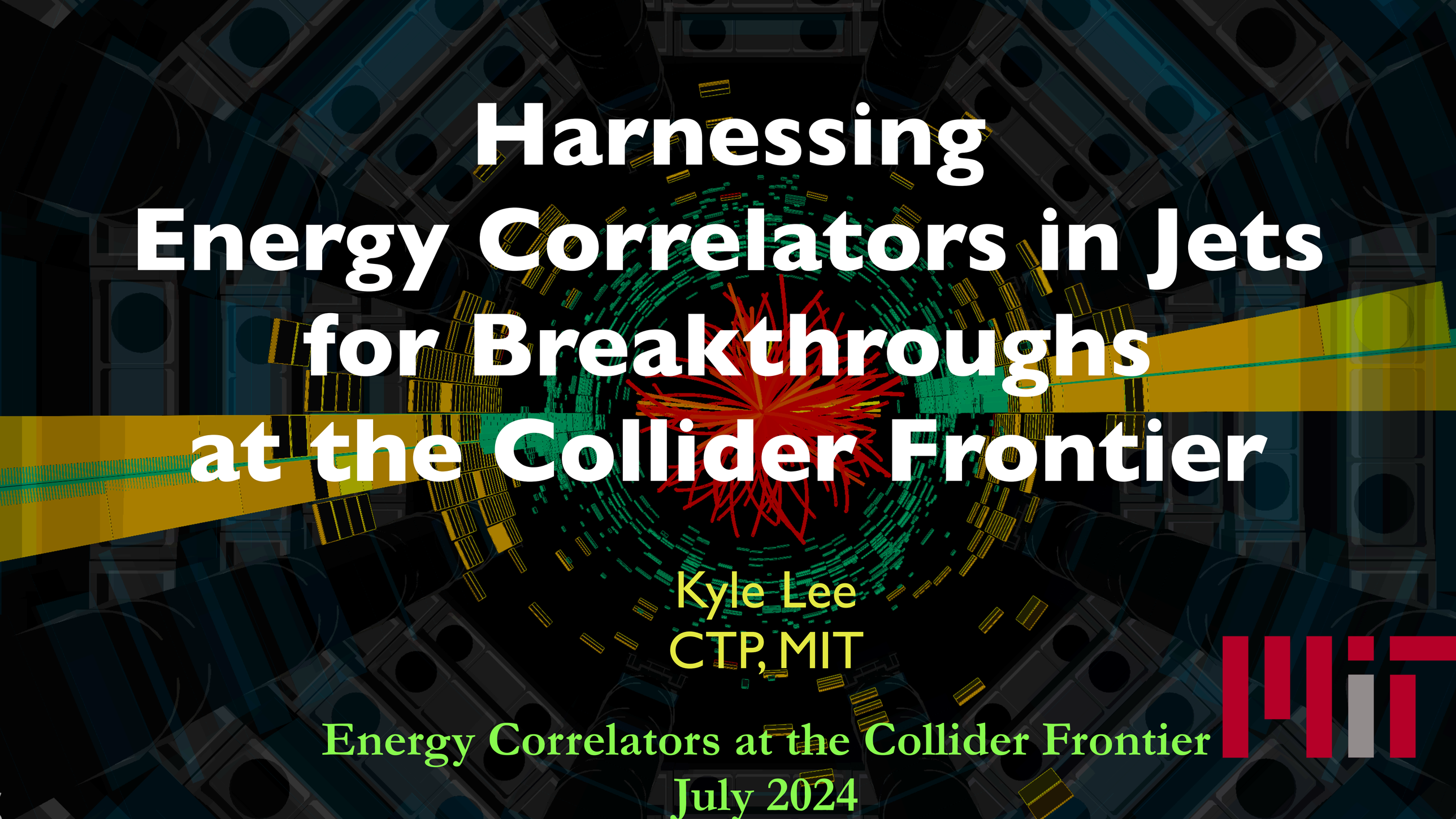
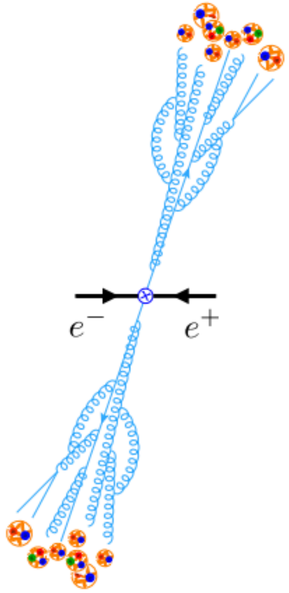


Harnessing Energy Correlators in Jets for Breakthroughs at the Collider Frontier

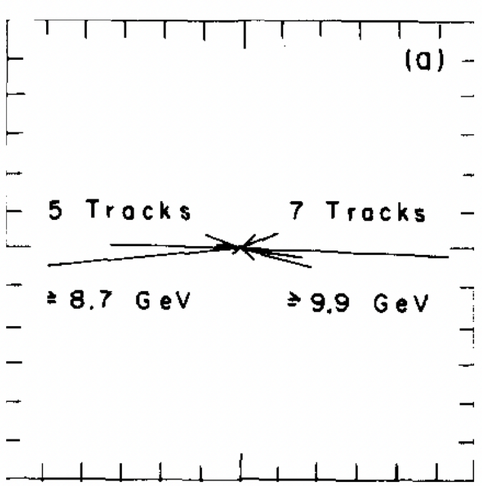
Kyle Lee
CTP, MIT

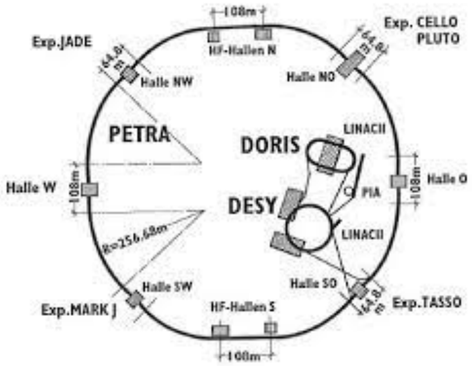
Energy Correlators at the Collider Frontier
July 2024

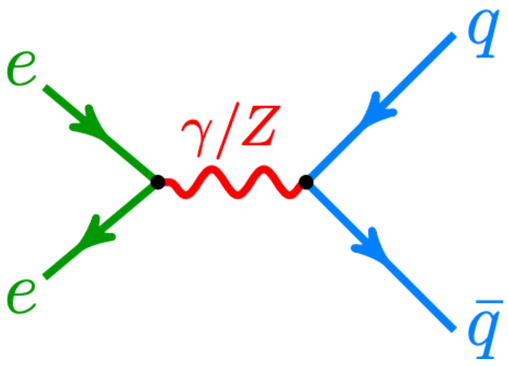
THE DAWN OF QCD: FROM PARTONS TO JETS



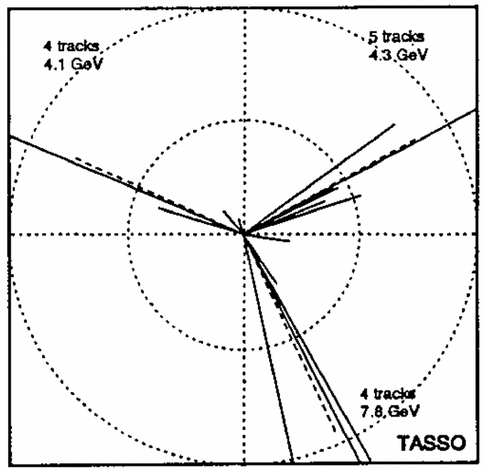
2-jet event

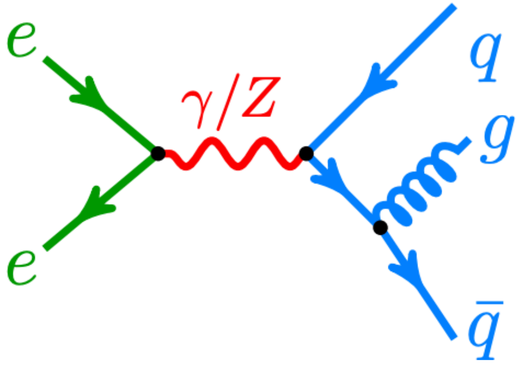




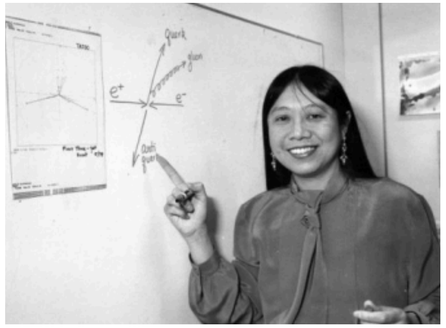


3-jet event





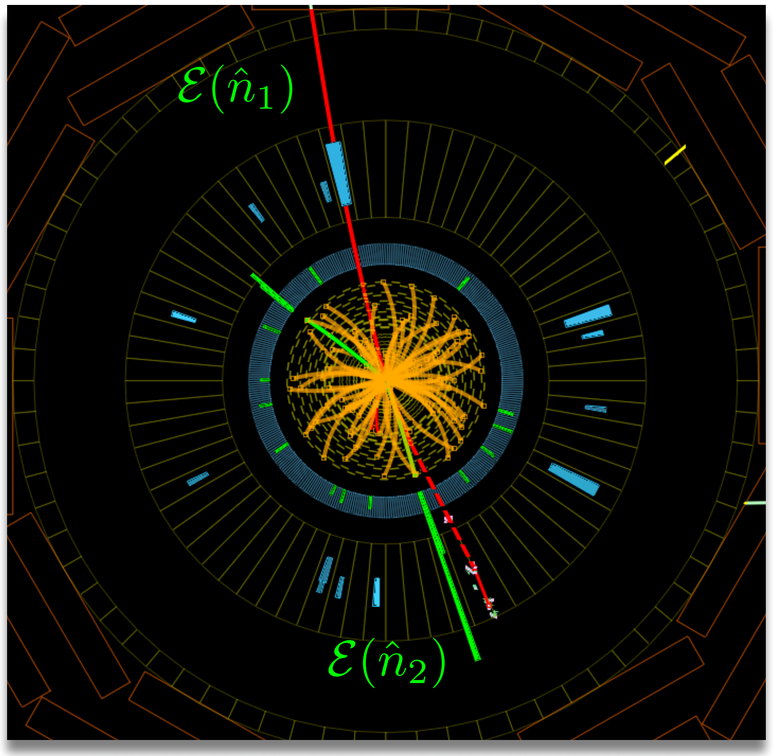
	$\sum_i \lvert p_i \rvert_{CHARGE}$	TOTAL ENERGY
JET 1	4.3 GEV	7.4 GEV
JET 2	7.8	8.9
JET 3	4.1	11.1



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

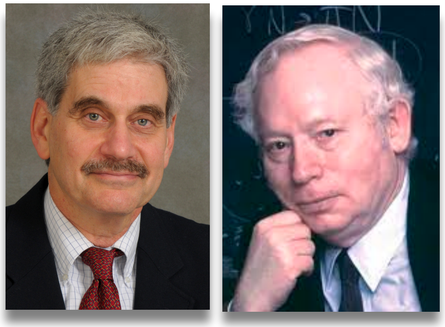


Energy Flow Operators

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

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

Basham, Brown, Ellis, Love, `78-79
Sveshnikov, Tkachov, `95
Korchemsky, Sterman, `01



Sterman `75
Sterman, Weinberg `77

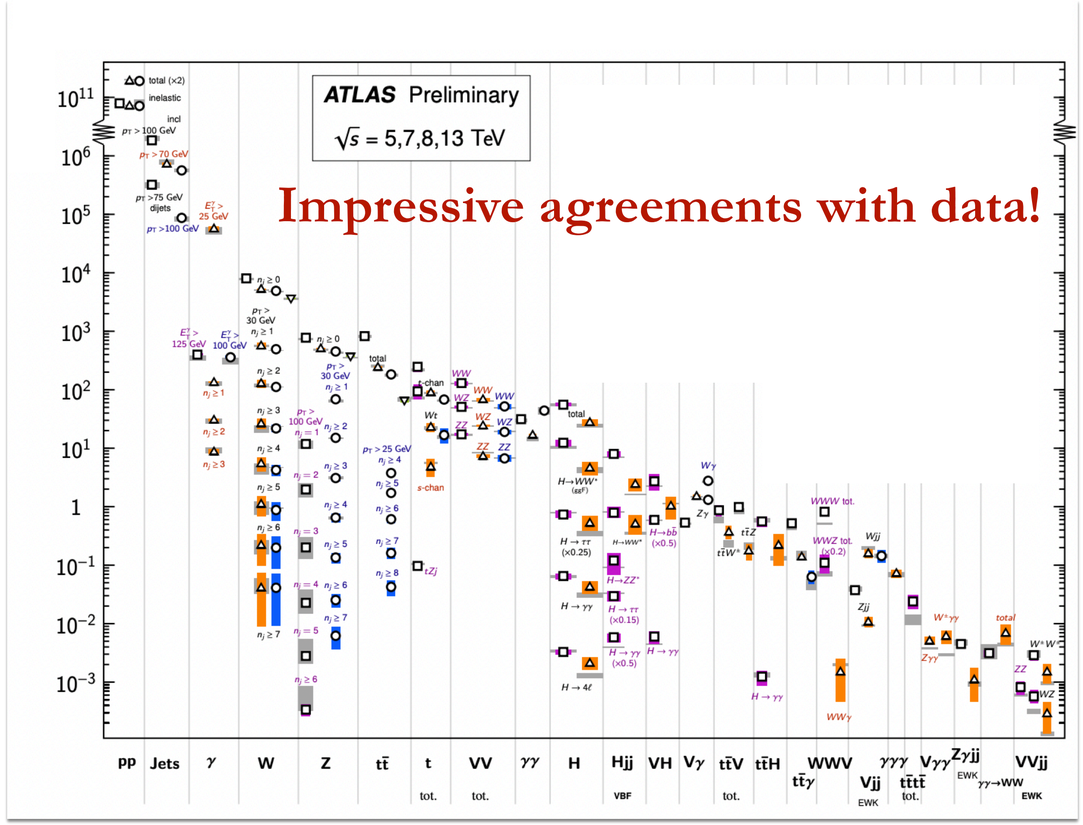
Caron-Huot, Kologlu, Kravchuk, Meltzer, Simmons-Duffin`22

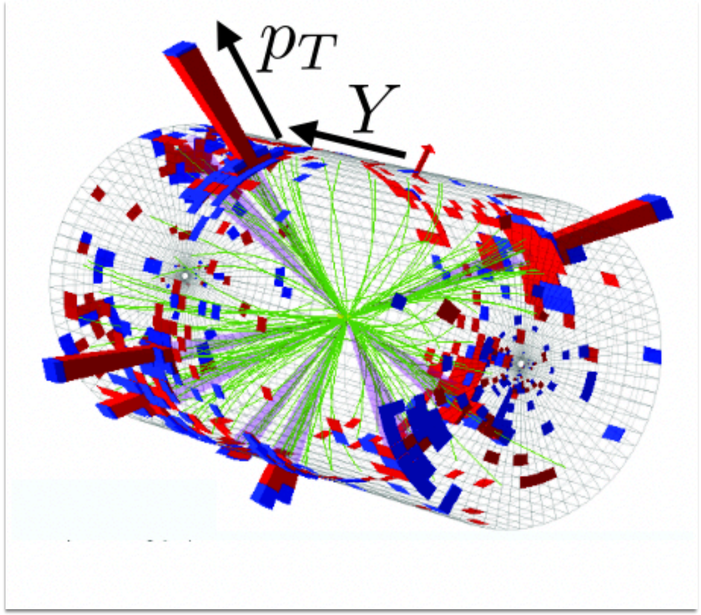
"Energy flow becomes the focus of computability"

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

JETS AT COLLIDERS

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

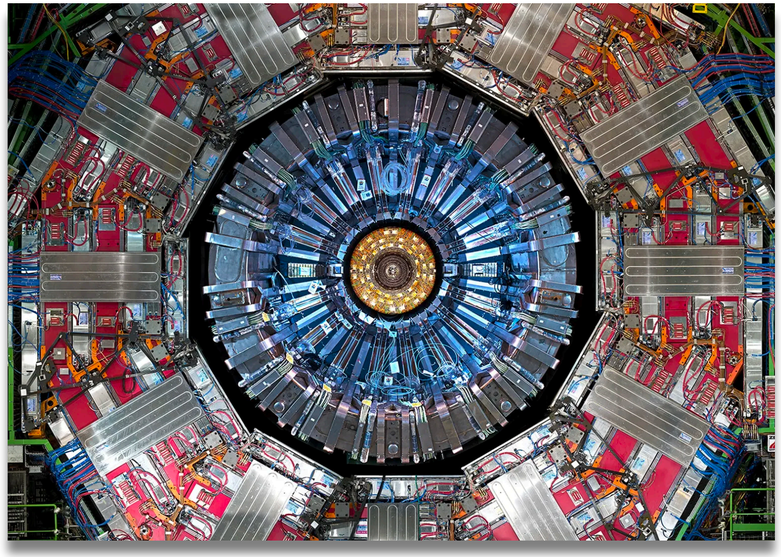




9-jet at the LHC

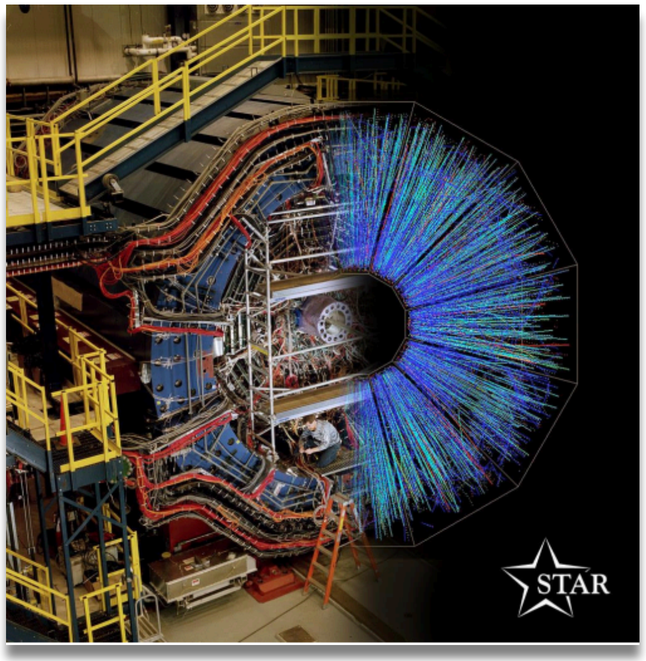
- **Field of jet physics (energy flow) have always been intricately connected to the success of the collider physics program!**

EXCITING COLLIDER PHYSICS ERA



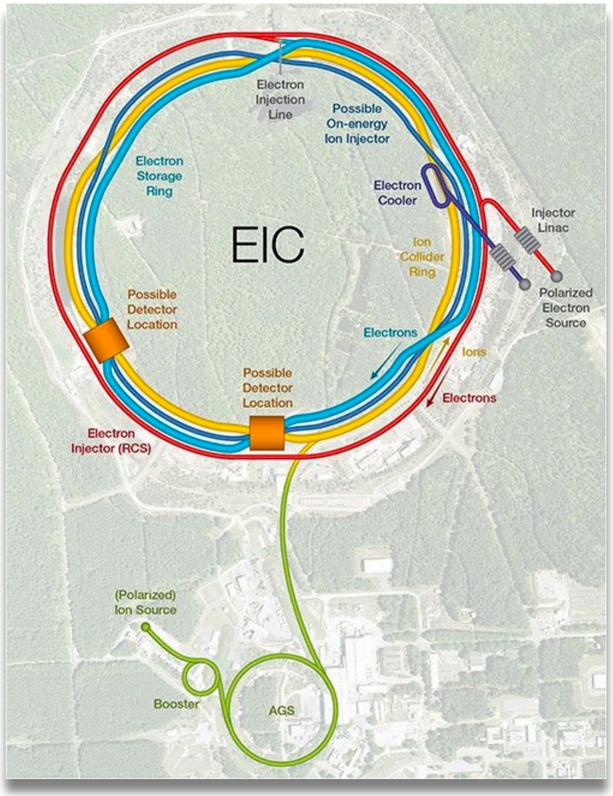
LHC, 2008 - Present

Run 3 running!



RHIC, 2000 - Present

sPHENIX: 2024-



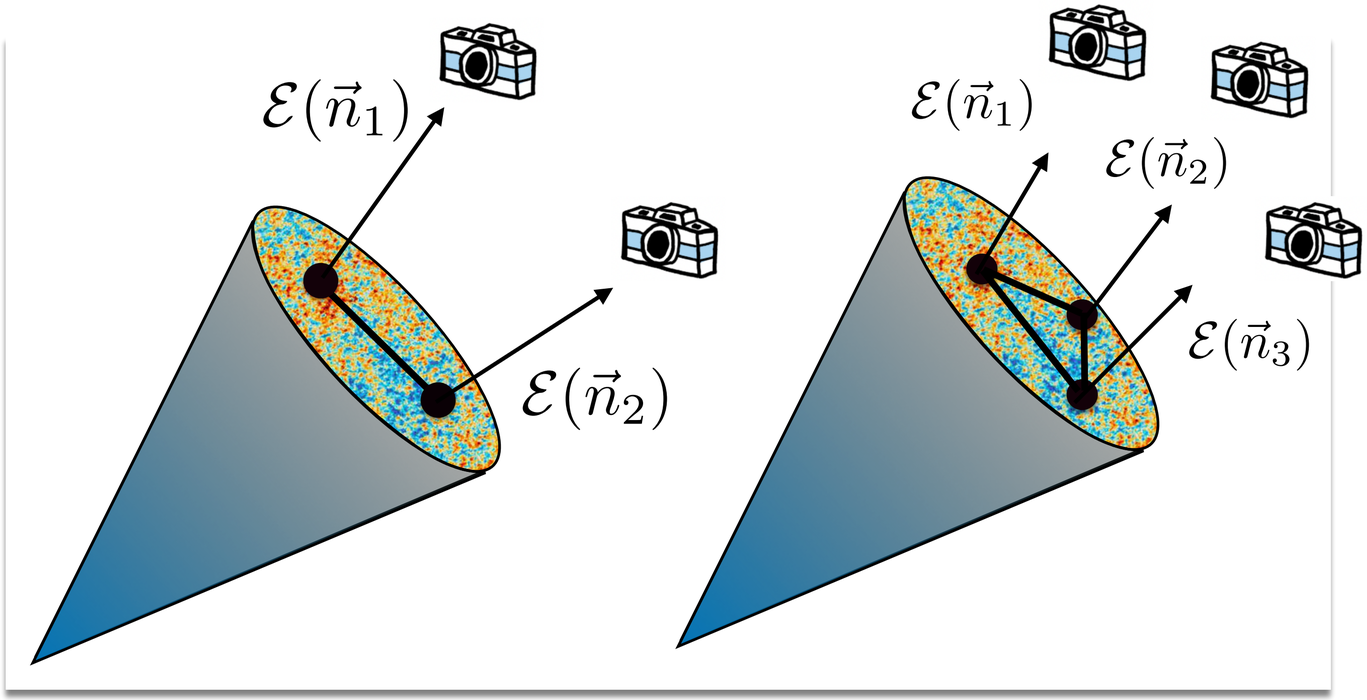
EIC, 2030s-

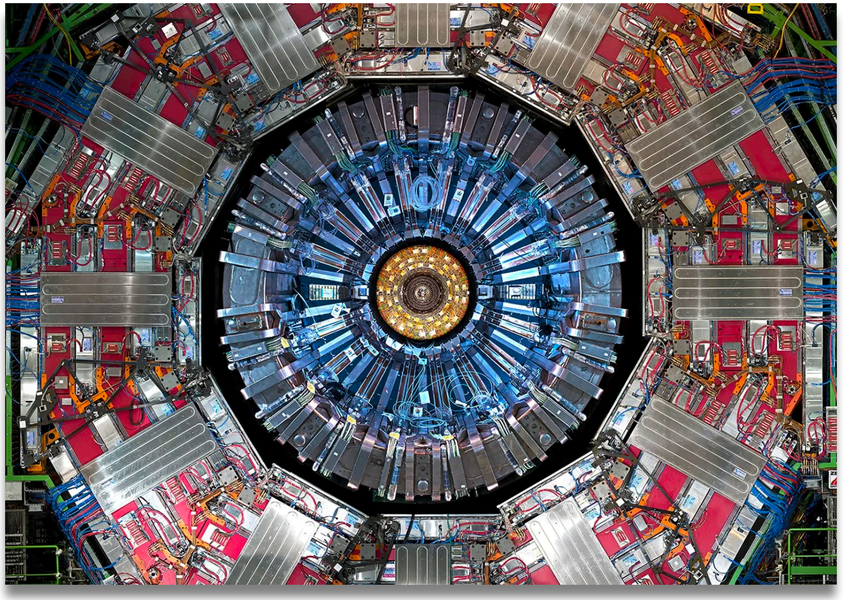
- **Jets at colliders give us the means to probe field theory in data!**

