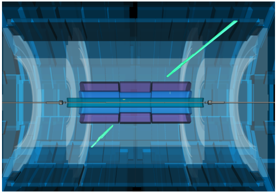
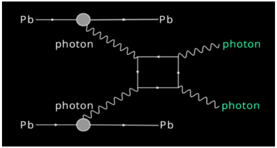
Energy Correlators at the Collider Frontier

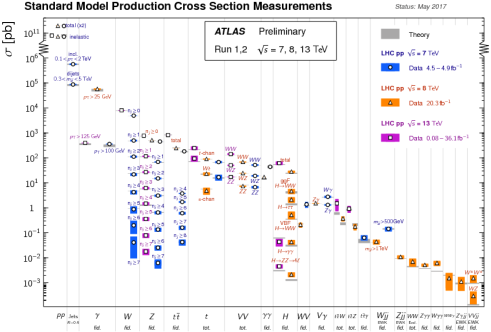
Ian Moult

Exclusive Processes: S-Matrix

- Tremendous progress in the understanding of exclusive scattering processes: analytic structure, multi-loop perturbative data, amplituhedron, S-matrix bootstrap,...



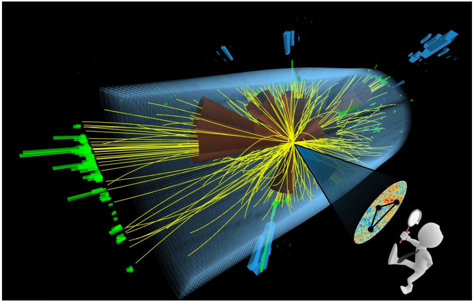


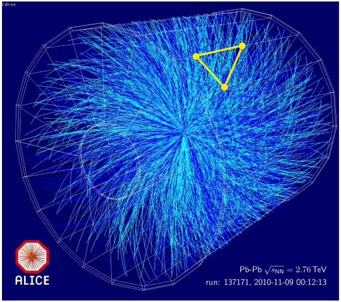


- Practical Outcome: Ability to accurately describe complicated SM scattering processes.

The High Multiplicity Regime

- A complementary regime: high multiplicity
  - Collisions with $E \gg m_{\text{gap}}$
  - Conformal Field Theories

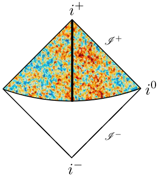




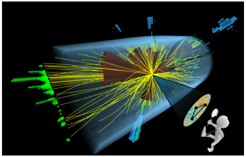
- Good observables are correlations in fluxes at (null) infinity.

Motivation

- How can we characterize a theory using asymptotic data?



- Theoretical motivation:
  - What is the space of observables at null infinity?
  - How are they related to (C)FT data?
  - How do we constrain theories in the absence of S-matrix and/ or local ops (e.g. CFT coupled to gravity) [Maldacena, Zhiboedov]
- Phenomenological motivation:
  - Can we relate asymptotic measurements to parameters of the underlying theory? (couplings, transport coefficients, ...)
  - Can we identify universal features that can be computed to high precision?



- Wealth of collider data provides a practical testing ground.

Energy Correlators: Past

To make this idea more quantitative we define for any state $\underline{a}$, an "angular energy current" in the e^+e^- CM frame:

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

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

Energy Flux

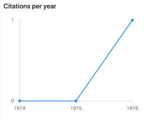
- The expectation value of energy flux, $\langle \mathcal{E}(\vec{n}_1) \rangle$, at specific angles on the celestial sphere is calculable in perturbation theory. (Sterman, 1975)

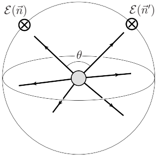
Jet Structure in e+ e- Annihilation with Massless Hadrons

George F. Sterman (Illinois U., Urbana)
Dec, 1975

10 pages
Report number: ILL-TH-75-32
View in: KEK scanned document

pdf cite claim reference search 1 citation





Our ensembles will thus be specified in terms of sets of jet-related states. To make this idea more quantitative we define for any state a, an "angular energy current" in the e^+e^- CM frame:

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

where the sum is over the n_a massless particles in a, with energies $\{\eta_i\}$ and momentum directions $\{\omega_i\}$ (ω_i stands for angles θ_i and φ_i). Jet-related states have the same $j(\Omega)$. Each group of particles with co-linear momenta may be described as a jet, and any set of jet-related states is characterized by the number of jets, as well as their energies and directions.

- "Energy Flow becomes the focus of calculability"

Detector Operators

- Are now known to be part of a wide class of "detector operators".
- Significant recent progress in understanding the classification of detector operators, and their algebras and OPEs.

Sterman 1975:

To make this idea more quantitative we define for any state $\underline{a}$, an "angular energy current" in the e^+e^- CM frame:

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

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

[Korchemsky, Sterman]
[Sveshnikov, Tkachov]
[Hofman, Maldacena]

ANEC

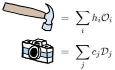
$$\mathcal{E}(\vec{n}) = \lim_{r\to\infty} r^2 \int_0^\infty dt\; n^i T_{0i}(t, r\vec{n})$$

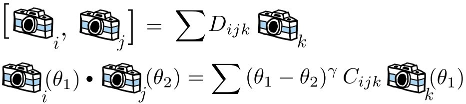
Light Transform

[Kravchuk, Simmons Duffin]

$$\mathcal{E}(\vec{n}) = 2\,\mathbf{L}[T](\infty, z)\big|_{z=(1,\vec{n})}$$

$$\mathbf{L}[\mathcal{O}](x,z) = \int_{-\infty}^{\infty} d\alpha (-\alpha)^{-\Delta-J} \mathcal{O}\left(x - \frac{z}{\alpha}, z\right)$$

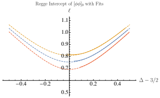




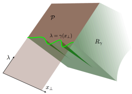
Detector Operators

- Now play a central role in many areas of theoretical physics.

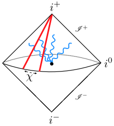
Conformal Bootstrap



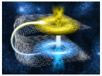
Modular Hamiltonians



Jet Substructure



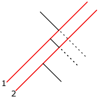
Energy Inequalities/ Operator Bounds

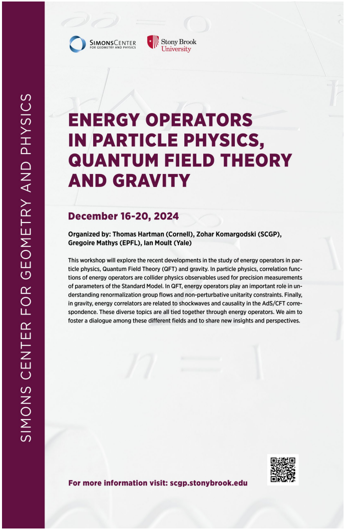


Average Null Energy Condition

$$\langle \psi | \mathcal{E} | \psi \rangle \geq 0$$

Gravitational Shocks





Energy Correlators

- Correlators of energy flow operators $\langle \mathcal{E}(\vec{n}_1) \cdots \mathcal{E}(\vec{n}_k) \rangle$ characterize the final state in collider experiments in QCD (Ellis et al. 1977)

Energy Correlations in electron - Positron Annihilation: Testing QCD

C.Louis Basham (Washington U., Seattle), Lowell S. Brown (Washington U., Seattle), Stephen D. Ellis (Washington U., Seattle), Sherwin T. Love (Washington U., Seattle)

Aug, 1978

13 pages

Published in: *Phys.Rev.Lett.* 41 (1978) 1585

DOI: 10.1103/PhysRevLett.41.1585

Report number: RLO-1388-759

View in: OSTI Information Bridge Server, ADS Abstract Service

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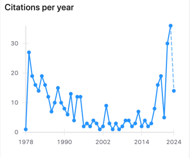


Abstract

The possible role of gluons in hadronic processes as suggested by the quark-parton model and QCD is discussed and evaluated.

Introduction

The most dramatic and encouraging development in Strong Interaction physics in the past few years has been the emergence of a candidate field theory to describe these interactions. This situation is in sharp contrast to that which obtained ten years ago when, at least at one well known institution of higher learning, it was "taught" that field theory was irrelevant to Strong Interactions[1)].

Footnote and References

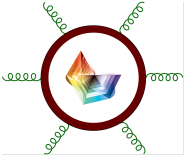
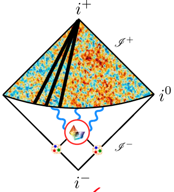
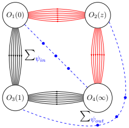
1) Recollections of a Caltech graduate student, S. D. Ellis, unpublishable.

