# Jet substructure in heavy-ion collisions with energy correlators

Carlota Andres (she/her)

LIP, Lisbon

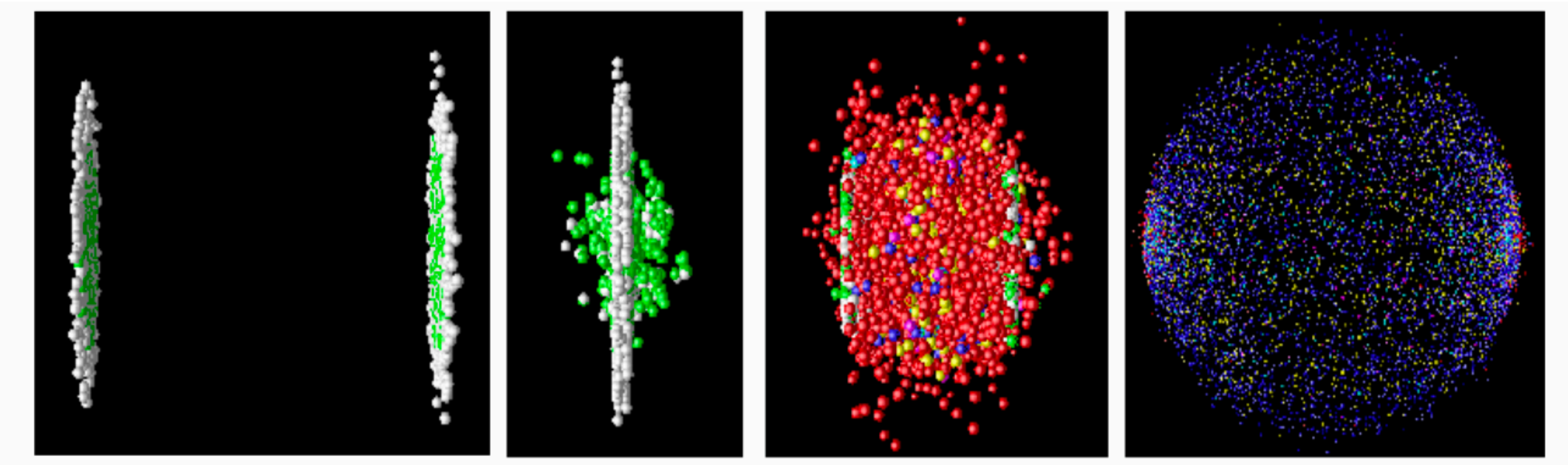
RPP, Paris, January 24-26, 2024

CA, Dominguez, Elayavalli, Holguin, Marquet, Moult, 2209.11236
CA, Dominguez, Holguin, Marquet, Moult, 2303.03413
CA, Dominguez,  Holguin, Marquet, I. Moult, 2307.15110

LIP

# Heavy-ion collisions

- One month of running time per year at the LHC is dedicated to **Pb-Pb collisions**



- Extremely high temperatures are achieved (300-500 MeV/trillions of $^{o}$C):
  - quarks and gluons are **deconfined**
  - new state of matter: **quark-gluon plasma (QGP)!**

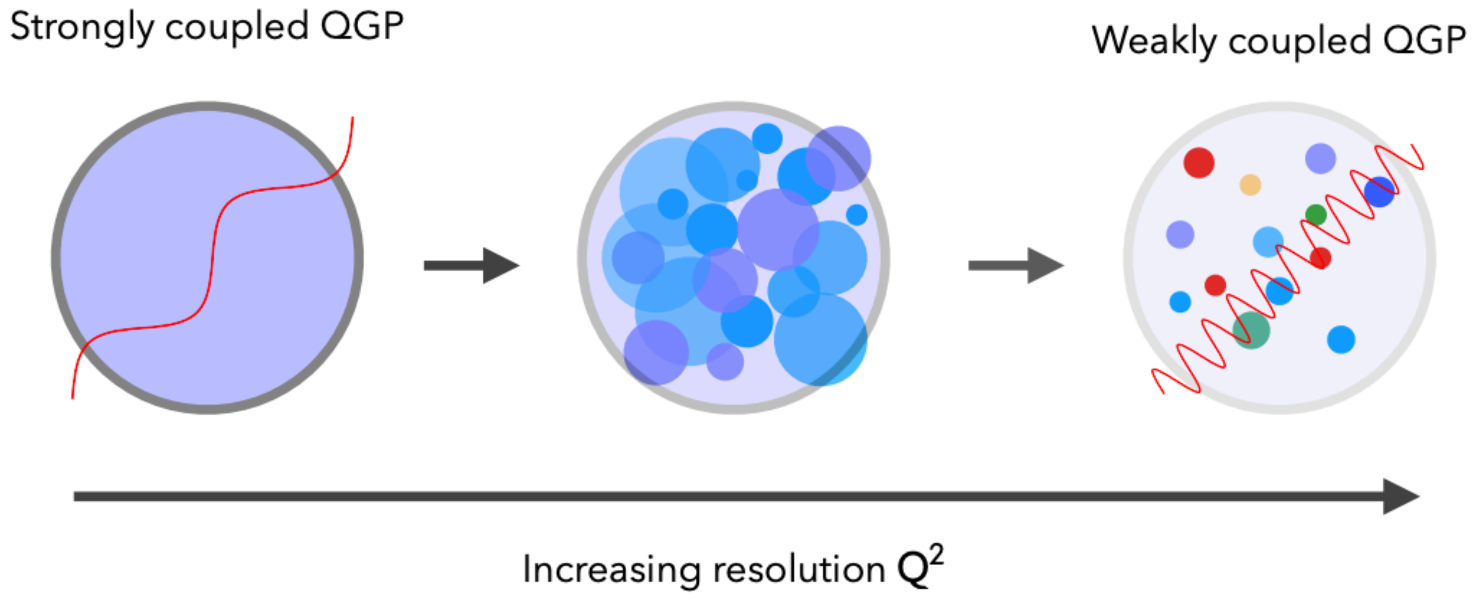
- Behaves as a liquid: very well described by relativistic hydrodynamics

Very small $\eta/s$: **most strongly-coupled** fluid in Nature

How does a **strongly-coupled fluid** emerge from the **weakly-coupled quarks and gluons**?

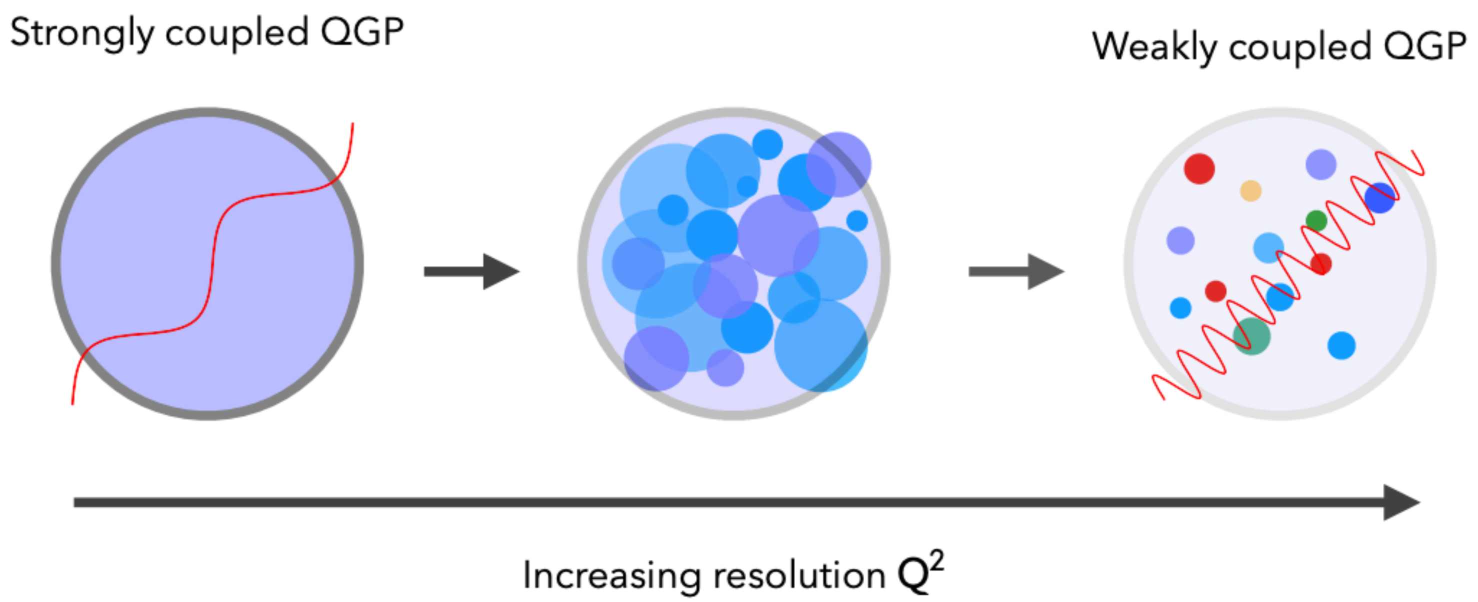
# How does a **strongly-coupled fluid** emerge from the **weakly-coupled quarks and gluons**?

We must probe the QGP at **various resolution scales**



# How does a **strongly-coupled fluid** emerge from the **weakly-coupled quarks and gluons**?

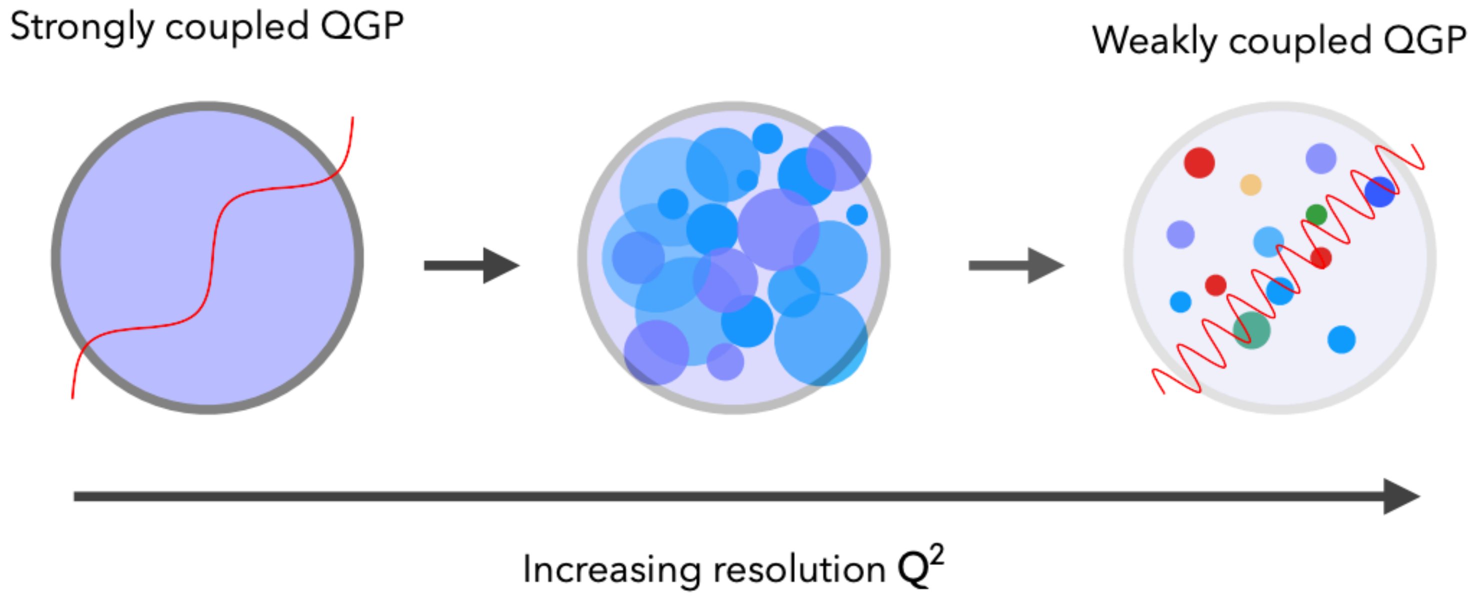
We must probe the QGP at **various resolution scales**