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**



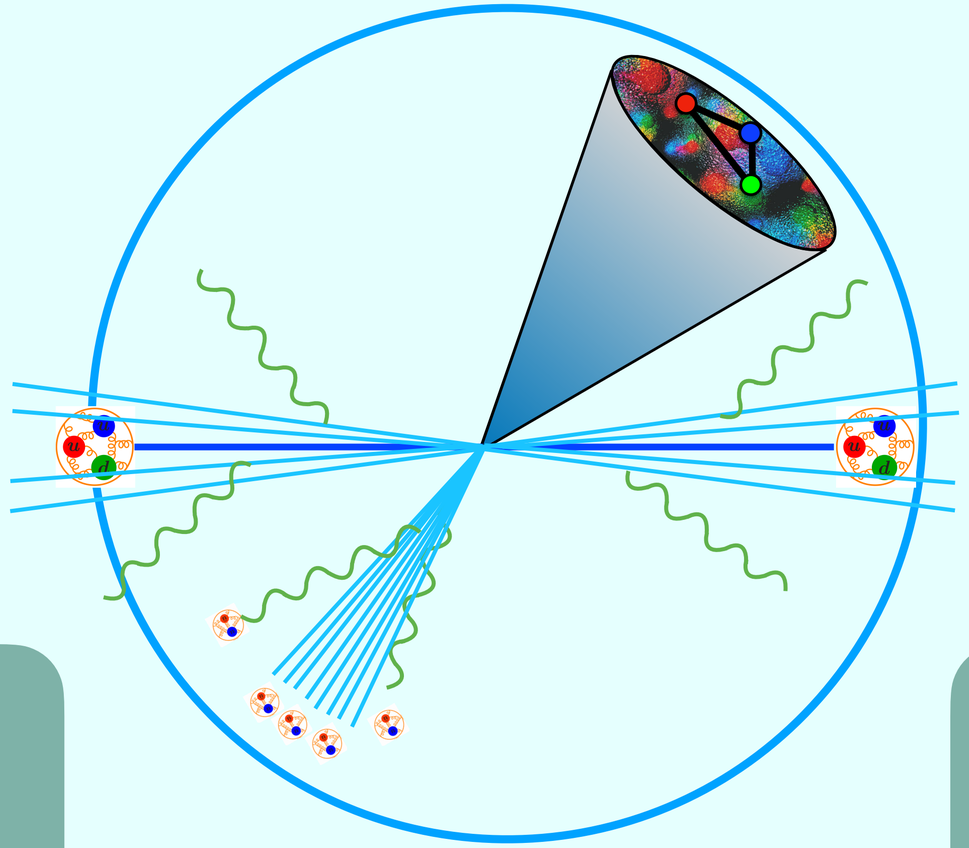


- **Relative to inclusive jet cross-section, or one-point energy correlation, jet substructure gives us opportunity to study multi-point correlations of energy within jets**

Overview

II. Precision QCD

I. Universal Scaling

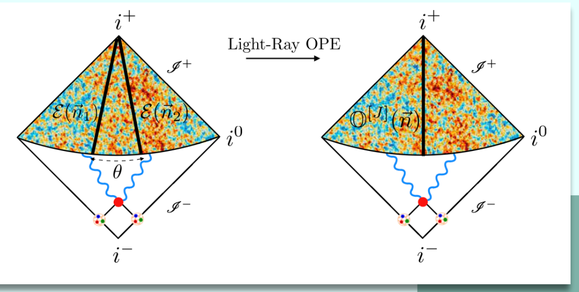


III. Heavy Flavor Physics

V. Hadronization

IV. Medium Dynamics

Overview

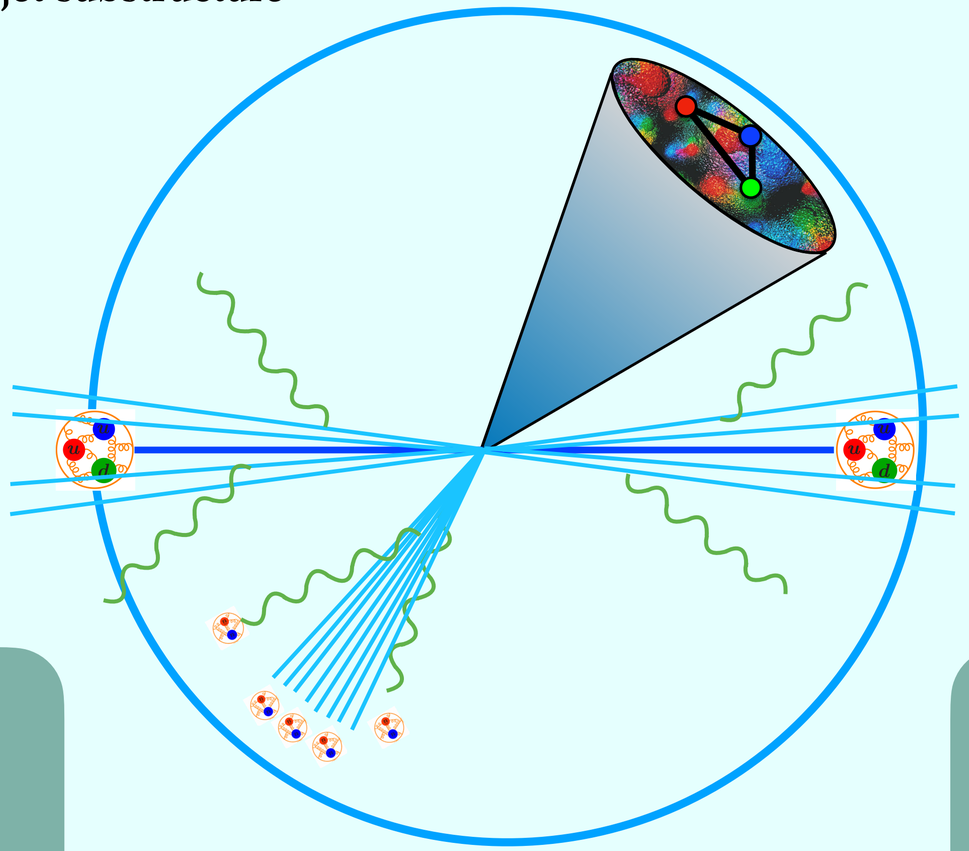


QFT perspective of jet substructure

I. Universal Scaling

II. Precision QCD

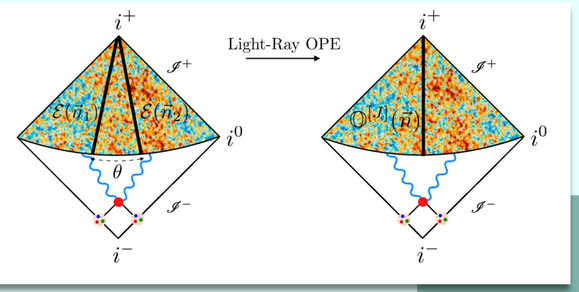
III. Heavy Flavor Physics



IV. Medium Dynamics

V. Hadronization

Overview



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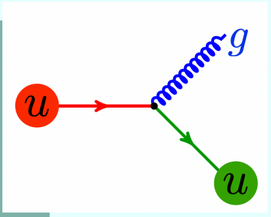

Precise determination of α_s

QFT perspective of jet substructure

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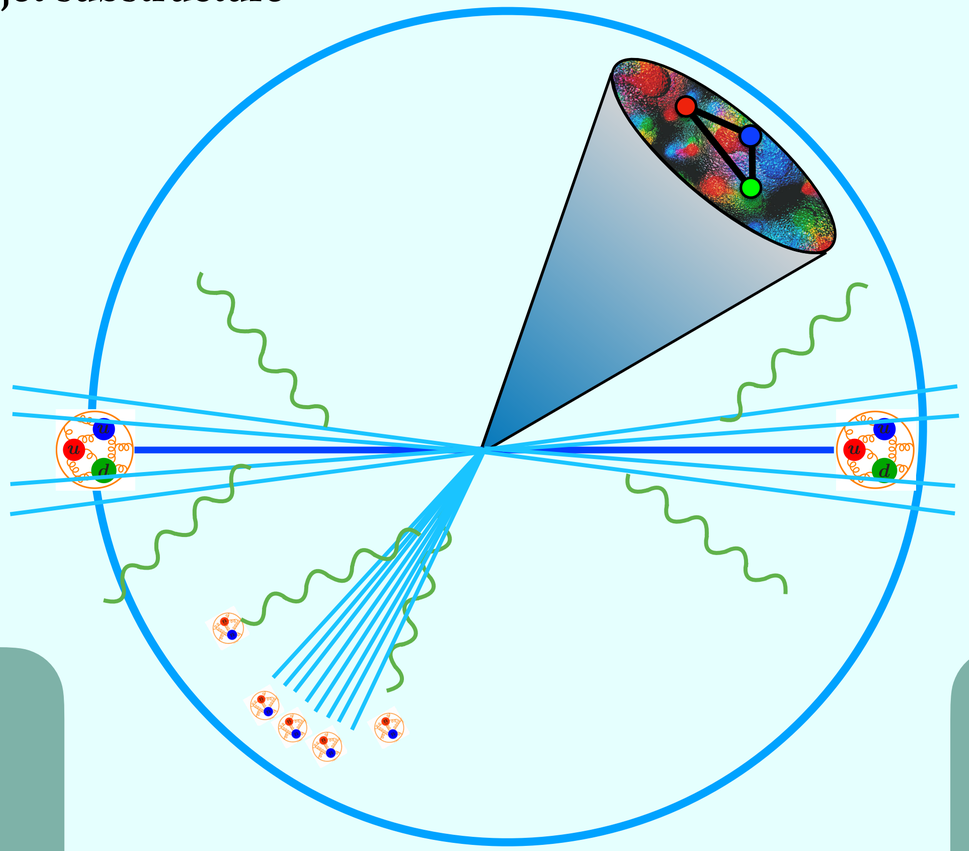

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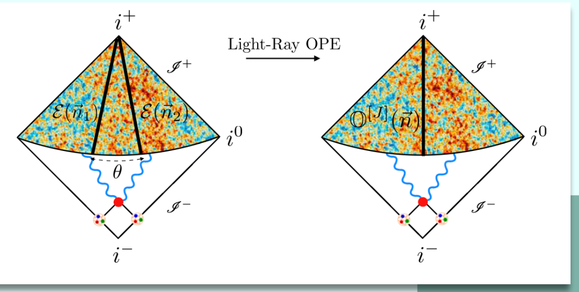

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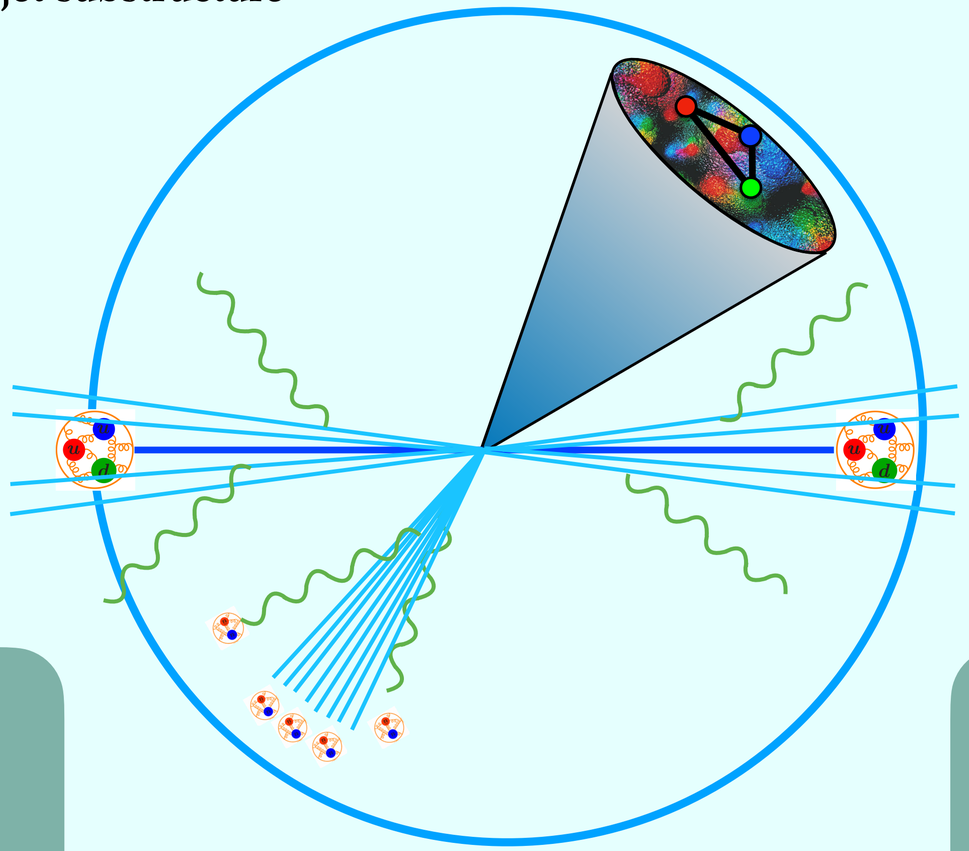

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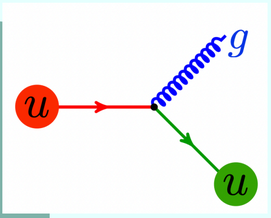

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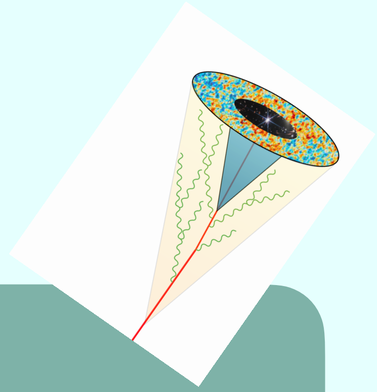


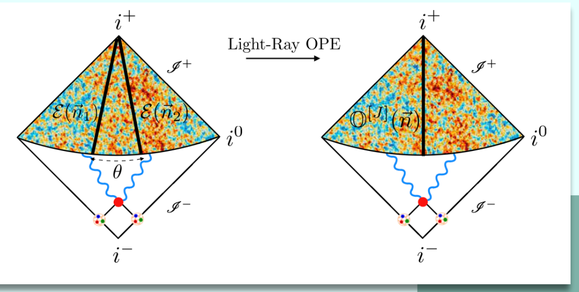
III. Heavy Flavor Physics

Revealing dead-cone

IV. Medium Dynamics

V. Hadronization

Overview



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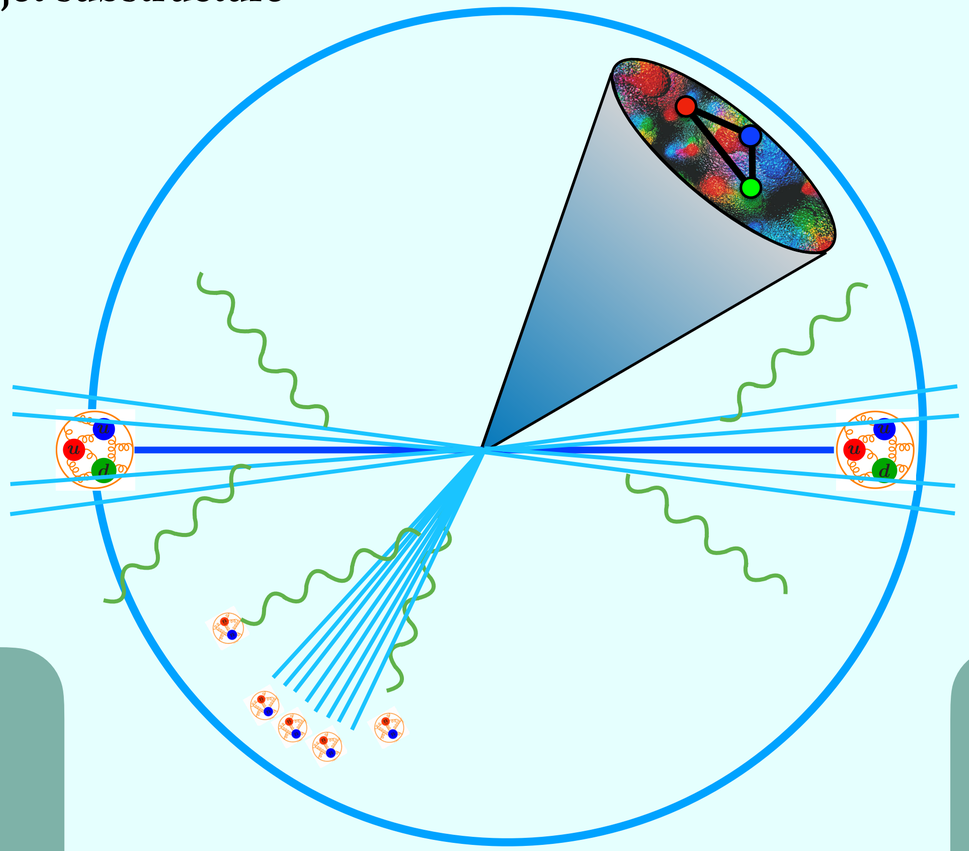

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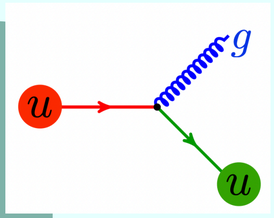

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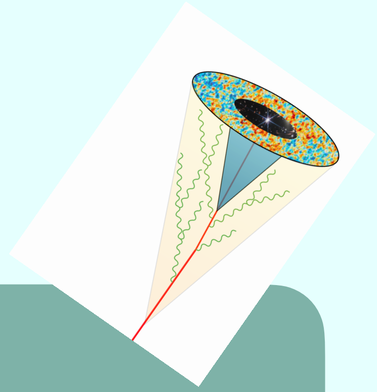

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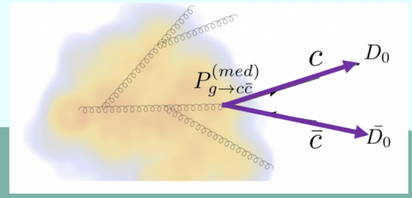
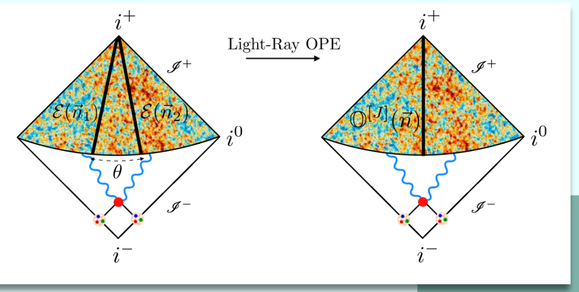


IV. Medium Dynamics

Revealing medium scale and modifications

V. Hadronization

Overview



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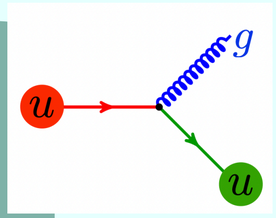

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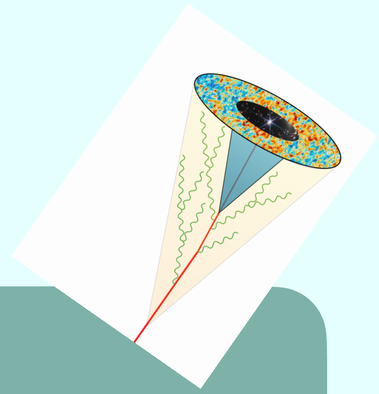

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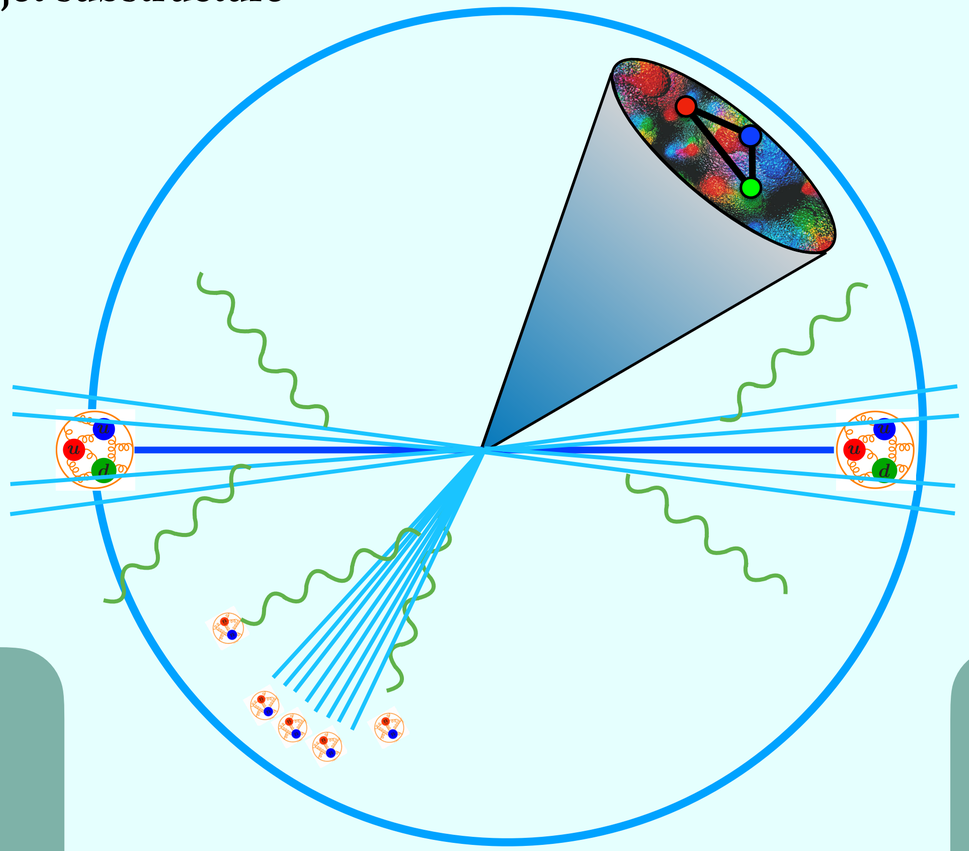
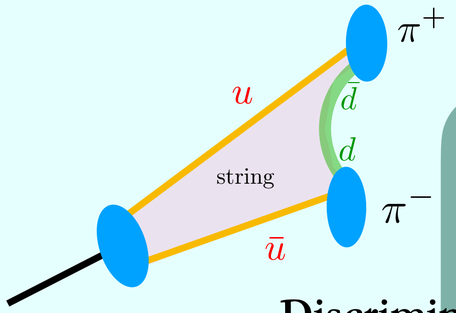
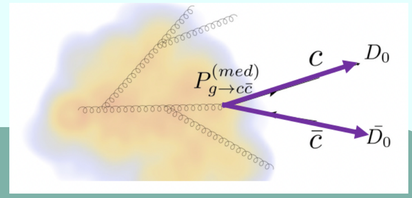




V. Hadronization

Discrimination between hadronization mechanisms



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Revealing medium scale and modifications

Overview

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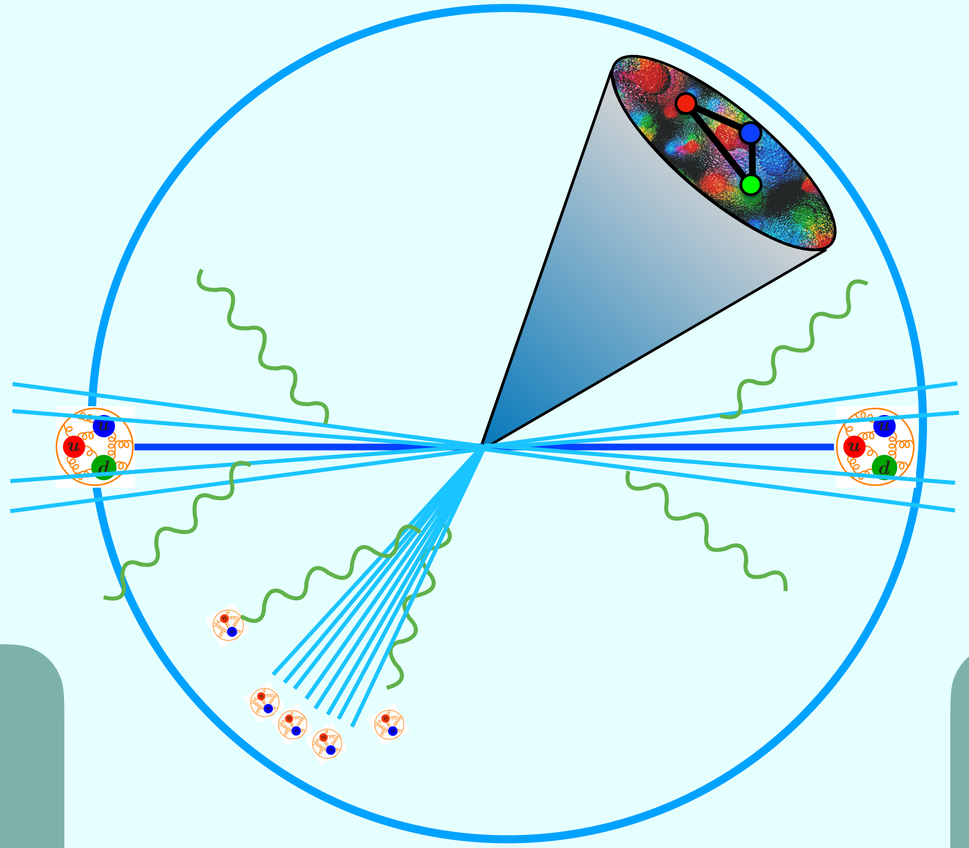


