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

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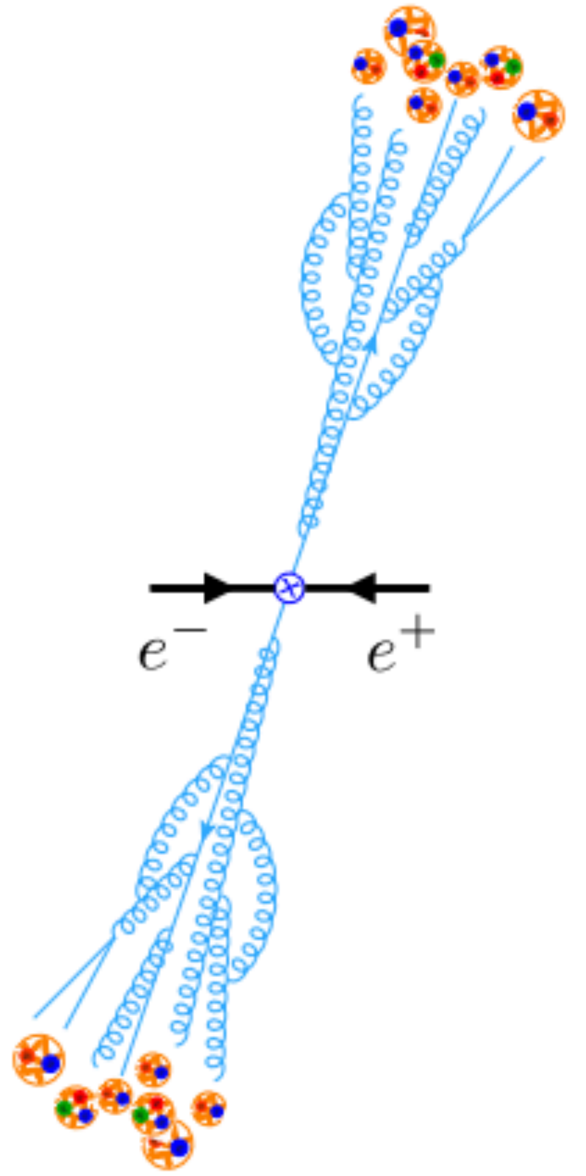
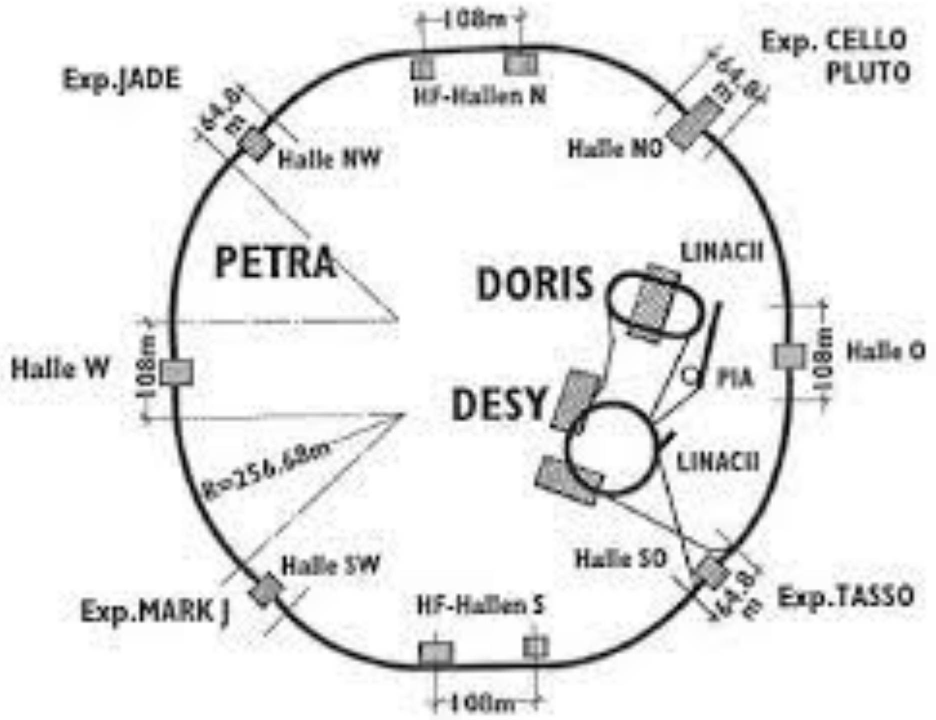
CTP, MIT

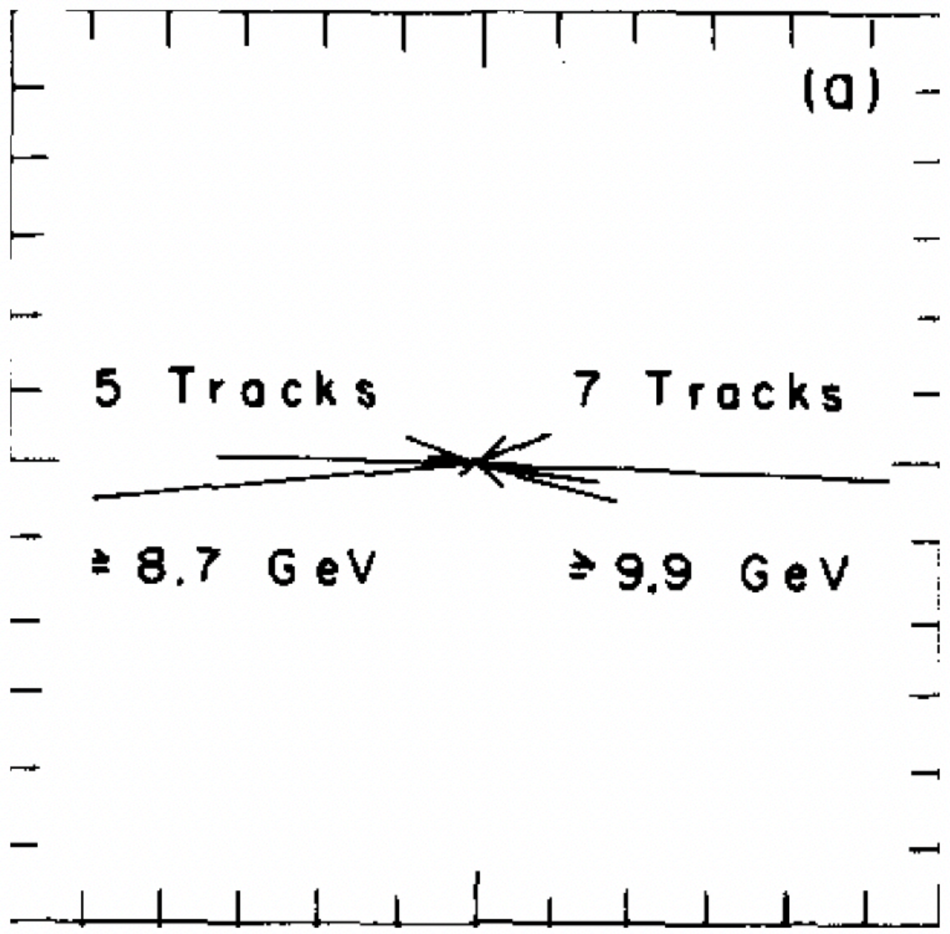
EICUG/ePIC meeting
July 2024

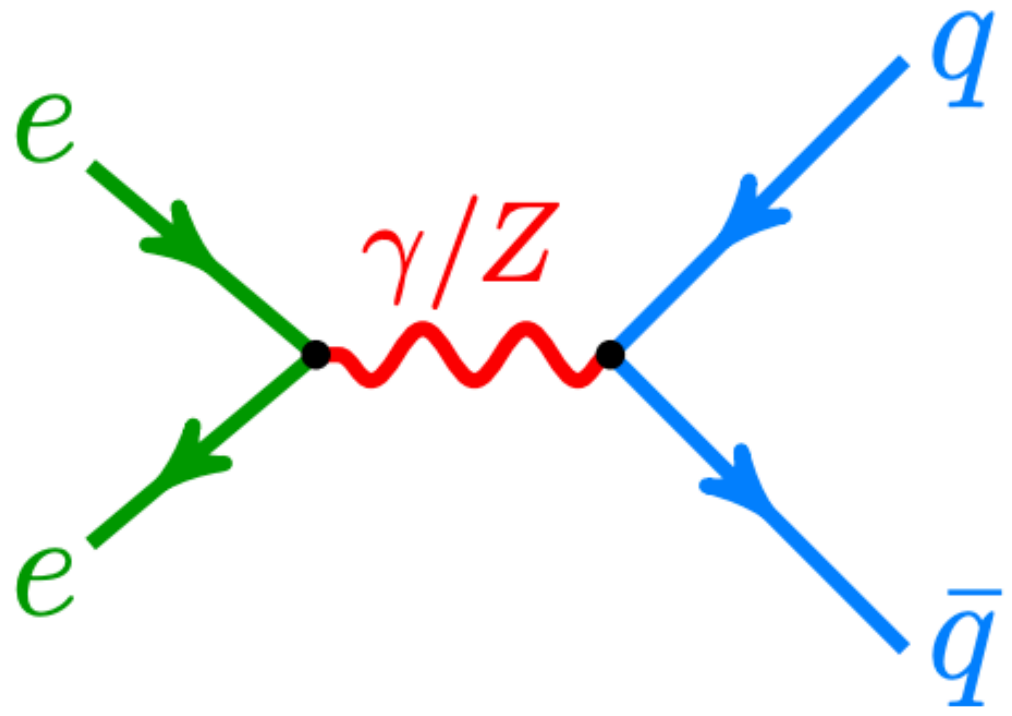
THE DAWN OF QCD: FROM PARTONS TO JETS



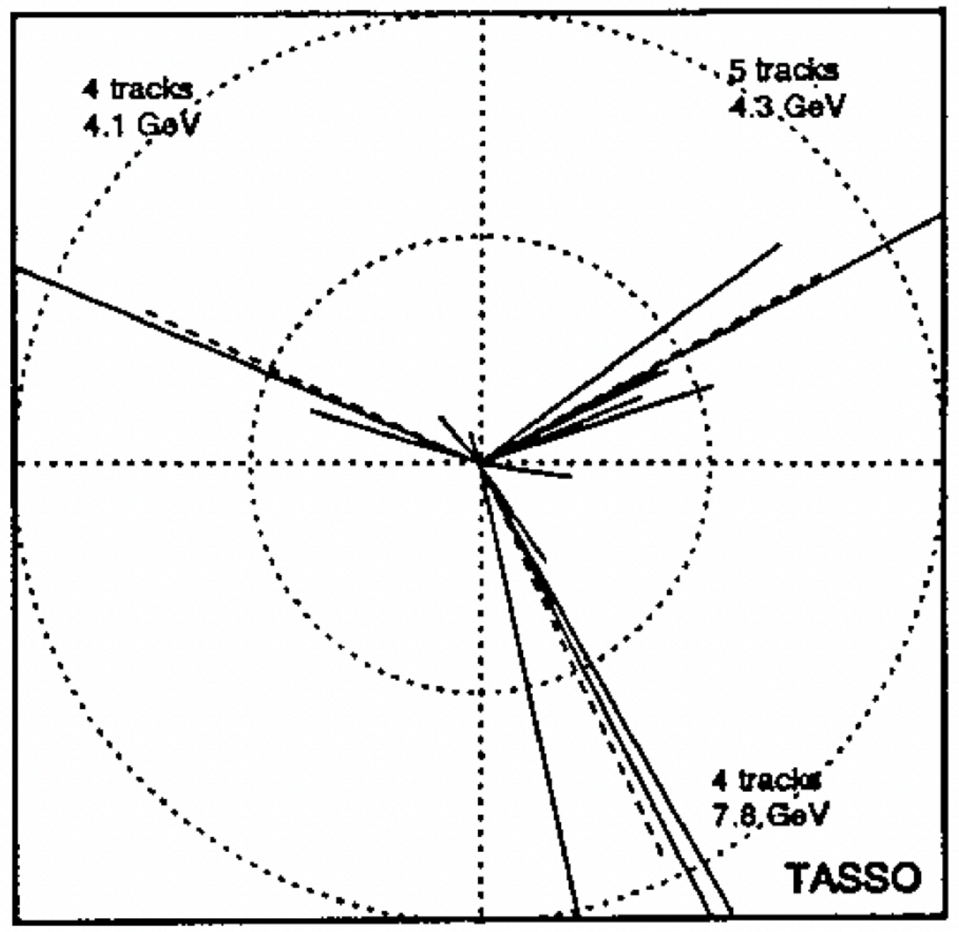


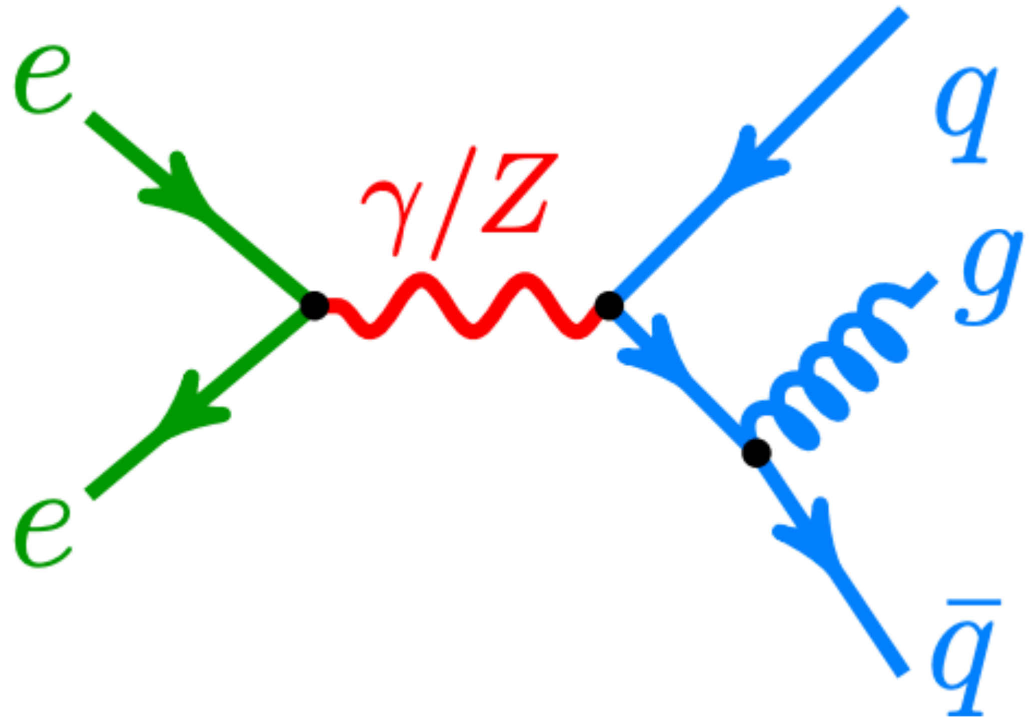
2-jet event



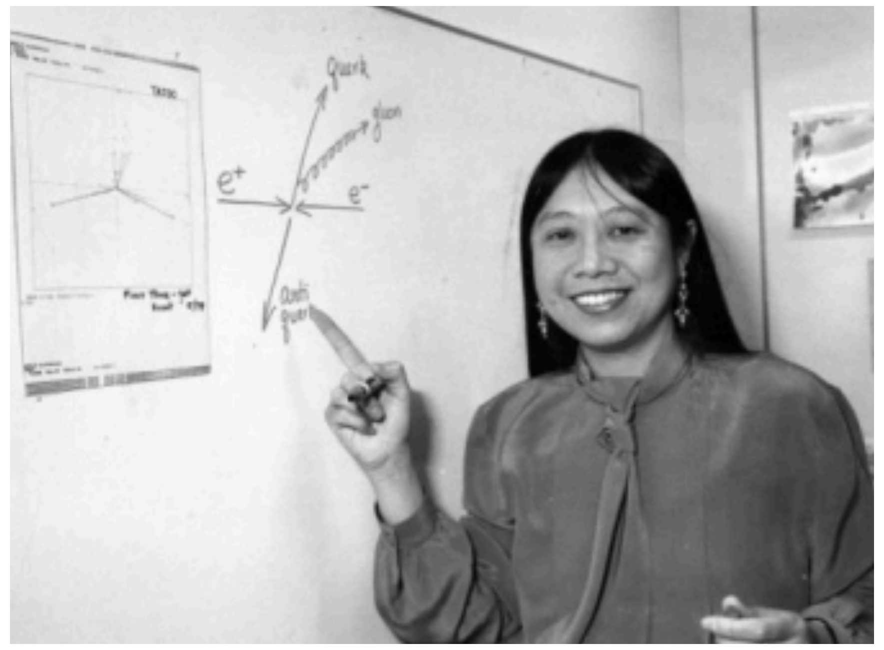


3-jet event





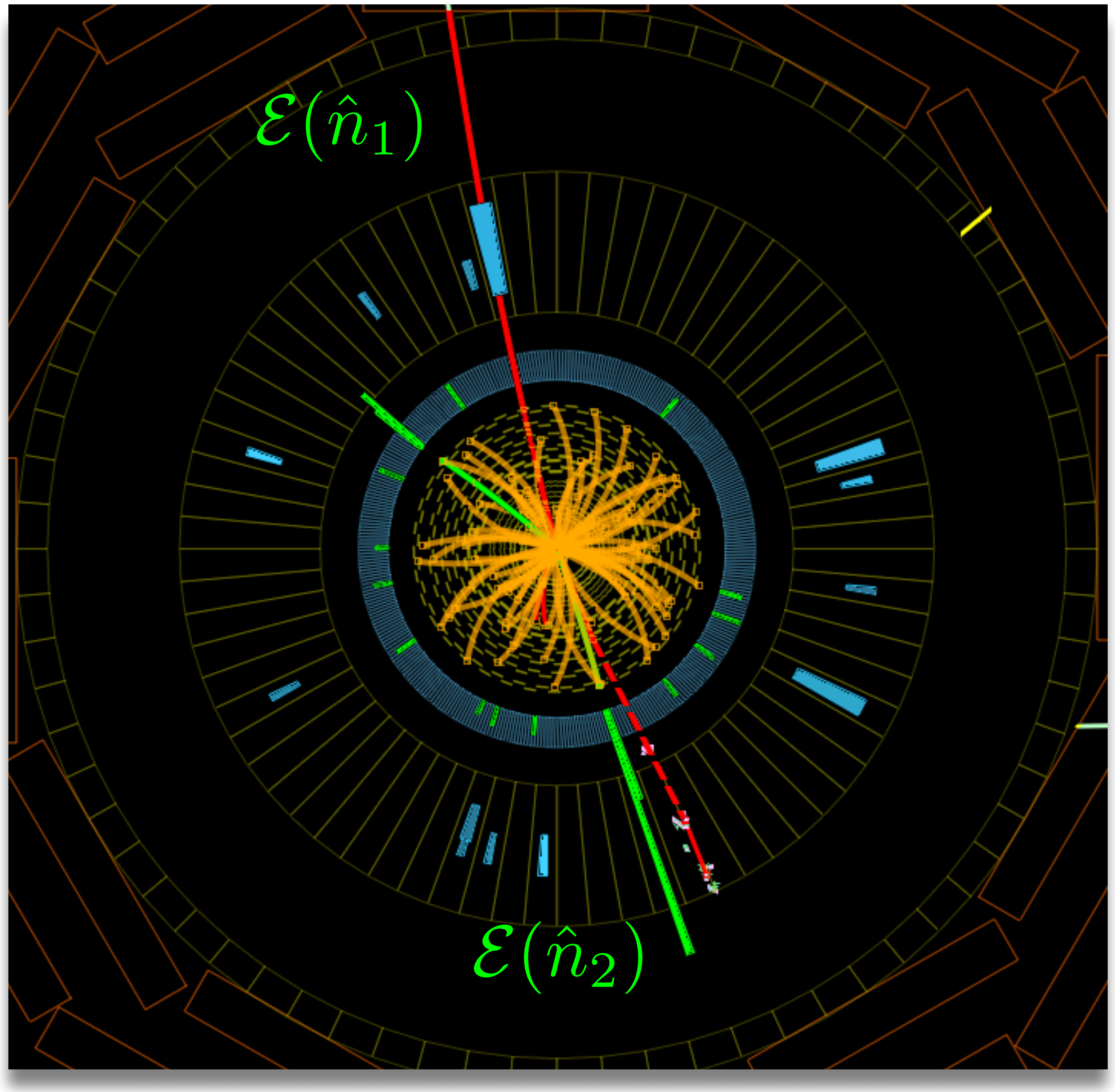
	$\sum_i \lvert P_i \rvert_{CHARGE}$	TOTAL ENERGY
JET 1	4.3 GEV	7.4 GEV
JET 2	7.8	8.9
JET 3	4.1	11.1



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

Sterman `75
Sterman, Weinberg `77

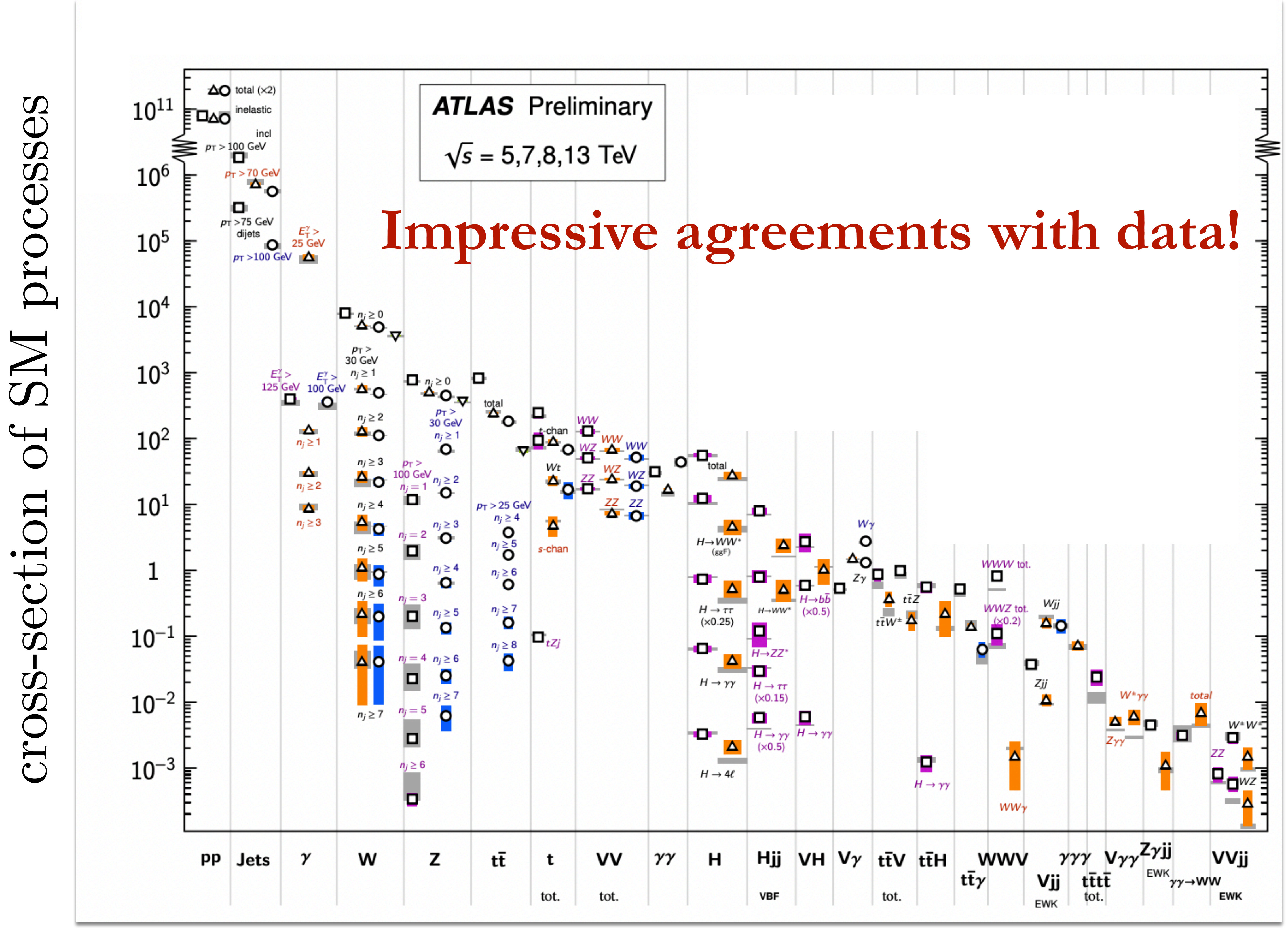
"Energy flow becomes the focus of computability"

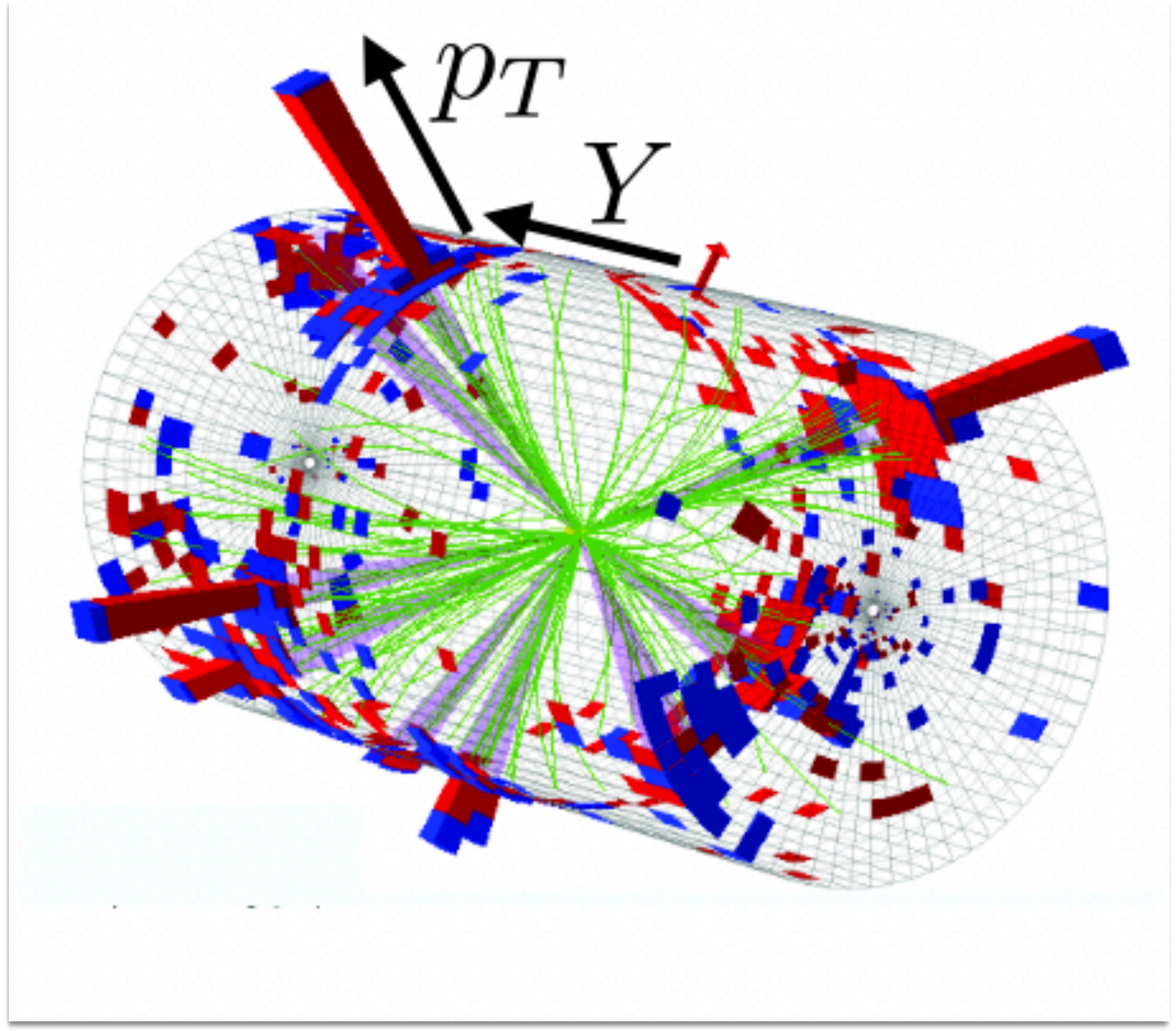
$\Longrightarrow$ **Sterman-Weinberg jets played a crucial role in formulating the first IRC definition to study energy flow, or jets**

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

JETS AT COLLIDERS

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

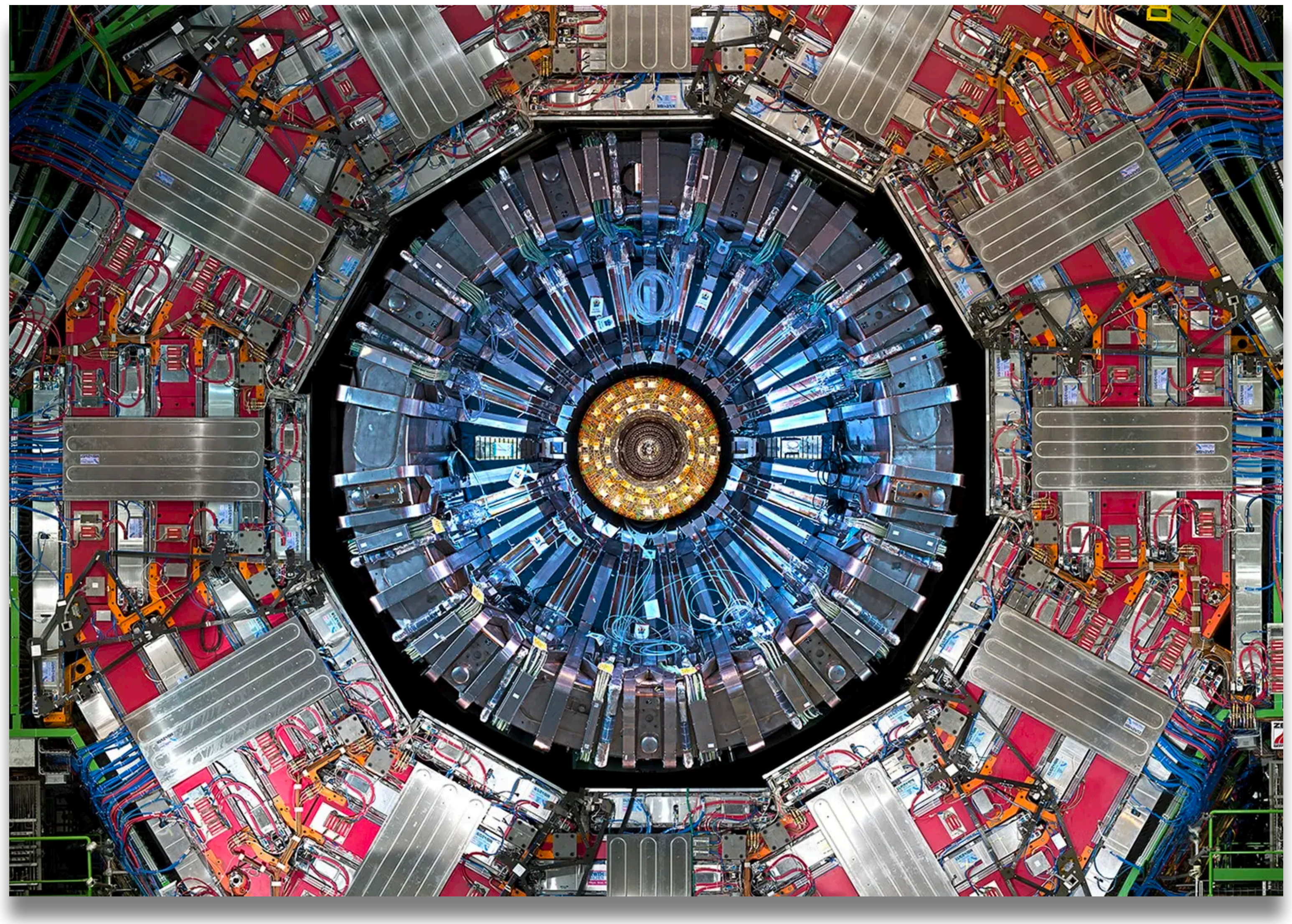




9-jet at the LHC

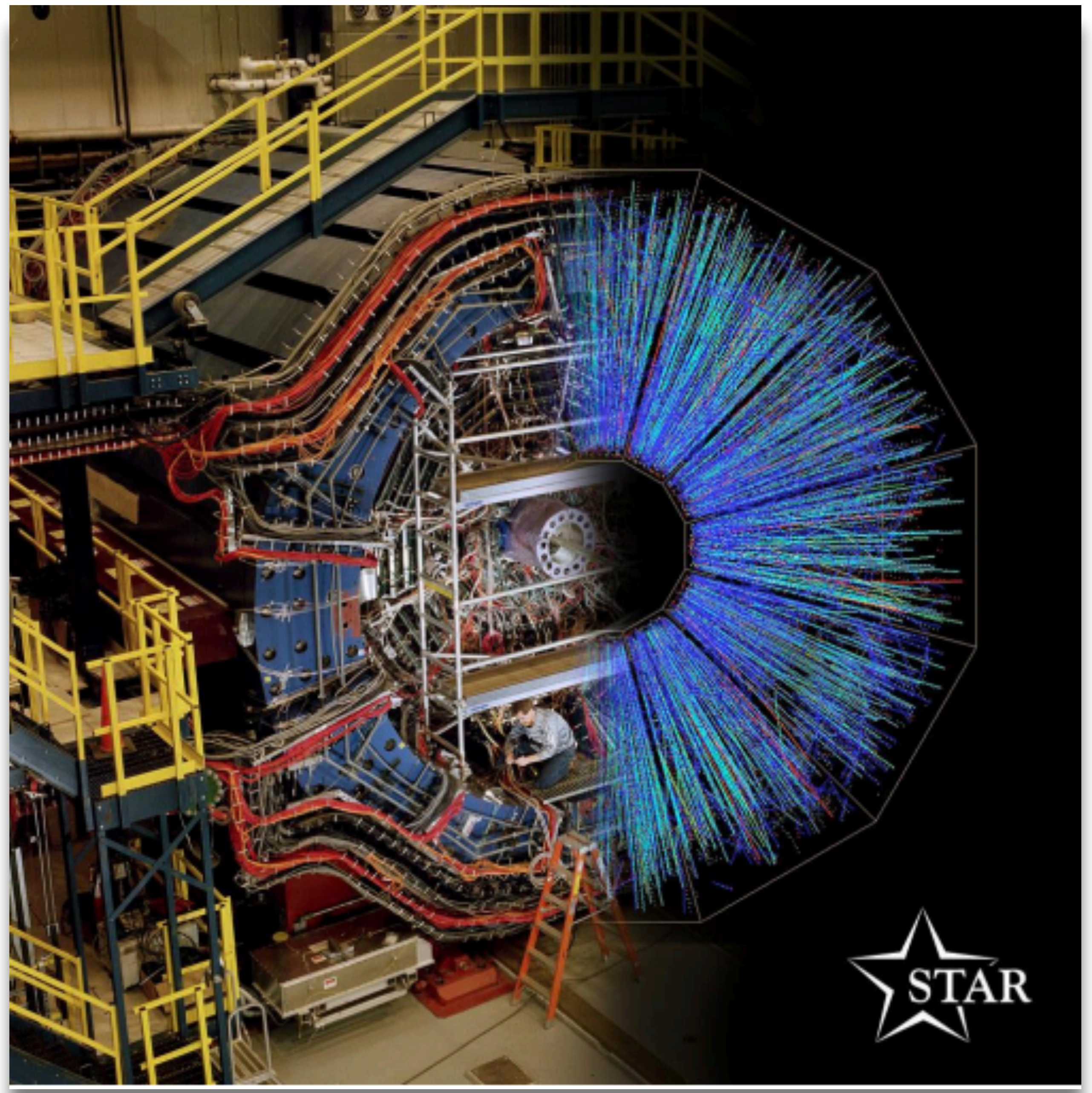
- **Field of jet physics (energy flow) have always been intricately connected to the success of the collider physics program!**

EXCITING COLLIDER PHYSICS ERA



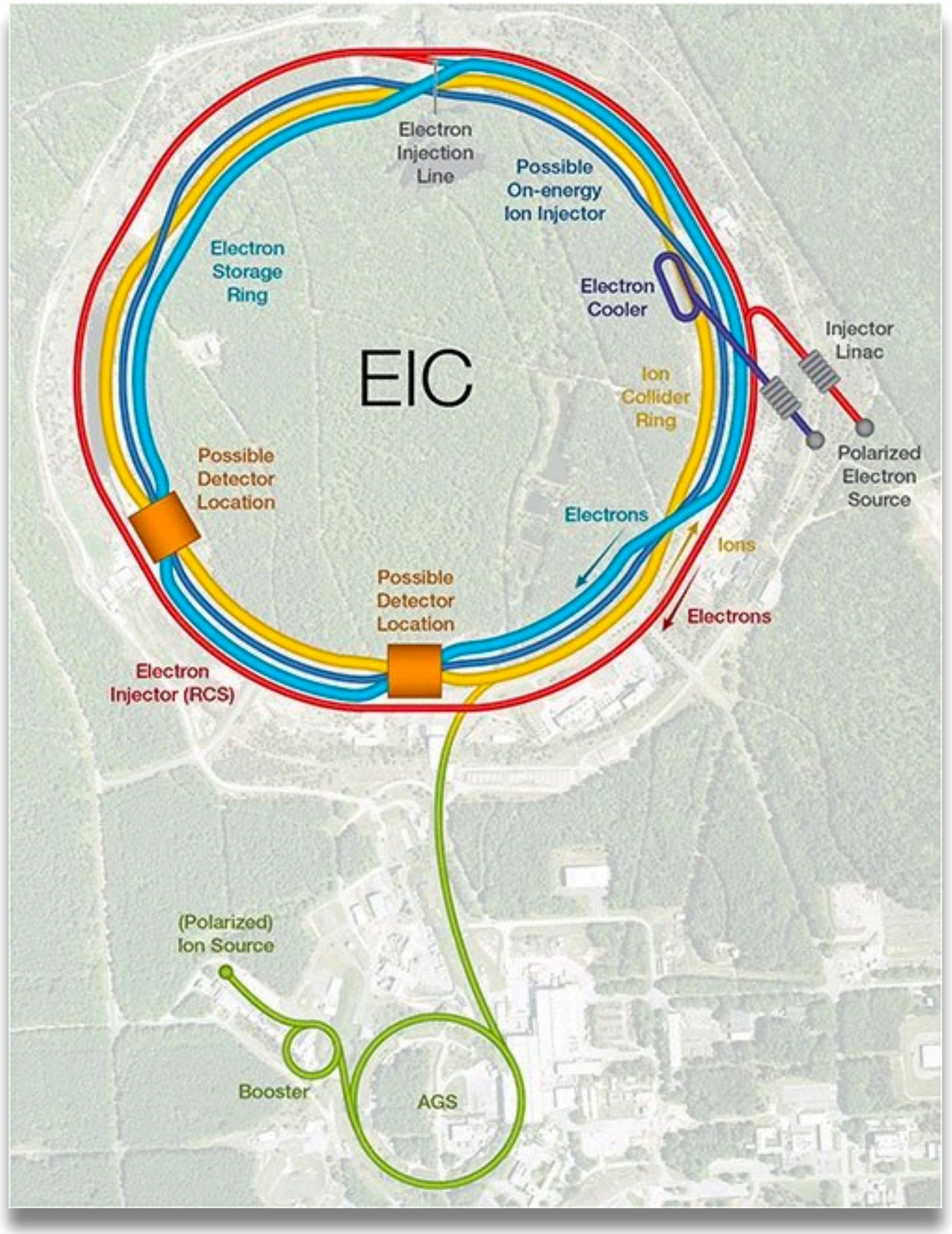
LHC, 2008 - Present

Run 3 running!



RHIC, 2000 - Present

sPHENIX: 2024-



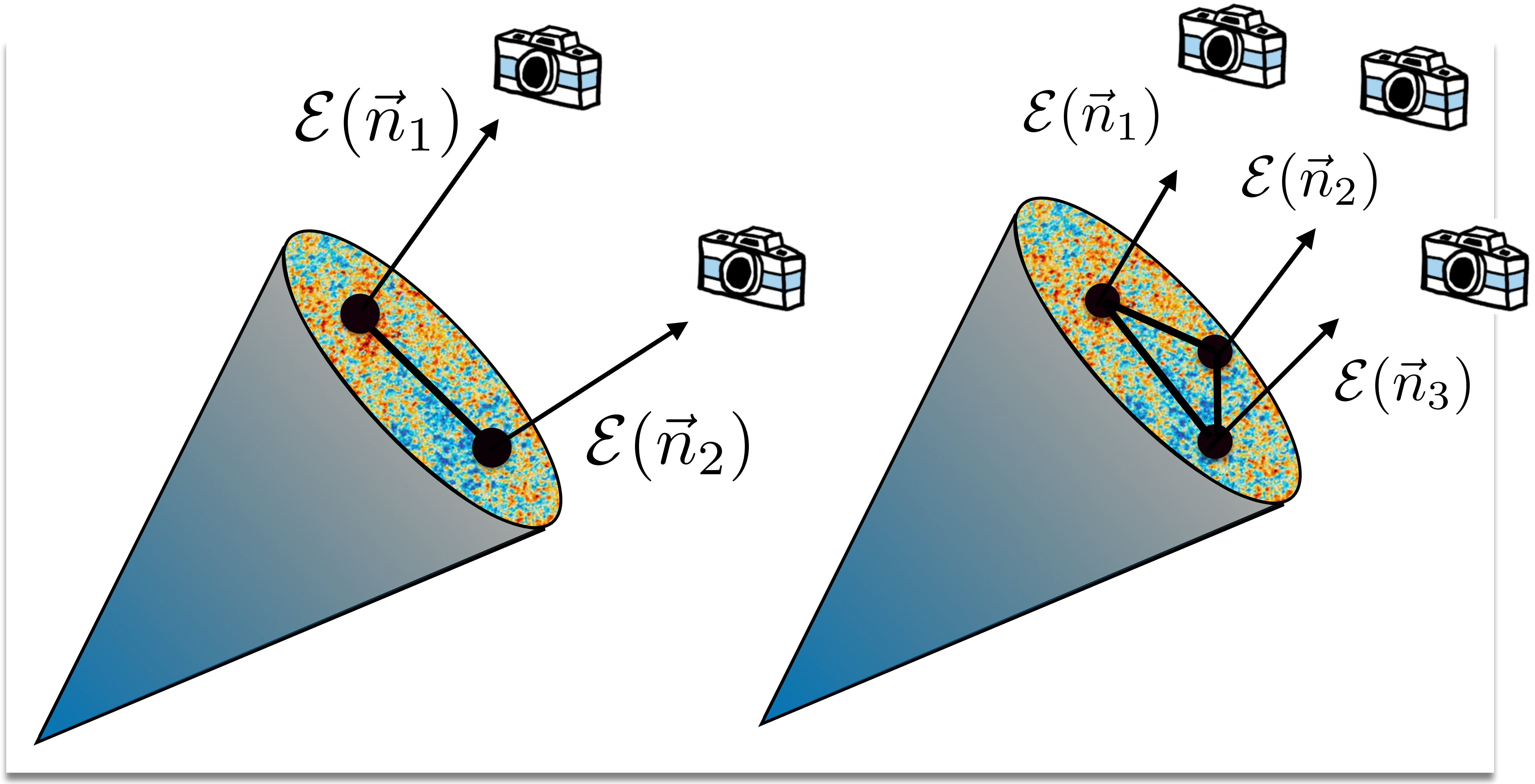
EIC, 2030s-

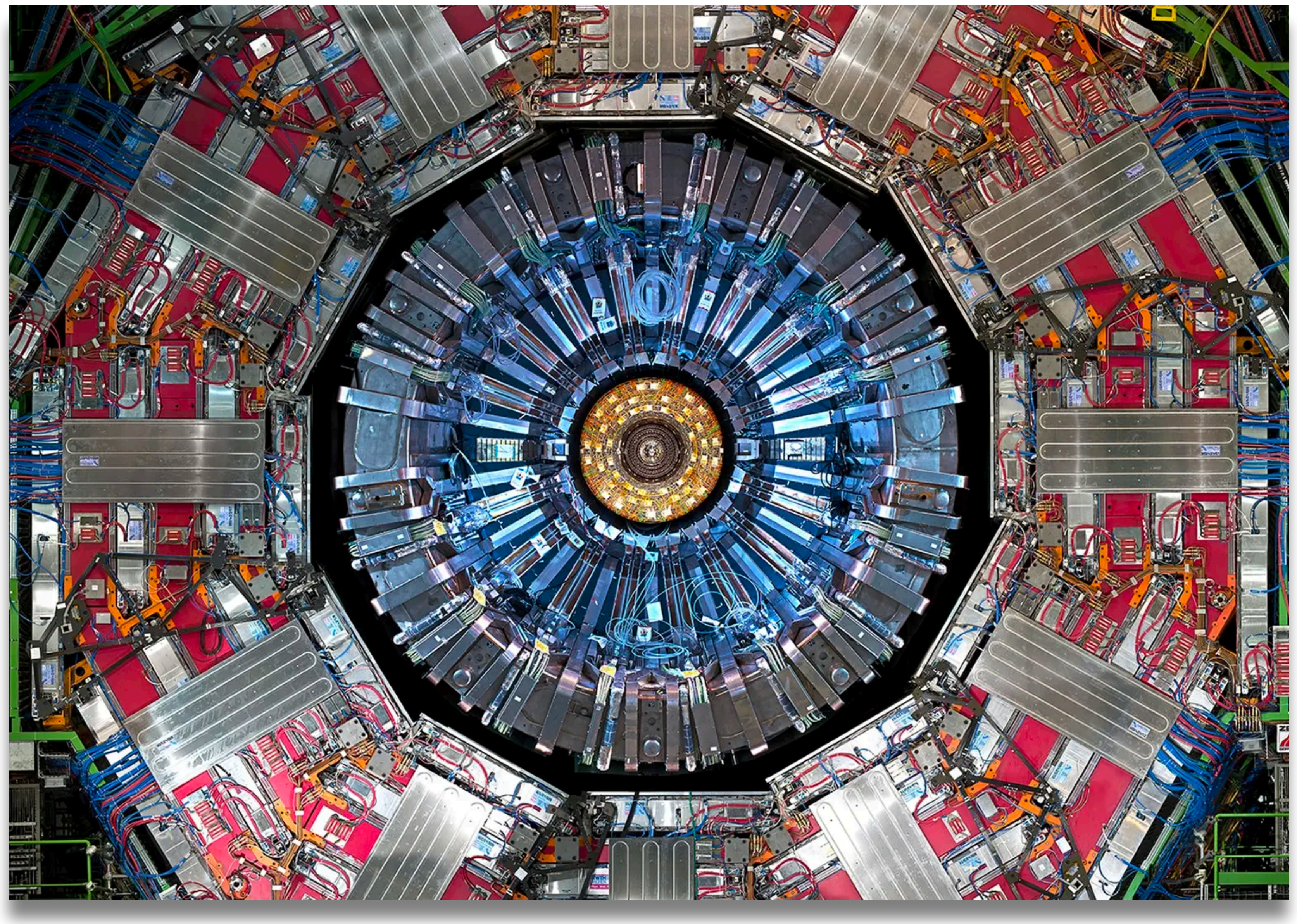
- **Jets at colliders give us the means to probe field theory in data!**