Energy Correlators: Beyond QCD

- Energy Correlators are interesting observables for characterizing generic quantum theories. (Hofman, Maldacena)

Conformal collider physics:
Energy and charge correlations

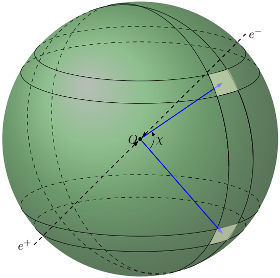
Diego M. Hofman[a] and Juan Maldacena[b]

	Amplitudes	Energy Correlators	Correlation Functions
			
Boundary Observable	✓	✓	
IR Finite		✓	✓

- Well defined at weak coupling, strong coupling, in a CFT, coupled to gravity, ...

Energy Correlators: Simplicity in Perturbation Theory

- Physical observables can be beautiful: Belitsky, Hohenegger, Korchemsky, Sokatchev, Zhiboedov (2013) illustrated the simplicity of energy correlators in perturbation theory.



$$F(z;a) = aF_1(z) + a^2\left[(1-z)F_2(z) + F_3(z)\right],$$

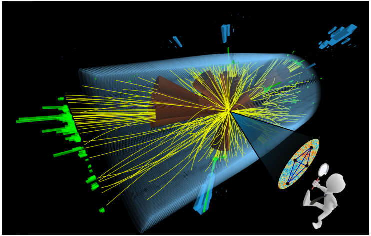
$$F_2(z) = 4\sqrt{z}\left[\mathrm{Li}_2\left(-\sqrt{z}\right) - \mathrm{Li}_2\left(\sqrt{z}\right) + \frac{\ln z}{2}\ln\left(\frac{1+\sqrt{z}}{1-\sqrt{z}}\right)\right] + (1+z)\left[2\mathrm{Li}_2(z) + \ln^2(1-z)\right] + 2\ln(1-z)\ln\left(\frac{z}{1-z}\right) + z\frac{\pi^2}{3},$$

$$\begin{aligned} F_3(z) = \frac{1}{4}\Big\{&(1-z)(1+2z)\left[\ln^2\left(\frac{1+\sqrt{z}}{1-\sqrt{z}}\right)\ln\left(\frac{1-z}{z}\right) - 8\mathrm{Li}_3\left(\frac{\sqrt{z}}{\sqrt{z}-1}\right) - 8\mathrm{Li}_3\left(\frac{\sqrt{z}}{\sqrt{z}+1}\right)\right] - 4(z-4)\mathrm{Li}_3(z) \\ &+ 6(3+3z-4z^2)\mathrm{Li}_3\left(\frac{z}{z-1}\right) - 2z(1+4z)\zeta_3 + 2\left[2(2z^2-z-2)\ln(1-z) + (3-4z)z\ln z\right]\mathrm{Li}_2(z) \\ &+ \frac{1}{3}\ln^2(1-z)\left[4(3z^2-2z-1)\ln(1-z) + 3(3-4z)z\ln z\right] + \frac{\pi^2}{3}\left[2z^2\ln z - (2z^2+z-2)\ln(1-z)\right]\Big\}. \quad (15) \end{aligned}$$

- Since then, extended in many directions, by many authors:
  - Higher loop $\mathcal{N} = 4$: Henn, Sokatchev, Yan, Zhiboedov
  - QCD: Dixon, Shtabovenko, Yang, Zhu
  - Higher Point: Yan, Yang, Zhang

Energy Correlators at the Collider Frontier

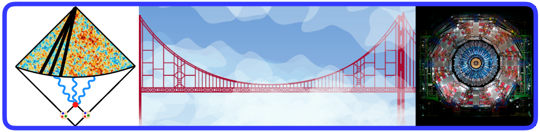
- Transition from GeV$\rightarrow$ TeV, and the experimental development of jet substructure, provides access to a new regime of QCD!



- Amazing dataset provides exciting opportunities:
  1. Experiment Informing Theory: Measurement of correlators, lightray OPE, etc. to reveal interesting behavior.
  2. Theory Informing Experiment: New sophisticated theory techniques to better study the SM at colliders.

Energy Correlators at the Collider Frontier

- Spectacular recent progress bridging theory and experiment!



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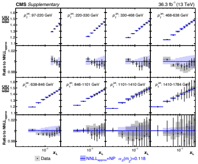
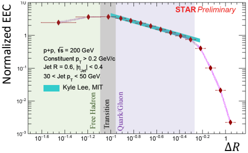
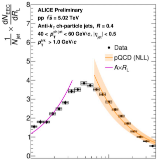
STRONG INTERACTIONS | NEWS

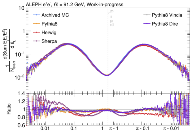
Measuring energy correlators inside jets

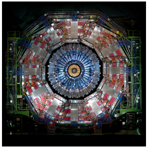
3 November 2023

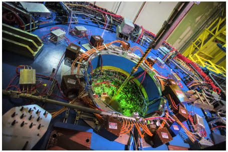


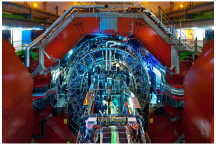


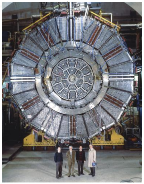




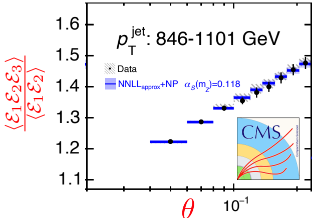


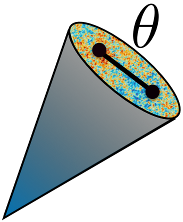


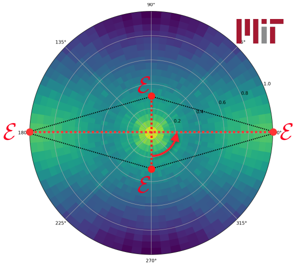


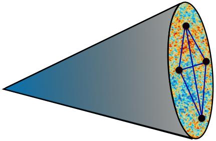


Energy Correlators: Present

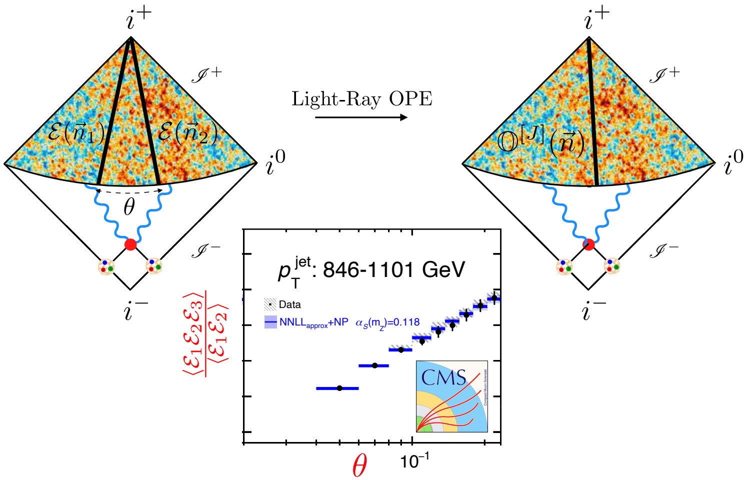








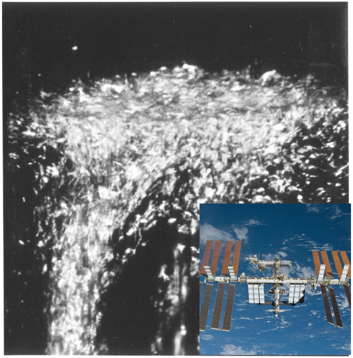
Scaling Behavior

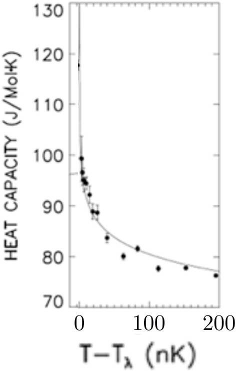


Scaling Behavior in QFT

- Euclidean scaling behavior is well understood.

