# 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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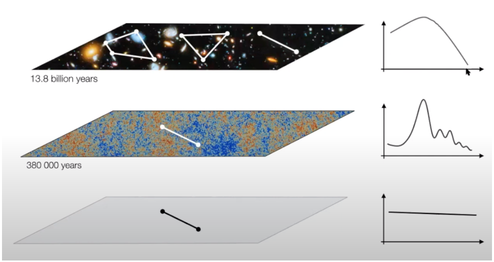
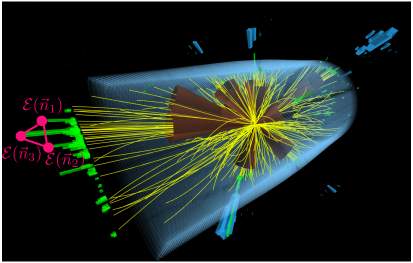
# What is a good collider observable?

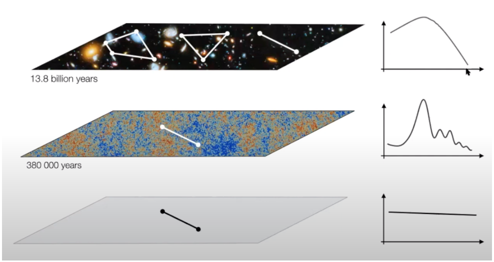


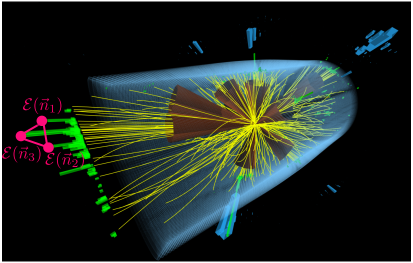




## Correlation functions

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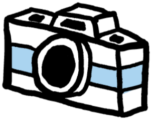
**We can study the system using correlation functions of asymptotic quantities!**

# 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



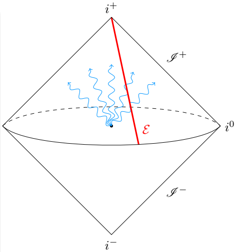
As an operator on multi-particle states $|X\rangle$

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

- Sees particles along direction $\widehat{n}$ 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 particular light-ray operator: $\mathcal{E}(z) \sim \mathbb{O}_2^+(\infty, z)$

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




[Hofman Maldacena '08]

# From operators to observables

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

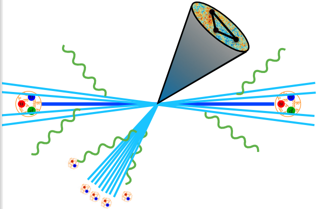
## Perturbative calculation

- 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]



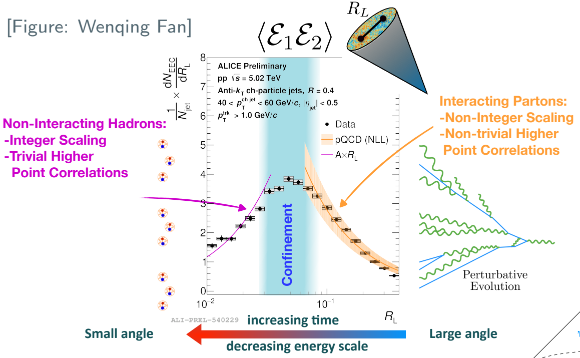
$$\frac{d\Sigma}{dp_T\, d\eta\, d\{\zeta\}} = \sum_i \mathcal{H}_i(p_T/z, \eta, \mu) \otimes \int_0^1 dx\, x^N \mathcal{J}_{ij}(z, x, p_T R, \mu) J_j^{[N]}(\{\zeta\}, x, \mu)$$

[Lee Mecaj Moult '22]

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

# The Energy-Energy Correlator

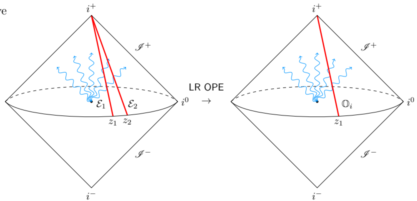
[Figure: Wenqing Fan]