III. Heavy Flavor Physics

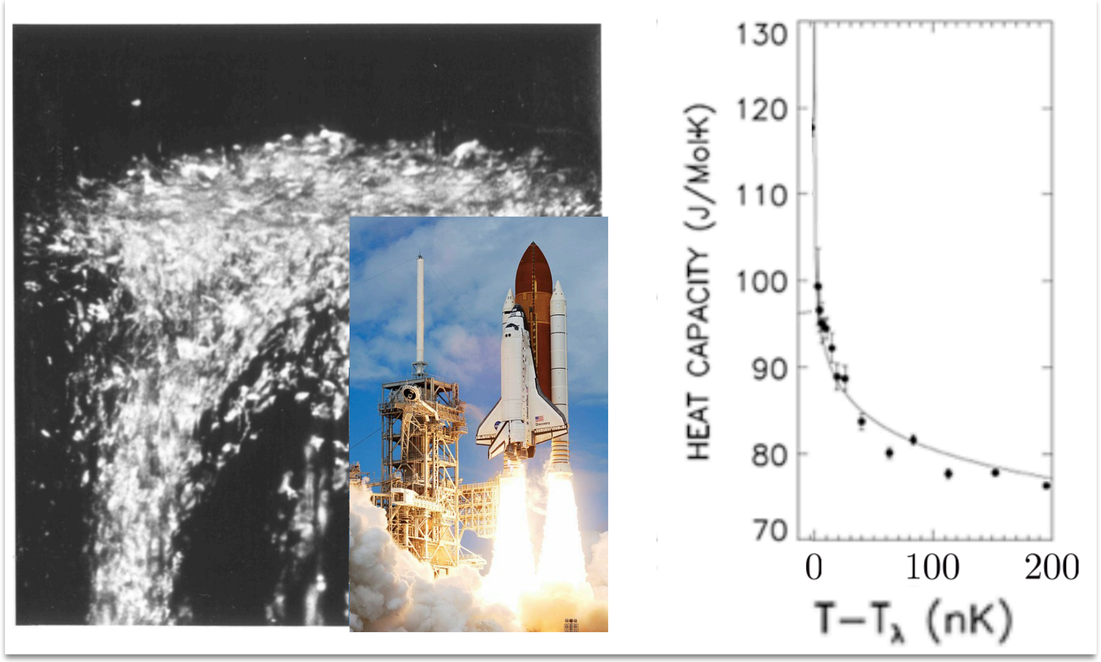
V. Hadronization

IV. Medium Dynamics

SCALING BEHAVIOR IN QFT

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

Wilson `70



Euclidean Operator Product Expansion

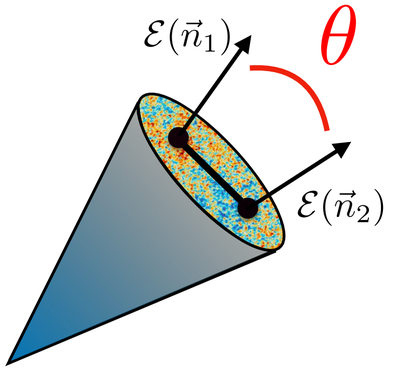
$$\mathcal{O}(x)\mathcal{O}(0) = \sum x^{\gamma_i} c_i \mathcal{O}_i$$

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

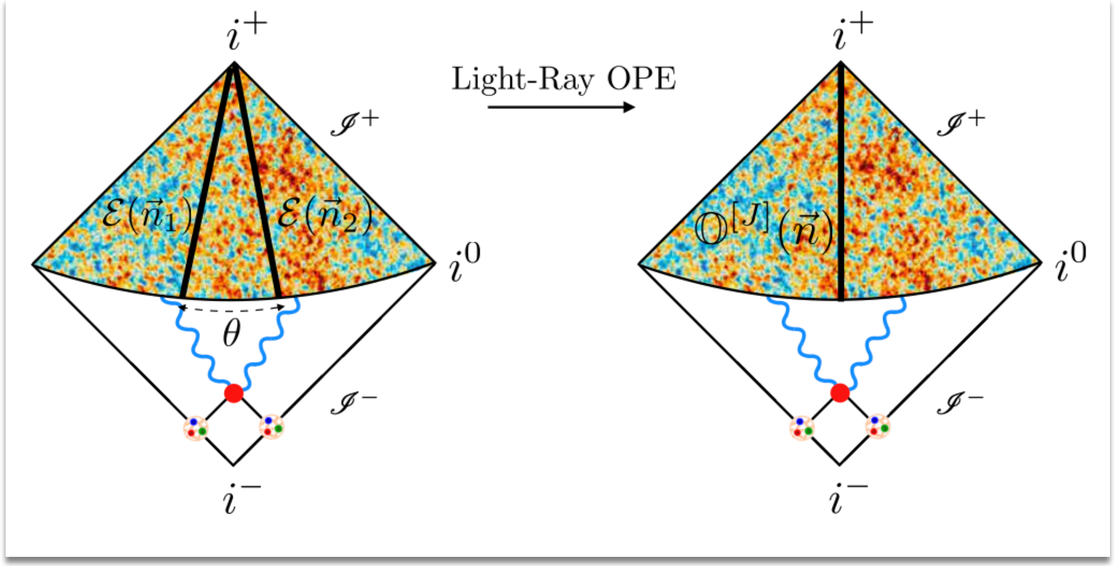
UNIVERSAL LORENTZIAN SCALING WITHIN JETS

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

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



Hofman, Maldacena `08



Light-ray Operator Product Expansion

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

quantum classical

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

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Much interests from the formal theory: (See also many exciting talks this week!)

Kravchuk, Simmons Duffin, `18* *Belitsky, Hohenegger, Korchemsky, Sokatchev, Zhiboedov, `13 *Firat, Monin, Rattazzi, Walters `23*
Henn, Sokatchev, Yan, Zhiboedov, `19* *Kologlu, Kravchuk, Simmons Duffin, Zhiboedov, `19 *Gonzo, Ilderton `23*
Korchemsky, `19* *Chang, Kologlu, Kravchuk, Simmons-Duffin, `20 *Hartman, Mathys `24*
Belin, Hofman, Mathys, `19* *Caron-Huot, Kologlu, Kravchuk, Meltzer, Simmons-Duffin, `22 *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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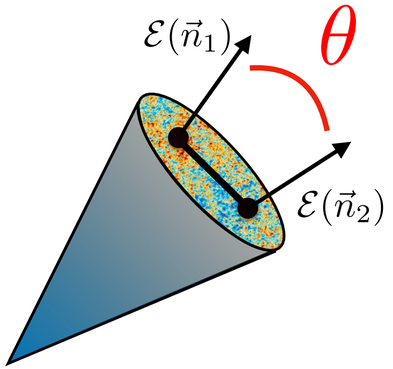
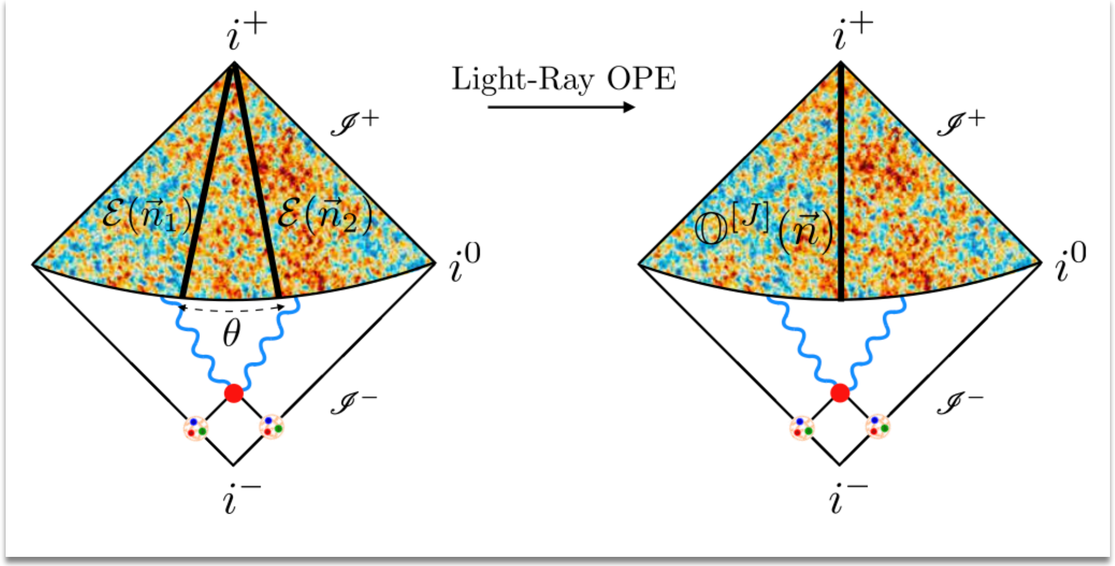


Hofman, Maldacena `08



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Korchemsky, `19 Chang, Kologlu, Kravchuk, Simmons-Duffin, `20
Belin, Hofman, Mathys, `19 Caron-Huot, Kologlu, Kravchuk, Meltzer, Simmons-Duffin, `22 Chen, Ka
… Chicherin, Moult, So…

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**

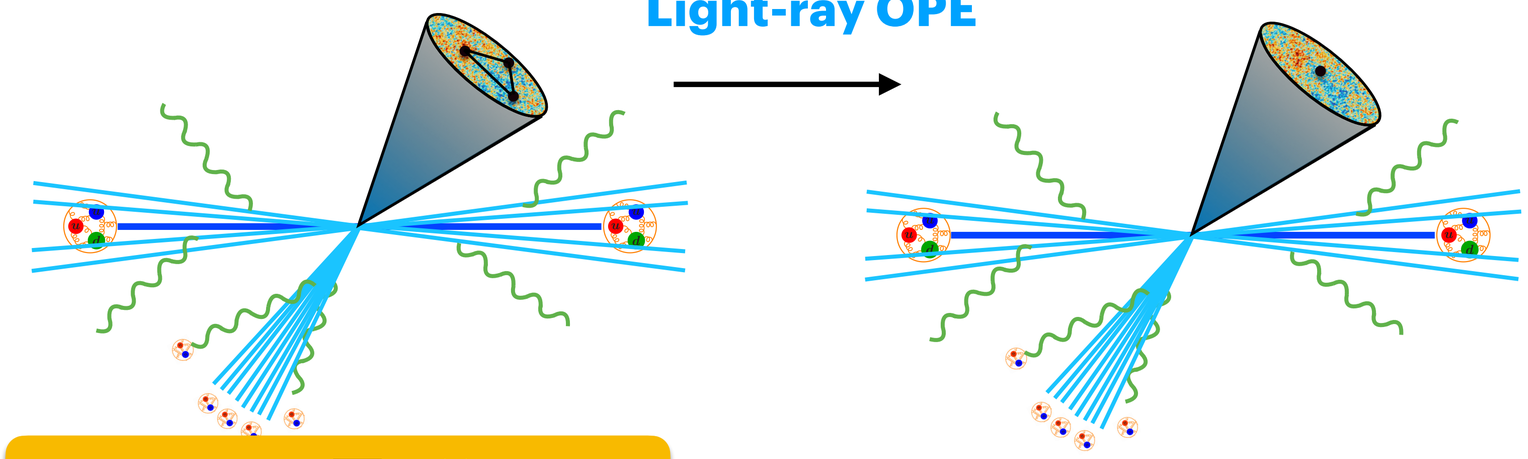
UNIVERSAL SCALING BEHAVIOR IN JETS!

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

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

$\langle\psi\,|\mathcal{E}\,(\vec{n}_1)\,\mathcal{E}\,(\vec{n}_2)|\,\psi\rangle$ $\qquad$ $\langle\psi|\mathbb{O}^{[3]}(\vec{n})|\psi\rangle$

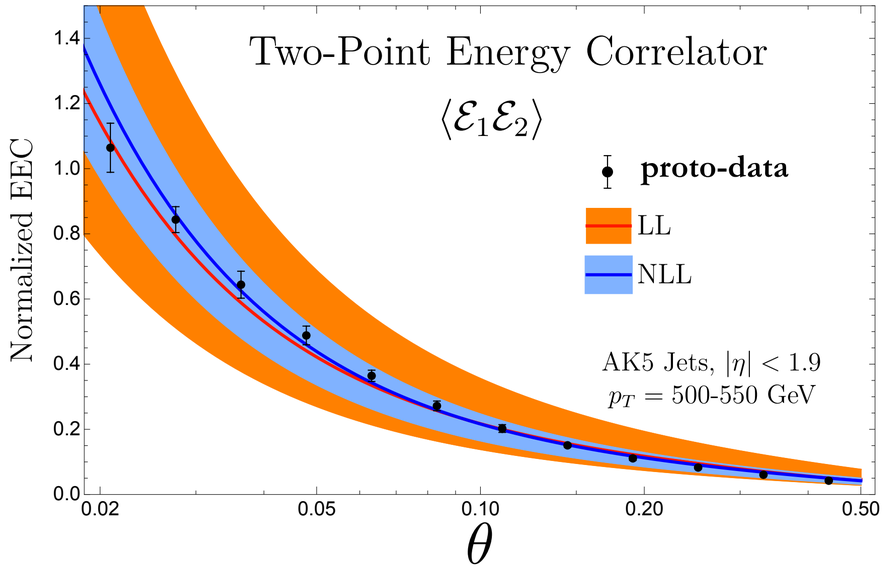
Light-ray OPE



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

quantum classical

$\gamma(N) \propto \alpha_s$

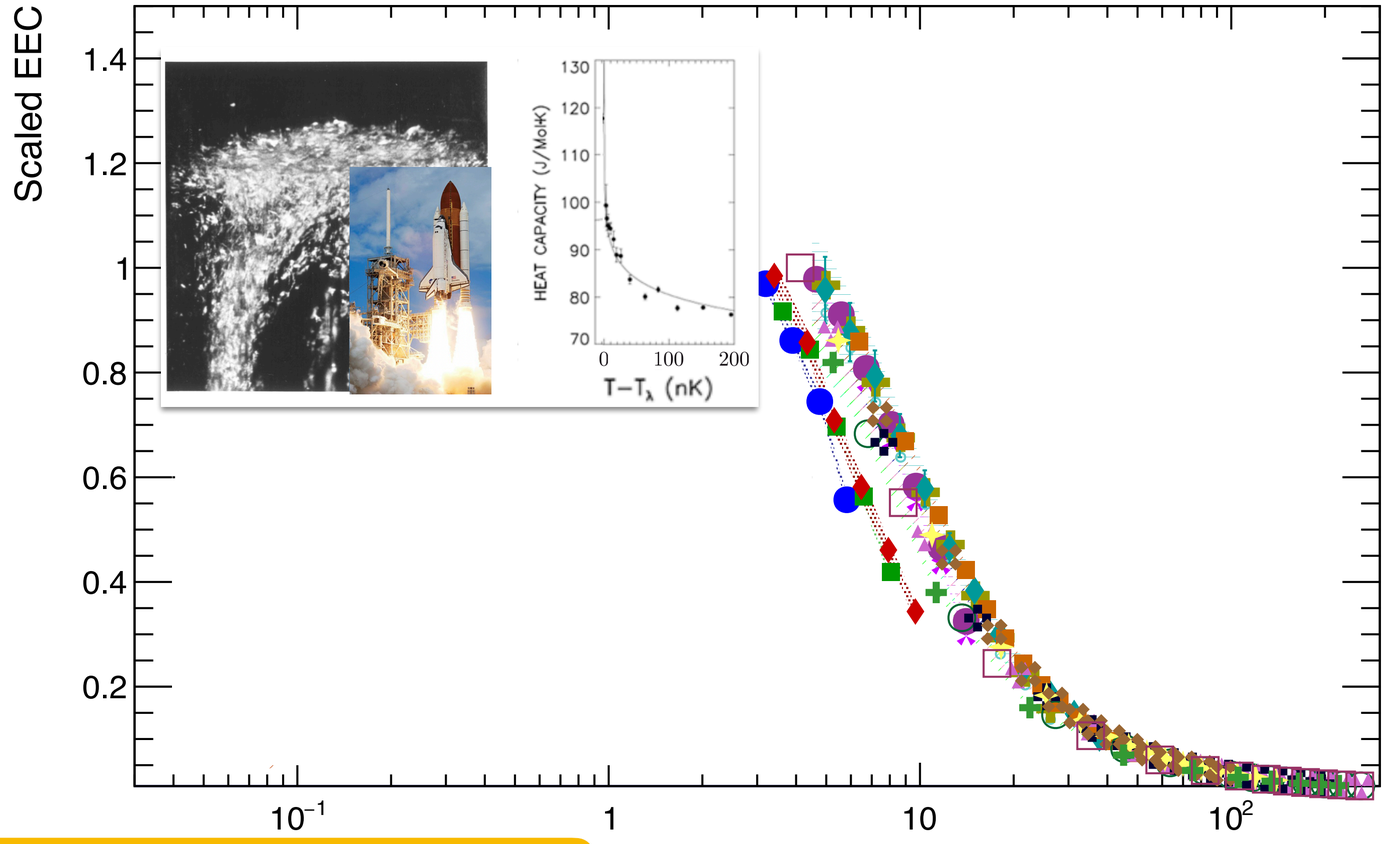


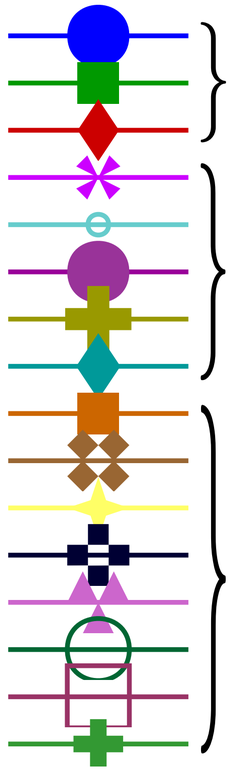
QCD factorization:

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

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

SCALING FROM 15 GEV TO 2 TEV!





STAR from 15 - 50 GeV

ALICE from 20 - 80 GeV

CMS from 97 - 1784 GeV

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

quantum classical

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

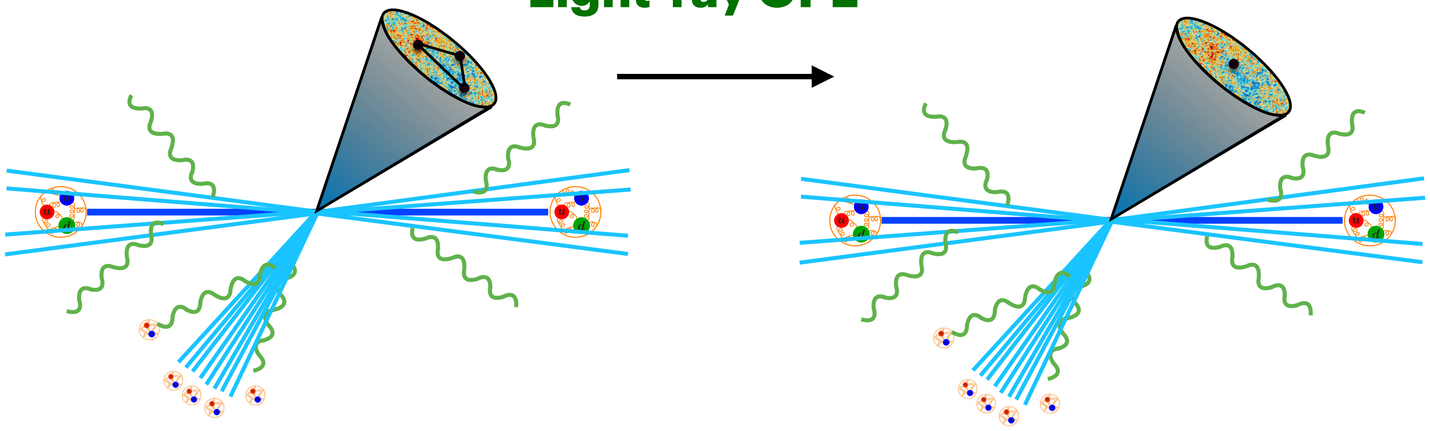
- **Universal scaling of QCD operators revealed in data from ALICE, CMS, and STAR, from 15 GeV to 1784 GeV!**

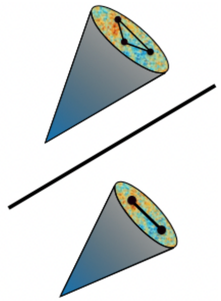
THE SPECTRUM OF A JET

- **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

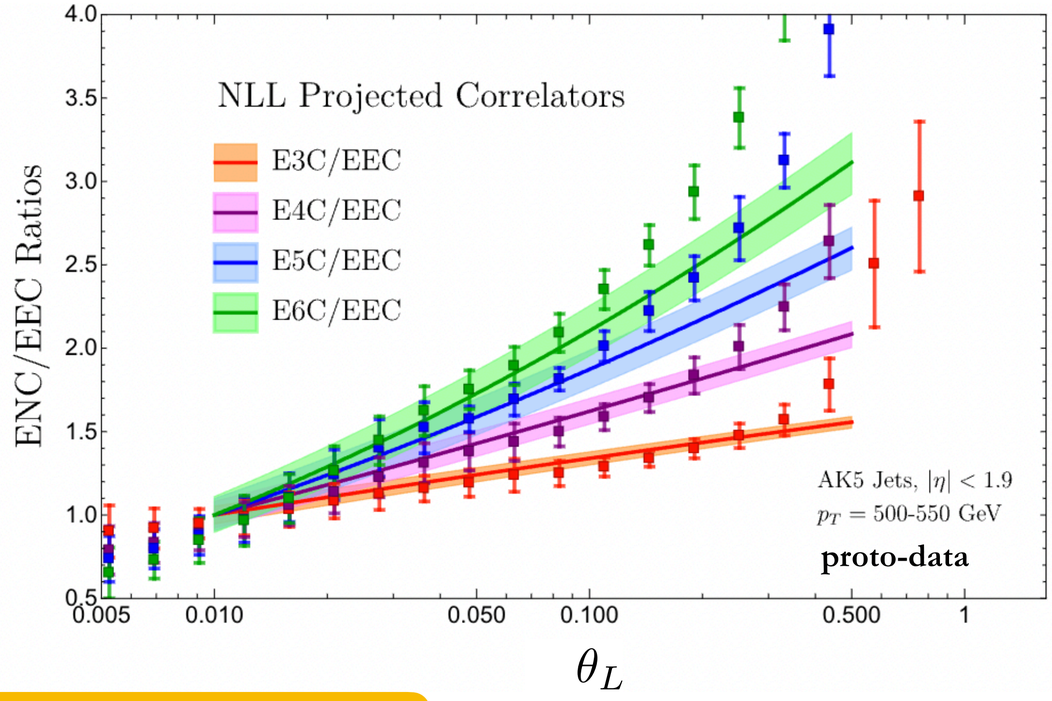
$\langle\psi\,|\mathcal{E}\,(\vec{n}_1)\cdots\mathcal{E}\,(\vec{n}_N)|\,\psi\rangle$ **Light-ray OPE** $\langle\psi|\mathbb{O}^{[J]}(\vec{n})|\psi\rangle$





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

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



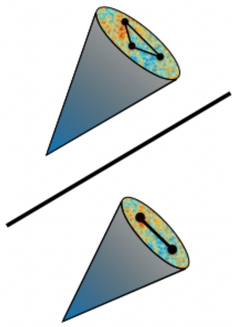
$$\mathcal{E}_1\cdots\mathcal{E}_N\sim\theta^{\gamma(N+1)-2}\mathbb{O}_i^{[N+1]}$$

quantum classical

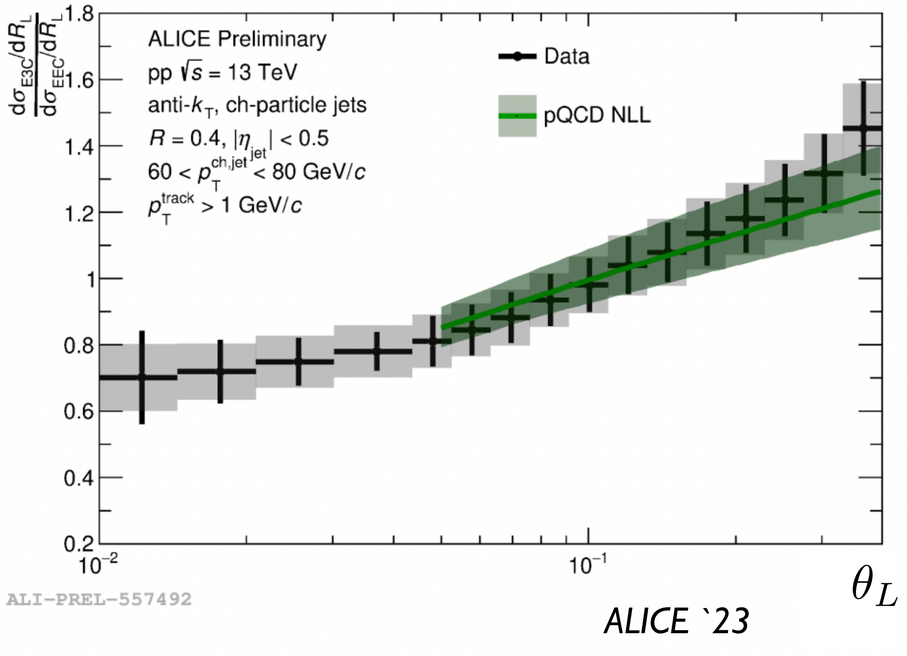
THE SPECTRUM OF A JET

- **Data for ratio of three-to-two point energy correlators exhibits predicted scaling!**