λ-point of Helium



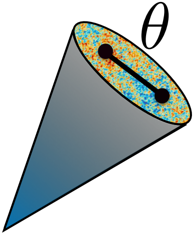


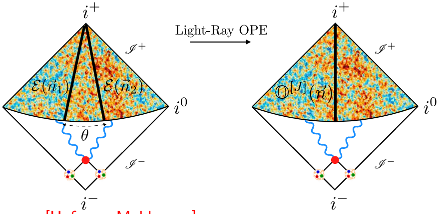
$$\mathcal{O}(x)\mathcal{O}(0) = \sum x^{\gamma_i} c_i \mathcal{O}_i$$

The OPE Limit of Lightray Operators

- Energy flow operators admit a Lorentzian OPE: “the lightray OPE”

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





[Hofman, Maldacena]
[Chang, Kologlu, Kravchuk, Simmons Duffin, Zhiboedov]

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

- Scaling can be derived in generic (non-conformal) theories using factorization theorems. [Dixon, Moult, Zhu] See early work by [Konishi, Ukawa, Veneziano]
- Predicts universal scaling behavior in correlations of energy flux at energies $E \gg \Lambda_{\rm QCD}$.

Theory-Experiment Gap

Conformal collider physics:
Energy and charge correlations

Diego M. Hofman[a] and Juan Maldacena[b]

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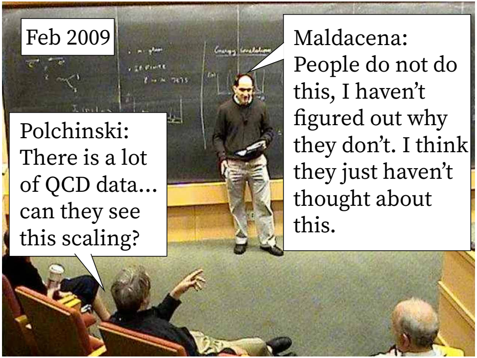
Princeton, NJ 08540, USA

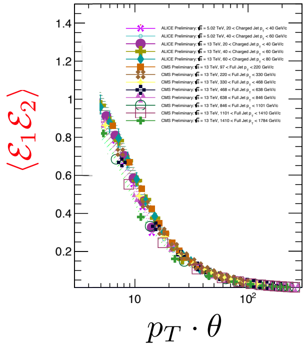


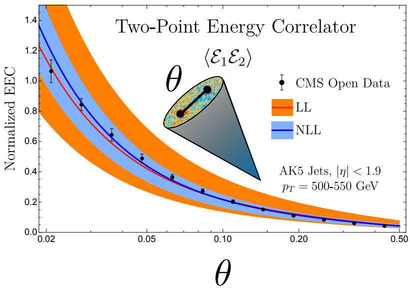
Still true as of 2023...

Scaling Behavior in Jets

- Scaling measured inside jets by STAR, ALICE and CMS from 15 GeV to 1784 GeV:

  An experimental realization of the detector OPE!



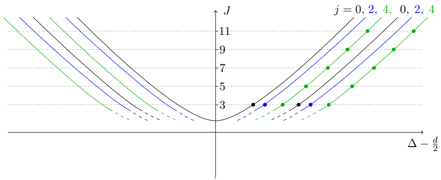


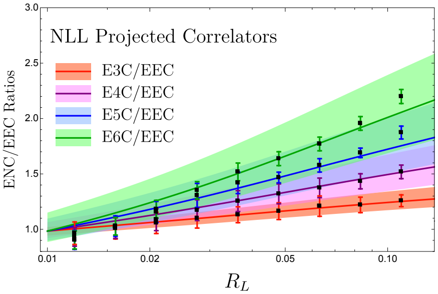
- Can we accurately extract anomalous exponents of different detectors?

The Spectrum of a Jet

- The light-ray OPE predicts that the N-point correlators develop an anomalous scaling that depends on N.
[Maldacena, Hofman]
[Chen, Moult Zhang, Zhu]

$$\frac{\langle \mathcal{E}_1 \mathcal{E}_2 \cdots \mathcal{E}_{J-1} \rangle}{\langle \mathcal{E}_1 \mathcal{E}_2 \rangle} \sim \frac{\langle \mathbb{O}^{[J]} \rangle}{\langle \mathbb{O}^{[3]} \rangle} \sim \theta^{\gamma(J)-\gamma(3)}$$





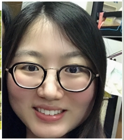
- Directly probes the spectrum of (twist-2) lightray operators from asymptotic energy flux.

Anomalous Scaling

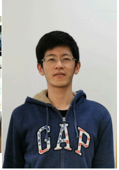
- Universal quantity in complicated hadronic environment.

$$\frac{\langle \mathcal{E}_1 \mathcal{E}_2 \mathcal{E}_3 \rangle}{\langle \mathcal{E}_1 \mathcal{E}_2 \rangle} \sim \frac{\langle \mathbb{O}^{[4]} \rangle}{\langle \mathbb{O}^{[3]} \rangle} \sim \theta^{\gamma(4)-\gamma(3)}$$

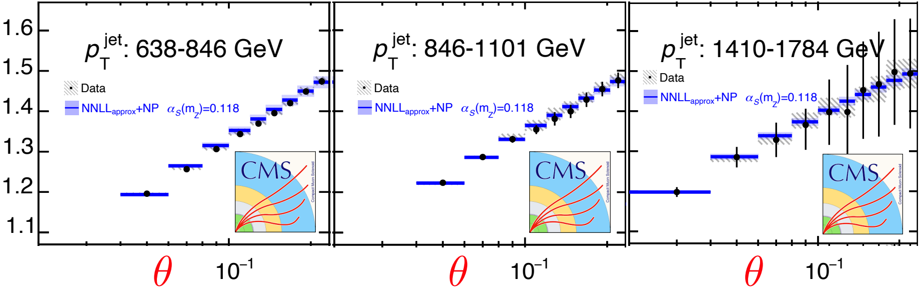
XiaoYuan Zhang



Yibei Li



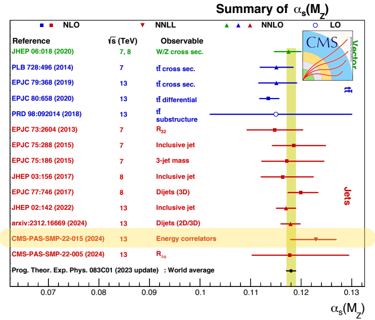
Hao Chen



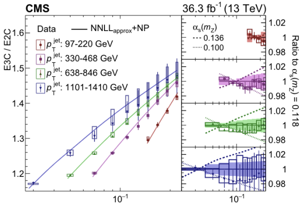
- Uses scaling anomalous dimensions at three-loop order.
- Beautiful quantitative test of QFT!

The Strong Coupling

- Use scaling to extract value of the strong coupling constant α_s at 4% accuracy.



$$\frac{\langle \mathcal{E}_1\mathcal{E}_2\mathcal{E}_3\rangle}{\langle \mathcal{E}_1\mathcal{E}_2\rangle}$$



θ

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

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

$$= 0.1229^{+0.0014(stat.)+0.0030(theo.)+0.0023(exp.)}_{-0.0012(stat.)-0.0033(theo.)-0.0036(exp.)}$$

- Very clear target for improved perturbative calculations. e.g. NNLO $2 \to 3$ hard functions, NP corrections, ... not yet included.

Strings 2024 Talk by David Simmons-Duffin

CMS determination of α_s from $\langle\mathcal{EEE}\rangle/\langle\mathcal{EE}\rangle$ [CMS '24]

CMS-SMP-22-015

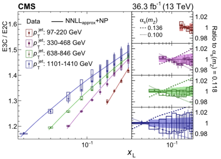
CERN-EP-2024-010
2024/02/22

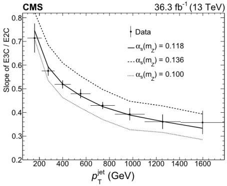
Measurement of energy correlators inside jets and determination of the strong coupling $\alpha_S(m_Z)$

The CMS Collaboration*

Abstract

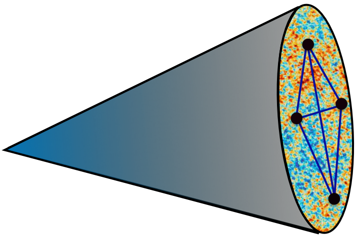
Energy correlators that describe energy-weighted distances between two or three particles in a jet are measured using an event sample of $\sqrt{s} = 13$ TeV proton-proton collisions collected by the CMS experiment and corresponding to an integrated luminosity of 36.3 fb^{-1}. The measured distributions reveal two key features of the strong interaction: confinement and asymptotic freedom. By comparing the ratio of the two measured distributions with theoretical calculations that resum collinear emissions at approximate next-to-next-to-leading logarithmic accuracy matched to a next-to-leading order calculation, the strong coupling is determined at the Z boson mass: $\alpha_S(m_Z) = 0.1229^{+0.0040}_{-0.0050}$, the most precise $\alpha_S(m_Z)$ value obtained using jet substructure observables.

