Jet substructure in heavy-ion collisions with energy correlators

Fabio Dominguez
IGFAE, Universidade de Santiago de Compostela

Probing QCD at High Energy and Density with Jets
INT, Seattle, USA
October 16th, 2023

C. Andres, FD, R. K. Elayavalli, J. Holguin, C. Marquet, I. Moult, arXiv:2209.11236
C. Andres, FD, J. Holguin, C. Marquet, I. Moult, arXiv:2303.03413
C. Andres, FD, J. Holguin, C. Marquet, I. Moult, arXiv:2307.15110

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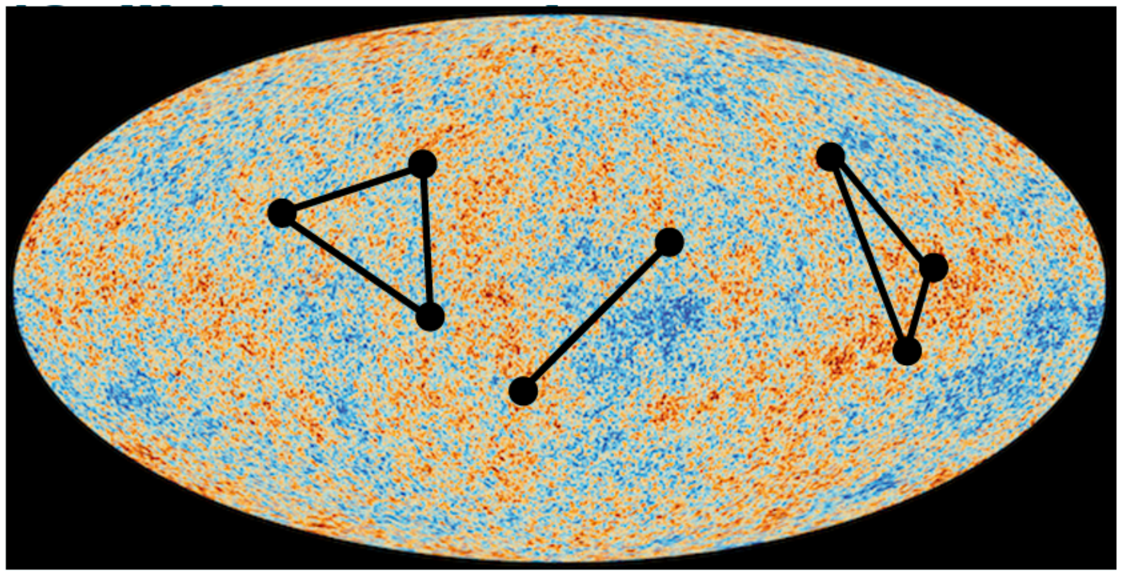
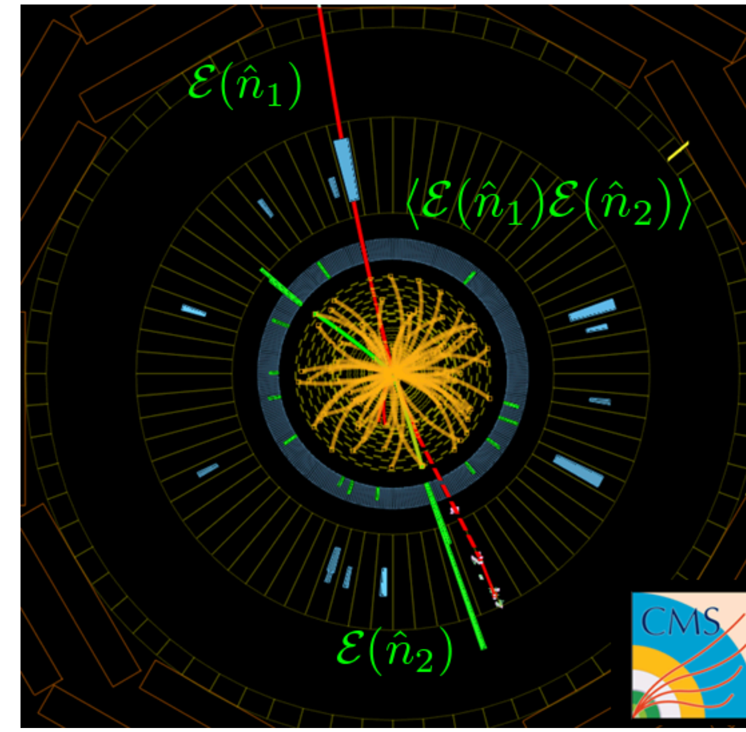
XUNTA DE GALICIA

Energy flux operators

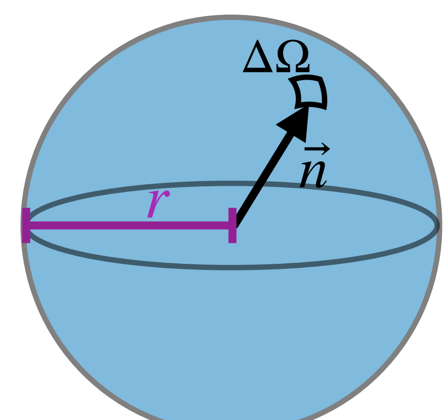




- Correlations of asymptotic energy flux provide valuable information about the underlying theory

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

$$\mathcal{E}(\vec{n})|X\rangle = \sum_a E_a \delta^{(2)}(\Omega_{\vec{p}_a} - \Omega_{\vec{n}})\,|X\rangle$$



Energy correlators

- 2-point function

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

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- Due to rotational symmetry, the only relevant variable is the opening angle

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

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- Can be expressed as a weighted average of the double-inclusive cross-section

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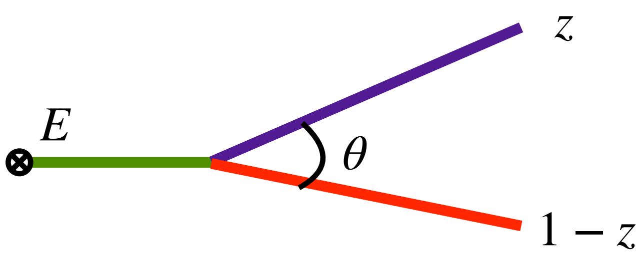
Energy correlators in vacuum



- At leading order

$$\frac{d\sigma_{qg}^{\rm vac}}{d\theta dz} = \frac{\alpha_s C_{\rm F}\sigma}{\pi}\frac{1+(1-z)^2}{z\ \theta}$$

$$\frac{d\Sigma^{(1)}}{d\theta} \sim \frac{1}{\theta}$$

D. Hoffman, J. Maldacena 0803.1467
H. Chen , I. Moult, J. Sandor, H. X. Zhu 2202.04085

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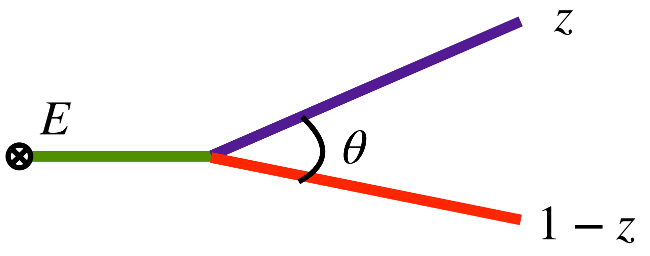

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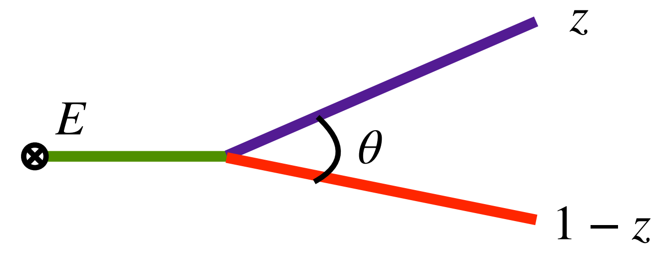

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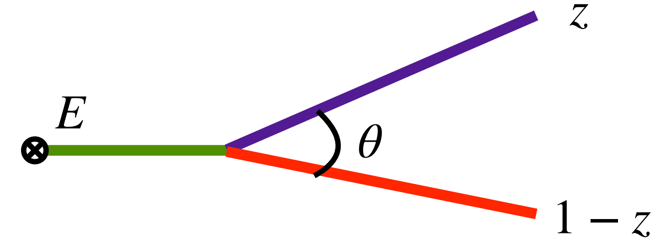

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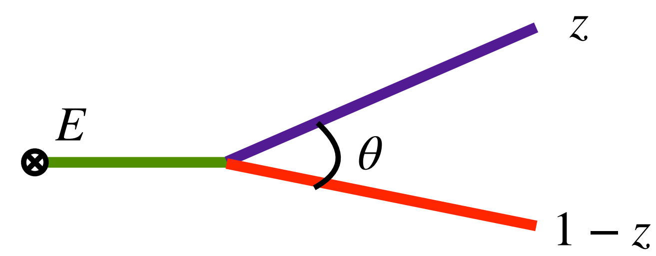

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In a CFT:

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$\gamma(3)$ is the twist-2 spin-3
QCD anomalous dimension

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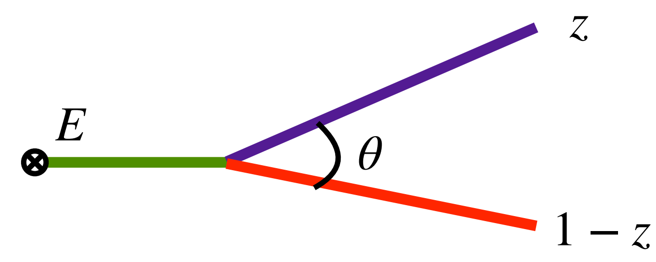

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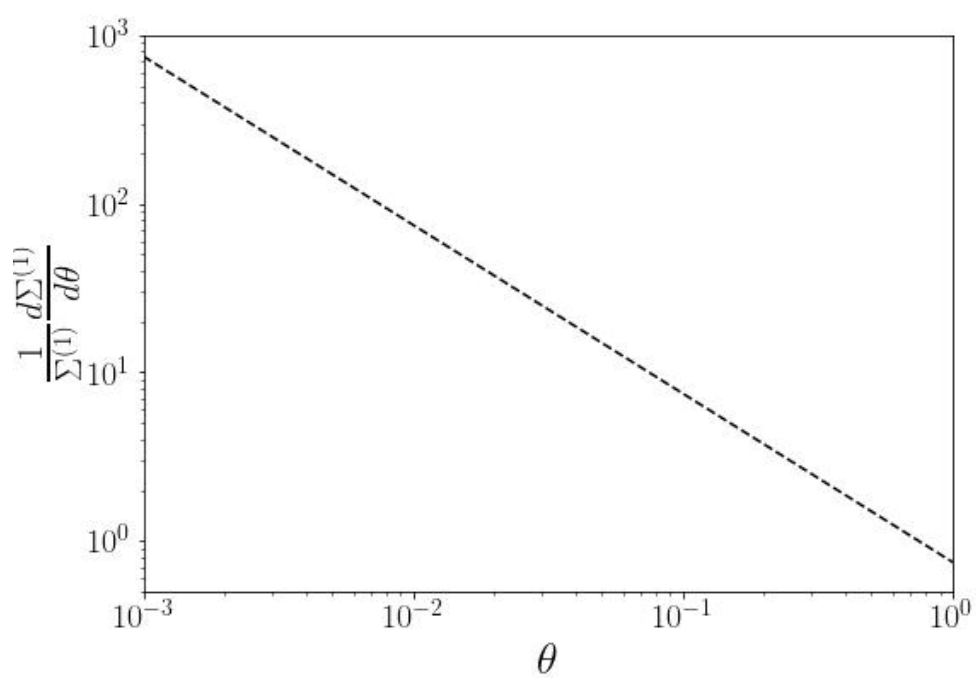

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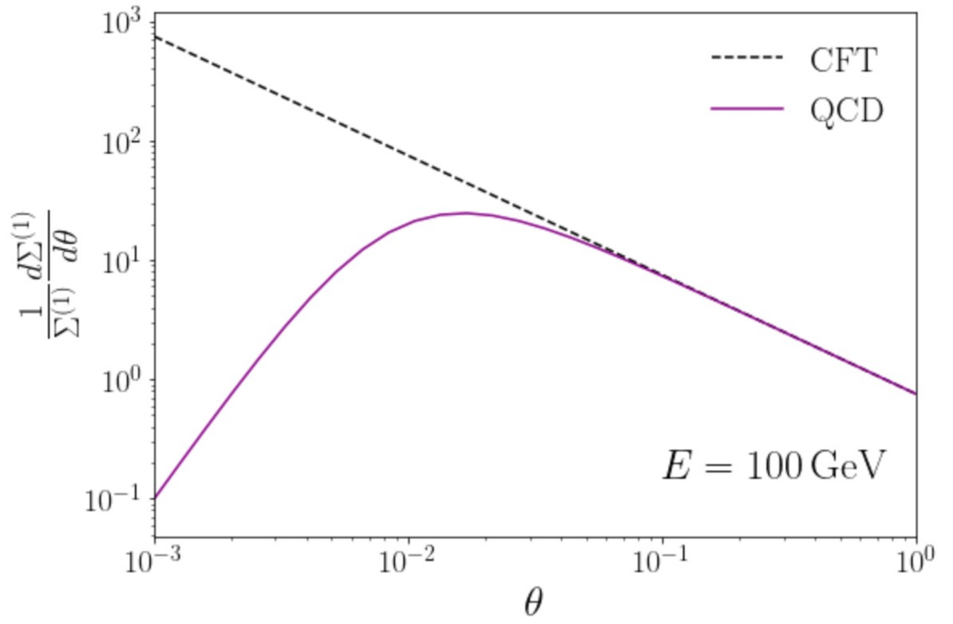
Energy correlators in vacuum

P. T. Komiske, I. Moult, J. Thaler, H. X. Zhu 2201.07800

- QCD is not conformal
- Confinement scale brakes power law behavior at angles below Λ_{QCD}/E
  - Small angles correspond to large times, where hadronization is dominant
  - Larger angles correspond to early times



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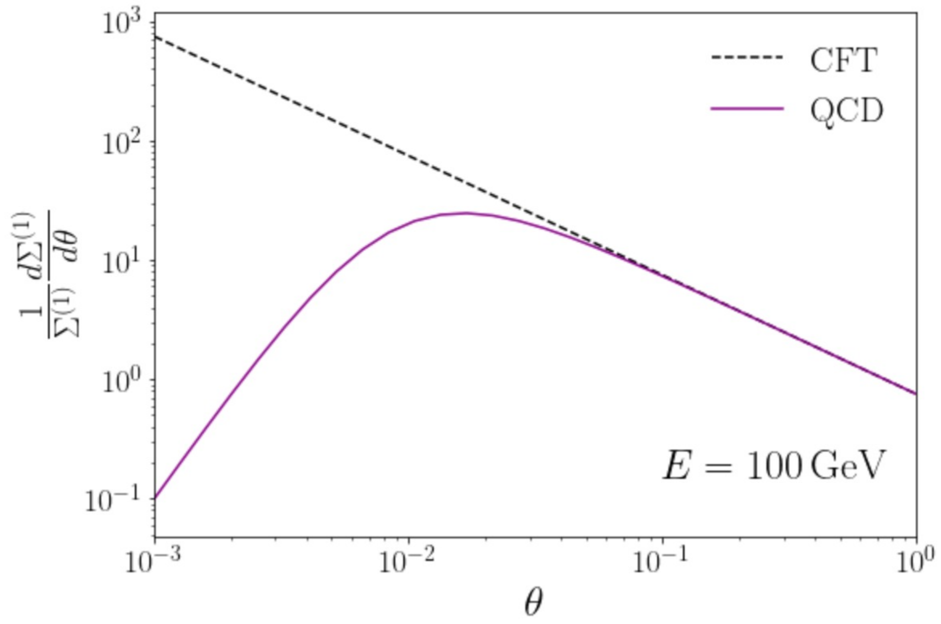

