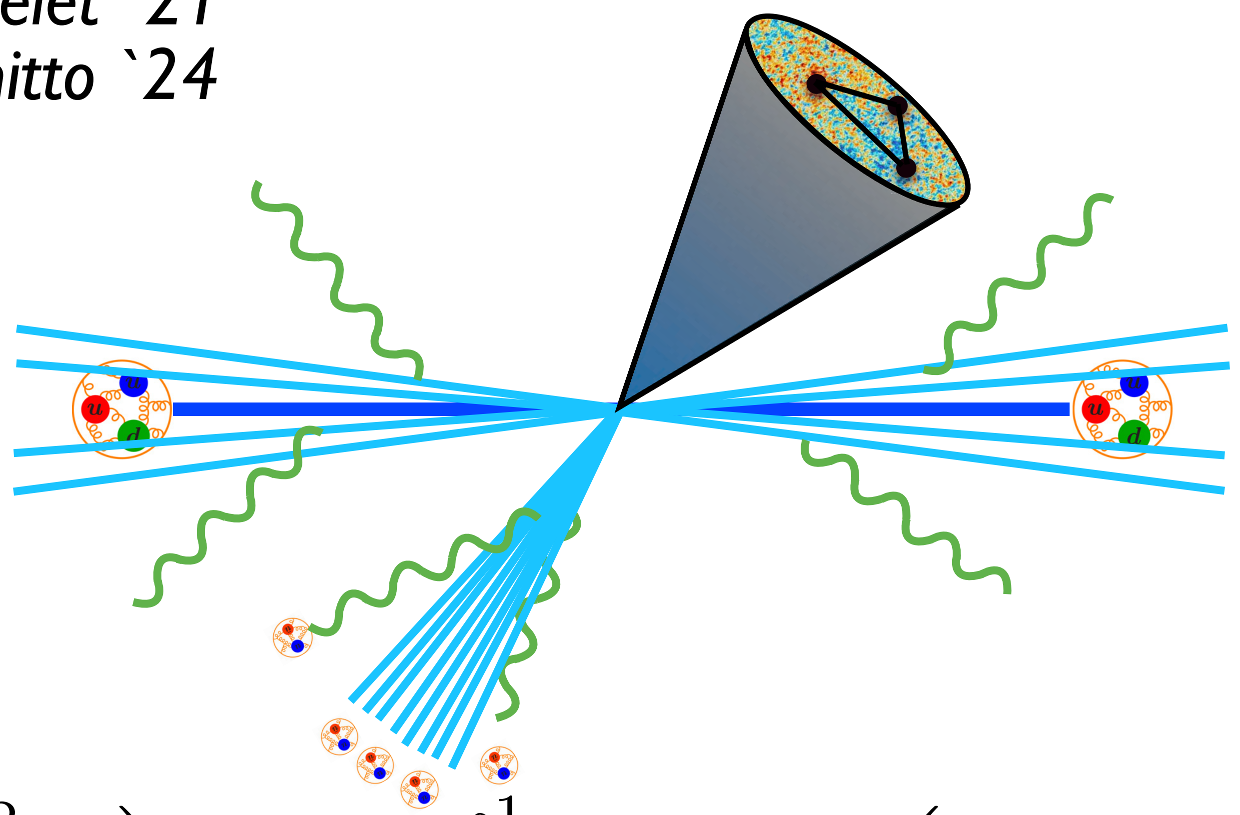
IMPROVING PERTURBATIVE ACCURACY

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

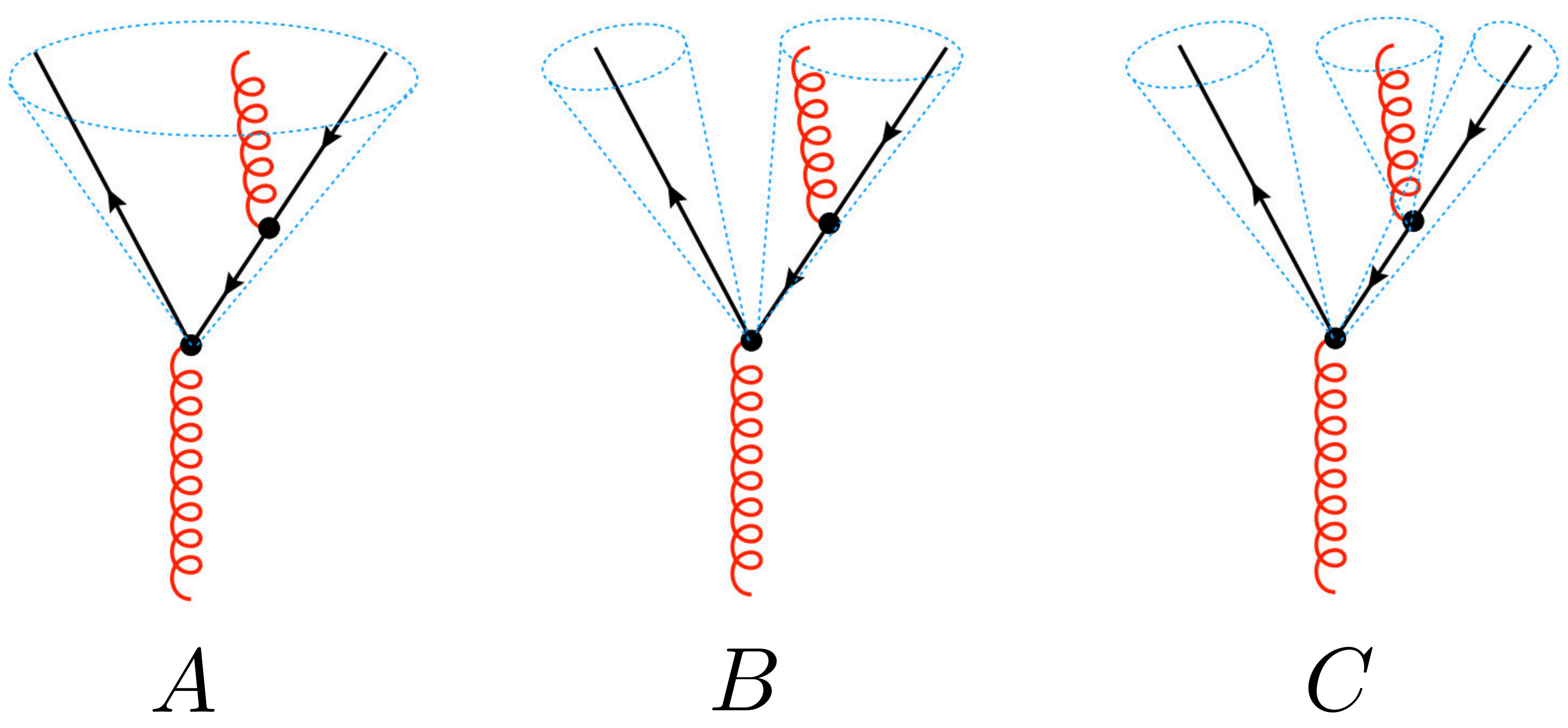
$$\langle\psi\left|\mathcal{E}\left(\vec{n}_1\right)\cdots\mathcal{E}\left(\vec{n}_{J-1}\right)\right|\psi\rangle$$

Czakon, Generet, Mitov, Poncelet `21
Bonino, Gehrmann, Stagnitto `24

$$\frac{d\sigma^{pp\to\text{jet}(\text{N}-\text{proj})X}}{dp_T\,d\eta\,d\theta_L}=\sum_{a,b,c}\underset{\Lambda_{\text{QCD}}}{f_{a/A}\otimes f_{b/B}}\otimes\underset{p_T}{H_{ab}^{c}}\otimes\underset{\substack{p_T R\\ p_T\theta_L}}{\mathcal{G}_c^{\text{N}-\text{proj}}}(\theta_L)$$



KL, Meçaj, Moult `22
Kang, KL, Zhao `20



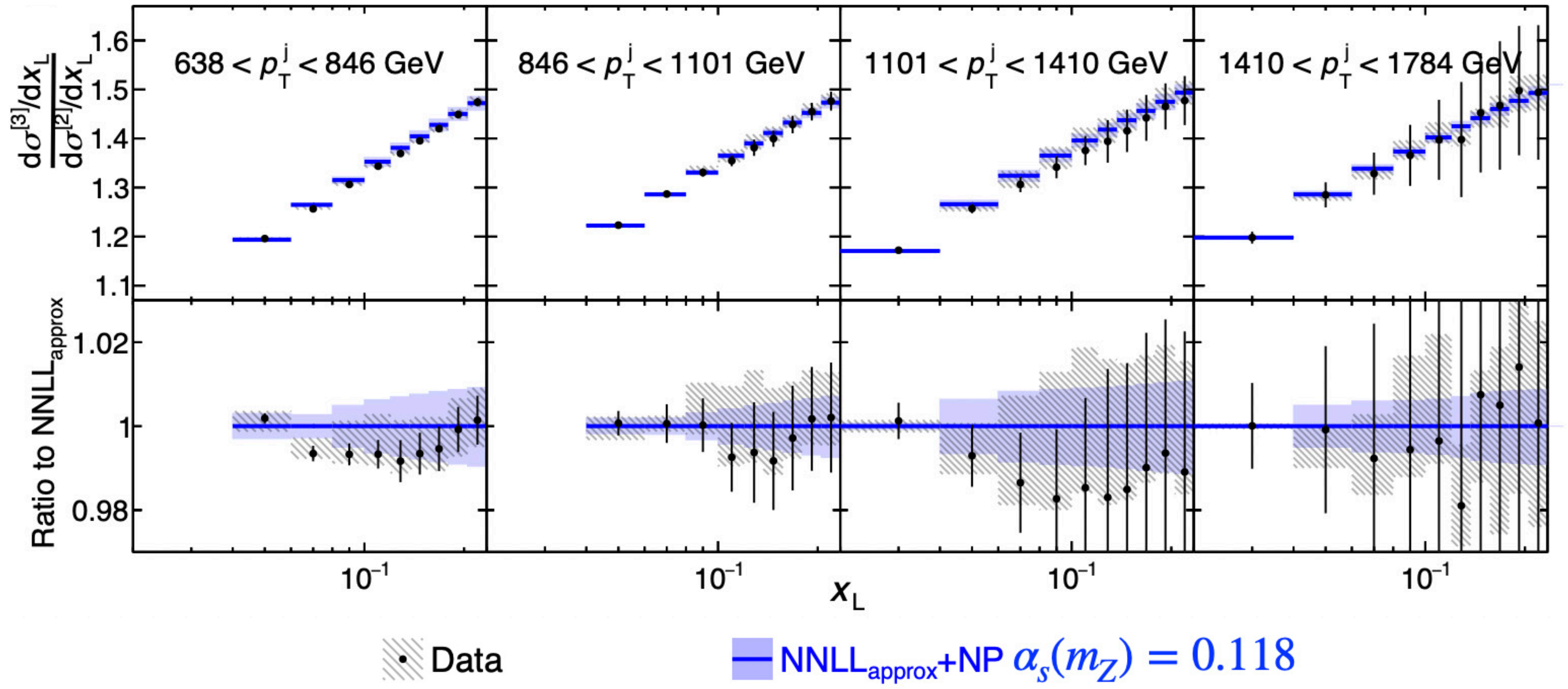
$\tilde{s}_{ik}$ = angle between i and k

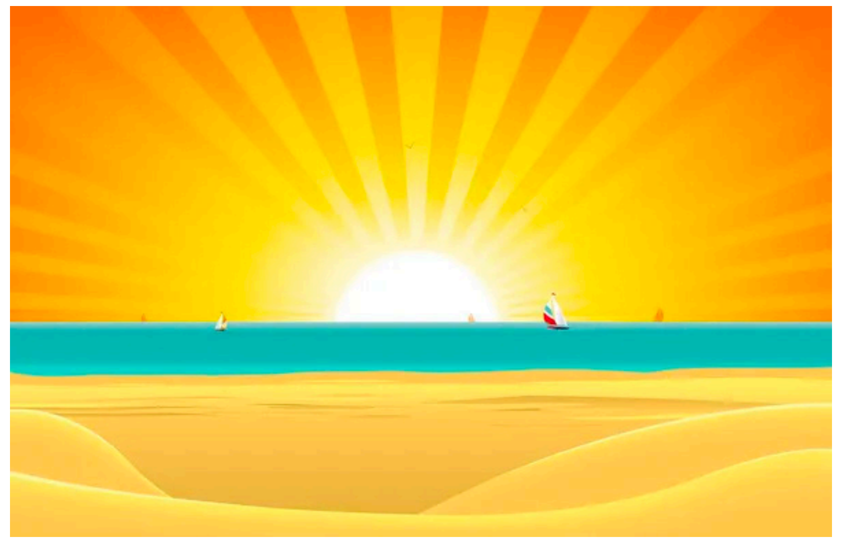
z_i = momentum fraction of i

$$\mathcal{G}_i\left(\frac{z_J}{x},\theta_L,\ln\frac{x^2Q^2R^2}{4\mu^2},\mu\right)=\sum_j\int_0^1 dy\,y^N\underbrace{\mathcal{J}_{ij}\left(\frac{z_J}{x},y,\ln\frac{x^2Q^2R^2}{4\mu^2},\mu\right)}\,J_j^{[N]}\left(\ln\frac{y^2Q^2\theta_L^2}{4\mu^2},\mu\right)$$

KL, Moult, Zhang `24,24
KL, Moult, Zhang `In Progress
Kang, Ringer, Vitev `16
Neill, Ringer, Sato, `21

Encodes complicated jet clustering algorithm details





> **Unprecedented precision calculation of jet substructure on the horizon!**

Overview

I. Universal Scaling

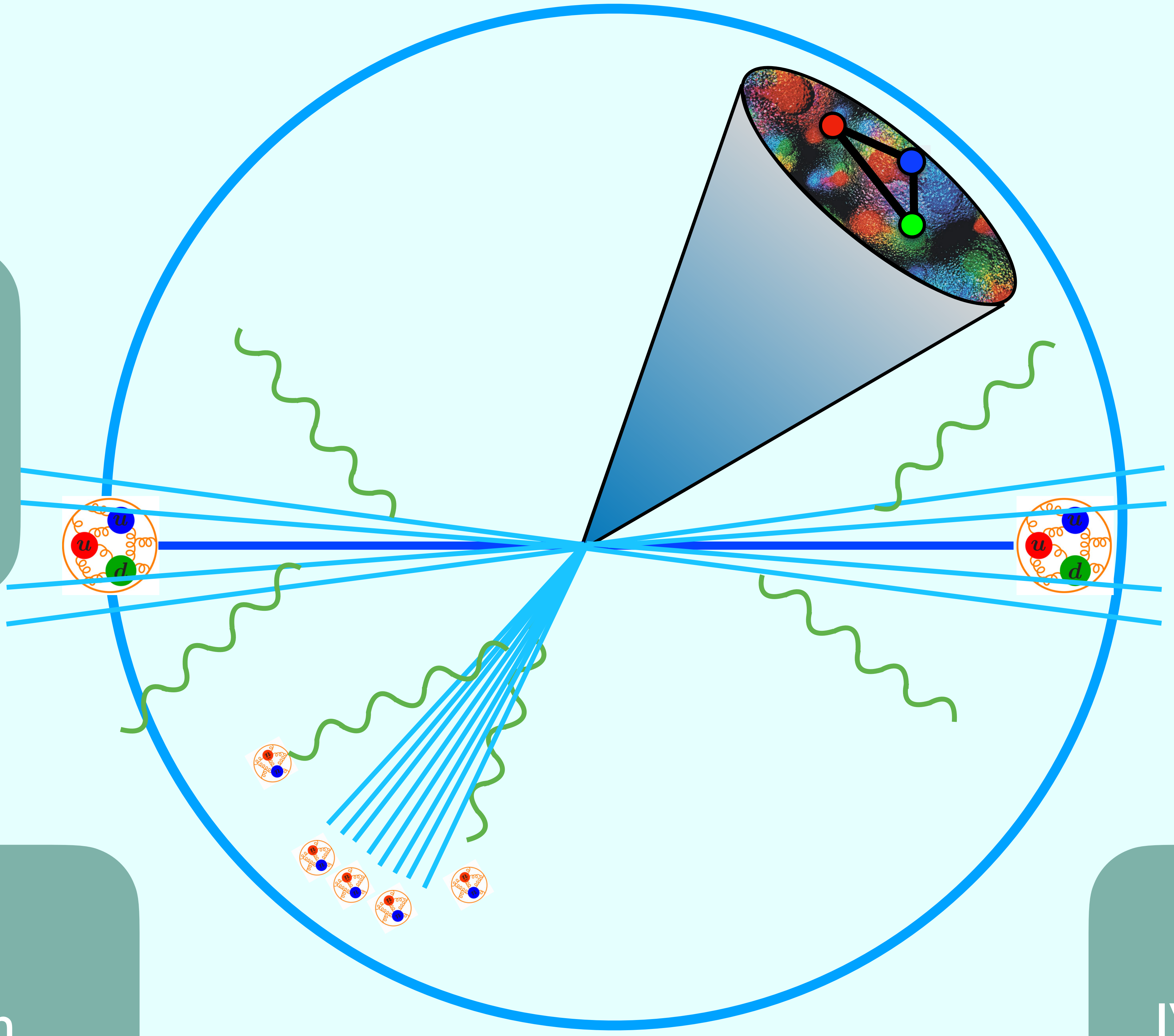
II. Precision QCD

III. Heavy Flavor Physics

IV. Medium Dynamics

V. Hadronization

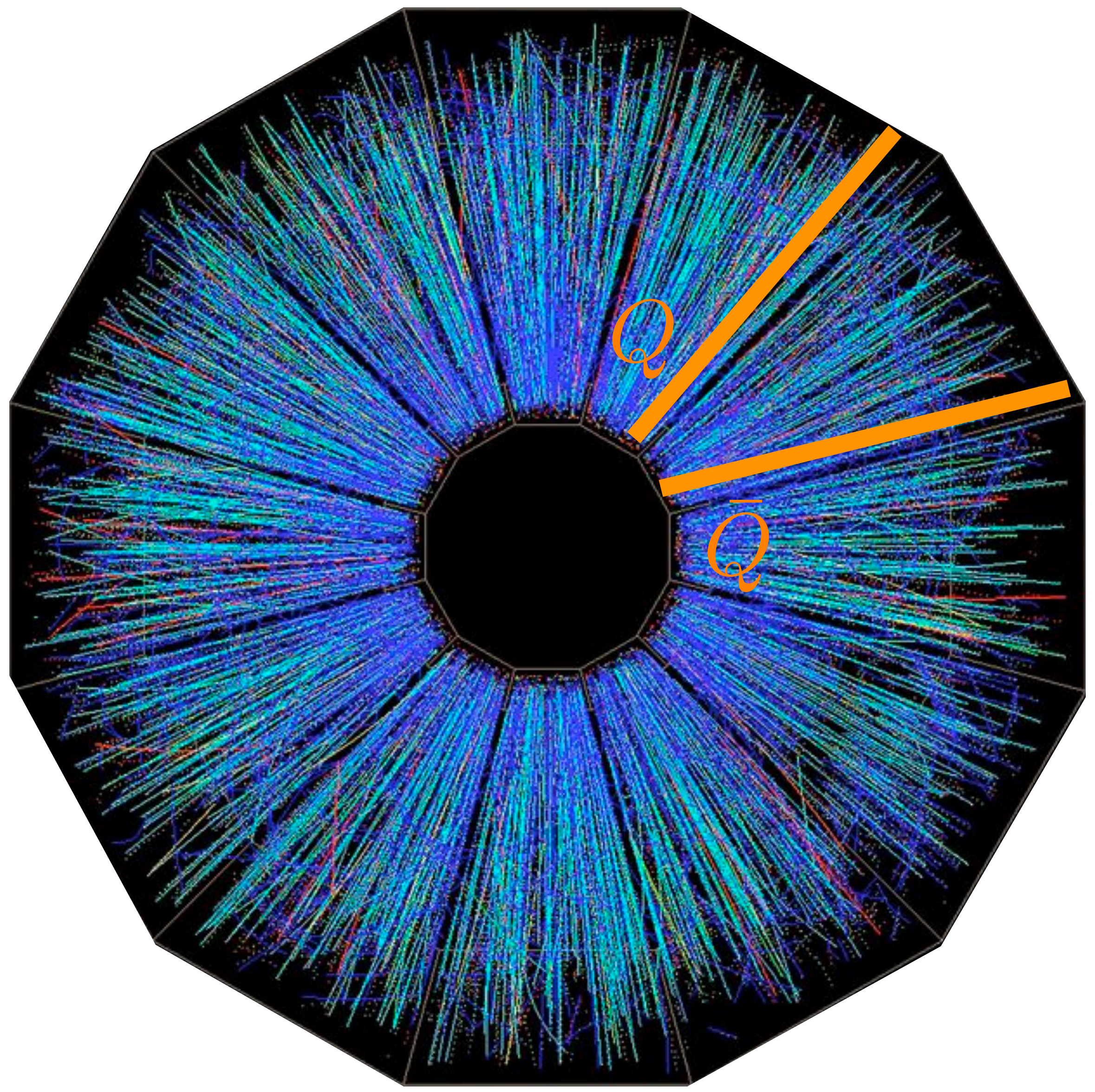
VI. Real-time Simulations

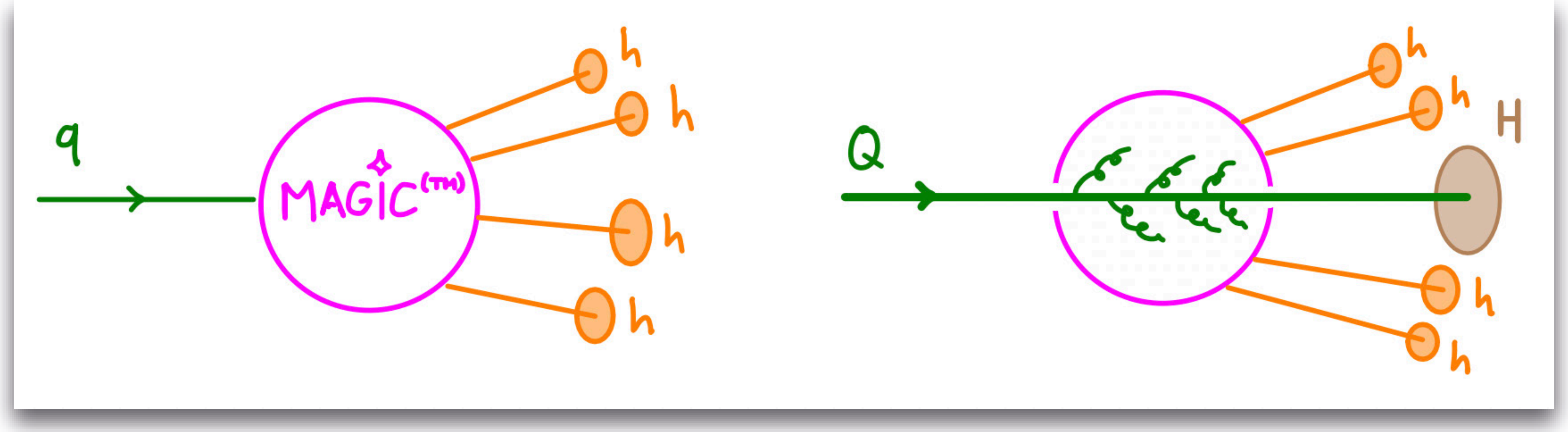


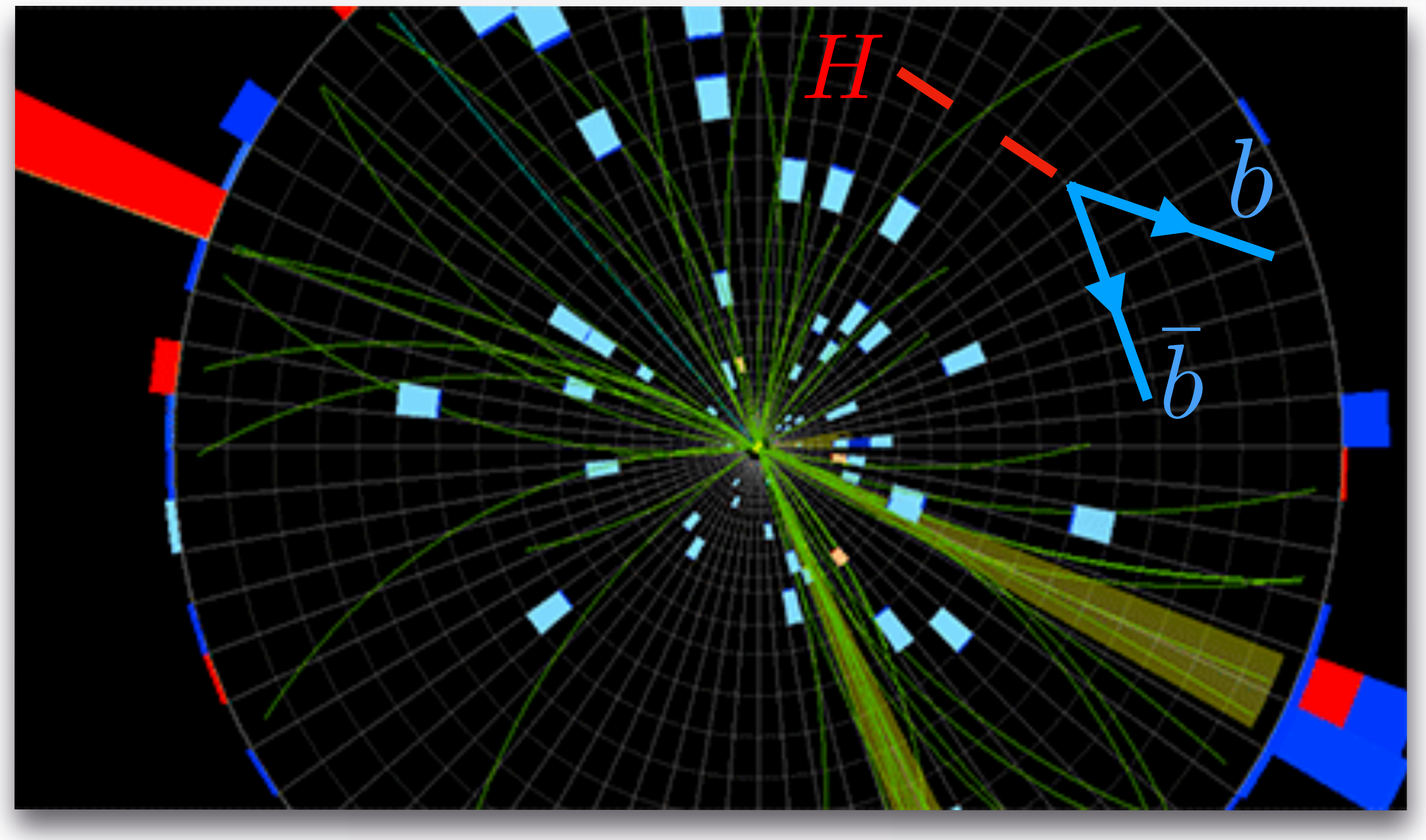
UNRAVELING HEAVY FLAVOR DYNAMICS

- **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
…







Run 3 and **sPHENIX** will give us a lot more access to **heavy quarks with precise data!**

- **Heavy quark introduces new mass scale** m_Q
- **Jet substructure allows us to precisely probe the dynamics from this new heavy quark scale**

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!**

Free hadrons

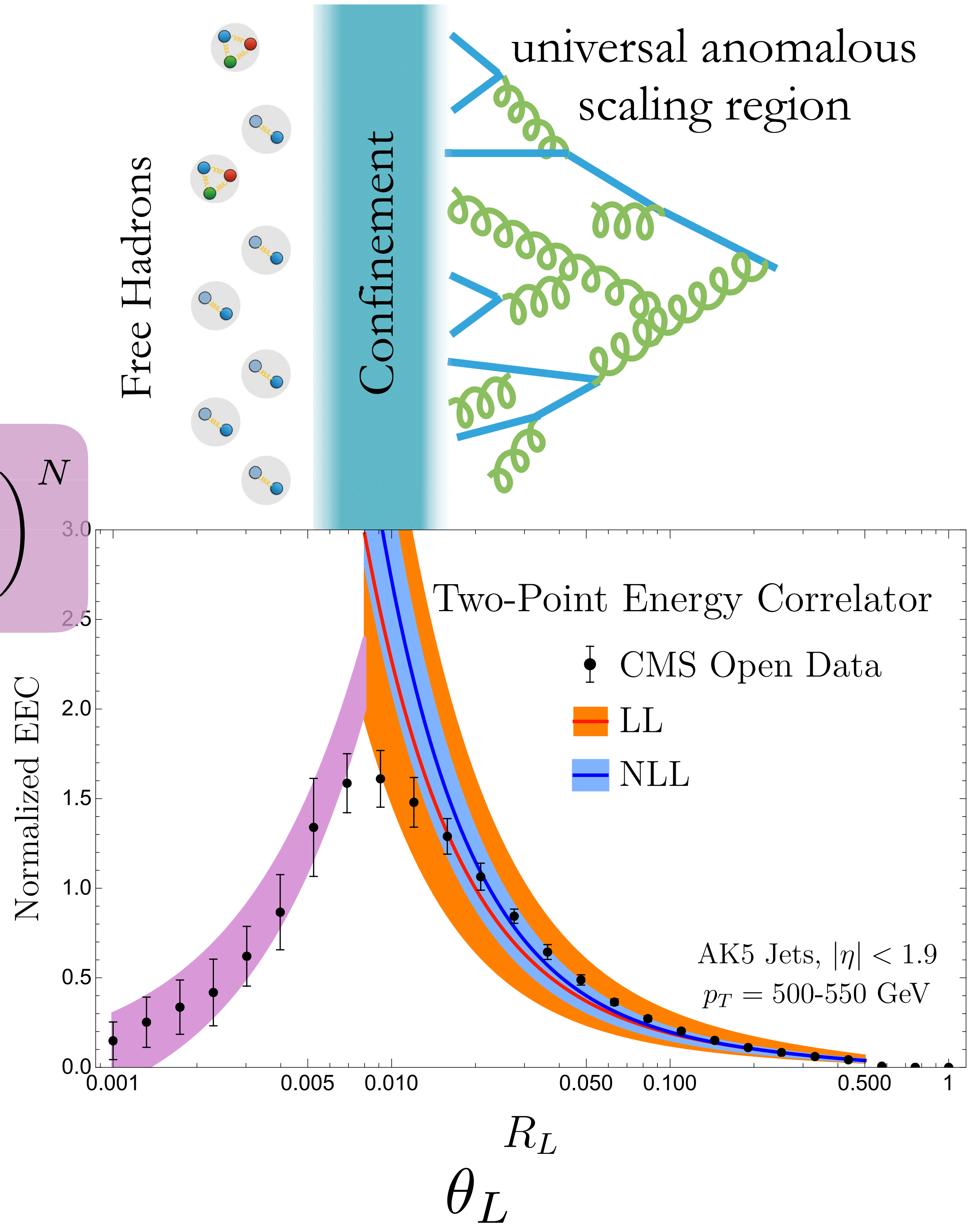
$$\langle \mathcal{E}(\vec{n}_1)\,\mathcal{E}(\vec{n}_2)\cdots\mathcal{E}(\vec{n}_N)\rangle \approx \langle\mathcal{E}\rangle^N = \left(\frac{Q}{\Omega_d}\right)^N$$

EEC gives angular scale

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

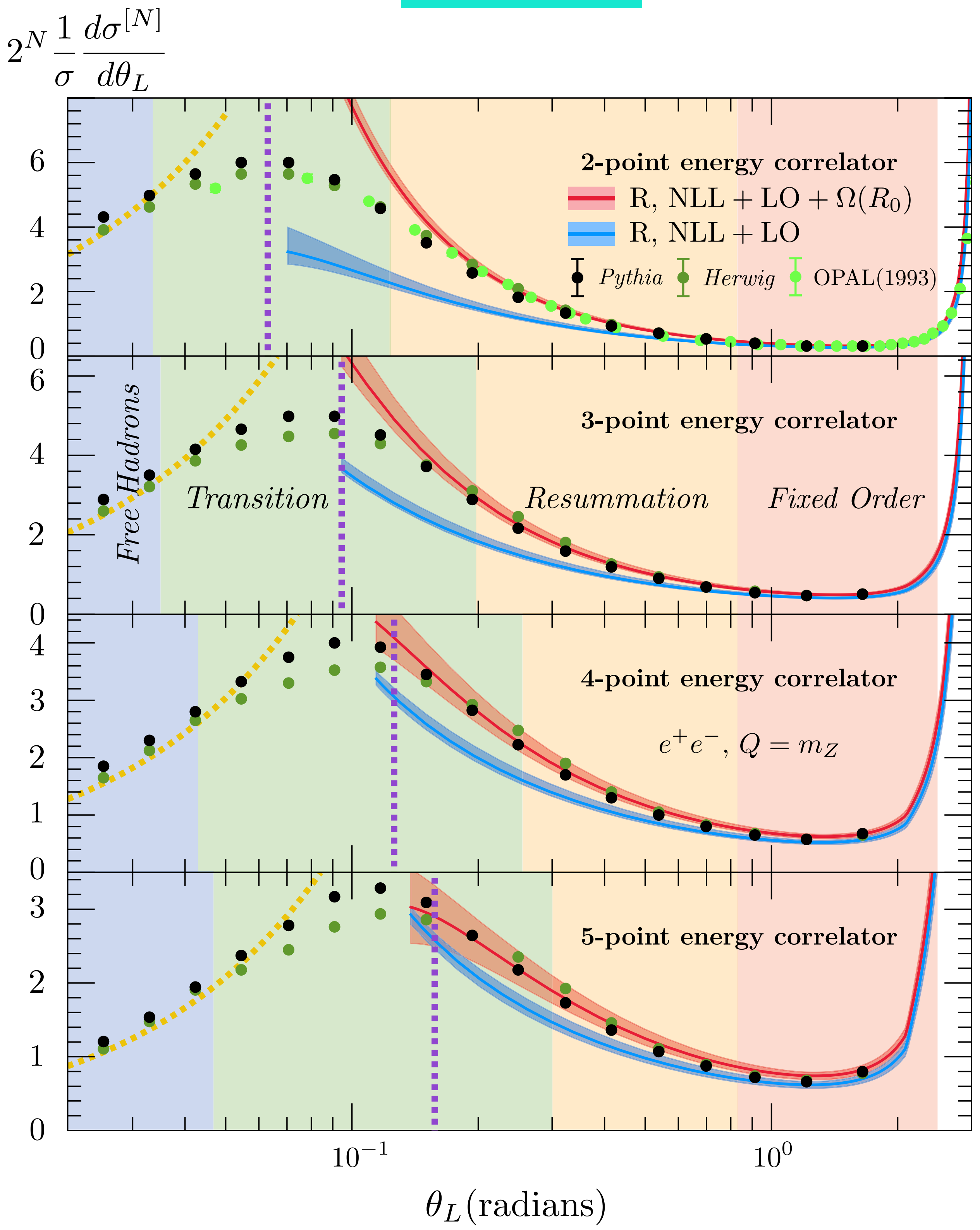
Csáki, Ismail `24

LHC



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

e^+e^-



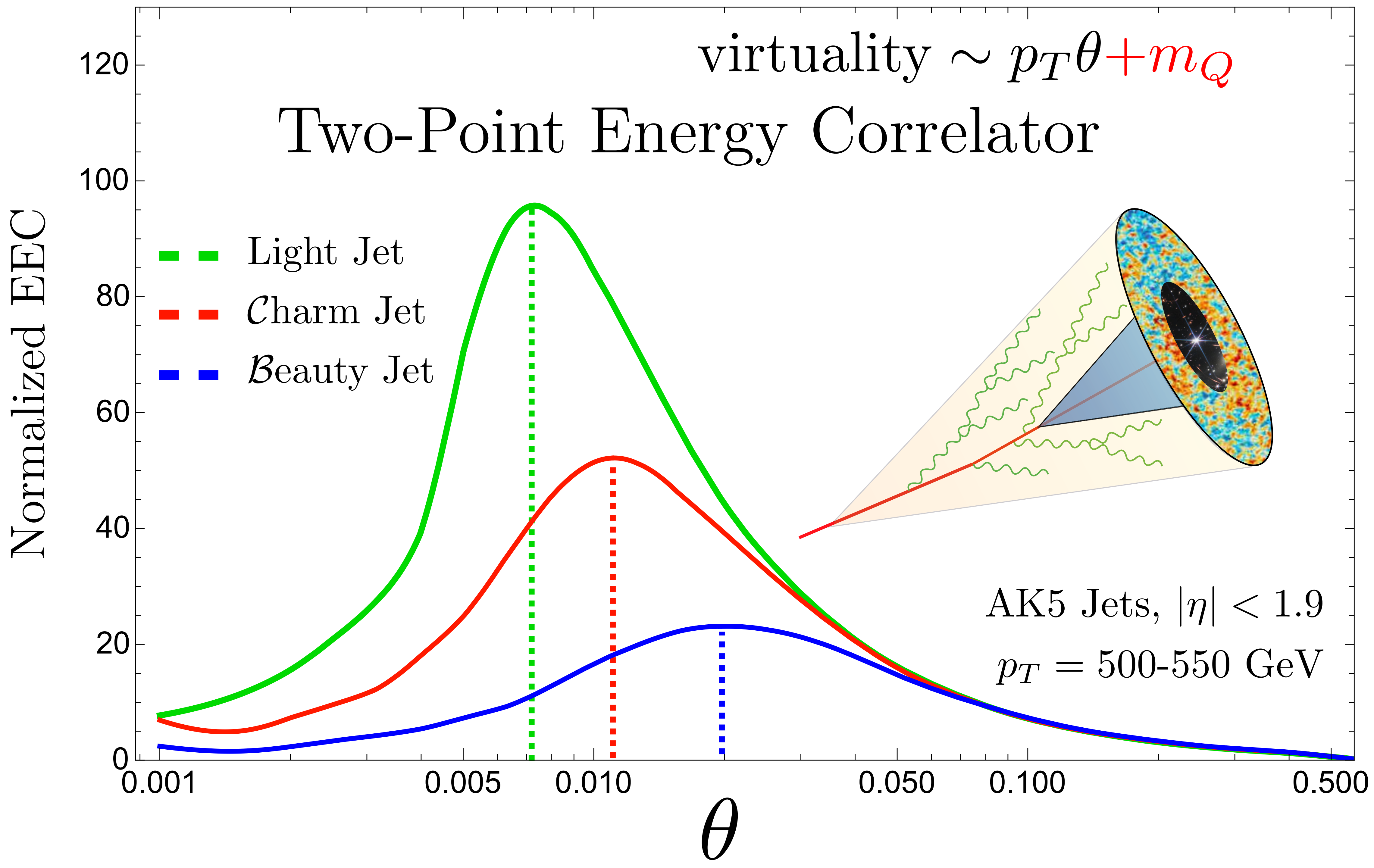
Interacting quarks and gluons

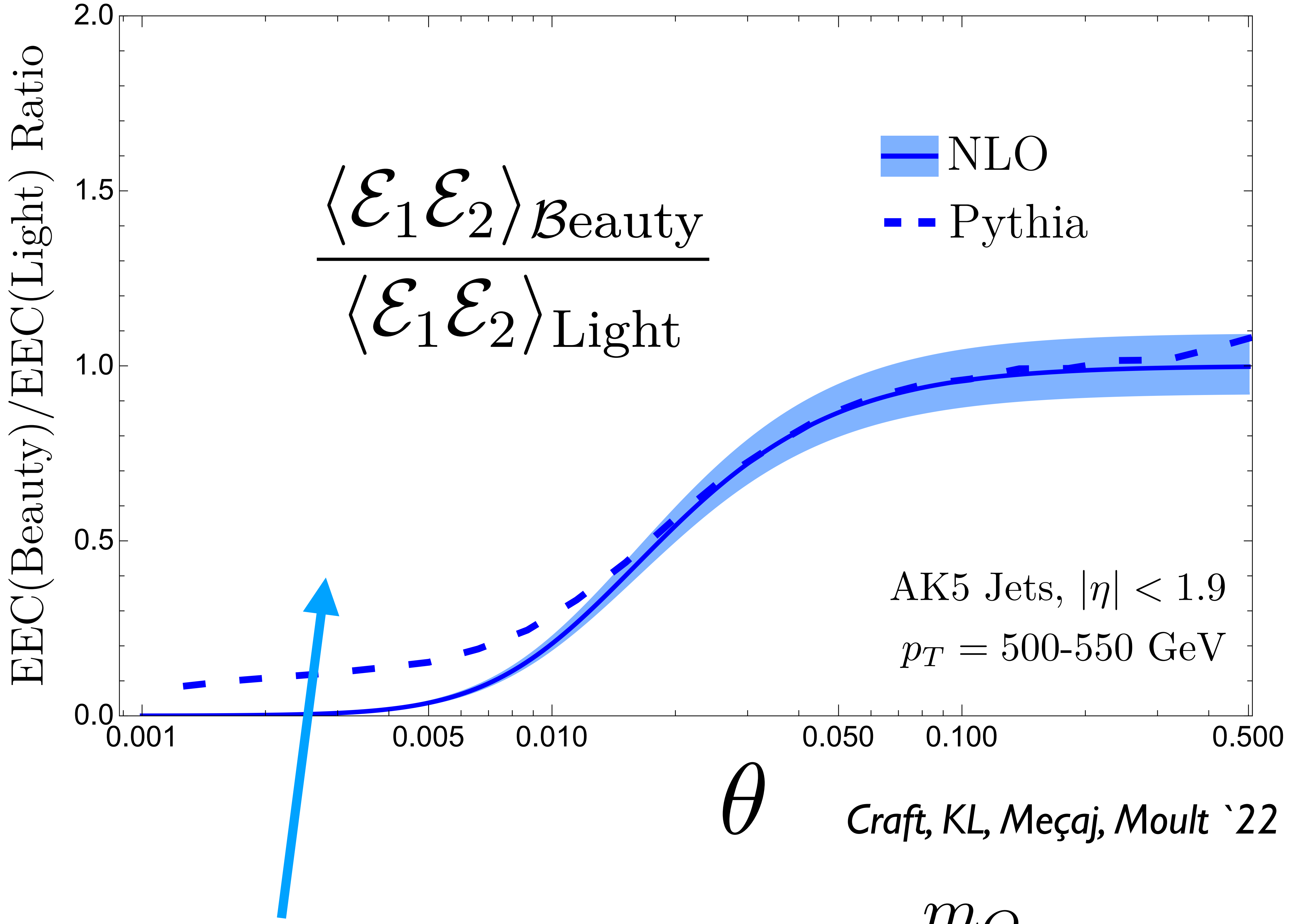
$$\mathcal{E}(\hat{n}_1)\,\mathcal{E}(\hat{n}_2) \sim \sum \theta^{\gamma(3)-2}\mathbb{O}_i(\hat{n}_1)$$