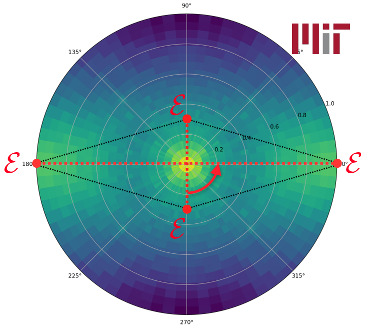




- First study of lightray OPE in *any system*!

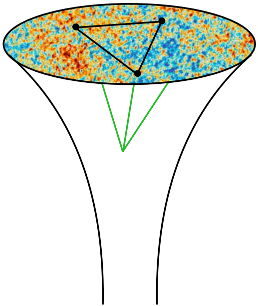
Higher Point Functions in Energy Flux

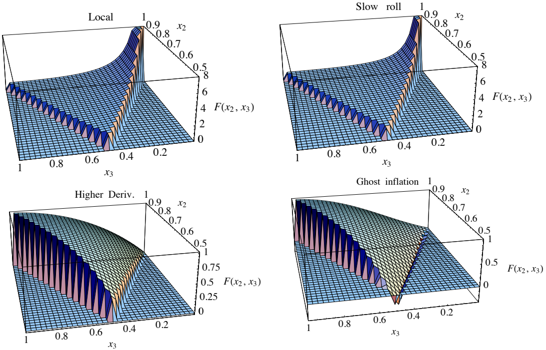




Multipoint Correlators

- Higher-point correlators probe detailed aspects of the underlying microscopic interactions. e.g. CMB three-point functions allow to distinguish models of inflation.





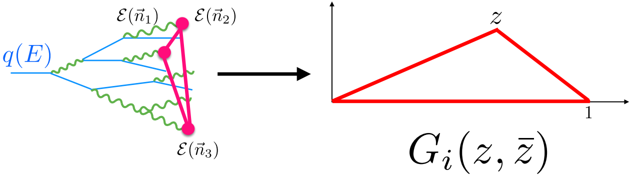
- What is the structure of higher-point functions of energy flux?

Multipoint Correlators

- The only explicit results for correlators with $N > 2$ were the remarkable strong coupling results of Hofman and Maldacena:

$$\langle \mathcal{E}(\vec{n}_1)\cdots\mathcal{E}(\vec{n}_n)\rangle = \left(\frac{q}{4\pi}\right)^n \left[1 + \sum_{i<j} \frac{6\pi^2}{\lambda}[(\vec{n}_i.\vec{n}_j)^2 - \frac{1}{3}] + \right.$$
$$\left. + \frac{\beta}{\lambda^{3/2}}[\sum_{i<j<k} (\vec{n}_i.\vec{n}_j)(\vec{n}_j.\vec{n}_k)(\vec{n}_i.\vec{n}_k) + \cdots] + o(\lambda^{-2})\right]$$

- The wealth of techniques developed to compute perturbative scattering amplitudes can be applied to multi-point correlators at weak coupling.



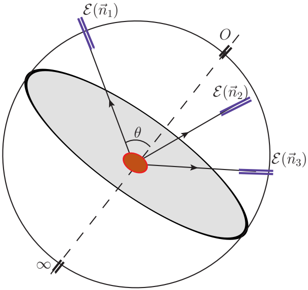
Correlators in Perturbation Theory

- Two approaches to calculate energy correlators:
  1. Light transforming N-point functions of stress tensors:

$$\langle 0|\mathcal{O}^\dagger T\cdots T\mathcal{O}|0\rangle \to \langle 0|\mathcal{O}^\dagger \mathcal{E}(\vec{n}_1)\cdots\mathcal{E}(\vec{n}_k)\mathcal{O}|0\rangle$$

Two Point NLO in $\mathcal{N}=4$: [Belitsky, Hohenegger, Korchemsky, Sokatchev, Zhiboedov]
Two Point NNLO in $\mathcal{N}=4$: [Henn, Sokatchev, Yan, Zhiboedov]
LO Charge-Charge Correlator in QCD: [Chicherin, Henn, Sokatchev, Yan]

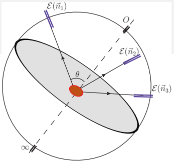
  2. Perturbative phase space integrals using (squared) form factors:



$$\frac{\langle\Psi|\mathcal{E}(\vec{n}_1)\cdots\mathcal{E}(\vec{n}_k)|\Psi\rangle}{\langle\Psi|\Psi\rangle} = \sum_{i_1,\dots,i_k}\int d\sigma \prod_{j=1}^{k} E_{i_j}\delta(\vec{n}_j - \vec{p}_{i_j}/p^0_{i_j})$$

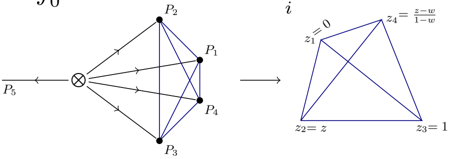
Two Point LO in QCD: [Basham, Ellis, Brown, Love]
Two Point NLO in QCD: [Dixon, Luo, Shtabovenko, Yang, Zhu]
Three Point Collinear LO in QCD: [Chen, Luo, Moult, Yang, Zhang, Zhu]
Three Point General Angle LO in $\mathcal{N}=4$: [Yan, Zhang]
Three Point General Angle LO in QCD: [Yang, Zhang]
Four Point Collinear LO in $\mathcal{N}=4$: [Chicherin, Moult, Sokatchev, Yan, Zhu]

Correlators in Perturbation Theory

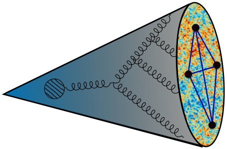


- For generic angles, the correlator depends on the cross ratios $\zeta_{ij} = \frac{1-\cos\theta_{ij}}{2}$, and the source.
- In the collinear (OPE) limit, $\zeta_{ij} \to 0$, it becomes a function of $2(N-2)$ variables that is independent of the source.
- The LO contribution to the N-point function is given by a *finite* integral in $(N-1)$ dimensional projective space of the *universal splitting functions*:

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

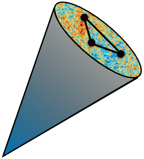


- This limit can be physically measured inside high energy jets at the LHC.



Three-Point Correlator at Weak Coupling

- First non-trivial correlator: tree level three-point correlator in the collinear limit $G(z,\bar{z})$. [Chen, Luo, Moult, Yang, Zhang, Zhu]
- Turns out to have an elegant perturbative structure. e.g. in $\mathcal{N}=4$



$$G_{\mathcal{N}=4}(z) = \frac{1+u+v}{2uv}(1+\zeta_2) - \frac{1+v}{2uv}\log(u) - \frac{1+u}{2uv}\log(v)$$
$$-(1+u+v)(\partial_u+\partial_v)\Phi(z) + \frac{(1+u^2+v^2)}{2uv}\Phi(z) + \frac{(z-\bar{z})^2(u+v+u^2+v^2+u^2v+uv^2)}{4u^2v^2}\Phi(z)$$
$$+\frac{(u-1)(u+1)}{2uv^2}D_2^+(z) + \frac{(v-1)(v+1)}{2u^2v}D_2^+(1-z) + \frac{(u-v)(u+v)}{2uv}D_2^+\left(\frac{z}{z-1}\right)$$

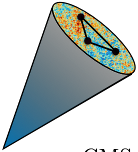
- where Φ and D_2^+ are

$$\Phi(z) = \frac{2}{z-\bar{z}}\left(\mathrm{Li}_2(z) - \mathrm{Li}_2(\bar{z}) + \frac{1}{2}\left(\log(1-z) - \log(1-\bar{z})\right)\log(z\bar{z})\right)$$
$$D_2^+(z) = \mathrm{Li}_2(1-|z|^2) + \frac{1}{2}\log(|1-z|^2)\log(|z|^2)$$

- Provides important perturbative data for the development of the lightray OPE.

