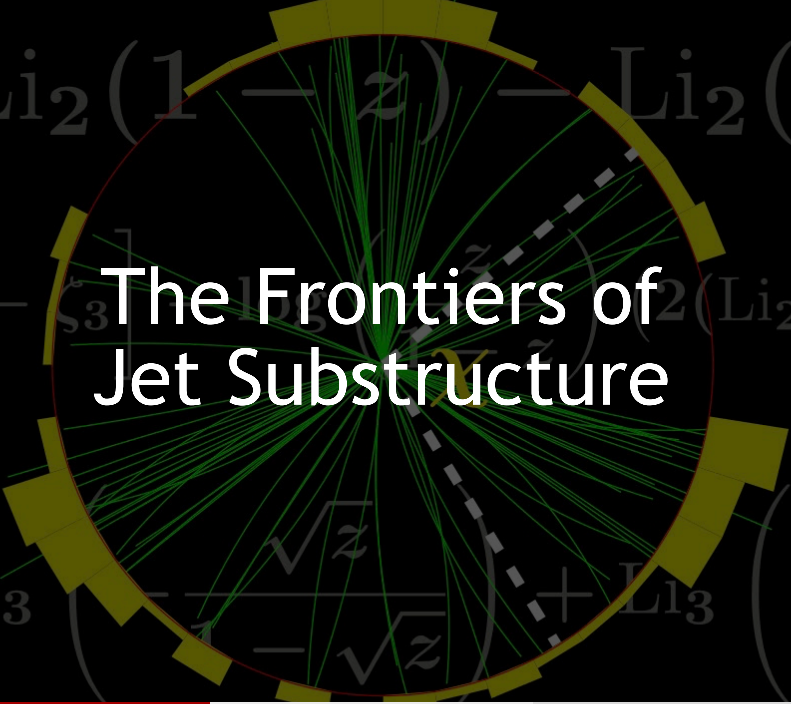
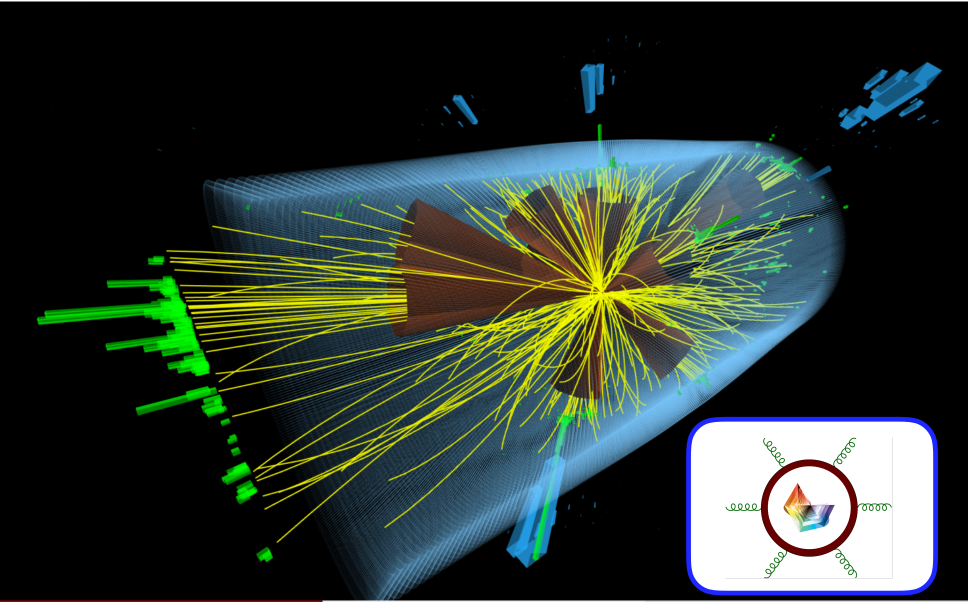


The Frontiers of Jet Substructure

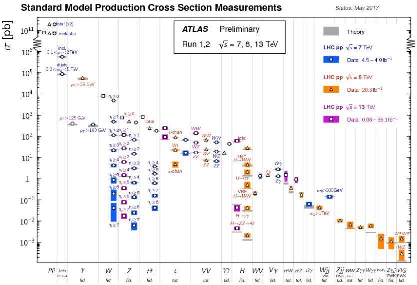
Jets!

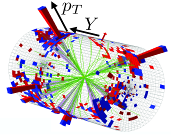


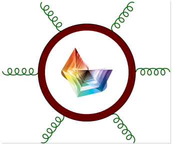
Jets at the LHC

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

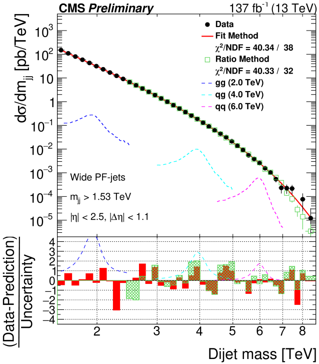
Jet Kinematic Distributions





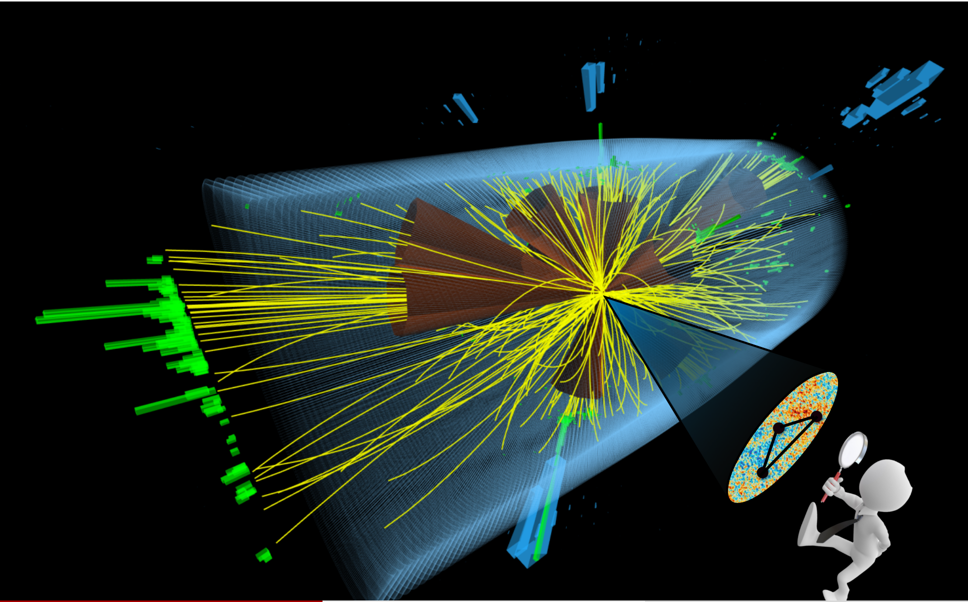


Dijet Mass



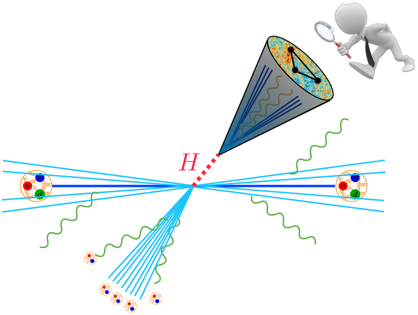
- Enables precision tests of QCD and searches for new physics.