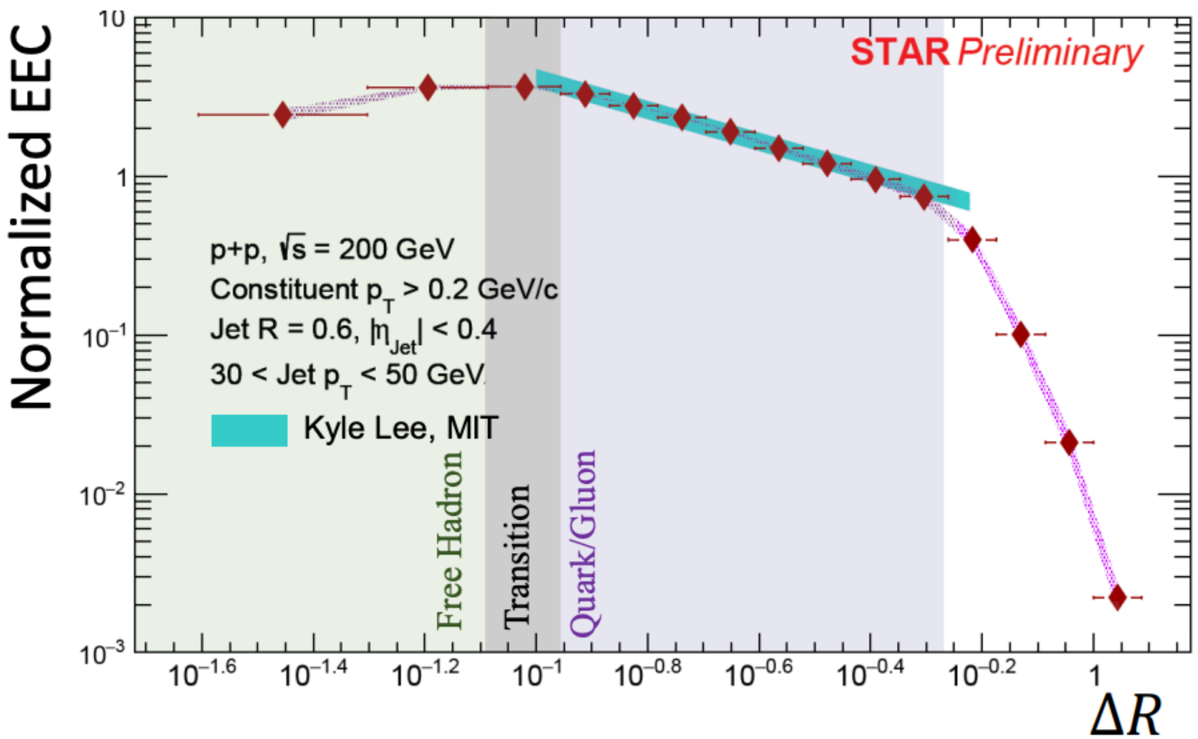

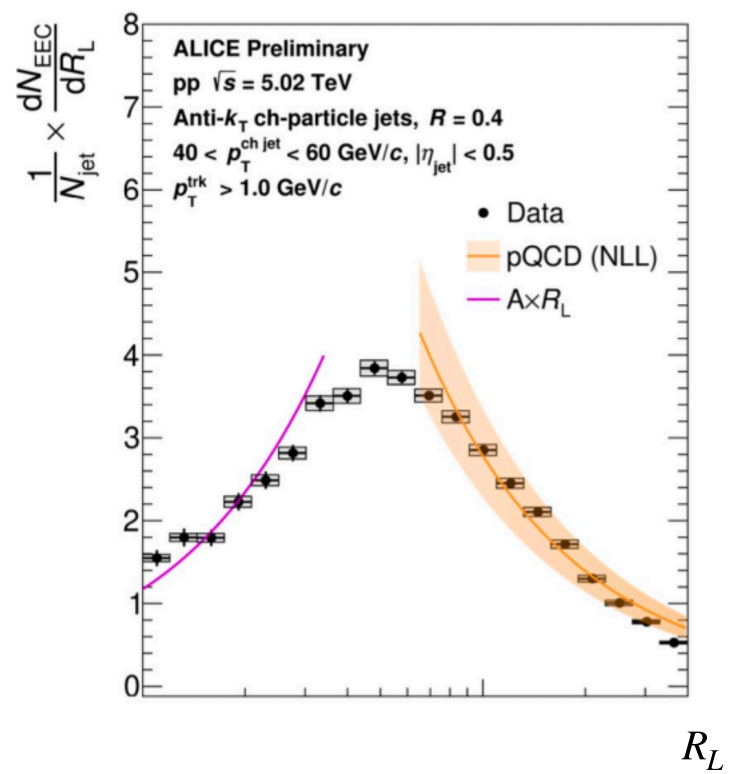

EECs from massive jets

- Dead-cone effect: radiation from heavy quarks is suppressed at small angles

$$\frac{d\sigma_M^{\text{vac}}}{d\theta dz} \sim \frac{\theta^3}{(\theta^2 + \frac{\theta_0^2}{1-z})^2} \frac{d\sigma^{\text{vac}}}{d\theta dz}$$

Dead-cone angle!

$$\theta_0 = \frac{M}{E}$$

E. Craft, K. Lee, B. Meçai, I. Moult 2210.09311

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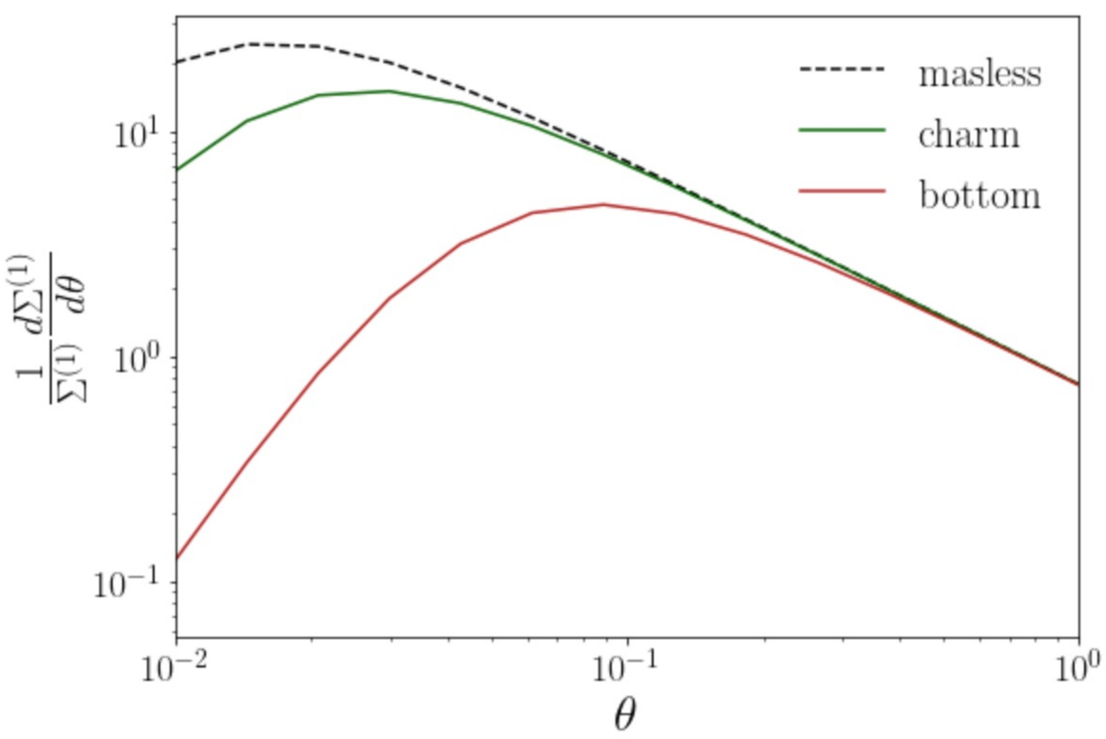
- Deviation from power-law behavior occurs at the dead-cone angle in the perturbative regime

- In the massless case, the transition to the non-perturbative regime can be modeled by putting a gluon mass



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Energy correlators in HIC

- pp baseline understood to a very high degree of accuracy in the perturbative regime
- Less sensitive to soft physics than other observables, better for higher powers of the energy weighting
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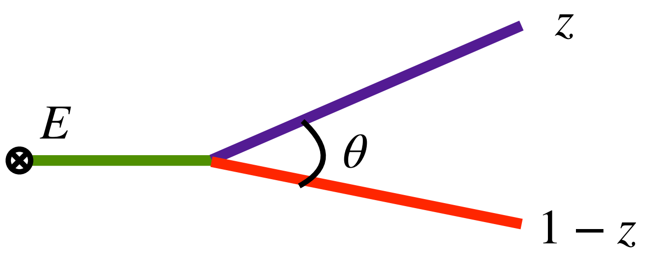
Allows us to isolate the modification of the hard splittings

Contribution from the QGP

- For simplicity, we consider a quark initiated jet where the initial energy is known (γ/Z-jet)

- Energy loss effects are subleading

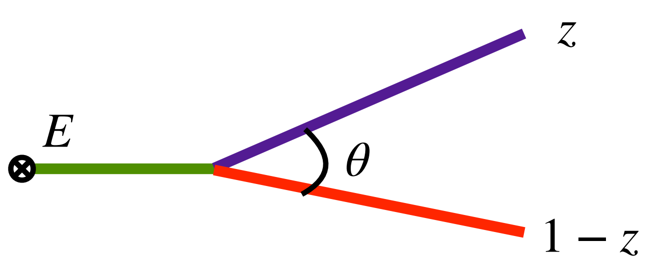
$$\frac{d\Sigma^{(n)}}{d\theta} = \frac{1}{\sigma_{qg}} \int dz \left(\frac{d\sigma_{qg}^{\rm vac}}{d\theta dz} + \frac{d\sigma_{qg}^{\rm med}}{d\theta dz} \right) z^n (1-z)^n + \mathcal{O}\left(\frac{\mu_s}{E}\right)$$



- The presence of the medium is not expected to affect the non-perturbative regime at very small angles, given that it corresponds to late emissions occurring outside of the medium

Evaluation of in-medium splittings must go beyond the soft limit $z \to 0$

Evaluation of in-medium splittings



- Most calculations of medium modifications and MCs restricted to the soft limit

- Only recently, there have been some advances in the full calculation of medium-modified splittings
  Isaksen, Tywoniuk 2303.12119

- Two available approximations:
  Sievert, Vitev 1807.03799
  - Opacity expansion ($N = 1$)
    - Unitarity problems can lead to negative cross sections
    - Recursive formulas to generate all orders (not yet implemented numerically)
  - Semi-hard approximation
    - Resums multiple scatterings in the eikonal approximation through Wilson lines in straight-line trajectories
    - Assumes semi-hard splittings (z not too small)
    - Neglects effects coming from broadening of transverse momenta of produced particles

FD, Milhano, Salgado, Tywoniuk, Vila 1907.03653
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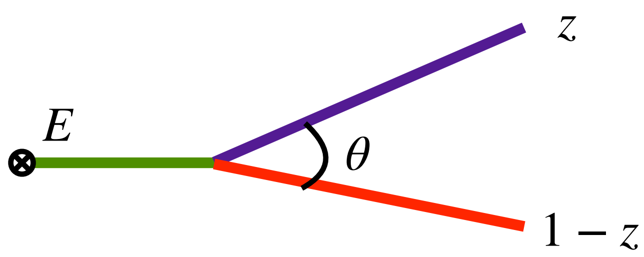

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Time and angular scales

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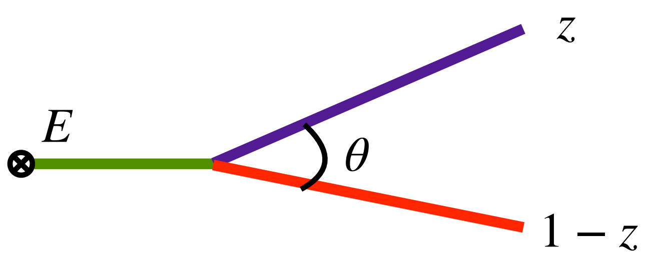

Time and angular scales

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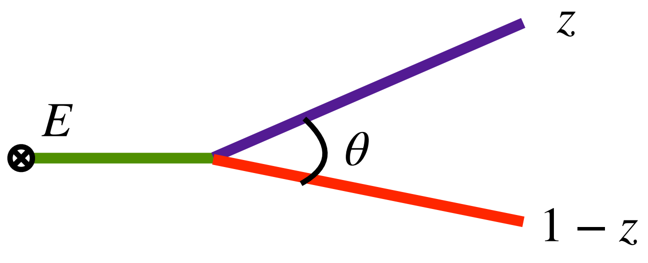
- For a static medium of length L within the harmonic approximation with jet quenching parameter $\hat{q}$ one can read off the relevant scales directly from the formulas



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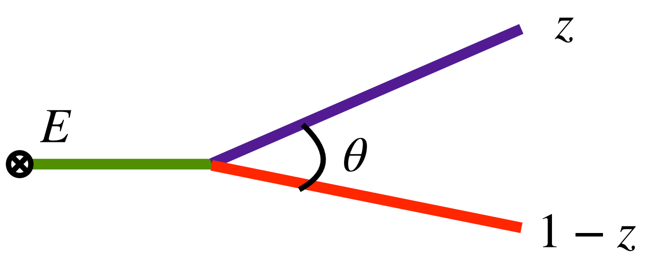

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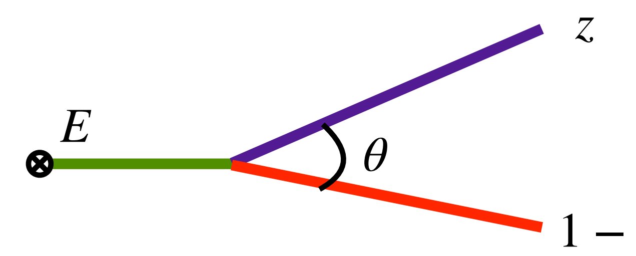

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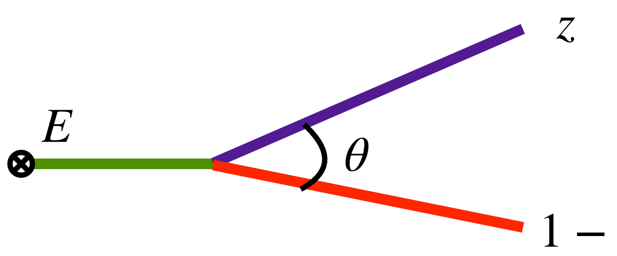

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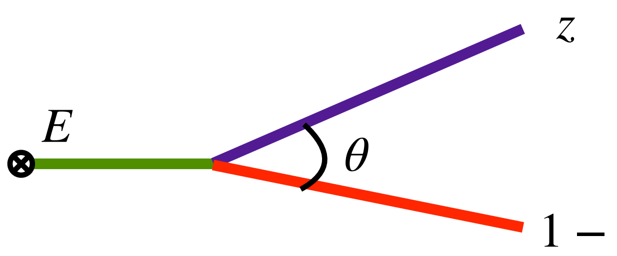

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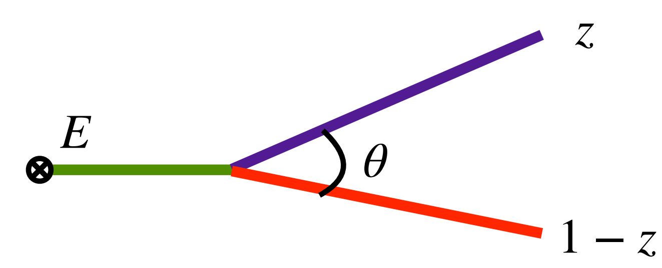

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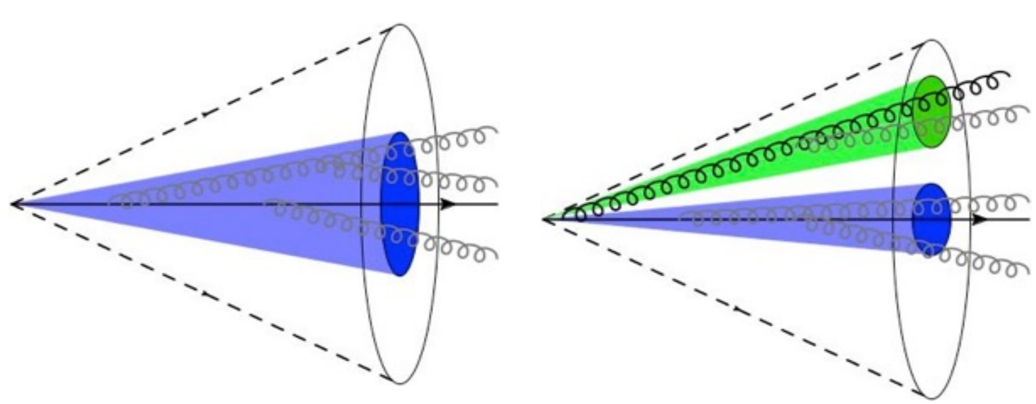

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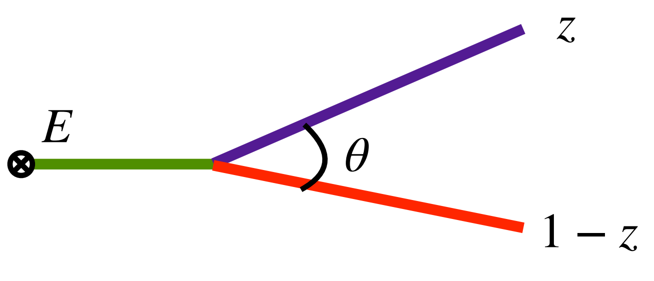

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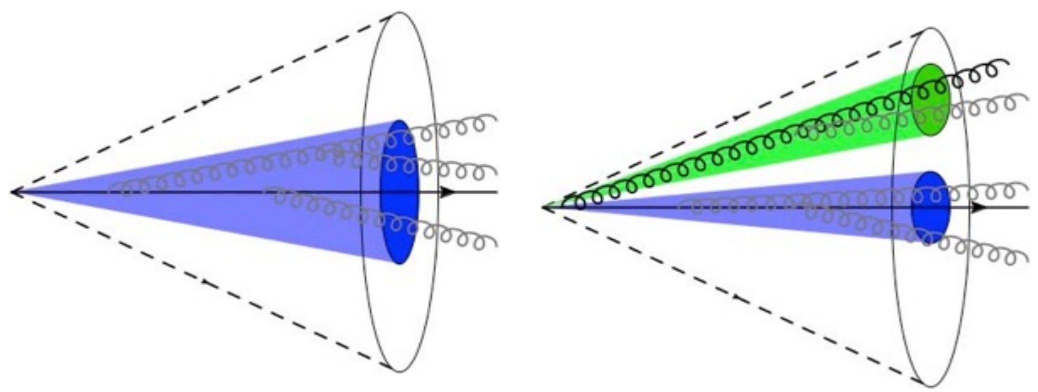