QGP **too short-lived** for external probes: need of **multi-scale probes produced in the same collision as the QGP**:

# How does a **strongly-coupled fluid** emerge from the **weakly-coupled quarks and gluons**?

We must probe the QGP at **various resolution scales**



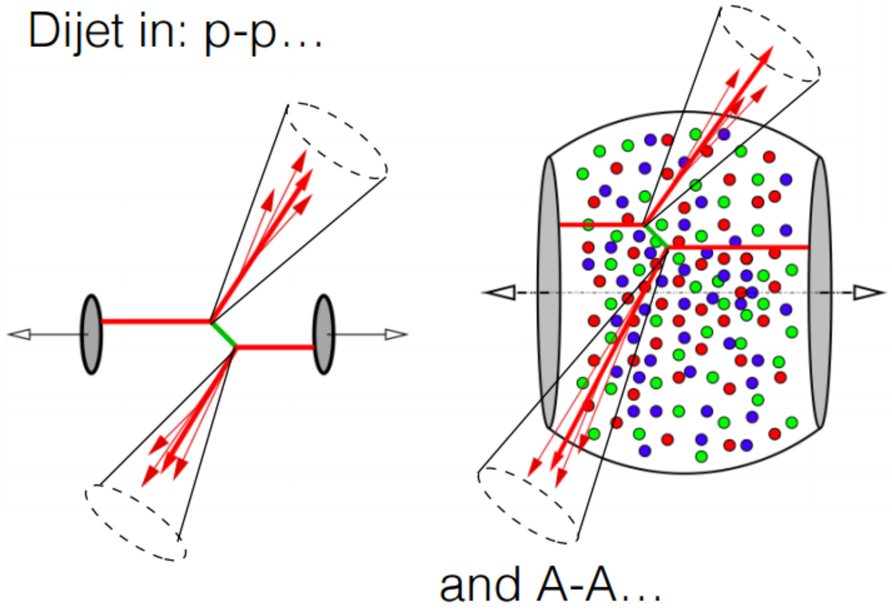

QGP **too short-lived** for external probes: need of **multi-scale probes produced in the same collision as the QGP**:

JETS

# Why jets?

- Production of high-energy partons unlikely to interfere with the medium formation

- Sensitive to the QGP dynamics through **jet quenching: jets interact with the QGP getting modified w.r.t p-p jets**




- In principle: under control in p-p collisions

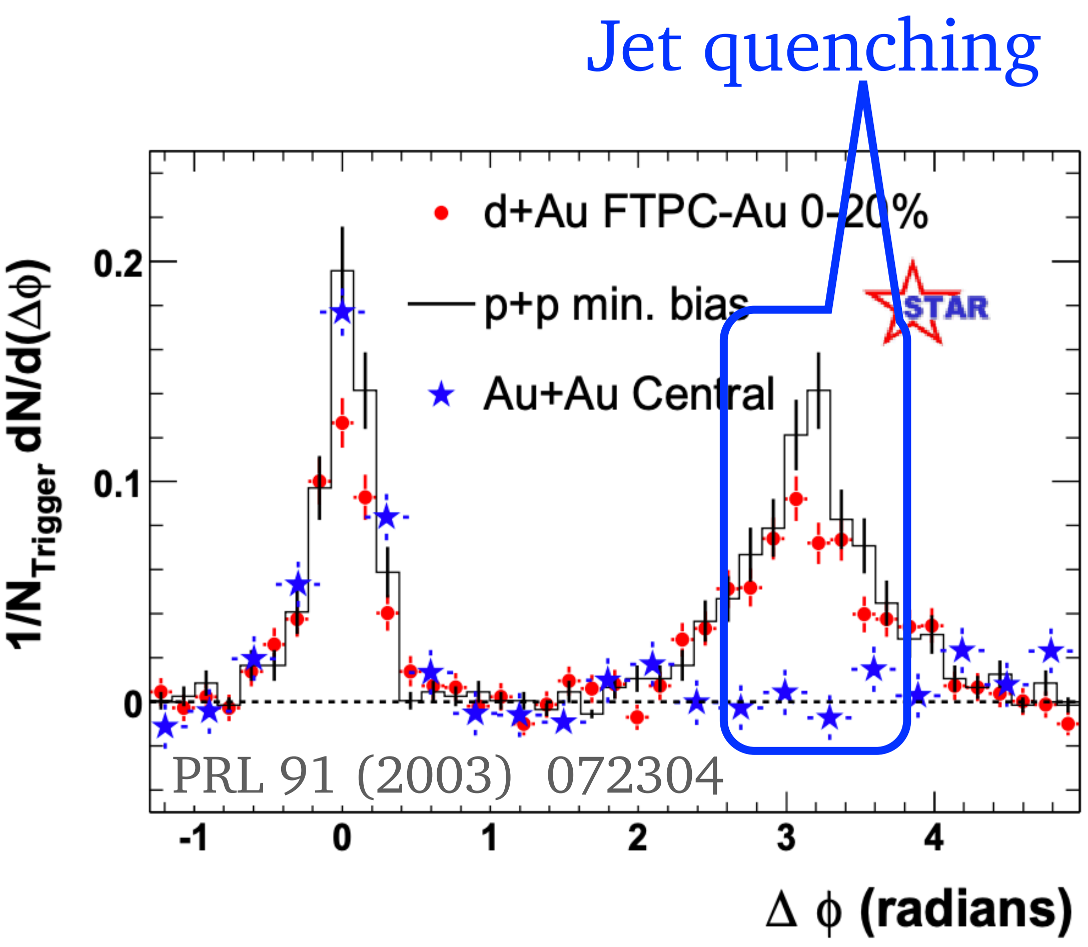
- **Multi-scale** objects: broad range of momentum and spatial scales involved in the jet evolution

- **Multi-observable**: different observable jet properties sensitive to different QGP scales and properties**?**

# Why jets?

- Production of high-energy partons unlikely to interfere with the medium formation

- Sensitive to the QGP dynamics through **jet quenching: jets interact with the QGP getting modified w.r.t p-p jets**

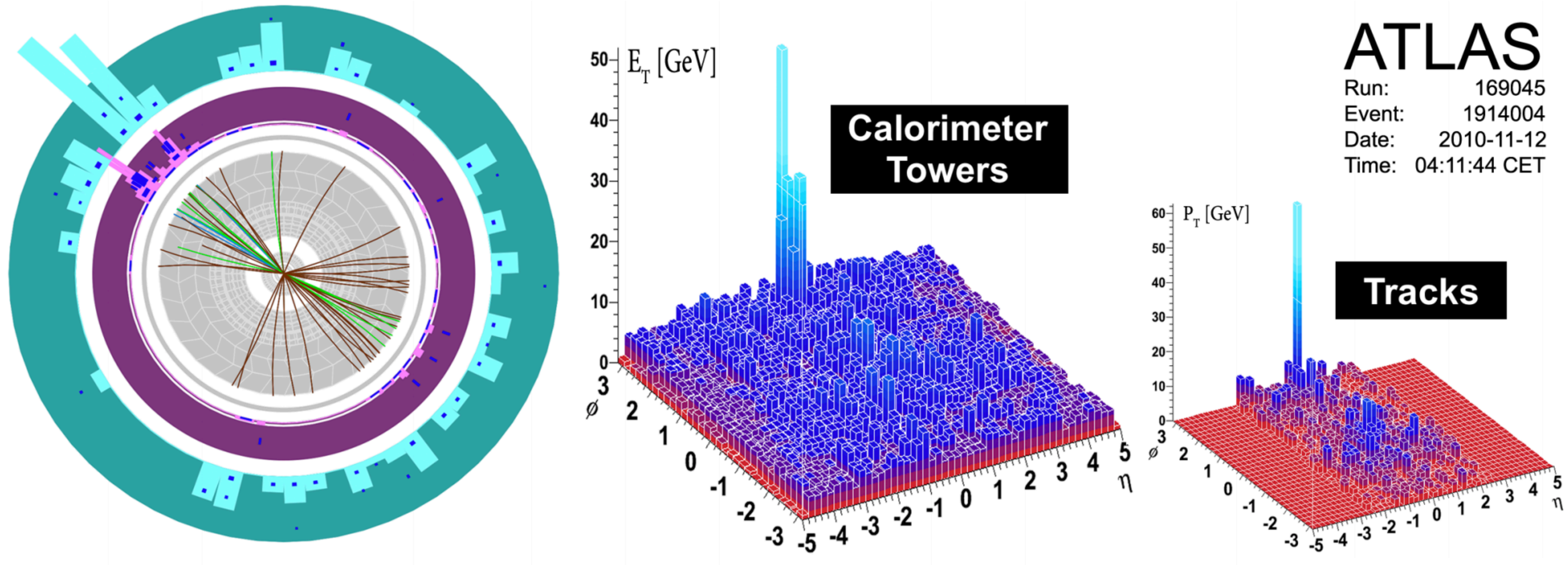



- In principle: under control in p-p collisions

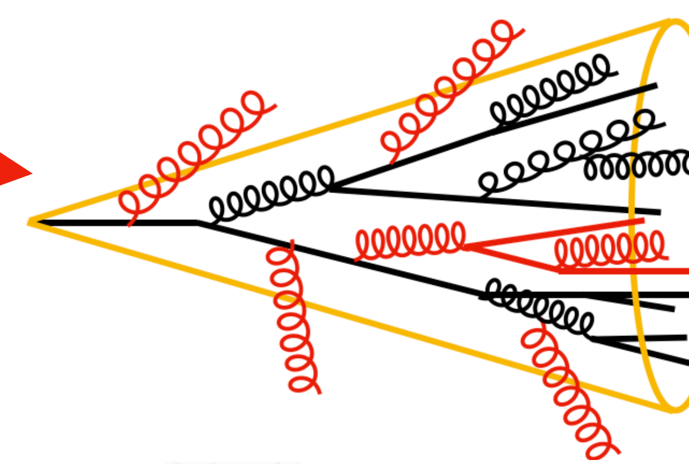
- **Multi-scale** objects: broad range of momentum and spatial scales involved in the jet evolution

- **Multi-observable**: different observable jet properties sensitive to different QGP scales and properties?

