Detectorology and its Phenomenological Applications

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based on work with M Koloğlu, G Korchemsky, K Lee, I Moult, and A Zhiboedov

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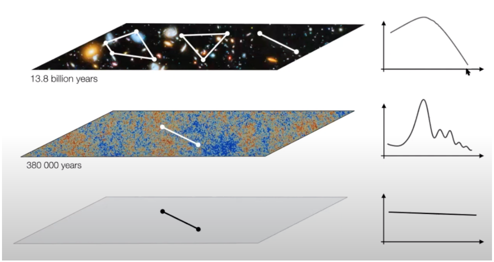
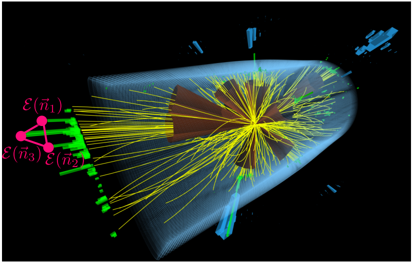
What is a good collider observable?

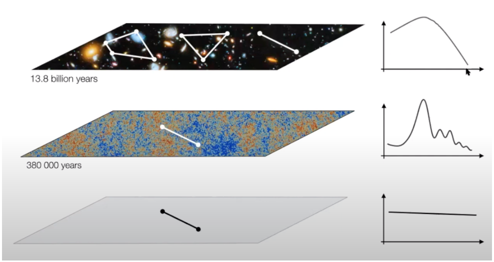


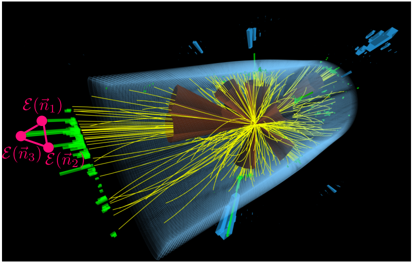


Correlation functions

- Simple observable
  - Requires direct measurement of the system
- In collider physics
  - Detectors are situated far away and only see the final state
  - High multiplicity states - descriptions in terms of individual particles are difficult/impractical

What is a good collider observable?





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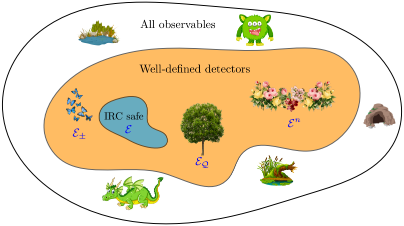
We can study the system using correlation functions of asymptotic quantities!

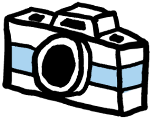
On hammers and cameras

[Caron-Huot Koloğlu Kravchuk Meltzer Simmons-Duffin '22]

- We understand the hammer in terms of local operators
- We can build cameras out of **well-defined** detector operators
- Particles have a number of properties such as energy and charge
- We want to understand detectors that can measure these various properties



Asymptotic Energy Flux Operators



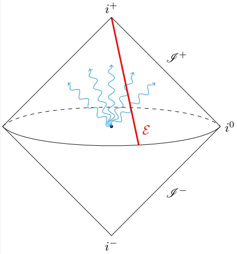
As an operator on multi-particle states $|X\rangle$

$$\mathcal{E}(\hat{n})|X\rangle = \sum_i E_{k_i} \delta^{d-2}(\Omega_{\hat{n}} - \Omega_{\hat{k}_i})|X\rangle$$

- Sees particles along direction $\hat{n}$ and measures their energy
  - Sensitive to asymptotic radiation along a particular direction - like a calorimeter cell!

- Formally, integrate the stress tensor T along future null infinity $\mathscr{I}^+$
  - Averaged Null Energy Condition (ANEC) operator
  - Well-defined in field theory as a light-ray operator
  - Admits an operator product expansion (OPE)

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



[Hofman Maldacena '08]

From operators to observables

We get observables by taking correlation functions of detectors
Two point correlator ⇒ Energy-energy correlator (EEC)

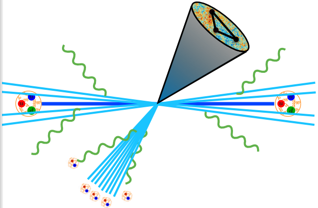
Perturbative calculation

- EEC is a weighted cross section
  - $d\sigma$: Phase space integral
  - Weighted by particle energies as a function of angular separation

$$\frac{d\sigma}{dz} = \sum_{i,j} \int d\sigma \, \frac{E_i E_j}{Q^2} \delta\left(z - \frac{1 - \cos\chi_{ij}}{2}\right)$$

- Infrared and collinear (IRC) safe

[Basham Brown Ellis Love '78]
[Ore Sterman '80] [Korchemsky Sterman '99]
[Hofman Maldacena '08] [Belitsky et al. '13]



