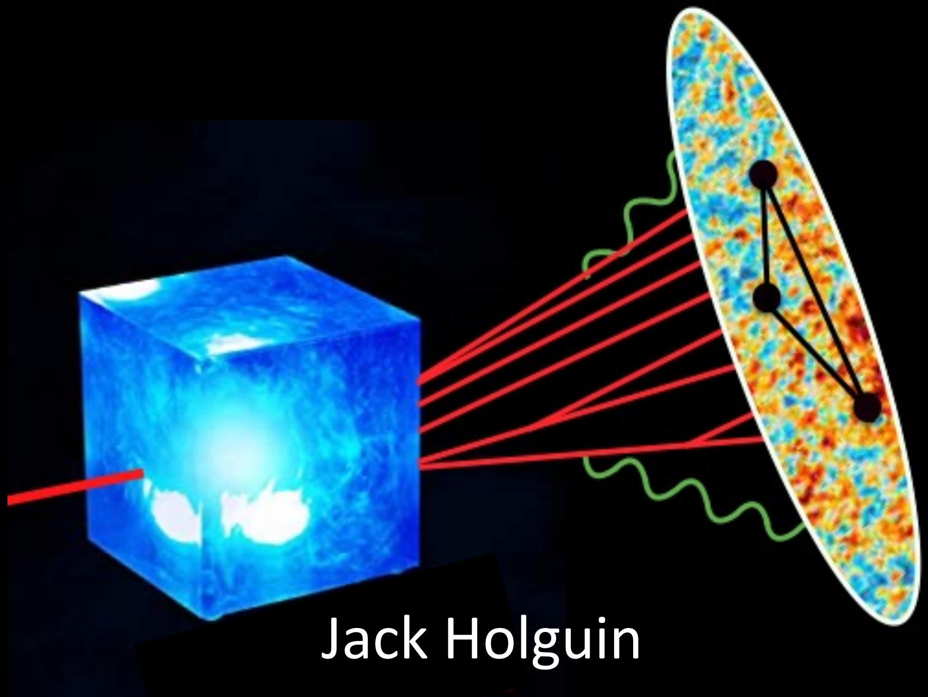
Energy Correlators: from pp to AA collisions



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In collaboration with Carlota Andres, Fabio Dominguez, Cyrille Marquet, Ian Moult

Based on [2303.03413](2303.03413) and work to come.

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Introduction

Very quickly, what is $\mathcal{E}(\vec{n})$?

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

$\mathcal{E}(\vec{n}) =$ "Idealised calorimeter" output at a solid angle labelled by $\vec{n}$.

Correlation functions of $\mathcal{E}(\vec{n})$ quantify the correlations between the average calorimeter outputs at different points across the celestial sphere from a particular process.

They are functions of the angles between the 'idealised' calorimeters.

Introduction

Recap

- Correlation functions in statistics:
  - $\mathrm{Corr}_2(X,Y) = \langle XY \rangle - \langle X \rangle \langle Y \rangle$ (also just the covariance)
  - $\mathrm{Corr}_3(X,Y,Z) = \langle XYZ \rangle - \langle X \rangle \big(\langle Y \rangle \langle Z \rangle - \mathrm{Corr}_2(Y,Z) \big)$
  - …

- In physics we usually refer to $\langle X_1 \ldots X_n \rangle$ as an n point correlator. This is just conventional and has origins in that often $\langle X_i \rangle = 0$.

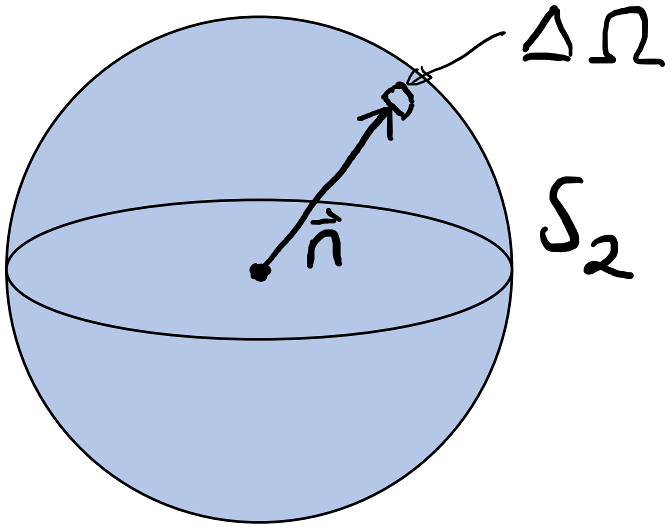
- QFT correlators (propogators) typically are time ordered coherent sums, not energy correlators! Energy correlators are equal time Wightman correlators. They are incoherent sums and, at the surface level, more in common with stat correlators than time-ordered correlators.

Introduction

$$\langle \mathcal{E}(\vec{n}_1) \dots \mathcal{E}(\vec{n}_i)\rangle = \sum_{j_1 \dots j_i} \int \frac{\mathrm{d}\,\sigma_{j_1 \dots j_i}}{\mathrm{d}\vec{n}_{j_1} \dots \mathrm{d}\vec{n}_{j_i}} E_{j_1} \dots E_{j_i} \delta^2(\vec{n}_1 - \vec{n}_{j_1}) \dots \delta^2(\vec{n}_i - \vec{n}_{j_i})$$

Where j index final state hadrons and $\sigma_{j_1 \dots j_i}$ is the inclusive cross section to produce i final state hadrons.

Observation: a function of $2i$ angles.



Important!

$$\langle \mathcal{E}(\vec{n}_1) \dots \mathcal{E}(\vec{n}_i)\rangle = \sum_{j_1 \dots j_i} \int \frac{\mathrm{d}\,\tilde{\sigma}_{k_1 \dots k_i}}{\mathrm{d}\vec{n}_{k_1} \dots \mathrm{d}\vec{n}_{k_i}} E_{k_1} \dots E_{k_i} \delta^2(\vec{n}_1 - \vec{n}_{k_1}) \dots \delta^2(\vec{n}_i - \vec{n}_{k_i})$$

Where k index calorimeter cells and $\tilde{\sigma}_{k_1 \dots k_i}$ is the inclusive cross section measure energies $E_{k_1} \dots E_{k_i}$ in calorimeter cells $k_1 \dots k_i$.

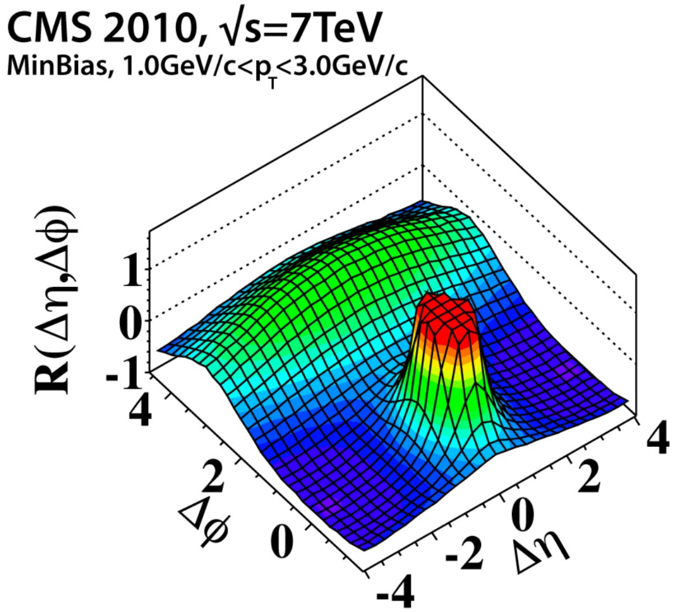
Introduction

$$\langle \mathcal{E}^n(\vec{n}_1) \dots \mathcal{E}^n(\vec{n}_i)\rangle = \sum_{j_1 \dots j_i} \int \frac{\mathrm{d}\,\sigma_{j_1 \dots j_i}}{\mathrm{d}\vec{n}_{j_1} \dots \mathrm{d}\vec{n}_{j_i}} E^n_{j_1} \dots E^n_{j_i} \delta^2\left(\vec{n}_1 - \vec{n}_{j_1}\right) \dots \delta^2(\vec{n}_i - \vec{n}_{j_i})$$

We can raise the energies to various (necessarily integer) powers. In doing so we can gain sensitivity to different physics, but the observable become not IRC safe. Non-perturbative input is needed.

$$\langle \mathcal{E}^0(\vec{n}_1)\mathcal{E}^0(\vec{n}_2)\rangle = \sum_{j_1 \dots j_i} \int \frac{\mathrm{d}\,\sigma_{j_1 j_2}}{\mathrm{d}\vec{n}_{j_1}\mathrm{d}\vec{n}_{j_2}} \delta^2\left(\vec{n}_1 - \vec{n}_{j_1}\right)\delta^2(\vec{n}_i - \vec{n}_{j_2}) = \langle n(\vec{n}_1)n(\vec{n}_2)\rangle$$

where $n(\vec{n}_1)$ is the number operator.



The prototypical EEC

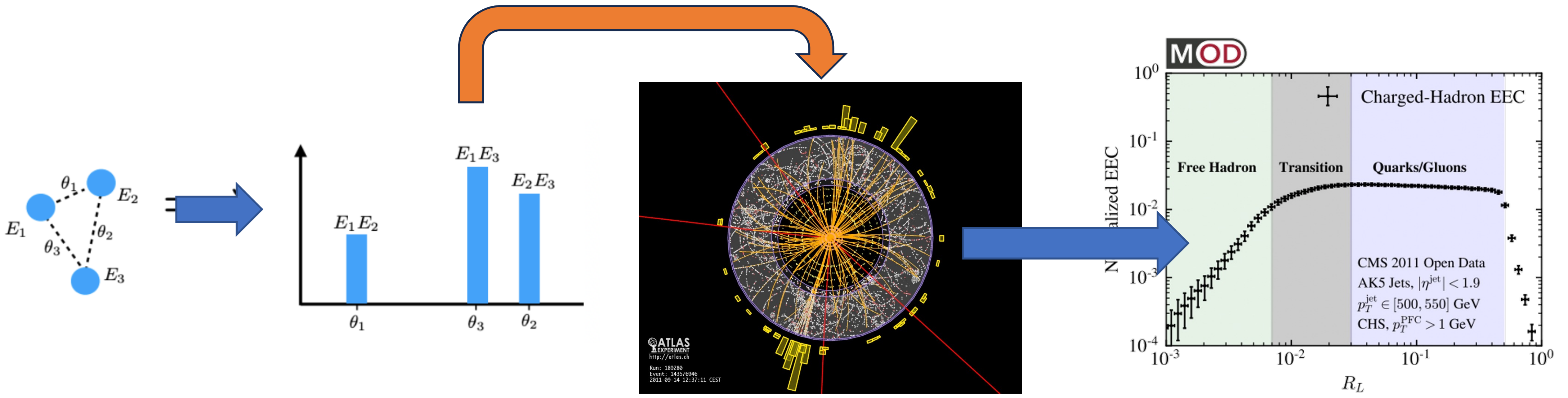
$$\frac{\langle \mathcal{E}^n(\boldsymbol{n}_1)\mathcal{E}^n(\boldsymbol{n}_2)\rangle}{Q^{2n}} = \frac{1}{\sigma}\sum_{ij}\int \frac{\mathrm{d}\sigma_{ij}}{\mathrm{d}\boldsymbol{n}_i \mathrm{d}\boldsymbol{n}_j}\frac{E_i^n E_j^n}{Q^{2n}}\delta^{(2)}(\boldsymbol{n}_i - \boldsymbol{n}_1)\delta^{(2)}(\boldsymbol{n}_j - \boldsymbol{n}_2)$$

Where i, j are final state hadrons and σ_{ij} is the inclusive cross section to produce i, j with a hard scale Q.

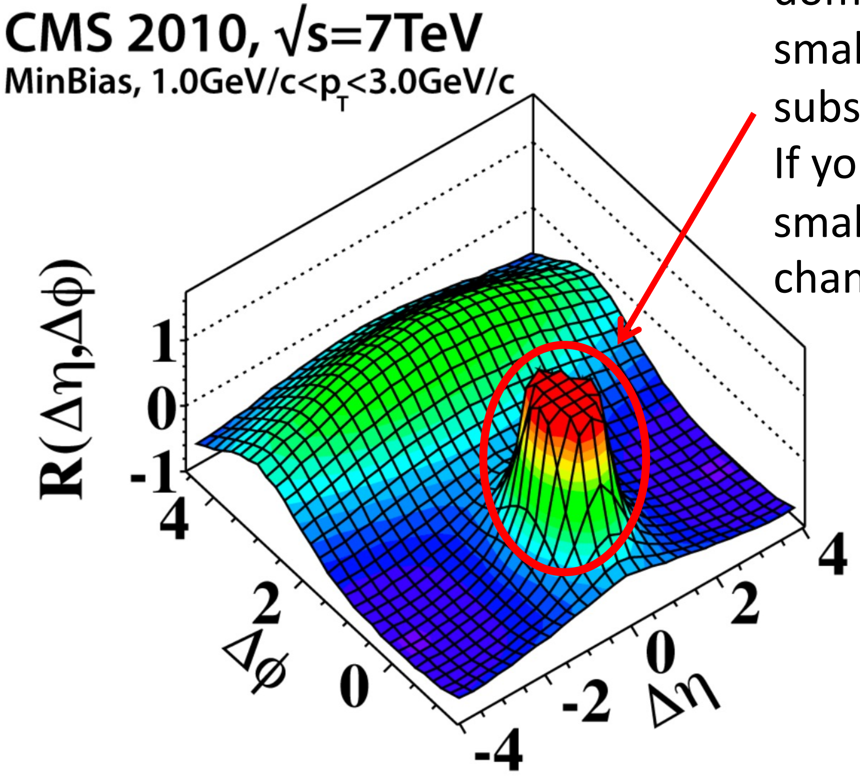
We integrate out the global $\mathrm{SO}(3)$ symmetry to find the distribution we're interested in.

$$\boxed{\frac{\mathrm{d}\Sigma^{(n)}}{\mathrm{d}\theta} = \int \mathrm{d}\boldsymbol{n}_{1,2}\frac{\langle \mathcal{E}^n(\boldsymbol{n}_1)\mathcal{E}^n(\boldsymbol{n}_2)\rangle}{Q^{2n}}\delta(\boldsymbol{n}_2 \cdot \boldsymbol{n}_1 - \cos\theta)}$$

Important difference between correlators and more ‘typical’ observables.