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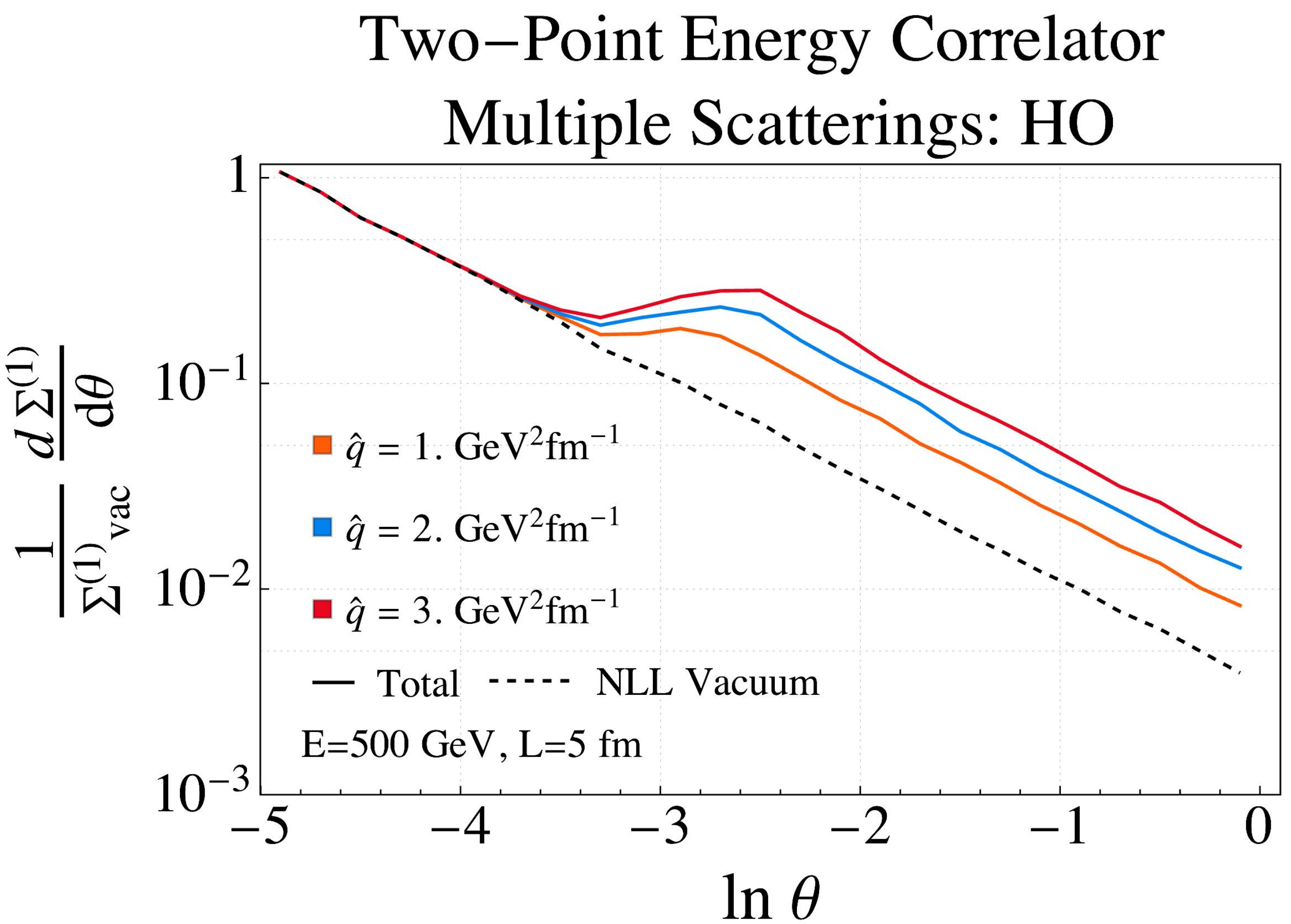
If $\theta_L > \theta_c$ then θ_c becomes irrelevant

Results HO

$\theta_c > \theta_L$



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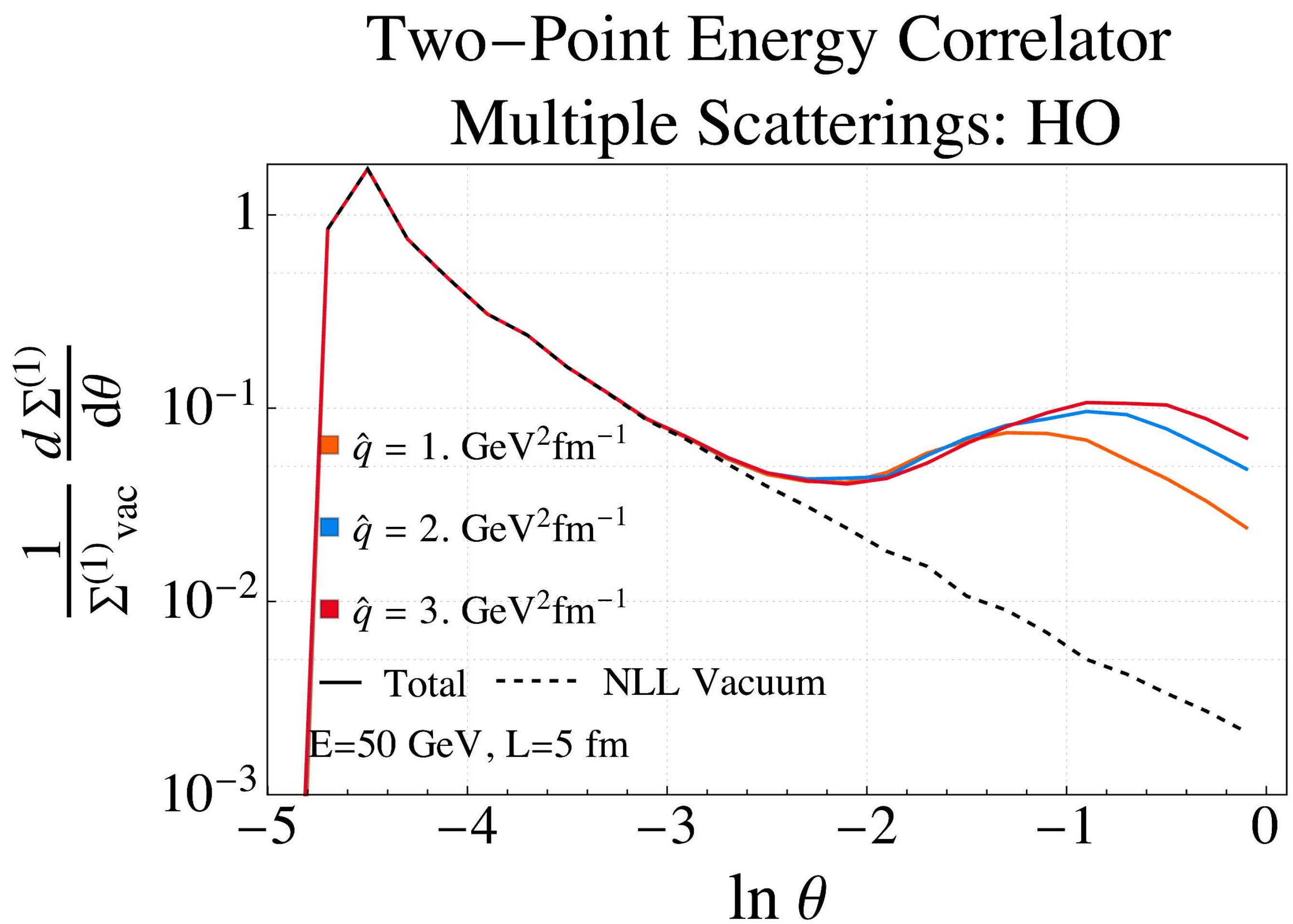

C. Andres, FD, R. K. Elayavalli, J. Holguin, C. Marquet, I. Moult, arXiv:2209.11236
C. Andres, FD, J. Holguin, C. Marquet, I. Moult, arXiv:2303.03413

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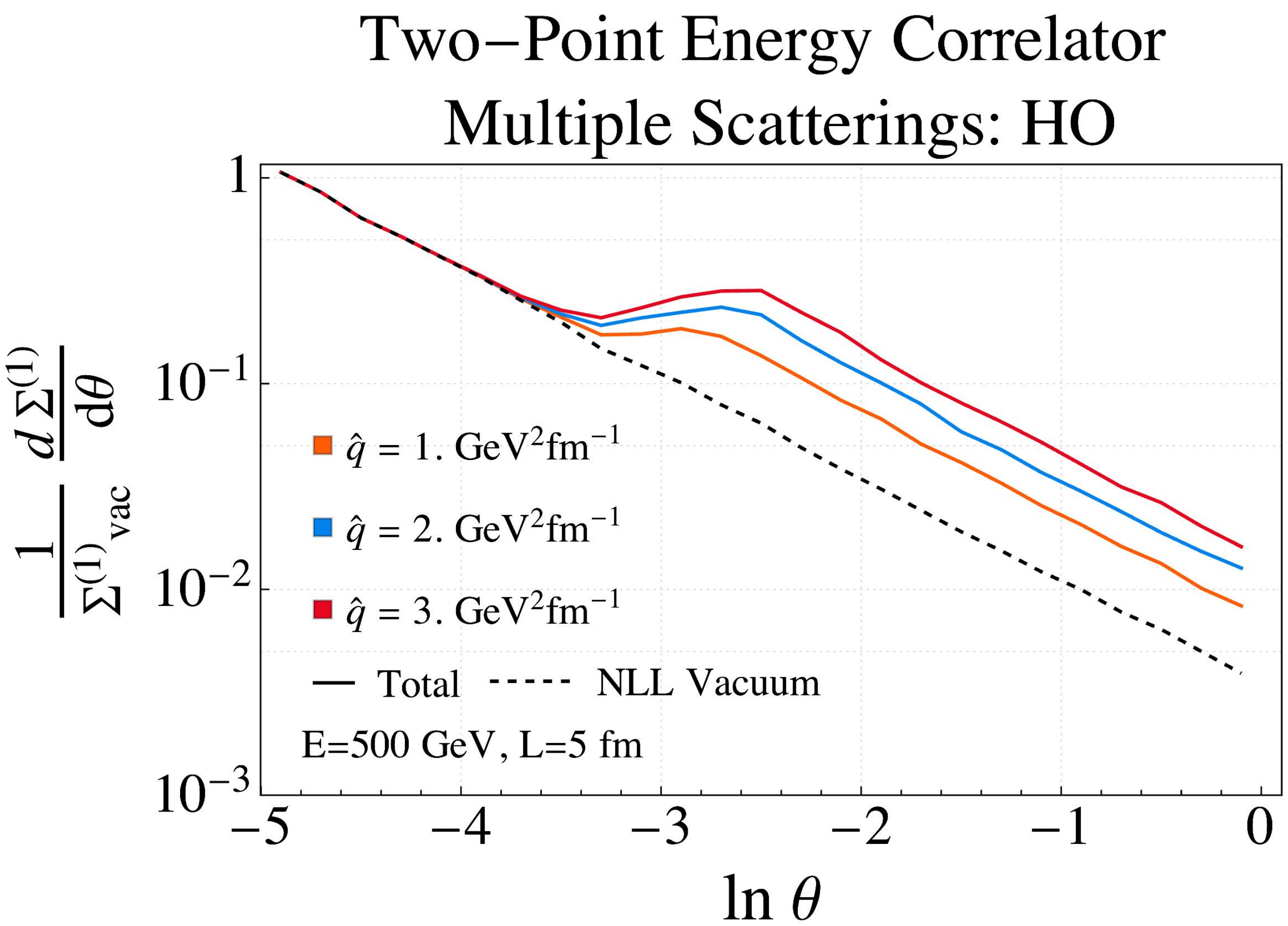

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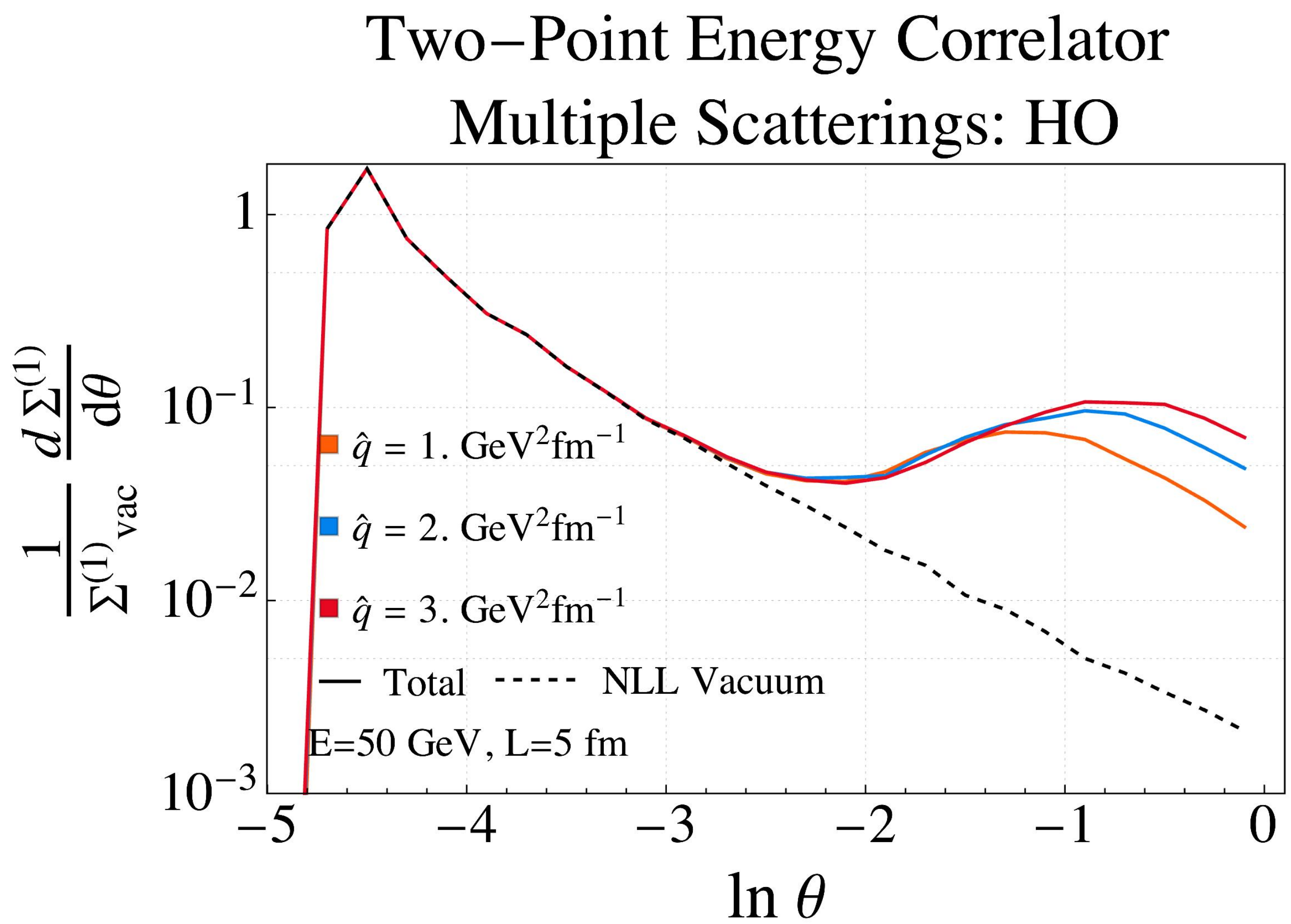

