Beautiful and Charming Energy Correlators

SCET 2022

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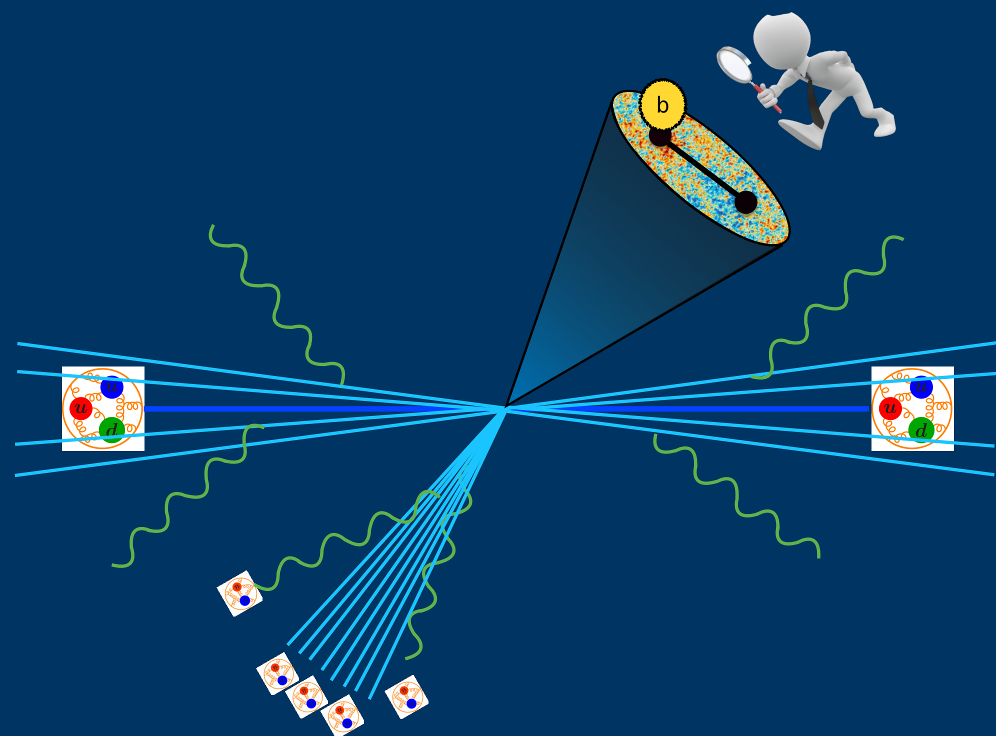
Work in preparation with Ian Moult and Kyle Lee



Talk layout

- Jet-substructure at particle colliders
- Introducing energy correlators to jet-substructure
- Energy-Energy correlators for light quarks
- Energy-energy correlators for heavy quarks: dead-cone effect
- Conclusions

Jet substructure (JSS) at particle colliders

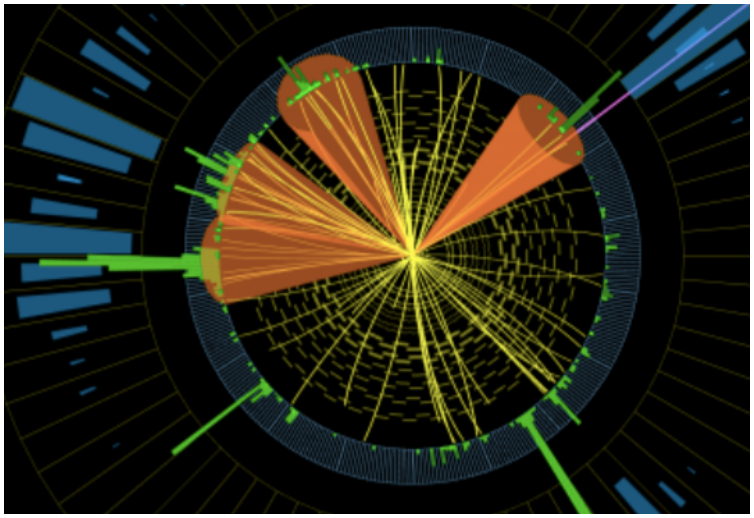
Study the internal kinematic properties of jets

- Powerful tool to study QCD dynamics and probe New Physics.

↓

- Is there a way to study JSS from field theory first principles (symmetries, computation techniques etc)?