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

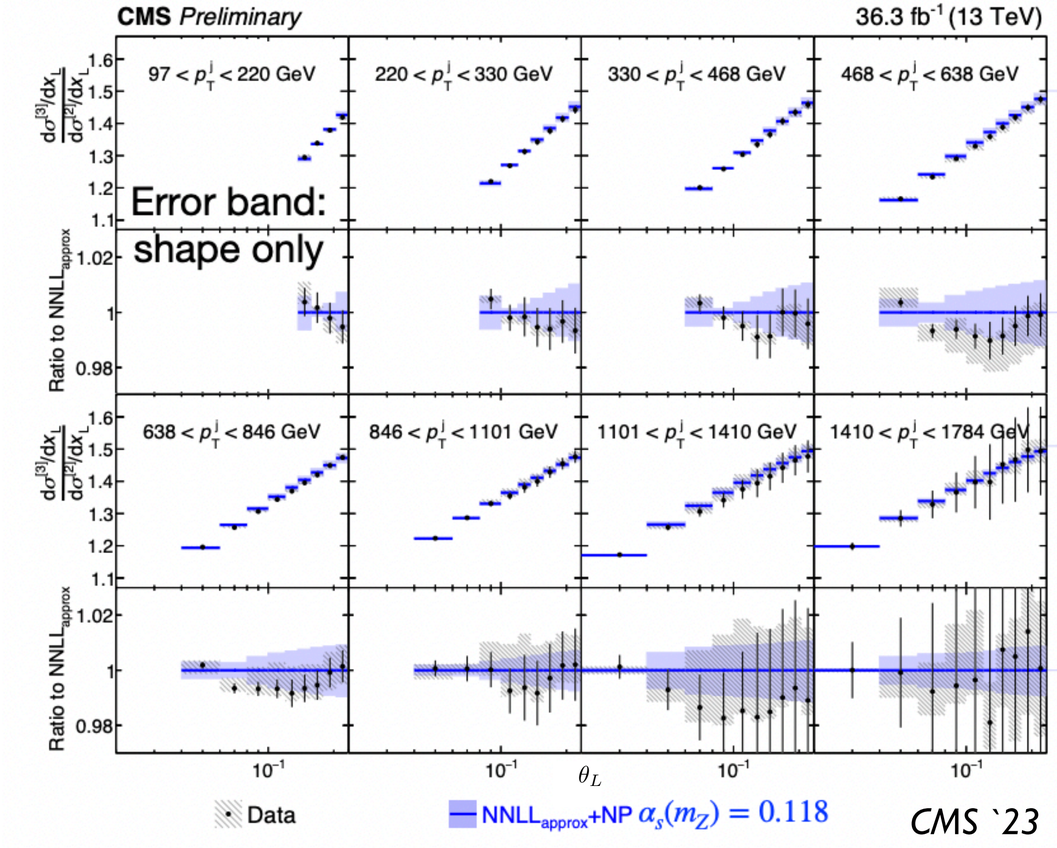


E3C/EEC



ALICE `23

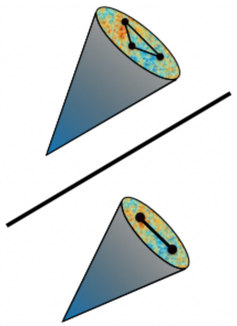
$$\frac{\langle \mathcal{E}_1 \mathcal{E}_2 \cdots \mathcal{E}_N \rangle}{\langle \mathcal{E}_1 \mathcal{E}_2 \rangle} \sim \frac{\langle \mathbb{O}^{[N+1]} \rangle}{\langle \mathbb{O}^{[3]} \rangle} \sim \theta_L^{\gamma(N+1)-\gamma(3)} \qquad \gamma(N) \propto \alpha_s$$

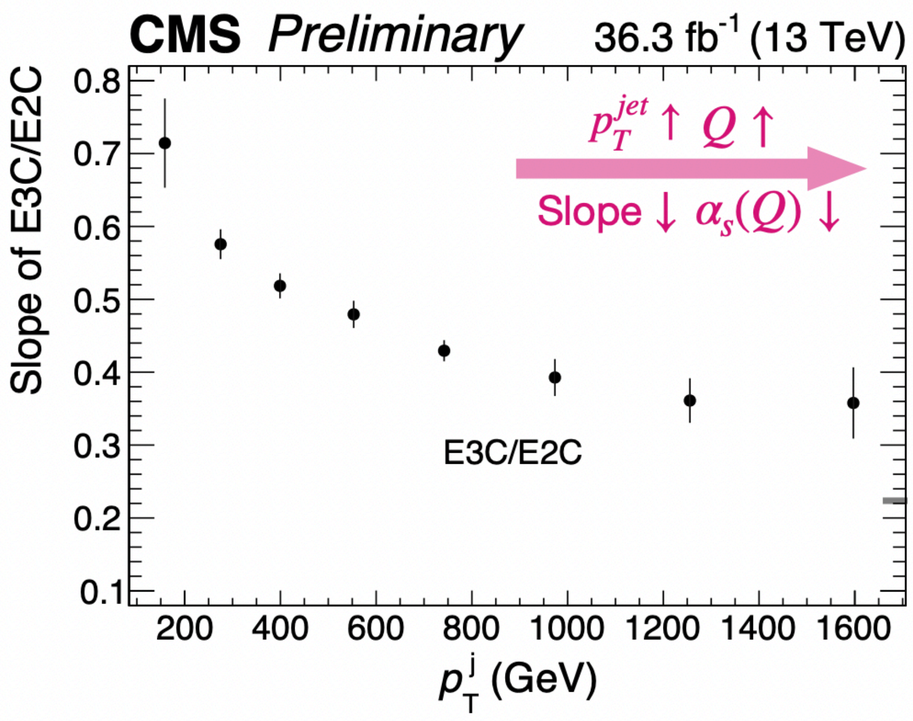


CMS `23

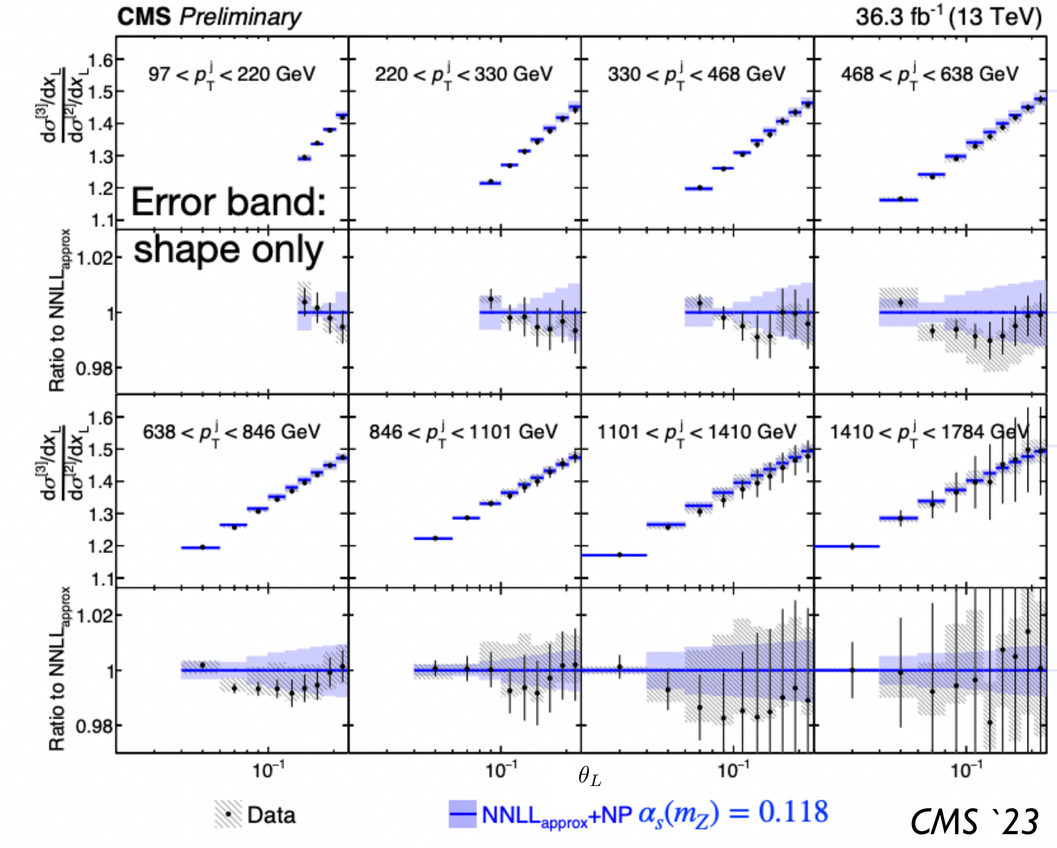
ASYMPTOTIC FREEDOM

- As the anomalous scaling exponent is proportional to the strong coupling constant, we are also able to see asymptotic freedom by eye in data!



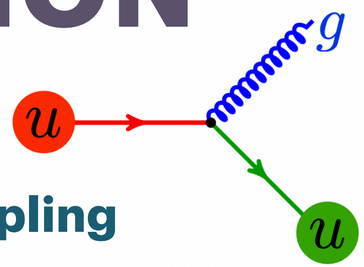


$$\frac{\langle \mathcal{E}_1 \mathcal{E}_2 \cdots \mathcal{E}_N \rangle}{\langle \mathcal{E}_1 \mathcal{E}_2 \rangle} \sim \frac{\langle \mathbb{O}^{[N+1]} \rangle}{\langle \mathbb{O}^{[3]} \rangle} \sim \theta_L^{\gamma(N+1)-\gamma(3)} \qquad \gamma(N) \propto \alpha_s$$

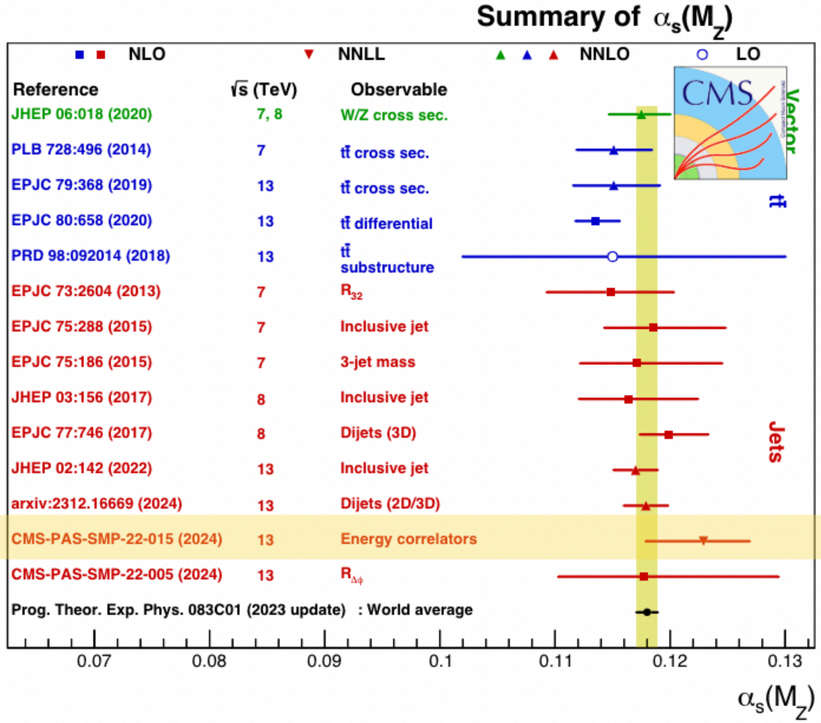


STRONG COUPLING DETERMINATION

- **How strong is the Strong Force?** In comparison, EM coupling: $\alpha_e = 0.00729735256 93(11)$



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

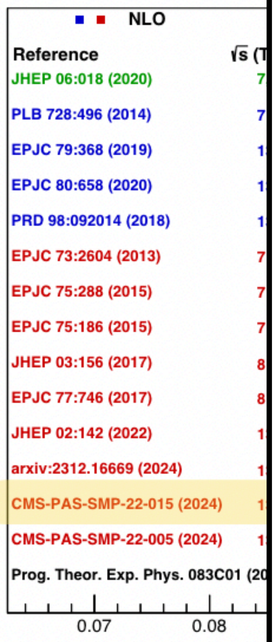
$$\alpha_s(m_Z) = 0.1229^{+0.0040}_{-0.0050}$$

CMS Collaboration `23

$\Longrightarrow$ 4% uncertainty

Energy Correlators in Jet

ROAD TO IMPROVED PRECISION



Road to precision

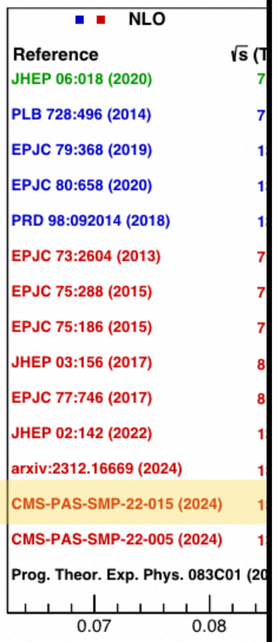
1.Measurements on Tracks

2.Power corrections

3.Improved perturbative accuracy

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

ROAD TO IMPROVED PRECISION



Road to precision

1.Measurements on Tracks

Tune into Wouter's talk!

2.Power corrections

See also Iain, Zhiquan, and Hua-Xing's talk from last week

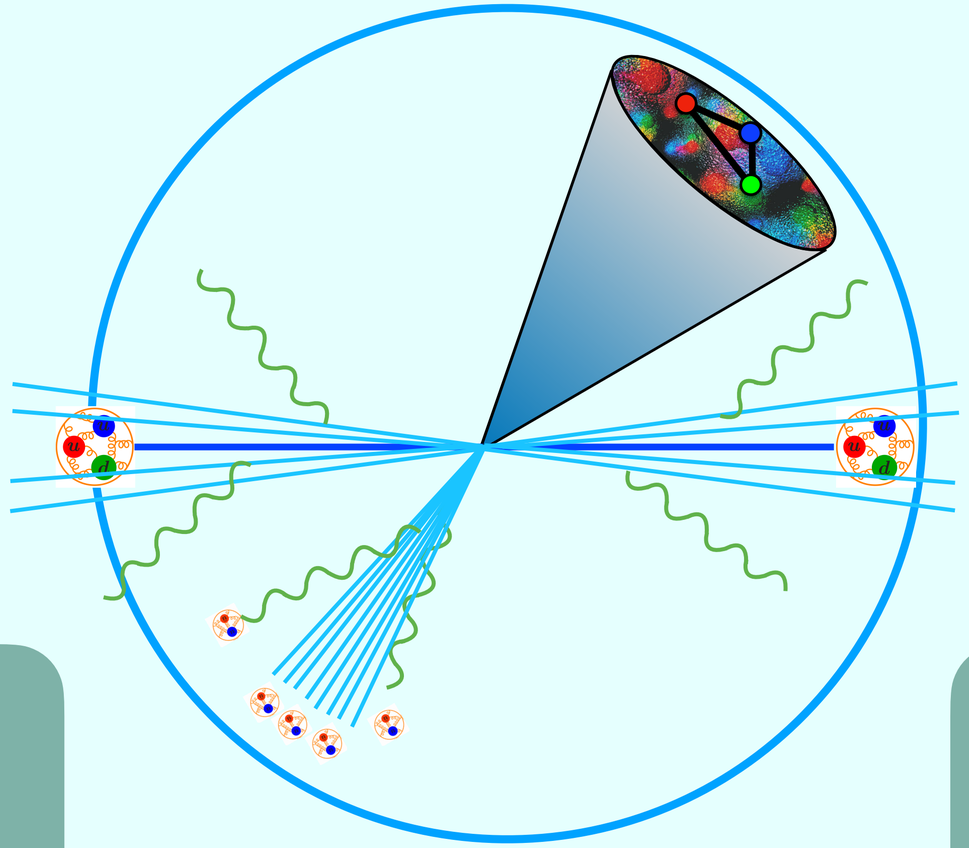
3.Improved perturbative accuracy

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

Overview

II. Precision QCD

I. Universal Scaling



III. Heavy Flavor Physics

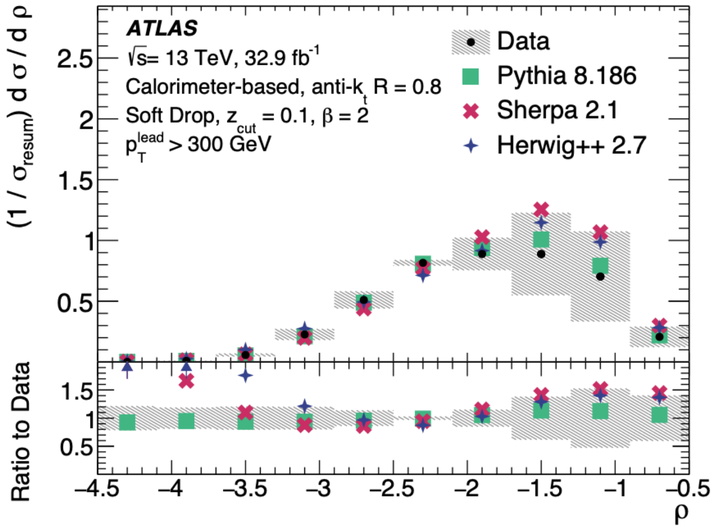
V. Hadronization

IV. Medium Dynamics

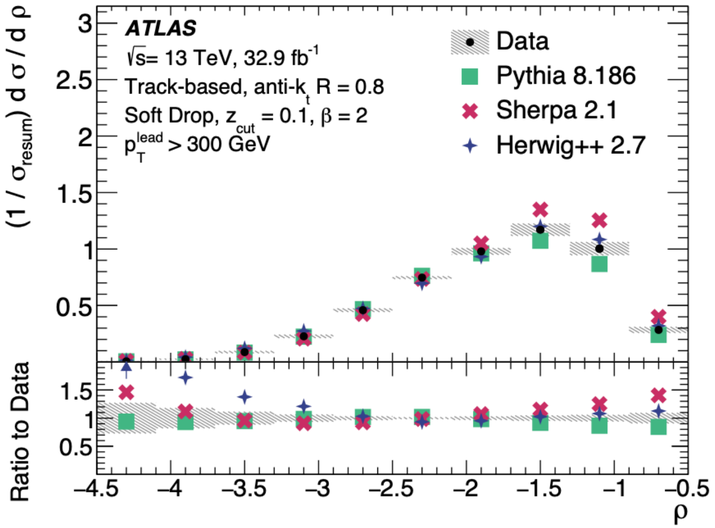
MEASURING TRACKS

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

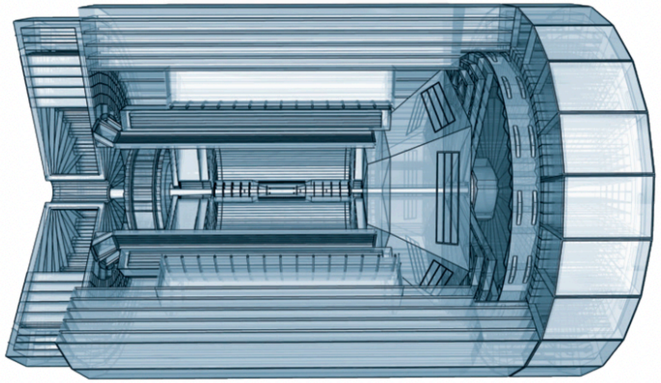
- **Measuring tracks provides much more precise experimental results**



All particles



Tracks

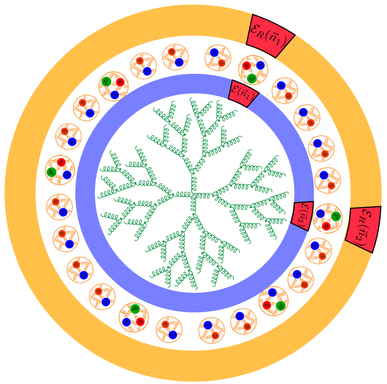


Modern detectors have state-of-the-art tracking systems!

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

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

We need QCD factorization



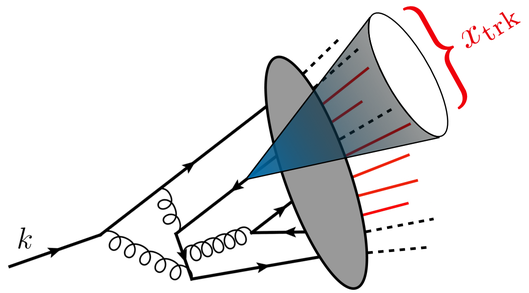
TRACK INSIDE JETS

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

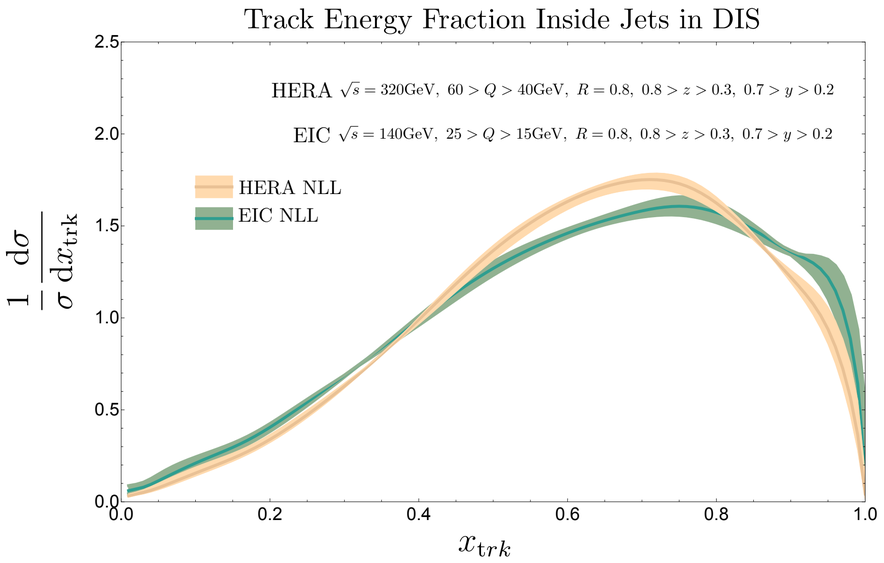
QCD factorization:

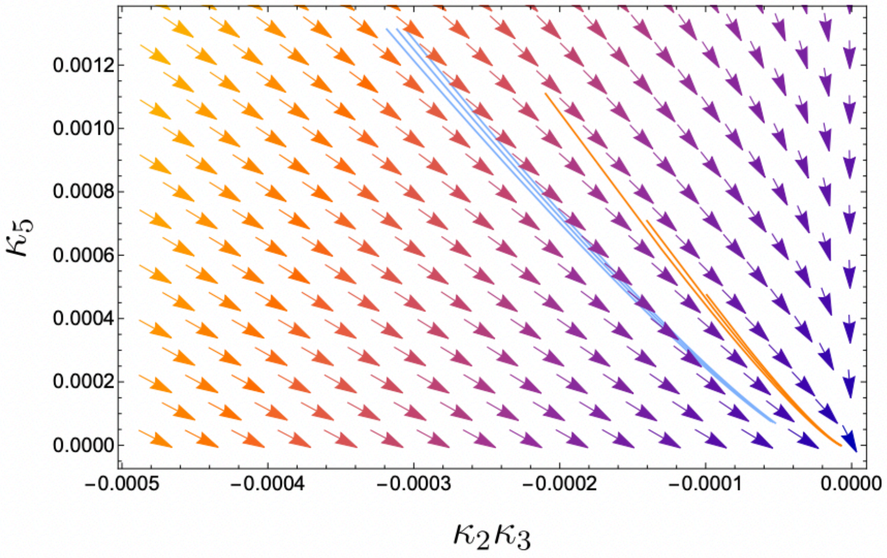
Requires separation of parts that are perturbative from universal non-perturbative functions

- **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
KL, Moult, Ringer, Waalewijn `23
KL, Moult `23

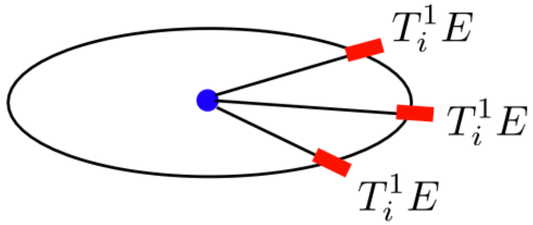




ENERGY CORRELATORS ON TRACK

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

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



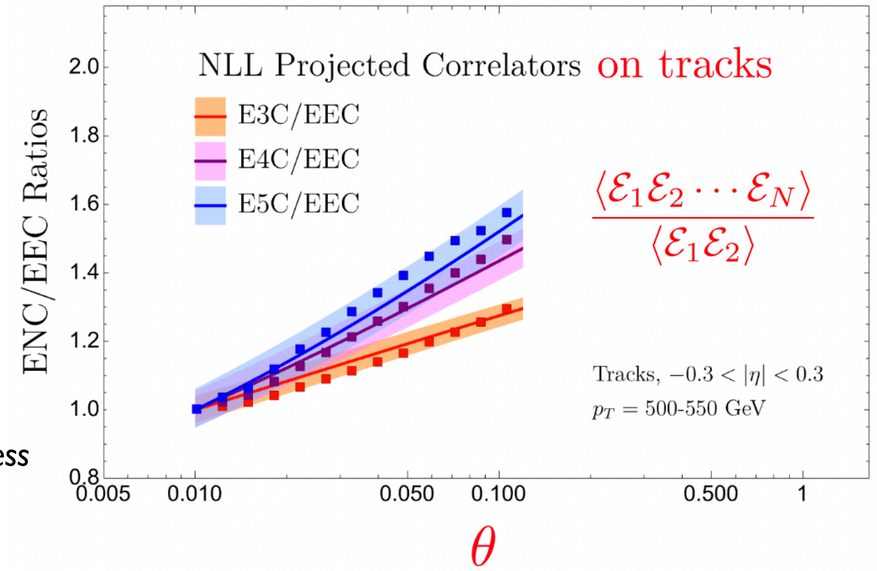
$$\langle \mathcal{E}_R(\vec{n}_1)\,\mathcal{E}_R(\vec{n}_2)\cdots\mathcal{E}_R(\vec{n}_k)\rangle = \sum_{i_1,i_2,\cdots i_k} T_{i_1}(1)\cdots T_{i_k}(1)\,\langle \mathcal{E}_{i_1}(\vec{n}_1)\,\mathcal{E}_{i_2}(\vec{n}_2)\cdots\mathcal{E}_{i_k}(\vec{n}_k)\rangle + \text{contact terms}$$

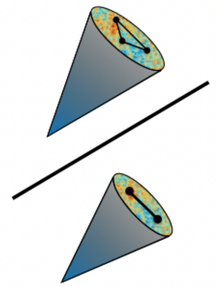
- **Only depends on the "moments" of track functions $\Longrightarrow$ Only involves NP *numbers*, not functions**