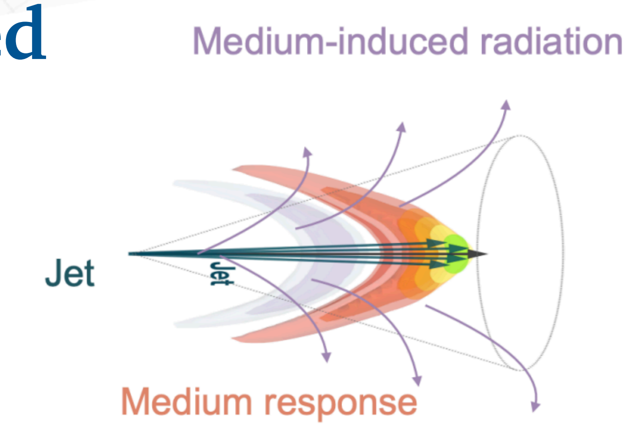
# Jet quenching




- **Energy loss** due to **QGP-induced radiation** that goes outside of the jet cone

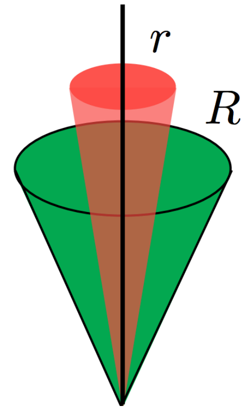


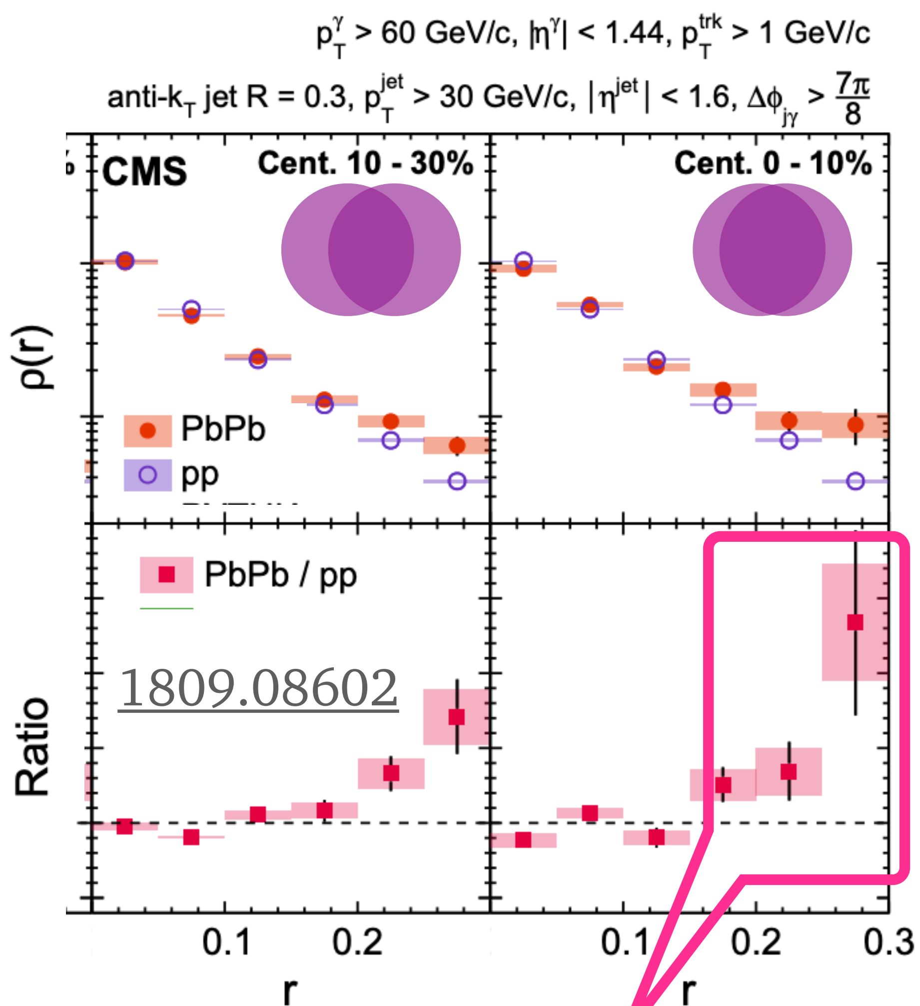
- **Jets inner structure** (jet substructure) also gets **modified**
    - Not only by medium-induced radiation (e.g. medium response)



# Jet substructure

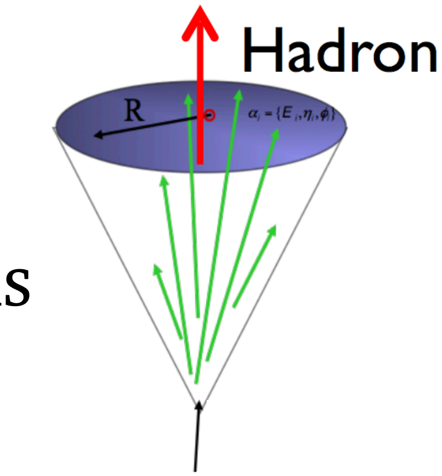
Jet shapes



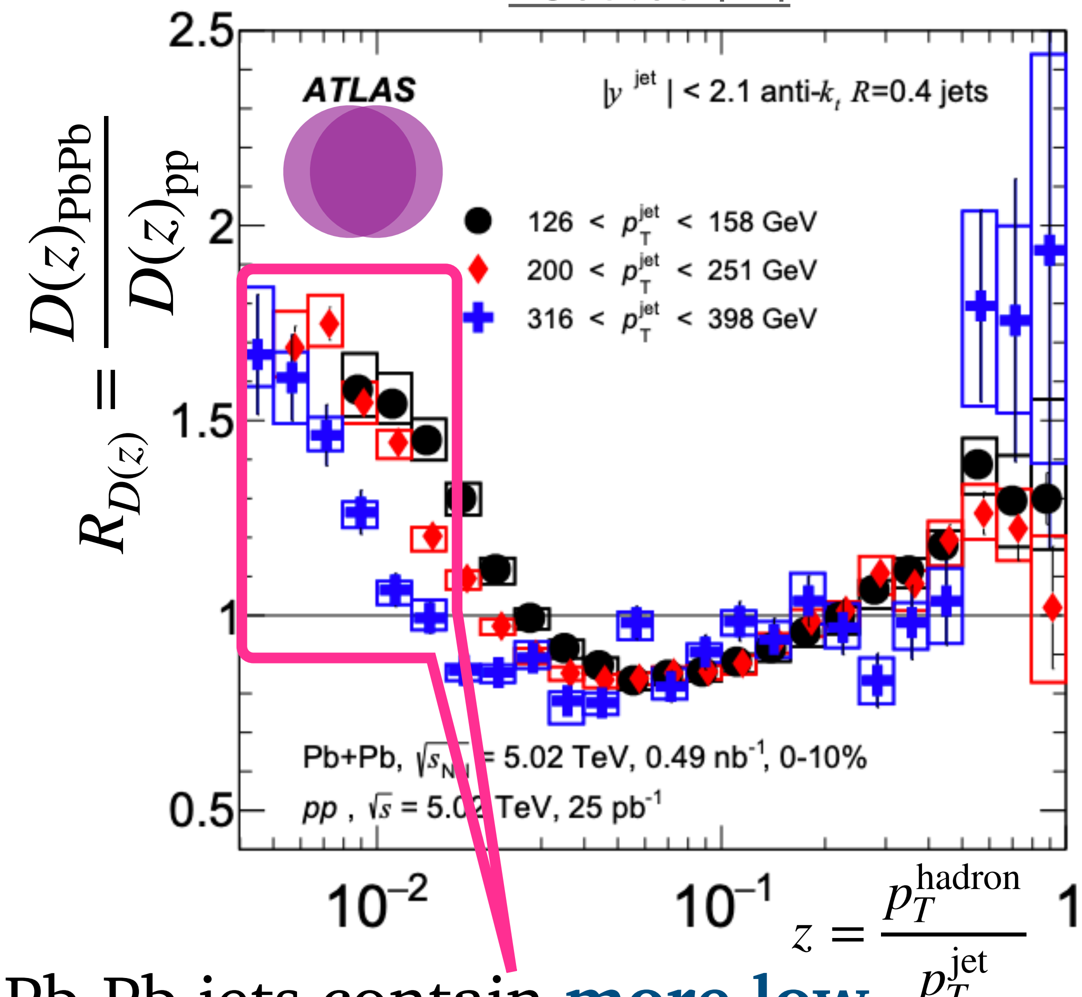




Pb-Pb jets **more energy toward the edge of the cone** than p-p jets

Jet fragmentations



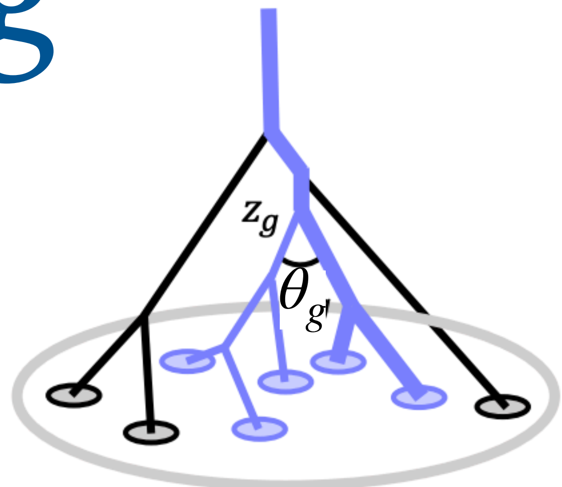

1805.05424




Pb-Pb jets contain **more low-$p_T$ particles** than p-p jets

$$D(z) = \frac{1}{N_{\rm jet}} \frac{dn_{\rm ch}}{dz}$$

# Jet substructure: grooming

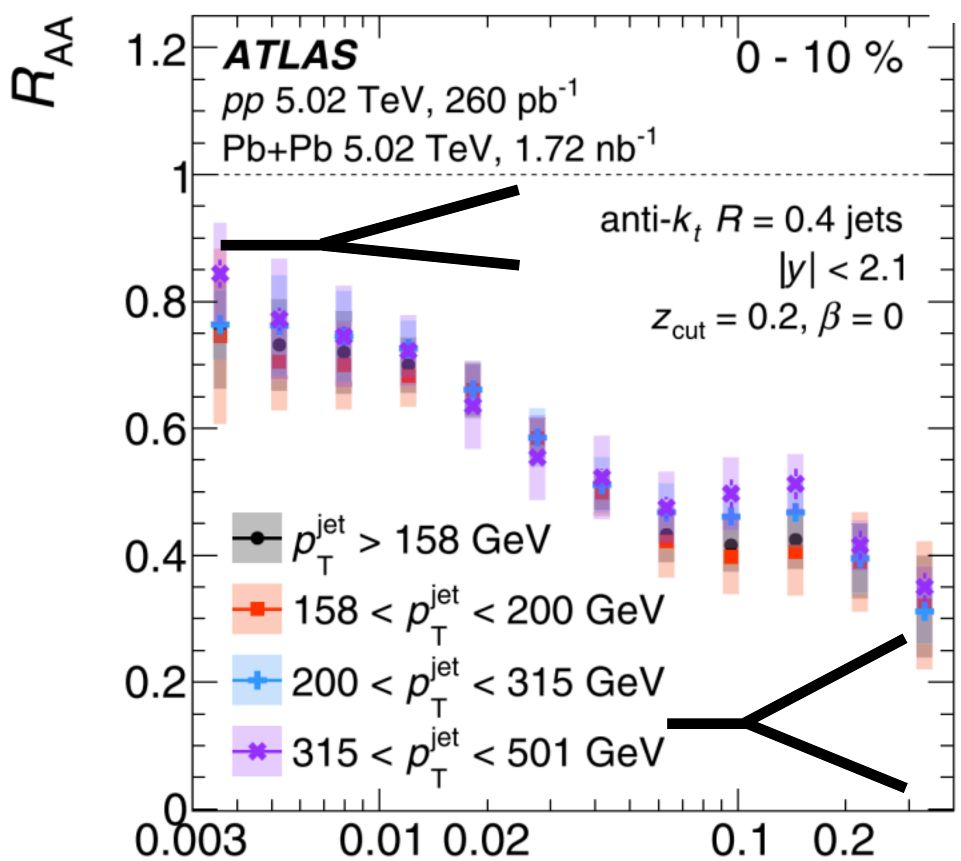



- What about grooming away soft physics?

