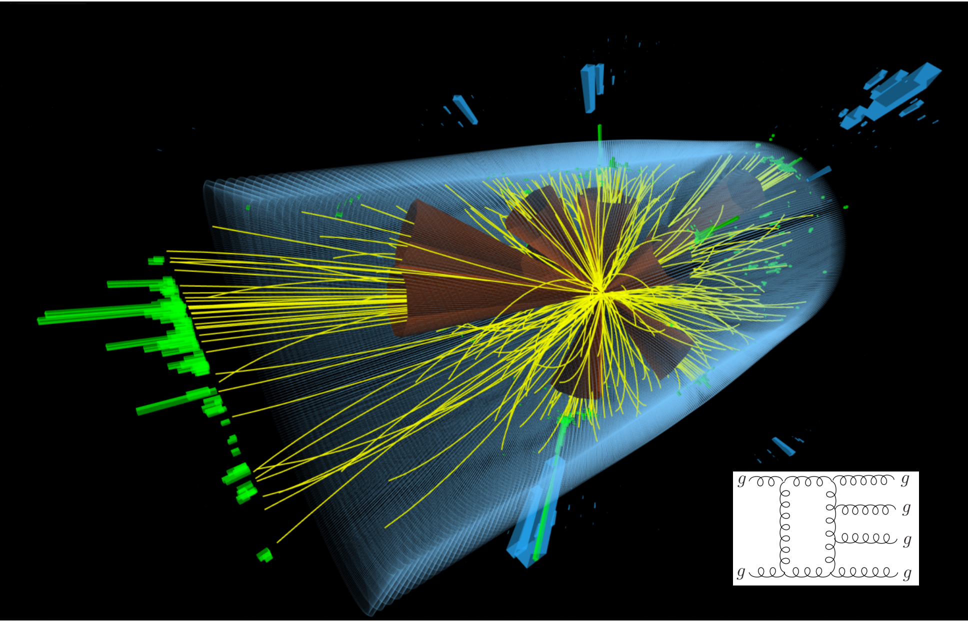
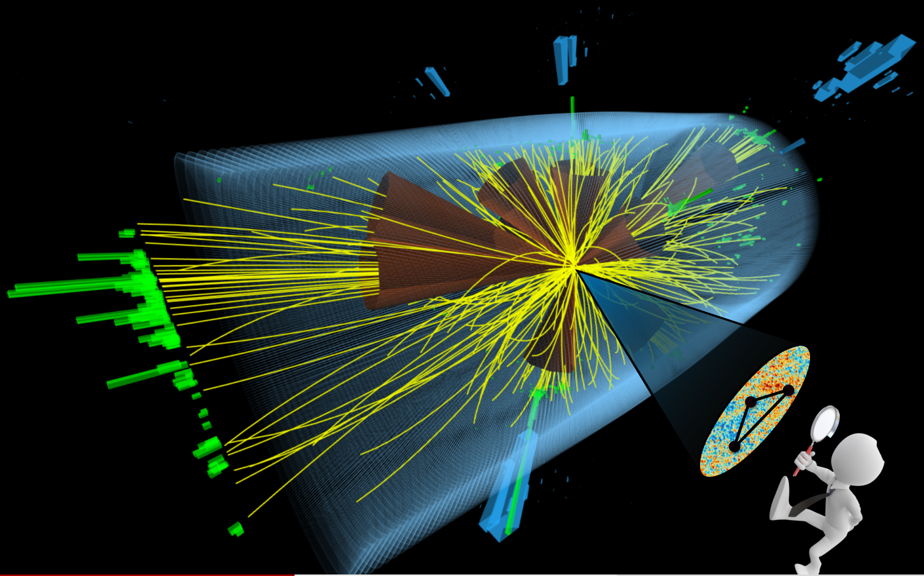
Conformal Colliders Meet the LHC

Ian Moult
Yale

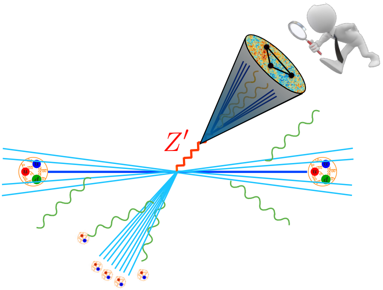

g
g
g
g
g
g

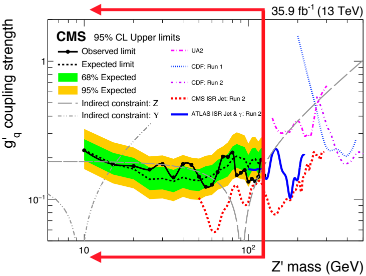
Jet Substructure!