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**





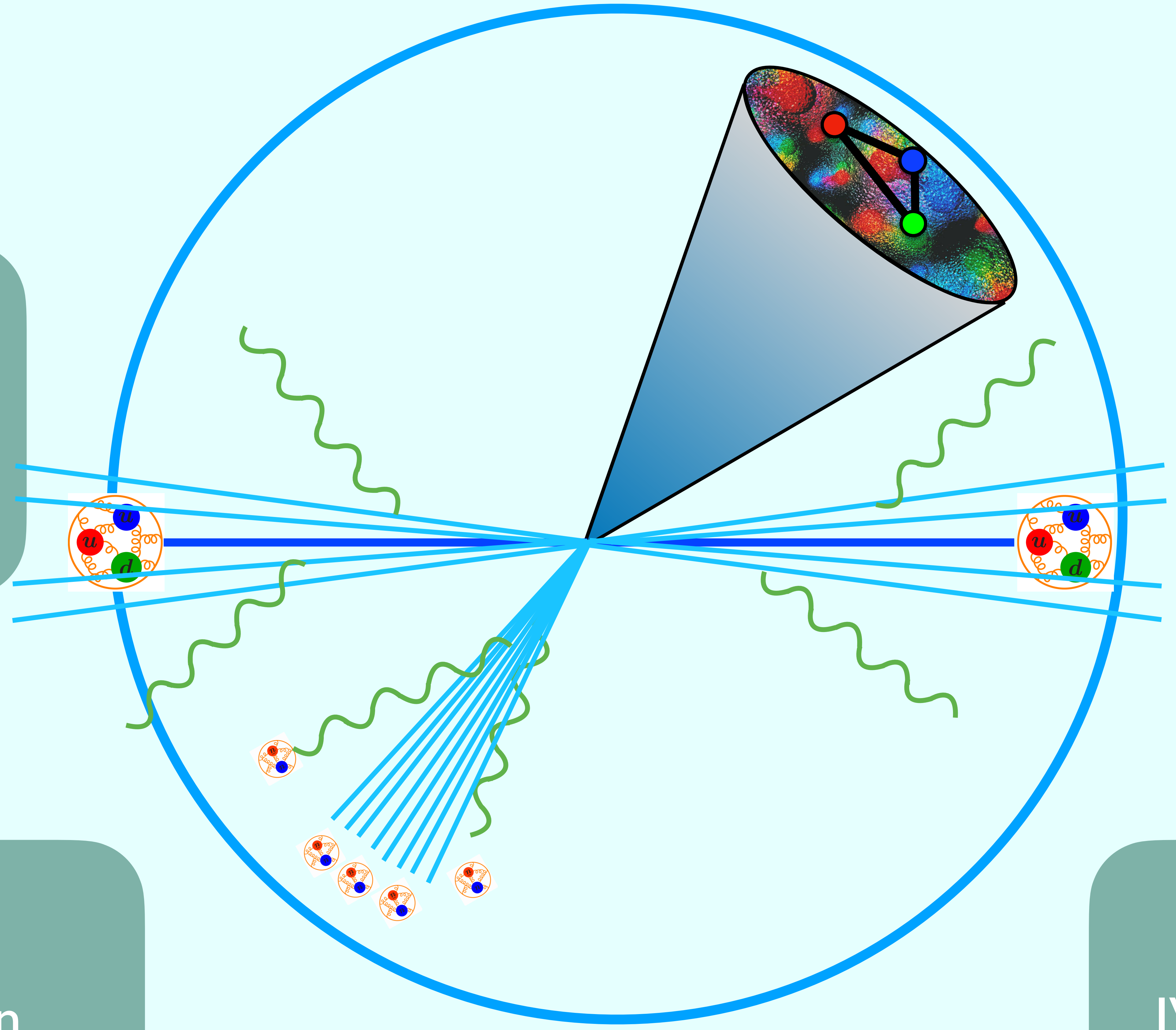
- **Relative to inclusive jet cross-section, or one-point energy correlation, jet substructure gives us opportunity to study multi-point correlations of energy within jets**

Overview

I. Universal Scaling

II. Precision QCD

VI. Nuclear Structure

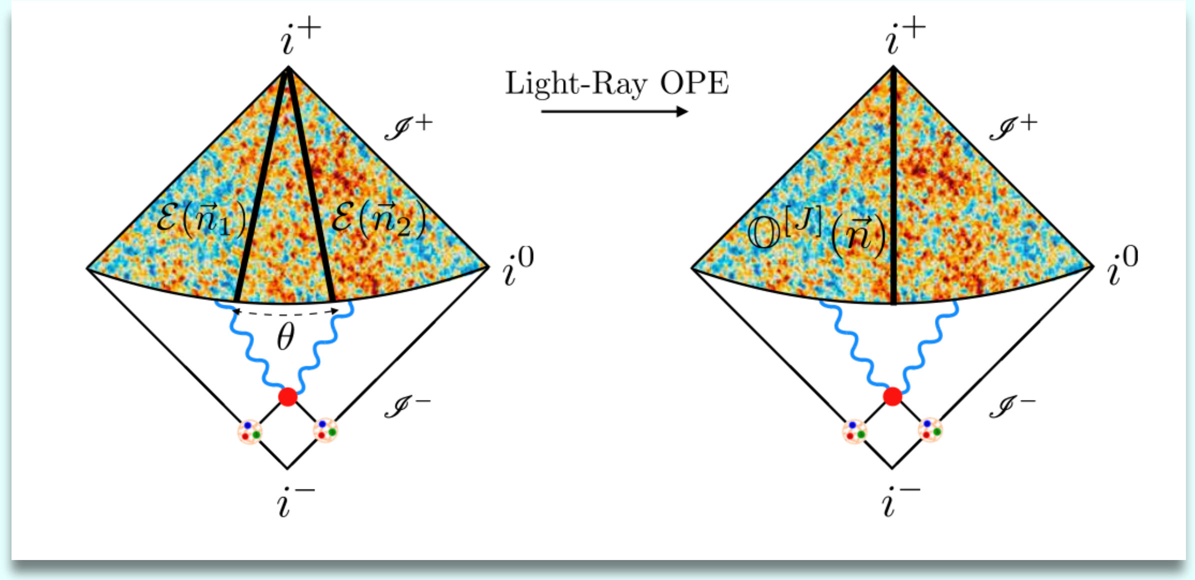


III. Heavy Flavor Physics

V. Hadronization

IV. Medium Dynamics

Overview



QFT perspective of jet substructure

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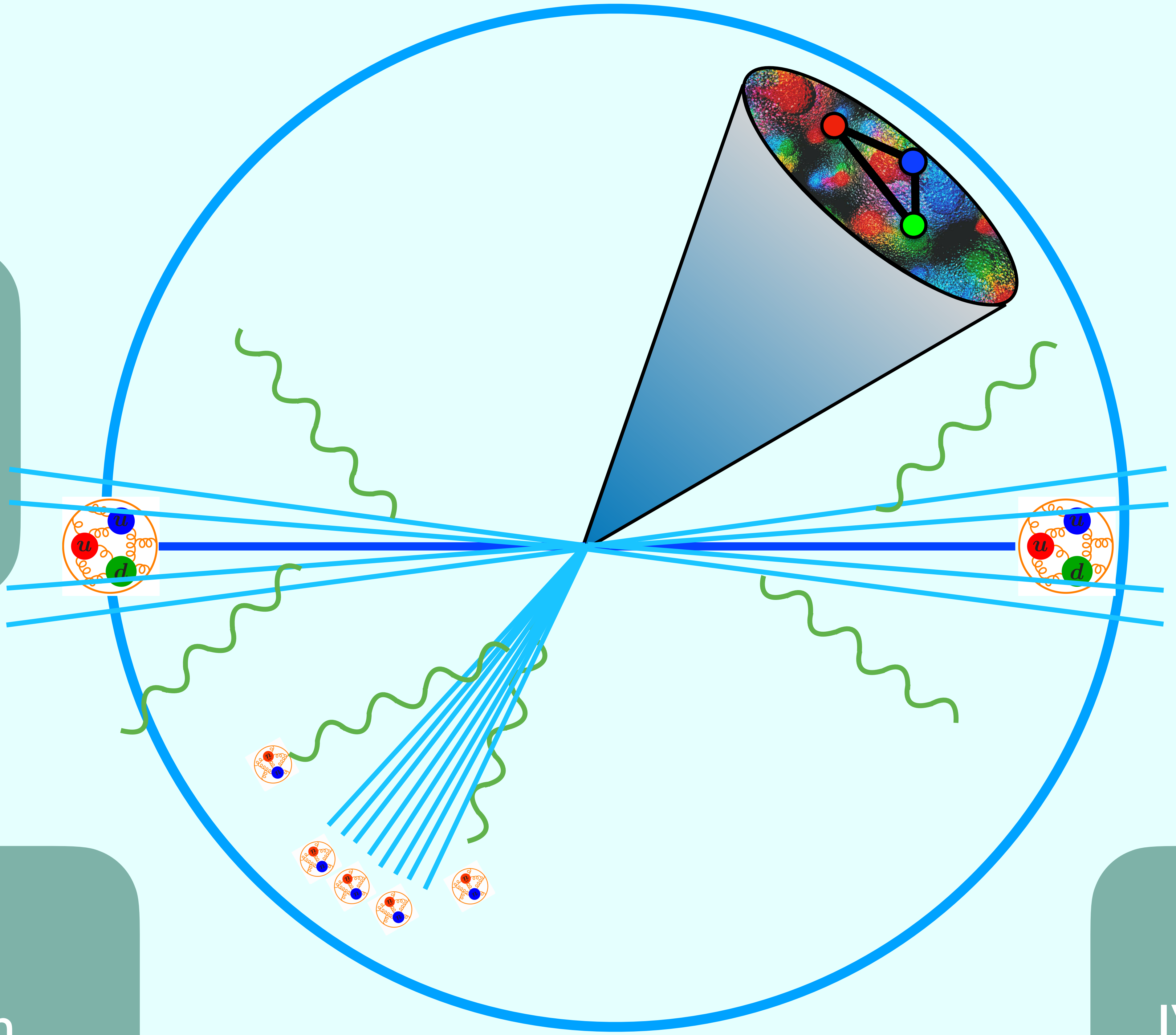

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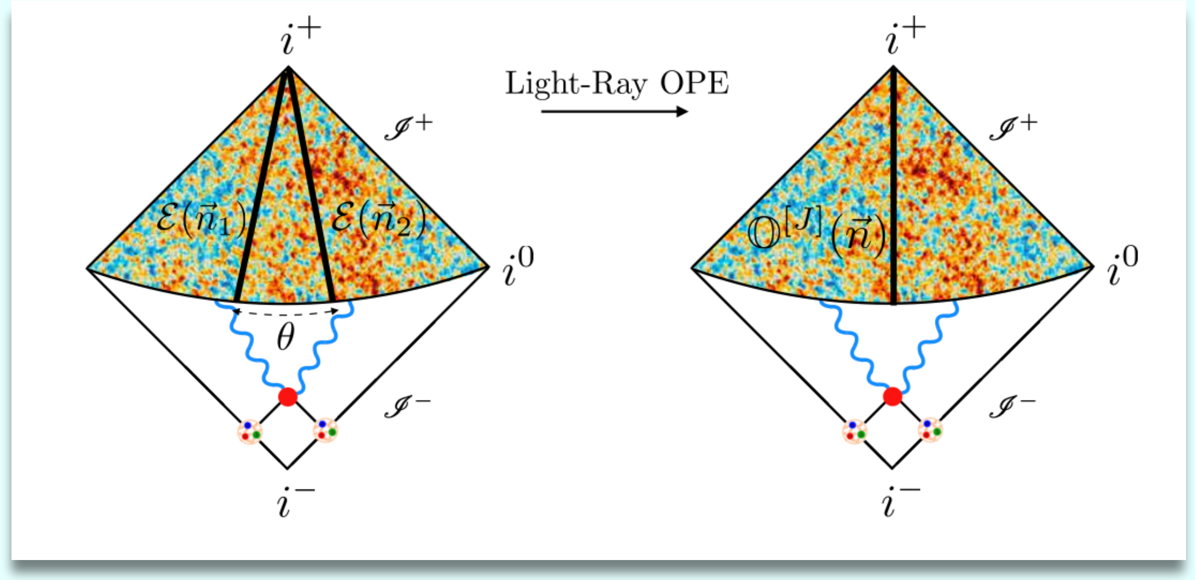

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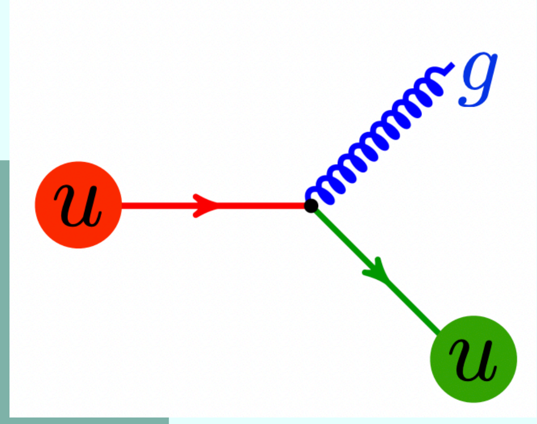
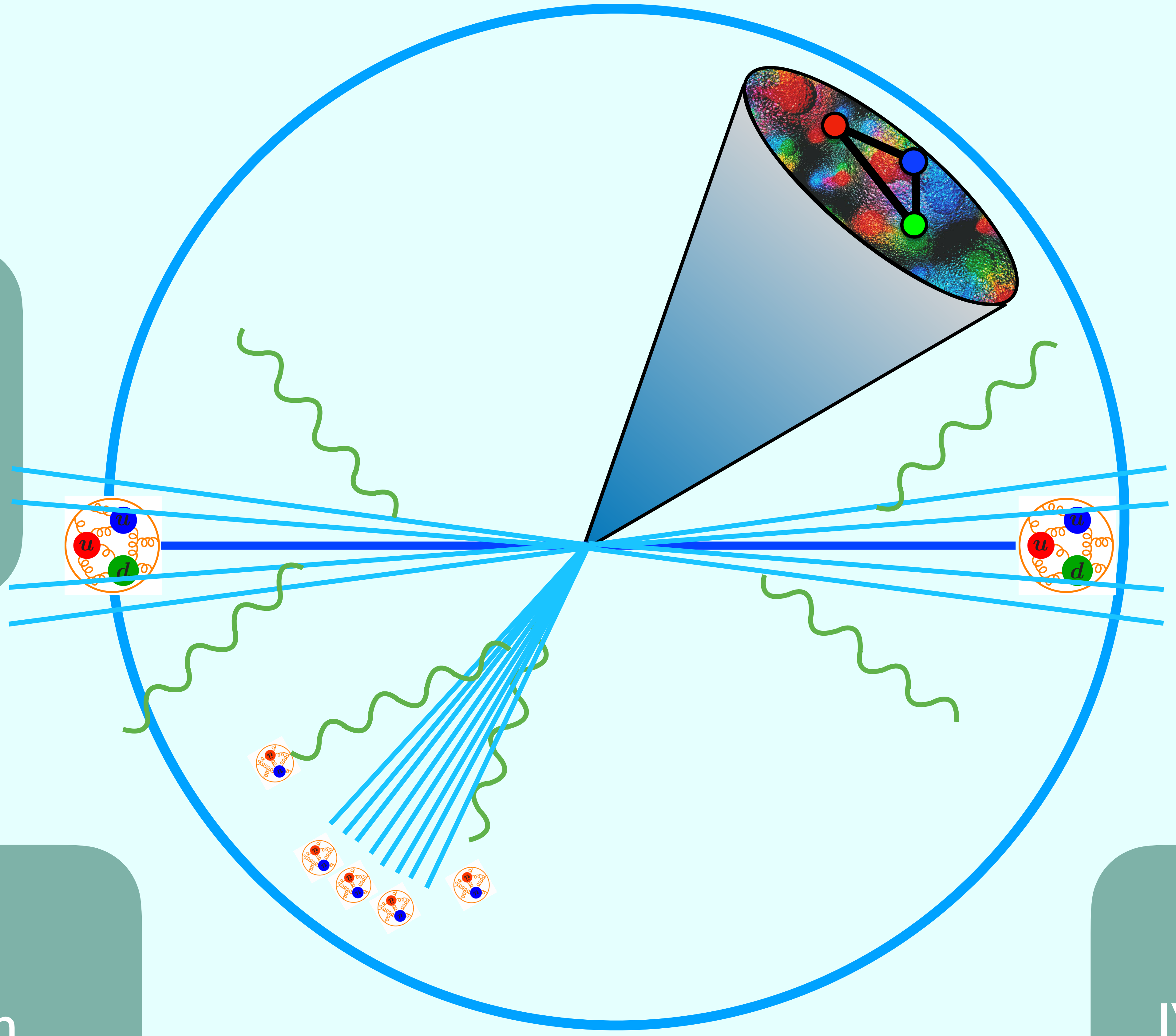


Precise determination of α_s



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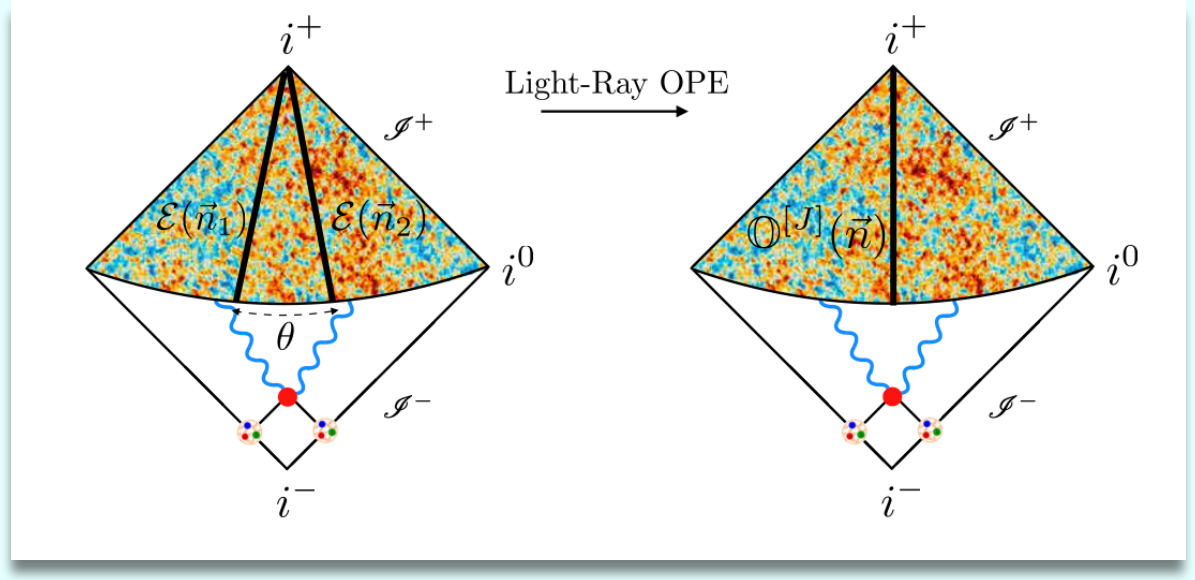

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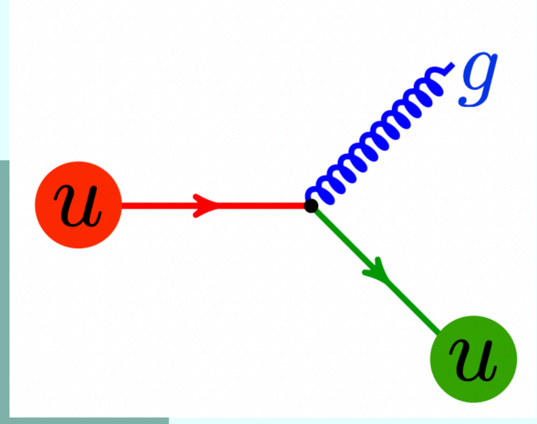

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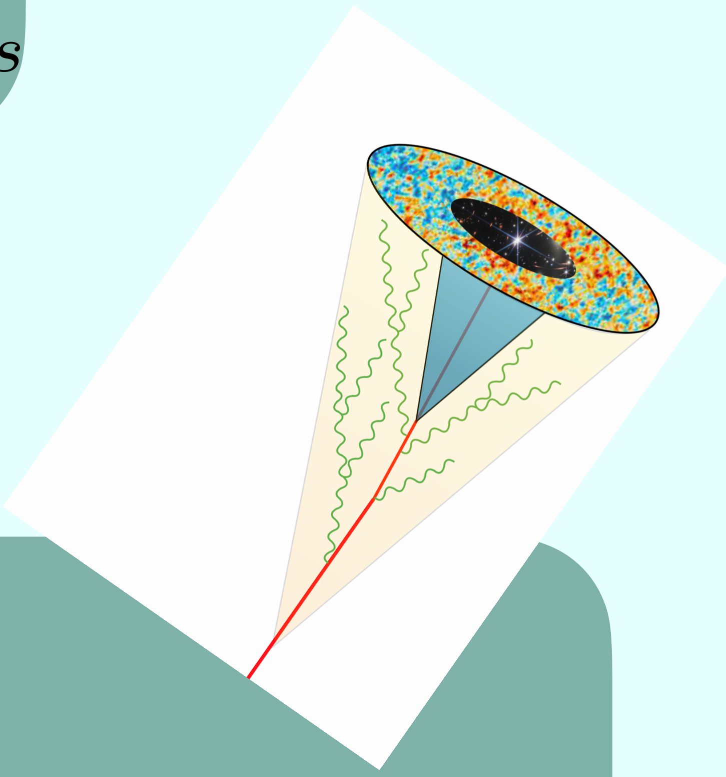

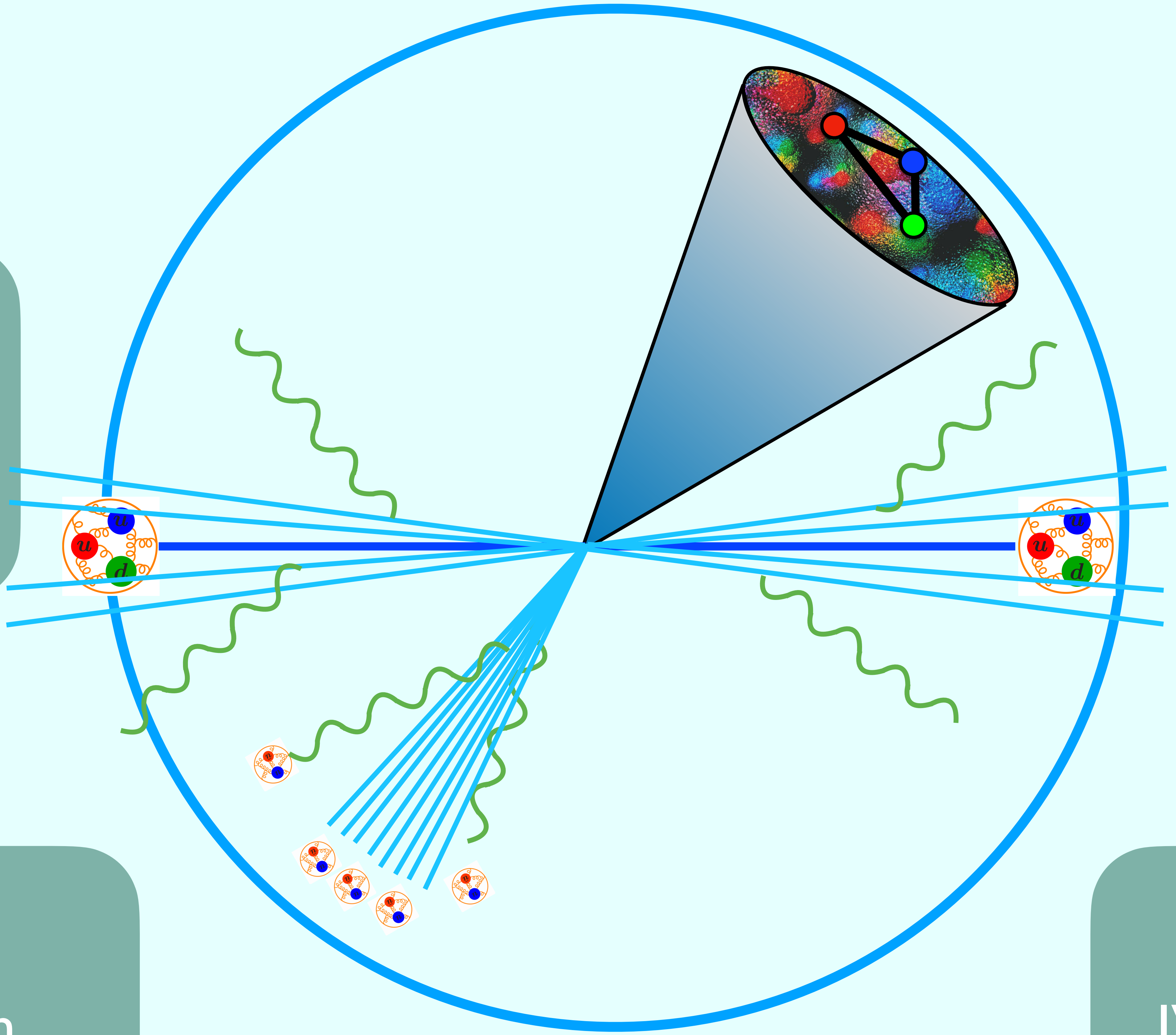

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Revealing dead-cone

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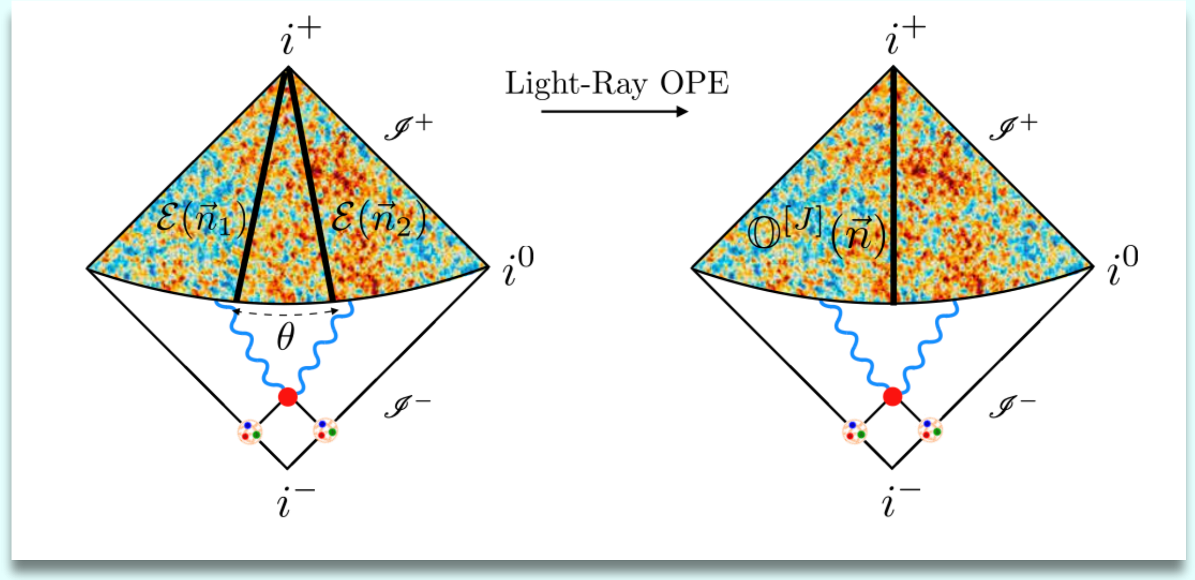

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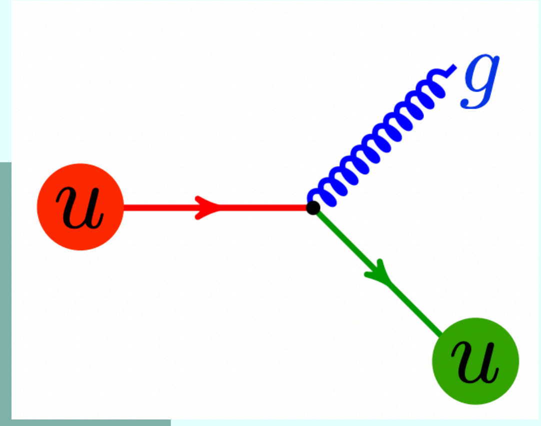

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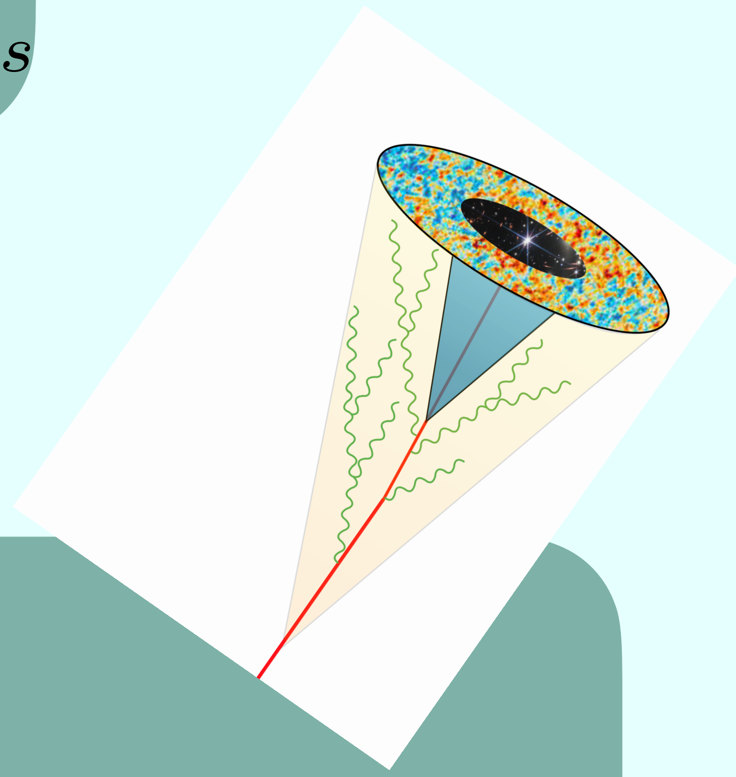
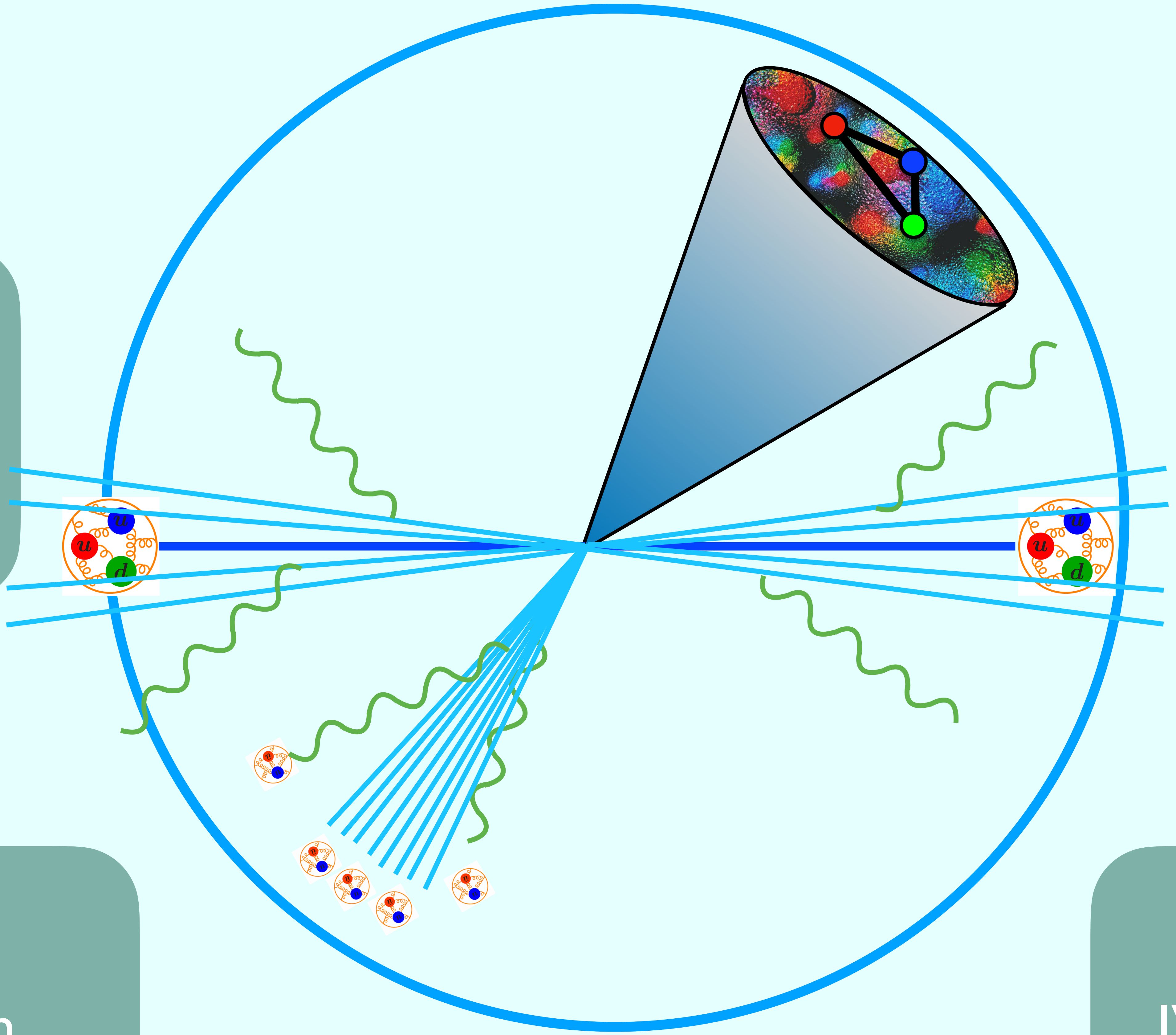
Precise determination of α_s





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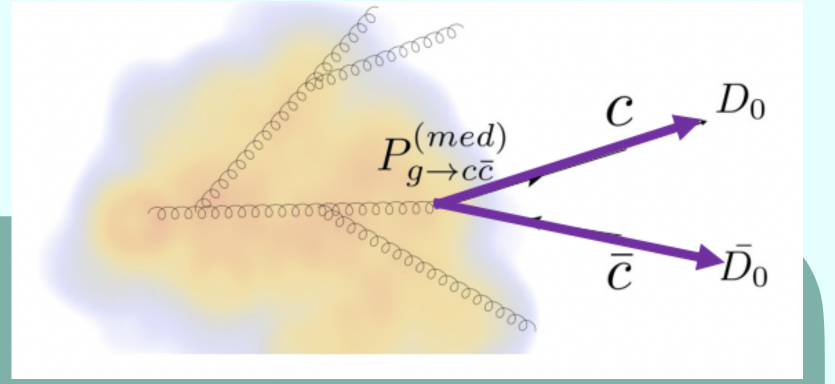
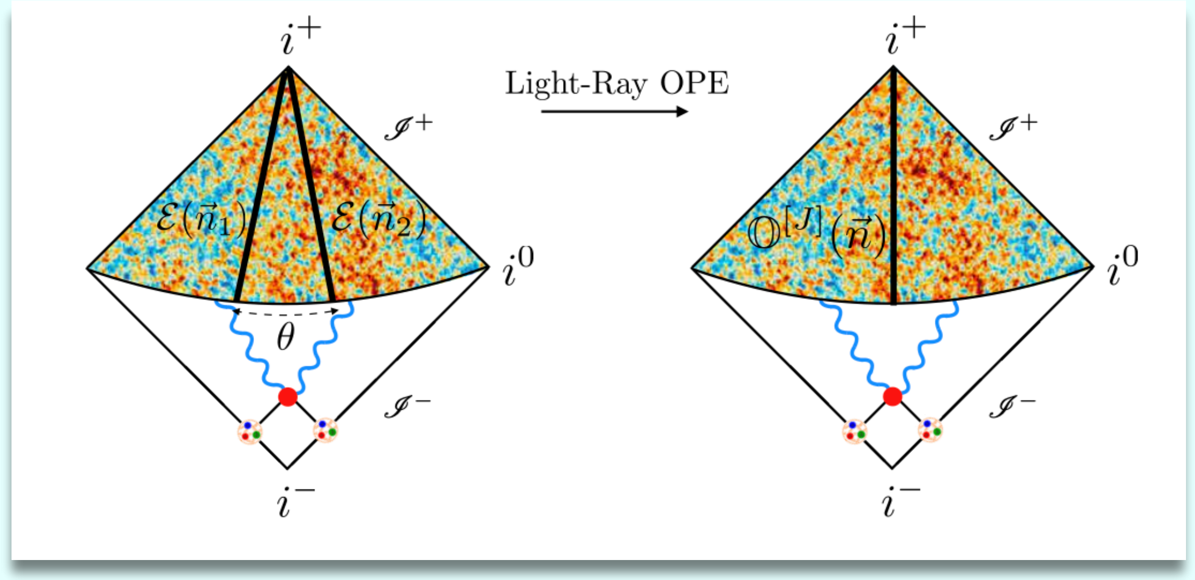


V. Hadronization

IV. Medium Dynamics

Revealing medium scale and modifications

Overview



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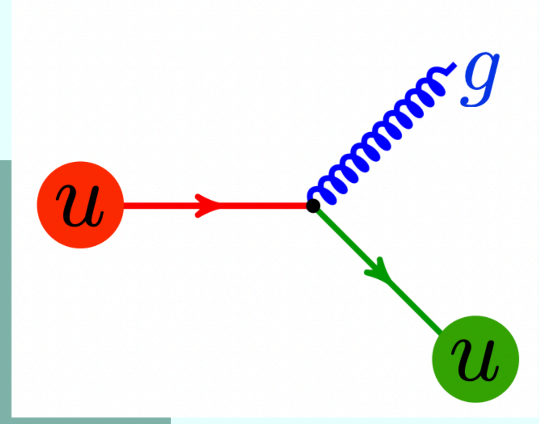

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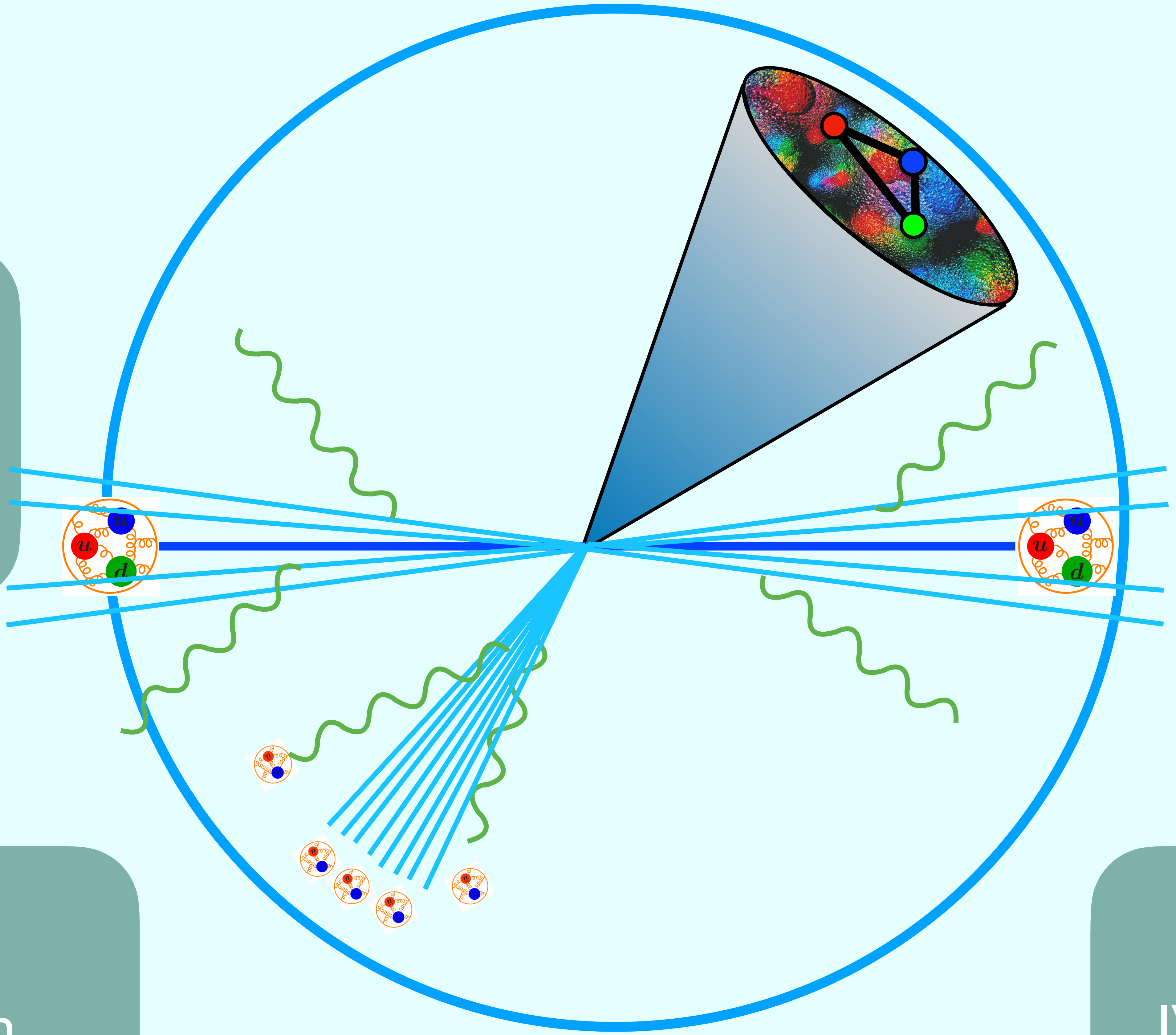

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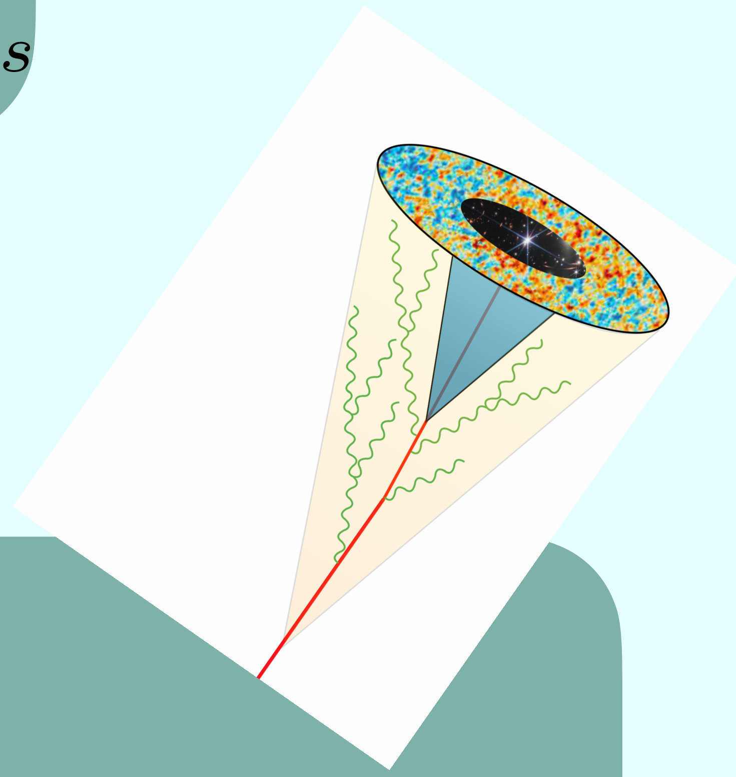
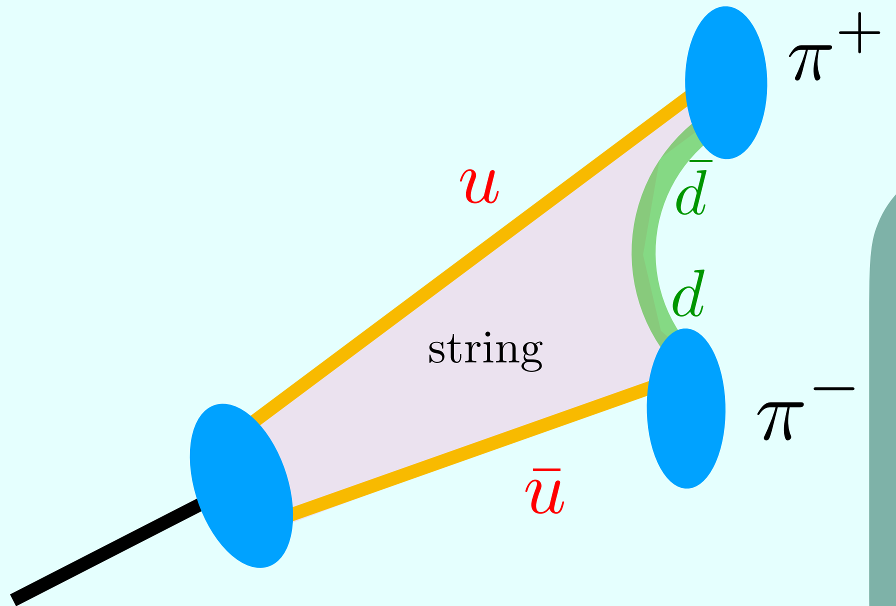
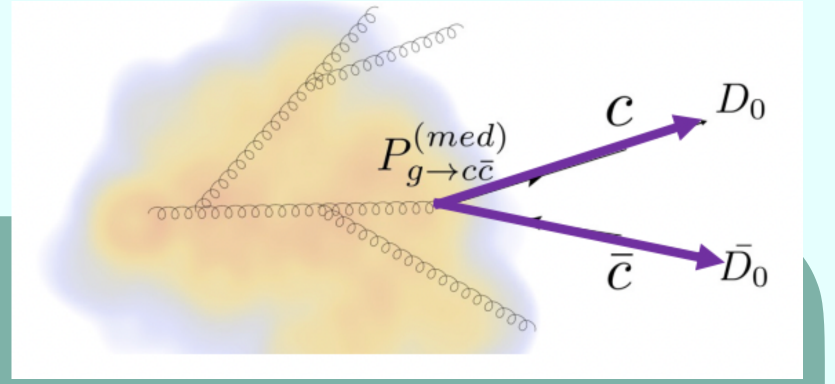




