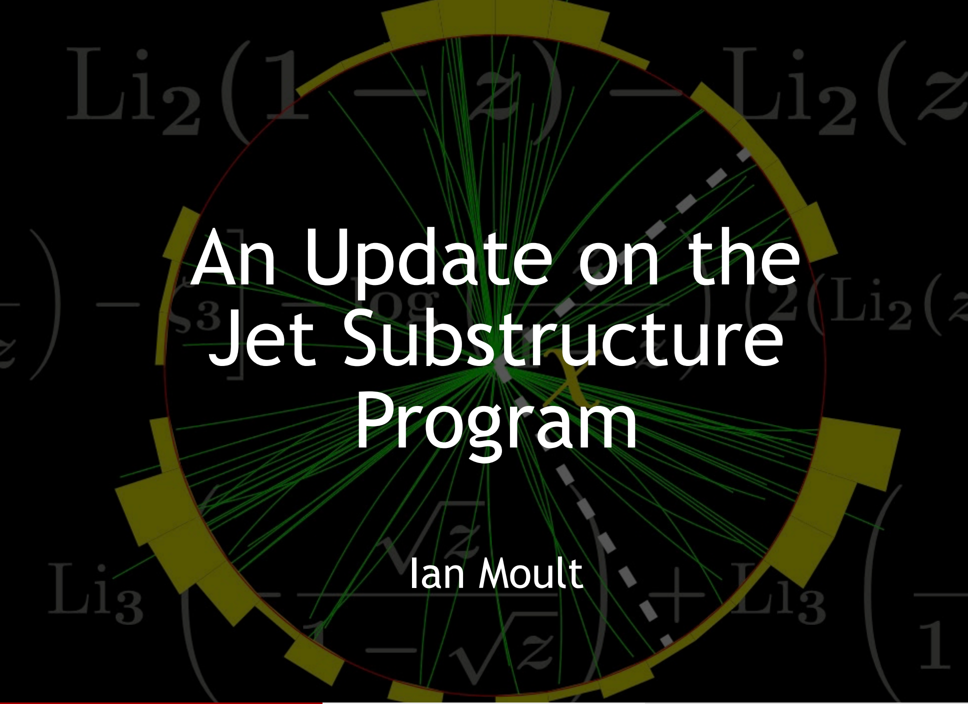
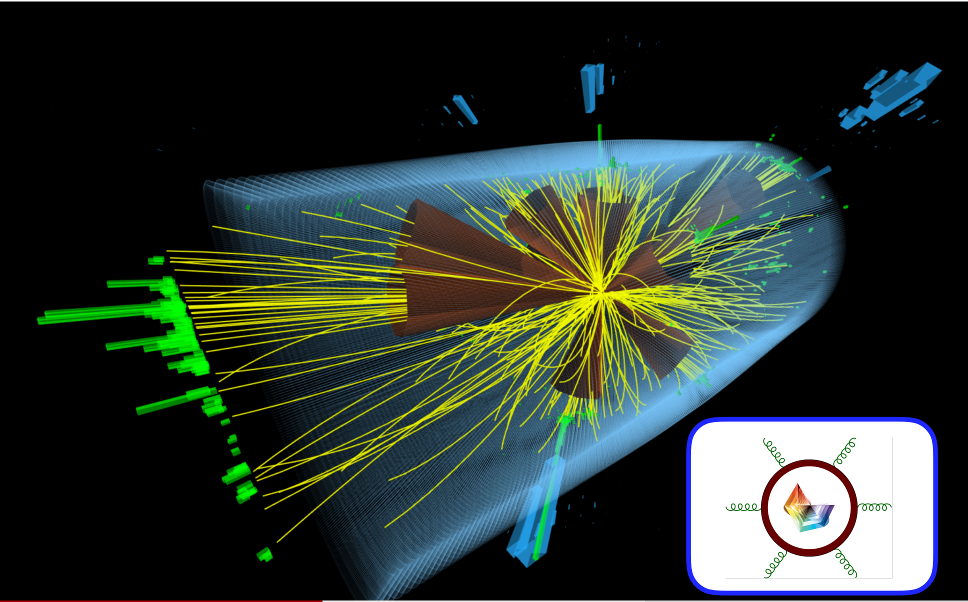


An Update on the Jet Substructure Program

Ian Moult

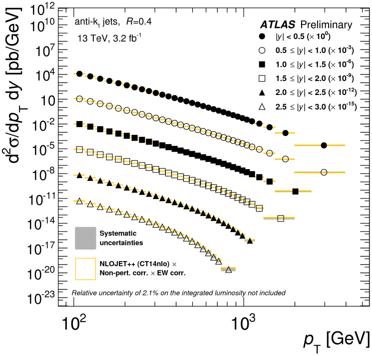
Jets at the LHC

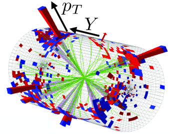


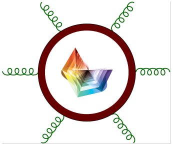
Jets at the LHC

- Obtaining a precise description of jet cross sections has been a significant driver of theory developments in Quantum Field Theory.

