College | Physical Sciences
Physics & Astronomy

Event Shapes in QFT and Gravity

Based on: 2104.03957, 2412.05384, WIP
with M. Kologlu, I. Moult; + K. Yan

Enrico Herrmann

Mani L. Bhaumik Institute for Theoretical Physics
University of California, Los Angeles

Roadmap

1 — QCD detectors

EEC as precise, measurable event shape

2 — Classical Gravity

one-point fluxes encode radiative observables

3 — Quantum Gravity

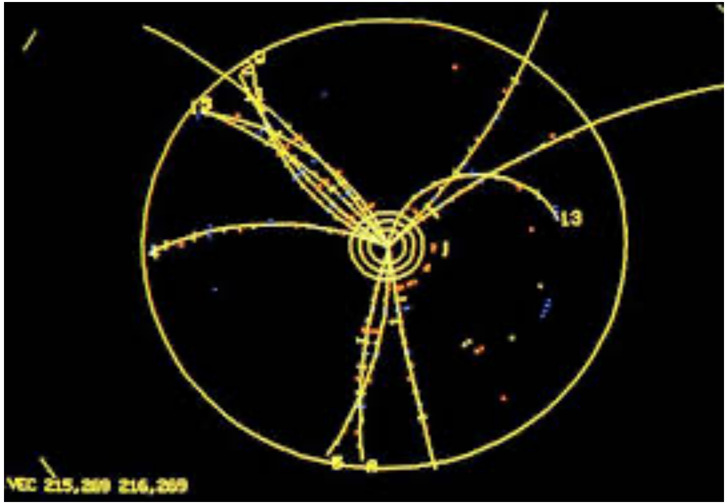
EEC & asymptotic operator data

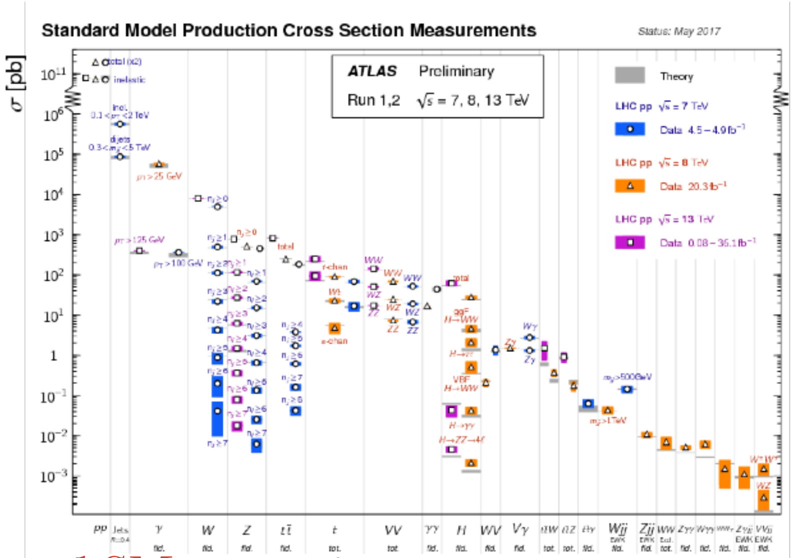
4 — Celestial OPE

boost sectors, blocks, Lorentzian inversion

Motivation - Exclusive Scattering

- enormous understanding of exclusive scattering processes:
  analytic structure, multi-loop pert. theory, amplituhedron, S-matrix bootstrap



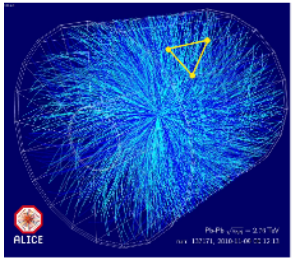


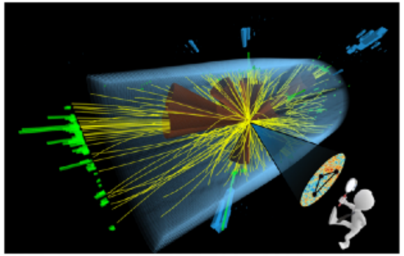
Ability to accurately describe complicated SM scattering processes

Motivation - Why Asymptotic Detectors?

Particle Colliders

- high multiplicity final states





- event shapes measure geometric properties of e.g. energy-momentum flow in collisions

Gravity

- Subtlety with local bulk observables
- Radiation and charges defined at asymptotic boundary
- Radiation and charges defined at asymptotic boundary

Common theme: characterize a theory using asymptotic fluxes.

Motivation - Energy Correlators

[Sterman:1975]

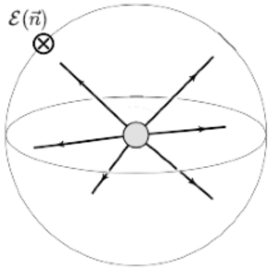
[Basham, Brown, Ellis, Love: 1978]

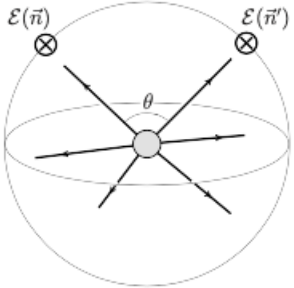
Jet Structure in e+ e- Annihilation with Massless Hadrons

George F. Sterman (Illinois U., Urbana)

Dec, 1975

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

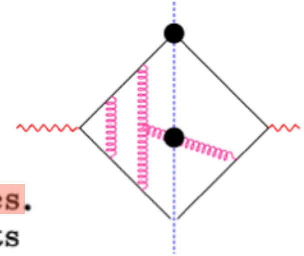




Energy Correlations in electron - Positron Annihilation: Testing QCD

C.Louis Basham (Washington U., Seattle), Lowell S. Brown (Washington U., Seattle), Stephen D. Ellis (Washington U., Seattle), Sherwin T. Love (Washington U., Seattle)

Aug, 1978



An experimental measure is presented for a precise test of quantum chromodynamics. This measure involves the asymmetry in the energy-weighted opening angles of the jets of hadrons produced in the process $e^+e^- \to$ hadrons at energy W. It is special for several reasons: It is reliably calculable in asymptotically free perturbation theory; it has rapidly vanishing (order $1/W^2$) corrections due to nonperturbative confinement effects; and it is straightforward to determine experimentally.

QFT operator definition of a calorimeter cell

Motivation - Energy Correlators: Beyond QCD

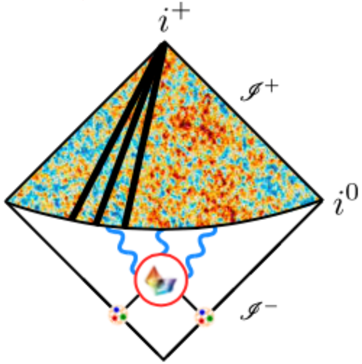
- Energy correlators: interesting observables for characterizing generic QFTs.

Conformal collider physics:
Energy and charge correlations

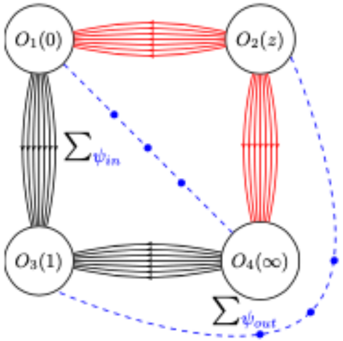
Diego M. Hofman[a] and Juan Maldacena[b]

Amplitudes

Energy Correlators



Correlation Functions

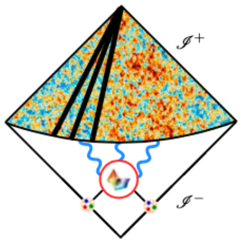


… AND experimentally measurable

Motivation - Beyond Energy Correlators

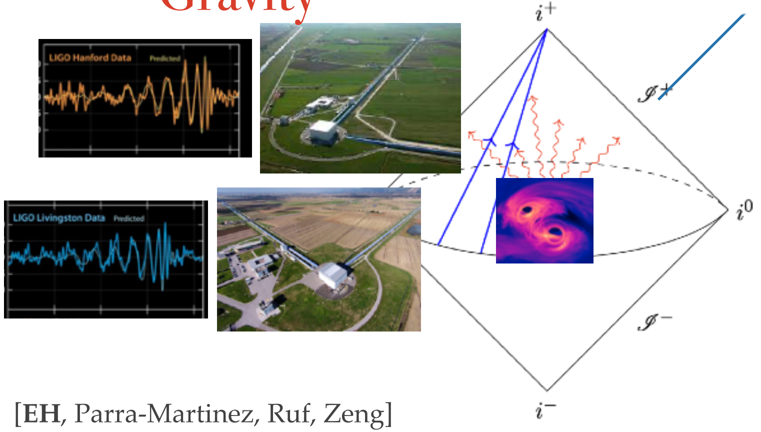
Formal Theory

[Hofman, Maldacena]
[Korchemsky, Sterman]
[Caron-Huot, Kologlu, Kravchuk, Meltzer,Simmons-Duffin]