Jet Substructure: Searches

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

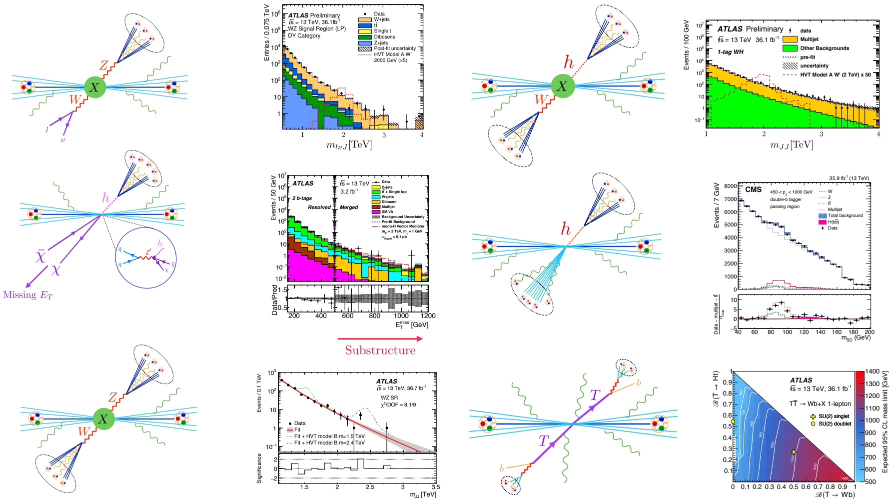




- Its introduction in 2008 by Butterworth, Davison, Rubin and Salam, along with anti-k_T by Cacciari, Soyez, Salam reinvigorated the study of jets in QCD.

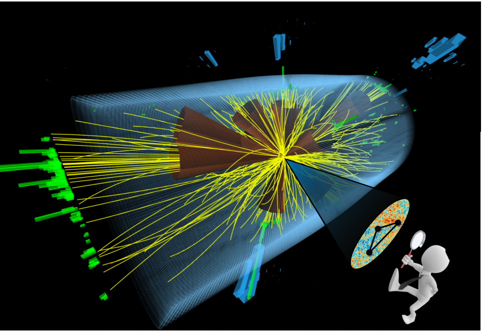
Jet Substructure: Searches

- Large impact on searches, and synergies with Machine Learning.

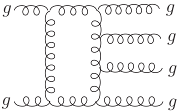


Changing the Perspective

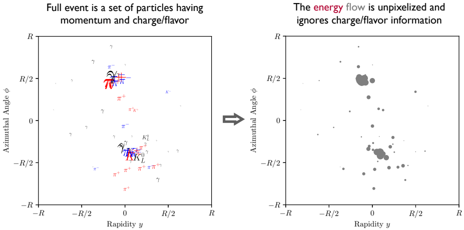
- This changes the problem from studying the production of jets (S-matrix elements) to studying the statistical properties of energy flux within jets.



S-Matrix



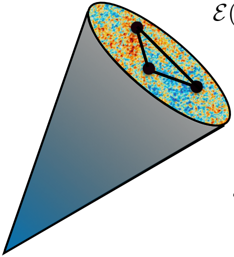
Energy Flux



- Requires the development of a new set of theoretical tools and new ways of thinking about jets.

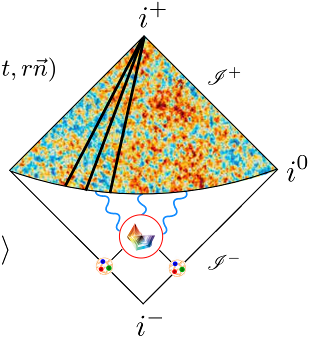
Insights from Conformal Field Theory

- Calorimeter cells can be given a field theoretic definition in terms of light-ray operators. [Hofman, Maldacena]



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

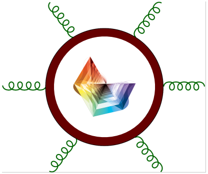
$$\langle \Psi | \mathcal{E}(\hat{n}_1) \cdots \mathcal{E}(\hat{n}_k) | \Psi \rangle$$

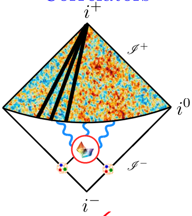


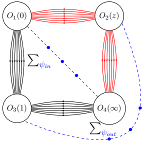
- From the perspective of QFT, jet substructure is the study of correlation functions of energy flow operators.