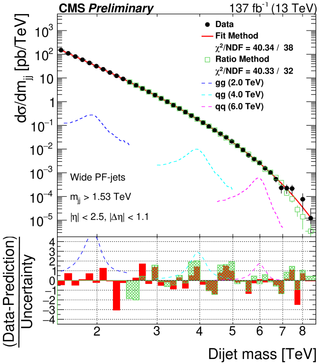
Jet Kinematic Distributions





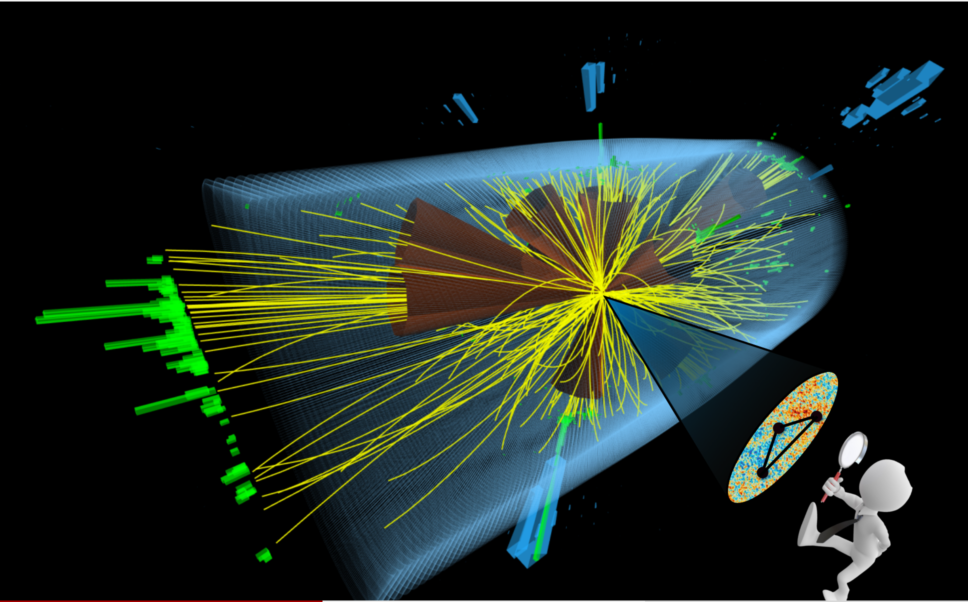


Dijet Mass



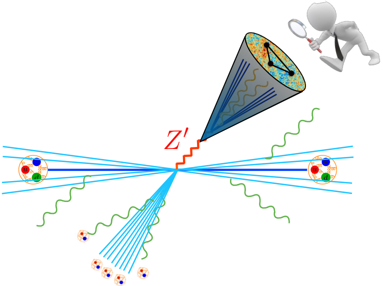
- Enables precision tests of QCD and searches for new physics.

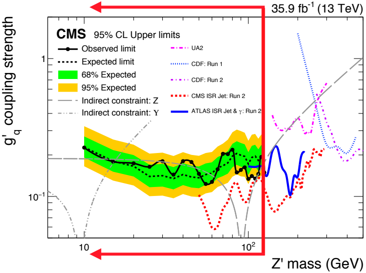
Jet Substructure!



Jet Substructure: Searches

- Jet Substructure uses the internal structure of jets to provide qualitatively new ways to study physics at colliders.

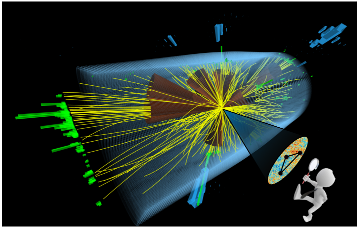


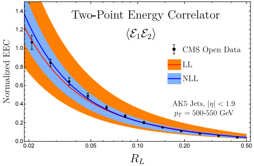


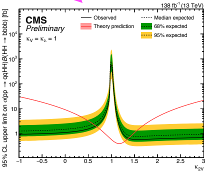
- Its introduction in 2008 by Butterworth, Davison, Rubin and Salam, along with anti-k_T by Cacciari, Soyez, Salam reinvigorated the study of jets in QCD.

The Boundaries of Collider Physics

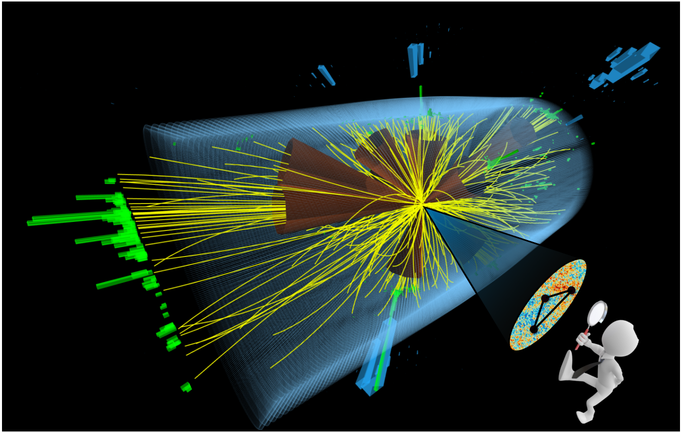
- Progress in formal theory and data science have transformed jet substructure, enabling new tests of QFT, and ever improving ways to search for fundamental physics.





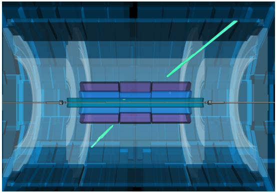


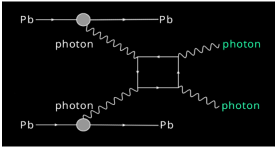
Decoding Energy Flux

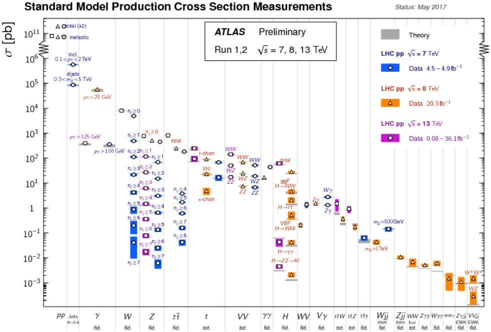


Exclusive Processes: S-Matrix

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



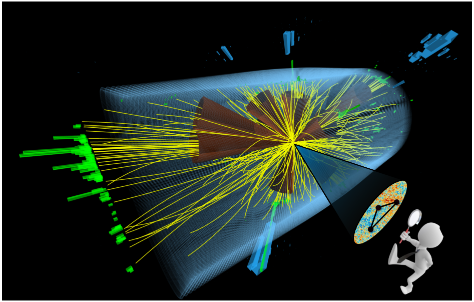


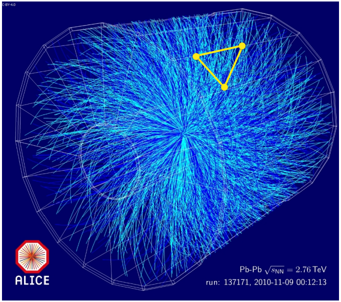


- Practical Outcome: Ability to accurately describe complicated SM scattering processes.

