# Medium modification of jets: angular scales and EEC

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based on:

C. Andres, F. Dominguez, R.K. Elayavalli, J. Holguin, C. Marquet, I. Moult, **PRL 130 (2023) 26, 262301**

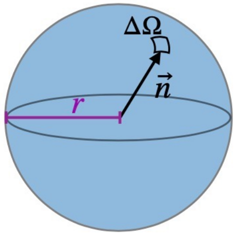
C. Andres, F. Dominguez, J. Holguin, C. Marquet, I. Moult, **JHEP 09 (2023) 088**

C. Andres, F. Dominguez, J. Holguin, C. Marquet, I. Moult, **2307.15110** + paper in preparation

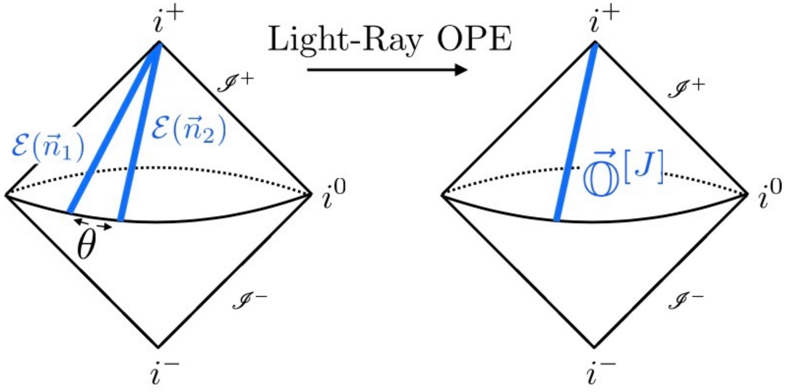
# Small-angle limit of EEC

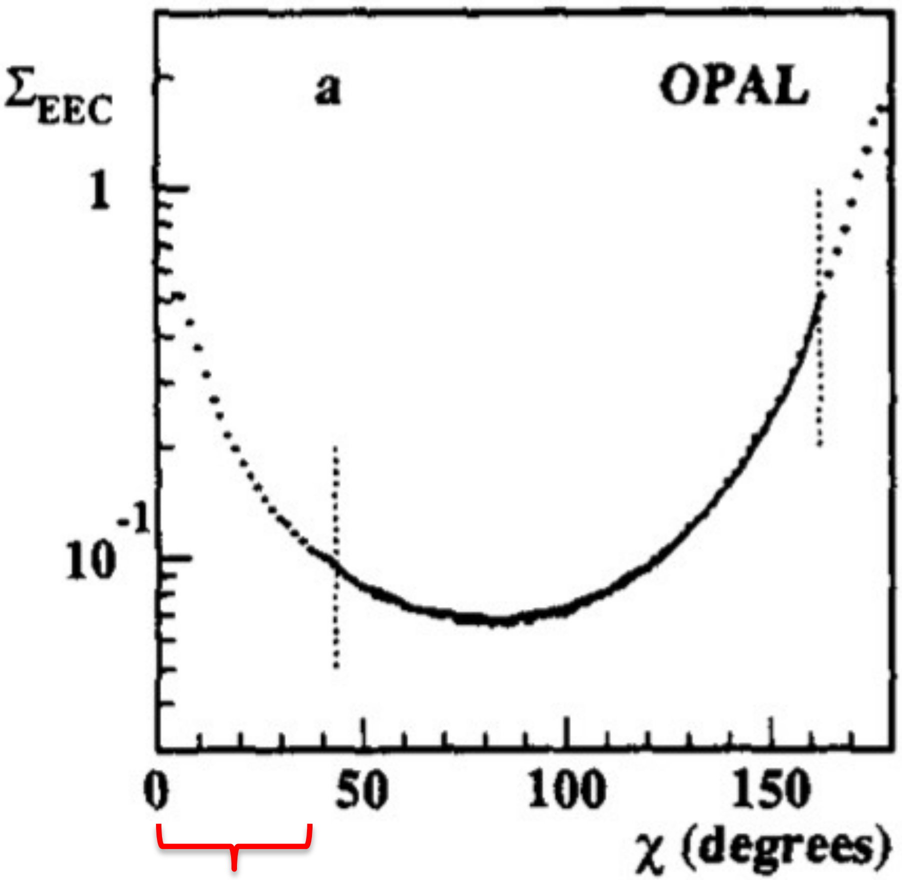
light-ray OPE in the collinear limit

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

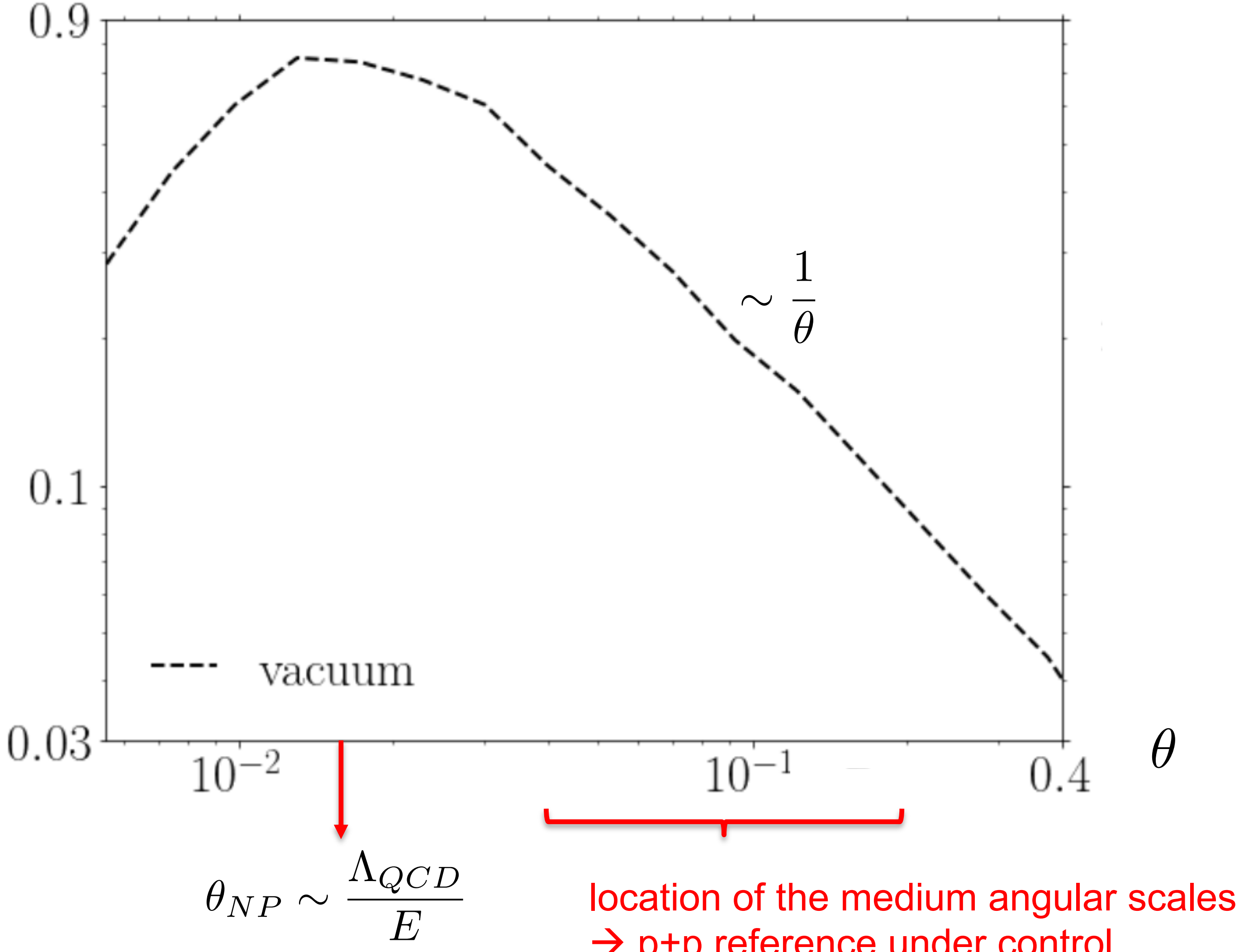



$$\mathcal{E}(\hat{n}_1)\mathcal{E}(\hat{n}_2) = \sum c_i \theta^{\tau_i - 4} \mathbb{O}_i(\hat{n}_1)$$



