Determining the onset of color coherence with energy correlators

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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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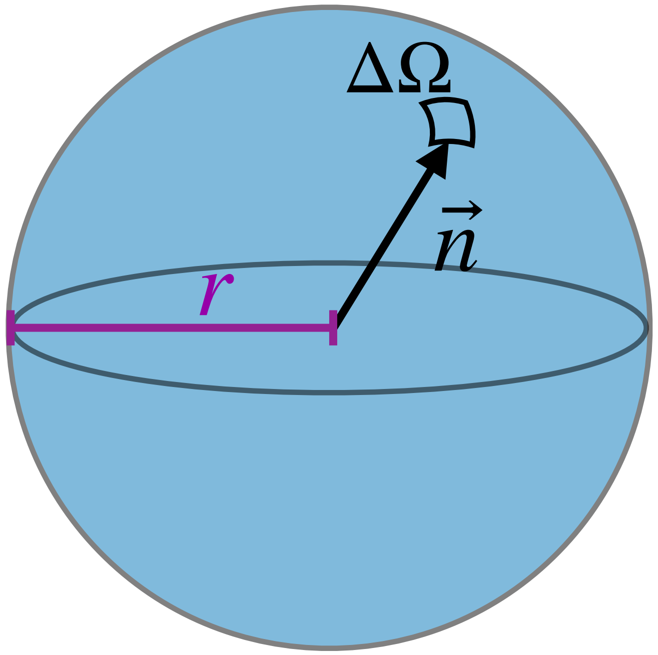
Energy flux operators

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



- The 1-point function measures the total energy flux through an area element

$$\langle \mathcal{E}(\vec{n}) \rangle \propto \sum_i E_i$$

Sum over all particles going through $\Delta\Omega$

- Its correlation functions provide valuable information about the collision process

D. Hoffman, J. Maldacena 0803.1467

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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Inclusive cross section to produce two particles

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Hard scale of the process

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Hard scale of the process

- As a function of the relative angle only

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

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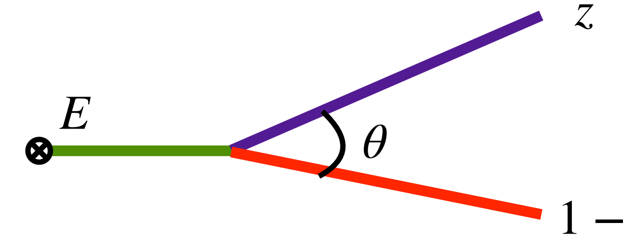
  - Infrared and collinear safe for $n = 1$
  - For $1 < n \leq 2$ divergences can be absorbed into track or fragmentation functions

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

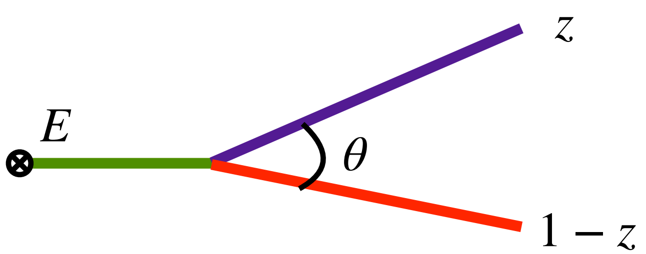
$$z = \frac{E_g}{E}$$

Energy correlators in vacuum

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

- At leading order

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



- Collinear emissions can be resummed using CFT techniques changing the scaling only by an anomalous dimension

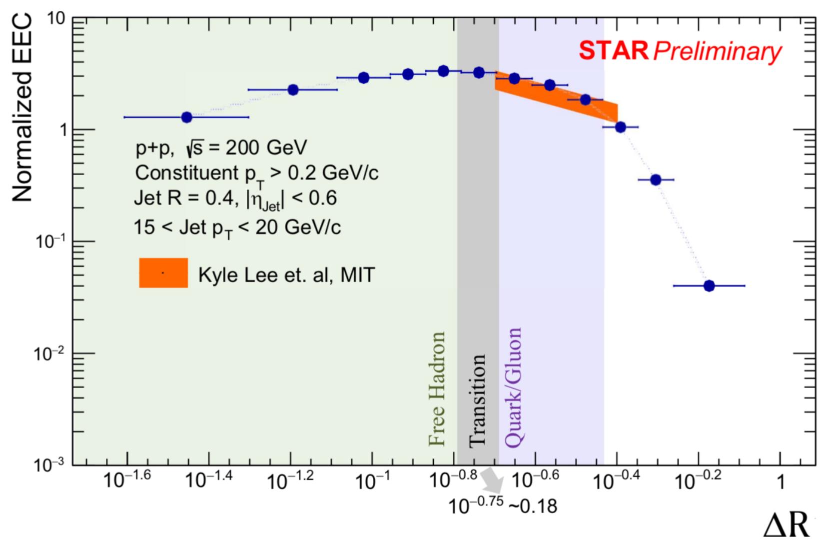
$$\frac{d\Sigma^{(1)}}{d\theta} \sim \frac{1}{\theta^{1-\gamma(3)}}$$

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

- Soft physics and quark/gluon ratios can change the overall normalization but not the power-law behavior

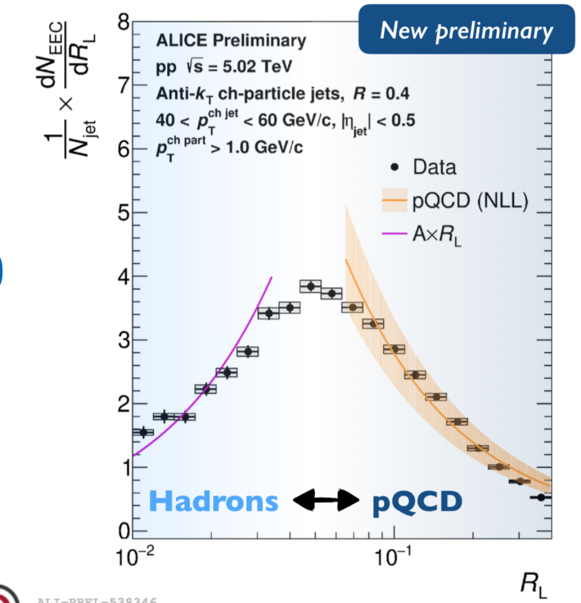
Energy correlators in vacuum

- New measurements announced at HP2023!



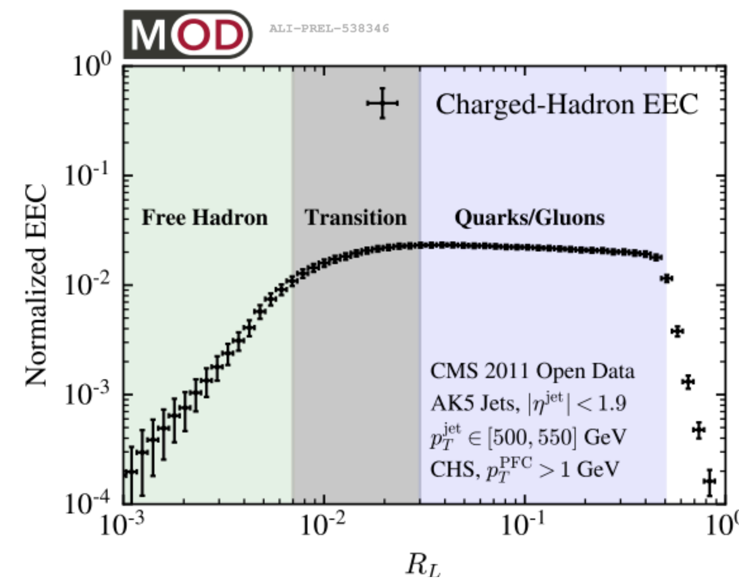
See R. Cruz-Torres's Talk Tue. 17:30

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



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

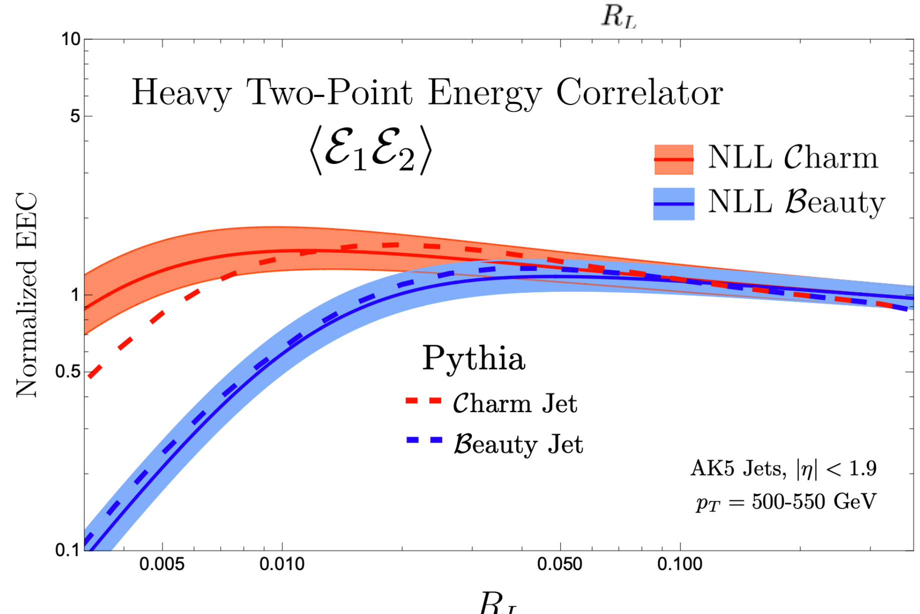
P. T. Komiske, I. Moult, J. Thaler, H. X. Zhu 2201.07800



- Dead cone for massive quarks

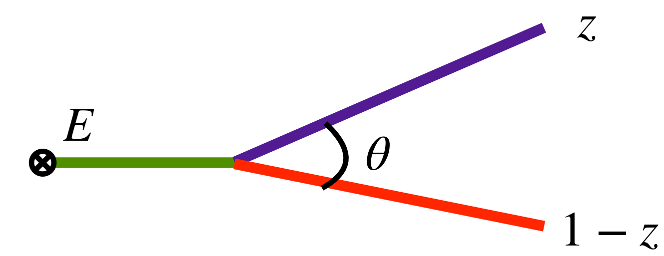
E. Craft, K. Lee, B. Meçai, I. Moult 2210.09311

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}

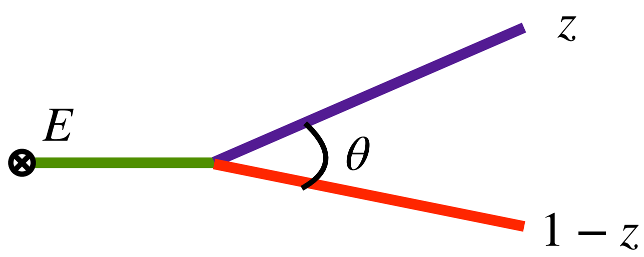
$$\frac{d\sigma_{qg}}{d\theta dz} = (1 + F_{\mathrm{med}}(z,\theta)) \frac{d\sigma_{qg}^{\mathrm{vac}}}{d\theta dz} \qquad F_{\mathrm{med}}(z,\theta) \xrightarrow{\theta < \theta_L} 0$$

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

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

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

Evaluation of in-medium splittings



- First results for full evaluation keeping z and θ announced at HP2023 (computationally costly)

See J. Isaksen's Talk Wed. 14:40

Isaksen, Tywoniuk 2303.12119

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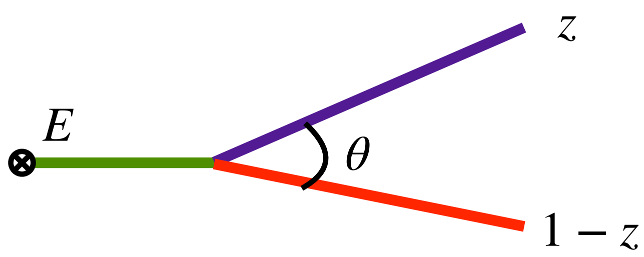

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Isaksen, Tywoniuk 2303.12119

- 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

Isaksen, Tywoniuk 2107.02542

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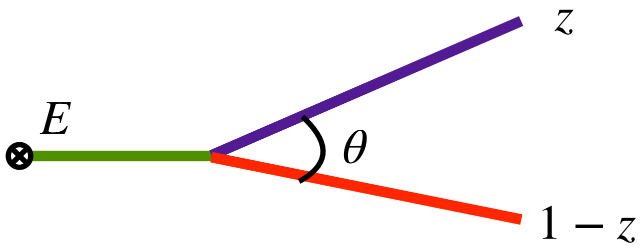

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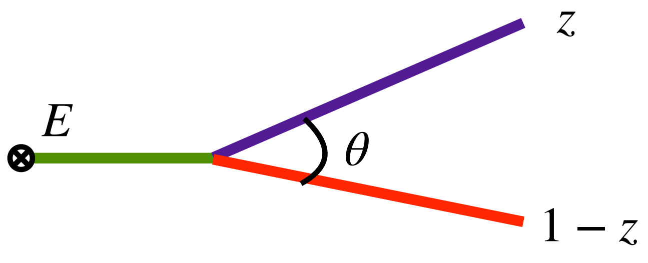
Time and angular scales

FD, Milhano, Salgado, Tywoniuk, Vila 1907.03653

- 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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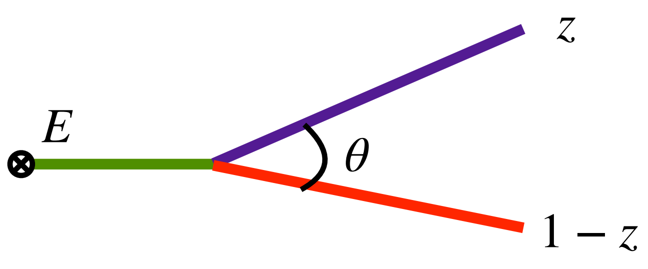

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$$t_f = \frac{2}{z(1-z)E\theta^2}$$

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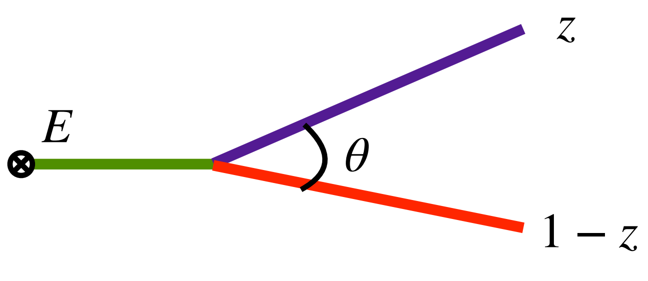

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Below θ_L all emissions have a formation time larger than L

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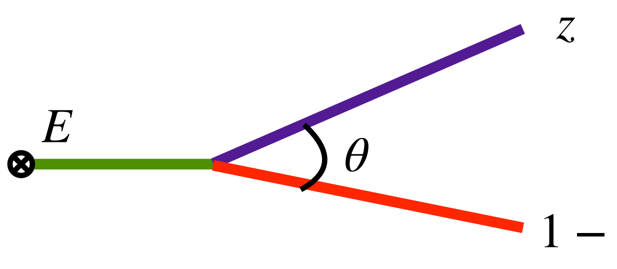

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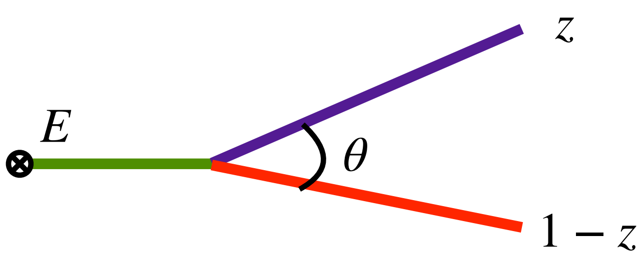

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Below θ_c splittings do not lose color coherence and the medium does not resolve them

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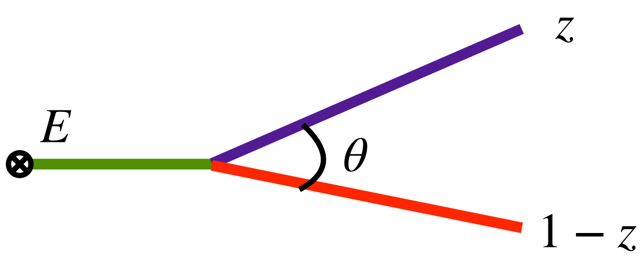

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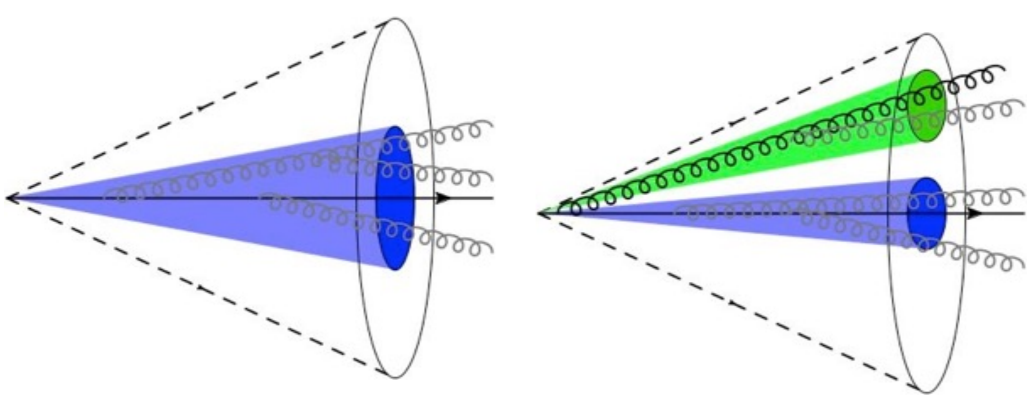

