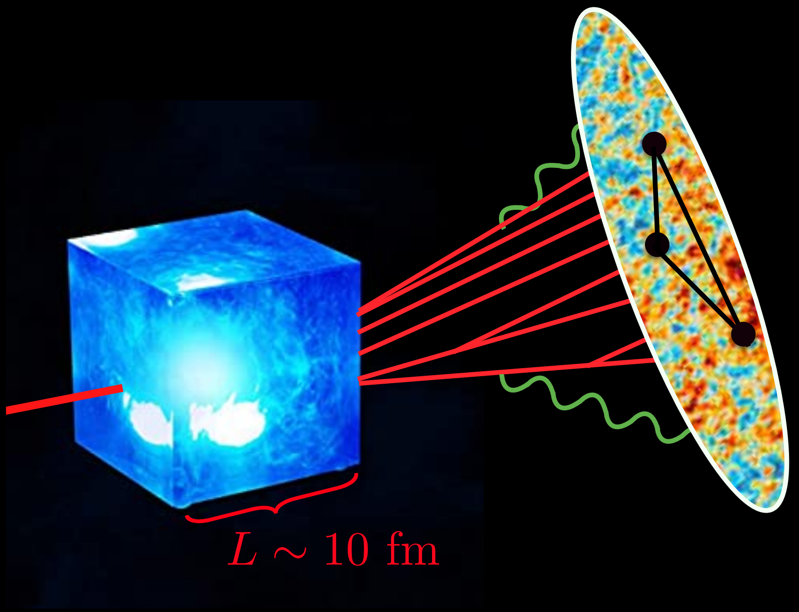
# Studying jet quenching with energy correlators




Carlota Andrés
CPhT, École polytechnique

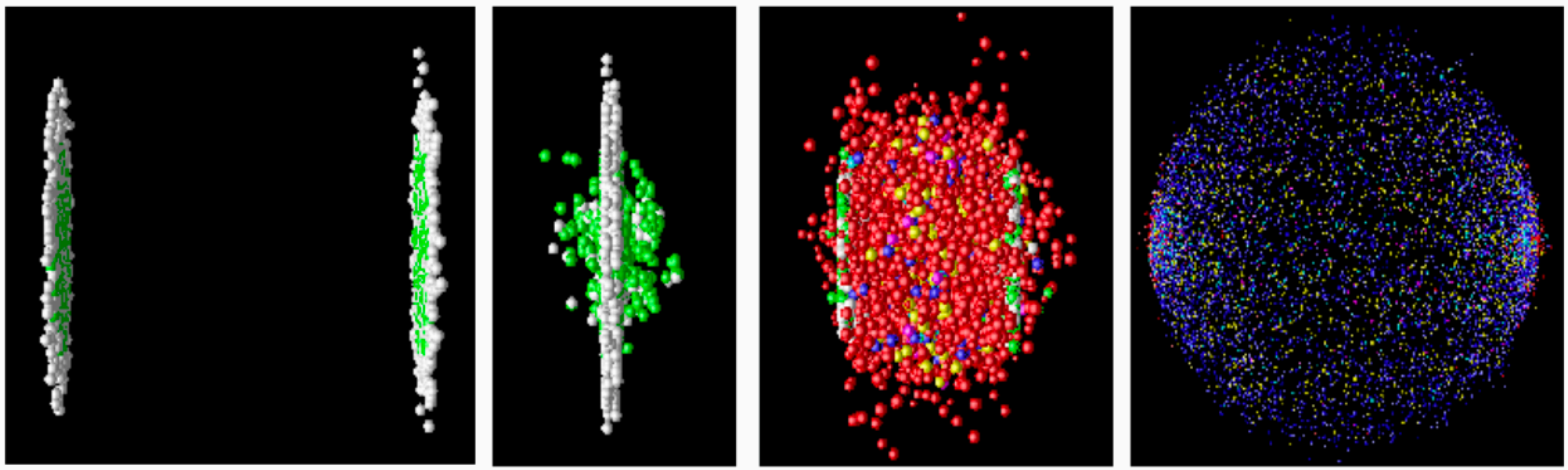
QCD@LHC2022, Orsay, Nov 28 - Dec 2 2022

Based on:
CA, Fabio Dominguez, Raghav Kunnawalkam Elayavalli, Jack Holguin, Cyrille Marquet, and Ian Moult
arXiv:2209.11236

CPHT Centre de Physique Théorique — MARIE CURIE ACTIONS — l'X ÉCOLE POLYTECHNIQUE

# Heavy-ion collisions

- 20 years of HICs at RHIC and 10 years of HICs at the LHC



- Why? To study the QGP!

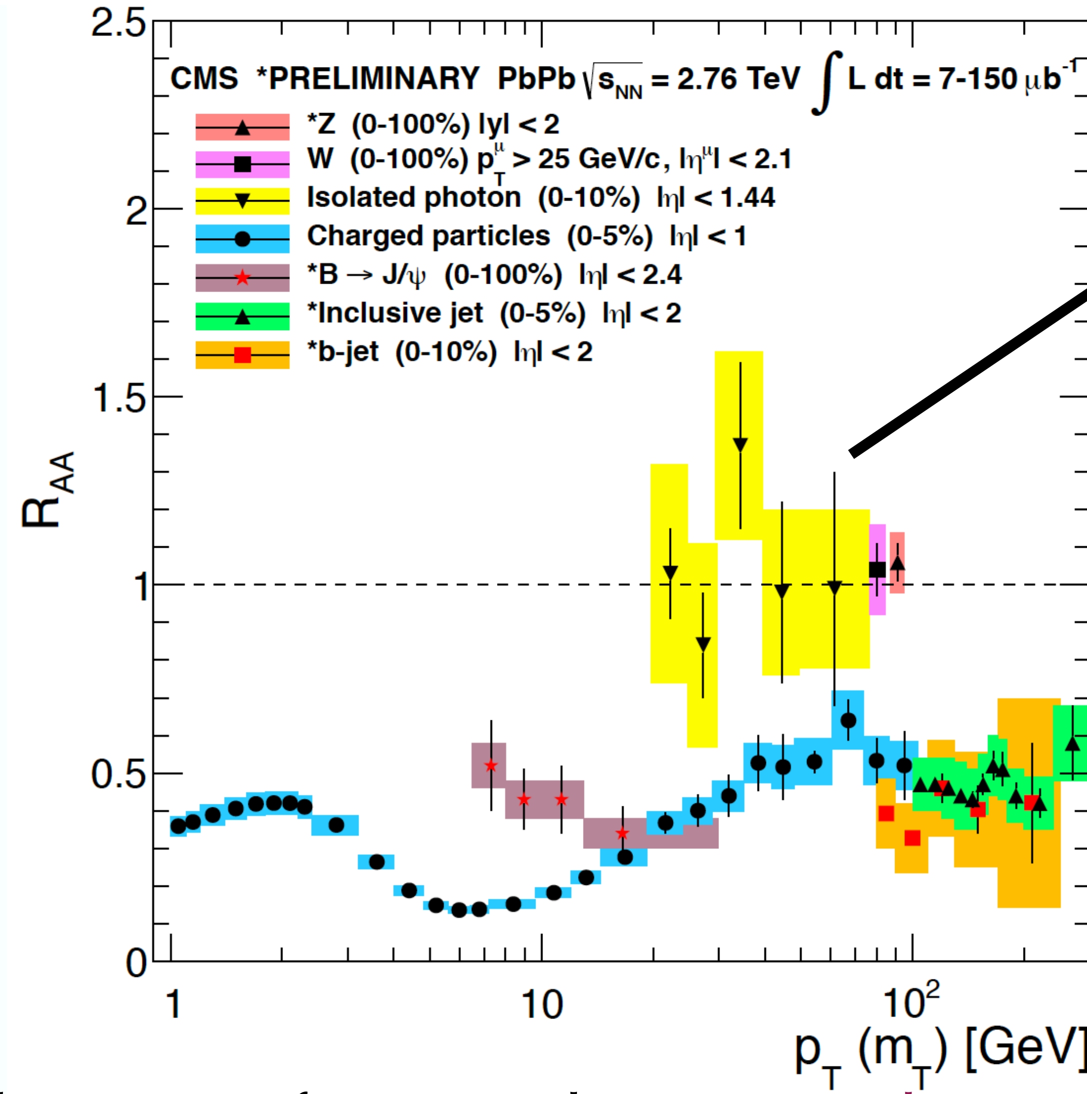
- How? Using probes **and observables** sensitive to the QCD matter
- Under experimental control
- Theoretically modeled
- Connect theory and experiments

Such as jets/high-$p_T$ particles. Which observables?