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



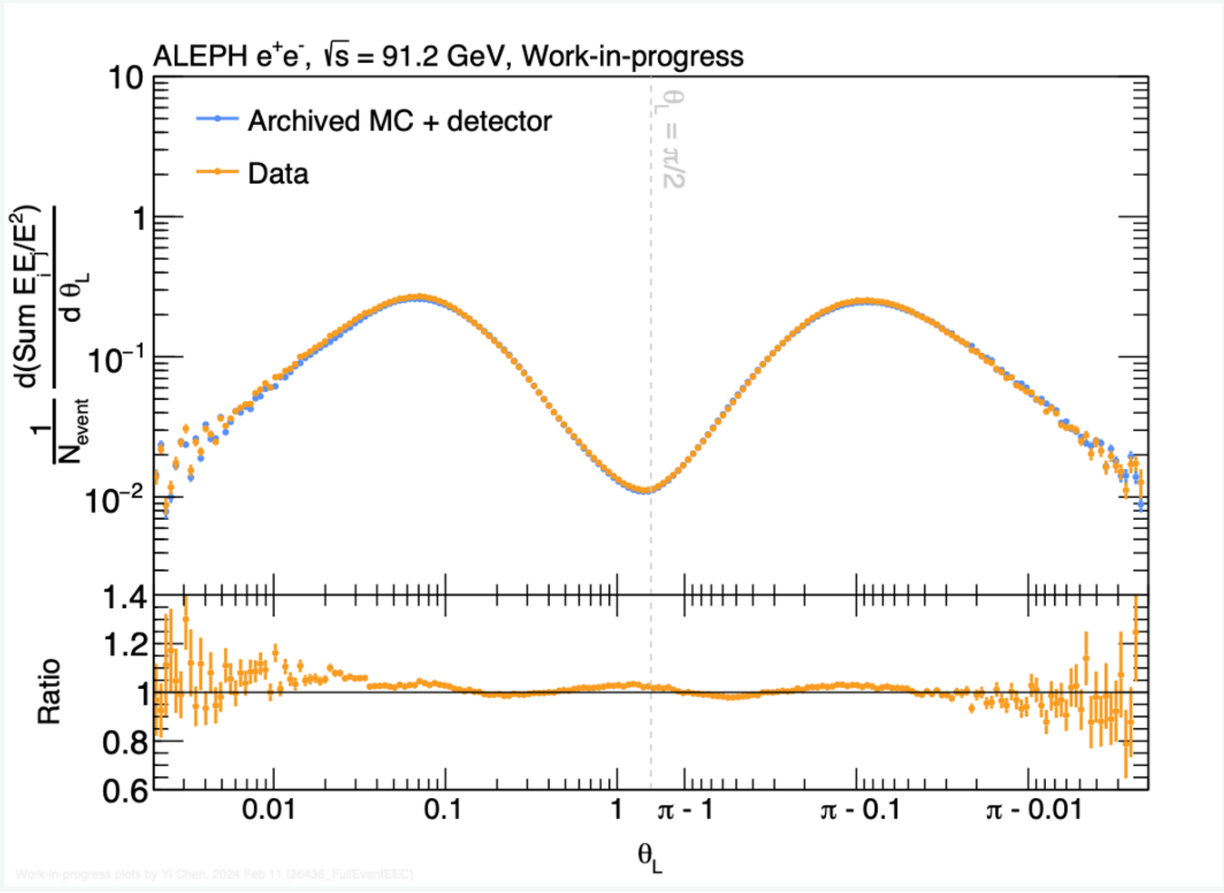


$$\frac{\langle \mathcal{E}_1\mathcal{E}_2\cdots\mathcal{E}_N\rangle}{\langle \mathcal{E}_1\mathcal{E}_2\rangle} \sim \frac{\langle \mathbb{O}^{[N+1]}\rangle}{\langle \mathbb{O}^{[3]}\rangle} \sim \theta_L^{\gamma(N+1)-\gamma(3)}$$

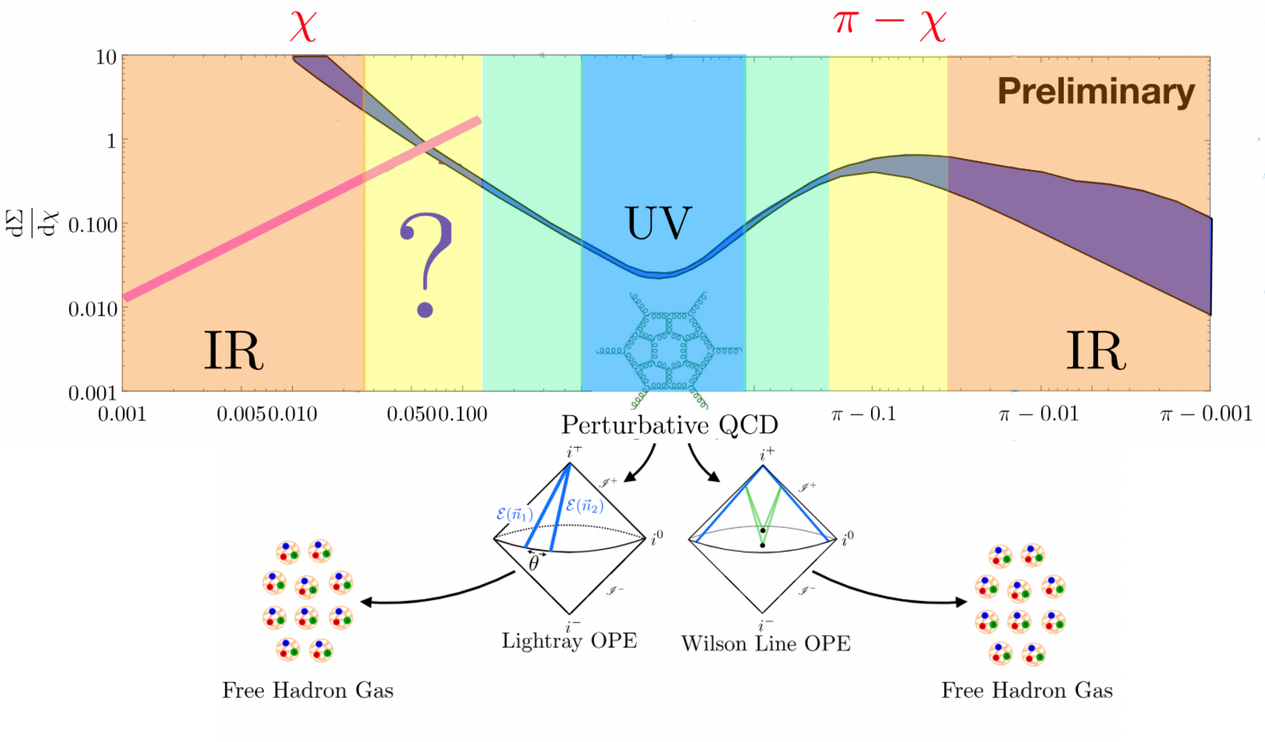
ENERGY CORRELATORS ON TRACK

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

Reanalysis of ALEPH data on tracks



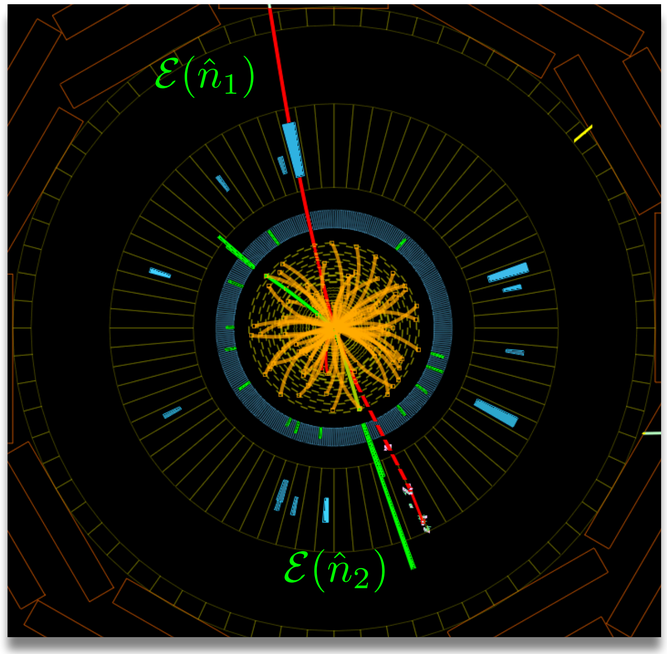
Jaarsma, Li, Moult, Waalewijn, Zhu `In Progress



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

POWER CORRECTIONS

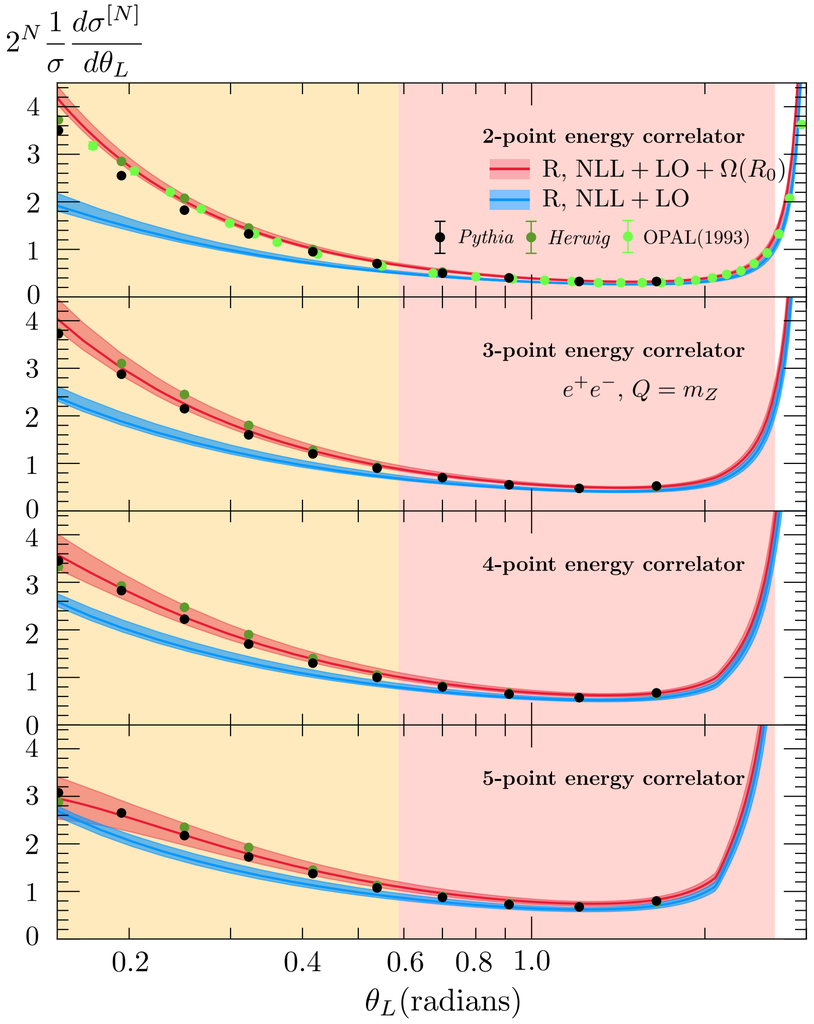
1. **Measurements on Tracks**
2. **Power corrections**
3. **Improved perturbative accuracy**



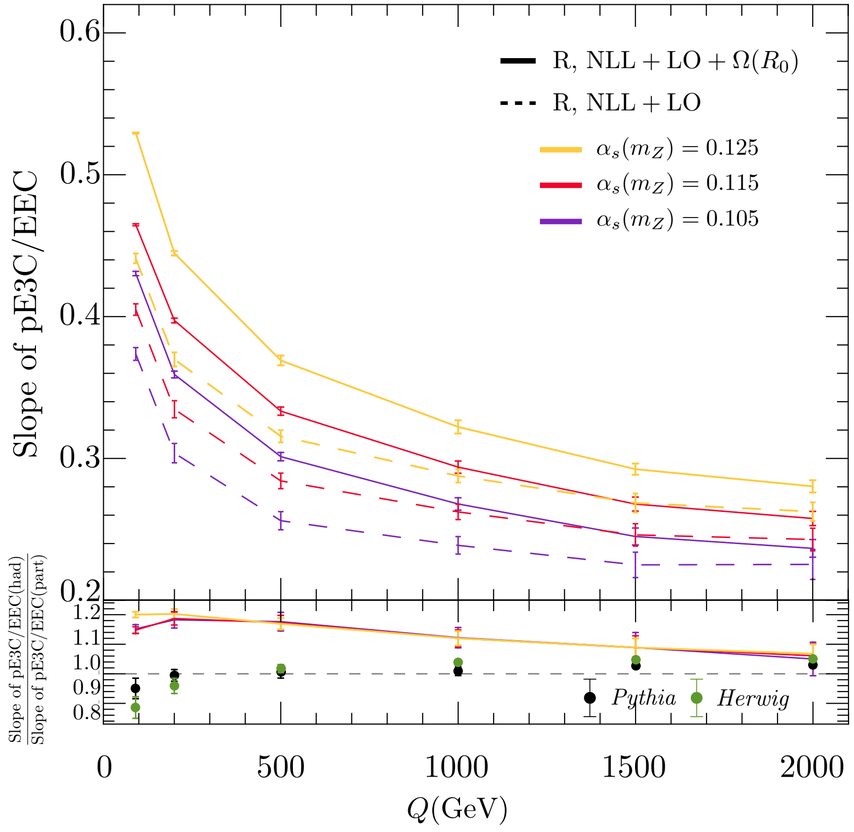
e^+e^- **in the collinear limit exhibits same universal behavior as hadron jets**

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

Universal Power Corrections



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

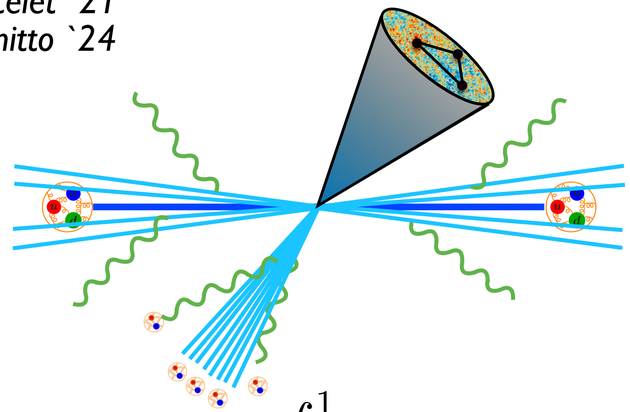
1. **Measurements on Tracks**
2. **Power corrections**
3. **Improved perturbative accuracy**

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

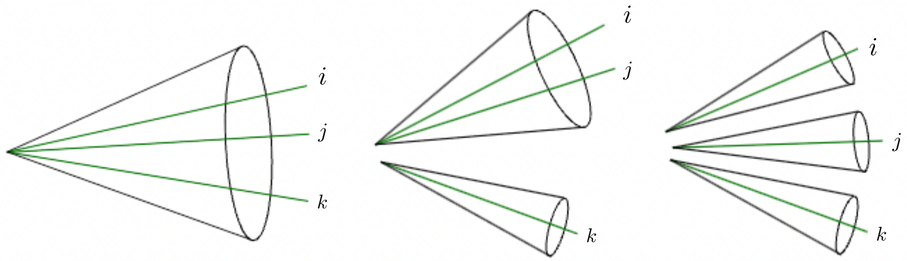
Czakon, Generet, Mitov, Poncelet `21
Bonino, Gehrmann, Stagnitto `24

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

$f_{a/A}\otimes f_{b/B}$: Λ_{QCD}; H^c_{ab}: p_T; $\mathcal{G}_c^{\text{N}-\text{proj}}(\theta_L)$: $p_T R$, $p_T\theta_L$



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



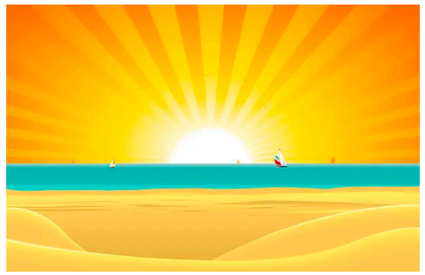
A B C

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

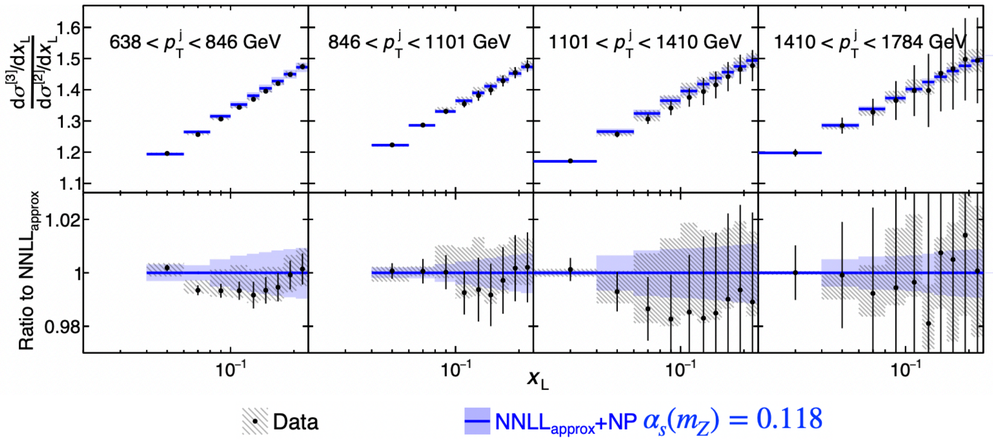
Encodes complicated jet clustering algorithm details

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

z_i = momentum fraction of i



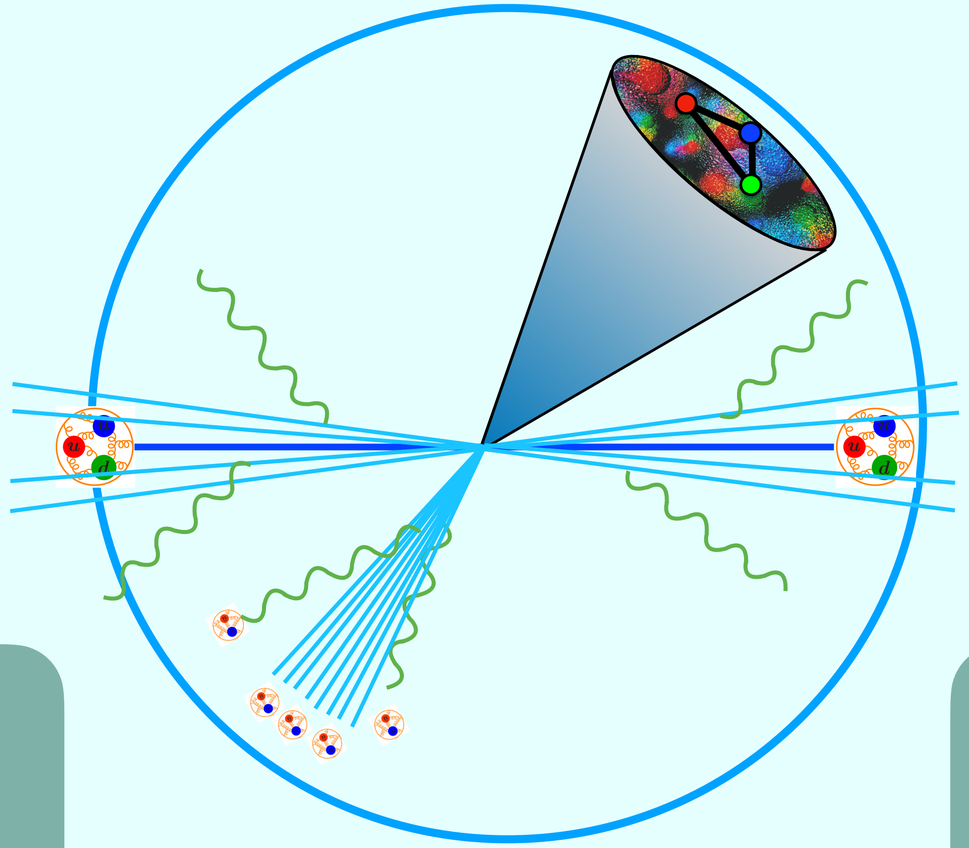
Unprecedented precision calculation of jet substructure on the horizon!



Overview

II. Precision QCD

I. Universal Scaling



III. Heavy Flavor Physics

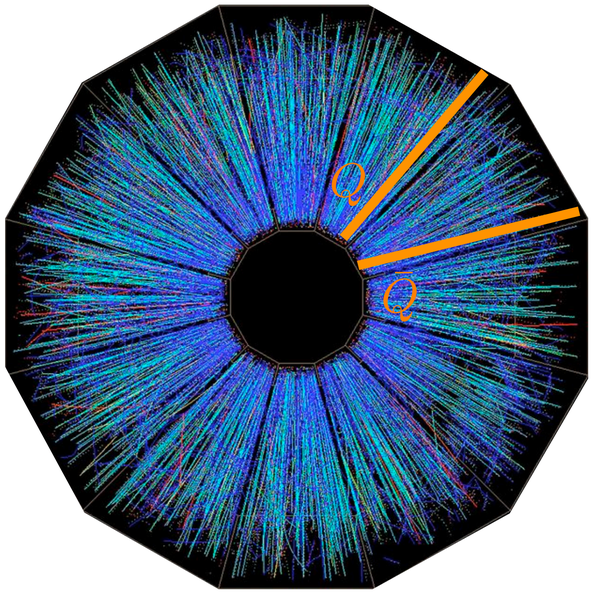
V. Hadronization

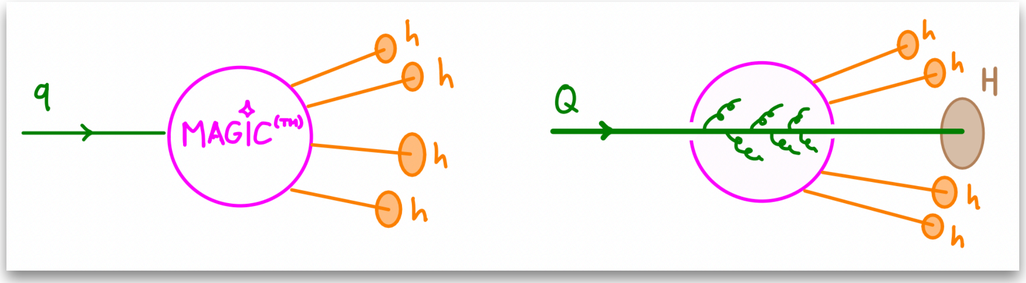
IV. Medium Dynamics

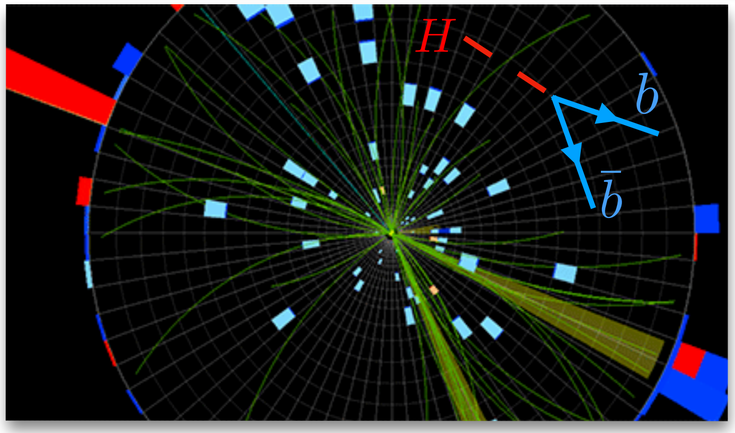
UNRAVELING HEAVY FLAVOR DYNAMICS

Tune into Evan's talk! See also Bianka's talk from last week!