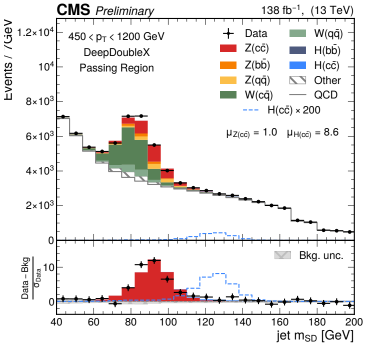
Jet Substructure!



Jet Substructure: Searches

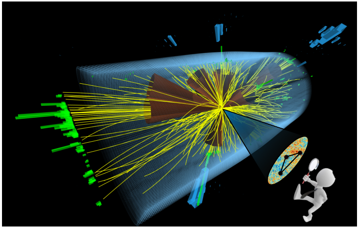
- Jet Substructure uses the internal structure of jets to provide qualitatively new ways to study physics at the LHC.

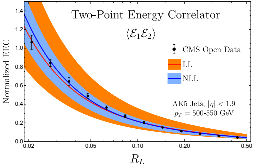


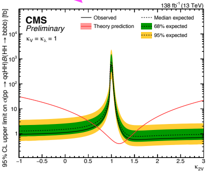


- Its introduction in 2008 by Butterworth, Davison, Rubin and Salam, along with anti-k_T by Cacciari, Soyez, Salam reinvigorated the study of jets in QCD.

- 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.

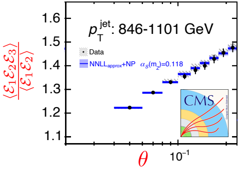




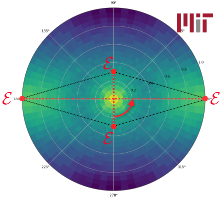


Outline

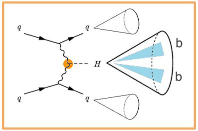
- Energy Correlators for Jet Substructure



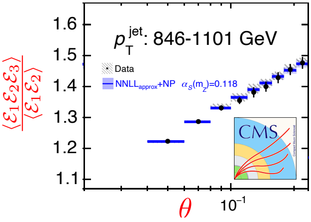
- Energy Correlators at the Collider Frontier

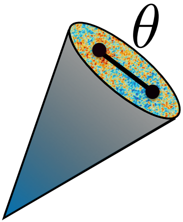


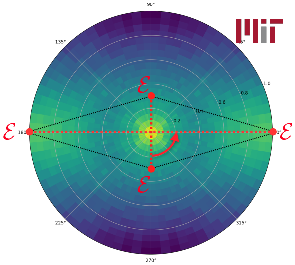
- Jet Substructure Searches

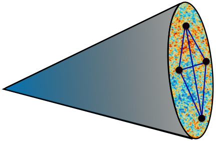


Energy Correlators for Jet Substructure



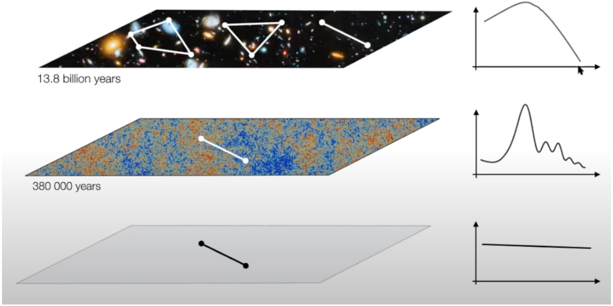


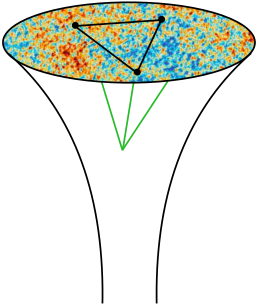




Correlation Functions

- In condensed matter physics or cosmology we decode the underlying dynamics using correlation functions.

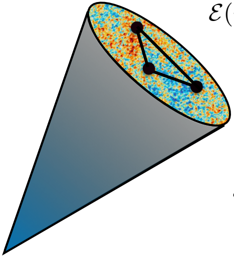




- Can we achieve a similarly coherent picture of collider physics?

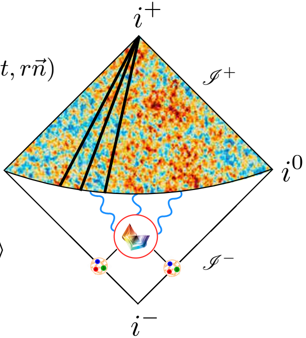
Calorimeter Cells in Field Theory

- Calorimeter cells can be given a field theoretic definition in terms of light-ray operators. [Hofman, Maldacena], [Belitsky, Hohenegger, Korchemsky, Sokatchev, Zhiboedov] [Korchemsky, Sterman] [Ore, Sterman] [Basham, Brown, Ellis, Love]



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

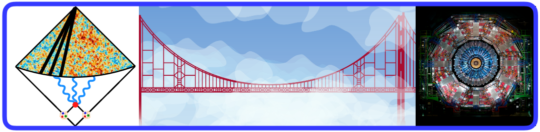
$$\langle \Psi | \mathcal{E}(\hat{n}_1) \cdots \mathcal{E}(\hat{n}_k) | \Psi \rangle$$



- From the perspective of QFT, jet substructure is the study of correlation functions of energy flow operators.

Energy Correlators in Data

- Spectacular recent progress bridging theory and experiment!