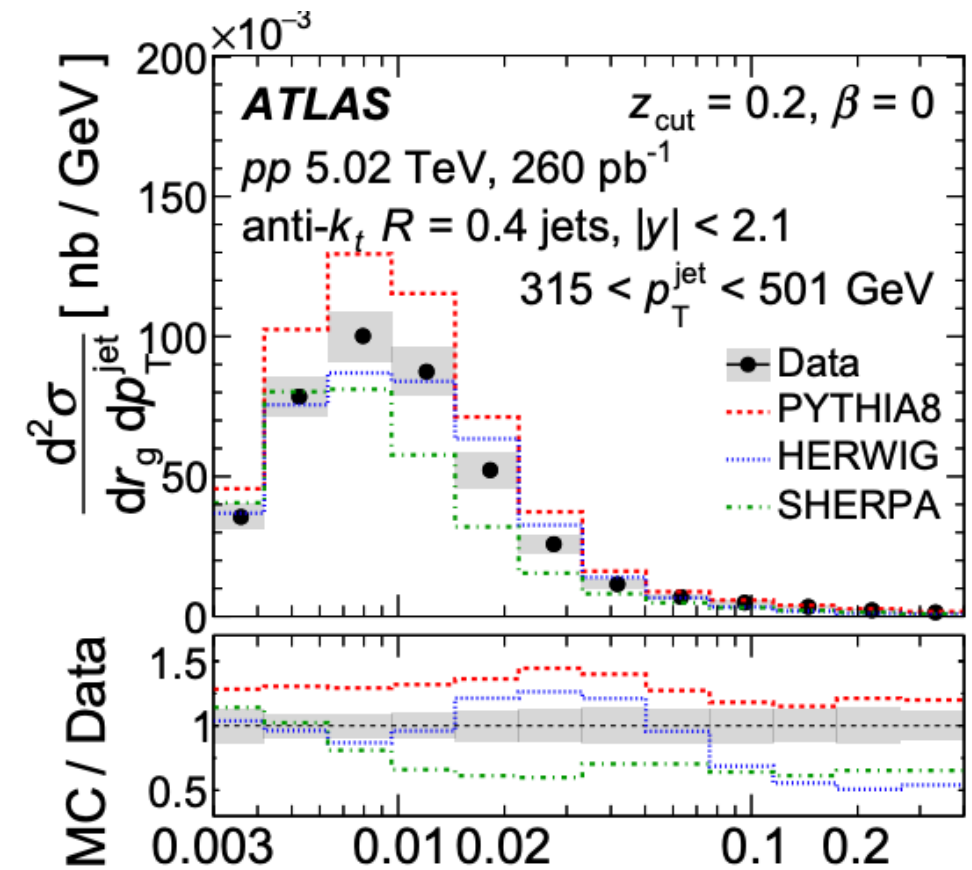
  Jet constituents are re-clustered (through C/A) and soft/ wide angle radiation is rejected in this process

**Groomed jet radius**

$R_{AA} = \frac{\text{Pb-Pb}}{\text{scaled}\otimes\text{pp}}$




ATLAS, PRC 107 (2023) 054909 $r_g = R\theta_g$




$r_g = R\theta_g$

Broad angular structures are more suppressed in PbPb collisions

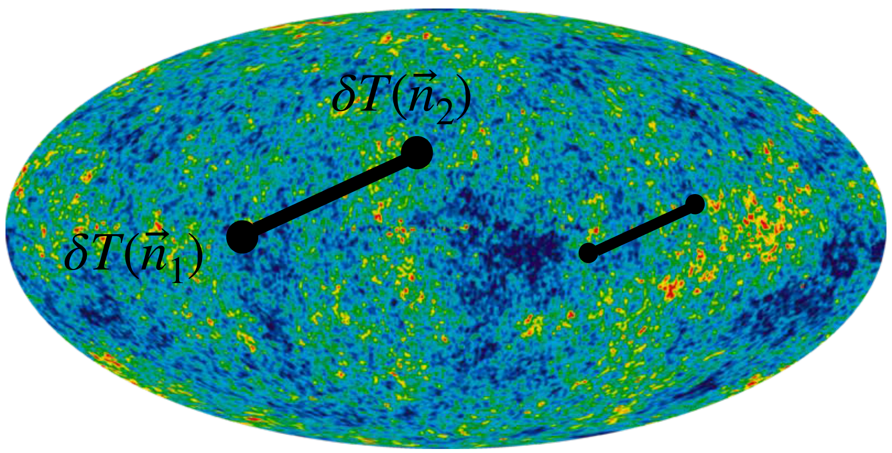
Large discrepancies between MC and data in p-p collisions

A new (old) idea?

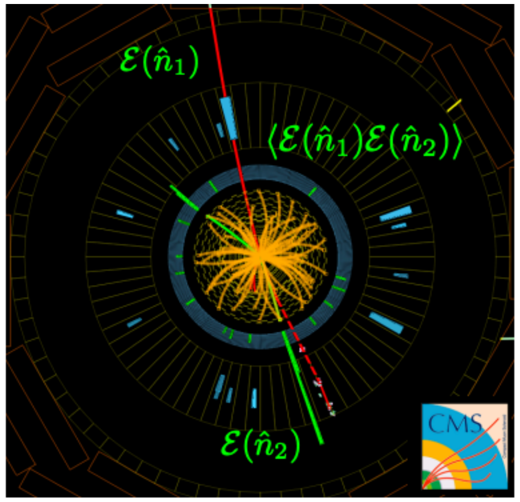
**Energy-Energy correlators!**

# Energy Correlators

- Fundamental objects that encode the dynamics of the underlying theory




$\Leftrightarrow$

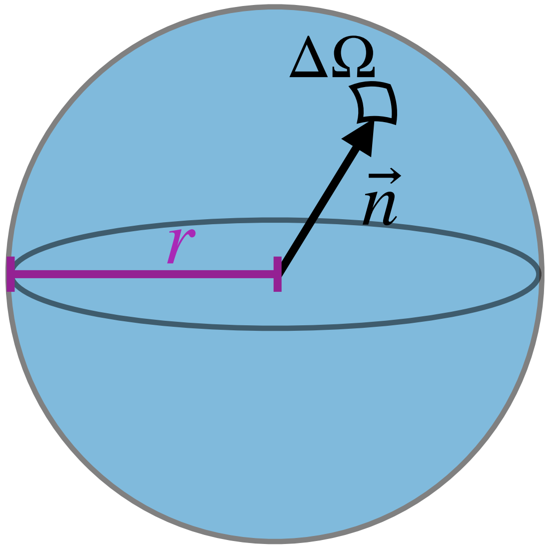



- Correlators $\langle \mathscr{E}(\vec{n}_1)\mathscr{E}(\vec{n}_2)\cdots\mathscr{E}(\vec{n}_k)\rangle$ of the **energy flux**:

Sterman, Korchemsky, Nucl. Phys. B 555 (1999) 335

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

$$\mathscr{E}(\vec{n})\,|X\rangle = \sum_i E_i\, \delta^{(2)}(\vec{n} - \vec{n}_i)\,|X\rangle$$




- 1-point correlator: $\langle X|\mathscr{E}(\vec{n})|X\rangle \propto \sum_i E_i$

Total energy flux through an area element

# Two-point correlator

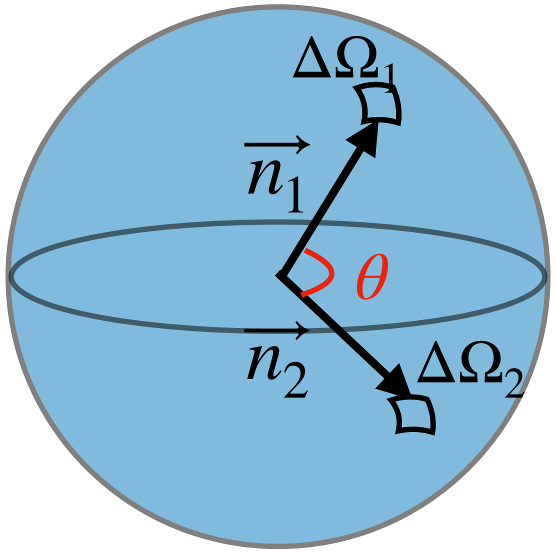
- 2-point correlator **(EEC):**

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

Energy weights

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

Hard scale of the process

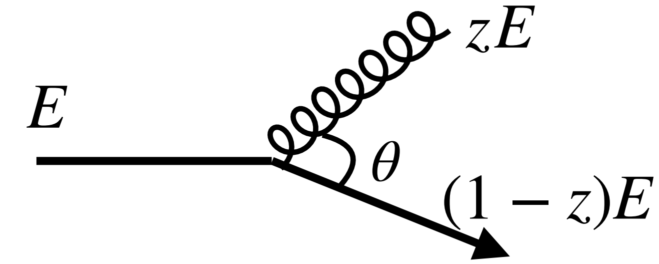



- As function of the **relative angle** only:

$$\frac{d\Sigma^{(n)}}{d\theta} = \frac{1}{\sigma}\sum_{i,j}\int dE_{i,j}\,\frac{d\sigma}{d\theta dE_i dE_j}\frac{E_i^n E_j^n}{Q^{2n}}$$

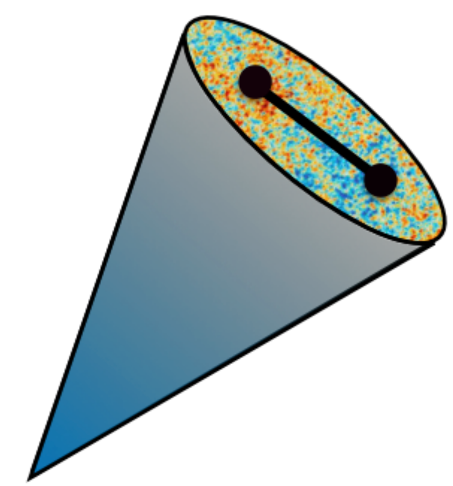
# EEC within p-p jets

$$\frac{d\Sigma^{(n)}}{d\theta} = \frac{1}{\sigma}\sum_{i,j}\int dE_{i,j}\,\frac{d\sigma}{d\theta dE_i dE_j}\,\frac{E_i^n E_j^n}{Q^{2n}}$$




- EEC for a massless quark jet in **vacuum** at LO:

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



- Within jets: **collinear** (or OPE) limit of EECs

$$\langle X|\,\mathcal{E}(\vec{n}_1)\mathcal{E}\vec{n}_2)\,|X\rangle \xrightarrow{\theta\to 0} \sum_i \theta^{(\tau_i-4)/2}\,\mathcal{O}_i(\vec{n}_1)$$

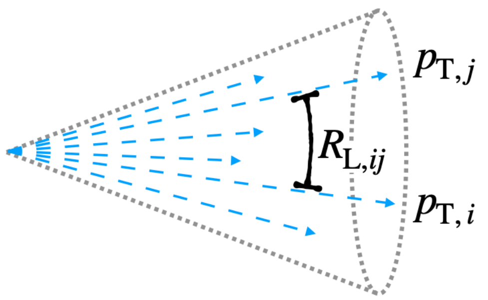
**Power-law scaling** according to CFT!