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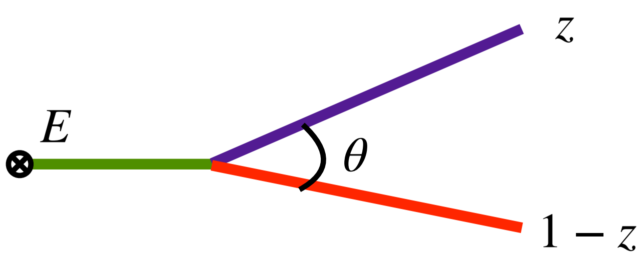

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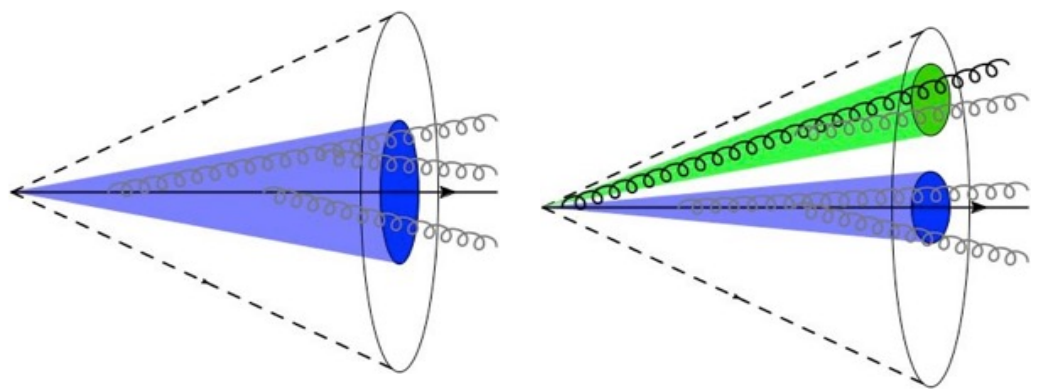

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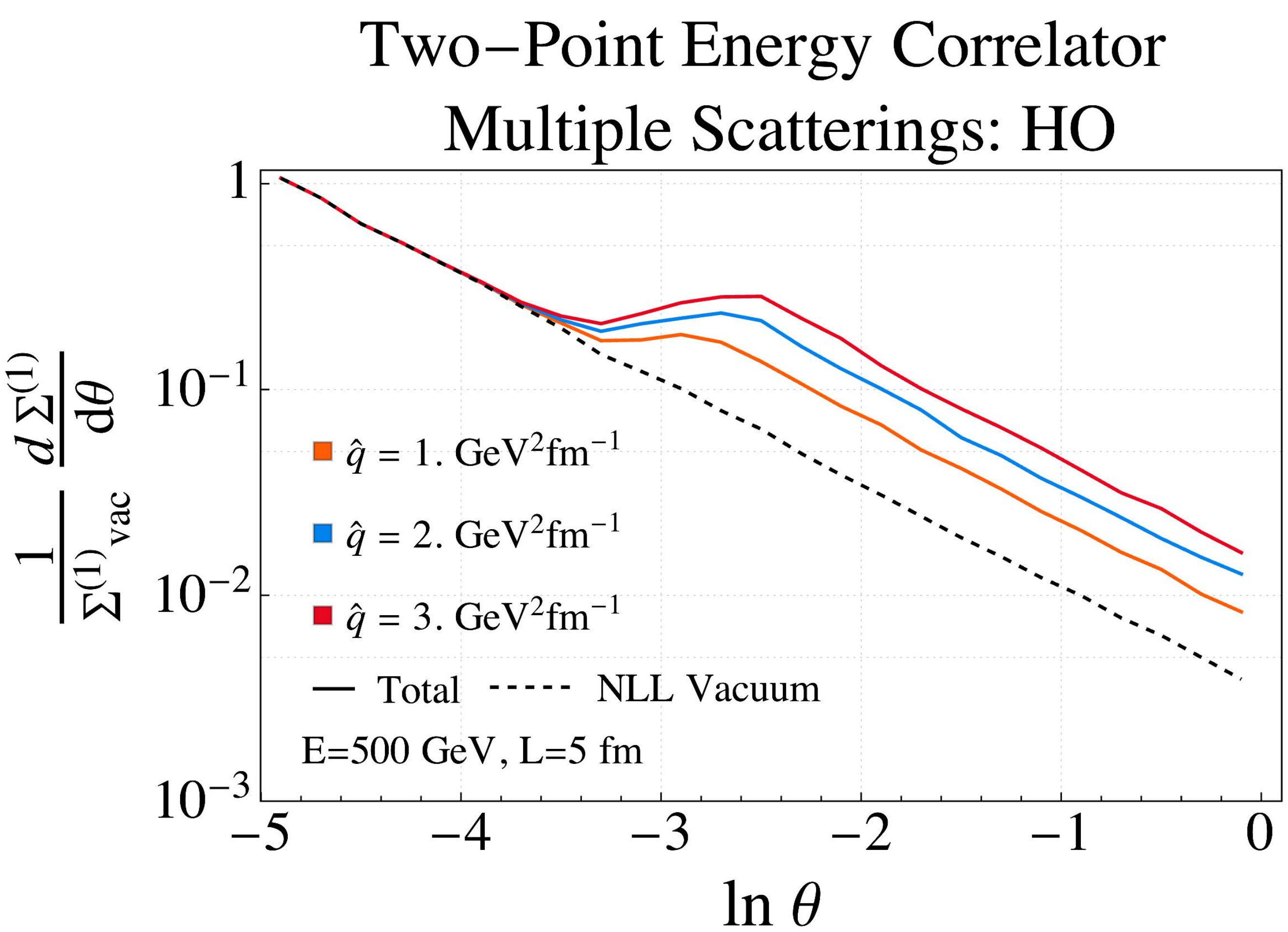
If $\theta_L > \theta_c$ then θ_c becomes irrelevant

Results HO

$\theta_c > \theta_L$



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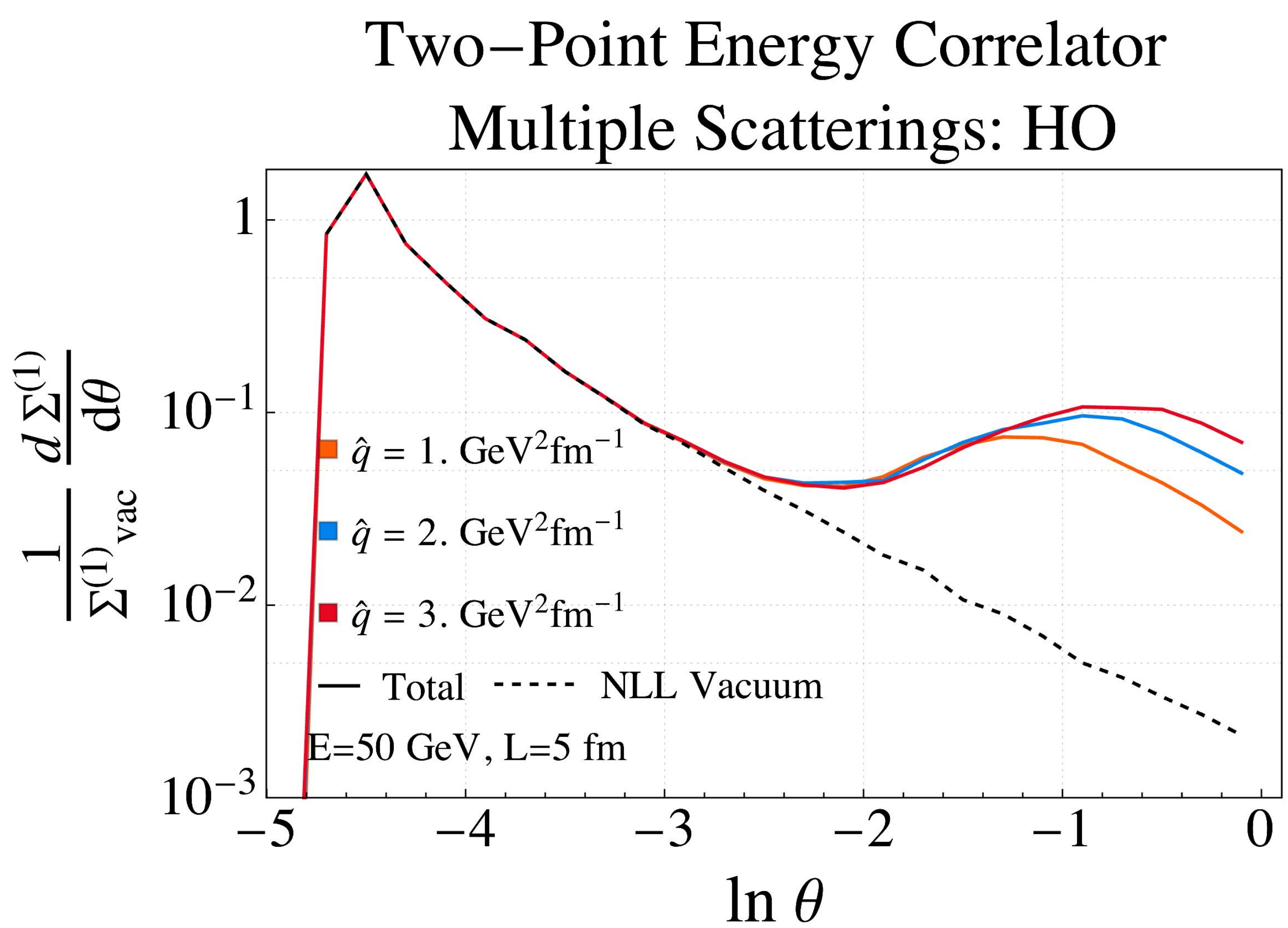

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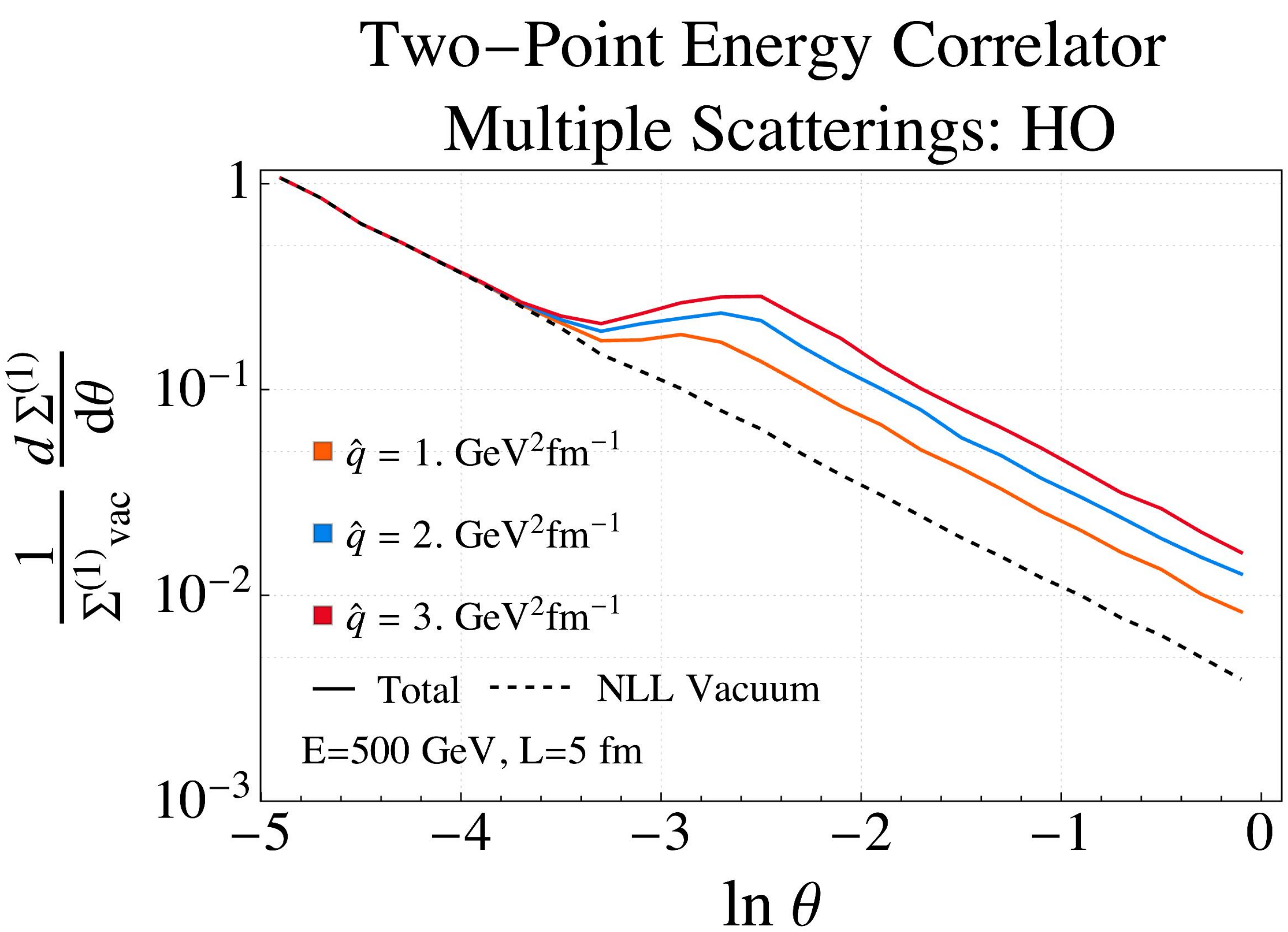

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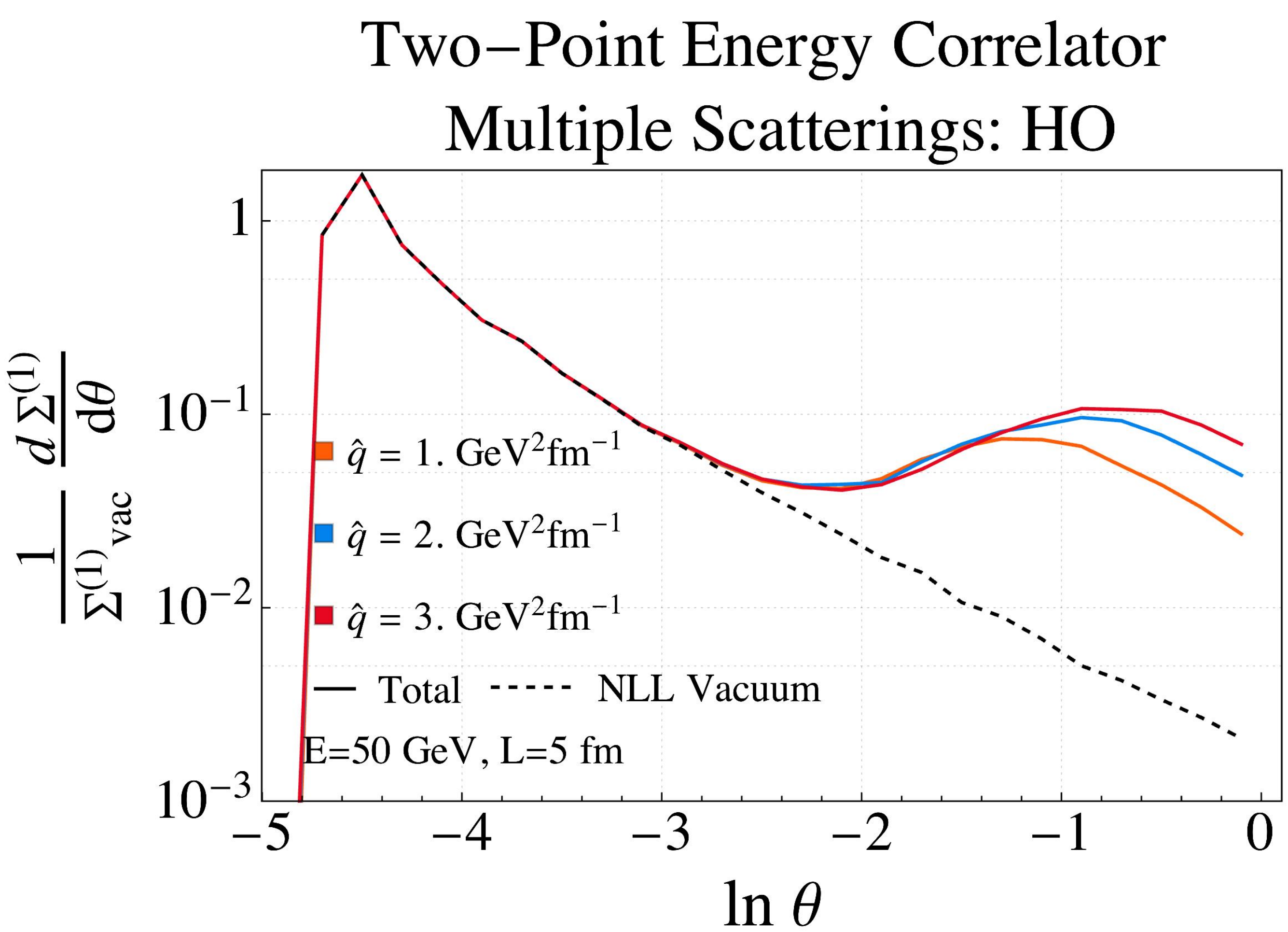