# Jet quenching

- Jet quenching: high-energy partons interact with the QGP losing energy

$$R_{AA} = \frac{dN_{AA}/d^2p_T\,dy}{\langle N_{coll}\rangle\, dN_{pp}/d^2p_T\,dy}$$



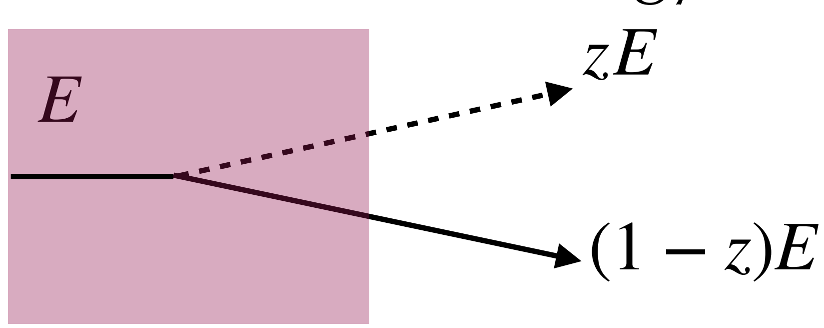

[A. Florent - Hard Probes 2013]

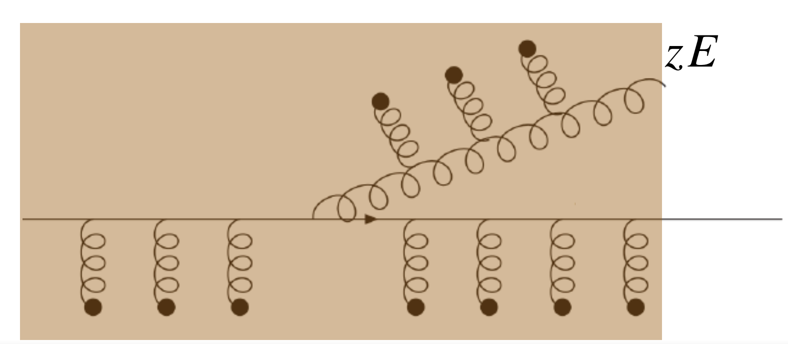
Colorless probes: no suppression

Jet quenching

- The principal mechanism of energy loss is medium-induced radiation

See Fabio Dominguez's talk Wed 15:00

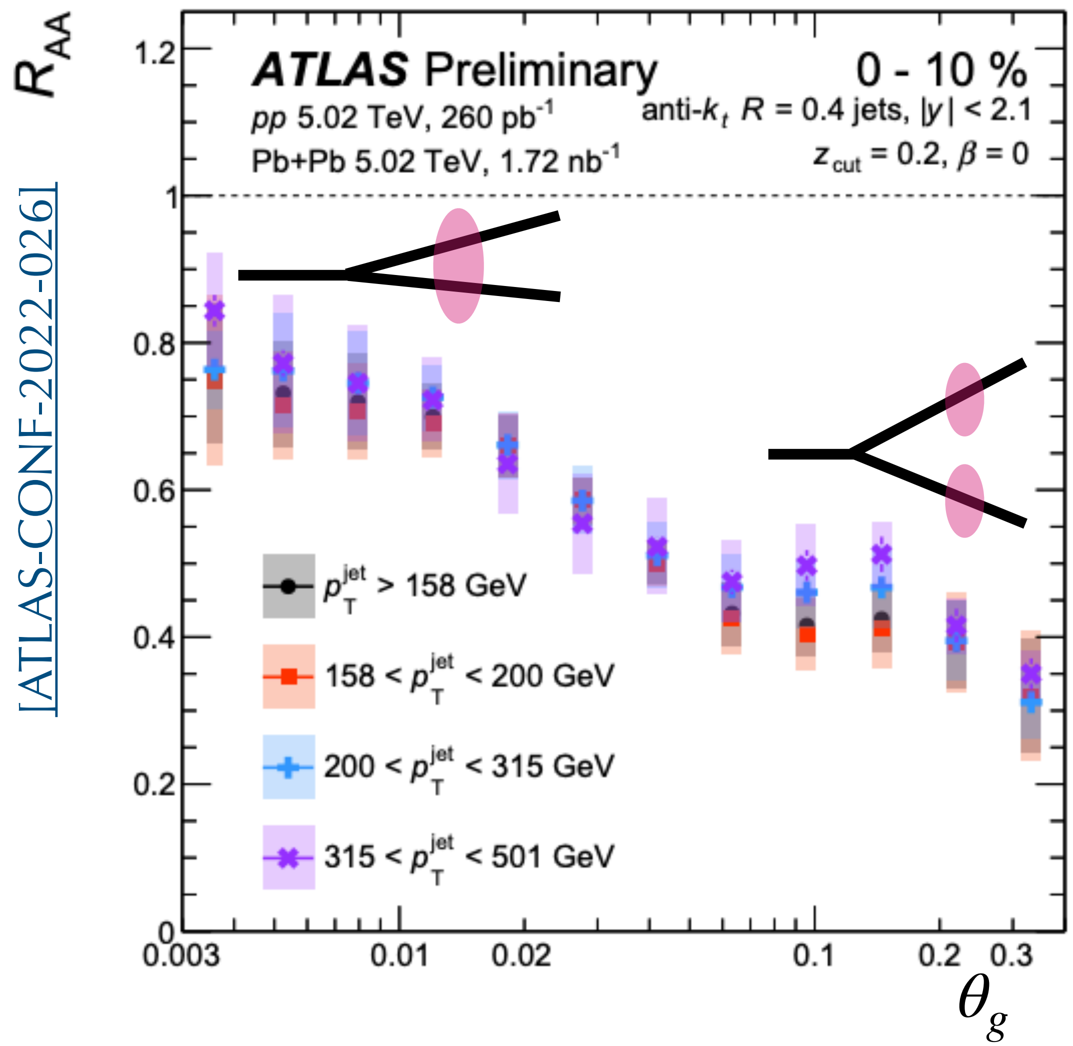


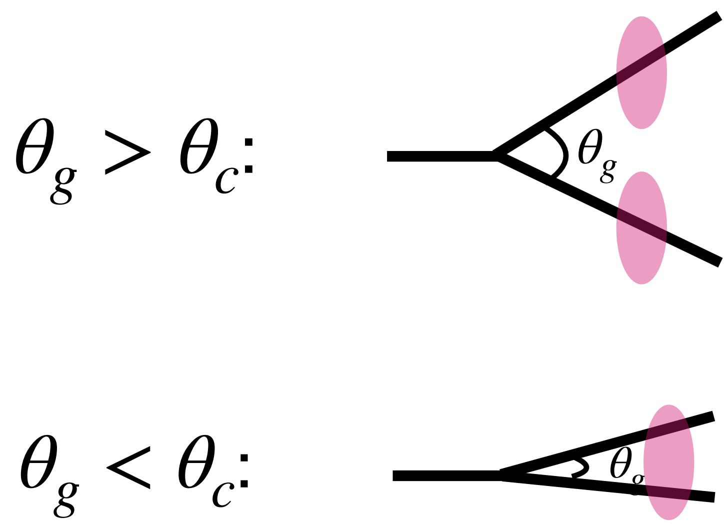
# Jet substructure

- Many works on introducing new observables

[ATLAS-CONF-2022-026]




- The medium introduces a new resolution scale: $\theta_c$




See Adam Takacs' talk Wed 14:00

- Grooming techniques inherited from *pp*. Significant missidentification due to the large background in HI found   Mulligan, Ploskon, 2006.01812