Hoffman, Maldacena, 0803.1467

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

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

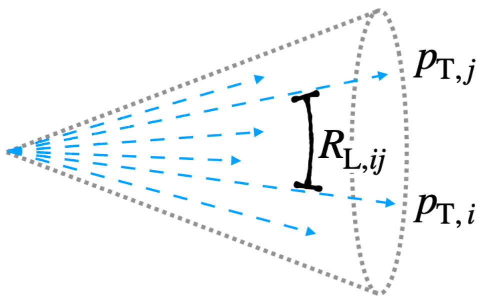
# EEC in p-p jets




$$R_L = \sqrt{\Delta\phi^2 + \Delta\eta^2}$$

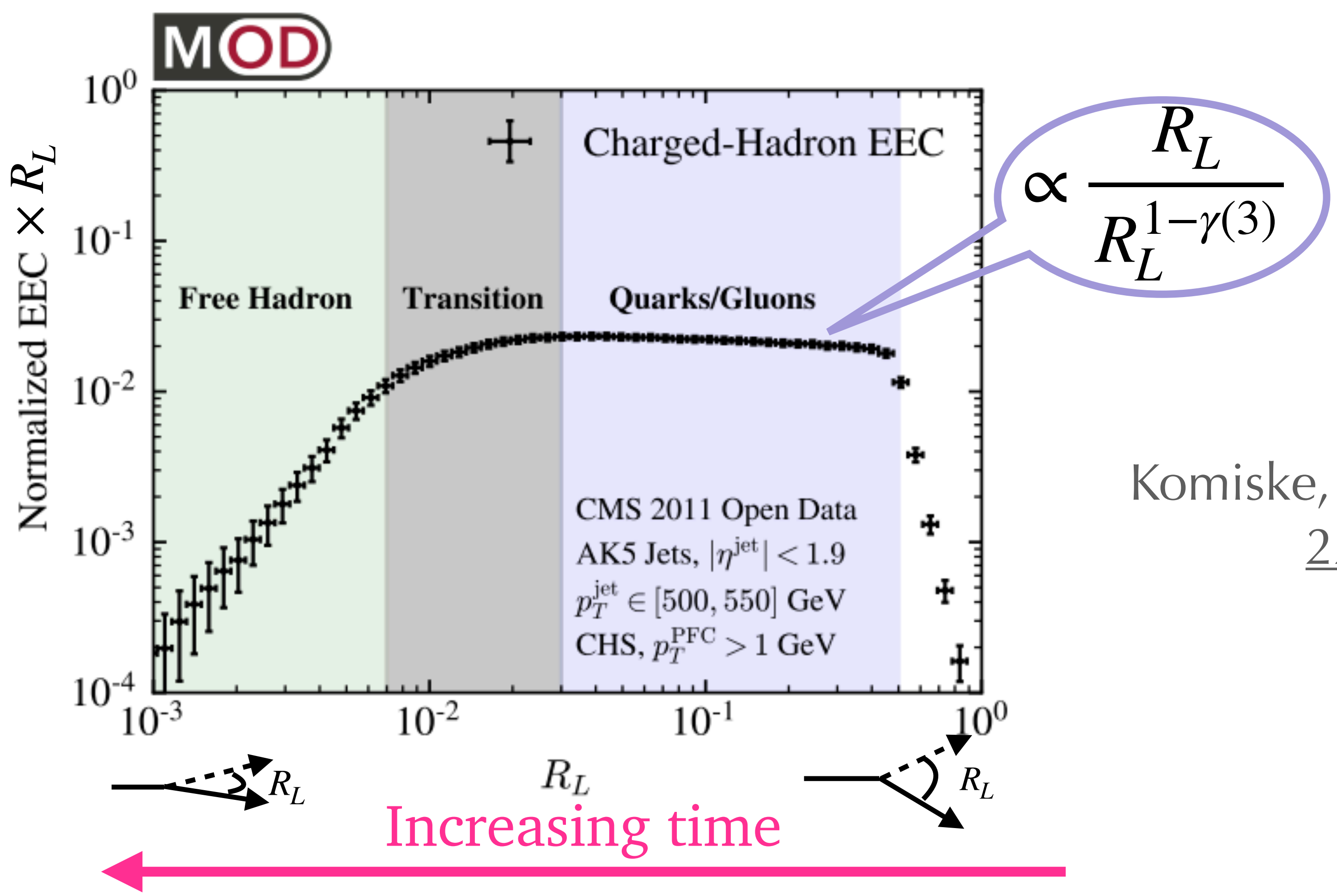
- QCD is **NOT** conformal
- Confinement must break the power-law behavior below: $\sim \Lambda_{QCD}/E$
  - Small angles (late times): hadronization is dominant
  - Large angles (initial times): power-law pQCD behavior

# EEC in p-p jets




$R_L = \sqrt{\Delta\phi^2 + \Delta\eta^2}$

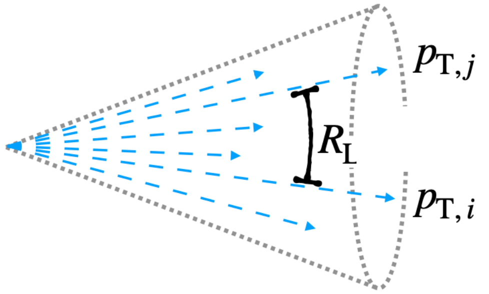
- QCD is **NOT** conformal
- Confinement must break the power-law behavior below: $\sim \Lambda_{QCD}/E$
  - Small angles (late times): hadronization is dominant
  - Large angles (initial times): power-law pQCD behavior



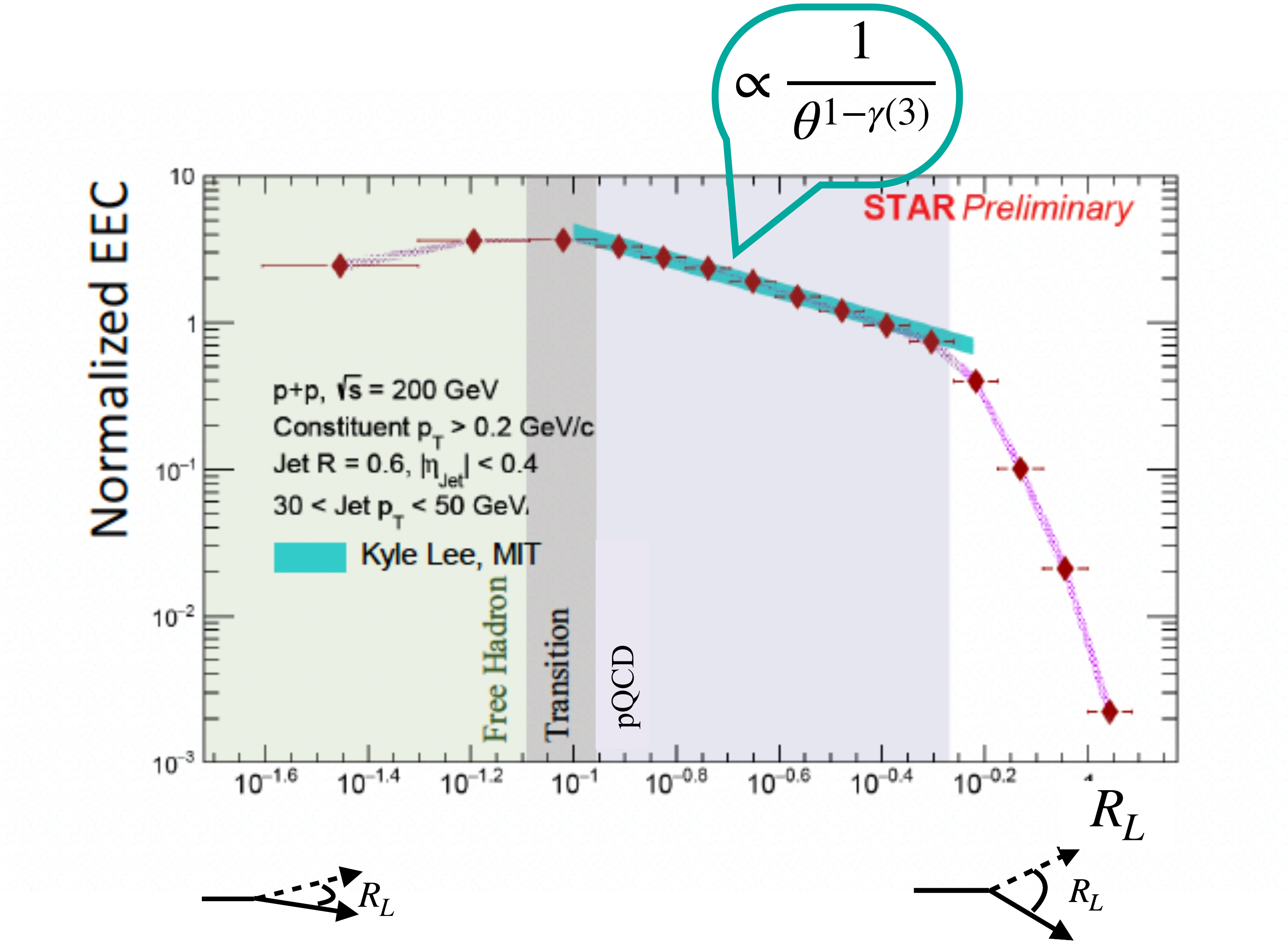

Komiske, Moult, Thaler, Zhu
2201.07800

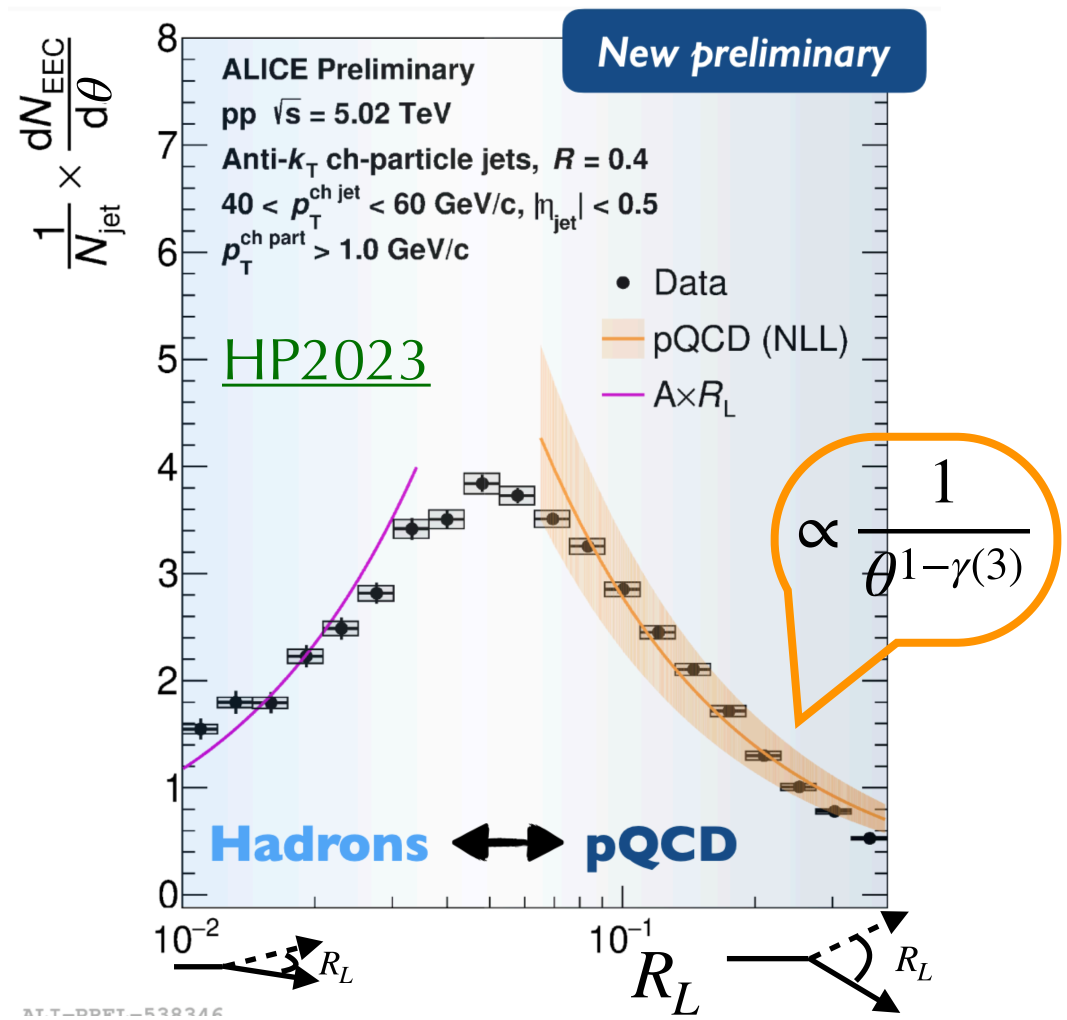
# EEC in p-p jets

$$R_L = \sqrt{\Delta\phi^2 + \Delta\eta^2}$$




- **First measurements** of the EEC in **p-p collisions** announced in HP2023 (03/2023)
- Observation of the universal power-law QCD behavior!