YES



Jet substructure (JSS) at particle colliders

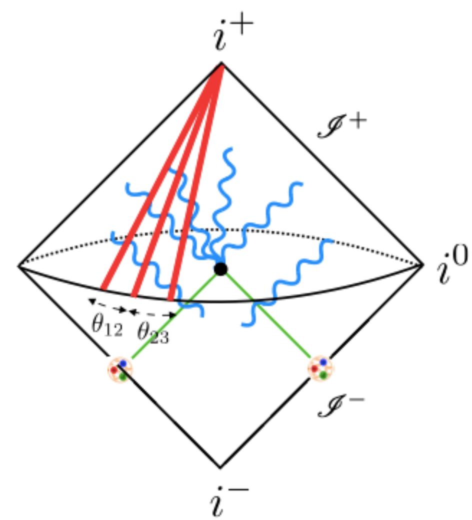
Energy Correlators

- Energy deposit in a calorimeter cell at infinity ⇒energy flow/light ray operators.

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

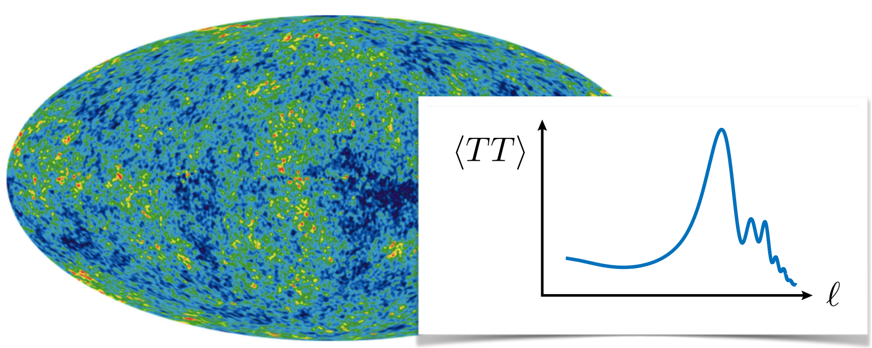
[Korchemsky, Tkachov, Sterman, Sveshnikov]

[Hofman and Maldacena 2008]



- Distribution of energy inside the jet is described by correlation functions of the energy flow operators ⇒energy correlators.

$$\langle \Psi \mid \varepsilon(\vec{n}_1)\varepsilon(\vec{n}_1)\ldots\varepsilon(\vec{n}_n) \mid \Psi \rangle$$



Similar idea with the CMB measurements!

Clearly illustrates dynamics at particular scale.

Energy correlators for JSS

They are intrinsically IR-safe observable and not sensitive to soft radiation!

$$\langle \Psi \mid \varepsilon(\overrightarrow{n}_1)\varepsilon(\overrightarrow{n}_1)\ldots\varepsilon(\overrightarrow{n}_n) \mid \Psi \rangle$$

- Here we focus on the two-point function: energy-energy correlators (EEC)

$$\langle \Psi \mid \varepsilon(\overrightarrow{n}_1)\varepsilon(\overrightarrow{n}_2) \mid \Psi \rangle$$

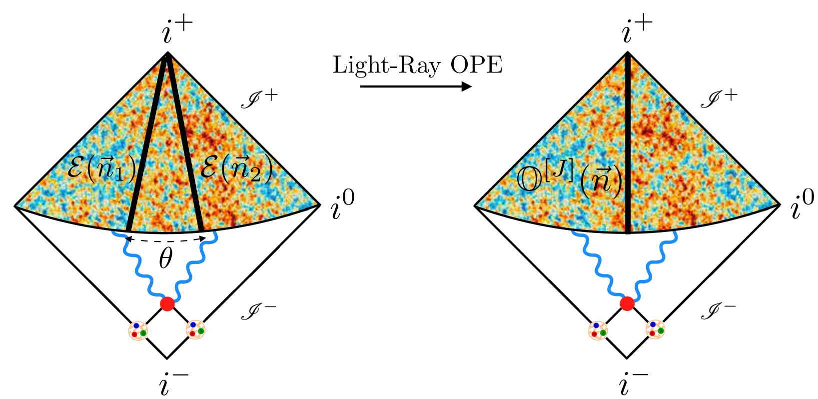
[Basham, Brown, Ellis, Love]

- Study of JSS at high energies corresponds to the small angle limit of the energy correlators (highly boosted).