The High Multiplicity Regime

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

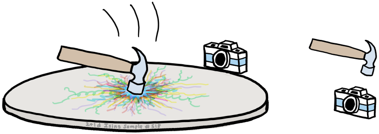




- Good observables are correlations in fluxes at (null) infinity.

Detectorology

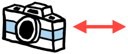
- What is a detector?



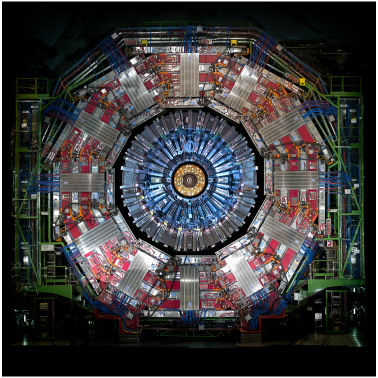
$$= \sum_i h_i \mathcal{O}_i$$

$$= \sum_j c_j \mathcal{D}_j$$

[Caron Huot, Kologlu, Kravchuk, Meltzer, Simmons Duffin]



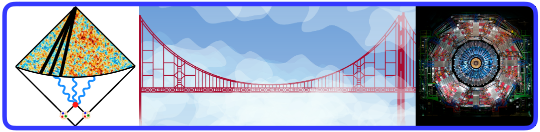
$$\mathcal{E}(\vec{n}) = \lim_{r\to\infty} r^2 \int_0^\infty dt\ n^i T_{0i}(t, r\vec{n})$$



- From the perspective of QFT, jet substructure is the study of correlation functions, $\langle\Psi|\mathcal{E}(\hat{n}_1)\cdots\mathcal{E}(\hat{n}_k)|\Psi\rangle$, of energy flow operators.

Energy Correlators at the Collider Frontier

- Spectacular recent progress bridging theory and experiment!

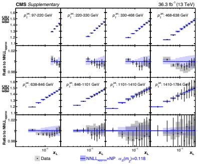


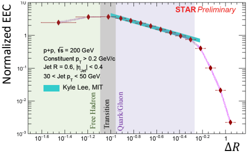
JETS ELUCIDATE HOW PARTONS EVOLVE INTO HADRONS

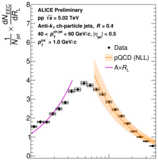
STRONG INTERACTIONS | NEWS

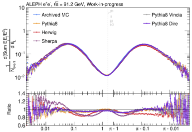
Measuring energy correlators inside jets

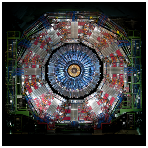
3 November 2023

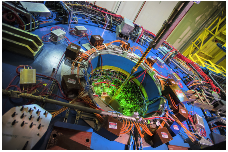


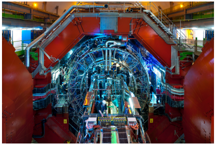


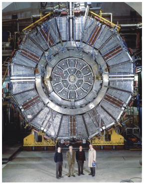




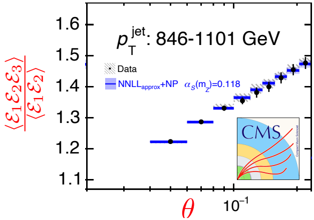


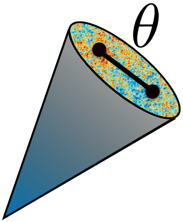


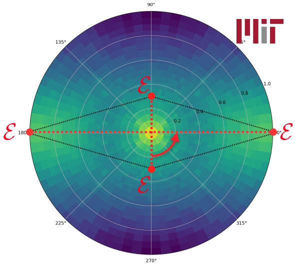


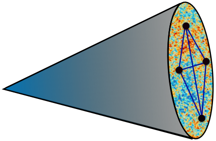


Energy Correlators: Present Status

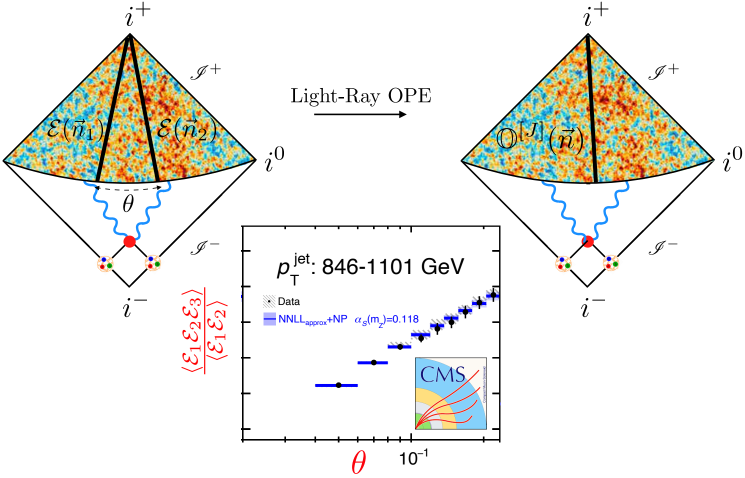








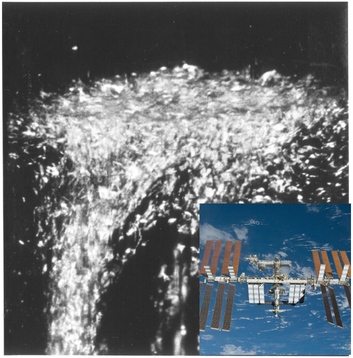
Scaling Behavior

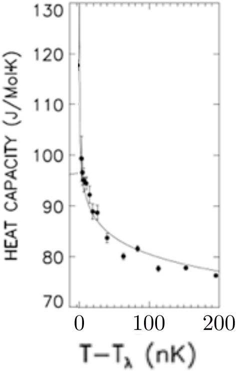


Scaling Behavior in QFT

- Euclidean scaling behavior is well understood.