KL, Pathak, Stewart, Sun `24
Chen, Moult, Zhang, Zhu `20
Dixon, Moult, Zhu `19

IDENTIFYING THE INTRINSIC HEAVY QUARK SCALE

- **Two-point correlators capture the effects of intrinsic mass, displaying earlier formation of heavy bound states due to their mass**





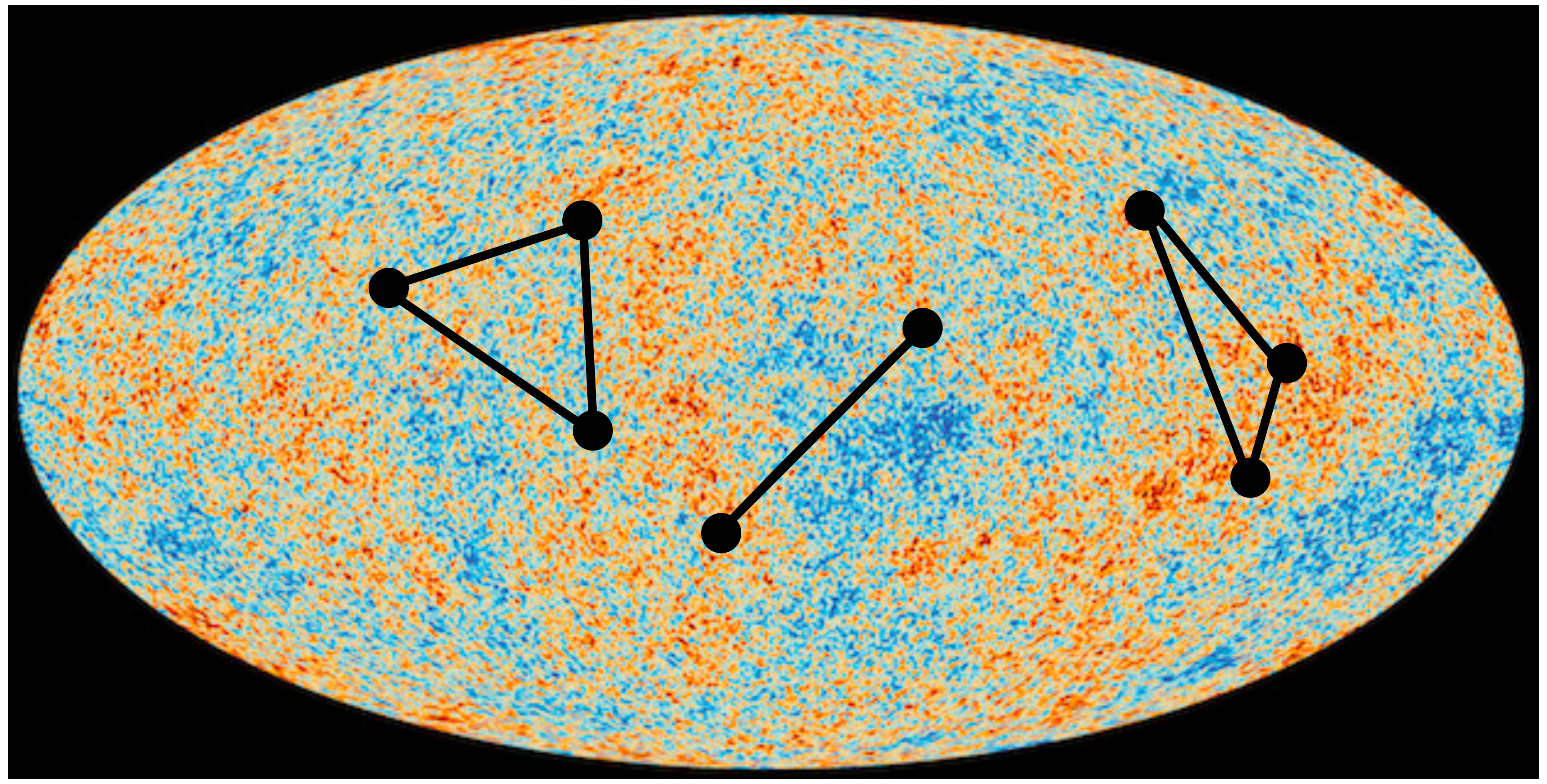
Craft, KL, Meçaj, Moult `22

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

HIGHER POINT CORRELATORS

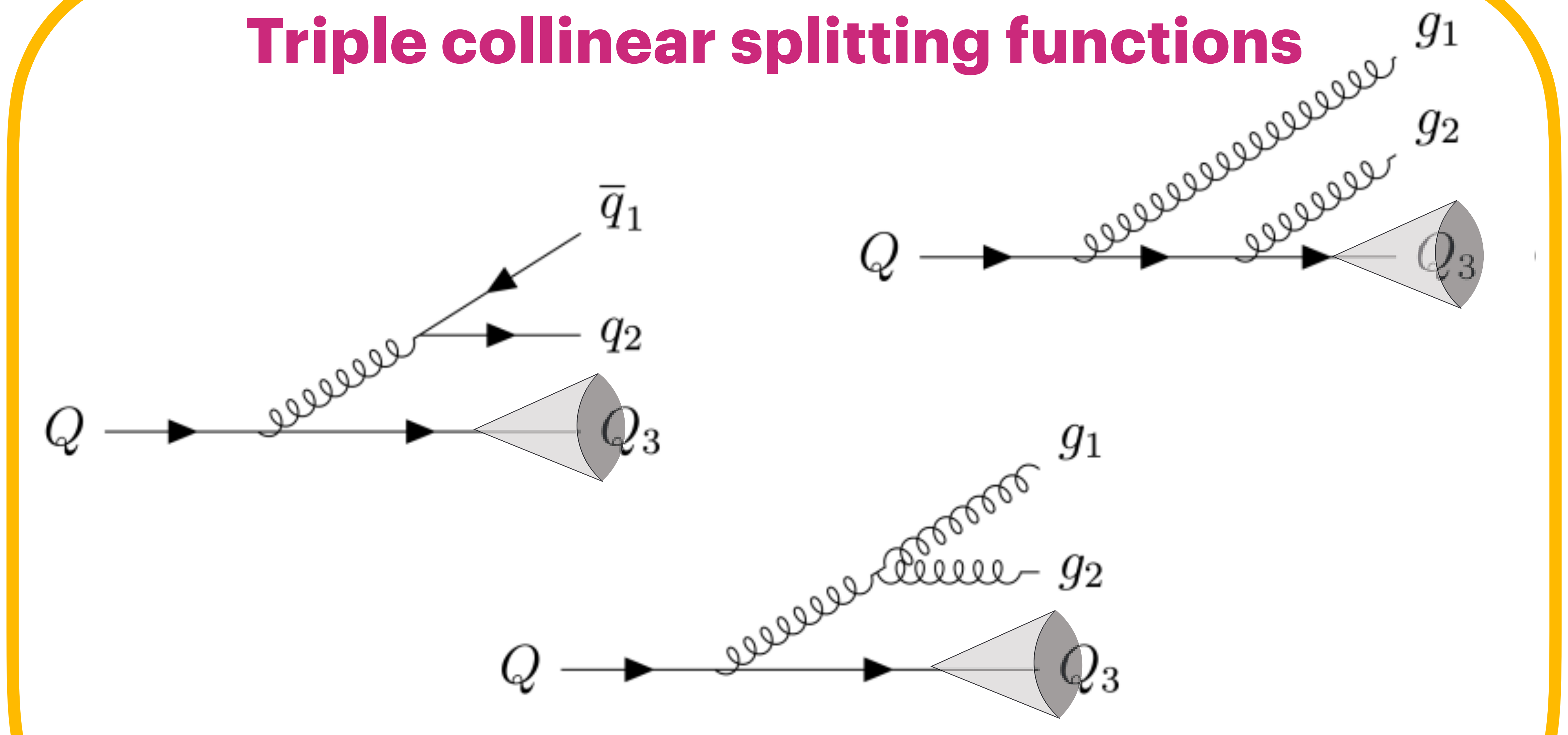
- **Higher-point correlators probe more detailed aspects of interactions**

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



Maldacena `02, Komatsu `10
Cabass, Pajer, Stefanyszyn, Supel `21,…

Triple collinear splitting functions



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

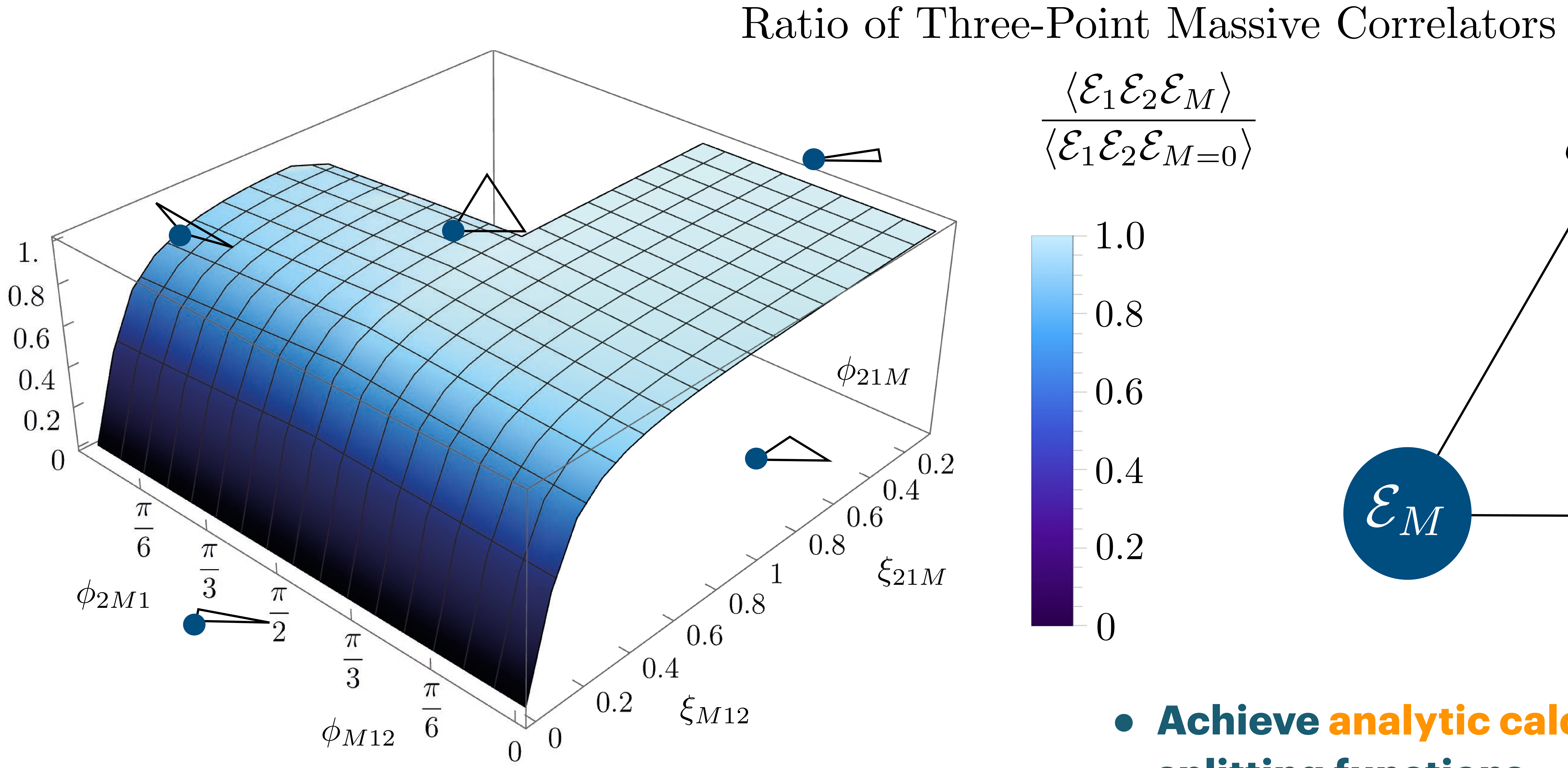
- **Cosmologists are hunting for non-gaussianities (genuine 3-pt correlation) in CMB to distinguish models of inflation**

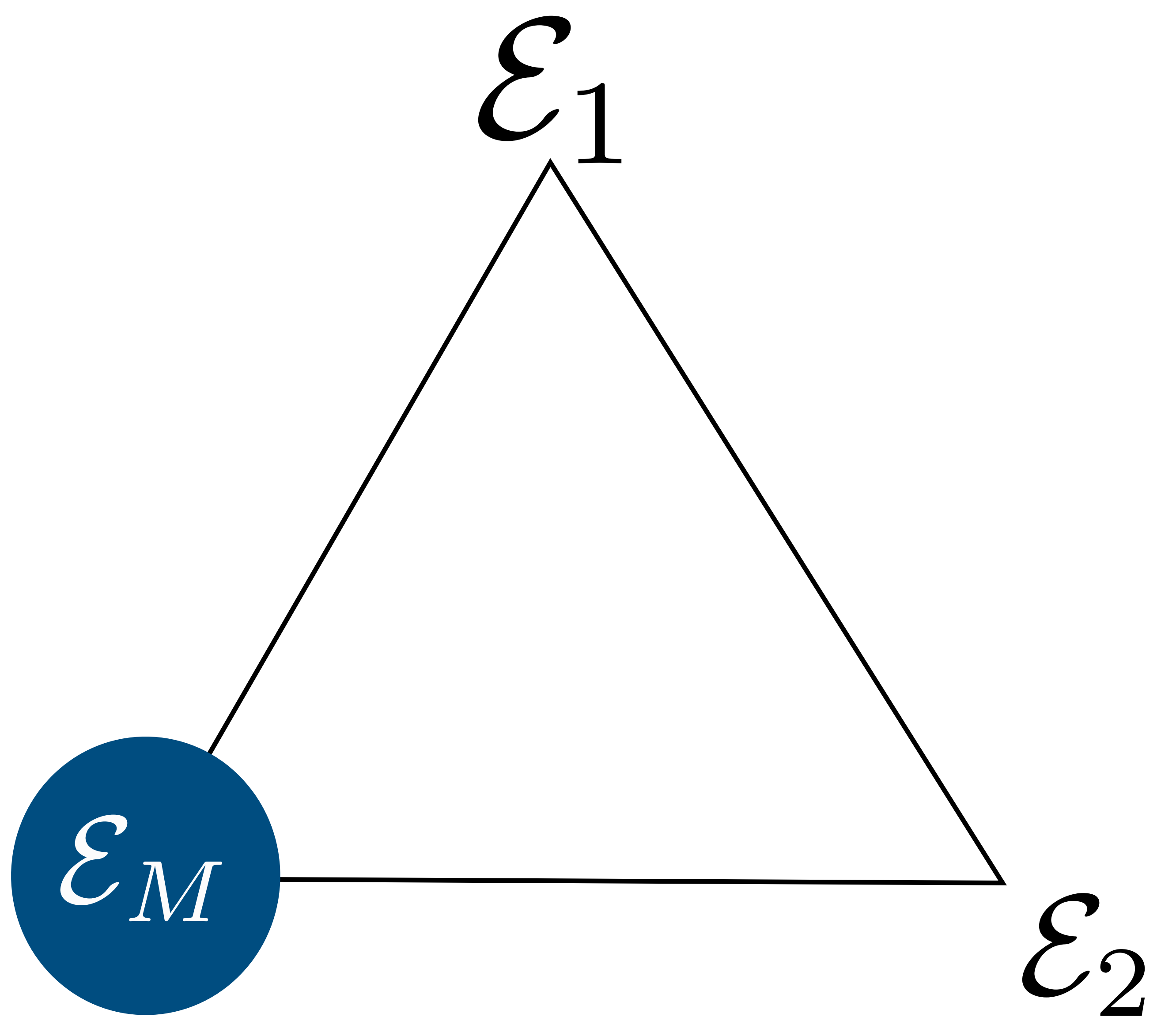
- **I have computed the first necessary analytical ingredients for 3-pt correlations within heavy jets!**

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





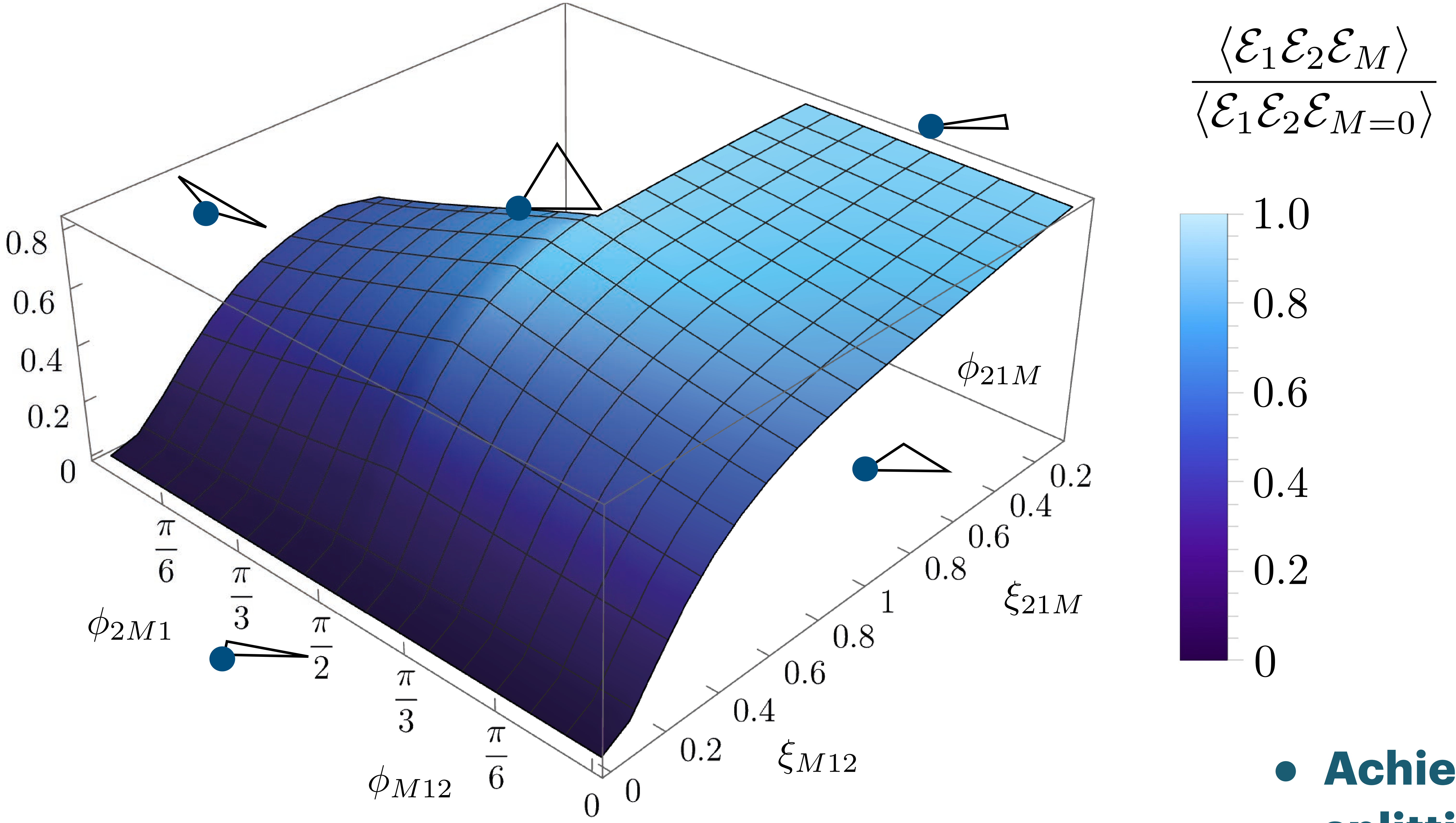
- **Achieve analytic calculation using our $1 \to 3$ splitting functions**

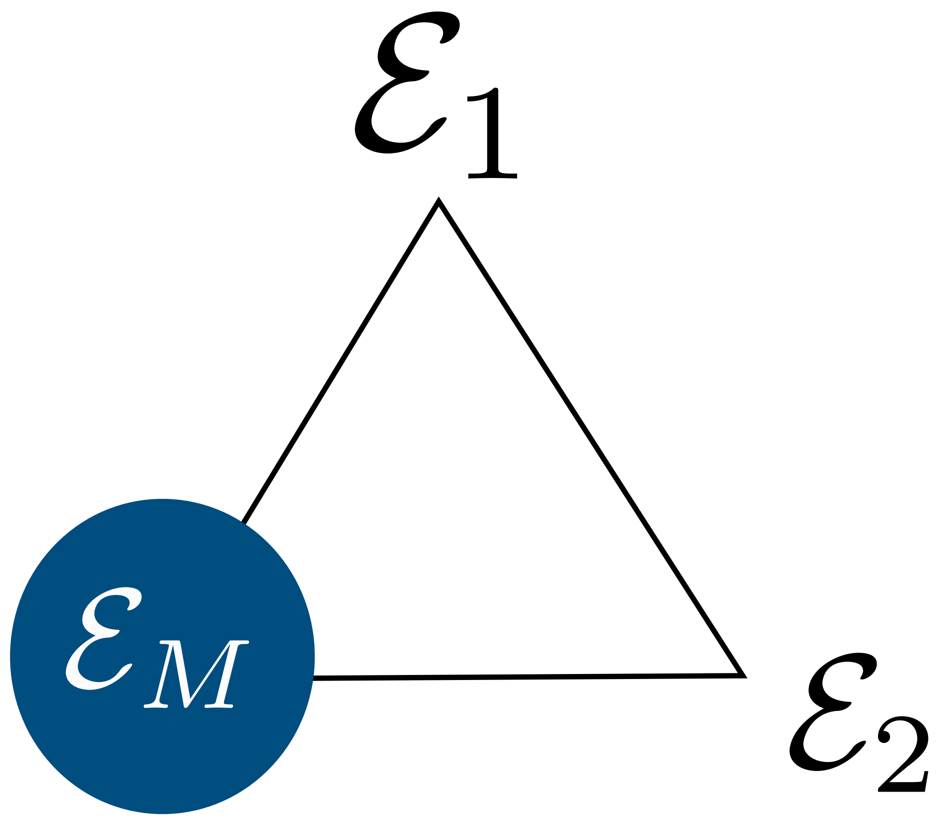
PROBING THE DYNAMICS OF THE DEAD-CONE

- **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





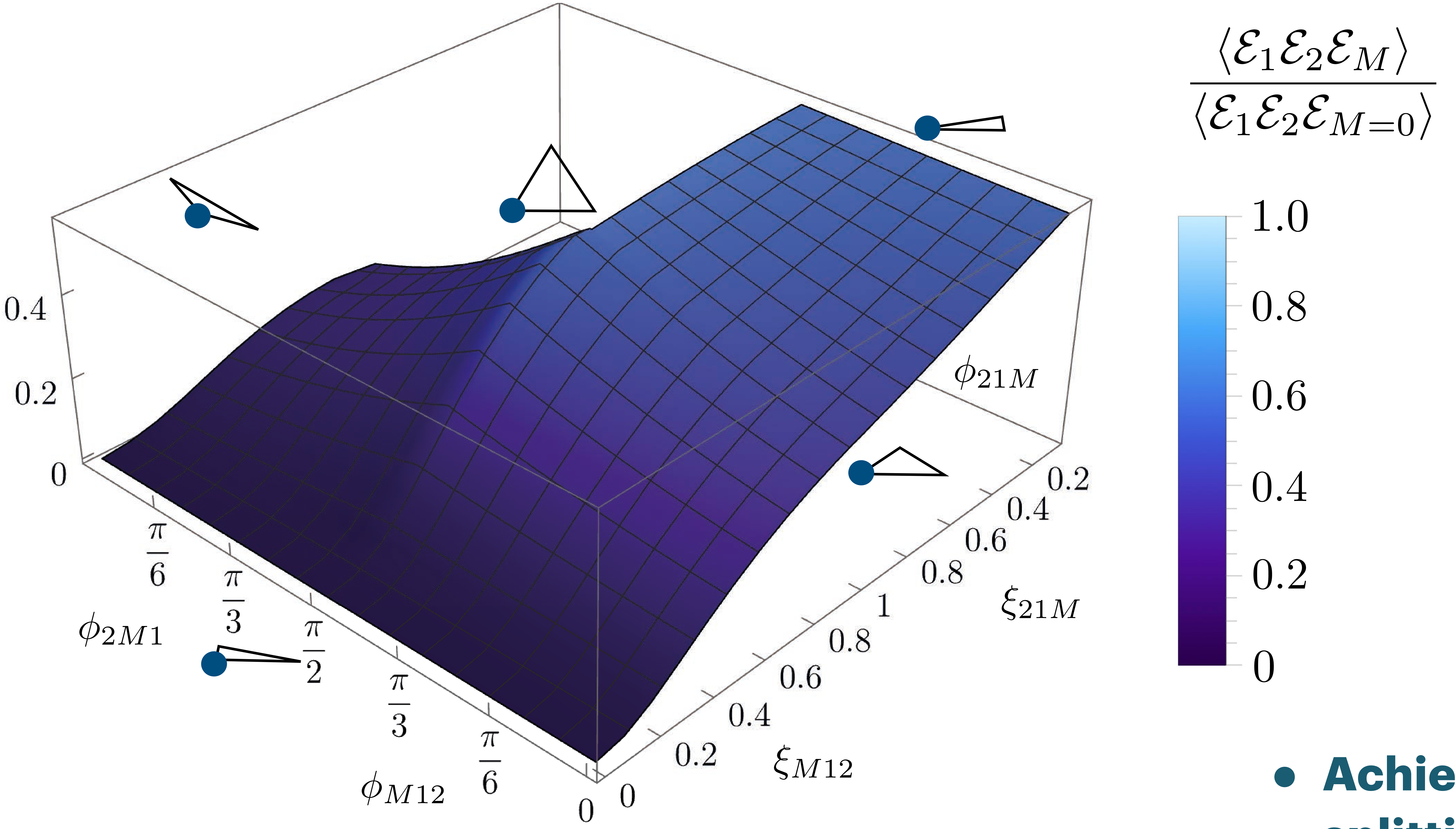
- **Achieve analytic calculation using our $1 \to 3$ splitting functions**

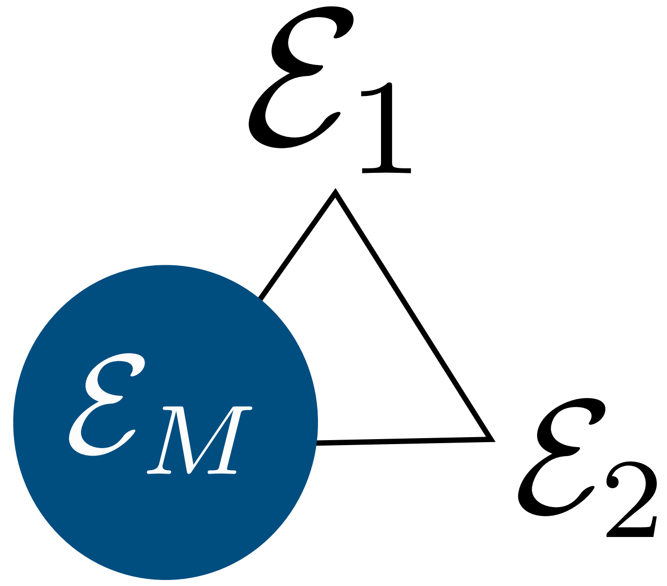
PROBING THE DYNAMICS OF THE DEAD-CONE

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

Craft, Gonzalez, KL, Meçaj, Moult `In Progress

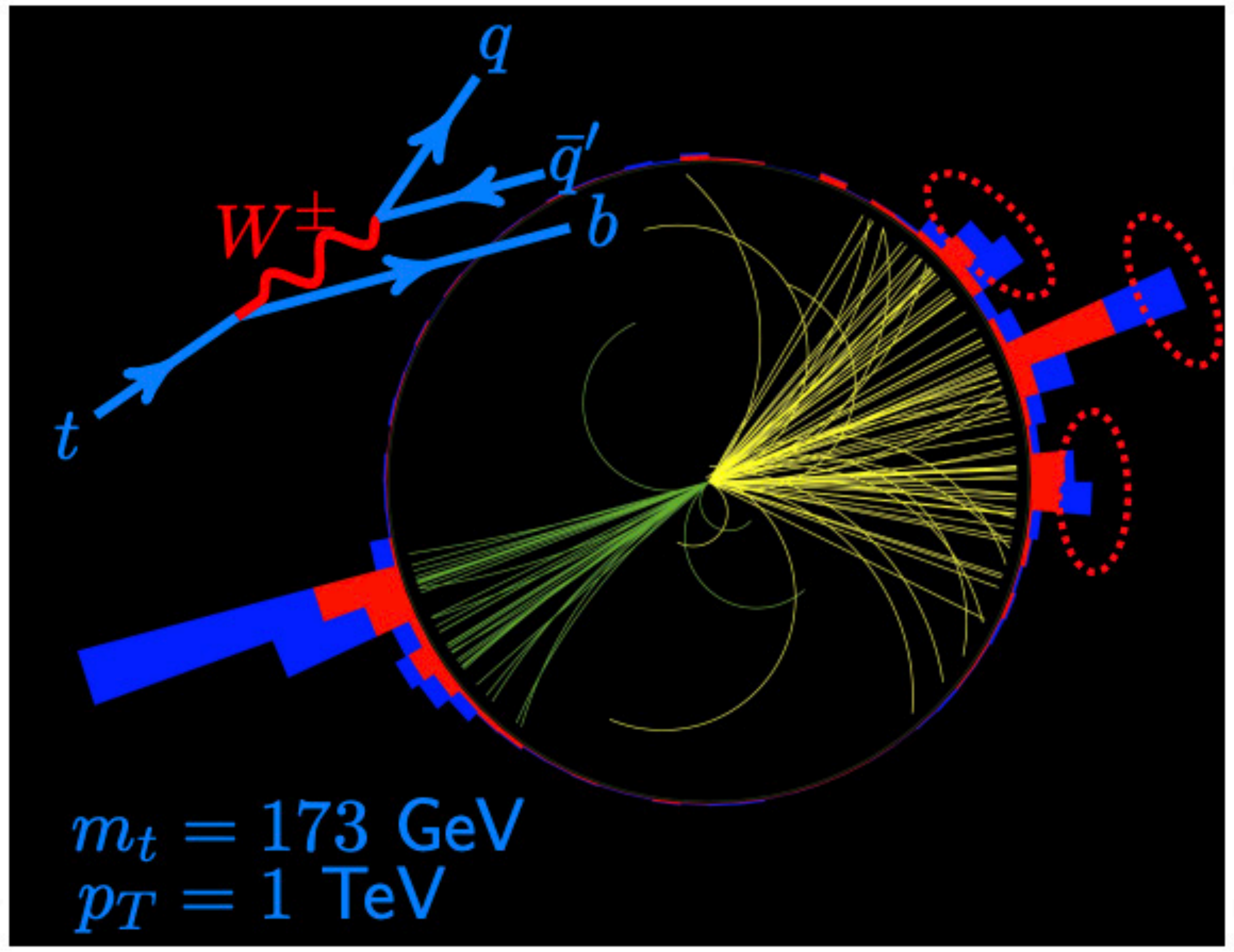
Ratio of Three-Point Massive Correlators