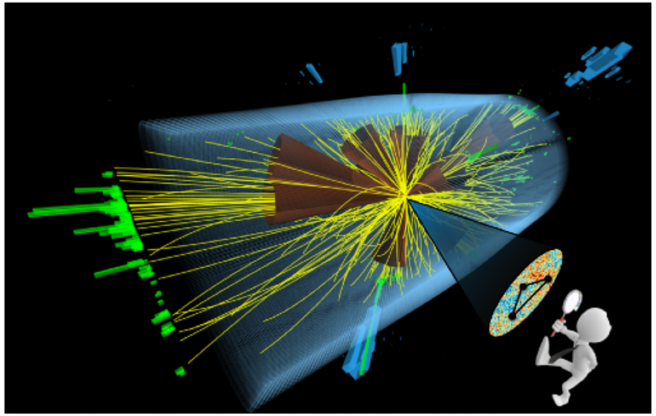
[Sterman] [Basham,Brown,Ellis,Love]
[Dixon, Moult, Zhu, …] […]
[**EH**, Kang, Penttala, Zhang]

Gravity



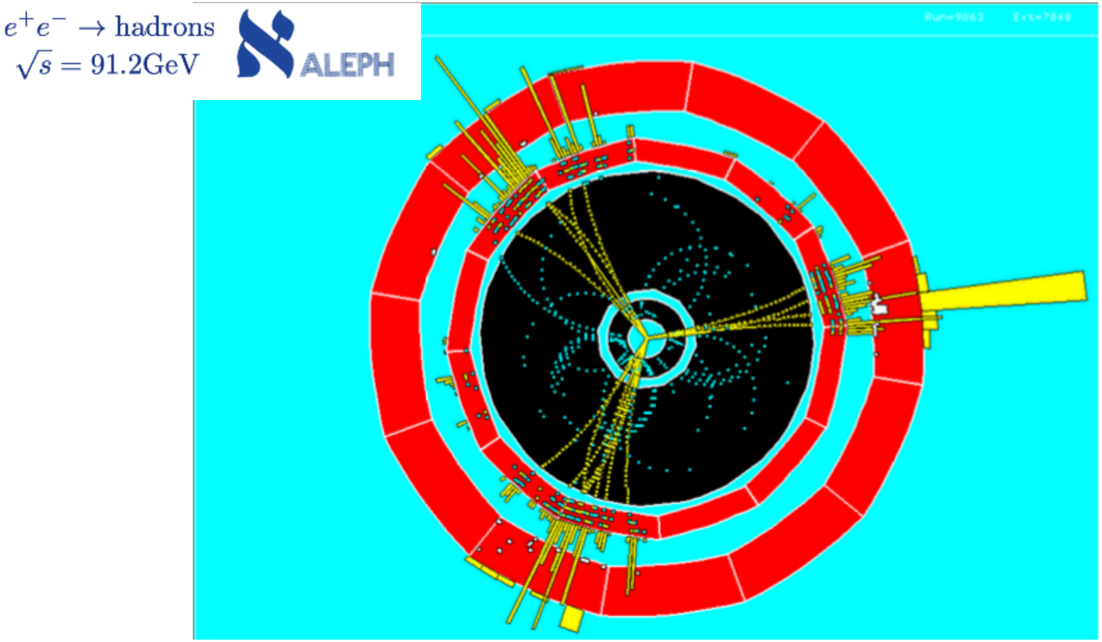
[**EH**, Parra-Martinez, Ruf, Zeng]
[**EH**, Kologlu, Moult] **EH**, Kologlu, Moult, Yan]

Colliders



(1) Event shapes in QFT

- Energy Correlators in e^+e^- Colliders (conceptually simpler)

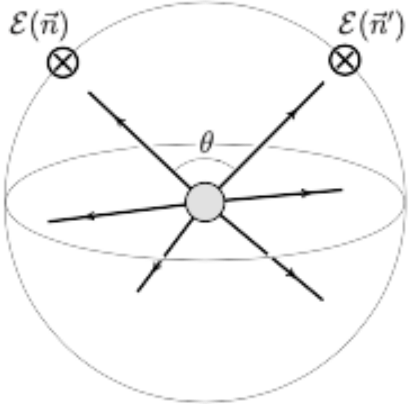


(1) Event shapes in QFT - EEC in e^+e^-

- energy correlator in initial state produced by local operator $\mathcal{O}$

$$\langle 0 | \mathcal{O}^\dagger \, \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2) \, \mathcal{O} | 0 \rangle \leftrightarrow$$

$$\frac{d\Sigma}{d\cos\theta} = \sum_{i,j} \int \frac{E_i E_j}{Q^2} \delta(\vec{n}_1 \cdot \vec{n}_2 - \cos\theta) \, d\sigma$$

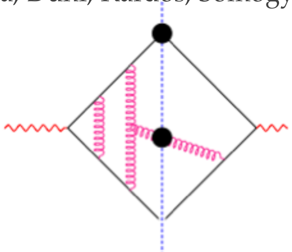


- remarkably rich observable, sensitive to dynamics of theory

- perturbative results in QCD @ NLO (analytically), NNLO numerically

[LO: Basham, Ellis, Brown, Love] [NLO: Dixon, Lou, Shtabovenko, Yang, Zhu] [NNLO numeric: Del Duca, Duhr, Kardos, Somogyi, Trocsanyi]

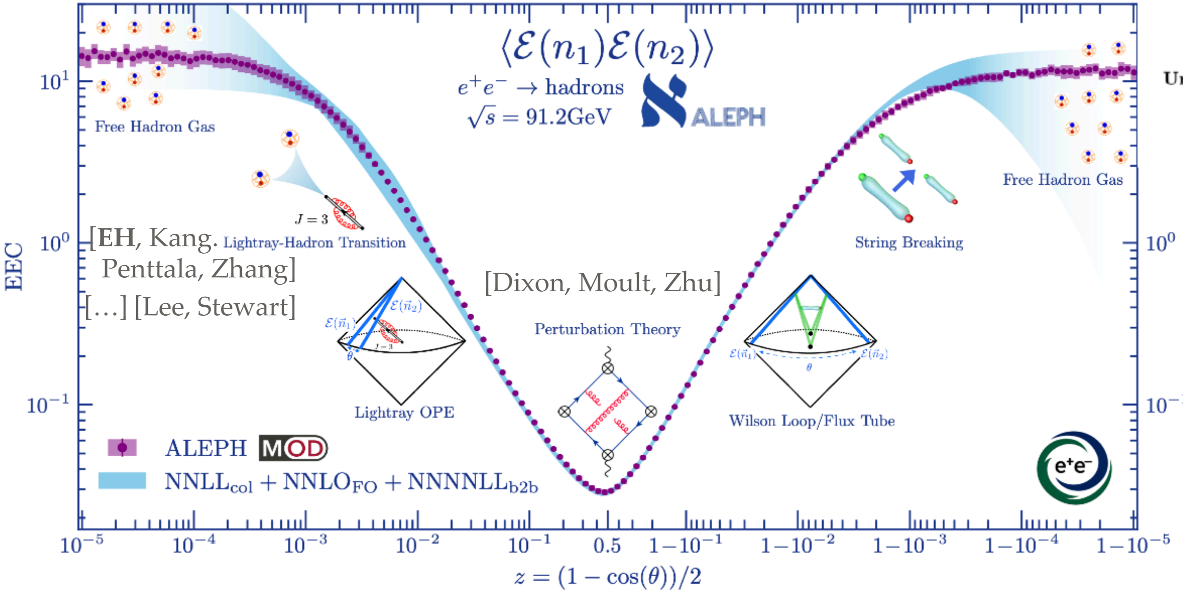
Physically realizable in e^+e^- collisions



(1) Event shapes in QFT - EEC in e^+e^-

- QCD (asymptotically free, confining gauge theory)

Image credit: [Bossi et al. 2511.00149]



MITP-25-057, MITHIG-MOD-24-001

Energy Correlators from Partons to Hadrons: Unveiling the Dynamics of the Strong Interactions with Archival ALEPH Data