- **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

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

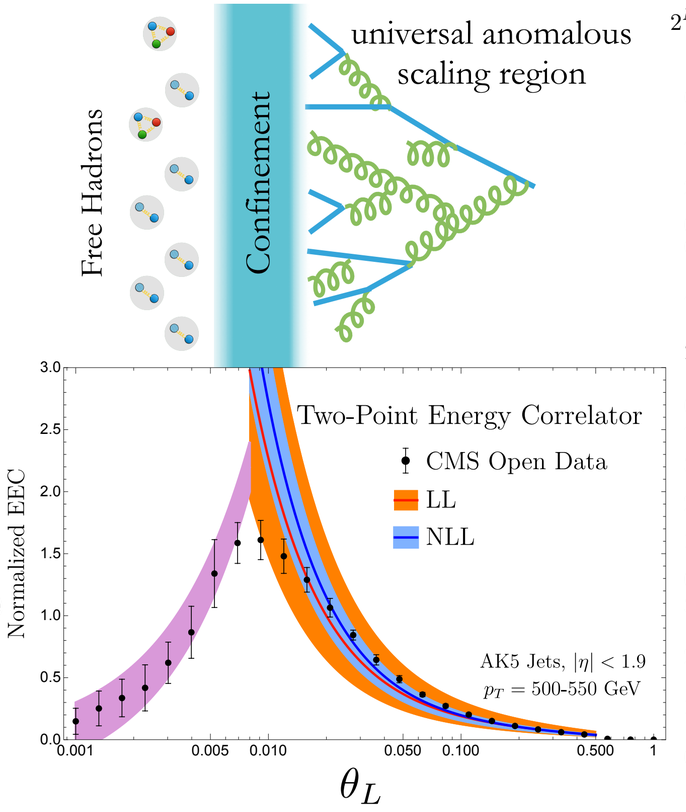
$$\frac{\mathrm{d}\sigma}{\mathrm{d}\theta} = \text{const} \times 2\theta$$

EEC gives angular scale

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

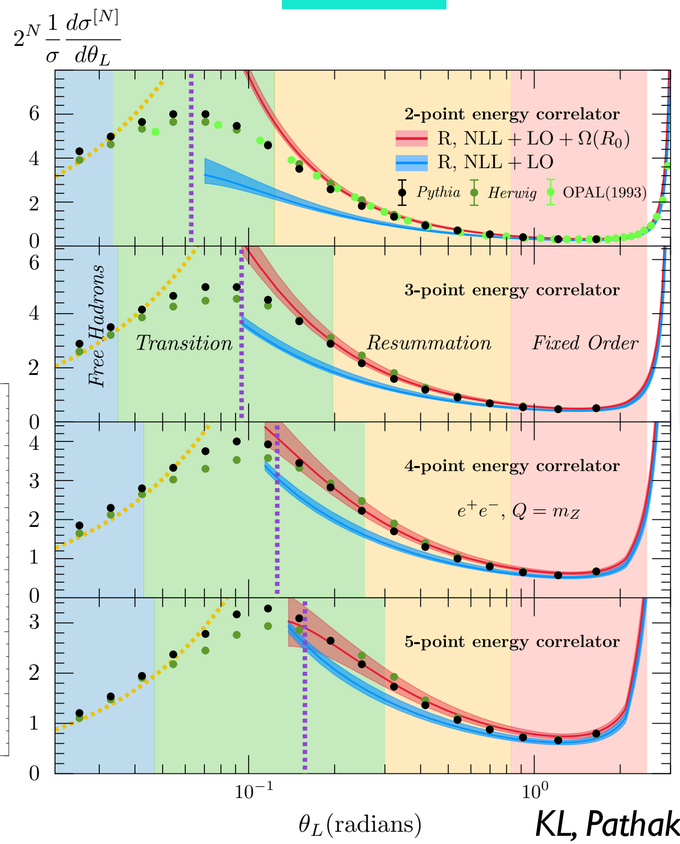
Csáki, Ismail `24

LHC



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

e^+e^-



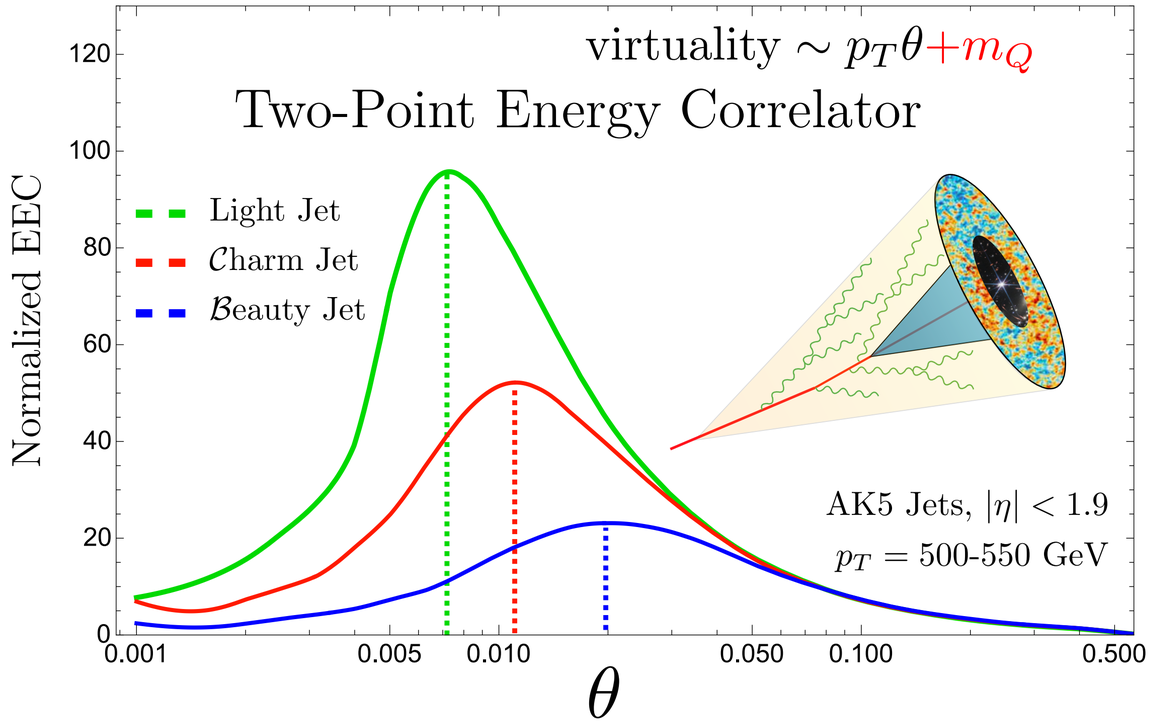
Interacting quarks and gluons

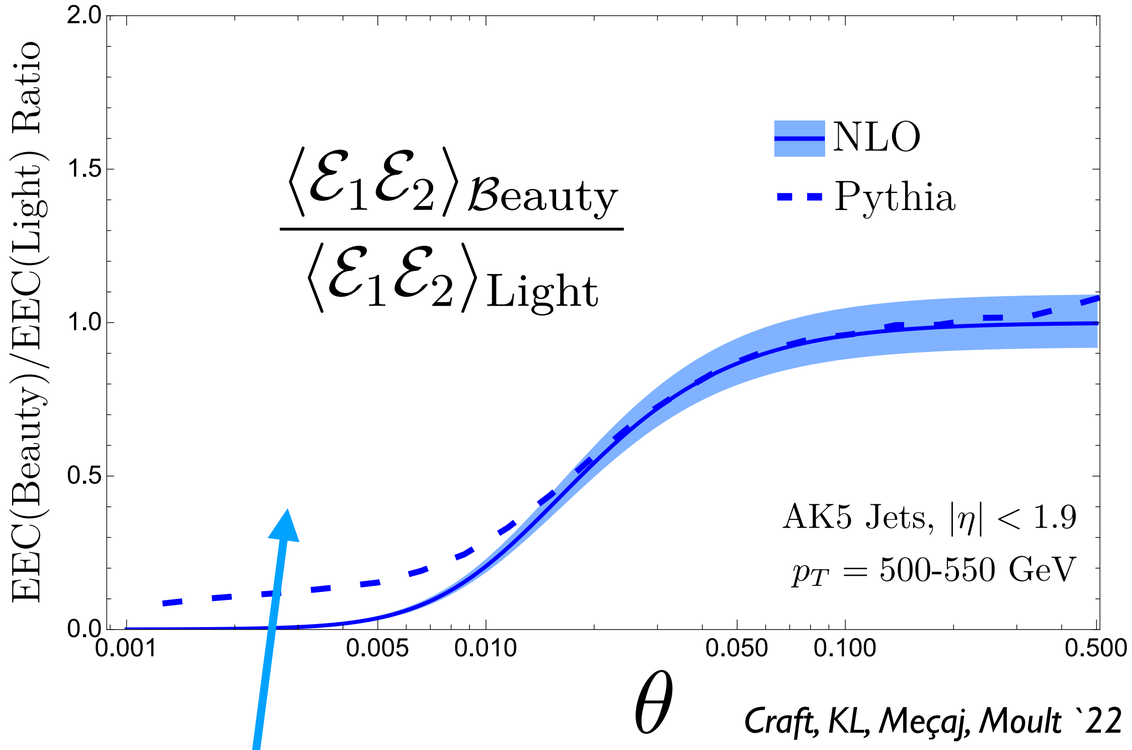
$$\mathcal{E}(\hat{n}_1)\,\mathcal{E}(\hat{n}_2) \sim \sum \theta^{\gamma^{(3)}-2} \mathbb{O}_i(\hat{n}_1)$$

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**



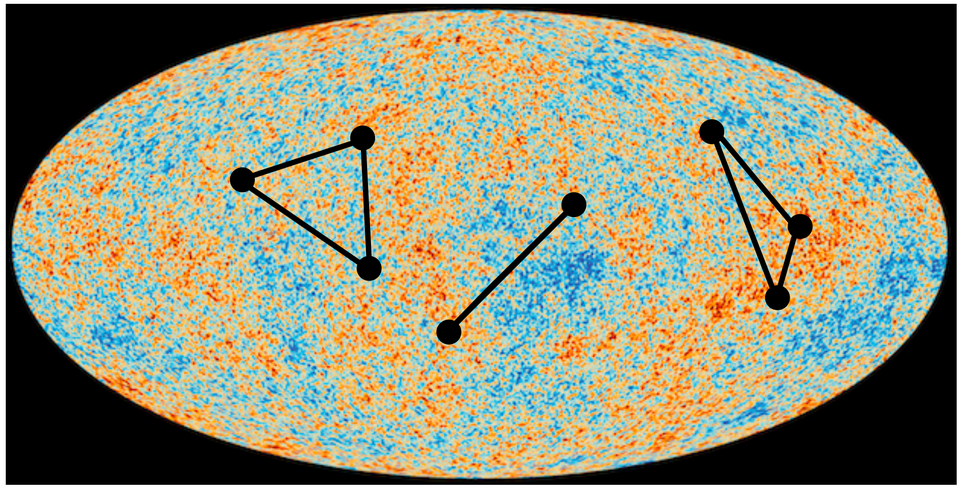


- **Ratio of the two-point correlators clearly shows the dead-cone region around** $\theta \lesssim \frac{m_Q}{E}$

HIGHER POINT CORRELATORS

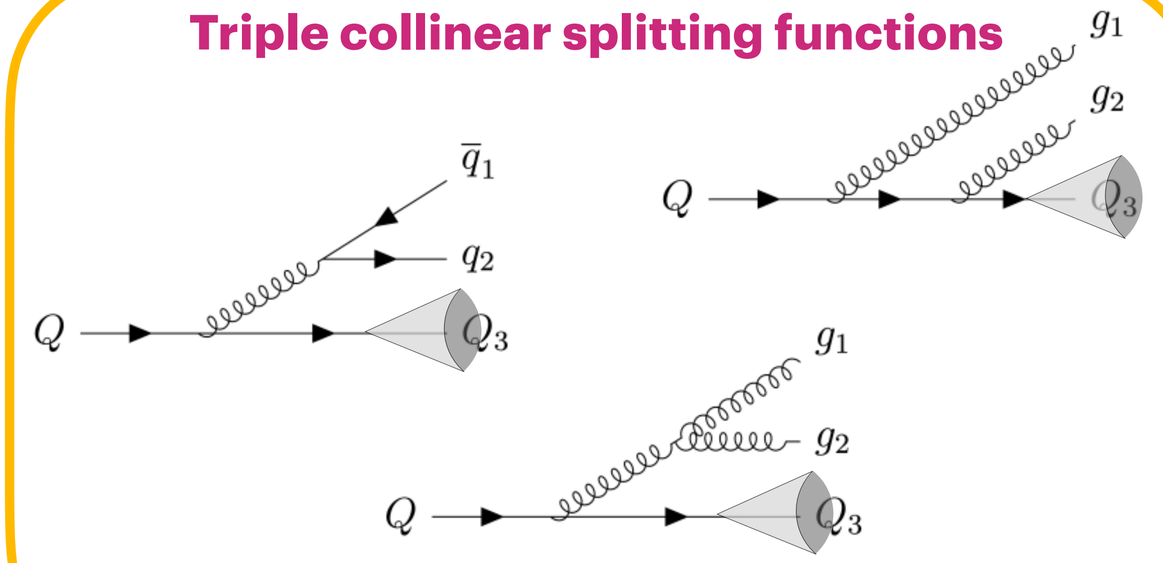
- **Higher-point correlators probe more detailed aspects of interactions**

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



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

Triple collinear splitting functions



⟹ ***Can now compute 3-point correlations!***

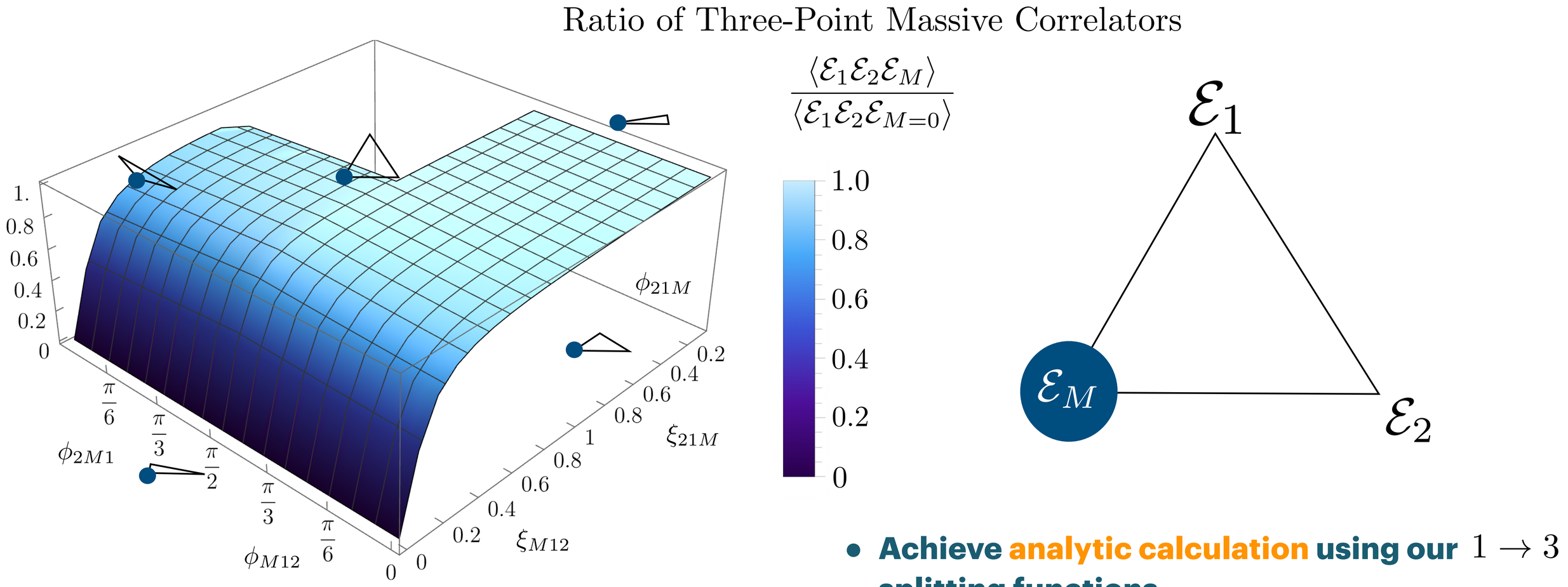
- **Cosmologists are hunting for non-gaussianities (genuine 3-pt correlation) in CMB to distinguish models of inflation**

- **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**

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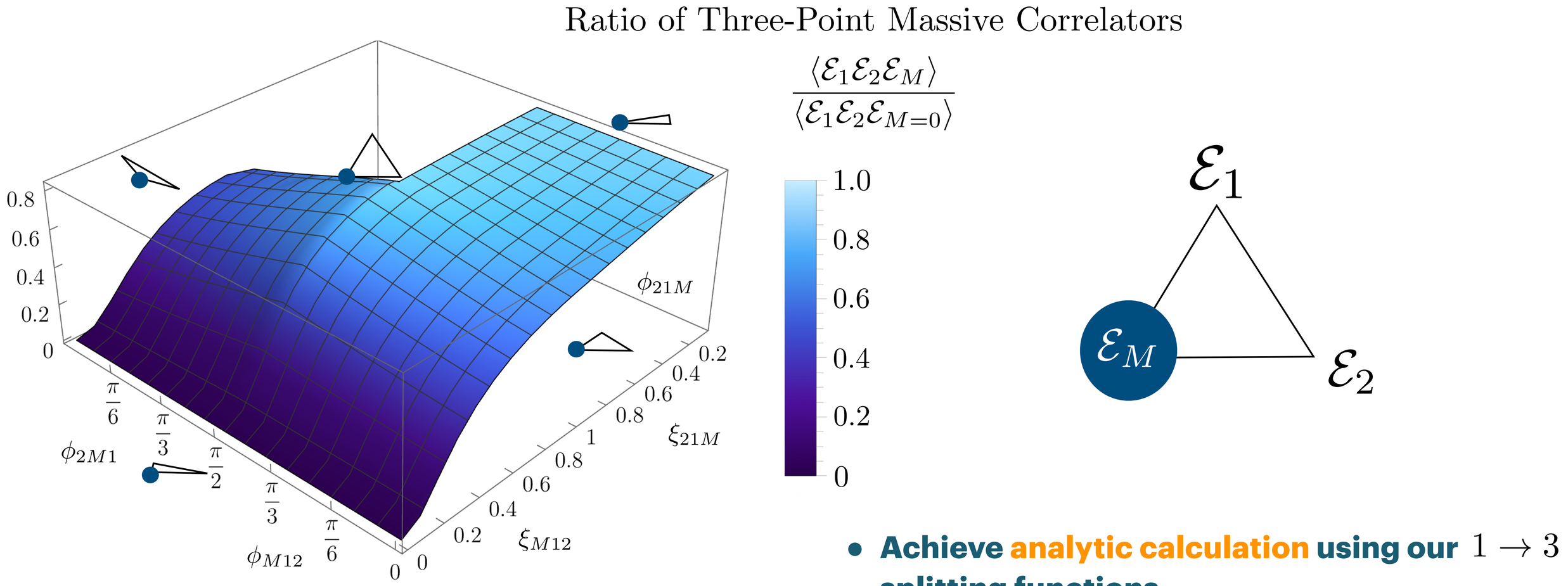
- **Application: three-point correlations probe the non-trivial dynamics of the dead-cone**

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



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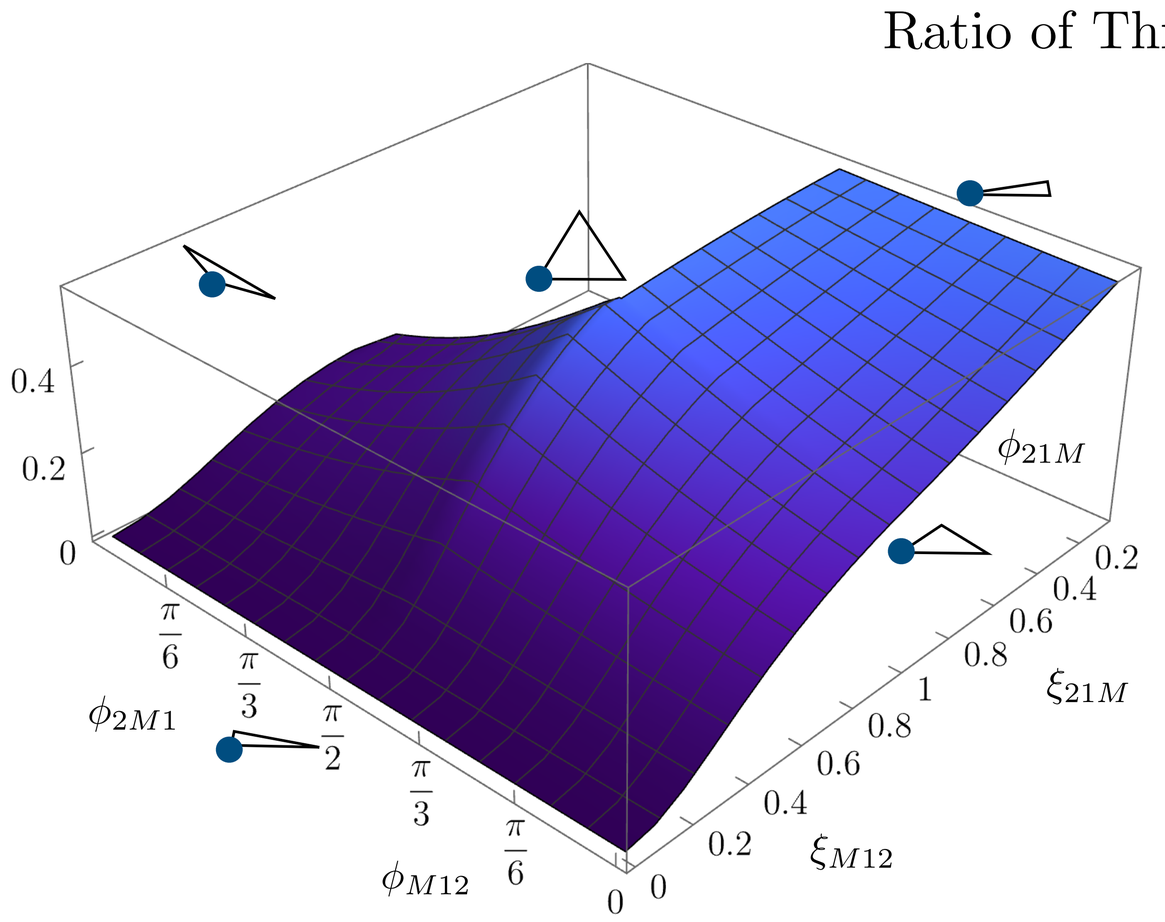
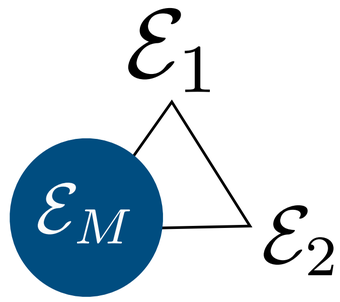
Craft, Gonzalez, KL, Meçaj, Moult `In Progress



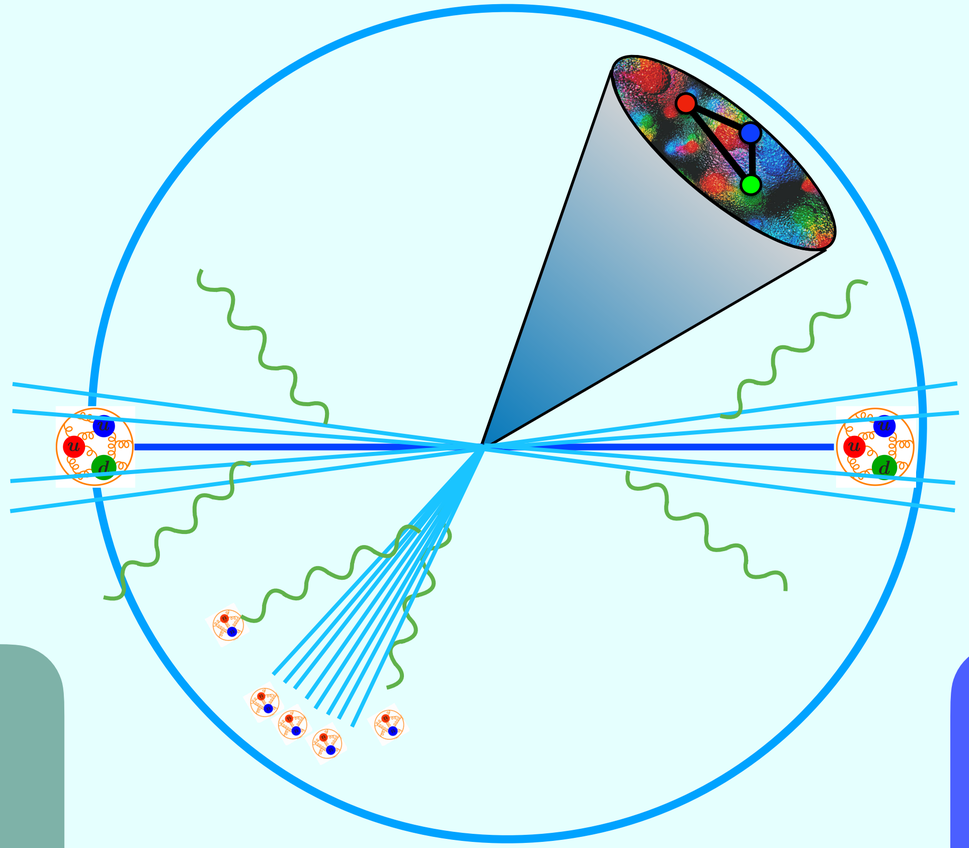


- **Achieve analytic calculation using our $1 \to 3$ splitting functions**

Overview

II. Precision QCD

I. Universal Scaling



III. Heavy Flavor Physics

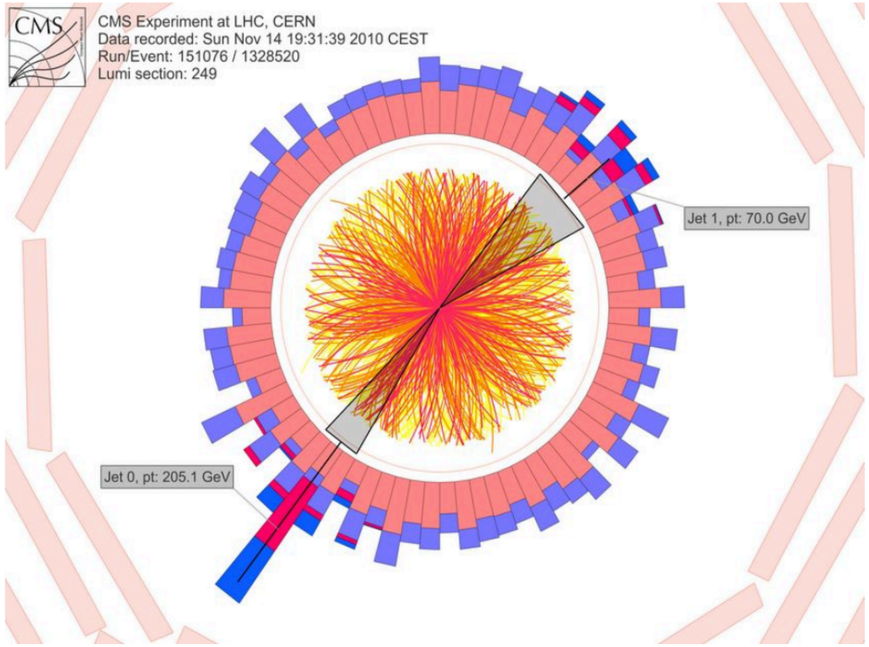
V. Hadronization

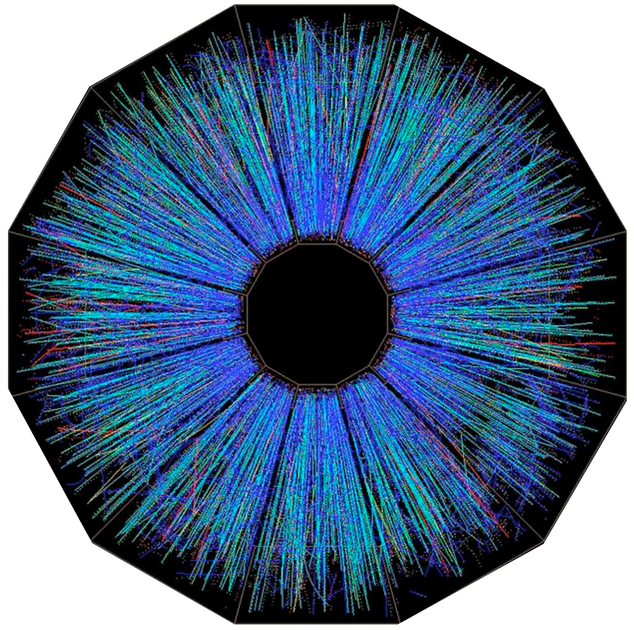
IV. Medium Dynamics

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?**

See many great talks from week 1!