- We propose a new approach to jet substructure in heavy-ions

# Correlation functions

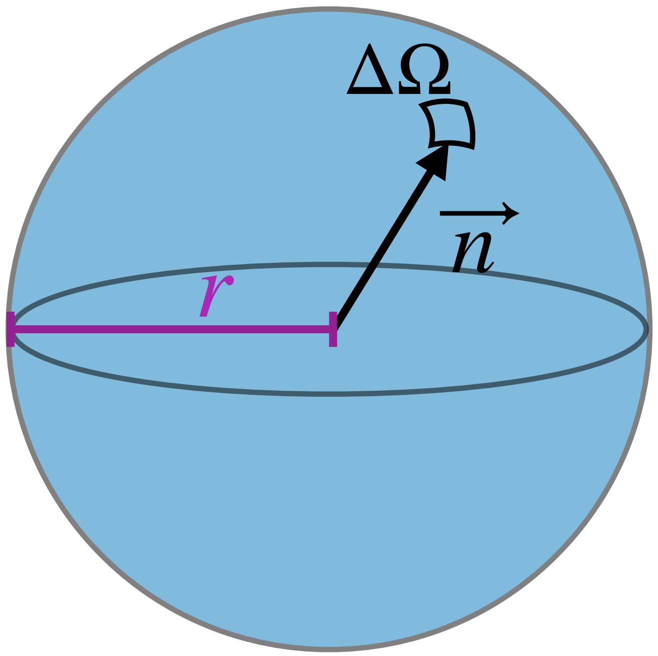
- What are they?

$$\text{Corr}_2(X,Y) = \langle XY \rangle - \langle X \rangle \langle Y \rangle$$

$$\text{Corr}_3(X,Y,Z) = \langle XYZ \rangle - \langle X \rangle \langle YZ \rangle - \langle Y \rangle \langle XZ \rangle - \langle Z \rangle \langle XY \rangle + 2 \langle X \rangle \langle Y \rangle \langle Z \rangle$$

- In physics: usually $\langle X_i \rangle = 0 \Rightarrow \langle X_1, X_2, \ldots X_n \rangle$ is the *n*-point correlator

- For QCD: Correlators of the energy flux

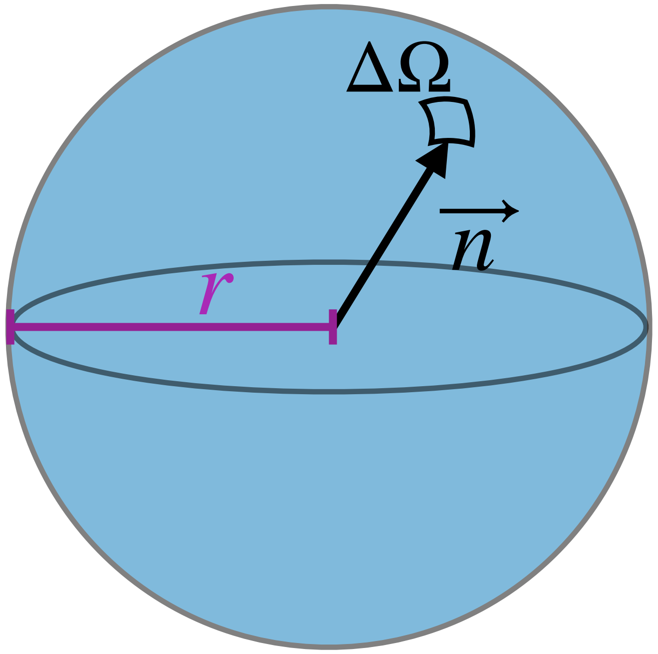



$$\varepsilon(\vec{n}) = \lim_{r\to\infty} \int \mathrm{d}t \, r^2 n^i \, T_{0i}(t, r\vec{n})$$

Hoffman, Maldacena, 0803.1467

They naturally remove the soft physics with NO grooming!

# Energy correlators




- 1-point correlator

$$\langle \varepsilon(\vec{n}) \rangle = \lim_{r\to\infty} \int \mathrm{d}t\, r^2 n^i \langle T_{0i}(t, r\vec{n}) \rangle$$

$\langle \varepsilon(\vec{n}) \rangle \propto \sum_i E_i$ where $E_i$ is the energy of the particle $i$ which passes through $\Delta\Omega$ (perpendicular to $\vec{n}$) at time $t$

- 2-point correlator:

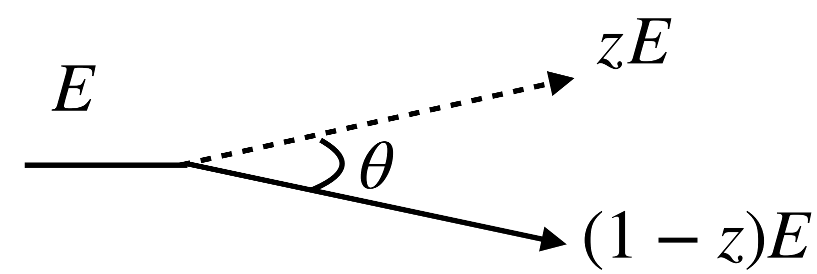
Inclusive cross section to produce two particles $i$ and $j$

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

Hard scale of the process

# 2-point correlator

- As function of the relative angle only:




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

- 2-point correlator for a quark jet: $Q = E$

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

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

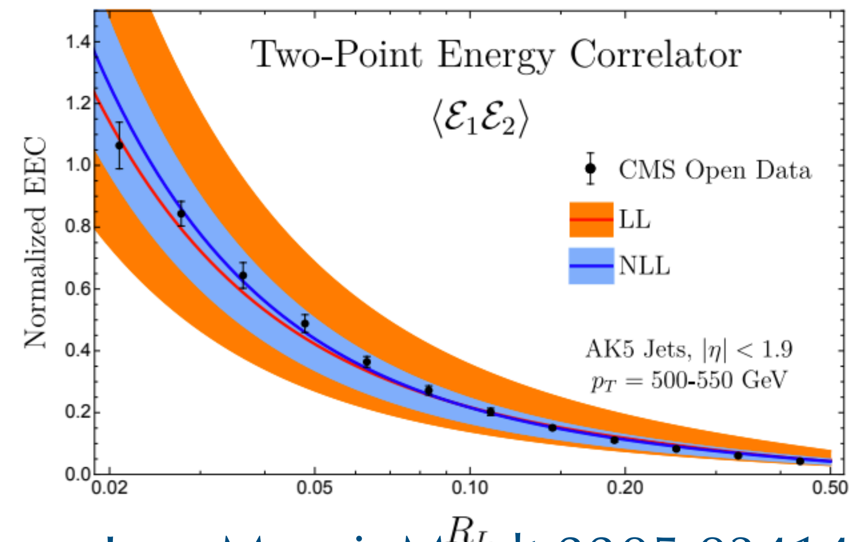
- In vacuum at LO:

$$\frac{\mathrm{d}\sigma^{\mathrm{vac}}_{qg}}{\mathrm{d}z\mathrm{d}\theta} = \frac{\alpha_s C_F \sigma}{\pi} \frac{1+(1-z)^2}{z\theta} + \mathcal{O}(\alpha_s^2, \theta) \Rightarrow \frac{\mathrm{d}\Sigma^{(1)}}{\mathrm{d}\theta} \sim \frac{1}{\theta}$$

Hoffman, Maldacena, 0803.1467

Chen, Moult, Sandor, Zhu, 2202.04085

# Correlation of $\varepsilon(\vec{n})$




Lee, Meçaj, Moult 2205.03414

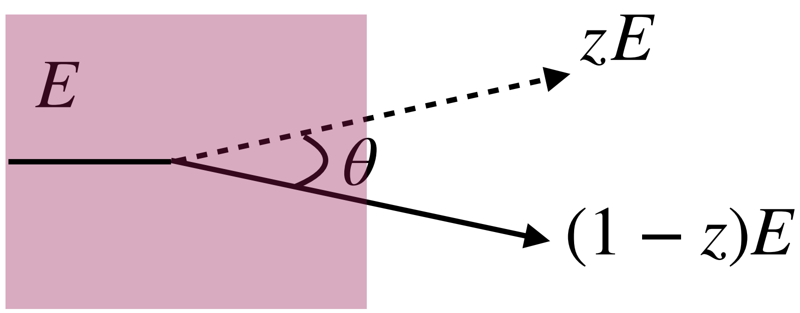
- Already starting to be used in pp
  - 2-point correlator found sensitive to hadronization