V. Hadronization

Discrimination between hadronization mechanisms



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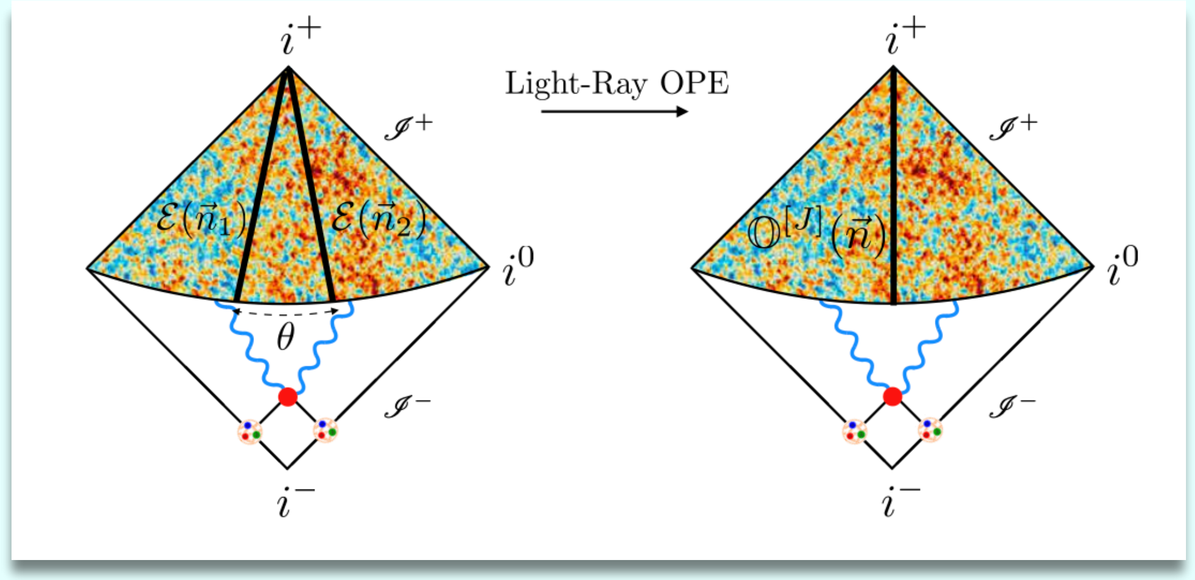

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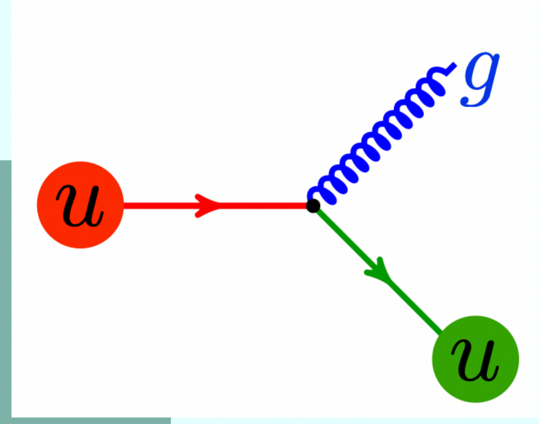

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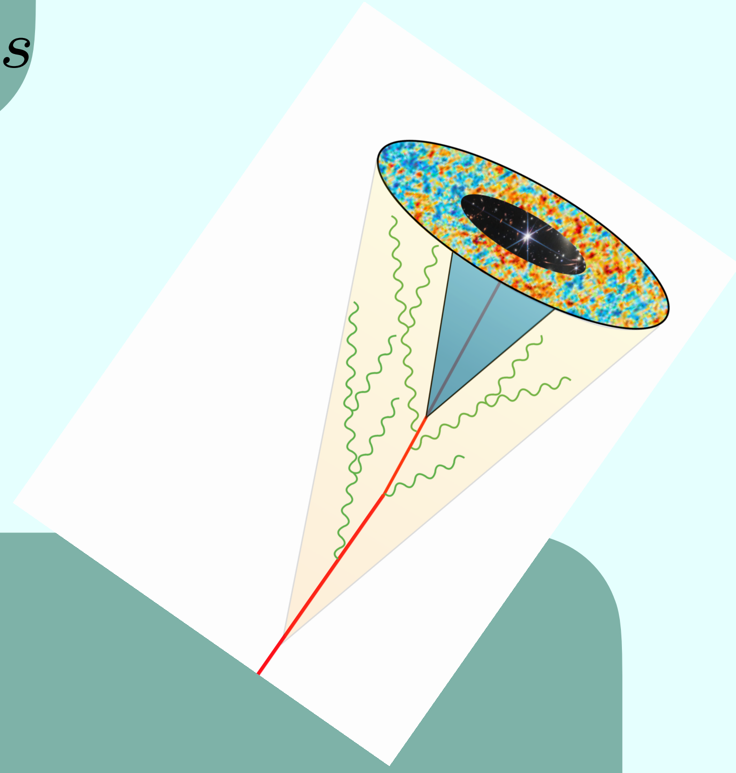
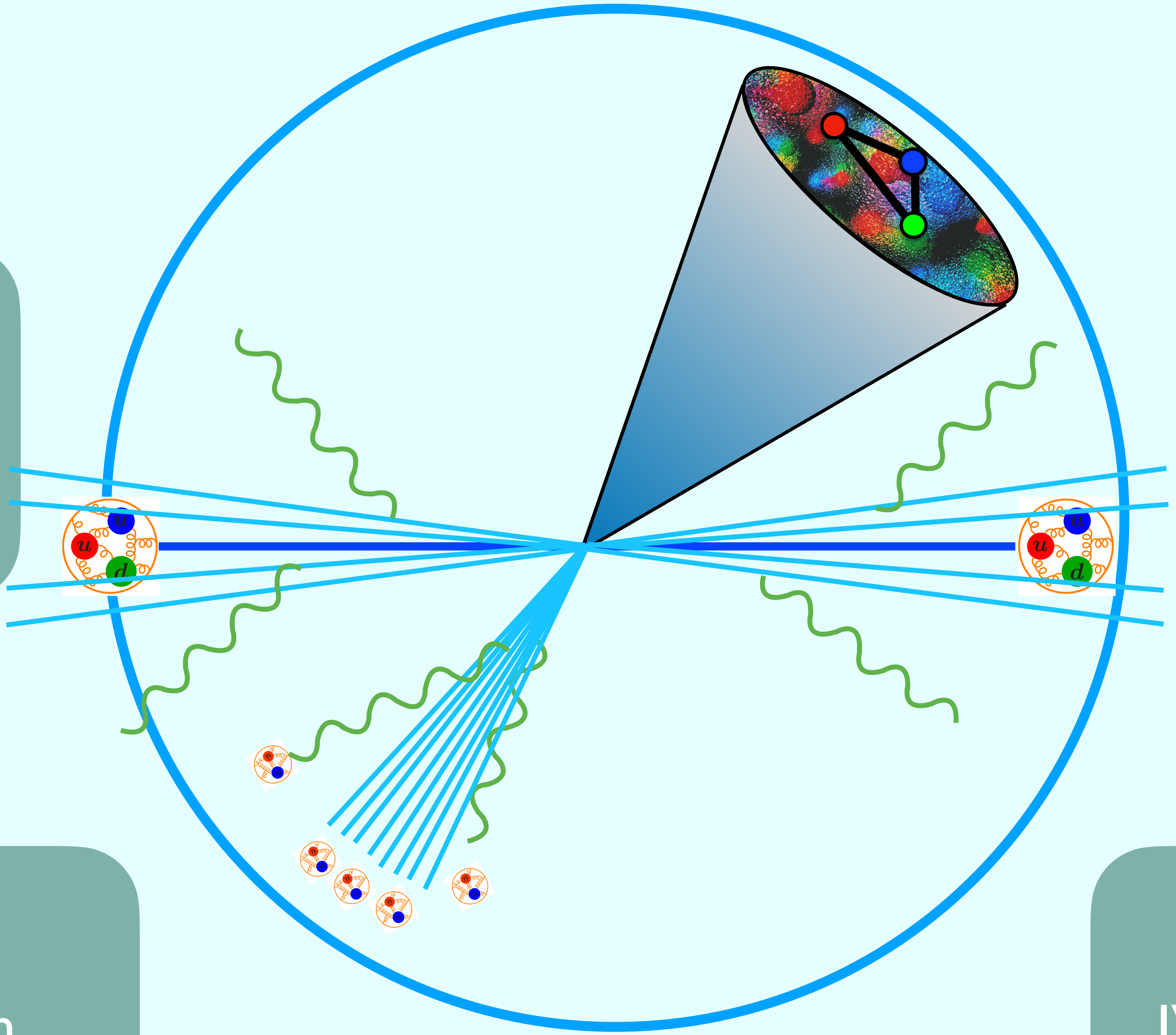
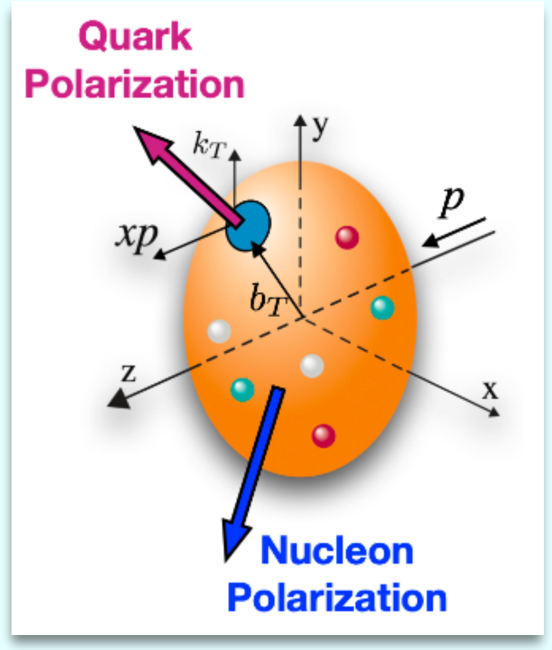
Precise determination of α_s





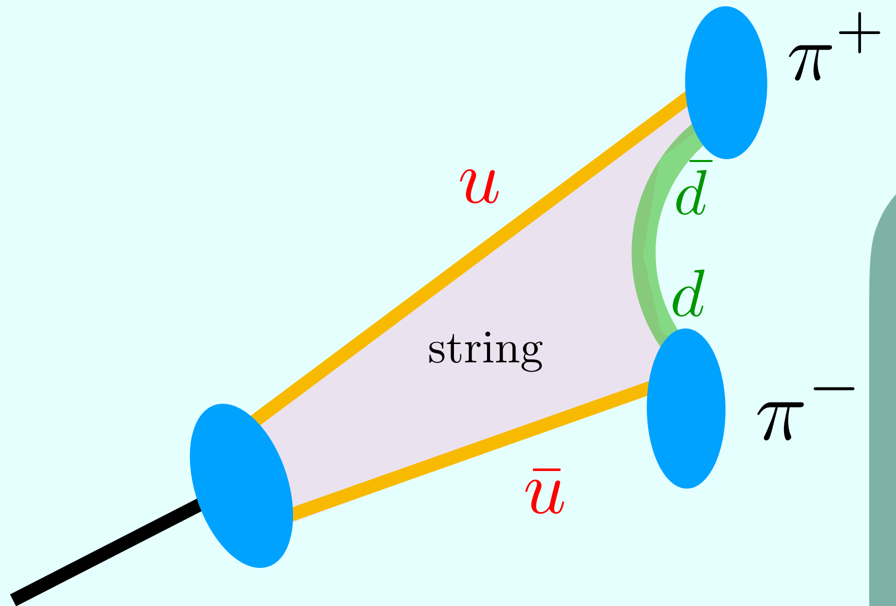


VI. Nuclear Structure

Nuclear tomography study

III. Heavy Flavor Physics

Revealing dead-cone



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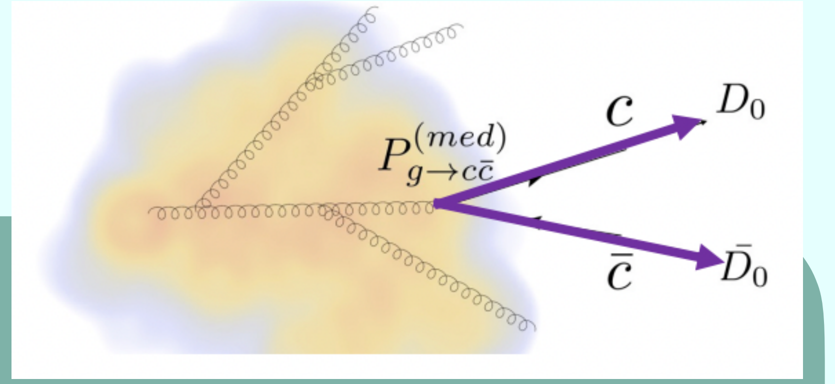

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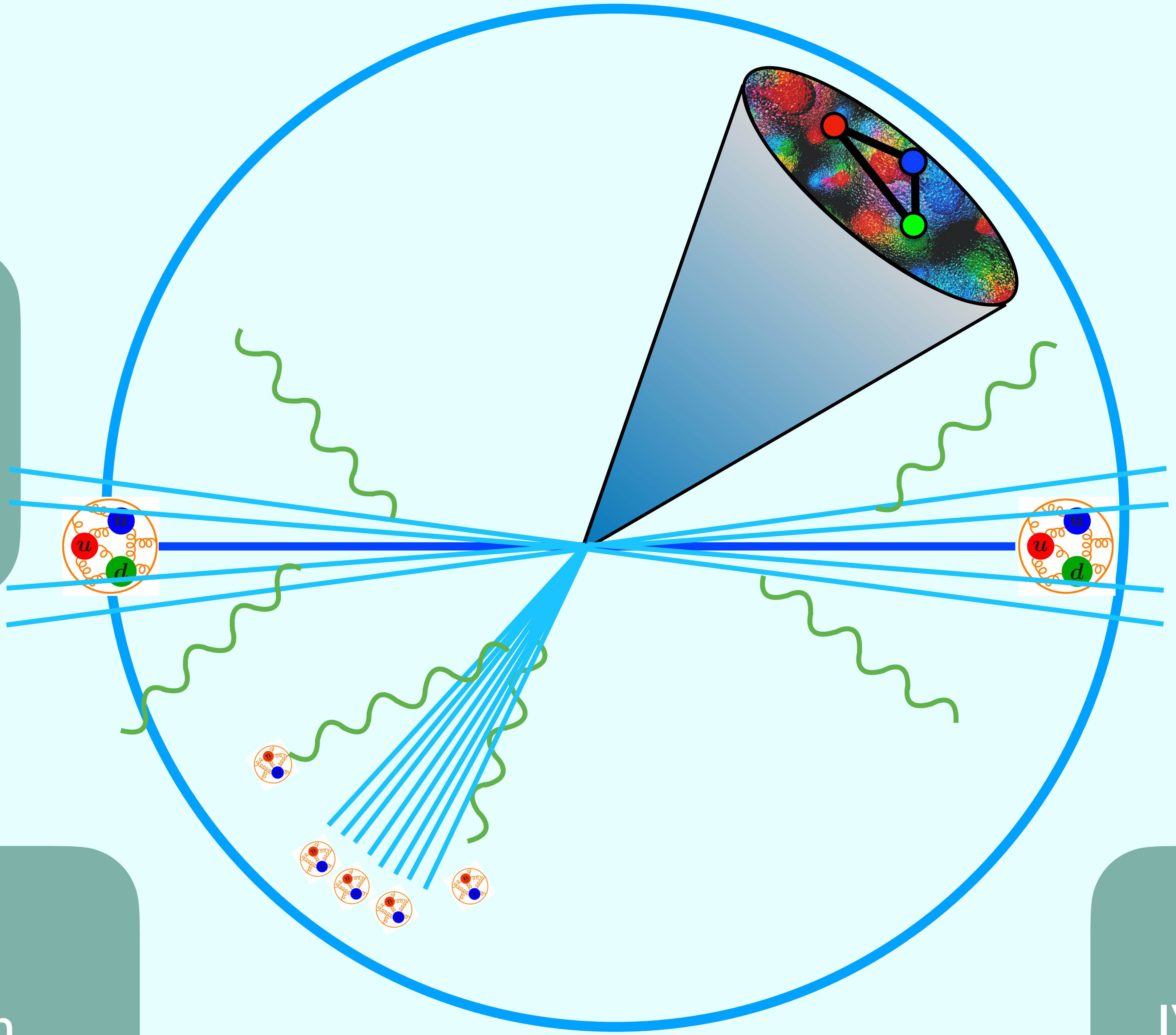

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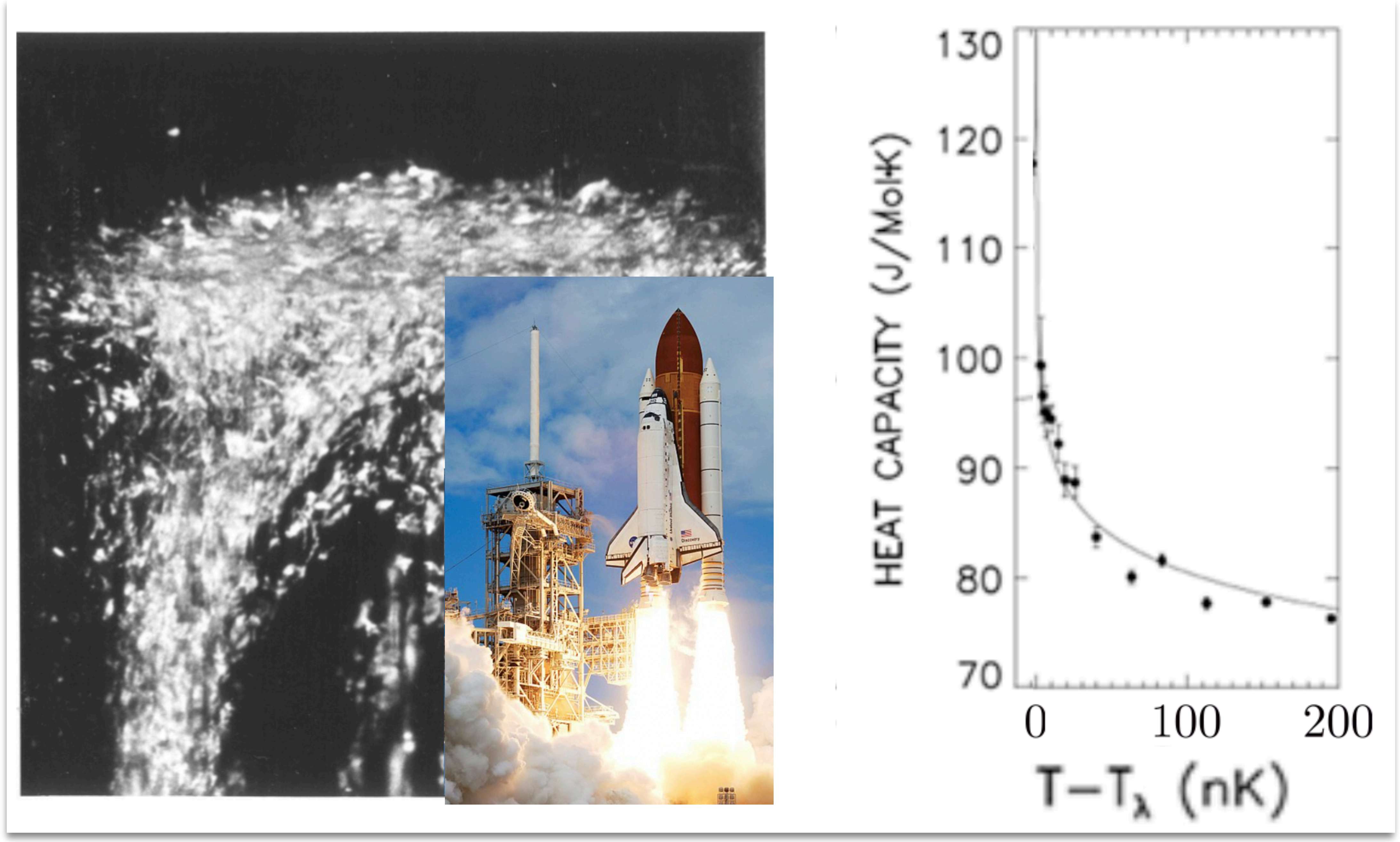
SCALING BEHAVIOR IN QFT

- **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

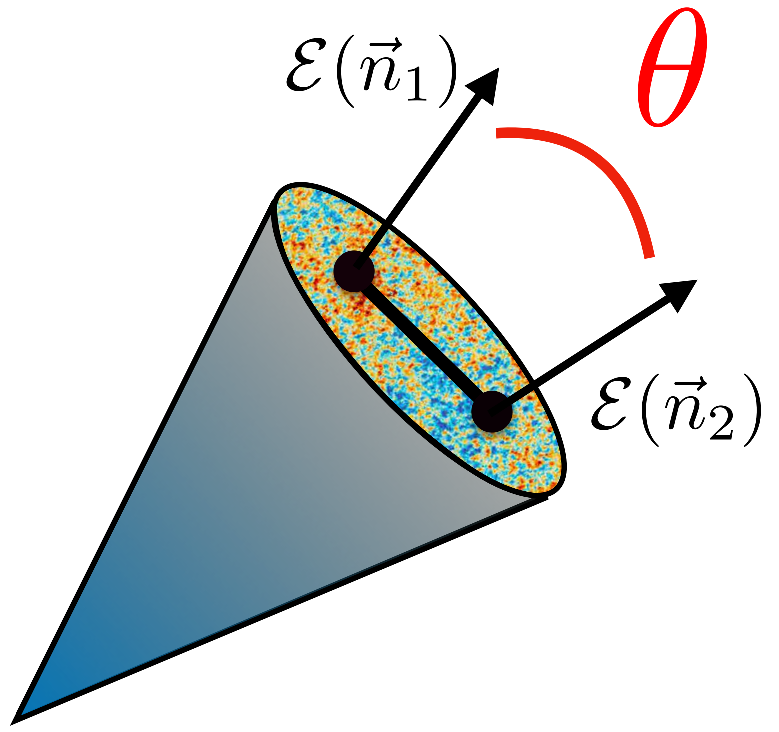
$$\mathcal{O}(x)\mathcal{O}(0) = \sum x^{\gamma_i} c_i \mathcal{O}_i$$

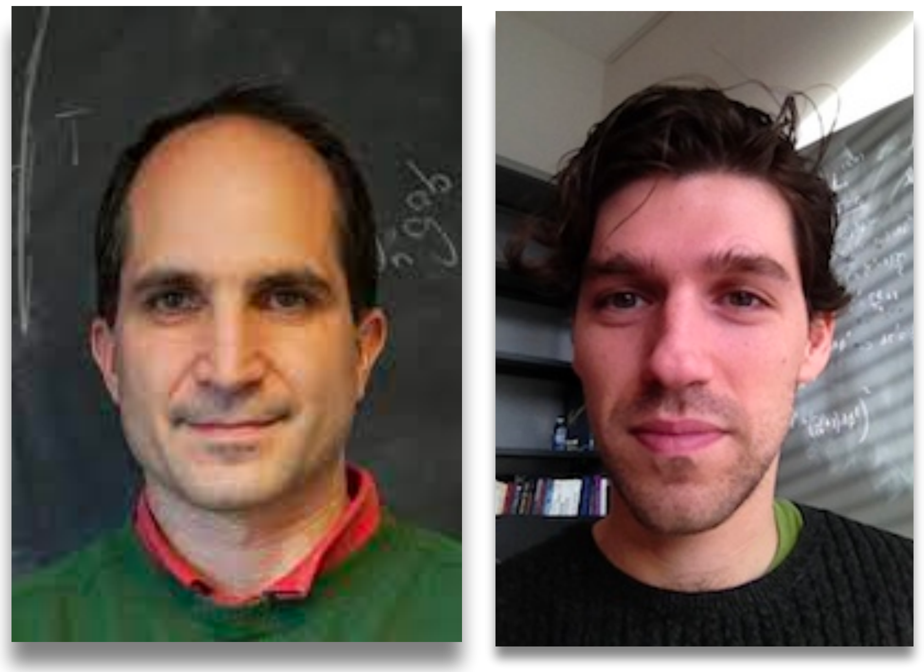
- **Critical phenomena give us access to universal scaling behavior as Euclidean operators are brought together**

UNIVERSAL LORENTZIAN SCALING WITHIN JETS

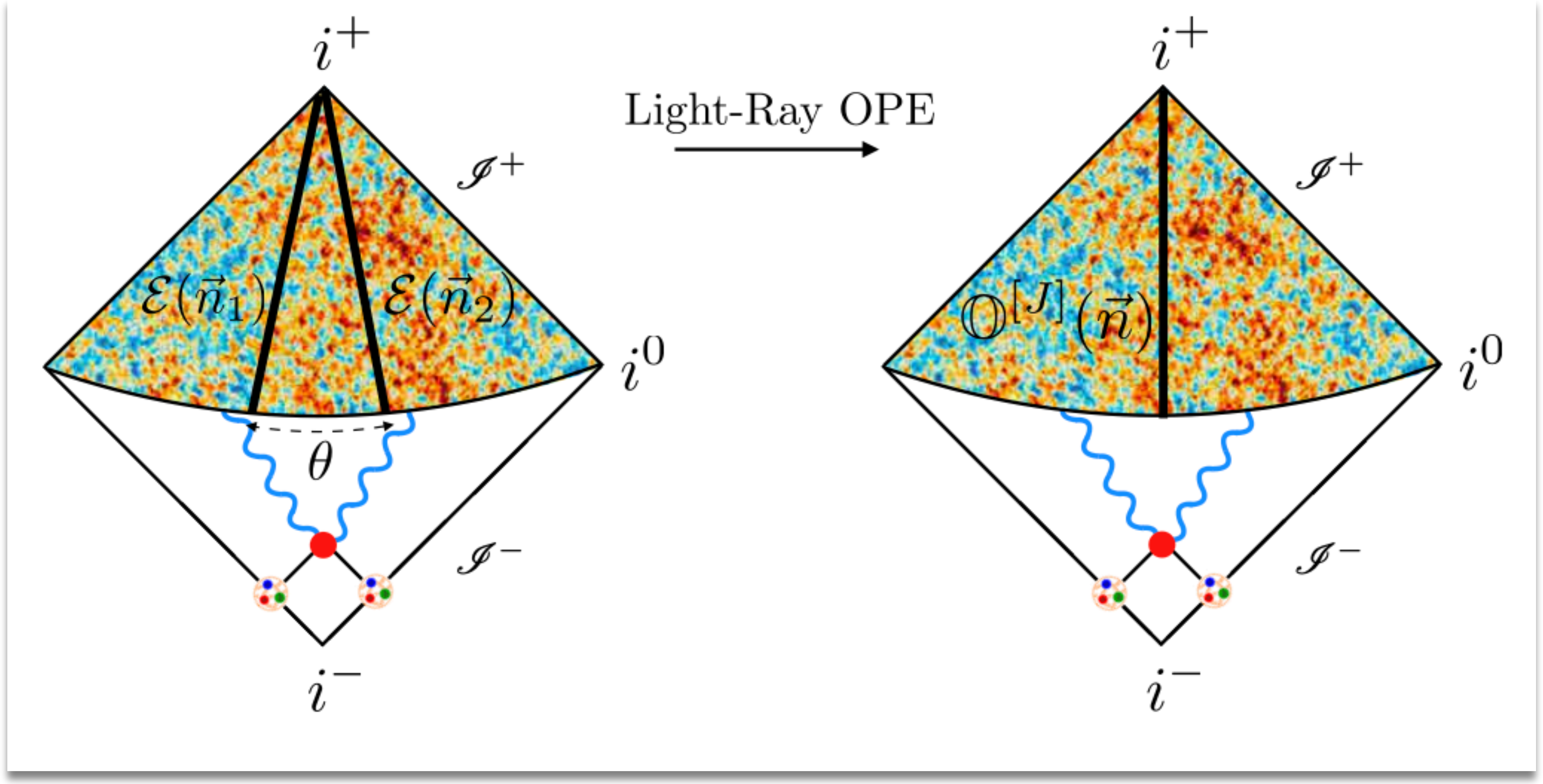
- **Jet substructure describes the limit where energy flow operators are brought together, thus probing the OPE limit of Lorentzian operators**

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





Hofman, Maldacena `08



Light-ray Operator Product Expansion

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

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

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

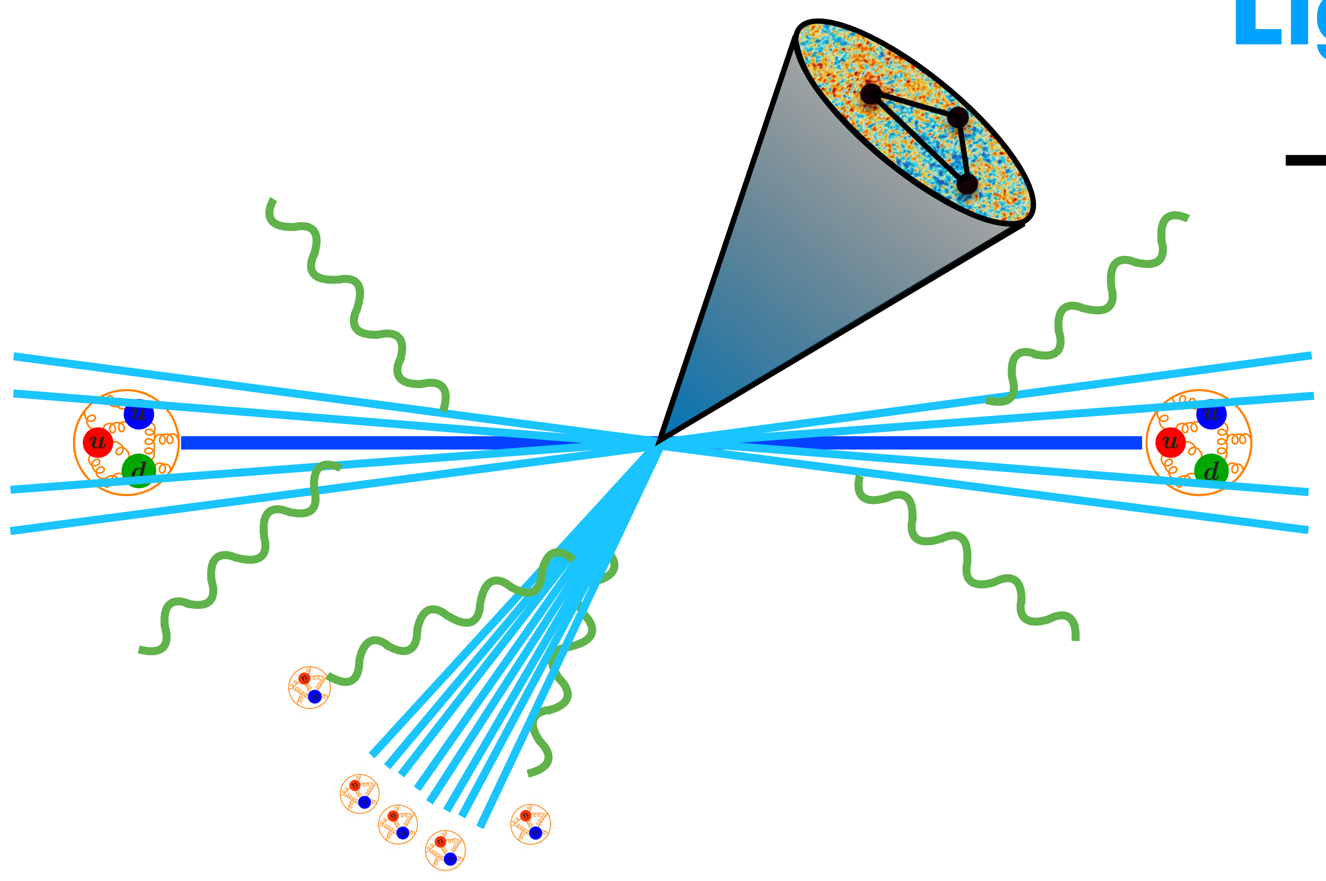
CAN THIS UNIVERSAL SCALING OF THE FIELD THEORY BE OBSERVED IN JETS???

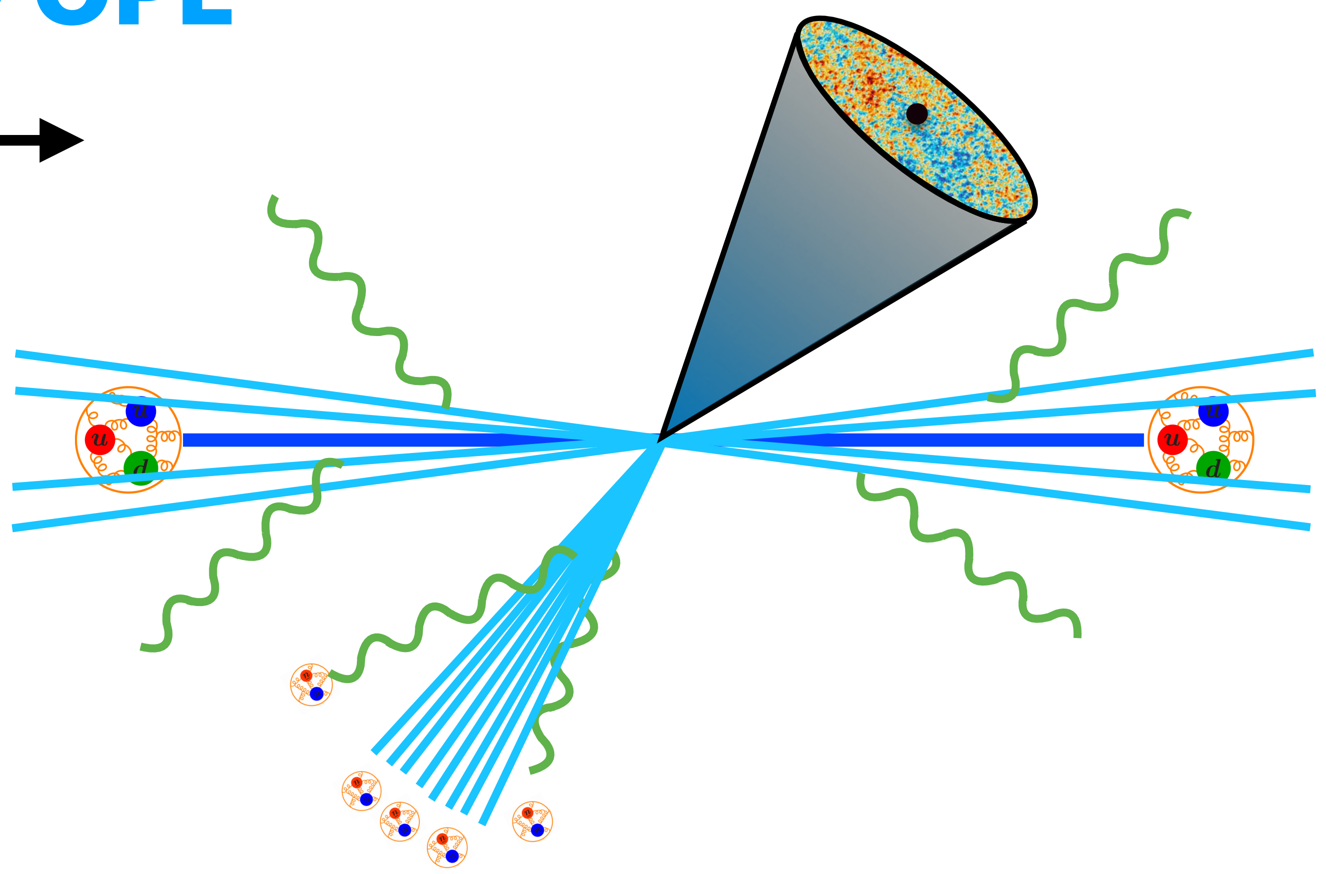
UNIVERSAL SCALING BEHAVIOR IN JETS!

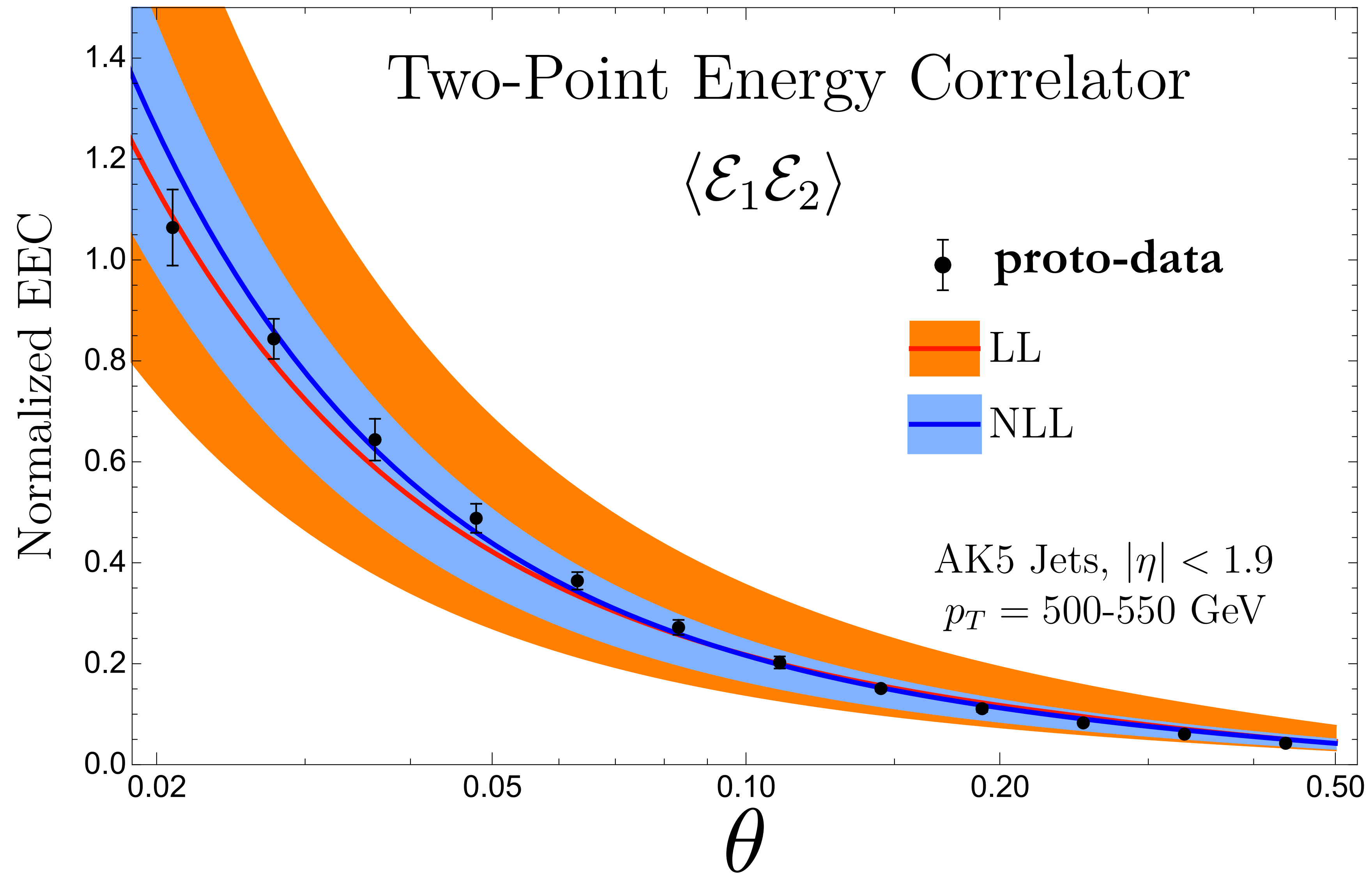
- **In QCD, we developed the proper framework to observe the universal scaling behavior within jets!**

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

$\langle\psi|\mathcal{E}(\vec{n}_1)\,\mathcal{E}(\vec{n}_2)|\psi\rangle$ **Light-ray OPE** → $\langle\psi|\mathbb{O}^{[3]}(\vec{n})|\psi\rangle$



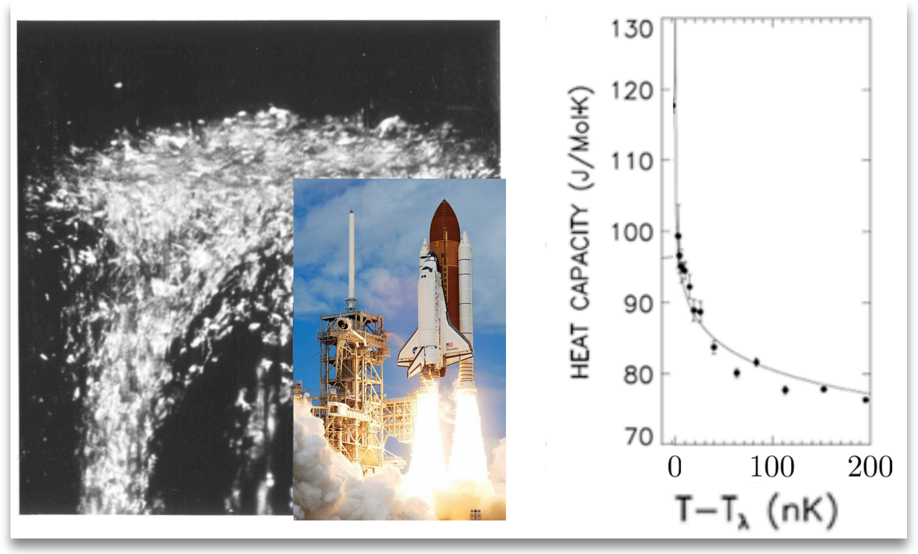




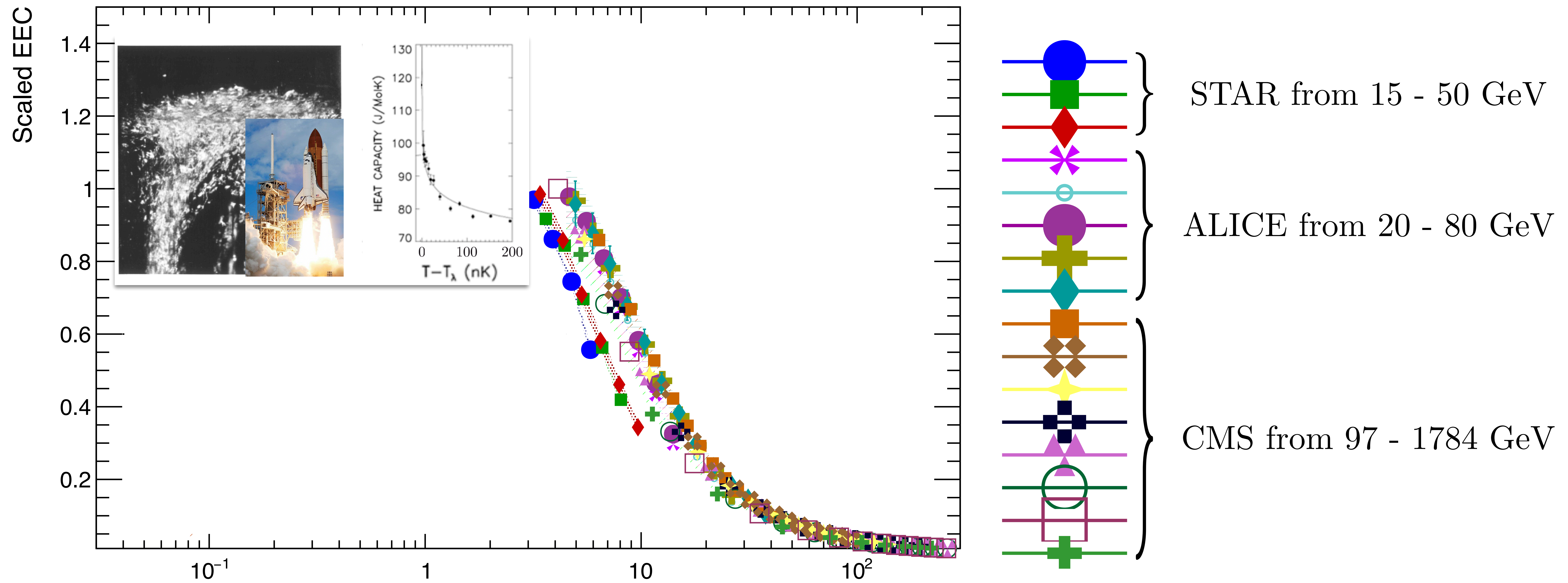
QCD factorization:

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

Λ_{QCD} p_T $p_T R$, $p_T\theta$



SCALING FROM 15 GEV TO 2 TEV IN DATA!