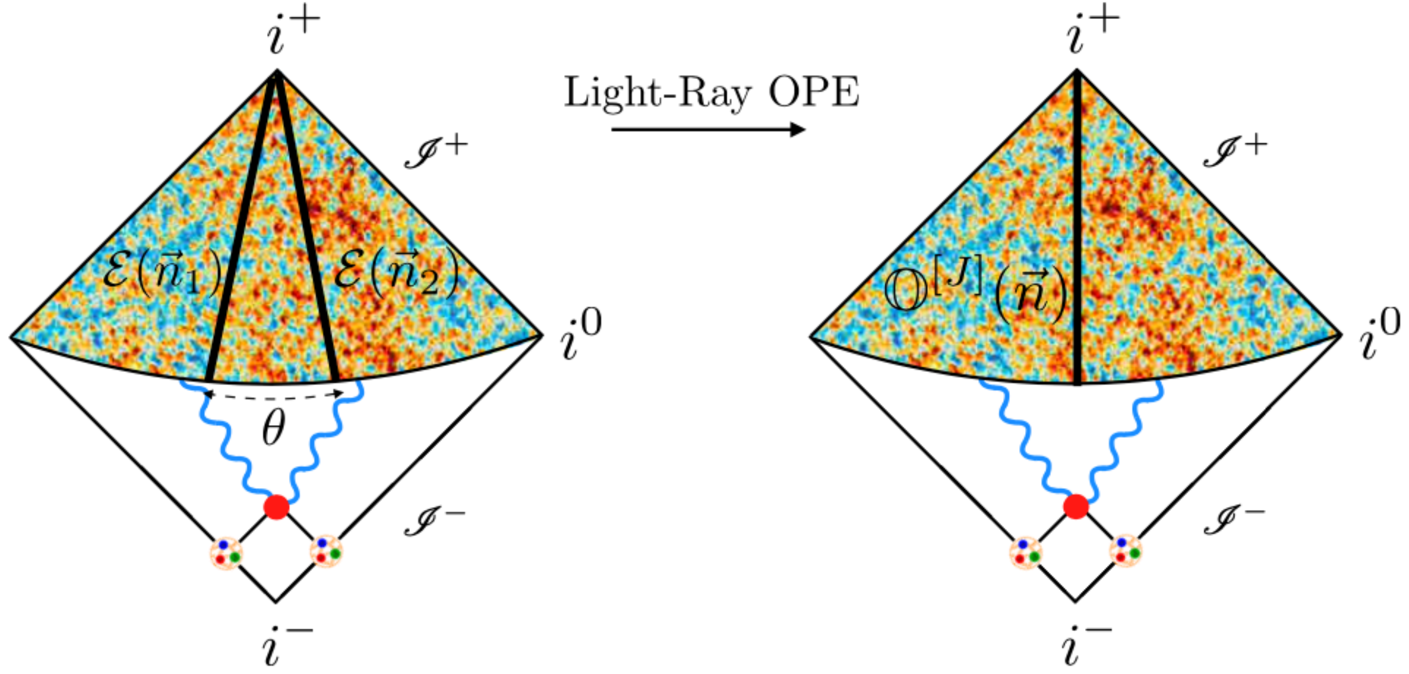
Hannah Bossi,[1] Yi Chen,[2] Yu-Chen Chen,[1] Max Jaarsma,[3,4] Yibei Li,[5] Jingyu Zhang,[2] Ian Moult,[6] Wouter Waalewijn,[3,4] Hua Xing Zhu,[7,8] Anthony Badea,[9] Austin Baty,[10] Christopher McGinn,[1] Gian Michele Innocenti,[1] Marcello Maggi,[11] and Yen-Jie Lee[1]

Why now?

- Experimental advances in unfolding
- Commensurate theory advances

Want Precision Theory Predictions for EEC event shape!

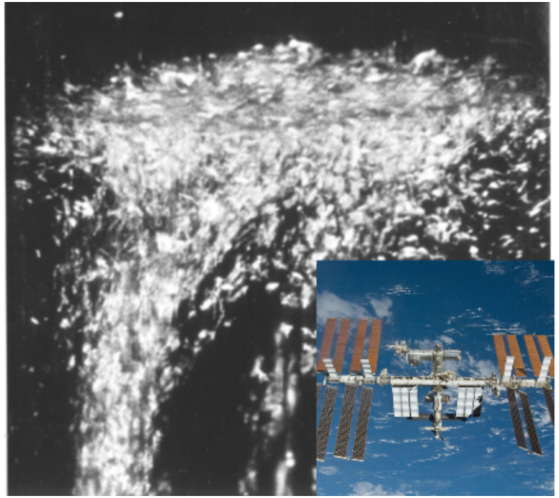
(1) Event shapes in QFT - OPE limit

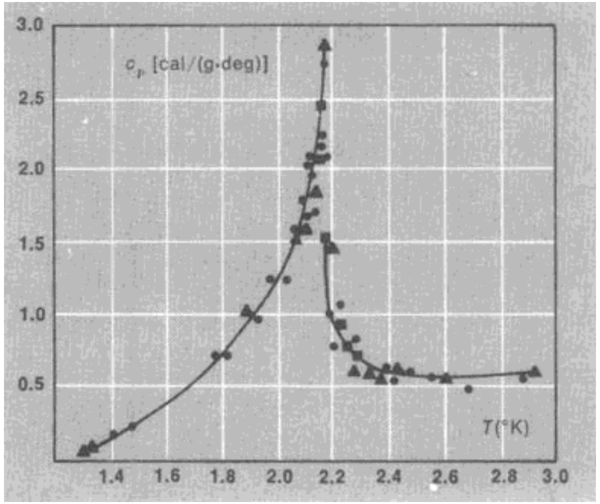


(1) Event shapes in QFT - OPE limit

- Euclidean scaling behavior is well understood in QFT

Superfluid He transition

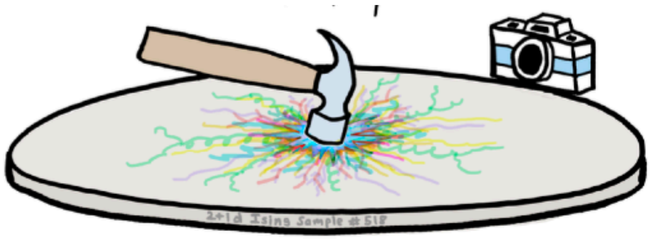




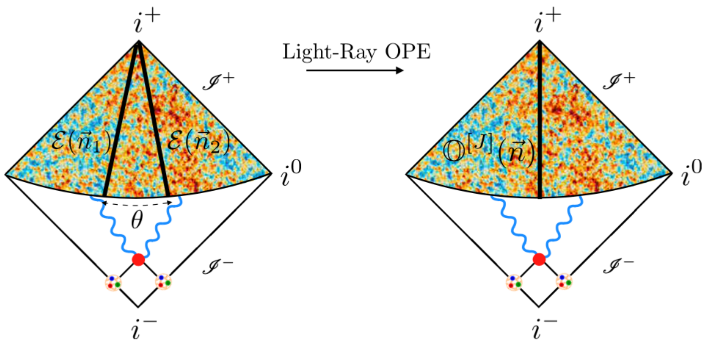
$$\mathcal{O}(x)\mathcal{O}(0) = \sum x^{\gamma_i} c_i \mathcal{O}_i$$

(1) Event shapes in QFT - OPE limit

- Formalization of "detector operators" in QFT [Caron-Huot, Kologlu, Kravchuk, Meltzer, Simmons-Duffin]



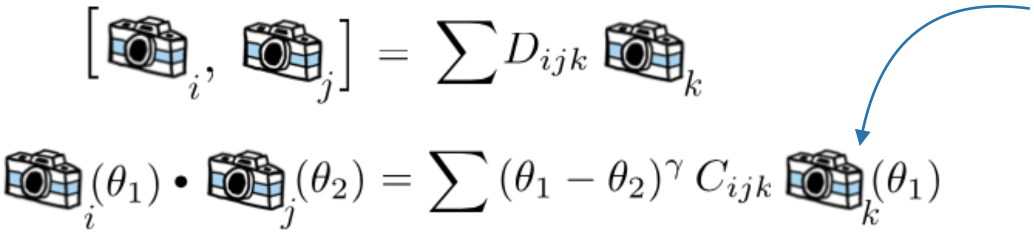
$$\mathcal{E}(\vec{n}) = \int_0^\infty dt \lim_{r\to\infty} r^2 n^i T_{0,i}(t, r\,\vec{n})$$



Light-Ray OPE is Lorentzian version

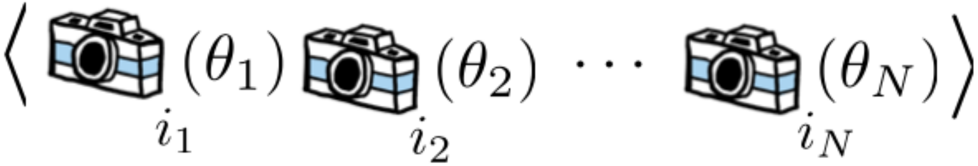
(1) Event shapes in QFT - QFT detectors

Algebra of detectors - commutators & OPE



new detectors

- “human made observables” expressed in terms of detector correlates



Can directly measure them

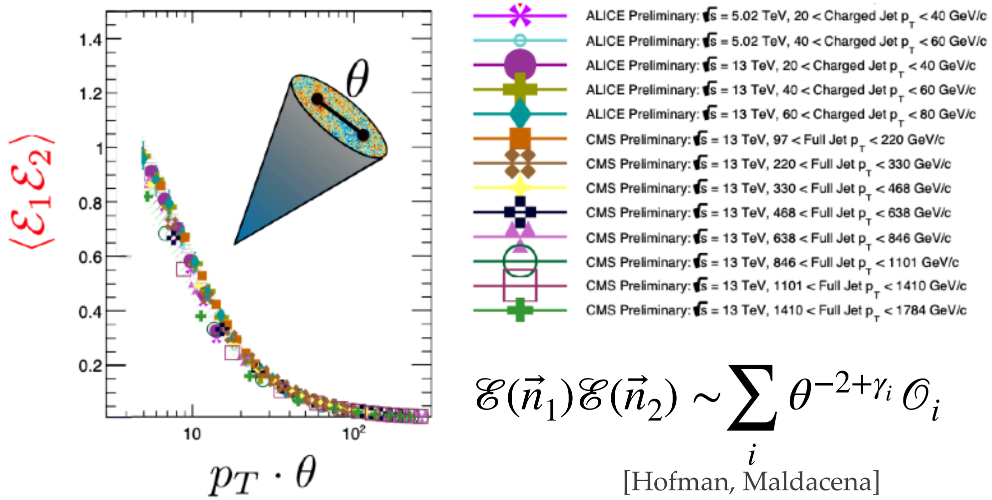
(1) Event shapes in QFT - Scaling at the LHC