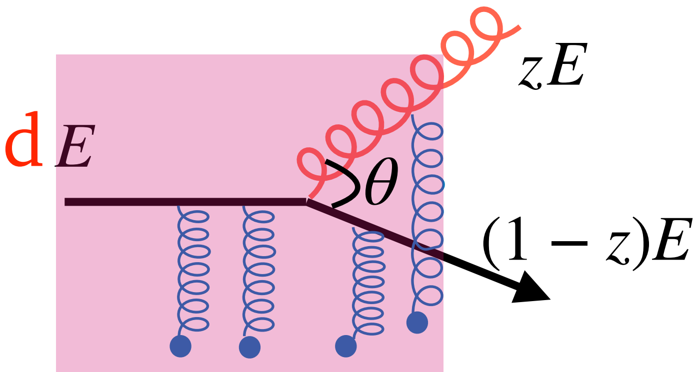



# Energy correlators in HICs

- Access to angular scales **without de-clustering**!
- In p-p: clear **separation between perturbative** and **non-perturbative regimes**
- pQCD **p-p baseline under control** (known at very high accuracy)
- Reduced sensitivity to soft physics ⇨ no grooming?
  - Infrared safe, inclusive, energy weights
- Increase energy weights to isolate hard splitting modifications?
- **Wide array of EECs can be defined** from only 2- and 3-point correlations

# EEC in A-A

Medium-induced radiation



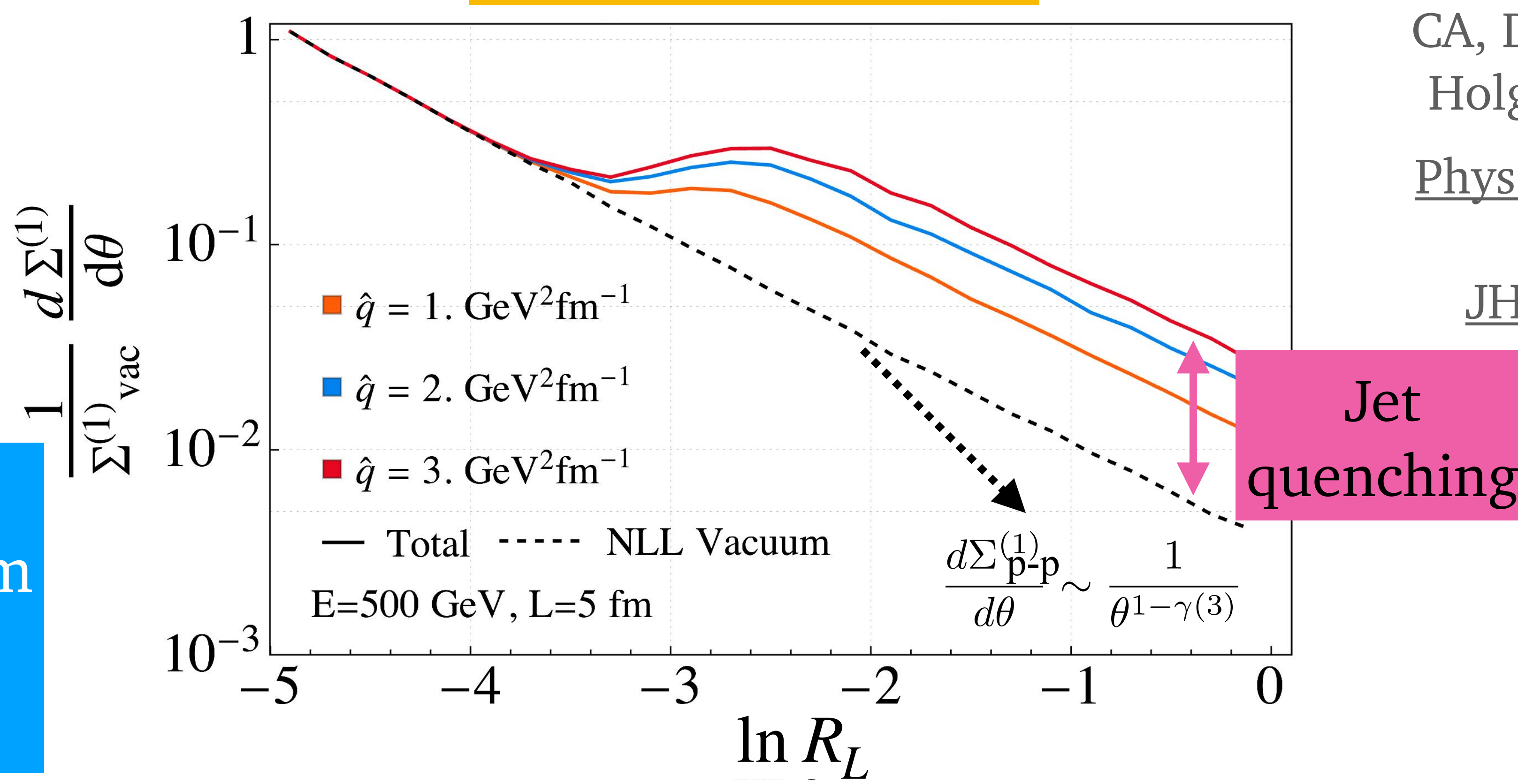

- EEC for a **massless quark jet**: $Q = E$

Thus, we are assuming we know the initial jet energy $E$ ($\gamma/Z$-jet)

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

$$\frac{d\sigma_{qg}}{d\theta dz} = \frac{d\sigma^{\text{vac}}_{qg}}{d\theta dz} + \frac{d\sigma^{\text{med}}_{qg}}{d\theta dz}$$

2-point EEC in A-A

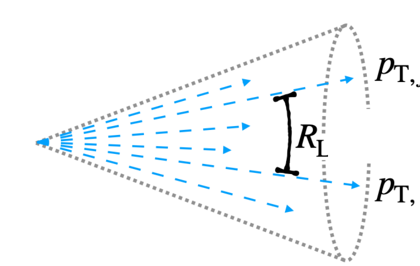



CA, Dominguez, Elayavalli, Holguin, Marquet, Moult,

Phys. Rev. Lett. 130 (2023) 262301,

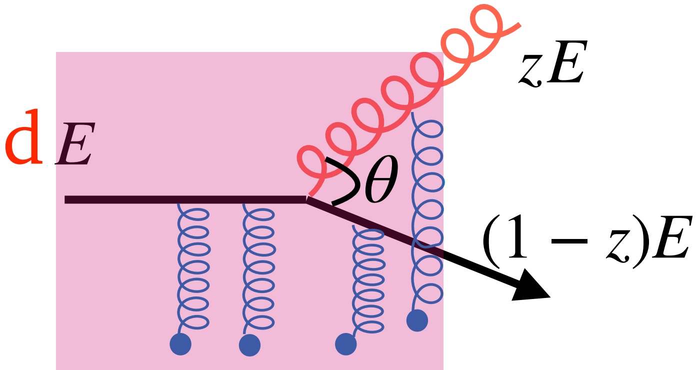
JHEP 09 (2023) 088

Results for inclusive jets from ALICE and CMS underway!



# EEC in A-A

Medium-induced radiation




- EEC for a **massless quark jet**: $Q = E$

Thus, we are assuming we know the initial jet energy $E$ ($\gamma/Z$-jet)

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

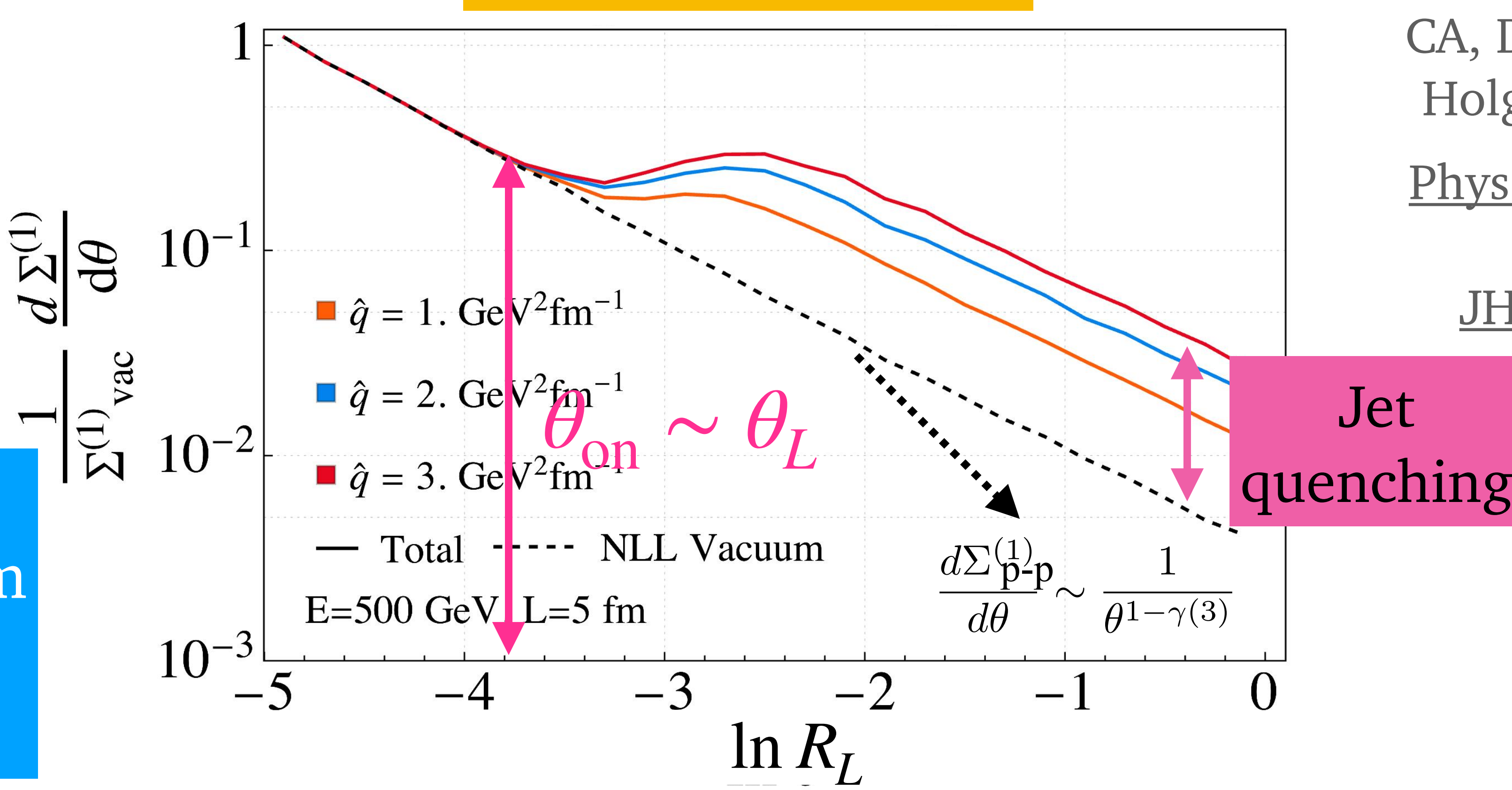
$$\frac{d\sigma_{qg}}{d\theta dz} = \frac{d\sigma^{vac}_{qg}}{d\theta dz} + \frac{d\sigma^{med}_{qg}}{d\theta dz}$$