λ-point of Helium

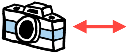




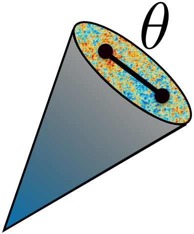
$$\boxed{\mathcal{O}(x)\mathcal{O}(0) = \sum x^{\gamma_i} c_i \mathcal{O}_i}$$

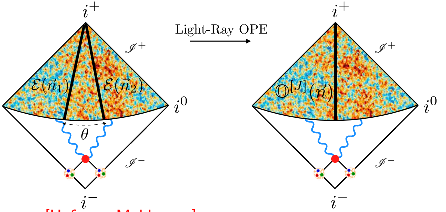
The OPE Limit of Lightray Operators

- 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]

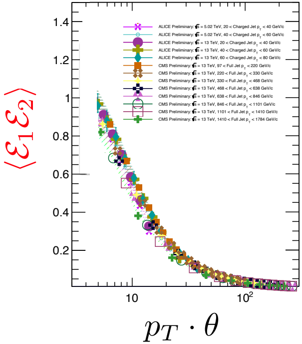
$$\mathcal{E}(\hat{n}_1)\mathcal{E}(\hat{n}_2) \sim \sum \theta^{\tau_i - 4}\mathbb{O}_i(\hat{n}_1)$$

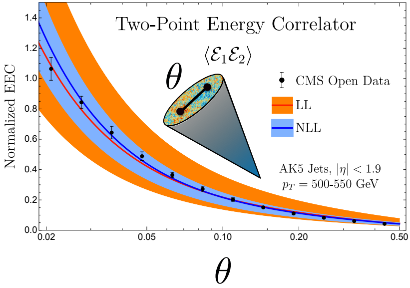
- Scaling can be derived in generic (non-conformal) theories using factorization theorems. [Dixon, Moult, Zhu] See early work by [Konishi, Ukawa, Veneziano]
- Predicts universal scaling behavior in correlations of energy flux at energies $E \gg \Lambda_{\text{QCD}}$.

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!



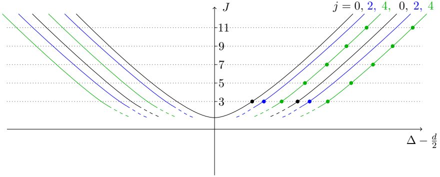


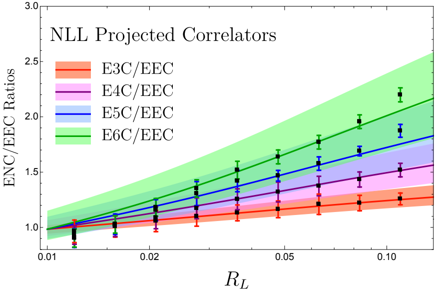
- Can we accurately extract anomalous exponents of different detectors?

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]

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





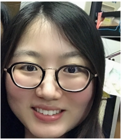
- Directly probes the spectrum of (twist-2) lightray operators from asymptotic energy flux.

Anomalous Scaling

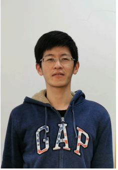
- Universal quantity in complicated hadronic environment.

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

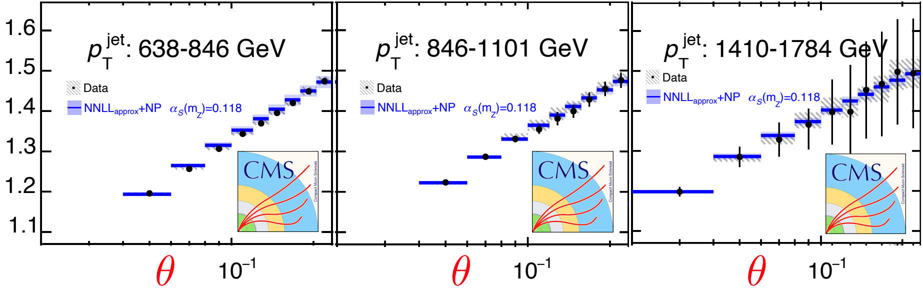
XiaoYuan Zhang



Yibei Li



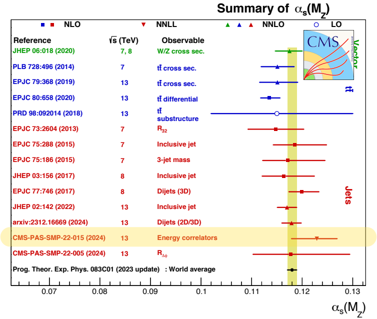
Hao Chen



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

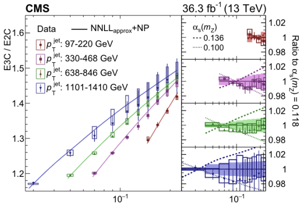
The Strong Coupling

- Scaling enables extraction of the strong coupling constant α_s at 4% accuracy.