⇒ Universal scaling behavior in this limit!

$$\langle \Psi \mid \varepsilon(\overrightarrow{n}_1)\varepsilon(\overrightarrow{n}_2) \mid \Psi \rangle \sim \sum \theta^{\gamma_i}\mathcal{O}_i(\overrightarrow{n}_1)$$

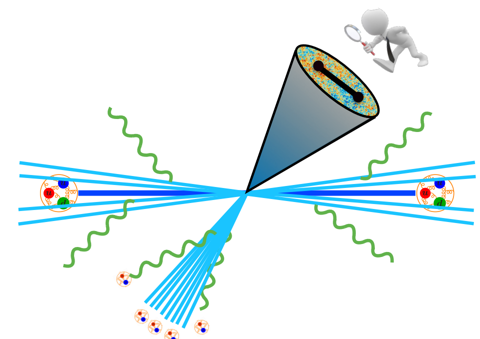
[Hofman, Maldacena]
[Chang, Kologlu, Kravchuk, Simmons Duffin, Zhiboedov]



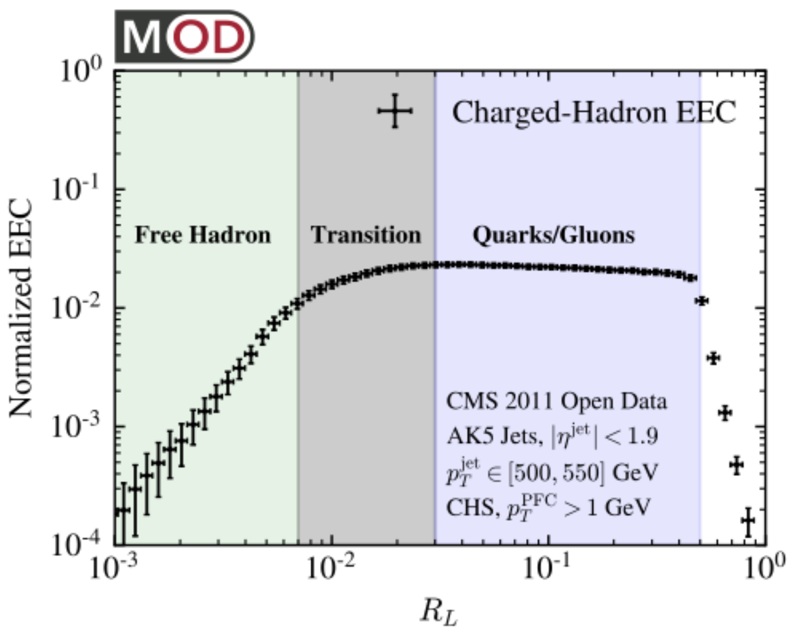
⇒Can probe the collinear substructure of the jet in a clean way.

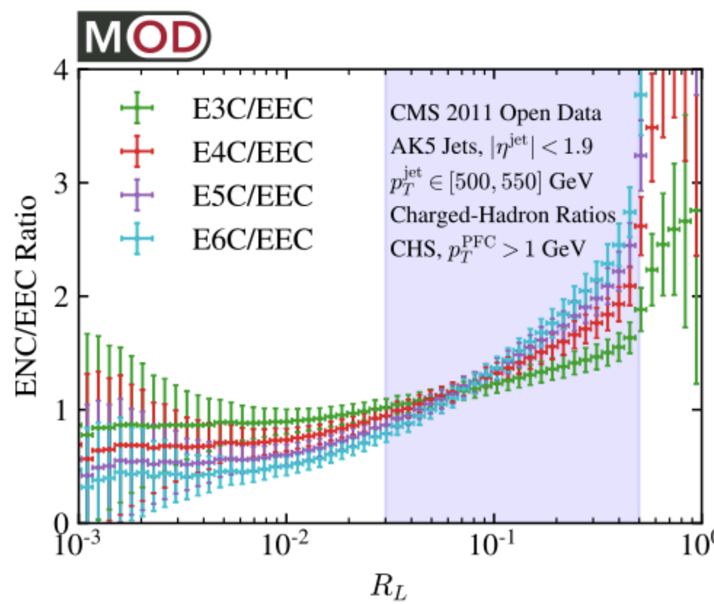
Looking inside the jets with EEC

Light quark jets from LHC open data



- **There is a distinct scaling behavior for uniformly distributed free-hadrons and free quarks/gluons.**





[Komiske, Moult, Taler, Zhu]

Anomalous scaling in the perturbative region .