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

$t_f \leq L$

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

2-point EEC in A-A

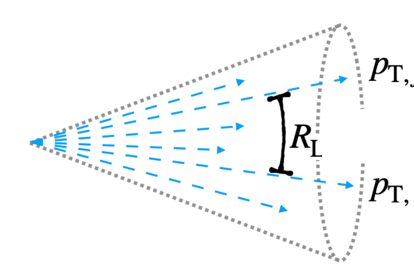



CA, Dominguez, Elayavalli, Holguin, Marquet, Moult,

Phys. Rev. Lett. 130 (2023) 262301,

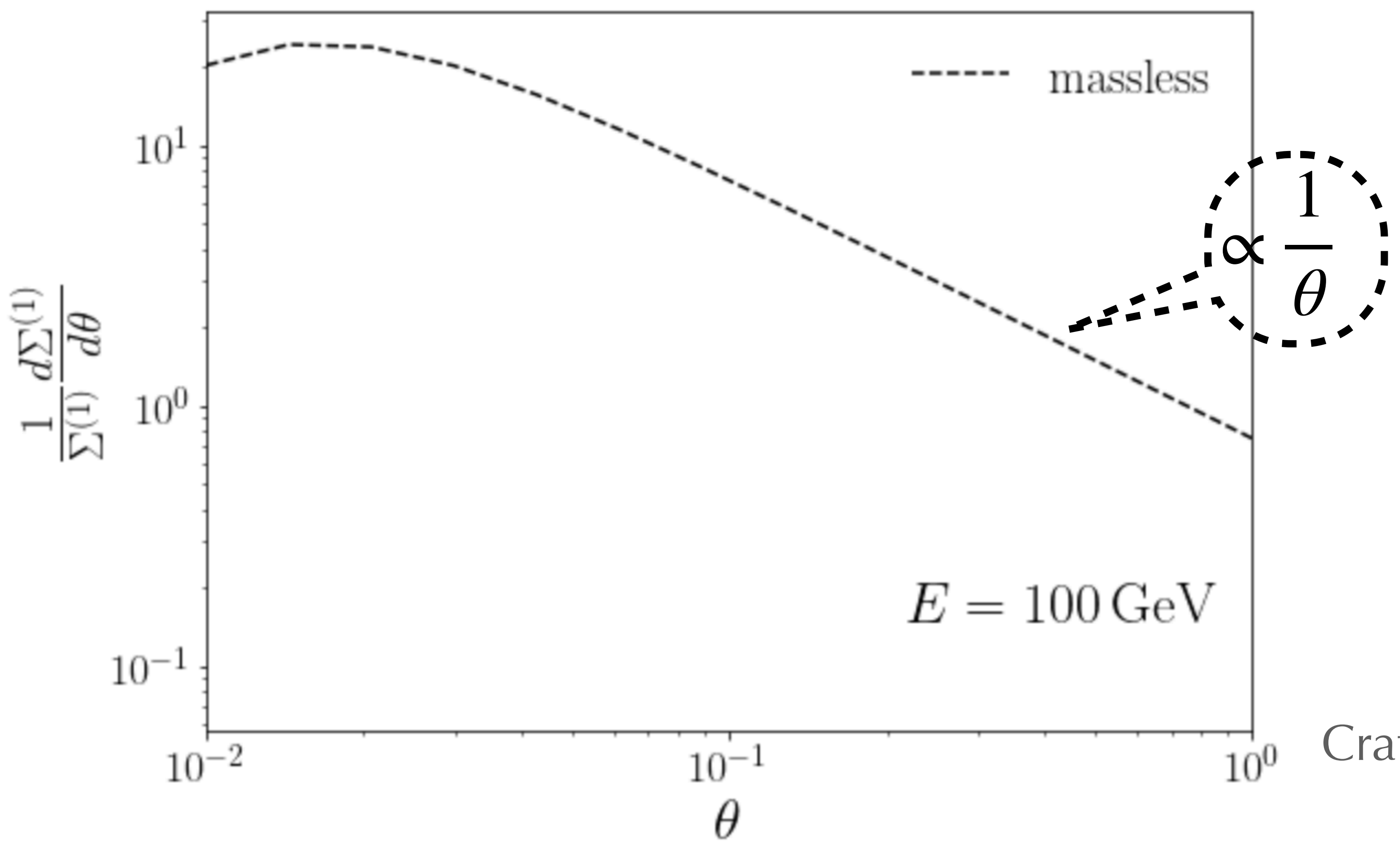
JHEP 09 (2023) 088

Results for inclusive jets from ALICE and CMS underway!



# EEC in HF p-p jets

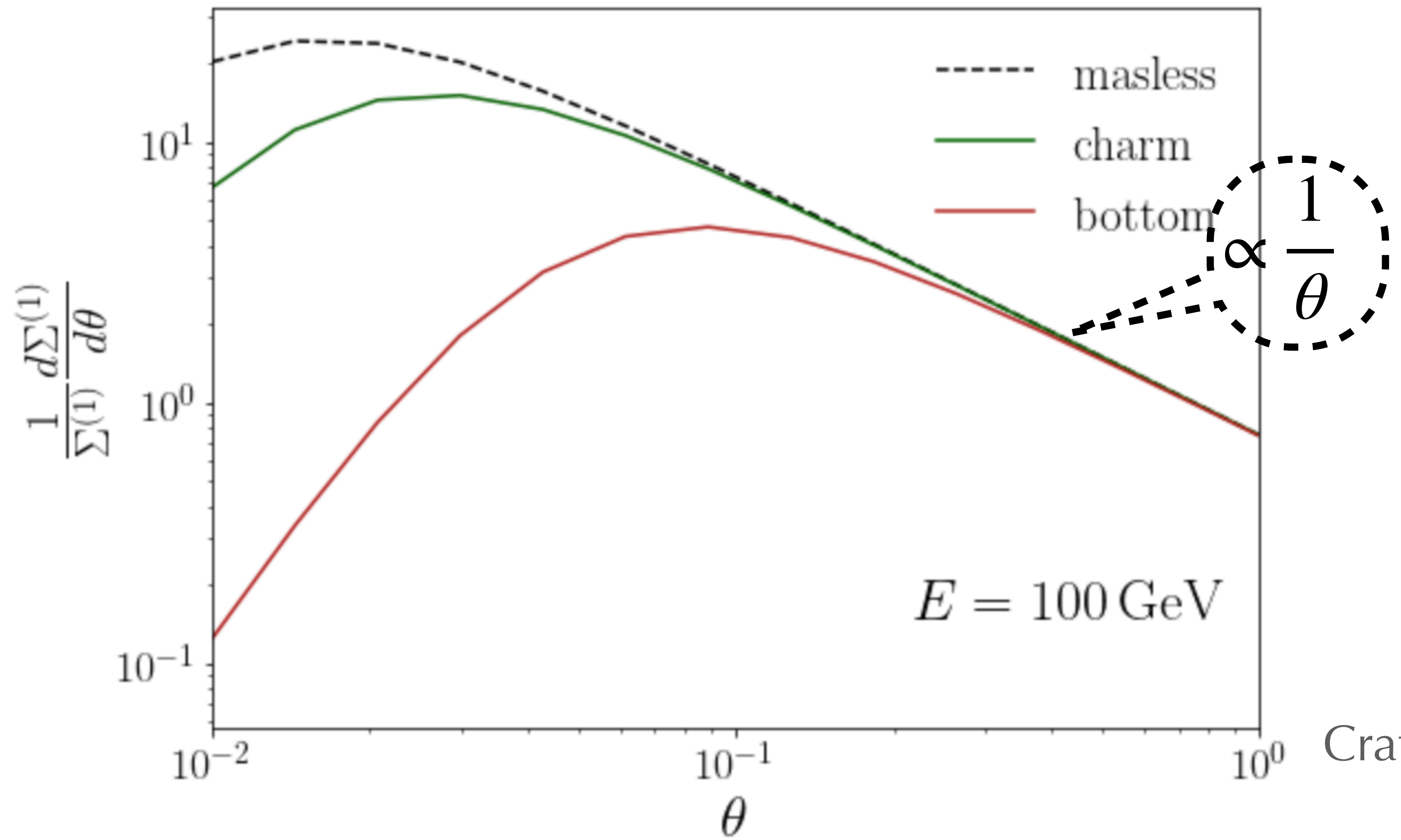
- **Dead-cone effect**: collider radiation off heavy quarks is suppressed at small angles
- Dead-cone angle: $\Theta_0 \propto \frac{m_Q}{E_Q}$
- $m_Q > \Lambda_{QCD}$: **deviation from power-law behavior in the pQCD regime**




Craft, Lee, Meçaj, Moult, arXiv:2210.09311

# EEC in HF p-p jets

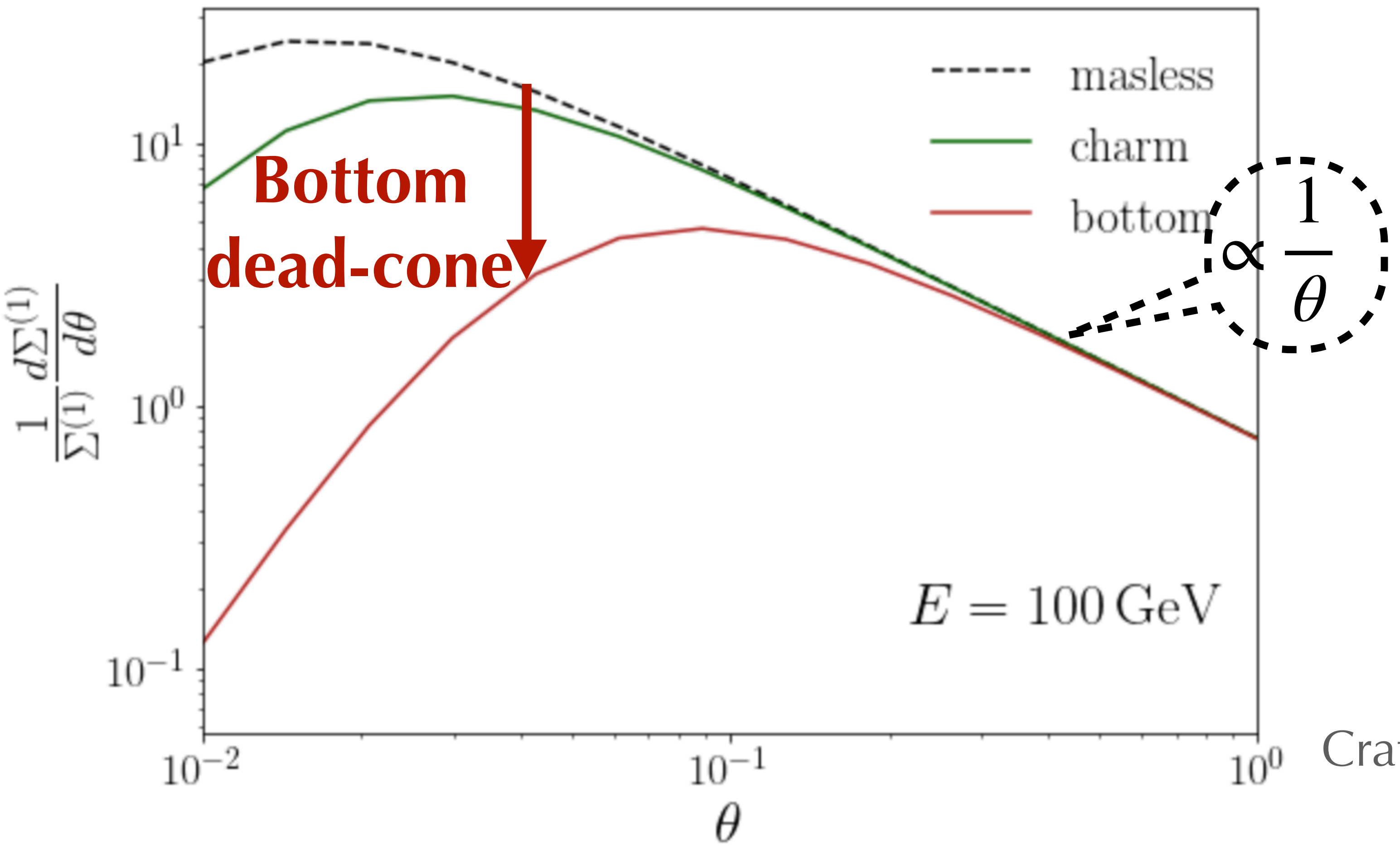
- **Dead-cone effect**: collider radiation off heavy quarks is suppressed at small angles
- Dead-cone angle: $\Theta_0 \propto \frac{m_Q}{E_Q}$
- $m_Q > \Lambda_{QCD}$: **deviation from power-law behavior in the pQCD regime**