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

quantum classical

$\gamma(N) \propto \alpha_s$

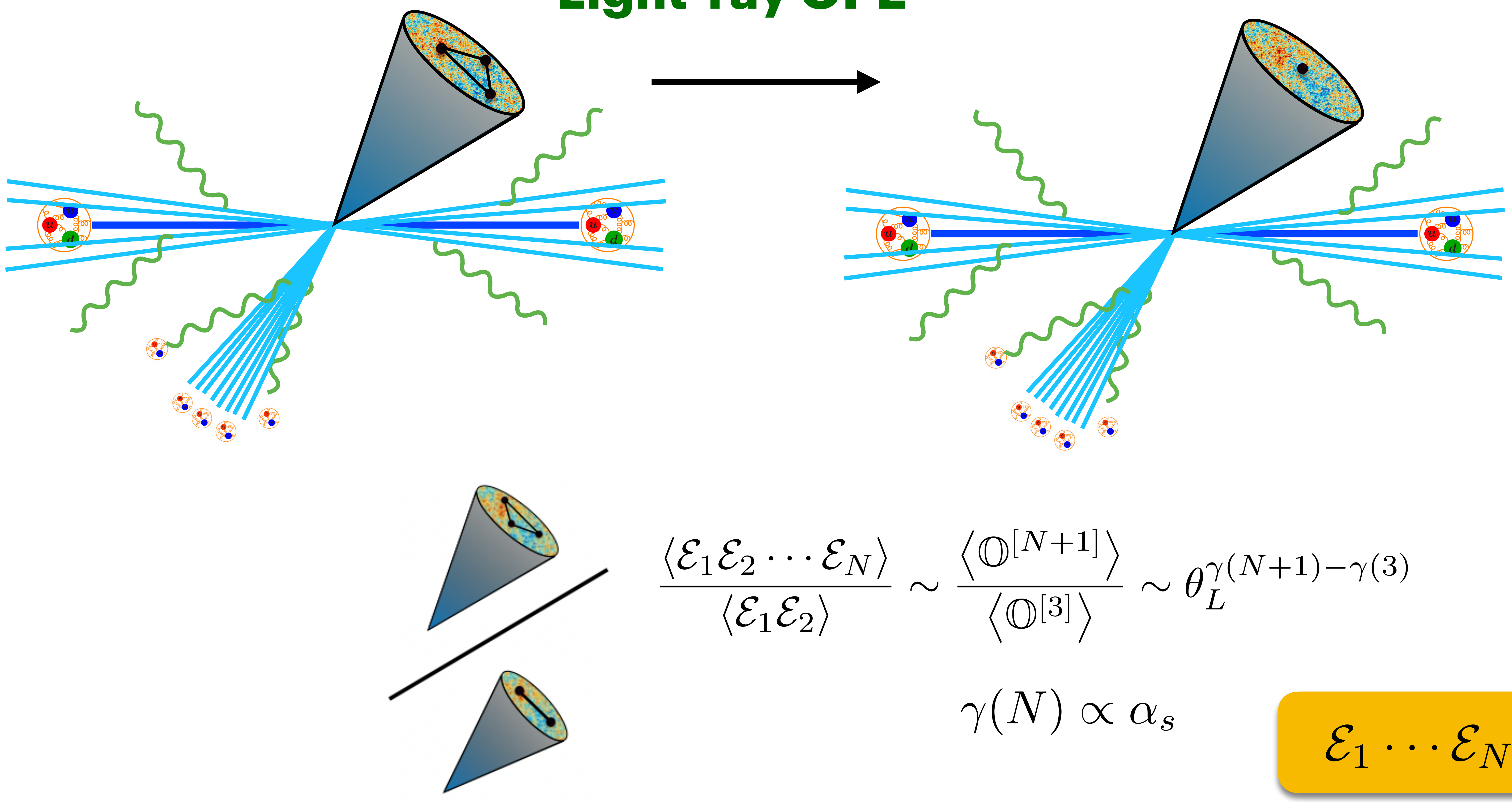
- **Universal scaling of QCD operators revealed in data from ALICE, CMS, and STAR, from 15 GeV to 1784 GeV!**

THE SPECTRUM OF A JET

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

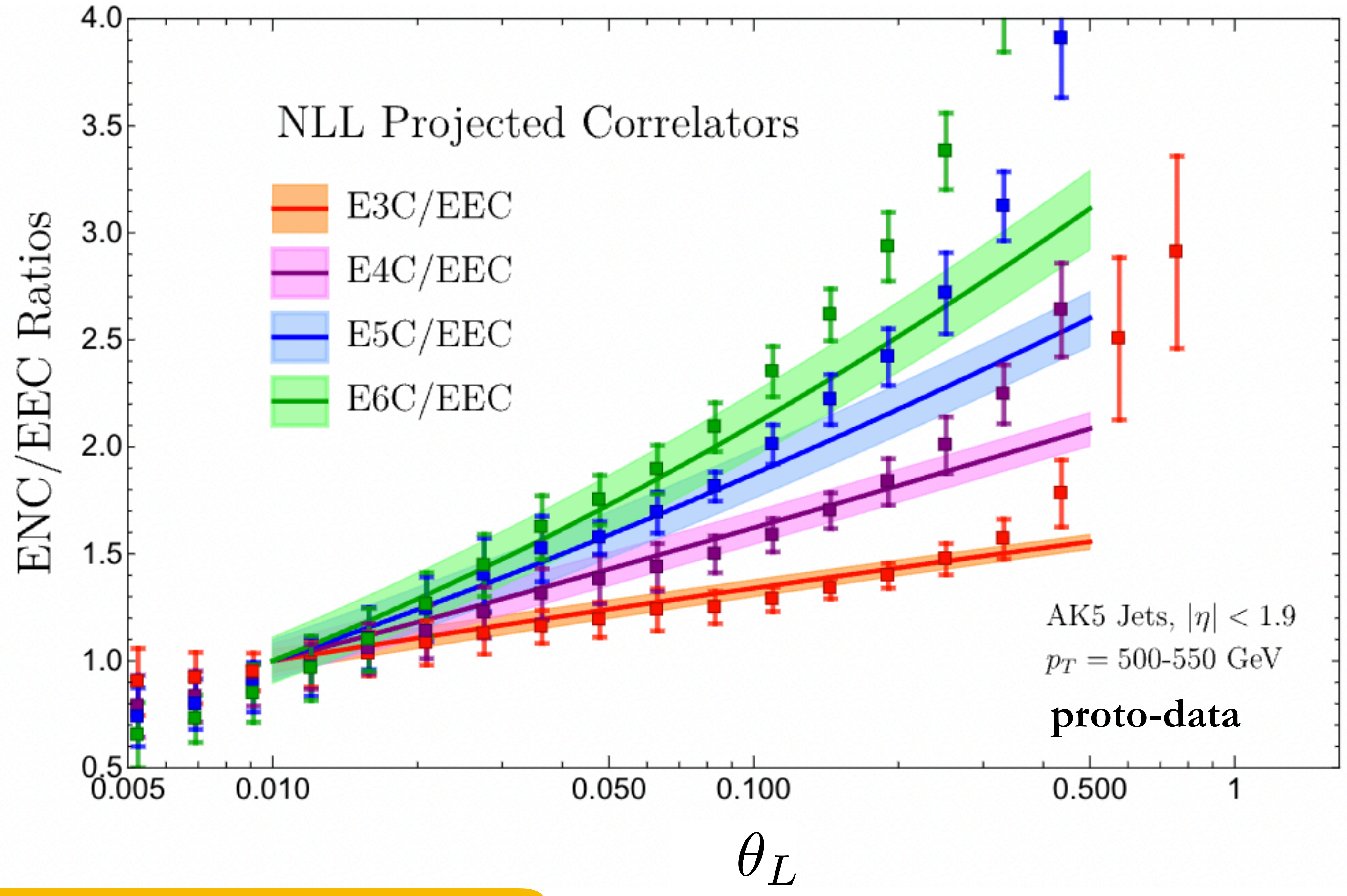
Chen, Moult, Zhang, Zhu `20
KL, Meçaj, Moult `22
Chen, Gao, Li, Xu, Zhang, Zhu `23

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



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

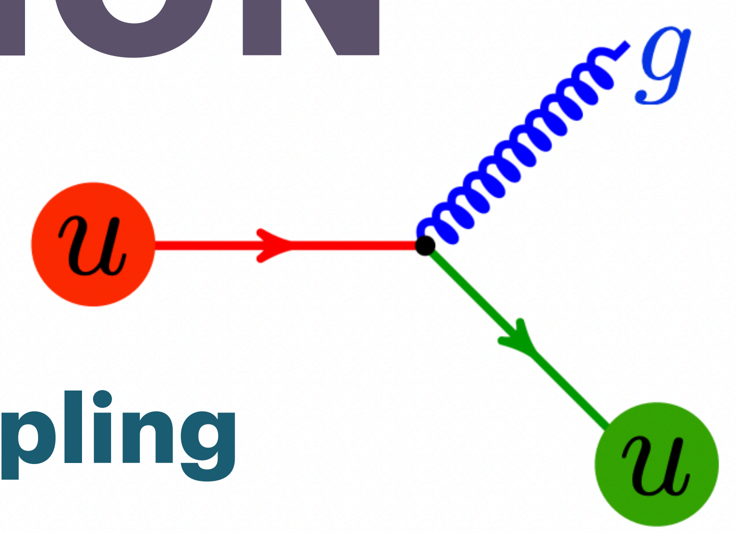
$$\gamma(N)\propto\alpha_s$$



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

quantum classical

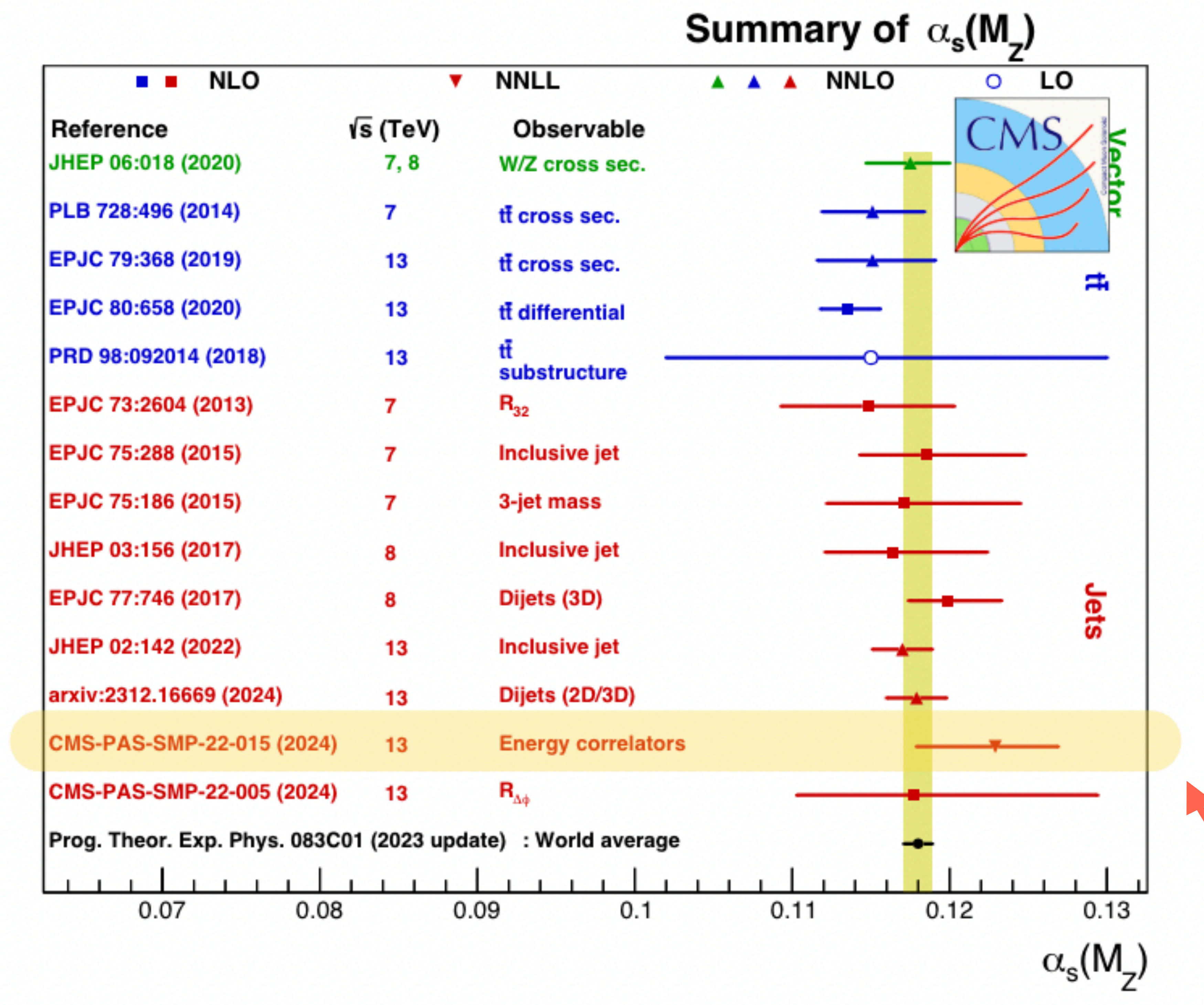
STRONG COUPLING DETERMINATION



- **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**

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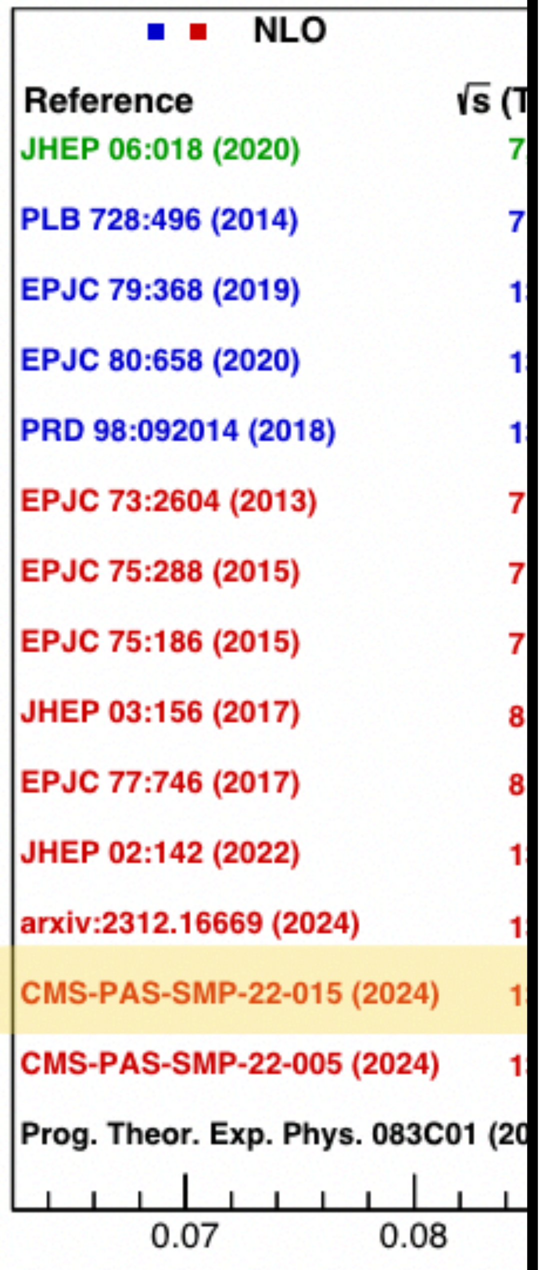
ROAD TO IMPROVED PRECISION



Road to precision

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

tion

3

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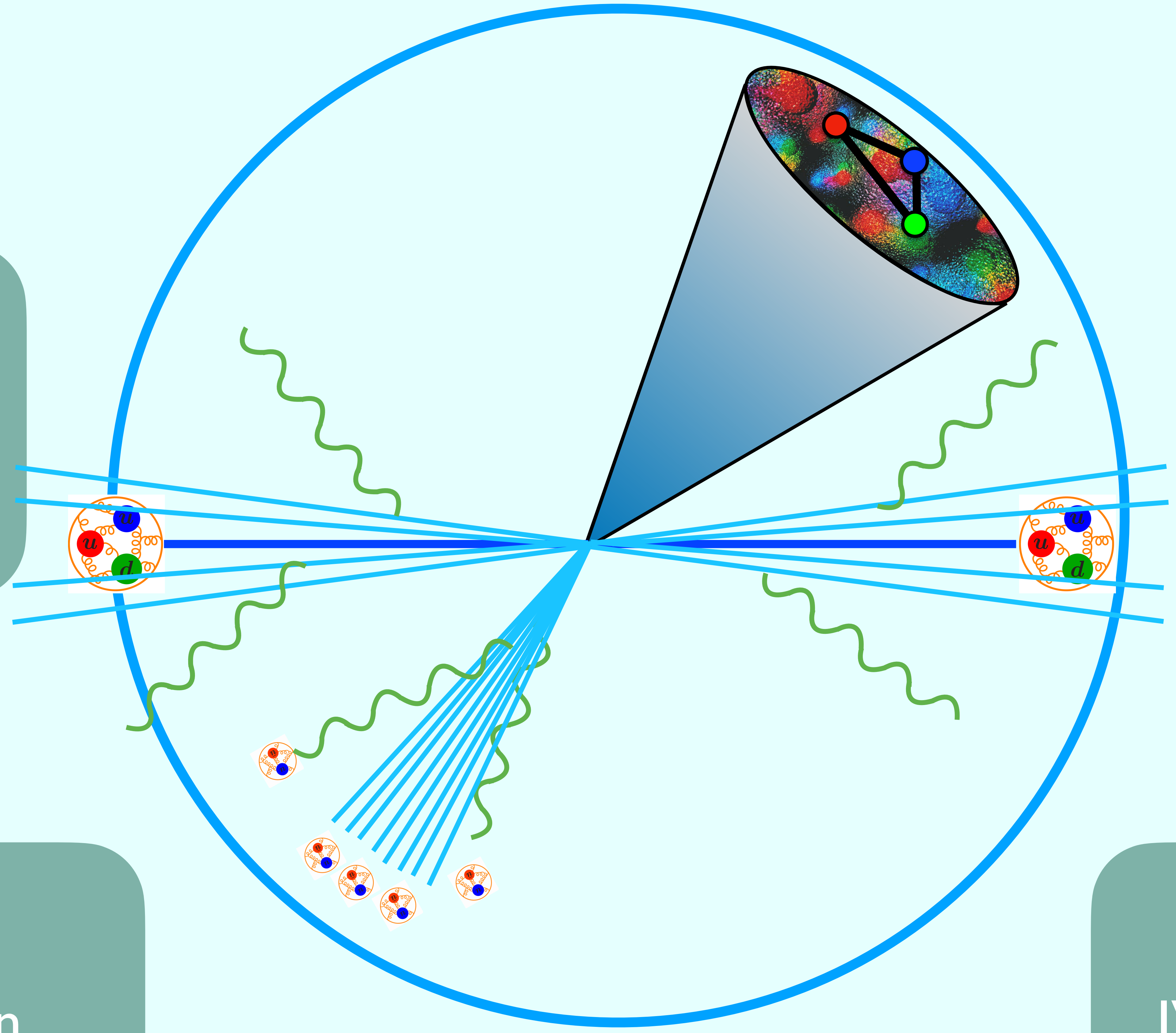


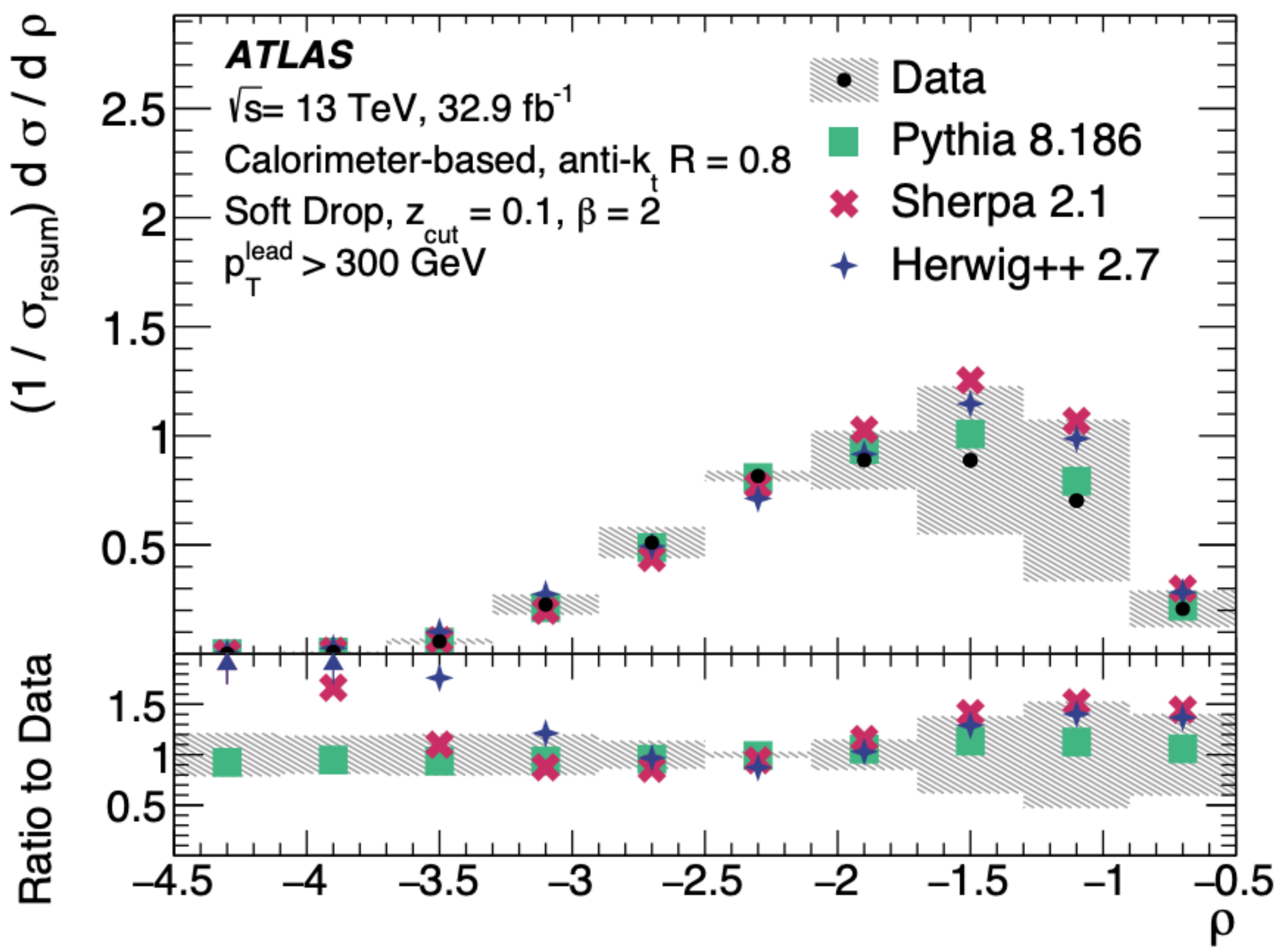
III. Heavy Flavor Physics

V. Hadronization

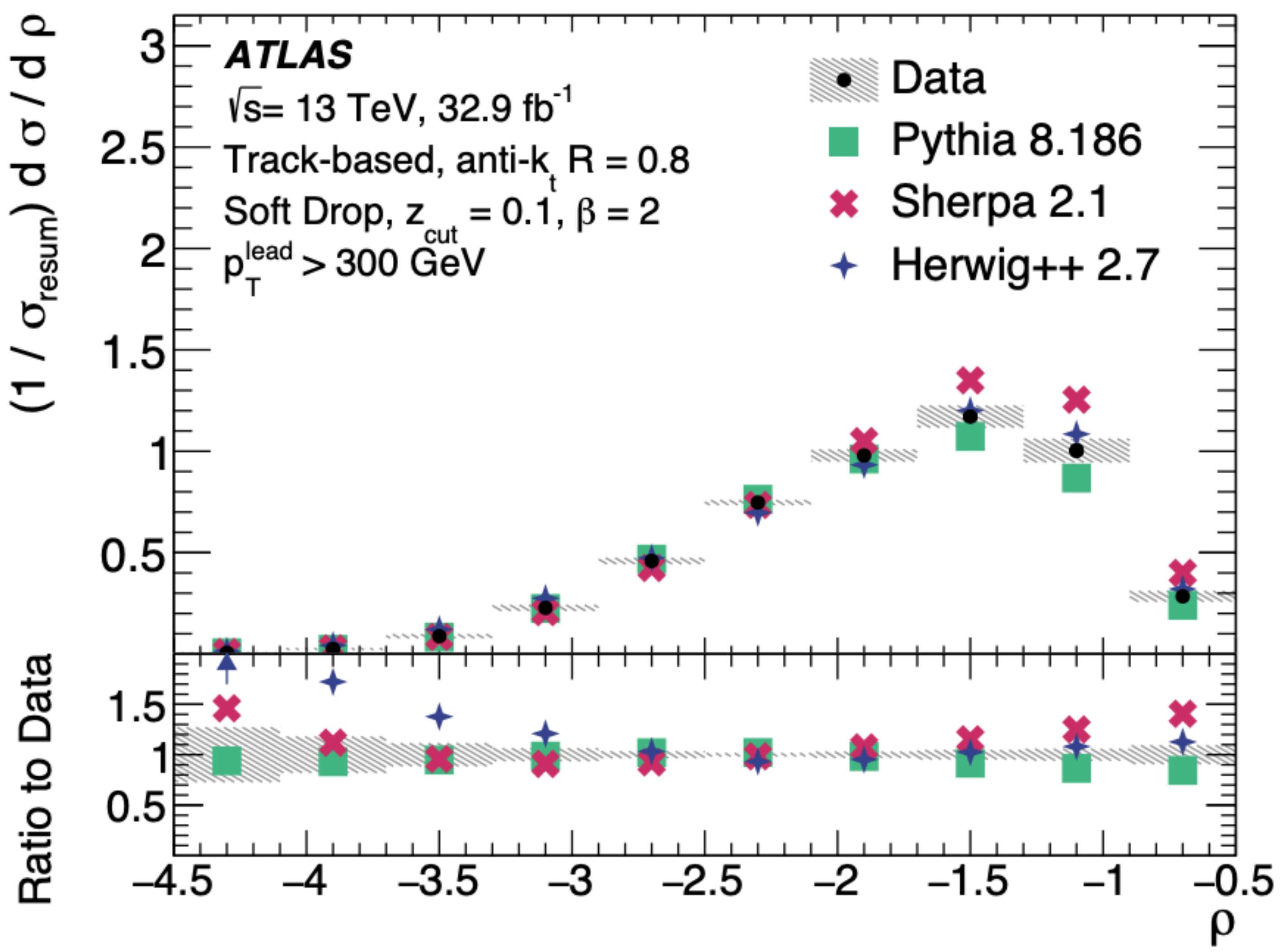
IV. Medium Dynamics

MEASURING TRACKS

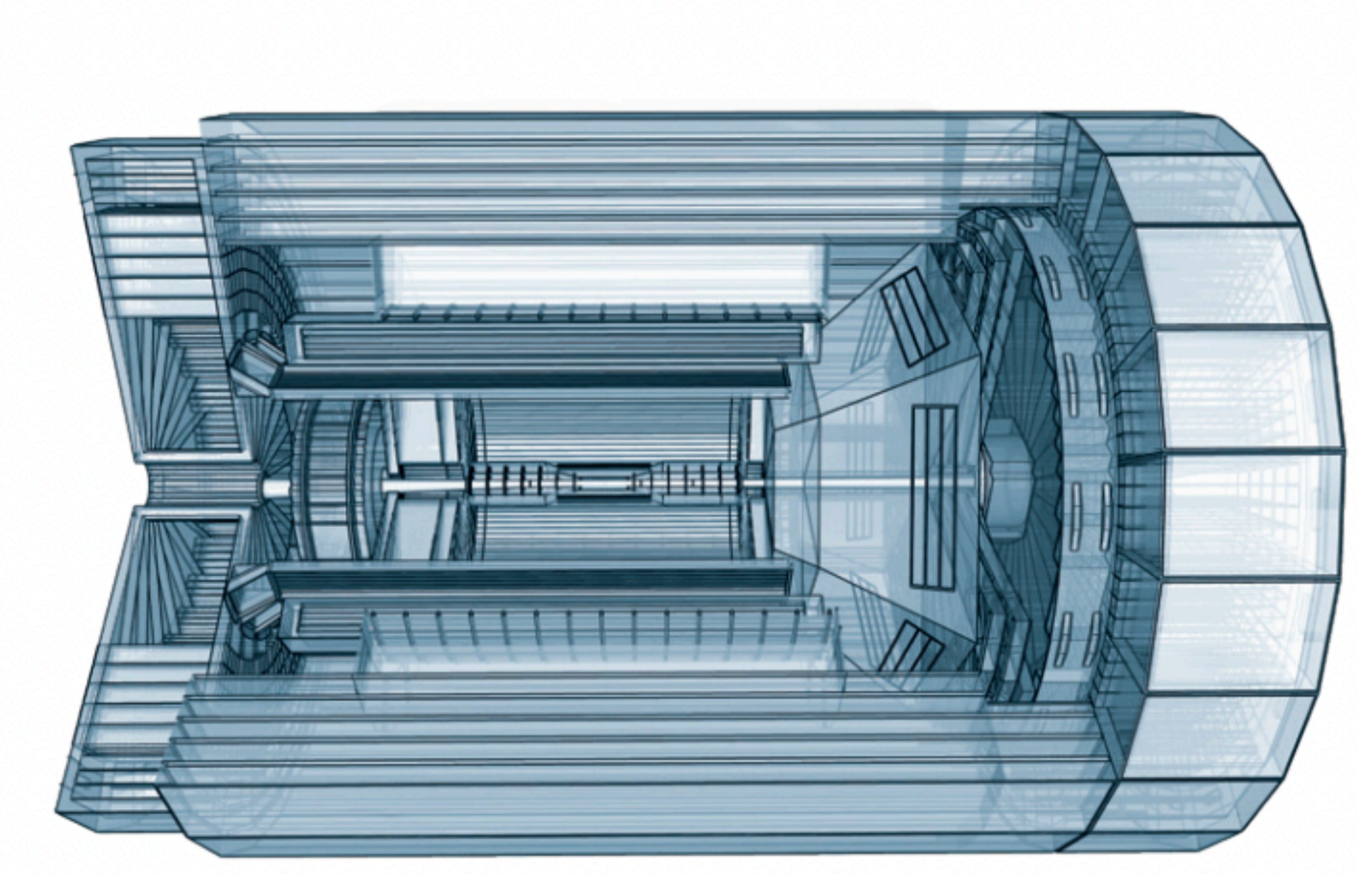
- Measuring tracks provides much more precise experimental results



All particles



Tracks



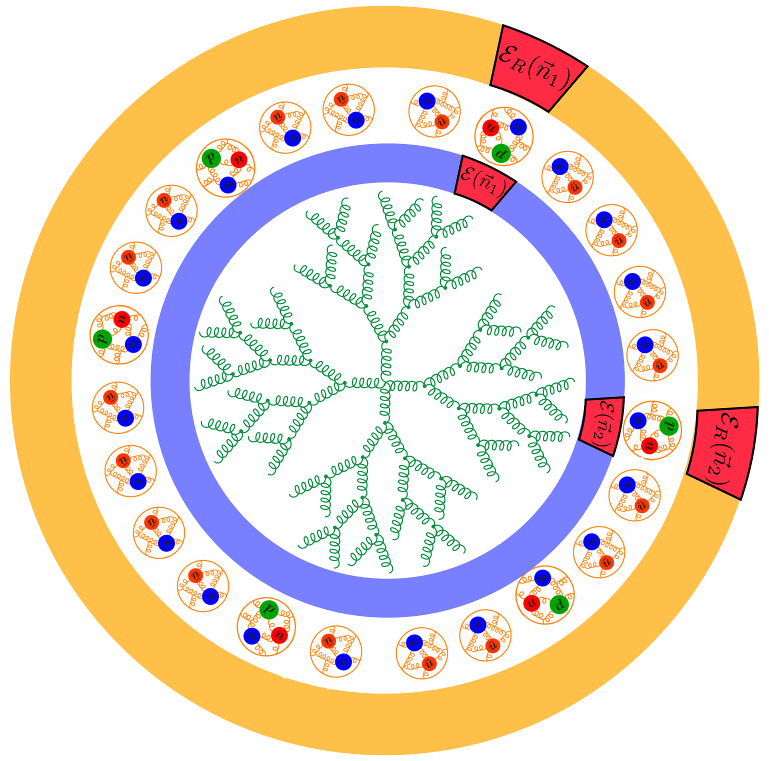
EIC detector

EIC will 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

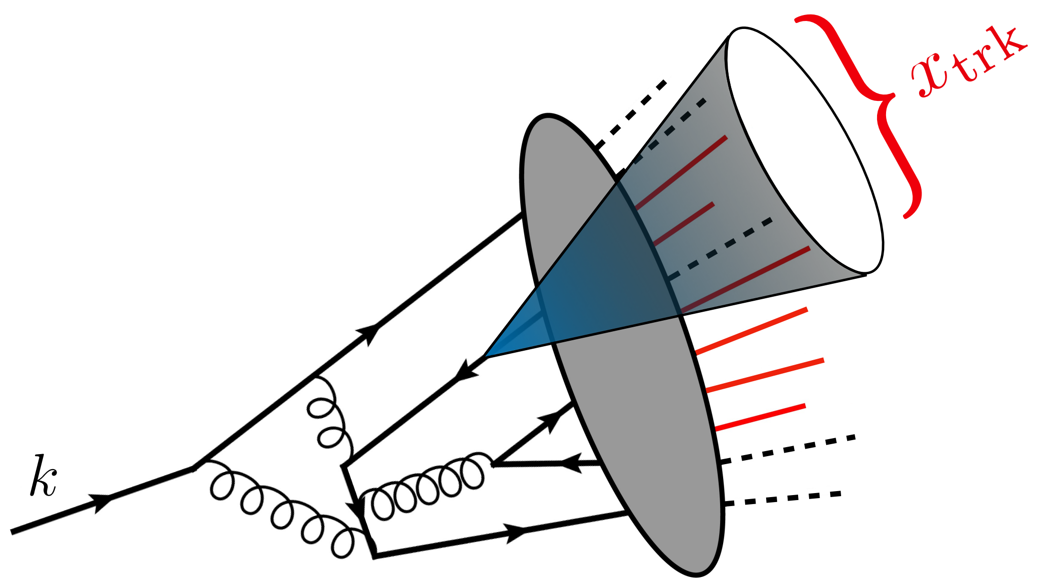


TRACK INSIDE JETS

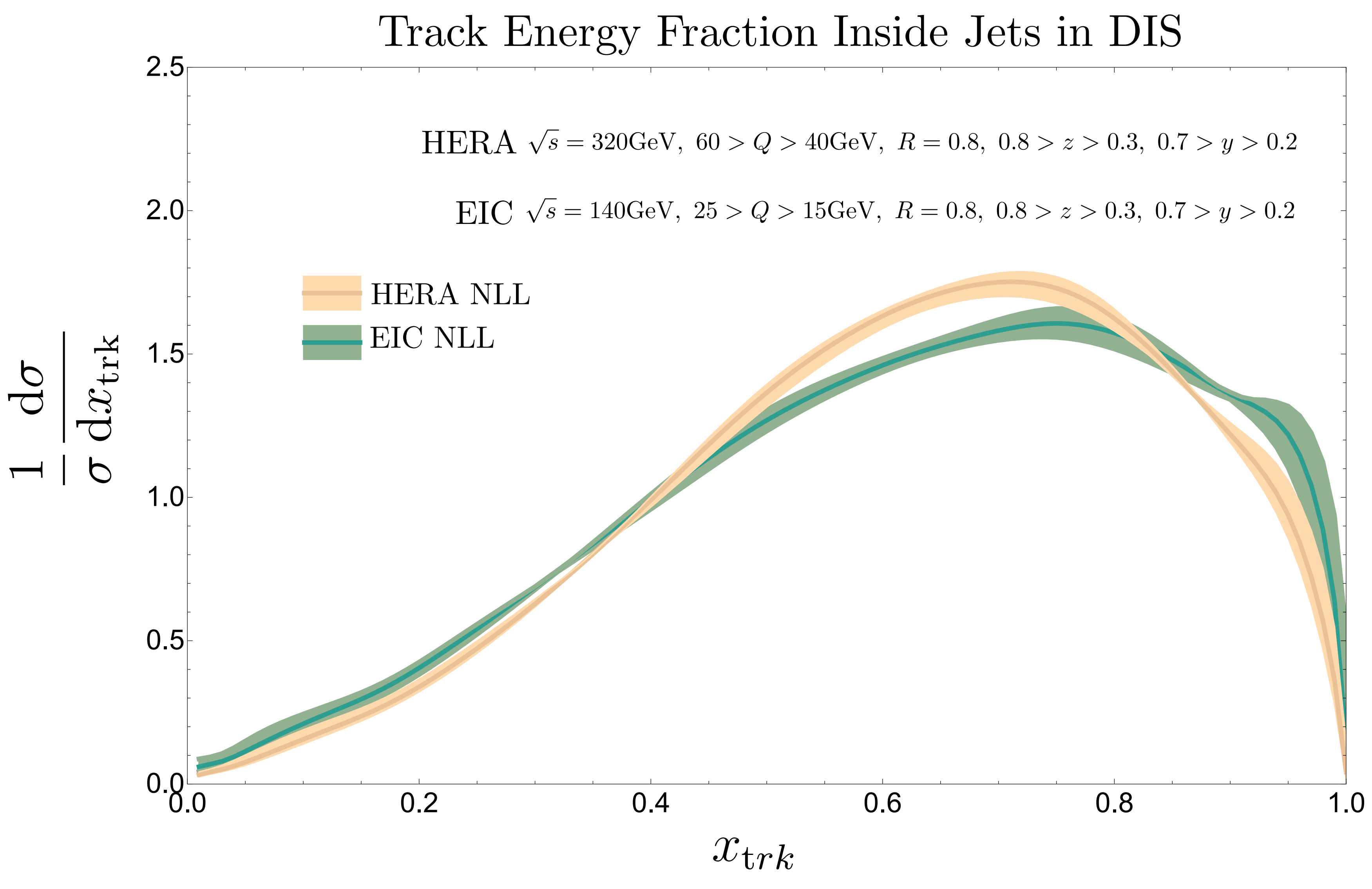
QCD factorization:

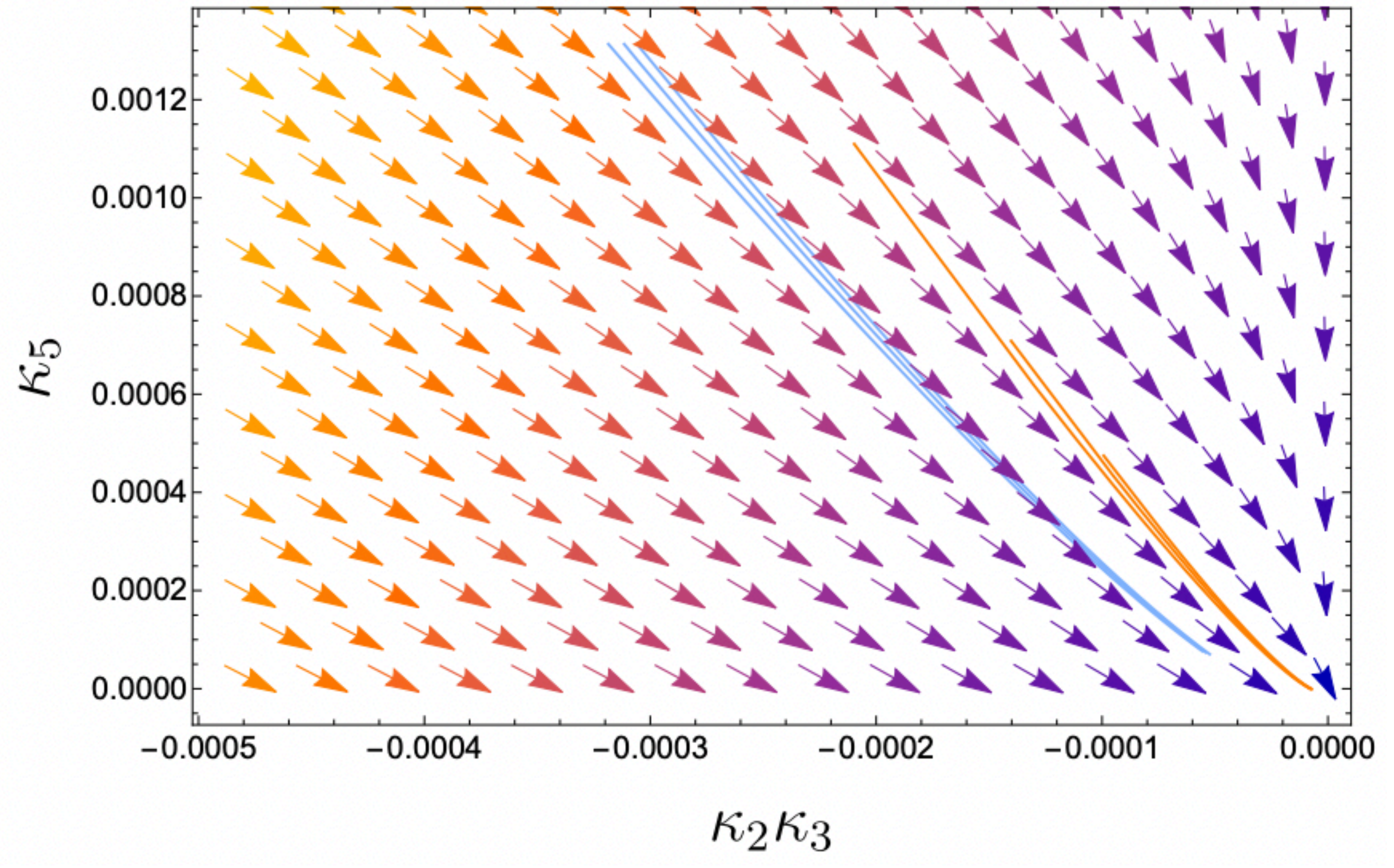
Requires separation of parts that are perturbative from universal non-perturbative functions

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



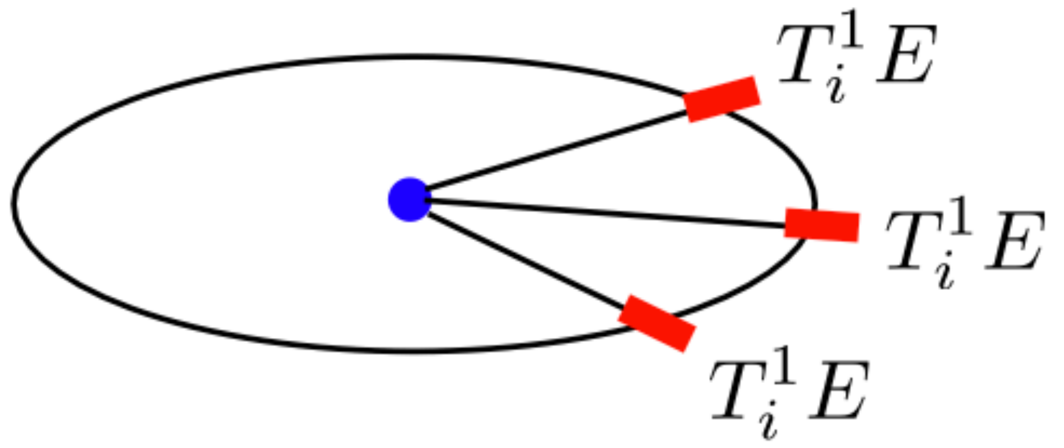
Chang, Procura, Thaler, Waalewijn `13
Jaarsma, Li, Moult, Waalewijn, Zhu et al `21, 22
KL, Moult, Ringer, Waalewijn `23
KL, Moult `23





ENERGY CORRELATORS ON TRACK

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



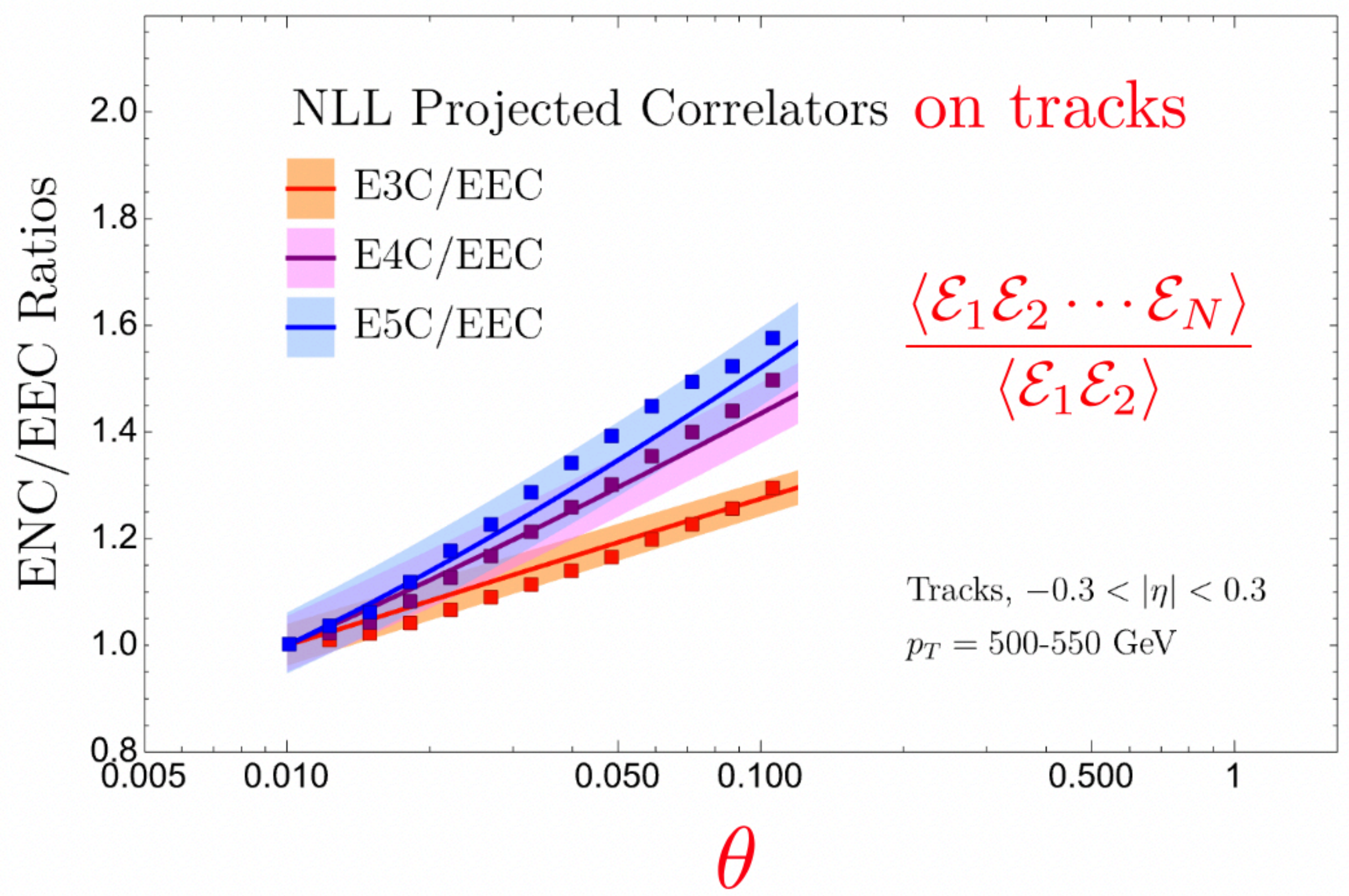
$$\langle \mathcal{E}_R(\vec{n}_1)\,\mathcal{E}_R(\vec{n}_2)\cdots\mathcal{E}_R(\vec{n}_k)\rangle = \sum_{i_1,i_2,\cdots i_k} T_{i_1}(1)\cdots T_{i_k}(1)\,\langle \mathcal{E}_{i_1}(\vec{n}_1)\,\mathcal{E}_{i_2}(\vec{n}_2)\cdots\mathcal{E}_{i_k}(\vec{n}_k)\rangle$$

$+$contact terms

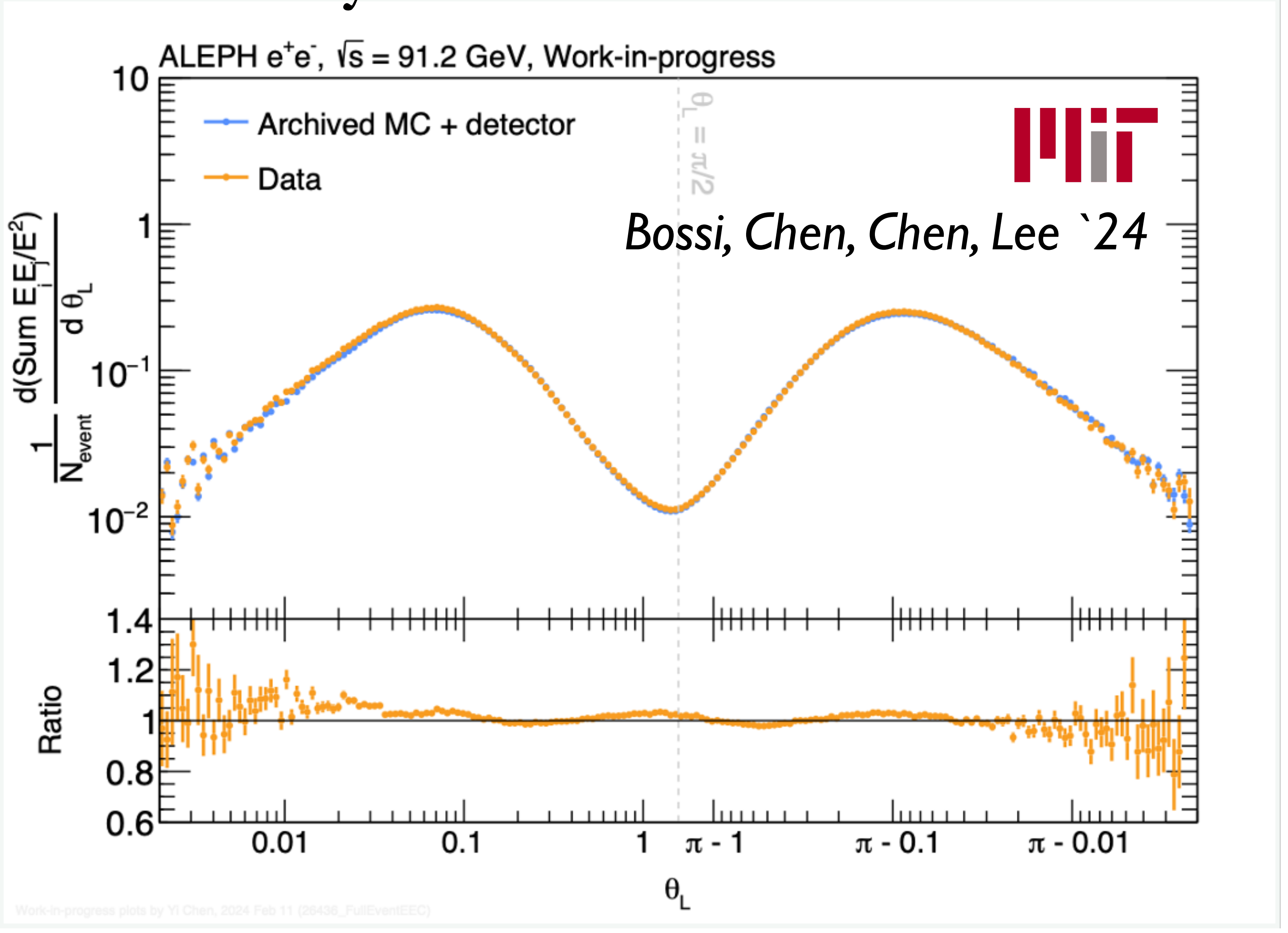
- **Only depends on the "moments" of track functions** $\Longrightarrow$ **Only involves NP *numbers*, not functions**