- No enhancement at small angles. Onset angle seems independent of $\hat{q}$ as expected

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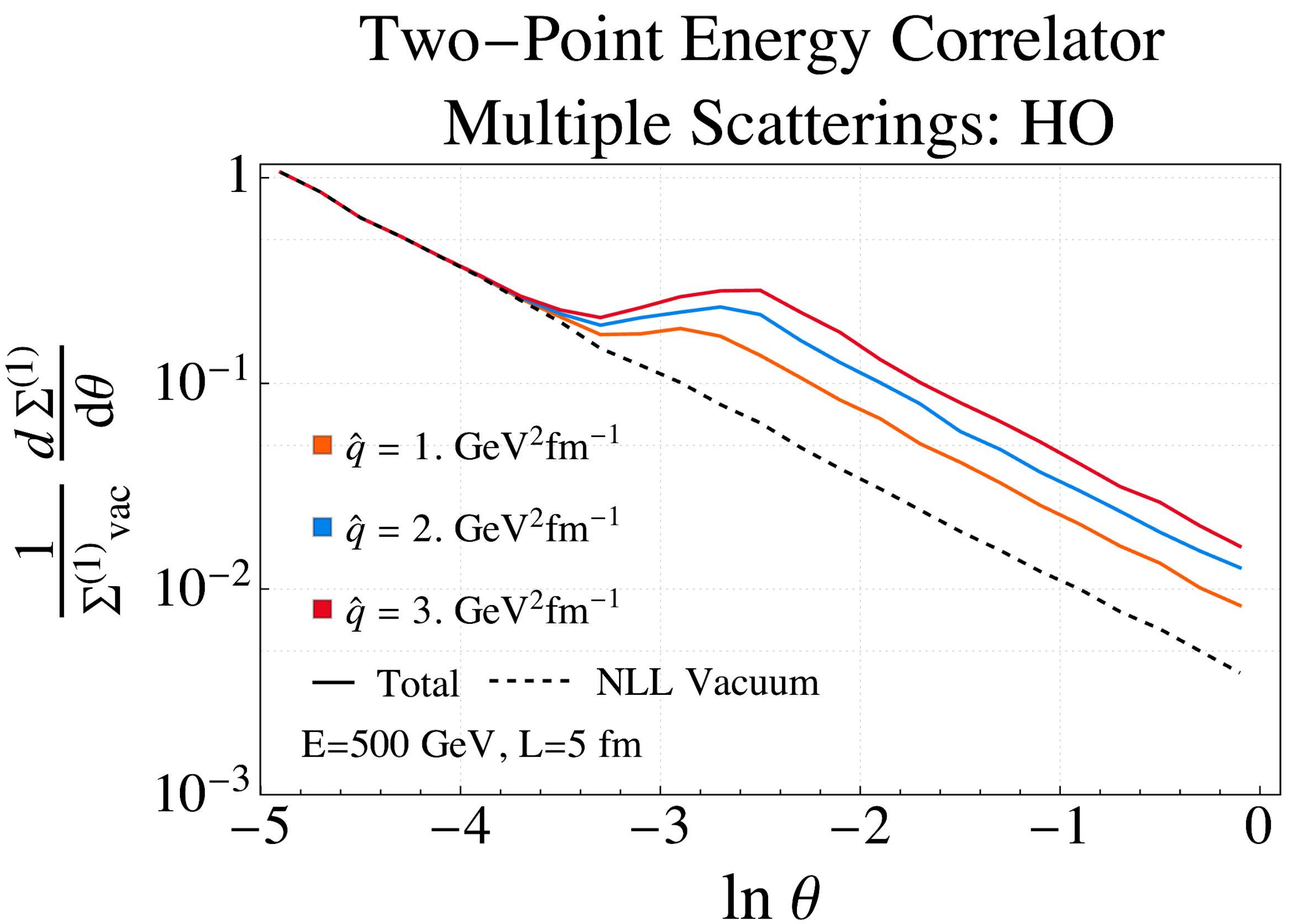

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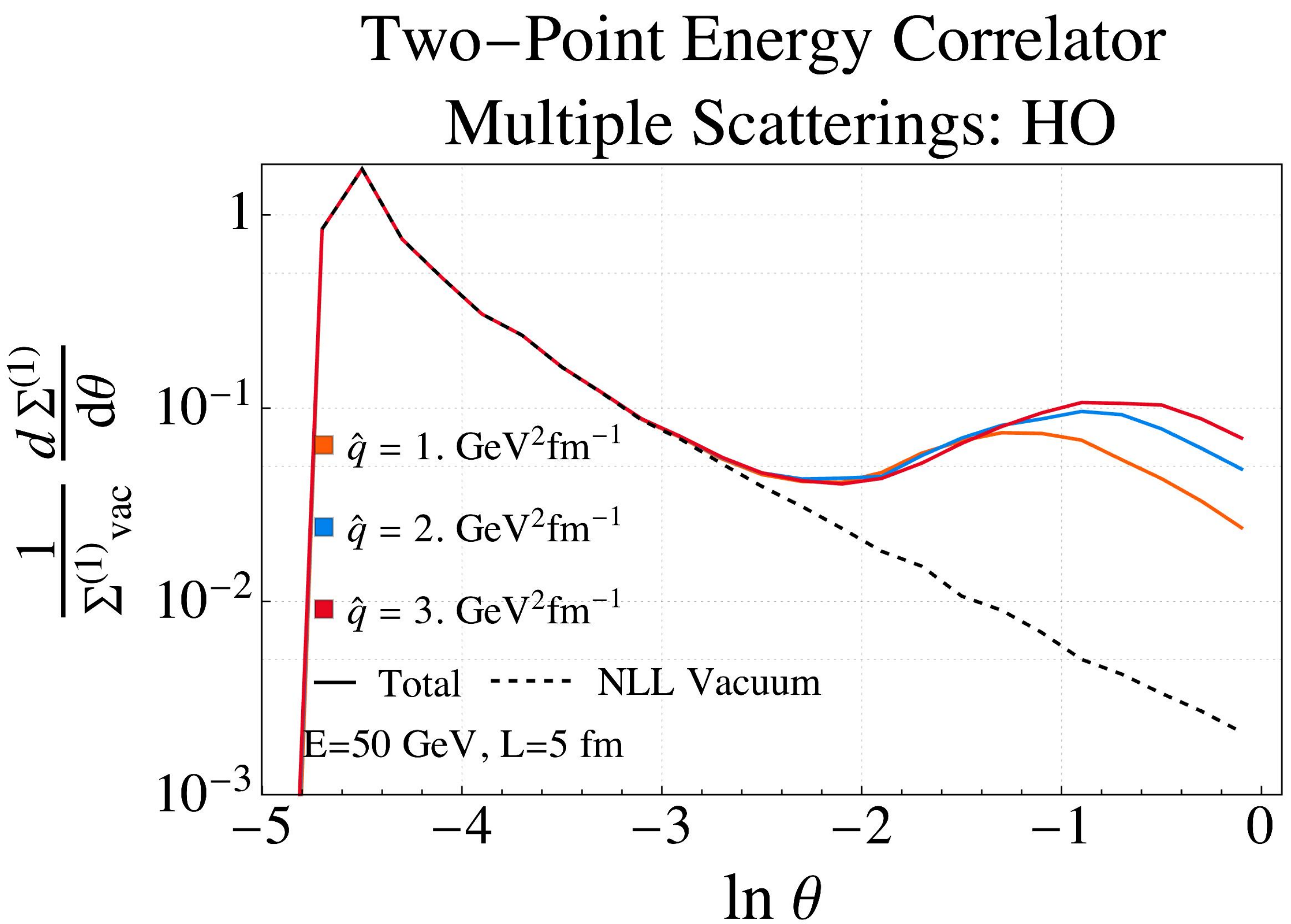

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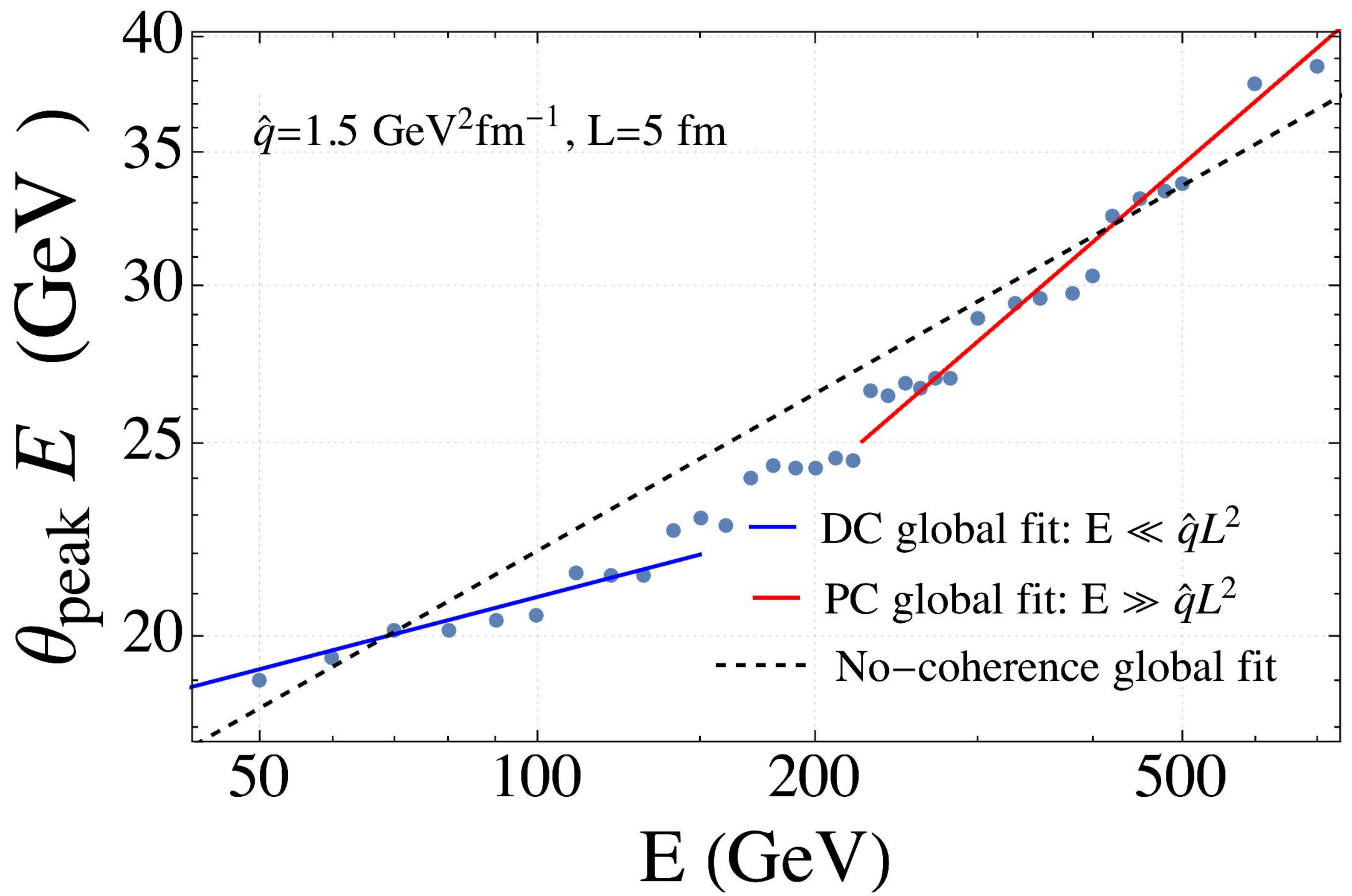
- Varying $\hat{q}$ has different effects in the two regions