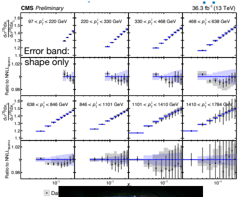


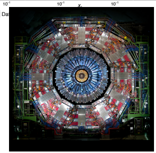
CERN COURIER

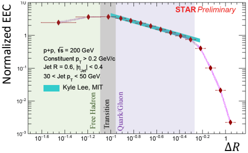
STRONG INTERACTIONS | NEWS

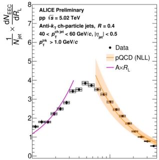
Measuring energy correlators inside jets

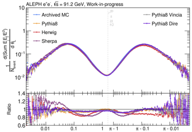
3 November 2023

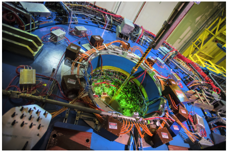


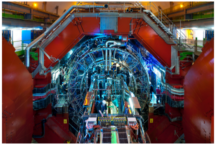


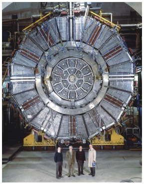




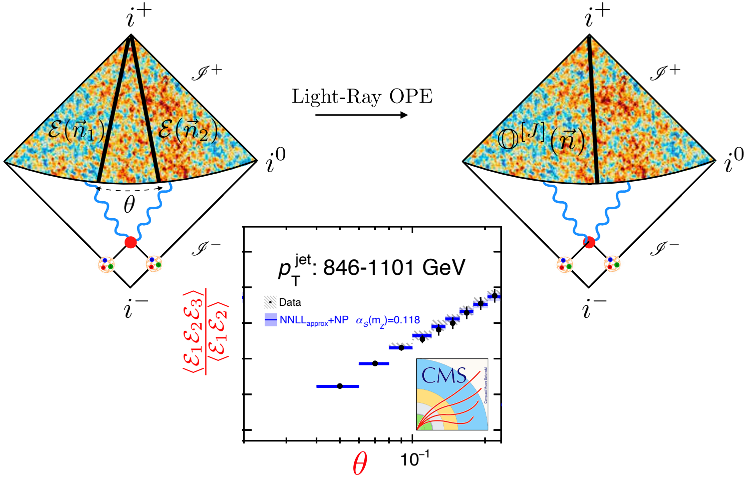








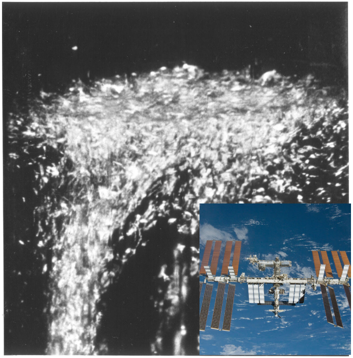
Scaling Behavior

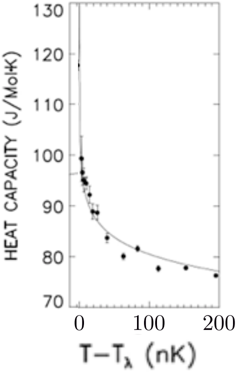


Scaling Behavior in QFT

- Scaling behavior in Euclidean regime well understood.

λ-point of Helium

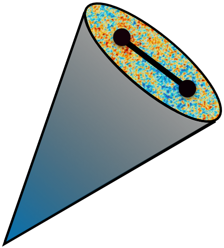


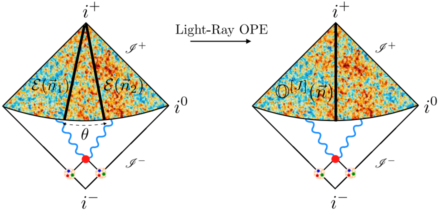


$$\mathcal{O}(x)\mathcal{O}(0) = \sum x^{\gamma_i} c_i \mathcal{O}_i$$

The OPE Limit of Lightray Operators

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





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

[Hofman, Maldacena]
[Chang, Kologlu, Kravchuk, Simmons Duffin, Zhiboedov]
QCD: [Dixon, Moult, Zhu]

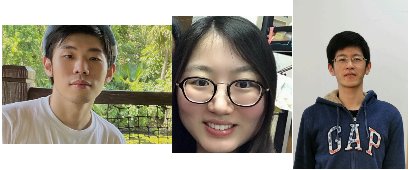
- Predicts universal scaling behavior in correlations of energy flux at energies $E \gg \Lambda_{\text{QCD}}$.

See early work by [Konishi, Ukawa, Veneziano]

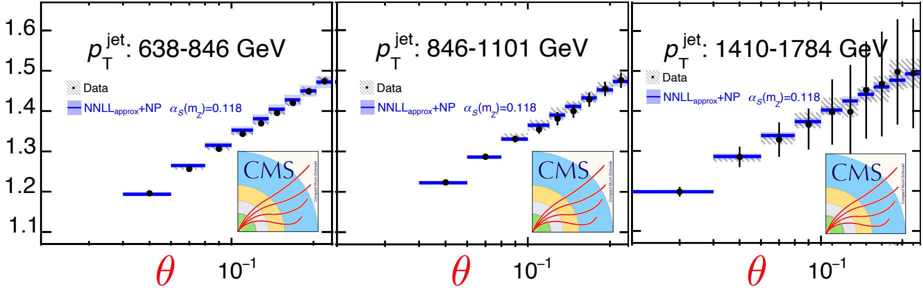
Anomalous Scaling

- Universal quantity in complicated hadronic environment.

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



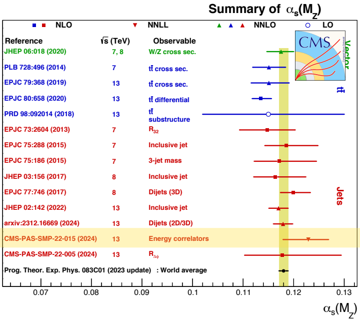
XiaoYuan Zhang Yibei Li Hao Chen



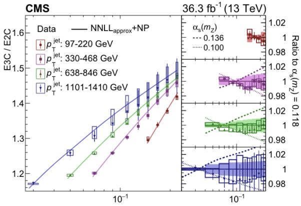
- Uses scaling anomalous dimensions at three-loop order.
- Beautiful quantitative test of QFT!