Energy Correlators

- Correlation functions of energy flow operators take an interesting intermediate position between amplitudes and correlation functions.





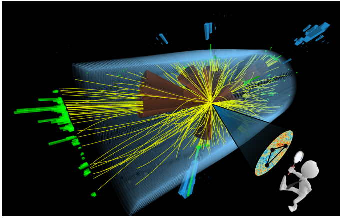


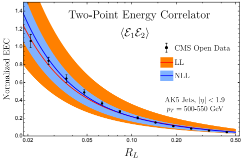
	Amplitudes	Energy Correlators	Correlation Functions
Asymptotic States	✓	✓	
IR Finite		✓	✓

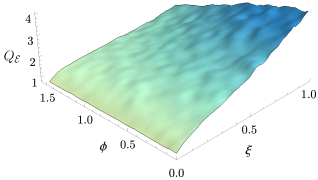
- Despite their physical importance, much less explored.

Conformal Colliders Meet the LHC

- Progress in the understanding of lightray operators allows the calculation and measurement of the shapes and scalings of multipoint correlators, inside high energy jets at the LHC.

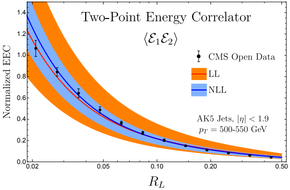




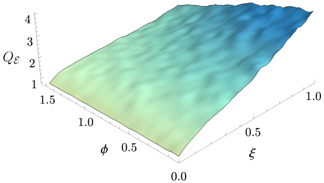


Outline

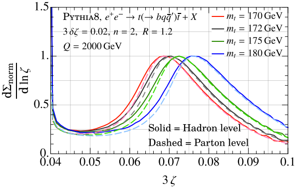
- Scaling Behavior in Jet Substructure



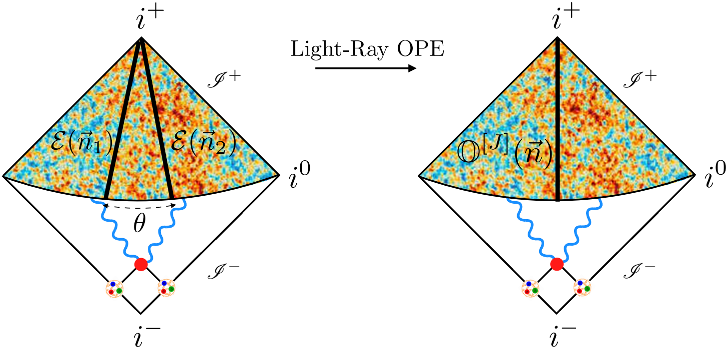
- Non-Gaussianities in Energy Flux



- Weighing the Top Quark



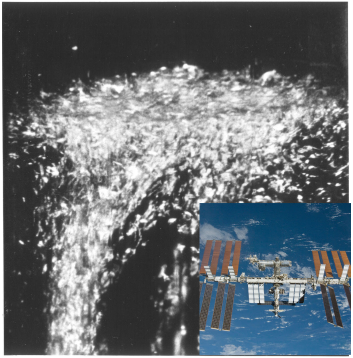
Scaling Behavior in Jet Substructure

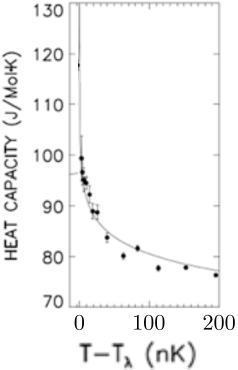


Scaling Behavior in QFT

- QFTs exhibit universal behavior as operators are brought together.
- For local operators, this is captured by the operator product expansion (OPE) $\Longrightarrow$ scaling behavior!

λ-point of Helium

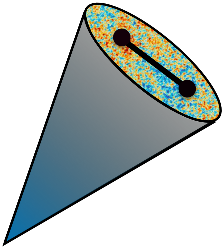


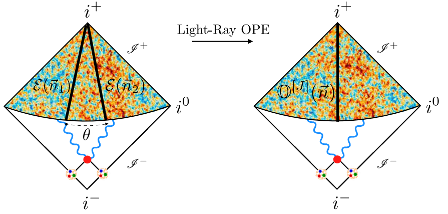


$$\mathcal{O}(x)\mathcal{O}(0) = \sum x^{\gamma_i} c_i \mathcal{O}_i$$

The OPE Limit of Lightray Operators

- Energy flow operators also admit an OPE!
- Jet Substructure is the study of the OPE limit of lightray operators.