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

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



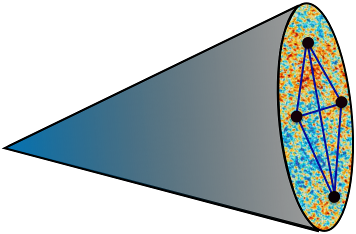
θ

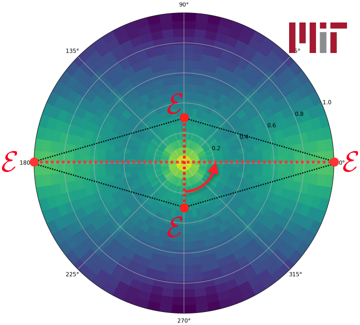
$$\alpha_s(m_Z) = 0.1229^{+0.0040}_{-0.0050}$$

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

- Jet substructure is a precision science!

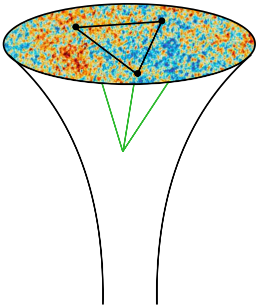
Higher Point Functions in Energy Flux

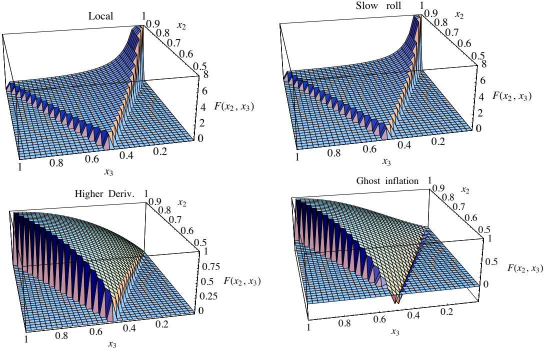




Multipoint Correlators

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





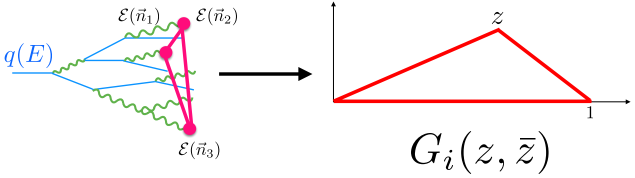
- What is the structure of higher-point functions of energy flux?

Multipoint Correlators

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

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

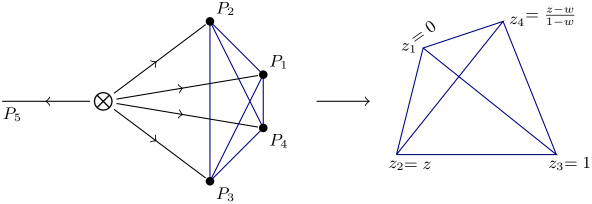
- The wealth of techniques developed to compute perturbative scattering amplitudes can be applied to multi-point correlators at weak coupling.



Multi-point Correlators at Weak Coupling

- Energy correlators define an interesting class of *finite* integrals.
- Provide a playground for the exploration of the perturbative structure of *physical observables*.

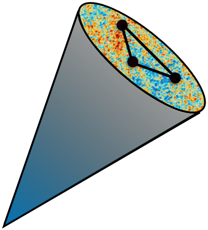
[Chicherin, Moult, Sokatchev, Yan, Zhu]



- Allow modern integration techniques to be used for directly measureable *physical observables*.

Multi-point Correlators at Weak Coupling

- Turn out to have an elegant perturbative structure. e.g. in $\mathcal{N}=4$



[Chen, Luo, Moult, Yang, Zhang, Zhu]

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

- Here Φ and D_2^+ are polylogarithmic functions

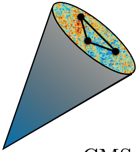
$$\Phi(z) = \frac{2}{z-\bar{z}}\left(\mathrm{Li}_2(z) - \mathrm{Li}_2(\bar{z}) + \frac{1}{2}\left(\log(1-z) - \log(1-\bar{z})\right)\log(z\bar{z})\right)$$

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

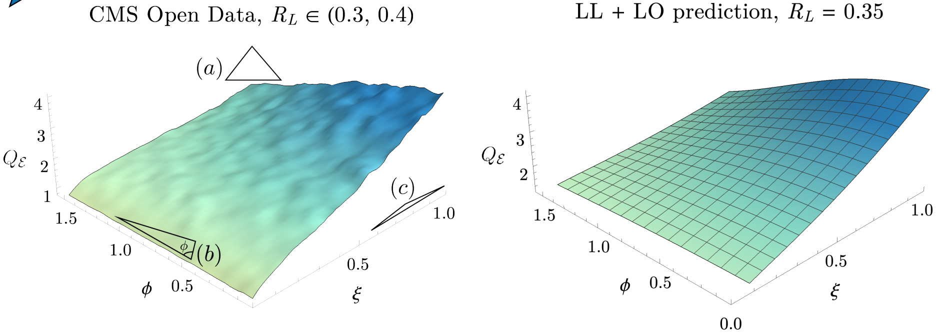
- Real world QCD involves more complicated polynomials, but is otherwise similar.