- No enhancement at small angles as expected

C. Andres, FD, R. K. Elayavalli, J. Holguin, C. Marquet, I. Moult, arXiv:2209.11236
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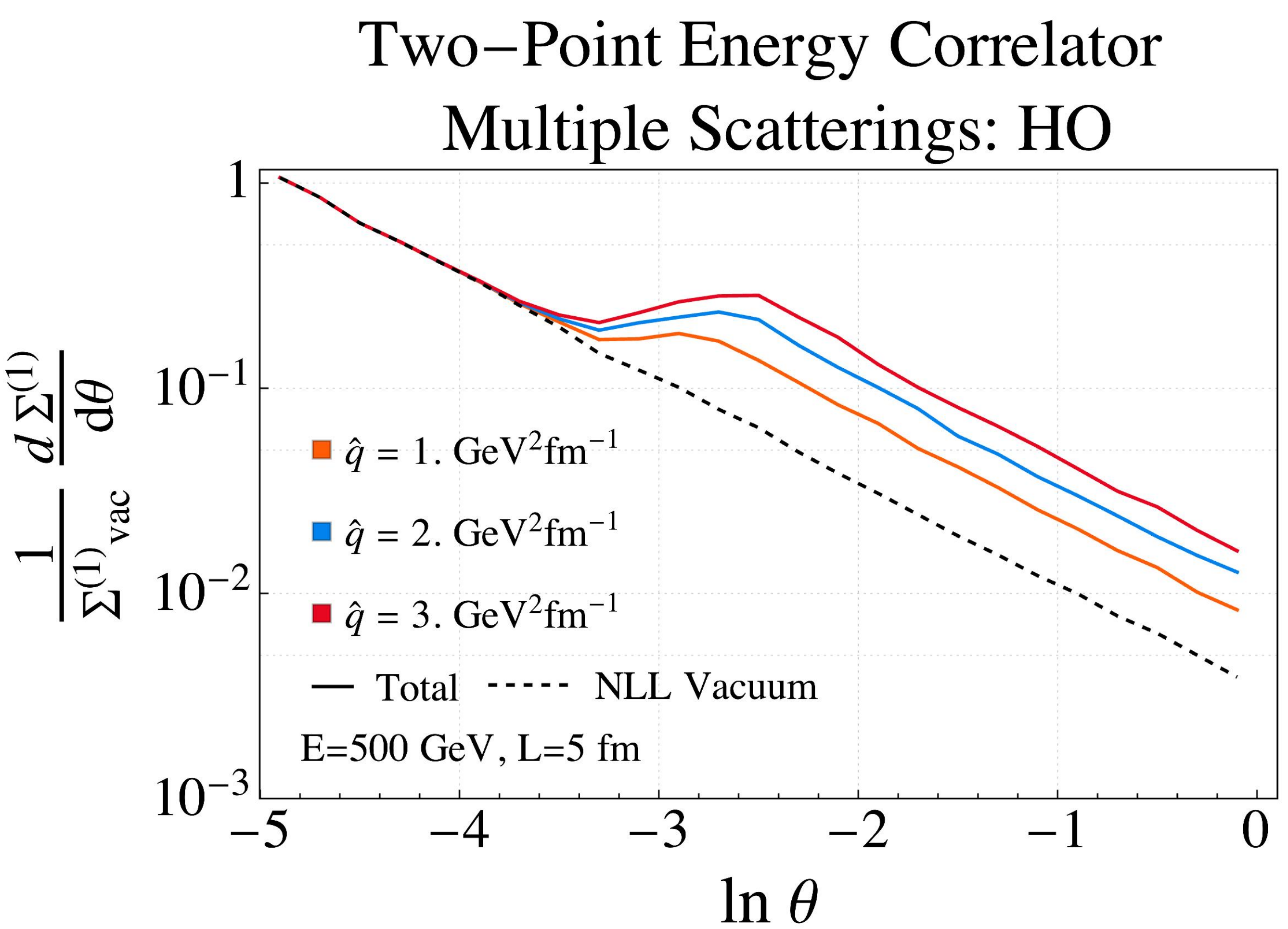

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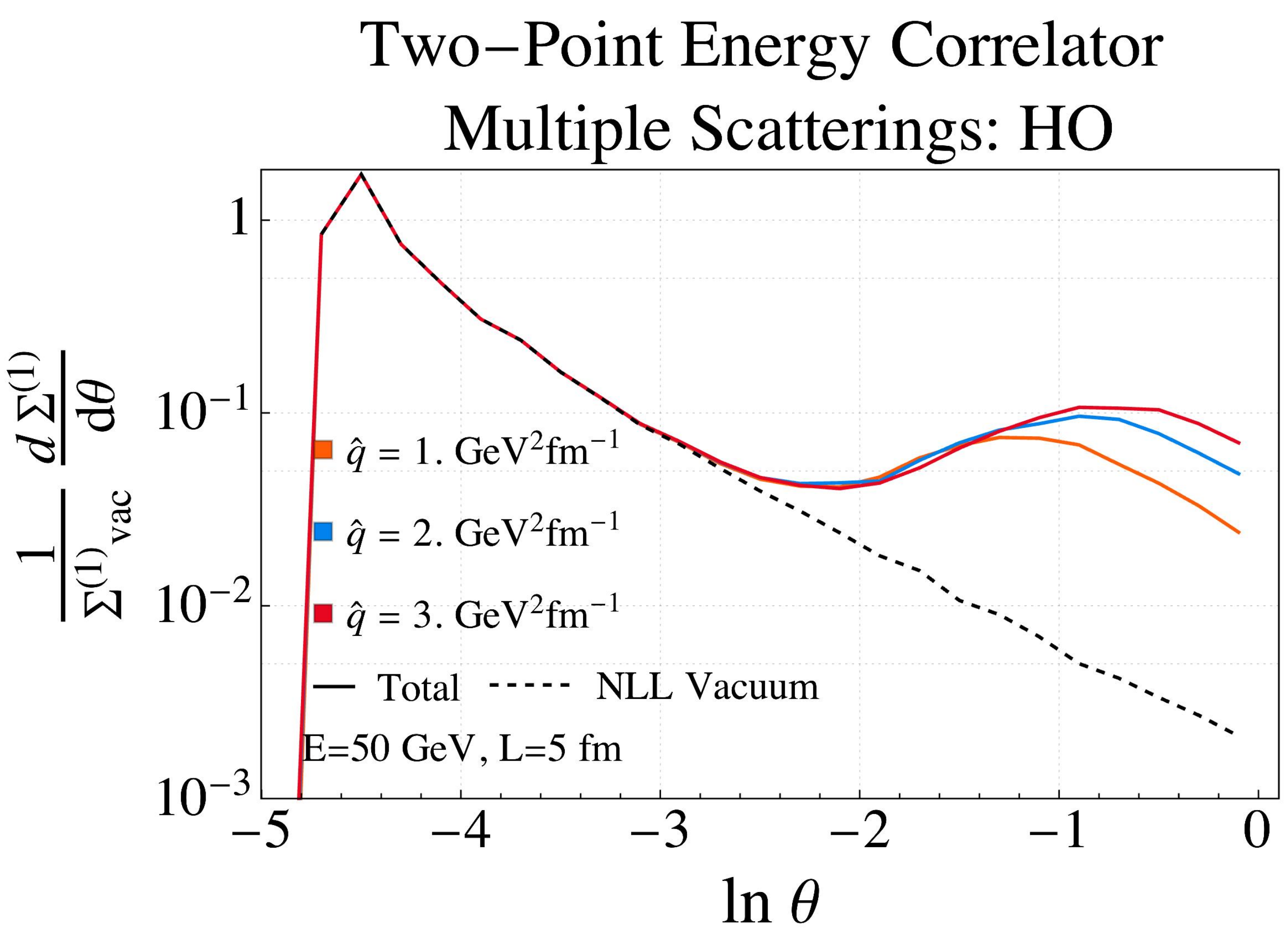
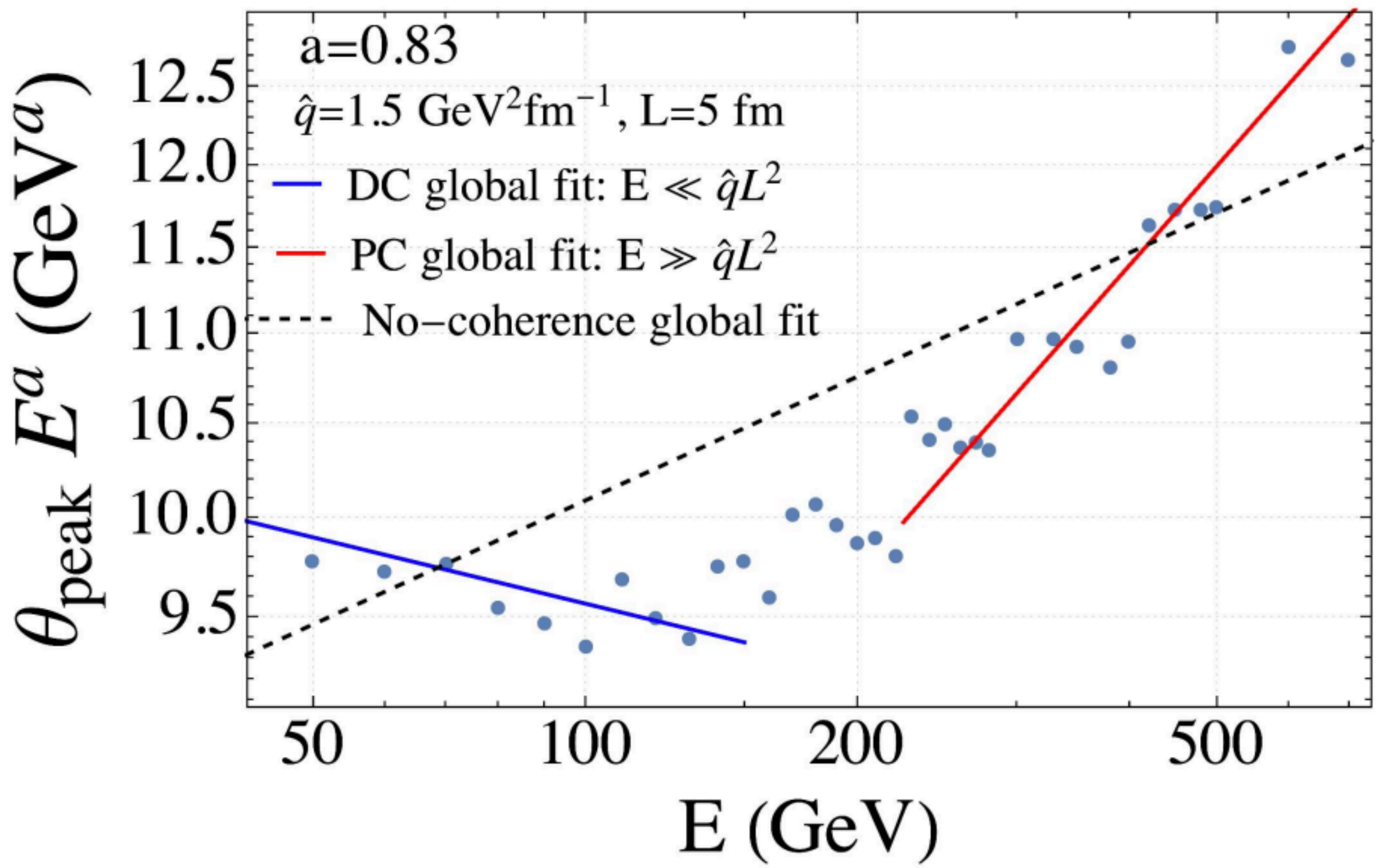


- No enhancement at small angles as expected
- Varying $\hat{q}$ has different effects in the two regions

C. Andres, FD, R. K. Elayavalli, J. Holguin, C. Marquet, I. Moult, arXiv:2209.11236
C. Andres, FD, J. Holguin, C. Marquet, I. Moult, arXiv:2303.03413

Coherence transition



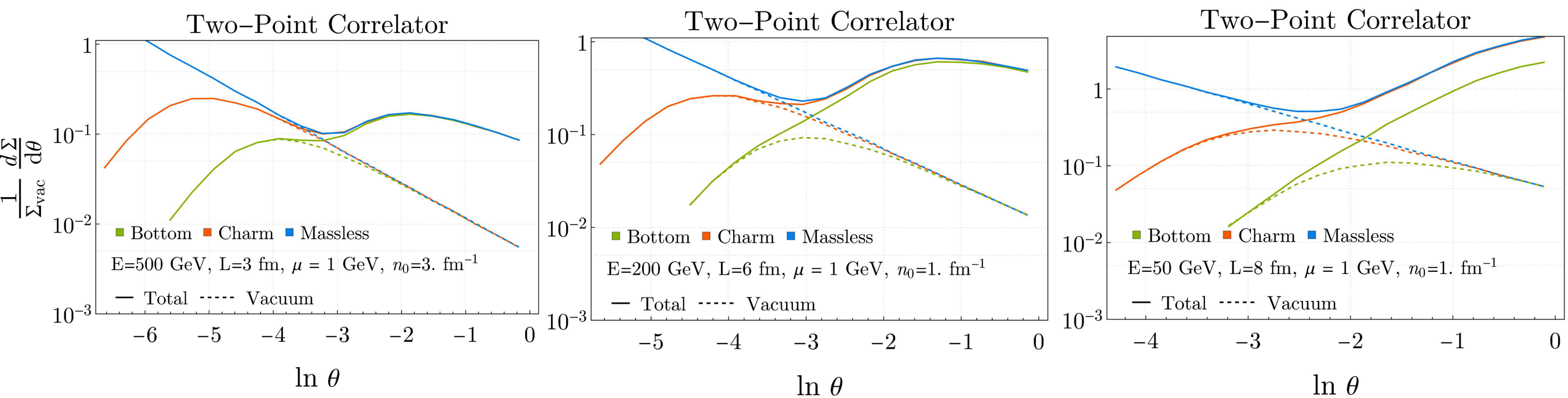
- Extracted the peak angle θ_{peak} for 332 sets of parameters with $E \in [50,700]$ GeV, $L \in [0.2,10]$ fm, $\hat{q} \in [1,3]$ GeV^2/fm

- Performed separate fits in the two different regions for the scaling behavior of the peak angle with respect to the 3 parameters

C. Andres, FD, R. K. Elayavalli, J. Holguin, C. Marquet, I. Moult, arXiv:2209.11236
C. Andres, FD, J. Holguin, C. Marquet, I. Moult, arXiv:2303.03413

Massive EEC in HIC

Including mass in medium-induced calculations is straightforward

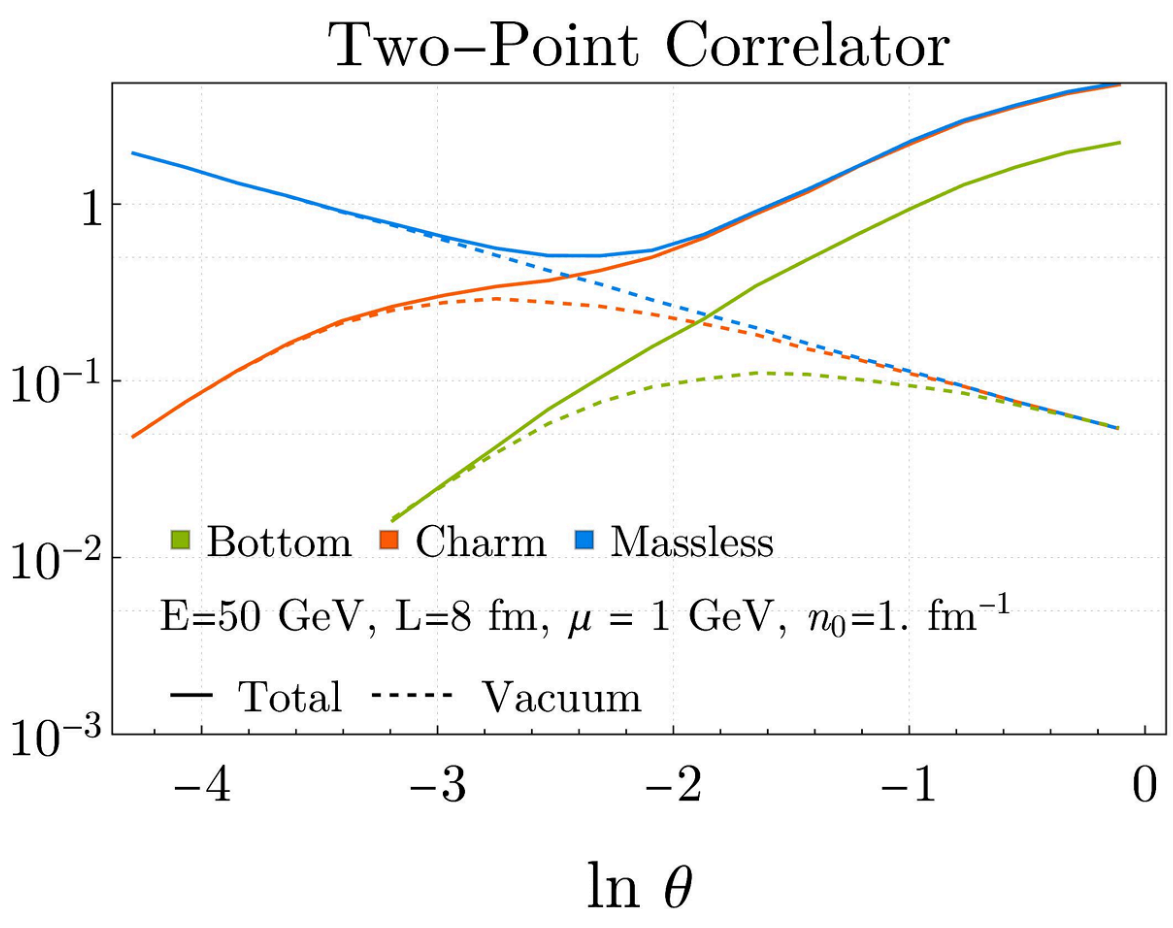


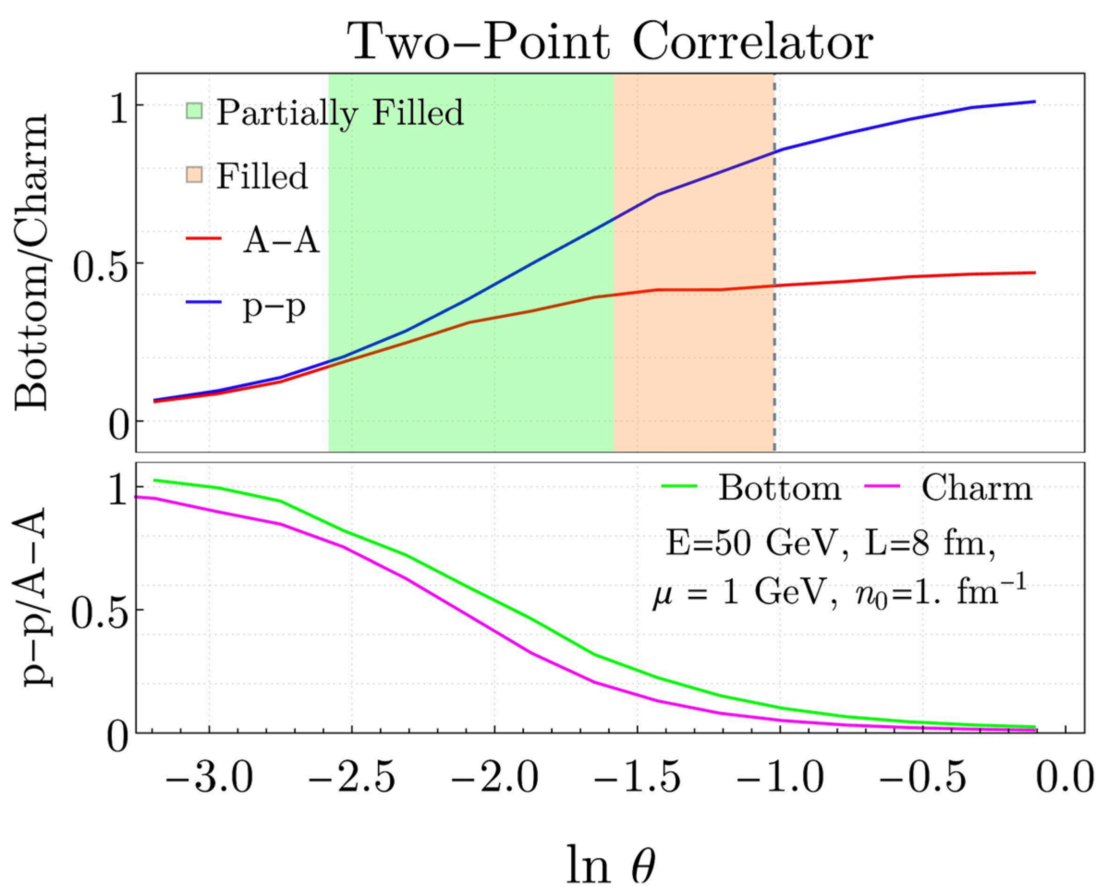
- Dead-cone is filled for lower energy jets
- When dead-cone is filled the mass changes also the large angle behavior