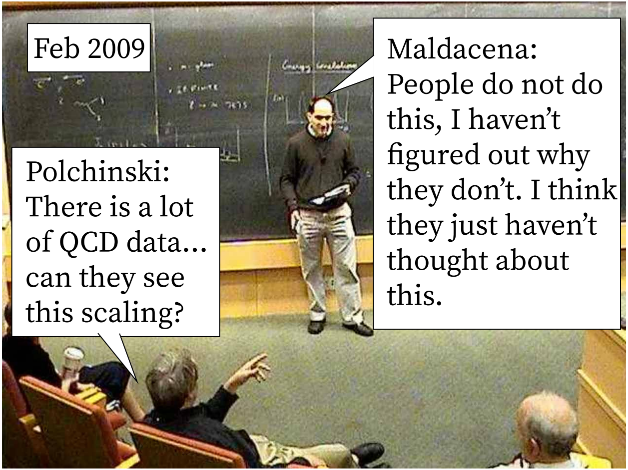
$$\mathcal{E}(\hat{n}_1)\mathcal{E}(\hat{n}_2) \sim \sum \theta^{\tau_i-4}\mathbb{O}_i(\hat{n}_1)$$

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

- Allows a complete new approach to jet substructure as the study of the symmetry and OPE structure of these operators.

Theory-Experiment Gap

- OPE scaling is the most basic prediction of QFT for jet substructure.

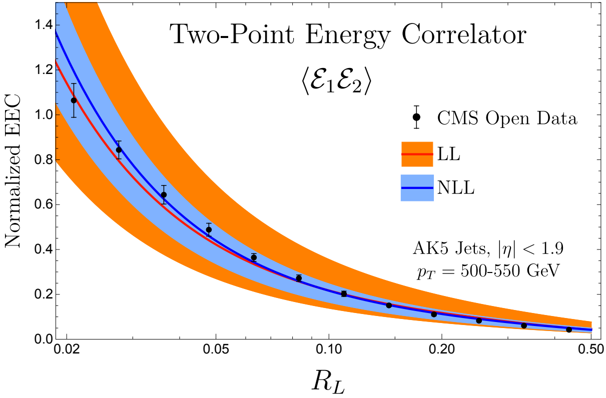


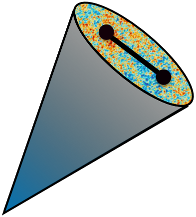
- Shockingly, still true as of 2022... lets change that...

The OPE Limit in Data

[Komiske, Moult, Thaler, Zhu]
[Dixon, Moult, Zhu]
[Lee, Mecaj, Moult]

- The $\mathcal{E}(\hat{n}_1)\mathcal{E}(\hat{n}_2)$ OPE inside high-energy jets!

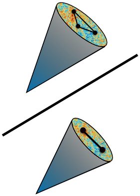




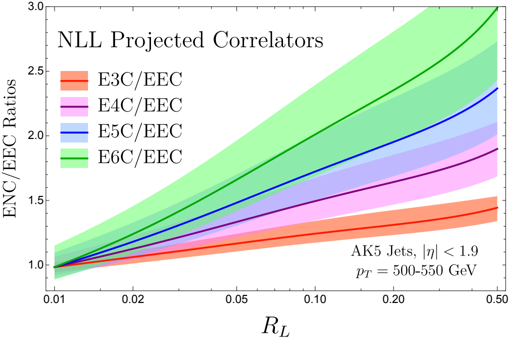
- Beautiful illustration of the universality of the OPE limit in QFT!
- Universality allows calculations in the complicated LHC environment.

Higher Point Scaling

- A remarkable prediction of the light-ray OPE is that at the quantum level, N-point correlators develop an anomalous scaling that depends on N.



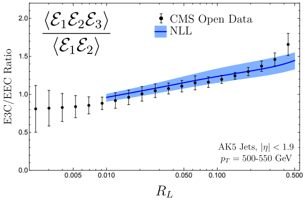
$$\frac{\langle \mathcal{E}_1 \mathcal{E}_2 \cdots \mathcal{E}_{J-1} \rangle}{\langle \mathcal{E}_1 \mathcal{E}_2 \rangle} \sim \frac{\langle \mathbb{O}^{[J]} \rangle}{\langle \mathbb{O}^{[3]} \rangle}$$

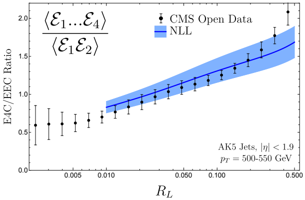


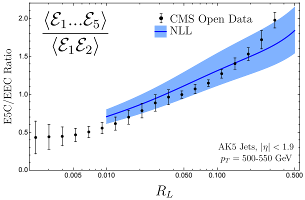
- Directly probes the spectrum of (twist-2) lightray operators in QCD.