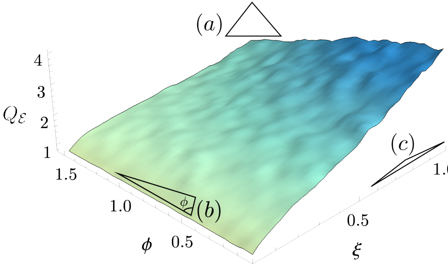
Shape Dependence of Non-Gaussianities

- Multipoint correlators can be directly measured in high energy jets: Simple analytic functions for the *actual measured observable!*

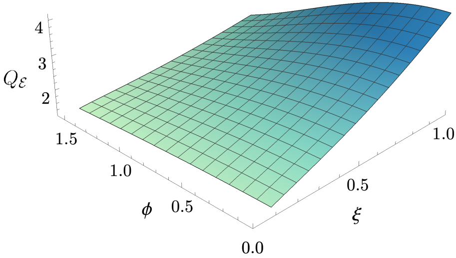


- Non-Gaussianities inside high energy jets at the LHC:

CMS Open Data, $R_L \in (0.3, 0.4)$



LL + LO prediction, $R_L = 0.35$

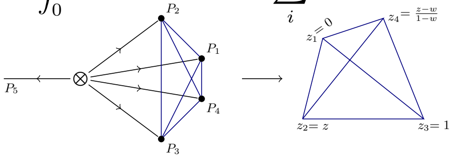


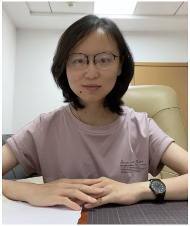
Four Point Correlator

[Chicherin, Moult, Sokatchev, Yan, Zhu]

- Simple structure makes energy correlators a nice playground for exploration of *physical observables* in perturbation theory.
- Four point correlator computed in $\mathcal{N}=4$ SYM by direct integration in parameter space, using simple form of $1 \to 4$ splitting function.

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



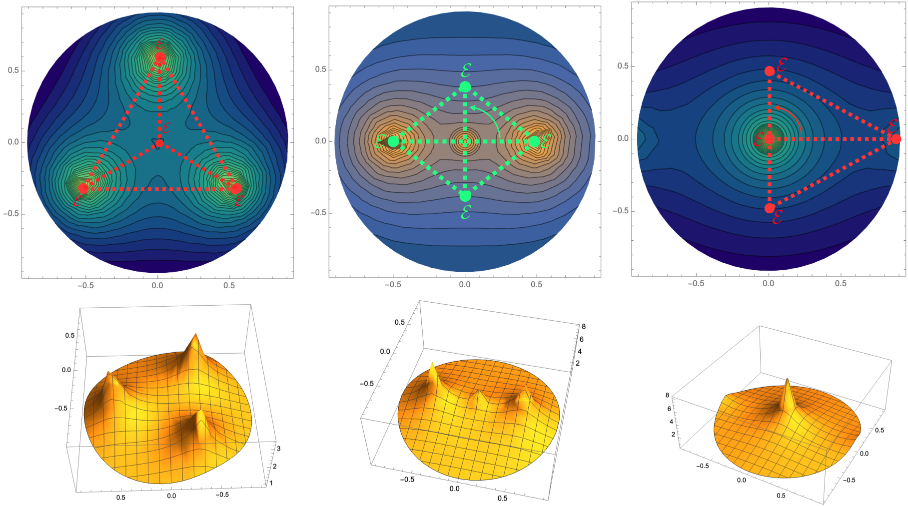


Kai Yan

- Compact result expressed in terms of weight three polylogarithms: much structure still to be explored.
- Would be interesting to extend to QCD using known $1 \to 4$ splitting functions. [Del Duca, Duhr, Haindl, Lazopoulos, Michel]
- Can one push to higher points or make general statements?.

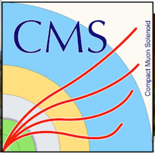
The Four Point Correlator

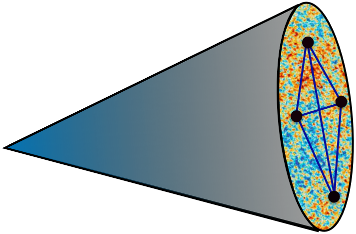
- Intricate view of correlations of energy flow. Access to OPE limits, spinning operators, ...



The Four Point Correlator

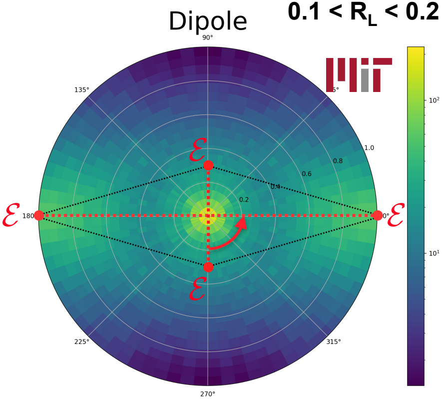
Experimental tour de force to enable precision measurements of higher point correlators.





p_T > 100 GeV

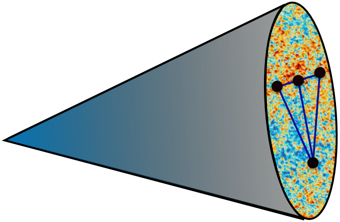
0.1 < R_L < 0.2

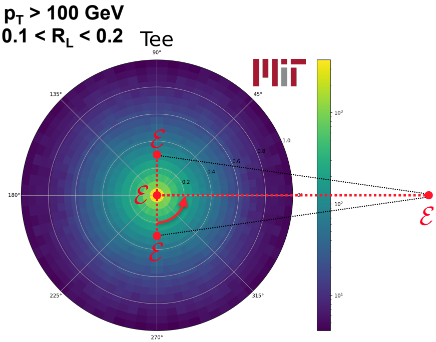


Thanks to Simon Rothman and Phil Harris!

The Four Point Correlator

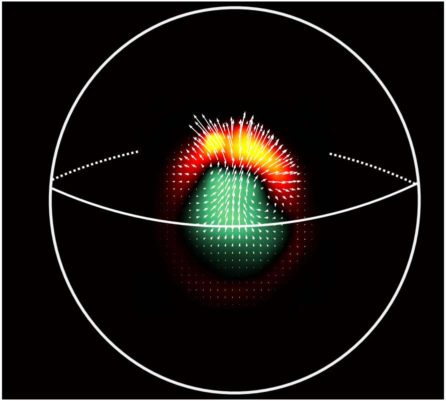
Experimental tour de force to enable precision measurements of higher point correlators.





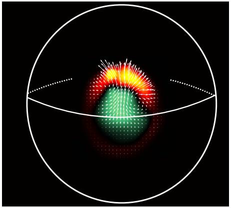
Thanks to Simon Rothman and Phil Harris!

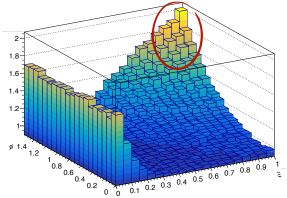
Energy Correlators:
The Future of the Collider Frontier



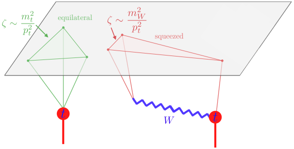
LHC Targets:

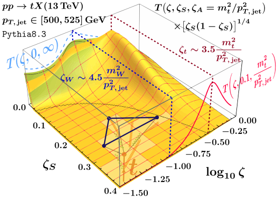
- Measurements on more complicated states:
  - Imaging the Quark Gluon Plasma



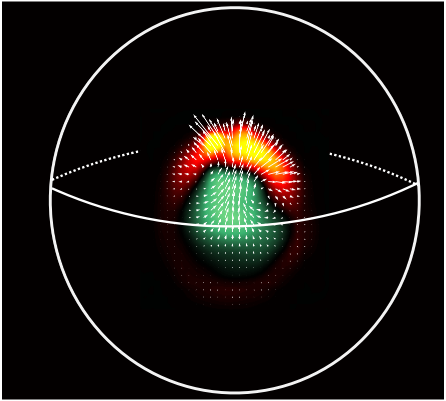


  - Weighing the Top Quark



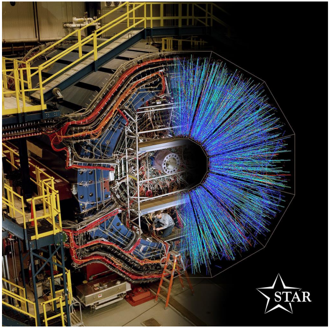


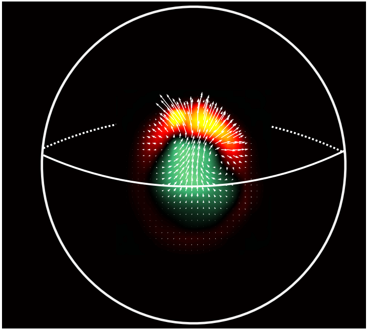
Resolving the Scales of the QGP



Quark Gluon Plasma

- Heavy ion collisions provide an example of an extremely complicated asymptotic state, where we do not understand the microscopic dynamics that created it.