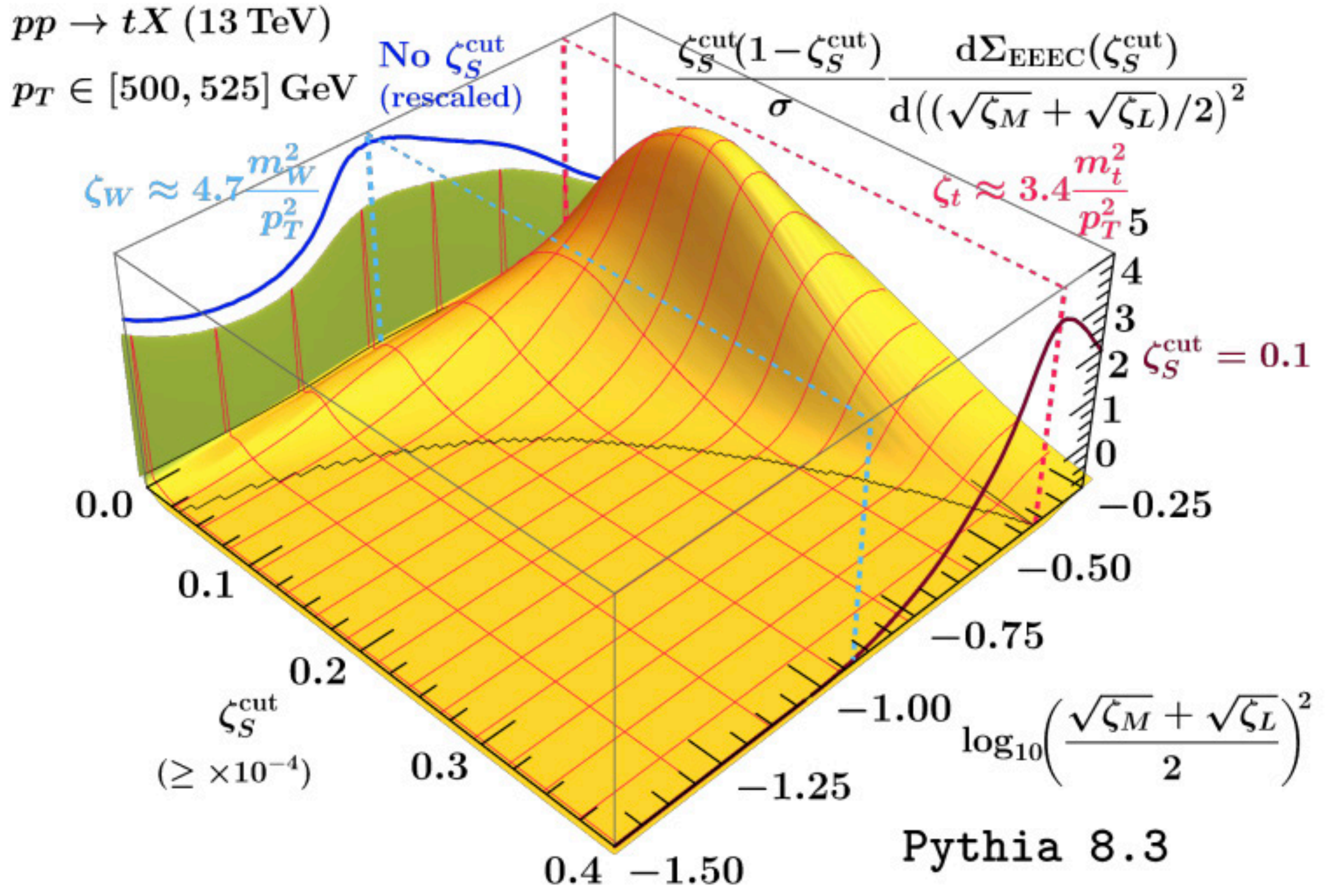


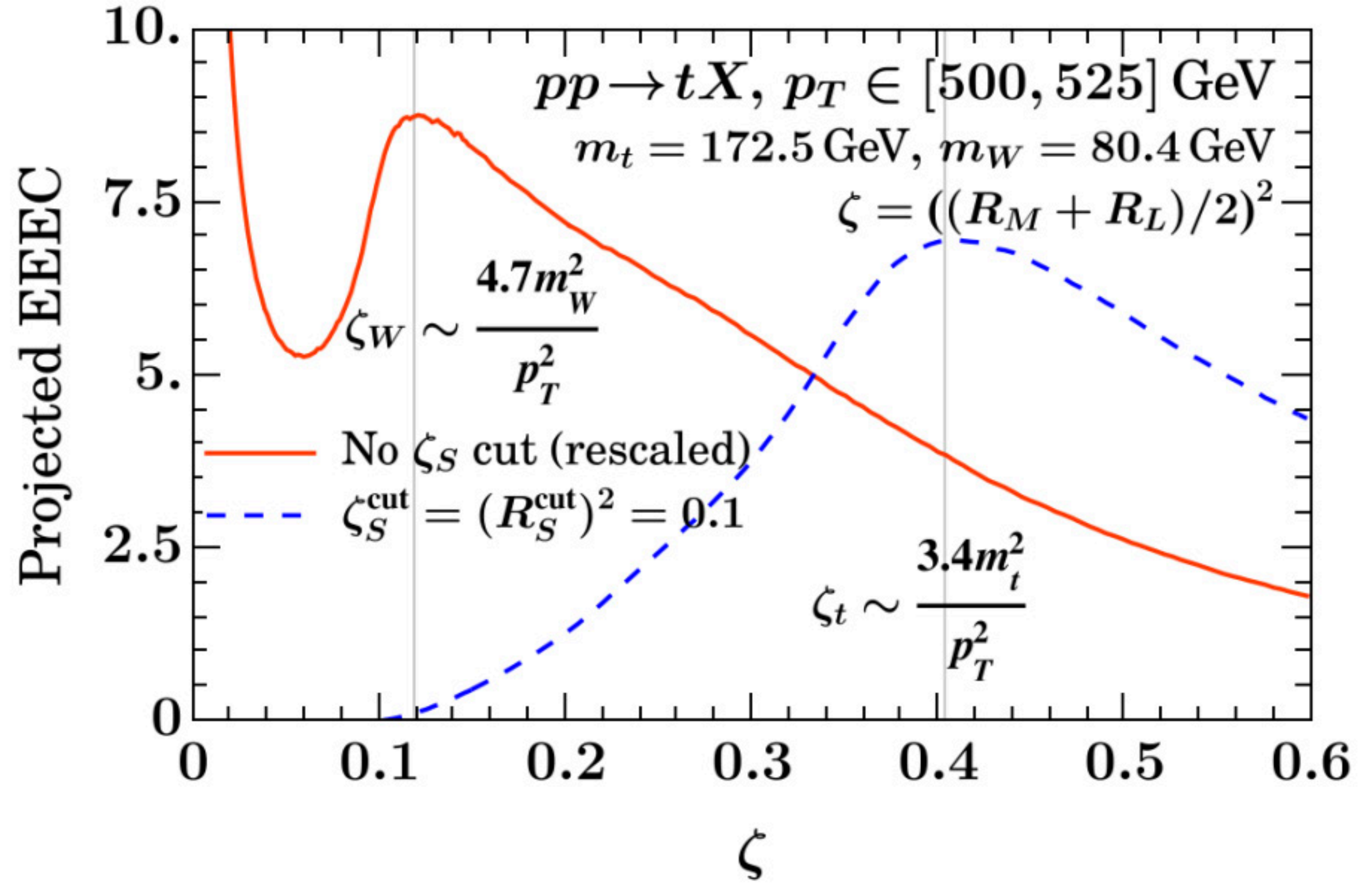


- **Achieve analytic calculation using our $1 \to 3$ splitting functions**

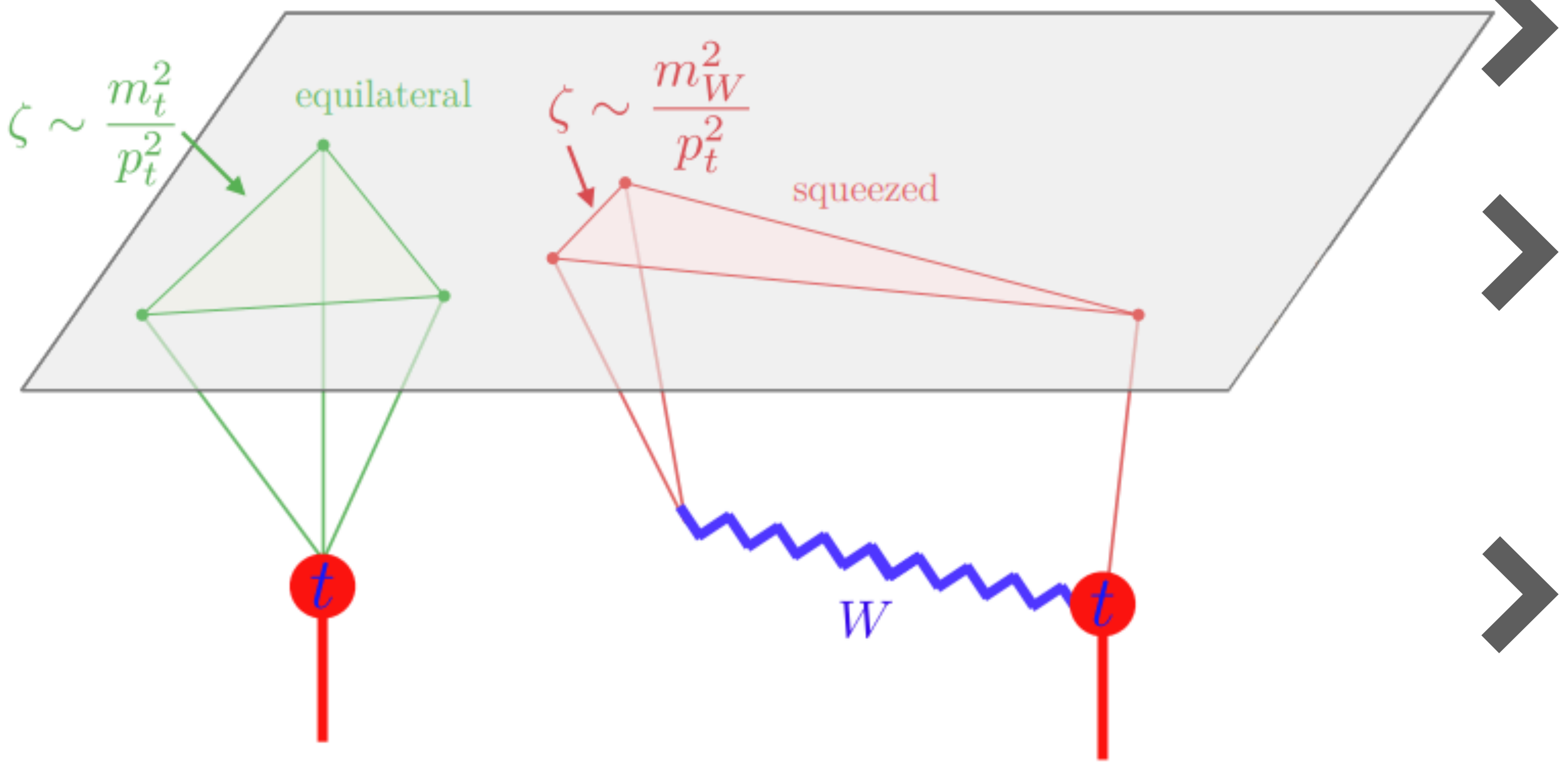
ENERGY ENERGY CORRELATORS ON TOP JET







Holguin, Moult, Pathak, Procura, Schöfbeck `22,23,24



- **Large samples of highly boosted top quarks produced at the LHC!**
- **W boson allows calibration of the top quark jet to circumvent determination of the NP effects in the hard scale!**
- **Yet another demonstration of higher-point correlator giving more rich information of the underlying dynamics**

PUSHING THE LIMIT OF HIGHER POINTS

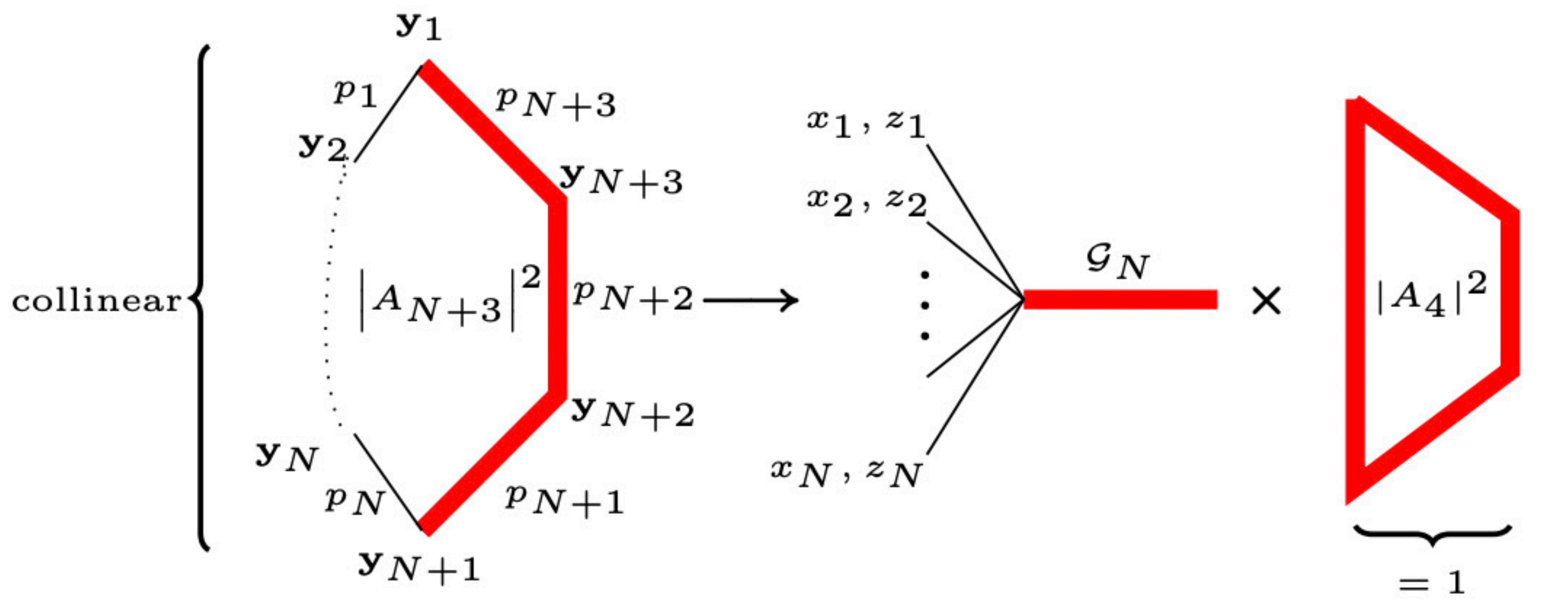
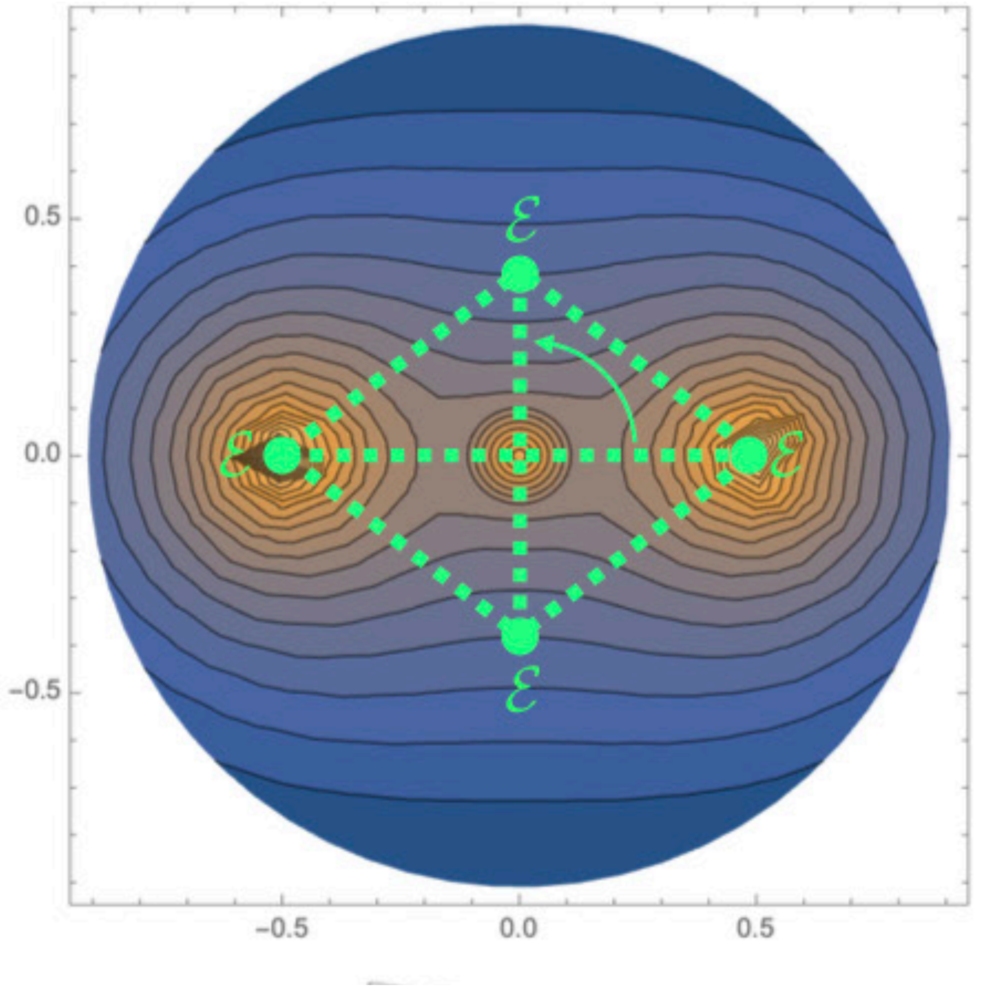
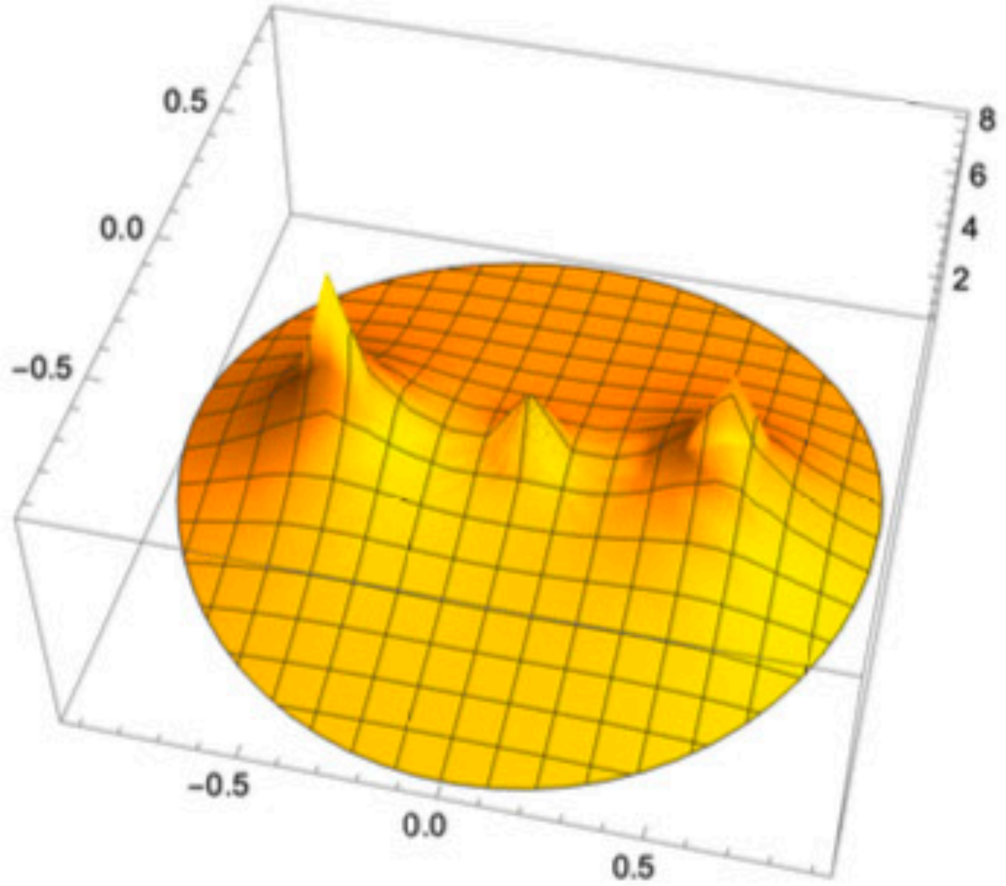


FIG. 1. The 1 → N splitting function from collinear limit of squared amplitudes with $n = N+3$ legs.

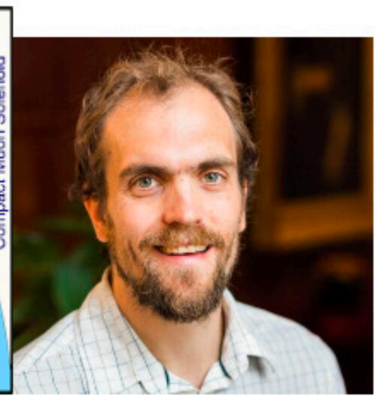


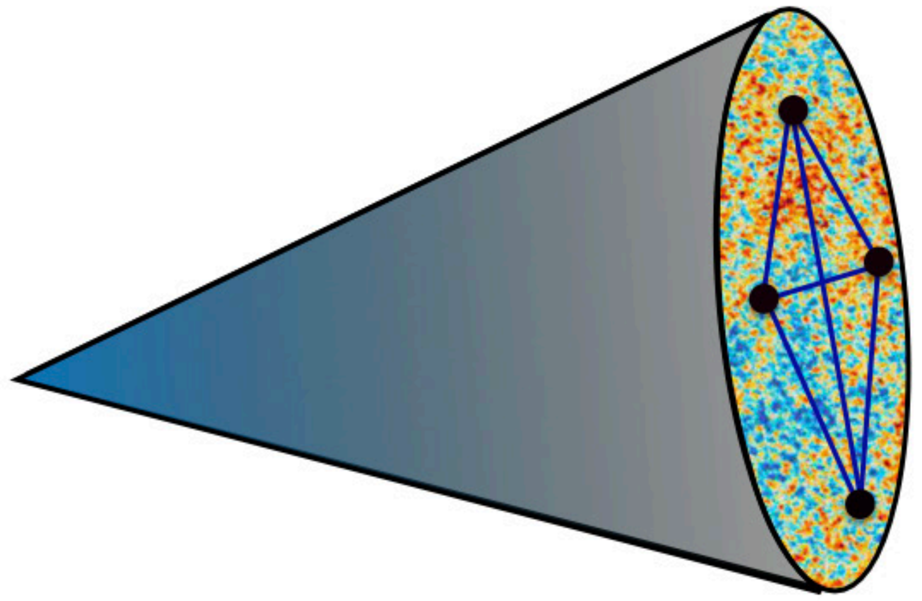


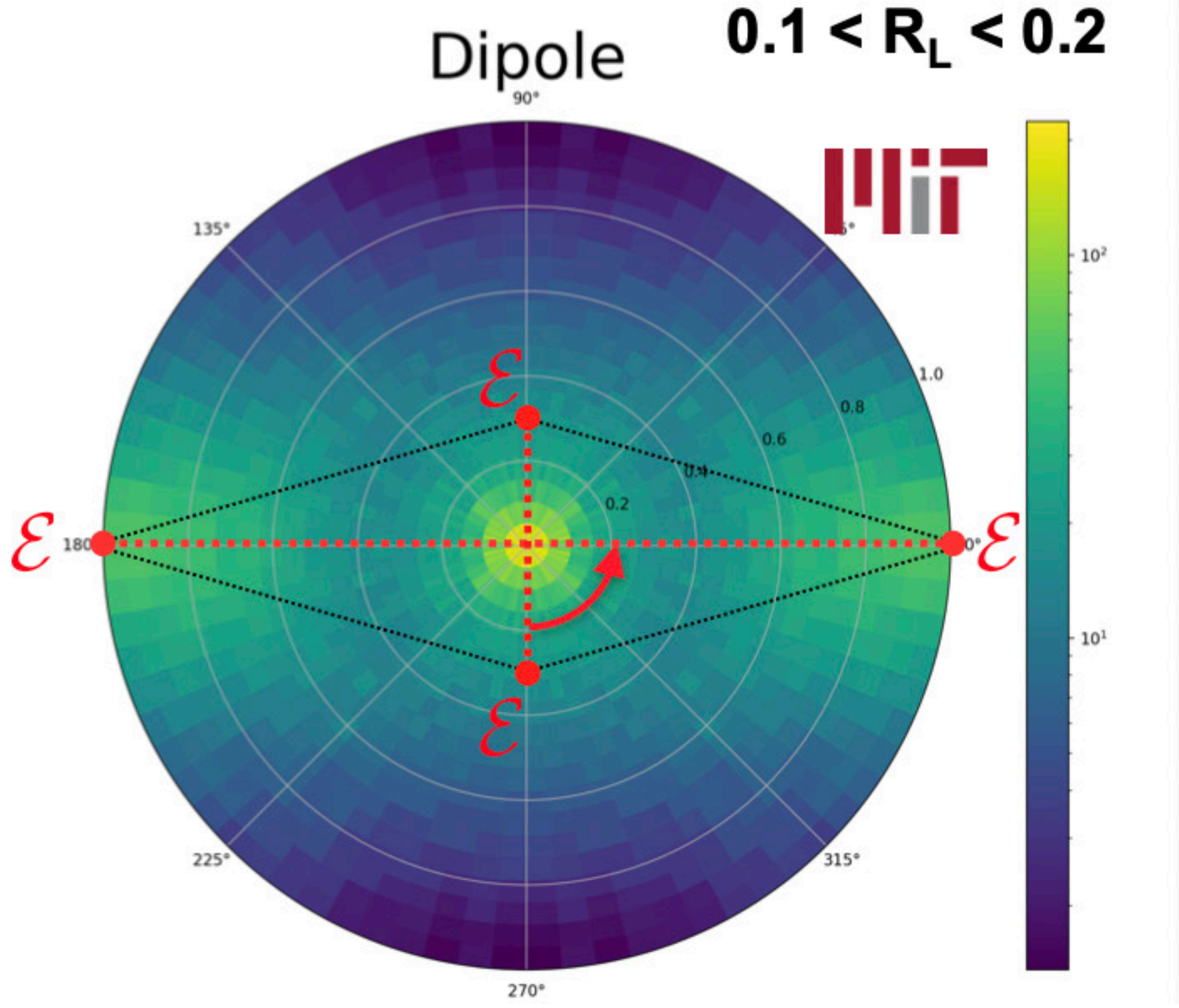
- **Modern amplitude method allows computation of the integrand up to 11-point for N=4.**

He, Jiang, Yang, Zhang `24

Chicherin, Moult, Sokatchev, Yan, Zhu `24



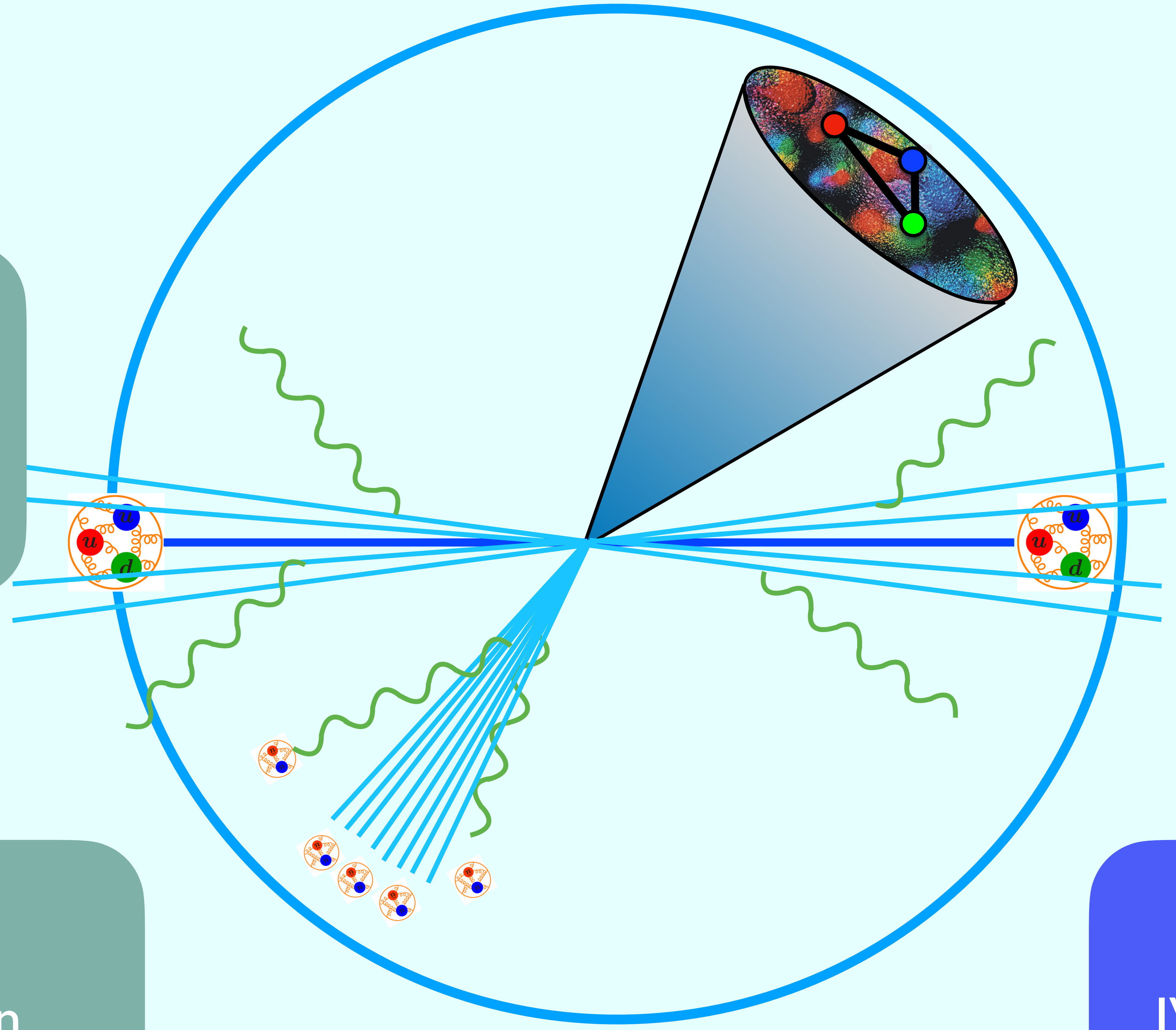




- **Intricate view of OPE and spinning operators in four-point.**

Gonzalez, KL, Harris, Moult, Rothman `In Progress

Overview



I. Universal Scaling

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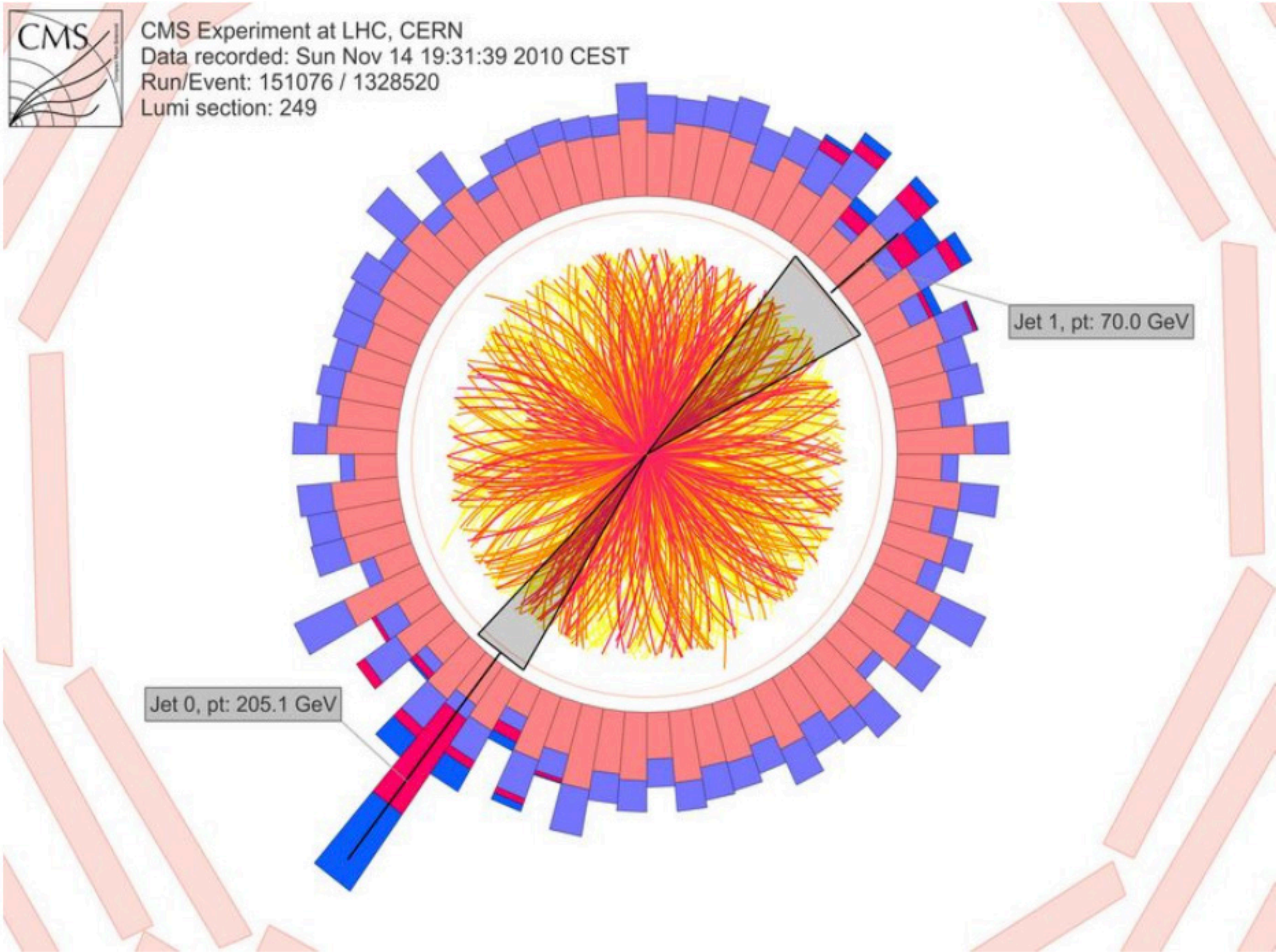
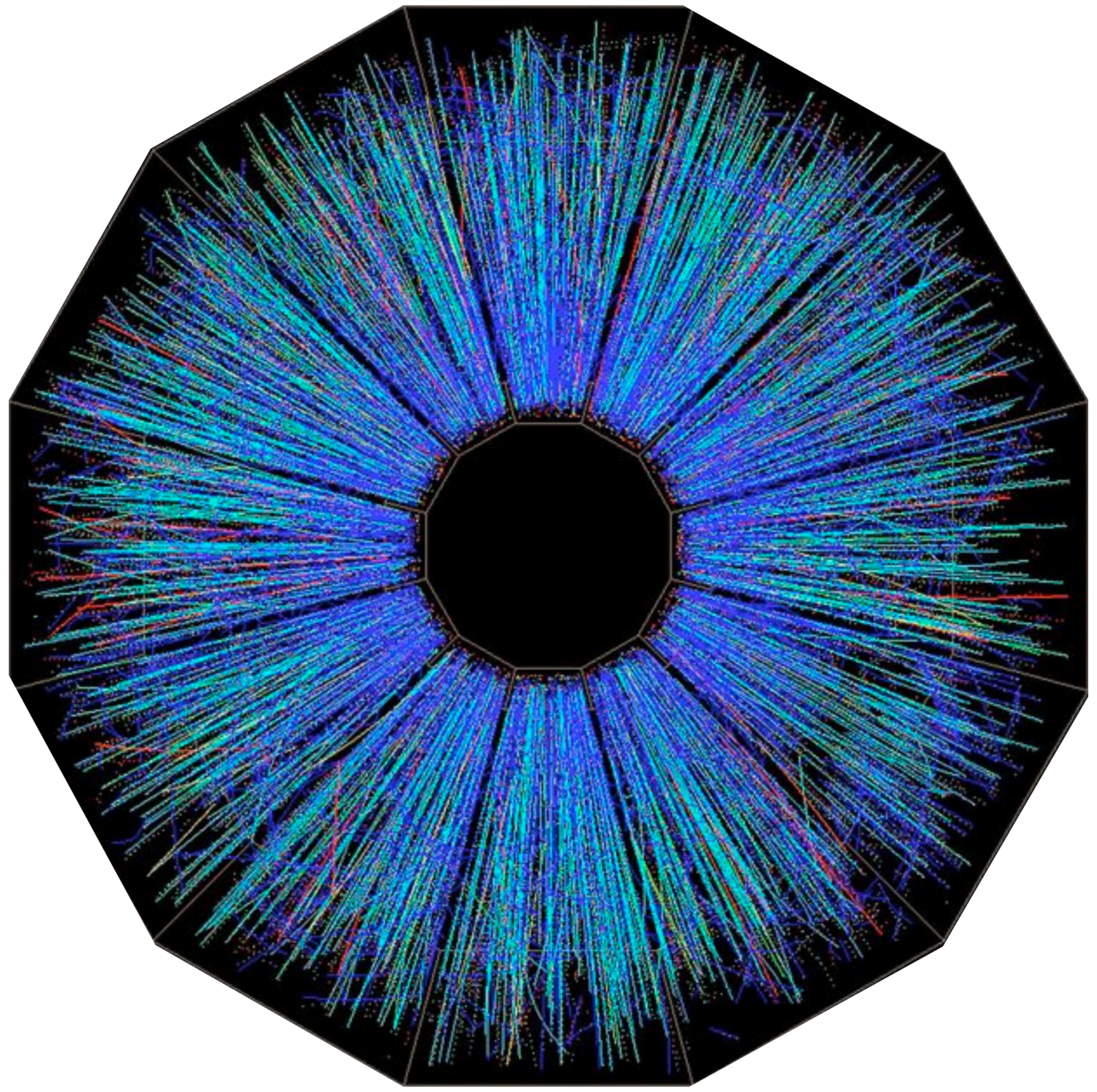
CREATING BIG BANG MATTER ON EARTH

- **Can we use asymptotic correlations to understand the complicated microscopic dynamics of the state created by Heavy Ion Collisions at the LHC?**