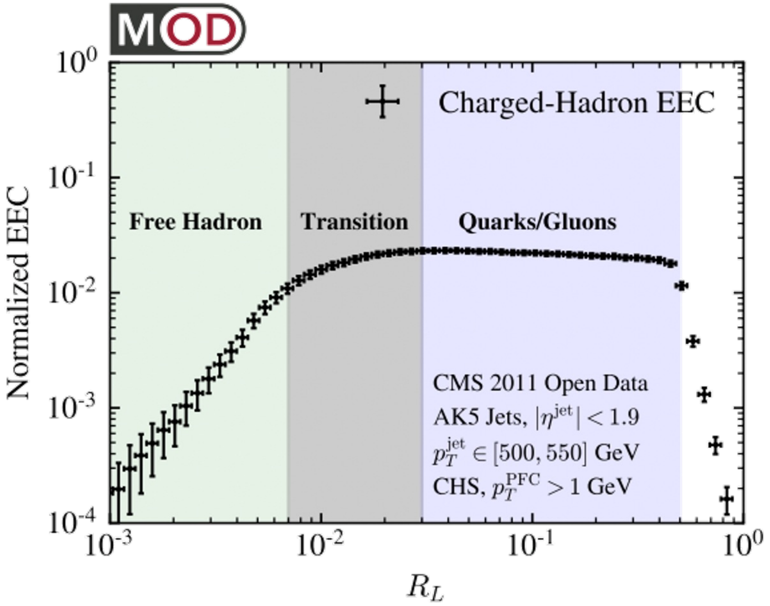


EEC jet substructure



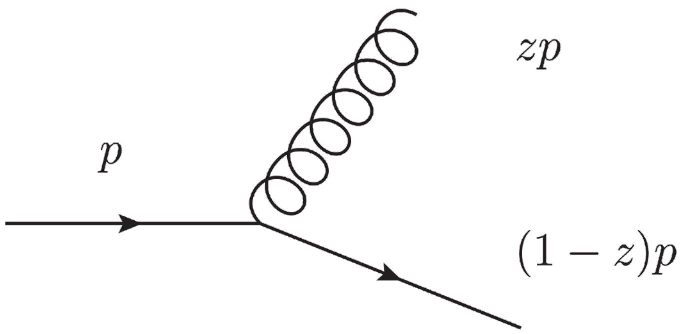
No jet algorithm but completely dominated "jet physics". The very small angle is dominated by "jet substructure".
If you used a jet algorithm, the very small angle structure does not change.

Same is true for the EEC. We study the very small angle region to analyse "jet substructure". A jet algorithm can be used but hasn't always been.



What drives EEC jet substructure?

Energy correlators are very good at isolating parts of multiscale dynamics.



$$t_f = \frac{2}{z(1-z)p_0\theta^2} \xrightarrow{z \approx \frac{1}{2}} \theta^2 \sim t_f^{-1} \sim p_{\text{exchanged}}^2$$

The angular size of a correlation often can be interpreted as a time parameter for the physics inducing the correlations.

What has been done* in pp Theory?

	$\langle \mathcal{E}(\vec{n}_1) \rangle$	$\langle \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2) \rangle$	$\langle \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\mathcal{E}(\vec{n}_3) \rangle$	$\langle \mathcal{E}(\vec{n}_1) \ldots \mathcal{E}(\vec{n}_i) \rangle$
Fixed order	Effectively as accurate as cross-section calculations	Complete NLO (2-loops) for colour singlet Dixon, Luo, Shtabovenko, Yang, Zhu arXiv:1801.03219	Complete LO (1-loop) for colour singlet Yang, Zhang arXiv:2402.05174	Tree-level
Resummation	N/A	Small angle NNLL & NNNLL Dixon, Moult, Zhu arXiv:1905.01310 Gao, Li, Moult, Zhu arXiv:2312.16408	Small angle NLL Cheng, Moult, Zhu arXiv:2011.02492	Small angle NLL Cheng, Moult, Zhu arXiv:2011.02492
Pheno	Extracting EW density matrices	Measuring α_s Komiske, Moult, Thaler, Zhu arXiv:2201.07800	Measuring α_s Komiske, Moult, Thaler, Zhu arXiv:2201.07800	Measuring α_s Komiske, Moult, Thaler, Zhu arXiv:2201.07800
Pheno	Small x proton structure Liu, Zhu arXiv:2209.02080	Extracting EW density matrices Ricci, Riembau arXiv:2207.03511	Measuring m_t JH, Moult, Pathak, Procura arXiv:2201.08393	
Pheno		Detecting the deadcone Craft, Lee, Meçaj, Moult arXiv:2210.09311	Measuring spin correlations Cheng, Moult, Zhu arXiv:2011.02492 Karlberg, Salam, Scyboz, Verheyen arXiv:2103.16526	

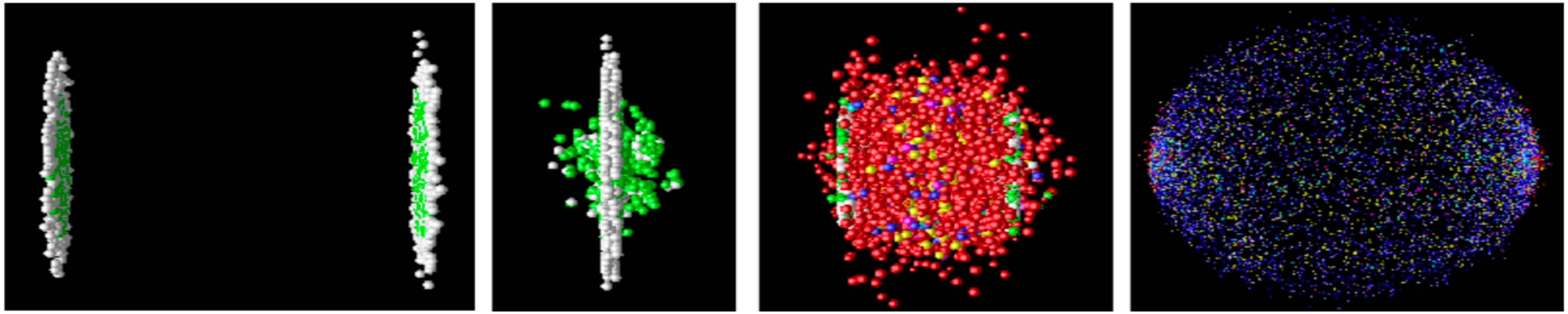
*These are some highlights focusing on the small angle limit QCD. There is a lot more literature away from that limit.

What has been done in AA Theory?

	$\langle \mathcal{E}(\vec{n}_1) \rangle$	$\langle \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2) \rangle$	$\langle \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\mathcal{E}(\vec{n}_3) \rangle$	$\langle \mathcal{E}(\vec{n}_1) \ldots \mathcal{E}(\vec{n}_i) \rangle$
Pheno/ Theory	No present interest	BDMPS-Z γ+jet Andres, Dominguez, Elayavalli, JH, Marquet, Moult arXiv:2209.11236 Andres, Dominguez, JH, Marquet, Moult arXiv:2303.03413		
Pheno/ Theory		Opacity Expansion γ+jet Andres, Dominguez, JH, Marquet, Moult arXiv:2303.03413		
Pheno/ Theory		NP effects Barata, Szafron arXiv:2401.04164		
Pheno		Jet and Groomed Jet Barata, Caucal, Soto-Ontoso, Szafron arXiv:2312.12527		
Pheno		Deadcone study Andres, Dominguez, JH, Marquet, Moult arXiv:2307.15110	Unpublished MC studies	Unpublished MC studies
Pheno		MC study Yang, He, Moult, Wang arXiv:2310.01500		
Pheno		See Fabio's talk	See Hannah's talk	

*Sorry if I have missed anything. Let me know and update for the future.

Energy correlations in AA



Time

t=0 to 1 fm/c c

t=1 to 10 fm/c

t>10 fm/c

$\theta^2 \sim t_f^{-1} \sim p^2_{\text{exchanged}}$

Plan:

- Provide an overview of the work I have been involved in so far.
- Highlight the limitations of this work. (See Fabio's talk for recent progress here)
- Point out possible future avenues.

Advertising

I won't have time today to discuss our recent HI deadcone studies.

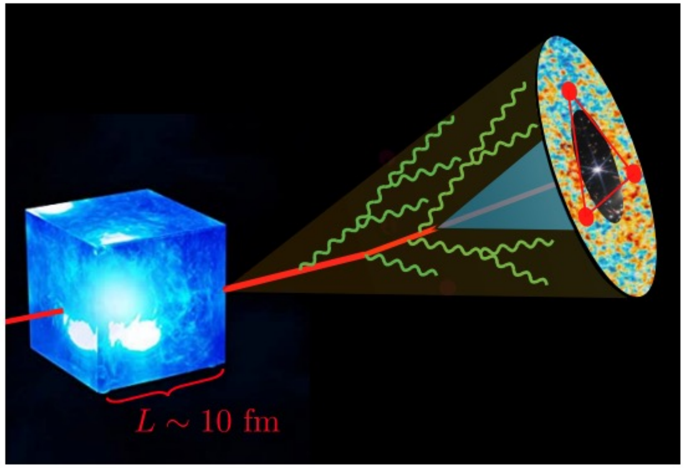


FIG. 1: A heavy-flavor jet propagating through the QGP forms a complicated energy pattern due to an interplay of two characteristic angular scales: the dead-cone angle θ_0 and the onset angle $\theta_{\rm on}$. These scales can be extracted from the asymptotic energy flux using energy correlators.

[2307.15110](2307.15110)

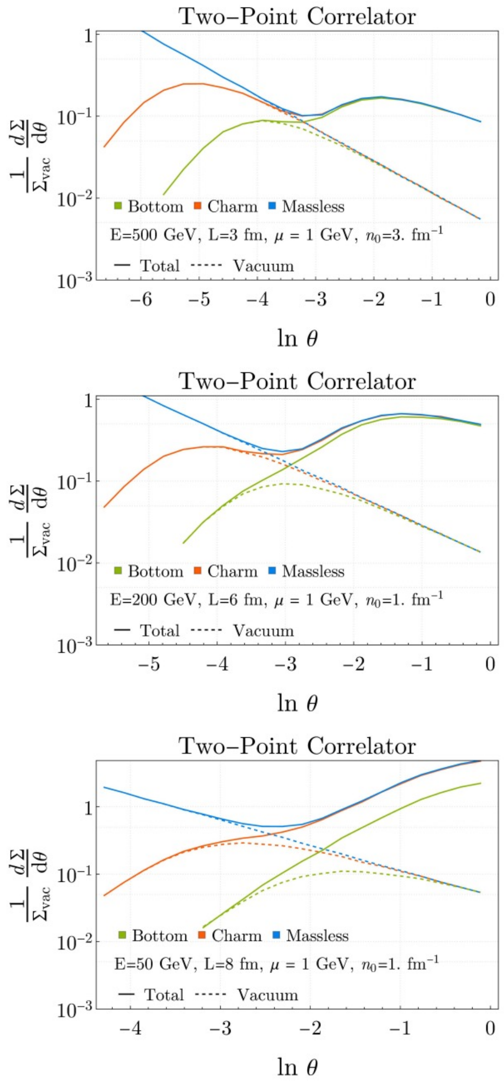
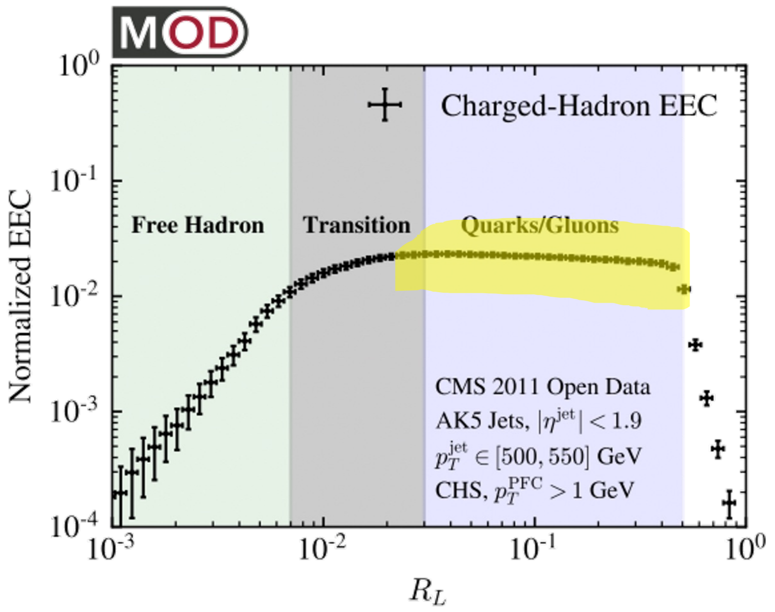


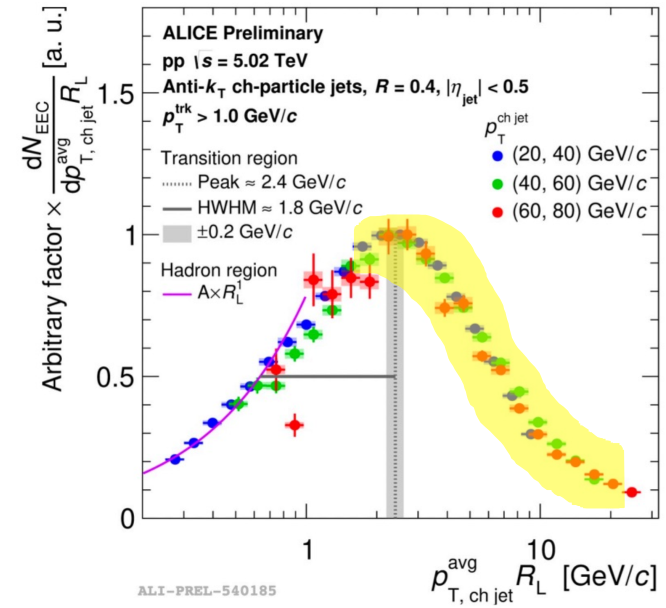
FIG. 2: EEC of a light-quark (blue), c-quark (orange), and b-quark (green) jet in p-p (dashed) and heavy-ion (solid) collisions. Different panels correspond to different jet energies and medium parameters. All curves are normalised by the integrated vacuum result $\Sigma_{\rm vac}$.