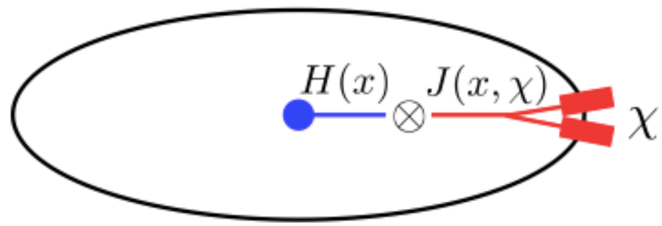
EEC correlators in light quarks

Small angle limit in $e^+e^- \to q\bar{q}g$

- EEC is the weighted cross-section by the energy in each detector separated by the small angle:

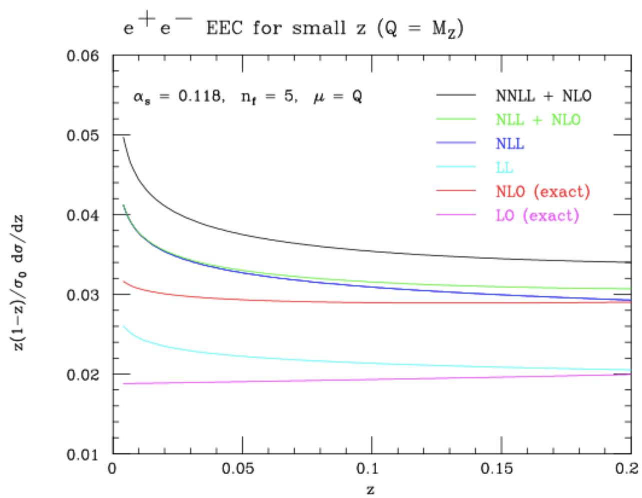
$$\frac{d\sigma}{dz} = \sum_{i,j} \int d\sigma \, \frac{E_i E_j}{Q^2} \delta\left(z - \frac{1 - \cos\chi_{ij}}{2}\right)$$

$$0 \leq z = \frac{1 - \cos\chi}{2} \leq 1$$



Factorization formula

$$\sum(z, \mu, \ln\frac{Q^2}{\mu^2}) = \vec{J}(\mu, \ln\frac{zx^2Q^2}{\mu^2}) \otimes \vec{H}(\mu, x, \frac{Q^2}{\mu^2})$$



[Dixon, Moult, Zhu]

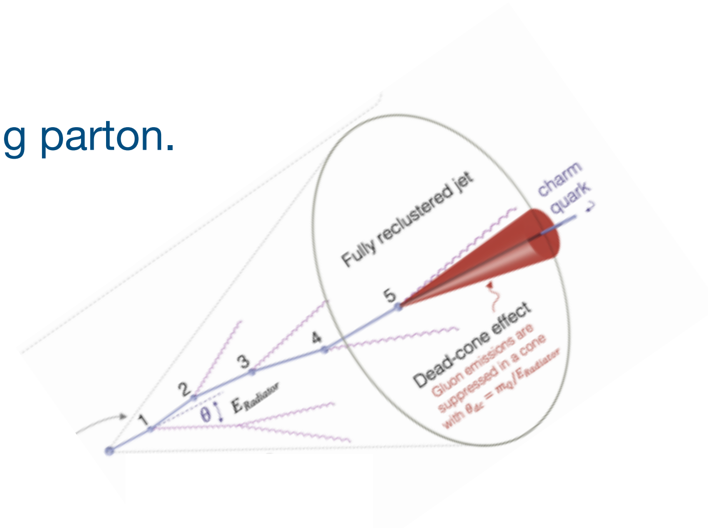
Scale evolution is governed by the time-like splitting kernels

$$\gamma_T^{(0)} = \begin{pmatrix} \frac{25}{6}C_F & -\frac{7}{15}n_f \\ -\frac{7}{6}C_F & \frac{14}{5}C_A + \frac{2}{3}n_f \end{pmatrix}$$

Dead-cone effect in QCD

Fundamental phenomena

- Parton-shower pattern depends on the mass of the emitting parton.
- Angular suppression $\propto \frac{M}{E}$.