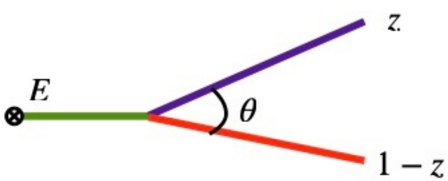
# EEC in p+p



0.9
0.1
0.03
vacuum
$\sim \frac{1}{\theta}$
$10^{-2}$
$10^{-1}$
0.4
$\theta$
$\theta_{NP} \sim \frac{\Lambda_{QCD}}{E}$
location of the medium angular scales
→ p+p reference under control

# EEC from inclusive cross-section

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



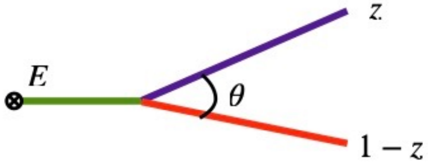

For a quark jet at leading order in the splittings, $Q = E$ the energy of the jet

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

$\mu_s$ a softer scale over which the cross section is inclusive

# EEC in p+p collisions

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




- At leading order

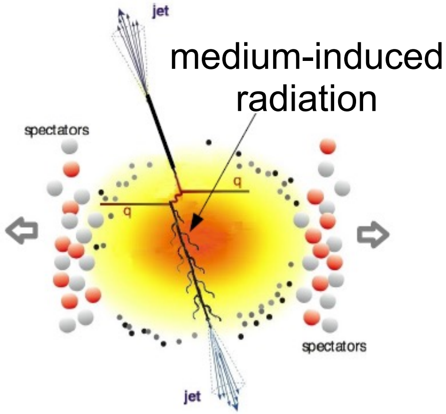
$$\frac{d\sigma_{qg}^{\rm vac}}{d\theta dz} = \frac{\alpha_s C_{\rm F}\sigma}{\pi}\frac{1+(1-z)^2}{z\;\theta} \quad \Rightarrow \quad \frac{d\Sigma^{(1)}}{d\theta} \sim \frac{1}{\theta}$$

- 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

# EEC in heavy-ion collisions




- We factor out the vacuum cross section and define the modification factor $\boldsymbol{F}_{\text{med}}$

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

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

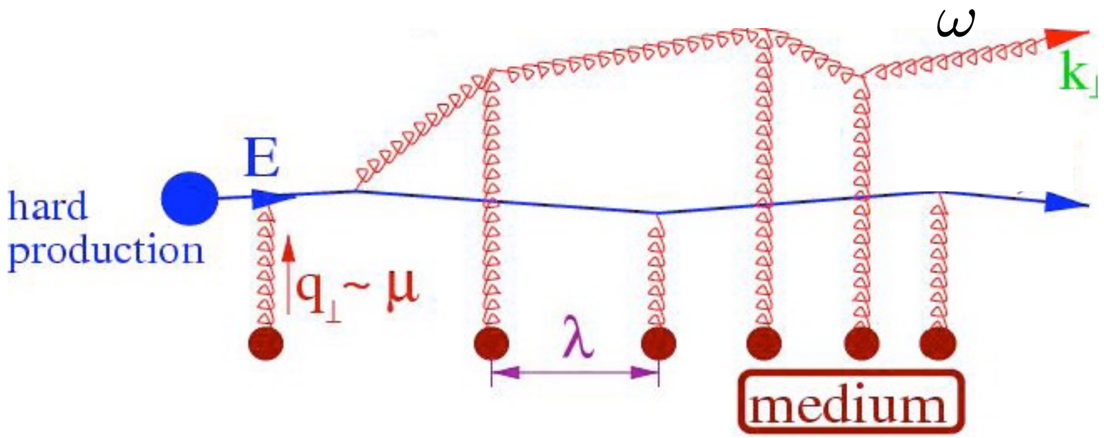
$$\frac{d\Sigma^{(n)}}{d\theta} = \frac{1}{\sigma_{qg}} \int dz \left( g^{(n)}(\theta, \alpha_s) + F_{\text{med}}(z,\theta) \right) \frac{d\sigma_{qg}^{\text{vac}}}{d\theta dz} z^n (1-z)^n \left( 1 + \mathcal{O}\left(\frac{\mu_s}{E}\right) + \mathcal{O}\left(\frac{\Lambda_{\text{QCD}}}{\theta Q}\right)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