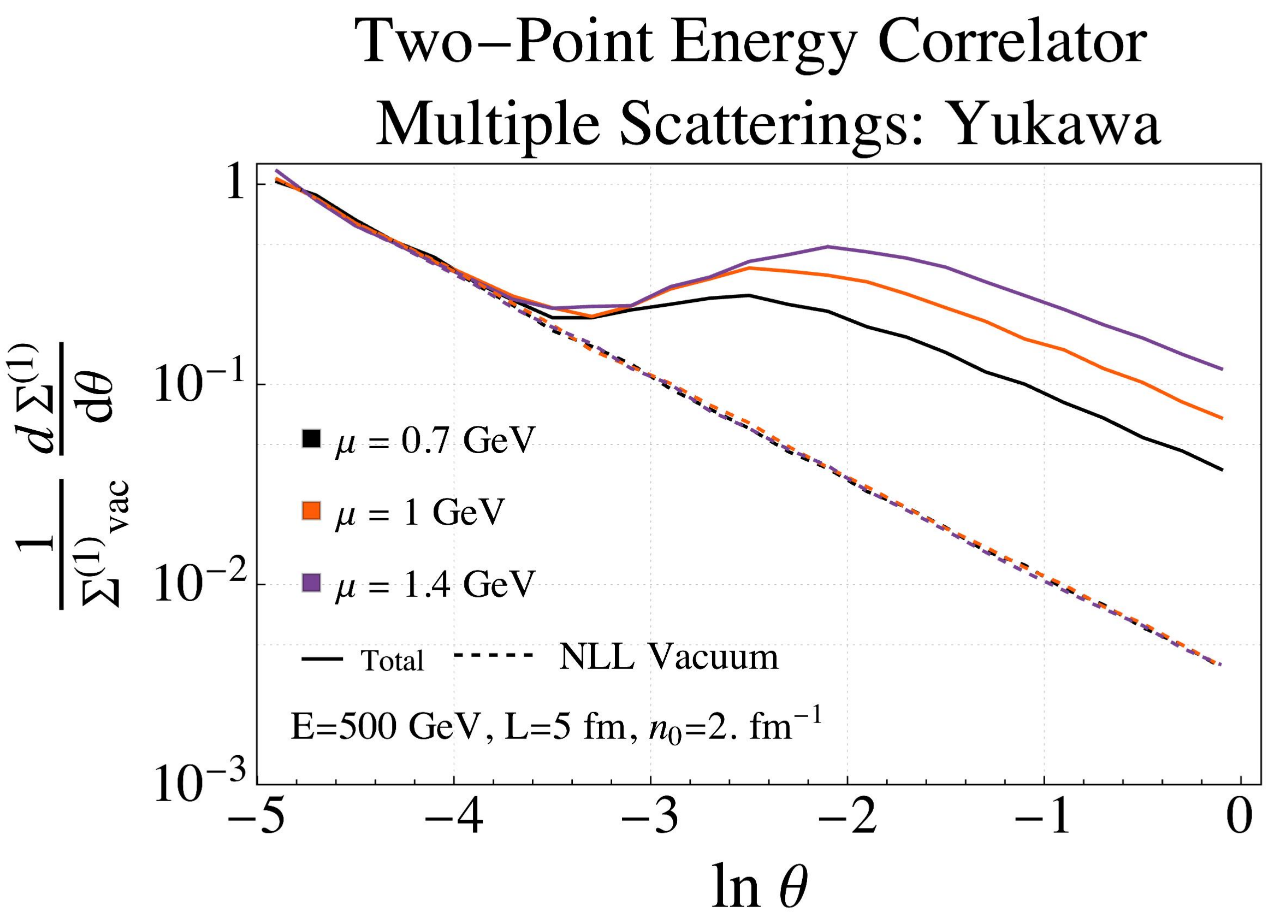
Coherence transition



- 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

Results with Yukawa interaction

$\theta_c > \theta_L$



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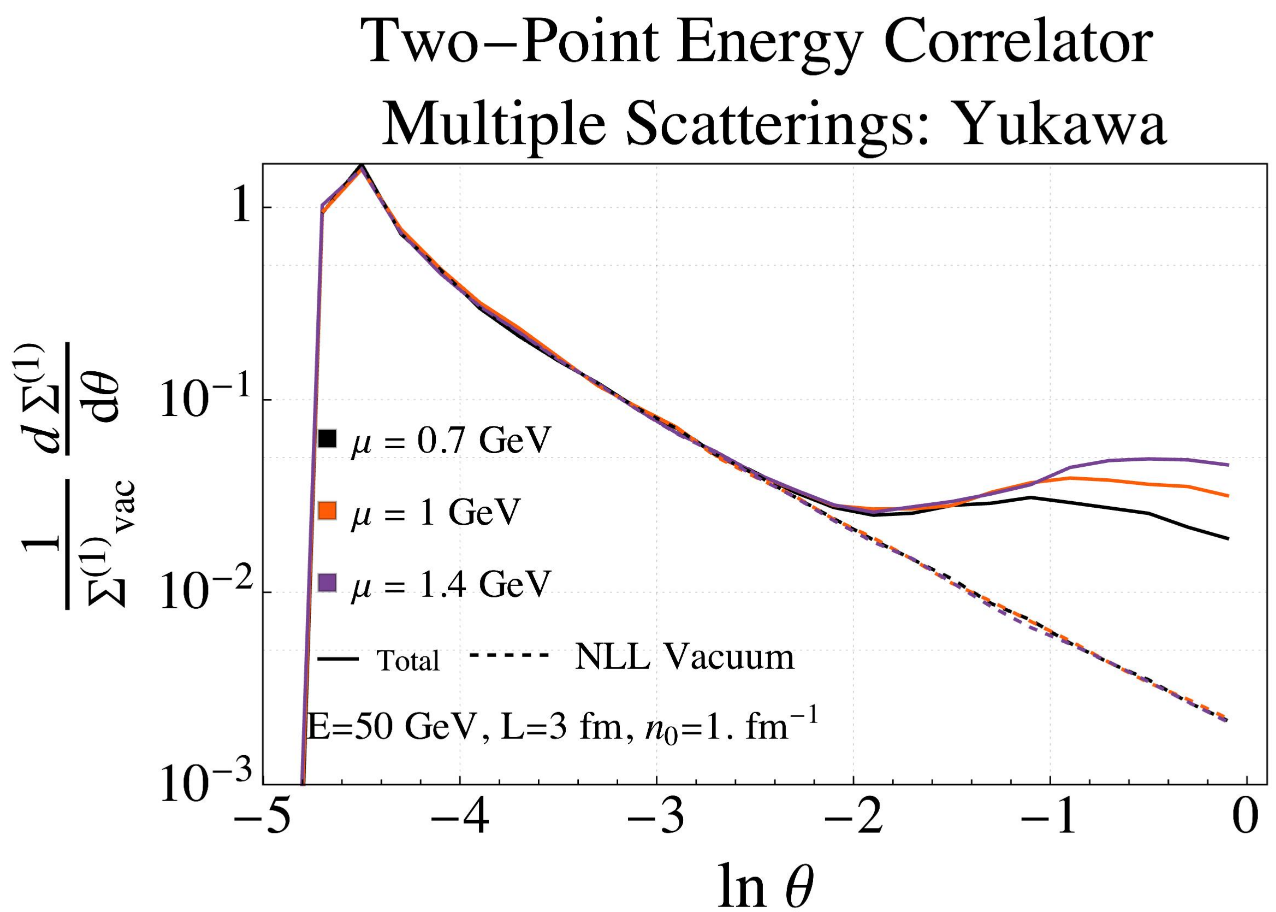

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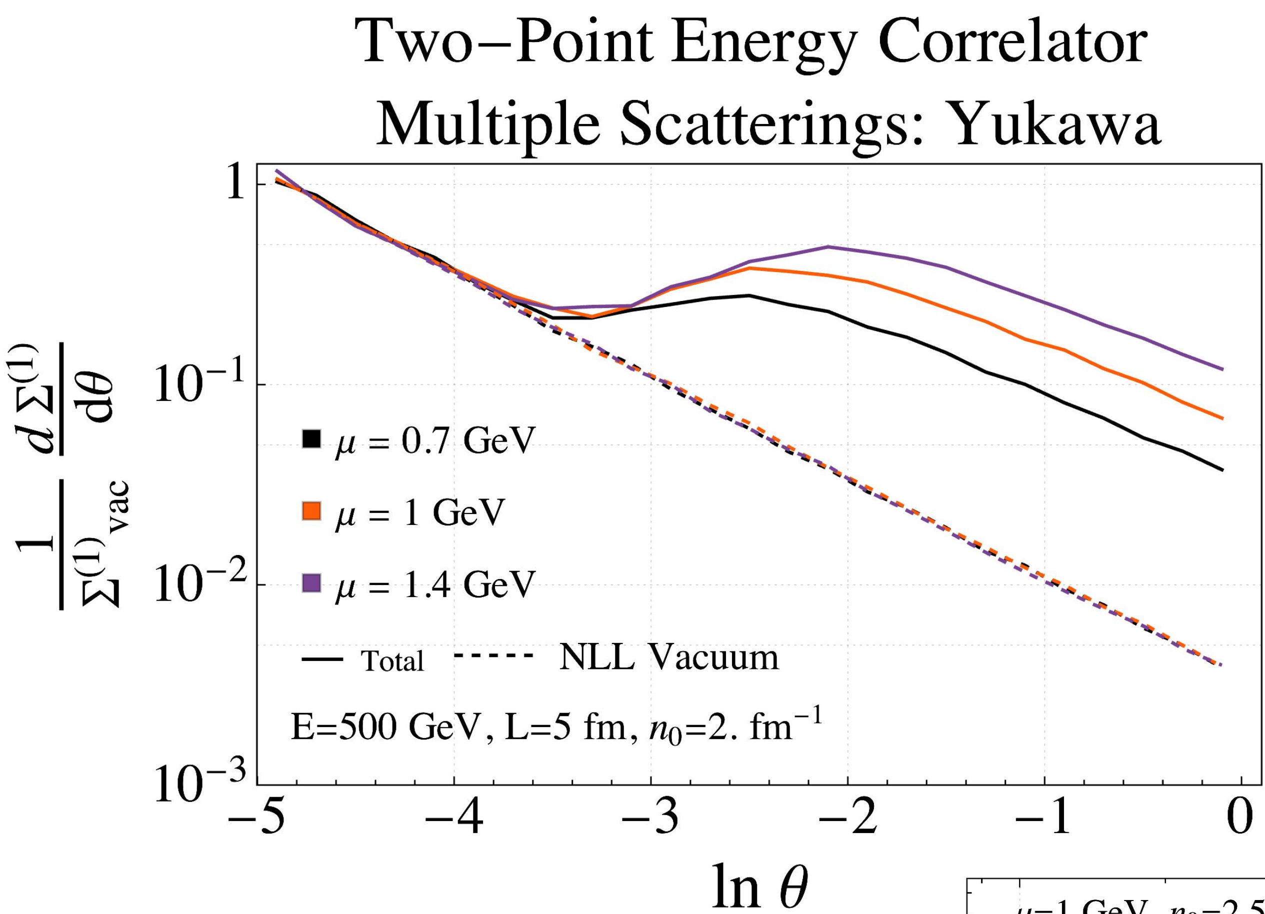

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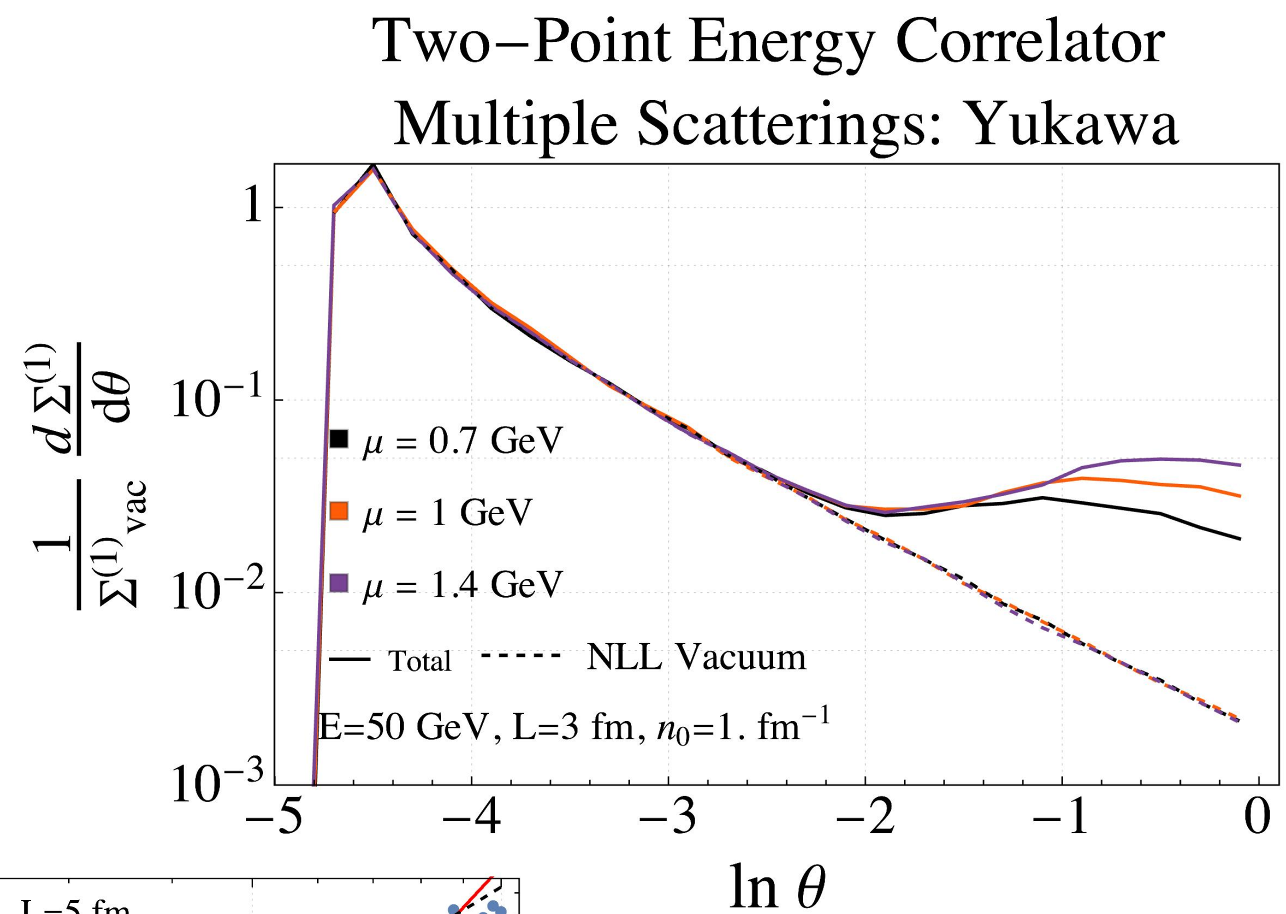

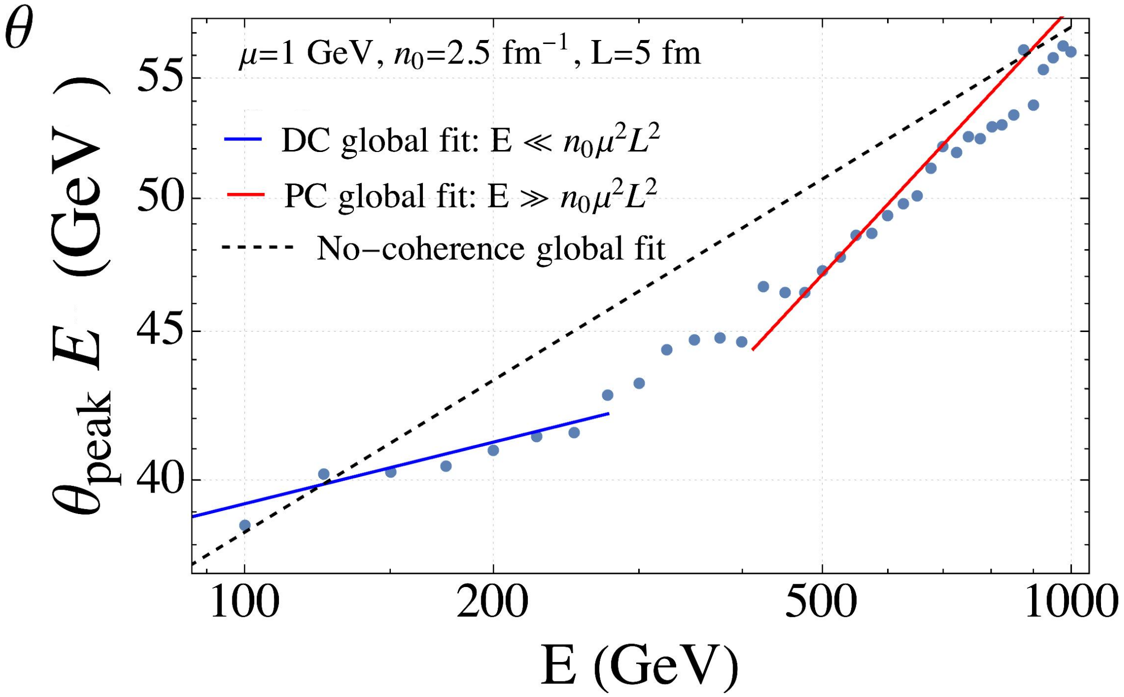

Results with single scattering (GLV)

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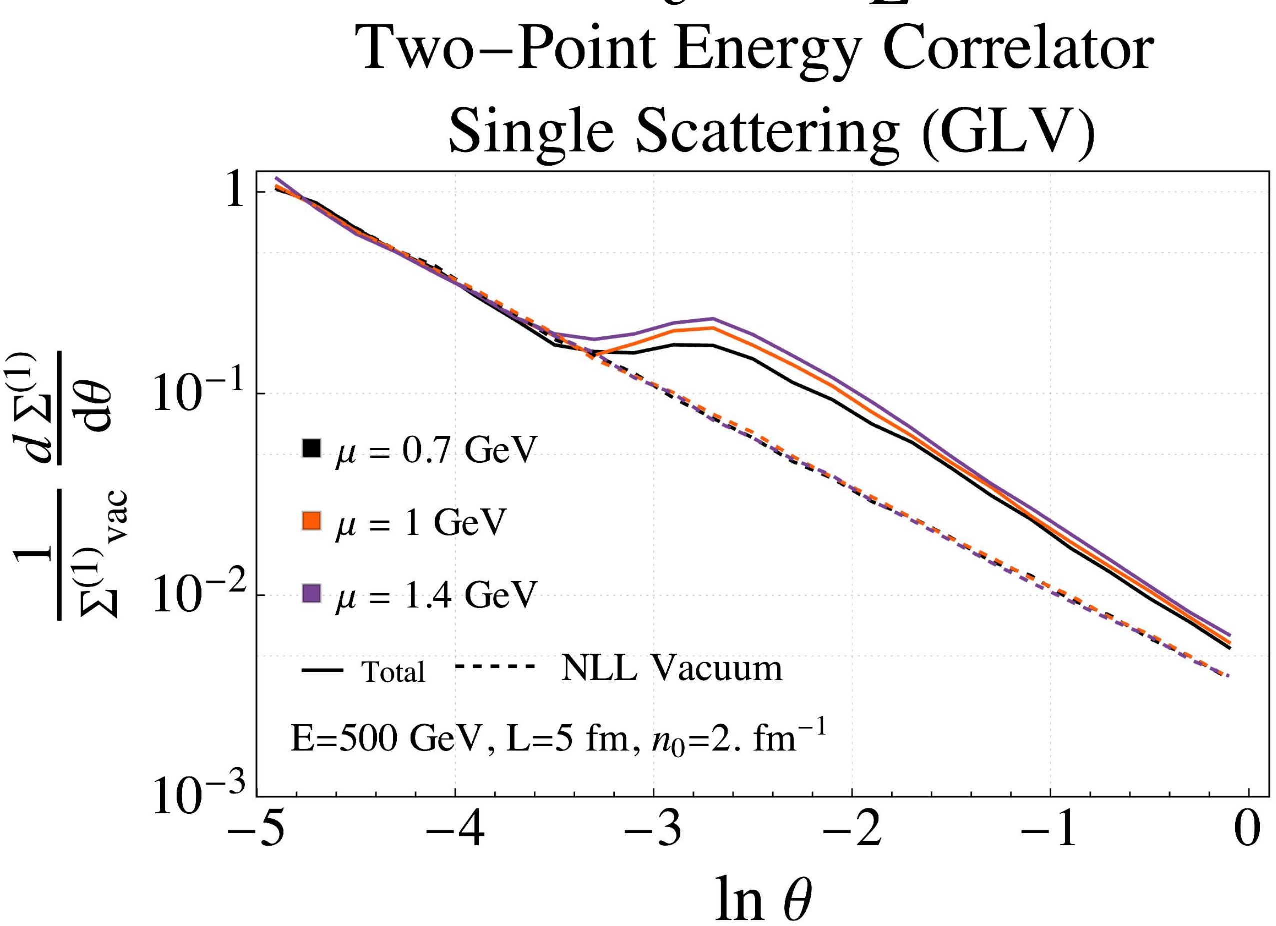