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

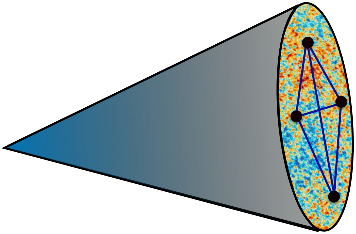
$$\alpha_s(m_Z) = 0.1229^{+0.0040}_{-0.0050}$$

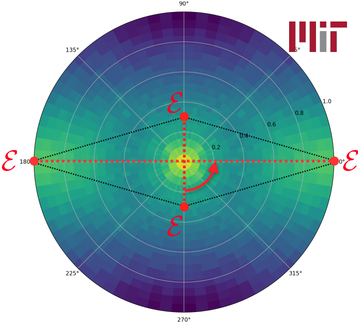
$$= 0.1229^{+0.0014(stat.)+0.0030(theo.)+0.0023(exp.)}_{-0.0012(stat.)-0.0033(theo.)-0.0036(exp.)}$$

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

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

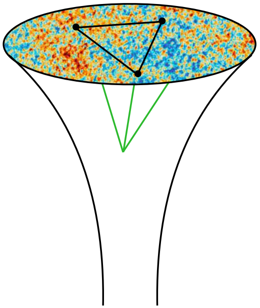
Higher Point Functions in Energy Flux

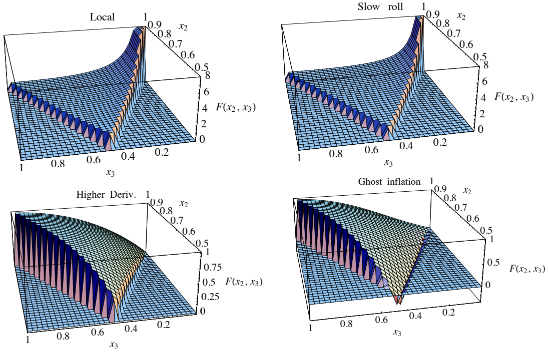




Multipoint Correlators

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





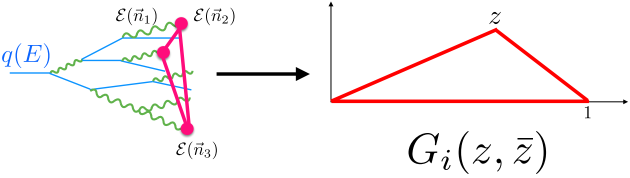
- What is the structure of higher-point functions of energy flux?

Multipoint Correlators

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

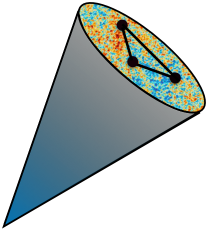
$$\langle \mathcal{E}(\vec{n}_1)\cdots\mathcal{E}(\vec{n}_n)\rangle = \left(\frac{q}{4\pi}\right)^n \left[1 + \sum_{i<j} \frac{6\pi^2}{\lambda}[(\vec{n}_i.\vec{n}_j)^2 - \frac{1}{3}] + \right.$$
$$\left. + \frac{\beta}{\lambda^{3/2}}[\sum_{i<j<k} (\vec{n}_i.\vec{n}_j)(\vec{n}_j.\vec{n}_k)(\vec{n}_i.\vec{n}_k)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

- 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

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



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

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

- Here Φ and D_2^+ are polylogarithmic functions

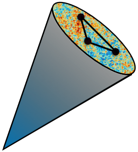
$$\Phi(z) = \frac{2}{z-\bar{z}}\left(\mathrm{Li}_2(z) - \mathrm{Li}_2(\bar{z}) + \frac{1}{2}\left(\log(1-z) - \log(1-\bar{z})\right)\log(z\bar{z})\right)$$
$$D_2^+(z) = \mathrm{Li}_2(1-|z|^2) + \frac{1}{2}\log(|1-z|^2)\log(|z|^2)$$

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

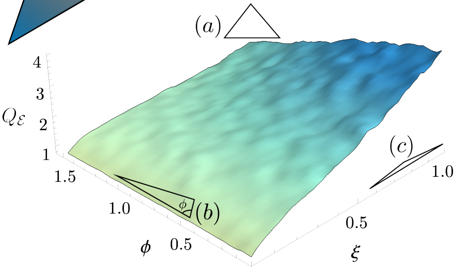
Shape Dependence of Non-Gaussianities

- Can directly study the three-point correlator of lightray operators inside high energy jets.

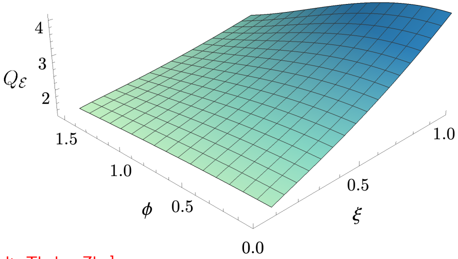
$$G_{\mathcal{N}=4}(z) = \frac{1+u+v}{2uv}(1+\zeta_2) - \frac{1+v}{2uv}\log(u) - \frac{1+u}{2uv}\log(v) - (1+u+v)(\partial_u+\partial_v)\Phi(z) + \frac{(1+u^2+v^2)}{2uv}\Phi(z) + \frac{(z-\bar{z})^2(u+v+u^2+v^2+u^2v+uv^2)}{4u^2v^2}\Phi(z) + \frac{(u-1)(u+1)}{2uv^2}D_2^+(z) + \frac{(v-1)(v+1)}{2u^2v}D_2^+(1-z)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



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



LL + LO prediction, $R_L = 0.35$

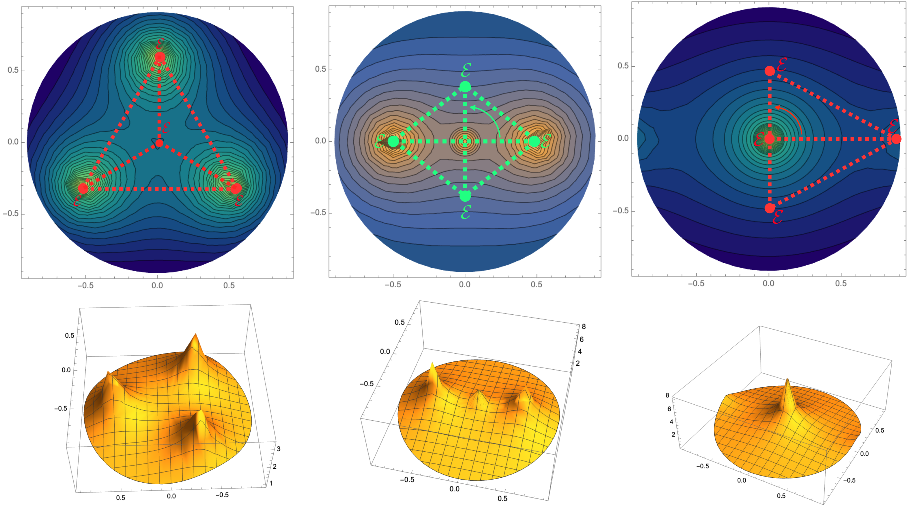


[Chen, Moult, Thaler, Zhu]

- Illustrates theoretical control over multi-point correlations!