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



Reanalysis of ALEPH data on tracks



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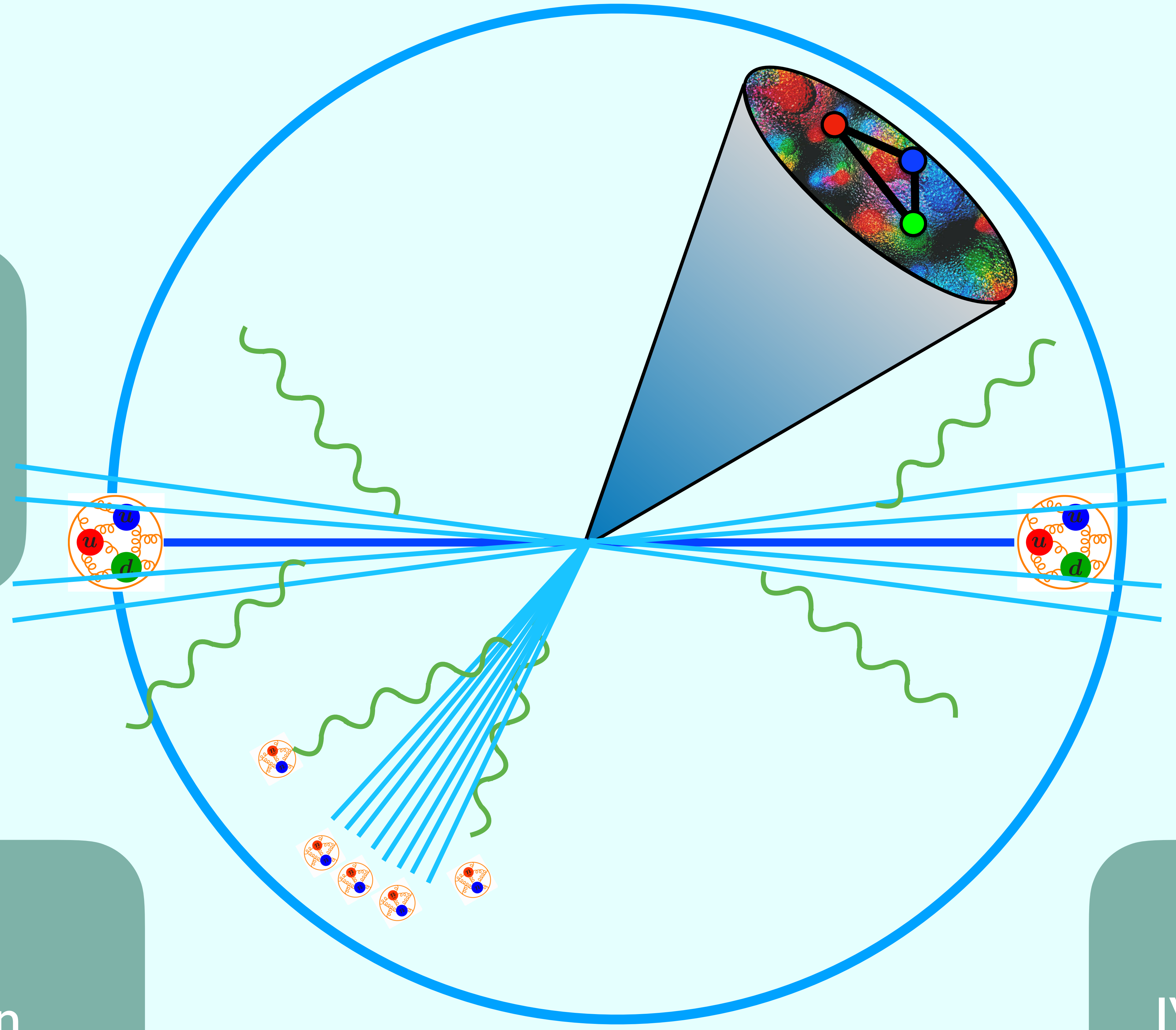


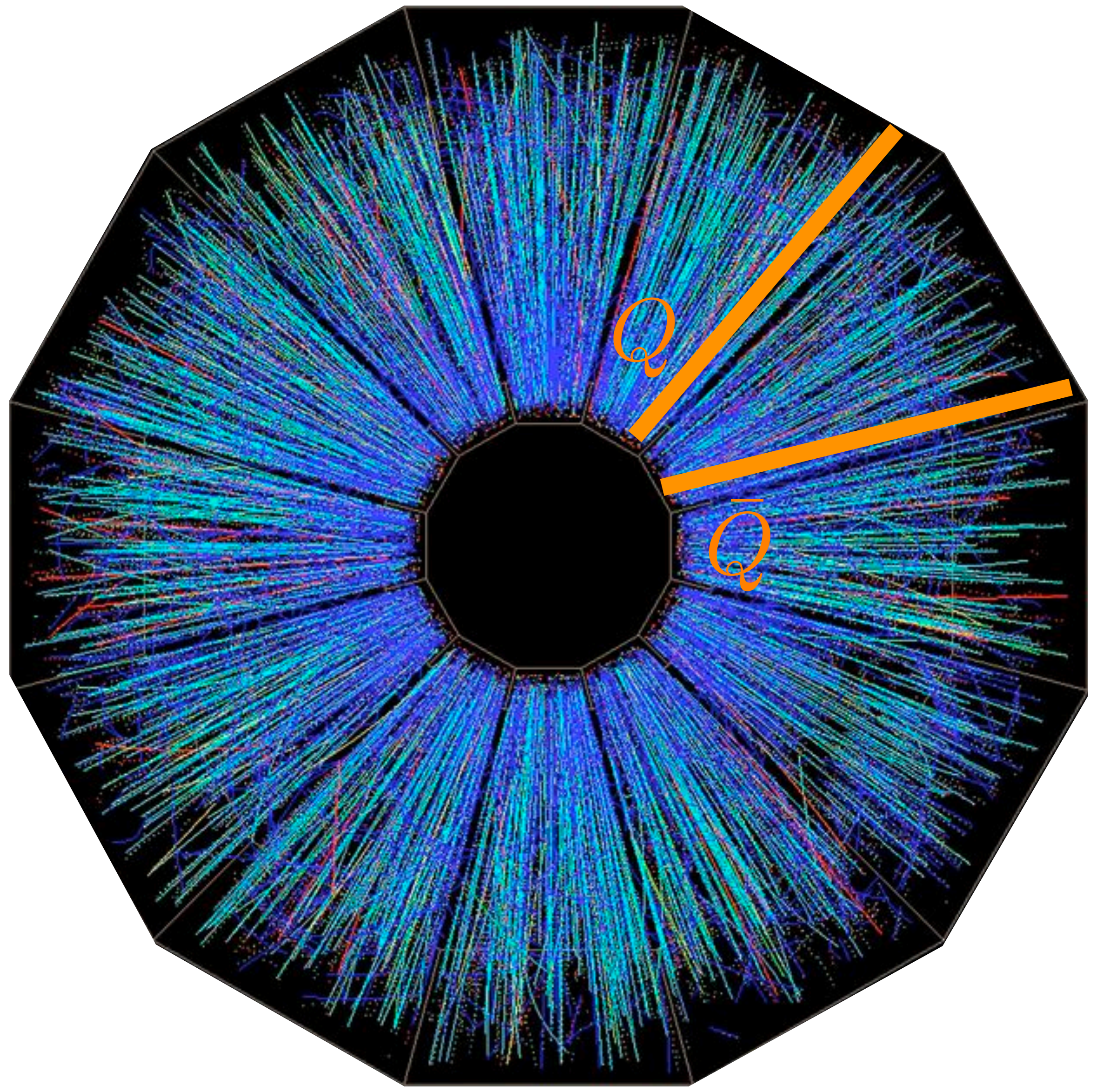
III. Heavy Flavor Physics

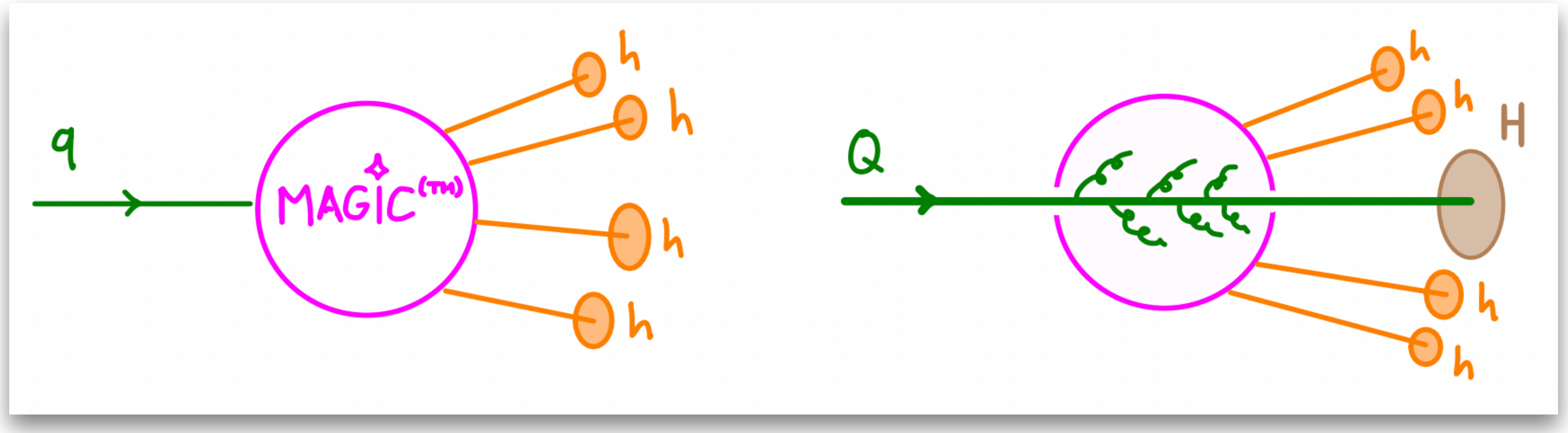
V. Hadronization

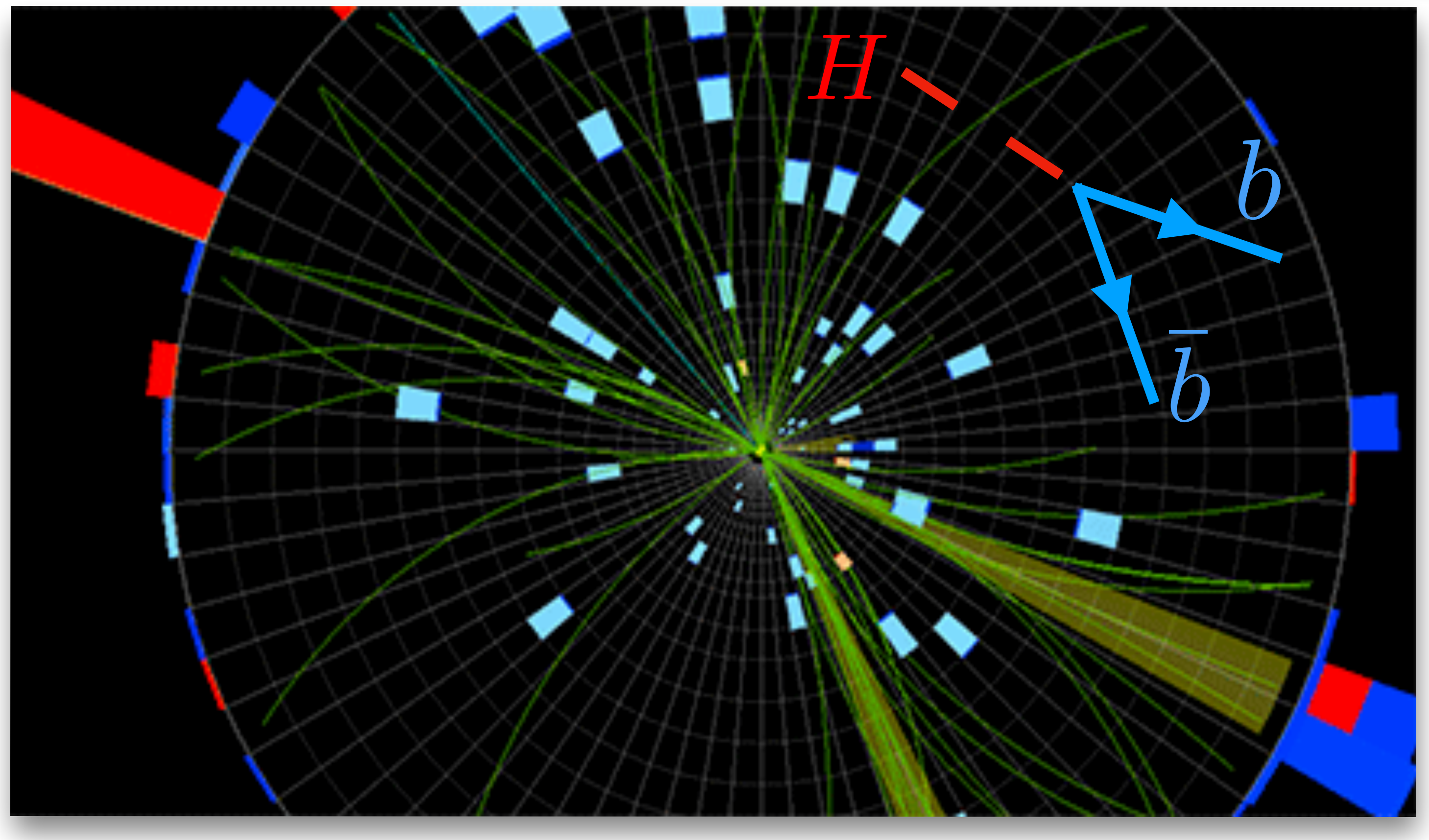
IV. Medium Dynamics

UNRAVELING HEAVY FLAVOR DYNAMICS

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







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!**

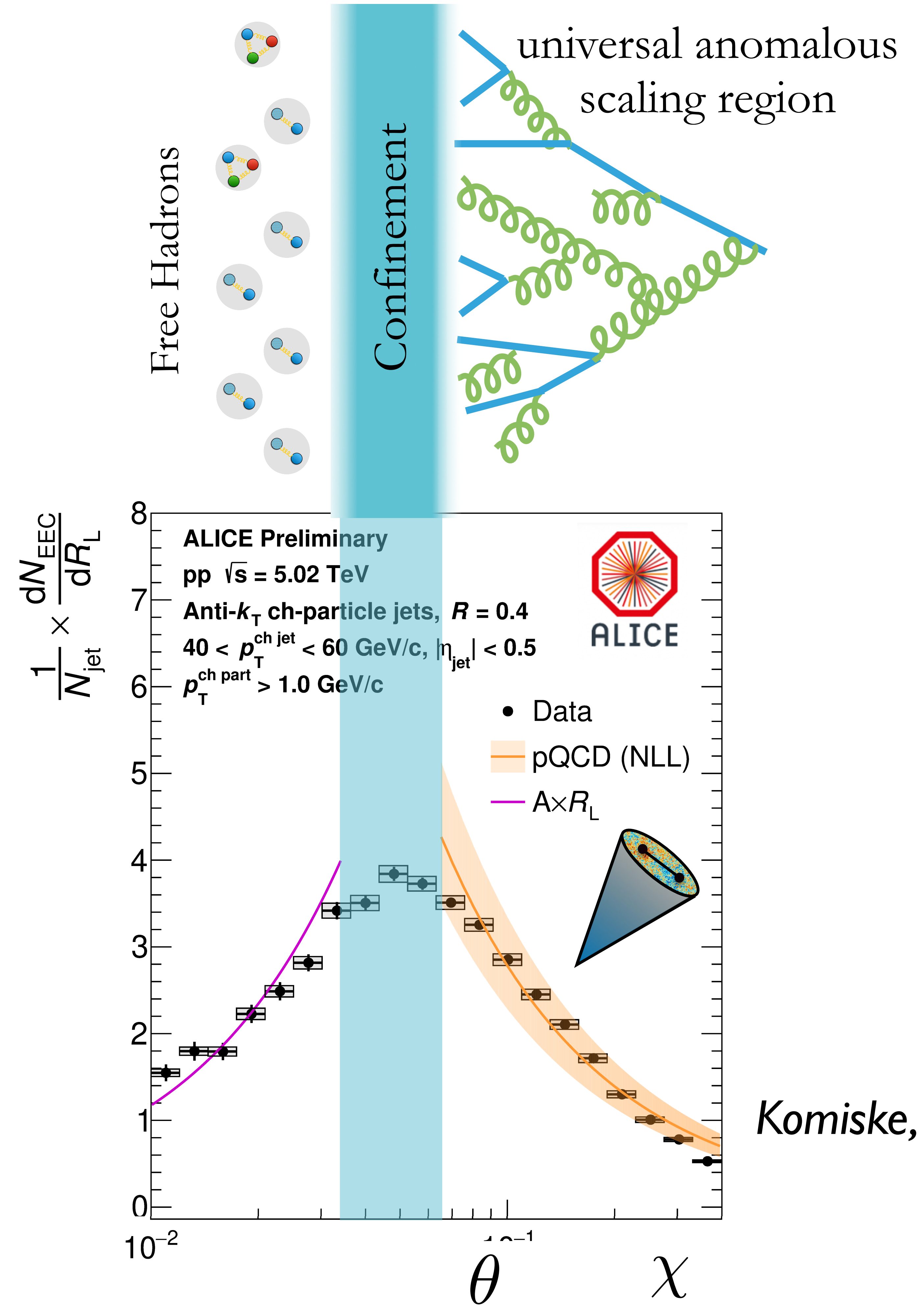
Free hadrons

$$\frac{d\sigma}{d\theta^2} = \text{const}$$

$$\frac{d\sigma}{d\theta} = \text{const} \times 2\theta$$

EEC gives angular scale

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



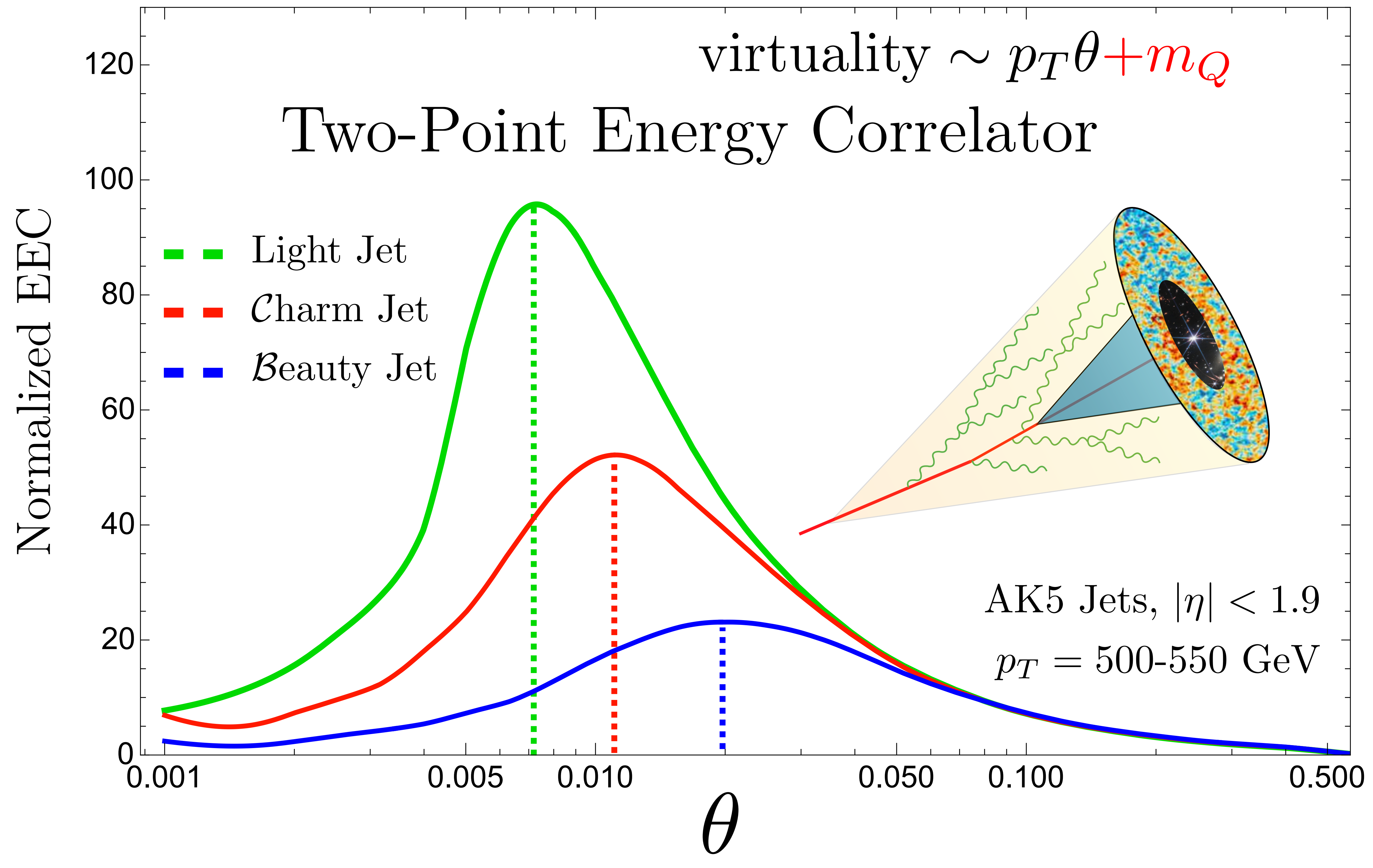
Interacting quarks and gluons

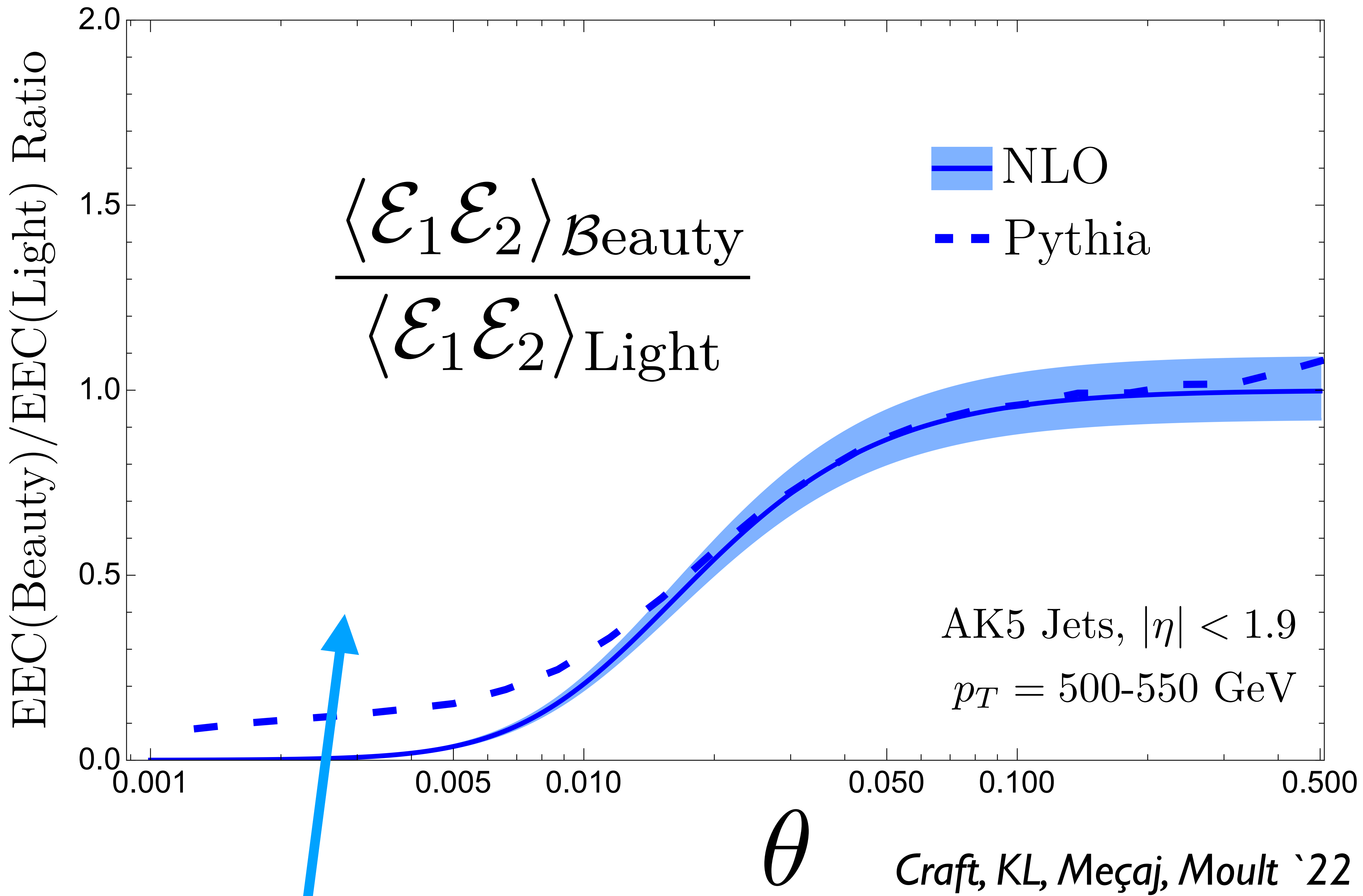
$$\mathcal{E}(\hat{n}_1)\,\mathcal{E}(\hat{n}_2) \sim \sum \theta^{\gamma(3)-2}\mathbb{O}_i(\hat{n}_1)$$

KL, Meçaj, Moult \`22
Komiske, Moult, Thaler, Zhu \`22
ALICE \`23

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**





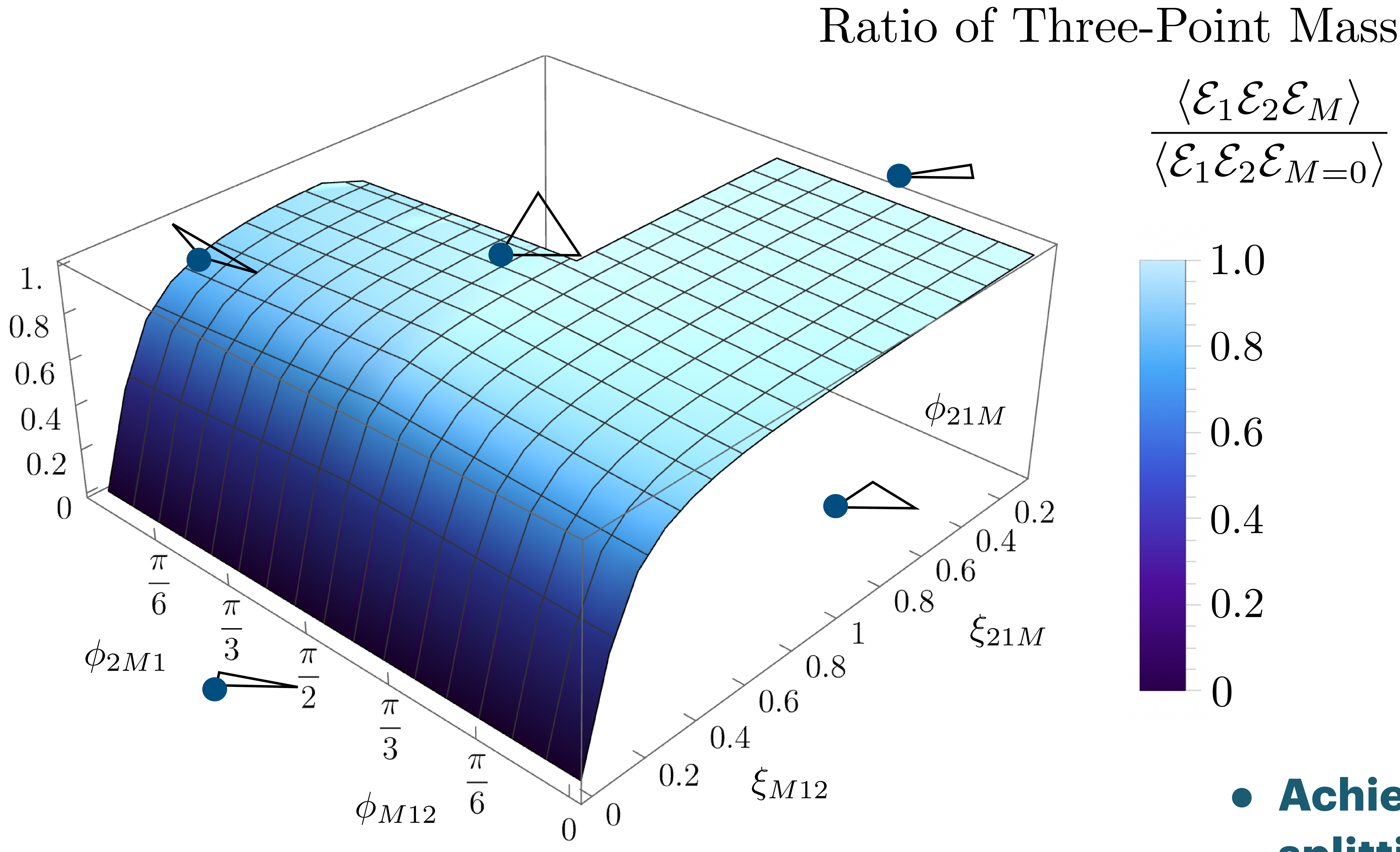
Craft, KL, Meçaj, Moult `22

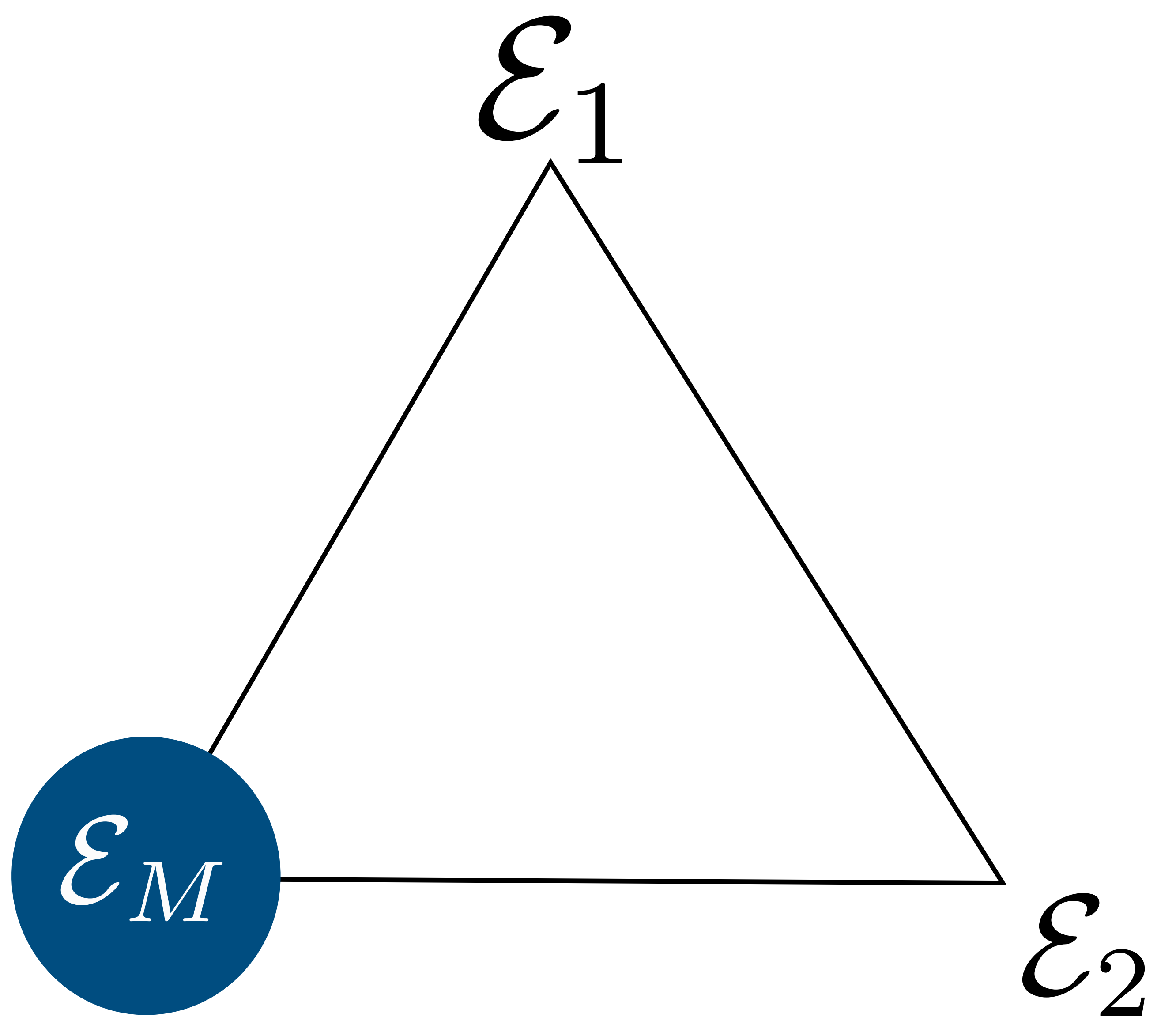
- **Ratio of the two-point correlators clearly shows the dead-cone region around** $\theta \lesssim \frac{m_Q}{E}$

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**

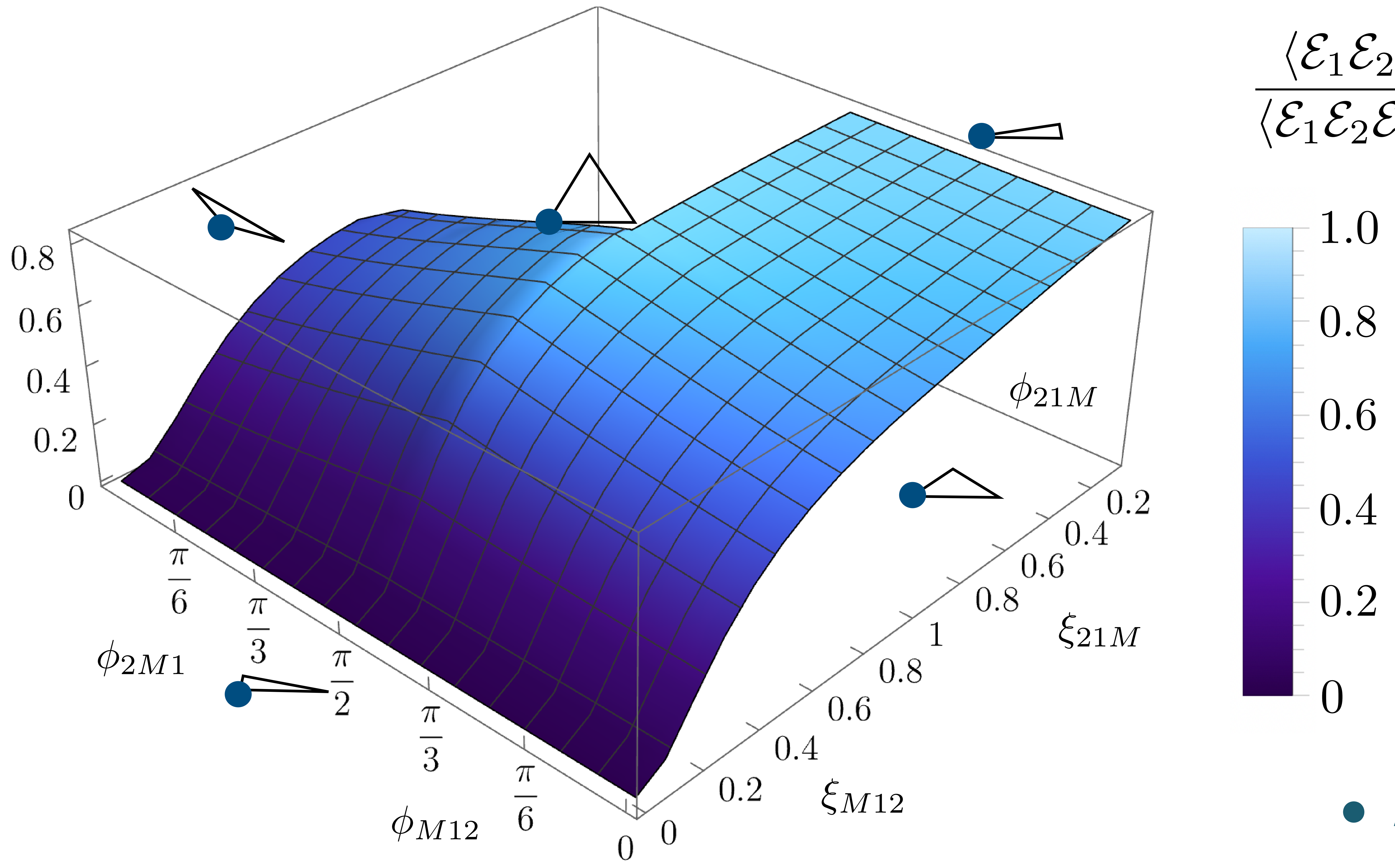
PROBING THE DYNAMICS OF THE DEAD-CONE

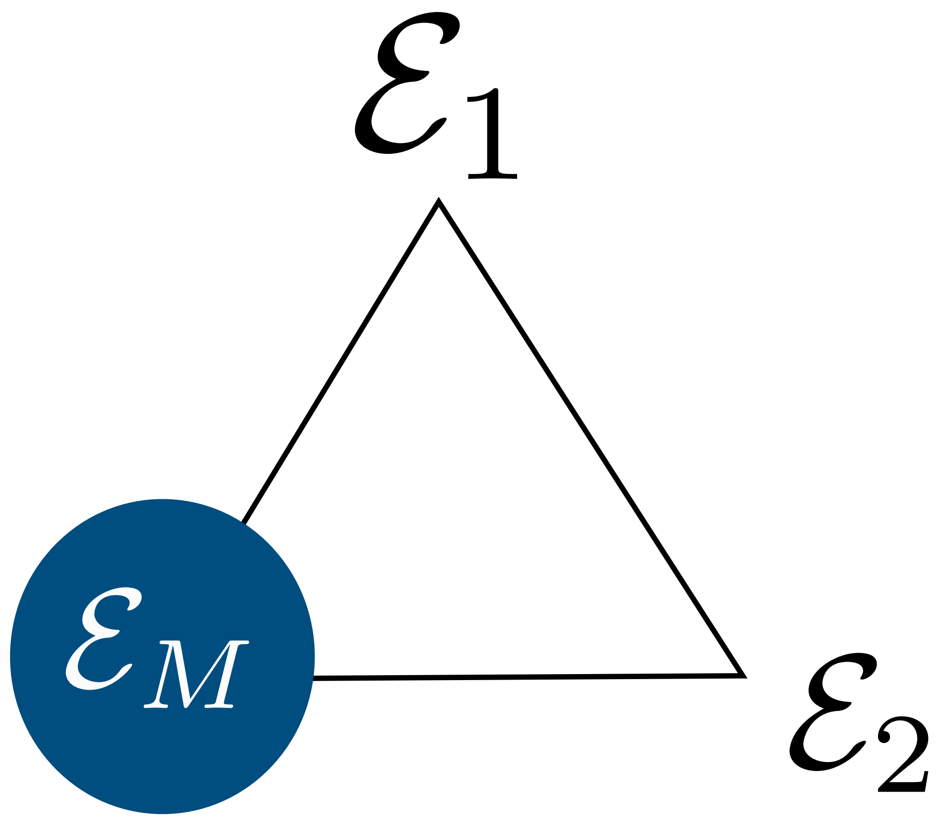
- **Application: three-point correlations probe the non-trivial dynamics of the dead-cone**

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

Ratio of Three-Point Massive Correlators

$$\frac{\langle \mathcal{E}_1 \mathcal{E}_2 \mathcal{E}_M \rangle}{\langle \mathcal{E}_1 \mathcal{E}_2 \mathcal{E}_{M=0} \rangle}$$





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

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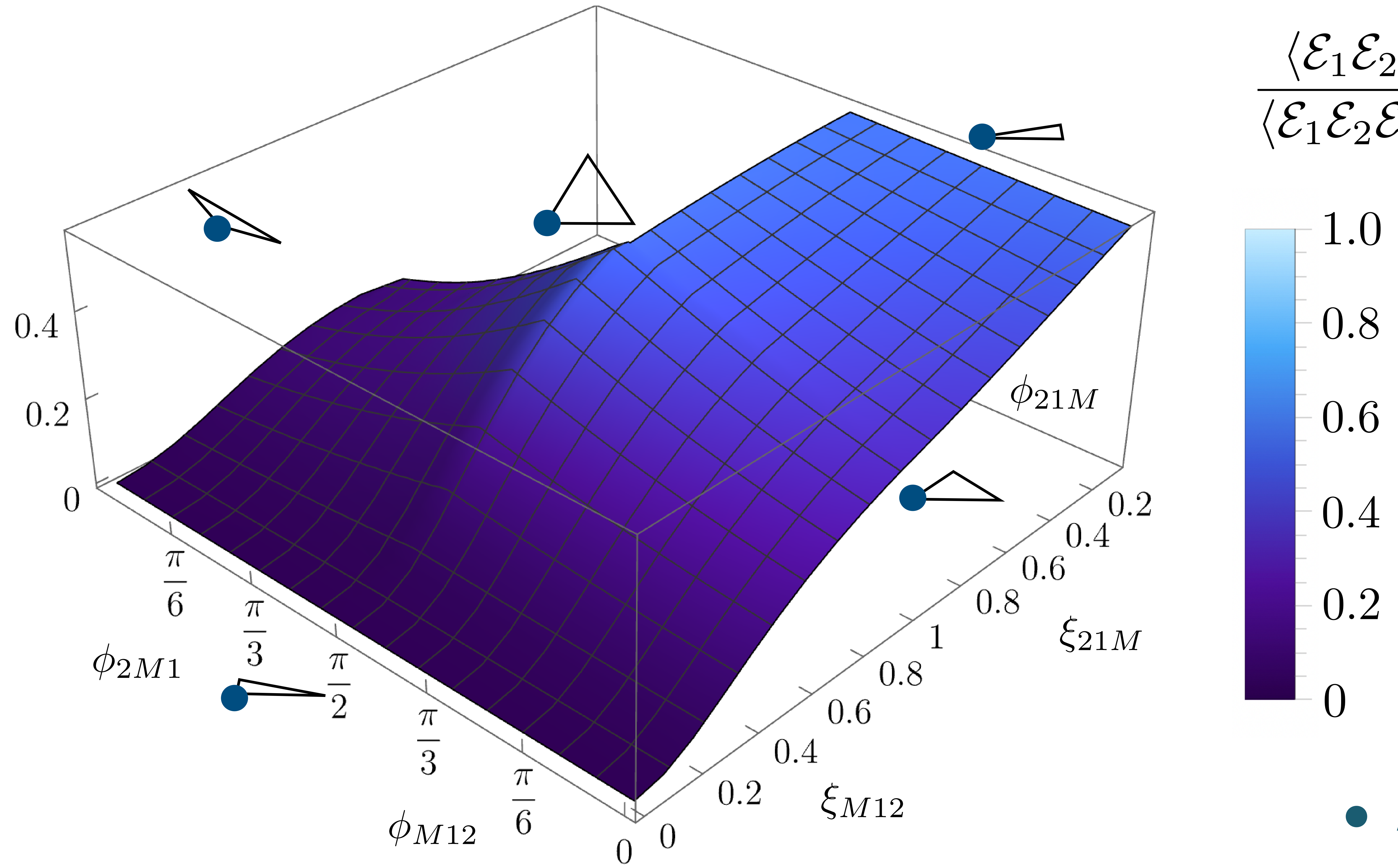

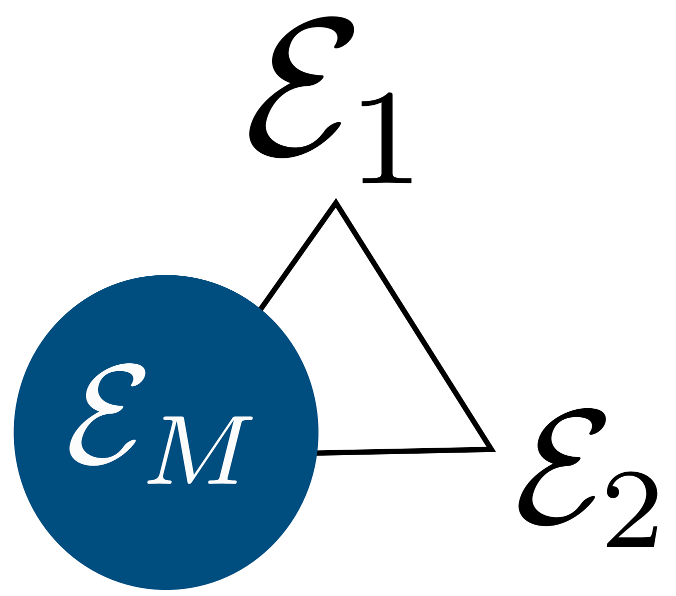

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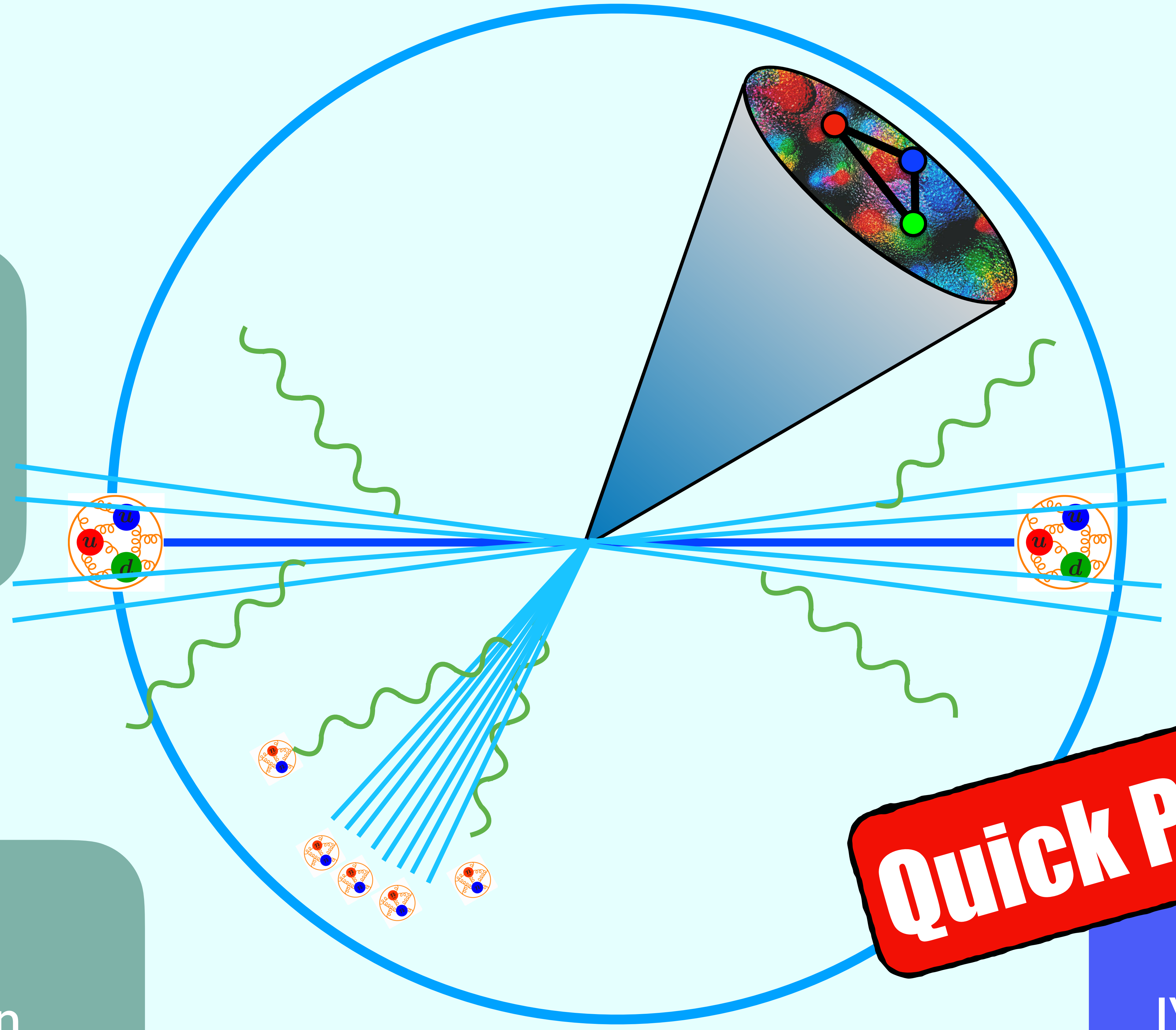