Shape Dependence of Non-Gaussianities

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



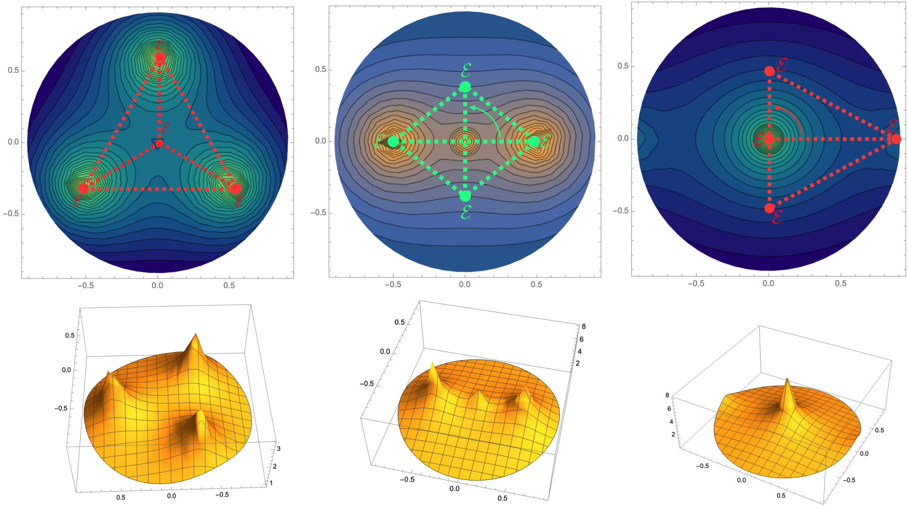
- Non-Gaussianities inside high energy jets at the LHC:


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

LL + LO prediction, $R_L = 0.35$

The Four Point Correlator

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

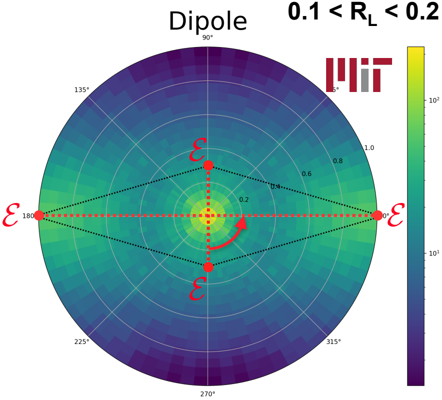


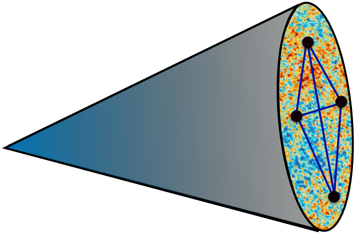
The Four Point Correlator

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

$p_T > 100$ GeV

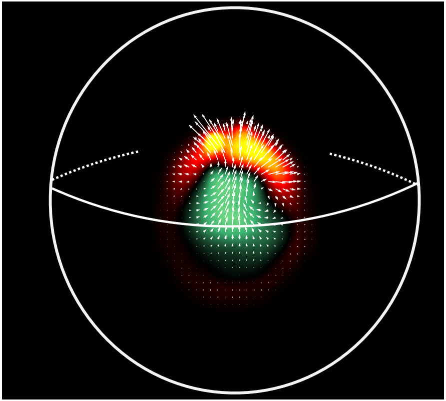
$0.1 < R_L < 0.2$





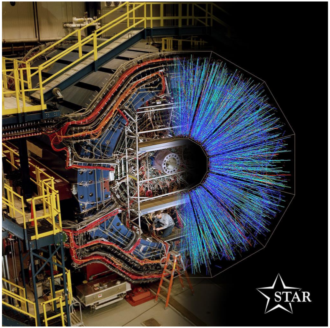
Thanks to Simon Rothman and Phil Harris!

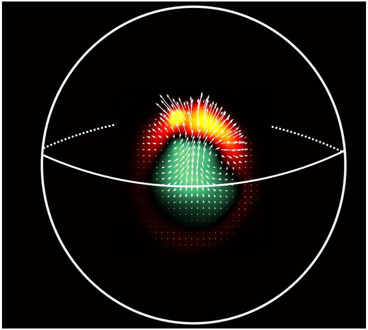
Resolving the Scales of the QGP



Quark Gluon Plasma

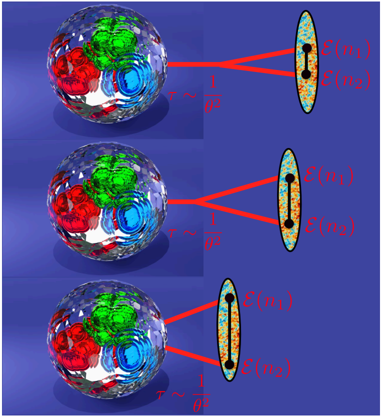
- Heavy ion collisions provide an example of an extremely complicated asymptotic state, where we do not understand the microscopic dynamics that created it.



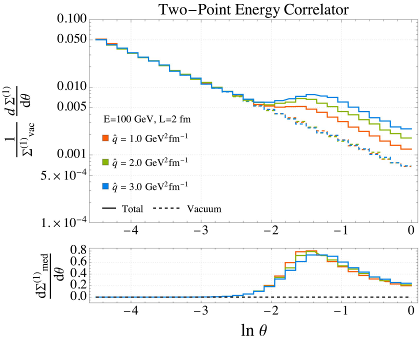


Imaging the Quark Gluon Plasma

- QGP scales cleanly imprinted in two-point correlation.



Increasing θ

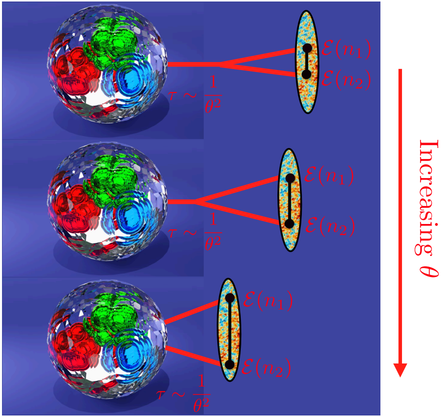


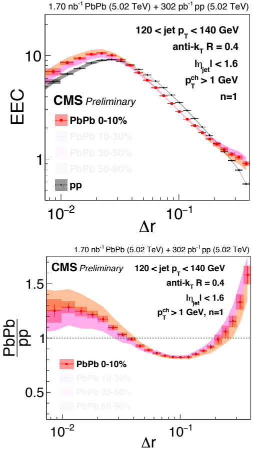
Increasing θ

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

New Measurements: Correlators in the QGP!