C. Andres, FD, J. Holguin, C. Marquet, I. Moult, arXiv:2307.15110

Massive EEC in HIC

- Experimentally, the cleanest observable would be the b/c ratio

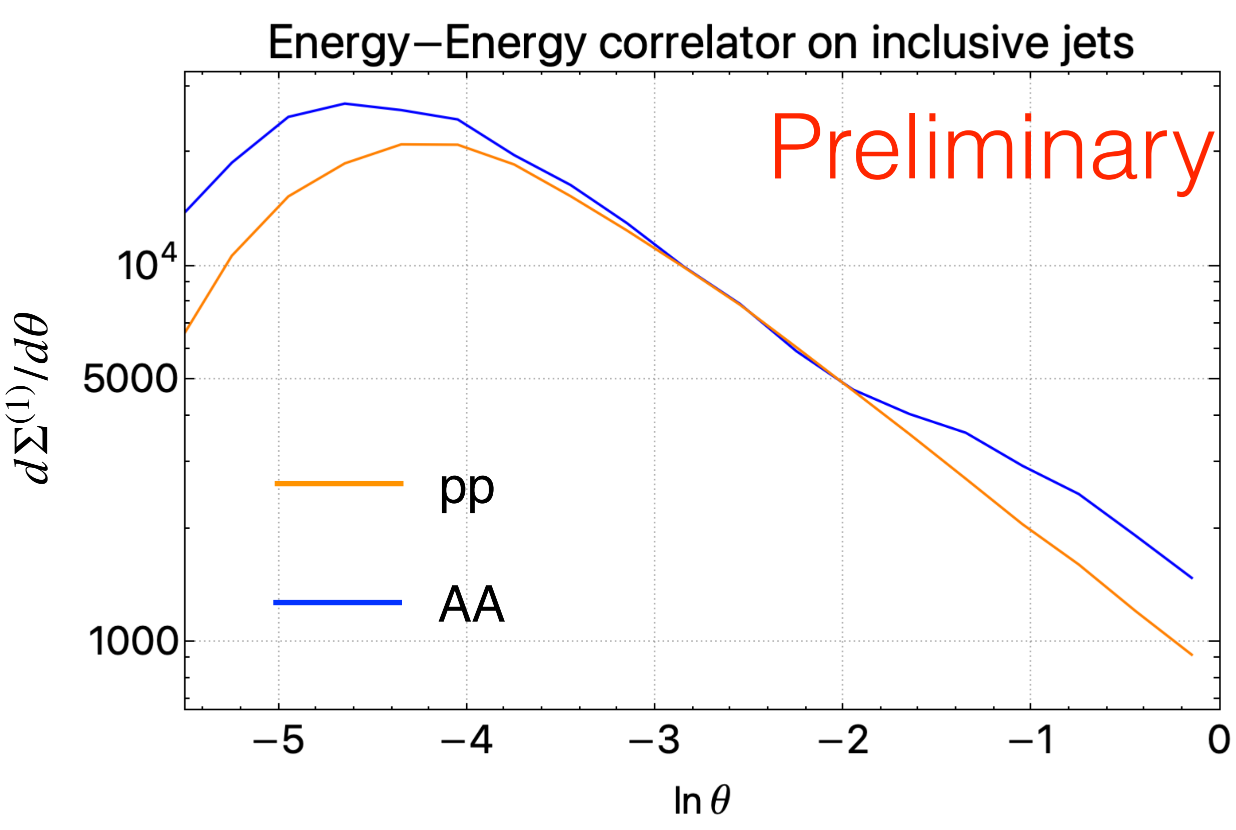


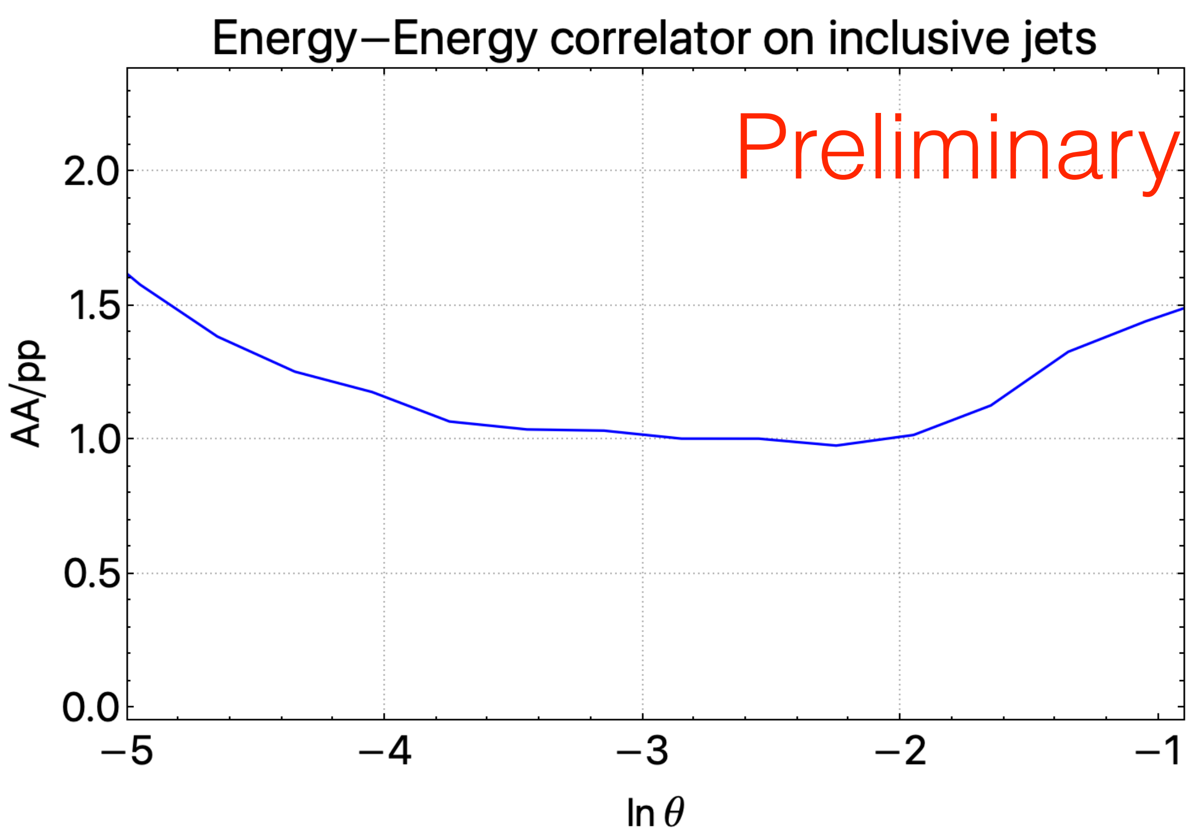


C. Andres, FD, J. Holguin, C. Marquet, I. Moult, arXiv:2307.15110

EECs for inclusive jets

- First measurements will be performed for inclusive jets
- In this case we do not know the energy of the initial parton and therefore energy loss becomes important
- HI-jets have a higher initial energy than pp-jets and therefore the transition to NP regime happens at smaller angles





Outlook

- Calculations of medium-modified splittings can be vastly improved:
  - ✦ Go beyond the brick setup and include medium expansion
  - ✦ Calculate corrections which account for transverse momentum broadening
- Additional angular structure due to inherent anisotropy

J. Barata, G. Milhano, A. Sadofyev, arXiv:2308.01294

- Better understanding of the role of energy loss
- Studies of how the background affects the EECs and what is the effect of increasing the power of the energy weights
- Medium response (see Xin-Nian's talk)

Z. Yang, Y. He, I. Moult, X.-N. Wang, arXiv:2310.01500

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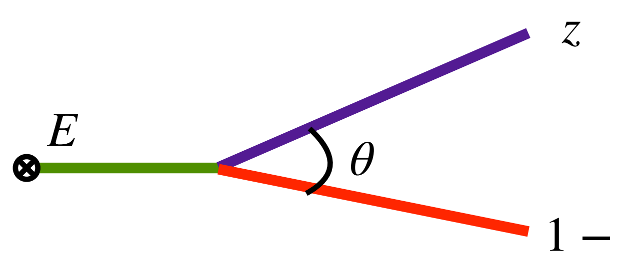
  Z. Yang, Y. He, I. Moult, X.-N. Wang, arXiv:2310.01500

Conclusions

- Energy correlators provide a powerful tool for understanding jets in HIC
  - Experimentally accesible
  - Can be calculated perturbatively thanks to insensitivity to soft physics and uncorrelated background
  - No need for de-clustering
  - Vacuum baseline well understood to a high degree of accuracy
- Characteristic features of the calculation for in-medium splittings are clearly imprinted in the observables

Thank you!

Energy correlators



- For a quark jet at leading order in the splittings, $Q = E$ the energy of the jet

$$\frac{d\Sigma^{(n)}}{d\theta} = \frac{1}{\sigma_{qg}} \int dz \frac{d\sigma_{qg}}{d\theta dz} z^n (1-z)^n + \mathcal{O}\left(\frac{\mu_s}{E}\right)$$

μ_s a softer scale over which the cross section is inclusive

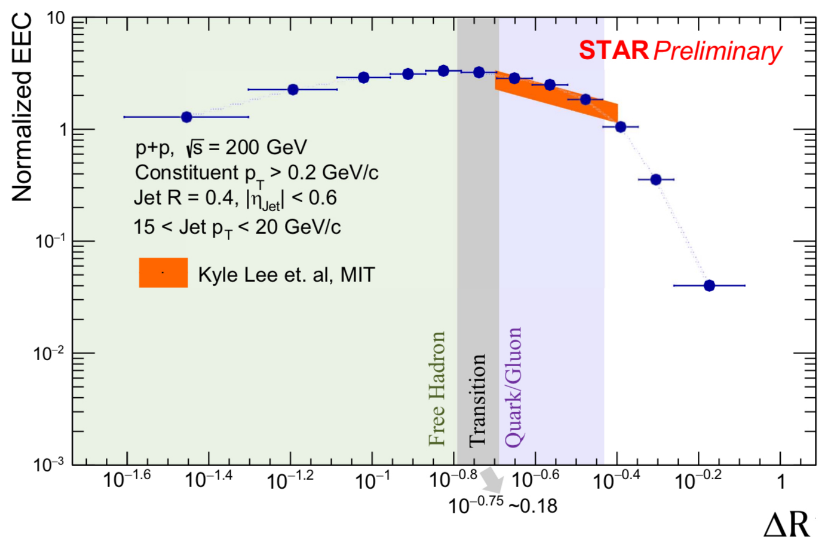
- qq and gg contributions are higher order

- Additional energy loss ($E_q + E_g \neq E$) is also subleading

$$z = \frac{E_g}{E}$$

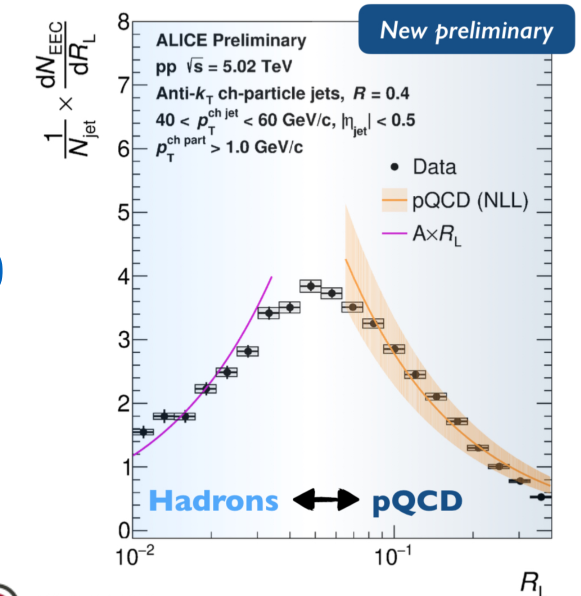
Energy correlators in vacuum

- New measurements announced at HP2023!



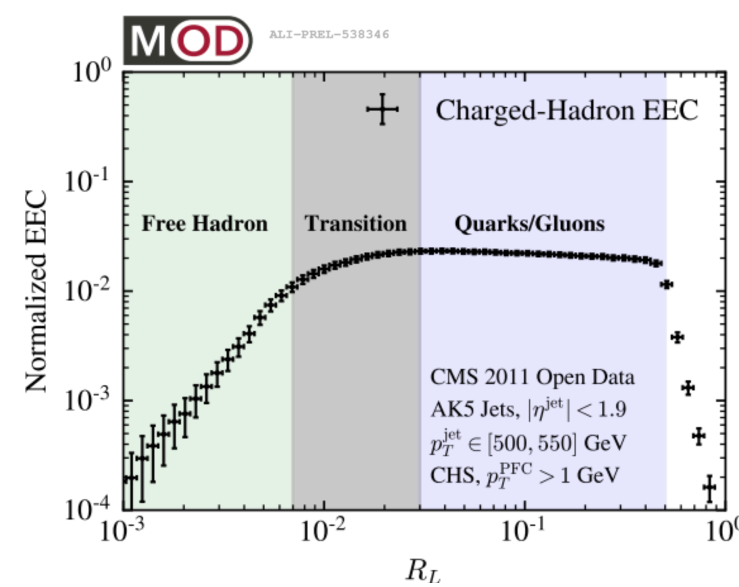
See R. Cruz-Torres's Talk Tue. 17:30

See A. Tamis's Talk Wed. 11:30



- Analyses done by theorists with CMS open data showing sensitivity to hadronization transition

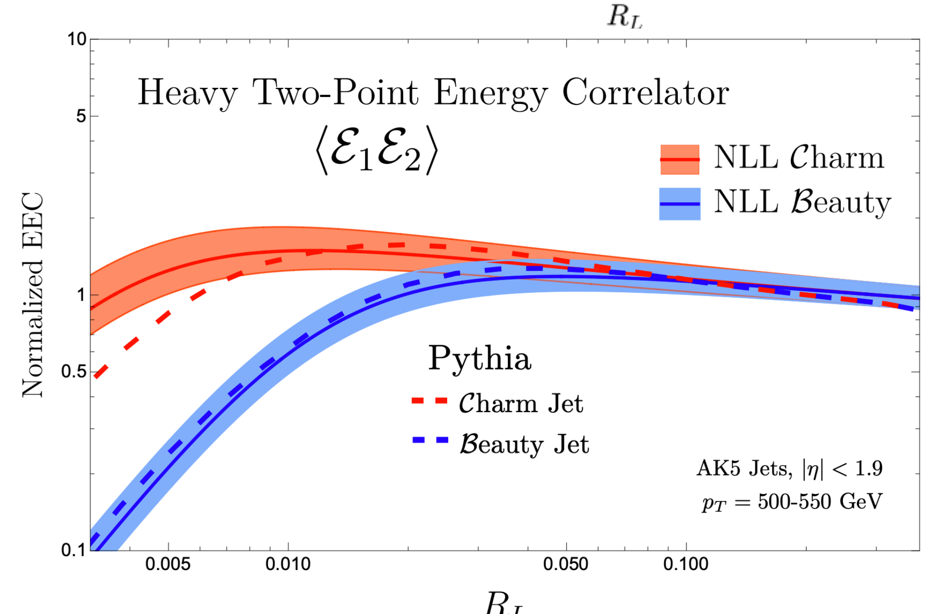
P. T. Komiske, I. Moult, J. Thaler, H. X. Zhu 2201.07800