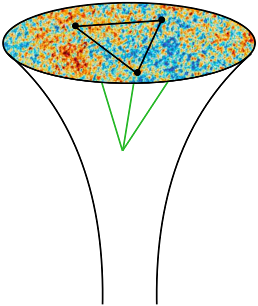


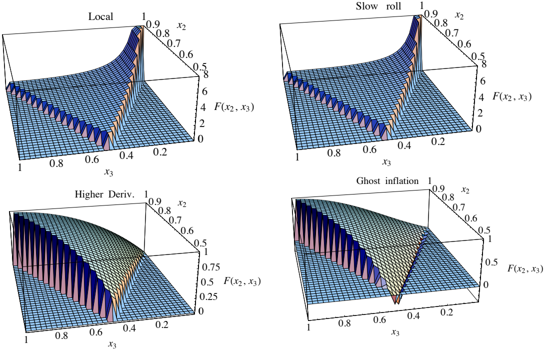


- Many physical effects: medium induced radiation, medium response, wake, ...

Multipoint Correlators

- Can we map out the space of “shapes” of models of the QGP?

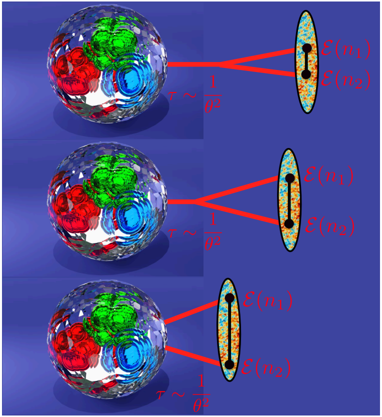




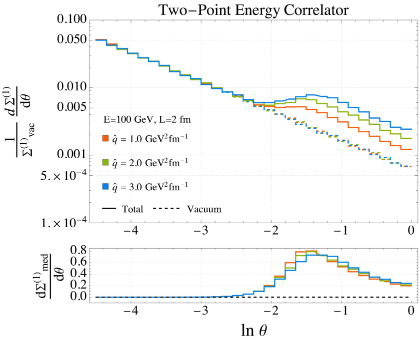
- Ability to understand energy correaltors at strong coupling, weak coupling, in different theories, will prove essential.

Imaging the Quark Gluon Plasma

- QGP scales cleanly imprinted in two-point correlation.



Increasing θ

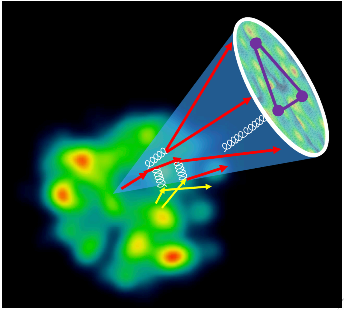


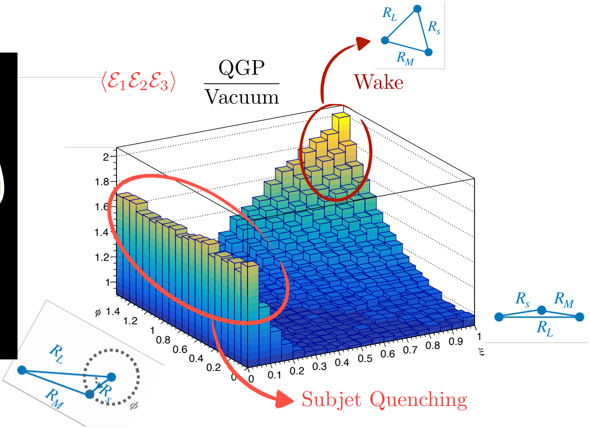
Increasing θ

[Andres, Dominguez, Holguin, Kunnawalkam Elayavalli, Marquet, Moult]

Imaging the Wake

- Higher point correlators allow the "shape" of the medium response to be imaged.





- See talk by Krishna, Ananya, Hannah, Arjun.

Quark Gluon Plasma

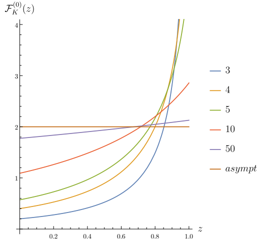
- Excited for forthcoming measurements and progress!

Quark Gluon Plasma

- Motivates understanding of asymptotic observables in thermal or large charge states.
- Two recent approaches:
  - Heavy half-BPS operators in $\mathcal{N} = 4$:

$$O_K(x) = \mathrm{tr}[\phi^K(x)]\,, \qquad \phi(x) = \sum_{I=1}^{6} Y^I X^I\,.$$

[Chicherin, Korchemsky, Sokatchev, Zhiboedov]

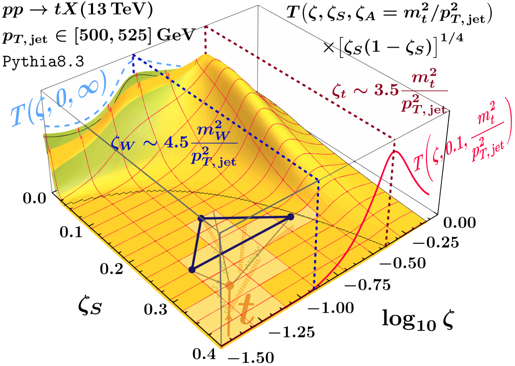


  - Large charge states using semi-classics:

$$\langle \mathcal{E}(\mathbf{n}_1)\mathcal{E}(\mathbf{n}_2)\rangle \approx \left(\frac{E}{\Omega_{d-2}}\right)^2 \left(1 + O(1/\Delta_Q)\right) \qquad (Q \to \infty).$$

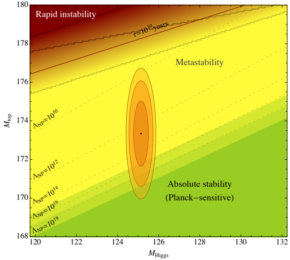
[Firat, Monin, Rattazzi, Walters]

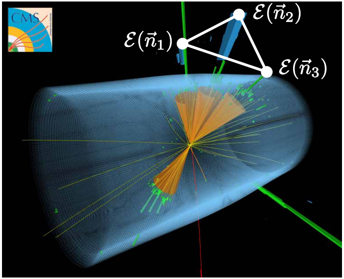
Weighing the Top Quark

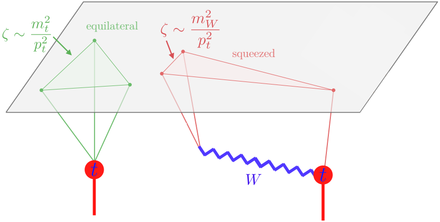


Weighing the Top Quark

- The top quark mass is one of the most important parameters of the SM. e.g. electroweak vacuum stability/criticality, electroweak fits, etc.
- Need simple observables with top mass sensitivity that can be computed from first principles field theory.

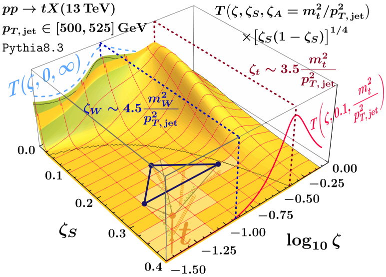


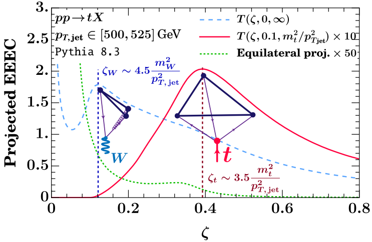


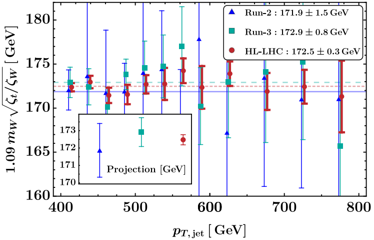


Weighing the Top Quark

- Extract the mass ratio between the W and top quark from the shape of the three-point correlator.







[Holguin, Moult, Pathak, Procura, Schofbeck, Schwarz]

See also: [Xiao, Ye, Zhu]

- Motivates precision calculations of correlators on top decays.

Weighing the Top Quark

- Initial investigations illustrate has minor sensitivity to experimental systematics, and global event: successfully isolates dynamics of top decay.

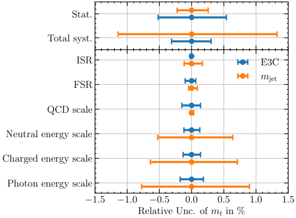
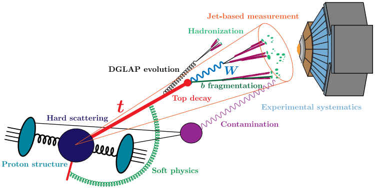
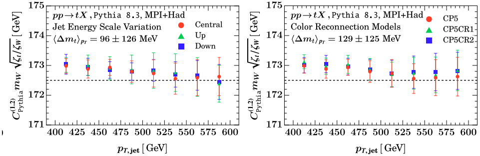


Figure 2. The expected uncertainties of m_t (in % of m_t = 171 GeV) using E3C and $m_{\rm jet}$ distributions, at $\mathcal{L} = 36\,\text{fb}^{-1}$. The statistical uncertainties and a breakdown of the systematic uncertainties are shown.