- Scaling inside jets measured by STAR, ALICE, CMS

[STAR collaboration @ RHIC: 2502.15925]

[CMS: 2402.13864]

[ALICE: 2409.12687]



$$\mathscr{E}(\vec{n}_1)\mathscr{E}(\vec{n}_2) \sim \sum_i \theta^{-2+\gamma_i} \mathcal{O}_i$$

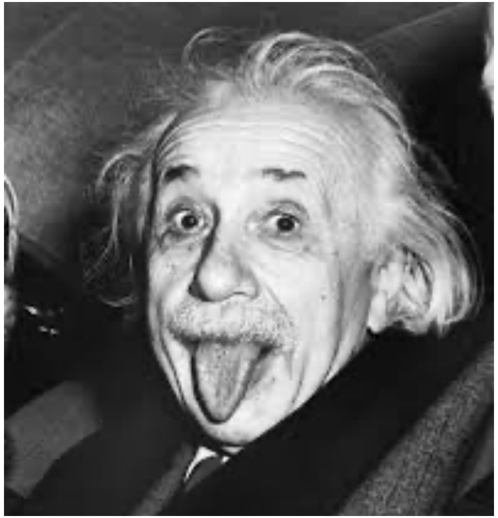
[Hofman, Maldacena]

- Related measurements allow precision extraction of α_s

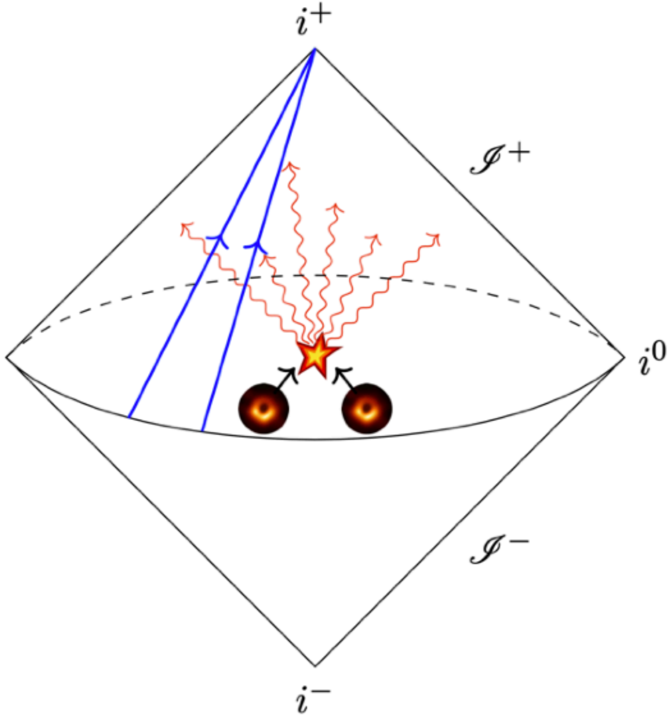
Experimental realization of detector OPE

From QCD to Gravity

$\Rightarrow$



(2) Event shapes in Gravity



(2) Event shapes in Gravity

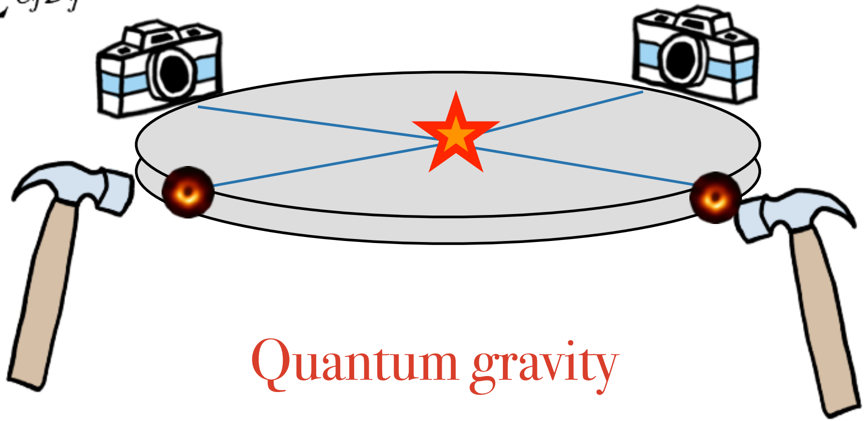
[**EH**, Kologlu, Moult: arXiv:2412.05384 + WIP]

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

QFT

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

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



Quantum gravity

Only asymptotic observables in quantum gravity

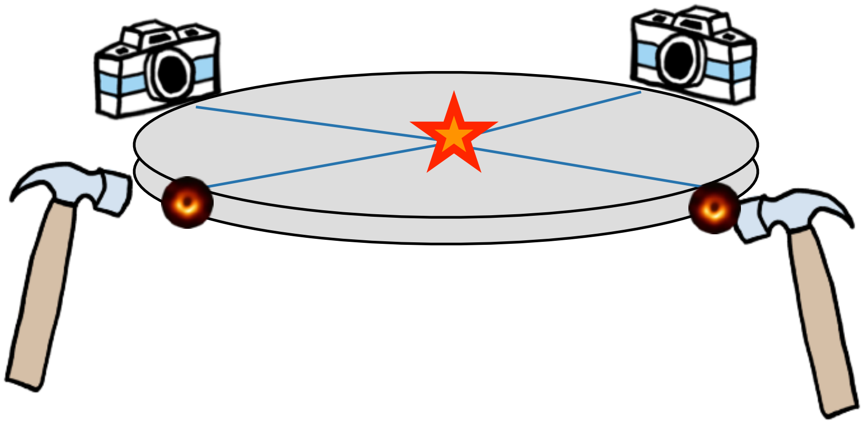
(2) Event shapes in Gravity

[**EH**, Kologlu, Moult: arXiv:2412.05384 + WIP]

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

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

local operator $\mathcal{O}$	detector $\mathcal{D}$
"measure at a point"	"measure in cross-sections"
QFT: ✓ GR: X	QFT: ✓ GR: ✓
UV divergence	IR divergence
need to renormalize	need to renormalize
theory-dependent	theory-dependent
OPE	light-ray OPE

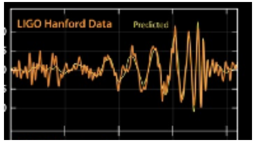


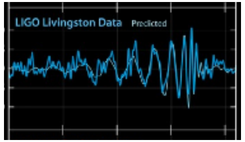
(2) Event shapes in Gravity

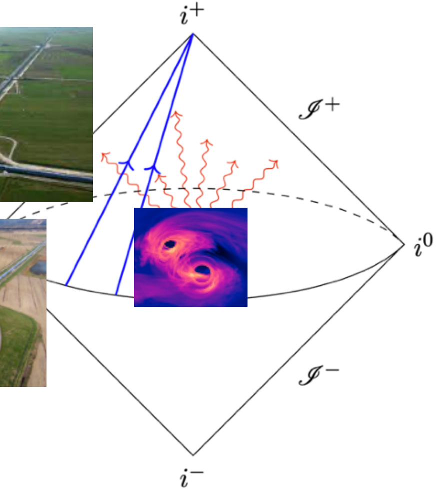
[**EH**, Kologlu, Moult: arXiv:2412.05384 + WIP]

Motivation

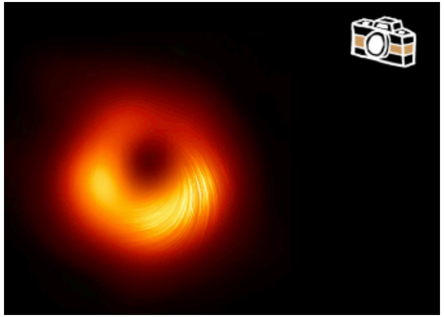
- precision calculation of classical GW observables



- What is the set of asymptotic observables in Quantum Gravity?



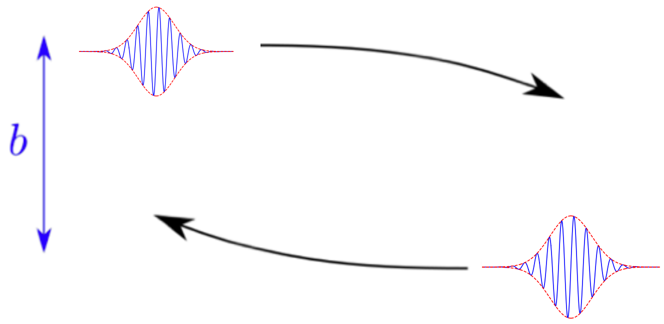
(2) Event shapes in classical Gravity

Start from quantum theory …

[Kovacs, Thorne 1978]

g) *The Feynman-Diagram Approach*

Any classical problem can be solved quantum-mechanically; and sometimes the quantum solution is easier than the classical. There is an extensive literature on the Feynman-diagram, quantum-mechanical treatment of gravita-