Computing Correlation Functions of $\mathcal{E}(\vec{n})$

$$\frac{\mathrm{d}\Sigma^{(n)}}{\mathrm{d}\theta} = \int \mathrm{d}\boldsymbol{n}_{1,2} \frac{\langle \mathcal{E}^n(\boldsymbol{n}_1)\mathcal{E}^n(\boldsymbol{n}_2)\rangle}{Q^{2n}} \delta(\boldsymbol{n}_2 \cdot \boldsymbol{n}_1 - \cos\theta)$$

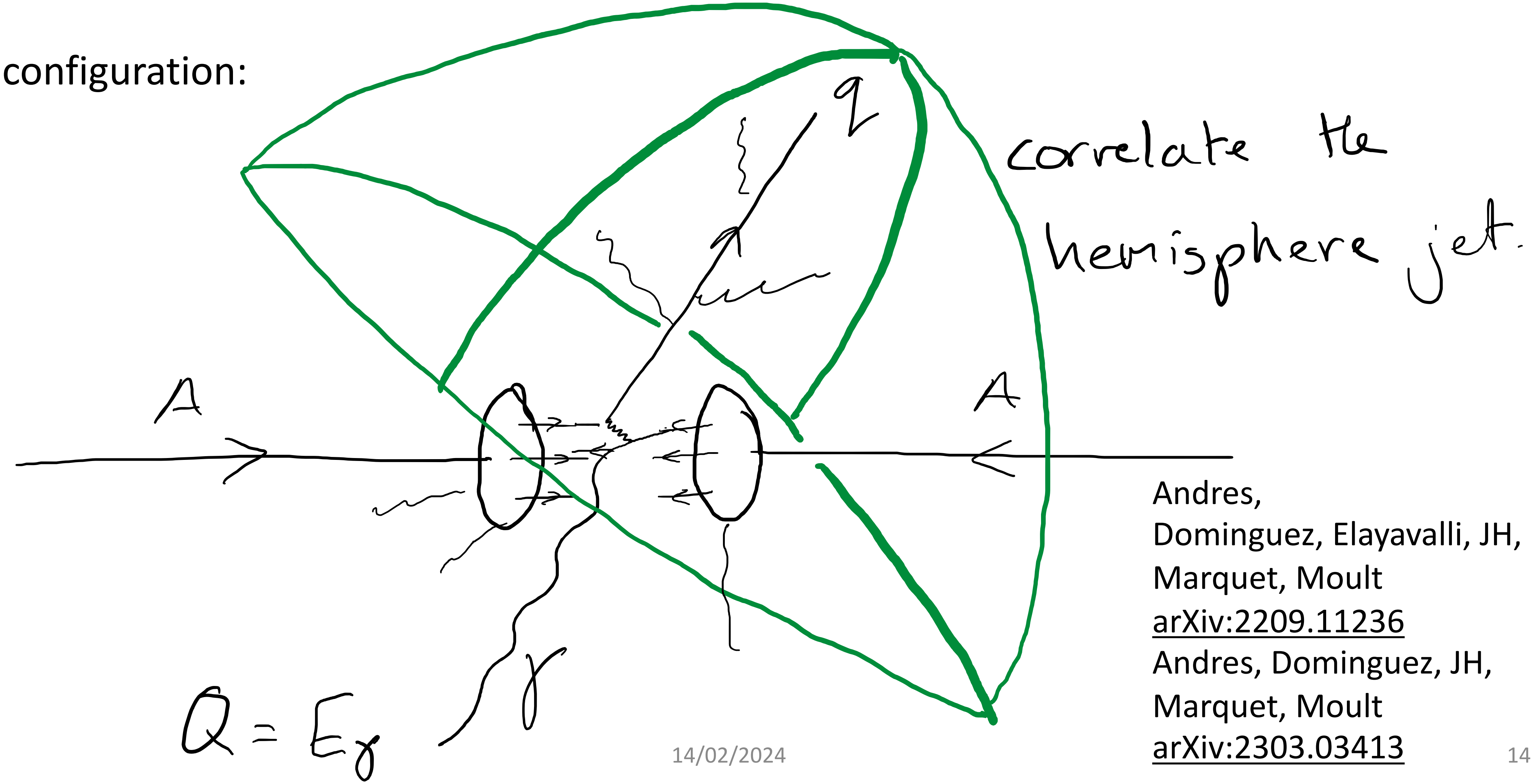
Let me now set up the perturbative calculation we perform.





Computing Correlation Functions of $\mathcal{E}(\vec{n})$

The configuration:



Andres, Dominguez, Elayavalli, JH, Marquet, Moult [arXiv:2209.11236](https://arxiv.org/abs/2209.11236)
Andres, Dominguez, JH, Marquet, Moult [arXiv:2303.03413](https://arxiv.org/abs/2303.03413)

The following 6 slides are my only technical ones.

Computing Correlation Functions of $\mathcal{E}(\vec{n})$

The average momentum exchange between the two correlator points goes as $\sim \theta Q$, the small angle region (where $\theta Q \gg \Lambda_{\text{QCD}}$) is largely determined by perturbative physics. We therefore write the observable as a sum over inclusive partonic cross-sections:

$$\frac{\mathrm{d}\Sigma^{(n)}}{\mathrm{d}\theta} = \frac{1}{\sigma}\int \mathrm{d}E_{q,g}\,\frac{\mathrm{d}\hat{\sigma}_{qg}}{\mathrm{d}\theta\mathrm{d}E_q\mathrm{d}E_g}\,\frac{E_g^n E_q^n}{Q^{2n}} + \frac{1}{\sigma}\int \mathrm{d}E_{g_1,g_2}\,\frac{\mathrm{d}\hat{\sigma}_{g_1g_2}}{\mathrm{d}\theta\mathrm{d}E_{g_1}\mathrm{d}E_{g_2}}\,\frac{E_{g_1}^n E_{g_2}^n}{Q^{2n}} + \frac{1}{\sigma}\int \mathrm{d}E_{q_1,q_2}\,\frac{\mathrm{d}\hat{\sigma}_{q_1q_2}}{\mathrm{d}\theta\mathrm{d}E_{q_1}\mathrm{d}E_{q_2}}\,\frac{E_{q_1}^n E_{q_2}^n}{Q^{2n}} + (\text{perm. } q \leftrightarrow \bar{q}) + \mathcal{O}\left(\frac{\Lambda_{\text{QCD}}}{\theta\, Q}\right)$$

In pp collisions this is a simple application of CSS inclusive factorisation and can be convoluted with fragmentation or track functions. We must assume this also holds in AA collisions.

Note the finite number of terms in the sum over partonic cross sections!

Computing Correlation Functions of $\mathcal{E}(\vec{n})$

We now re-parameterise the medium contribution to each partonic cross section. This is not a factorisation, just a parameterisation.

$$\frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}\theta \mathrm{d}E_i \mathrm{d}E_j} = \left(1 + F_{\mathrm{med}}^{(ij)}(E_i, E_j, \theta)\right) \frac{\mathrm{d}\hat{\sigma}_{ij}^{\mathrm{vac}}}{\mathrm{d}\theta \mathrm{d}E_i \mathrm{d}E_j}$$

And using this parameterisation we can now compute terms not dependent on $F_{med}^{(ij)}$ using the well developed frameworks from pp physics (pick your favourite between the celestial OPE, SCET, or jet calculus).

I'll show results at LO+NLL for the pp-like terms later on. NLO+NNLL is available in the literature. This part is well understood and not the focus of my talk.

Computing Correlation Functions of $\mathcal{E}(\vec{n})$

Now we must focus on the 'medium' terms that contain the physics intrinsic to HI collisions. So far, we've not approximated anything other than assuming perturbative factorisation. Let's introduce some new helpful variables:

$$\int \mathrm{d}E_{q,g}\; F_{\mathrm{med}}^{(qg)} \frac{\mathrm{d}\hat{\sigma}_{qg}^{\mathrm{vac}}}{\mathrm{d}\theta \mathrm{d}E_q \mathrm{d}E_g} \frac{E_q^n E_g^n}{Q^{2n}} = \int \mathrm{d}z\, \mathrm{d}\mu_{\mathrm{s}}\; F_{\mathrm{med}}^{(qg)} \frac{\mathrm{d}\hat{\sigma}_{qg}^{\mathrm{vac}}}{\mathrm{d}\theta \mathrm{d}z \mathrm{d}\mu_{\mathrm{s}}} z^n (1 - z - \mu_{\mathrm{s}}/Q)^n$$

where $z = E_q/Q$ and $\mu_s = Q - E_q - E_g > 0$ is the energy scale of the radiation over which the perturbative cross sections are inclusive.

With this parameterisation and assuming we are measuring quark jets:

$$\sum_{ij\in\{g,q,\bar{q}\}} \int \mathrm{d}E_{i,j}\; F_{\mathrm{med}}^{(ij)} \frac{\mathrm{d}\hat{\sigma}_{ij}^{\mathrm{vac}}}{\mathrm{d}\theta \mathrm{d}E_i \mathrm{d}E_j} \frac{E_i^n E_j^n}{Q^{2n}}$$

$$= \int \mathrm{d}z\; F_{\mathrm{med}}^{(qg)} \frac{\mathrm{d}\hat{\sigma}_{qg}^{\mathrm{vac}}}{\mathrm{d}\theta \mathrm{d}z} z^n (1-z)^n \left(1 + \mathcal{O}\left(\frac{\bar{\mu}_{\mathrm{s}}}{Q}\right) + \mathcal{O}\left(\alpha_{\mathrm{s}}(\theta Q) \ln \theta \frac{\bar{\mu}_{\mathrm{s}}^n}{Q^n}\right)\right)$$

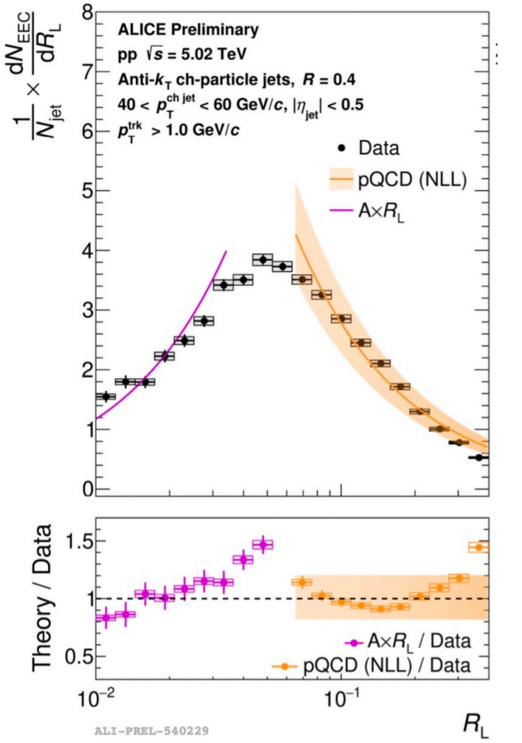
$$\bar{\mu}_{\mathrm{s}}/Q \sim \sqrt{\mu/Q}$$

Debye mass

Computing Correlation Functions of $\mathcal{E}(\vec{n})$

Thus we will compute our observable from the master formula:

$$\frac{\mathrm{d}\Sigma^{(n)}}{\mathrm{d}\theta} = \frac{1}{\sigma}\int \mathrm{d}z \left(g^{(n)}(\theta,\alpha_{\mathrm{s}}) + F_{\mathrm{med}}(z,\theta)\right)\frac{\mathrm{d}\sigma_{qg}^{\mathrm{vac}}}{\mathrm{d}\theta\mathrm{d}z} z^n(1-z)^n \left(1+\mathcal{O}\left(\frac{\bar{\mu}_{\mathrm{s}}}{Q}\right)\right) + \mathcal{O}\left(\frac{\Lambda_{\mathrm{QCD}}}{\theta\ Q}\right)$$



As promised, the pp-like part at LO+NLL:

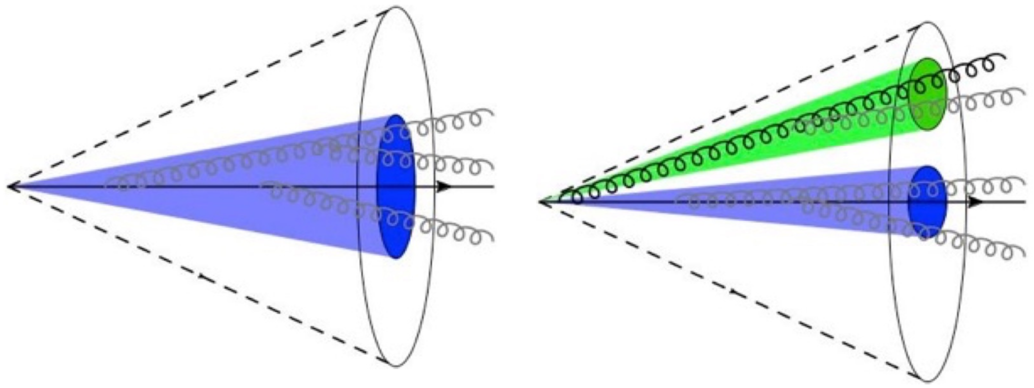
$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma_{qg}^{\mathrm{vac}}}{\mathrm{d}\theta\mathrm{d}z} = \frac{\alpha_{\mathrm{s}}(\theta Q)}{\pi}\ C_{\mathrm{F}}\frac{1+(1-z)^2}{z\ \theta} + \mathcal{O}(\alpha_{\mathrm{s}}^2,\theta^0)$$

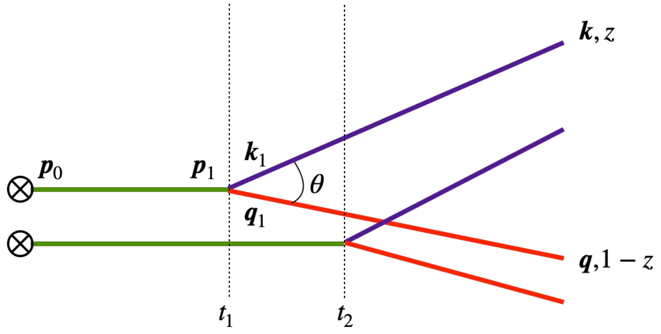
$$g^{(1)} = \left(\left[\left(\frac{\alpha_{\mathrm{s}}(Q)}{\alpha_{\mathrm{s}}(\theta Q)}\right)^{\frac{\hat{\gamma}(3)}{\beta_0}}\right]_{qq} + \frac{2n_f(\gamma_{qg}(2)-\gamma_{qg}(3)) + \gamma_{gg}(2)-\gamma_{gg}(3)}{\gamma_{qq}(2)-\gamma_{qq}(3)+\gamma_{gq}(2)-\gamma_{gq}(3)}\left[\left(\frac{\alpha_{\mathrm{s}}(Q)}{\alpha_{\mathrm{s}}(\theta Q)}\right)^{\frac{\hat{\gamma}(3)}{\beta_0}}\right]_{gq}\right)$$
$$+\,\mathcal{O}\left(\alpha_{\mathrm{s}}(Q)^n \ln(\theta)^{n-1}\big|_{n\geq 1}\right) + \mathcal{O}(\theta), \qquad \text{(A.23)}$$

where $\hat{\gamma}(J) = \begin{pmatrix} \gamma_{qq}(J), & 2n_f\gamma_{qg}(J), & 0 \\ \gamma_{gq}(J), & \gamma_{gg}(J), & 0 \\ 0, & 0, & \gamma_{g\tilde{g}}(J) \end{pmatrix}$ is the spin-J twist-2 QCD anomalous dimension matrix.