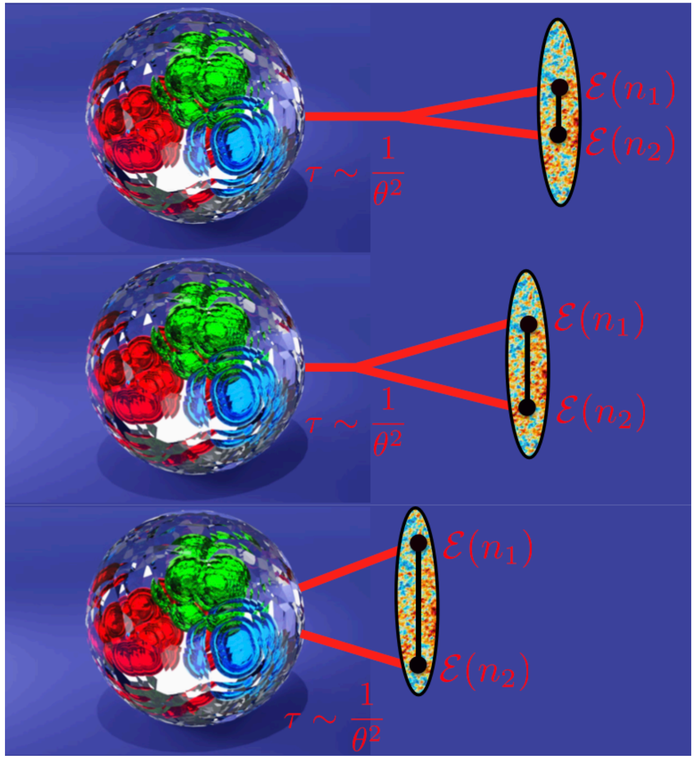




RESOLVING THE QGP USING ENERGY CORRELATORS

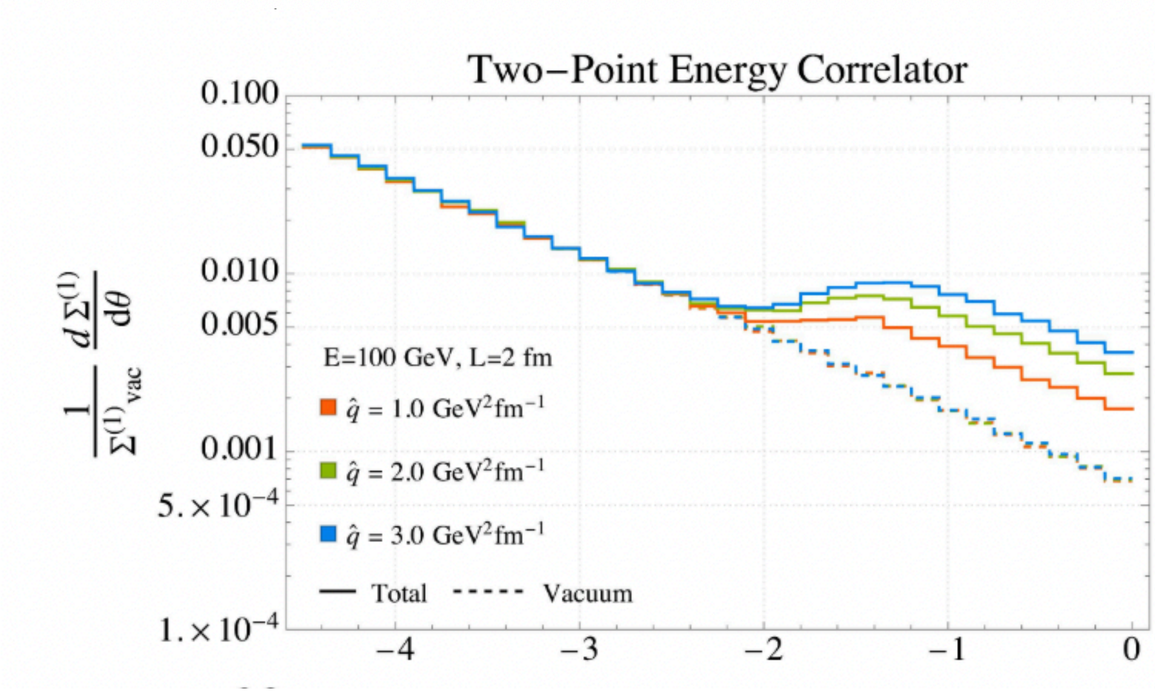
- **Two-point energy correlators clearly identify the medium angular scale at which correlations are modified!**

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



Resolving the Scales of the Quark-Gluon Plasma with Energy Correlators

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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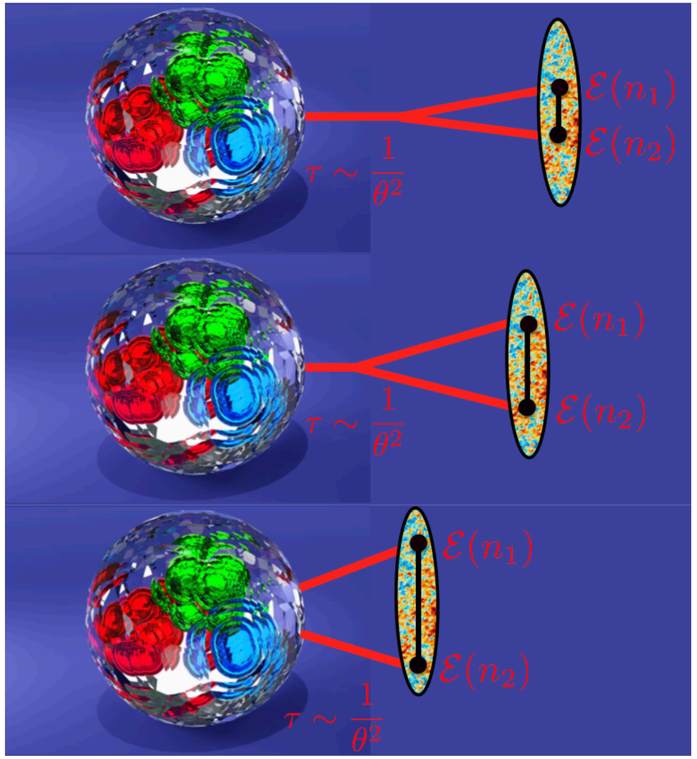


12th International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions

HP2024 NAGASAKI

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

Enter your search term

21 talks / posters at hard probe on energy correlators!

Overview
Scientific Program
Timetable
Call for Abstracts
Registration/Apply for Young Scientist Support

Contribution List

21 / 338 correlator

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

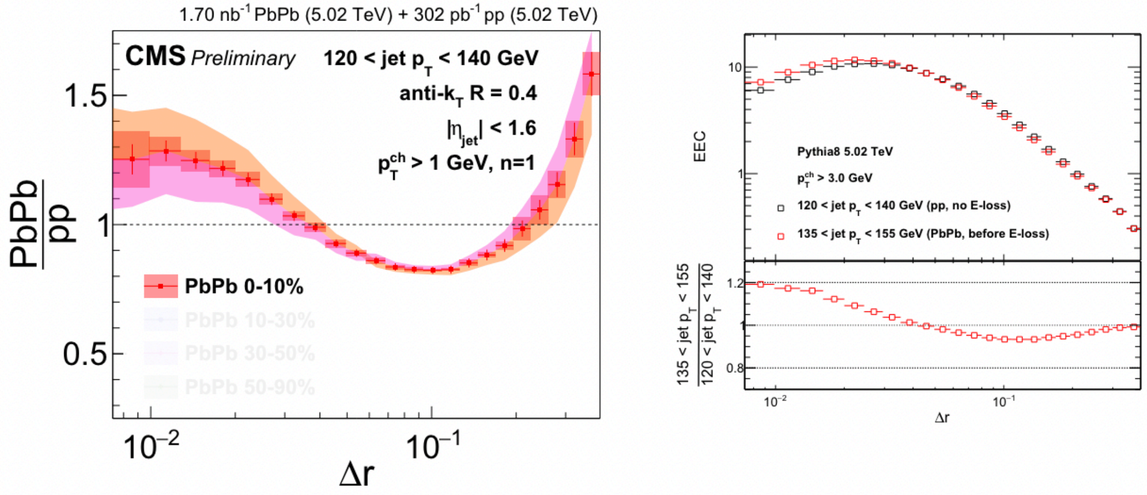
Barata, Milano, Sadofyev `23
Barata, Caucal, Soto-Ontoso, Szafron `23
Yang, He, Moult, Wang `23
Devereaux, Fan, Ke, KL, Moult `23
Andres, Dominguez, Holguin, Kunnawalkam Elayavalli, Marquet, Moult `22
Andres, Dominguez, Holguin, Marquet, Moult `23,24
Bossi, Kudinoor, Moult, Pablos, Rai, Rajagopal `In Progress
…

- **Pioneering work on energy correlators for heavy-ion collisions generating much excitement and progress!**

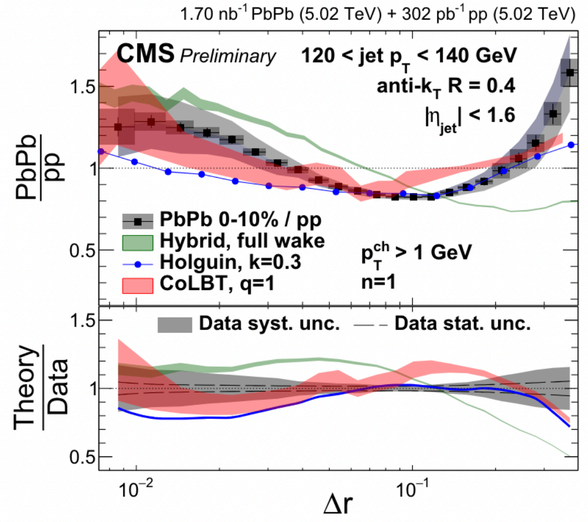
...AND DATA!

PbPb to pp ratio, centrality evolution

CMS-PAS-HIN-23-004



CMS-PAS-HIN-23-004

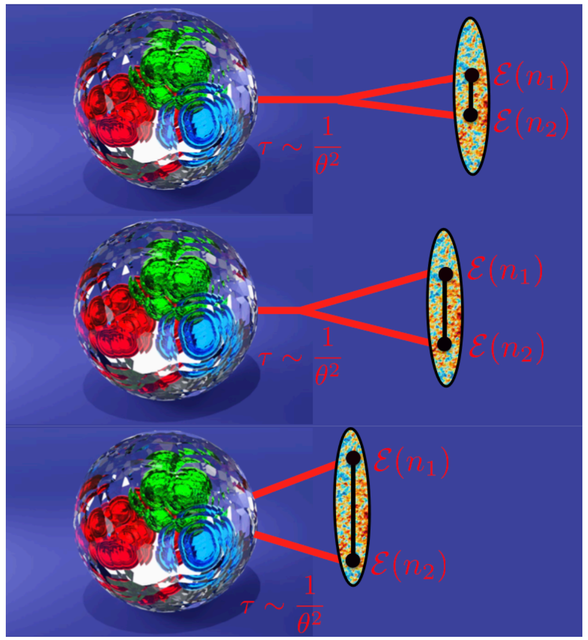


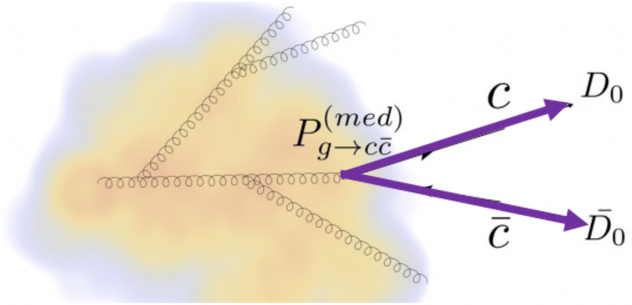
Pablos, Kudinoor, Rajagopal
Holguin, Andrés, Dominguez, Marquet, Moult
Yang, He, Wang

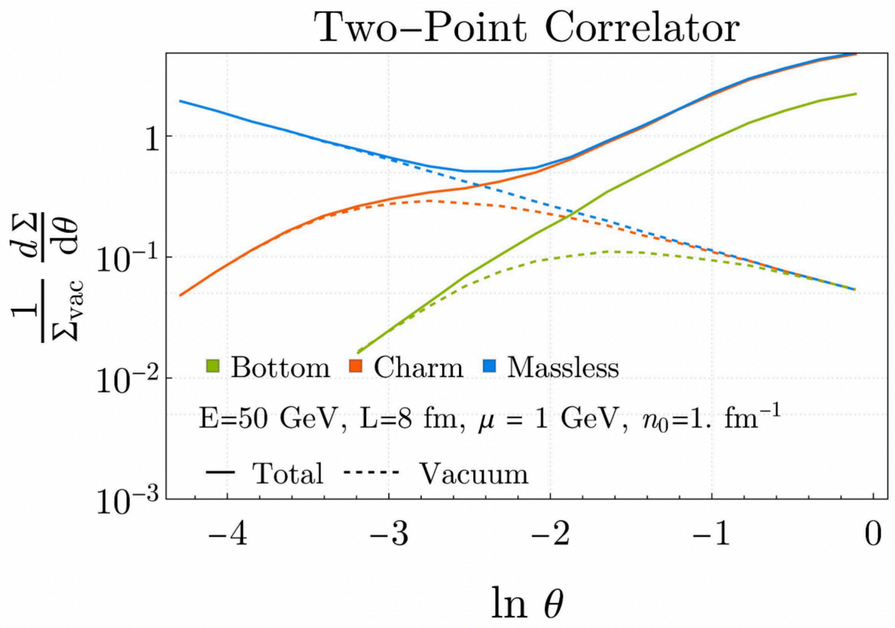
- **Week 1 featured the very exciting first public reveal of the experimental data, which showed clear signs of the medium angular scale being resolved!**

RESOLVING THE QGP USING ENERGY CORRELATORS

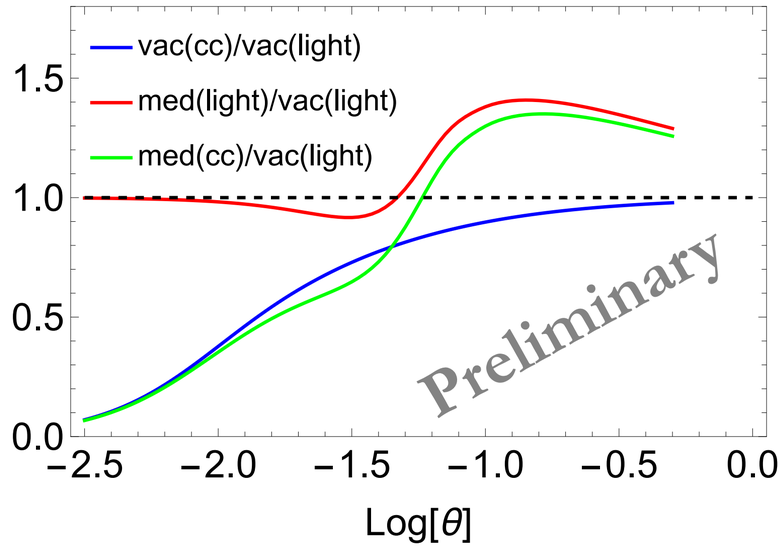
EEC gives angular scale $\mu \sim p_T \theta_{ij}$







Andres, Dominguez, Holguin, Marquet, Moult `23



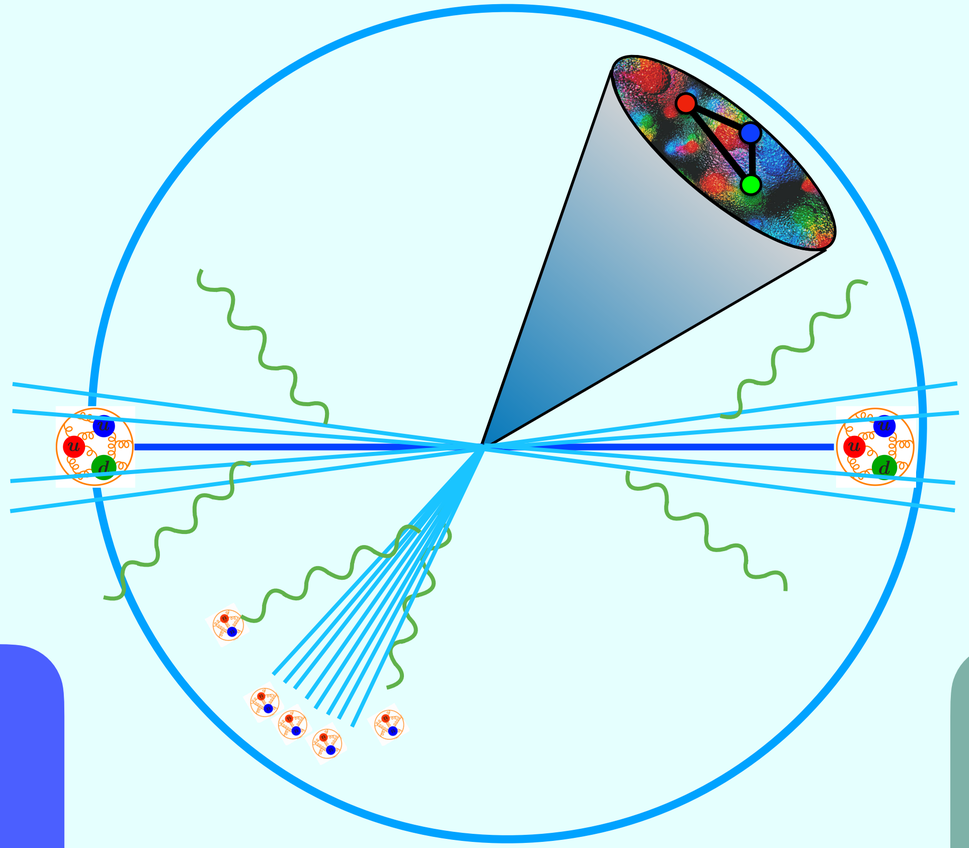
Brewer, KL `In Progress

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

Overview

II. Precision QCD

I. Universal Scaling



III. Heavy Flavor Physics

V. Hadronization

IV. Medium Dynamics

WHAT IS A DETECTOR?

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

Tune into Mark's talk!

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

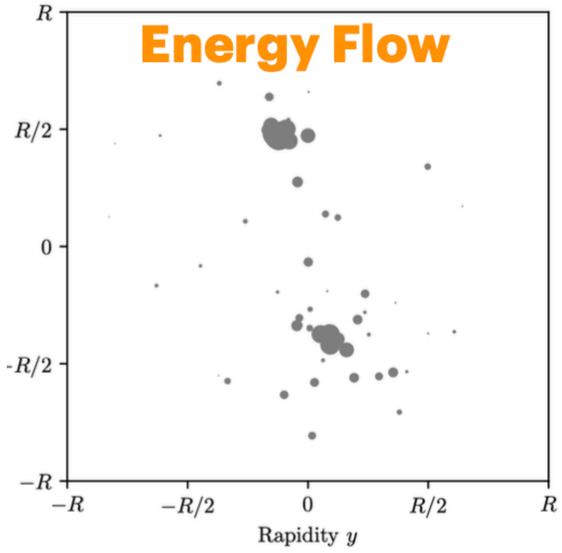
- **Interesting measurements of energy flow can be made on a restricted set of hadronic states, R, for example, charged hadrons (tracks)**

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

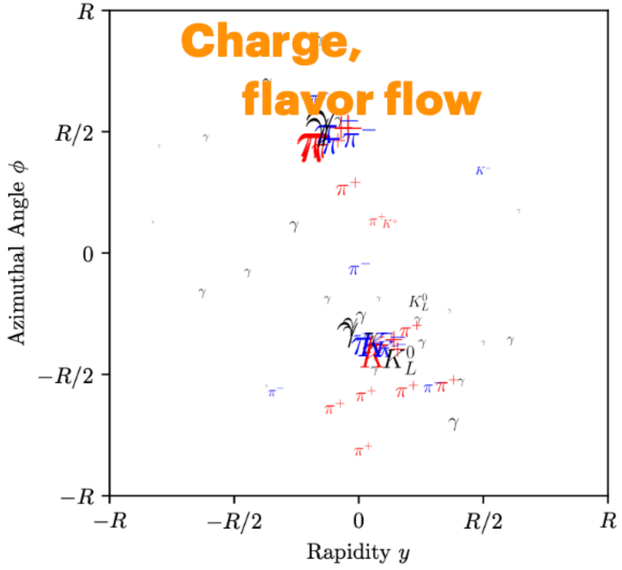
- **Provides a sharp link between underlying field theory and observables**