    Komiske, Moult, Thaler, Zhu, 2201.07800
  - 3-point correlator found sensitive to the top mass

    Holguin, Moult, Pathak, Procura, 2201.0839 See Jack Holguin's talk (Tuesday 16:40 CET)
  - Factorization theorem for energy correlator on heavy quark jets

    Craft, Lee, Meçaj, Moult 2210.09311
- What do we propose in HI?
  - The $R_{AA}$ can be viewed as a 1-point correlator
  - We propose to look at **in-medium emissions with the 2-point correlator**

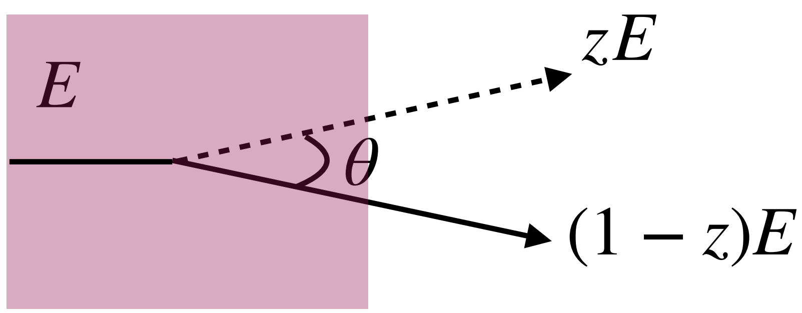
# Our observable




- The observable

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

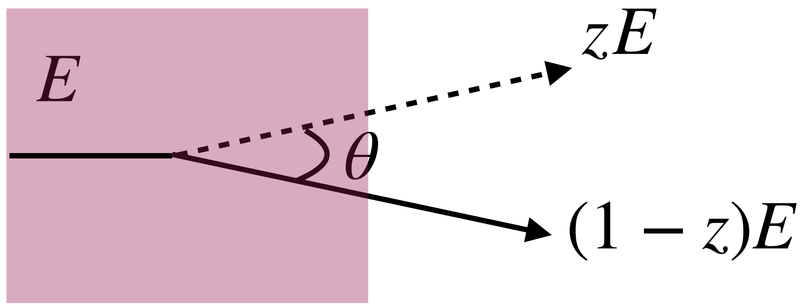
# Our observable




- The observable

$$\frac{\mathrm{d}\Sigma^{(n)}}{\mathrm{d}\theta} = \left( \frac{1}{\sigma_{qg}} \int \mathrm{d}z \left( \frac{\mathrm{d}\sigma_{qg}^{\mathrm{vac}}}{\mathrm{d}z\mathrm{d}\theta} + \frac{\mathrm{d}\sigma_{qg}^{\mathrm{med}}}{\mathrm{d}z\mathrm{d}\theta} \right) z^n (1-z)^n \right) \left( 1 + \mathcal{O}\left( \alpha_s \ln \theta_L^{-1}, \frac{\mu_s}{zE} \right) \right) + \mathcal{O}\left( \frac{\mu_s}{E} \right)$$

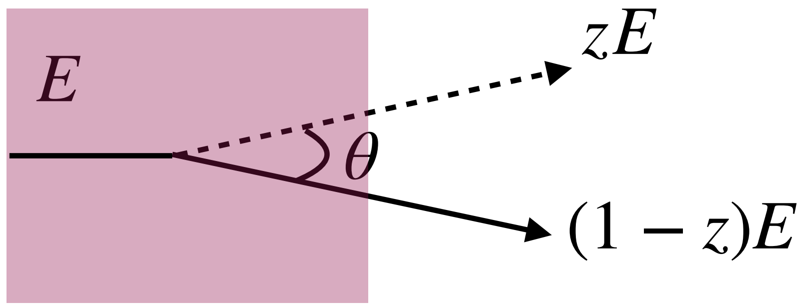
# Our observable




- The observable

$$\frac{\mathrm{d}\Sigma^{(n)}}{\mathrm{d}\theta} = \left( \frac{1}{\sigma_{qg}} \int \mathrm{d}z \left( \frac{\mathrm{d}\sigma_{qg}^{\text{vac}}}{\mathrm{d}z\mathrm{d}\theta} + \frac{\mathrm{d}\sigma_{qg}^{\text{med}}}{\mathrm{d}z\mathrm{d}\theta} \right) z^n (1-z)^n \right) \left( 1 + \mathcal{O}\left( \alpha_s \ln \theta_L^{-1}, \frac{\mu_s}{zE} \right) \right) + \mathcal{O}\left( \frac{\mu_s}{E} \right)$$

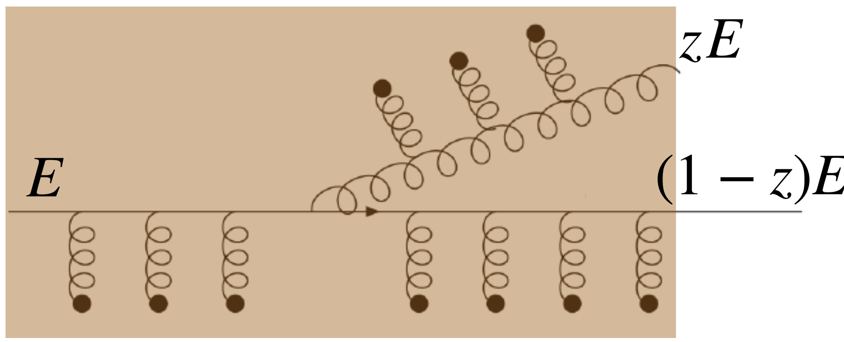
# Our observable




- The observable

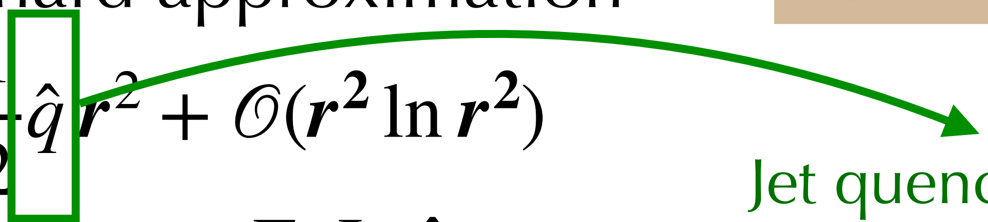
$$\frac{d\Sigma^{(n)}}{d\theta} = \left(\frac{1}{\sigma_{qg}}\int dz \left(\frac{d\sigma_{qg}^{\text{vac}}}{dz\,d\theta} + \frac{d\sigma_{qg}^{\text{med}}}{dz\,d\theta}\right) z^n(1-z)^n\right)\left(1 + \mathcal{O}\left(\alpha_s \ln\theta_L^{-1}, \frac{\mu_s}{zE}\right)\right) + \mathcal{O}\left(\frac{\mu_s}{E}\right)$$

- Medium-induced contribution: $\theta > \theta_L \equiv (EL)^{-1/2}$



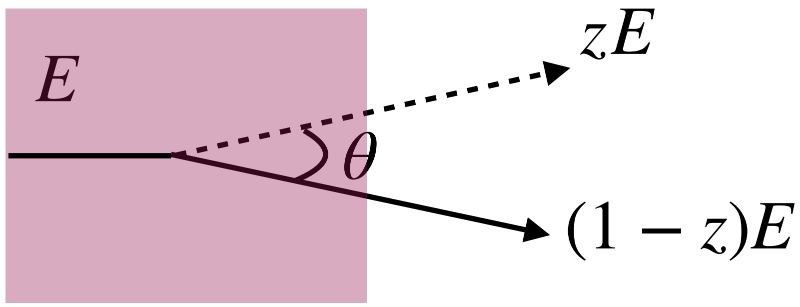

BDMPS-Z formalism in a semi-hard approximation

Harmonic Oscillator: $nv(\boldsymbol{r}) \approx \frac{1}{2}\hat{q}\,\boldsymbol{r}^2 + \mathcal{O}(\boldsymbol{r}^2 \ln \boldsymbol{r}^2)$