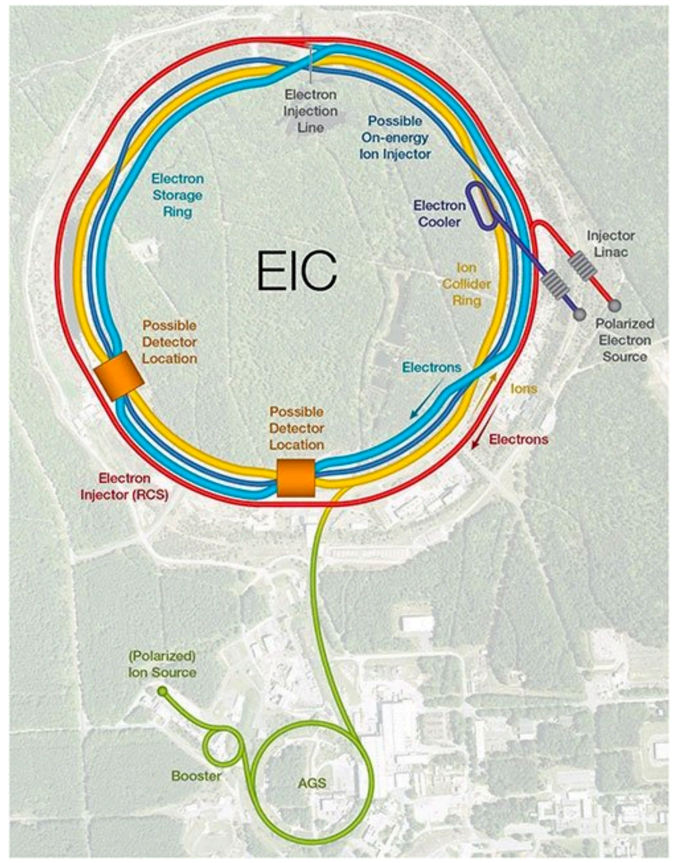
III. Heavy Flavor Physics

V. Hadronization

Quick Peek

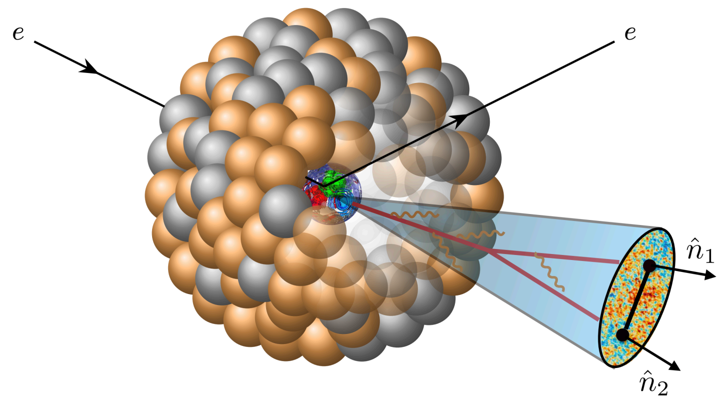
IV. Medium Dynamics

RESOLVING THE FEMTOSCALE IN JETS

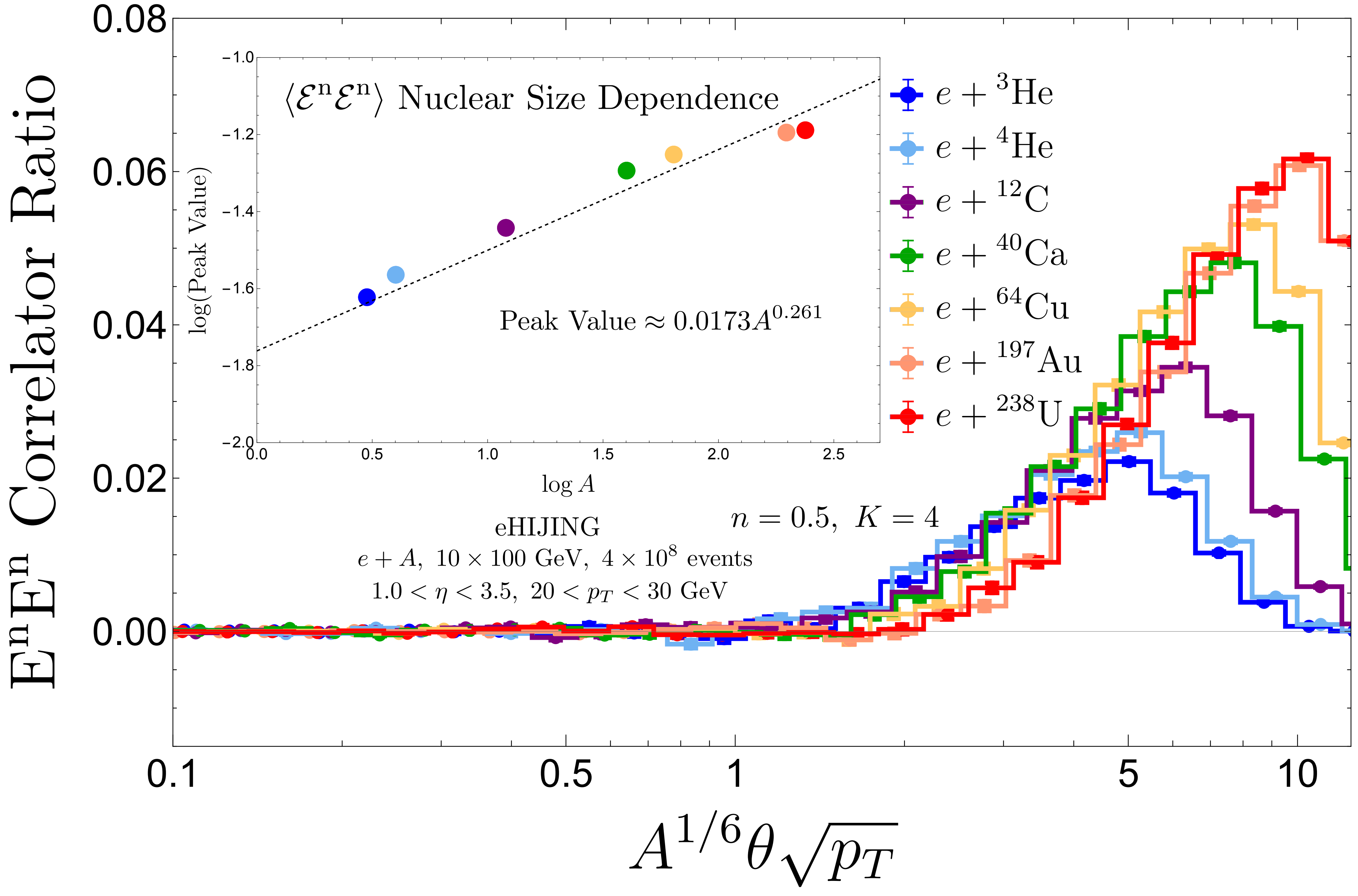


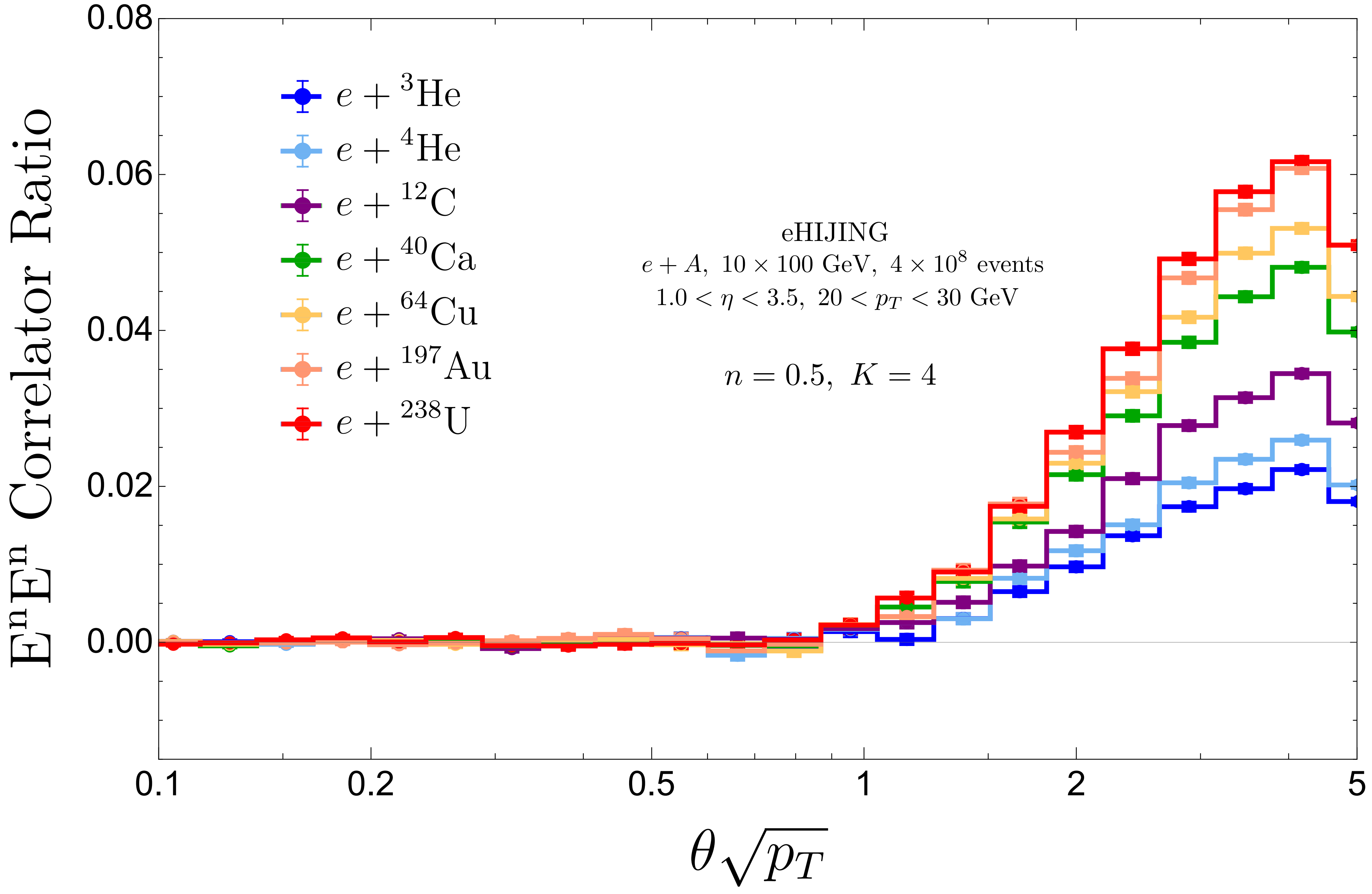
Devereaux, Fan, Ke, KL, Moult `23

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



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





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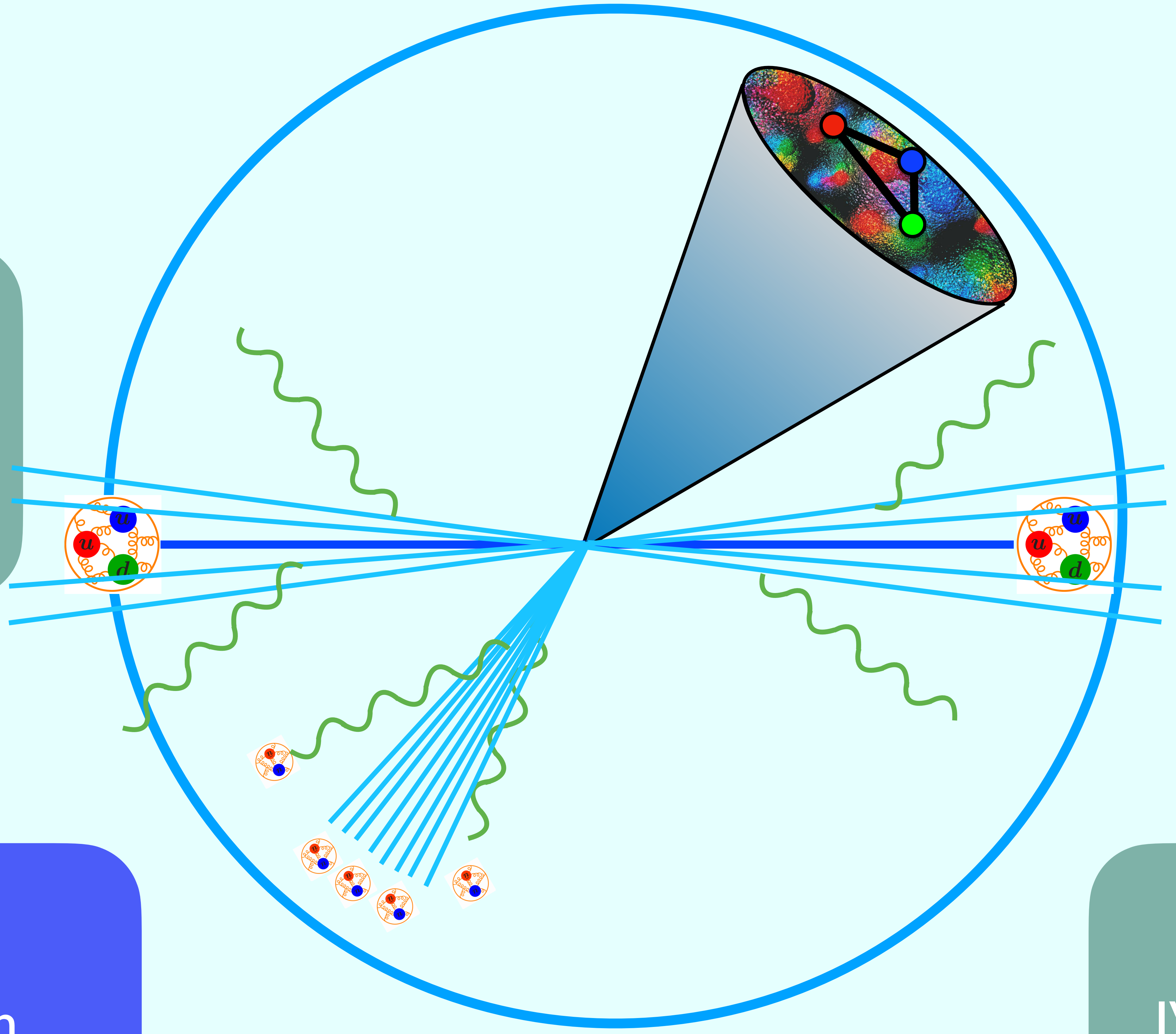

III. Heavy Flavor Physics

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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

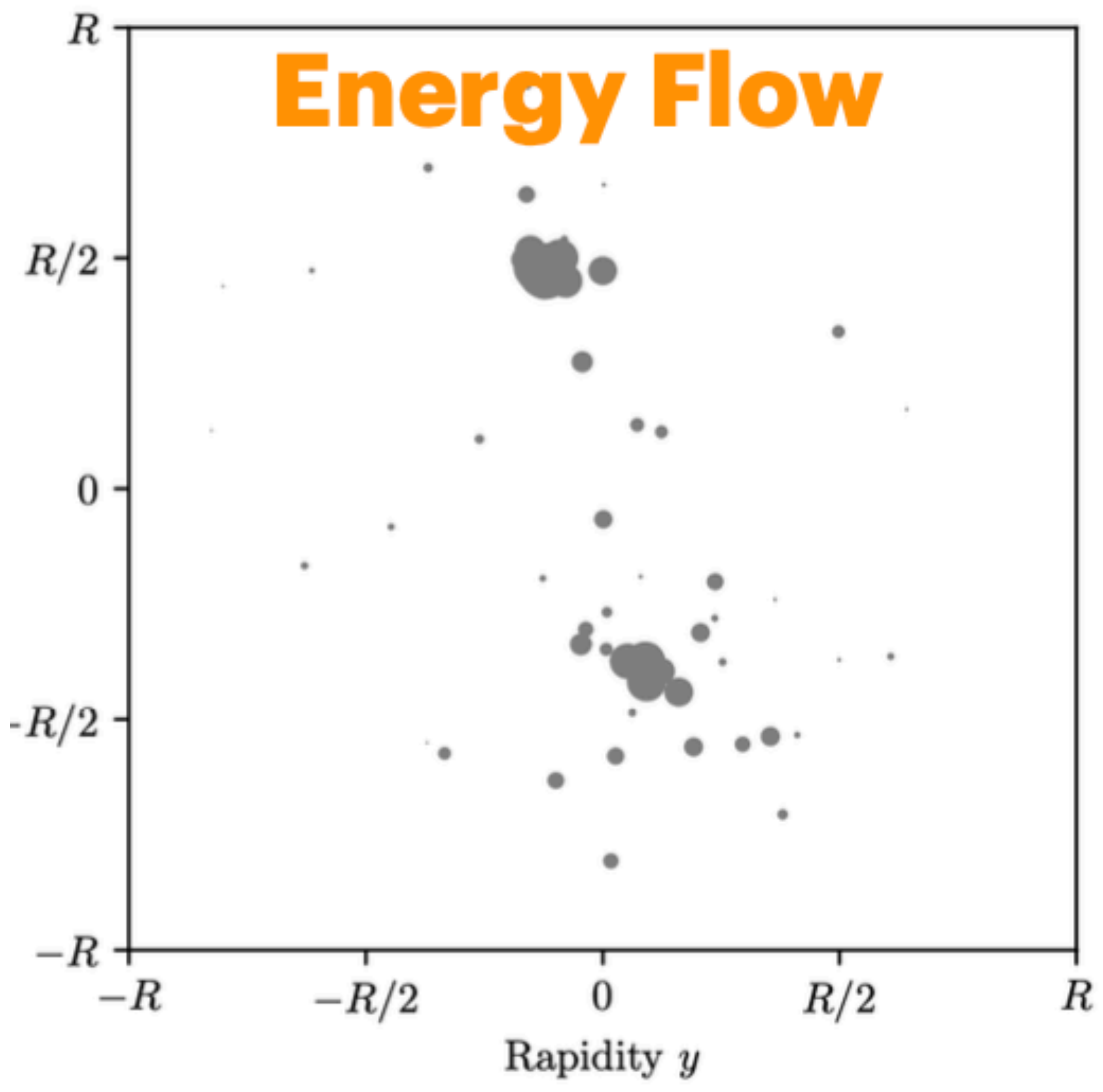
- **Interesting measurements of energy flow can be made on a restricted set of hadronic states, R, for example, charged hadrons (tracks)**

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

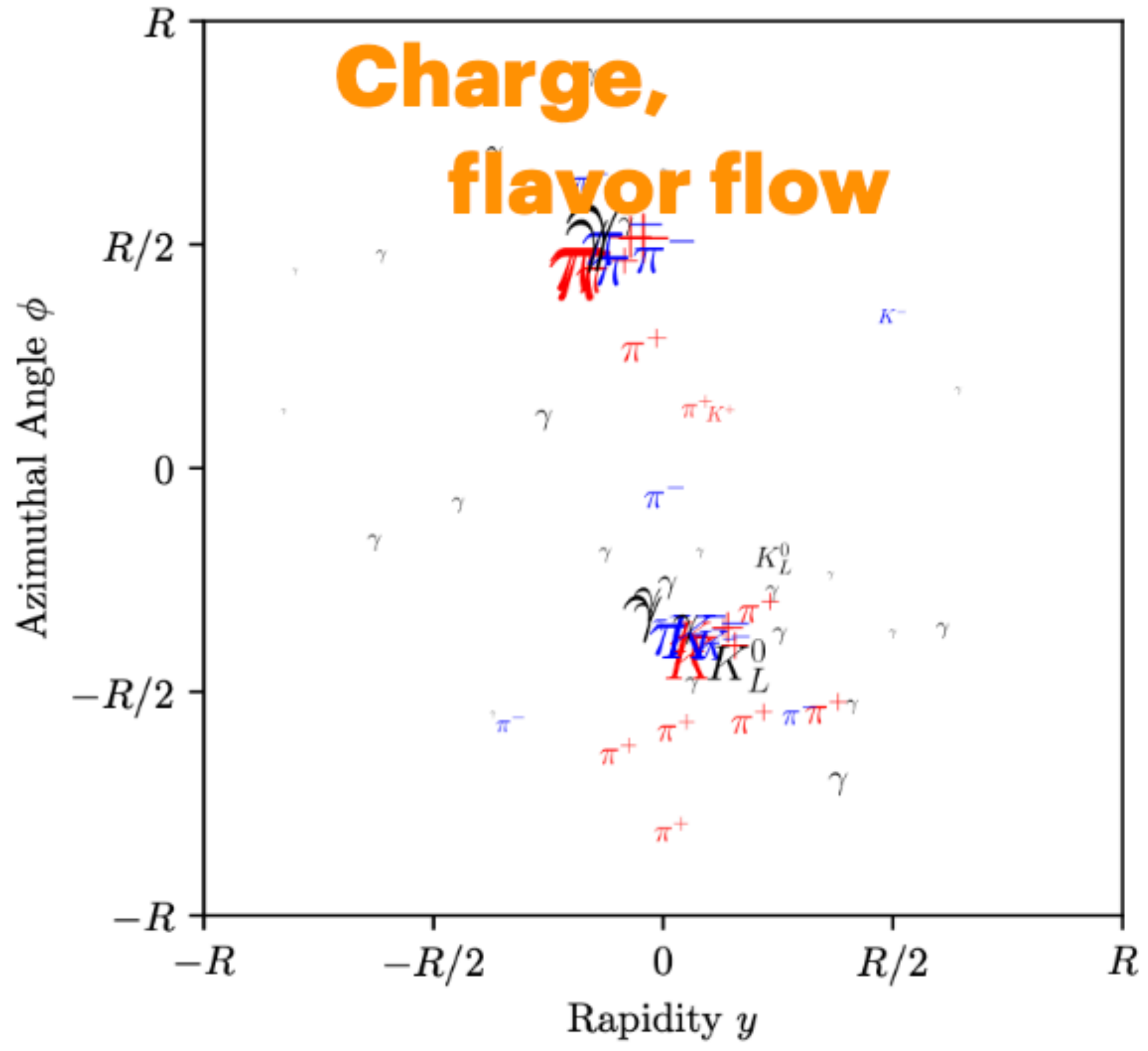
- **Provides a sharp link between underlying field theory and observables**

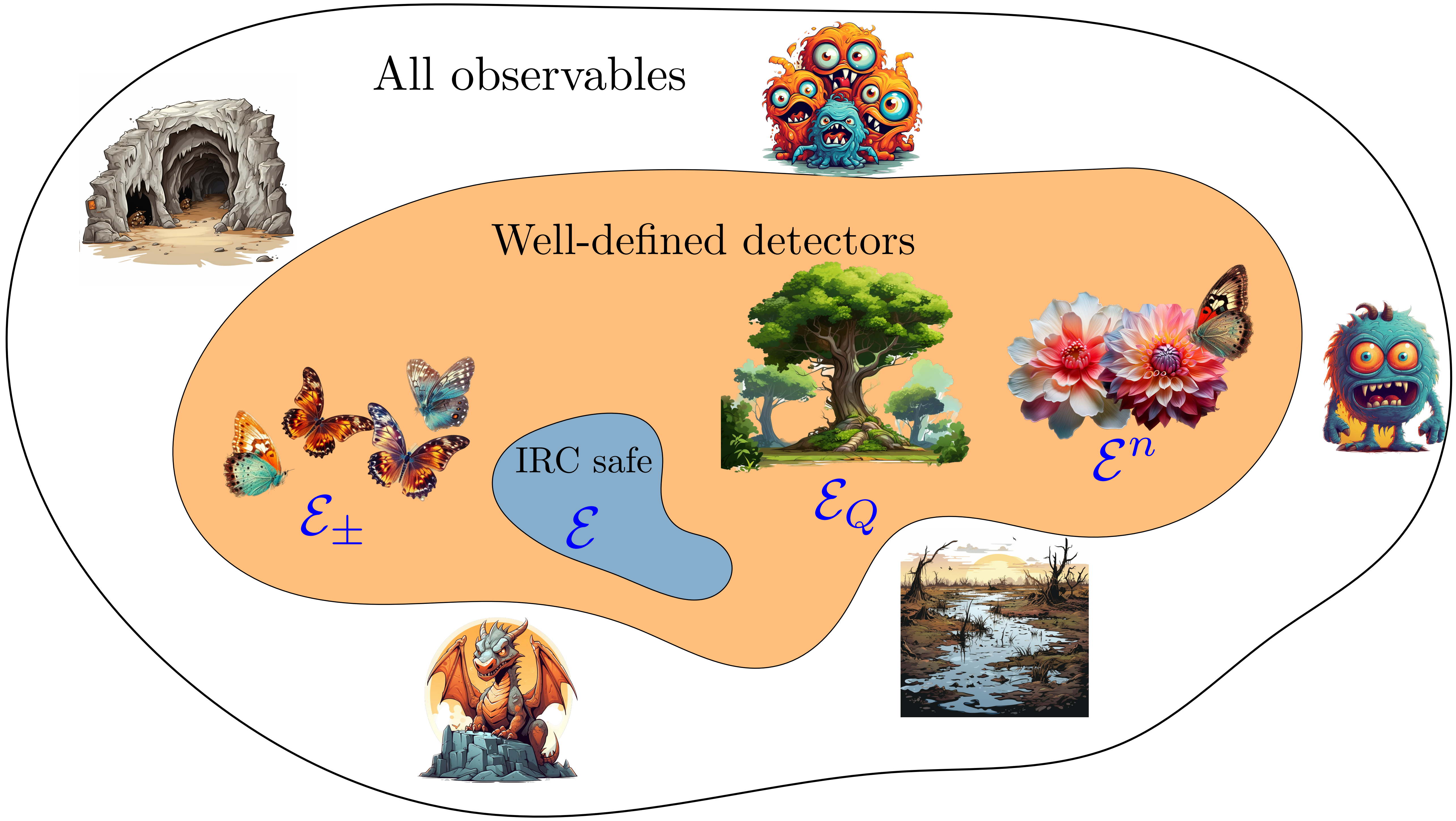
KL, Moult `23

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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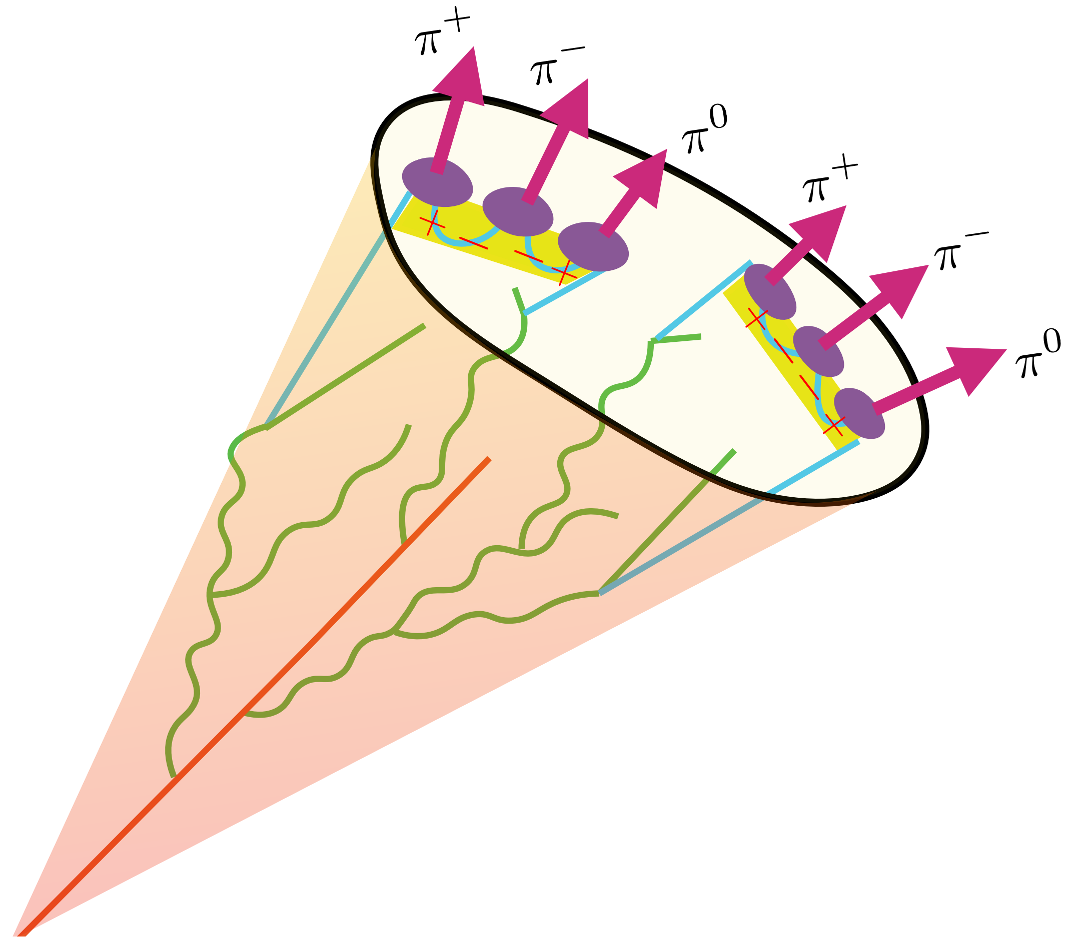
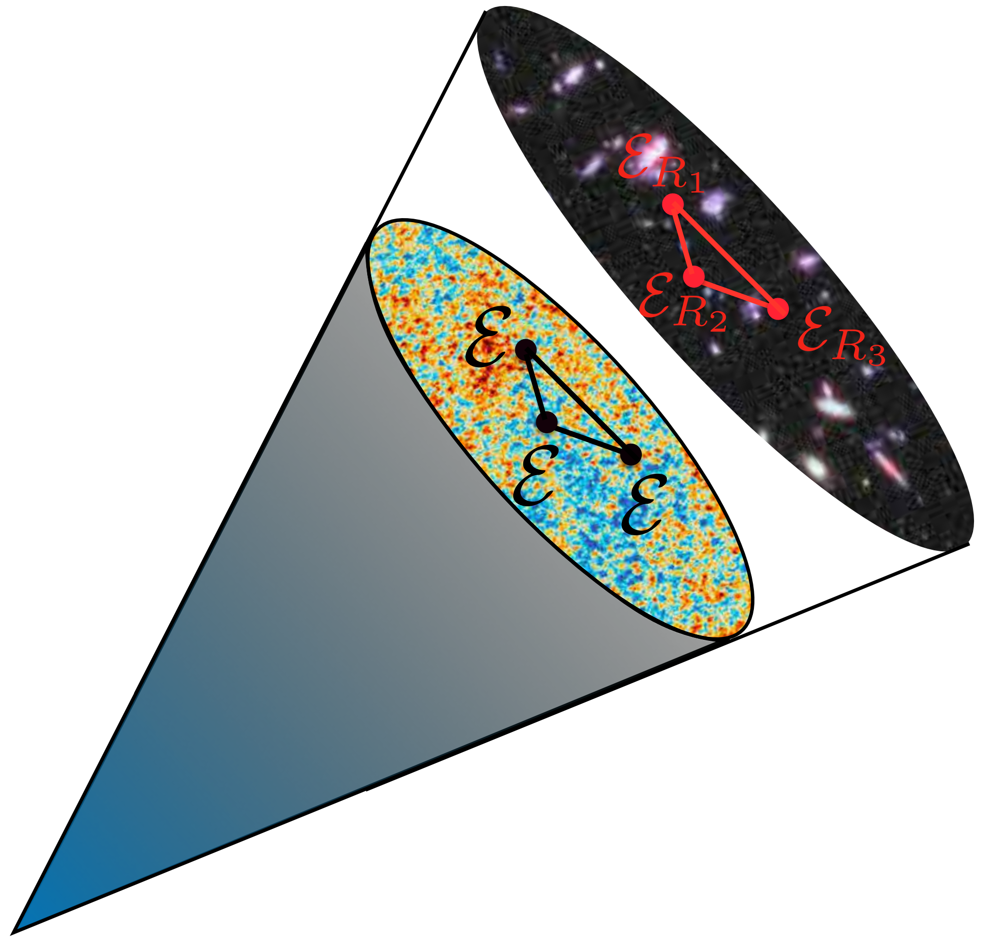
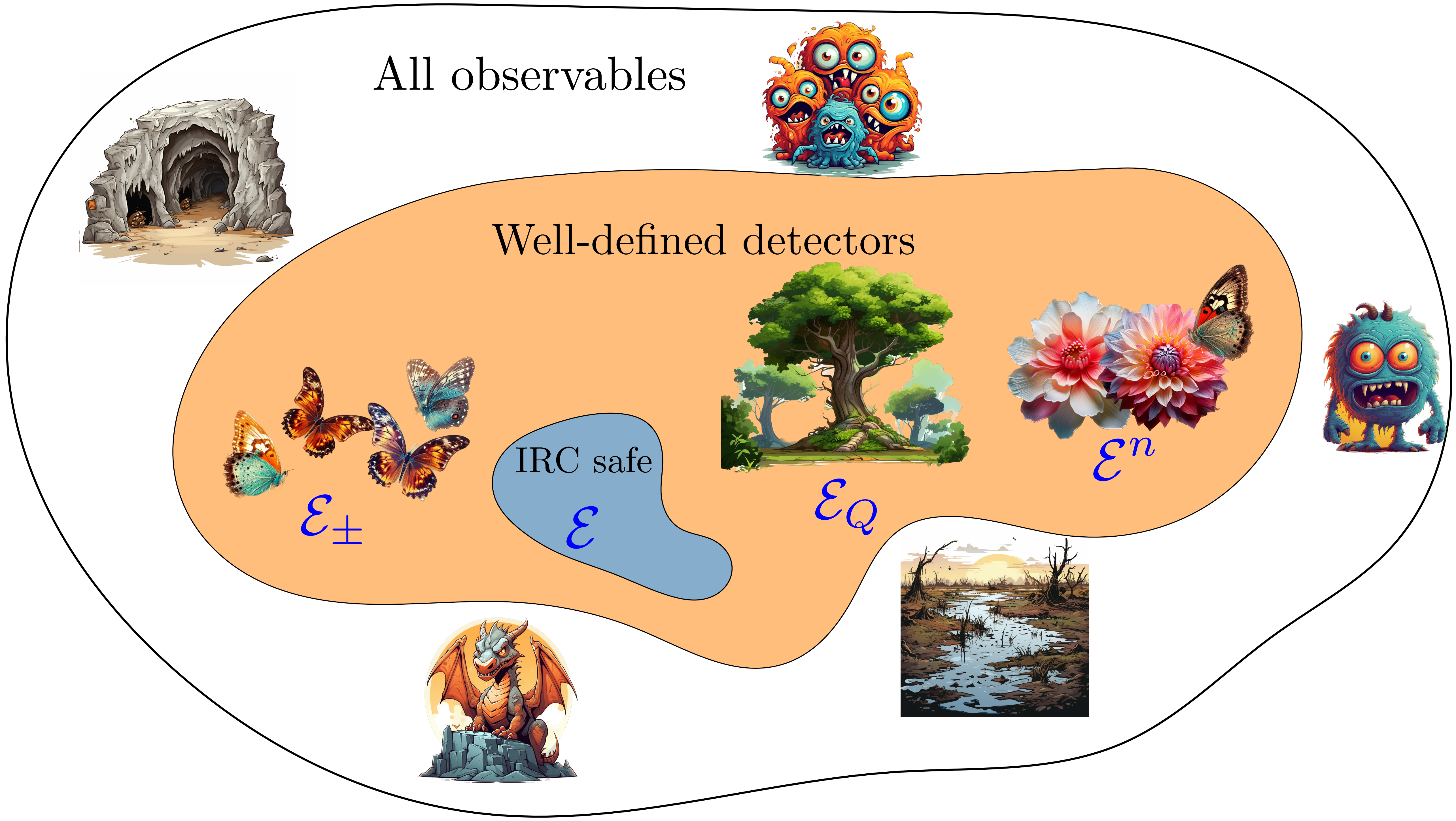
KL, Moult `23



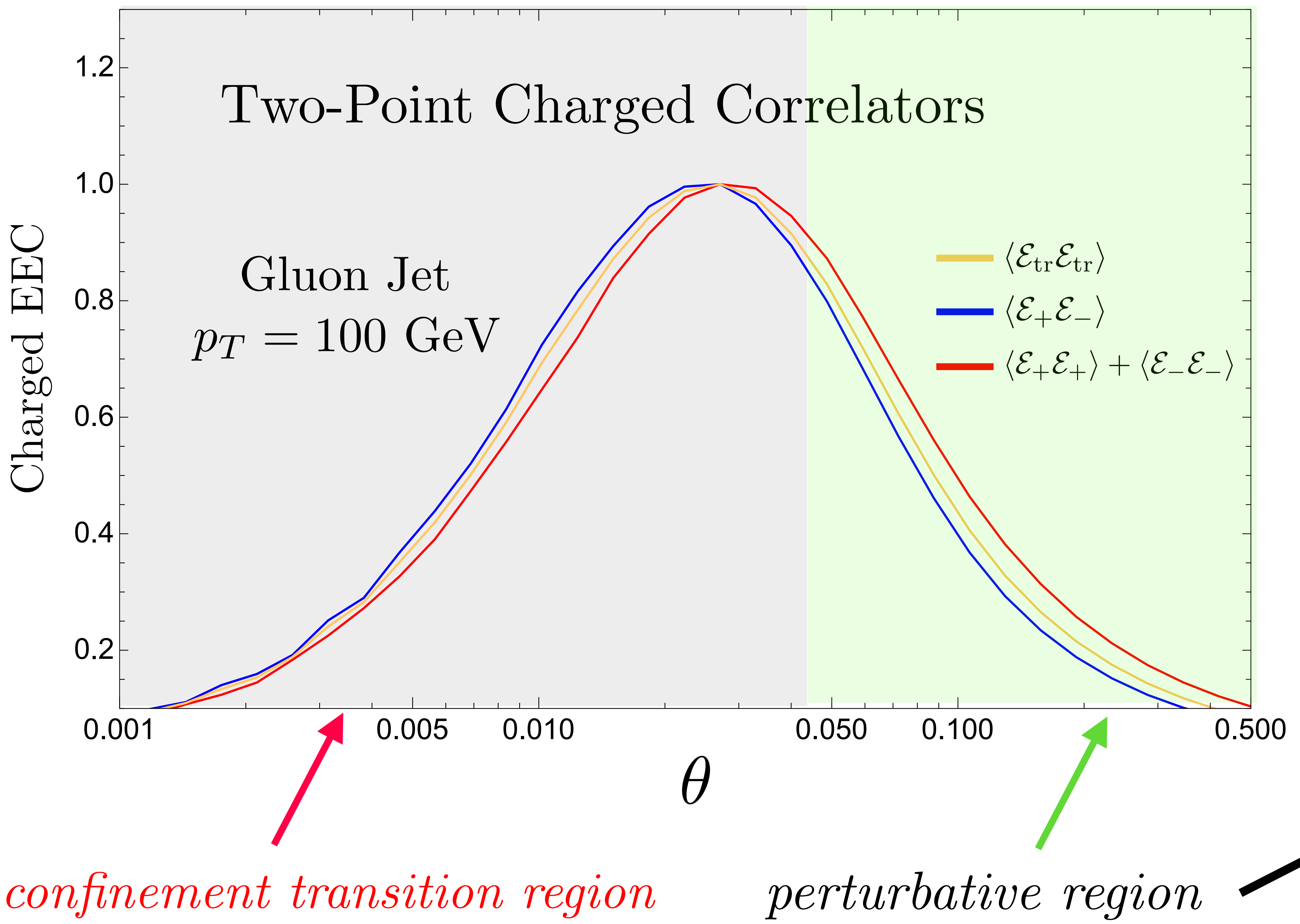


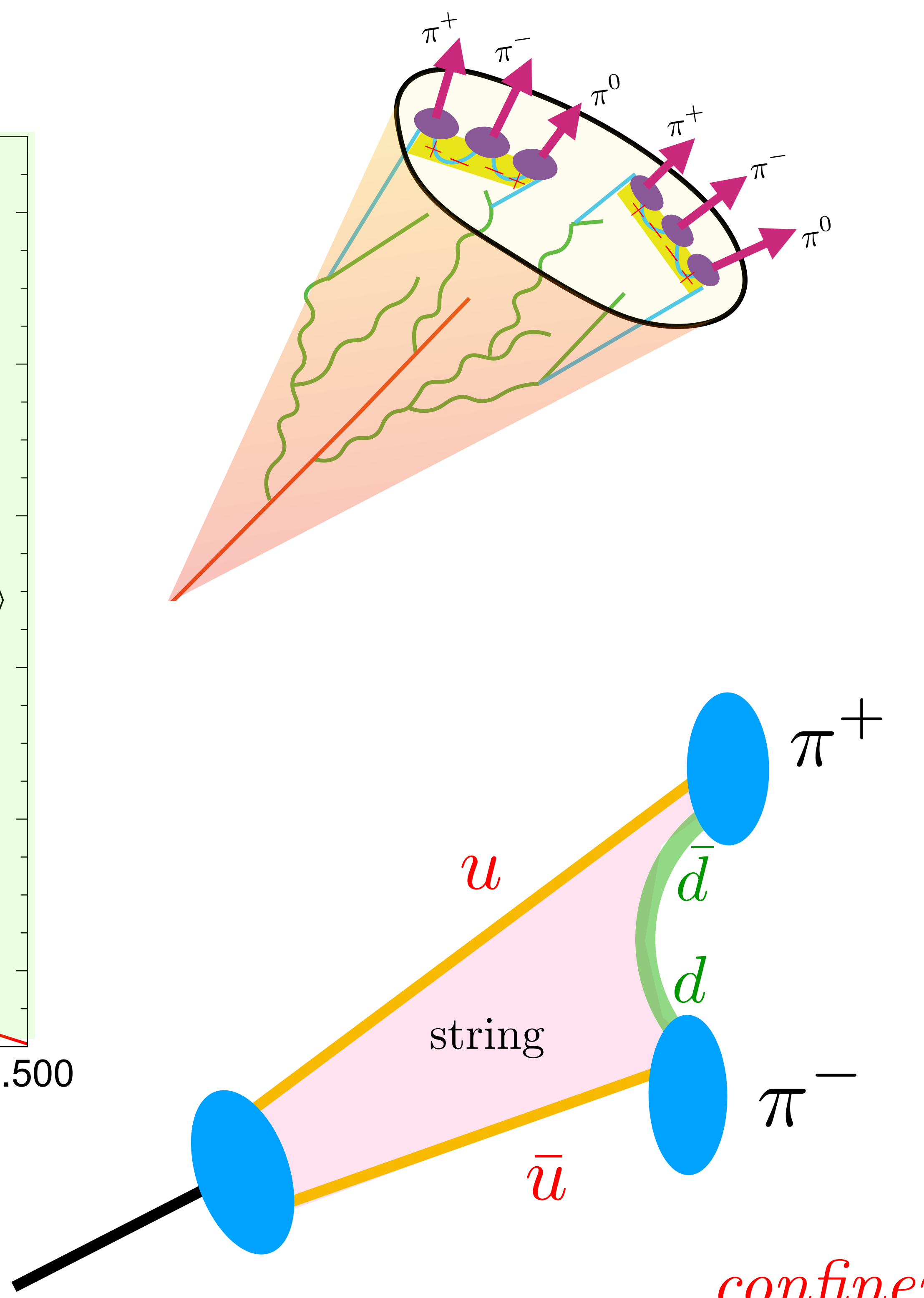


CORRELATION BETWEEN CHARGED HADRONS

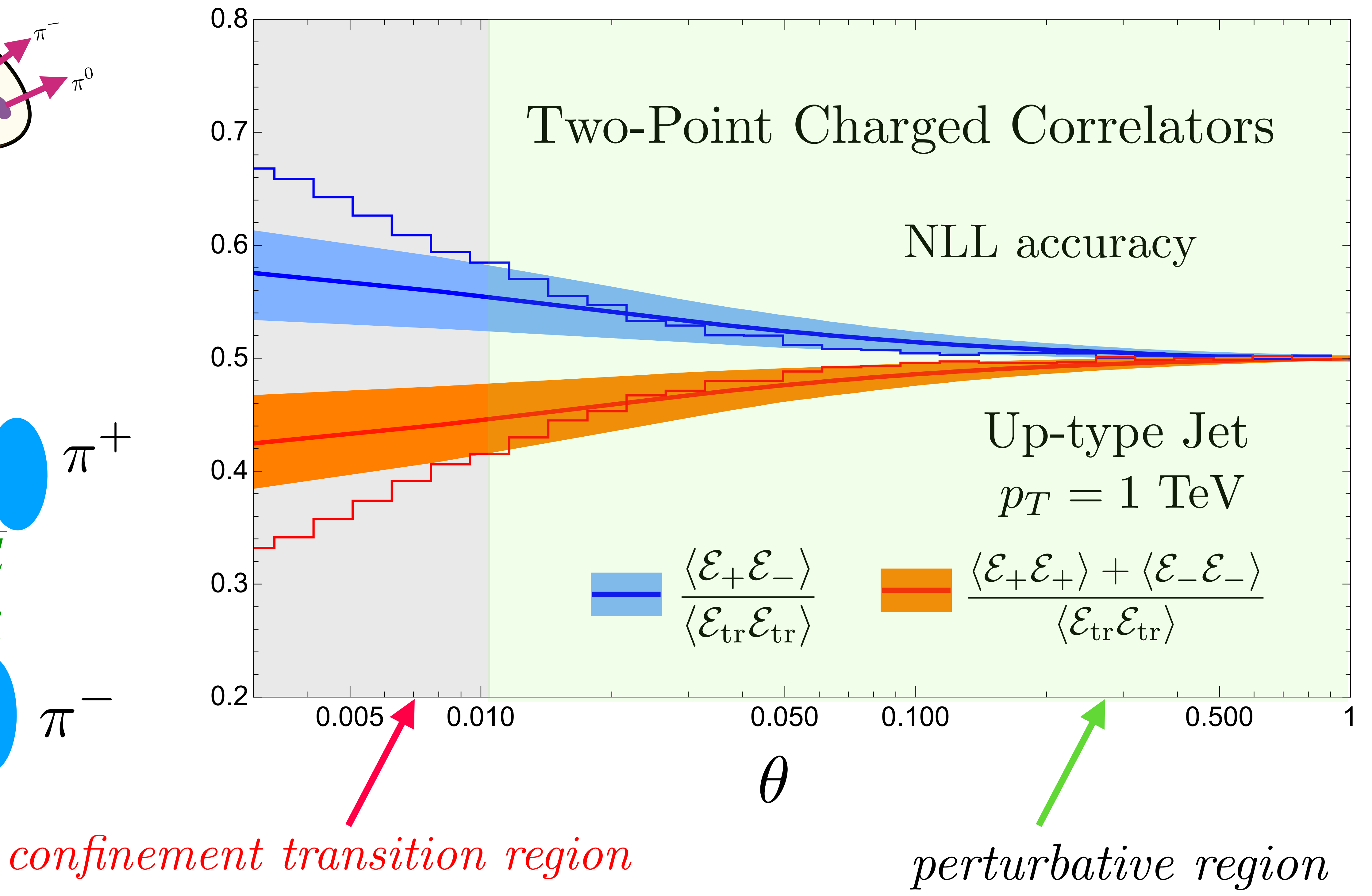
KL, Moult `23

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



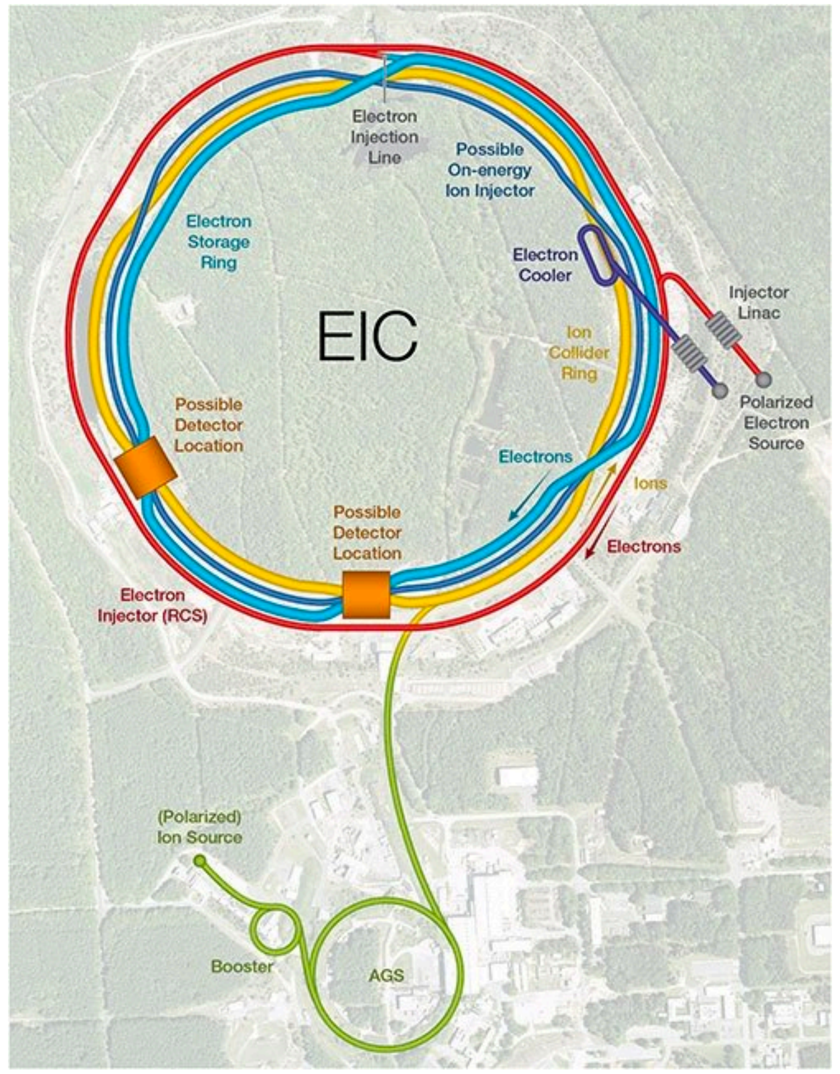


$$\langle \mathcal{E}_{+}\mathcal{E}_{-} \rangle, \langle \mathcal{E}_{+}\mathcal{E}_{+} \rangle, \langle \mathcal{E}_{-}\mathcal{E}_{-} \rangle$$