observable $\mathcal{O} \leftrightarrow \mathbb{O}$ quantum operator

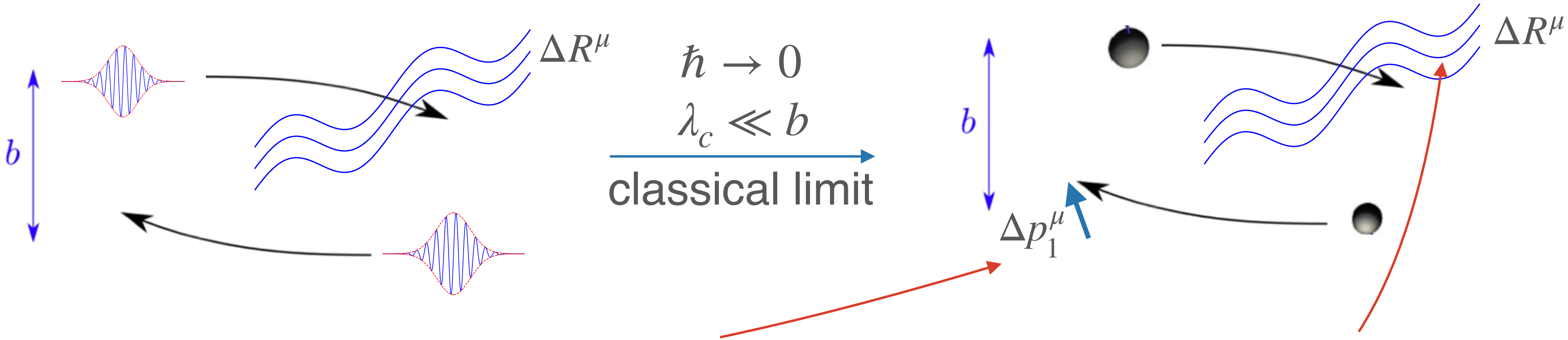
S-matrix

$$\Delta\mathcal{O} = \langle \text{out} | \mathbb{O} | \text{out} \rangle - \langle \text{in} | \mathbb{O} | \text{in} \rangle \qquad | \text{out} \rangle = S | \text{in} \rangle$$

Scattering amplitudes enter through $S = 1 + i\,\mathcal{M}$

(2) Event shapes in classical Gravity

… and take classical limit
[Kosower, Maybee, O'Connell]



Observe e.g.: deflection Δp_i^μ

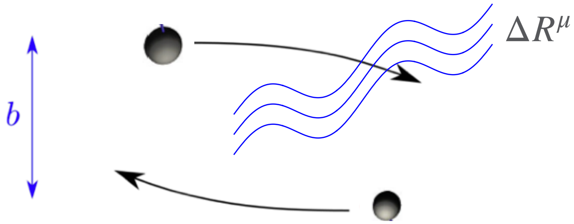
radiated momentum ΔR^μ
waveform $h^{\mu\nu}$

Black Holes effectively modeled by field theory of point particles

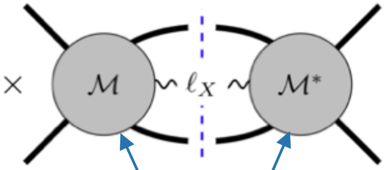
(2) Event shapes in classical Gravity

example: radiated momentum ΔR^μ & total energy loss

Gravity:

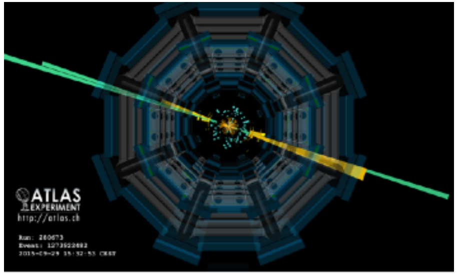


$$\Delta R^\mu = \int d\Omega \;\; \ell_X^\mu \times$$

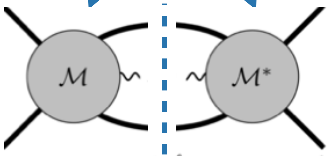


on-shell scattering amplitudes

Collider:



$$\mathbb{E}_1 = \int d\Omega \; E$$

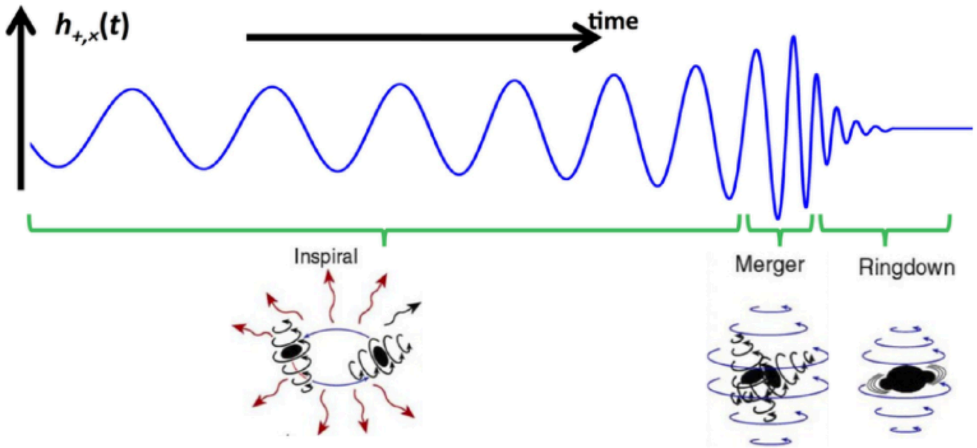


Harness progress in collider calculations for gravitational waves

(2) Event shapes in classical Gravity

example: waveform

[Bini, Damour, Geralico]
[De Angelis, Herderschee, Roiban, Teng]
[Georgoudis, Heissenberg, Russo]
[Cristofoli, Gonzo, Kosower, O'Connell]
[Jakobsen, Mogull, Plefka, Steinhoff]
[Shen]
[Buonanno et al.]
[…]



$$\langle\text{LIGO detector}\rangle \sim \text{gravitational waveform} \sim \left\langle \int d\alpha\, e^{i\omega\alpha} h_{+,\times} \right\rangle$$

c.f. "lost collider time"
[Korchemsky, Sokatchev, Zhiboedov]

Object of interest for gravitational wave astronomy

(2) Event shapes in classical Gravity

From Classical to Quantum Gravity

Classical Physics $\leftrightarrow$ No uncertainty $\langle \mathcal{O}_1 \mathcal{O}_2 \rangle = \langle \mathcal{O}_1 \rangle \langle \mathcal{O}_2 \rangle + \mathcal{O}(\hbar)$

[Cristofoli, Gonzo, Moynihan, O'Connell, Ross, Sergola, White; Gonzo Pokraka]

In the classical limit, multi-point correlators factorize

(3) Event shapes in quantum Gravity

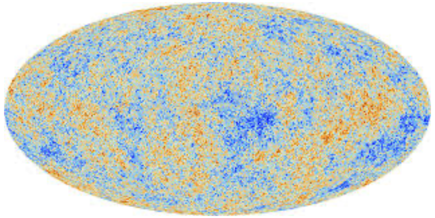
[**EH**, Kologlu, Moult: arXiv:2412.05384
[**EH**, Kologlu, Moult, Yan: SUGRA WIP]

today: focus on energy correlators

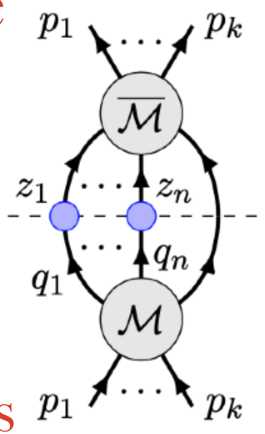
$$\mathcal{E}(z) \sim \int dt \lim_{r\to\infty} r^{d-2}\hat{n}^i T_{0i}(t, r\hat{n}) \qquad z_i = \begin{pmatrix} 1 \\ \hat{\mathbf{n}}_i \end{pmatrix}$$

energy-flow operator (ANEC)

$$\mathbb{E}_n = \langle \psi | \mathcal{E}(z_1) \cdots \mathcal{E}(z_n) | \psi \rangle$$



on-shell (amplitudes) perspective



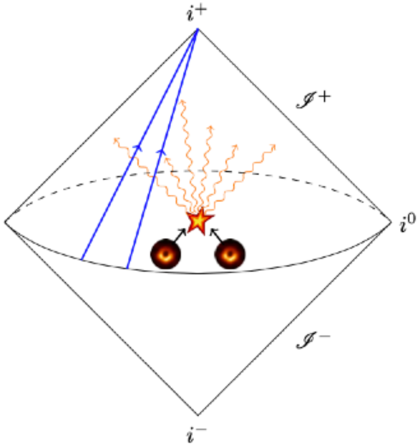
$$\mathcal{E}(z)|q_1, \ldots, q_m\rangle = \sum_{i=1}^{m} E_i\, \delta^{d-2}(\Omega_{\hat{q}_i} - \Omega_{\hat{n}})|q_1, \ldots, q_m\rangle$$

"Data Driven" approach: compute EEC and study properties

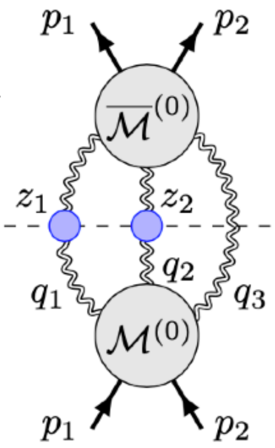
(3) Event shapes in quantum Gravity

- Simplest setup: state generated by annihilation of massive scalars

$$S_{\mathrm{EH}+\Phi} = \int d^d x \sqrt{-\mathfrak{g}} \left(\frac{1}{16\pi G_N} R + \frac{1}{2} \Phi \left(\Box - m^2 \right) \Phi \right)$$



$$\mathbb{E}_2 = \langle \Phi(p_1)\Phi(p_2) \,|\, \mathscr{E}(z_1)\mathscr{E}(z_2) \,|\, \Phi(p_1)\Phi(p_2) \rangle$$