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

# Medium-induced radiation

Baier, Dokshitzer, Mueller, Peigne and Schiff (1997)
Zakharov (1997)

computed in the context of parton energy loss




the accumulated transverse momentum picked up by a gluon of formation time *t*

$$p_T^2 = \mu^2 \frac{t}{\lambda} = \hat{q}\ t$$

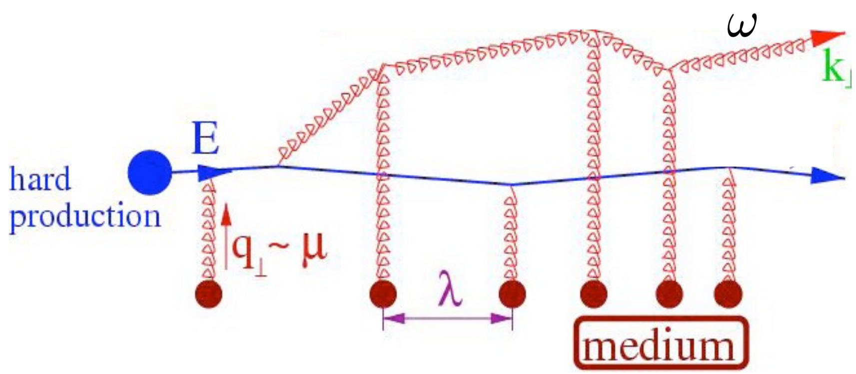
average $p_T^2$ picked up in each scattering

mean free path

$$\hat{q} \equiv \mu^2/\lambda \sim T^3$$

the relevant medium parameter needed along with the length L

# Radiative energy loss in pQCD




- emission of the radiated gluon

its formation time $\omega/k_\perp^2$ must be smaller than the medium length *L* : $\omega < L\ k_\perp^2$

it must pick up enough transverse momentum: $k_\perp^2 < \hat{q}\ L \equiv Q_s^2$

maximum radiated gluon energy $\omega_c = \hat{q}L^2$

total energy lost by the quark $\Delta E \propto \alpha_s \omega_c$

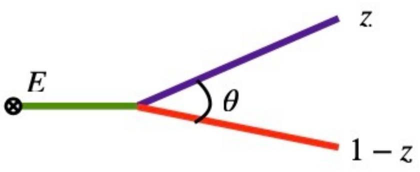
- how does medium-induced radiation affect jet substructure ?

let's look at the Lund plane, then compute the EEC

# Time and angular scales

Dominguez, 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




  - (Vacuum) formation time:

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

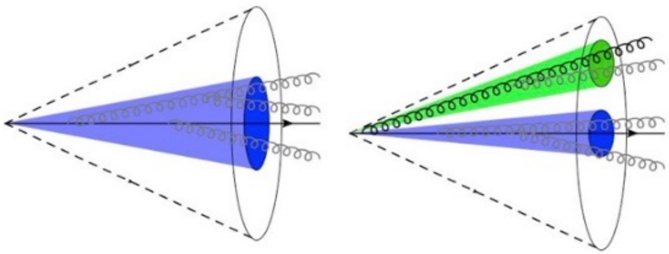
$$\theta_L \sim (EL)^{-1/2}$$

Below $\theta_L$ all emissions have a formation time larger than $L$

  - Decoherence time:

$$t_d \sim (\hat{q}\theta^2)^{-1/3}$$

$$\theta_c \sim (\hat{q}L^3)^{-1/2}$$

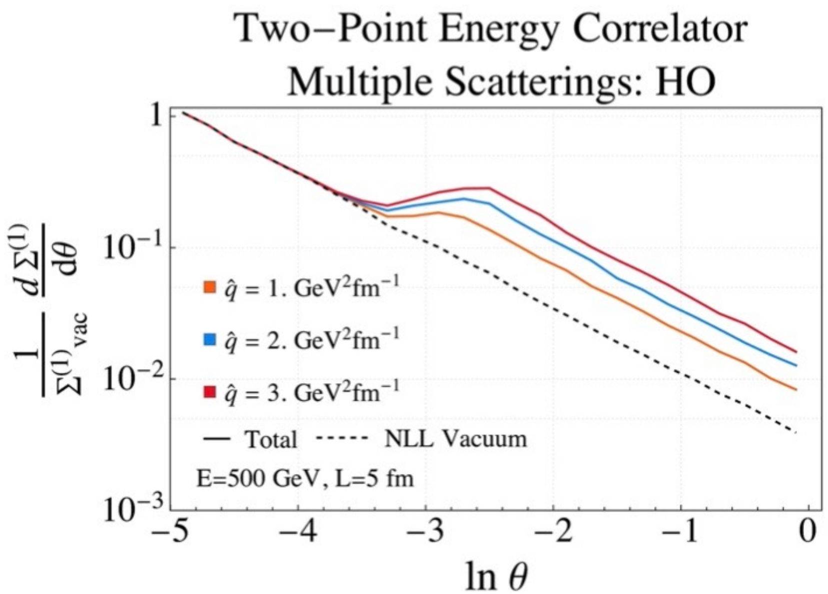


Below $\theta_c$ splittings do not lose color coherence and the medium does not resolve them

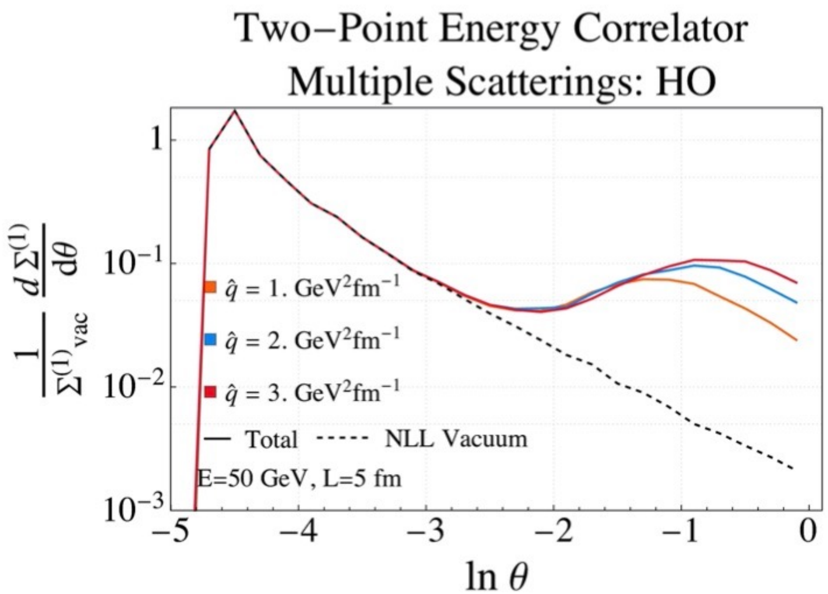
If $\theta_L > \theta_c$ then $\theta_c$ becomes irrelevant