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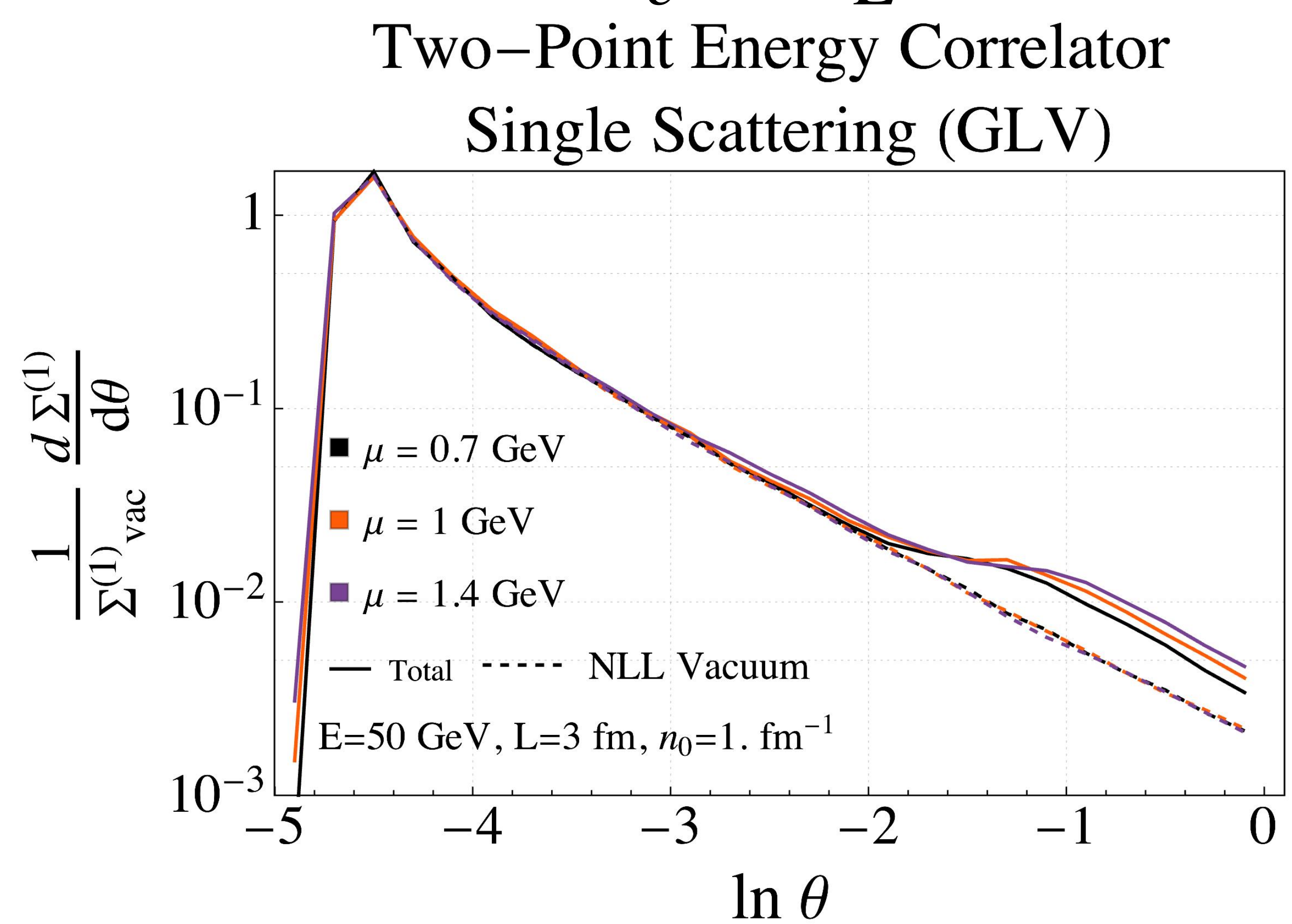

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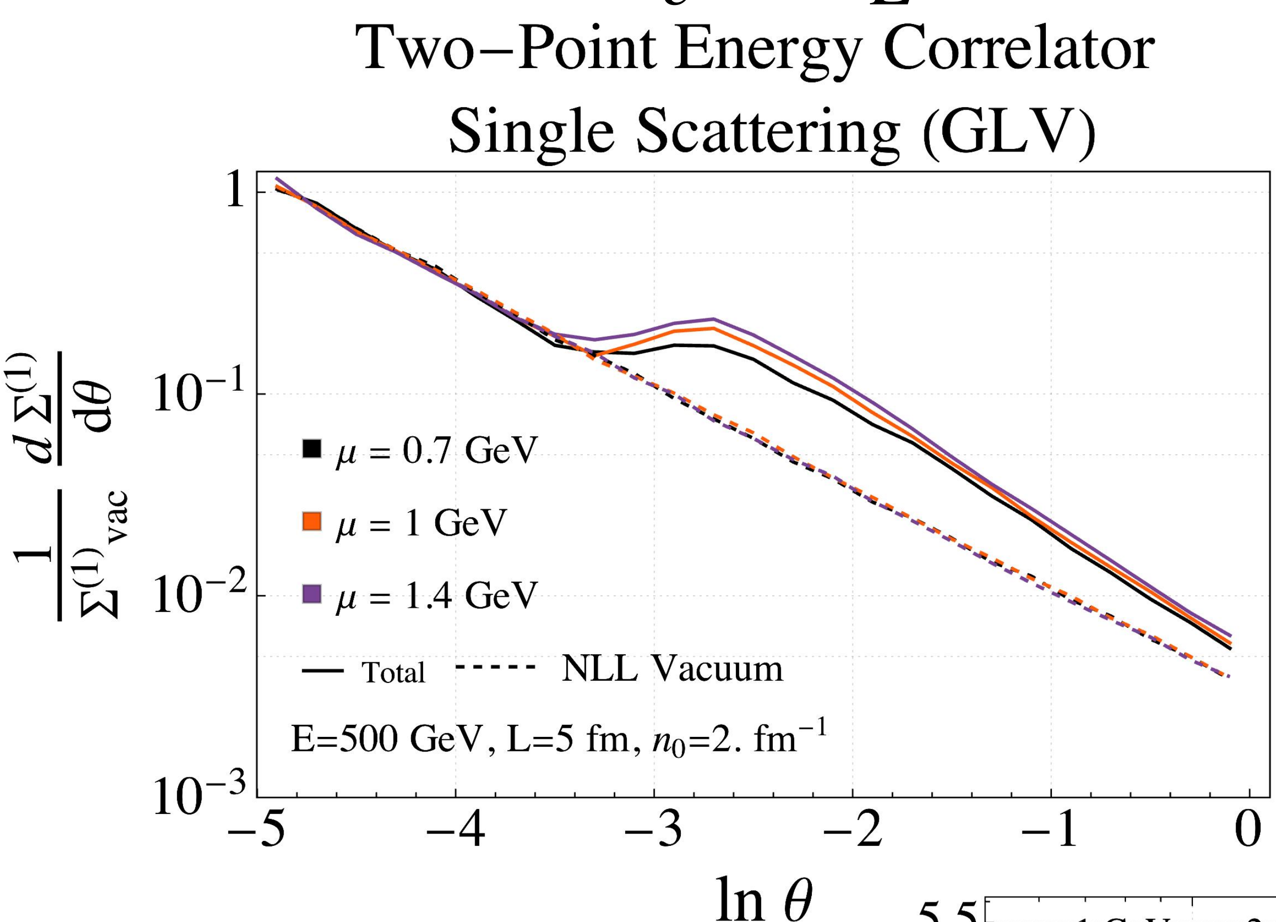

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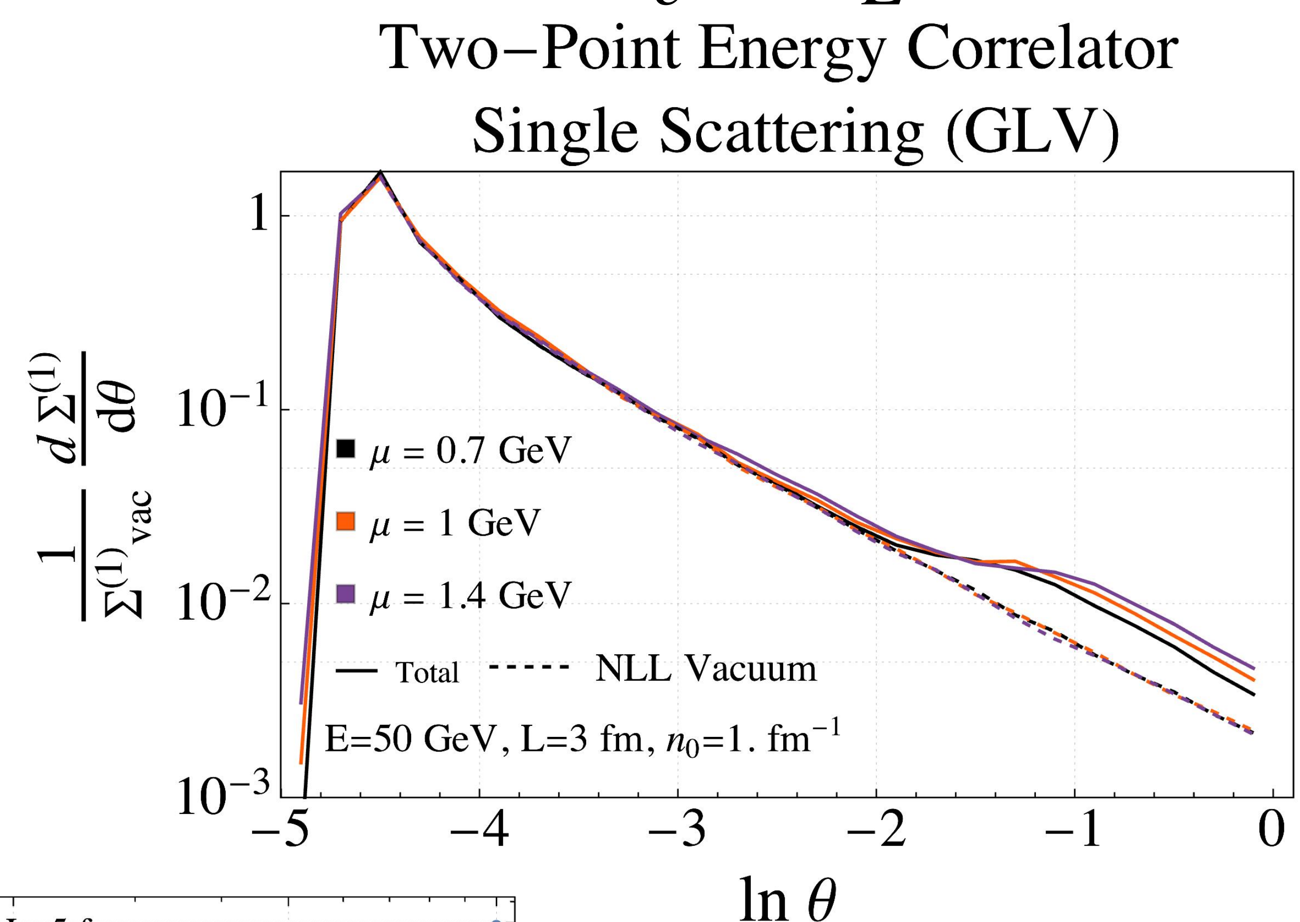
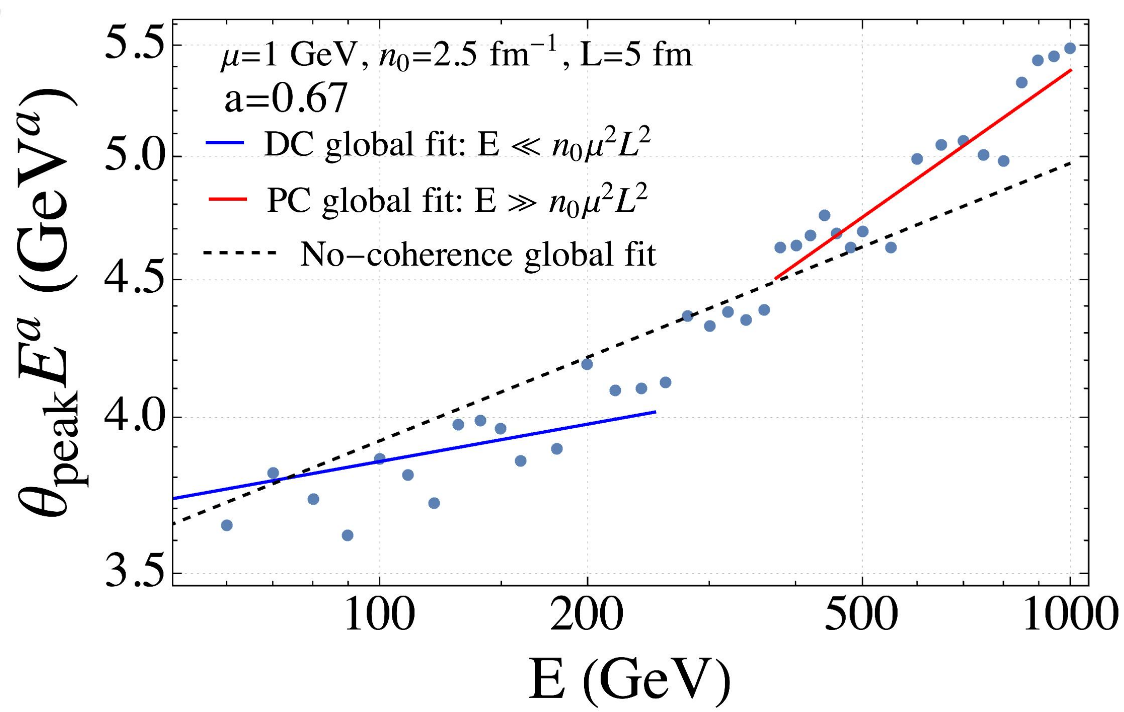
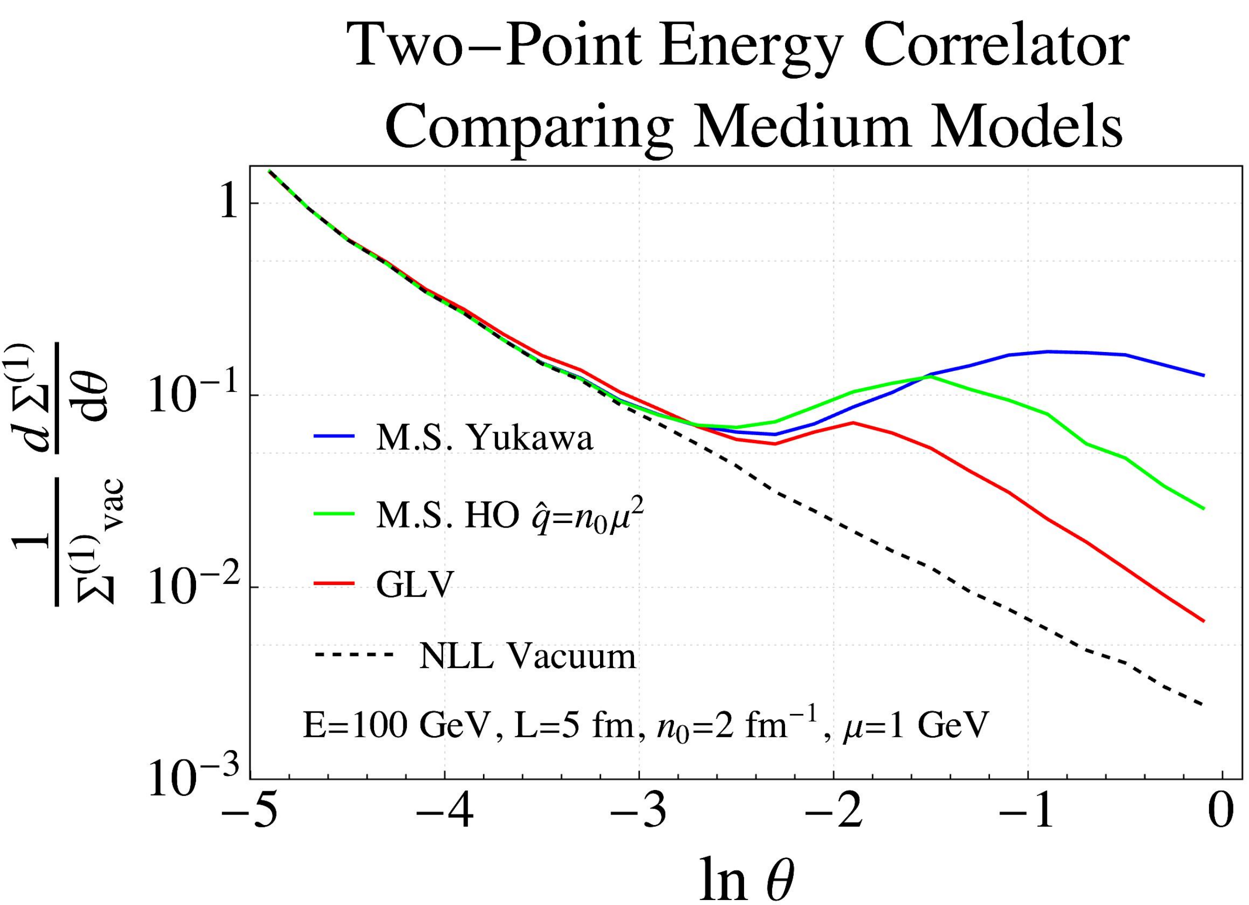
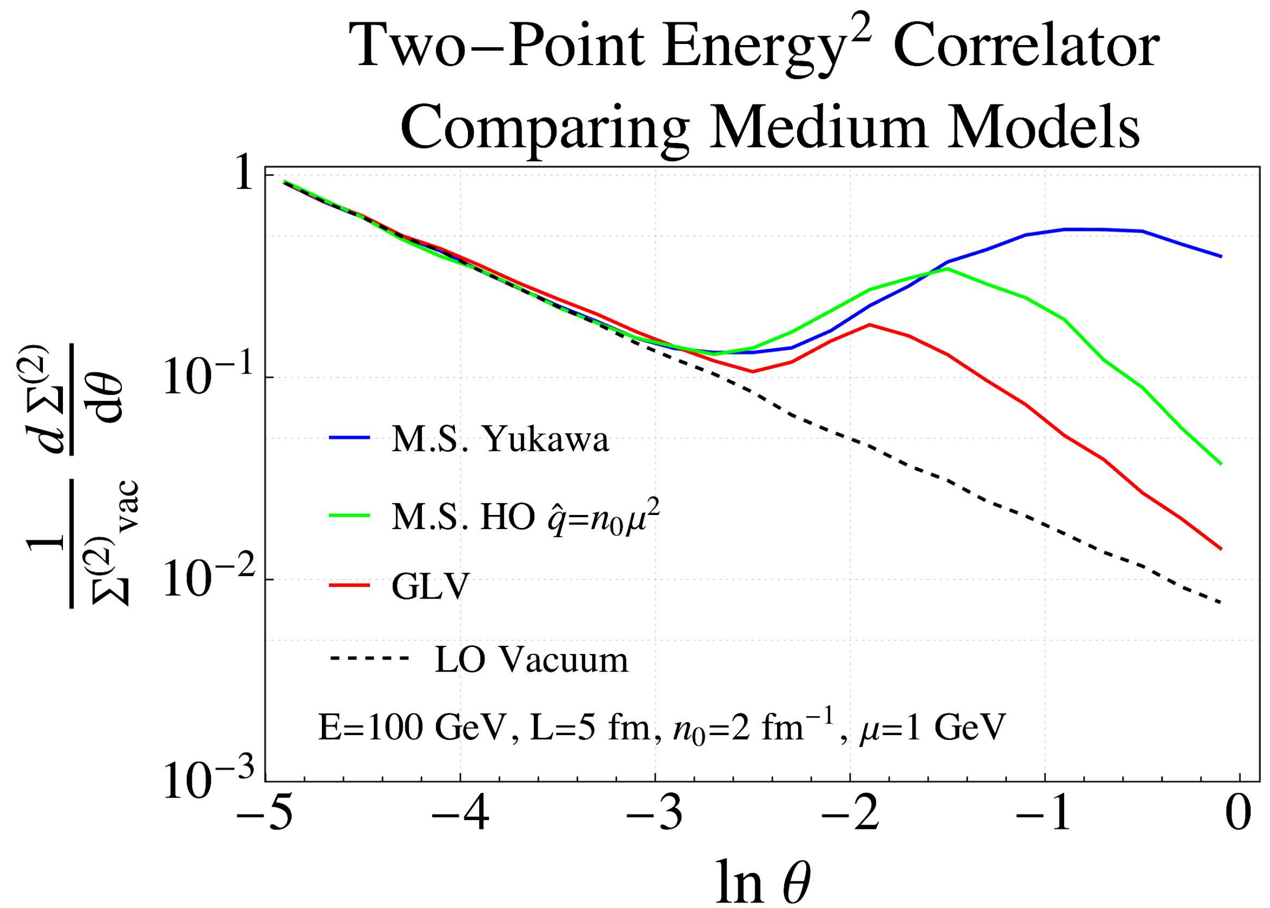