Leading finite angle contribution

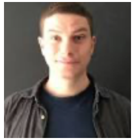
(3) Event shapes in quantum Gravity

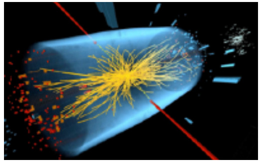
Hidden structures in Quantum Amplitudes

e.g. BCJ double-copy

[Bern, Carrasco, Johansson]



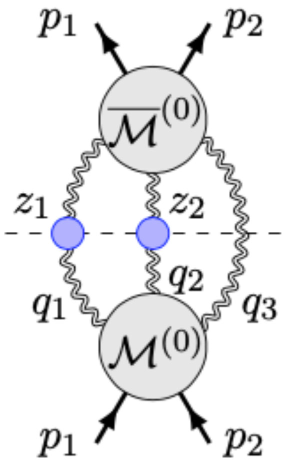



Gravity = $(\text{Yang-Mills})^2$

(3) Event shapes in quantum Gravity

$$\mathbb{E}_2^{(1)}(p_1, p_2; z_1, z_2) =$$



$$\propto \int_0^1 d\alpha \alpha^2 (1-\alpha)^2 (1-\alpha\zeta)^{-3} \left| \mathscr{M}^{\text{tree}}_{2\to 3}\left(\frac{p_i}{\sqrt{s}}; \frac{q_i^*}{\sqrt{s}}\right)\right|^2$$

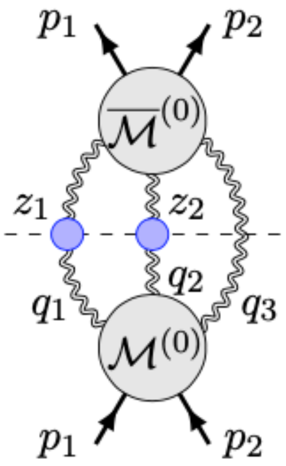
$$\zeta = \frac{1}{2}\frac{(z_1 \cdot z_2)(P \cdot P)}{(z_1 \cdot P)(z_2 \cdot P)} \qquad \chi_a = \frac{-Q \cdot z_a}{P \cdot z_a}$$

$P = p_1 + p_2 \qquad Q = p_1 - p_2$

(3) Event shapes in quantum Gravity

$$\zeta = \frac{1}{2}\frac{(z_1 \cdot z_2)(P \cdot P)}{(z_1 \cdot P)(z_2 \cdot P)} \qquad \chi_a = \frac{-Q \cdot z_a}{P \cdot z_a}$$

$\mathbb{E}_2^{(1)}(p_1, p_2; z_1, z_2) =$



$$= r^{(0)}(\zeta, \chi_1, \chi_2, x) + \sum_{i=1}^{7} r^{(i)}(\zeta, \chi_1, \chi_2, x) \times f^{(i)}(\zeta, \chi_1, \chi_2)$$

$$f^{(1)}(\zeta, \chi_1, \chi_2) = \frac{\arctan\left[\frac{\chi_2 - \chi_1 + 2\zeta\chi_1}{\sqrt{\Delta}}\right] - \arctan\left[\frac{\chi_2 - \chi_1 - 2\zeta}{\sqrt{\Delta}}\right]}{\sqrt{\Delta}},$$

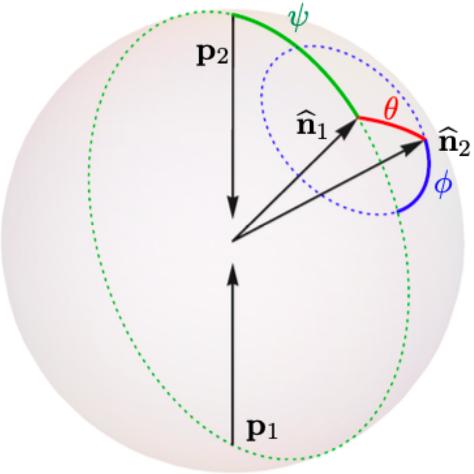
$$f^{(2)}(\zeta, \chi_1, \chi_2) = \frac{\arctan\left[\frac{\chi_2 - \chi_1 + 2\zeta}{\sqrt{\Delta}}\right] - \arctan\left[\frac{\chi_2 - \chi_1 - 2\zeta}{\sqrt{\Delta}}\right]}{\sqrt{\Delta}},$$

$$f^{(3)}(\zeta, \chi_1, \chi_2) = \log(1 - \chi_1), \qquad f^{(4)}(\zeta, \chi_1, \chi_2) = \log(1 + \chi_1),$$

$$f^{(5)}(\zeta, \chi_1, \chi_2) = \log(1 + \chi_2), \qquad f^{(6)}(\zeta, \chi_1, \chi_2) = \log(1 - \chi_2),$$

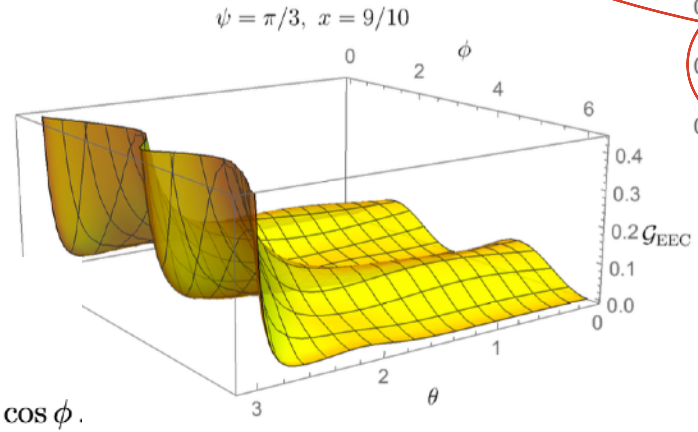
$$f^{(7)}(\zeta, \chi_1, \chi_2) = \log(1 - \zeta).$$

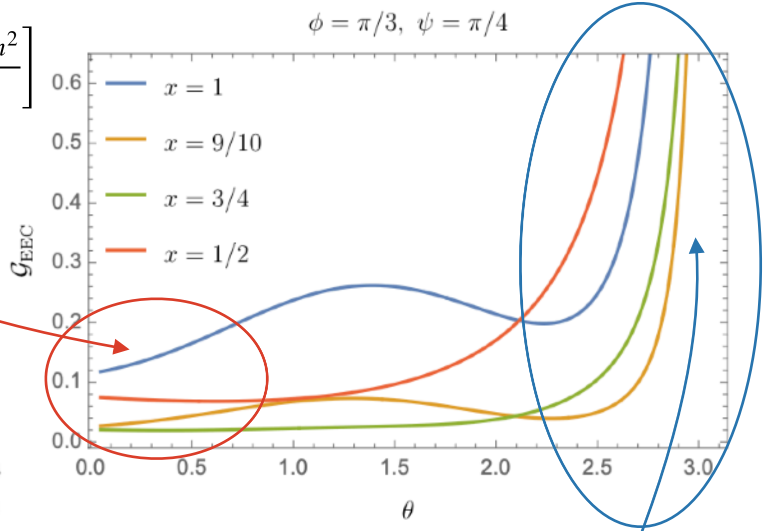
(3) Event shapes in quantum Gravity



$$\left[x^2 = \frac{-Q^2}{P^2} = \frac{s - 4m^2}{s} \right]$$

finite in collinear limit





[COM coordinates]

$$\zeta = \frac{1 - \cos\theta}{2},$$

$$\chi_1 = x \cos\psi,$$

$$\chi_2 = x \cos\theta \cos\psi - x \sin\theta \sin\psi \cos\phi \,.$$

back-to-back
soft singularity

$$\mathbb{E}_2(\theta \to \pi) \sim \frac{\#}{(\theta - \pi)^2}$$

(4) Celestial OPE

[EH, Kologlu, Moult, Yan]

Diagonalizing boosts

[see also Chen, Ruan, Zhu]

- For $p_i^2 = 0$ (massless initial state particles), close to conformal correlators on S^2

$$\mathbb{E}_n = \langle p_1, p_2 | \mathcal{E}(z_1) \cdots \mathcal{E}(z_n) | p_1, p_2 \rangle$$

- Homogeneous in z_a with celestial scaling dim. $\delta_a = -J_{La}$
- Overall scaling in $p_i \sim \lambda\, p_i$ fixed by total energy dimension Δ_E

Relative boost $p_1 \sim \lambda^{\frac{1}{2}} p_1\,, \quad p_2 \sim \lambda^{-\frac{1}{2}} p_2$ not fixed!