- Dead cone for massive quarks

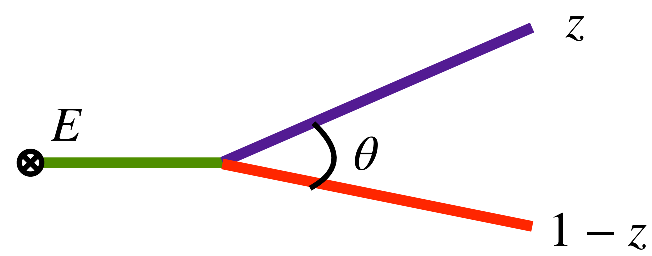
E. Craft, K. Lee, B. Meçai, I. Moult 2210.09311

See J. Holguin's Talk Wed. 11:50



Energy correlators in HIC

$$\frac{d\Sigma^{(n)}}{d\theta} = \frac{1}{\sigma_{qg}} \int dz \frac{d\sigma_{qg}}{d\theta dz} z^n (1-z)^n + \mathcal{O}\left(\frac{\mu_s}{E}\right)$$



- We factor out the vacuum cross section and define the modification factor F_{med}

$$\frac{d\sigma_{qg}}{d\theta dz} = (1 + F_{\text{med}}(z,\theta)) \frac{d\sigma_{qg}^{\text{vac}}}{d\theta dz} \qquad F_{\text{med}}(z,\theta) \xrightarrow{\theta<\theta_L} 0$$

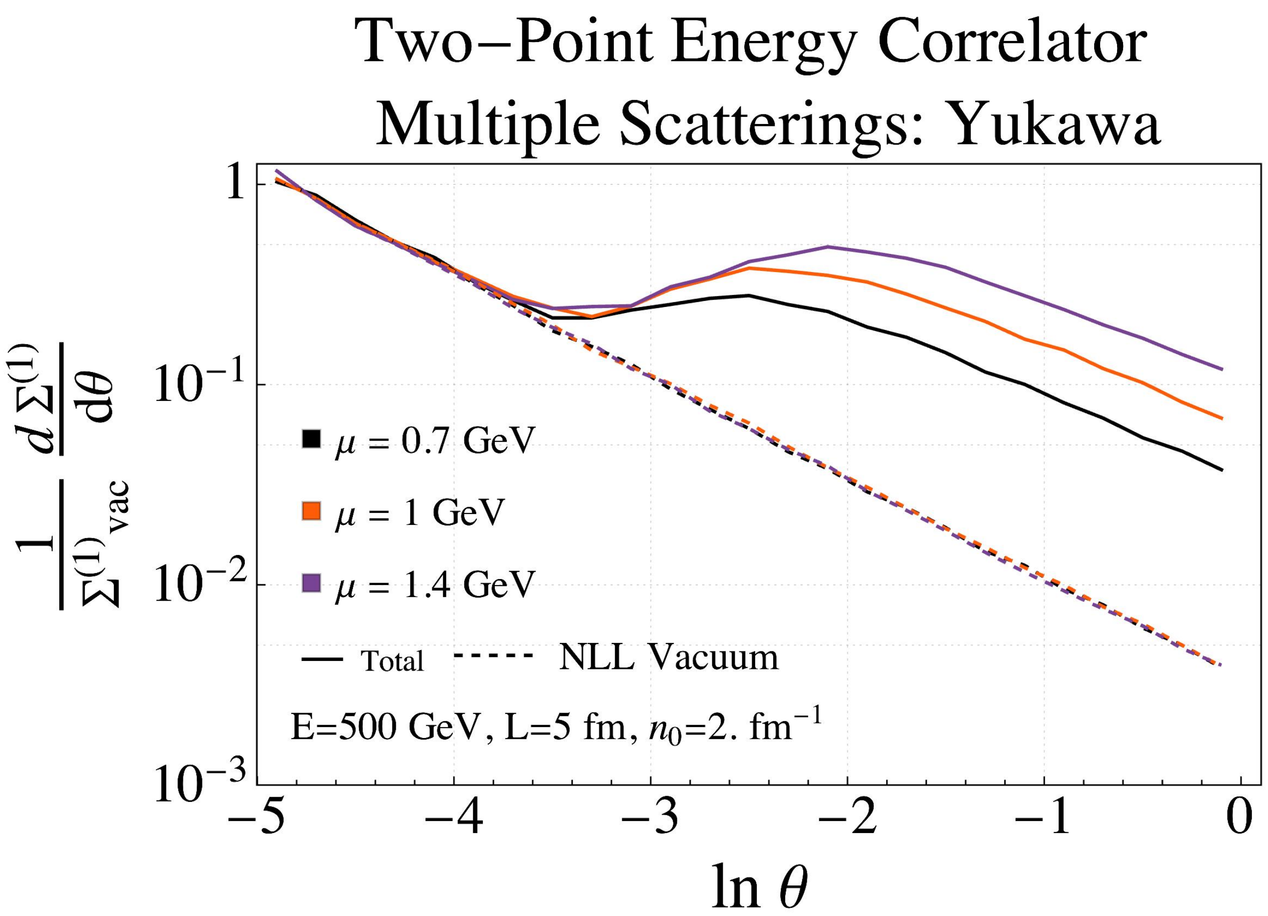
- We do not expect medium modification at small angles, thus vacuum collinear resummation should still be valid

$$\frac{d\Sigma^{(n)}}{d\theta} = \frac{1}{\sigma_{qg}} \int dz \left(g^{(n)}(\theta,\alpha_s) + F_{\text{med}}(z,\theta)\right) \frac{d\sigma_{qg}^{\text{vac}}}{d\theta dz} z^n (1-z)^n \left(1 + \mathcal{O}\left(\frac{\mu_s}{E}\right)\right) + \mathcal{O}\left(\frac{\Lambda_{\text{QCD}}}{\theta Q}\right)$$

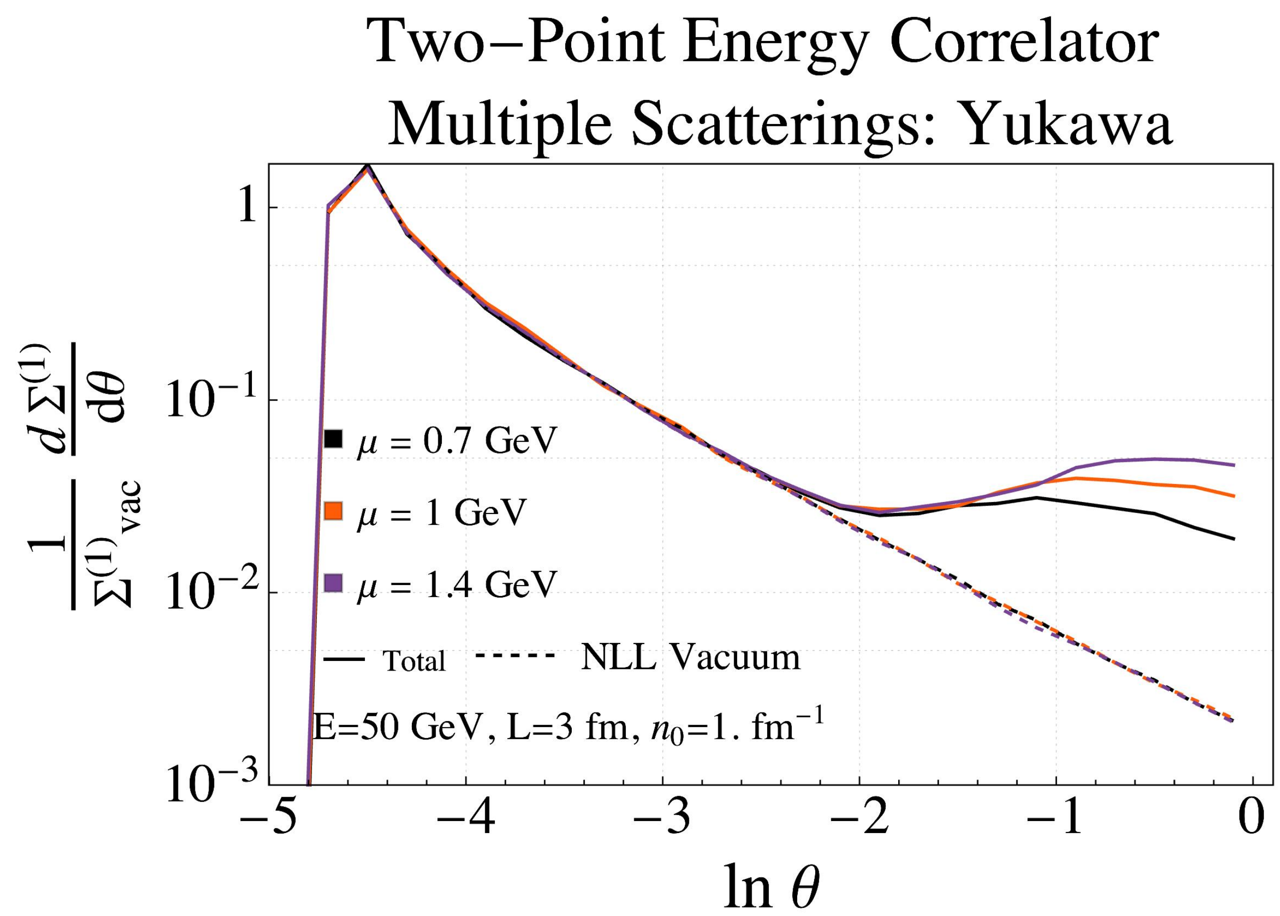
$$g^{(1)} = \theta^{\gamma(3)} + \mathcal{O}(\theta)$$

Results with Yukawa interaction

$\theta_c > \theta_L$



$\theta_c < \theta_L$



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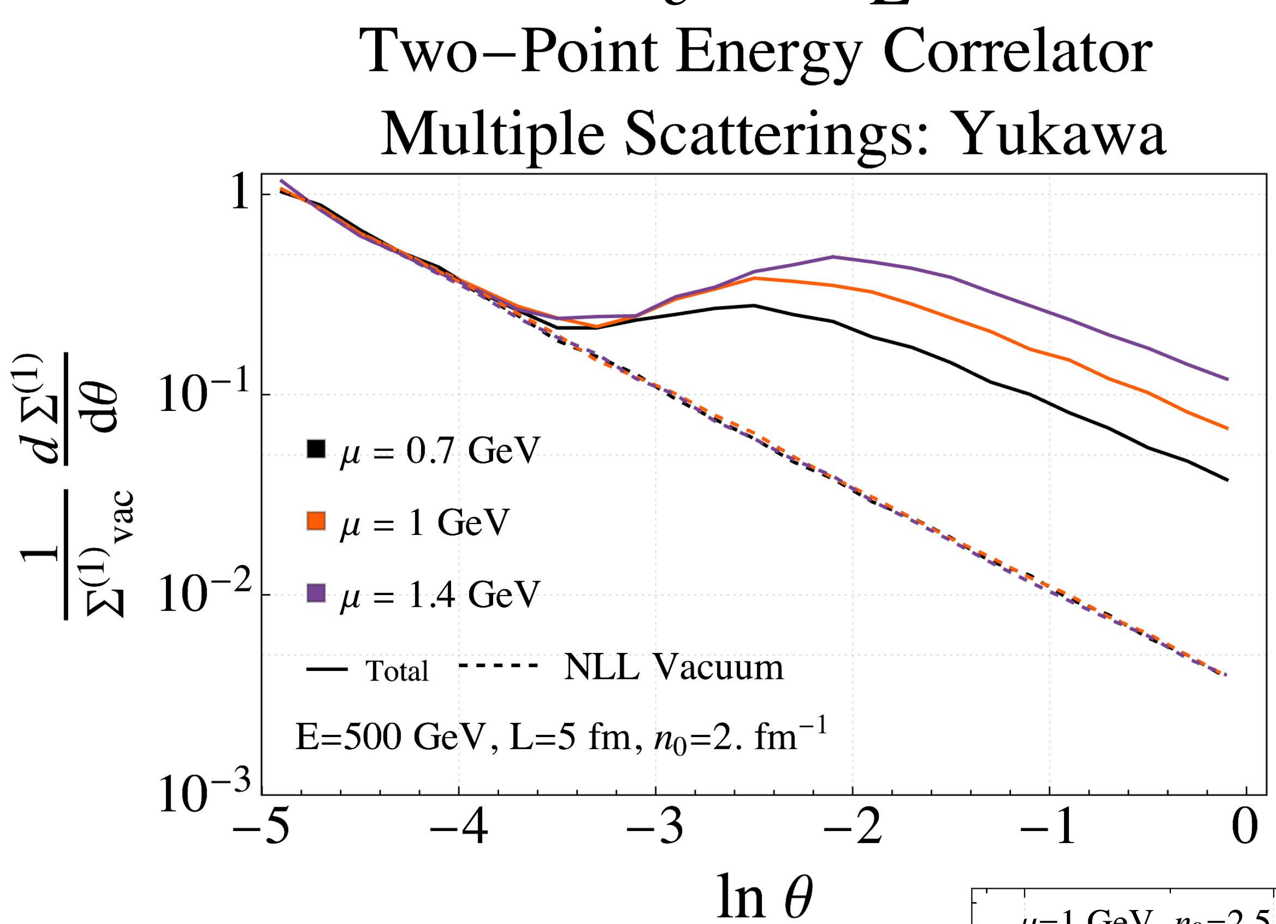

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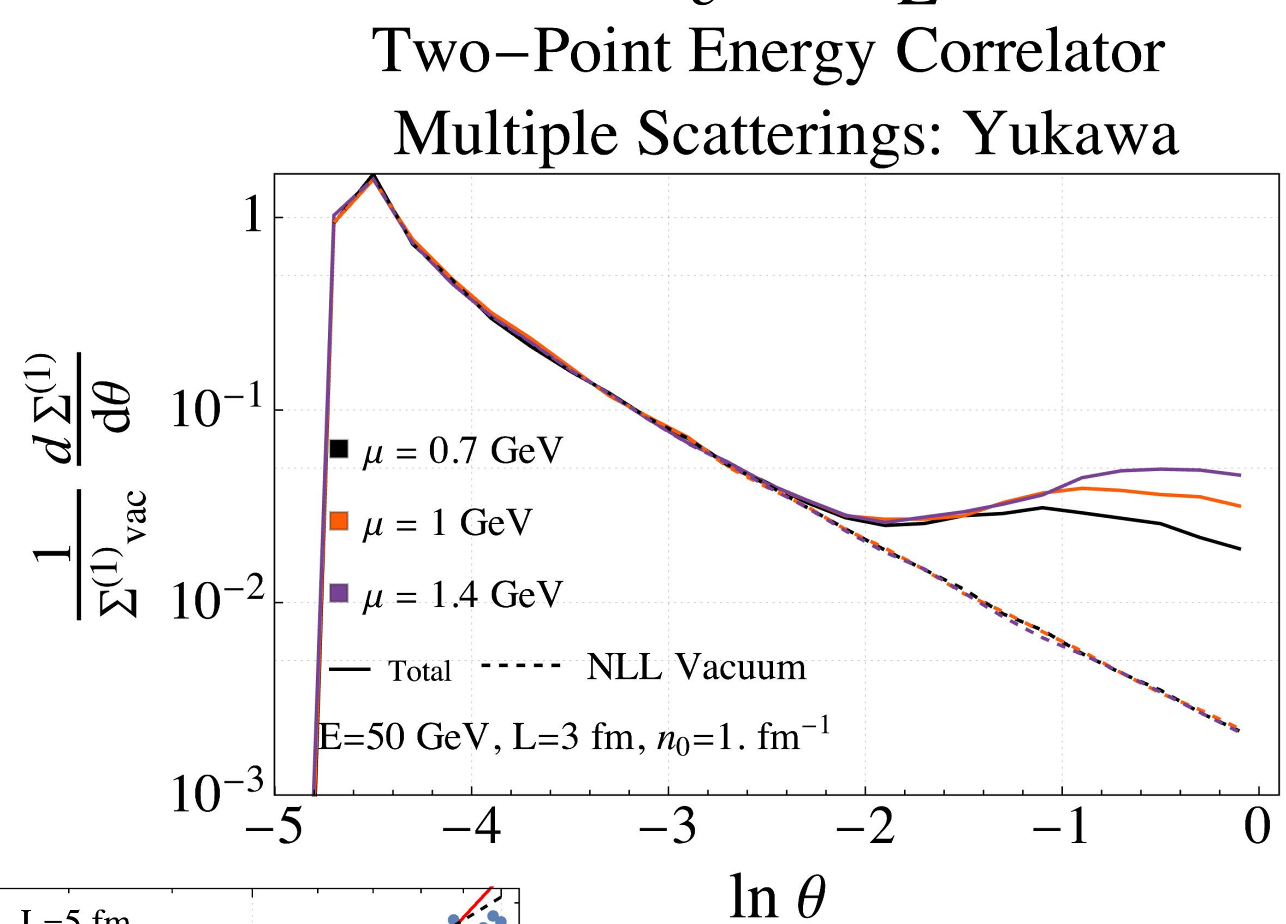