Computing F_{med}

Leading structure to study is a (quark) jet fragmenting into a jet and a subjet in the presence of a medium.



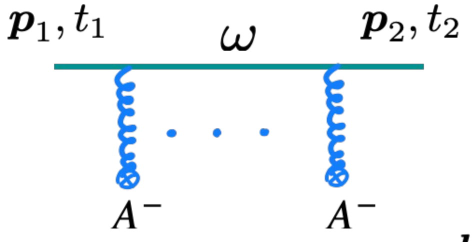


$$\mathcal{M}^{\alpha\beta} = \frac{1}{2E}\int_{\boldsymbol{p}_0\boldsymbol{p}_1\boldsymbol{k}_1\boldsymbol{q}_1}\int_{t_0}^{\infty} dt_1\,(2\pi)^2\delta^{(2)}(\boldsymbol{p}_1-\boldsymbol{k}_1-\boldsymbol{q}_1)\mathcal{G}_{R_b}^{\alpha\alpha_1}(\boldsymbol{k},L;\boldsymbol{k}_1,t_1;zE)$$
$$\times\,\mathcal{G}_{R_c}^{\beta\beta_1}(\boldsymbol{q},L;\boldsymbol{q}_1,t_1;(1-z)E)\,V(\boldsymbol{k}_1-z\boldsymbol{p}_1,z)T^{\alpha_1\beta_1\gamma_1}\,\mathcal{G}_{R_a}^{\gamma_1\gamma}(\boldsymbol{p}_1,t_1;\boldsymbol{p}_0,t_0;E)\,\mathcal{M}_0^{\gamma}(E,\boldsymbol{p}_0)$$

Computing F_{med}

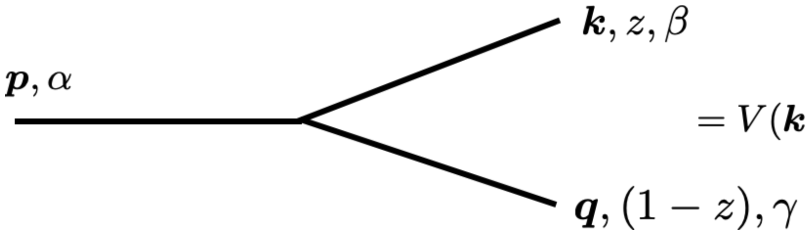
The formalism we use, based in BDMPS-Z:

- All particles have a large longitudinal momentum compared to their transverse momenta and therefore there is a decoupling between transverse and longitudinal dynamics
- We work in a mixed representation with momentum coordinates in the transverse direction and “time” (+ coordinate) in the longitudinal direction.
- Multiple scatterings resumed through propagators in a background field



$$= \mathcal{G}_R(\boldsymbol{p}_2, t_2; \boldsymbol{p}_1, t_1; \omega)$$

- Vacuum vertices



$$= V(\boldsymbol{k} - z\boldsymbol{p}, z) T^{\alpha\beta\gamma} (2\pi)^2 \delta^{(2)}(\boldsymbol{p} - \boldsymbol{k} - \boldsymbol{q})$$

- Background field averaged at the level of the cross section

$$\left\langle A^{a-}(\boldsymbol{q}_1, t_1) A^{b-\dagger}(\boldsymbol{q}_2, t_2) \right\rangle = \delta^{ab} \delta(t_2 - t_1) \delta^{(2)}(\boldsymbol{q}_1 - \boldsymbol{q}_2) v(\boldsymbol{q}_1)$$

Computing F_{med}

- Full evaluation keeping z and θ not yet achieved (Isaksen, Tywoniuk arXiv:2303.12119).

Two available approximations:

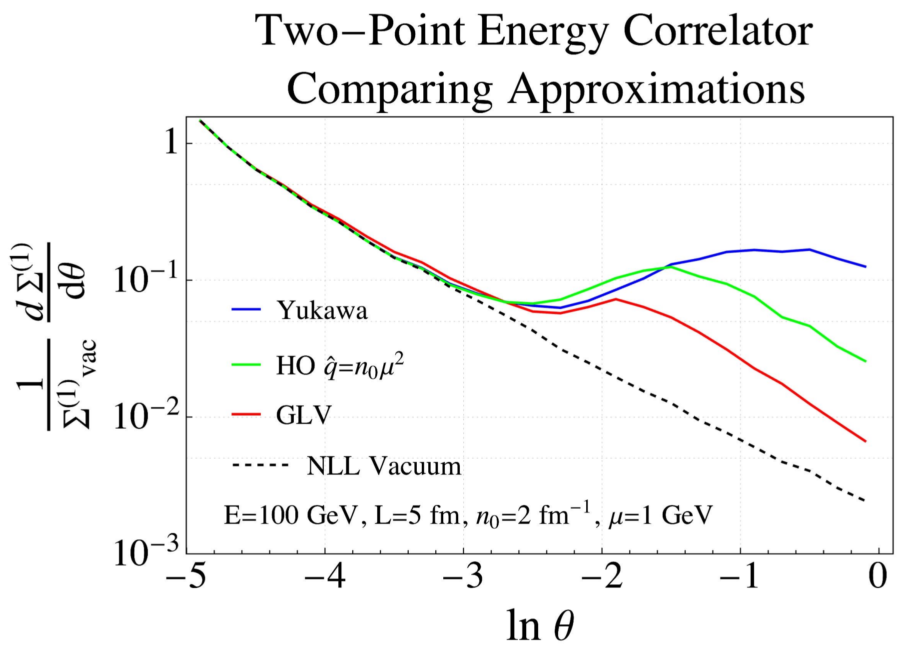
- Opacity expansion ($N = 1$) arXiv:1807.03799
  - Unitarity problems can lead to negative cross sections.
  - Recursive formulas to generate all orders (not yet implemented numerically).

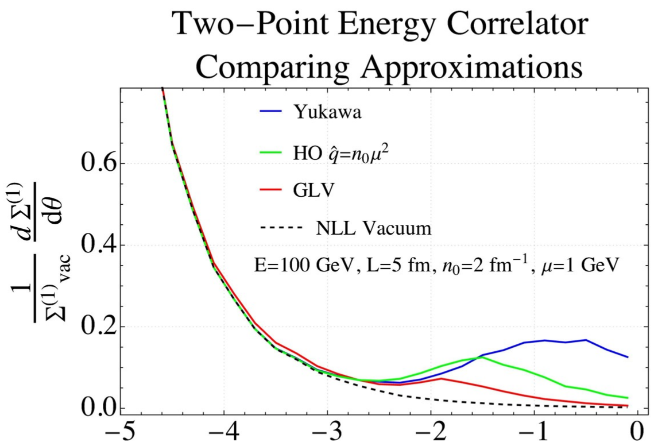
- "Tilted" Wilson lines
  - Resums multiple scatterings in the eikonal approximation.
  - Assumes semi-hard splittings (z not too small).
  - We implement this using both a Yukawa and HO potential for medium scatterings and for now using the leading colour limit.

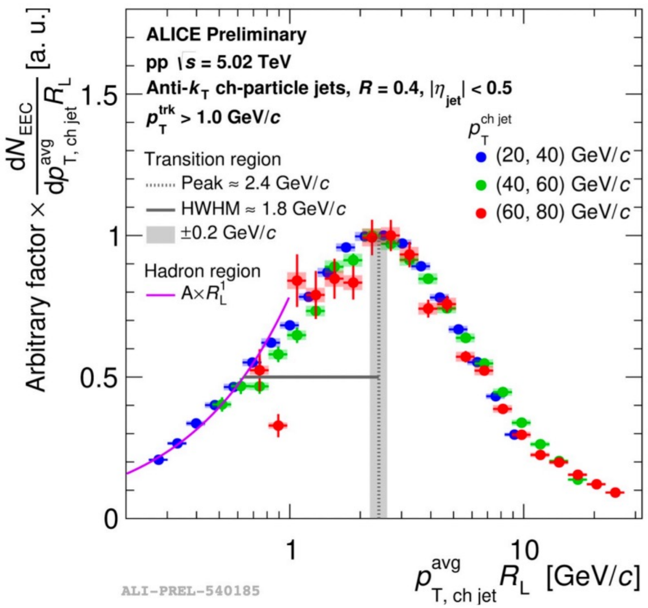
arXiv:1907.03653

arXiv:2107.02542

Numerical evaluation of F_{med}



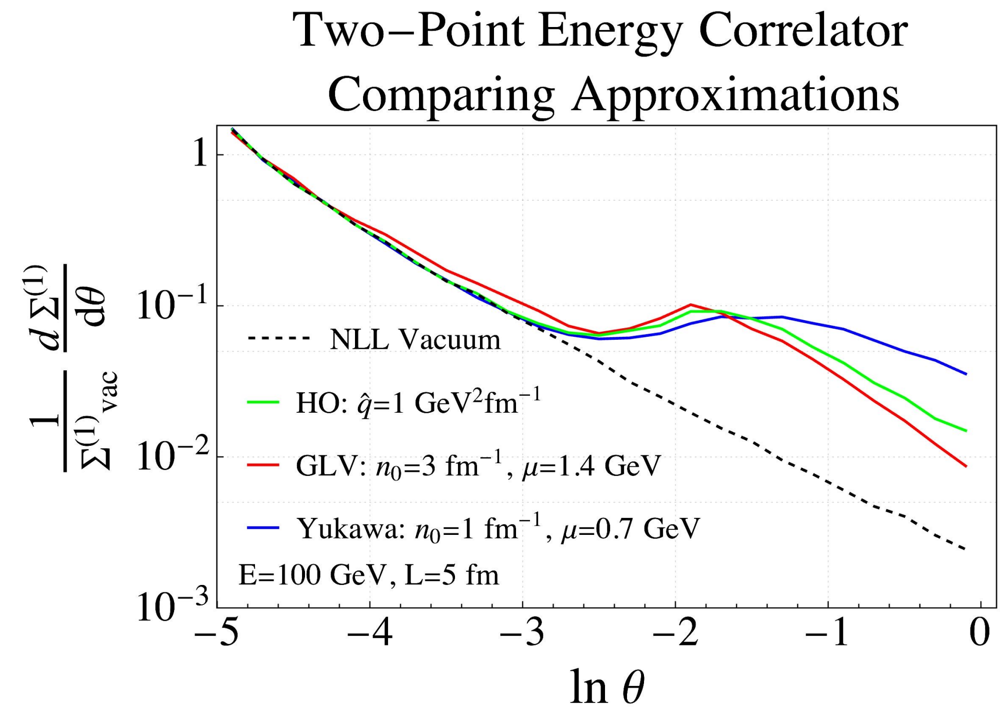




General features: an enhancement which begins above θ_L, at $\theta \gg \theta_L$ the enhancement peaks and then settles into a new medium dependent scaling law.

Amplitudes appear model dependent.

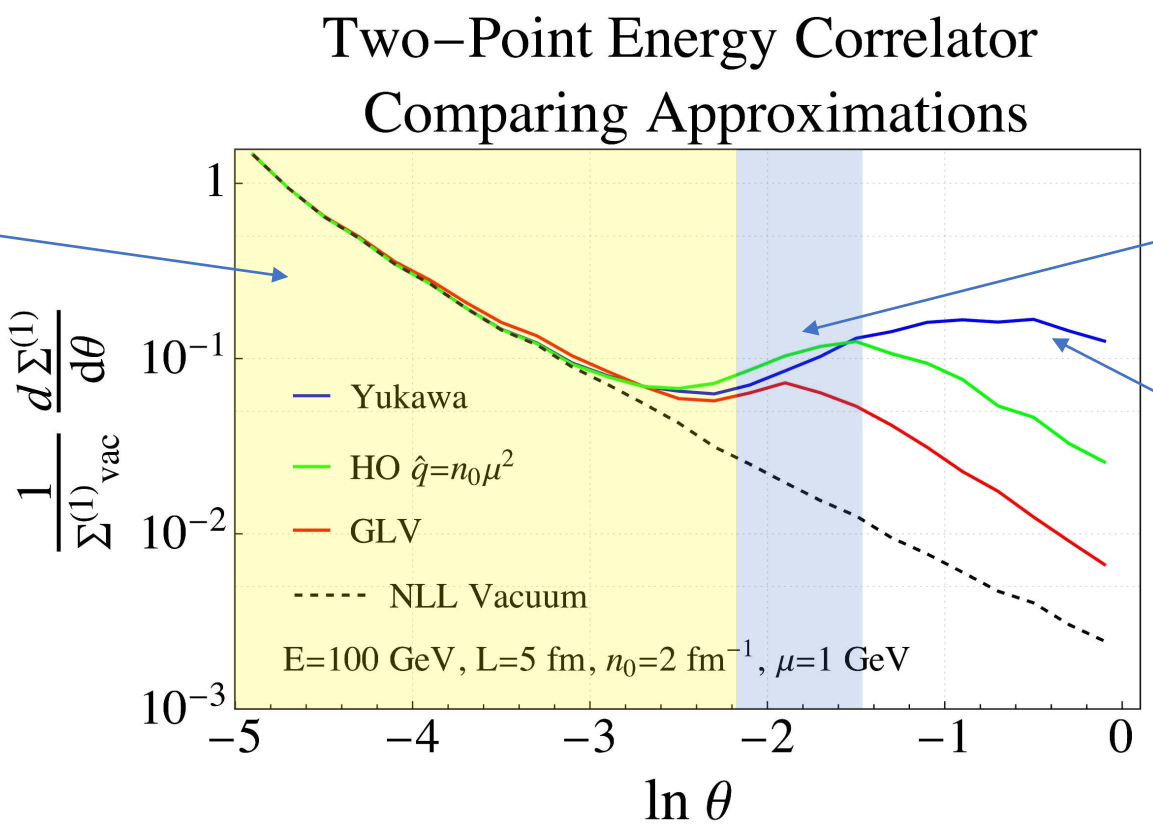
Numerical evaluation of F_{med}



Whilst amplitudes are very model dependent, the differences can be fairly well absorbed into variation of the model parameters (not so much the wide angle though).