First observation for QCD by ALICE collab in [2106.05713]

Observable used for the observation of the dead-cone effect in LHC data

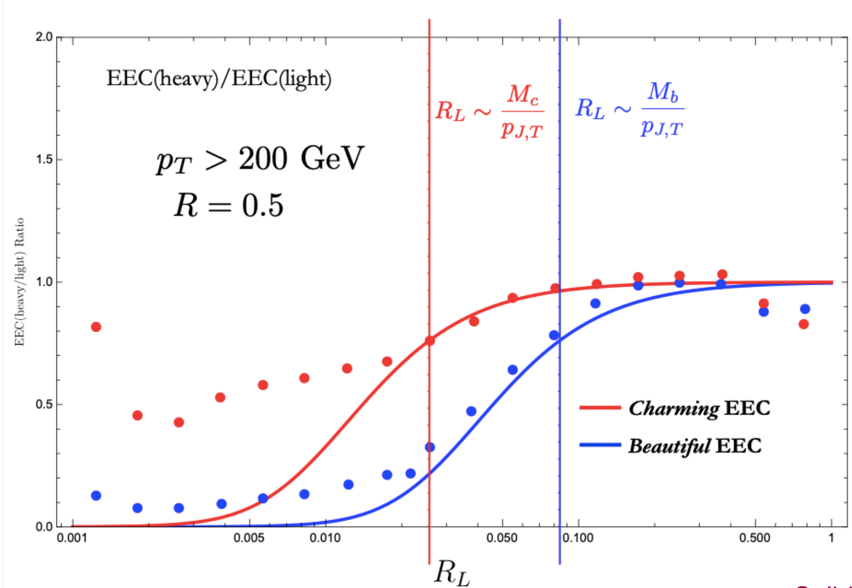
$$R(\theta) = \frac{1}{N^{\mathrm{D^0\,jets}}} \frac{\mathrm{d}n^{\mathrm{D^0\,jets}}}{\mathrm{d}\ln(1/\theta)} \Bigg/ \frac{1}{N^{\mathrm{inclusive\,jets}}} \frac{\mathrm{d}n^{\mathrm{inclusive\,jets}}}{\mathrm{d}\ln(1/\theta)} \Bigg|_{k_{\mathrm{T}}, E_{\mathrm{Radiator}}}$$

- This is not an IR-safe observable.
- Not possible to calculate it from first principles in QFT.

Dead-cone effect with energy correlators

Probe it from bottom and charm quarks EEC

- EEC can be computed in perturbation theory ⇒ compare measurements with predictions.
- It can be a very clean observable due to the advantage of the small angle limit.



- **Can easily observe the change of shape around the heavy quark scale.**
- **Both MC and fixed order results have a suppression at small angles.**

⇓

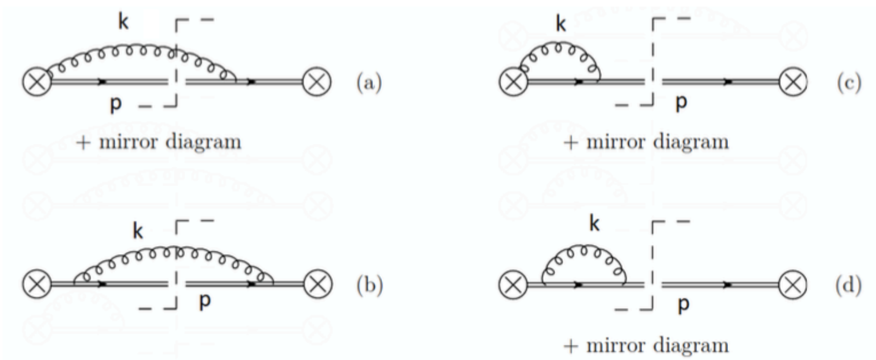
Possibly a manifestation of the dead-cone effect

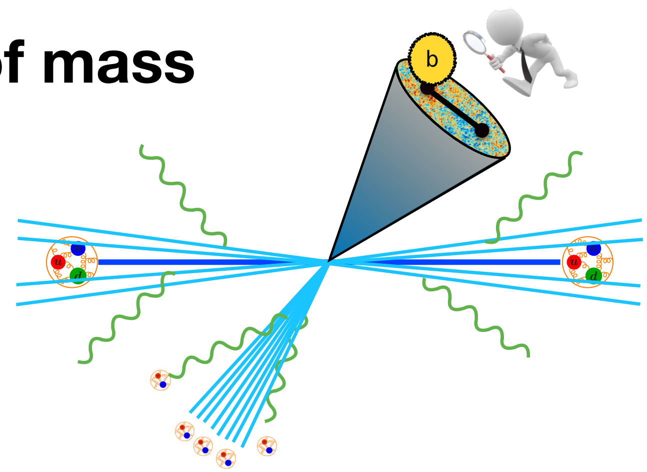
Solid line: Fixed order
Points are generated with Pythia