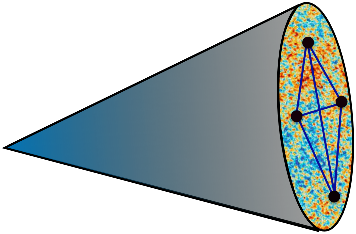
The Four Point Correlator

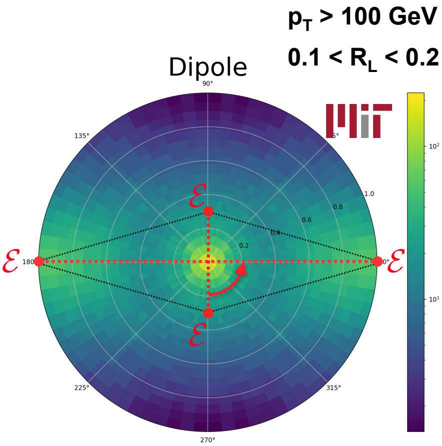
- Intricate view of correlations of energy flow. Access to OPE limits, spinning operators, ...



The Four Point Correlator

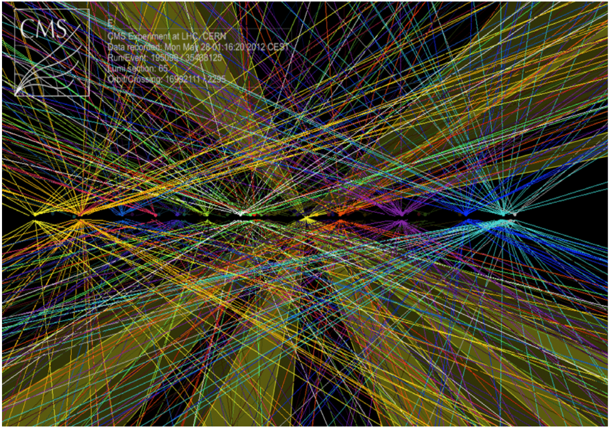
Can now (soon) measure higher point correlators inside high energy jets.





Thanks to Simon Rothman and Phil Harris for plots!

Putting Jet Substructure on Track(s)



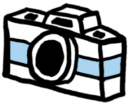
Practical Spinoffs

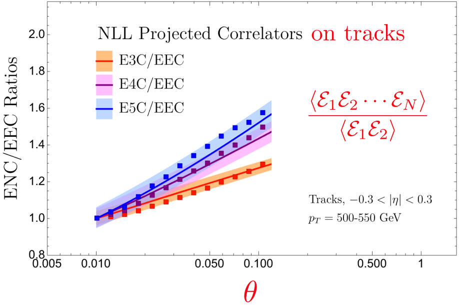
- Incorporating tracking in higher order pertubative calculations is absolutely crucial to advance sophistication of jet substructure!

> observables. For all of these observables, the uncertainties for the track-based observables are significantly smaller than those for the calorimeter-based observables, particularly for higher values of β, where more soft radiation is included within the jet. However, since no track-based calculations exist at the present time, calorimeter-based measurements are still useful for precision QCD studies.

[ATLAS Collaboration, 1912.09837]

- Thinking in terms of "detector operators" has enabled precise higher order calculations for track based observables.



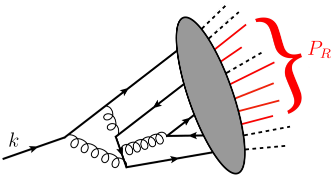


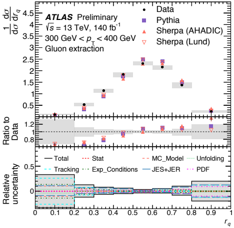
[Lee, Li, Moult, Waalewijn, Zhu]

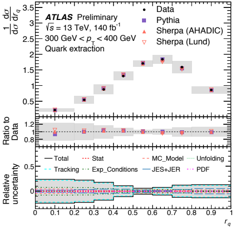
Track Functions

- Track functions are a non-perturbative function describing the total energy fraction going into hadrons with a particular property, R, (e.g. charge) from a fragmenting quark or gluon state:

$$T_q(x) = \int dy^+ d^2 y_\perp e^{ik^- y^+/2} \frac{1}{2N_c} \sum_X \delta\left(x - \frac{P_R}{k_-}\right) \text{tr}\left[\frac{\gamma^-}{2} \langle 0|\psi(y^+, 0, y_\perp)|R\bar{R}\rangle \langle R\bar{R}|\bar{\psi}(0)|0\rangle\right]$$







- Measured by the ATLAS collaboration.

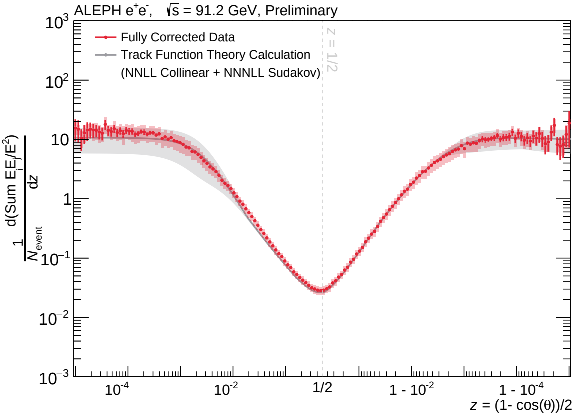
Current Developments: ALEPH Re-Analysis

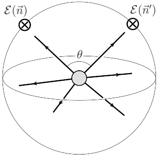
- MIT Group has measured the two-point energy correlator $\langle \mathcal{E}(n_1)\mathcal{E}(n_2) \rangle$ on archival ALEPH data with spectacular resolution.

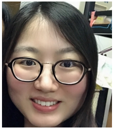
Hannah Bossi

Janice Chen

Yi Chen







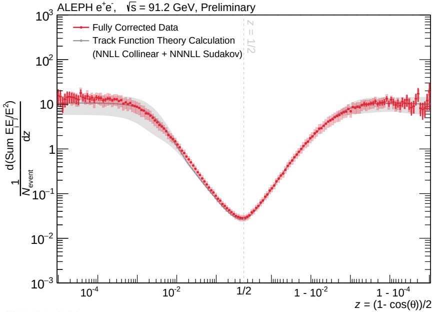
Yibei Li

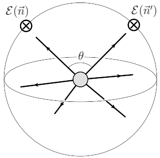
Max Jaarsma

- Exciting laboratory for precision QCD.