Numerical evaluation of F_{med}

Controlled by θ_L



Controlled by $(\theta_c - \theta_L)$

Controlled by the large number of scatters limit. Behaves as if medium is infinitely long and so always decoherent.

Also, where the model is worst.

Provided $E \gg E_c \sim \hat{q}L^2$

*For the model used

Limitations

There are many limitations to this work which prevents it from being usable for pheno. For a thorough discussion see Andres, Dominguez, JH, Marquet, Moult arXiv:2303.03413.

- Unlikely this calculation can be compared to data (at least for a long time). Early measurements will be on inclusive jets.

- We are using a new(ish) approximation to resum, the eikonal approx., at zeroth order. This clearly needs improvement. Isaksen, Tywoniuk arXiv:2303.12119

- We look at γ+jet so that to first order there is no quenching. To do pheno with the experimental reality, we will need to understand how quenching interacts with the observable.

- Static medium needs replacing with a “physical” medium.

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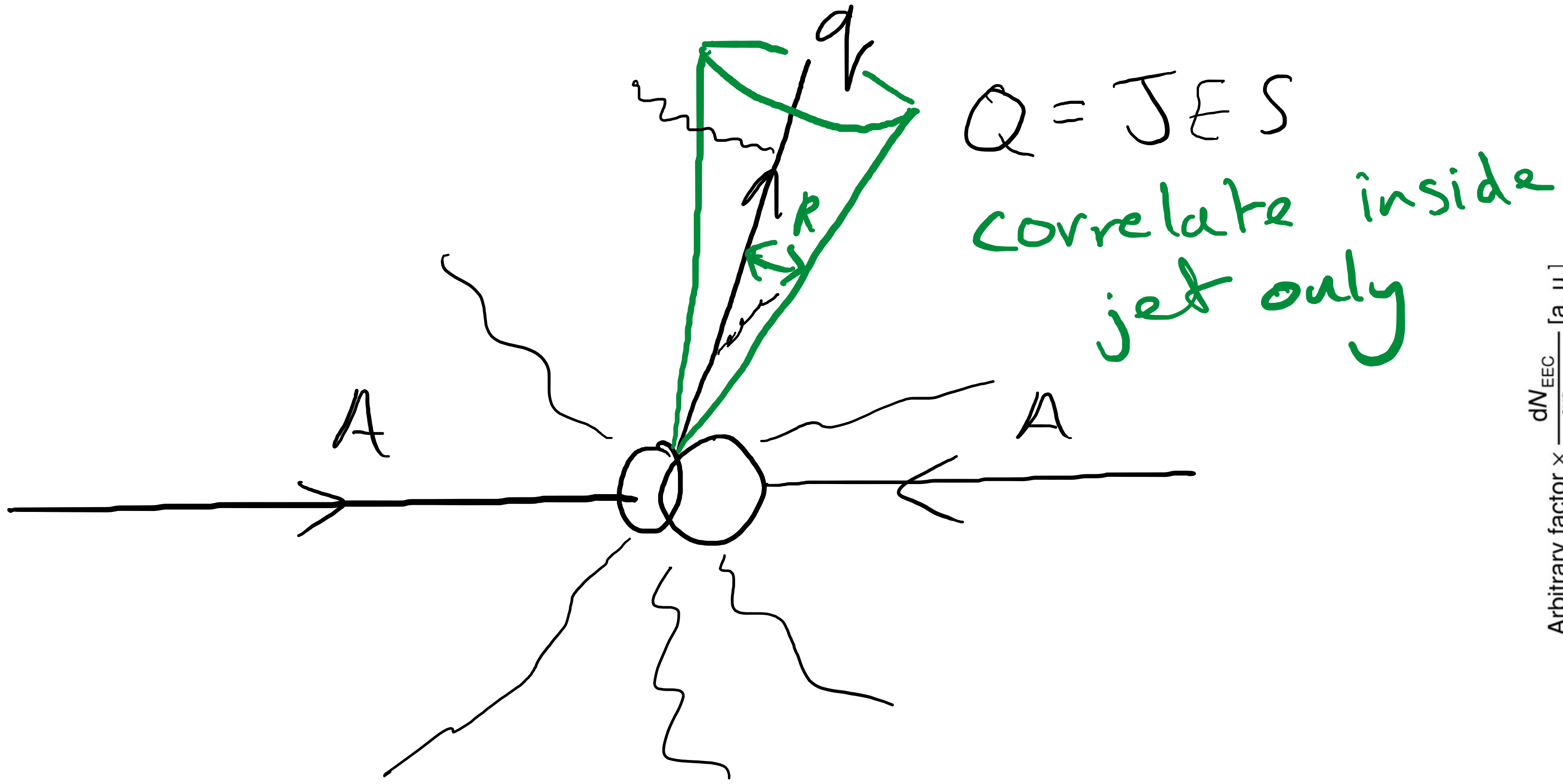
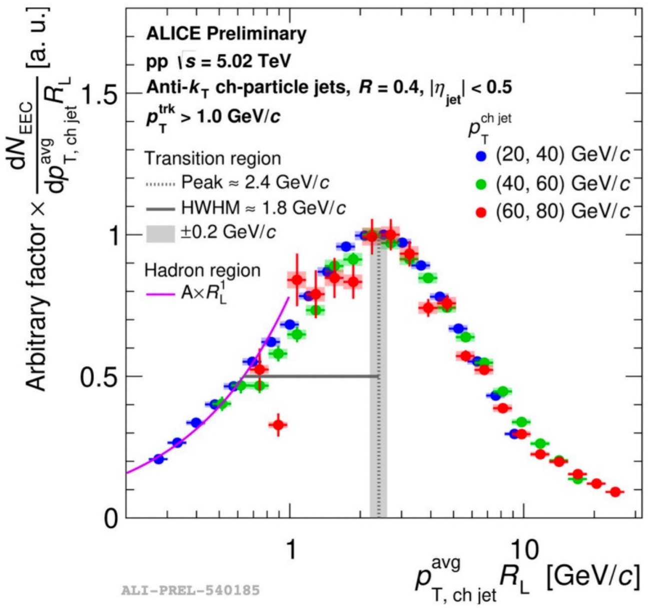
Computation on inclusive jets

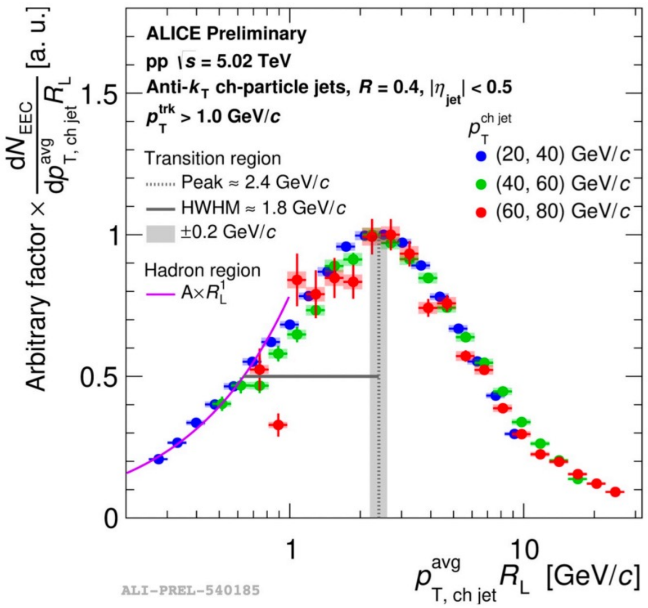




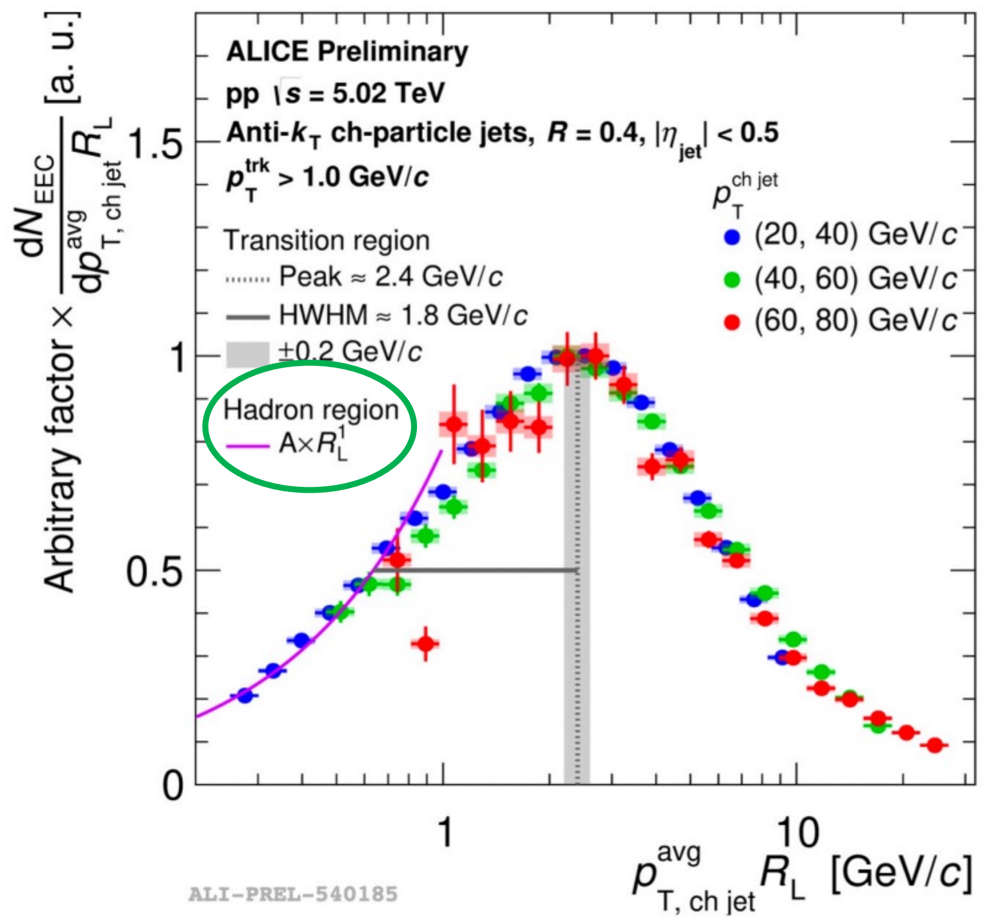
Computation on inclusive jets

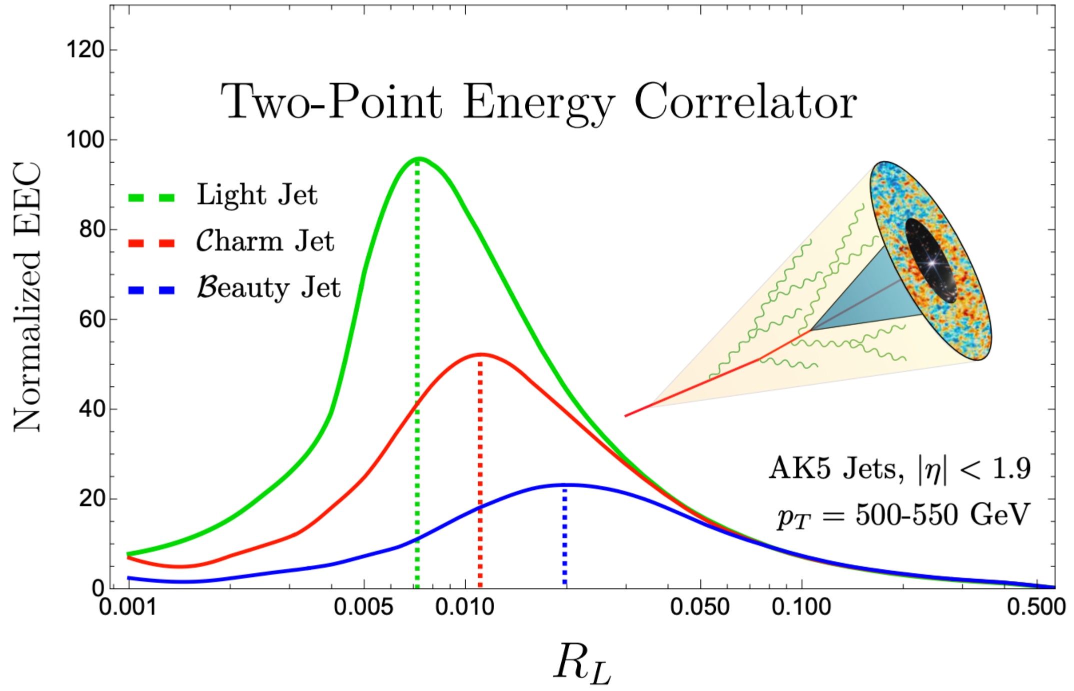
Energy loss will now be important because of the dependence on the JES and due to its large overall effect on narrower jets. Quenching weights now are an important addition to the calculation. 2307.08943

Additionally, the NP transition is a large JES dependent feature. It will be subject to energy loss with small knock-on effects throughout the spectrum. A model is needed, we use a finite NP gluon mass. 0802.1870 hep-ph/9808392



The NP transition





Notice that the NP transition looks just like a deadcone but at a smaller angle. Perhaps a NP propagator mass will model the transition?