[Lee, BM, Moult-in preparation]

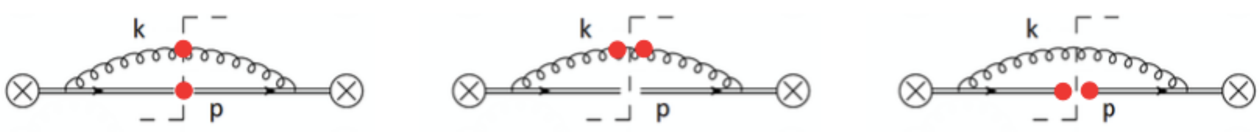
Heavy quark jet function

Non-trivial calculation due to the presence of mass

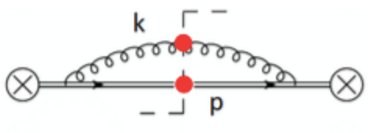




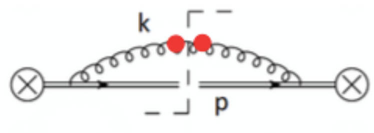
- The quark and gluon here share energy fractions x and (1-x) of the initial heavy quark energy.
- For the EEC the jet function is weighted by these energies.
- This corresponds to three different ways the “detectors” can be places.



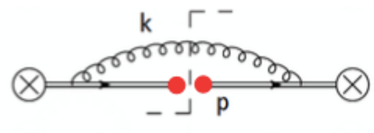
Heavy quark jet function



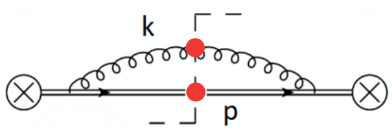
$\ni x(1-x)\delta(z - \frac{1-\cos\chi_{12}}{2})$



$\ni (1-x)^2\delta(z)$



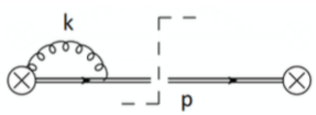
$\ni x^2\delta(z)$



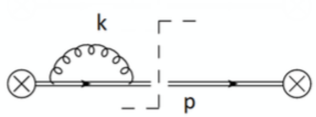
$$= \frac{\alpha_s C_F}{\pi}\frac{1}{z}\left[\frac{3}{4} - \frac{5}{2}\delta^2 - \frac{\delta^4}{1+\delta^2} + 3\delta^3 \arctan\left(\frac{1}{\delta}\right) + \frac{1}{2}\delta^2(1-\delta^2)\ln\frac{\delta^2}{1+\delta^2}\right]$$

$$\delta^2 = \frac{M^2}{Q^2 z^2}$$

For the virtual diagrams the dependance is trivial, namely multiply the result by $\delta(z)$



$$-\frac{3}{4}\frac{\alpha_s C_F}{\pi}\delta(z)\left[\frac{1}{\epsilon} + \ln\frac{\mu^2}{M^2}\right]$$

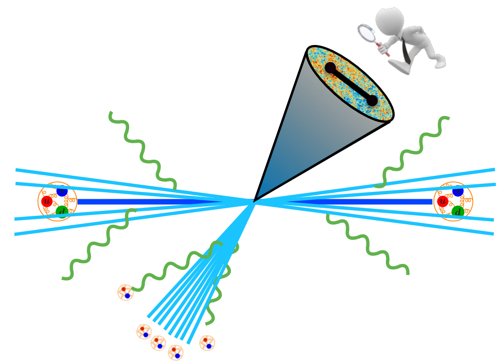


$$\frac{\alpha_s C_F}{\pi}\delta(z)\left[\frac{1}{2\epsilon^2} + \frac{1}{\epsilon}\left(1 + \frac{1}{2}\ln\frac{\mu^2}{M^2}\right) + \frac{1}{4}\ln^2\frac{\mu^2}{M^2} + \ln\frac{\mu^2}{M^2} + \frac{\pi^2}{24} + 2\right]$$

[Lee, BM, Moult-in preparation]