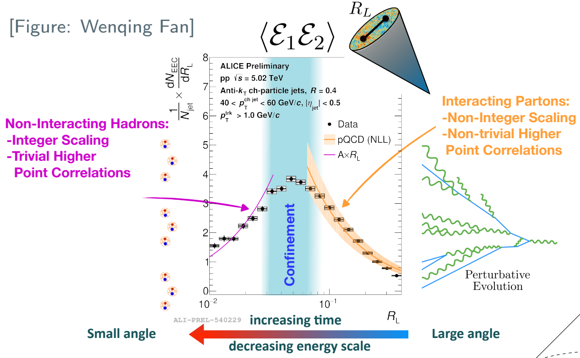
$$\frac{d\Sigma}{dp_T\, d\eta\, d\{\zeta\}} = \sum_i \mathcal{H}_i(p_T/z, \eta, \mu)$$
$$\otimes \int_0^1 dx\, x^N \mathcal{J}_{ij}(z, x, p_T R, \mu) J_j^{[N]}(\{\zeta\}, x, \mu)$$

[Lee Mecaj Moult '22]

Factorization theorem in the collinear limit ⇒ **LHC jet substructure measurements!**

The Energy-Energy Correlator

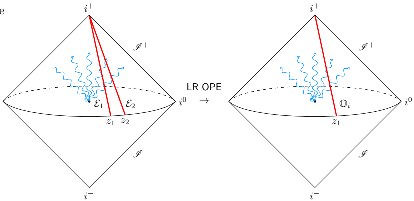
[Figure: Wenqing Fan]



Correlation function of detectors ⇒ jet substructure observable

A clear link between theory and experiment!

- Evolution of the jet goes from right to left
  - Distinct scaling regimes corresponding to partonic and hadronic physics
  - Transitions image the physical scales of QCD

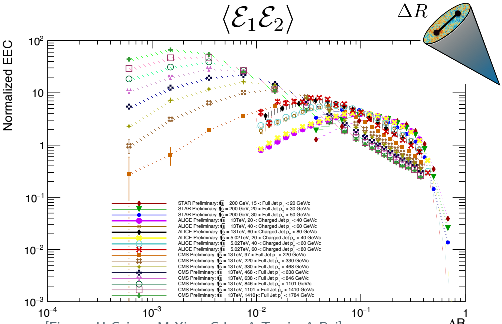


Perturbative scaling predicted by the light-ray OPE

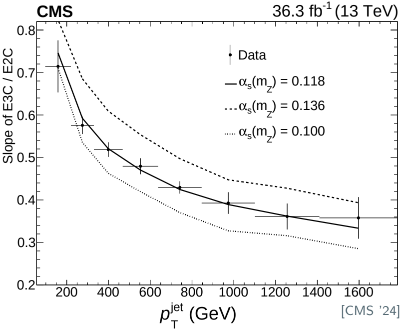
⇒ **Universal scaling behavior!**

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

EECs in Data



[Figure: H Caines, M Xiao, C Lu, A Tamis, A Rai]



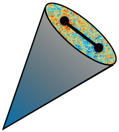
[CMS '24]

Many ongoing and future measurements

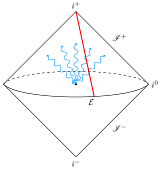
- Precision measurement of strong coupling constant
  - $\alpha_s(m_Z) = 0.1229^{+0.0040}_{-0.0050}$ [arXiv:2402.13864]
- In-medium (quark-gluon plasma)
- Higher point correlators
- Massive quark effects (see E Craft's talk)

Anomalous scaling at the LHC!

$$\frac{\langle \mathcal{E}_1 \mathcal{E}_2 \cdots \mathcal{E}_{J-1} \rangle}{\langle \mathcal{E}_1 \mathcal{E}_2 \rangle} \sim R_L^{\gamma(J)-\gamma(3)}$$

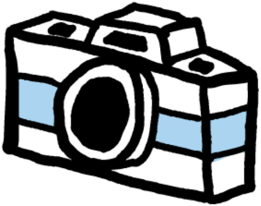


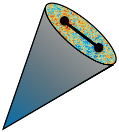
Additional Cameras?



The ANEC is a well-defined operator from which we can construct useful observables...

Are there other cameras from which we can build phenomenologically useful observables???





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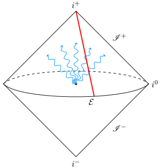

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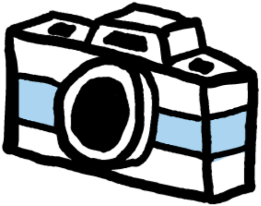


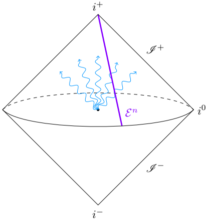
Yes!

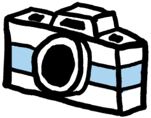
What do they measure?