# Brick-QGP hemisphere-jet EEC

$\theta_c > \theta_L$



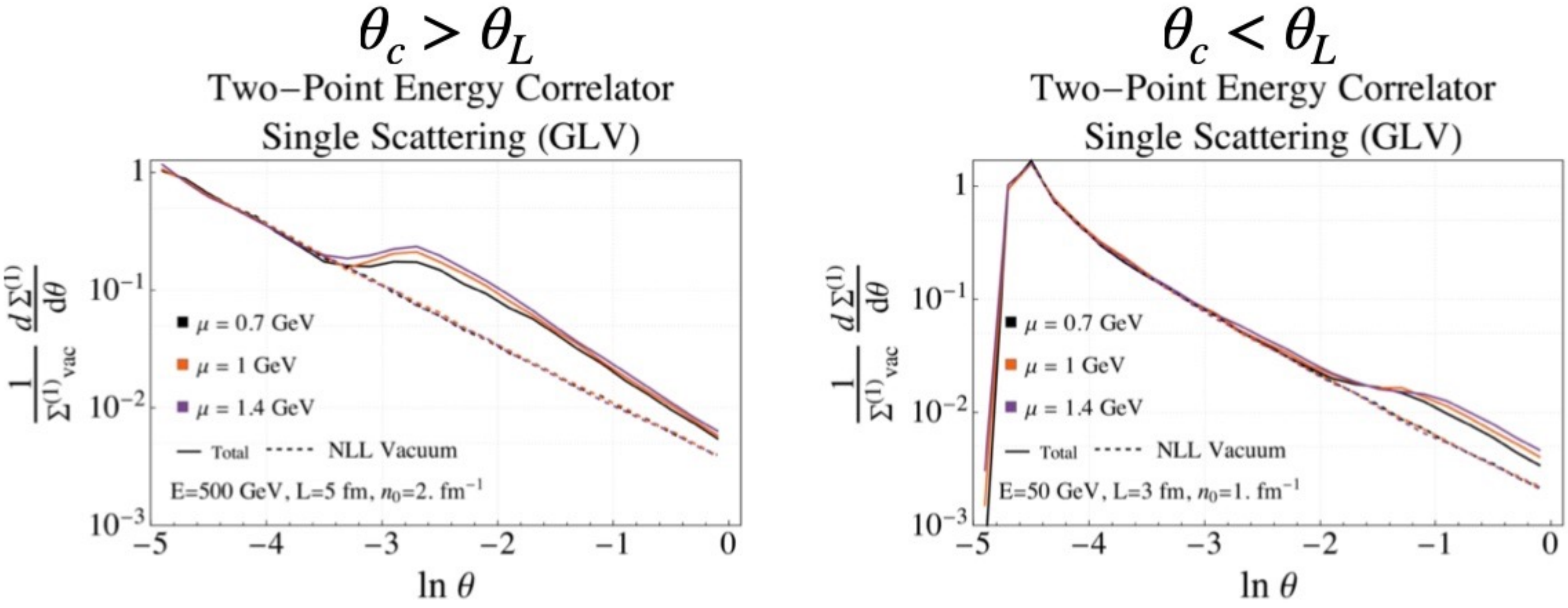

$\theta_c < \theta_L$




- No enhancement at small angles. Onset angle seems independent of $\hat{q}$ as expected
- Varying $\hat{q}$ has different effects in the two regions

# Single hard scattering (GLV)

Gyulassy, Levai and Vitev (2000-2001)




- onset of medium effects is not as sharp in the GLV case
- the coherence transition is very smooth: mild difference in behavior when varying the medium parameters in the two regions

# Conclusions

- Energy-Energy correlators (EECs) for jet substructure in p+p collisions

  - correlations functions of the energy flow operator formulated in QFTs
  - obey factorization theorems and computed to high accuracy in QCD
  - now being measured at RHIC and the LHC

- EECs for jet substructure in heavy-ion collisions

  - complementary approach to traditional observables
  - novel attempt to try and identify the scales of jet evolution inside the QGP, in particular those related to color coherence

- Work in progress

  more realistic calculations (dynamic QGP, experimental constrains, …)