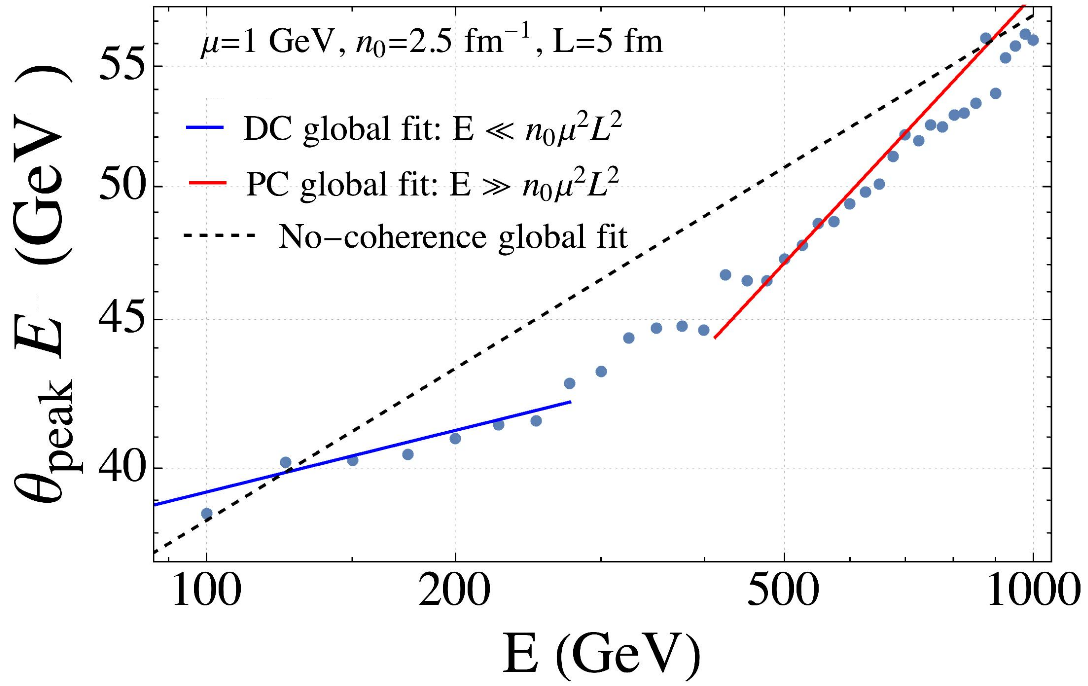

Results with single scattering (GLV)

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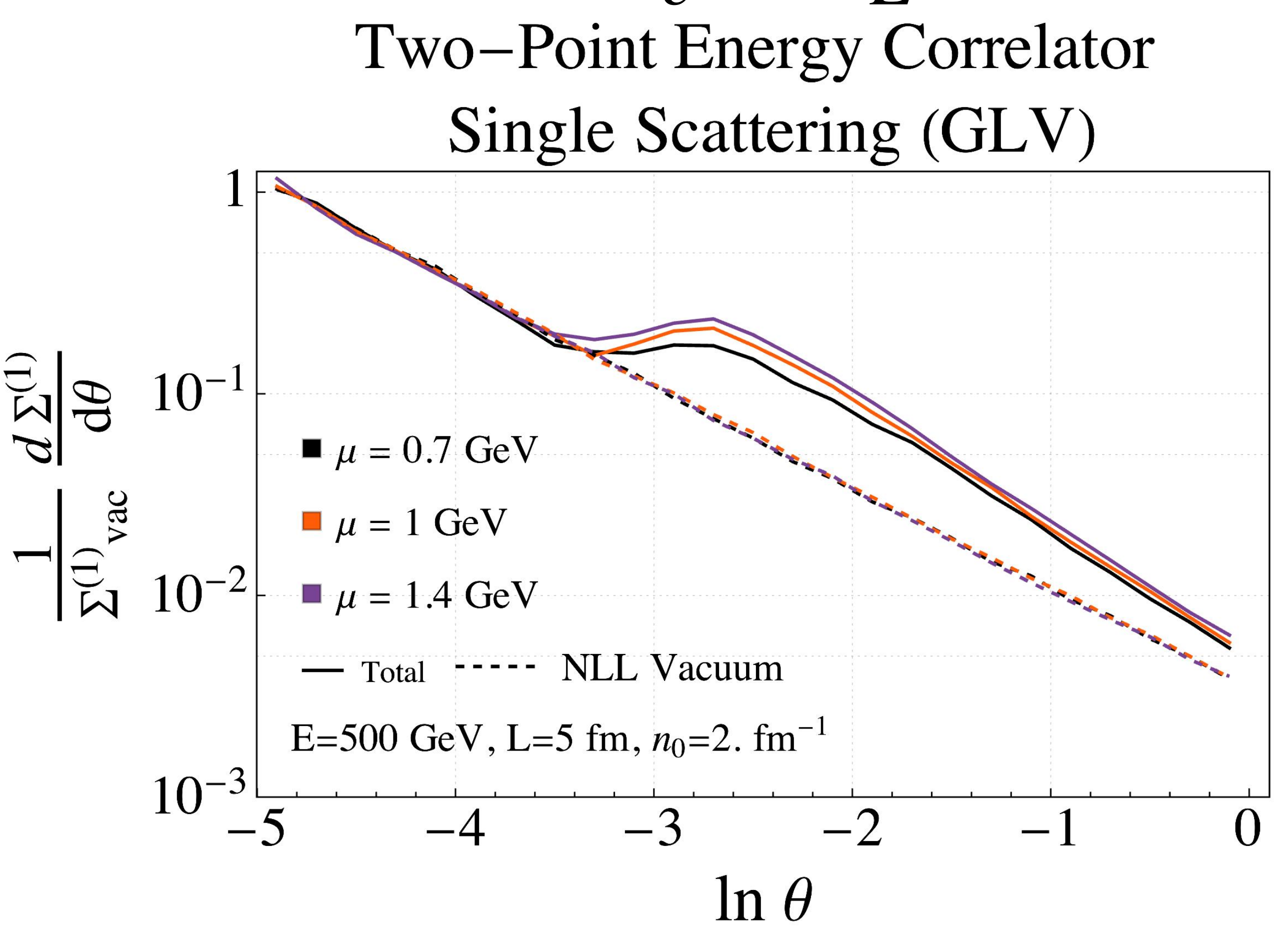

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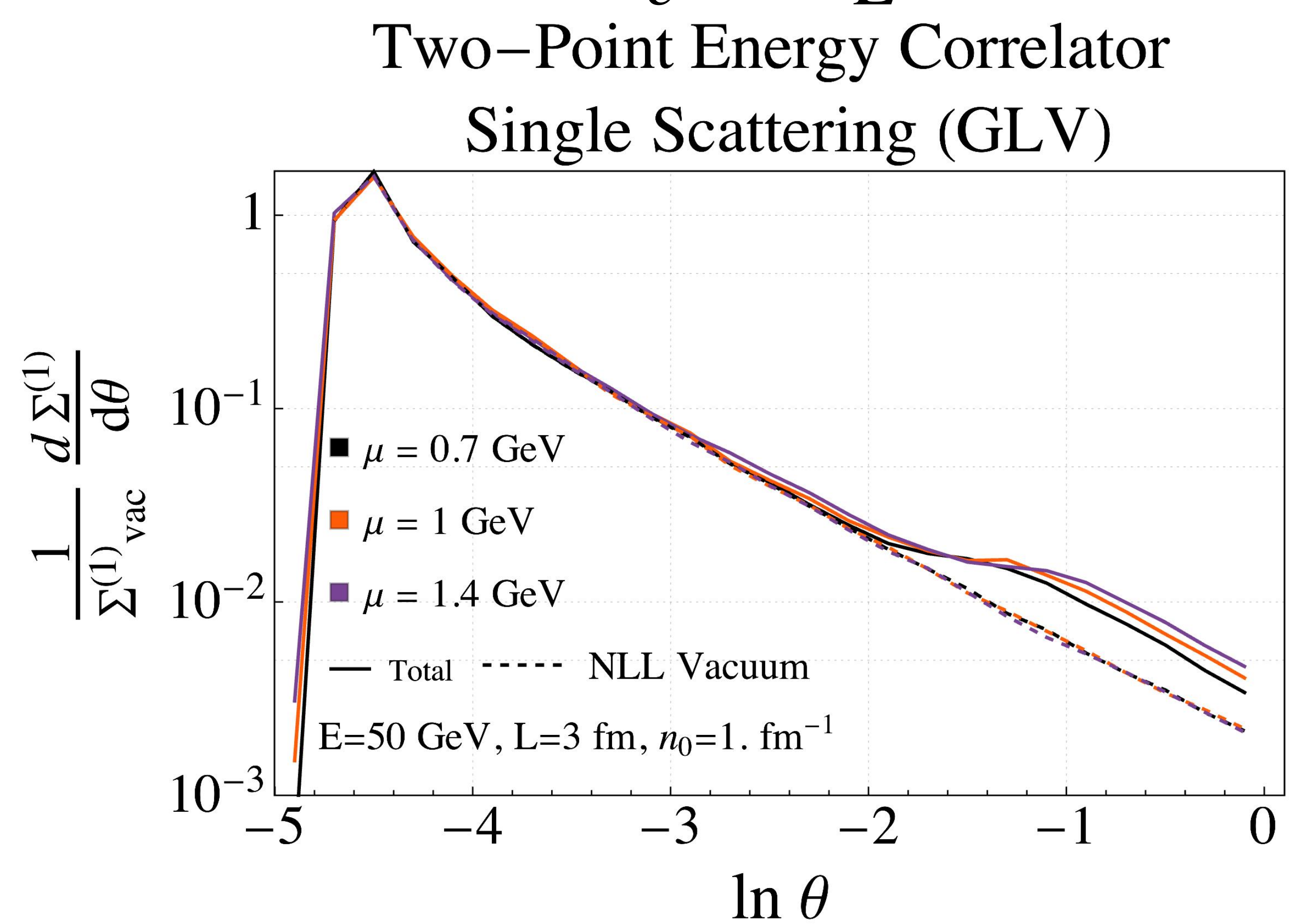

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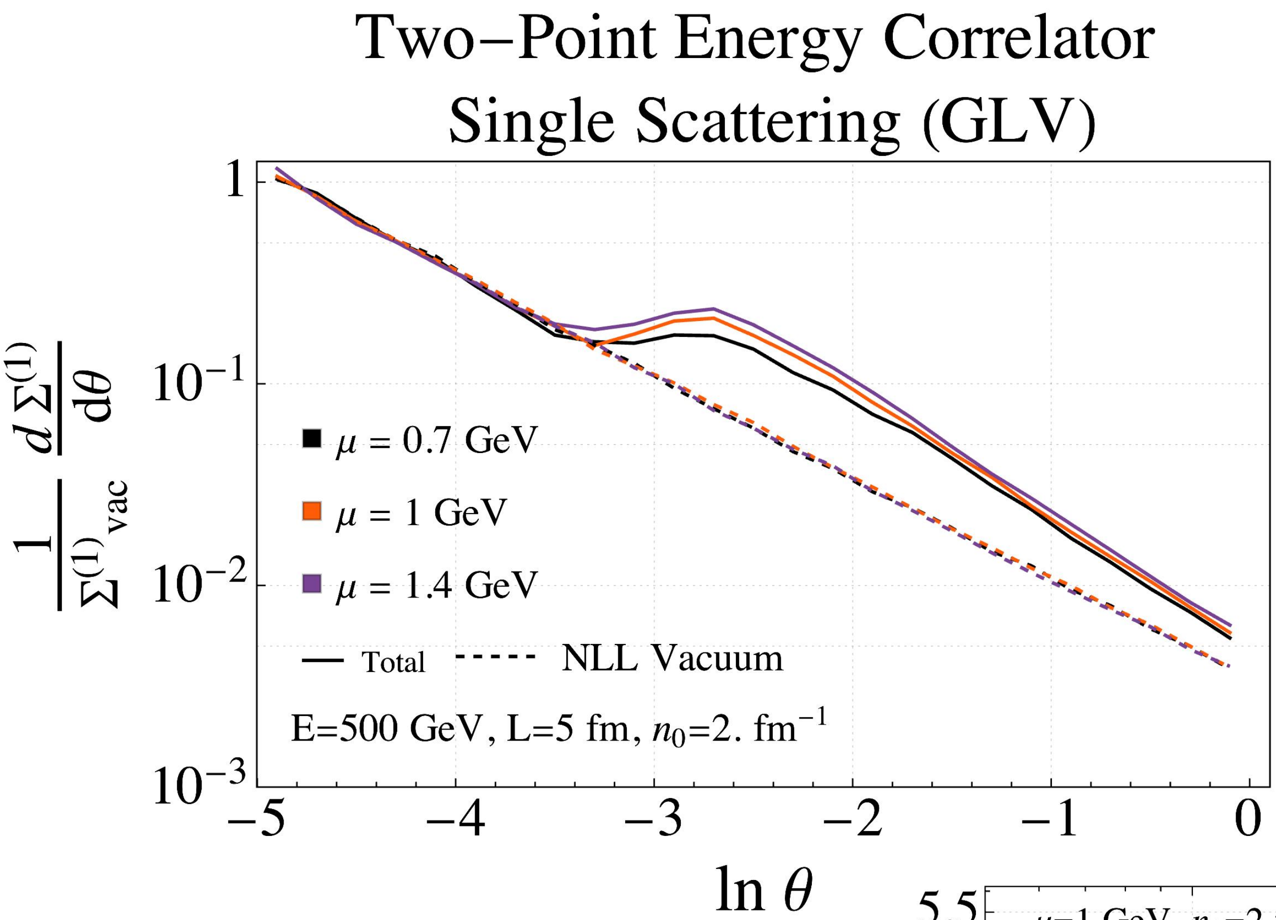