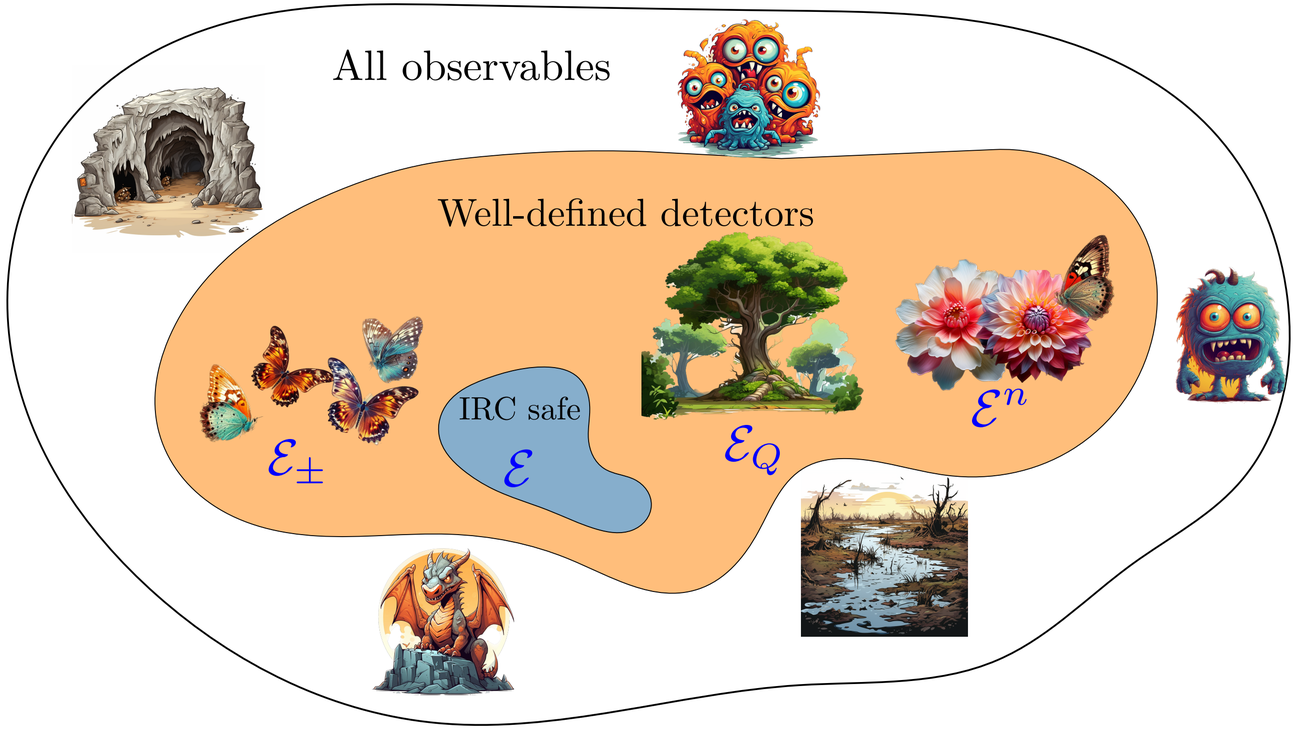
KL, Moult `23

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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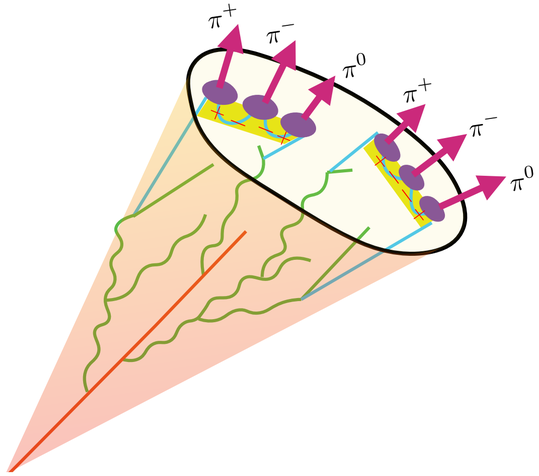
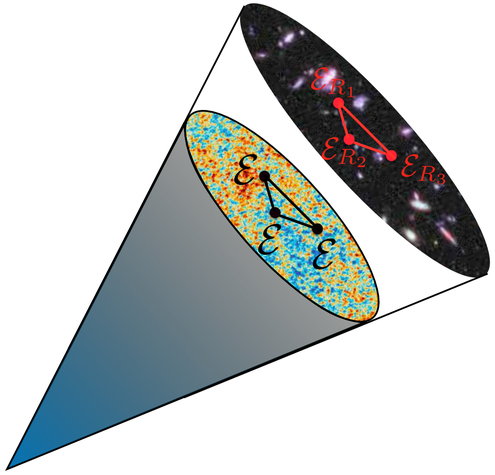
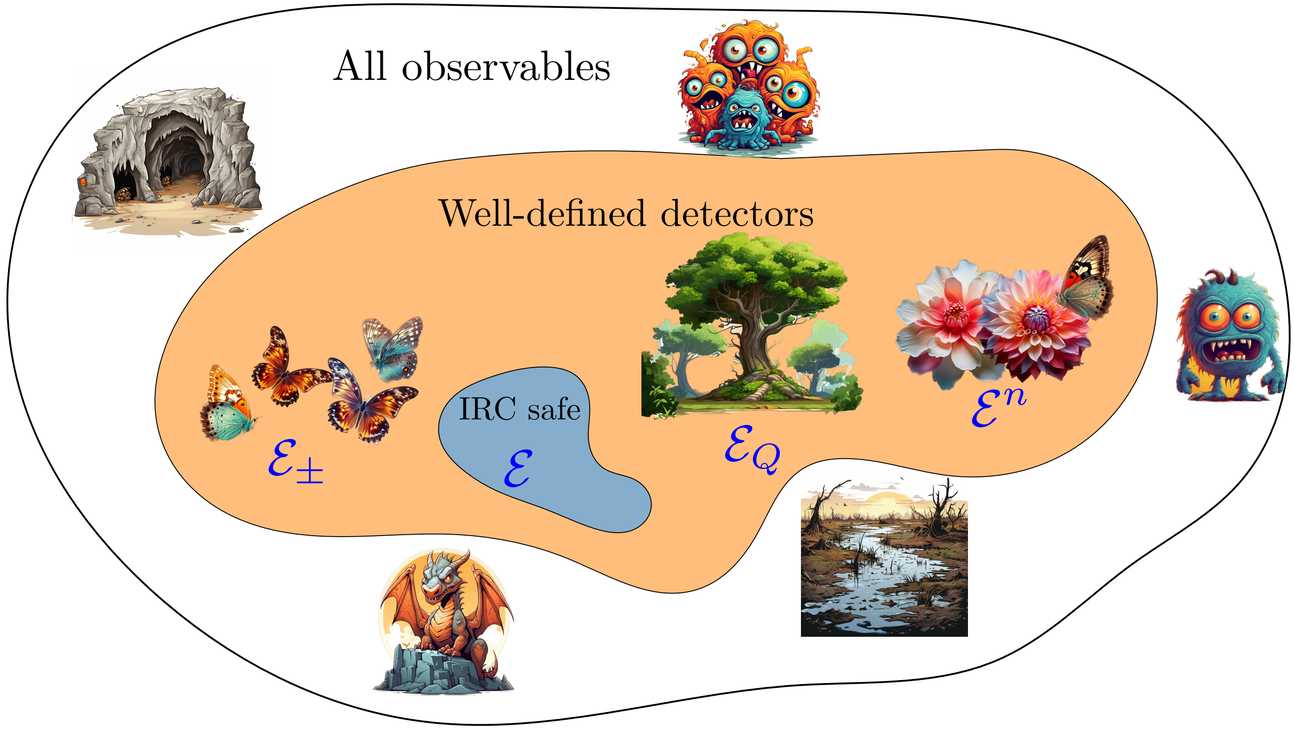
KL, Moult `23





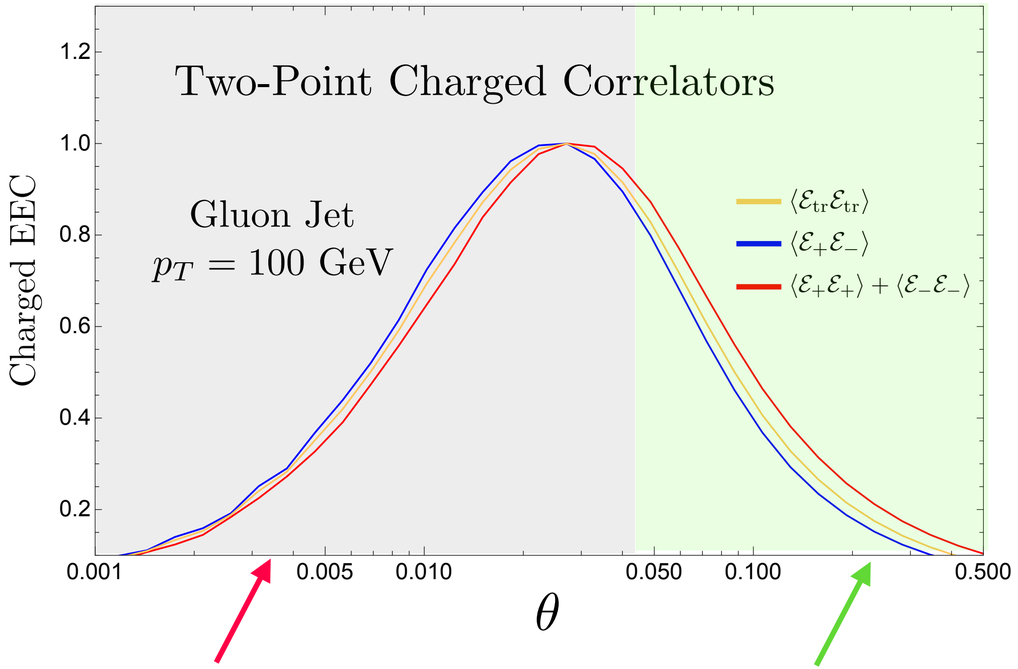


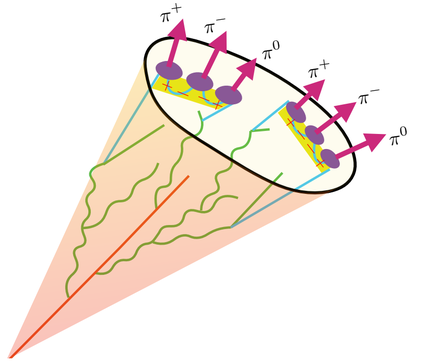
CORRELATION BETWEEN CHARGED HADRONS

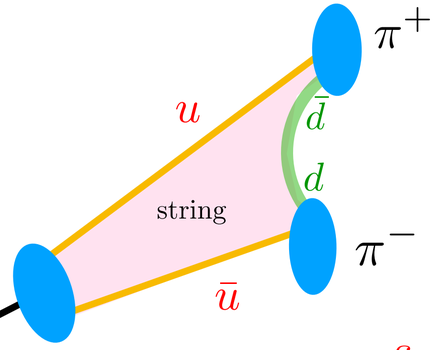
- **Unlike-signed charged correlators are correlated more as the angle becomes smaller!**

KL, Moult `23

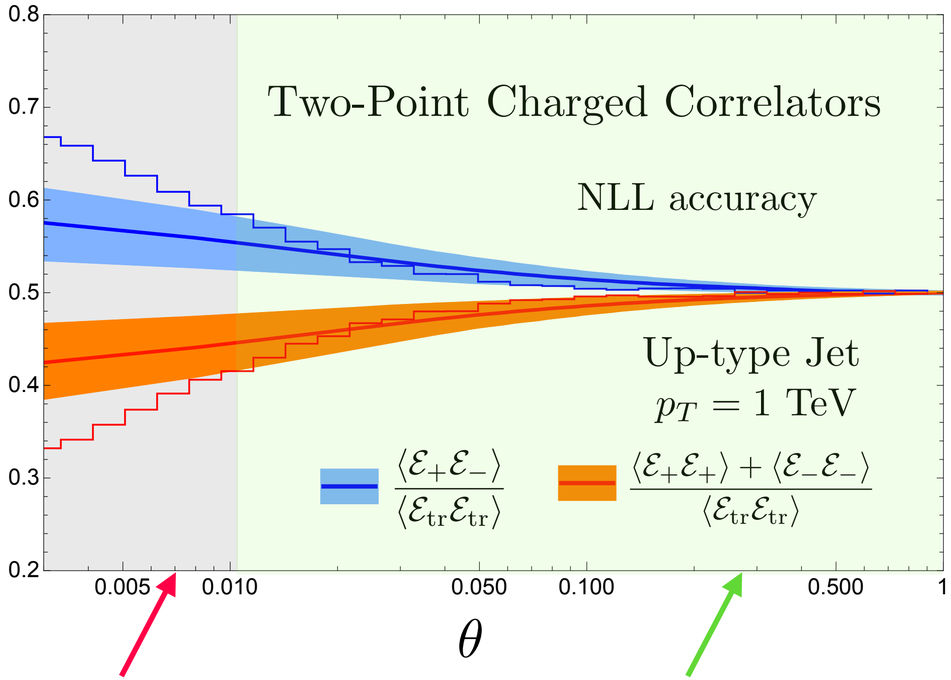
See also Andrew's talk from last week!





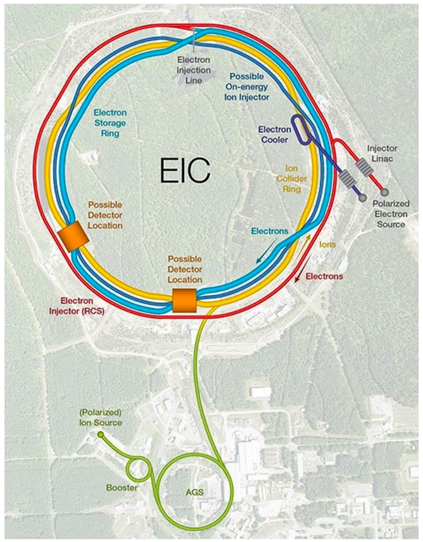


$\langle \mathcal{E}_+\mathcal{E}_-\rangle, \langle \mathcal{E}_+\mathcal{E}_+\rangle, \langle \mathcal{E}_-\mathcal{E}_-\rangle$

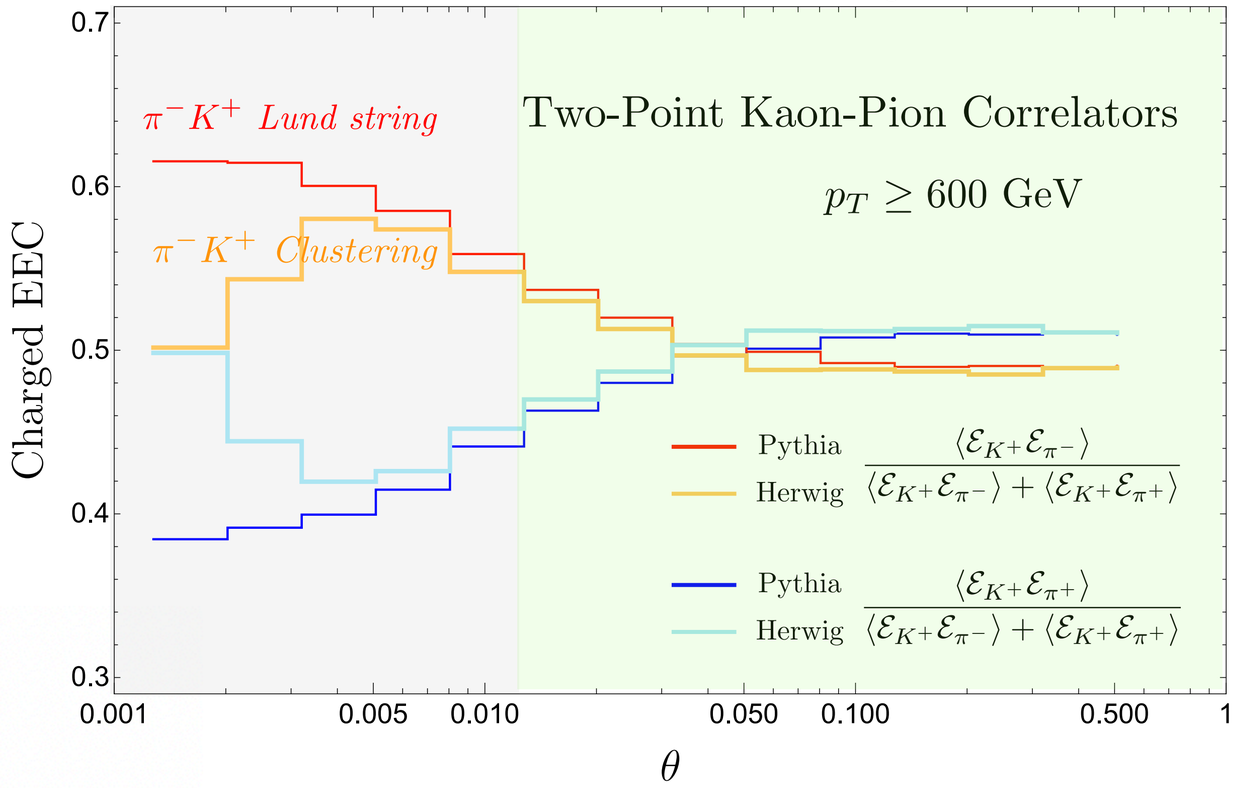


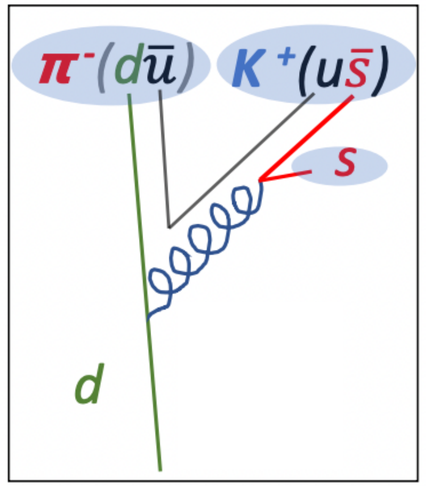
- **The correlation between unlike-signed hadron pair is expected to grow in string-like hadronization**

DISCRIMINATING HADRONIZATION MECHANISMS



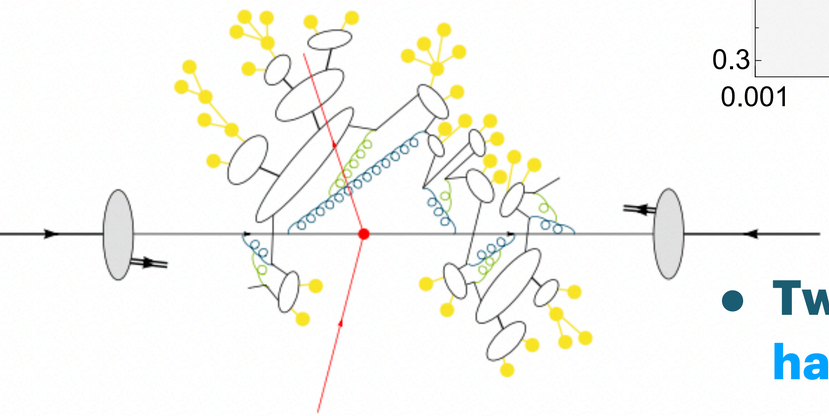
KL, Moult, Song, Sterman `In Progress





Lund string model (Pythia)

Clustering model (Herwig)



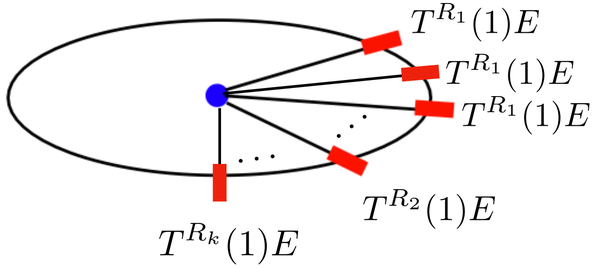
See also Chien, Deshpande, Mondal, Sterman

- **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!**

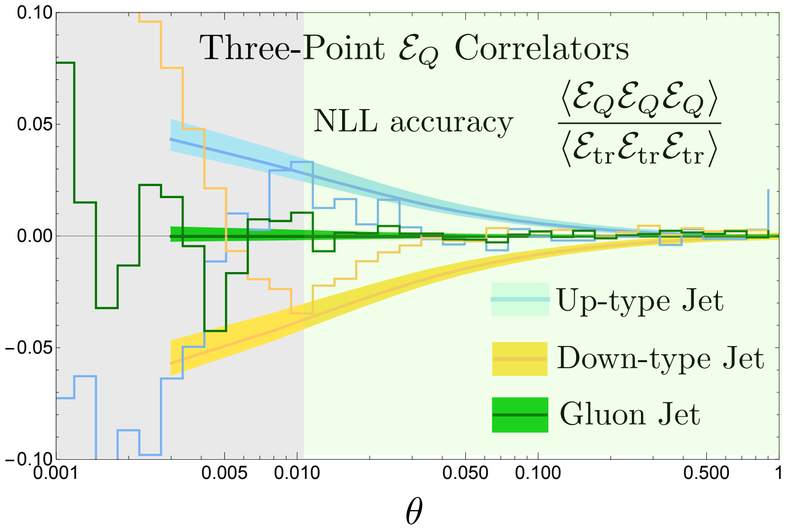
KL, Moult `23



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

Higher-point charged correlators

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



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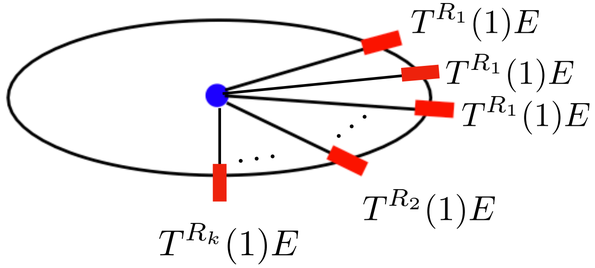
KL, Moult `23



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

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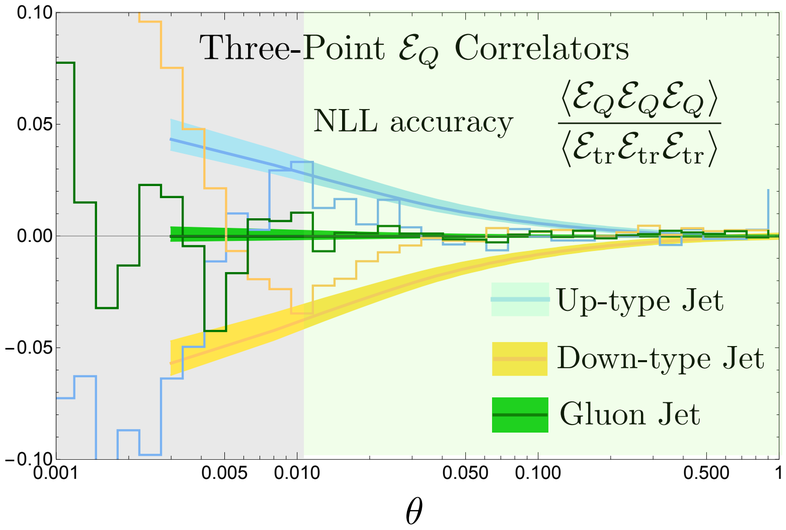
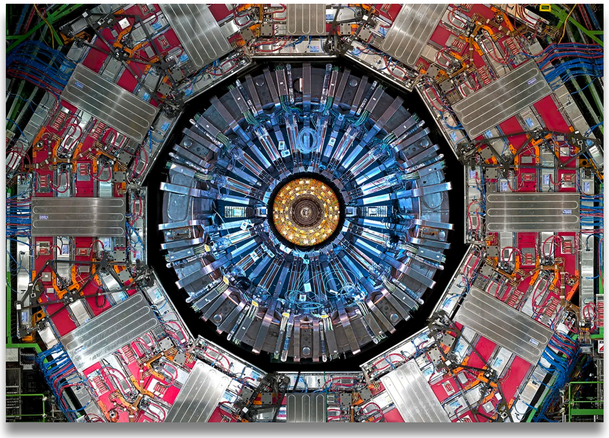


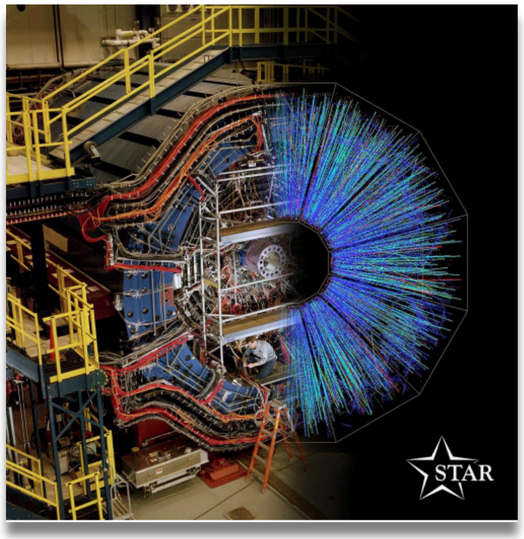
Tune into many great talks this week! See also overview by Ian Moult last week!

...and much more that I could not cover in the talk: nucleon EECs, spinning correlators, back-to-back correlators, top quark mass determination, 4-point correlators, etc...

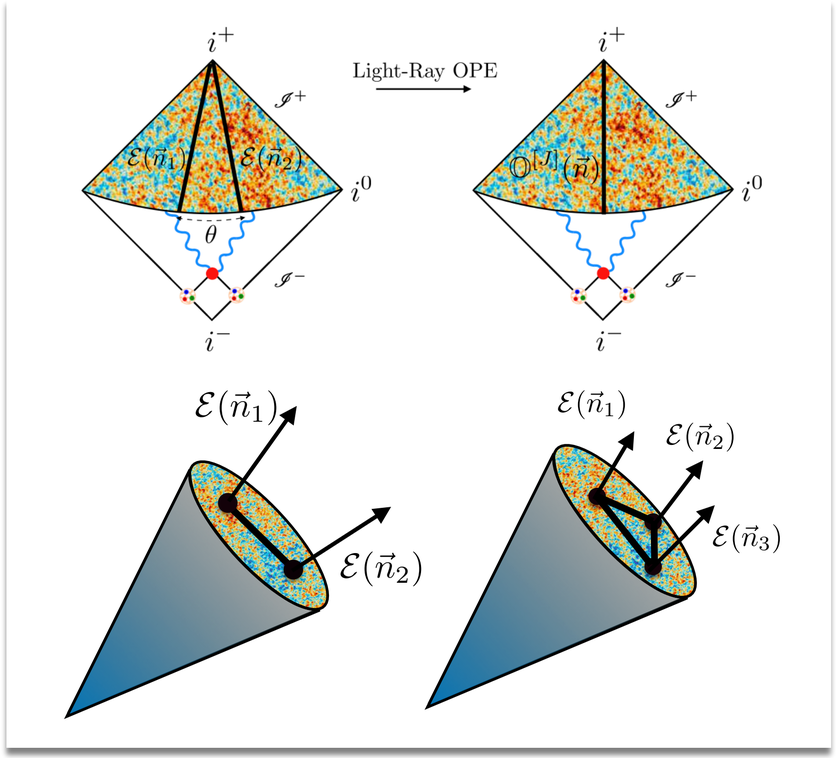
Conformal Colliders meet Jets in Particle Colliders!



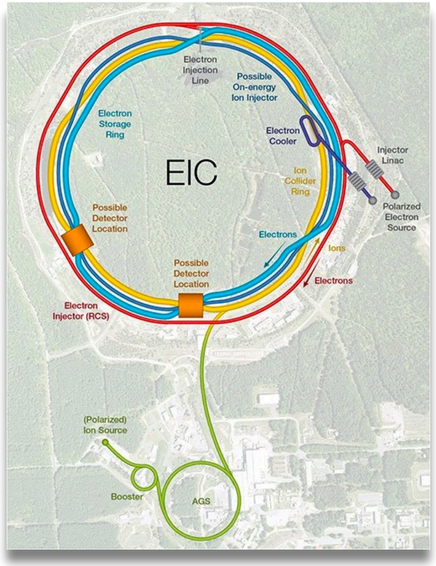
LHC



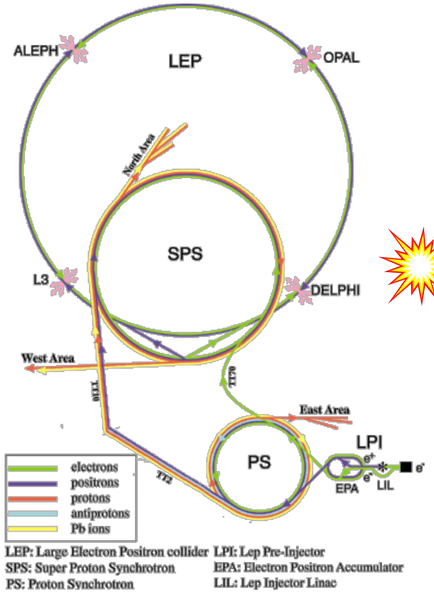
RHIC



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



EIC



LEP