The NP transition

Why would this work. Consider an approximate functional form for the full curve.
Given the curve has two distinct limiting behaviours, a Laurent series is not sufficient. Instead, we can use a Padé approximant:

$$\frac{\mathrm{d}\,\Sigma}{\mathrm{d}\,\theta} = \frac{\sum_n c_n\,\theta^n}{\sum_n b_n\,\theta^n}.$$

The lowest order Padé with the correct boundary conditions is

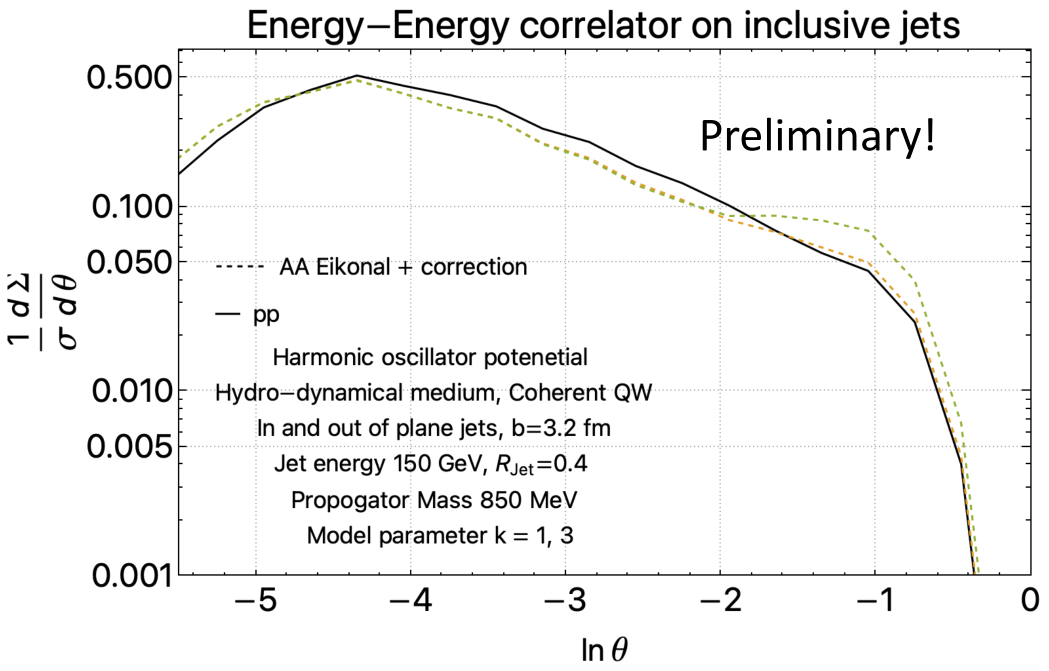
$$\frac{\mathrm{d}\,\Sigma}{\mathrm{d}\,\theta} = \frac{\theta}{b_0 + b_2\,\theta^2}.$$

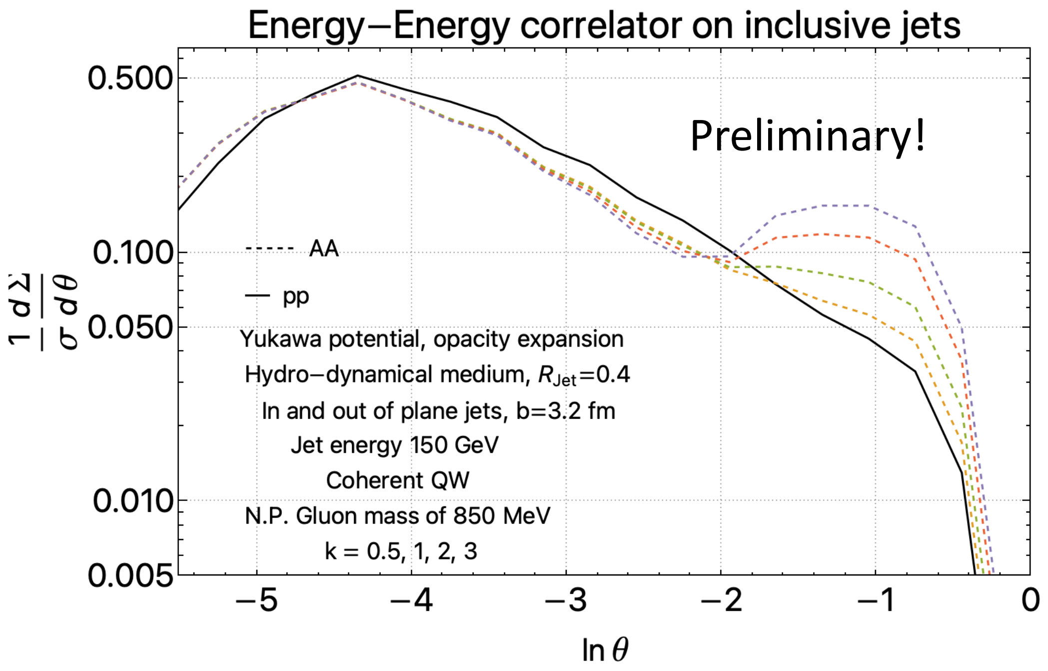
What is the collinear limit of the deadcone (from the massive collinear splitting function)?

$$\frac{\mathrm{d}\,\Sigma}{\mathrm{d}\,\theta} \sim \frac{\theta}{\Theta_0 + \theta^2}.$$

where $\Theta_0 \approx m/E$ is the deadcone angle.

Inclusive jets - see Fabio's talk





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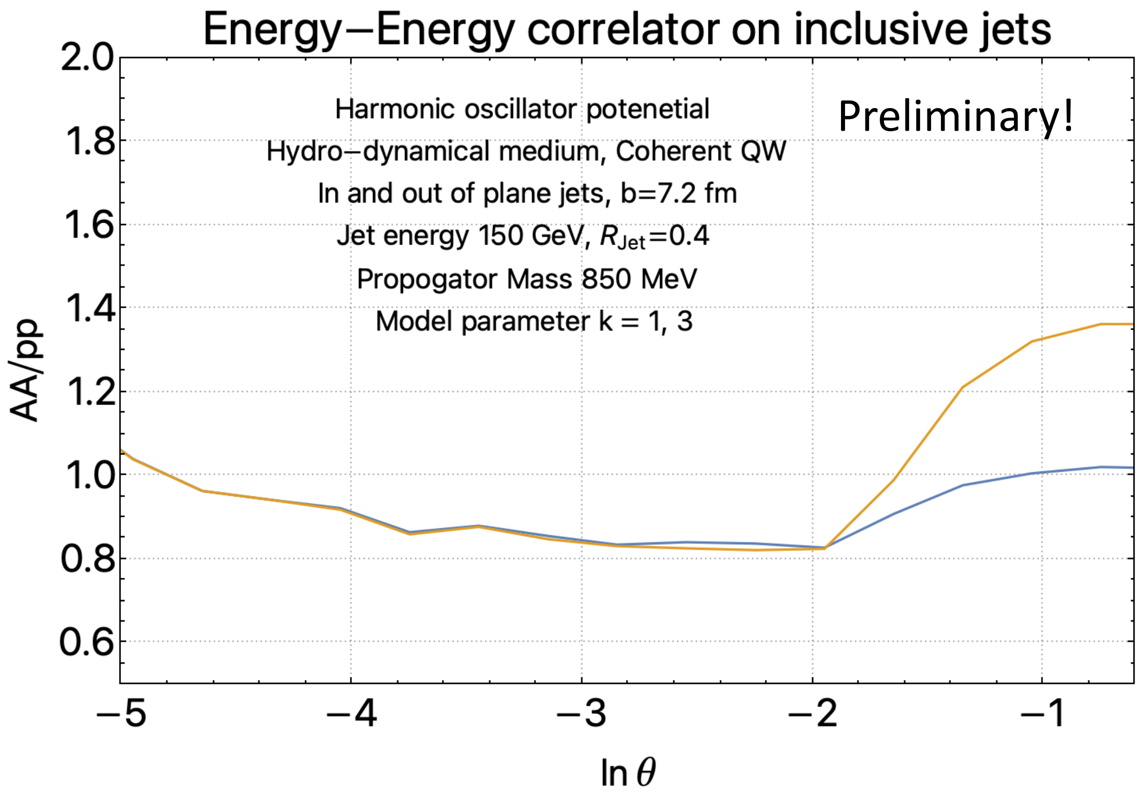

For the future

	$\langle \mathcal{E}(\vec{n}_1) \rangle$	$\langle \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2) \rangle$	$\langle \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\mathcal{E}(\vec{n}_3) \rangle$	$\langle \mathcal{E}(\vec{n}_1) \ldots \mathcal{E}(\vec{n}_i) \rangle$
Pheno/ Theory	No present interest	BDMPS-Z γ+jet Andres, Dominguez, Elayavalli, JH, Marquet, Moult arXiv:2209.11236 Andres, Dominguez, JH, Marquet, Moult arXiv:2303.03413		
		Opacity Expansion γ+jet Andres, Dominguez, JH, Marquet, Moult arXiv:2303.03413		
Pheno		Jet and Groomed Jet Barata, Caucal, Soto-Ontoso, Szafron arXiv:2312.12527		
		Deadcone study Andres, Dominguez, JH, Marquet, Moult arXiv:2307.15110	Unpublished MC studies	Unpublished MC studies
		MC study Yang, He, Moult, Wang arXiv:2310.01500		
		… see slide 10	See Hannah’s talk	

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I'd like to see these columns fill out.

It is unlikely that analytical theory will take the lead here. There are many hurdles to computing this differentially. BUT there is a very well controlled pp baseline with a lot of interesting physics. If done carefully, this is ideal playground for experimental lead MC studies and pheno studies.

For the future

	$\langle\mathcal{E}(\vec{n}_1)\rangle$	$\langle\mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\rangle$	$\langle\mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\mathcal{E}(\vec{n}_3)\rangle$	$\langle\mathcal{E}(\vec{n}_1)\ldots\mathcal{E}(\vec{n}_i)\rangle$
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Pheno/ Theory		Opacity Expansion γ+jet Andres, Dominguez, JH, Marquet, Moult arXiv:2303.03413		
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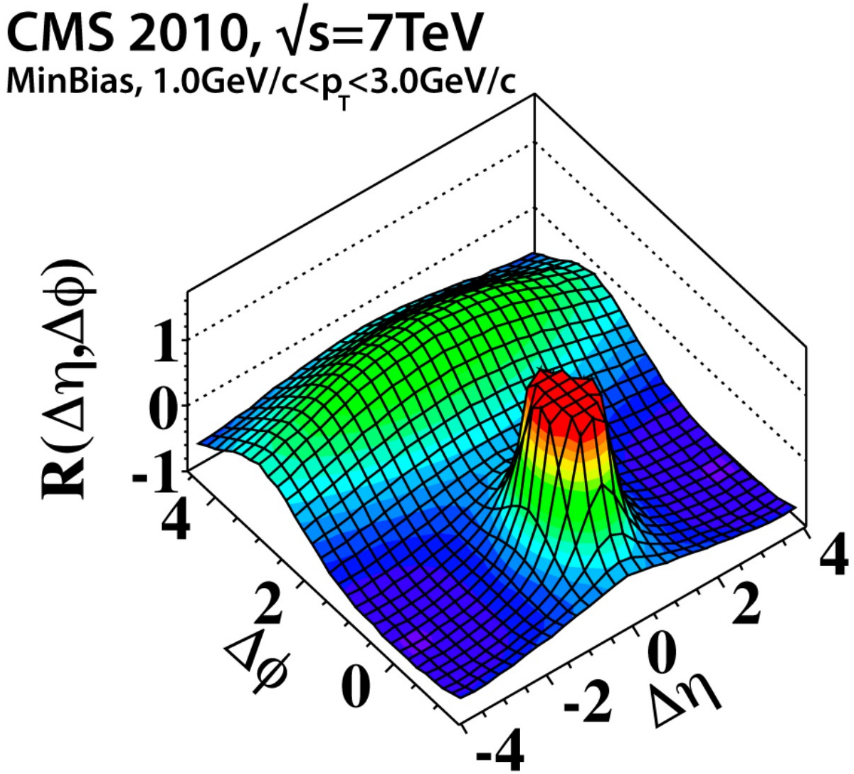
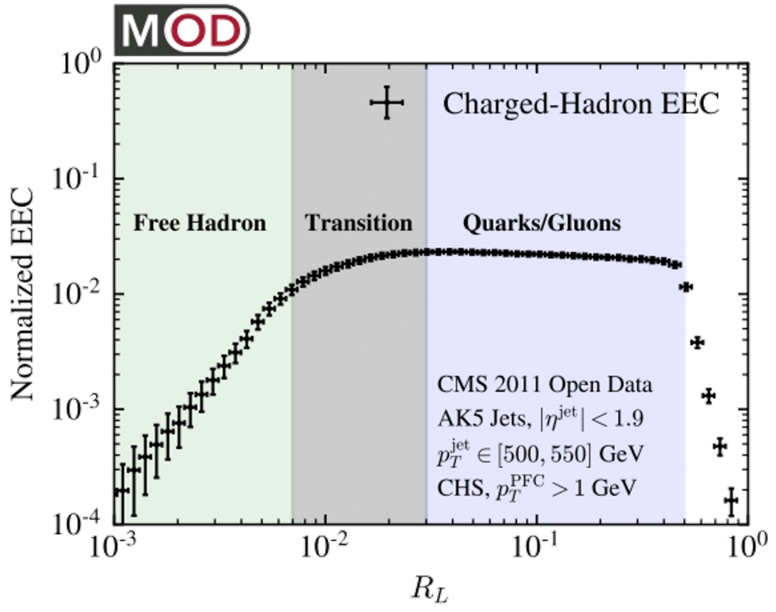
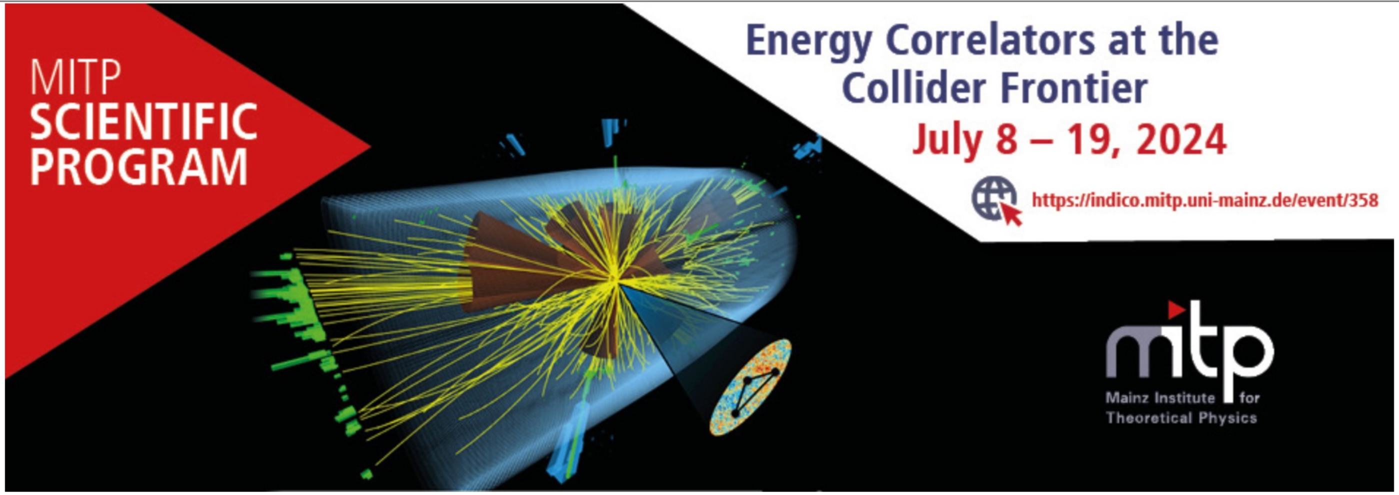
For the future



Look outside the substructure limit?