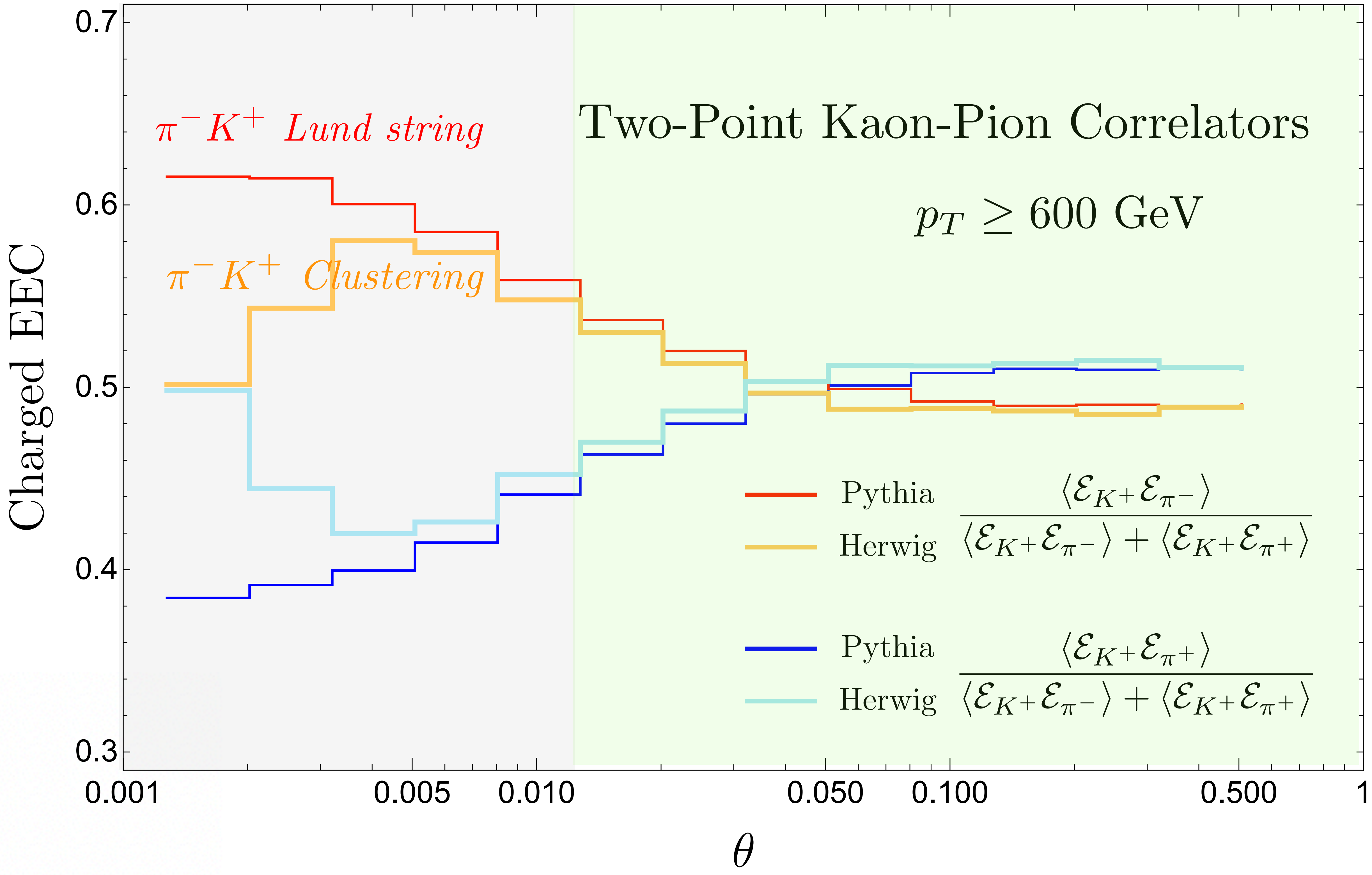
- **The correlation between unlike-signed hadron pair is expected to grow in string-like hadronization**

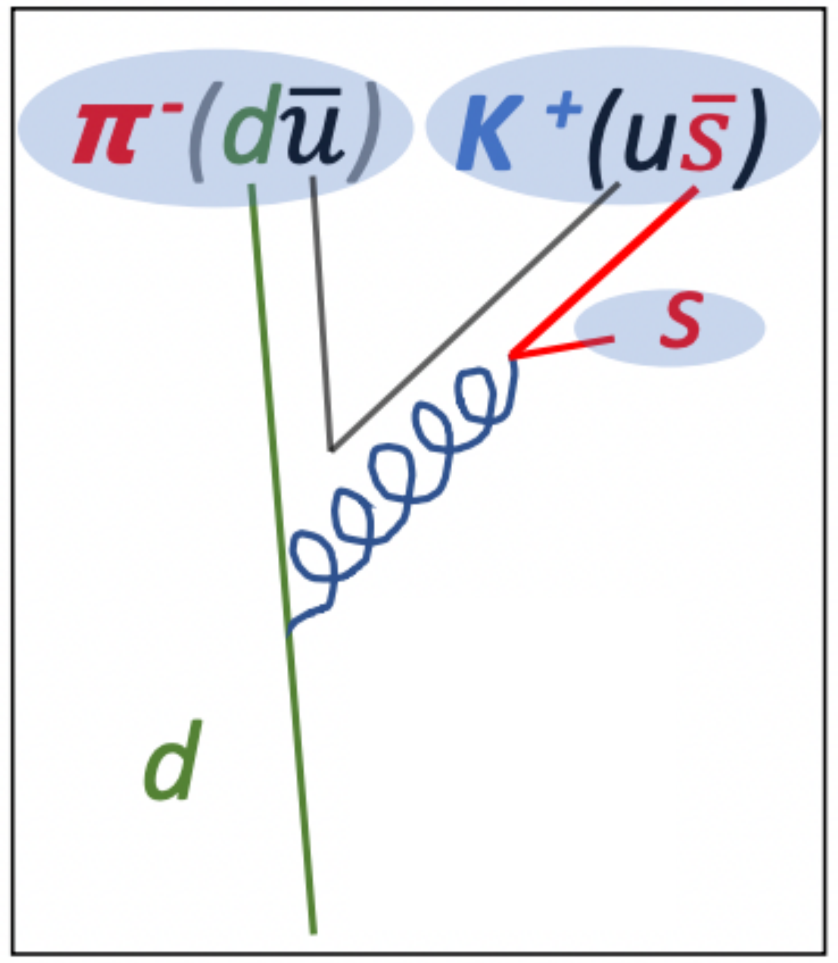
DISCRIMINATING HADRONIZATION MECHANISMS



Clustering model (Herwig)

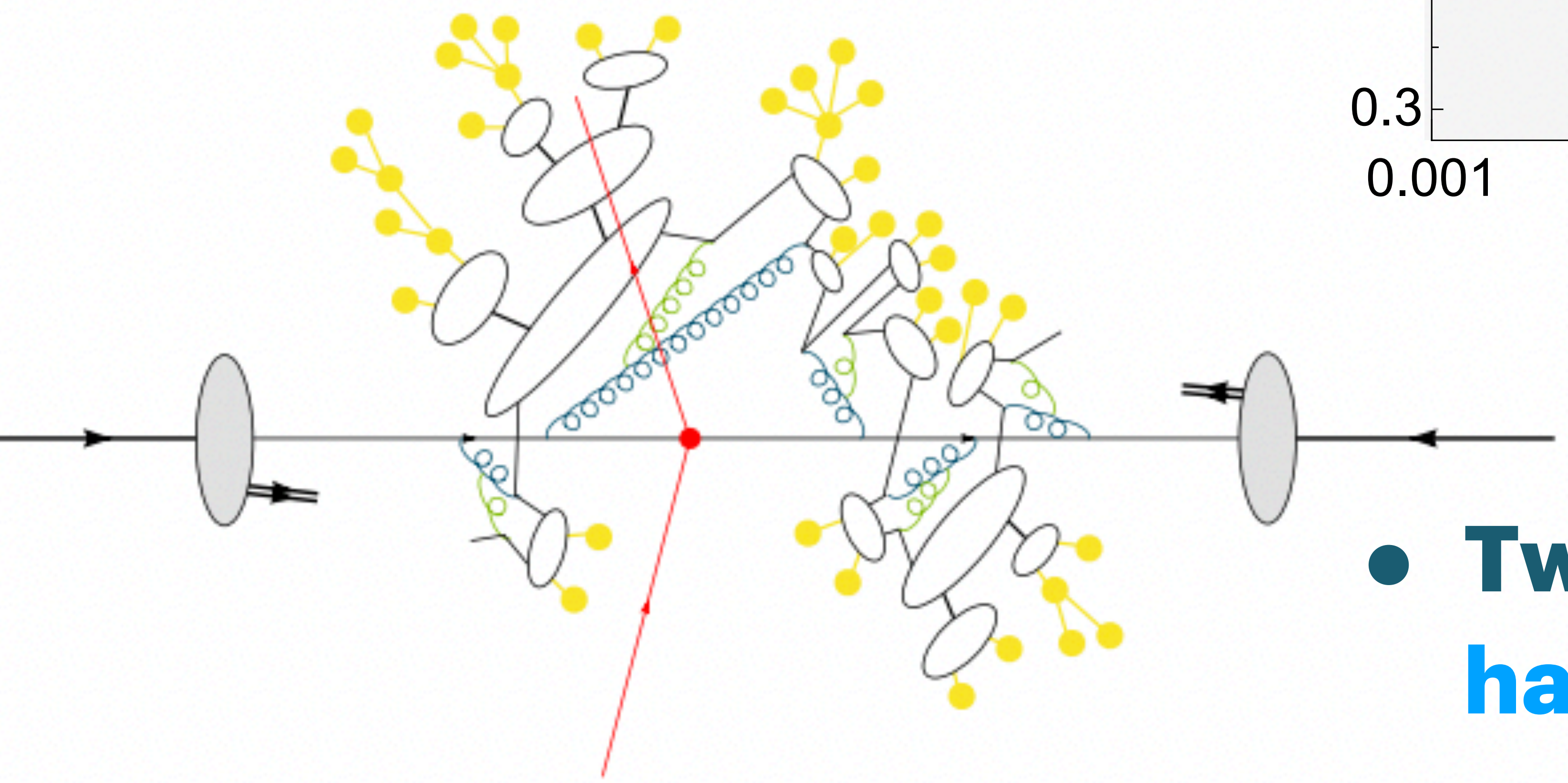
KL, Moult, Song, Sterman `In Progress





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!**

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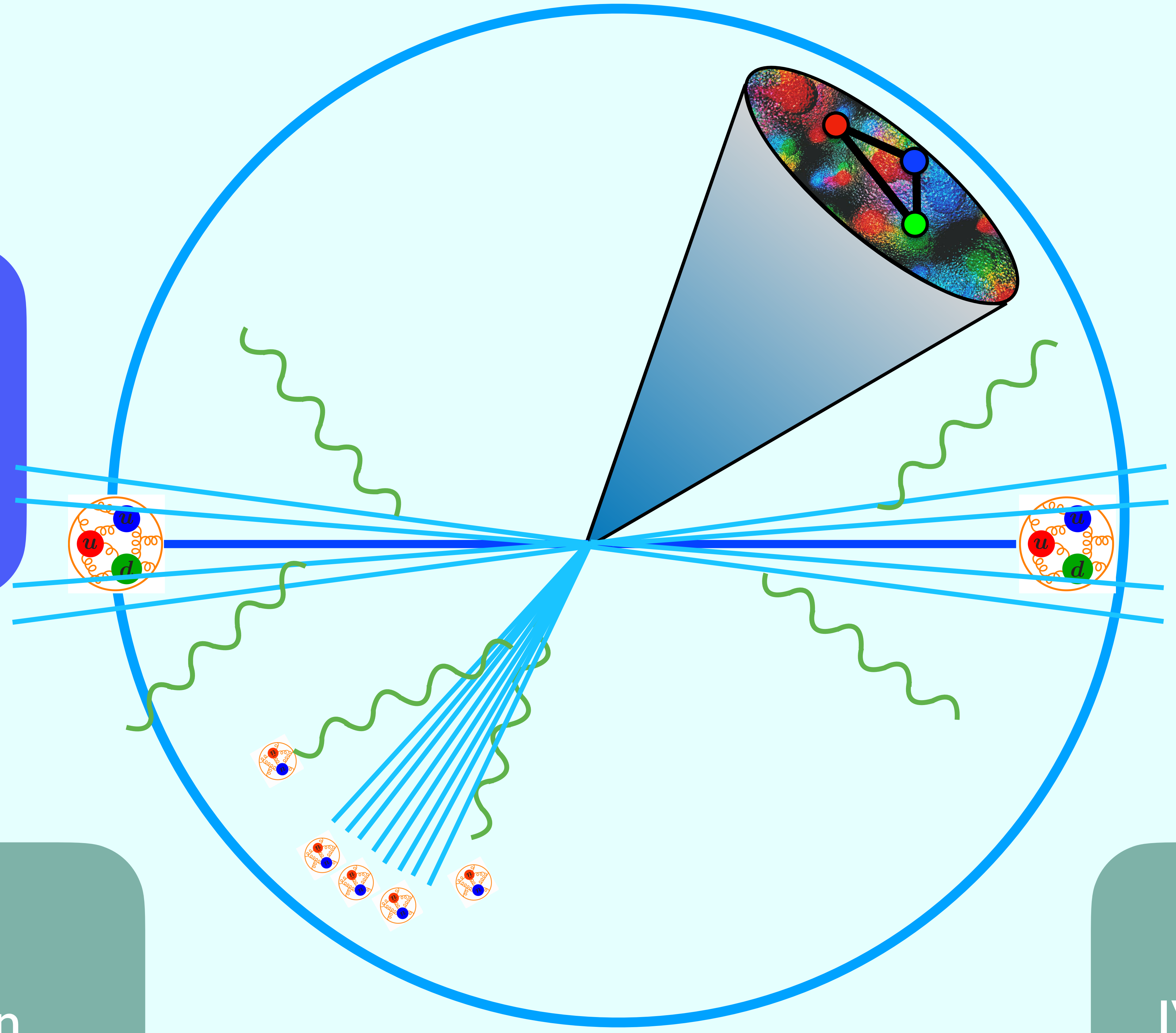


V. Hadronization

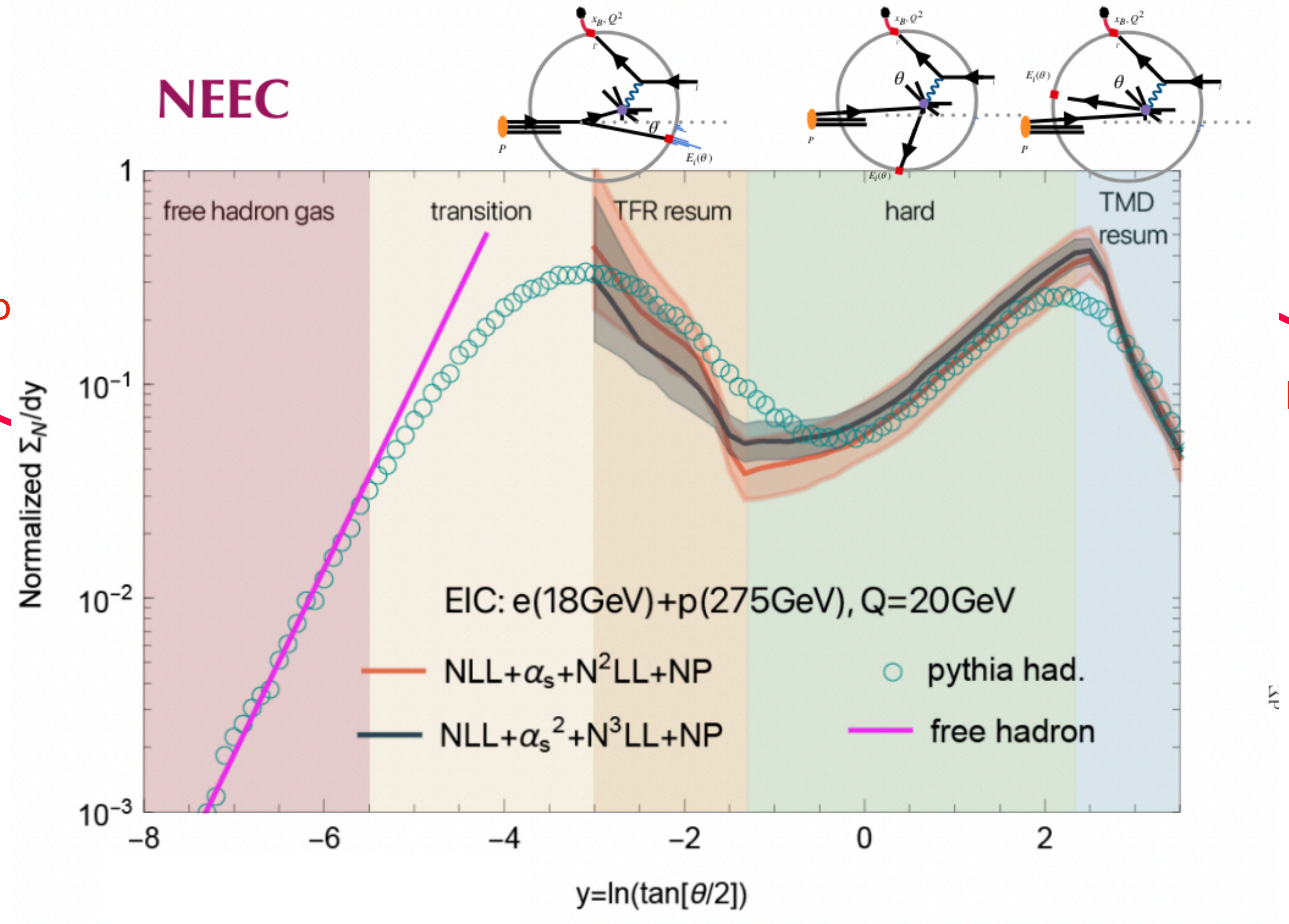
IV. Medium Dynamics

NUCLEON ENERGY CORRELATORS

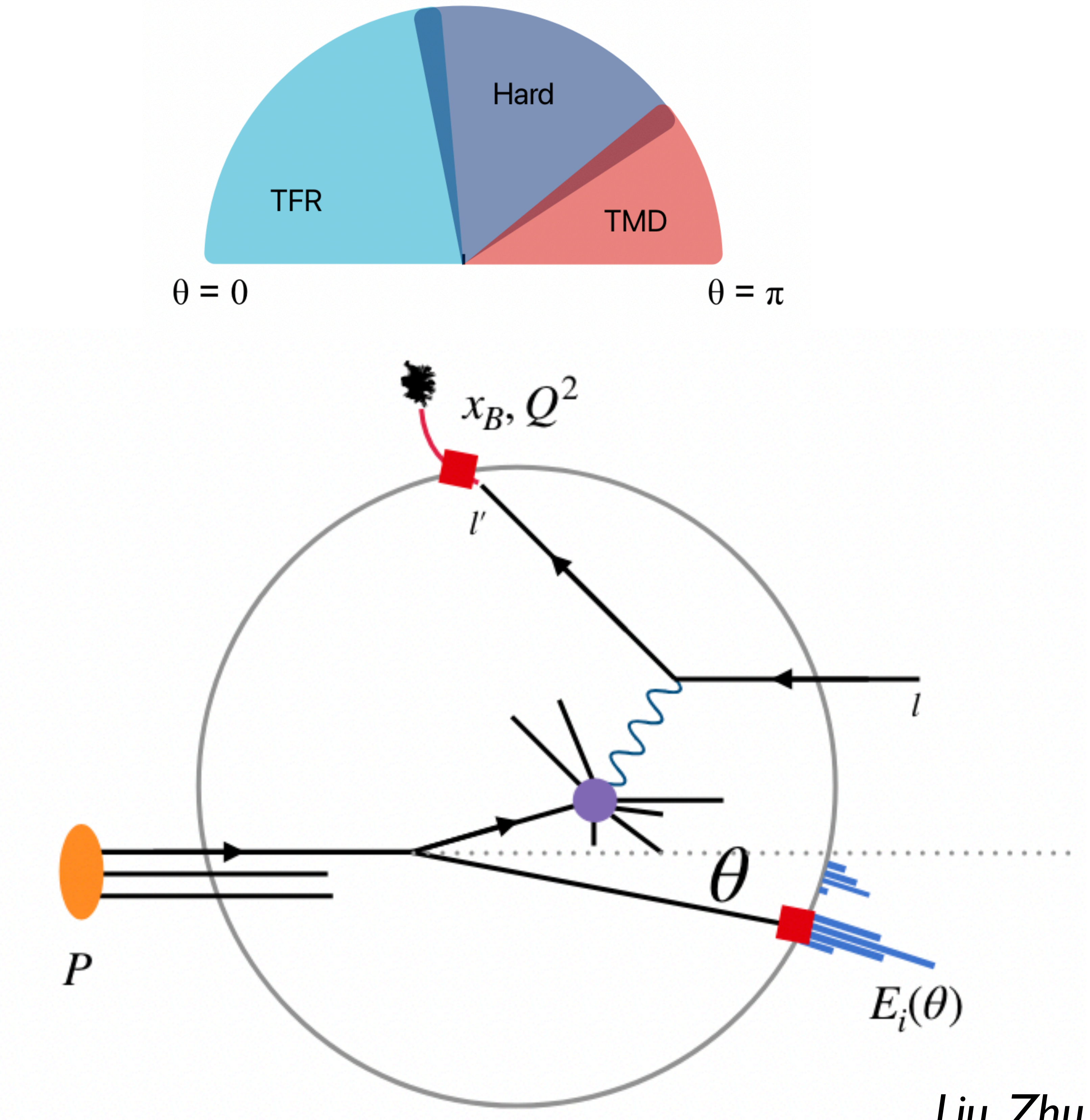
- **Recent proposal to measure the target remnants can probe nuclear structure directly!**

Collinear PDFs and Fracture Functions

NP hadronizatio



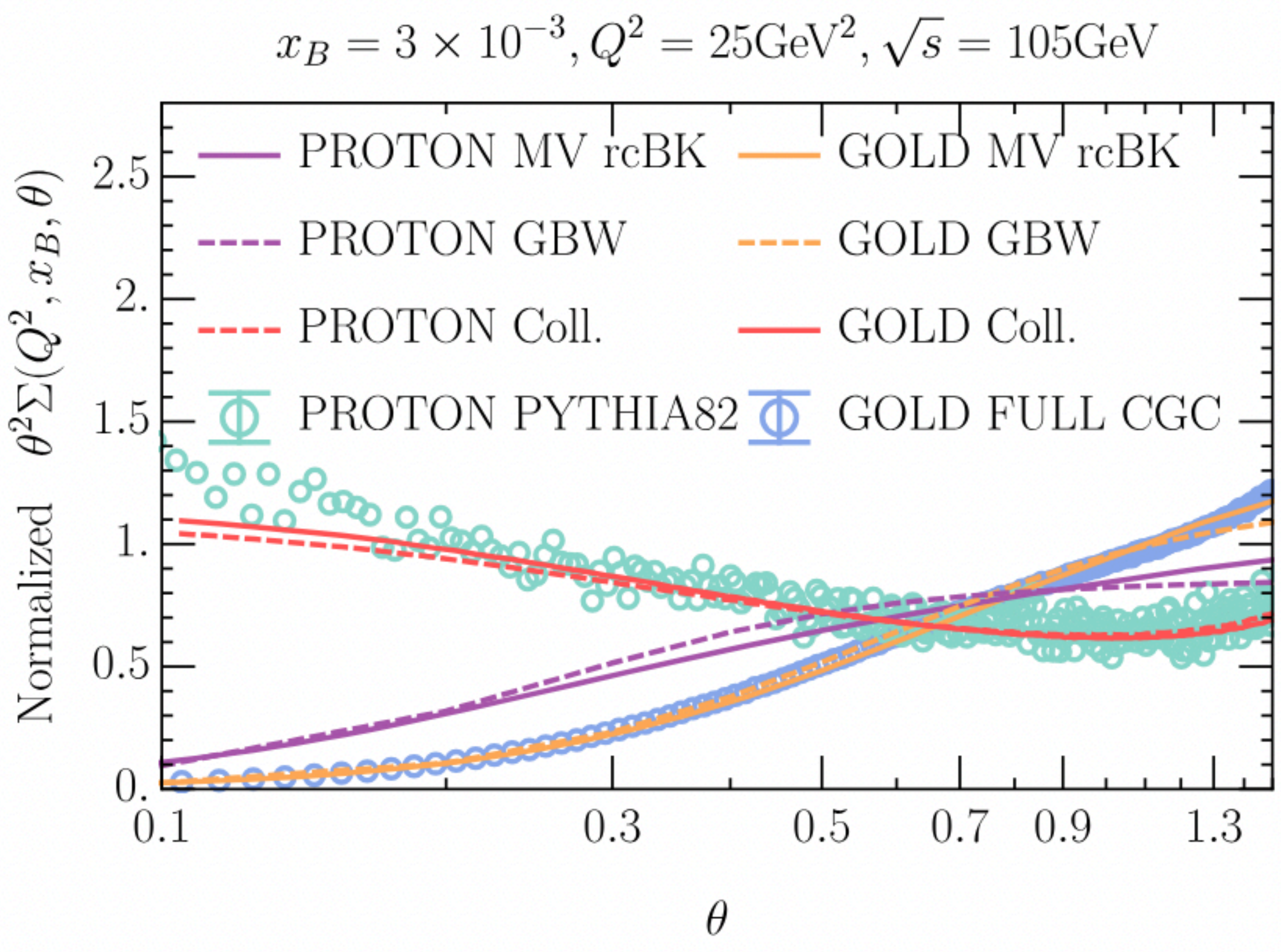
Probes TMD structure

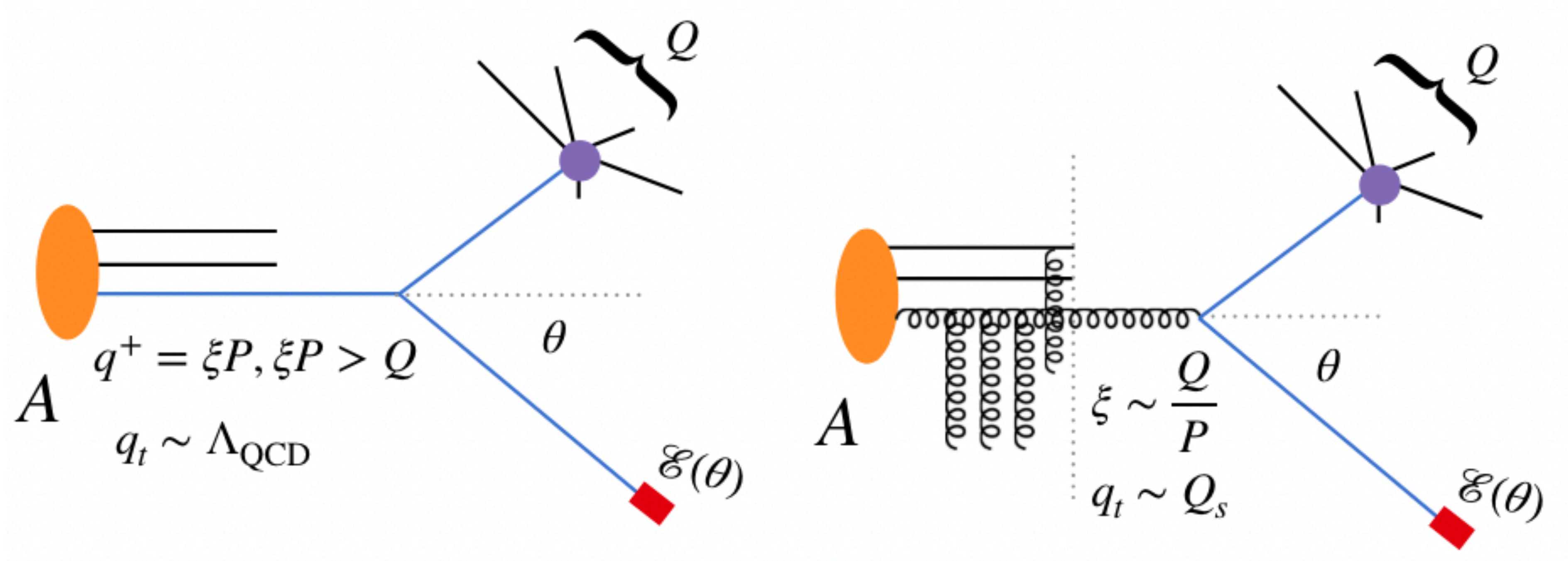


Liu, Zhu `24
Can, Li, Mi `23
Liu, Zhu `22

NUCLEON ENERGY CORRELATORS

- **Deviation from collinear factorization showing sensitivity to the saturation scale Q_s!**

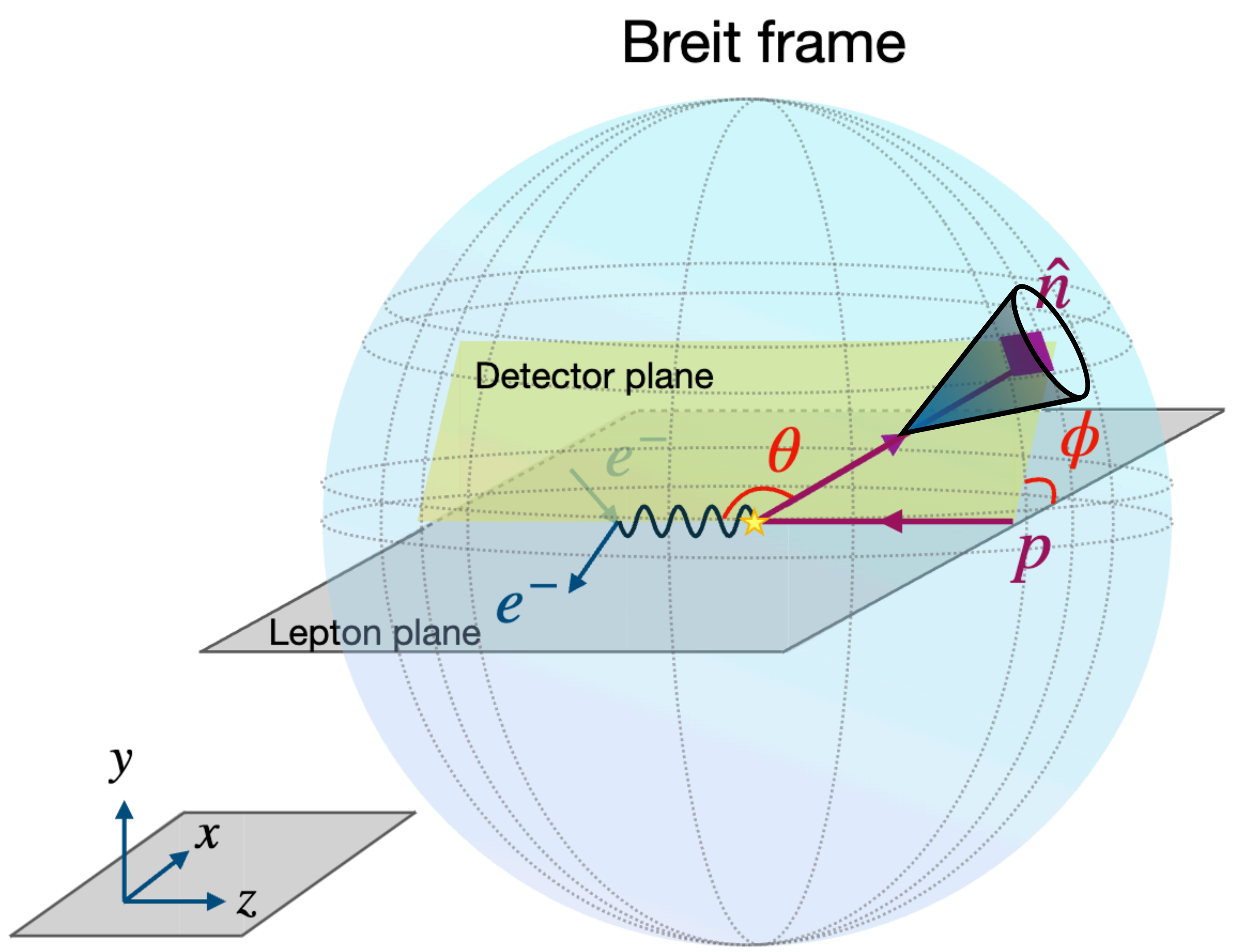


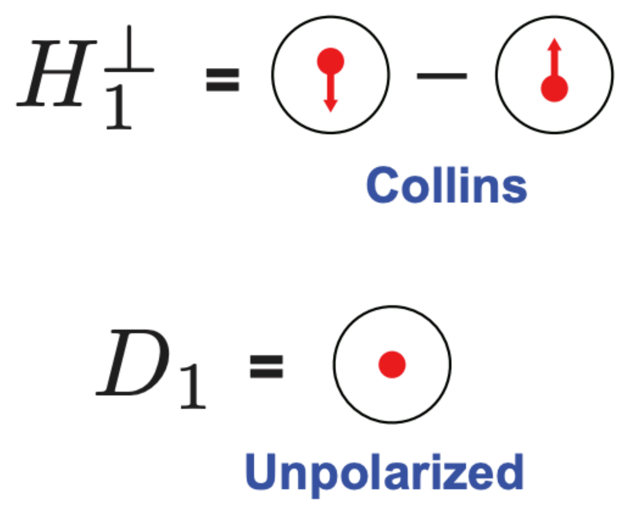


Liu, Liu, Pan, Yuan, Zhu `23

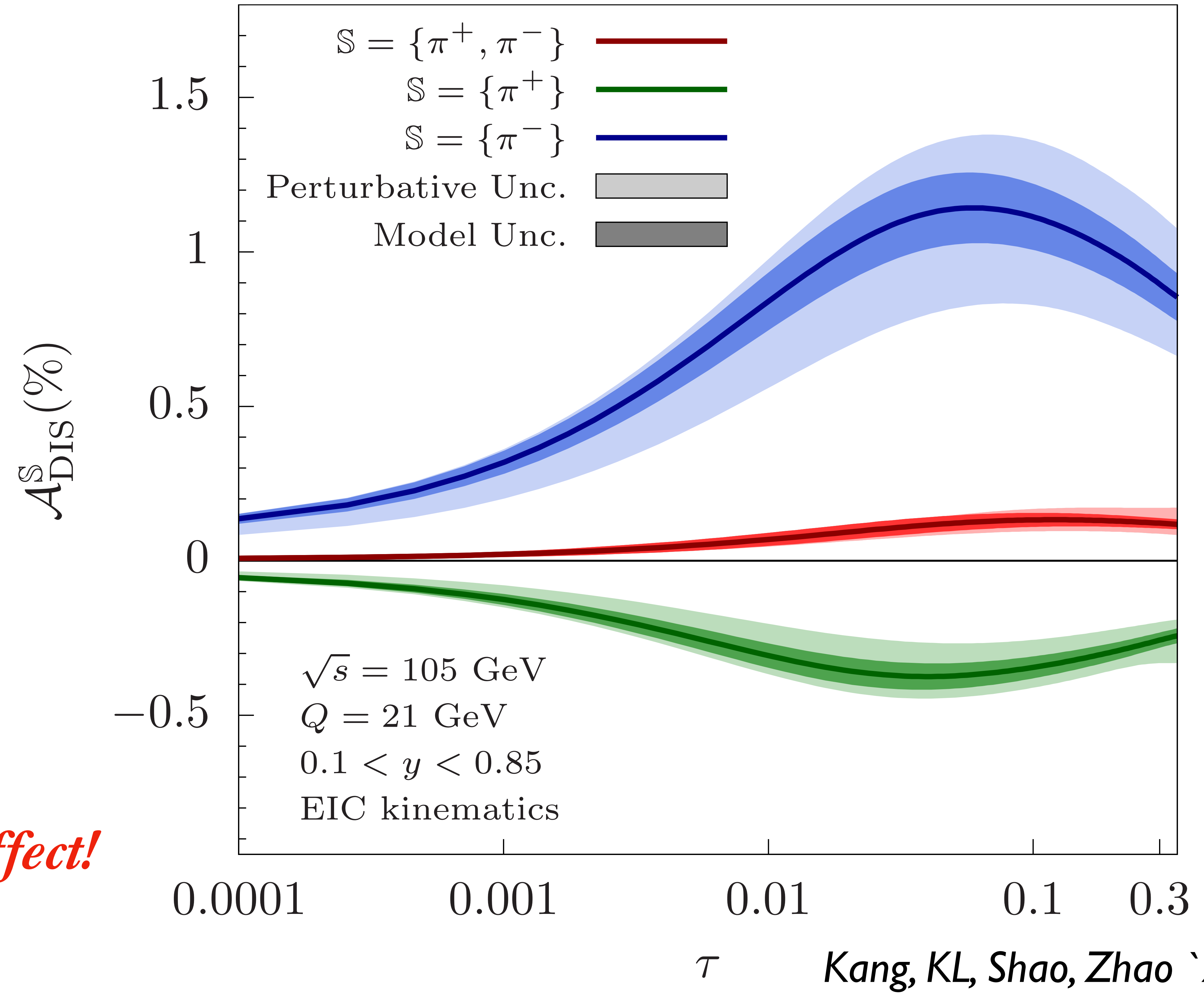
MOMENTUM IMBALANCE OF ENERGY FLOW

- **One can further measure azimuthal angle dependence of the momentum imbalance of jets in order to study spin correlations**

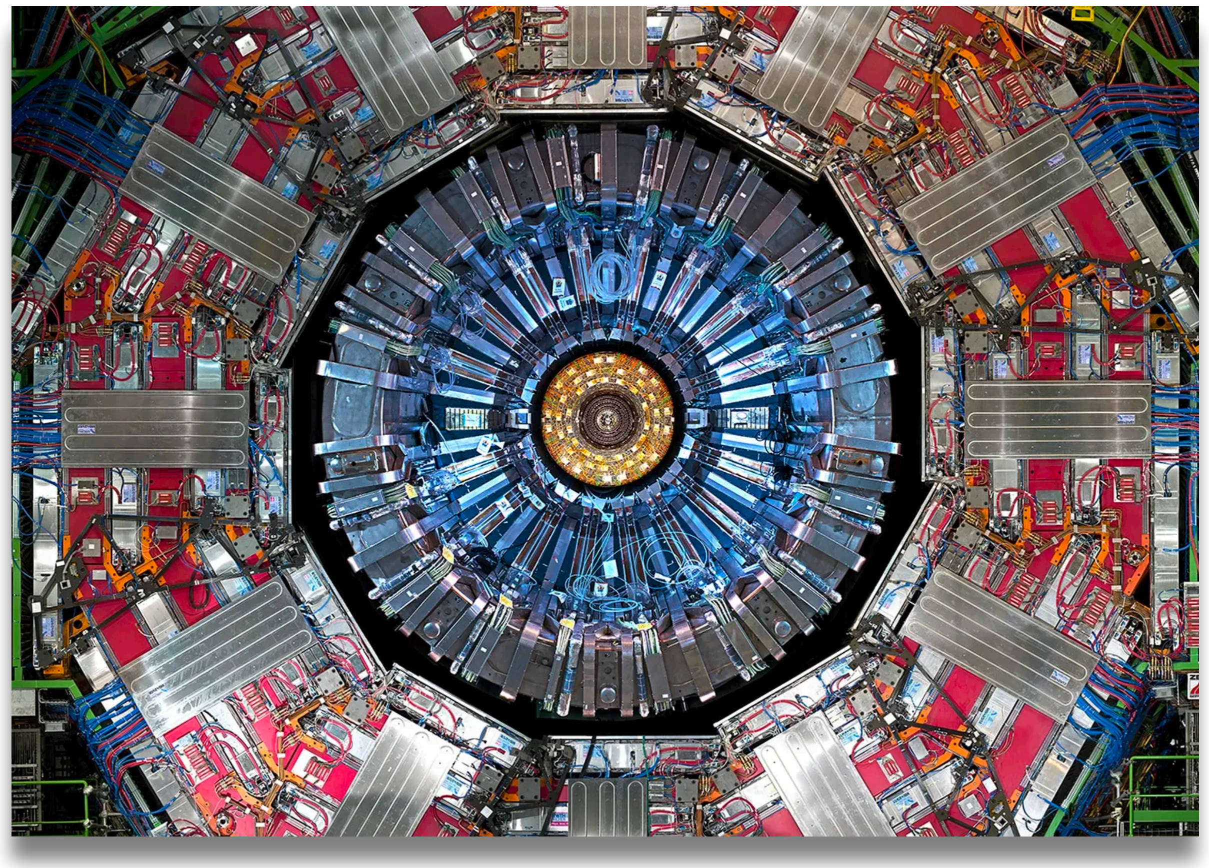




EIC can measure this collins effect!