**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

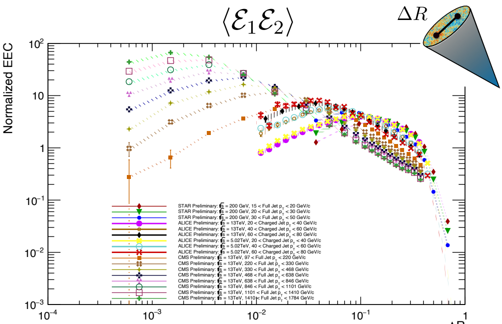



Perturbative scaling predicted by the light-ray OPE

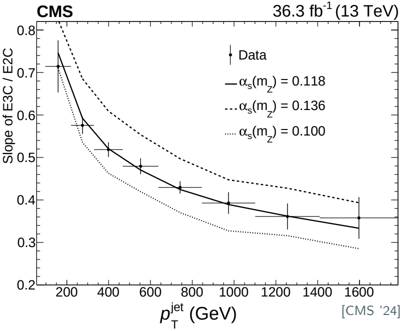
⇒ **Universal scaling behavior!**

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

# EECs in Data




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



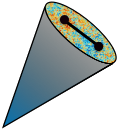

[CMS '24]

## Many ongoing and future measurements

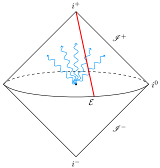
- Precision measurement of strong coupling constant
  - $\alpha_s(m_Z) = 0.1229^{+0.0040}_{-0.0050}$ [arXiv:2402.13864]
- In-medium (quark-gluon plasma)
- Higher point correlators
- Massive quark effects [see E Craft, S Alipour-fard, A Pathak talks]

**Anomalous scaling at the LHC!**

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

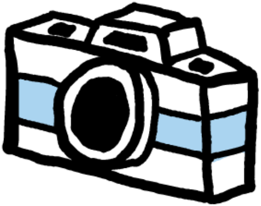


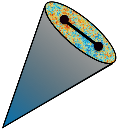
# Additional Cameras?




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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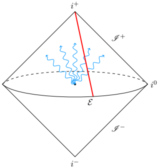


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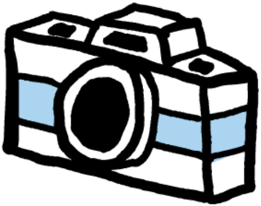


**Yes!**

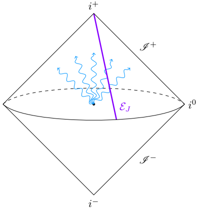
What do they measure?

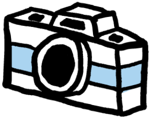
# $\mathcal{E}_J$ Detectors

A new camera which measures the energy flux to an arbitrary power, $E^{J-1}$ with $J \in \mathbb{C}$

$$\mathcal{E}_J(\widehat{n})|X\rangle = \sum_i E_{k_i}^{J-1} \delta^{d-2}(\Omega_{\widehat{n}} - \Omega_{\widehat{k}_i})|X\rangle$$

- Formally: $\mathcal{E}_J(z) \sim \mathbb{O}_J^+(\infty, z)$
  - Analytically continued twist-2, spin-$J$ light-ray operator
  - Energy weighting is related to spin



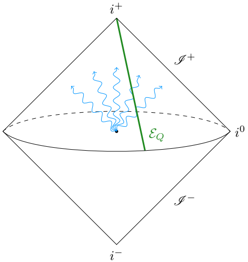
## As an operator in a perturbative scalar field theory

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

- Twist-2, spin-$J_L$, and "charge/spin even"
- Observables are no longer collinear safe due to energy weighting
  - Access to universal non-perturbative physics through multi-hadron fragmentation functions

[Kravchuk Simmons-Duffin '18]

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



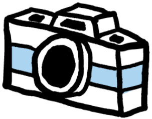

# $\mathcal{E}_Q$ Detectors

**We can also build cameras that probe different quantum numbers!**

Sensitivity to a charge $Q$ (times the energy)

$$\mathcal{E}_Q(\widehat{n})|X\rangle = \sum_i E_{k_i}^{J-1} Q_{k_i} \delta^{d-2}(\Omega_{\widehat{n}} - \Omega_{\widehat{k_i}})|X\rangle$$

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



- **Nearly identical to the $\mathcal{E}_J$ detector!**
- Same perturbative vertex factor (up to signs)
- $\pm$ sign: Definite sign under charge conjugation
  - $-$ sign: "charge/spin-odd" light-ray operators $\mathbb{O}_J^-$
- Valid for any global $U(1)$ symmetry

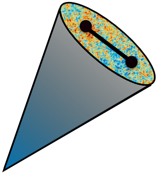
**Tree-level perturbative vertex**

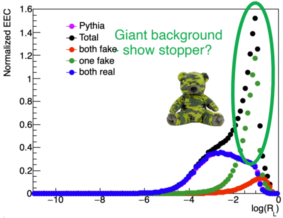
$$\langle \varphi(-q)|\mathcal{D}^{\pm}_{J_L}(z)|\overline{\varphi}(p)\rangle$$
$$= \pm(2\pi)^d \delta^d(p-q) V_{J_L}(z;p)$$