(4) Celestial OPE

[EH, Kologlu, Moult, Yan]

Mellin transform in the relative boost

$$\mathbf{E}_{n,\gamma}(p_1, p_2; z_a) = \int_0^\infty d\lambda \lambda^{-\gamma-1} \mathbf{E}_n(\lambda^{1/2} p_1, \lambda^{-1/2} p_2; z_a) .$$

Now eigenstates under individual boosts:

$$\mathbf{E}_{n,\gamma}(\lambda_1 p_1, \lambda_2 p_2; z_a) = \lambda_1^{\gamma+\Delta_E/2} \lambda_2^{-\gamma+\Delta_E/2} \mathbf{E}_{n,\gamma}(p_1, p_2; z_a) .$$

Defined celestial scaling dimensions

$$\delta_0 = -\gamma - \Delta_E/2 \quad \text{and} \quad \delta_{\bar{0}} = \gamma - \Delta_E/2 .$$

Inverse given by

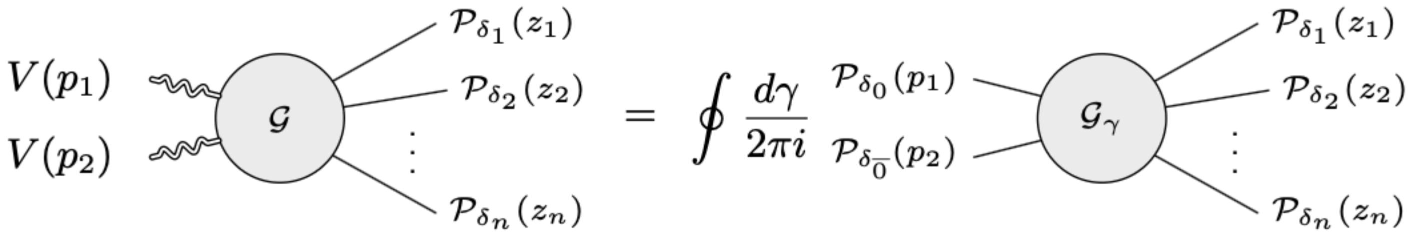
$$\mathbf{E}_n(p_i; z_a) = \oint \frac{d\gamma}{2\pi i} \mathbf{E}_{n,\gamma}(p_i; z_a) .$$

(4) Celestial OPE

[EH, Kologlu, Moult, Yan]

Celestial conformal correlators

$$\mathbf{E}_n(p_1, p_2; z_a) = \langle\!\langle V(p_1)V(p_2)\mathcal{P}_{\delta_1}(z_1)\cdots\mathcal{P}_{\delta_n}(z_n)\rangle\!\rangle$$
$$= \oint \frac{d\gamma}{2\pi i}\langle\!\langle \mathcal{P}_{\delta_0}(p_1)\mathcal{P}_{\delta_{\bar{0}}}(p_2)\mathcal{P}_{\delta_1}(z_1)\cdots\mathcal{P}_{\delta_n}(z_n)\rangle\!\rangle\,.$$

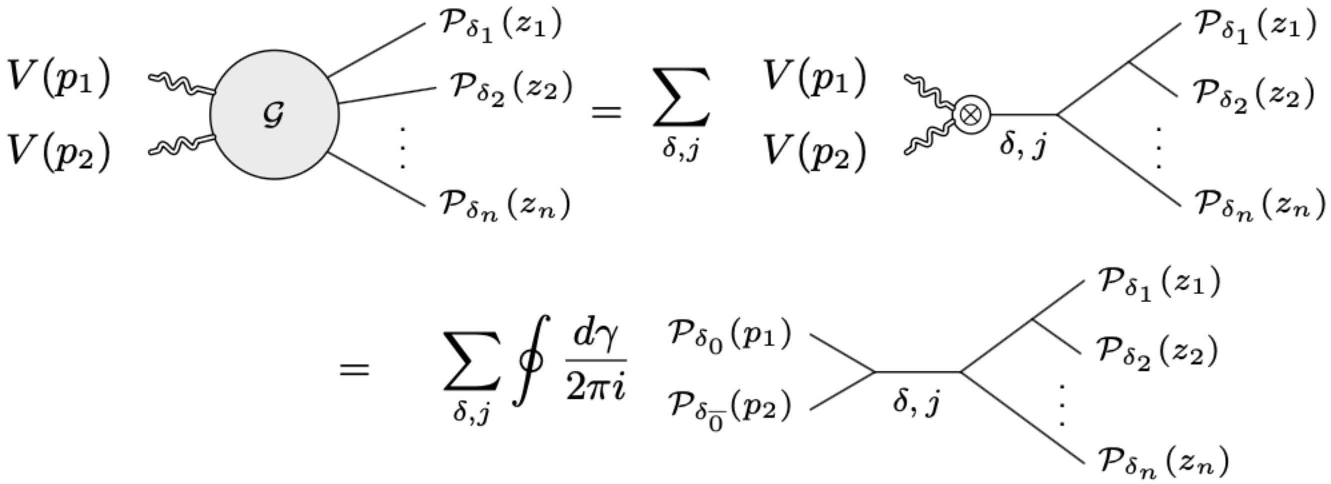


RHS are conformal structures $\quad p_1 = \omega_1 z_0\,, \quad p_2 = \omega_2 z_{\bar{0}}$

(4) Celestial OPE

[EH, Kologlu, Moult, Yan]

Celestial conformal correlators and the OPE



Expand in conformal partial waves as consequence of Lorentz symmetry

(4) Celestial OPE

[EH, Kologlu, Moult, Yan]

Collider Cross Ratios

$$U \equiv Z\bar{Z} = \frac{(p_1 \cdot p_2)(z_1 \cdot z_2)}{(p_1 \cdot z_1)(p_2 \cdot z_2)}, \quad V \equiv (1-Z)(1-\bar{Z}) = \frac{(p_1 \cdot z_2)(p_2 \cdot z_1)}{(p_1 \cdot z_1)(p_2 \cdot z_2)}, \quad W = \frac{(p_1 \cdot z_1)}{(p_2 \cdot z_1)}.$$

Related to previous CoM cross ratios as

$$\zeta = \frac{UW}{(1+W)(1+VW)}, \quad \chi_1 = \frac{1-W}{1+W}, \quad \chi_2 = \frac{1-VW}{1+VW}.$$

Mellin transform in γ ~ Mellin transform in W

(4) Celestial OPE

[EH, Kologlu, Moult, Yan]

EEC in $\mathcal{N} = 8$ Supergravity

$$\langle p_1 p_2 | \mathcal{E}(z_1) \mathcal{E}(z_2) | p_1 p_2 \rangle = \frac{2 p_1 \cdot p_2}{(2 z_1 \cdot z_2)^3} \mathcal{G}(Z, \overline{Z}, W) \,.$$

In collider variables,

$$\mathcal{G}^{(1),\mathcal{N}=8}_{\text{EEC}} = \frac{W (Z\overline{Z})^3 \left(Z - \overline{Z}\right)}{8(1-Z)\left(1-\overline{Z}\right)\left(1+W(1-Z)\right)\left(1+W\left(1-\overline{Z}\right)\right)} \times \left(\frac{\log[1-Z]}{\overline{Z}\left(Z + W\overline{Z}(1-Z)\right)} - \frac{\log\left[1-\overline{Z}\right]}{Z\left(\overline{Z} + WZ\left(1-\overline{Z}\right)\right)} + \frac{\left(1 - W^2(1-Z)\left(1-\overline{Z}\right)\right)\log\left[\frac{1+W\left(1-\overline{Z}\right)}{1+W(1-Z)}\right]}{\left(\overline{Z} + WZ\left(1-\overline{Z}\right)\right)\left(Z + W\overline{Z}(1-Z)\right)} \right) .$$

(4) Celestial OPE

[EH, Kologlu, Moult, Yan]

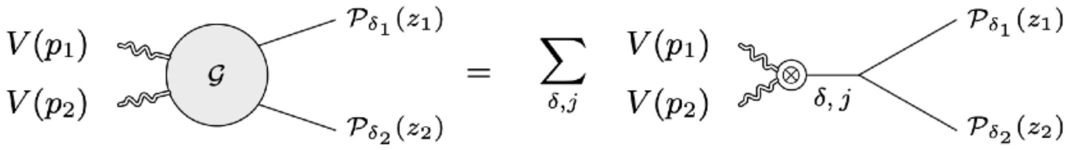
Mellin transform

$$
\begin{aligned}
\mathcal{G}_{\gamma}^{(1),\mathcal{N}=8} = {} & \frac{\pi \csc(\pi\gamma)(Z\overline{Z})^3}{8(1-Z)(1-\overline{Z})(\overline{Z}-Z)} \Bigg[\left((1-Z)^{\gamma} - (1-\overline{Z})^{\gamma}\right) \\
& \times \left(\frac{(1-Z)\log(1-\overline{Z})}{Z} + \frac{(1-\overline{Z})\log(1-Z)}{\overline{Z}} + \log(\overline{Z}-Z) + H(\gamma) \right) \\
& + \left(\frac{\overline{Z}}{Z}\right)^{\gamma} (1-Z)^{\gamma} B\left(\frac{Z}{\overline{Z}};\gamma+1,0\right) - \left(\frac{Z}{\overline{Z}}\right)^{\gamma} (1-\overline{Z})^{\gamma} B\left(\frac{\overline{Z}}{Z};\gamma+1,0\right) \\
& + (1-Z)^{\gamma} B\left(\frac{1-\overline{Z}}{1-Z};\gamma+1,0\right) - (1-\overline{Z})^{\gamma} B\left(\frac{1-Z}{1-\overline{Z}};\gamma+1,0\right) \\
& + \left(\frac{Z}{\overline{Z}}\right)^{\gamma} (1-\overline{Z})^{\gamma} B\left(\frac{\overline{Z}(1-Z)}{Z(1-\overline{Z})};\gamma+1,0\right) \\
& - \left(\frac{\overline{Z}}{Z}\right)^{\gamma} (1-Z)^{\gamma} B\left(\frac{Z(1-\overline{Z})}{\overline{Z}(1-Z)};\gamma+1,0\right) \Bigg].
\end{aligned}
$$