For the future



Energy Correlators at the Collider Frontier

8–19 Jul 2024
MITP - Mainz Institute for Theoretical Physics, Johannes Gutenberg University Mainz
Europe/Berlin timezone

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Contact @ MITP : Dominika Barrington
ECCF2024@uni-mainz.de

Energy-energy correlators (EECs) are powerful tools for collider QCD. They simultaneously enable precision measurements of complex collider phenomena whilst retaining strong links with highly developed techniques from conformal field theory and light-ray operator product expansions. The last decade has seen substantial growth in the field of EECs and the deep connections among conformal theories, jet substructure, heavy-ion physics and analytic QCD have just started to be explored. This scientific program aims to enable researchers across these different fields to meet and elaborate concrete strategies to fully exploit the potential of the EEC framework for collider phenomenology.

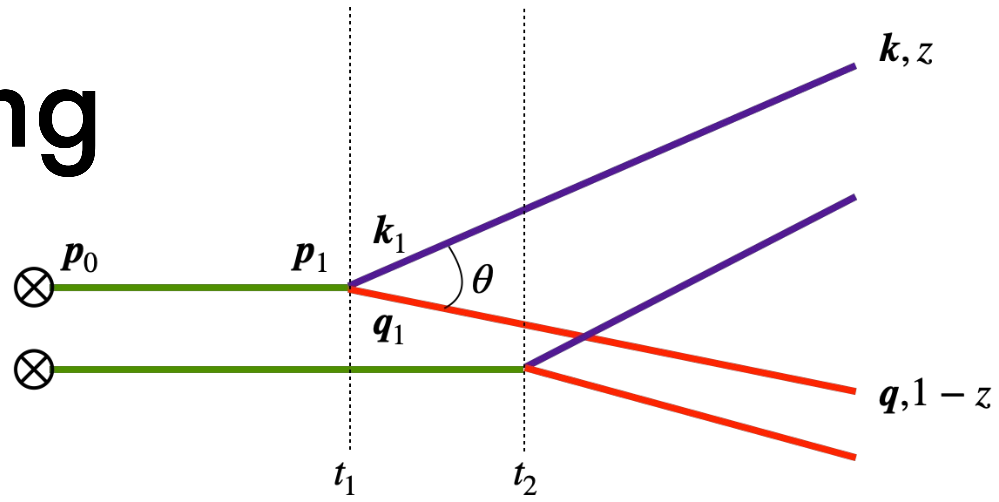
Some keys areas of focus include:

- Identifying new/unique phenomenological applications
- Developing techniques for computations of energy correlators in QCD
- Extending the links between EECs in conformal theories and EECs in QCD.
- Finding synergy between jet physics and heavy-ion physics within the EEC framework.
- Identifying how recent EEC developments can feedback into broader collider phenomenology and Monte Carlo generators.

Thanks!

Part N/A: Supplemental Material

Jet Quenching



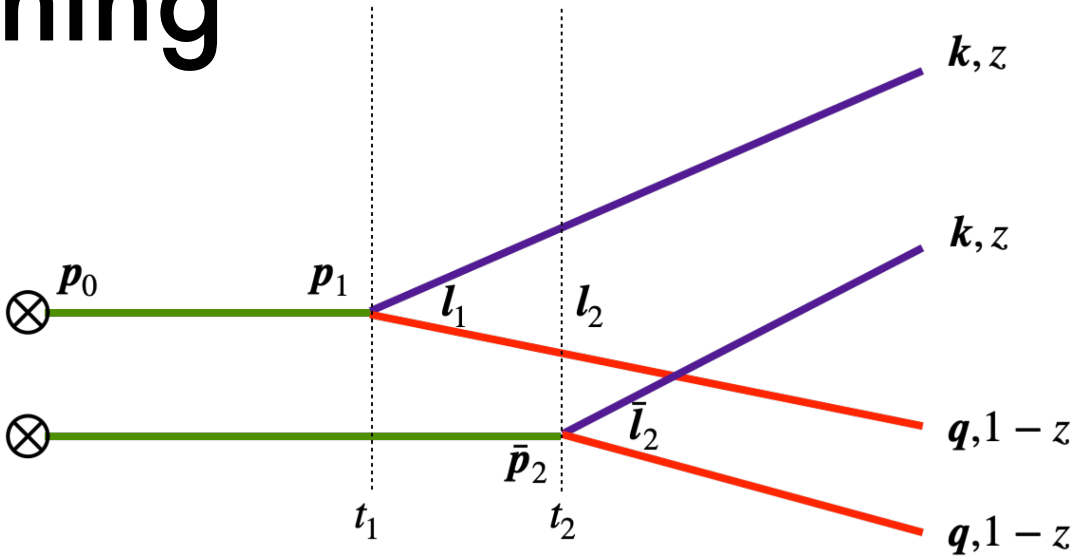
$$\mathcal{M}^{\alpha\beta} = \frac{1}{2E}\int_{\boldsymbol{p}_0\boldsymbol{p}_1\boldsymbol{k}_1\boldsymbol{q}_1}\int_{t_0}^{\infty} dt_1\,(2\pi)^2\delta^{(2)}(\boldsymbol{p}_1-\boldsymbol{k}_1-\boldsymbol{q}_1)\mathcal{G}_{R_b}^{\alpha\alpha_1}(\boldsymbol{k},L;\boldsymbol{k}_1,t_1;zE)$$
$$\times\,\mathcal{G}_{R_c}^{\beta\beta_1}(\boldsymbol{q},L;\boldsymbol{q}_1,t_1;(1-z)E)\,V(\boldsymbol{k}_1-z\boldsymbol{p}_1,z)T^{\alpha_1\beta_1\gamma_1}\,\mathcal{G}_{R_a}^{\gamma_1\gamma}(\boldsymbol{p}_1,t_1;\boldsymbol{p}_0,t_0;E)\,\mathcal{M}_0^{\gamma}(E,\boldsymbol{p}_0)$$

Where each of the in-medium propagators is of the form:

$$\mathcal{G}_R(t_2,\boldsymbol{x}_2;t_1,\boldsymbol{x}_1;\omega) = \int_{\boldsymbol{x}_1}^{\boldsymbol{x}_2}\mathcal{D}\boldsymbol{r}\,\exp\left\{\frac{i\omega}{2}\int_{t_1}^{t_2}d\xi\;\dot{\boldsymbol{r}}^2(\xi)\right\}\underbrace{\mathrm{P}\exp\left\{ig\int_{t_1}^{t_2}d\xi\;A_R^-(\xi,\boldsymbol{r}(\xi))\right\}}_{V_R(t_2,t_1;[\boldsymbol{r}])}$$

$$\left\langle|\mathcal{M}|^2\right\rangle \propto \Big\langle\mathcal{G}_{R_b}^{\alpha\alpha_1}(\boldsymbol{k},L;\boldsymbol{k}_1,t_1;zE)\mathcal{G}_{R_c}^{\beta\beta_1}(\boldsymbol{q},L;\boldsymbol{q}_1,t_1;(1-z)E)\mathcal{G}_{R_b}^{\dagger\bar{\alpha}_2\alpha}(\bar{\boldsymbol{k}}_2,t_2;\boldsymbol{k},L;zE)$$
$$\times\mathcal{G}_{R_c}^{\dagger\bar{\beta}_2\beta}(\bar{\boldsymbol{q}}_2,t_2;\boldsymbol{q},L;(1-z)E)\mathcal{G}_{R_a}^{\gamma_1\gamma}(\boldsymbol{p}_1,t_1;\boldsymbol{p}_0,t_0;E)\mathcal{G}_{R_a}^{\dagger\bar{\gamma}\bar{\gamma}_2}(\bar{\boldsymbol{p}}_0,t_0;\bar{\boldsymbol{p}}_2,t_2;E)\Big\rangle$$

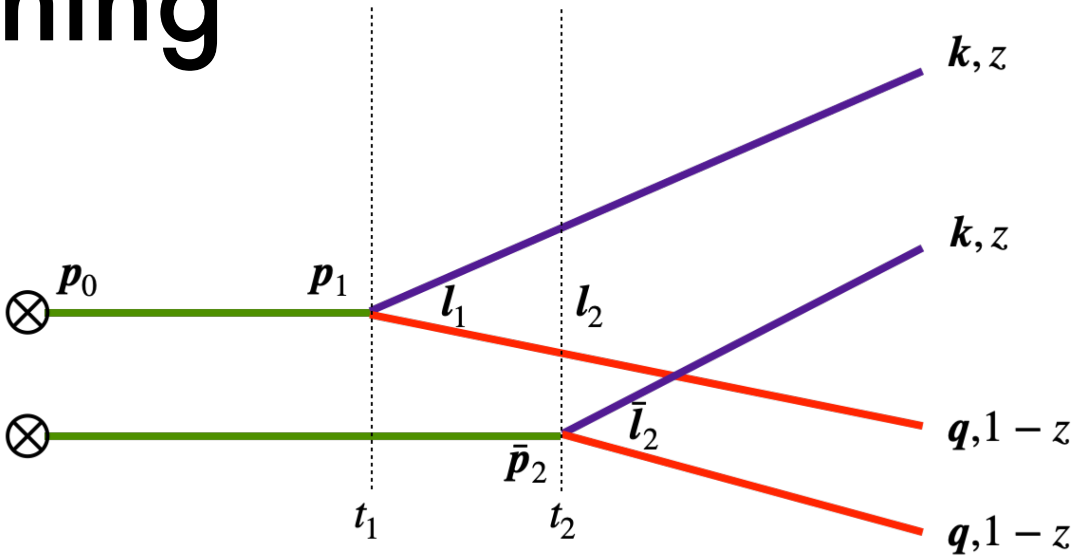
Jet Quenching



$$\frac{d\sigma}{d\Omega_k d\Omega_q} = \frac{g^2}{z(1-z)E^2} P_{a\to bc}(z)\, 2\mathrm{Re} \int_{\boldsymbol{p}_0 \boldsymbol{p}_1 \bar{\boldsymbol{p}}_2 \boldsymbol{l}_1 \boldsymbol{l}_2 \bar{\boldsymbol{l}}_2} \int_{t_0}^{\infty} dt_1 \int_{t_1}^{\infty} dt_2 (\boldsymbol{l}_1 \cdot \bar{\boldsymbol{l}}_2)$$
$$\times\, \mathcal{S}^{(4)}((1-z)\boldsymbol{k} - z\boldsymbol{q}, L; \boldsymbol{l}_2, \bar{\boldsymbol{l}}_2, t_2; \boldsymbol{k}+\boldsymbol{q}-\bar{\boldsymbol{p}}_2, z)$$
$$\times\, \mathcal{K}^{(3)}(\boldsymbol{l}_2, t_2; \boldsymbol{l}_1, t_1; \bar{\boldsymbol{p}}_2 - \boldsymbol{p}_1, z)\, \mathcal{P}_{R_a}(\boldsymbol{p}_1 - \boldsymbol{p}_0; t_1, t_0) \frac{d\sigma_{hard}}{d\Omega_{p_0}}$$

Jet Quenching

BDMPS-Z



$$\frac{d\sigma}{d\Omega_k d\Omega_q} = \frac{g^2}{z(1-z)E^2} P_{a\to bc}(z)\, 2\mathrm{Re}\int_{\boldsymbol{p}_0\boldsymbol{p}_1\bar{\boldsymbol{p}}_2\boldsymbol{l}_1\boldsymbol{l}_2\bar{\boldsymbol{l}}_2} \int_{t_0}^{\infty} dt_1 \int_{t_1}^{\infty} dt_2 (\boldsymbol{l}_1 \cdot \bar{\boldsymbol{l}}_2)$$

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$\langle \mathcal{G}\mathcal{G}\mathcal{G}^\dagger\mathcal{G}^\dagger \rangle$