Heavy quark jet function

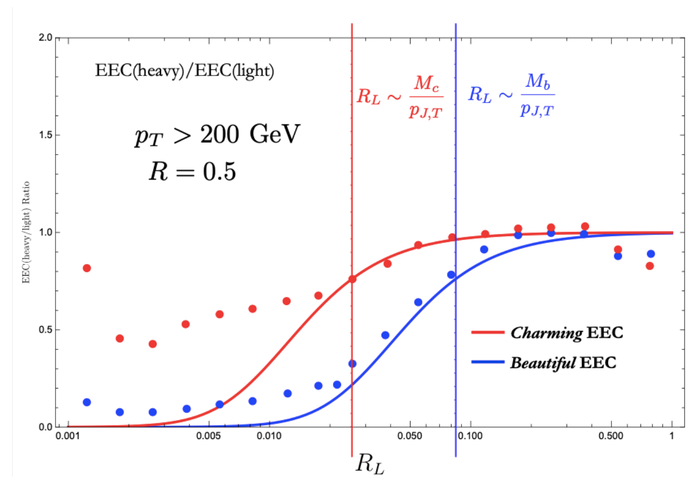
Result



$$J_Q^{\mathrm{bare}}(z,M,\mu) = \delta(z)\left(1+\frac{\alpha_s C_F}{4\pi}\left[-\left(\gamma_{qq}^{(0)}(3)+\gamma_{gq}^{(0)}(3)\right)\left(\frac{1}{\epsilon_{\mathrm{UV}}}+\ln\frac{\mu^2}{M^2}\right)-\frac{19}{6}\right]\right)$$
$$+\frac{\alpha_s C_F}{\pi}\frac{1}{z}\left[\frac{3}{4}-\frac{5}{2}\delta^2-\frac{\delta^4}{1+\delta^2}+3\delta^3\arctan\left(\frac{1}{\delta}\right)+\frac{1}{2}\delta^2(1-\delta^2)\ln\frac{\delta^2}{1+\delta^2}\right]$$

The mass should not affect the UV behavior of the jet function.
This can be seen from comparing the UV poles with the light quark jet function.

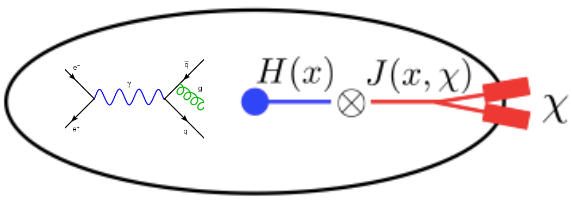
$$J_q^{\mathrm{bare}}(z,\mu) = \delta(z)+\frac{\alpha_s C_F}{4\pi}\left[\delta(z)\left(-\frac{3}{\epsilon_{\mathrm{UV}}}-\frac{37}{3}\right)+3\frac{Q^2}{\mu^2}\mathcal{L}_0\left(\frac{Q^2}{\mu^2}z\right)\right]$$
$$= \delta(z)+\frac{\alpha_s C_F}{4\pi}\left[\delta(z)\left(-\left(\gamma_{qq}^{(0)}(3)+\gamma_{gq}^{(0)}(3)\right)\frac{1}{\epsilon_{\mathrm{UV}}}-\frac{37}{3}\right)+3\frac{Q^2}{\mu^2}\mathcal{L}_0\left(\frac{Q^2}{\mu^2}z\right)\right]$$



[Lee, BM, Moult-in preparation]

Factorization formula

The heavy quark EEC factorizes into a jet function and the hard function (the same as for the light quarks) similarly to the light quark case.



$$\propto \overrightarrow{J}_Q(z, M, \mu) \otimes \overrightarrow{H}(z, \mu) \qquad \overrightarrow{J}_Q = \{J_Q, J_q, J_g\}$$

For resummation beyond LL there will be mixing between J_Q and J_q!

From this result one can derive the scale evolution of the EEC.
Anomalous dimensions are related to moments of the heavy quark jet function with respect to x and (1-x).

Nevertheless resummation should not change the shape of the energy distribution.

Conclusions

- Collinear limit of the energy correlators provides a useful tool to study JSS
- They are well-defined field theory object $\Rightarrow$take advantage of theory advances
- Energy correlators on heavy particles inside a jet can probe their mass scale
- They can be measured at colliders to observe the dead-cone effect

Thank you!