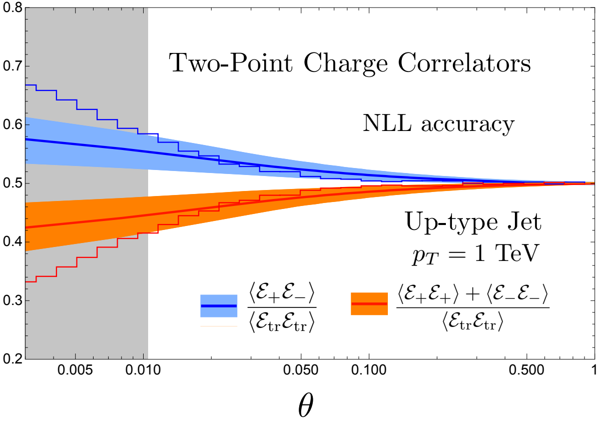




[Xiao, Ye, Zhu]

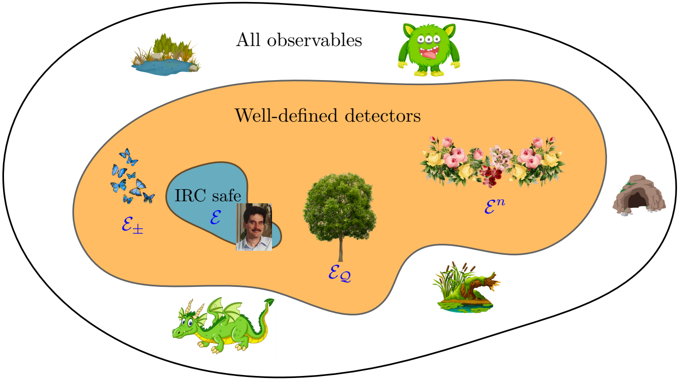
- Motivates precision calculations of correlators on top decays, and further experimental investigation.

Beyond Energy Flux



The Space of Detectors

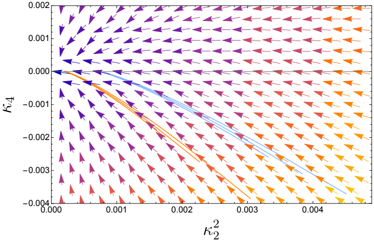
- Details of the hadronization process are encoded in the quantum numbers (charge, flavor, ...): By definition, energy flux is insensitive!
- What is the space of detectors over which we can gain theoretical control?

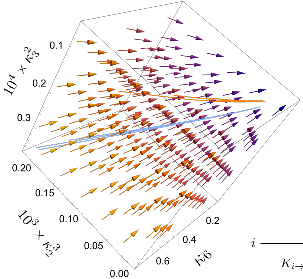


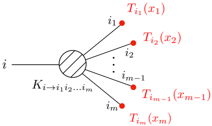
Factorization

[Chen, Jaarsma, Li, Moult, Waalewijn, Zhu]

- More general observables can be calculated by combining factorization into universal matrix elements, with the Renormalization Group.
- Tremendous recent progress in understanding renormalization group evolution of functions characterizing correlations in the hadronization process (beyond DGLAP).





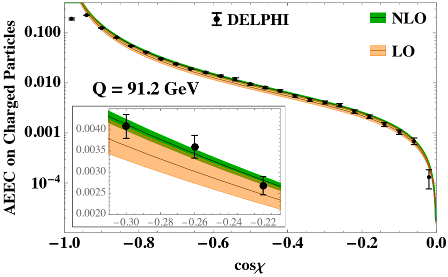


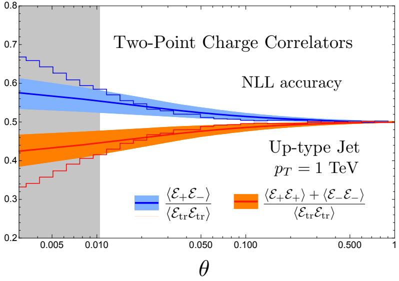
- Enables the calculation of correlations on energy flux carried by hadrons of specific quantum numbers: e.g. $\langle \Psi | \mathcal{E}_+(\hat{n}_1) \cdots \mathcal{E}_-(\hat{n}_k) | \Psi \rangle$

Charged Energy Flux

[Moult, Lee] [Li, Moult, Waalewijn, Zhu]

- Two examples of experimental interest involving electromagnetic charge:
  - $\langle\Psi|\mathcal{E}_{\text{charged}}(\hat{n}_1)\mathcal{E}_{\text{charged}}(\hat{n}_2)|\Psi\rangle$
  - $\langle\Psi|\mathcal{E}_{+}(\hat{n}_1)\mathcal{E}_{-}(\hat{n}_2)|\Psi\rangle$, $\langle\Psi|\mathcal{E}_{+}(\hat{n}_1)\mathcal{E}_{+}(\hat{n}_2)|\Psi\rangle$

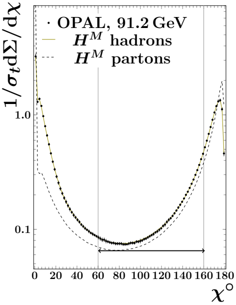


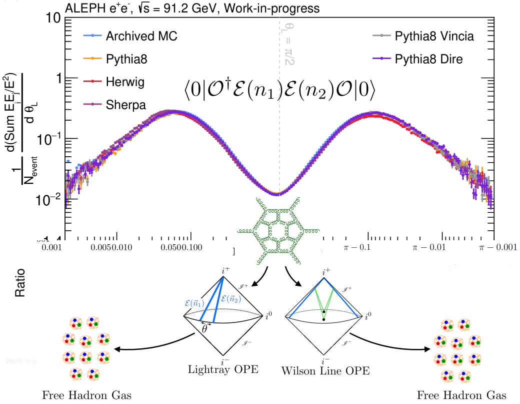


- How far can we push into the confinement transition? Experimental measurements will be crucial.

Revisiting Old Data with New Resolution

- Reanalysis of ALEPH data has measured the two-point energy correlator $\langle \mathcal{E}(n_1)\mathcal{E}(n_2)\rangle$ on tracks with spectacular resolution.

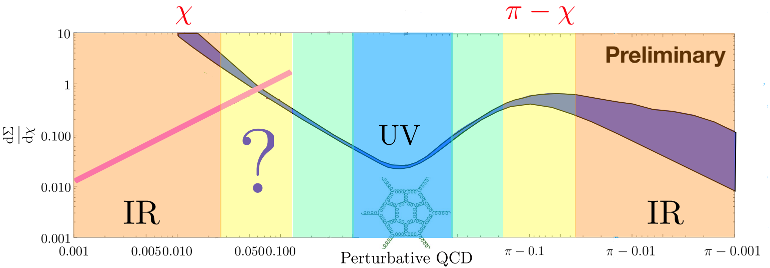


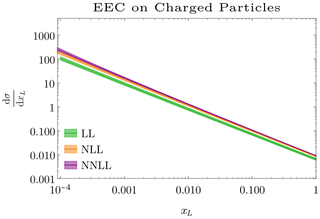


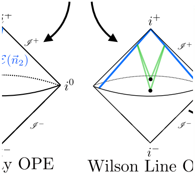
- Combined with precision track based calculations, opens up a new playground for precision studies of QFT.

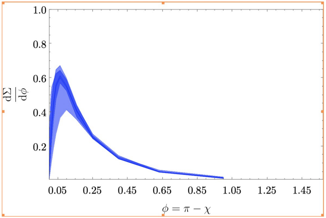
Revisiting Old Data with New Resolution

- Detector based formalism enables calculation at NNLL-collinear and N^3LL back-to-back *on tracks*!

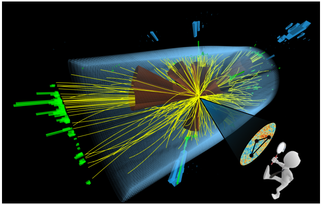


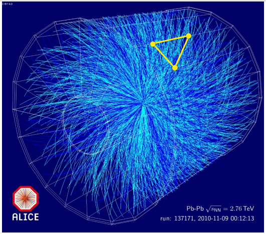


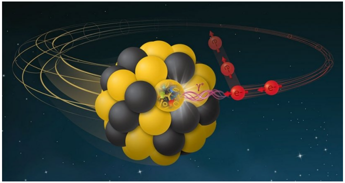


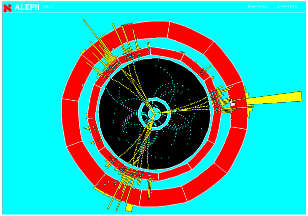


NEECs and the EIC:
Will be Covered by Others...