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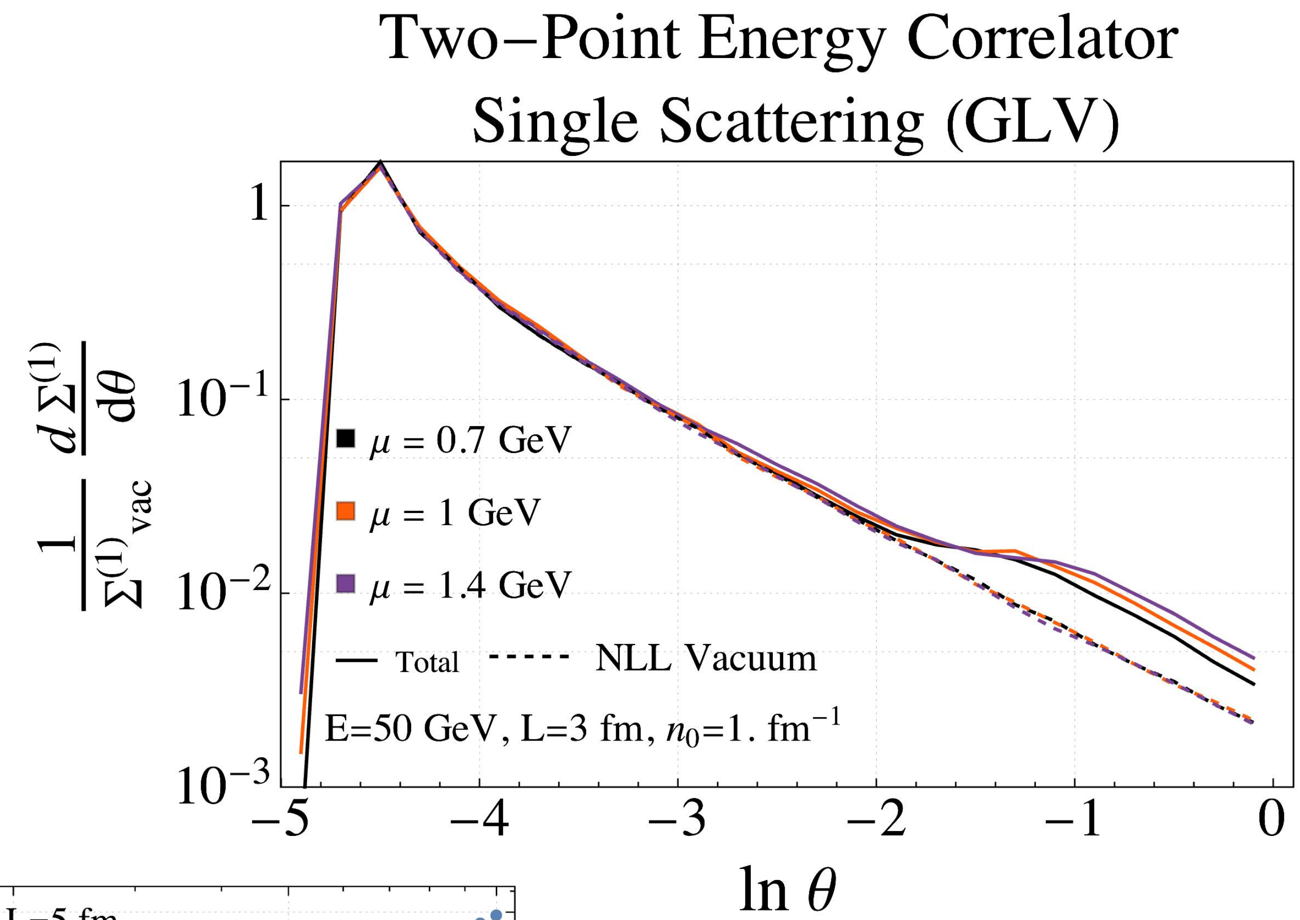
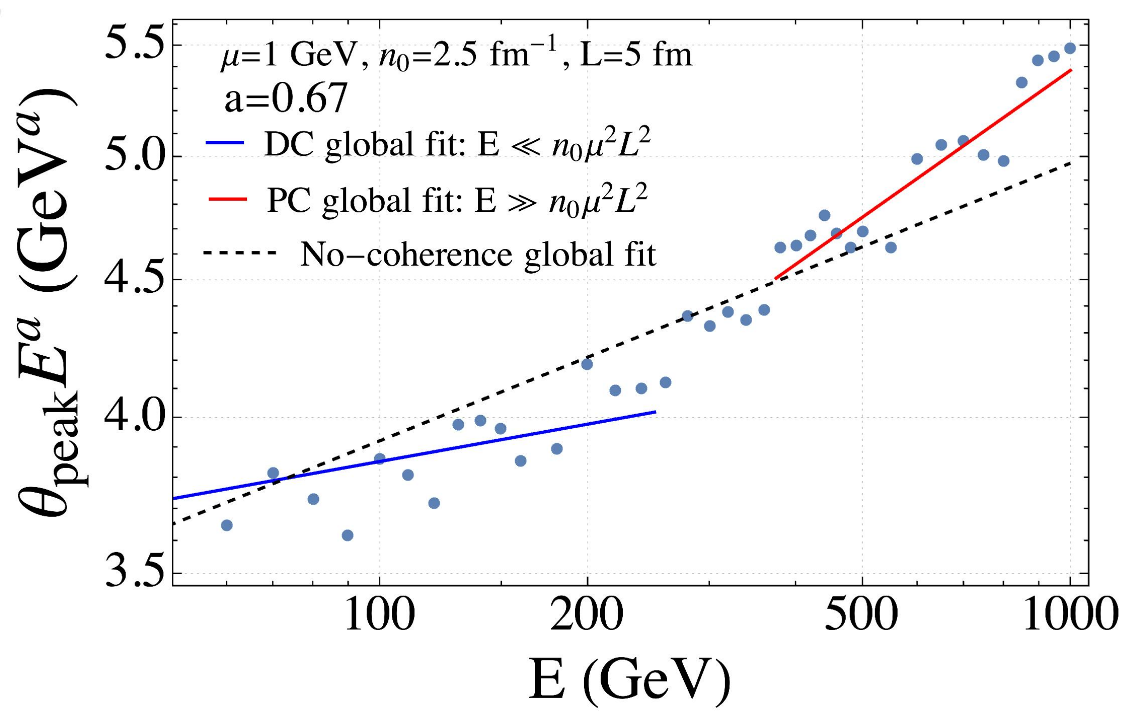
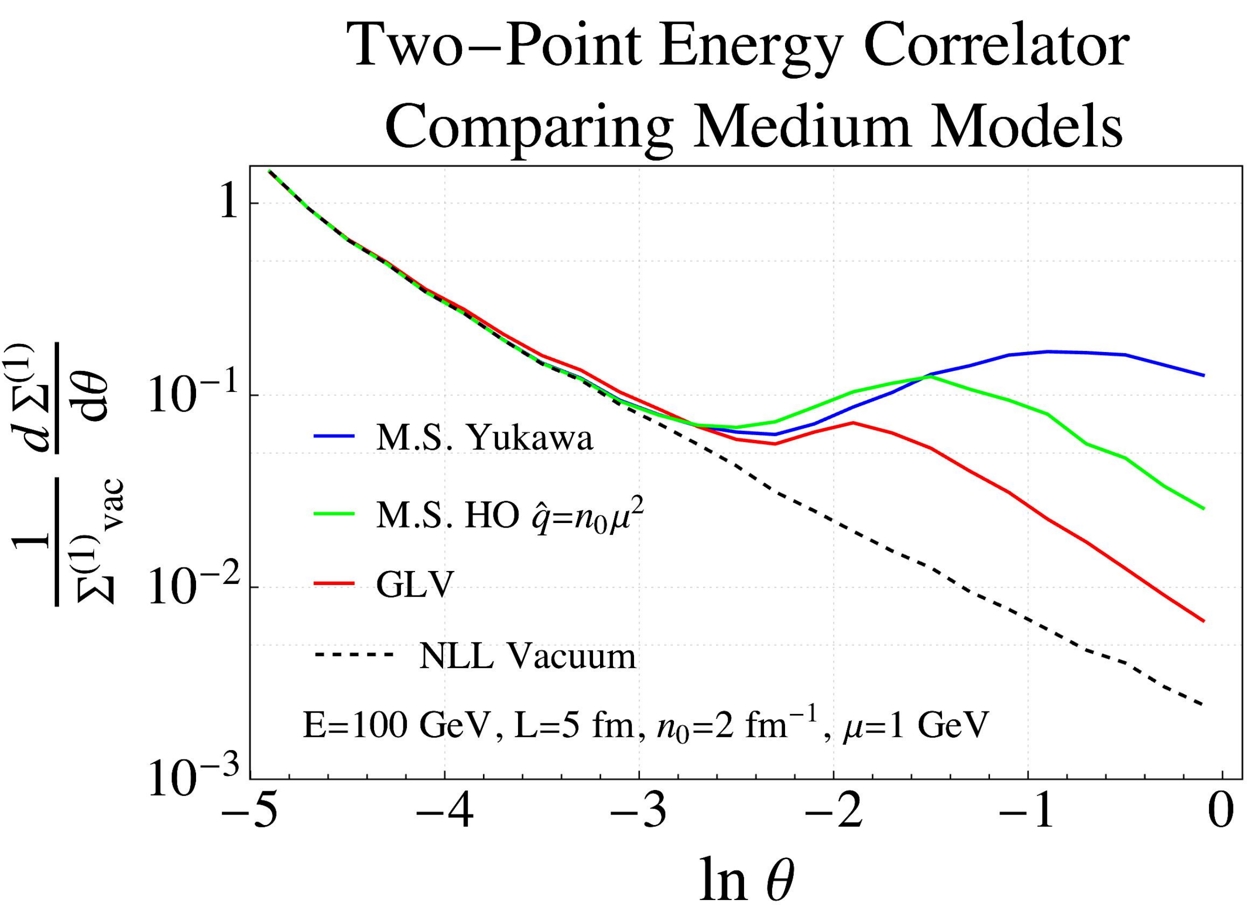
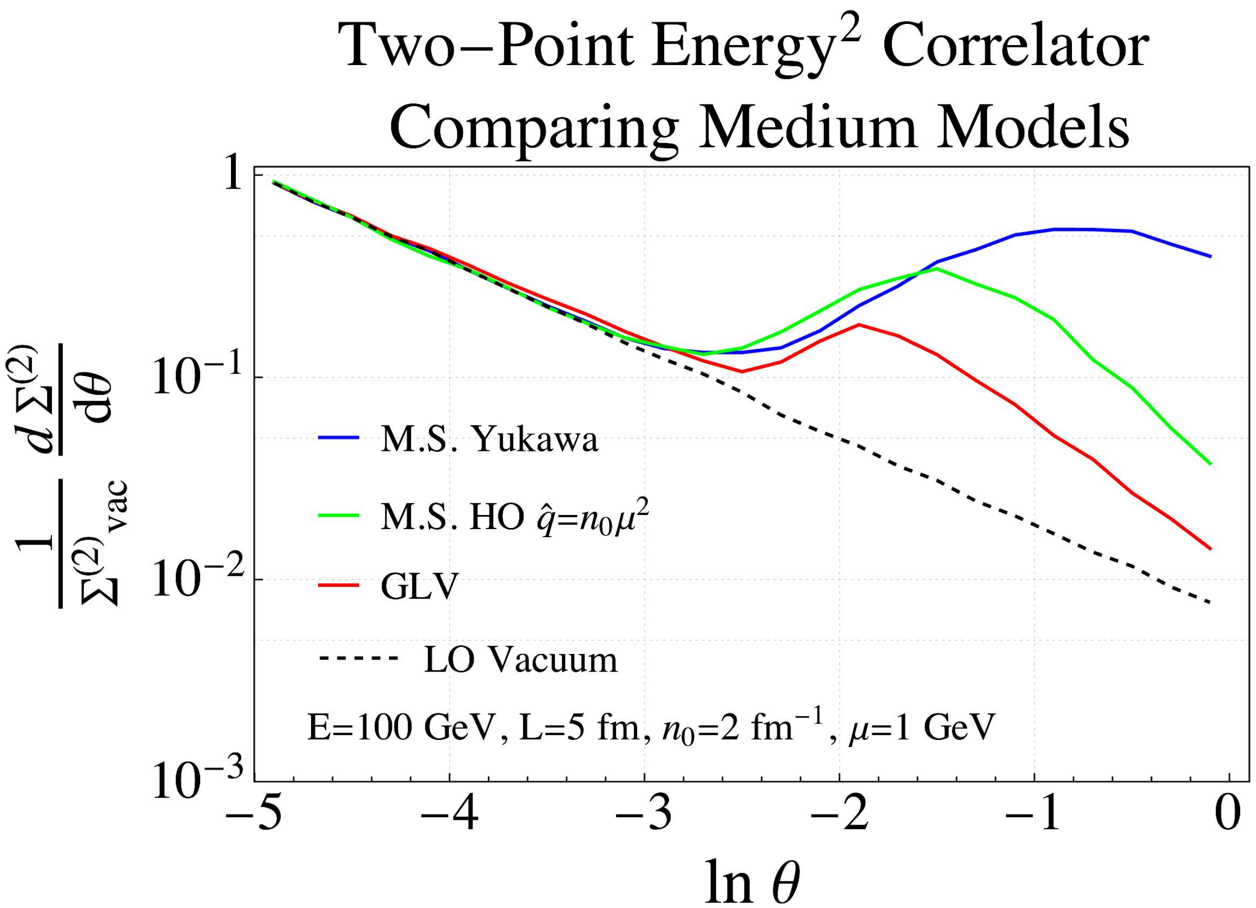




Higher energy power





Tilted Wilson lines

FD, Milhano, Salgado, Tywoniuk, Vila 1907.03653
Isaksen, Tywoniuk 2107.02542

- Use high-energy limit of propagators: vacuum propagator times a Wilson line in the classical trajectory

$$\mathcal{G}_R(t_2, \boldsymbol{p}_2; t_1, \boldsymbol{p}_1; \omega) \to (2\pi)^2 \delta^{(2)}(\boldsymbol{p}_2 - \boldsymbol{p}_1)\, e^{-i\frac{p_2^2}{2\omega}(t_2 - t_1)} V_R(t_2, t_1; [\boldsymbol{n}t])$$

- Calculate averages of Wilson lines in the large-N_c limit (calculations also available for finite N_c). All averages can be expressed in terms of fundamental dipoles and quadrupoles

$$\frac{1}{N_c}\left\langle \mathrm{Tr}\, V_1 V_2^\dagger \right\rangle = S_{12} \qquad \frac{1}{N_c}\left\langle \mathrm{Tr}\, V_1 V_2^\dagger V_{\bar{2}} V_{\bar{1}}^\dagger \right\rangle = Q$$

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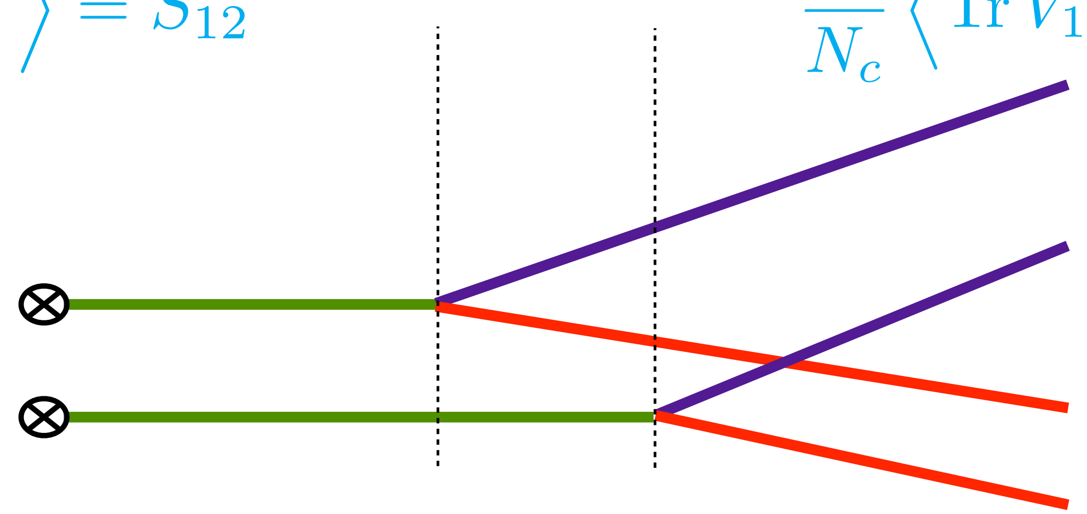

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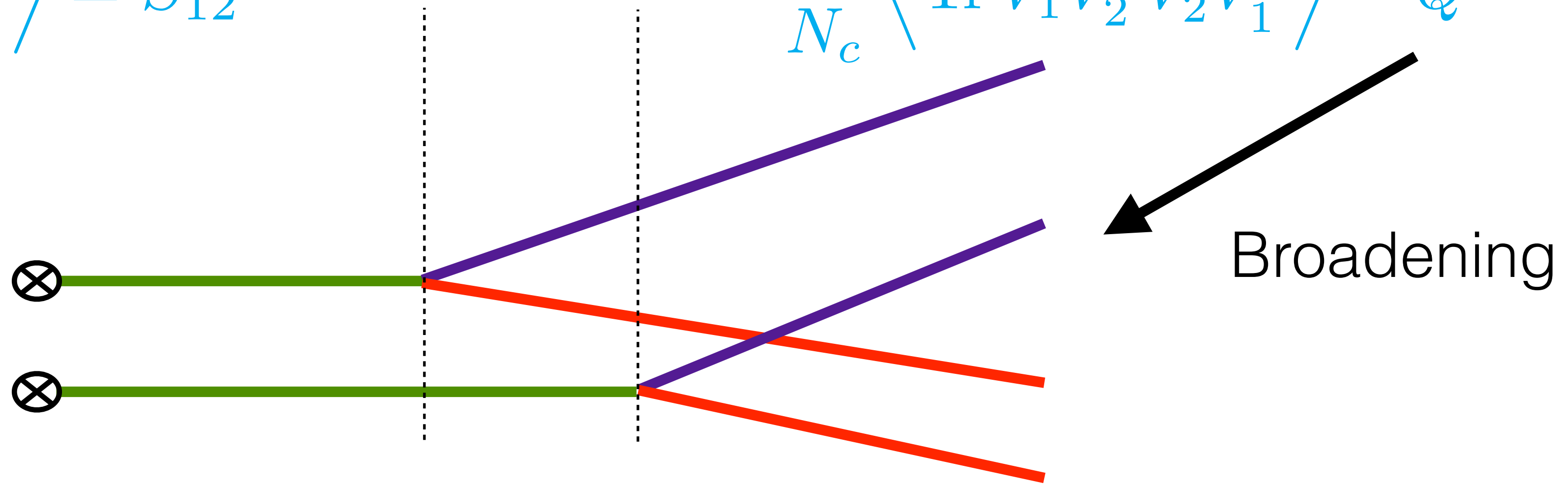

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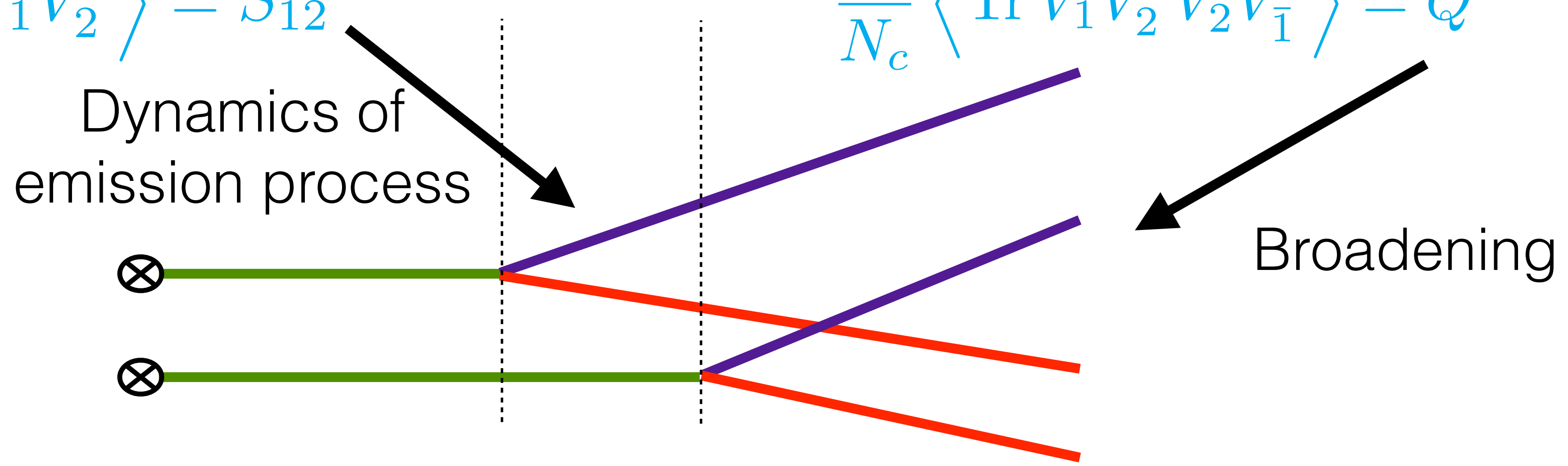

EECs and color coherence