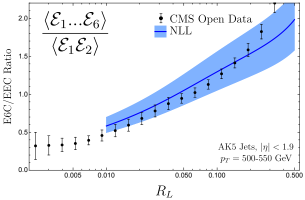
[Chen, Moult, Zhang, Zhu]
[Lee, Mecaj, Moult]

- The remarkable LHC dataset allows these scalings to be measured at the quantum level.





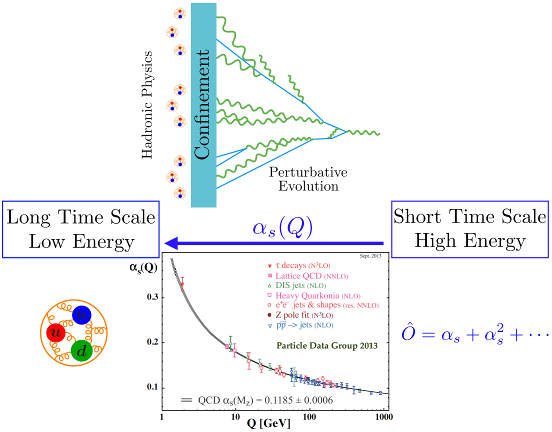




- Fundamentally new probes of jets at colliders!!

The Confinement Transition

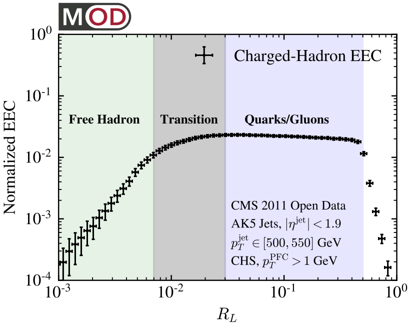
- Jets exhibit a transition from weakly coupled quarks and gluons to freely propagating hadrons.

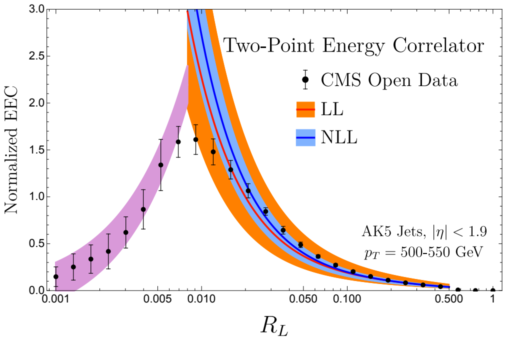


- Can it be directly imaged?

The Confinement Transition

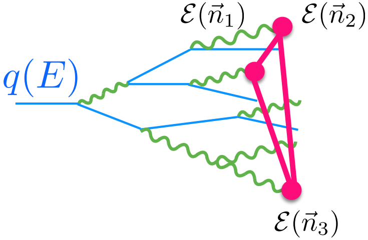
- Distinct scalings associated with interacting quarks and gluons and free hadrons clearly visible!

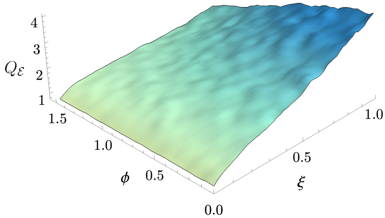




- Precision measurements of the confinement transition possible.
- https://www.youtube.com/watch?v=ORwDv1KTB5U

Non-Gaussianities in Energy Flux

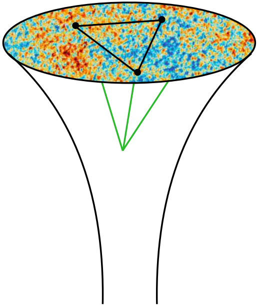


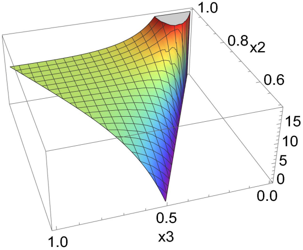


[Chen, Moult, Thaler, Zhu]

Non-Gaussianities

- Higher-point correlators probe more detailed aspects of interactions.
- e.g. Non-Gaussianities allow one to distinguish models of inflation.
- Three-point function, $\langle \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \zeta_{\vec{k}_3} \rangle$, first computed by Maldacena.