Numerics in a static brick. Parameters: $E, L, \hat{q}$

# Our observable




- The observable

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

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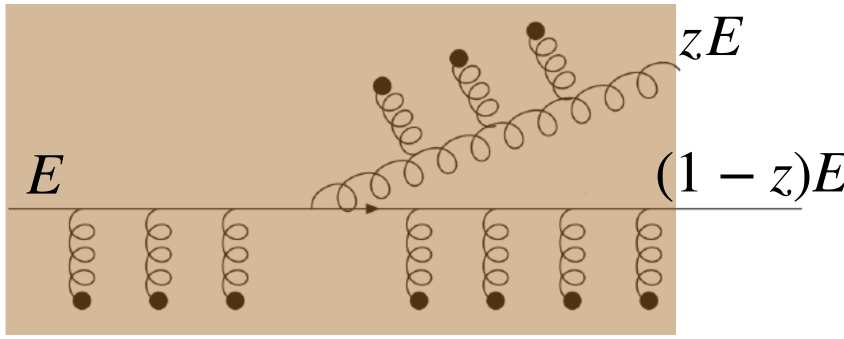


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Harmonic Oscillator: $nv(\boldsymbol{r}) \approx \frac{1}{2}\hat{q}\,\boldsymbol{r}^2 + \mathcal{O}(\boldsymbol{r}^2 \ln \boldsymbol{r}^2)$

Jet quenching parameter

Numerics in a static brick. Parameters: $E, L, \hat{q}$

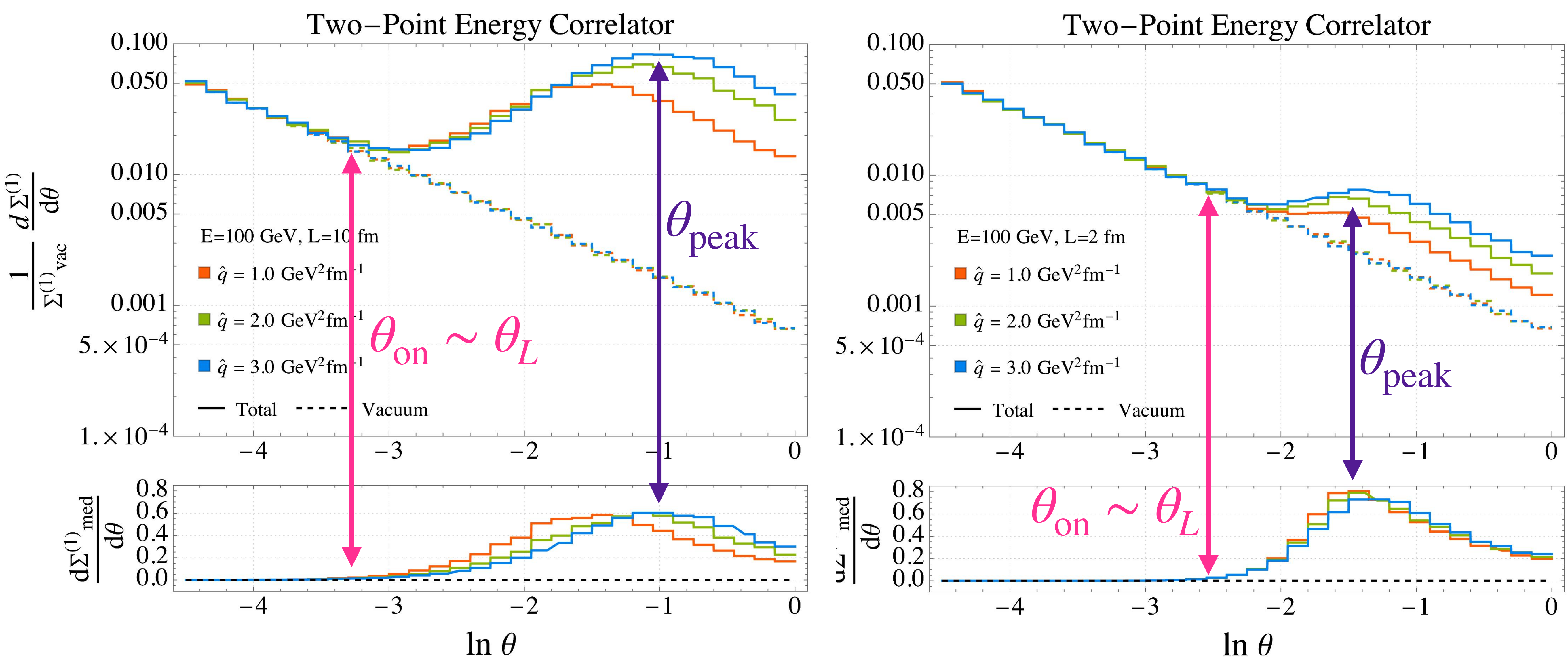
- For $\theta < \theta_L$: splitting occurs outside of the medium, no medium modification is expected

2 competing angular scales: $\theta_L, \theta_c$

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

# Results

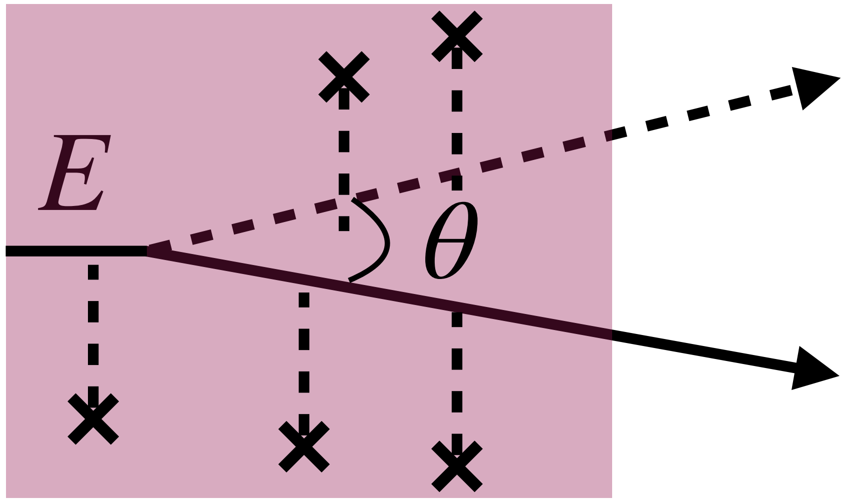
$\theta_L \gg \theta_c \quad (E \ll \hat{q}L^2)$ $\theta_L \ll \theta_c \quad (E \gg \hat{q}L^2)$