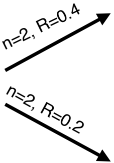
$$V_{J_L}(z;p) = \int_0^\infty d\beta\, \beta^{-1-J_L}$$
$$\times \delta^d(p - \beta z)$$

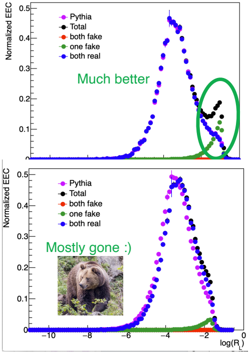
# Detector Applications

[Figure: L Havener, A Rai]





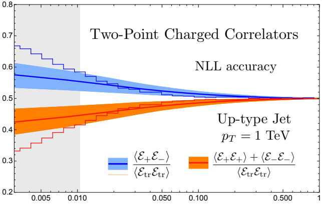




## $\mathcal{E}_J$ Detectors

Large (small) powers of energy suppress (enhance) soft physics:

**Applications in hot and cold QCD**

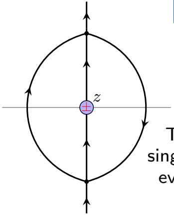



[Lee Moult '23] $\theta$

## $\mathcal{E}_Q$ Detectors

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

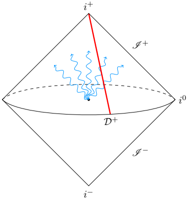
# Event Shapes and "Renormalization"




Two-loop, single-detector event shape

**Loop-level event shapes are IR divergent!**

- Define counterterms $Z_{J_L}$ which absorb IR divergences
  - Renormalized detector: $[\mathcal{D}_{J_L}(z)]_R = Z_{J_L}^{-1}\mathcal{D}_{J_L}(z)$
- $Z_{J_L}$ gives the detector's "anomalous spin"




$$-\gamma_L(J_L) = \frac{\partial \ln Z_{J_L}}{\partial\lambda}\beta(\lambda)$$

  - Dimension and spin are flipped in the detector picture
- Gives $J(\Delta) = \Delta - (d-2) - \gamma_L(1-\Delta)$
  - When solved for $\Delta(J)$, reproduces anomalous dimensions of twist-2 local operators in Wilson-Fisher and $O(N)$ CFTs

The takeaway: Renormalizing detectors is familiar

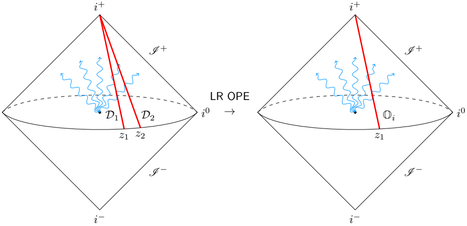
[Caron-Huot Koloğlu Kravchuk Meltzer Simmons-Duffin '22]

# Multi-Detector Event Shapes

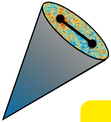
- Event shapes with multiple renormalized detectors have contact term singularities in the collinear limit

$$\langle \overline{\varphi}_R(-p) | \left[\mathcal{D}_{J_{L_1}}(z_1)\right]_R \left[\mathcal{D}_{J_{L_2}}(z_2)\right]_R |\varphi_R(p)\rangle \propto \frac{1}{\epsilon}\delta^{d-2}(z_1, z_2) V_{J_{L_1}+J_{L_2}+d-2}(z_1; p)$$

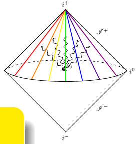
  - Proportional to the tree level vertex $V_{J_L}$
  - Spin is consistent with $E^n \times E^m \sim E^{n+m}$
- Renormalization of individual detectors is not sufficient to renormalize the product




Renormalization perturbatively probes the structure and operators of the light-ray OPE
**Operator definition of fragmentation functions**

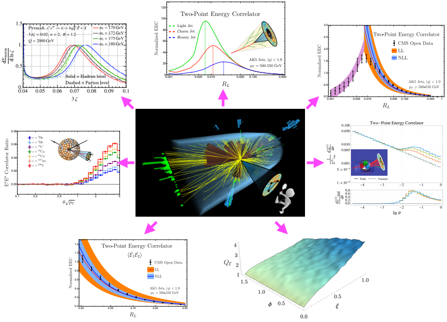


# Discussion and Future Directions



**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
    - The light-ray OPE
- How can we use these?
  - Precision jet substructure
  - Hot and cold nuclear environments

# Thanks!