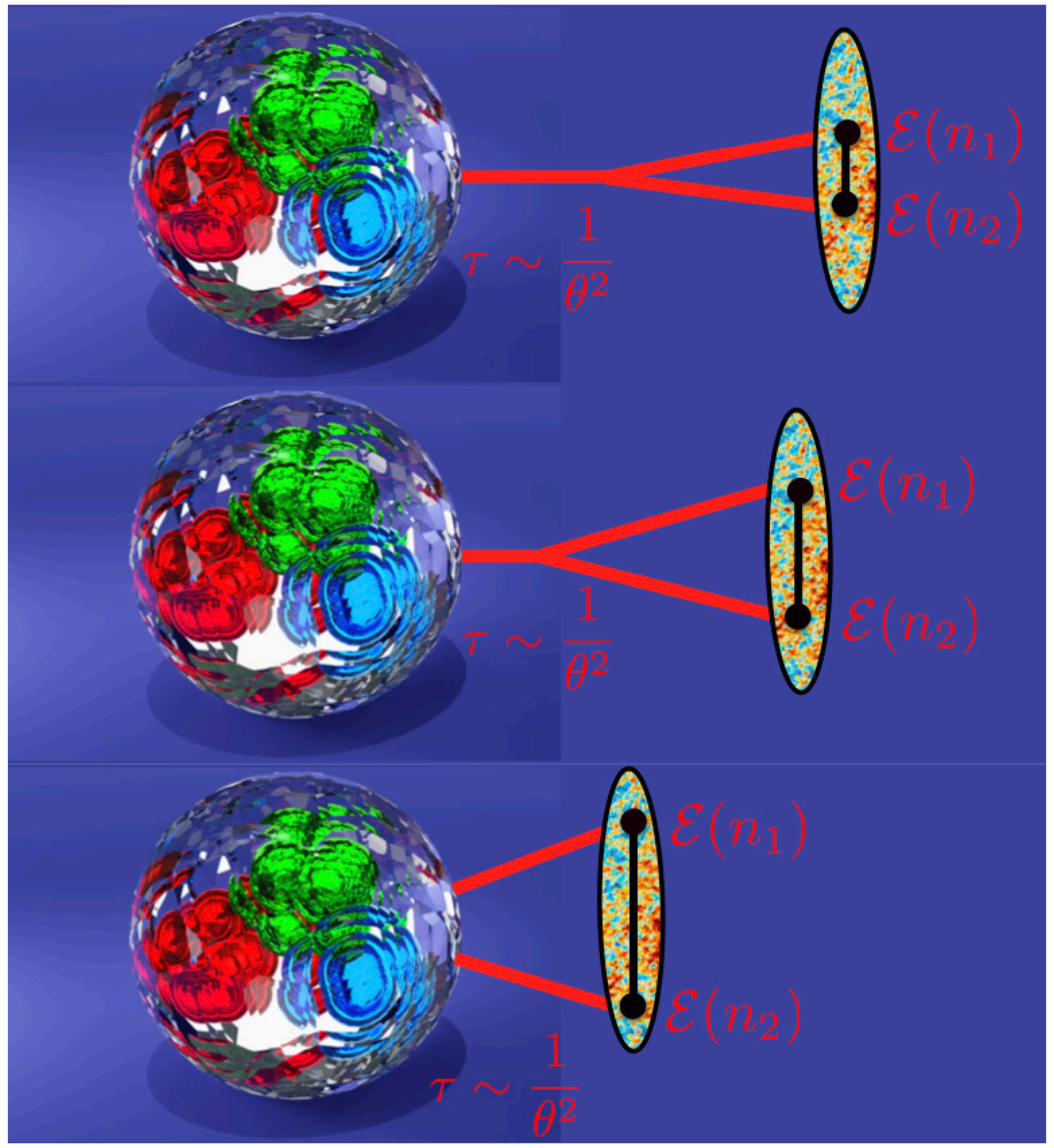




RESOLVING THE QGP USING ENERGY CORRELATORS

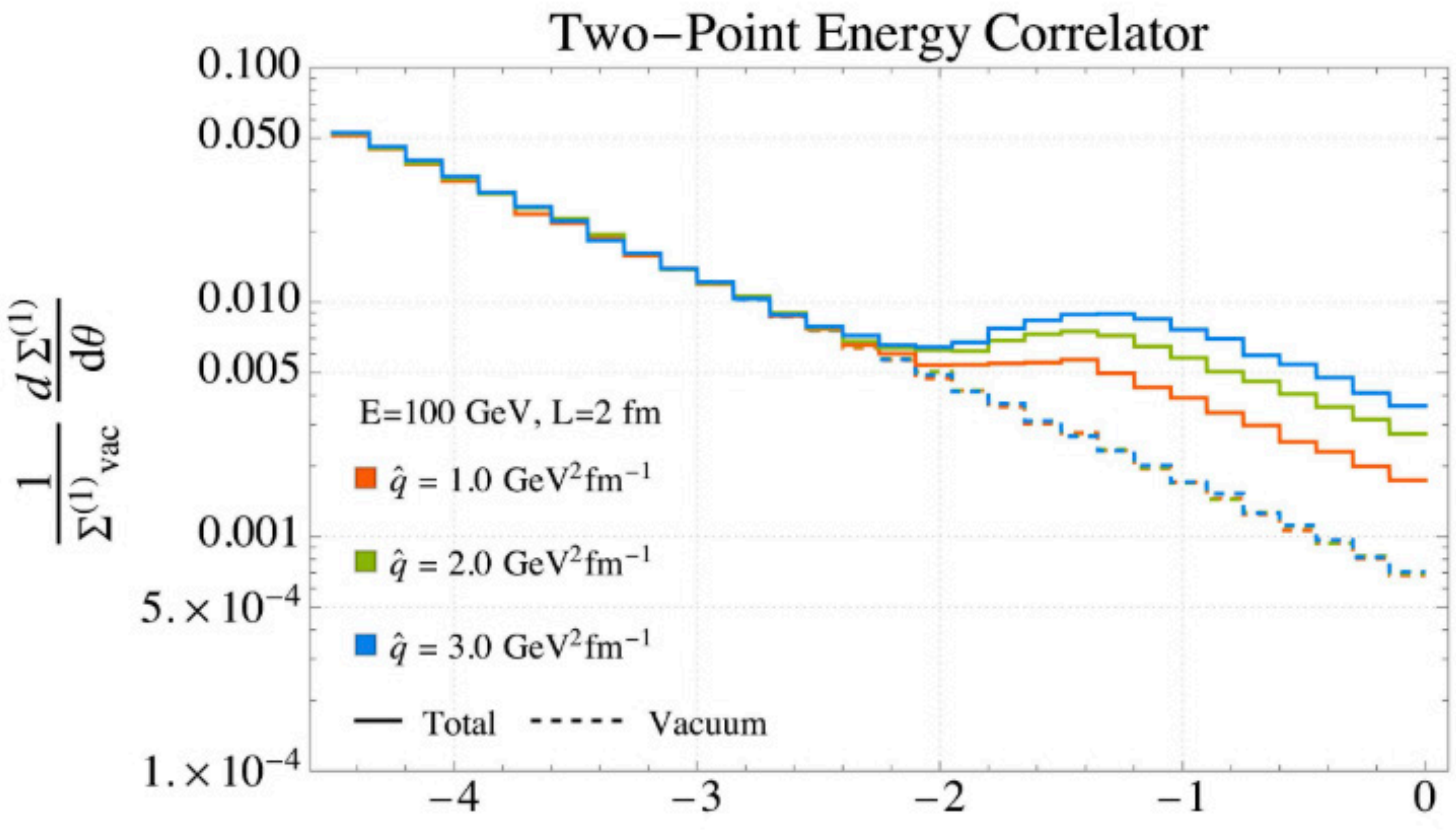
- **Two-point energy correlators** **clearly identify the medium angular scale at which correlations are modified!**

EEC gives angular scale $\mu \sim p_T \theta_{ij}$



Resolving the Scales of the Quark-Gluon Plasma with Energy Correlators *(2022)*

Carlota Andres,[1] Fabio Dominguez,[2] Raghav Kunnawalkam Elayavalli,[3, 4, 5] Jack Holguin,[1] Cyrille Marquet,[1] and Ian Moult[6]



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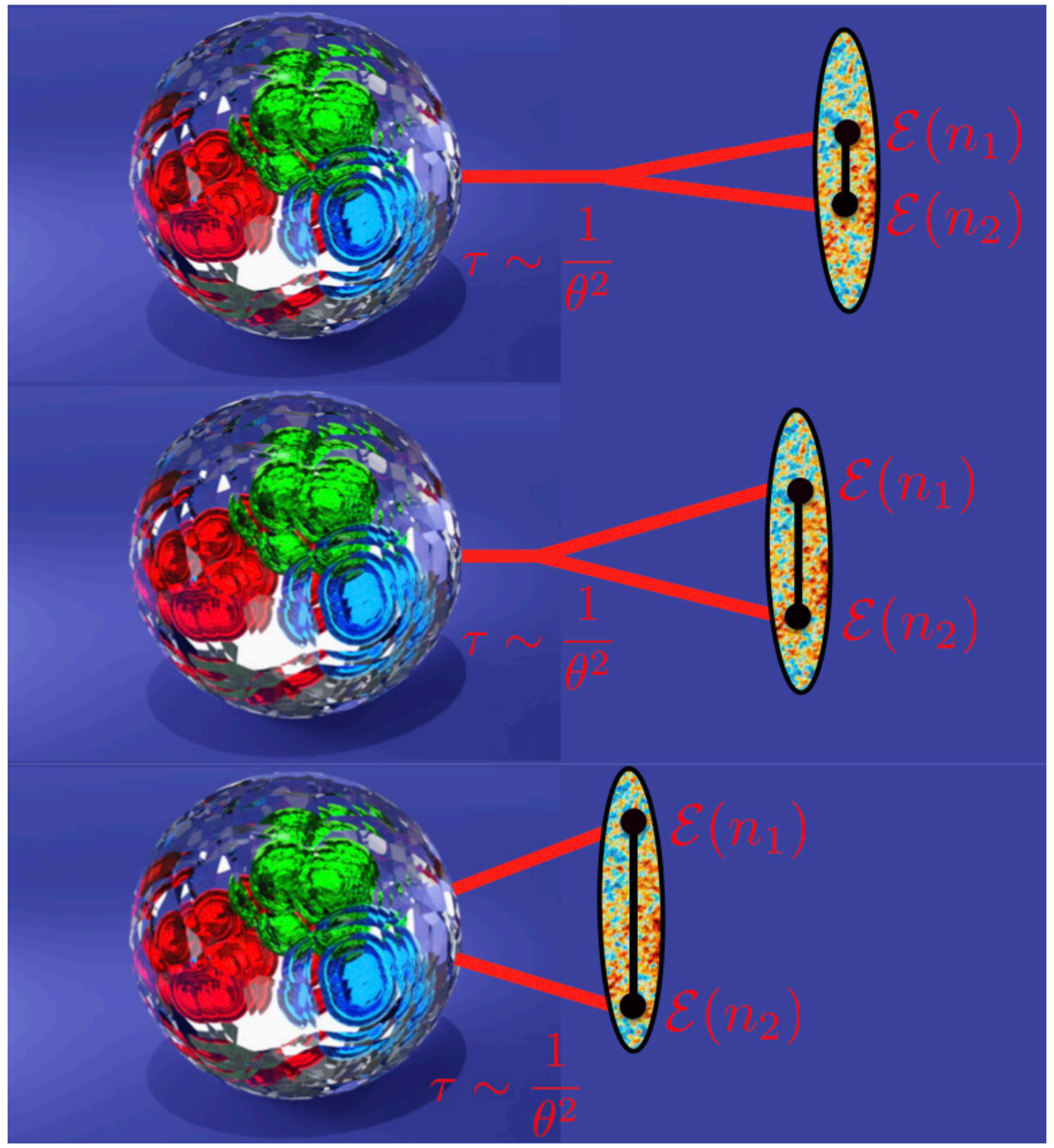
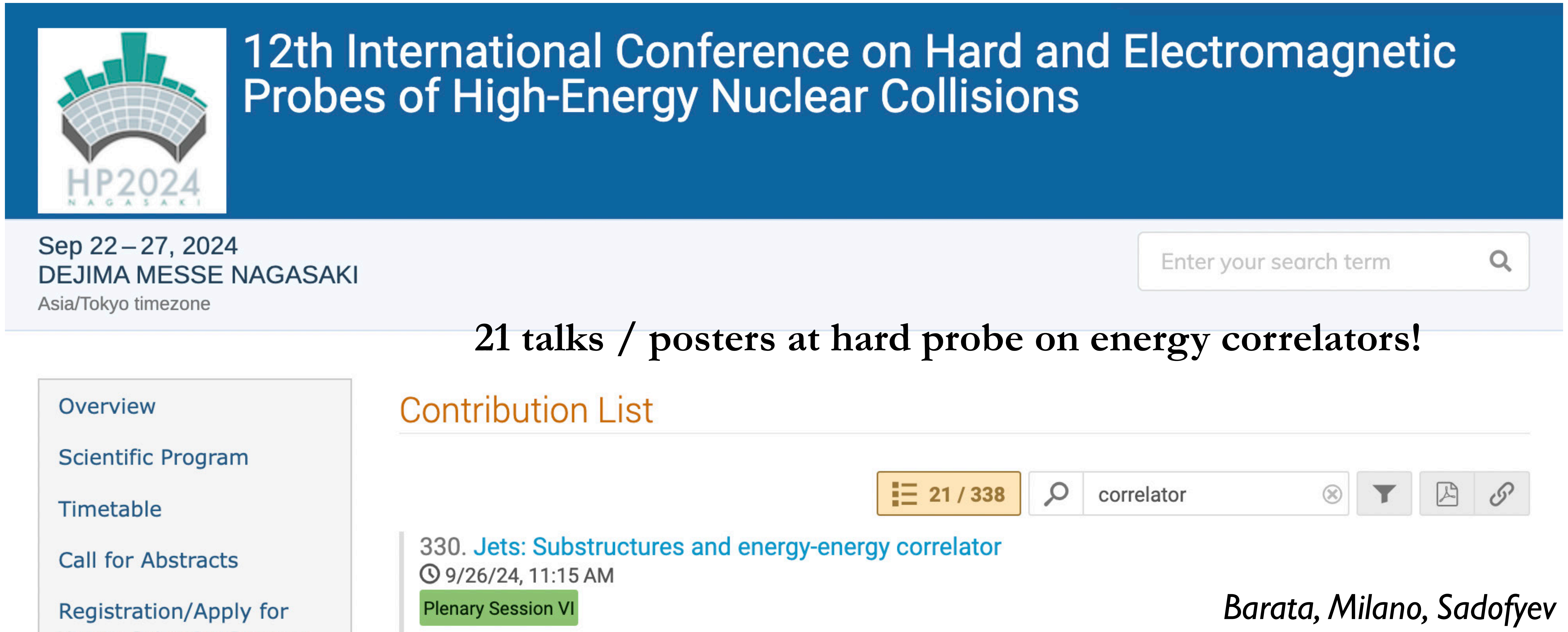




12th International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions

Sep 22 – 27, 2024
DEJIMA MESSE NAGASAKI
Asia/Tokyo timezone

Contribution List

330. Jets: Substructures and energy-energy correlator
9/26/24, 11:15 AM
Plenary Session VI

21 talks / posters at hard probe on energy correlators!

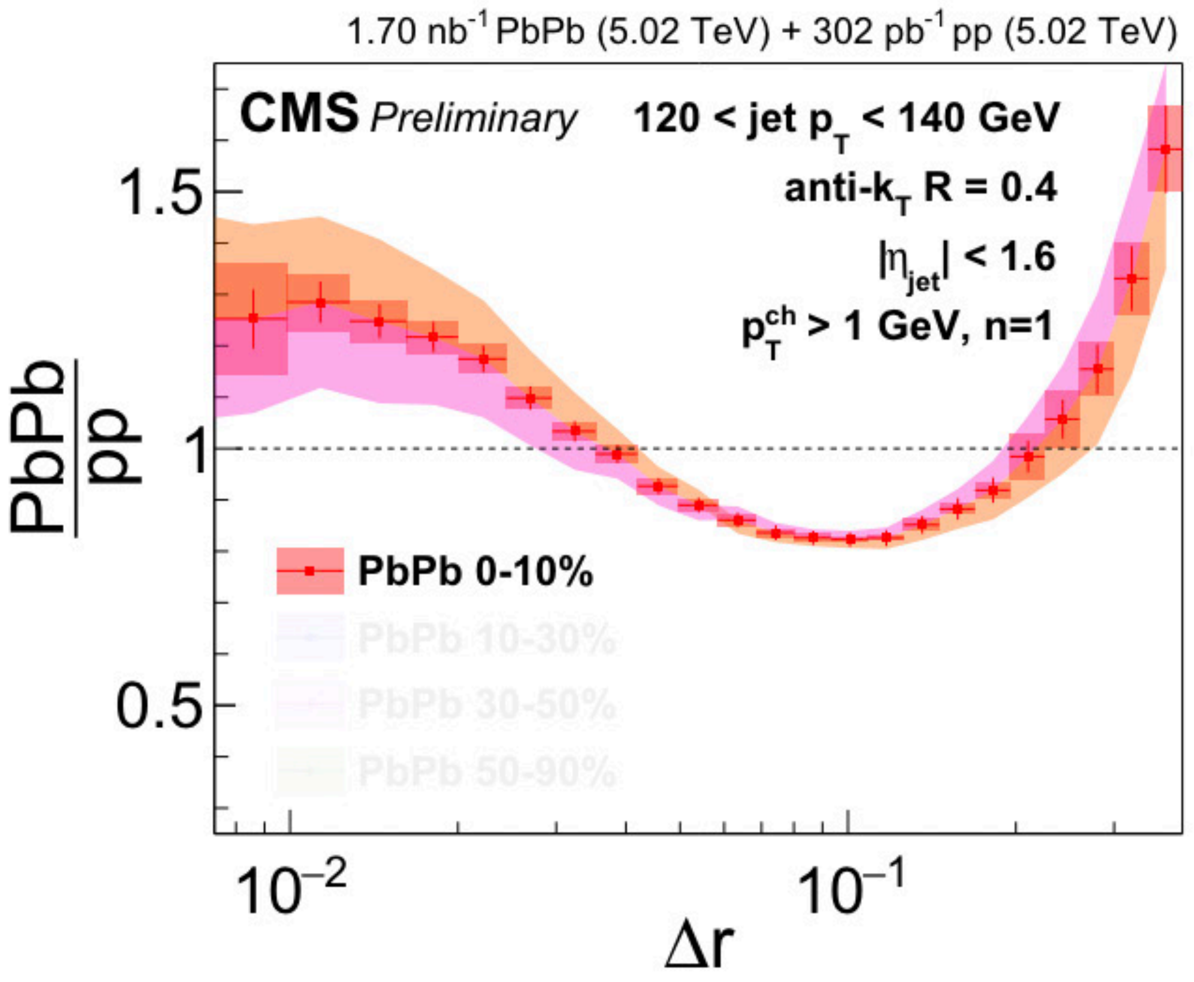
Barata, Milano, Sadofyev `23
Barata, Caucal, Soto-Ontoso, Szafron `23
Yang, He, Moult, Wang `23
Devereaux, Fan, Ke, KL, Moult `23
Andres, Dominguez, Holguin, Marquet, Moult `23,24
Bossi, Kudinoor, Moult, Pablos, Rai, Rajagopal `24 …

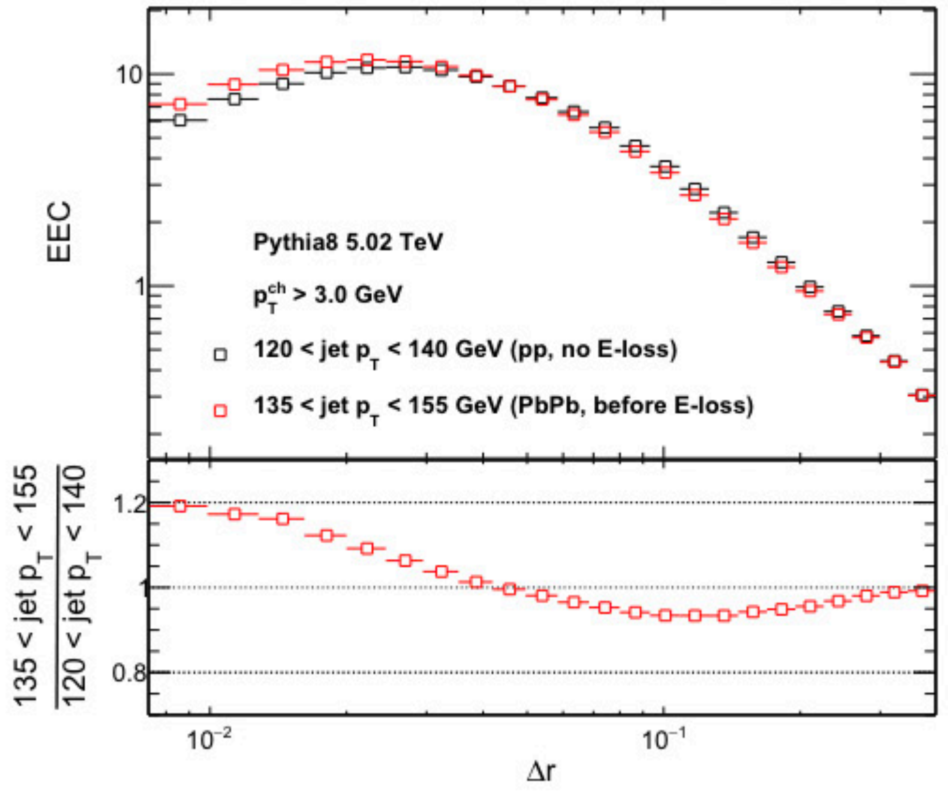
- **Energy correlators for heavy-ion collisions generating much excitement and progress!**

...AND DATA!

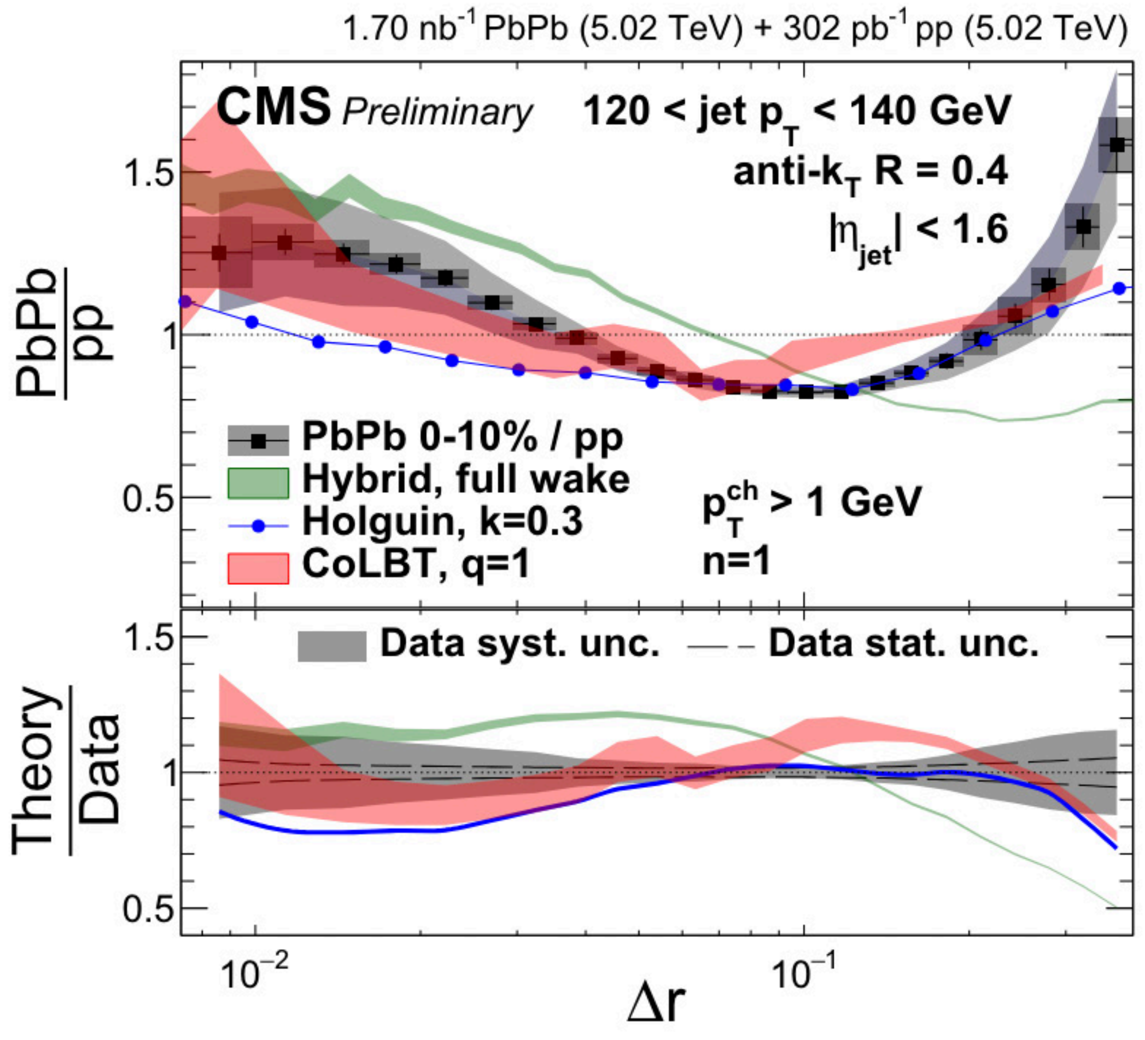
PbPb to pp ratio, centrality evolution

CMS-PAS-HIN-23-004





CMS-PAS-HIN-23-004



Pablos, Kudinoor, Rajagopal
Holguin, Andrés, Dominguez, Marquet, Moult
Yang, He, Wang

RESOLVING THE QGP USING ENERGY CORRELATORS

EEC gives angular scale

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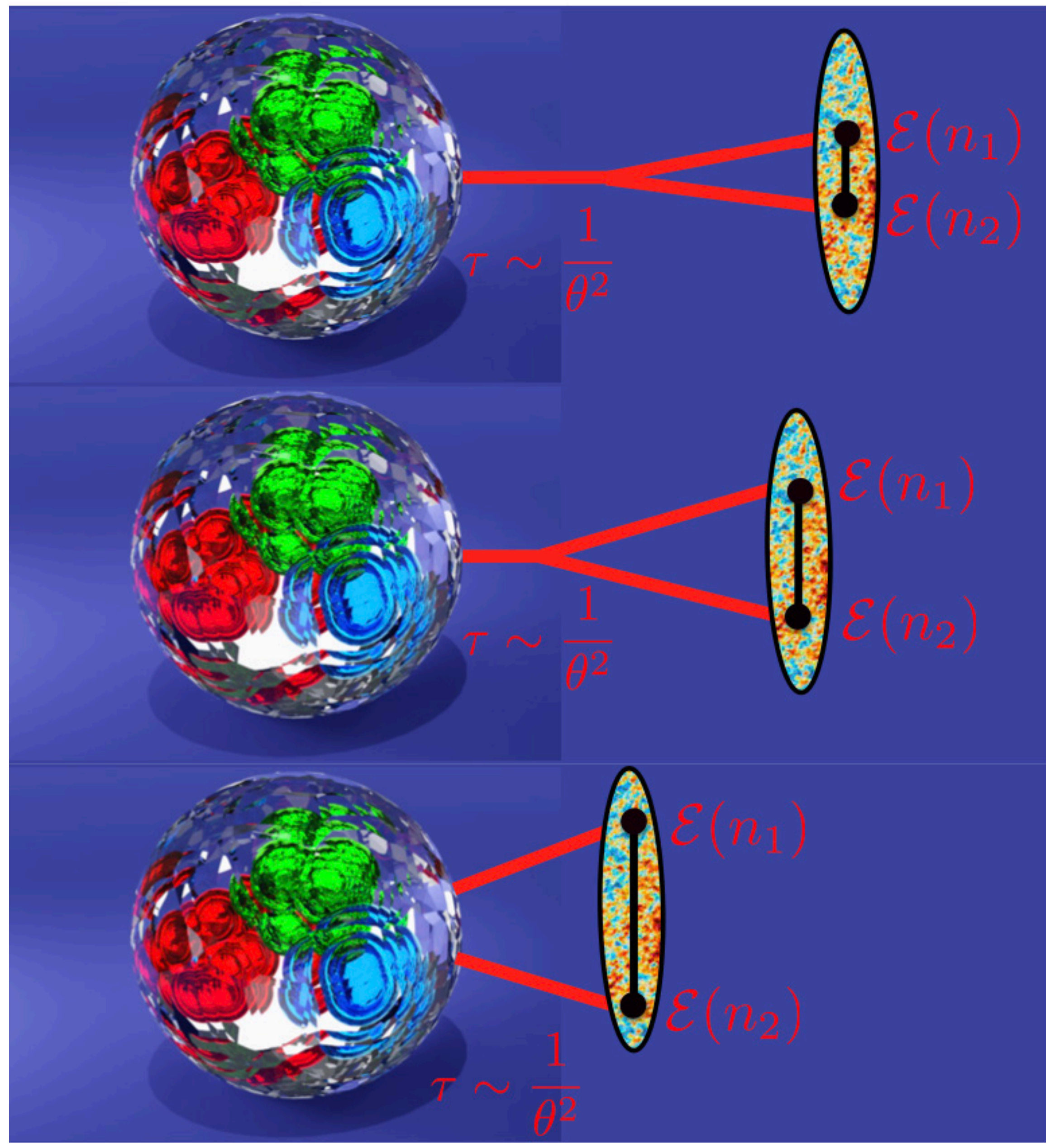
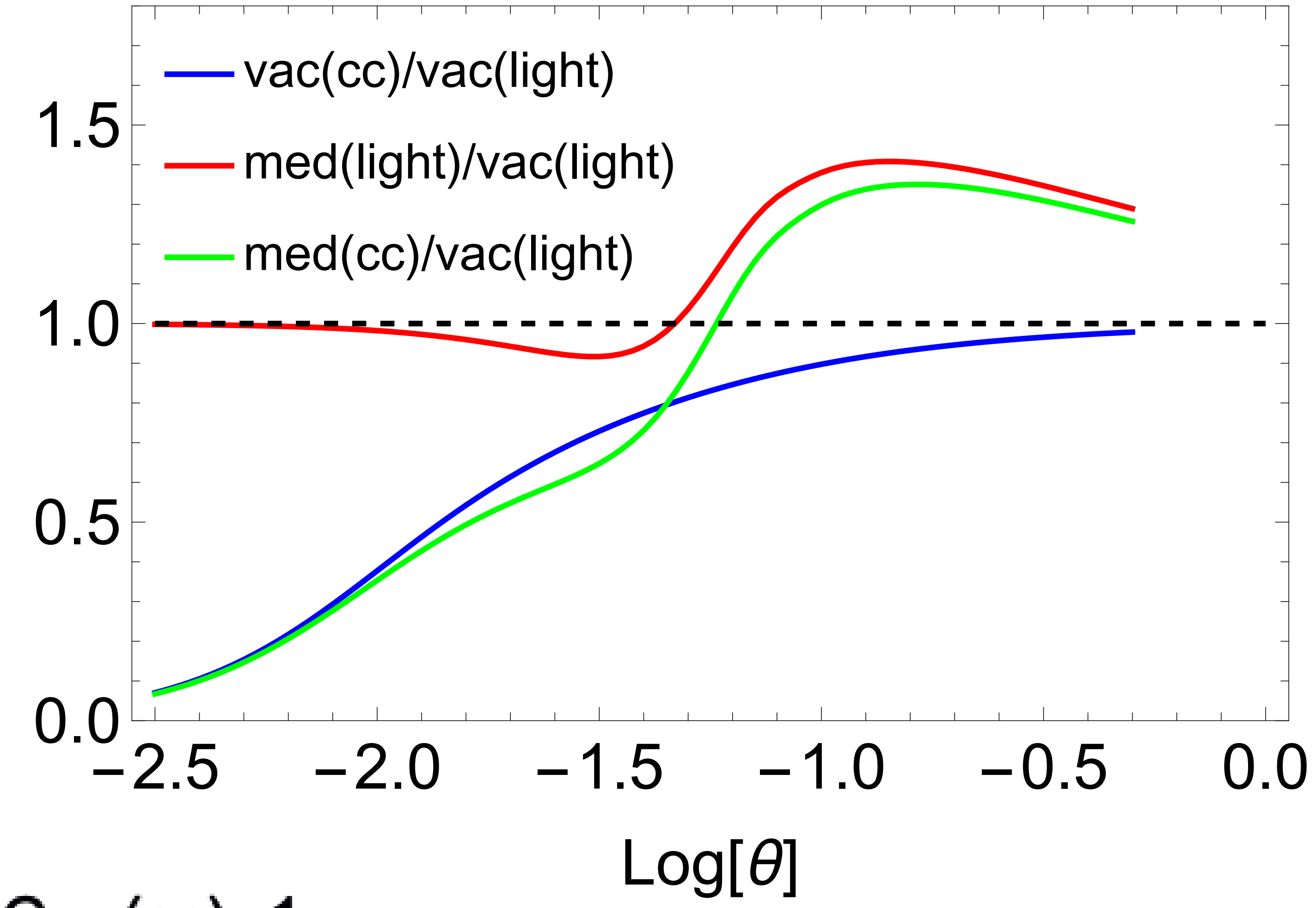
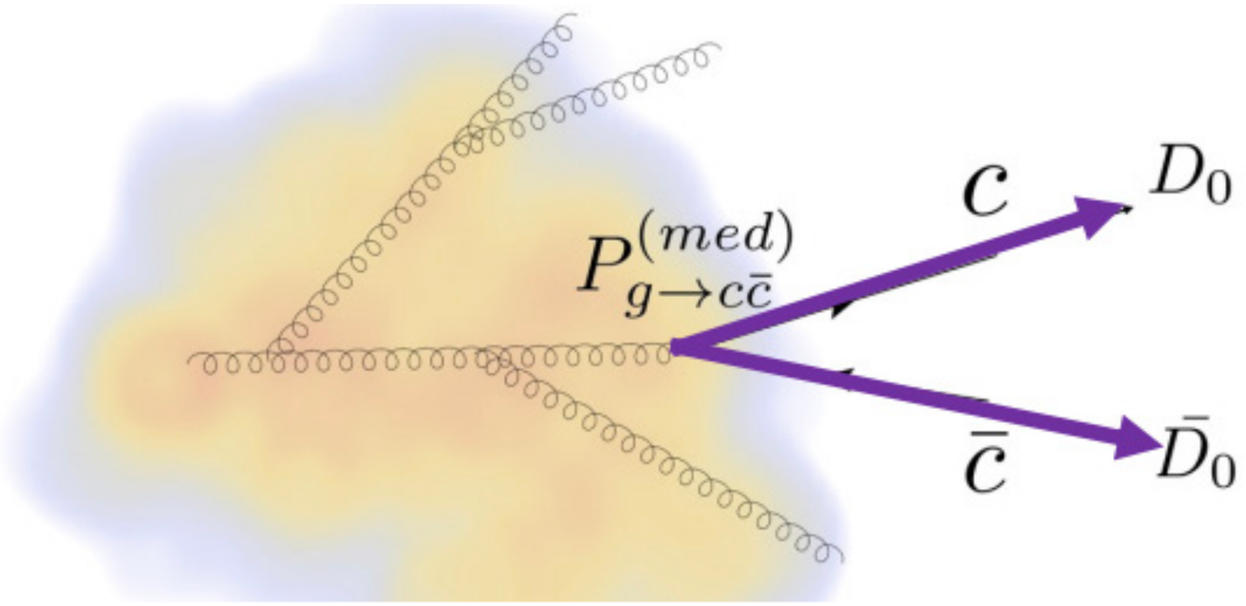
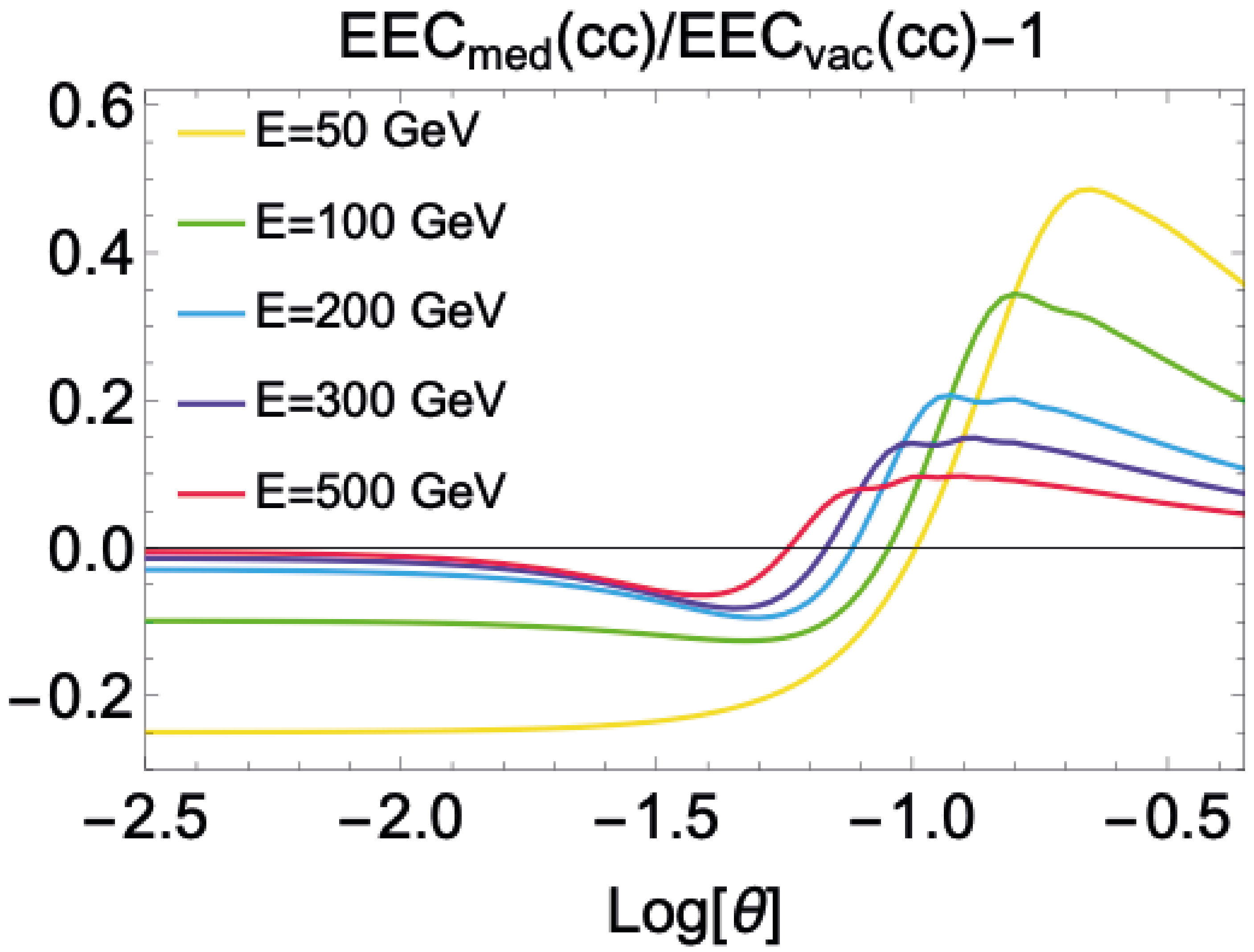
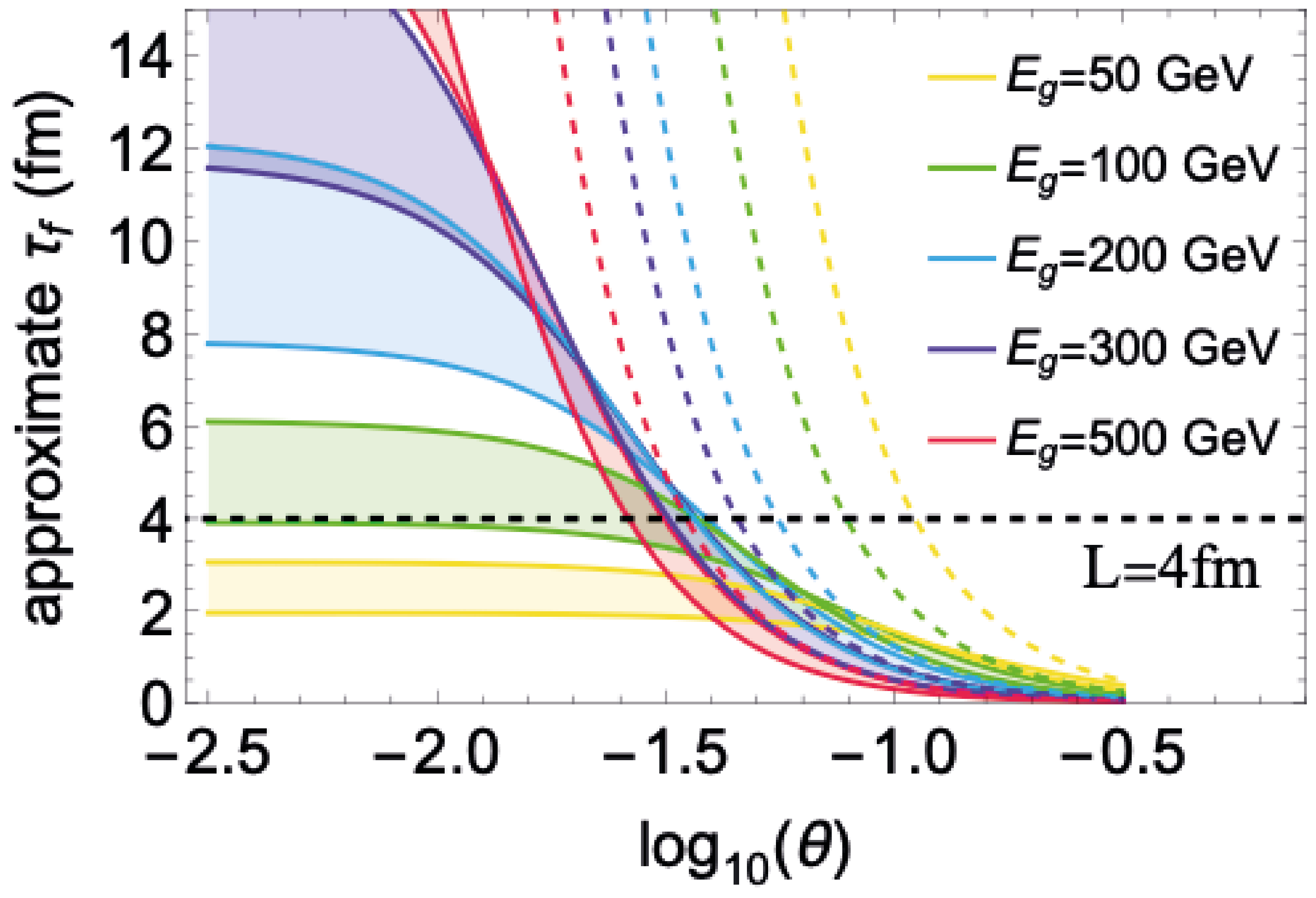