$\mathcal{E}^n$ Detectors

A new camera which measures the energy flux to an arbitrary power, E^n

$$\mathcal{E}^n(\widehat{n})|X\rangle = \sum_i E^n_{k_i} \delta^{d-2}(\Omega_{\widehat{n}} - \Omega_{\widehat{k}_i})|X\rangle$$





As an operator in a perturbative scalar field theory

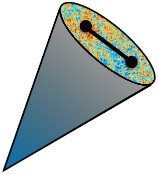
$$\mathcal{D}^+_{J_L}(z) = \frac{1}{C_{J_L}} \int d\alpha_1\, d\alpha_2 : \overline{\varphi}(\alpha_1, z)\varphi(\alpha_2, z) :$$
$$\times \left[(\alpha_1 - \alpha_2 + i\epsilon)^{2(\Delta_\varphi - 1) + J_L} + (\alpha_2 - \alpha_1 + i\epsilon)^{2(\Delta_\varphi - 1) + J_L} \right]$$

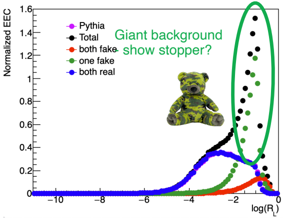
- Twist 2 with spin J_L
  - Energy weighting related to spin: $J_L = -2 - n$
- Well-defined operators with the ANEC as a special case
- Observables are no longer collinear safe due to energy weighting
  - Access to universal non-perturbative physics through multi-hadron fragmentation functions

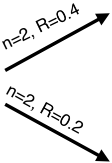
[Caron-Huot Koloğlu Kravchuk Meltzer Simmons-Duffin '22]

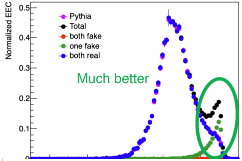
$\mathcal{E}^n$ Applications

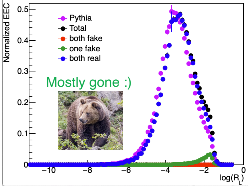
[Figure: L Havener, A Rai]





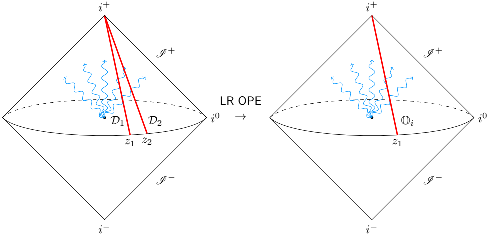






Large (small) values of n, m suppress (enhance) soft physics:

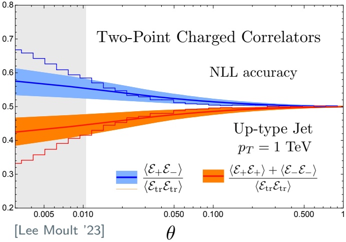
Applications in hot and cold QCD



Collinear limit gives access to structure and operators of the light-ray OPE:

Operator definition of fragmentation functions?

$\mathcal{E}_Q$ Detectors



[Lee Moult '23]

We can also build cameras that probe different quantum numbers!

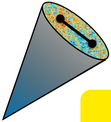
Sensitivity to a charge Q (times the energy)

$$\mathcal{E}_Q(\widehat{n})|X\rangle = \sum_i E_{k_i} Q_{k_i} \delta^{d-2}(\Omega_{\widehat{n}} - \Omega_{k_i})|X\rangle$$

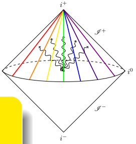
- Great resolution on charged tracks
- **More hadronization/non-perturbative information**

$$\mathcal{D}^{\pm}_{J_L}(z) = \frac{1}{C'_{J_L}} \int d\alpha_1\, d\alpha_2 : \overline{\varphi}(\alpha_1, z)\varphi(\alpha_2, z) :$$
$$\times \left[(\alpha_1 - \alpha_2 + i\epsilon)^{2(\Delta_\varphi - 1) + J_L} \pm (\alpha_2 - \alpha_1 + i\epsilon)^{2(\Delta_\varphi - 1) + J_L} \right]$$

- **Nearly identical to our $\mathcal{E}^n$ detector!**
- $\pm$ sign: Definite sign under charge conjugation
- Valid for any global $U(1)$ symmetry

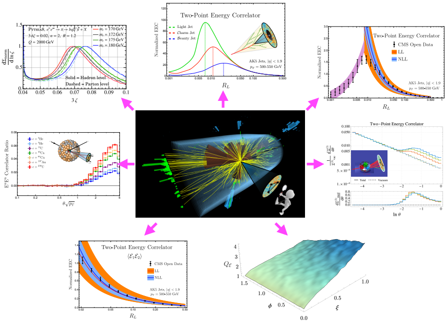


Discussion and Future Directions



Study the system in terms of asymptotic observables built out of well-defined operators

Allows for a link between operators in a field theory and phenomenologically useful observables!



Looking forward:

- What other cameras are out there?
  - What is the full space of detectors?
  - What can these tell us about non-perturbative physics?
- How can we use these?
  - Precision jet substructure
  - Hot and cold nuclear environments
  - See E Craft talk for more

Thanks!