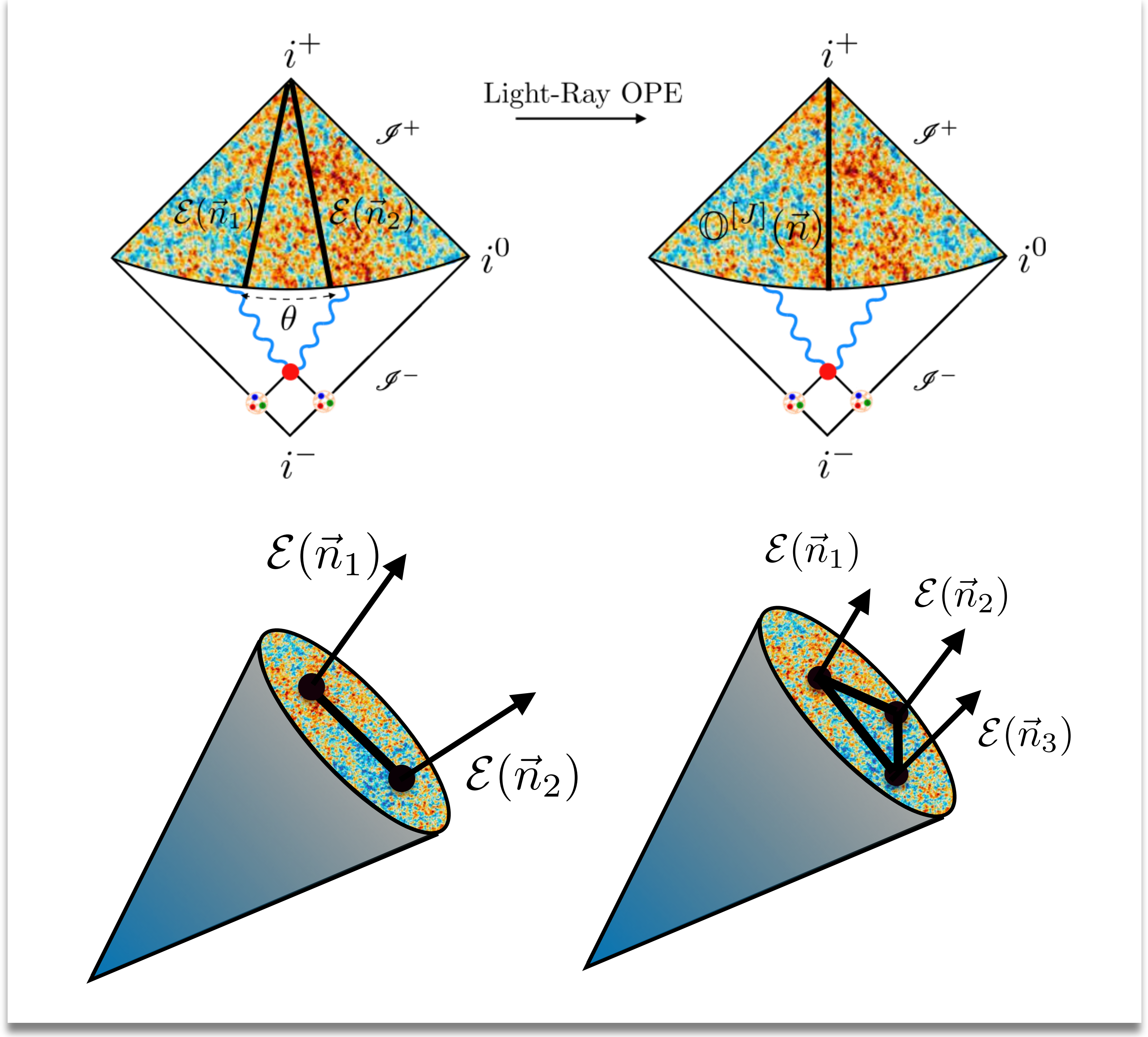


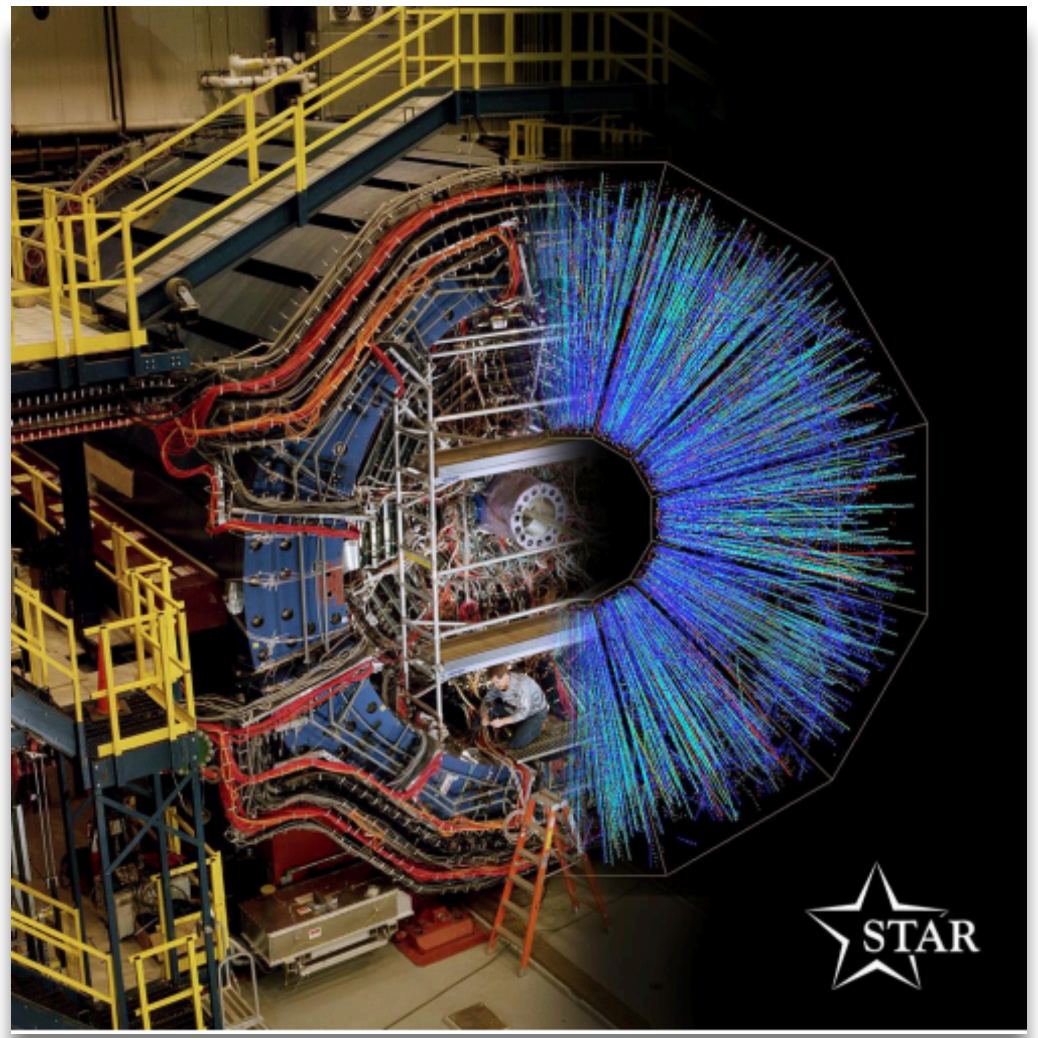
Kang, KL, Shao, Zhao `23



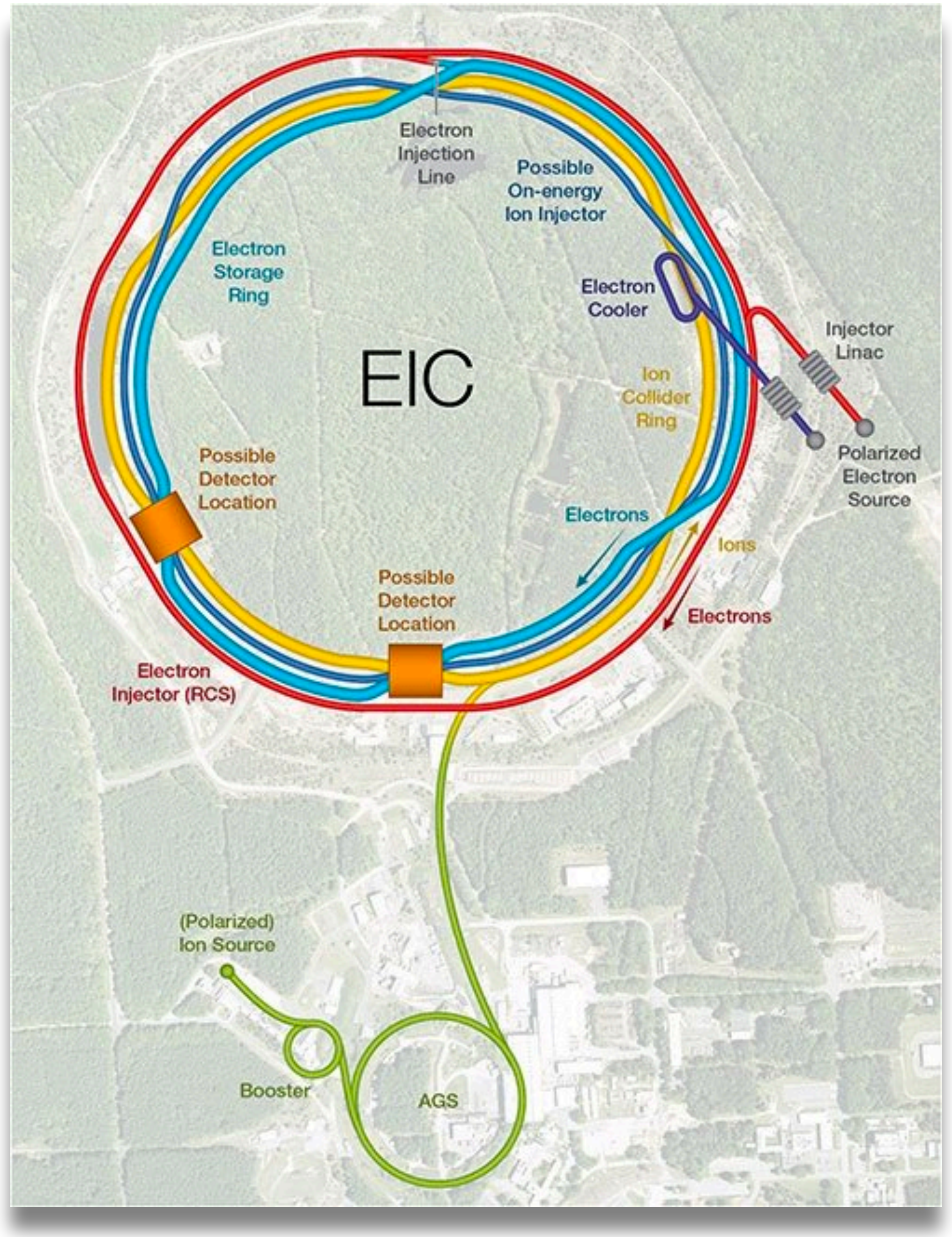
LHC

Conformal Colliders meet Jets in Particle Colliders!





RHIC



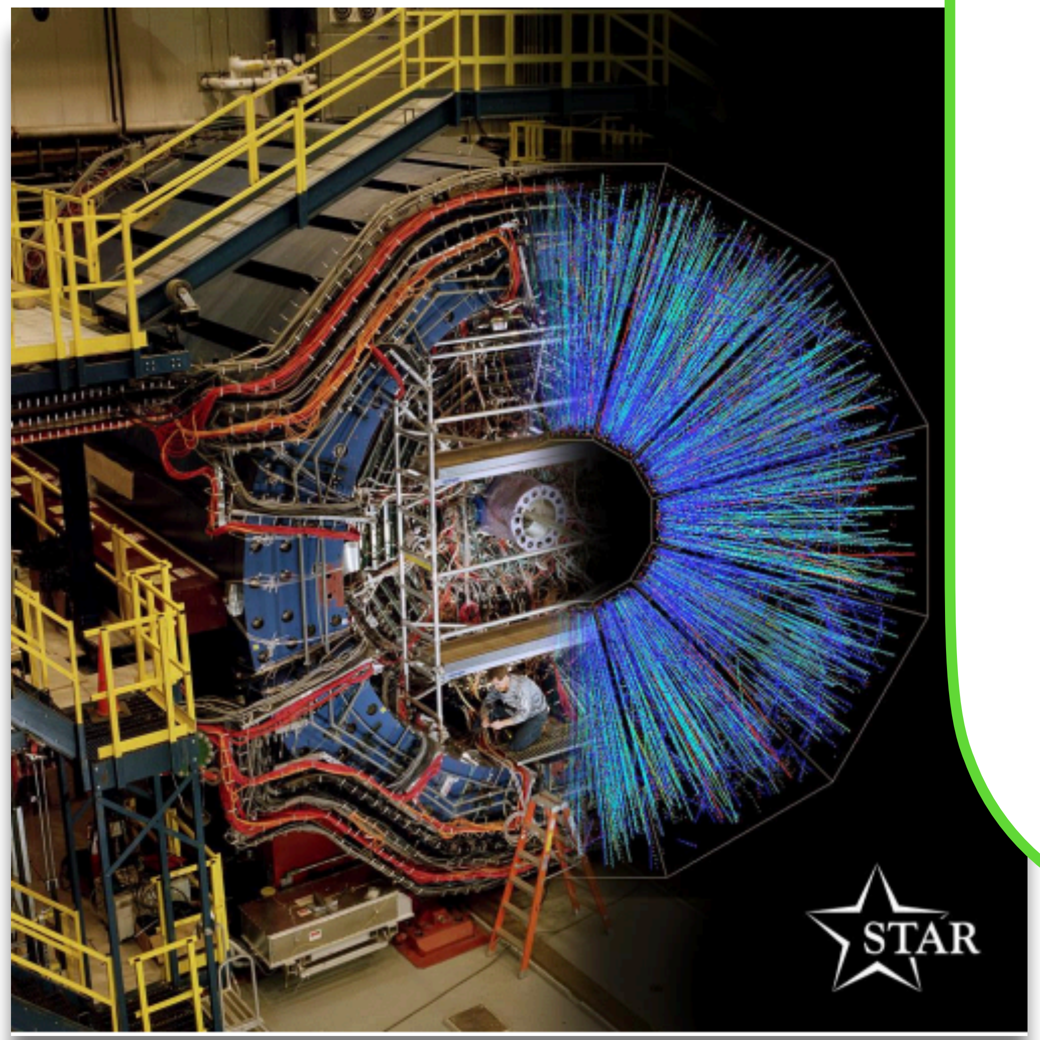
EIC

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

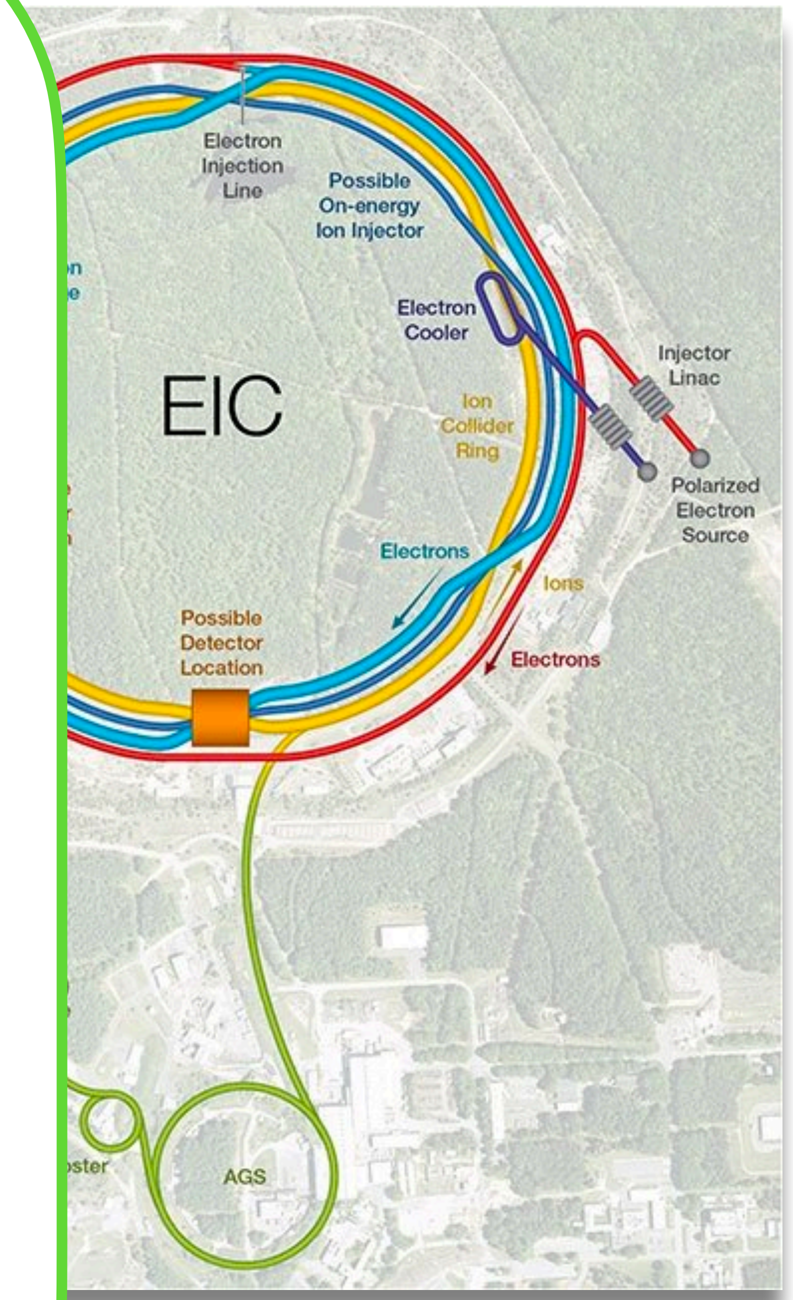
LHC

Conformal Colliders meet Jets in Particle Colliders!

Jets form a universal language, uniting studies across all colliders. They create a bridge between the underlying field theory and the real world!



RHIC



EIC

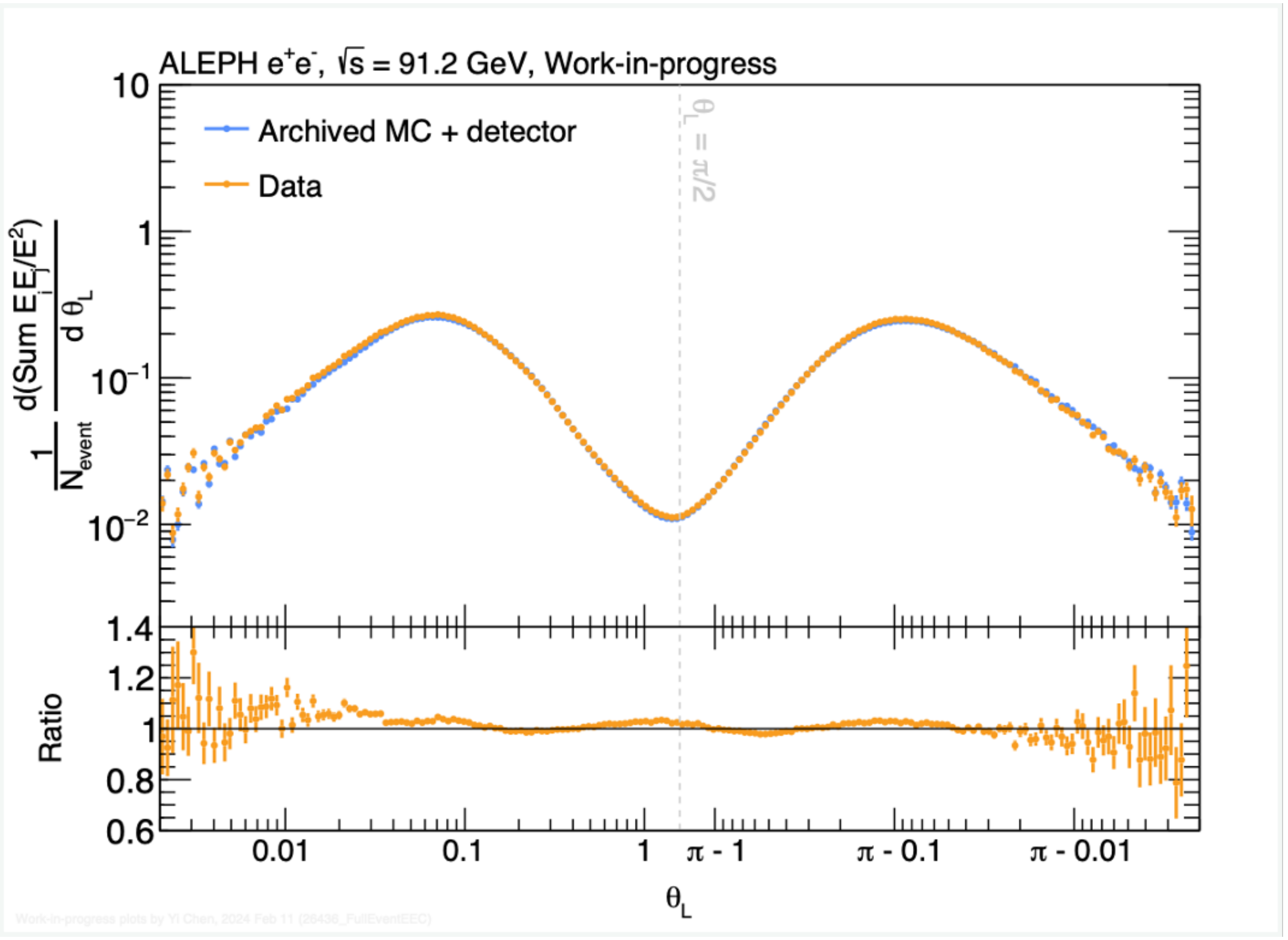
Jets provide sharp link between underlying field theory and real world!

Backup slides

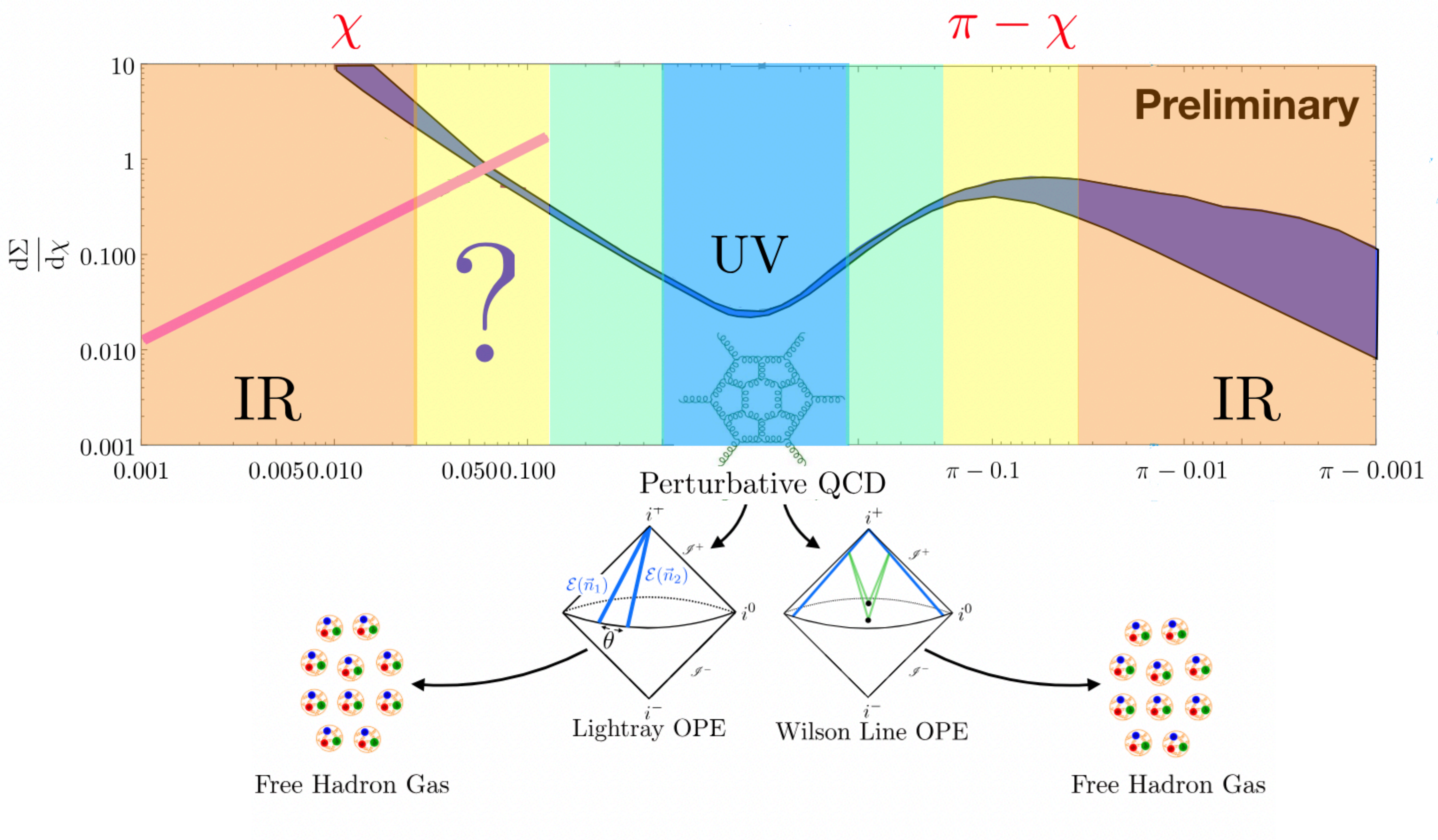
ENERGY CORRELATORS ON TRACK

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

Reanalysis of ALEPH data on tracks



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

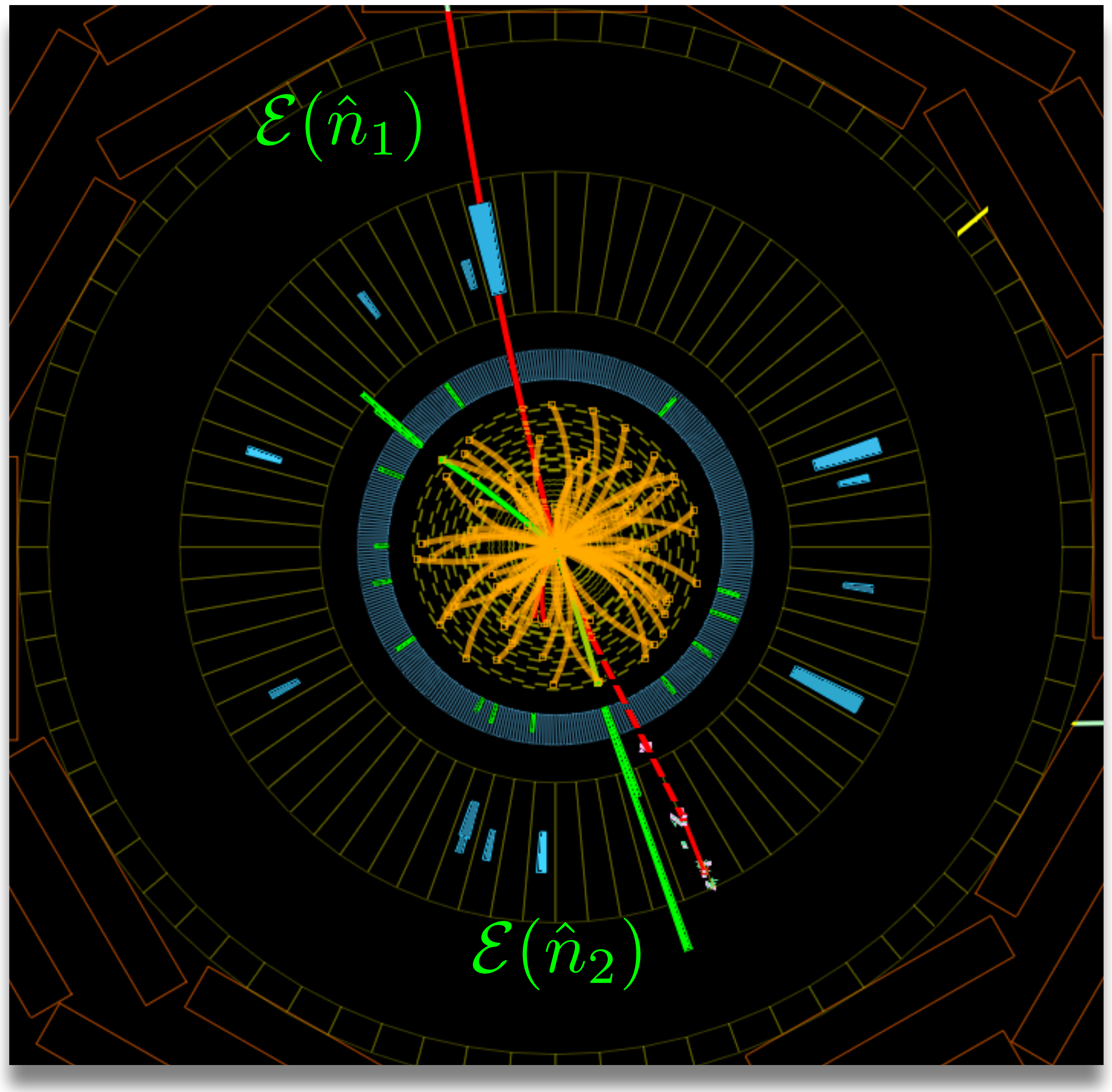


EEC on track for e^+e^- allows one to study event-wide correlations very precisely!

POWER CORRECTIONS

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

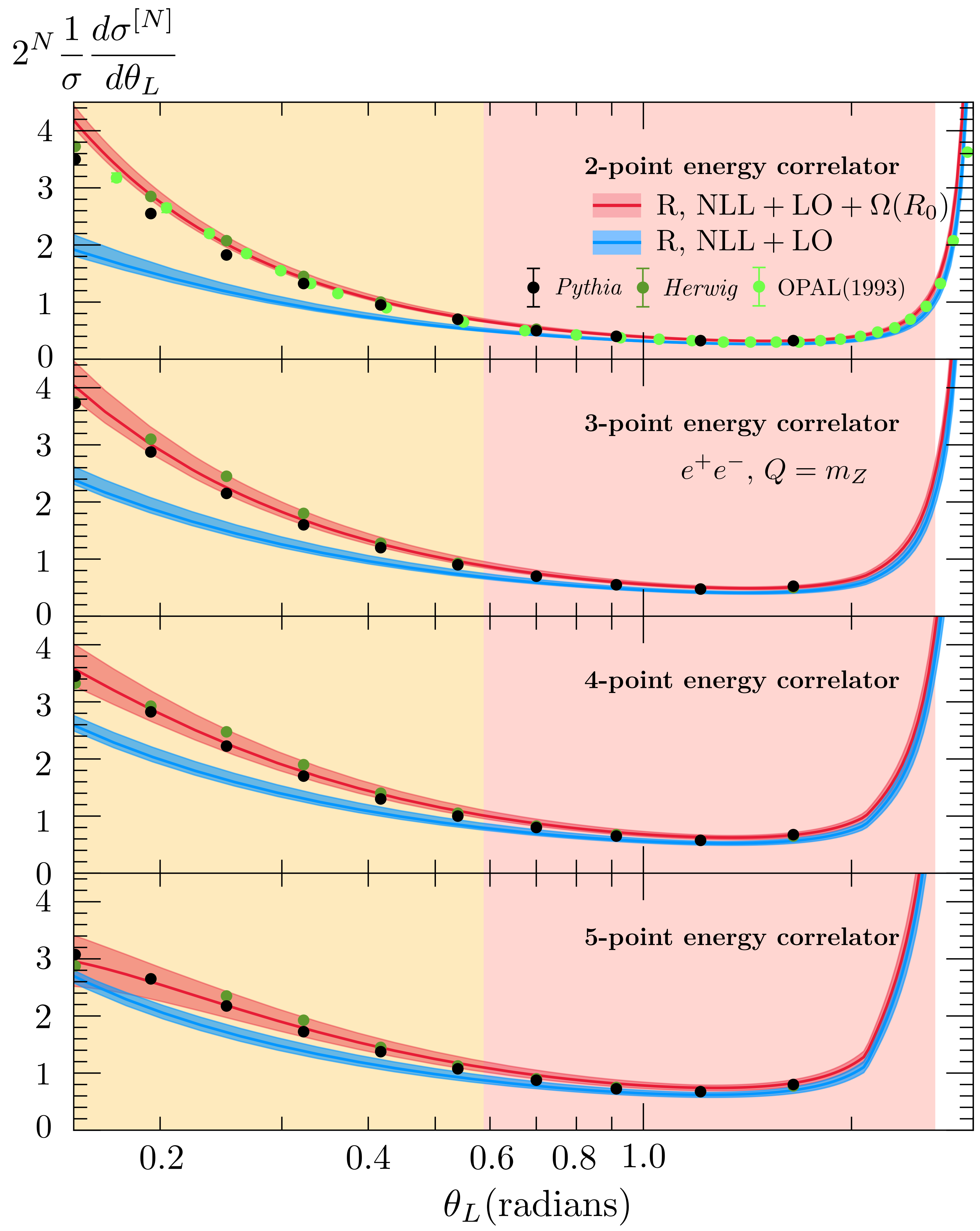
Schindler, Stewart, Sun `23
KL, Pathak, Stewart, Sun `24
Chen, Monni, Xu, Zhu `24

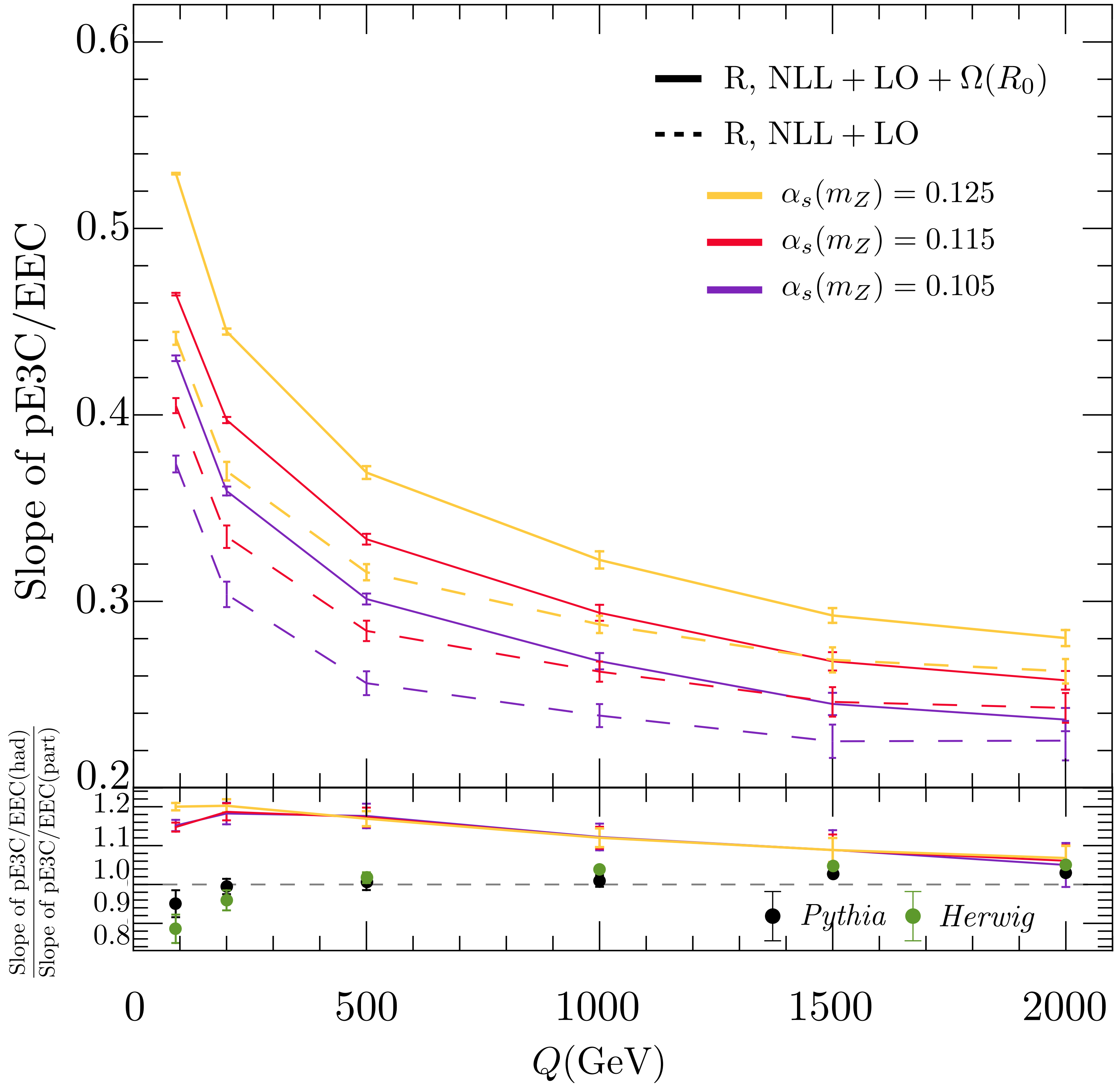


e^+e^- **in the collinear limit exhibits same universal behavior as hadron jets**

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

Universal Power Corrections





At Q=1000, 10% impact of power correction

IMPROVING PERTURBATIVE ACCURACY

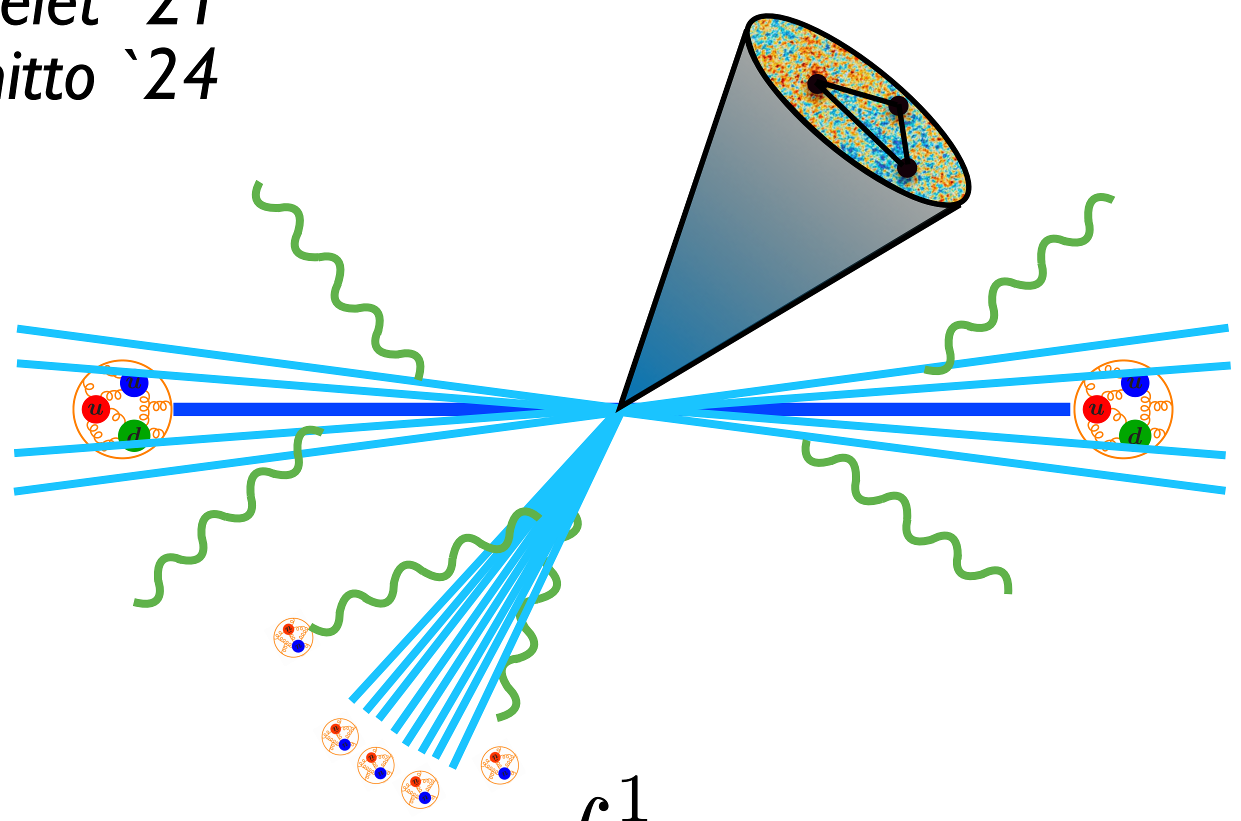
1. Measurements on Tracks
2. Power corrections
3. **Improved perturbative accuracy**

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

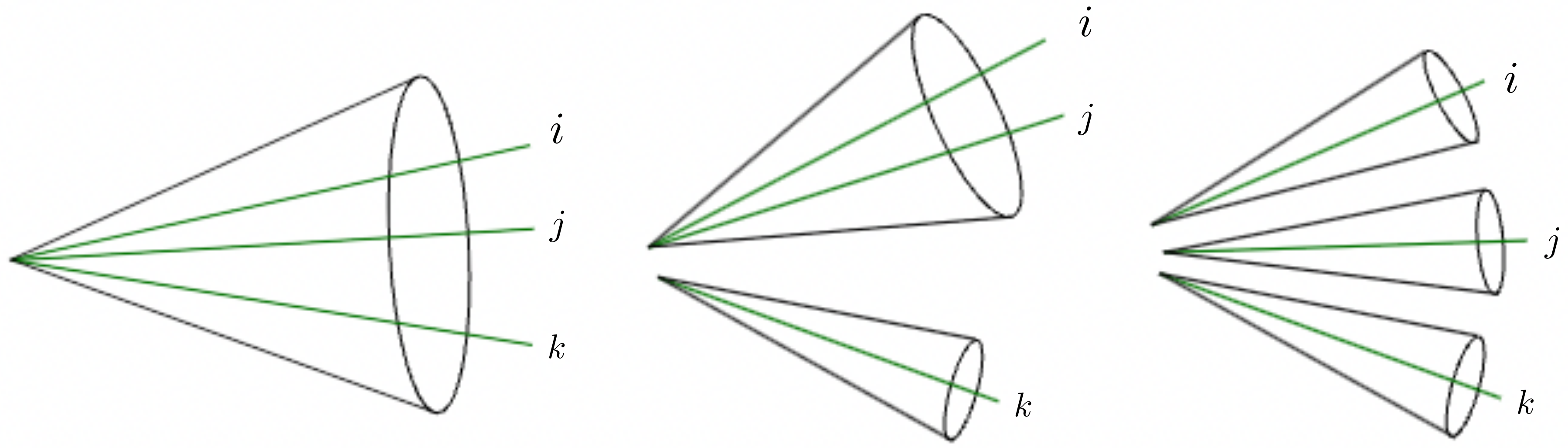
Czakon, Generet, Mitov, Poncelet `21
Bonino, Gehrmann, Stagnitto `24

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

Λ_{QCD} $\quad p_T \quad p_T R \quad p_T\theta_L$



KL, Meçaj, Moult `22
Kang, KL, Zhao `20
KL, Moult, Zhang `In Progress

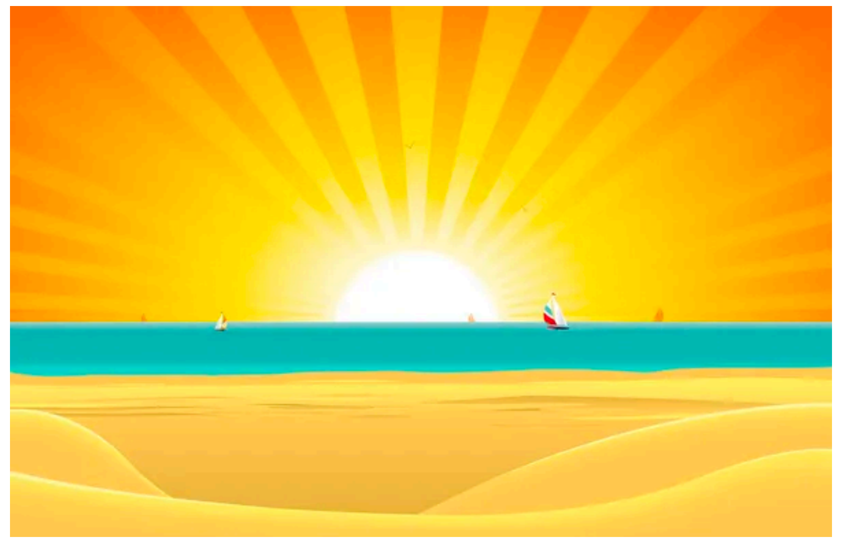


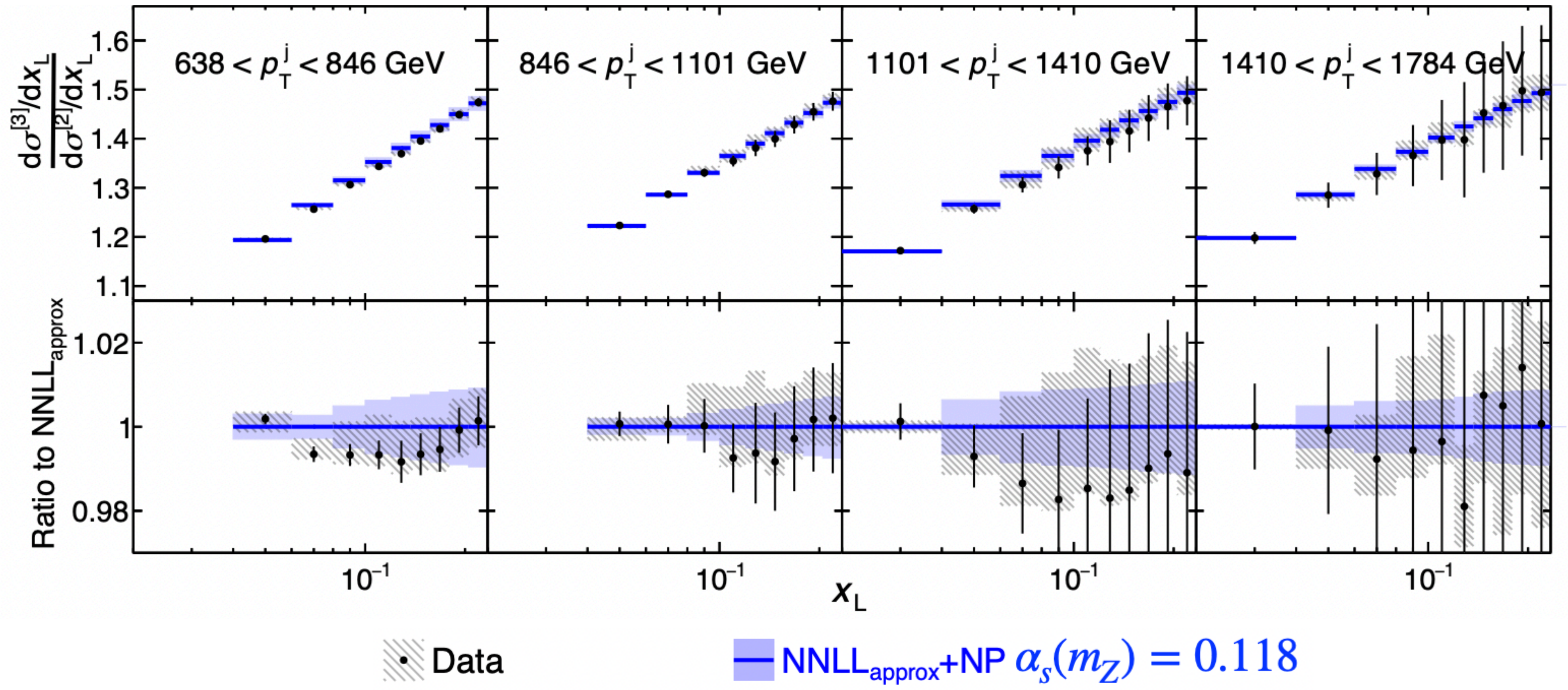
$A \qquad B \qquad C$

$$\mathcal{G}_c^{\text{N}-\text{proj}}(z, R_L, p_T R, \mu) = \sum_j \int_0^1 dx\, x^N \underbrace{\mathcal{J}_{ij}(z, x, p_T R, \mu)}\, J_{\text{EEC}}^{\text{N}-\text{proj}}(R_L, x, \mu)$$

Encodes complicated jet clustering algorithm details

$\tilde{s}_{ik}$ = angle between i and k $\qquad z_i$ = momentum fraction of i





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