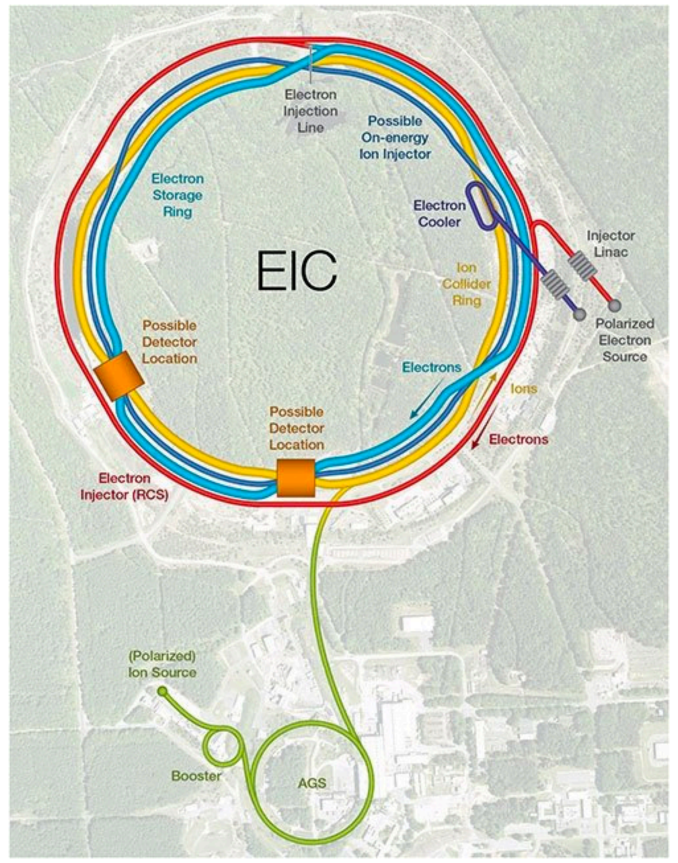




Barata, Brewer, KL, Silva `In Progress

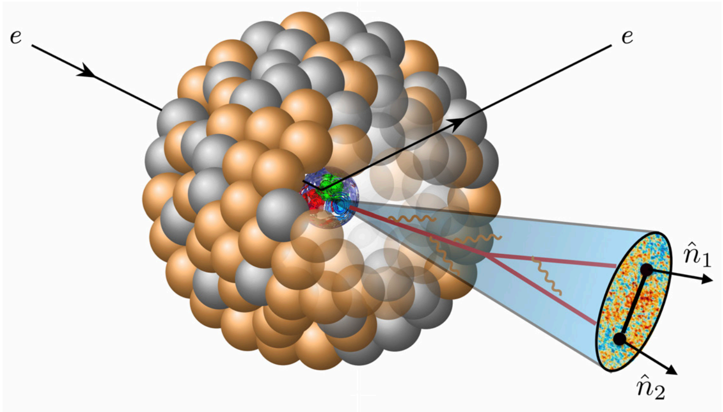
- **Heavy quarks are effective probe of the medium. Nontrivial interaction between intrinsic mass and medium effects!**

RESOLVING THE FEMTOSCALE IN JETS

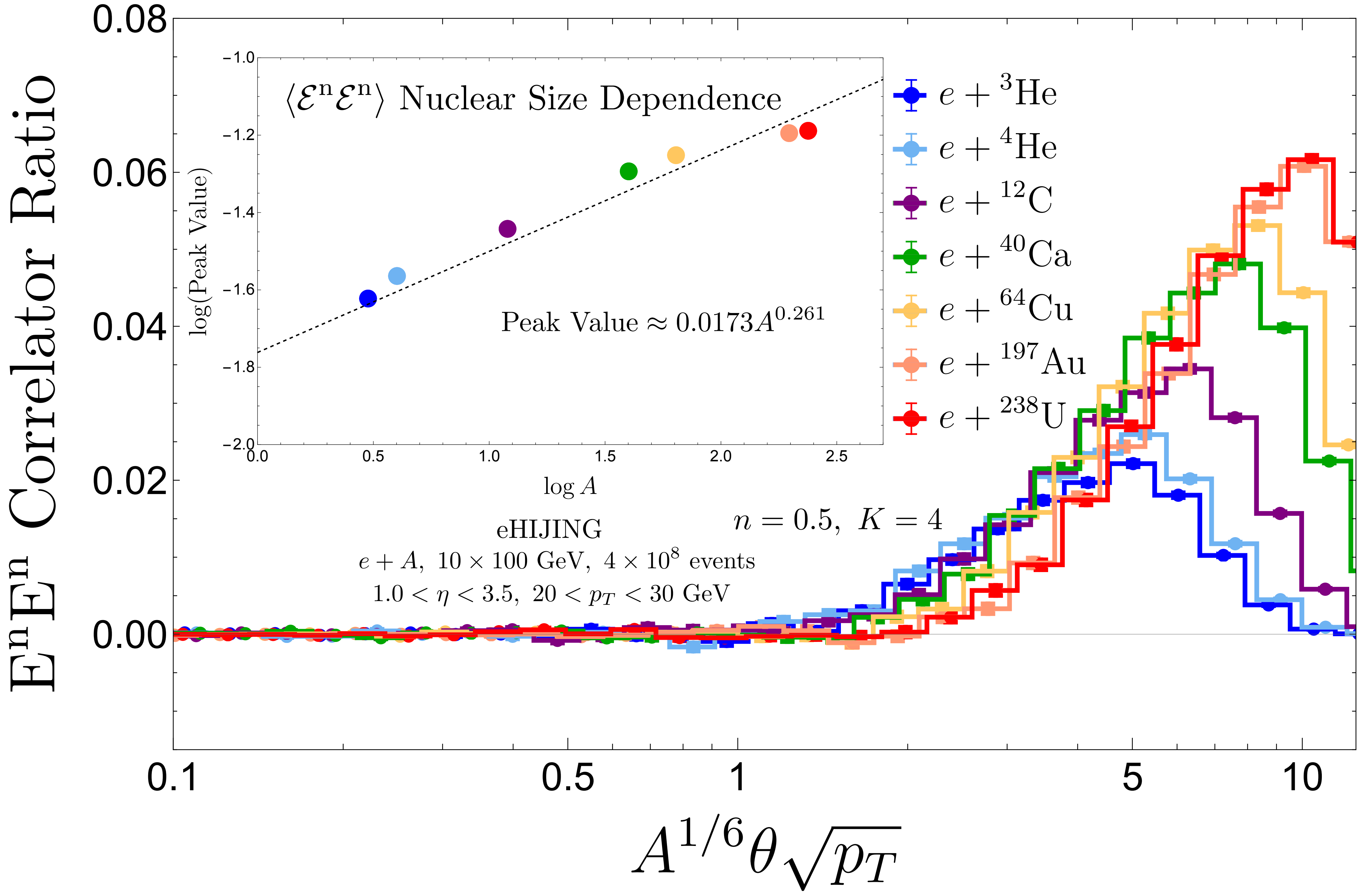


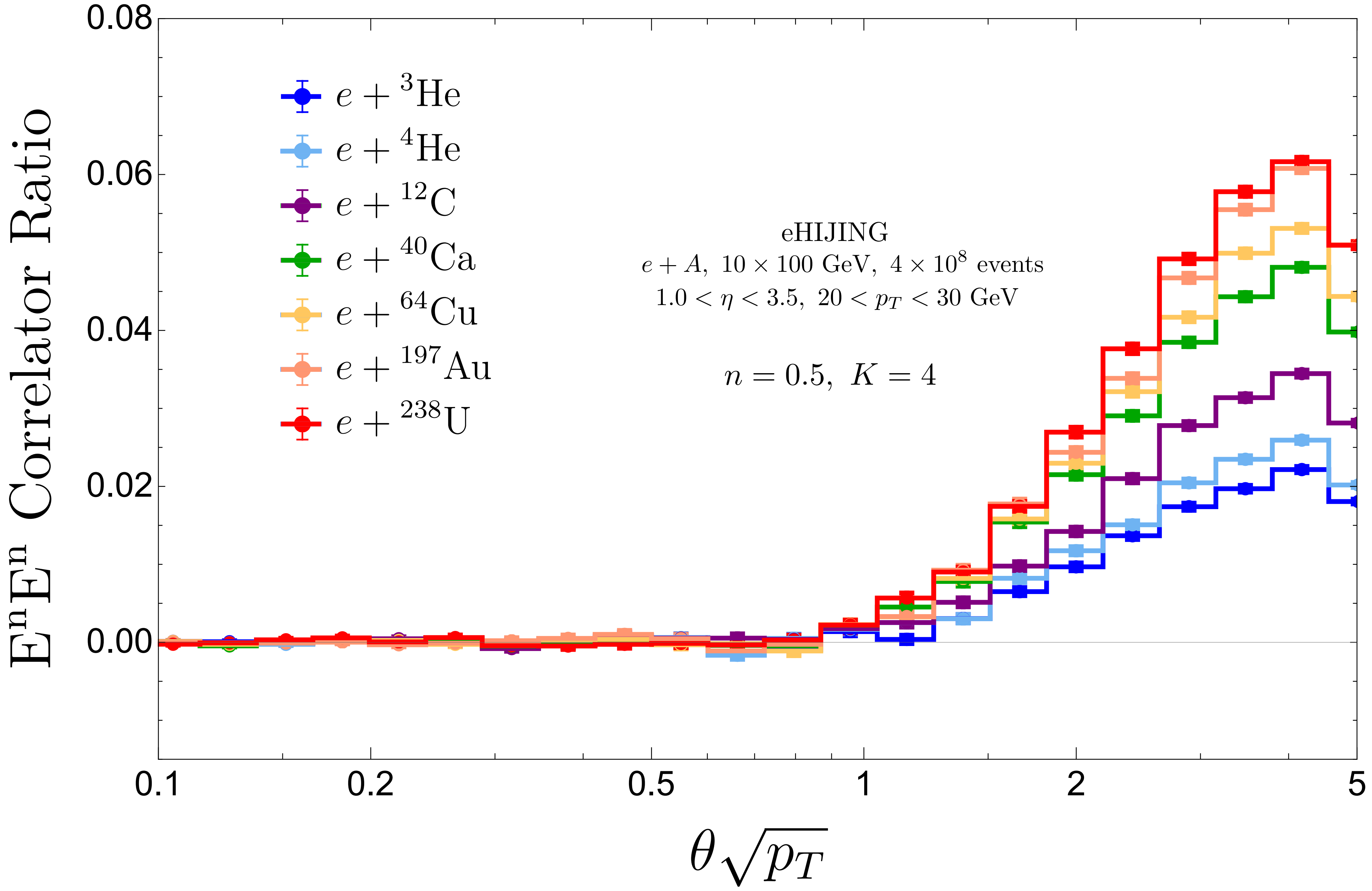
Devereaux, Fan, Ke, KL, Moult `23

- **Femtoscale nuclear size dependence can be resolved within jets using two-point correlations**

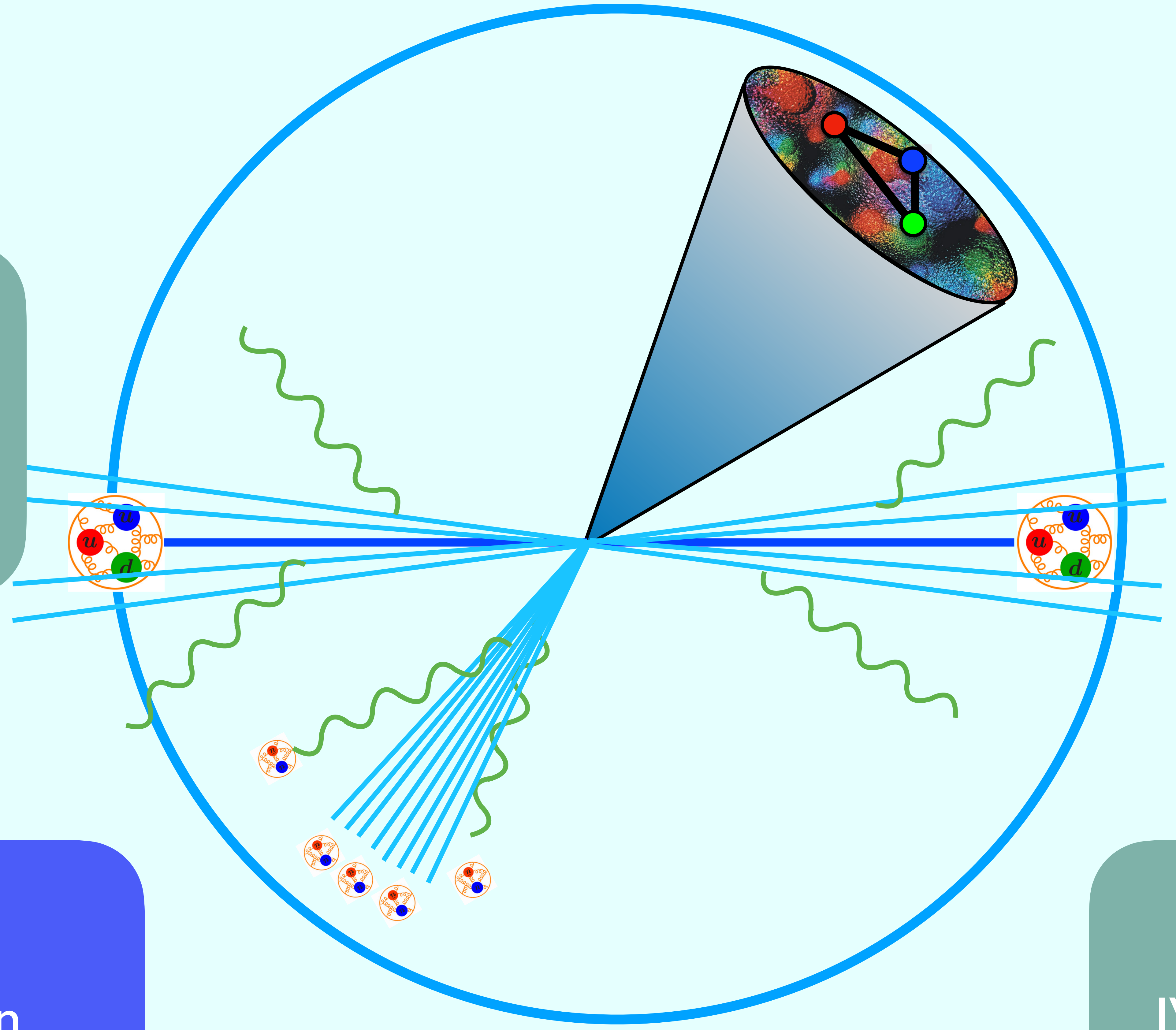


$$\theta_{\text{nucl}} \sim \frac{1}{\sqrt{p_T L}} \sim \frac{1}{\sqrt{p_T} A^{1/6}}$$





Overview



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WHAT IS A DETECTOR?

- **What constitutes a well-defined field theory definition for a detector?**

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

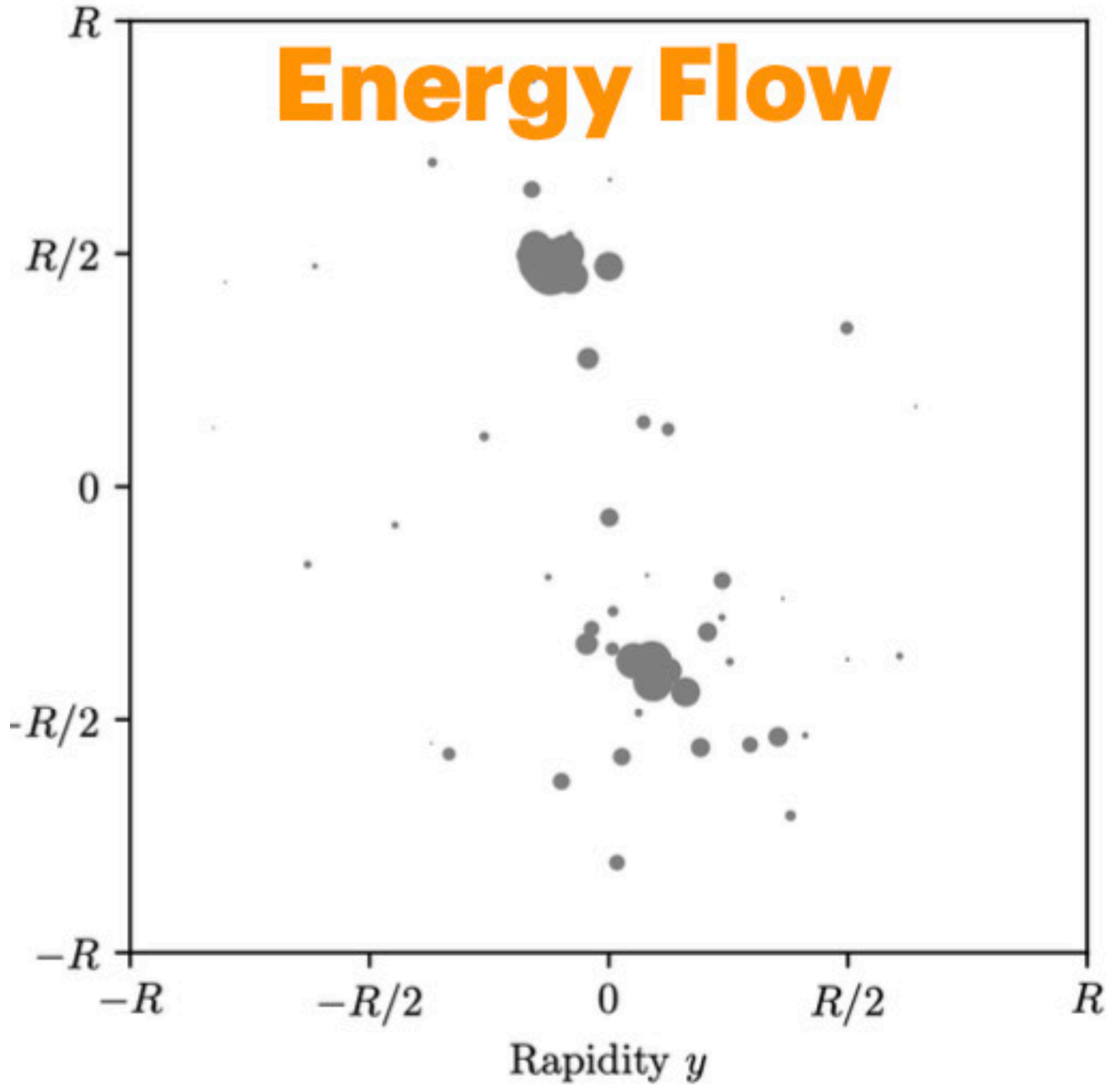
- **Interesting measurements of energy flow can be made on a restricted set of hadronic states, R, for example, charged hadrons (tracks)**

$$\mathcal{E}_R = \sum_{i\in R} \mathcal{E}_i$$

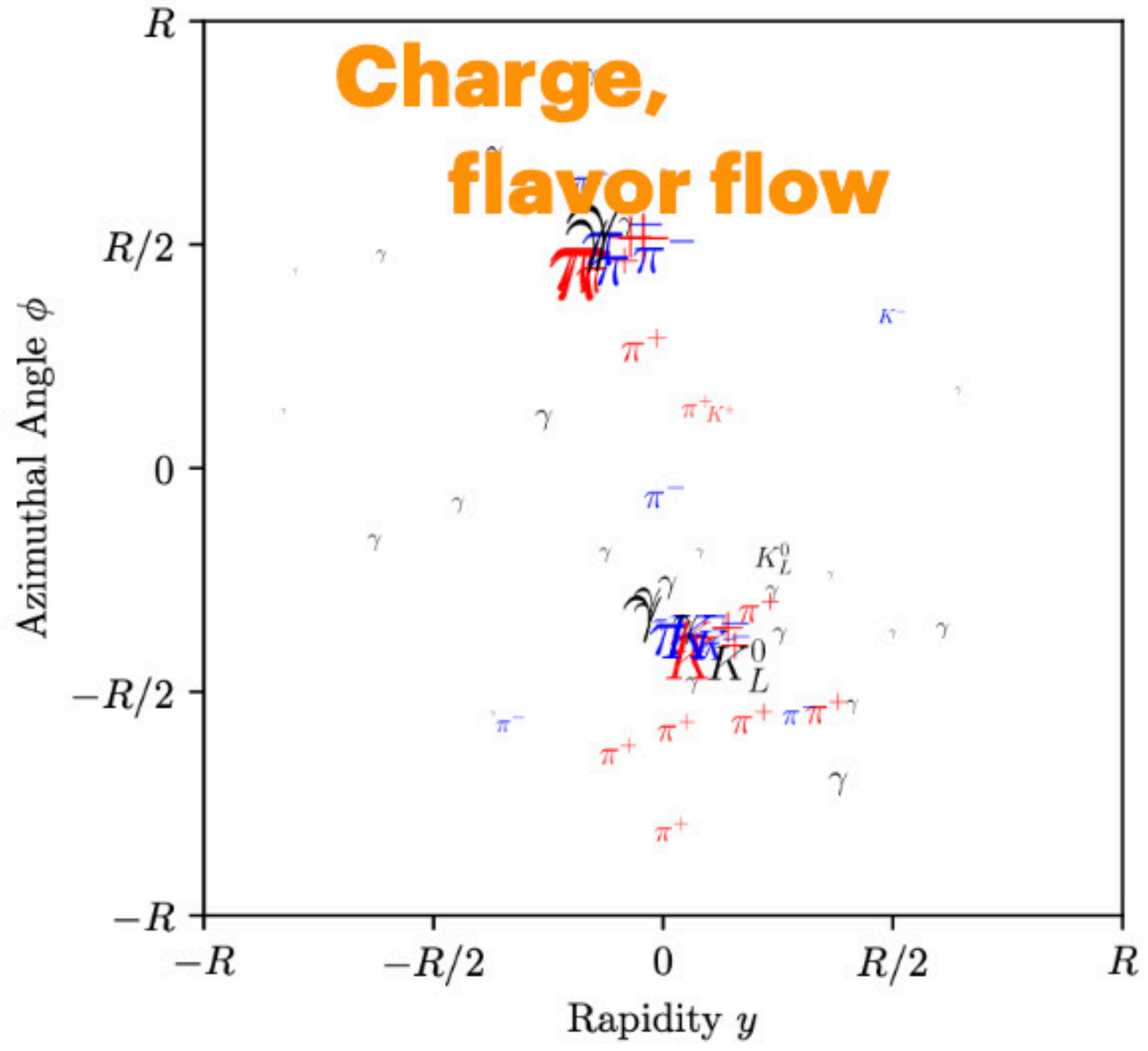
- **Provides a sharp link between underlying field theory and observables**

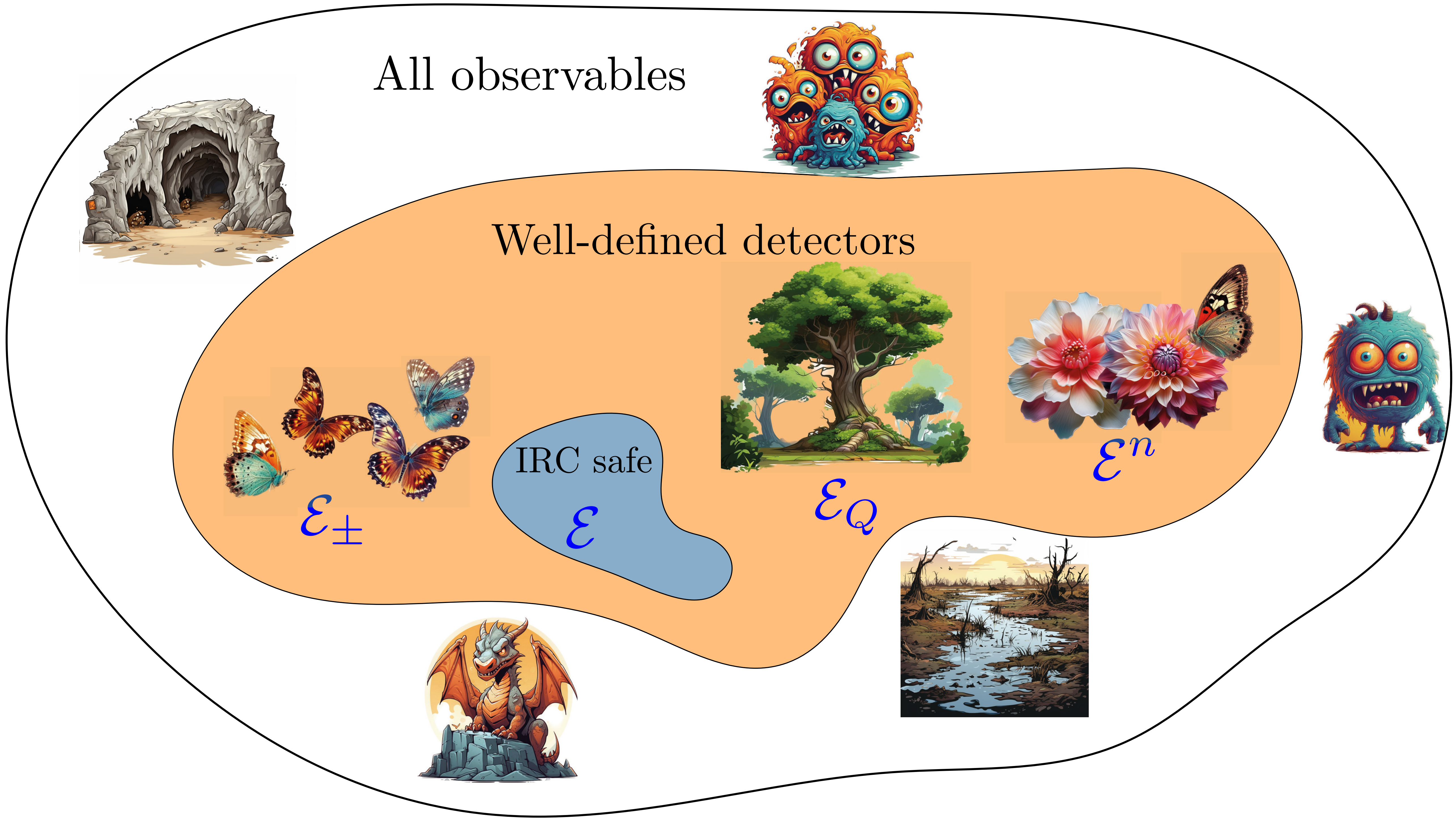
KL, Moult `23

The energy flow is unpixelized and ignores charge/flavor information



Full event is a set of particles having momentum and charge/flavor





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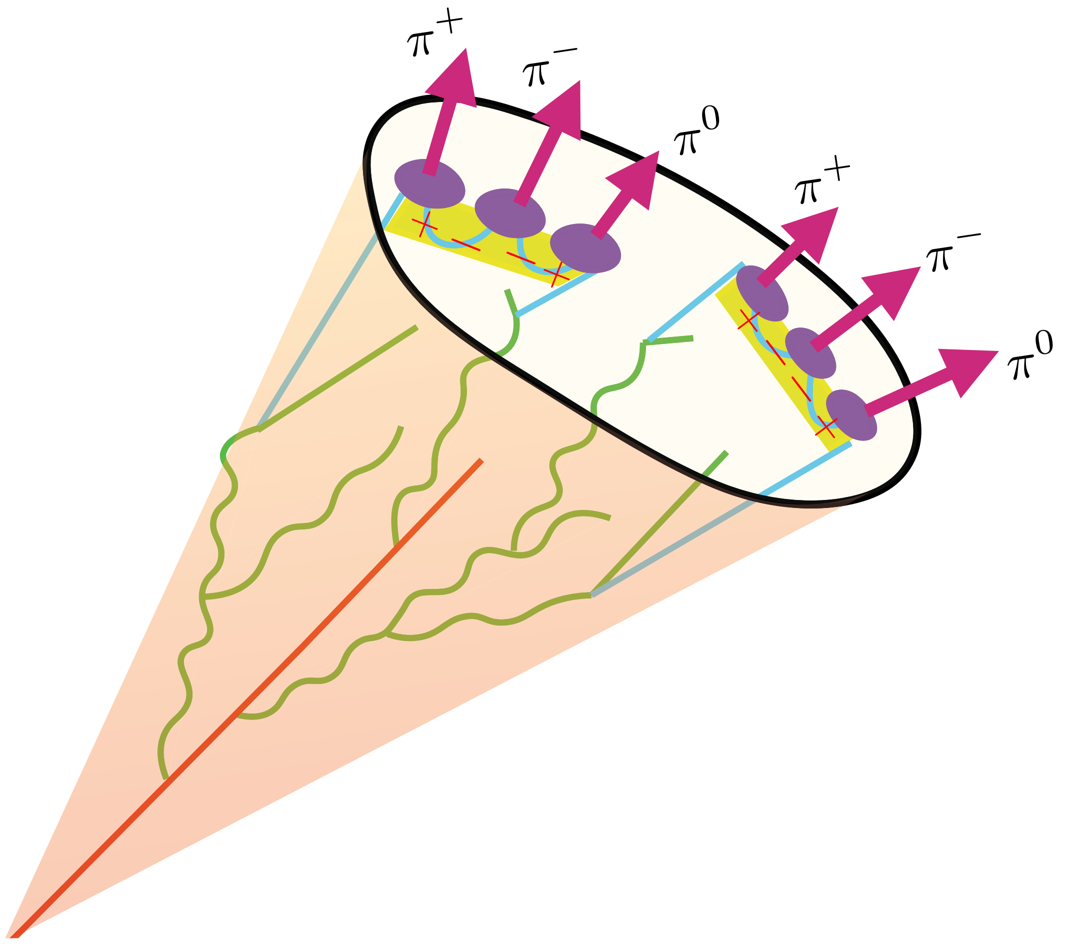
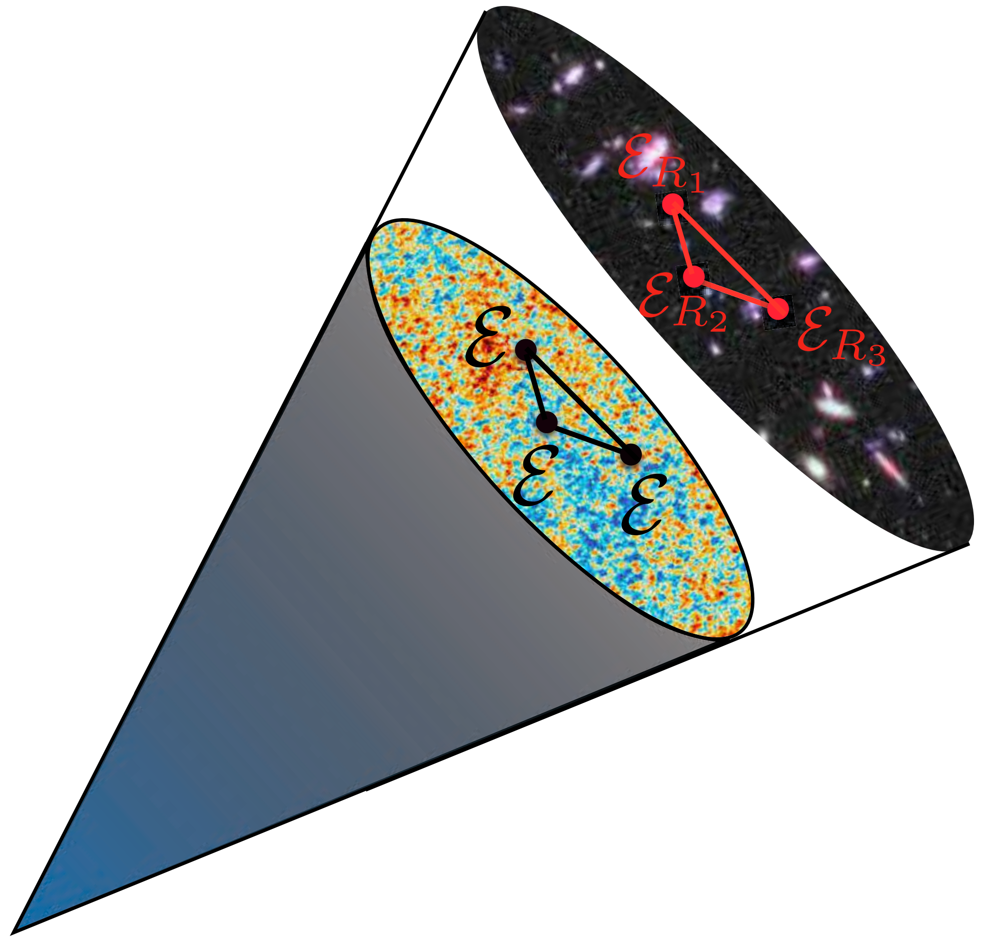
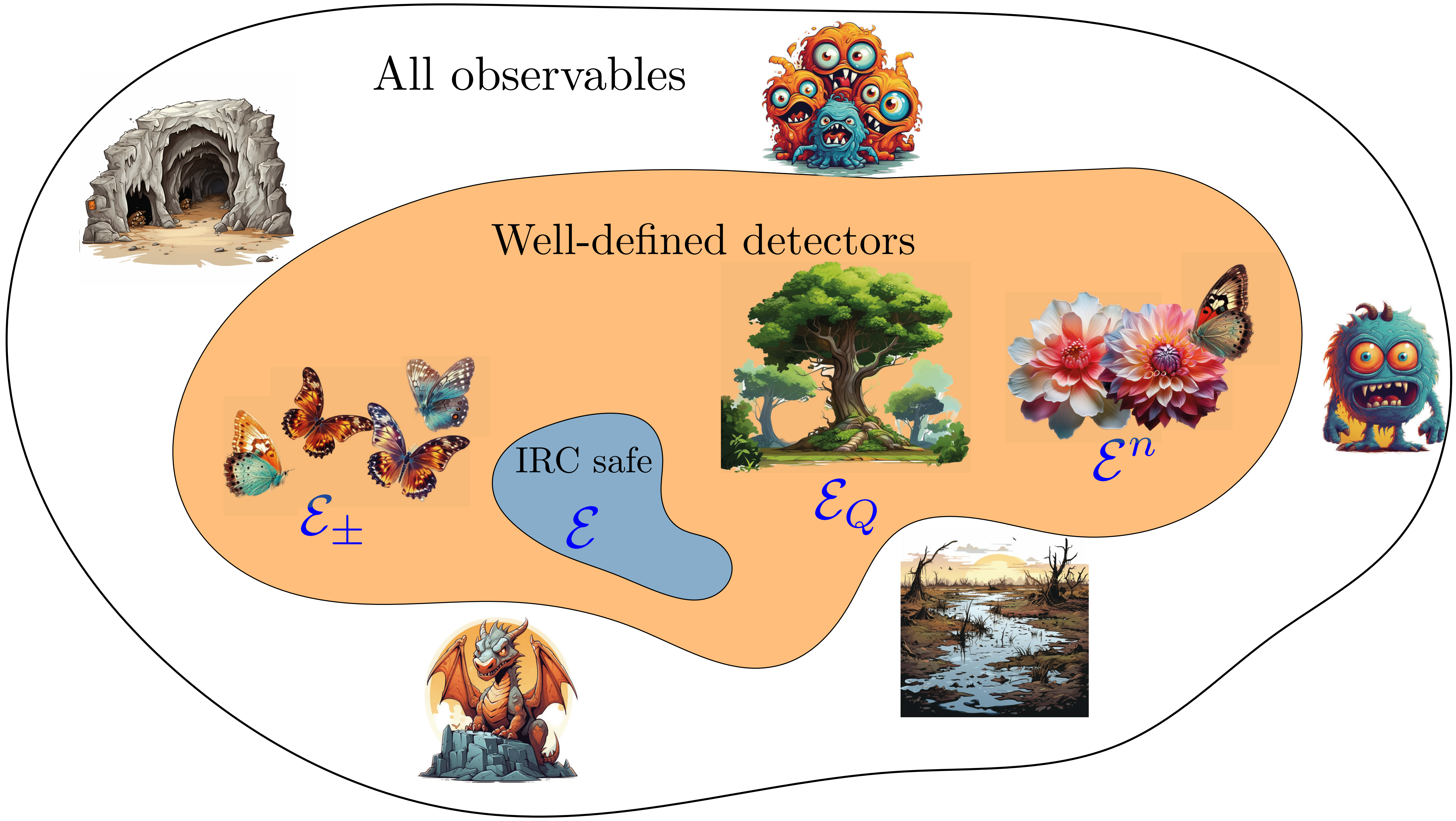
KL, Moult `23