- QGP scales cleanly imprinted in two-point correlation.



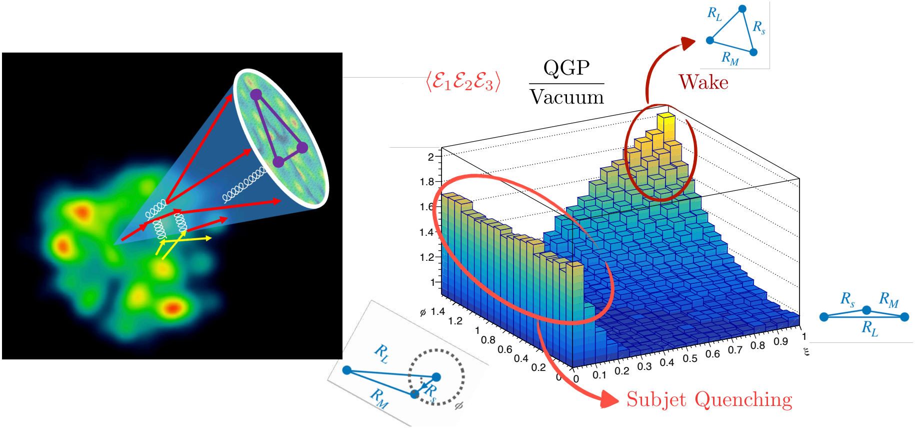


[CMS-PAS-HIN-23-004]

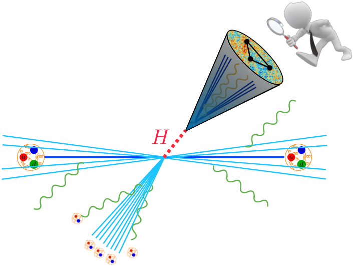
[Andres, Dominguez, Holguin, Kunnawalkam Elayavalli, Marquet, Moult]

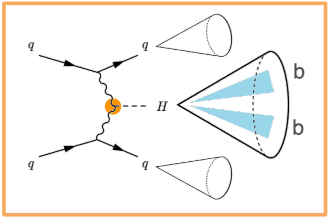
Imaging the Wake

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



Jet Substructure Searches



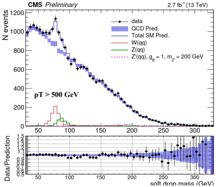


Light Z' Searches

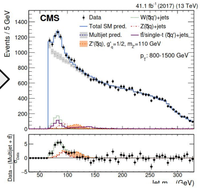
- Tremendous improvement in last 5 years. e.g. Light Z' searches

Evolution of boosted dijet tagging

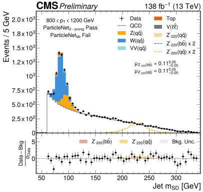
2017

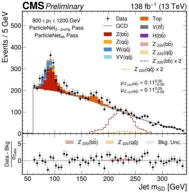


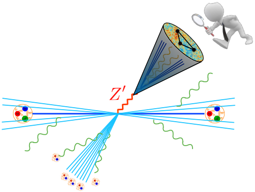
2020



2024





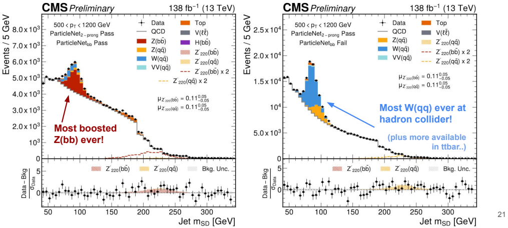


[Figures from Simon Rothman]

Light Z' Searches

- Tremendous improvement in last 5 years. e.g. Light Z' searches

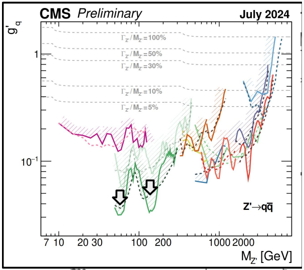
Boosted hadronic resonances: results



Most boosted Z(bb) ever!

Most W(qq) ever at hadron collider!

(plus more available in ttbar..)



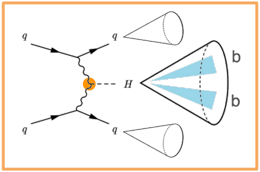
World-leading limits on BSM

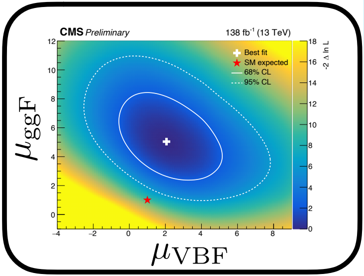
- **Interpret in terms of vectors, scalars, pseudoscalars**
- **Limits on g_q scale like lumi^{-4}**
- **New techniques are driving improvements!**

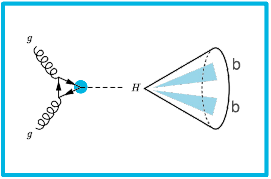
[Figures from Simon Rothman]

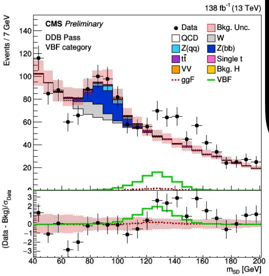
Boosted Higgs

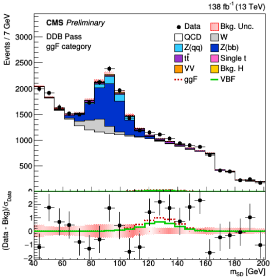
- Searches for modifications of Higgs couplings at high p_T.