Higher energy power





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
- Characteristic features of the calculation for in-medium splittings are clearly imprinted in the observables
- Main features seem to be model independent, though transitions between regions are less sharp for the single scattering case

Outlook

- Lots of new exciting developments!
- Improvements in the calculation of the splittings will be incorporated in the computation of energy correlators
- Need to take into account better models for the medium, including longitudinal expansion
- Can be used to study the dead cone for heavy quarks

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

- Monte Carlo studies also needed

Thank you!

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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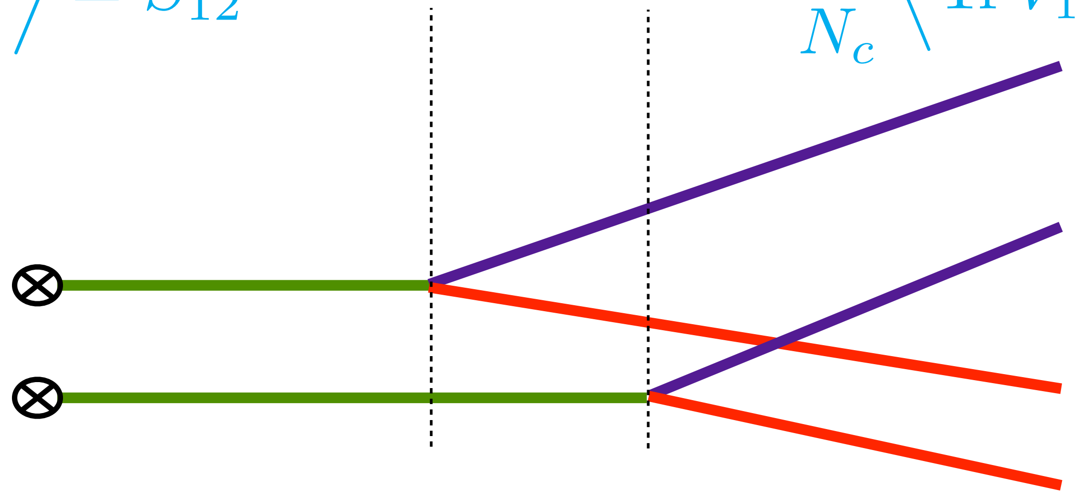

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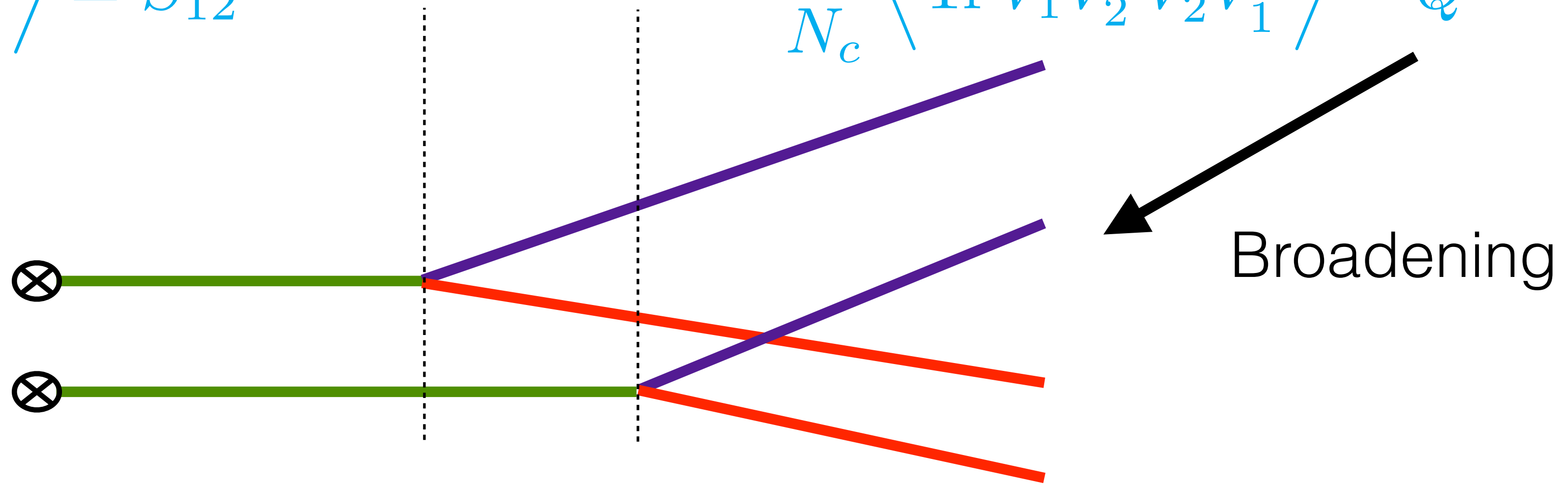

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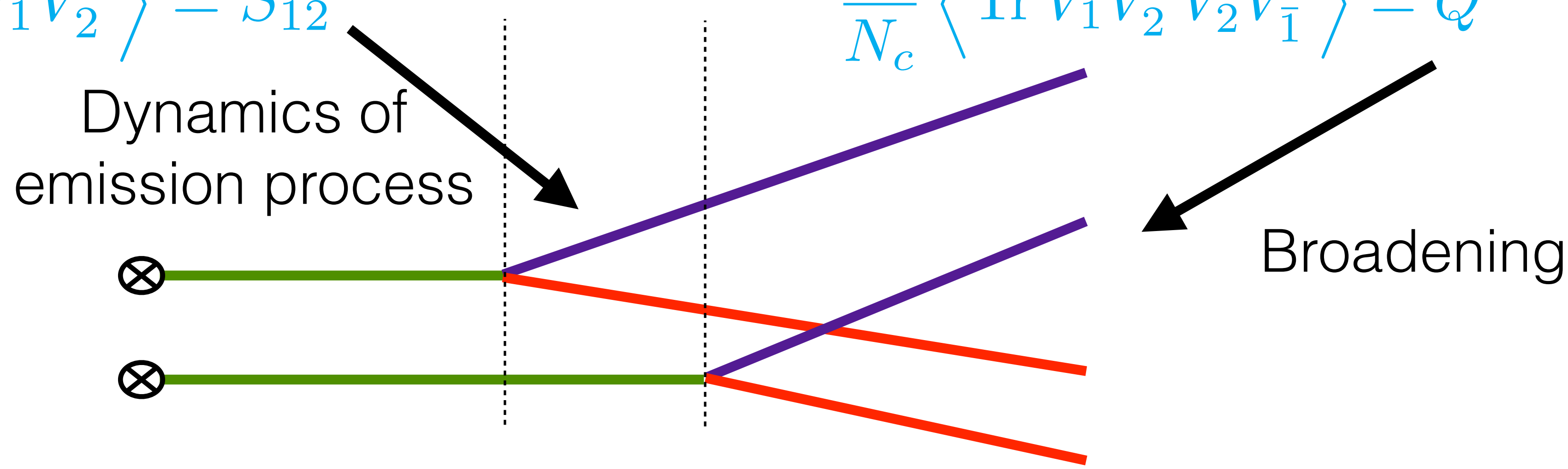

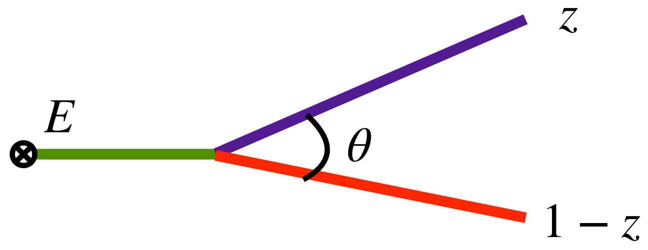

Lund plane

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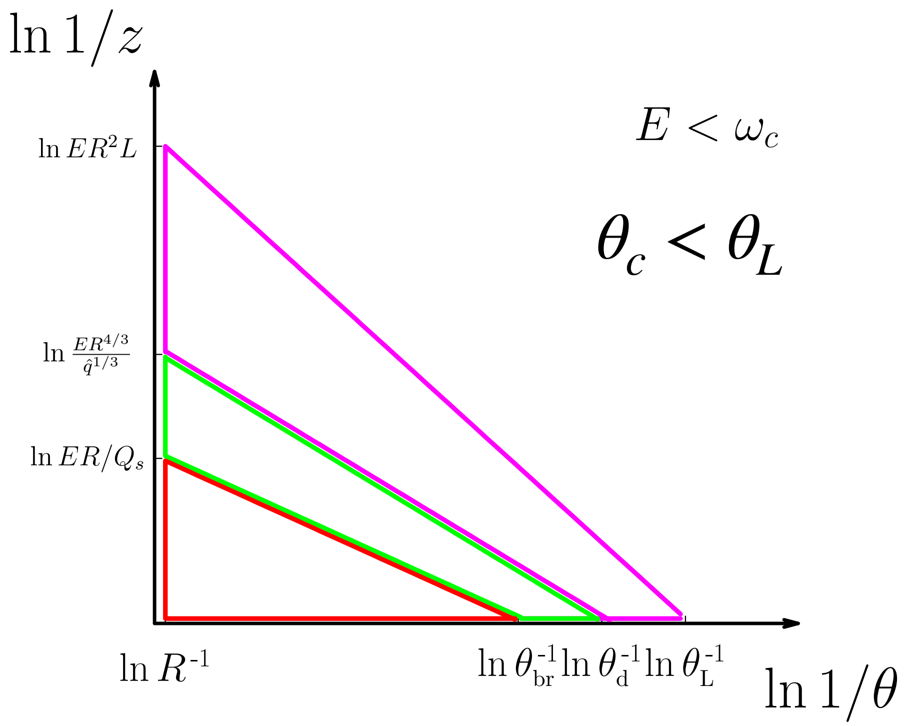
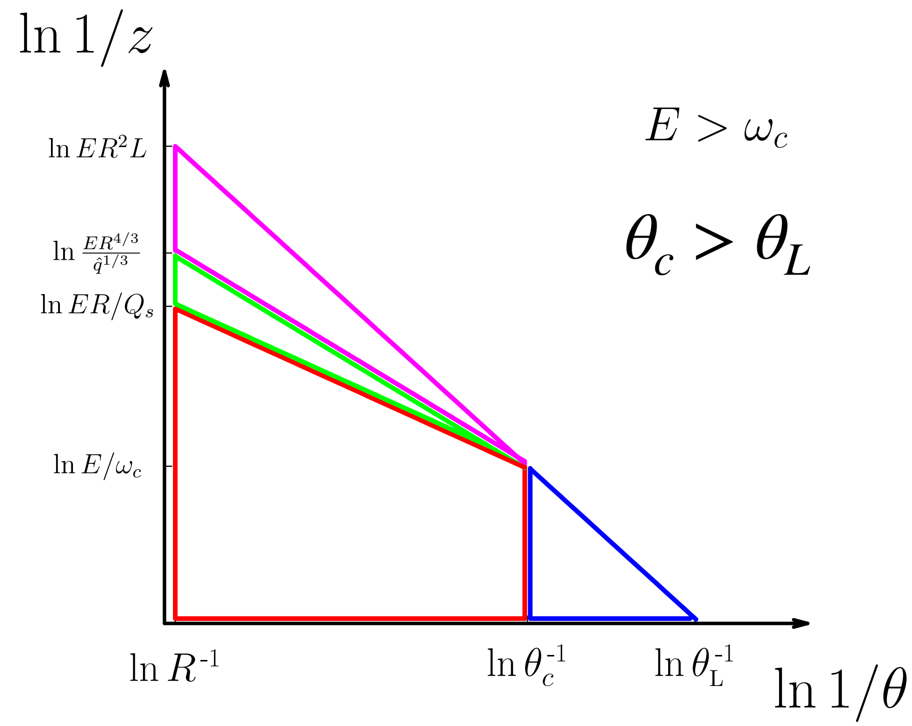
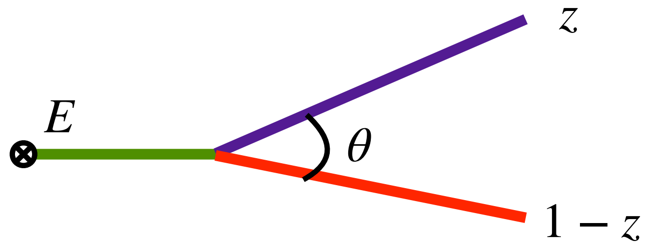




$\omega_c \sim \hat{q}L^2$



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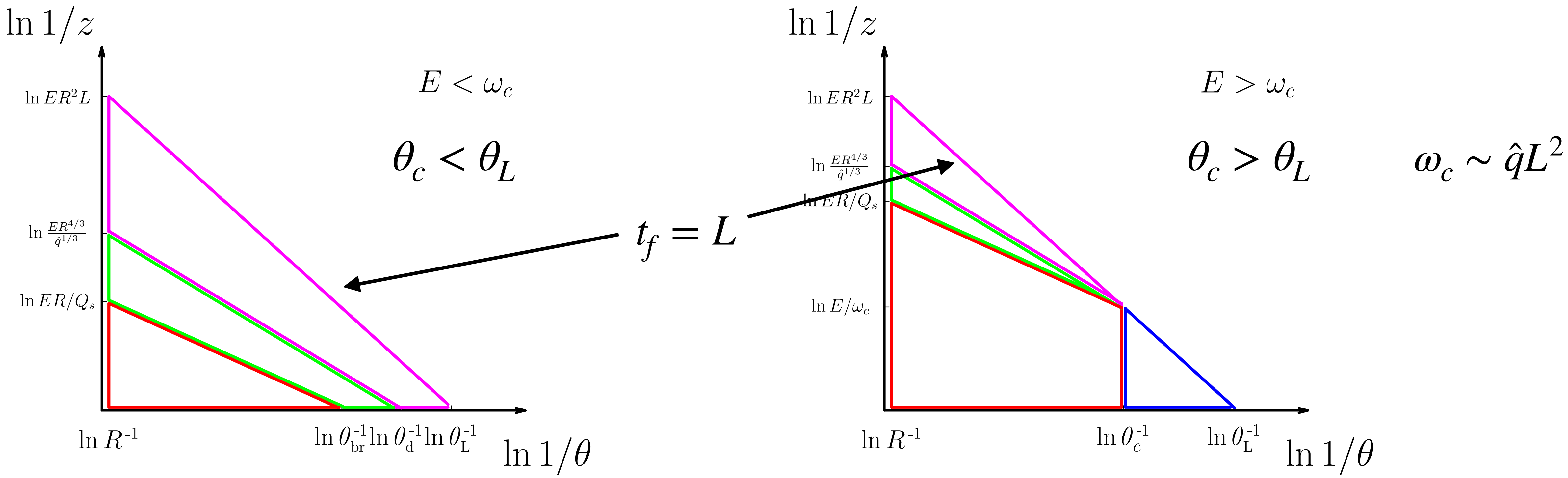