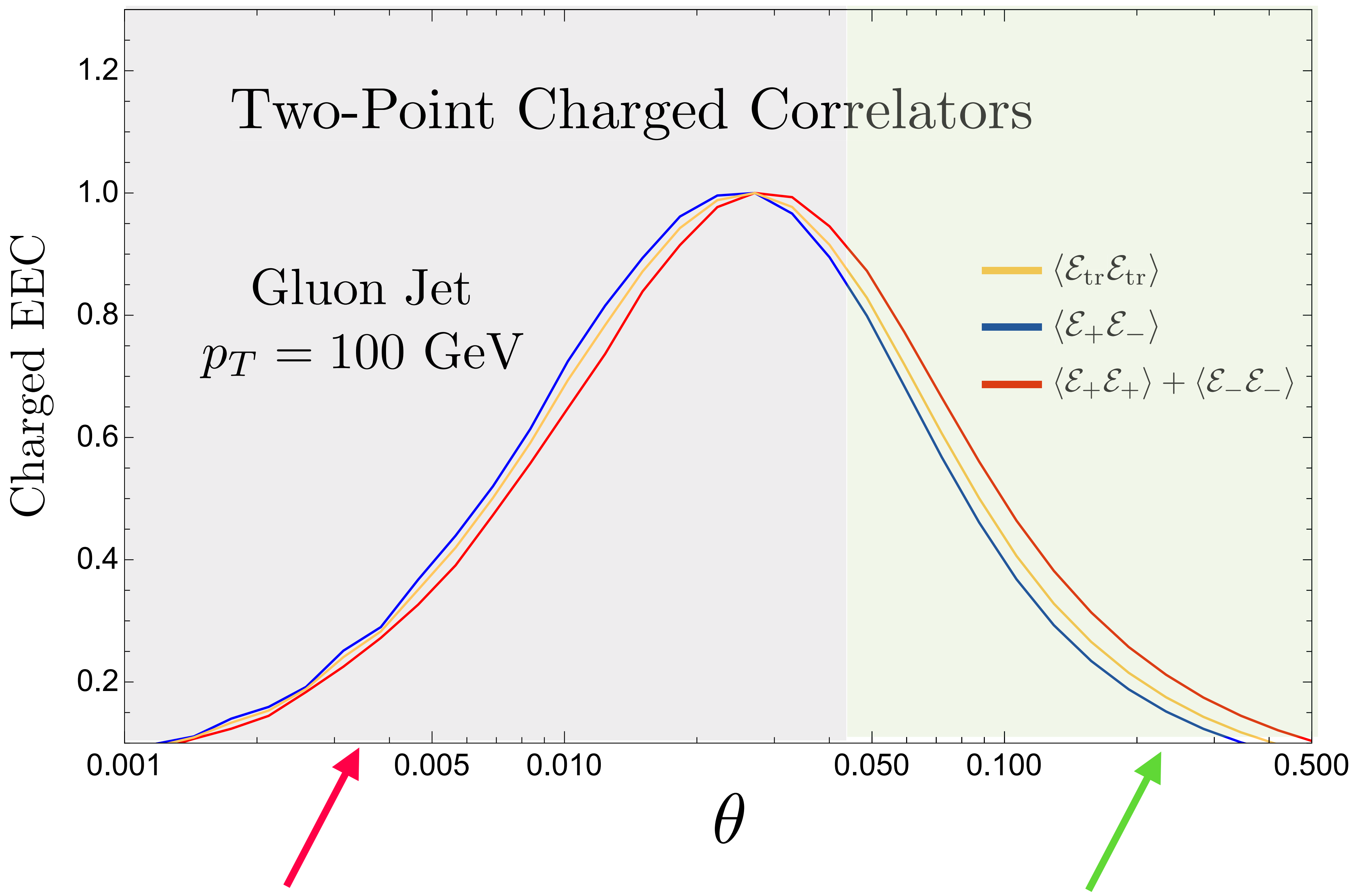




CORRELATION BETWEEN CHARGED HADRONS

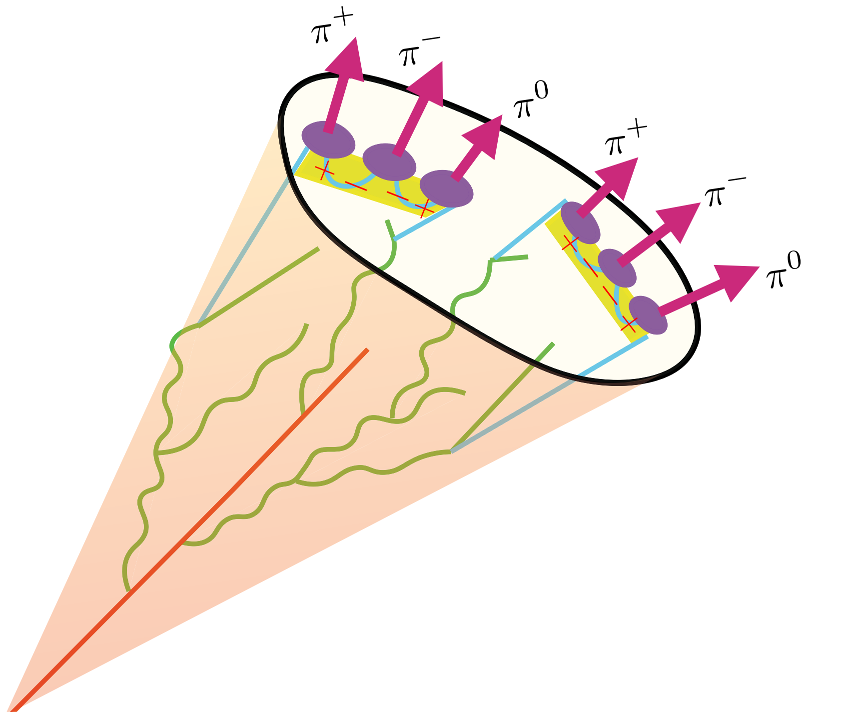
KL, Moult `23

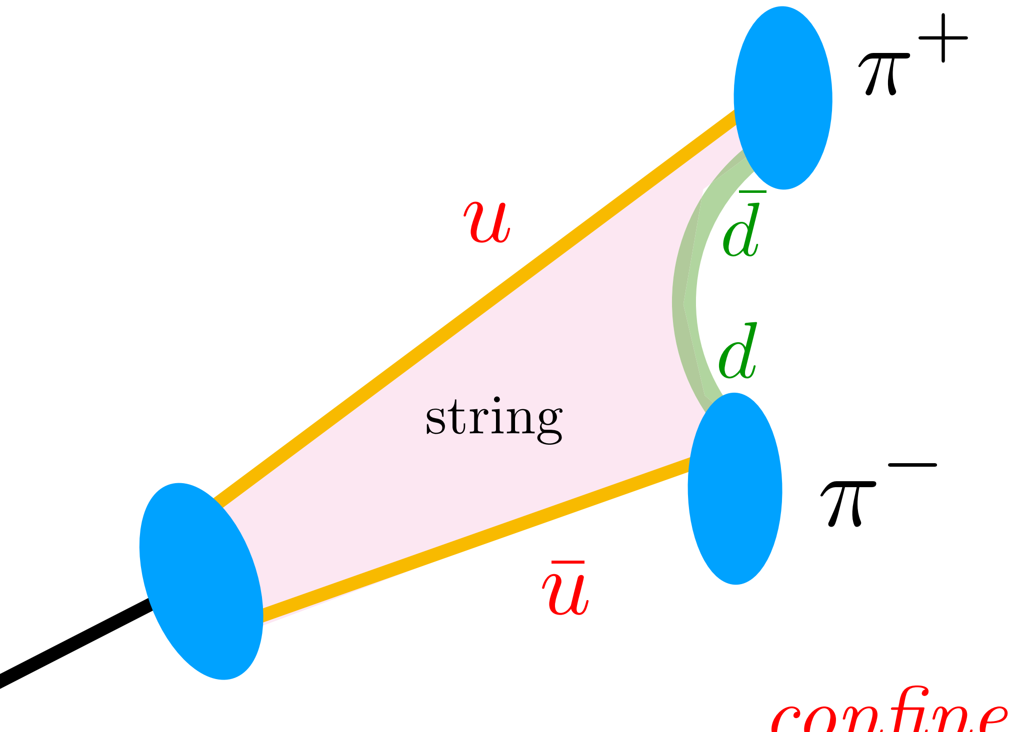
- **Unlike-signed charged correlators are correlated more as the angle becomes smaller!**



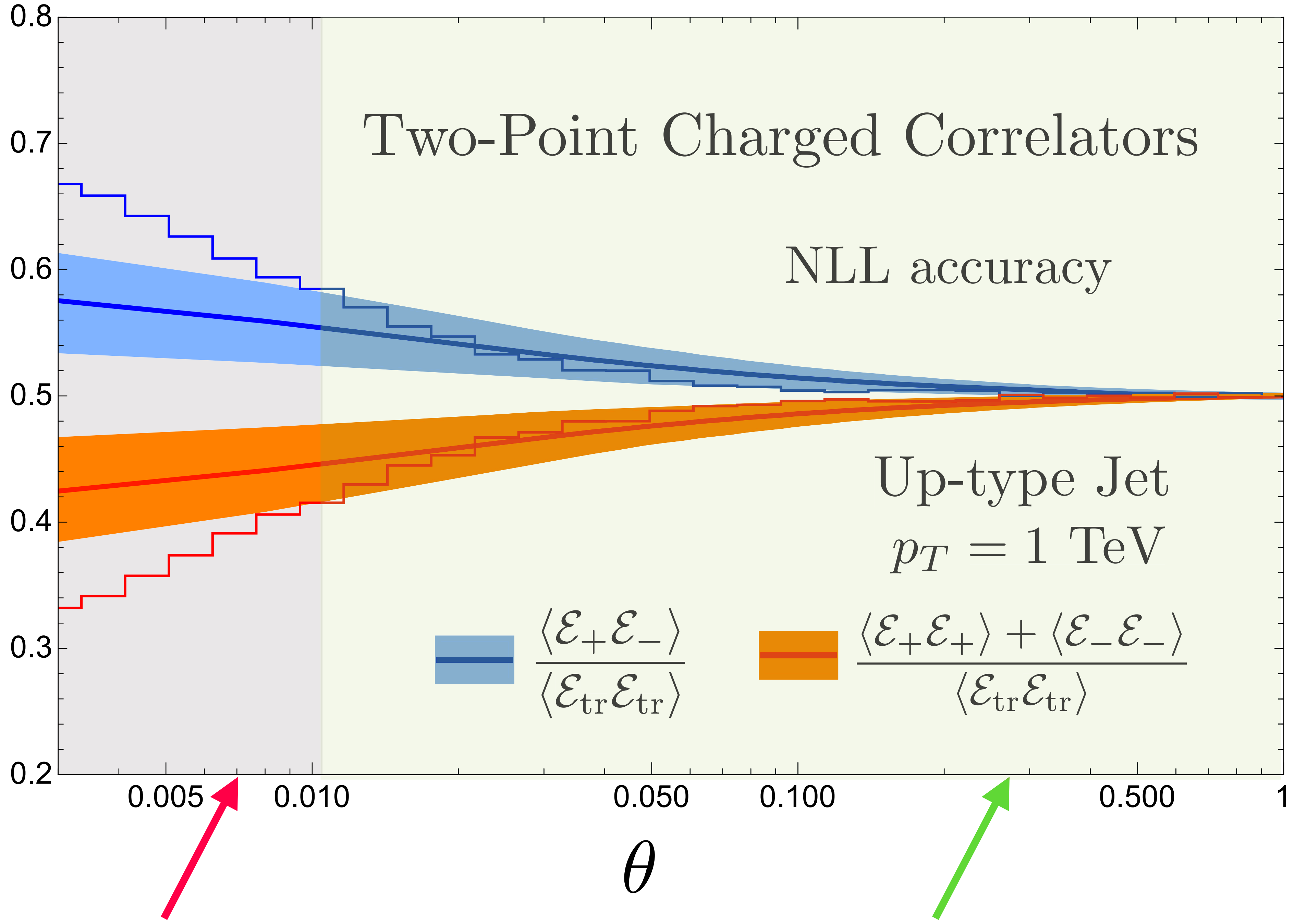
confinement transition region

perturbative region





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

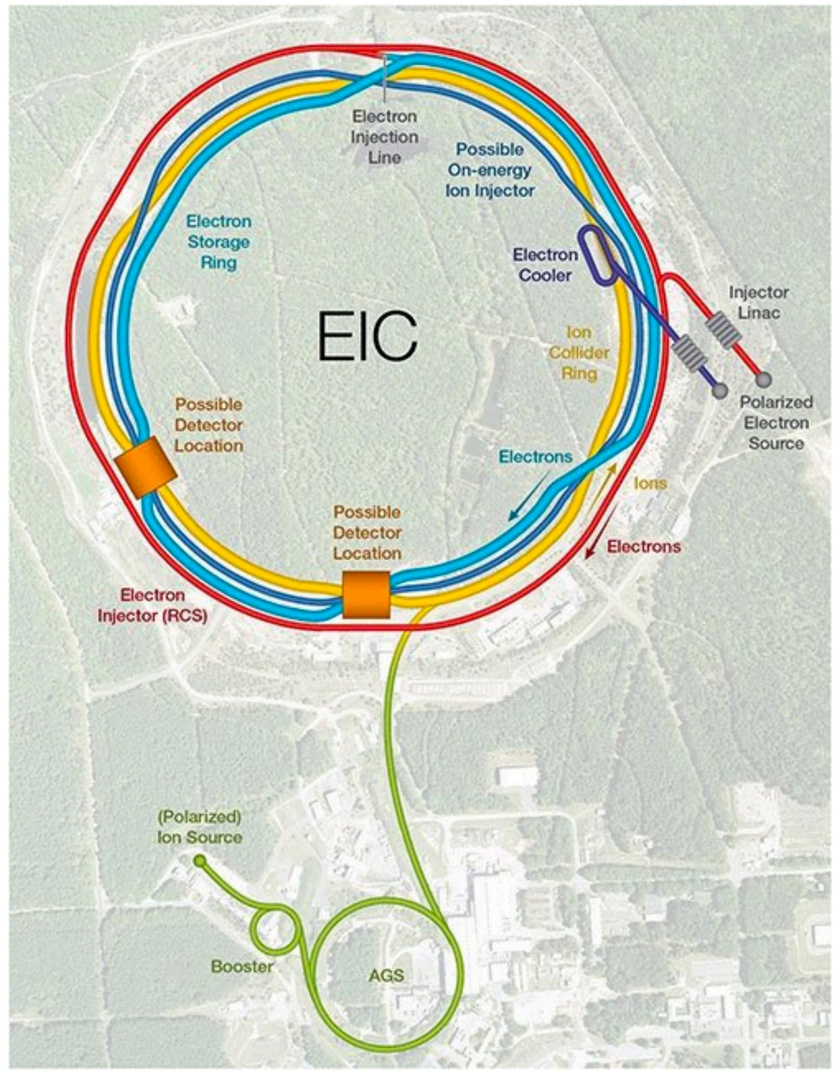


confinement transition region

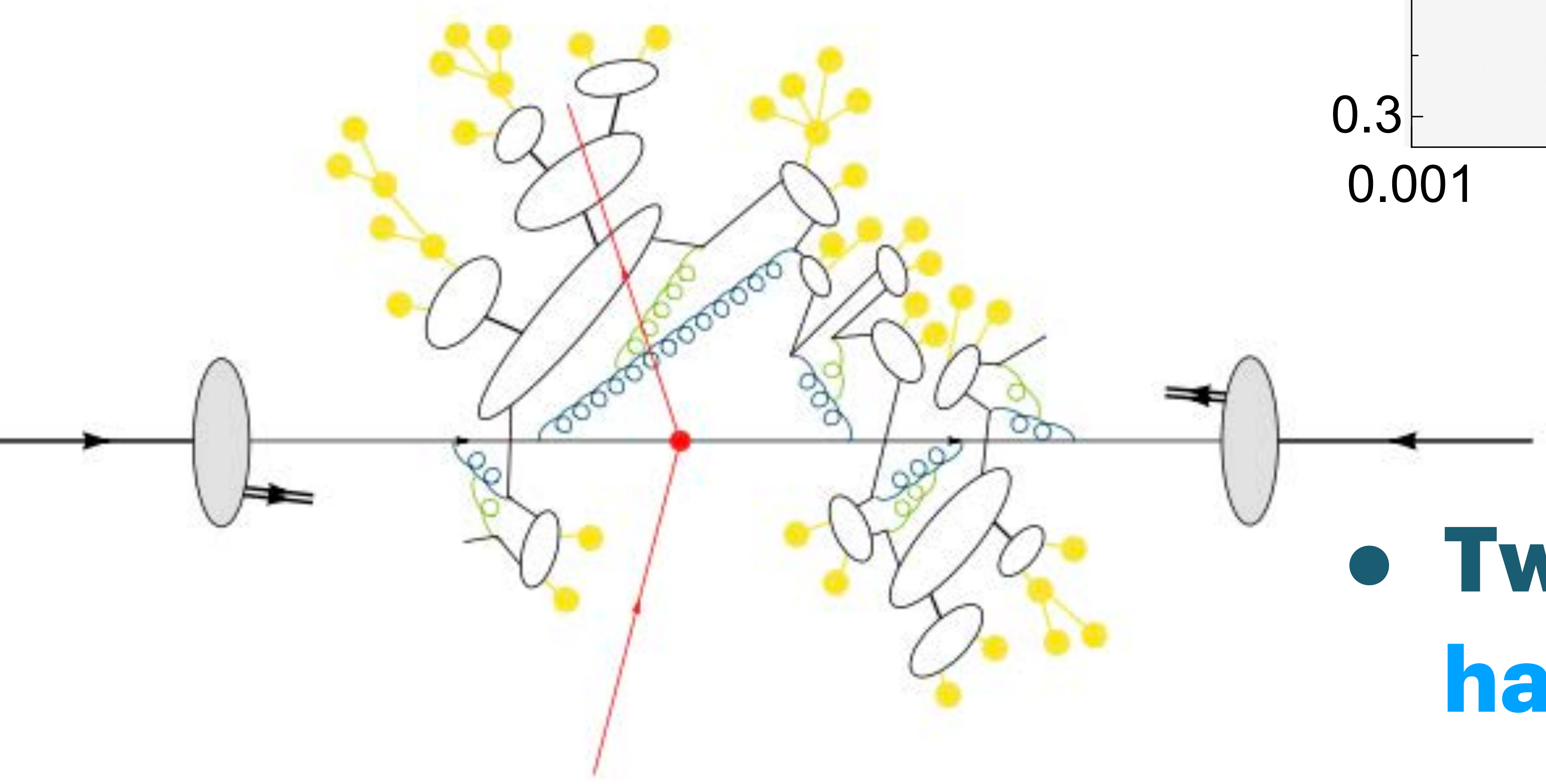
perturbative region

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

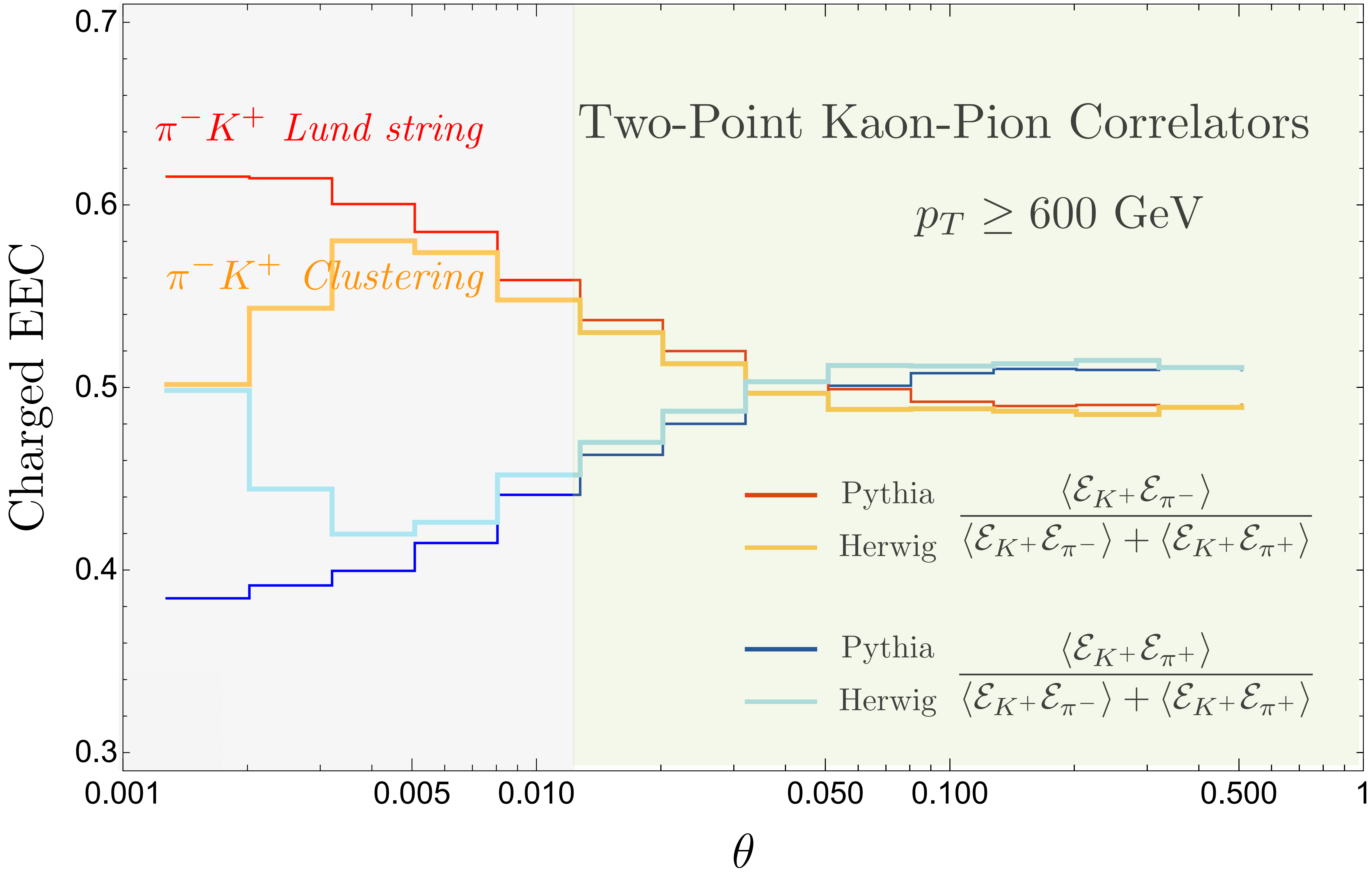
DISCRIMINATING HADRONIZATION MECHANISMS

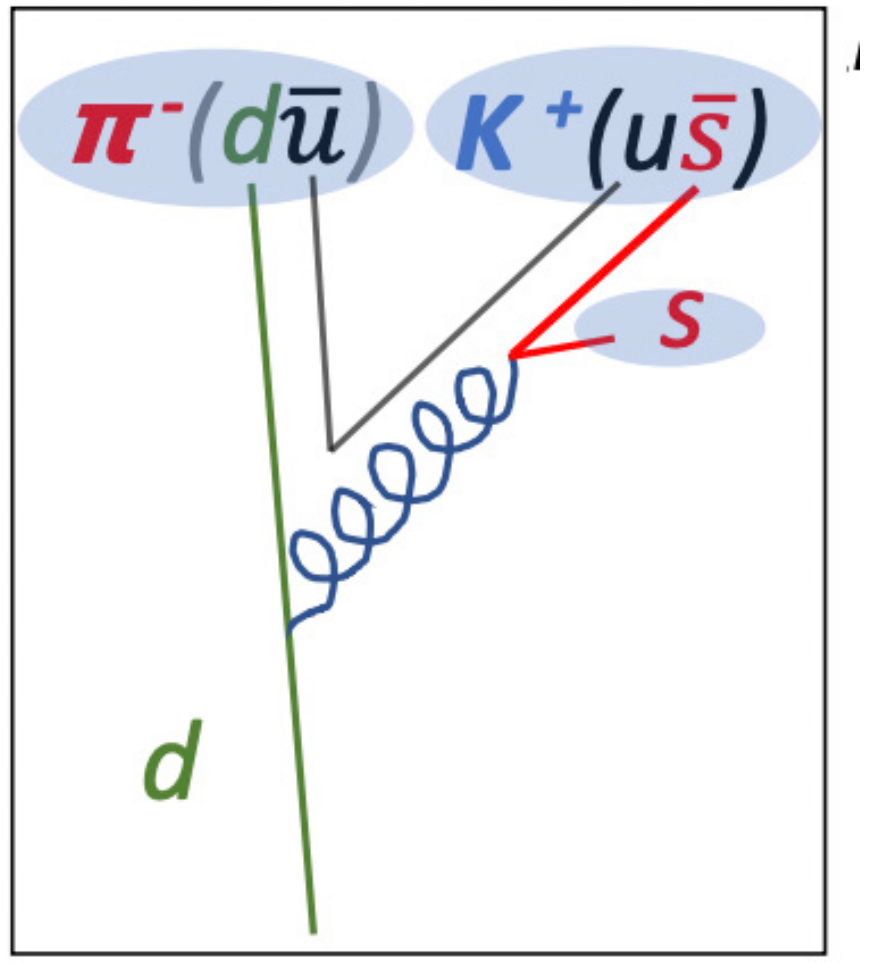


Clustering model
(Herwig)



KL, Moult, Song, Sterman `In Progress





Lund string model
(Pythia)

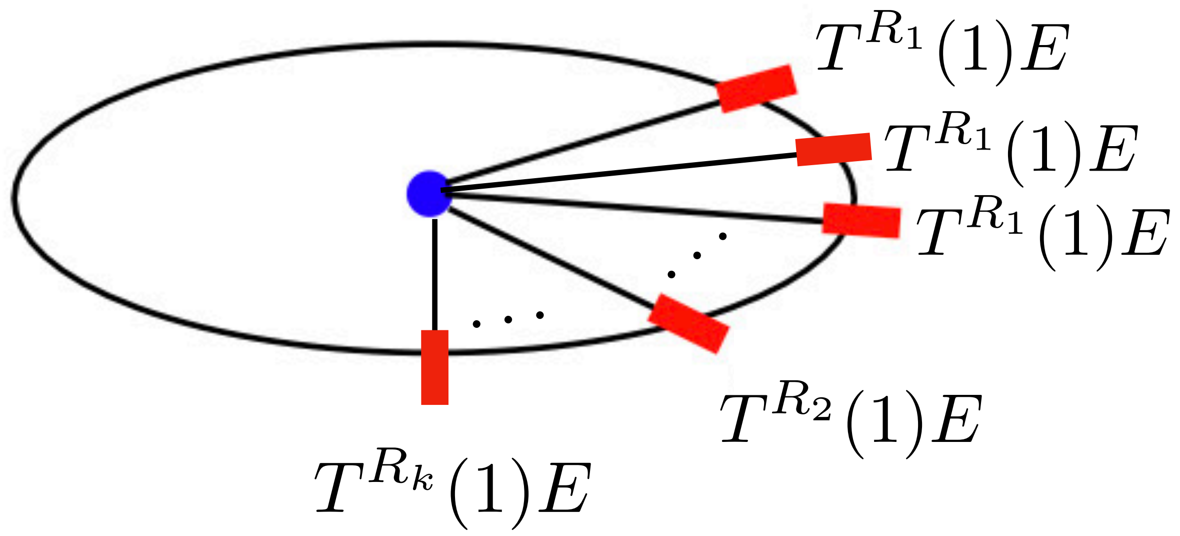
See also Chien, Deshpande, Mondal, Sterman

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

GENERALIZING ENERGY FLOW CORRELATIONS

- **Writing down more general detectors allows us to systematically consider more general correlations!**

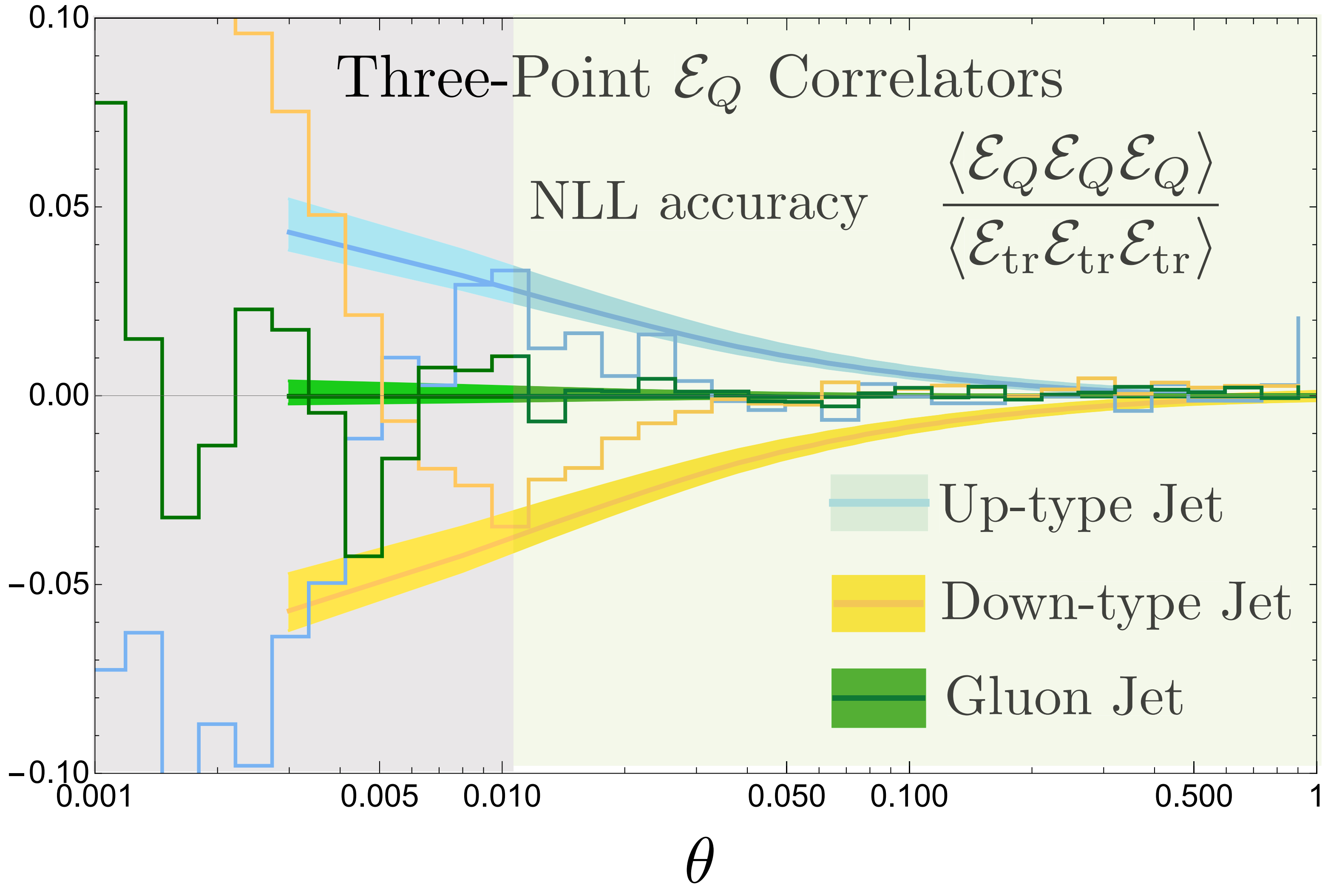
KL, Moult `23



$$\langle \underbrace{\mathcal{E}_{R_1}(\vec{n}_1^{R_1})\cdots\mathcal{E}_{R_1}(\vec{n}_{N_1}^{R_1})}_{N_1\ \text{times}} \underbrace{\mathcal{E}_{R_2}(\vec{n}_1^{R_2})\cdots\mathcal{E}_{R_2}(\vec{n}_{N_2}^{R_2})}_{N_2\ \text{times}} \cdots \underbrace{\mathcal{E}_{R_k}(\vec{n}_1^{R_k})\cdots\mathcal{E}_{R_k}(\vec{n}_{N_k}^{R_k})}_{N_k\ \text{times}} \rangle$$

Higher-point charged correlators

$$\mathcal{E}_{\mathcal{Q}}\left(\vec{n}_1\right)|k\rangle = E_k Q_k \delta\left(\hat{n}_1 - \hat{k}\right)|k\rangle$$



Overview

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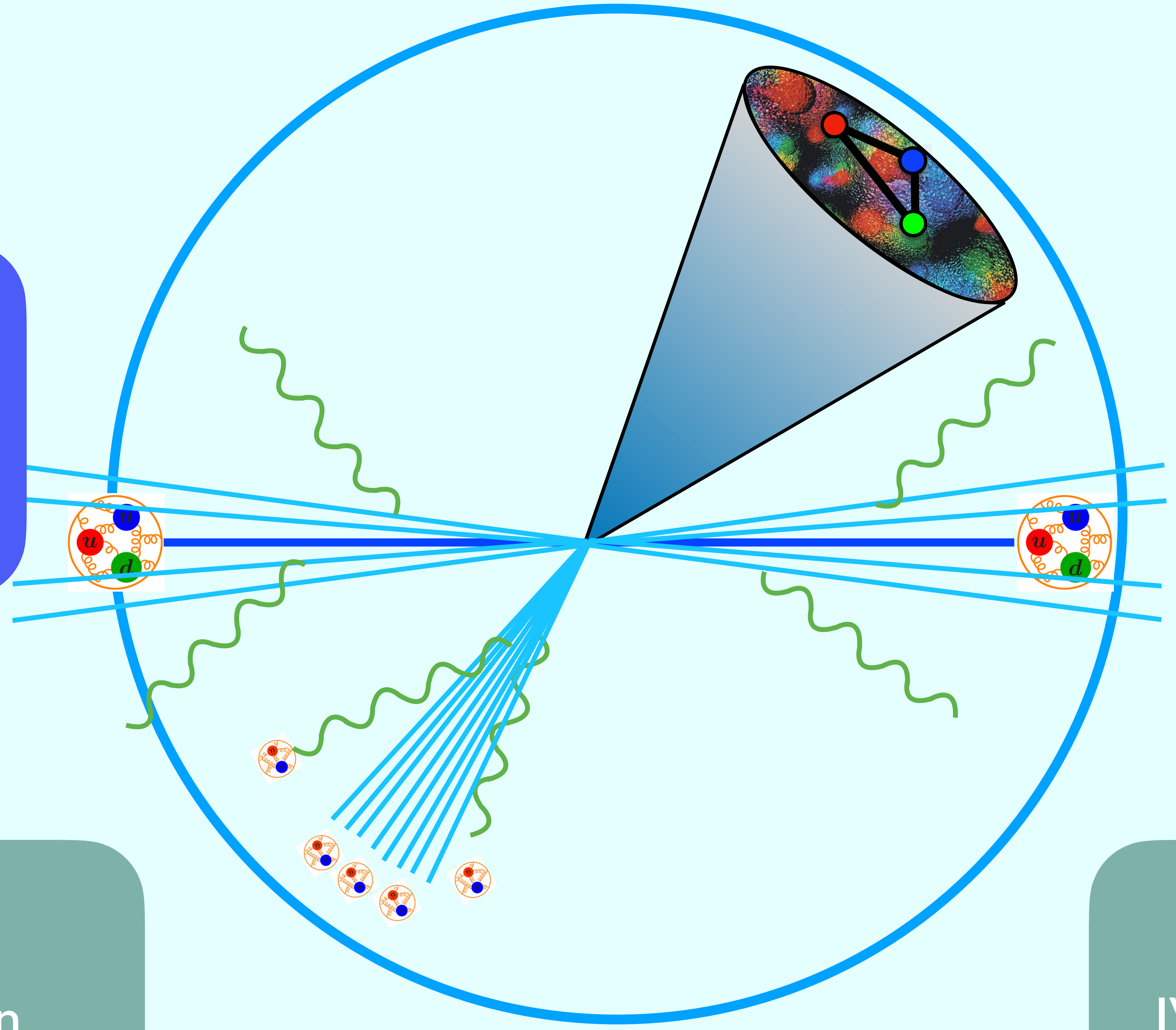