arXiv:2209.11236

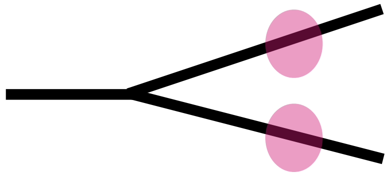
# Interpretation

$\theta_L \gg \theta_c \quad (E \ll \hat{q}L^2)$

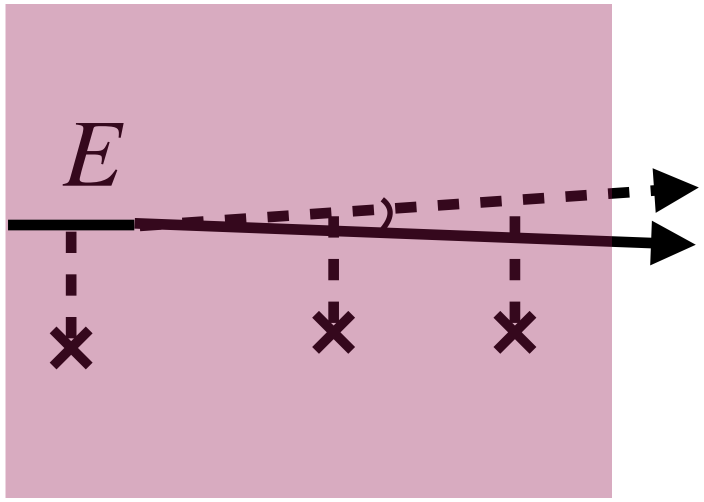



For $\theta \gg \theta_L \Rightarrow \theta \gg \theta_c$

The medium resolves the emission

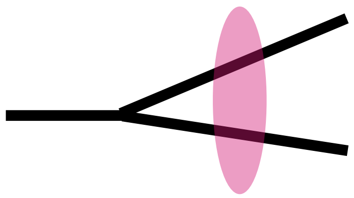


$\theta_L \ll \theta_c \quad (E \gg \hat{q}L^2)$



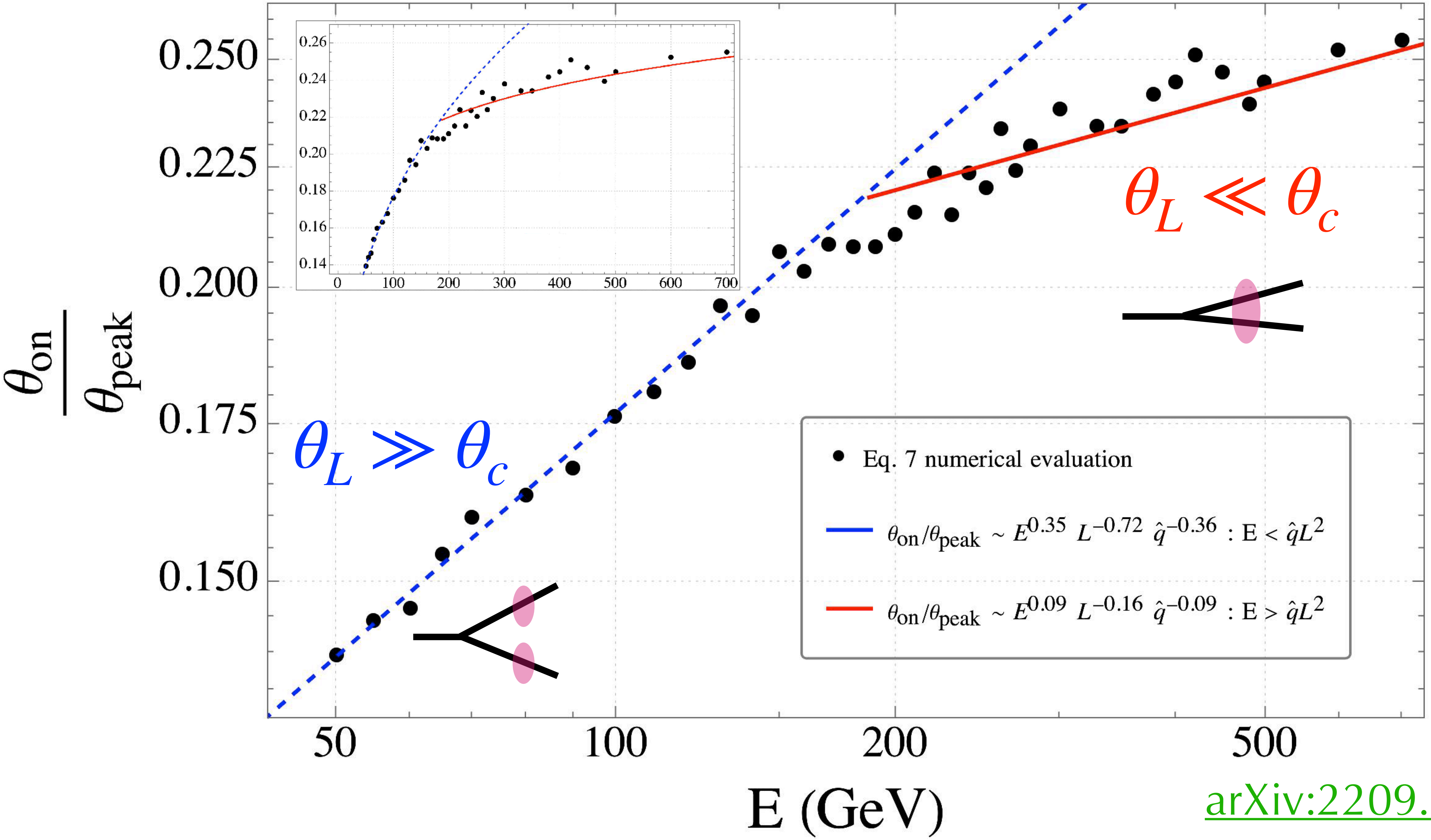

For $\theta_c \gg \theta \gg \theta_L$:

The medium does NOT resolve the emission



# Results

$\hat{q} = 1.5\,\mathrm{GeV}^2/\mathrm{fm} \quad L = 5\,\mathrm{fm}$

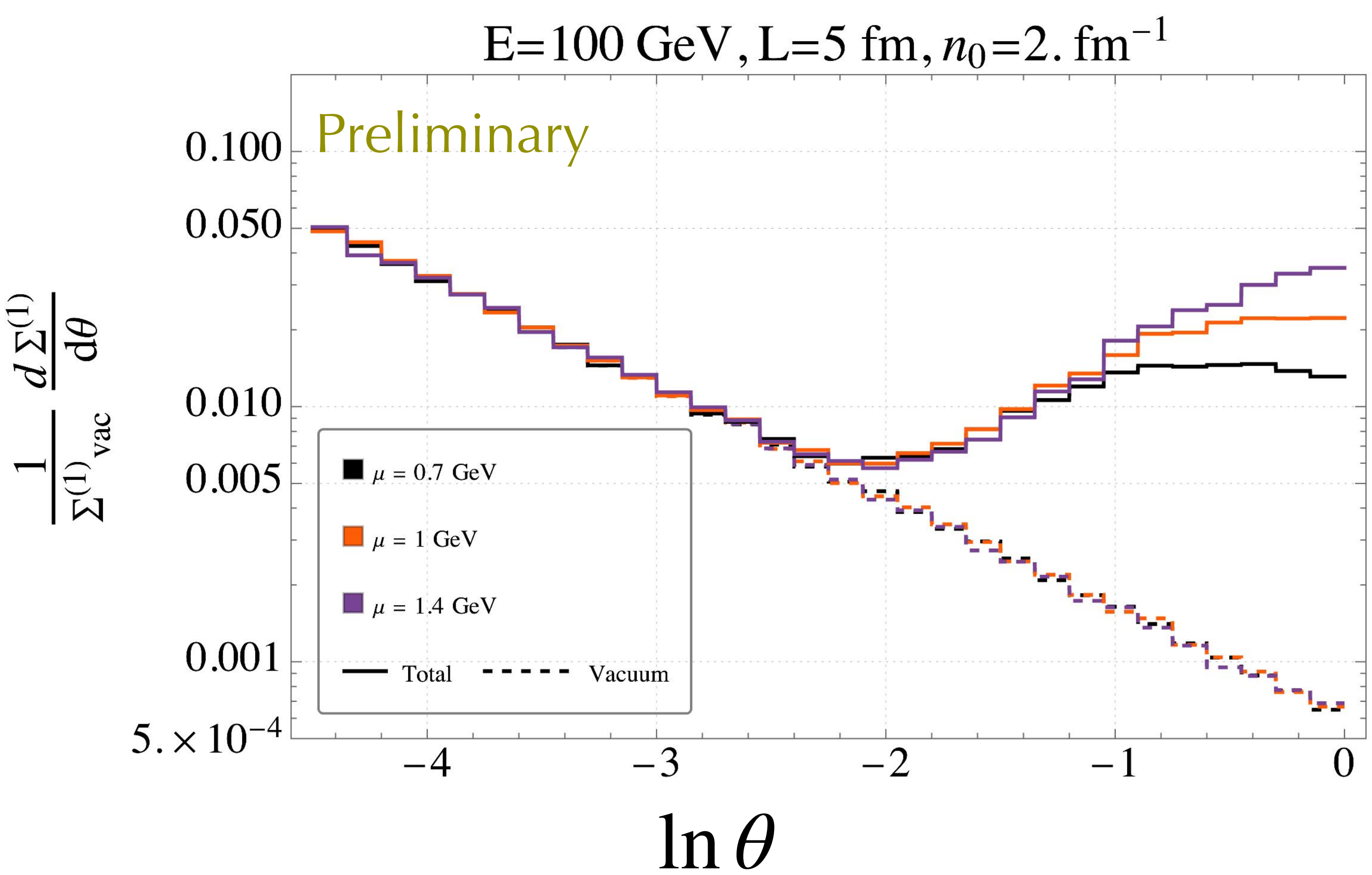


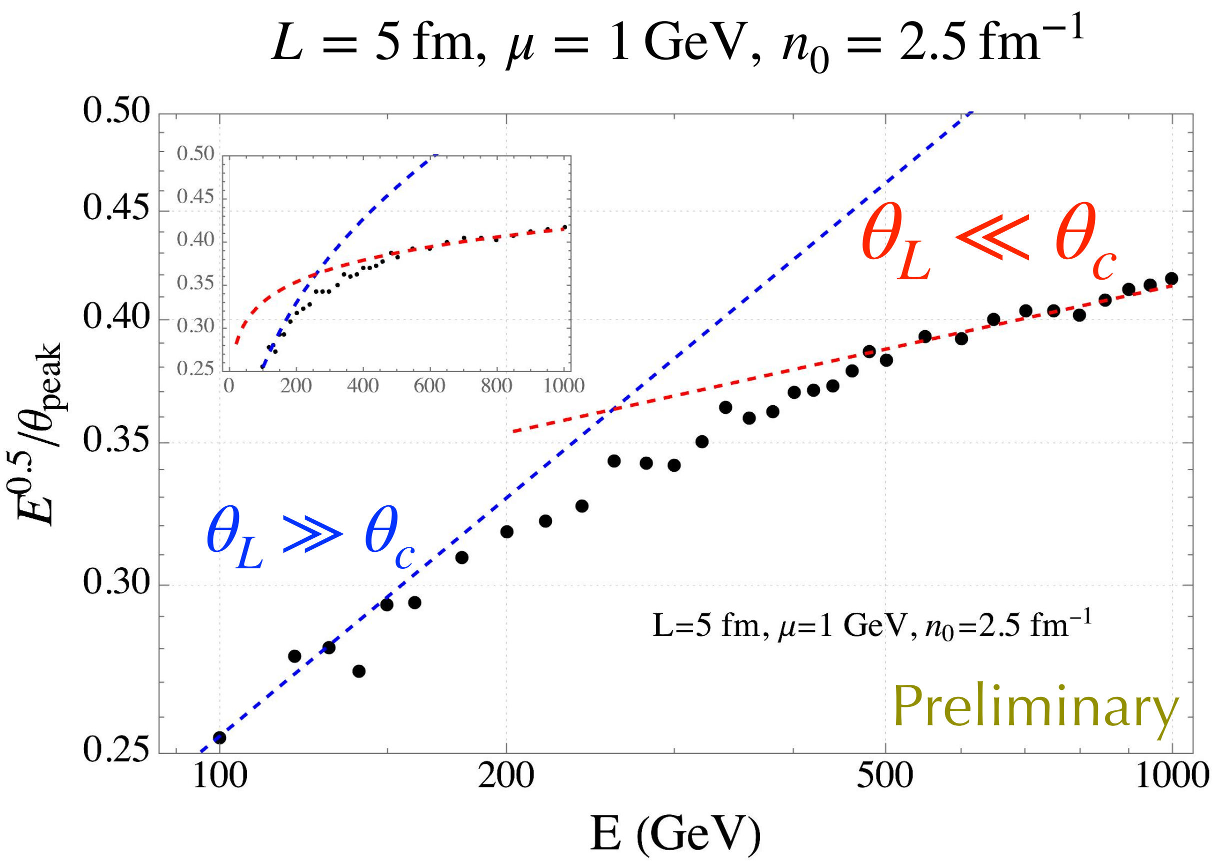

arXiv:2209.11236

Change of regime occurring at the critical energy $E_c \sim \hat{q}L^2$

# Yukawa potential

$$V_{\text{yuk}}(\boldsymbol{q}) = \frac{8\pi\mu^2}{\left(\boldsymbol{q}^2+\mu^2\right)^2}$$