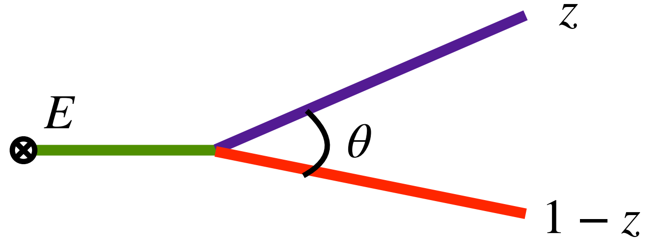

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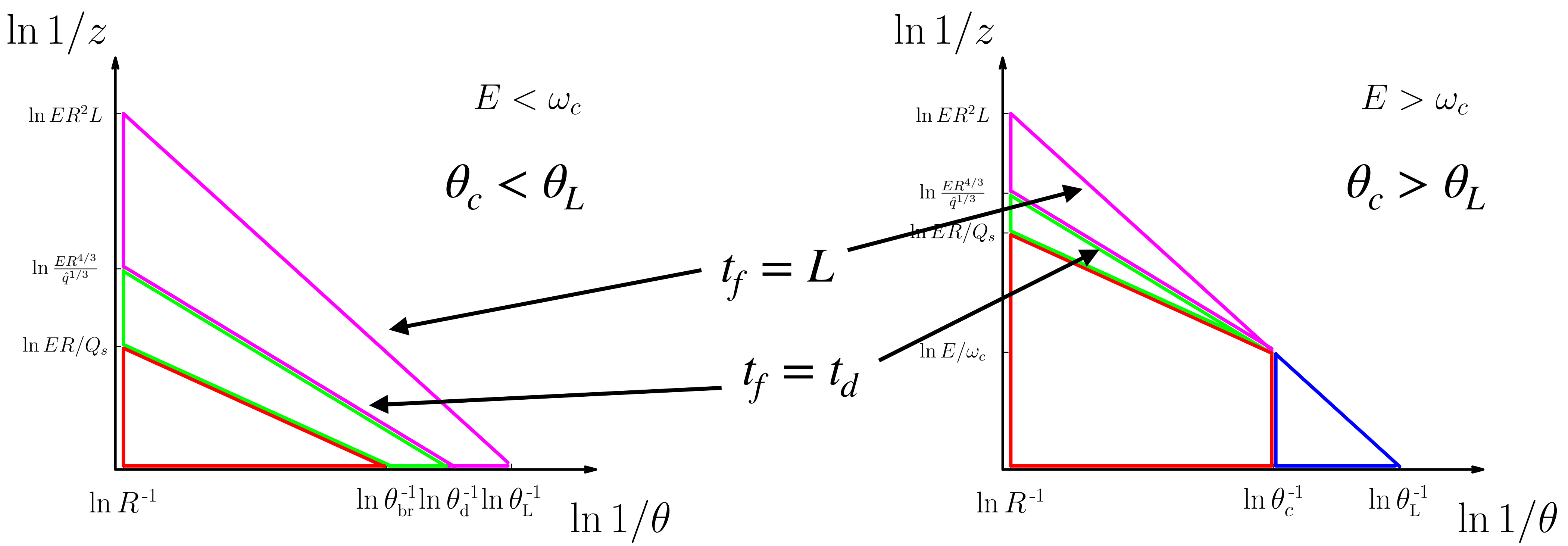

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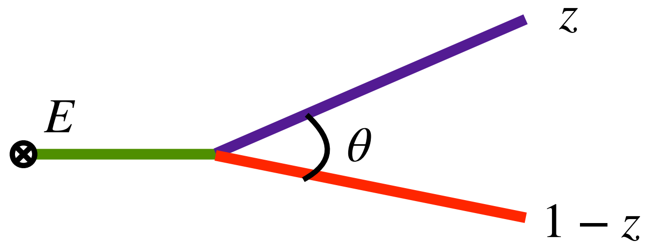

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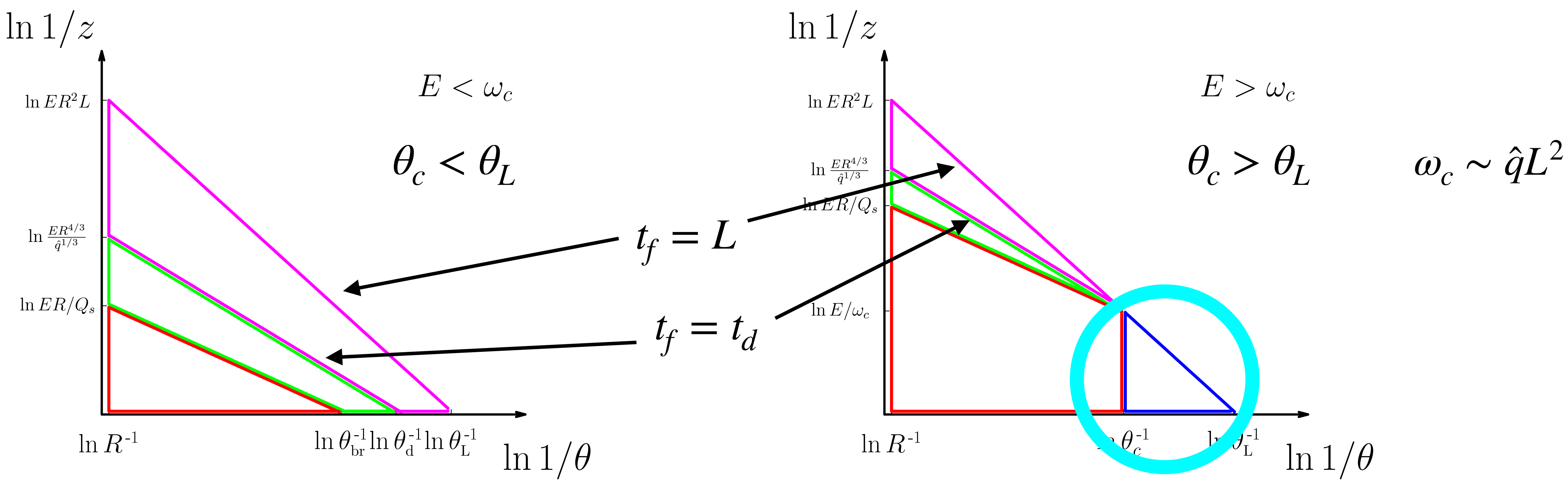

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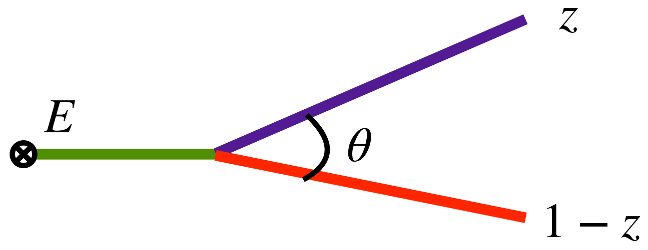
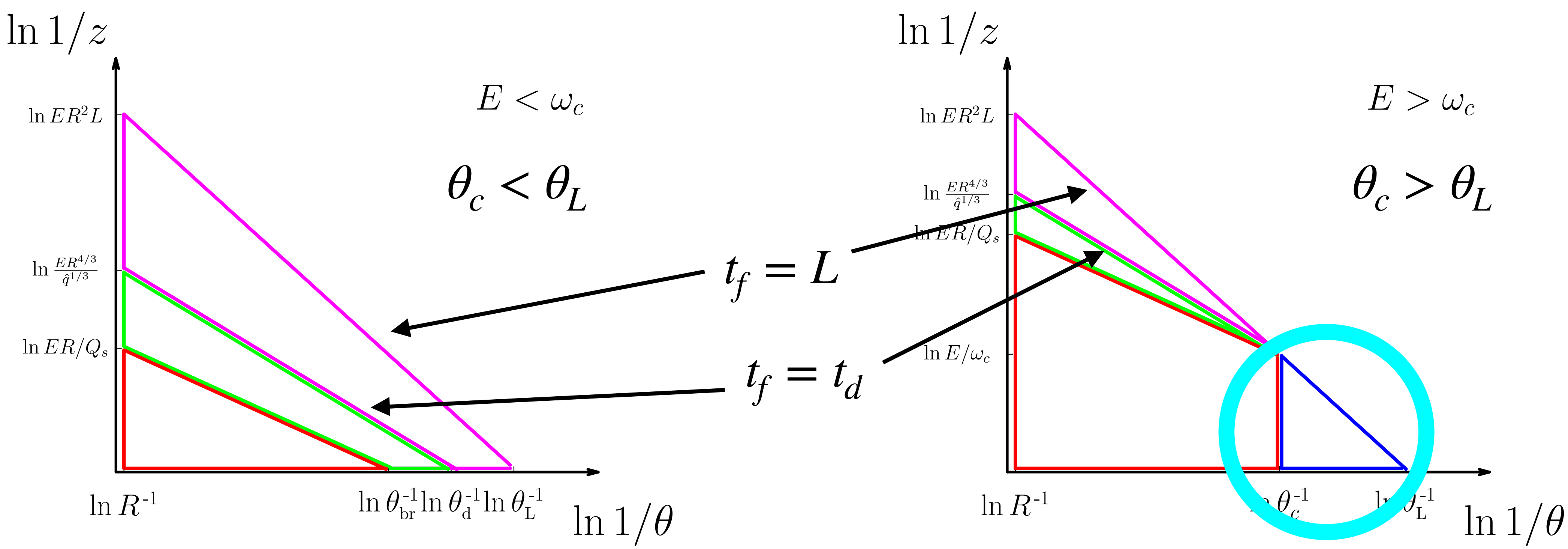
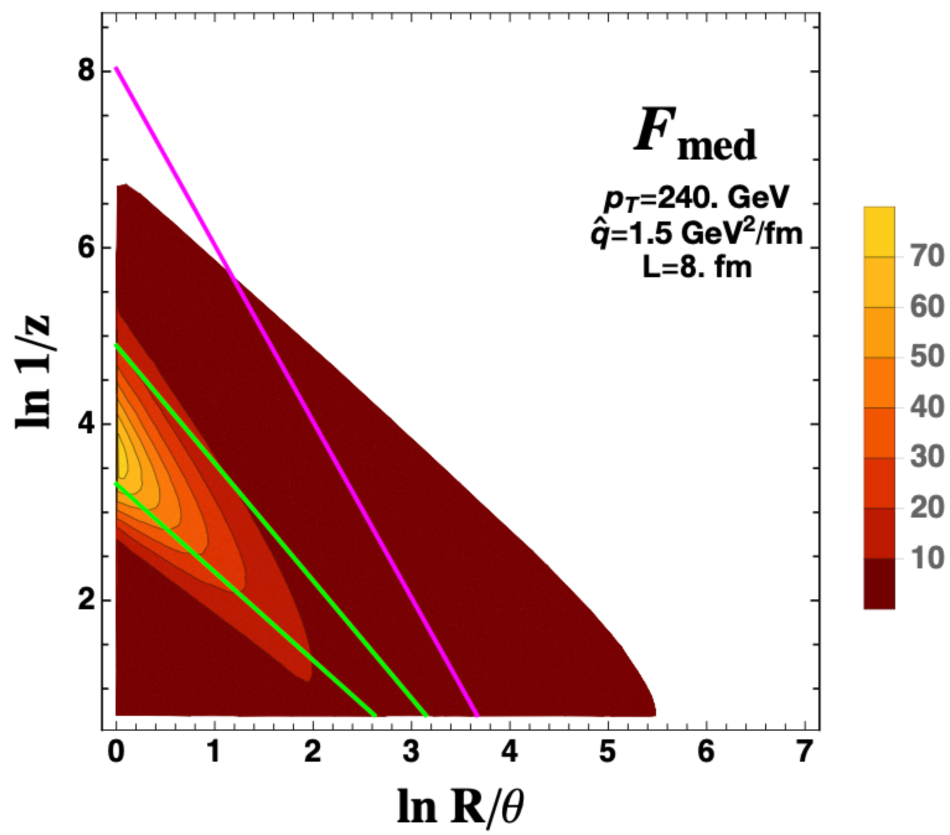
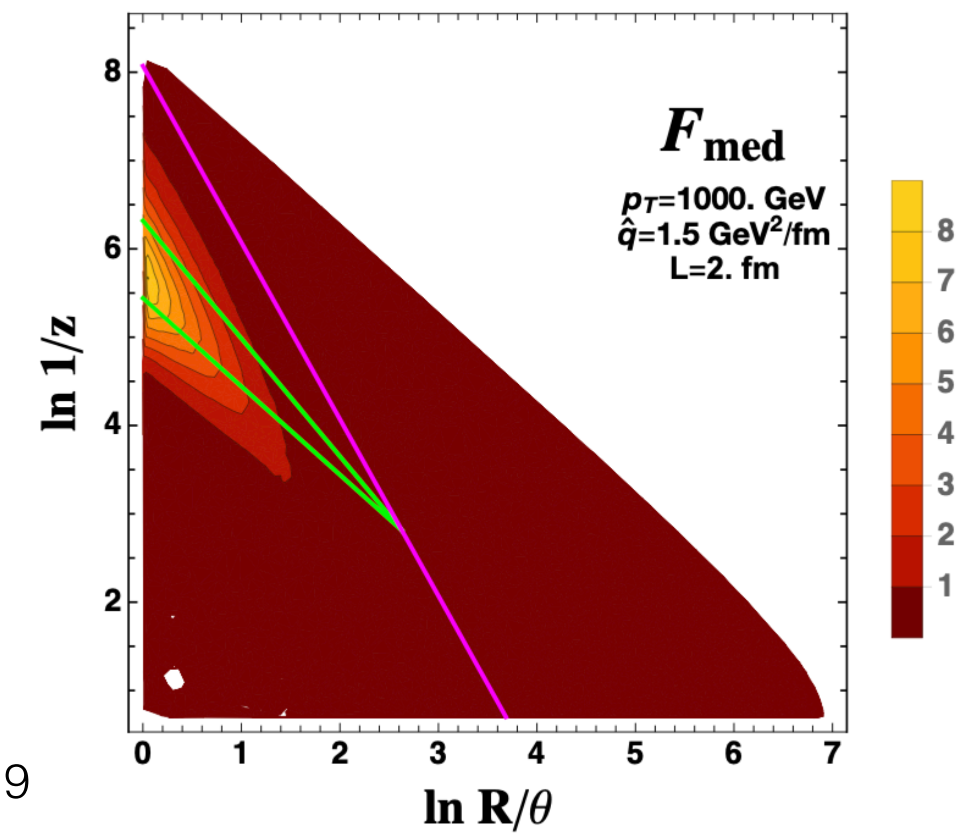




$$\frac{d\sigma_{qg}}{d\theta dz} = (1 + F_{\text{med}}(z,\theta))\,\frac{d\sigma_{qg}^{\text{vac}}}{d\theta dz}$$