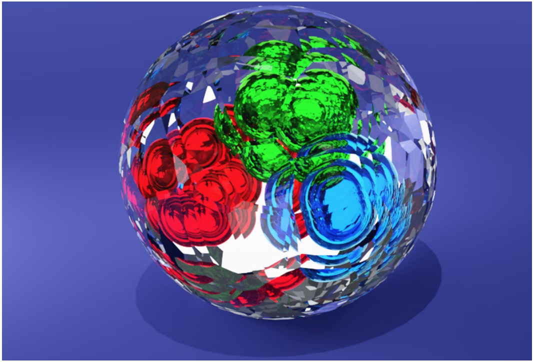






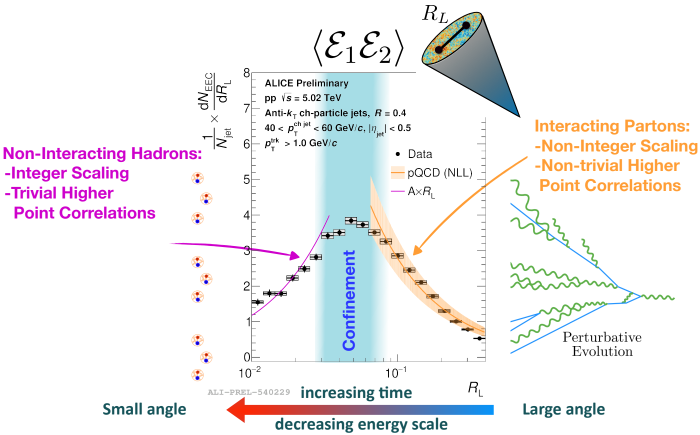


Towards a Non-Perturbative Understanding



Confinement

Figure: Wenqing Fan



Non-Perturbative Structure

- Formulating collider physics in terms of energy correlators allows us to reduce it to the study of the four-point correlator: $\langle \mathcal{O}TT\mathcal{O} \rangle$

- CFTs:
  - Planar $\mathcal{N}=4$ (CFT bootstrap + Integrability)
  - 3d Ising (CFT bootstrap, Fuzzy sphere)
- Gapped Theories:
  - Form factor + S-matrix bootstrap

Yifei He, Martin Kruczenski

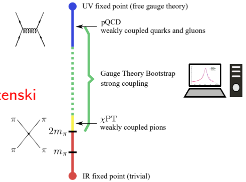
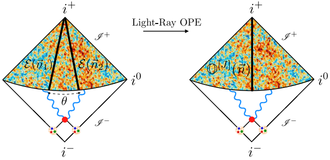


Figure 1: The Gauge Theory Bootstrap builds a (strongly coupled) bridge between the weakly coupled QCD at high energies and a weakly coupled EFT of pions at low energy.

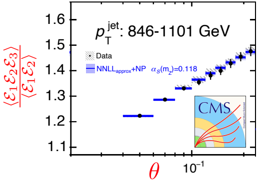
- Provides significant motivation to push towards understanding of analyticity properties of the four point correlator in gapped theories, and its simplification in the lightray limit.

Summary

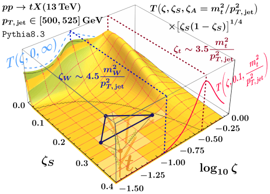
- Recent progress understanding correlation functions of detector operators from explicit perturbative calculations, and the light-ray OPE.



- Multi-point correlators of lightray operators can be directly measured at the LHC: How can we best use them?



- Provides the opportunity to use theoretically beautiful objects to learn about the real world.



Open Questions: "Phenomenologist"

- General structure of N-point energy correlators in perturbation theory? Efficient IBP for finite integrals in Feynman parameter space.
- What is the "light transform of the correlahedron"? [Eden, Heslop, Mason] [He, Huang, Kuo]
- What other matrix elements of lightray operators are well defined? Relation to IR finite S-matrices?
- What are the implications of asymptotic symmetry algebras? [Cordova, Shao] [Korchemsky, Sokatchev, Zhiboedov]
- What is the structure of the lightray OPE in non-conformal theories?
- How to incorporate data from (multiparticle) S-matrix bootstrap? [Guerrieri, Homrich, Vieira]
- What other systems have interesting detector operators and how can we experimentally access them?
- Correlators in thermal states? transport? confining theories? [Csaki, Ismail]
- How to interpolate between weak and strong coupling? Integrability?
- How to relate colllider measurements of detector operators to other Lorentzian singularities (Pomeron,...)? [Caron-Huot, Kologlu, Kravchuk, Meltzer, Simmons Duffin]

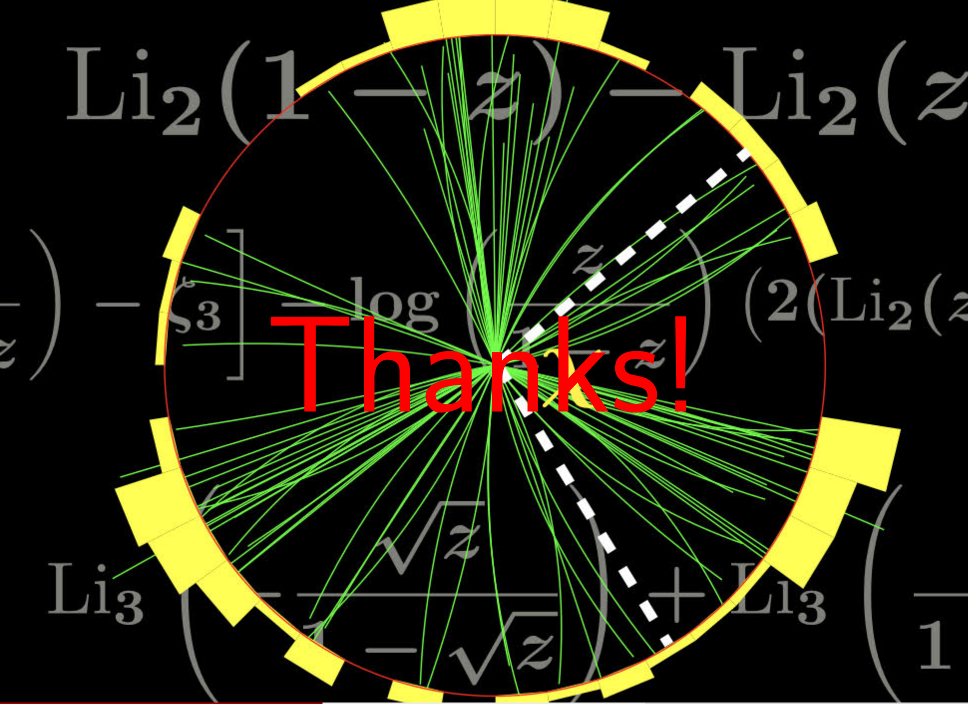
Open Questions: "Formal Field Theorist"

- Open Questions from David Simmons Duffin "Strings 2024" Talk:

Some open questions

- How do you measure a general detector operator at a collider?
- Can we measure detectors in a condensed matter system?
- Can we formulate EFT running and matching for detectors? (Could help organize understanding of confinement effects in $\langle \mathcal{E} \cdots \mathcal{E} \rangle$ [Jaarsma, Li, Moult, Waalewijn, Zhu '23; Csaki, Ismail '24].)
- What does the Chew-Frautschi plot look like at finite λ and finite N?
- Can we find positivity/rigidity conditions for light-ray operators? Can we formulate bootstrap conditions?
- What behavior in the deep Regge limit is possible? Transparency vs. chaos? [Stanford '15; Murugan, Stanford, Witten '17; Caron-Huot, Gobeil, Zahree '20]
- Are other Lorentzian singularities described by other types of operators?
- Does "factorization theorem" $=$ OPE? [Chen '23]
- What is the general form of the light-ray OPE?
- How are light-ray operators and conformal line defects related?
- Do light-ray operators participate in interesting algebras? [Casini, Teste, Torroba '17; Cordova, Shao '18; Korchemsky, Sokatchev, Zhiboedov '21; Korchemsky, Zhiboedov '21; Faulkner, Speranza '24]

- Conformal Colliders have met the Collider Frontier!


Thanks!