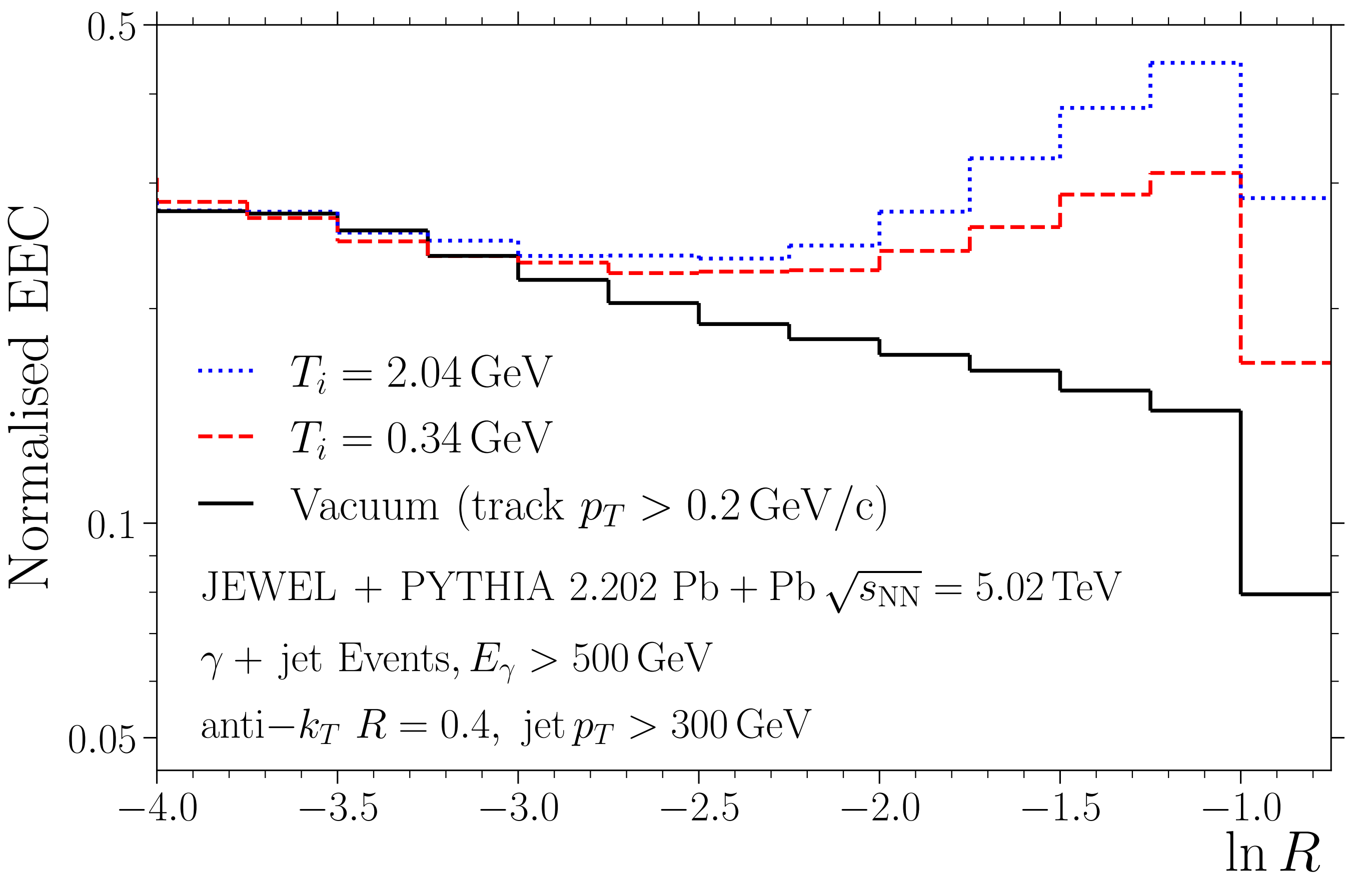


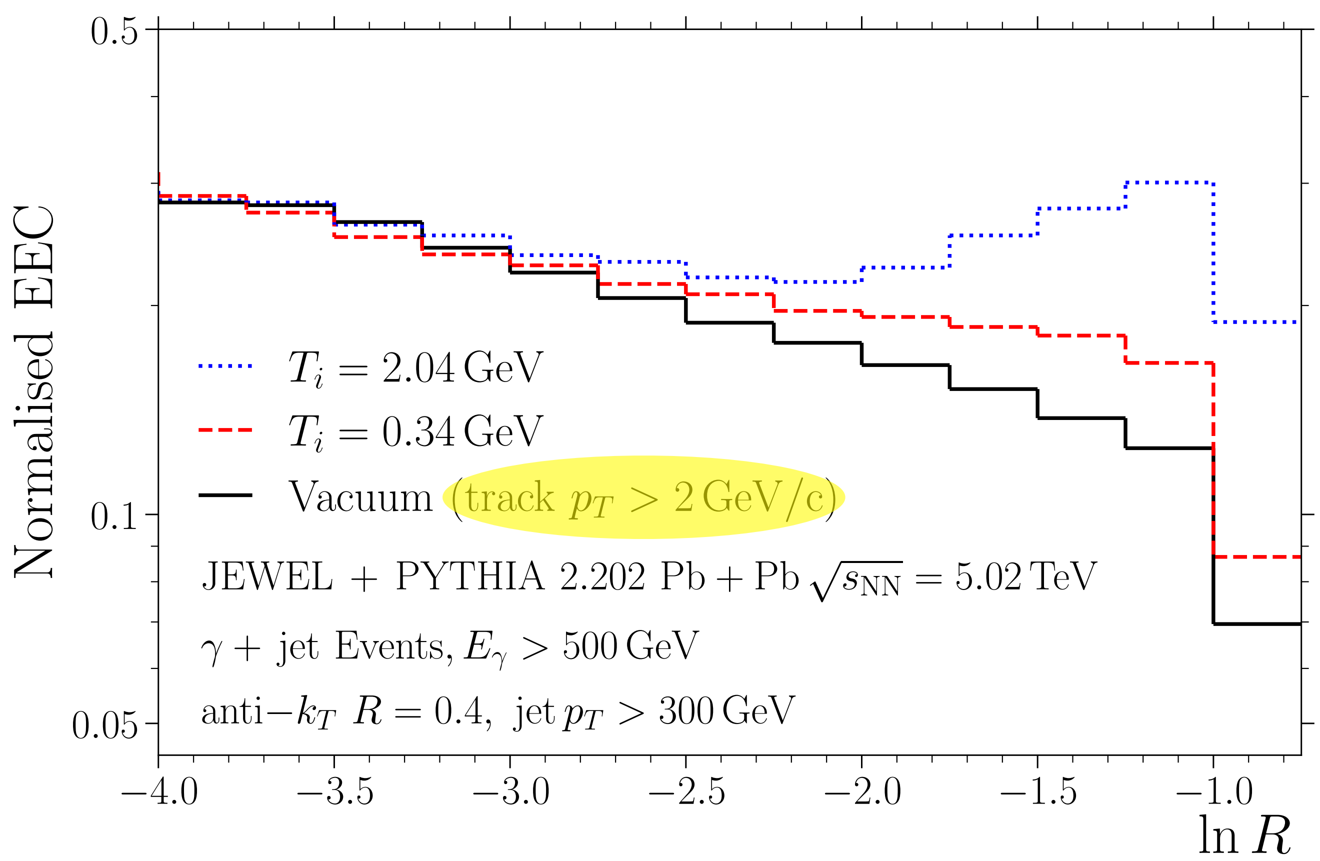




Change of regime clearly visible!

# Results from JEWEL

- An analysis on JEWEL is on the way




Features in the curves seem resilient against a hadron cut $p_T \gtrsim 2\,\text{GeV}$

# Conclusions

- Energy Correlators for jet substructure can be used for resolving properties of the QGP

- Correlators are broadly insensitive to soft physics: hadronization, and background are usually subleading

- Correlators can be computed perturbatively

- 2-point correlator provides a robust angular variable that can be used to probe color coherence in jets in the QGP

- Numerics done within BDMPS-Z in the HO. Basics features expected to be model independent, since they are set by formation time relations

  Preliminary results with other jet quenching formalisms

# Thanks

# Semi-hard approximation

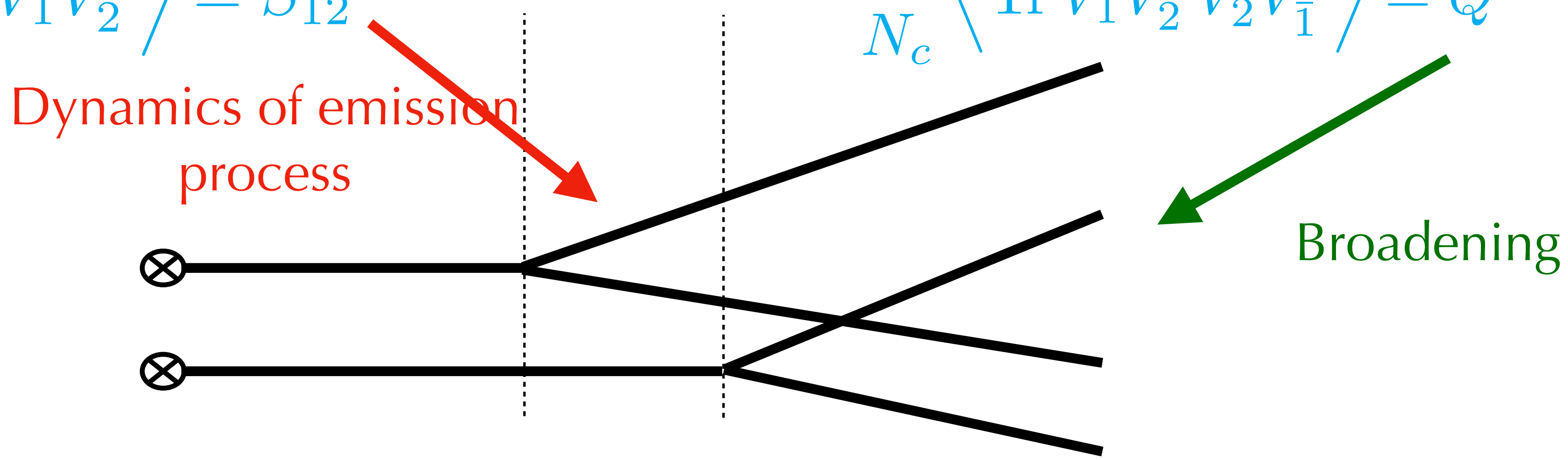
Dominguez, Milhano, Salgado, Tywoniuk, Vila 1907.03653
Isaksen, Tywoniuk 2107.02542

- 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

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



# Time and angular scales

Dominguez, Milhano, Salgado, Tywoniuk, Vila 1907.03653

- For a static medium of length $L$ within the harmonic approximation one can read off the relevant scales directly from the formulas
  - (Vacuum) formation time:

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

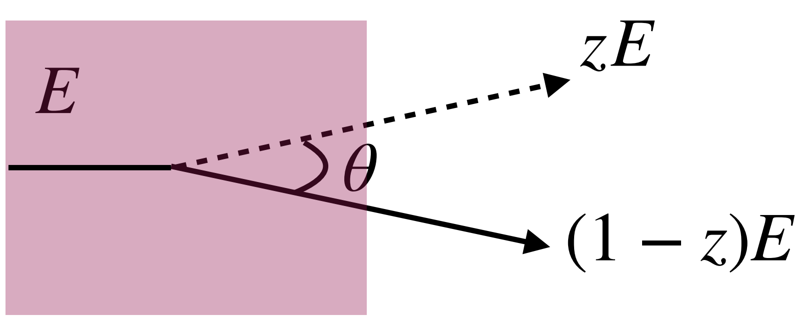
$$\theta_L \sim (EL)^{-1/2}$$

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

  - Decoherence time:

$$S_{12}(\tau) = e^{-\frac{1}{12}\hat{q}(1+z^2)\theta^2\tau^3} \qquad t_d \sim (\hat{q}\theta^2)^{-1/3} \qquad \theta_c \sim (\hat{q}L^3)^{-1/2}$$

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




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

# Vacuum NLL resummation