$\gamma \to q\bar{q}$



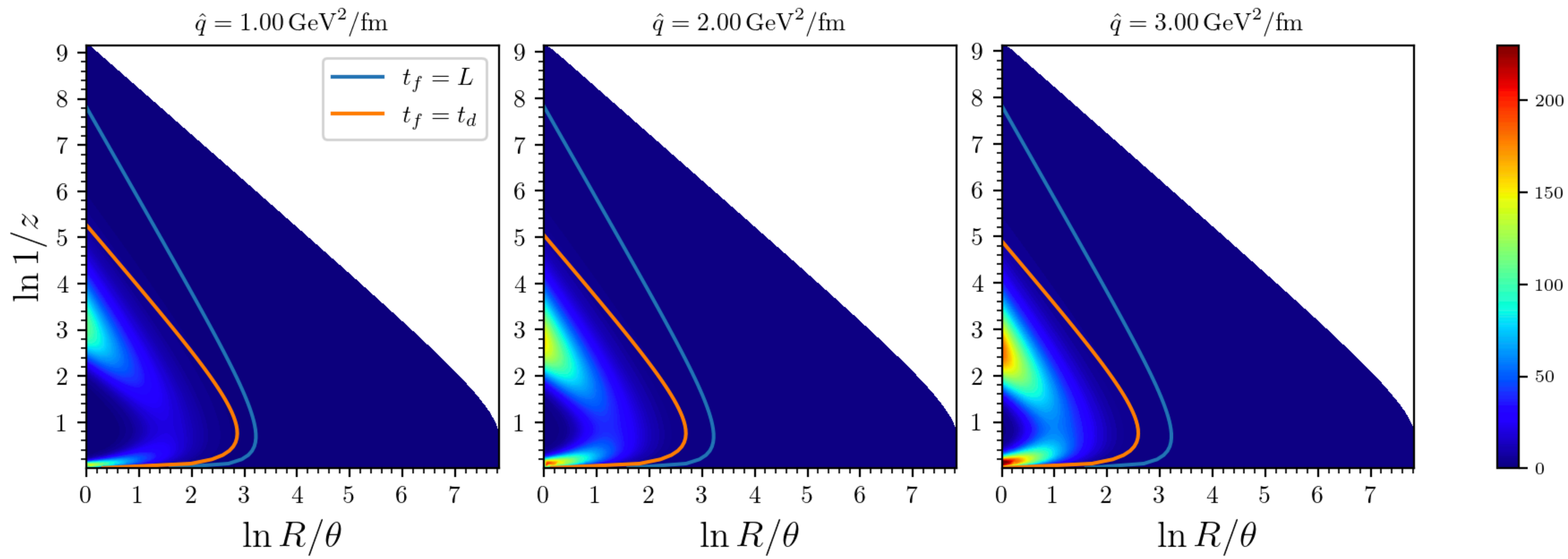
Lund planes $q \to qg$

$$\frac{d\sigma_{qg}}{d\theta dz} = (1 + F_{\rm med}(z,\theta))\ \frac{d\sigma^{\rm vac}_{qg}}{d\theta dz}$$

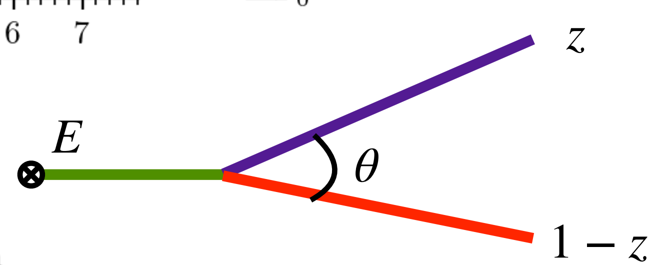
Isaksen, Tywoniuk 2107.02542

$E = 100.0\,\mathrm{GeV}\ \ L = 10.0\,\mathrm{fm}$

$\theta_c < \theta_L$



$E = 100.0\,\mathrm{GeV}\ \ L = 2.0\,\mathrm{fm}$



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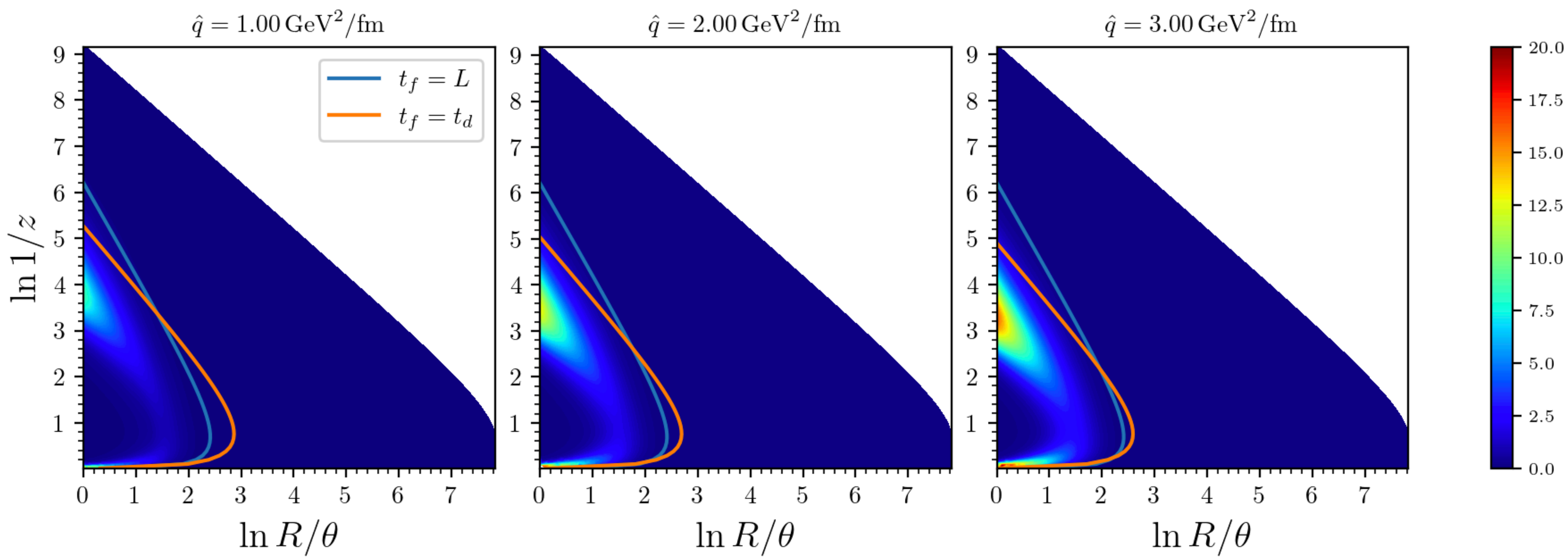

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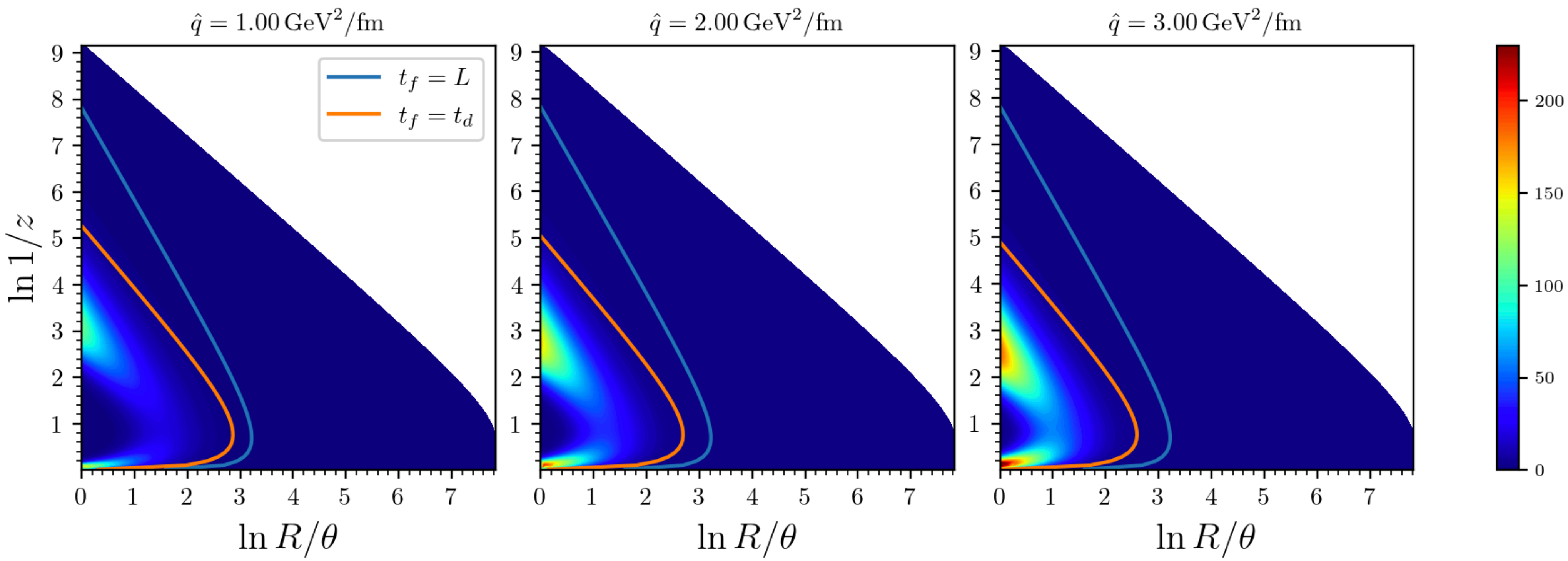

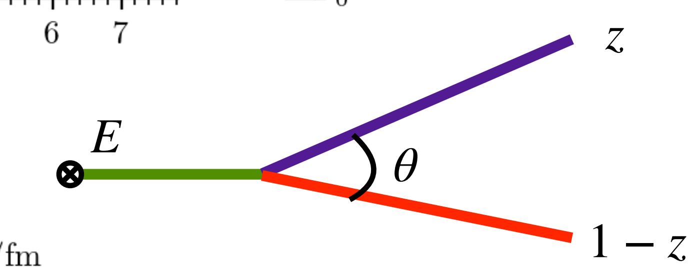

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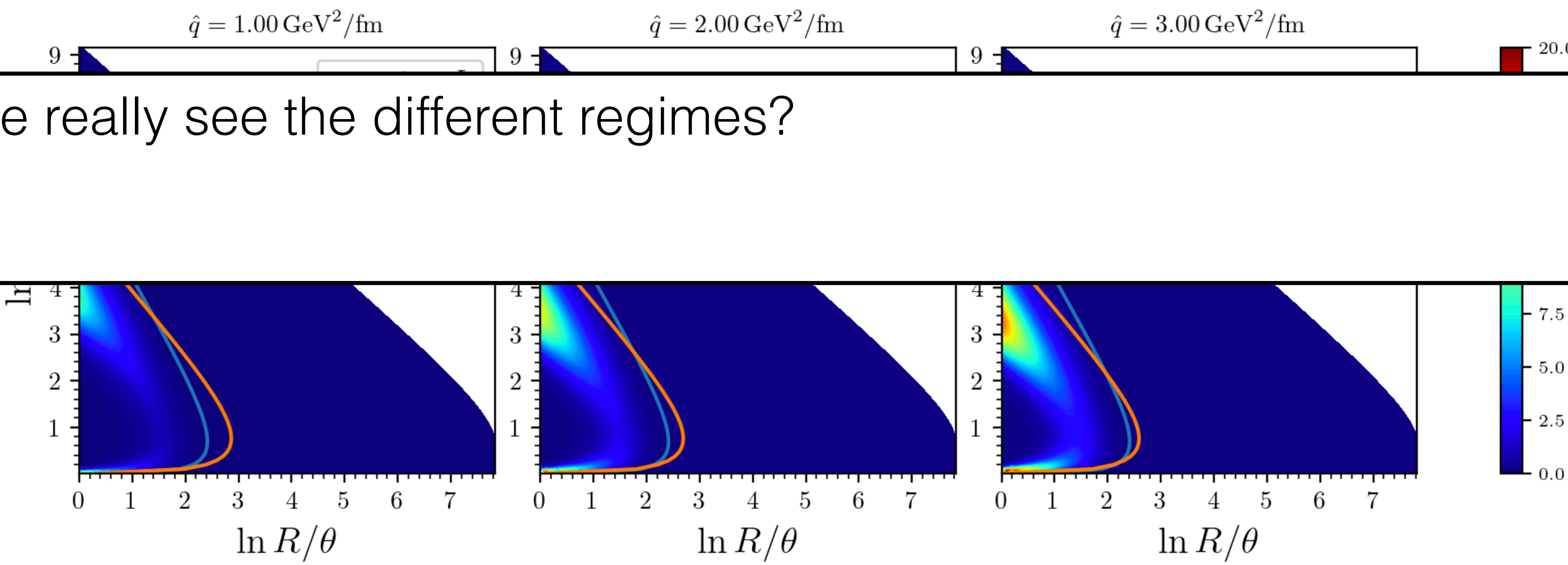

- Can we really see the different regimes?

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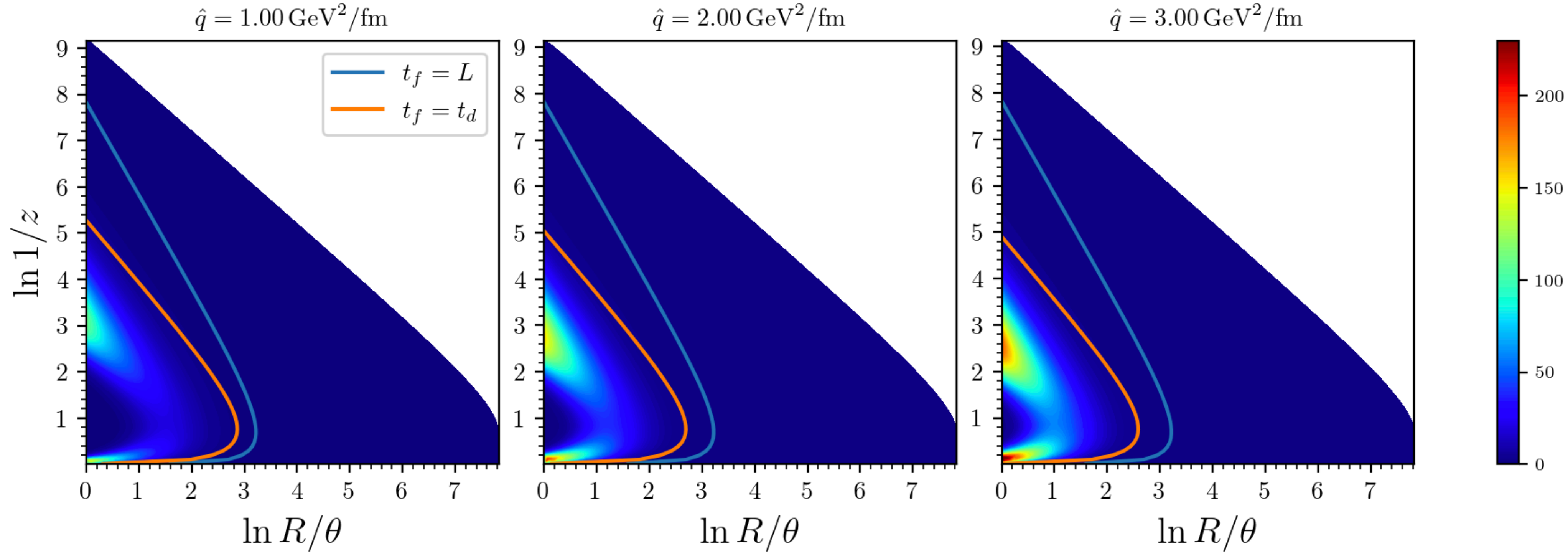
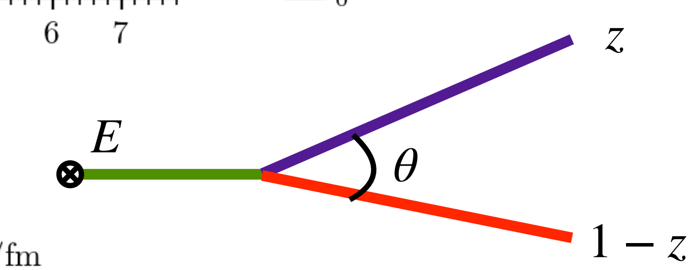


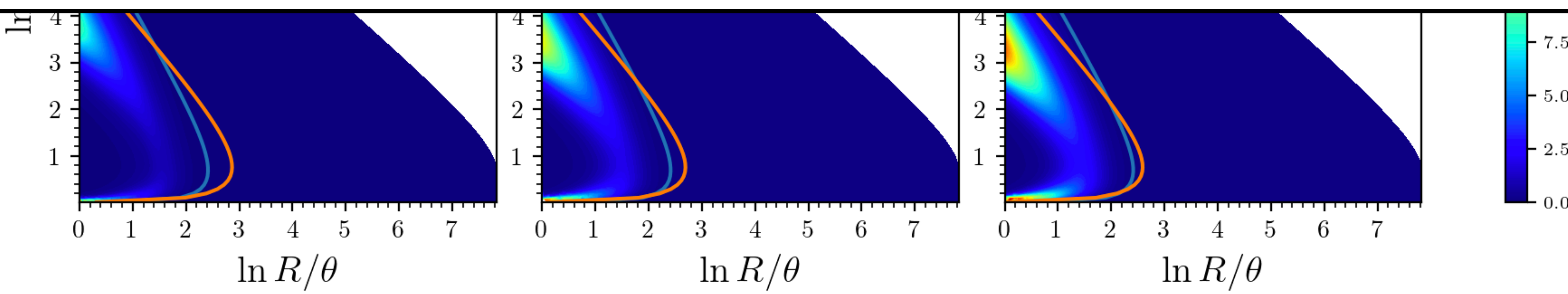


$E = 100.0\,\text{GeV}\ \ L = 2.0\,\text{fm}$

$\hat{q} = 1.00\,\text{GeV}^2/\text{fm}$ $\hat{q} = 2.00\,\text{GeV}^2/\text{fm}$ $\hat{q} = 3.00\,\text{GeV}^2/\text{fm}$

- Can we really see the different regimes?
- If this is the case for a simple model, what will happen for more realistic setups?

$\theta_c > \theta_L$



EECs and color coherence