Current Developments: ALEPH Re-Analysis

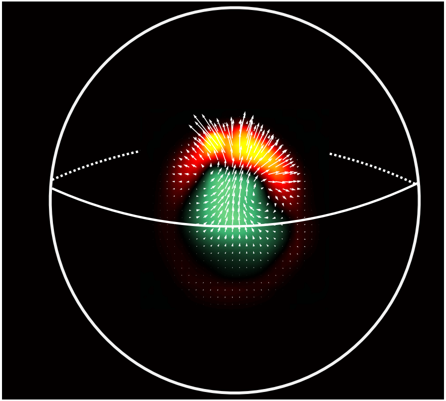
- Energy correlators have a different perturbative structure compared to most event shapes (thrust, C-parameter)
- Leading non-perturbative correction is fixed by symmetry: $\Lambda/(z(1-z))^{3/2}$





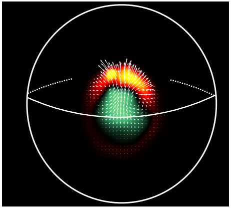
- Optimistic that they can resolve "tensions" in current α_s extractions from event shapes.

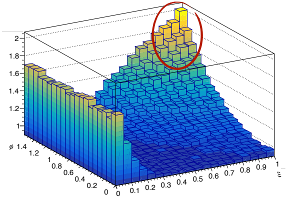
Energy Correlators:
The Future of the Collider Frontier



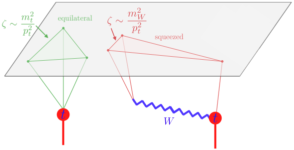
LHC Targets:

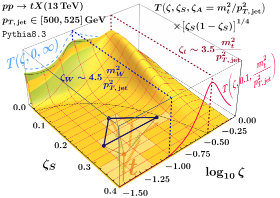
- Measurements on more complicated states:
  - Imaging the Quark Gluon Plasma



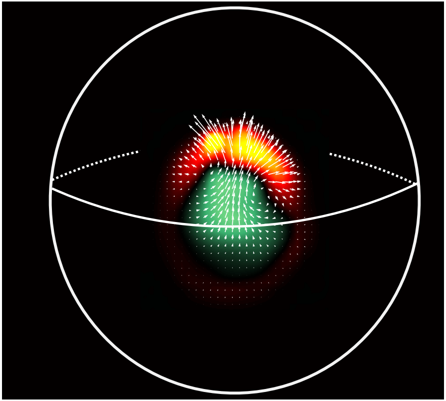


  - Weighing the Top Quark





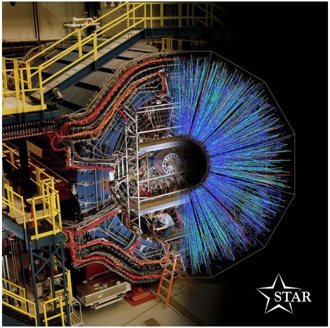
Resolving the Scales of the QGP

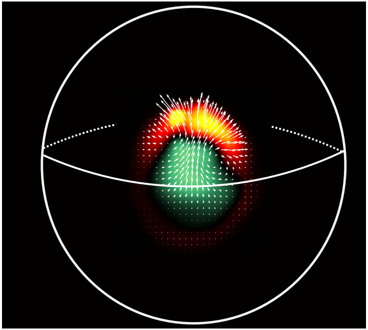


[Andres, Dominguez, Holguin, Kunnawalkam Elayavalli, Marquet, Moult]

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.

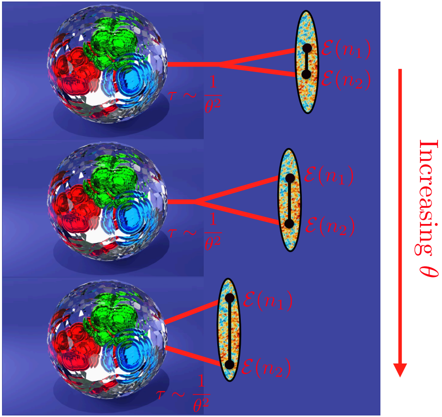


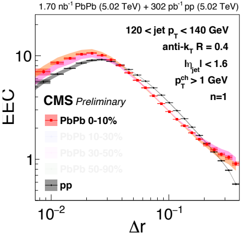


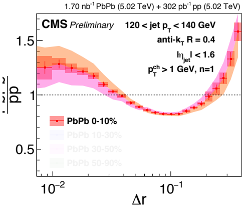
- Nice interplay between pp and heavy ion jet substructure communities.

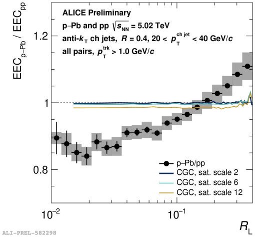
New Measurements: Correlators in the QGP!

- QGP scales cleanly imprinted in two-point correlation.







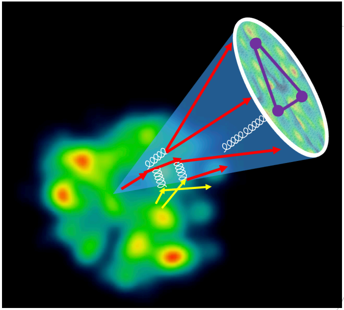


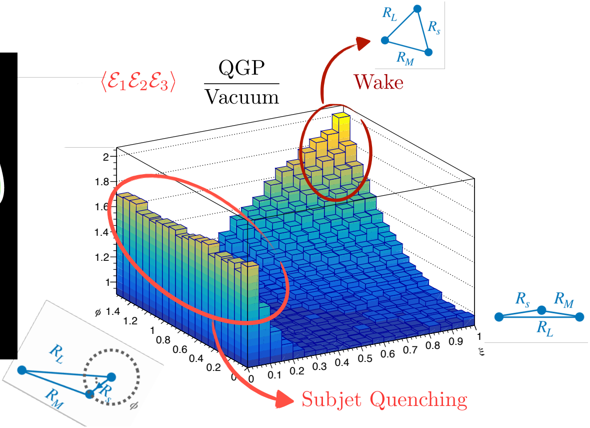
[CMS-PAS-HIN-23-004]

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

Imaging the Wake

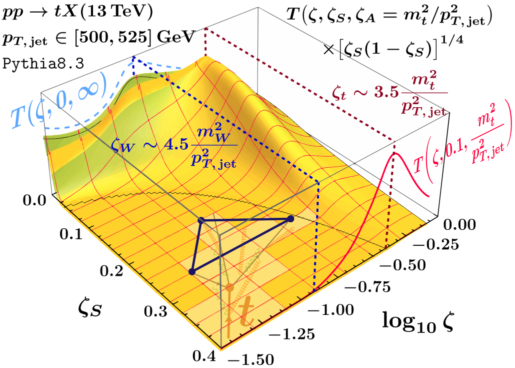
- Higher point correlators allow the "shape" of the medium response to be imaged.