[Cabass, Pajer, Stefanysyzn, Supel]

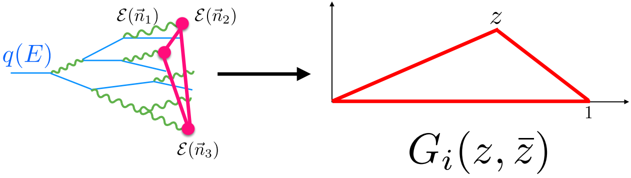
- Can we compute higher-point functions of energy flux?

Multipoint Correlators

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

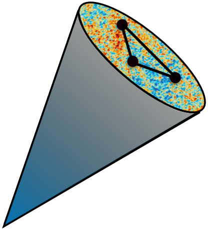
$$\langle \mathcal{E}(\vec{n}_1)\cdots\mathcal{E}(\vec{n}_n)\rangle = \left(\frac{q}{4\pi}\right)^n \left[1 + \sum_{i<j}\frac{6\pi^2}{\lambda}[(\vec{n}_i.\vec{n}_j)^2 - \frac{1}{3}] + \right.$$
$$\left. + \frac{\beta}{\lambda^{3/2}}[\sum_{i<j<k}(\vec{n}_i.\vec{n}_j)(\vec{n}_j.\vec{n}_k)(\vec{n}_i.\vec{n}_k)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

- 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]

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

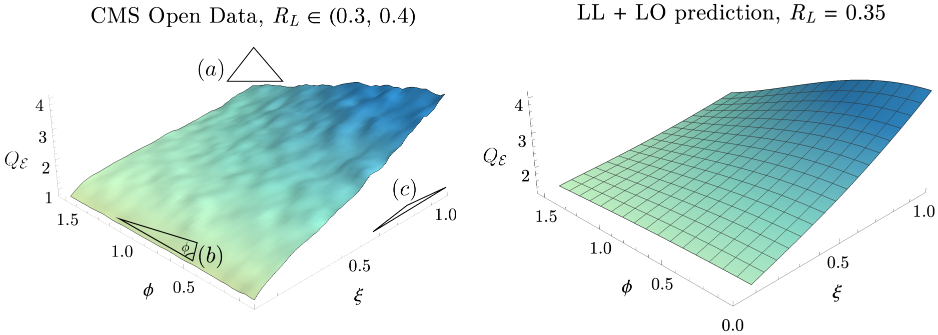
- Here Φ and D_2^+ are polylogarithmic functions

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

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

Shape Dependence of Non-Gaussianity in Data

- Can directly study non-gaussianities inside high energy jets.

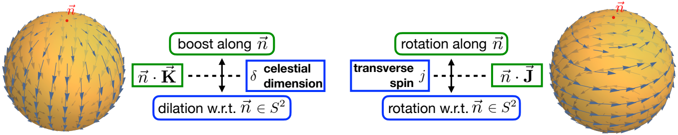


- Illustrates theoretical control over multi-point correlations!

Celestial Partial Waves

- An honest to goodness correlation function living on the detector!
- Beautiful theoretical properties in a measurable observable!
- Exhibits a Celestial Block decomposition:

[Chang, Simmons-Duffin], [Chen, Moult, Sandor, Zhu]



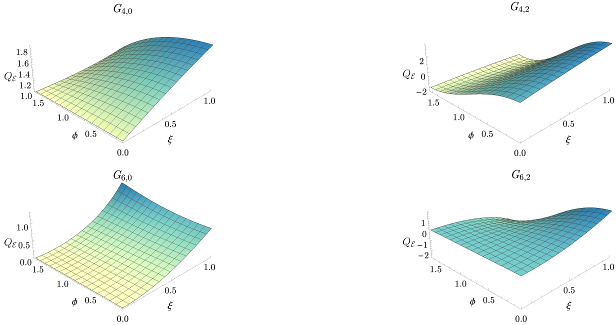
$$g(z,\bar{z}) = \sum_{\delta,j} c_{\delta,j}\, g_{\delta,j}(z,\bar{z})$$

$$g_{\delta,j}(z,\bar{z}) = \frac{1}{1+\delta_{j,0}}\left(k_{\delta-j}(z)k_{\delta+j}(\bar{z}) + k_{\delta+j}(z)k_{\delta-j}(\bar{z})\right)$$

$$k_\beta(x) = x^{\beta/2}\,{}_2F_1\left(\frac{\beta}{2}, \frac{\beta}{2}-1, \beta, x\right)$$

Celestial Partial Waves

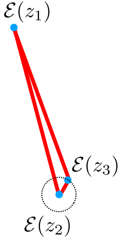
- These are partial waves living on the detector:

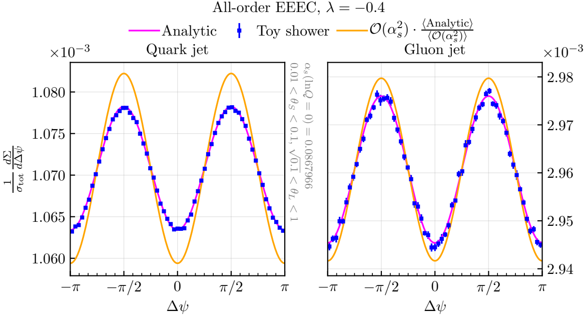


- Celestial block expansion converges rapidly. Genuinely new approach!