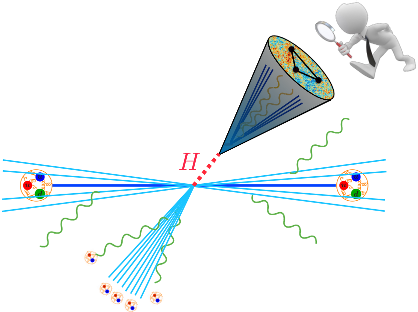


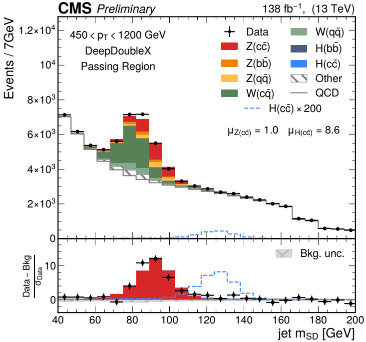


[Figures from Jennet Dickinson]

Charm Yukawa

- Measurements of the Higgs couplings to light quarks provide a crucial test of the Yukawa sector of the SM.
- Jet substructure provides the most stringent bound on the charm Yukawa, $1.1 < \kappa_c < 5.5$.

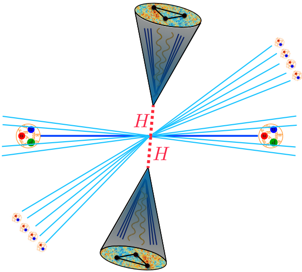


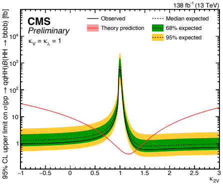


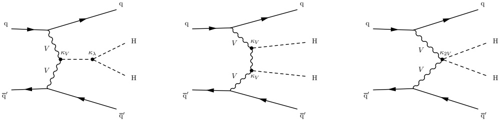
- Matches the original projected sensitivity with 3000 fb^{-1}!

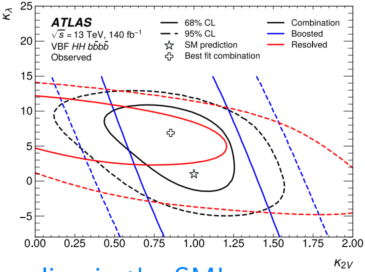
Higgs Self Interaction

- The Higgs self interaction accesses the Higgs potential.
- Jet Substructure exploits the high branching ratio to b-quarks.





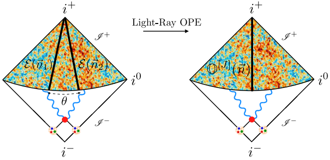




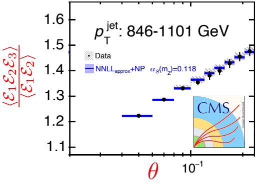
- First observation of the $VV \to HH$ coupling in the SM!

Summary

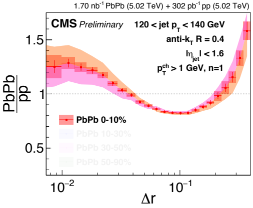
- Significant recent progress in the theoretical characterization of asymptotic energy flux.

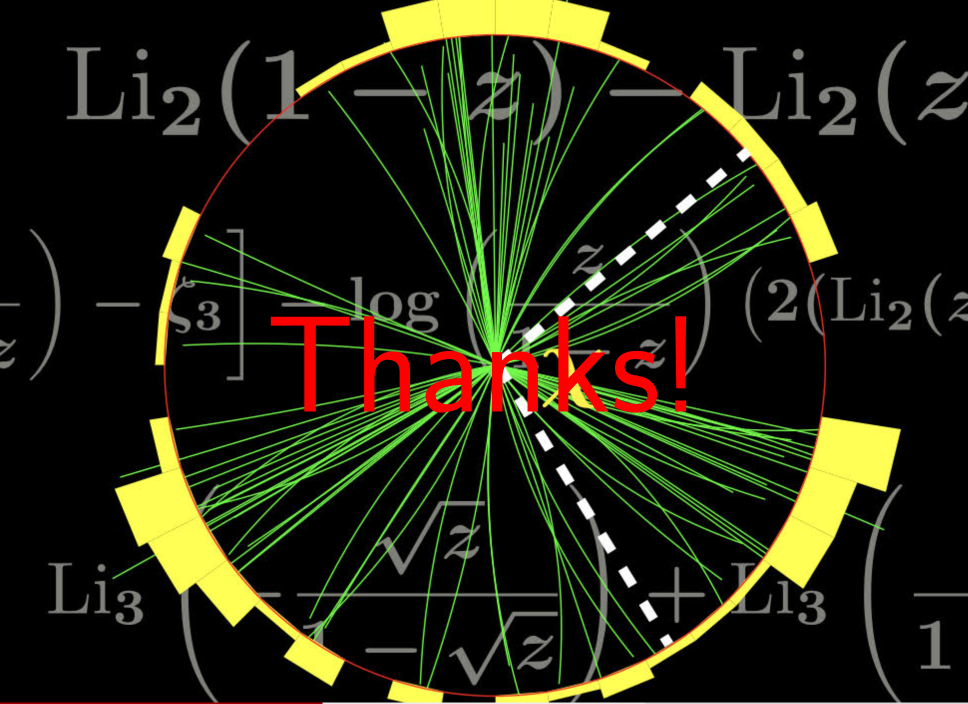


- Scaling and shape dependence of multi-point energy correlators can be directly measured at the LHC: How can we best use them?



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





Thanks!