$\langle \mathcal{G}\mathcal{G}\mathcal{G}^\dagger \rangle$

$\langle \mathcal{G}\mathcal{G}^\dagger \rangle$

Part N/A: Supplemental Material

$$\mathcal{M}_{\gamma\to q\bar{q}} = \frac{e}{E}\mathrm{e}^{i\frac{\boldsymbol{p}_1^2}{2zE}L + i\frac{\boldsymbol{p}_2^2}{2(1-z)E}L}\int_0^\infty \mathrm{d}t \int_{\boldsymbol{k}_1,\boldsymbol{k}_2} \left[\mathcal{G}(\boldsymbol{p}_1, L; \boldsymbol{k}_1, t|zE)\,\bar{\mathcal{G}}(\boldsymbol{p}_2, L; \boldsymbol{k}_2, t|(1-z)E)\right]_{ij}$$
$$\times\, \gamma_{\lambda,s,s'}(z)\boldsymbol{k}\cdot\boldsymbol{\epsilon}^*_\lambda\,\mathcal{G}_0(\boldsymbol{k}_1+\boldsymbol{k}_2, t|E)$$

$$\mathcal{G}(\boldsymbol{p}_1, t_1; \boldsymbol{p}_0, t_0) = \int_{\boldsymbol{x}_1,\boldsymbol{x}_2} \mathrm{e}^{-i\boldsymbol{p}_1\cdot\boldsymbol{x}_1 + i\boldsymbol{p}_0\cdot\boldsymbol{x}_0}\mathcal{G}(\vec{x}_1, \vec{x}_0)$$

$$\mathcal{G}(\vec{x}_1, \vec{x}_0) = \int_{\boldsymbol{r}(t_0)=\boldsymbol{x}_0}^{\boldsymbol{r}(t_1)=\boldsymbol{x}_1} \mathcal{D}\boldsymbol{r}\,\exp\left[i\frac{E}{2}\int_{t_0}^{t_1}\mathrm{d}s\,\dot{\boldsymbol{r}}^2\right] V(t_1, t_0; [\boldsymbol{r}])$$

$$V(t_1, t_0; [\boldsymbol{r}]) = \mathcal{P}\exp\left[ig\int_{t_0}^{t_1}\mathrm{d}t\,\mathbf{t}^a A^{-,a}(t, \boldsymbol{r}(t))\right]$$

$$\frac{\mathrm{d}N^{\mathrm{med}}}{\mathrm{d}z\mathrm{d}\boldsymbol{p}^2} = \frac{1}{4(2\pi)^2\,z(1-z)}\langle|\mathcal{M}_{\gamma\to q\bar{q}}|^2\rangle = \frac{1}{4(2\pi)^2\,z(1-z)}\langle\left|\mathcal{M}^{\mathrm{in}}_{\gamma\to q\bar{q}} + \mathcal{M}^{\mathrm{out}}_{\gamma\to q\bar{q}}\right|^2\rangle$$

Part N/A: Supplemental Material

$$\frac{\mathrm{d}\sigma_{qg}}{\mathrm{d}\theta\mathrm{d}z} = \frac{\mathrm{d}\sigma_{qg}^{\mathrm{vac}}}{\mathrm{d}\theta\mathrm{d}z}(1 + F_{\mathrm{med}}(z, \theta, \hat{q}, L))$$

$$F_{\mathrm{med}} = 2\int_0^L \frac{\mathrm{d}t_1}{t_{\mathrm{f}}}\left[\int_{t_1}^L \frac{\mathrm{d}t_2}{t_{\mathrm{f}}}\cos\left(\frac{t_2 - t_1}{t_{\mathrm{f}}}\right)\mathcal{C}^{(4)}(L, t_2)\mathcal{C}^{(3)}(t_2, t_1) - \sin\left(\frac{L - t_1}{t_{\mathrm{f}}}\right)\mathcal{C}^{(3)}(L, t_1)\right]$$

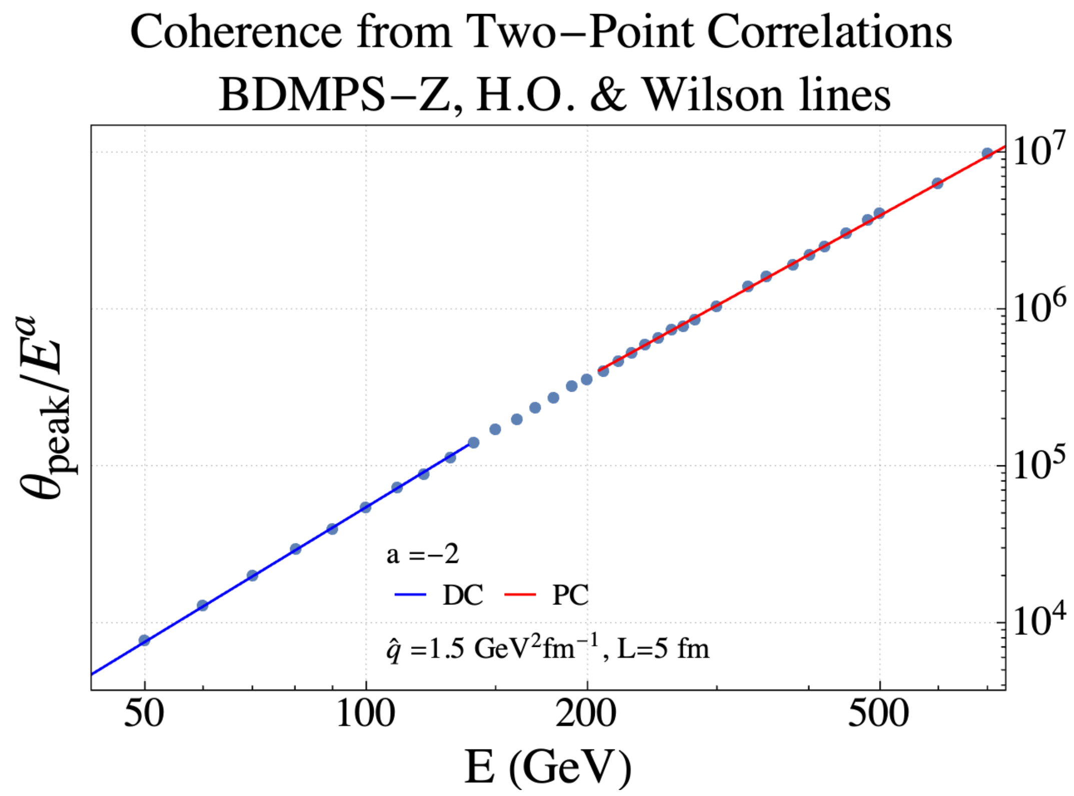
$$\mathcal{C}_{gq}^{(3)}(t_2, t_1) = \frac{1}{N_c^2 - 1}\left\langle \mathrm{tr}[V_2^\dagger V_1]\,\mathrm{tr}[V_0^\dagger V_2] - \frac{1}{N_c}\,\mathrm{tr}[V_0^\dagger V_1]\right\rangle .$$

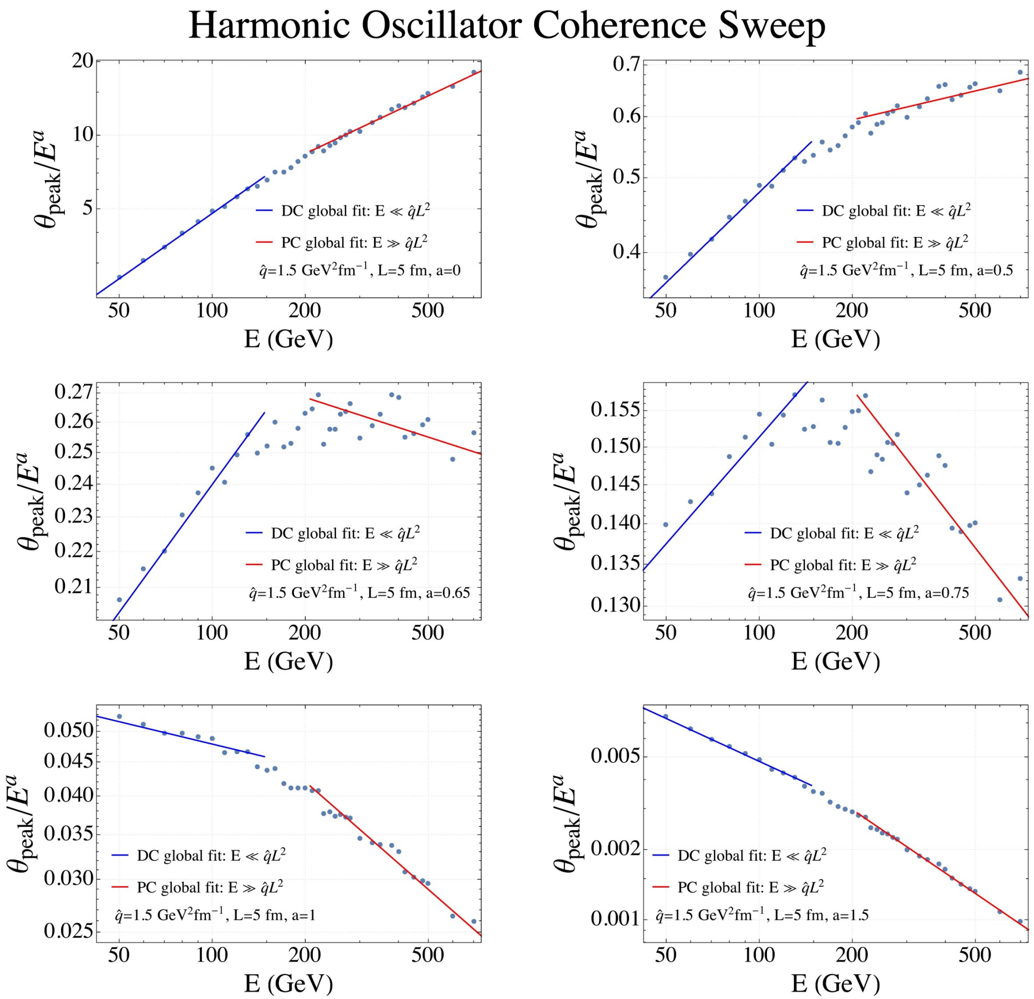
$$\begin{aligned}\mathcal{C}_{gq}^{(3)}(t_2, t_1) &= \mathrm{e}^{-\frac{1}{2}\int_{t_1}^{t_2}\mathrm{d}s\, n(s)[N_c(\sigma_{02}+\sigma_{12}) - \frac{1}{N_c}\sigma_{01}]} \\ &= \mathrm{e}^{-\frac{1}{12}\hat{q}(t_2-t_1)^3\theta^2\left(1+z^2+\frac{2z}{N_c^2-1}\right)} .\end{aligned}$$

$$\mathcal{C}_{gq}^{(4)}(L, t_2) = \frac{1}{N_c^2 - 1}\left\langle \mathrm{tr}[V_{\bar{1}}^\dagger V_1 V_2^\dagger V_{\bar{2}}]\,\mathrm{tr}[V_{\bar{2}}^\dagger V_2] - \frac{1}{N_c}\,\mathrm{tr}[V_{\bar{1}}^\dagger V_1]\right\rangle ,$$

$$\begin{aligned}&\frac{1}{N_c^2}\langle \mathrm{tr}[V_1 V_2^\dagger V_{\bar{2}} V_{\bar{1}}^\dagger]\,\mathrm{tr}[V_2 V_{\bar{2}}^\dagger]\rangle \simeq \mathrm{e}^{-\frac{1}{4}\hat{q}\theta^2(t-t_2)(t_2-t_1)^2(1-2z+3z^2)} \\ &\times\left(1 - \frac{1}{2}\hat{q}\theta^2 z(1-z)(t_2 - t_1)^2\int_{t_2}^t \mathrm{d}s\,\mathrm{e}^{-\frac{1}{12}\hat{q}\theta^2\left[(s-t_2)^2(2s-3t_1+t_2)+6z(1-z)(s-t_2)(t_2-t_1)^2\right]}\right)\end{aligned}$$

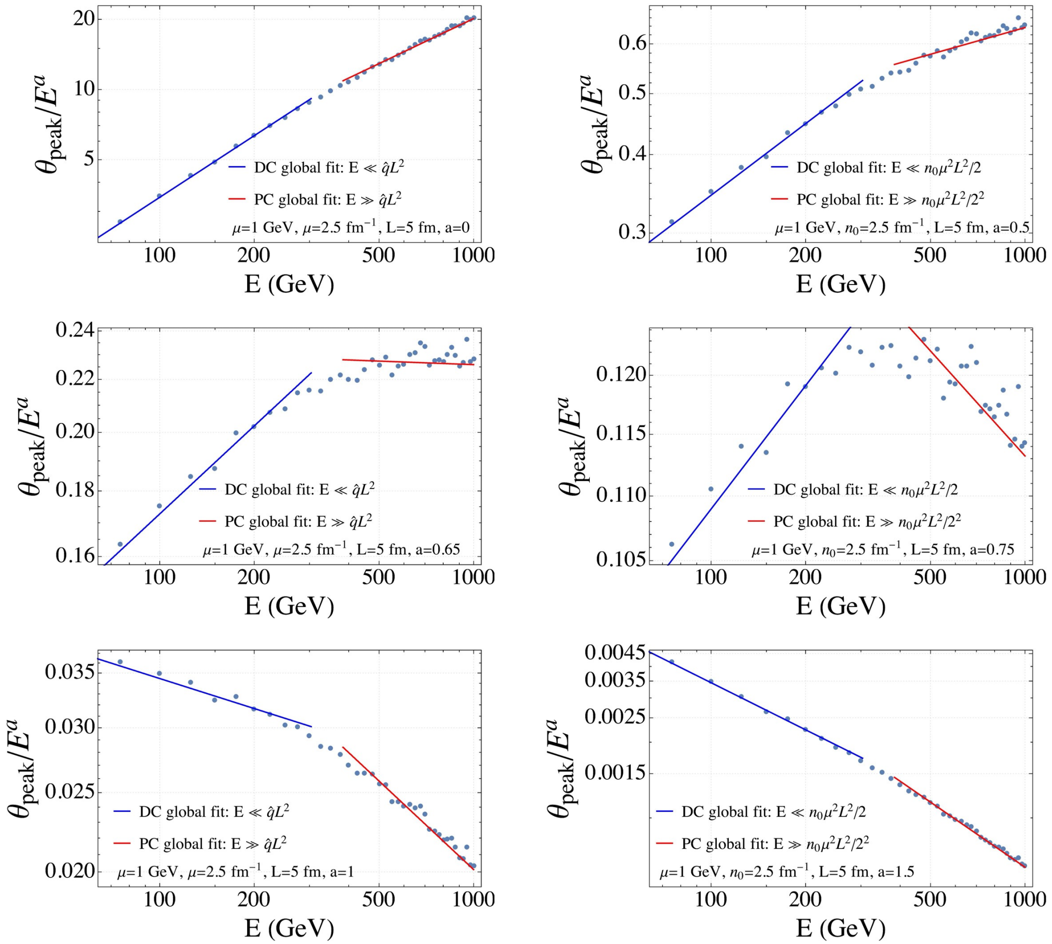
Numerical evaluation of F_{med}





Numerical evaluation of F_{med}

Yukawa Potential Coherence Sweep



GLV Approximation Coherence Sweep