VI. Real-time Simulations

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QUANTUM COMPUTING PLATFORMS

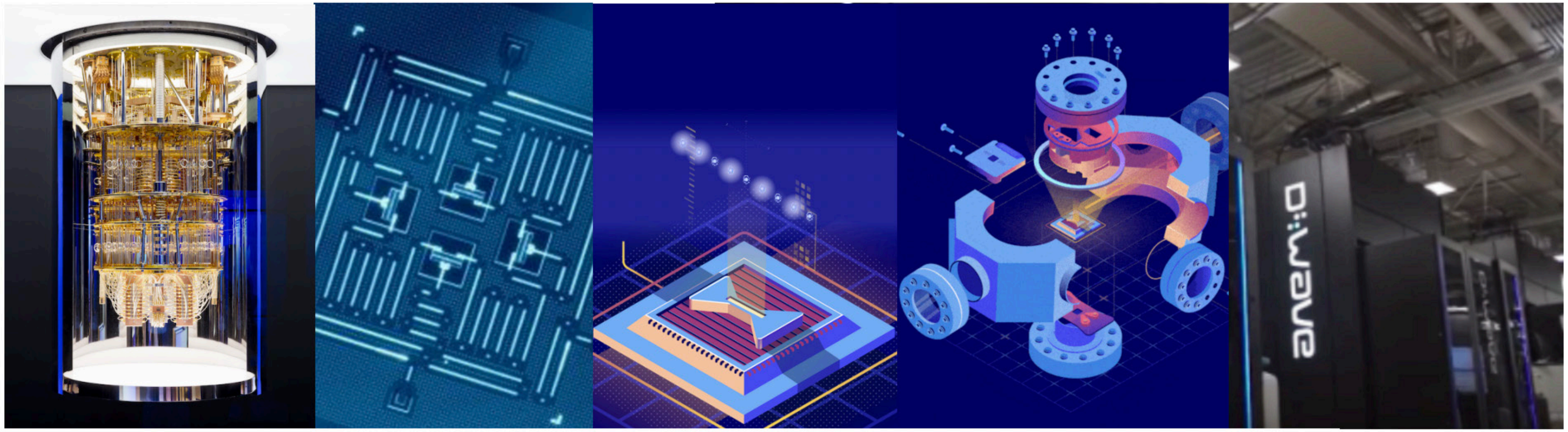
For example

- Superconducting qubits
- Trapped ion devices

IBM Q rigetti

Google IONQ

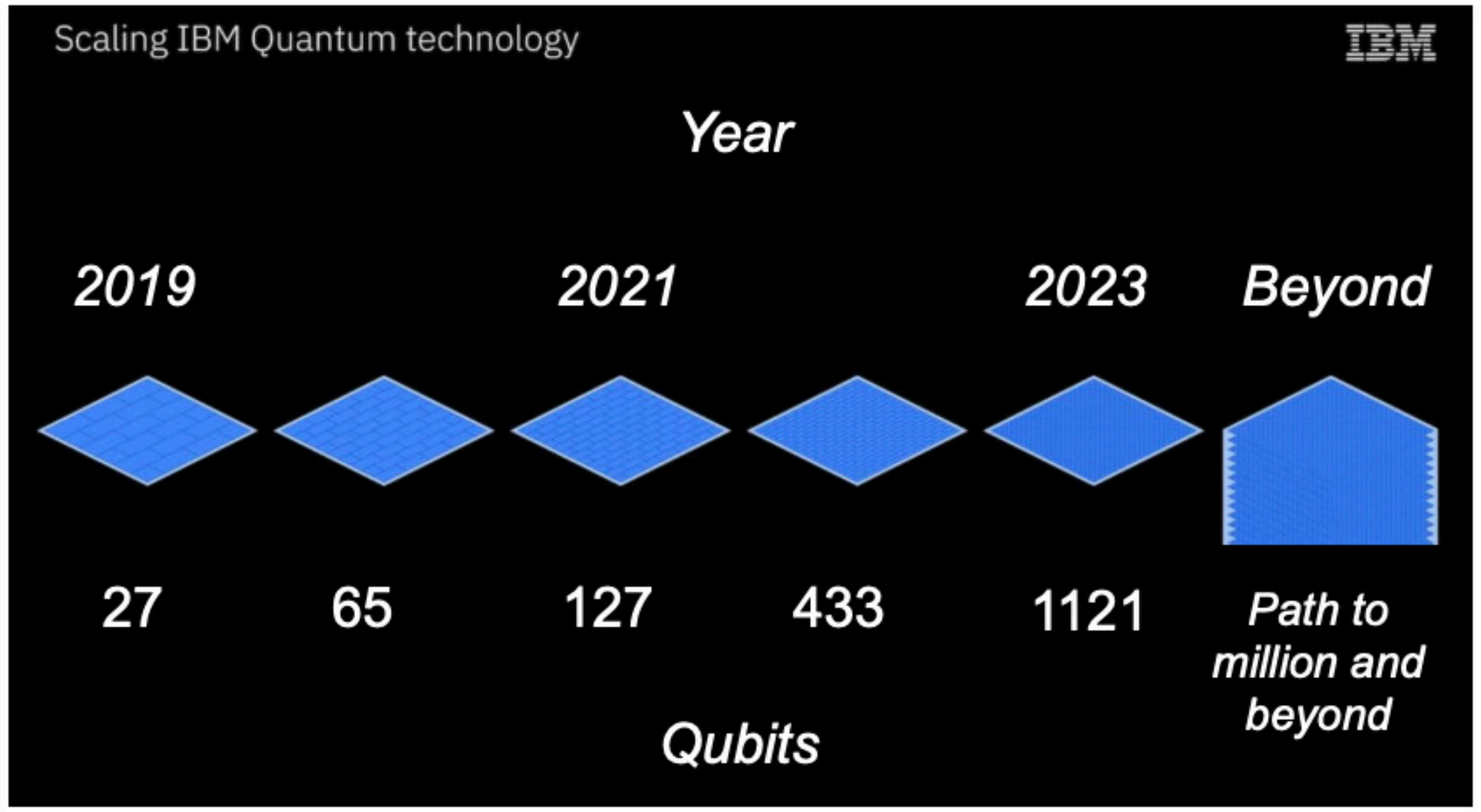
Honeywell D:Wave …



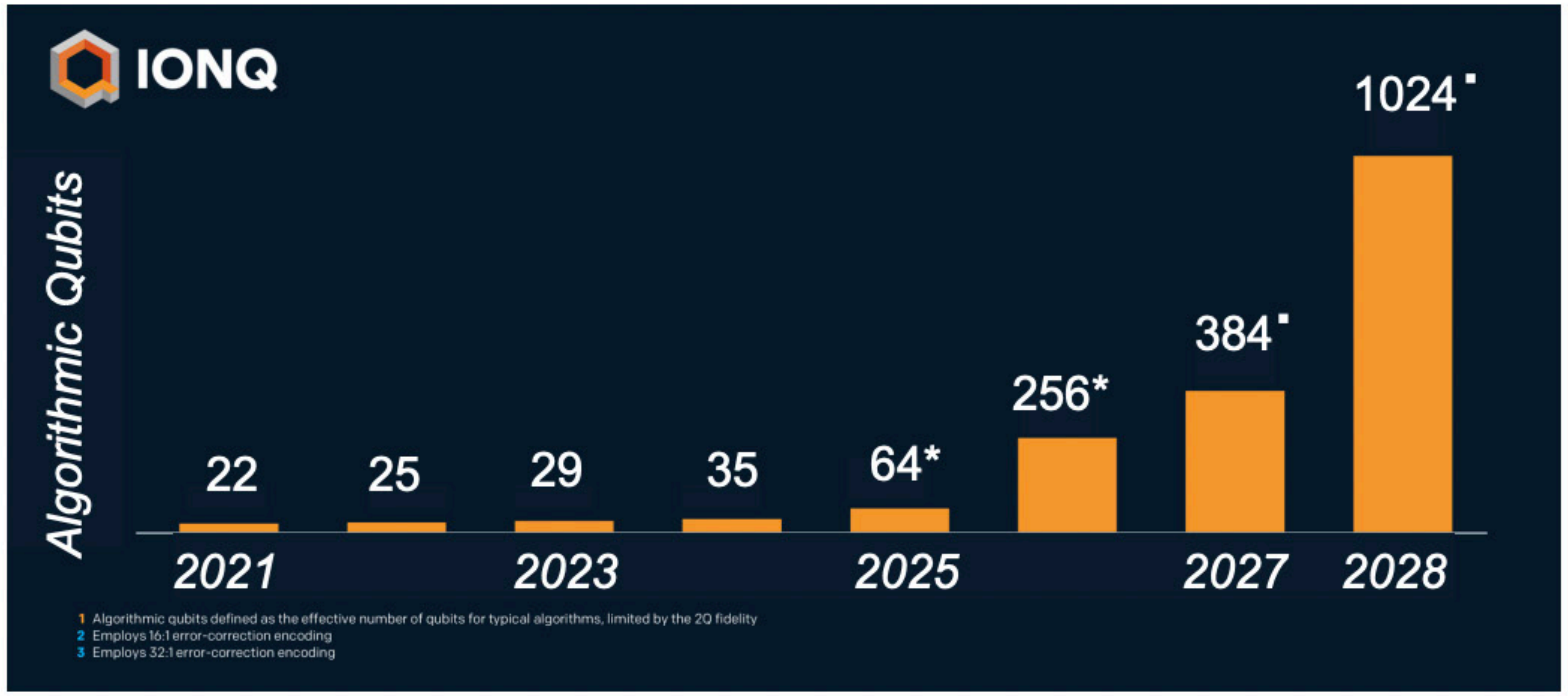
- **We are living in the era of quantum computing revolution**

REAL-WORLD DIGITAL COMPUTING HARDWARE

Many "commercial" computers are networking together ever-growing number of qubits



IBM Quantum Roadmap, 2020
Superconducting Qubits



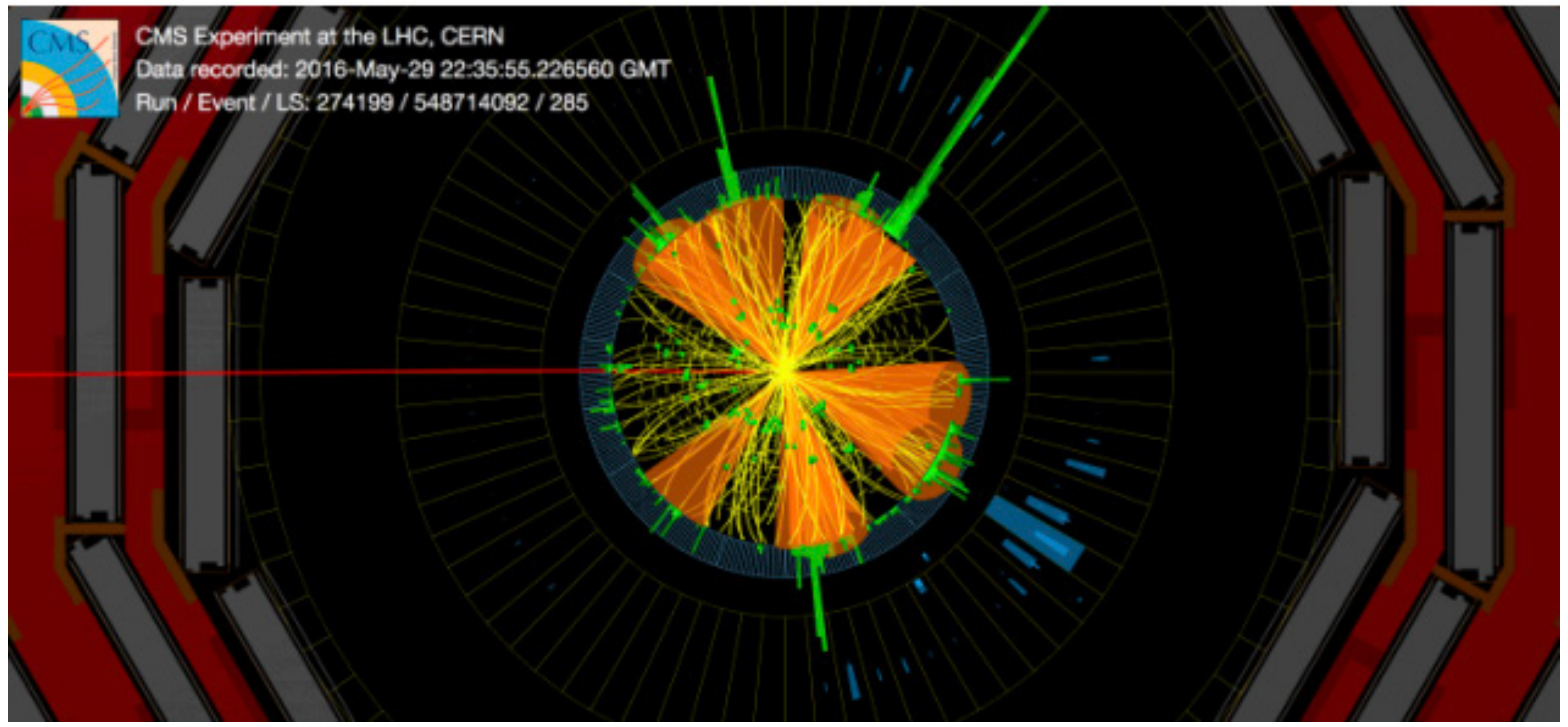
1 Algorithmic qubits defined as the effective number of qubits for typical algorithms, limited by the 2Q fidelity
2 Employs 16:1 error-correction encoding
3 Employs 32:1 error-correction encoding

IonQ Roadmap, 2020
Trapped Ion

- **We are living in the era of quantum computing revolution**
- **Can these devices be utilized to simulate our nature?**

SIMULATING SCATTERING PROCESSES

Jordan, Lee, Preskill `11-`17

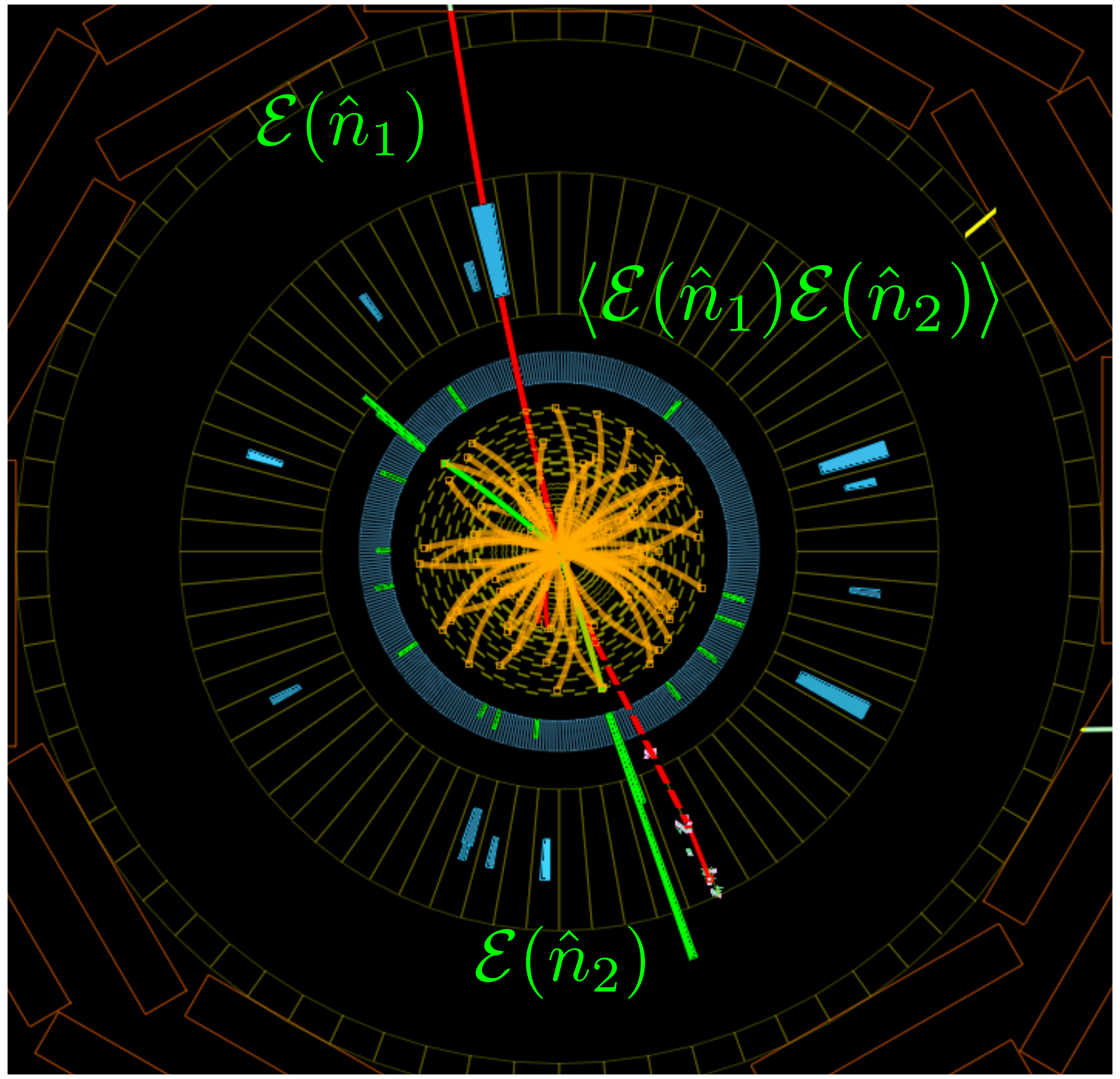


Simulation protocol

1. Digitize the field theory on a spatial lattice
2. Prepare wave packets of the free field theory
3. Turn on interactions adiabatically
4. Unitary time evolution
5. After the scattering turn interactions off adiabatically
6. Perform measurement

- **Shown to be BQP in complexity for Scalar Field Theory, but each step requires significant amount of resources**

SIMULATING ENERGY CORRELATORS



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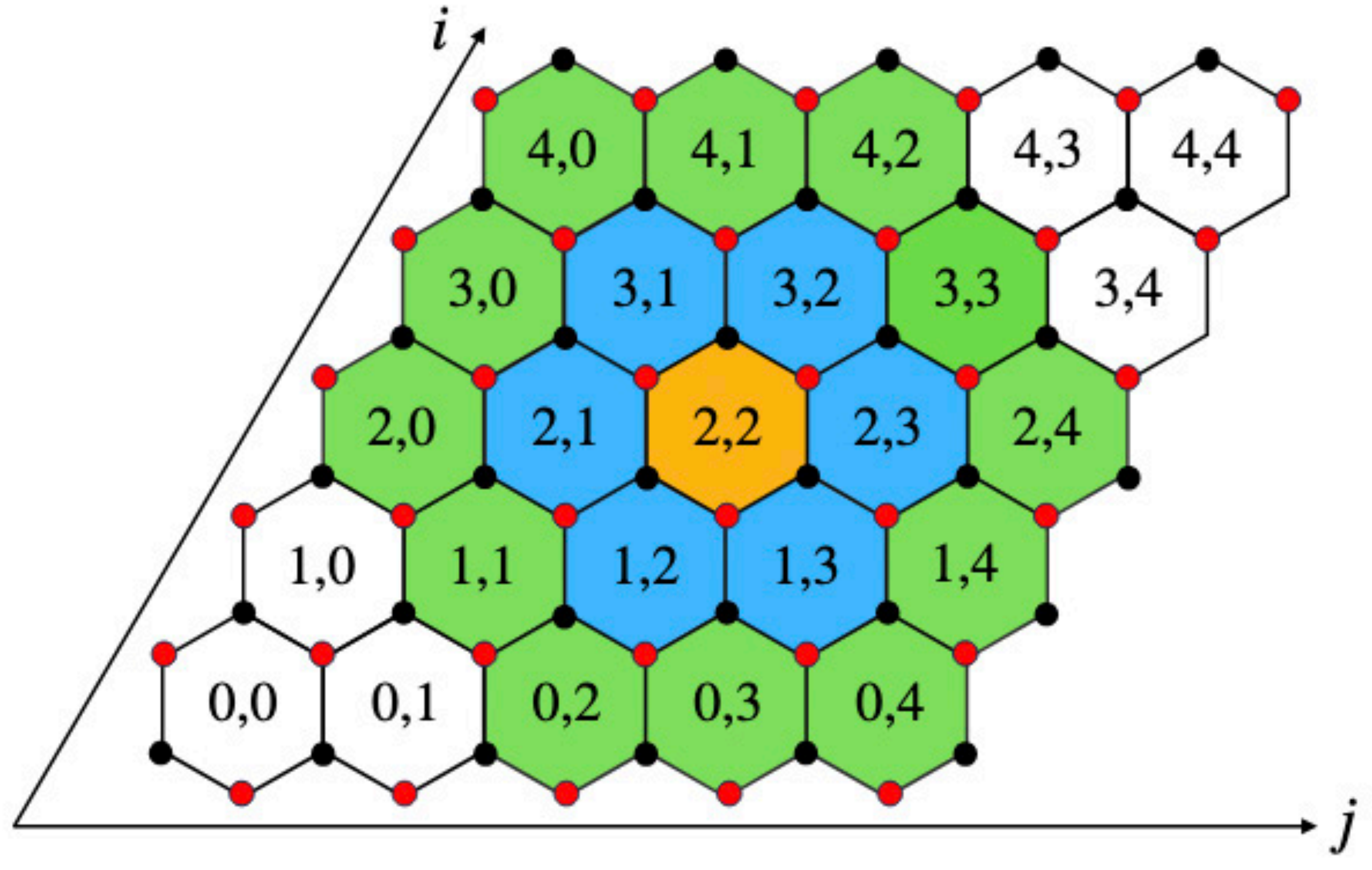
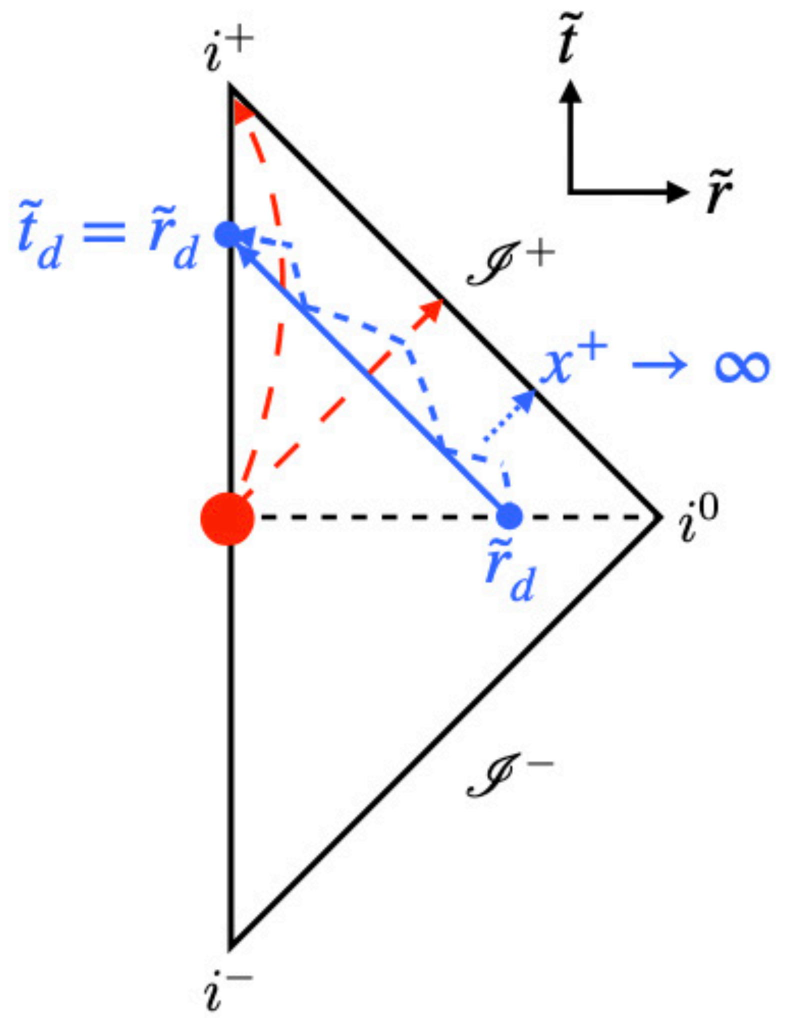
5. After the scattering turn interactions off adiabatically
6. Perform measurement

$$\langle\mathcal{E}(\vec{n}_1)\,\mathcal{E}(\vec{n}_2)\rangle_q \equiv \frac{1}{\sigma_{\text{tot}}}\underbrace{\int \mathrm{d}^4x\, e^{iq\cdot x}\langle 0|J^\dagger_\mu(x)}\underbrace{\mathcal{E}(\vec{n}_1)\,\mathcal{E}(\vec{n}_2)}\underbrace{J^\mu(0)|0\rangle}$$

- **Everything can be formulated at the operator level, which one can construct in the Hamiltonian formulation**

SIMULATING ENERGY CORRELATORS



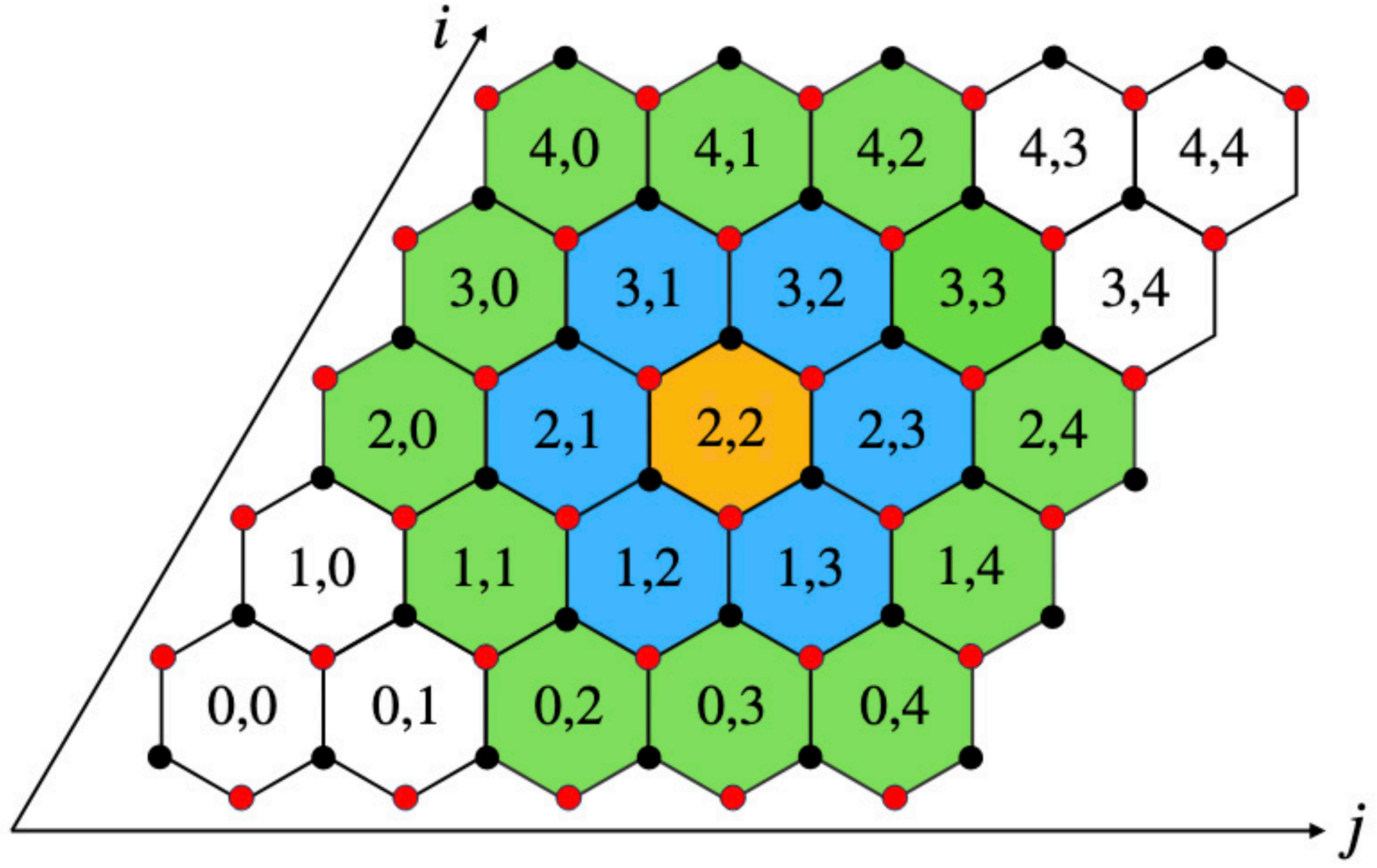


- **Key tasks**

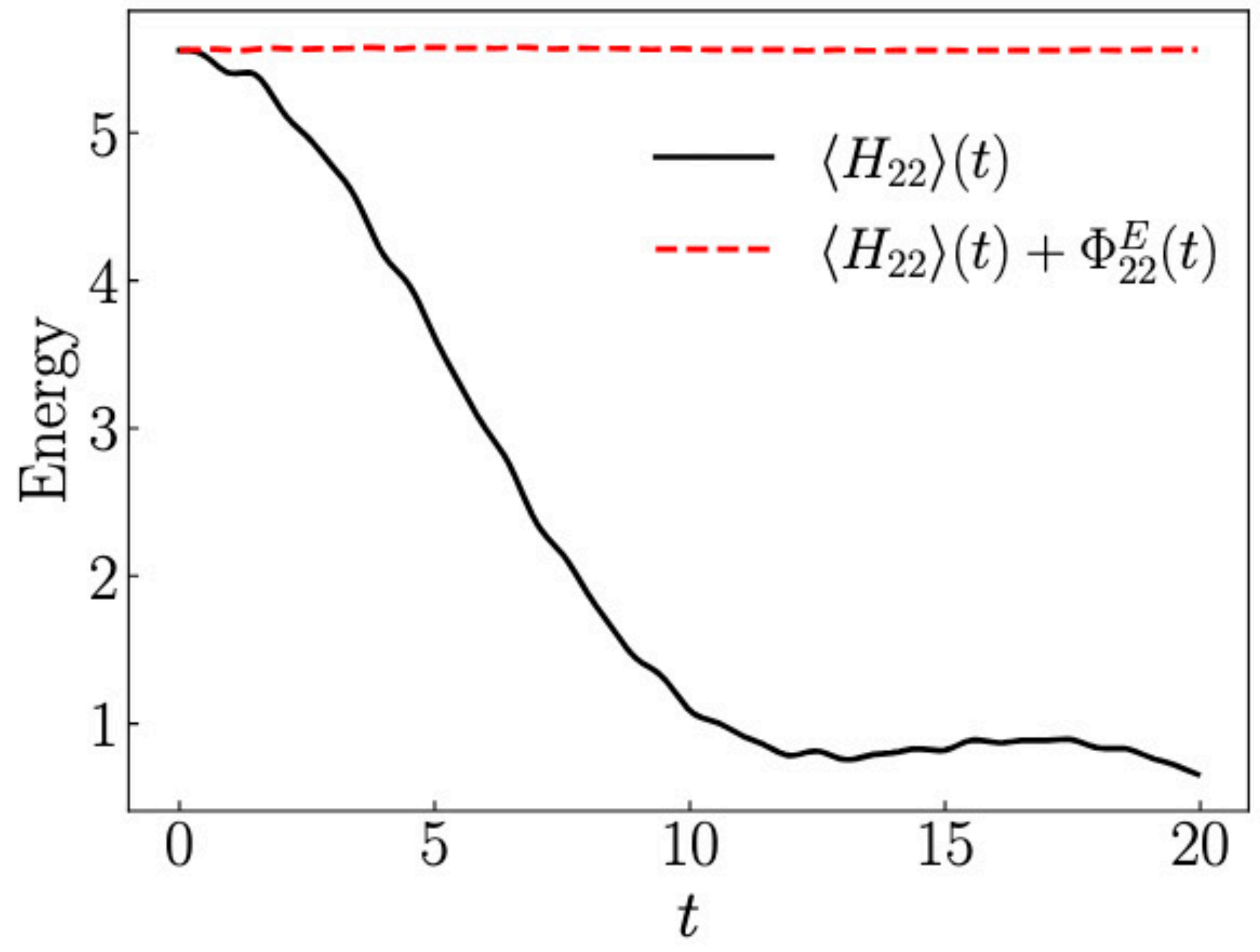
1. Develop the Hamiltonian formulation of field theory of interest on lattice
2. Write down the appropriate operators in the Hamiltonian formulation
3. Compute time evolution and correlations

$$\mathcal{E}(\vec{n}) = \lim_{r\to\infty}\int_0^\infty \mathrm{d}t\, r^{d-1} n^i T_{0i}(t, r\vec{n})$$

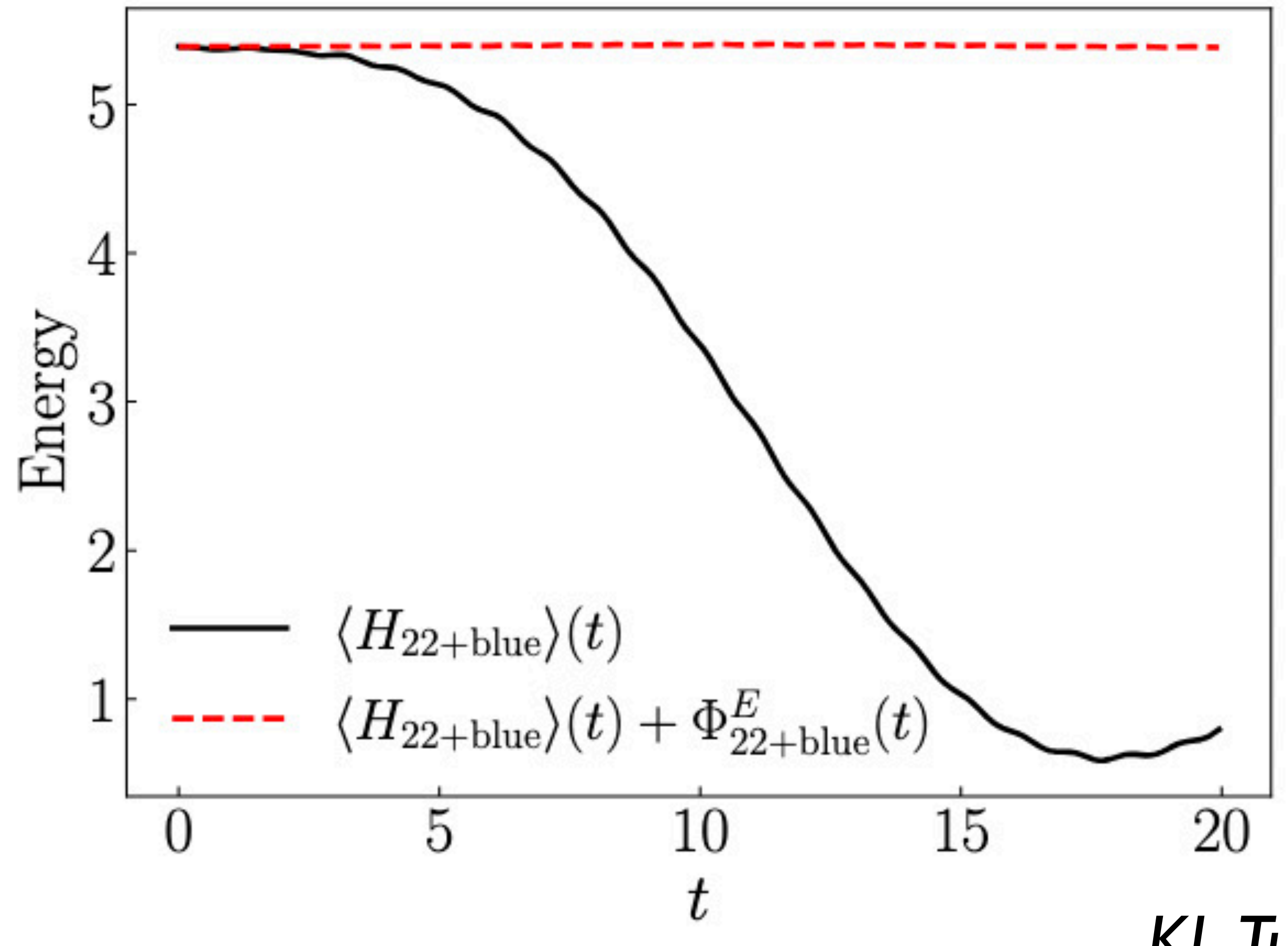
SIMULATING ENERGY CORRELATORS



- **Energy flow being captured in real time on lattice**



(a) Orange region.



(b) Orange and blue regions.