(4) Celestial OPE

[EH, Kologlu, Moult, Yan]

Detector OPE in gravity



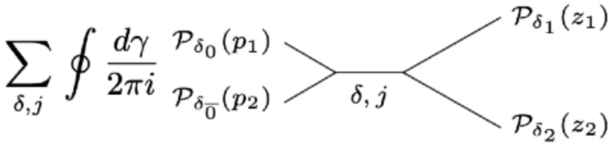
$\mathcal{G}_\gamma$ can be decomposed into conformal blocks on the celestial sphere,

$$\mathcal{G}_\gamma(Z, \overline{Z}) = \sum_{\delta,j} c_{\delta,j,\gamma}\, g^{(\gamma)}_{\delta,j}(Z, \overline{Z})\,.$$

First few terms in the detector OPE, for celestial dimensions $\delta = 6$

$$c_{\delta=6,j=0,\gamma} = \frac{1}{4}\pi\gamma\csc(\pi\gamma)\,,$$

$$c_{\delta=6,j=2,\gamma} = -\frac{1}{8}\pi\gamma\csc(\pi\gamma)\,,$$



(4) Celestial OPE

[EH, Kologlu, Moult, Yan]

Detector OPE in gravity from Lorentzian Inversion Formula

[Caron-Huot]

Can perform this analytically via the LIF on the celestial sphere.

For example, for the pole at $\gamma = 1$, we get for twist $\tau = 4, 6, 8$ trajectories:

$$c_{\gamma=1}(\delta = 4 + j, j) = \frac{1 + (-1)^j}{2} \frac{\Gamma(j+1)\Gamma(j+2)}{4\,\Gamma(2j+3)} \Big[2 + (j+1)(j+2)\big(1 - 2H_{j+1}\big)\Big],$$

$$c_{\gamma=1}(\delta = 6 + j, j) = \frac{1 + (-1)^j}{2} \frac{\Gamma(j+3)\Gamma(j+4)}{8\,\Gamma(2j+5)} \Big[1 + 2H_{j+2}\Big],$$

$$c_{\gamma=1}(\delta = 8 + j, j) = \frac{1 + (-1)^j}{2} \frac{\Gamma(j+3)\Gamma(j+4)}{40\,\Gamma(2j+7)} \Big[4 - (j+3)(j+4)\big(3 + 4H_{j+3}\big)\Big].$$

(4) Celestial OPE

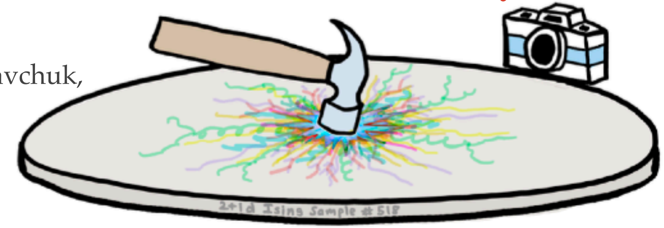
What is the celestial OPE good for?

Simplify computations using conformal symmetry

Expose universal kinematic structures based on symmetry alone (conformal blocks)

Completing the circle

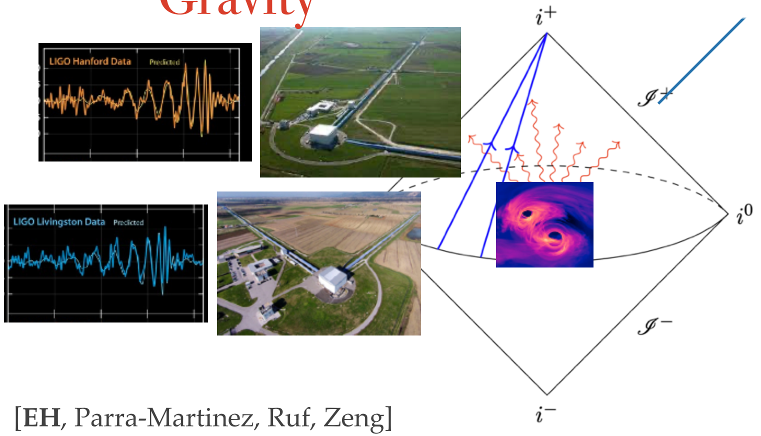
Formal Theory

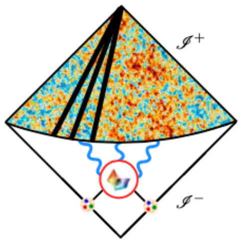


[Hofman, Maldacena]
[Korchemsky, Sterman]
[Caron-Huot, Kologlu, Kravchuk, Meltzer,Simmons-Duffin]

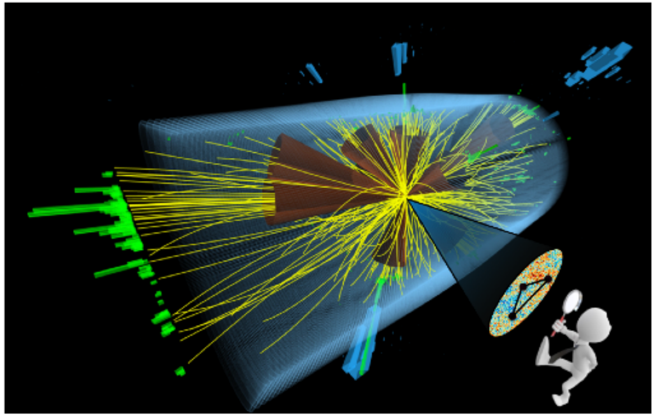
[Sterman] [Basham,Brown,Ellis,Love]
[Dixon, Moult, Zhu, …] […]
[**EH**, Kang, Penttala, Zhang]

Gravity





Colliders



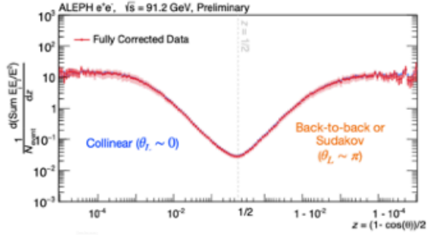
[**EH**, Parra-Martinez, Ruf, Zeng]
[**EH**, Kologlu, Moult] **EH**, Kologlu, Moult, Yan]

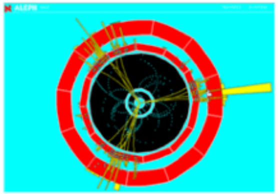
Future Directions

(5) Future directions - Colliders

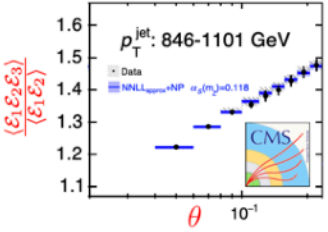
- Bridge theory and experiment across collider systems
- QCD precision studies
- Hadronization

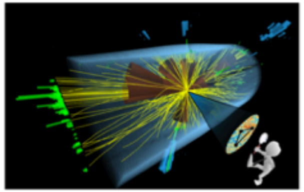
e^+e^-





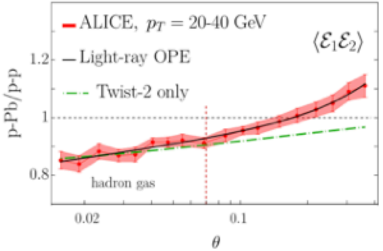
p-p

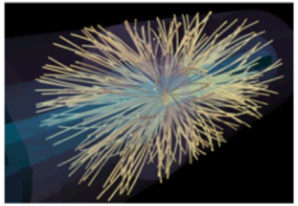




- Nuclear Physics

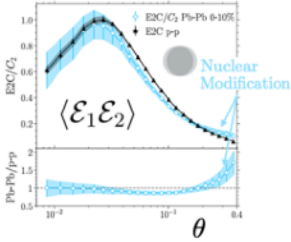
p-Pb

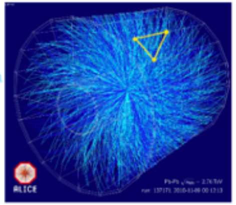




Pb-Pb

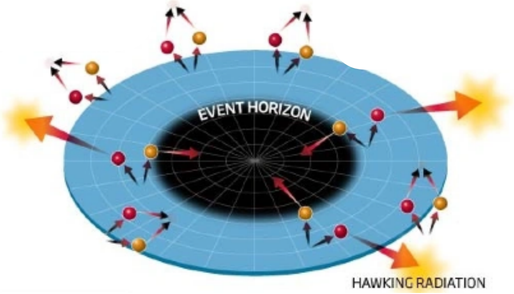
- Quark Gluon Plasma





(5) Future directions - Quantum Gravity

- full spectrum of asymptotic observables in gravity?
- beyond S-matrices, new flagship observables in gravity?
- unified description of scattering states and detectors?
- more general detectors and their renormalization
- correlations in Hawking radiation processes?
- Improved understanding of asymptotic symmetries (BMS) and organization of detectors in representations?



Thank you!