Parton Shower Development

- Illustrates complete control of three-point correlations in jets.
- Crucial for validating implementations of higher order effects in parton showers. e.g. Spin Correlations (transverse spin operators)



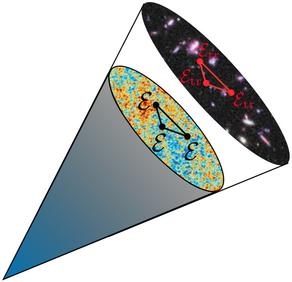


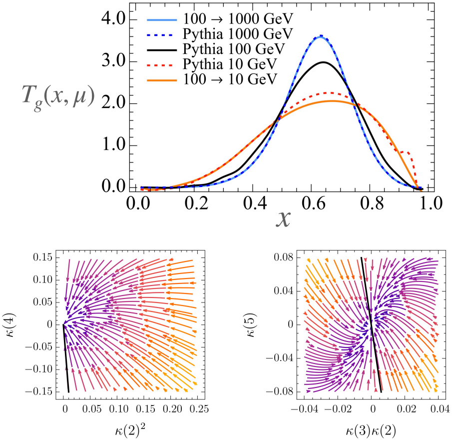
[Karlberg, Salam, Scyboz, Verheyen]

- Full incorporation of higher-point correlations in parton showers will play an important role in enhancing the LHC search program.

[Chang, Procura, Thaler, Waalewijn]
[Li, Moult, Van Velzen, Waalewijn, Zhu]
[Jaarsma, Li, Moult, Waalewijn, Zhu]

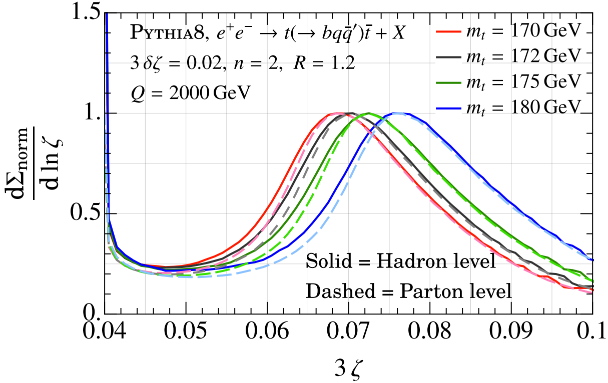
- A key in the ability to study higher point correlations has been the development of QFT formalisms for performing calculations on charged particles (tracks).





- Described by non-perturbative track functions satisfying non-linear RG evolution, encoding correlations in the hadronization process.

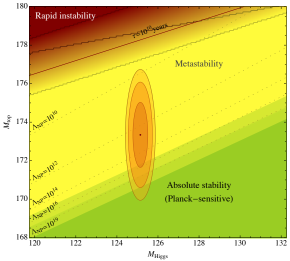
Weighing the Top Quark



[Holguin, Moult, Pathak, Procura]

Top Quark Mass

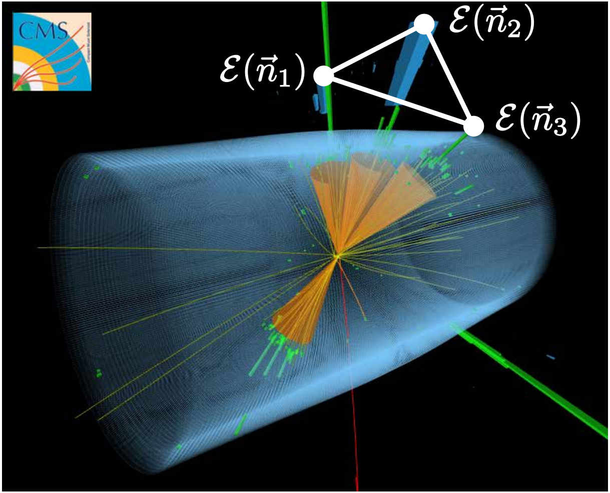
- The top quark mass is one of the most important parameters of the SM. e.g. electroweak vacuum stability/criticality, electroweak fits, etc.