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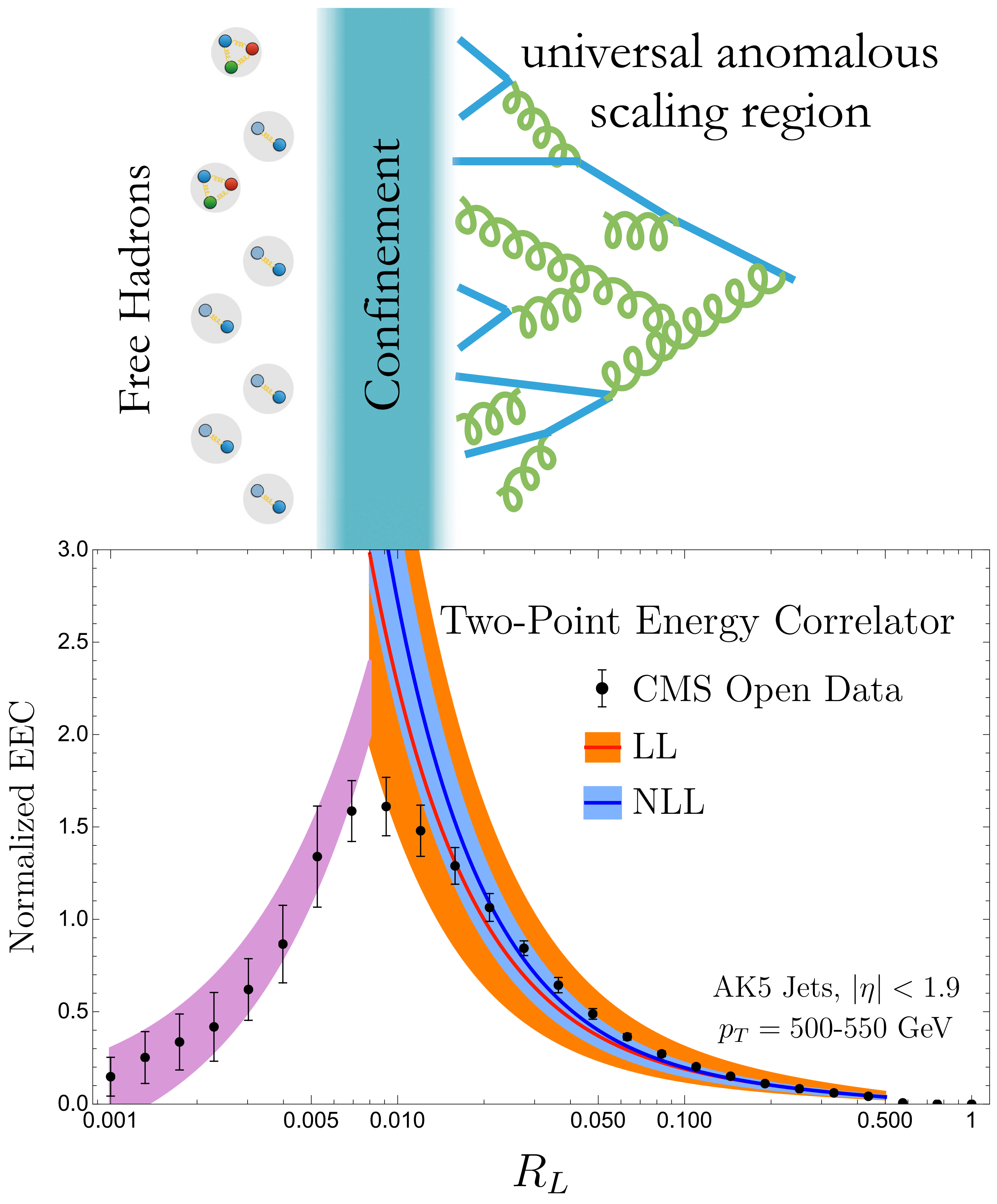
NONPERTURBATIVE TRANSITION

Free hadrons

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

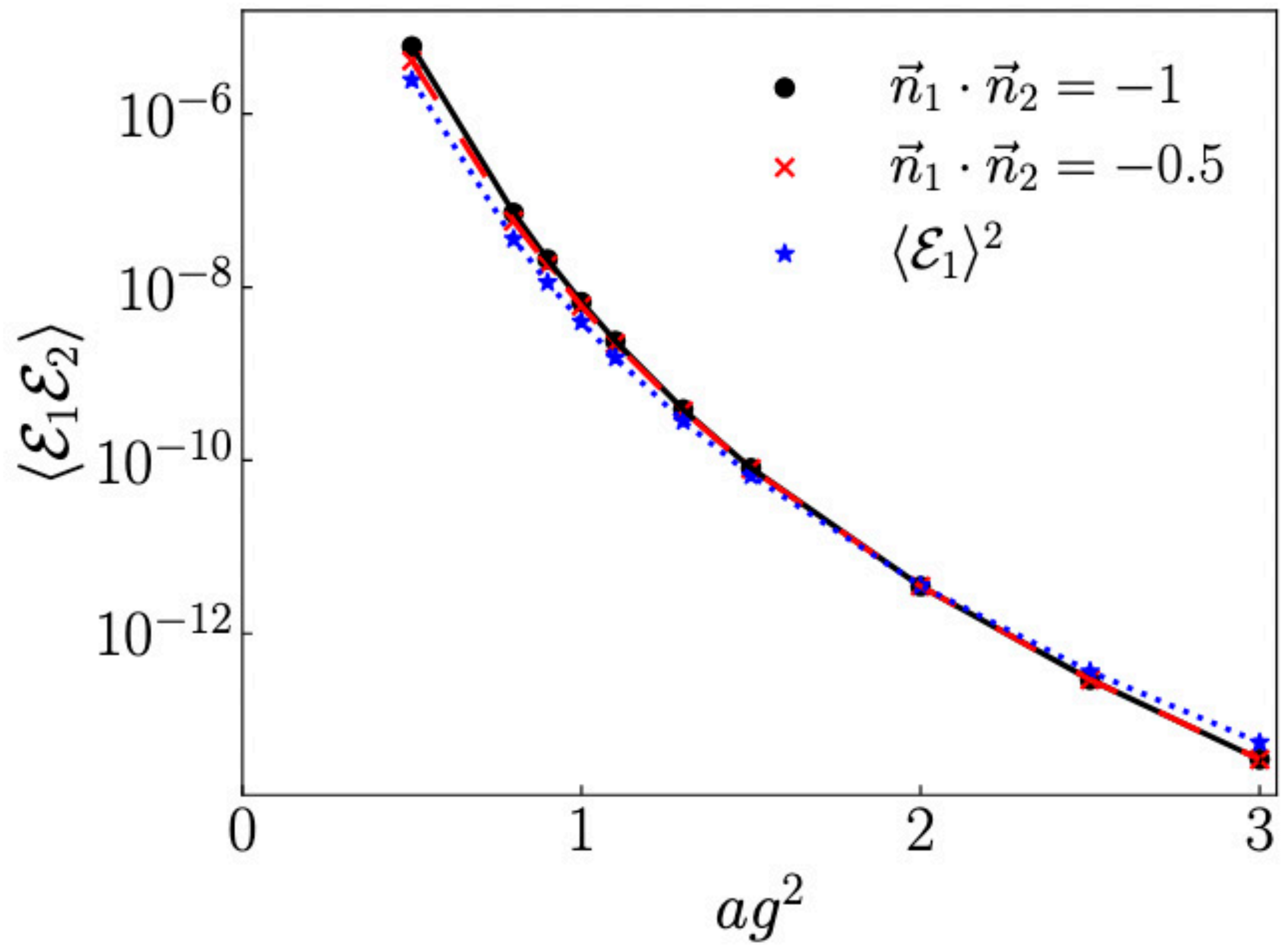


Interacting quarks and gluons

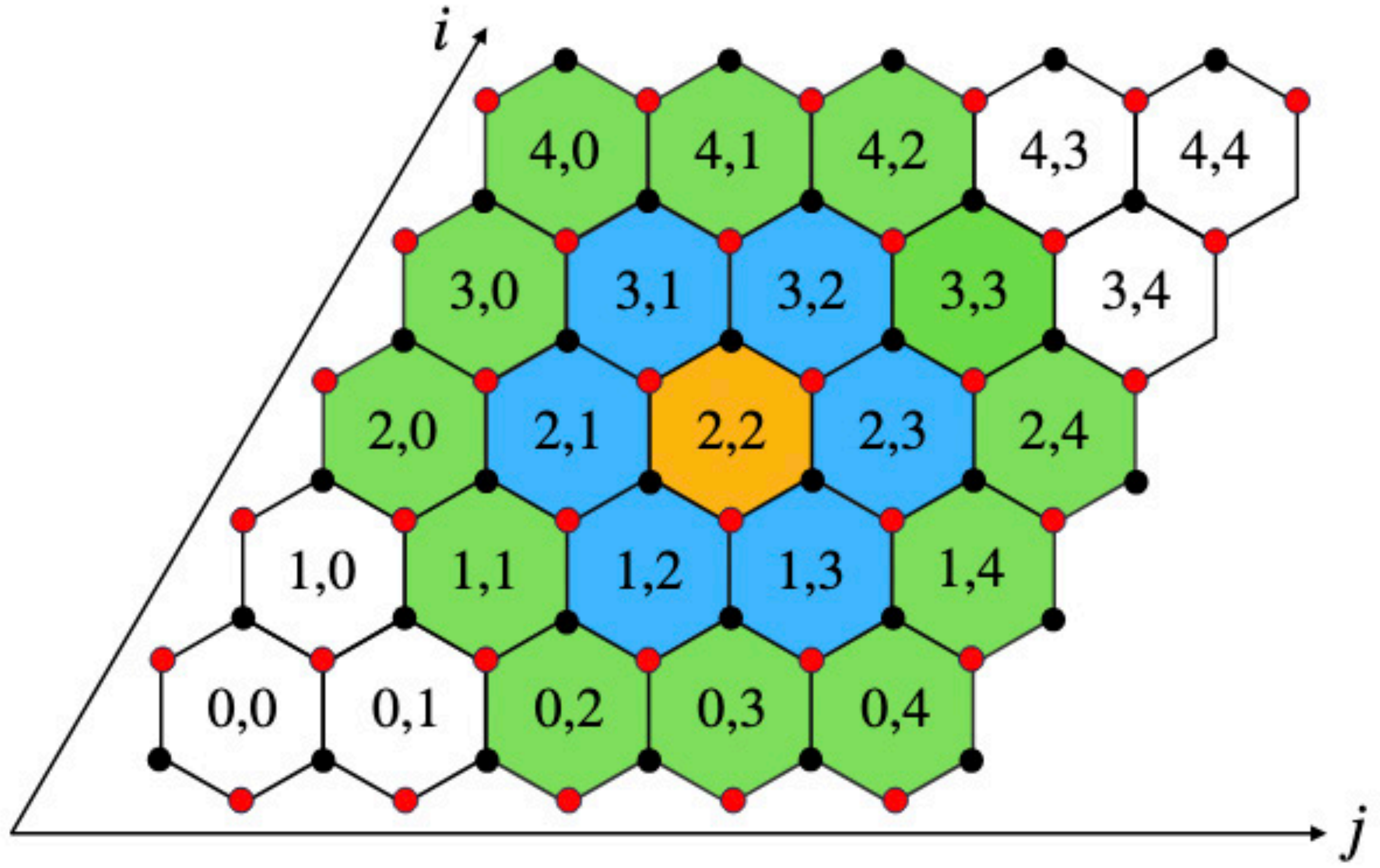
$$\mathcal{E}(\hat{n}_1)\,\mathcal{E}(\hat{n}_2) \sim \sum \theta^{\gamma(3)-2}\mathbb{O}_i(\hat{n}_1)$$

- **Can we see observe nontrivial confinement transition between the two regions?**

NONPERTURBATIVE TRANSITION



KL, Turro, Yao `24

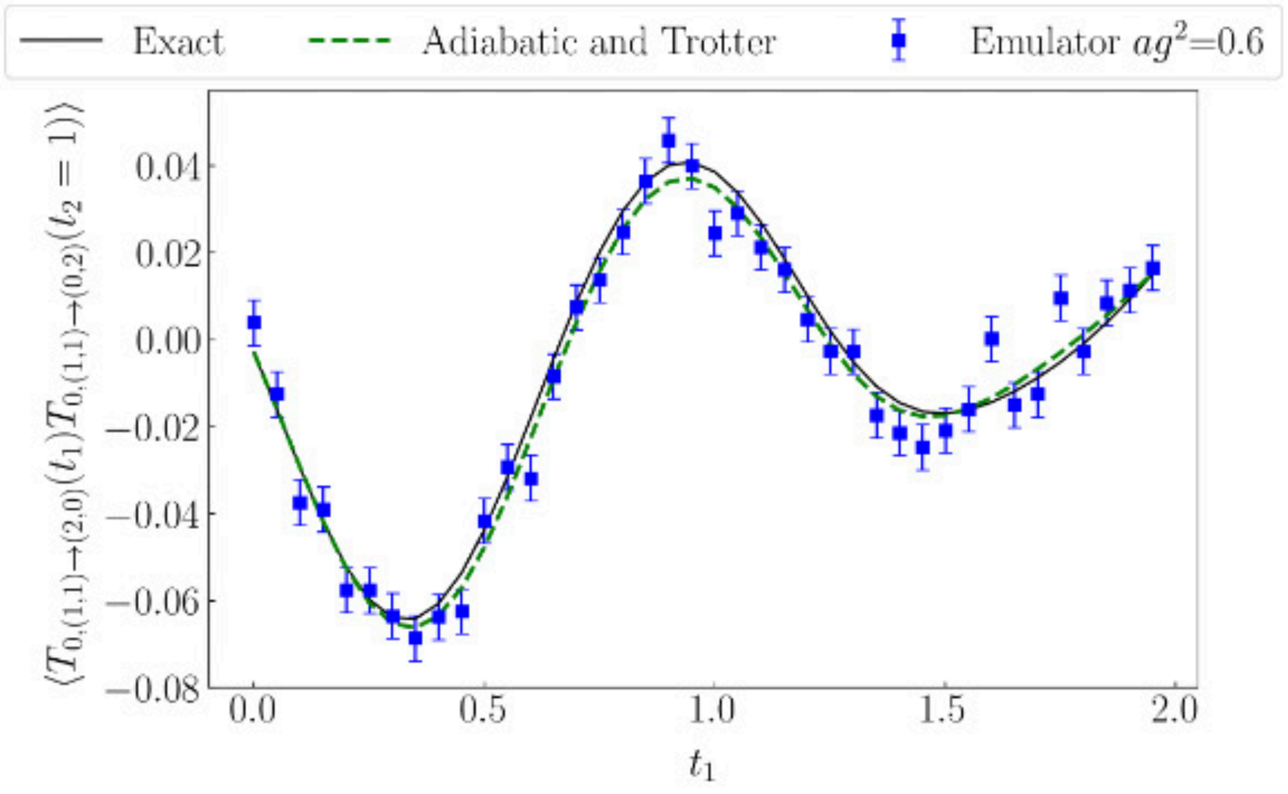


Free hadrons

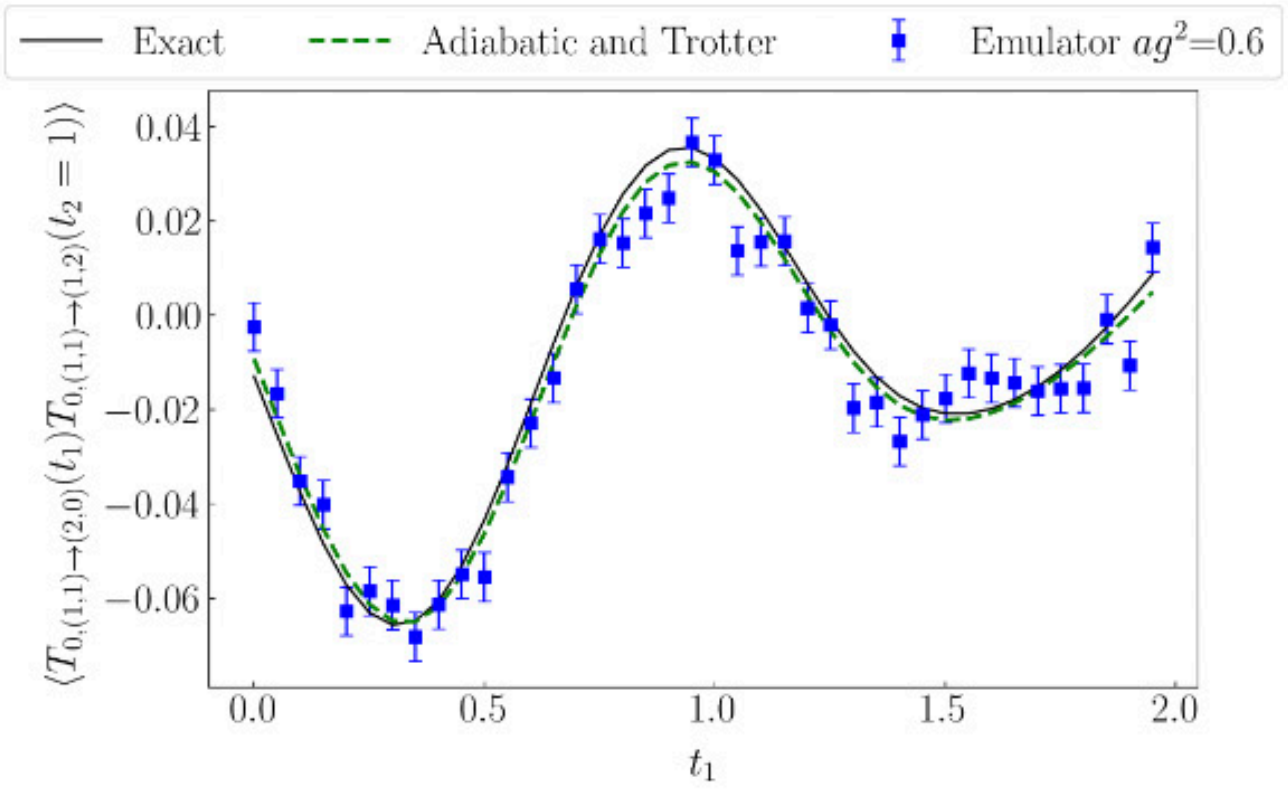
$$\langle \mathcal{E}(\vec{n}_1)\, \mathcal{E}(\vec{n}_2) \cdots \mathcal{E}(\vec{n}_N) \rangle \approx \langle \mathcal{E} \rangle^N = \left(\frac{Q}{\Omega_d} \right)^N$$

- **Consistent with the free hadron region!**

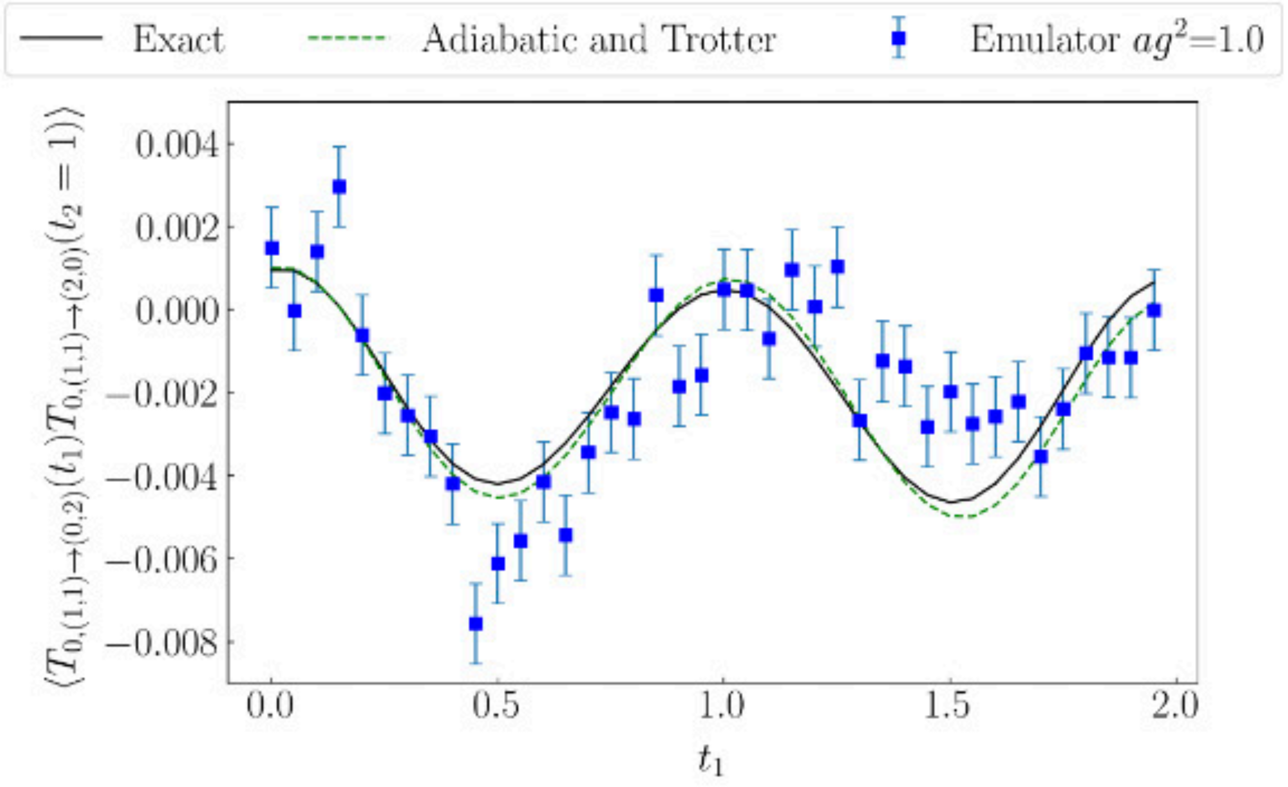
QUANTUM SIMULATIONS



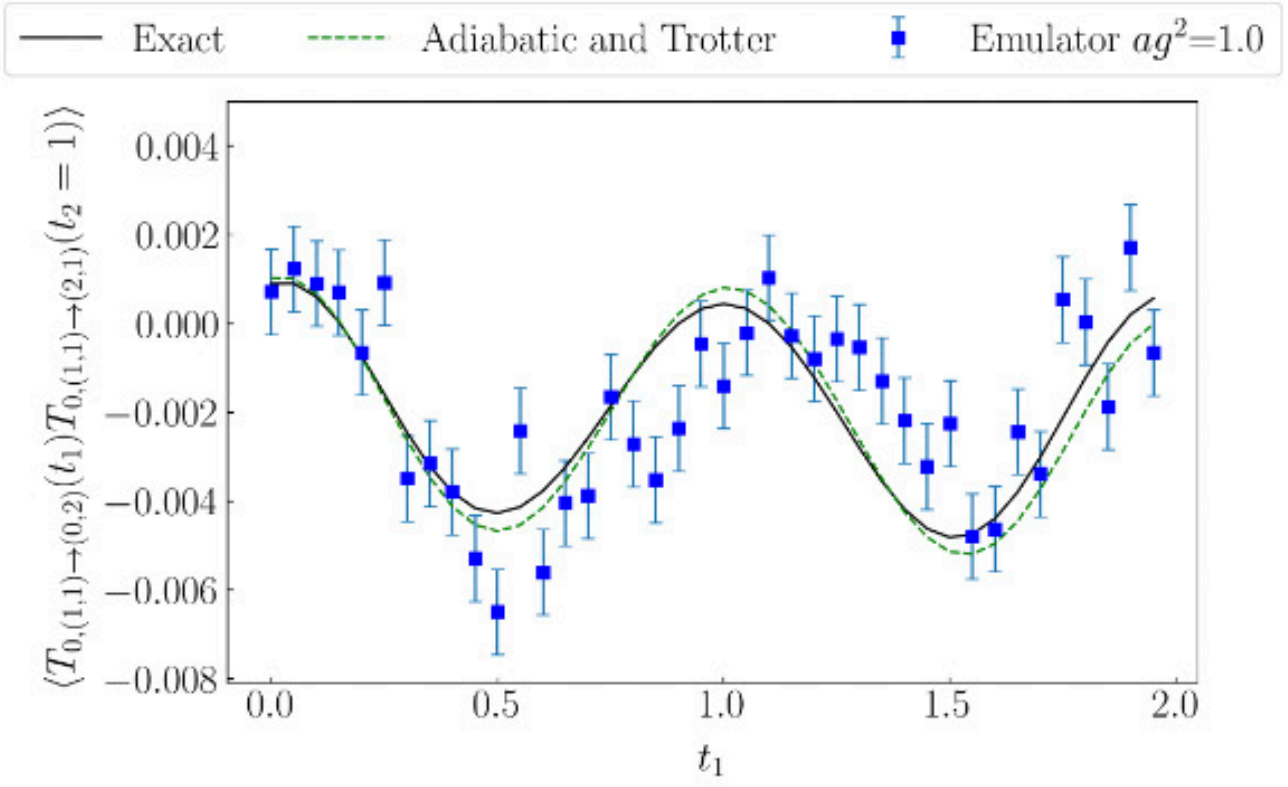
(a) Results for $ag^2 = 0.6$ with the two detectors at $(2, 0)$ and $(0, 2)$.



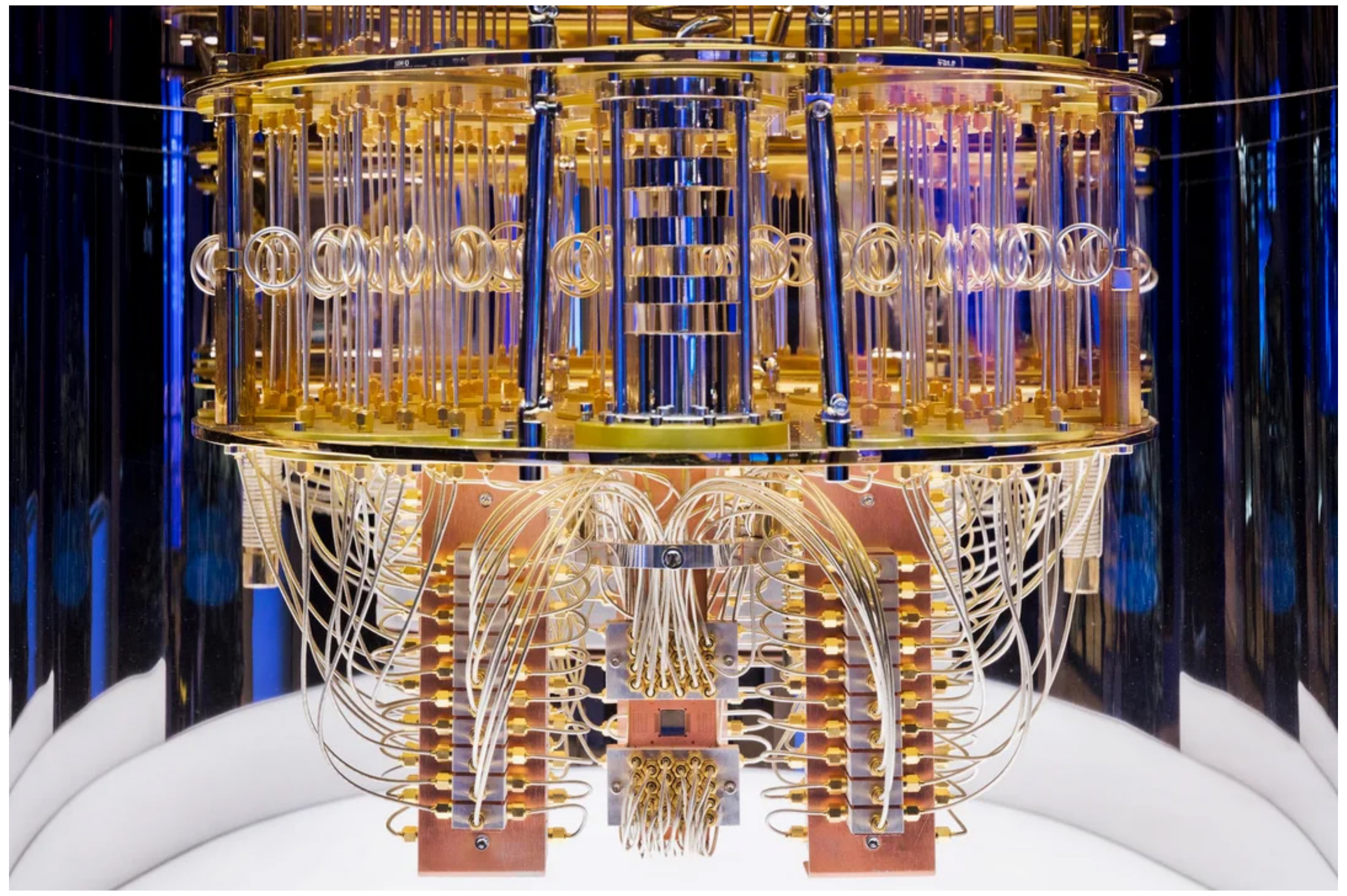
(b) Results for $ag^2 = 0.6$ with the two detectors at $(2, 0)$ and $(1, 2)$.



(c) Results for $ag^2 = 1$ with the two detectors at $(0, 2)$ and $(2, 0)$.

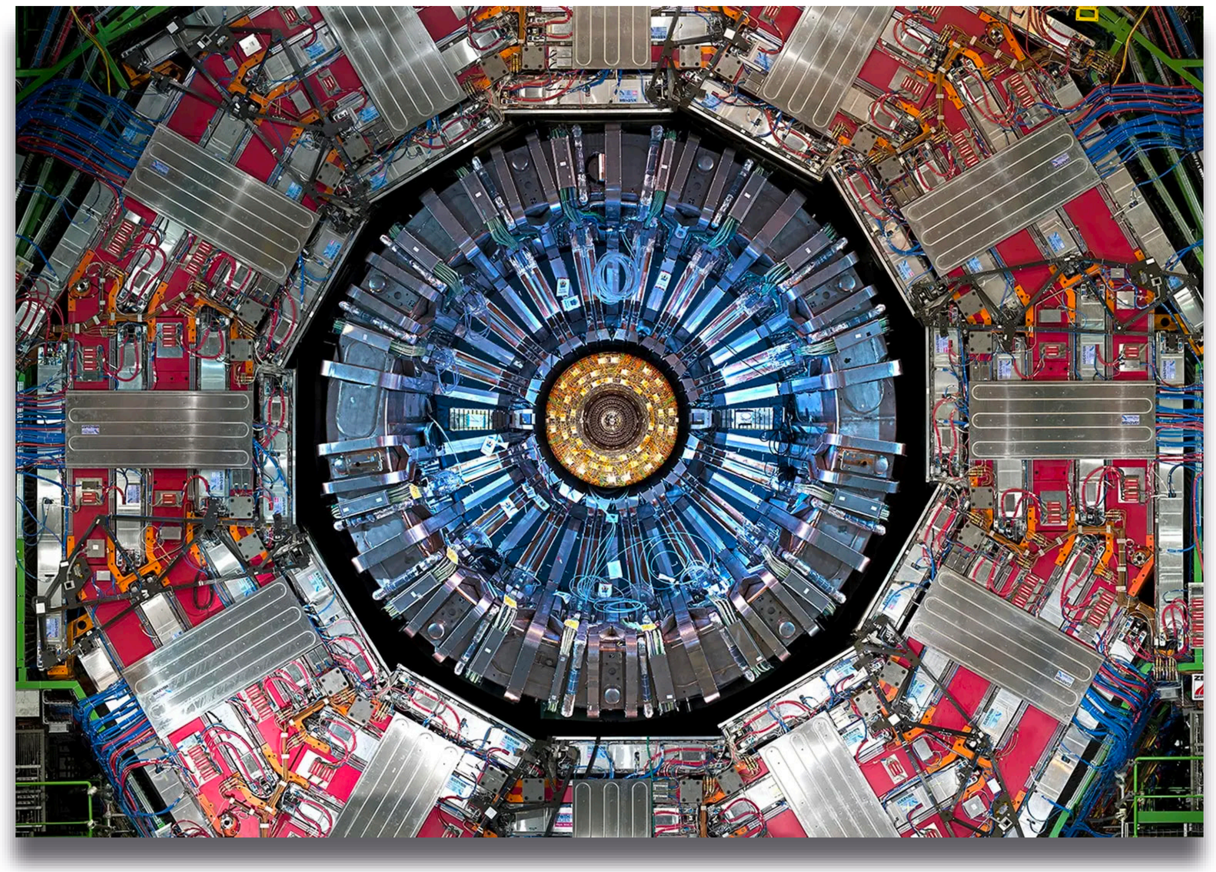


(d) Results for $ag^2 = 1$ with the two detectors at $(0, 2)$ and $(2, 1)$.

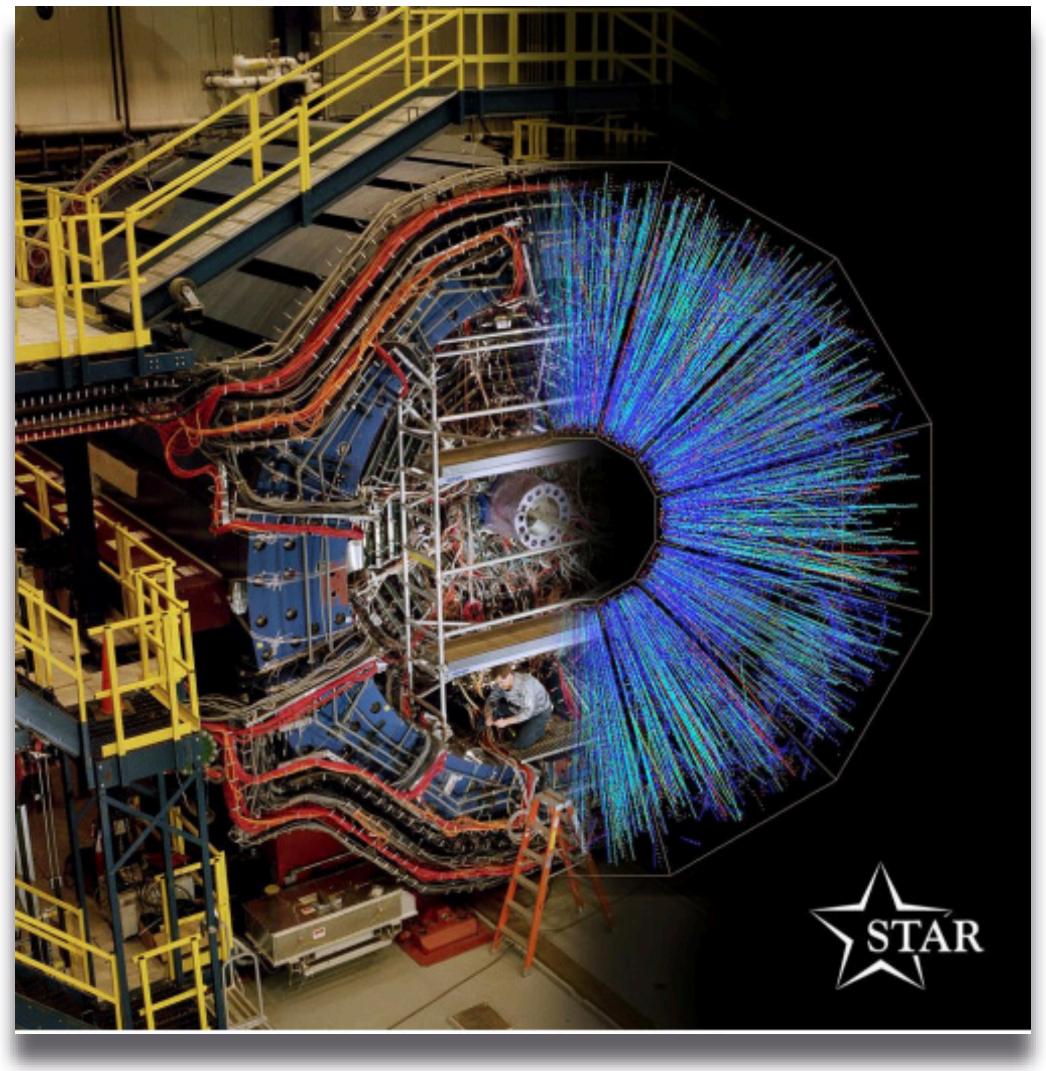


- **Quantum devices can simulate energy correlators!**

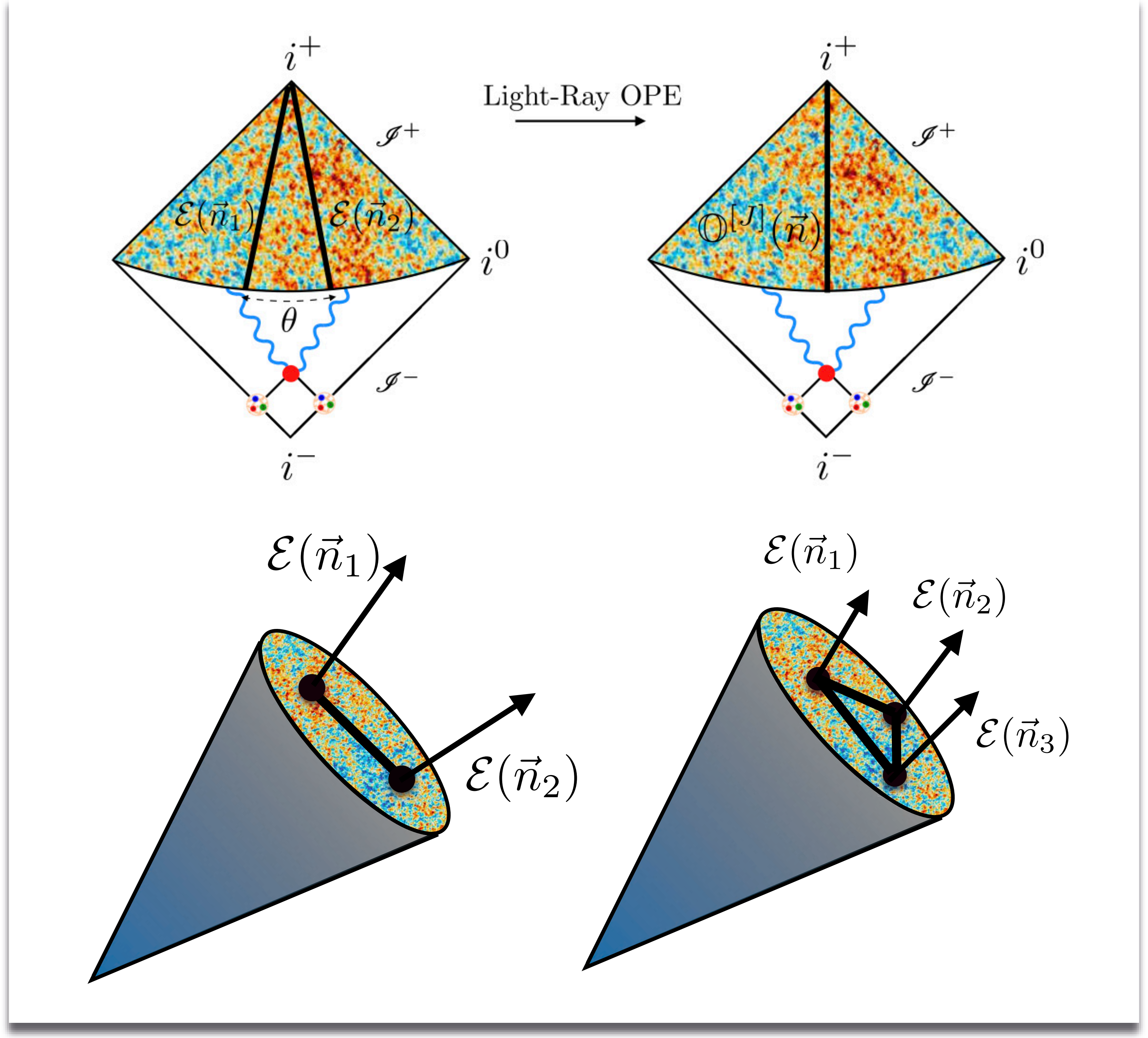
Conformal Colliders meet Jets in Particle Colliders!



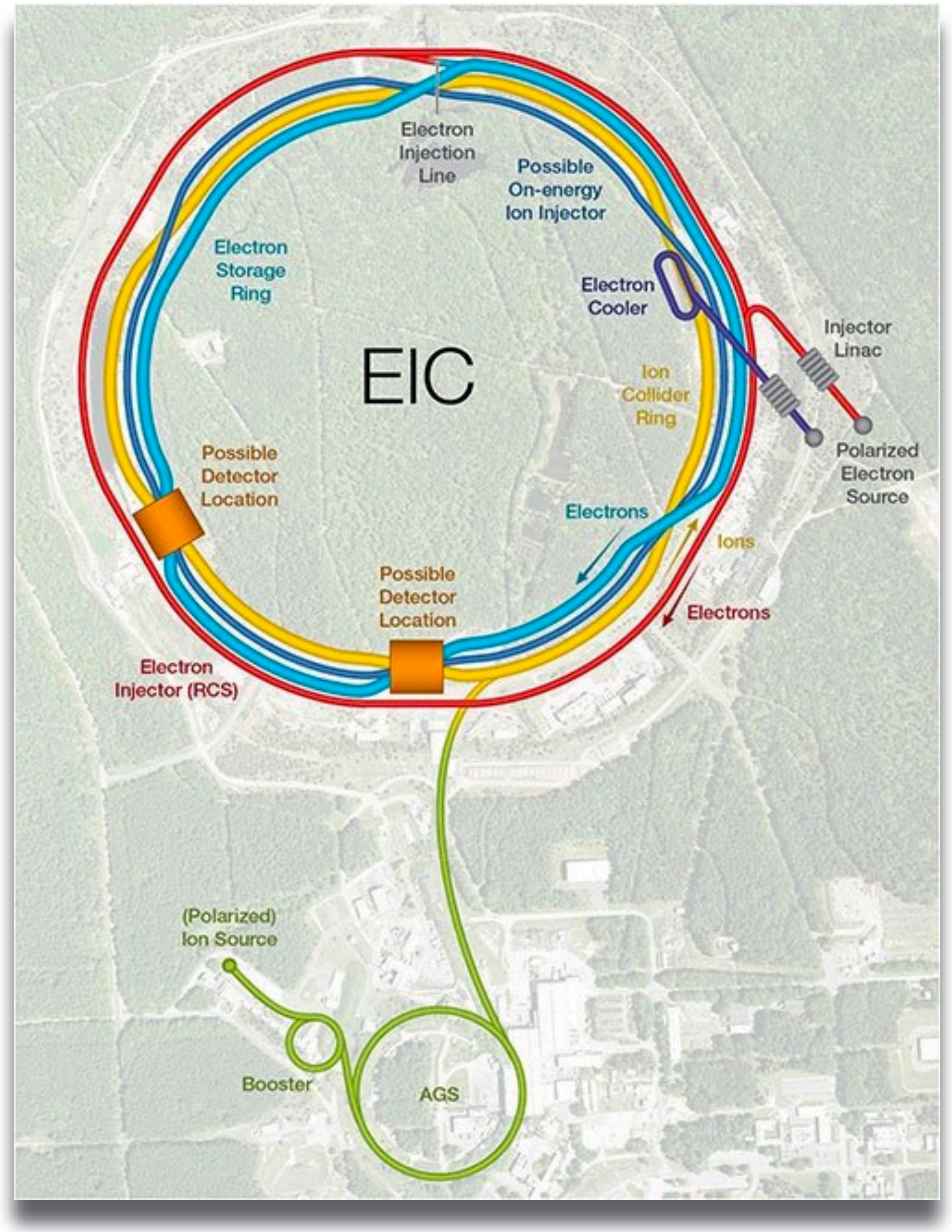
LHC



RHIC



Jets provide sharp link between underlying field theory and real world!



EIC