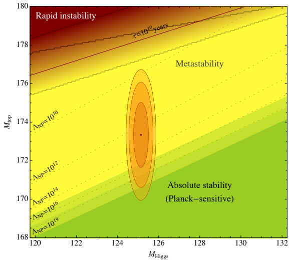
[Bossi, He, Kudinoor, Moult, Pablos, Rai, Rajagopal]

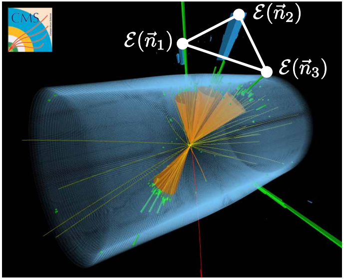
Weighing the Top Quark

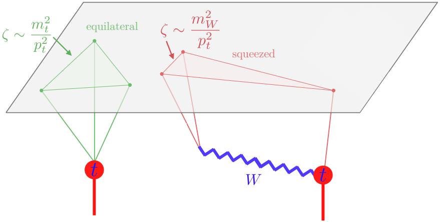


Weighing the Top Quark

- 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.

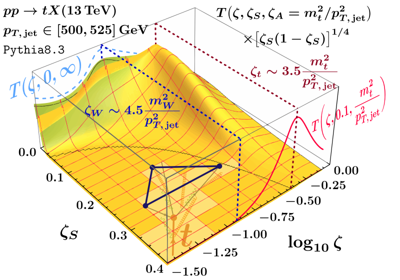


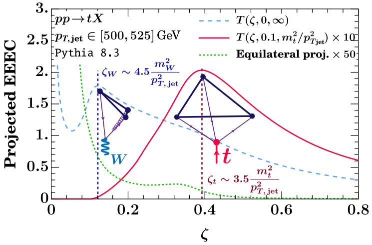


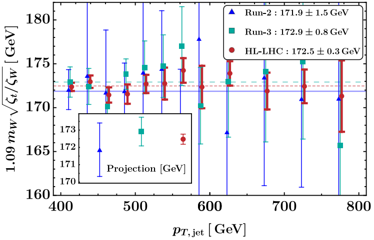


Weighing the Top Quark

- 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.

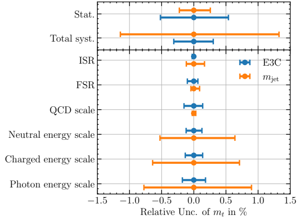
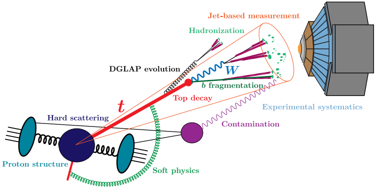
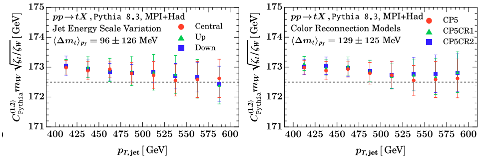


Figure 2. The expected uncertainties of m_t (in % of $m_t = 171$ GeV) using E3C and m_{jet} distributions, at $\mathcal{L} = 36\,\mathrm{fb}^{-1}$. The statistical uncertainties and a breakdown of the systematic uncertainties are shown.

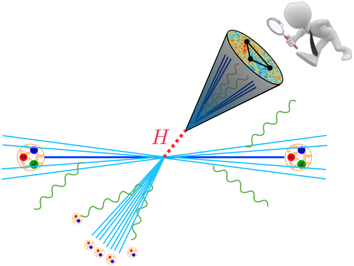


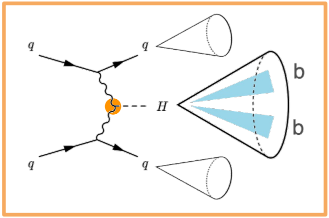


[Xiao, Ye, Zhu]

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

Jet Substructure Searches



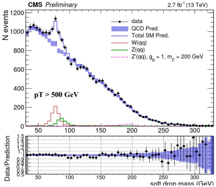


Light Z' Searches

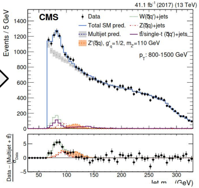
- Tremendous improvement in last 5 years. e.g. Light Z' searches

Evolution of boosted dijet tagging

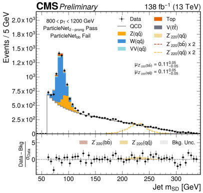
2017

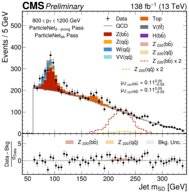


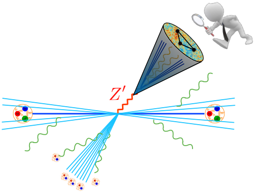
2020



2024



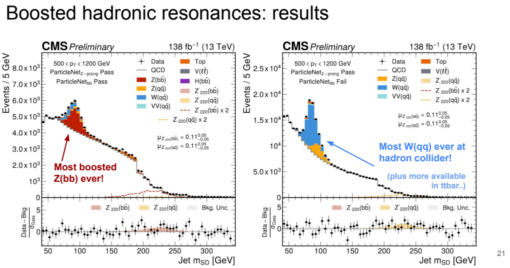


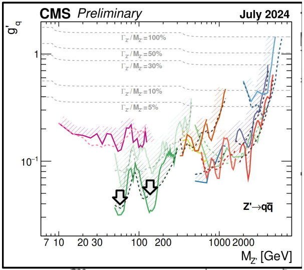


[Figures from Simon Rothman]