- A leading uncertainty ($\gtrsim 1$ GeV) is that it is not understood what has been measured: $m_T^{mc} = 172.26 \pm 0.61$GeV.
- Need simple observables with top mass sensitivity that can be computed from first principles field theory.

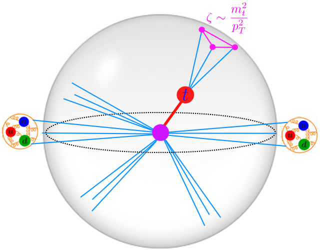
A Top Event

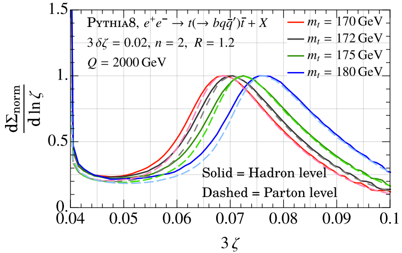
- Massive particles leave clear imprints in correlation functions:



Top Quark Mass Measurement

- Massive particles imprint their existence at a characteristic angular scale $\zeta \sim m^2/Q^2$

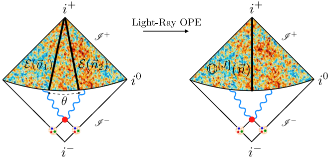




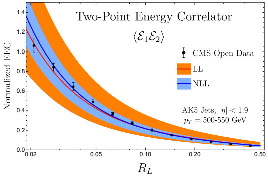
- Optimistic for a precision ($\lesssim 1$ GeV) top mass extraction at LHC from jet substructure!
- Motivates further understanding of the mathematical structure of higher point correlators.

Summary

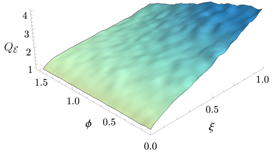
- Insights from formal theory are transforming the way we think about jet substructure.

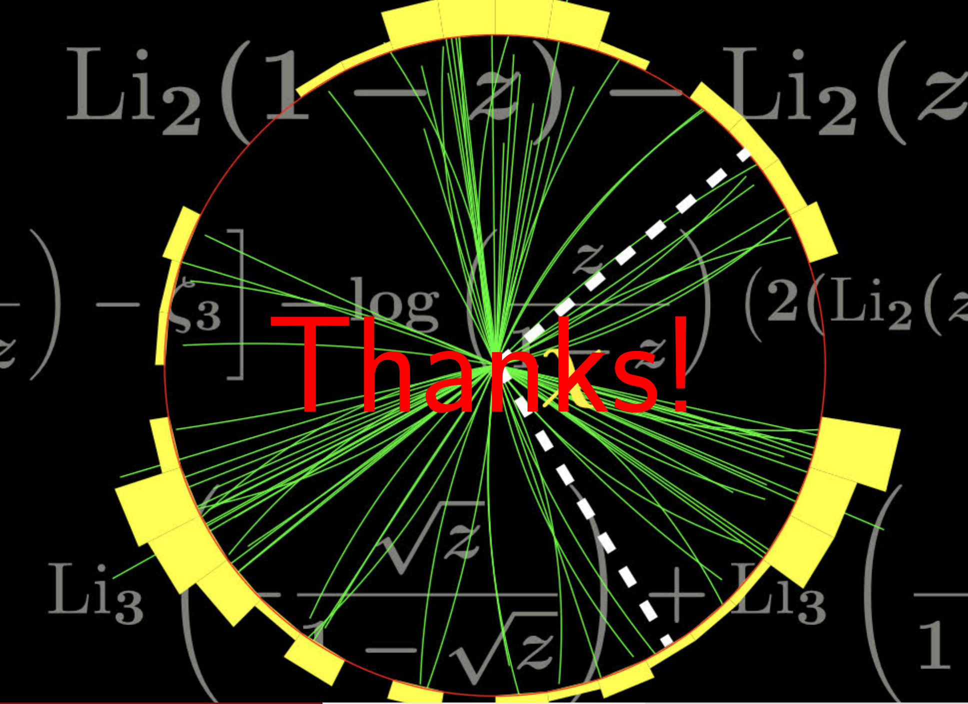


- Jet Substructure provides a physical realization of the OPE limit of lightray operators $\Longrightarrow$ direct bridge between recent field theory developments and QCD phenomenology.



- Opens the door to a precision physics program using jet substructure, and many new opportunities to search for new physics!





Thanks!