Light Z' Searches

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





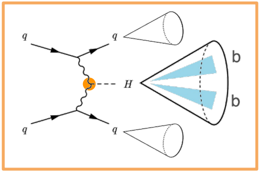
World-leading limits on BSM

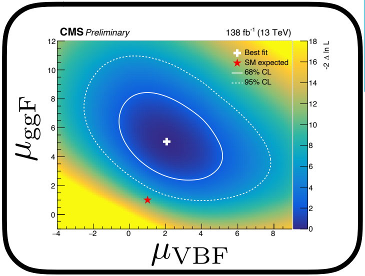
- **Interpret in terms of vectors, scalars, pseudoscalars**
- **Limits on g_q scale like lumi^{-4}**
- **New techniques are driving improvements!**

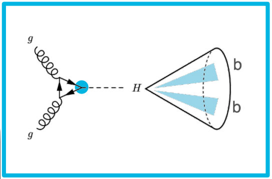
[Figures from Simon Rothman]

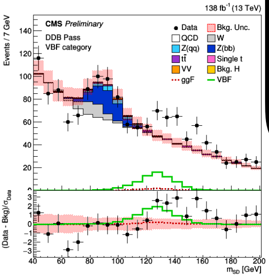
Boosted Higgs

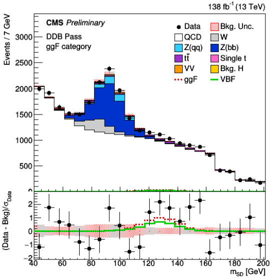
- Searches for modifications of Higgs couplings at high p_T.







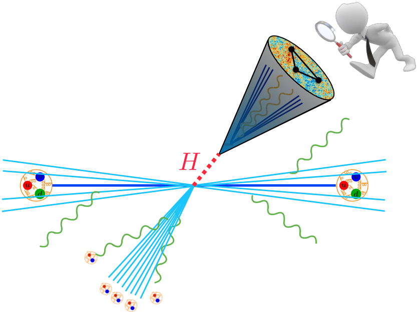


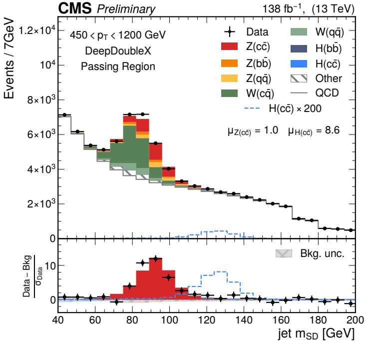


[Figures from Jennet Dickinson]

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, $1.1 < \kappa_c < 5.5$.

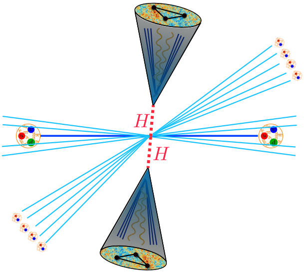


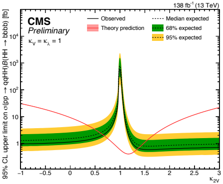


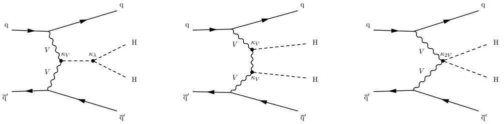
- Matches the original projected sensitivity with $3000\ \mathrm{fb}^{-1}$!

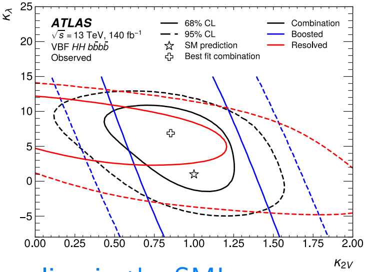
Higgs Self Interaction

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





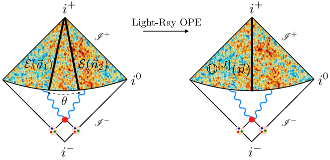




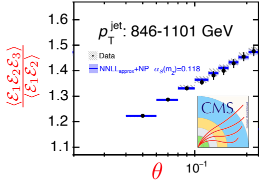
- First observation of the $VV \to HH$ coupling in the SM!

Summary

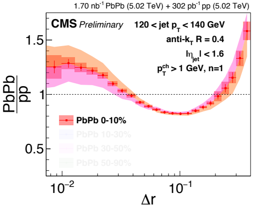
- Significant recent progress in the theoretical characterization of asymptotic energy flux.

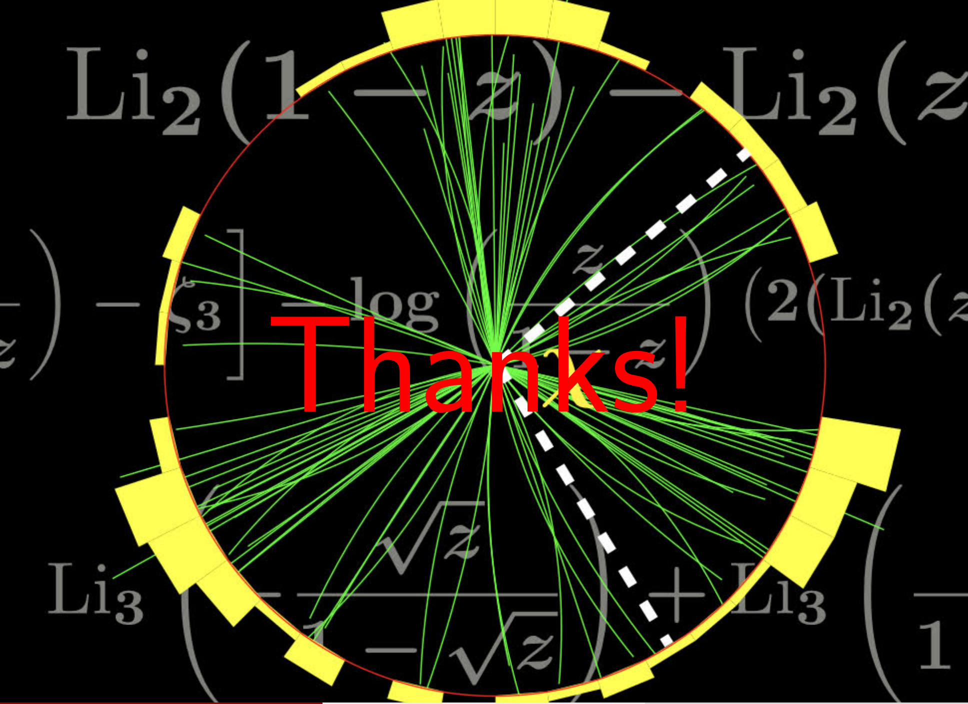


- Scaling and shape dependence of multi-point energy correlators can be directly measured at the LHC: How can we best use them?



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





Thanks!