Craft, Lee, Meçaj, Moult, arXiv:2210.09311

# EEC in HF p-p jets

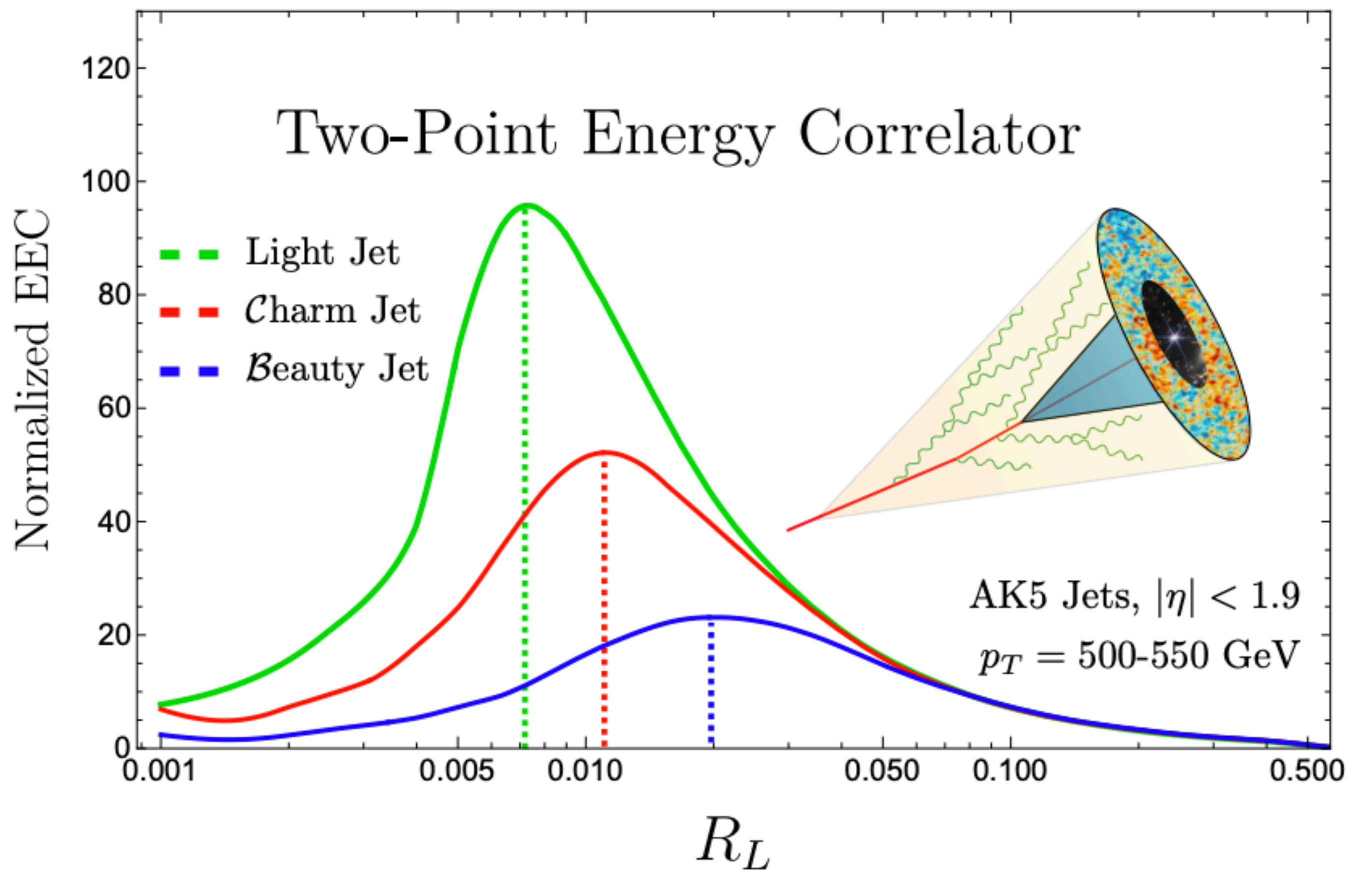
- **Dead-cone effect**: collider radiation off heavy quarks is suppressed at small angles
- Dead-cone angle: $\Theta_0 \propto \frac{m_Q}{E_Q}$
- $m_Q > \Lambda_{QCD}$: **deviation from power-law behavior in the pQCD regime**




Craft, Lee, Meçaj, Moult, arXiv:2210.09311

# EEC in HF p-p jets

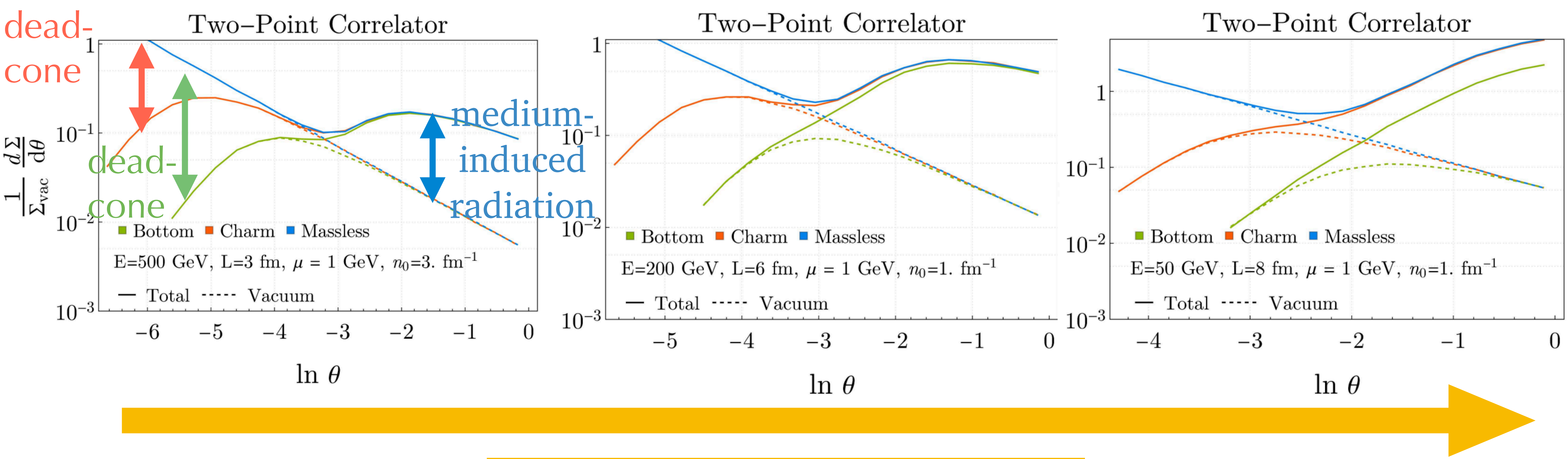
- **Dead-cone effect**: collider radiation off heavy quarks is suppressed at small angles
- Dead-cone angle: $\Theta_0 \propto \frac{m_Q}{E_Q}$
- $m_Q > \Lambda_{QCD}$: **deviation from power-law behavior in the pQCD regime**




Results from ALICE expected in the next few months!

Craft, Lee, Meçaj, Moult, arXiv:2210.09311

# HF jets: filling the dead-cone




Armesto, Salgado, Wiedemann, arXiv: hep-ph/0312106

$\frac{\theta_L}{\Theta_0} \to 1$: Filling the dead-cone

EEC sensitive to t**two different scales**: HQ mass and onset of medium-induced radiation

CA, Dominguez, Holguin, Marquet, I. Moult, 2307.15110

# Conclusions

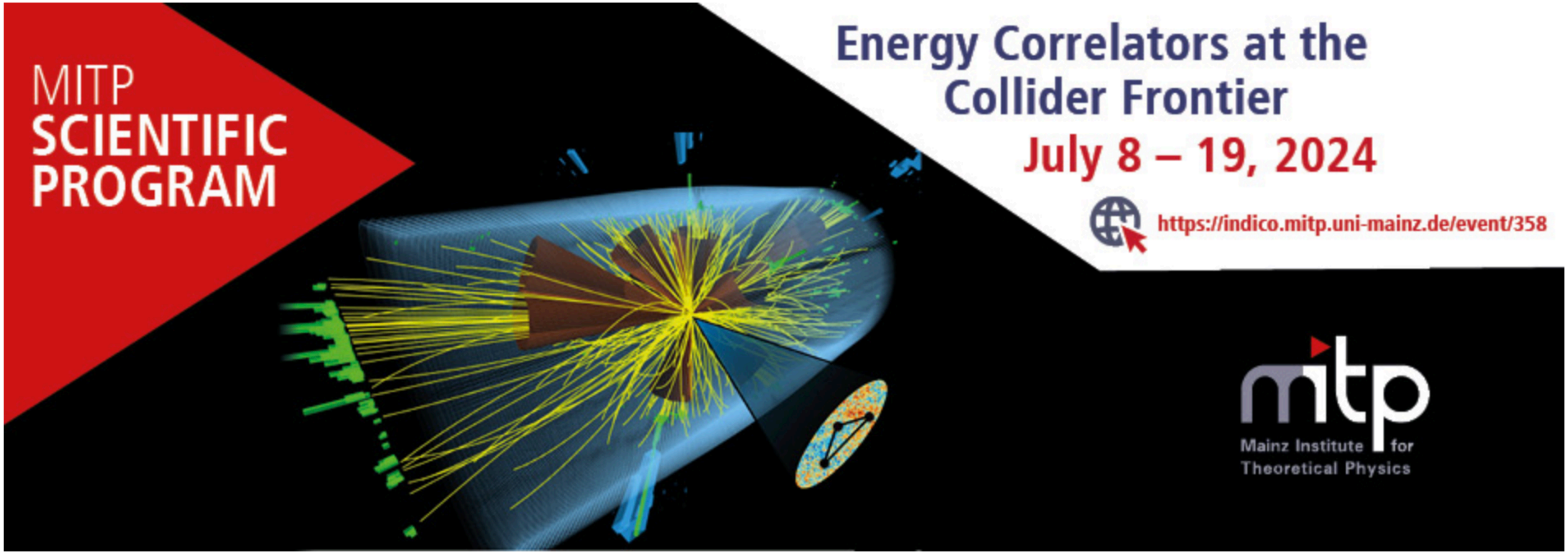
- **QCD collectivity at experimental reach** at RHIC and the LHC
  - Continuous progress on the characterization of the QGP
  - Many interesting questions to be answered in the next 15 years of HICs

**How does a strongly-coupled fluid emerge from an asymptotically free gauge theory?**

- Use **jets as *microscope* of the QGP**

- **Energy Correlators:** great potential for jet substructure studies of the QGP

- Many theoretical developments and experimental measurements on EECs to come!



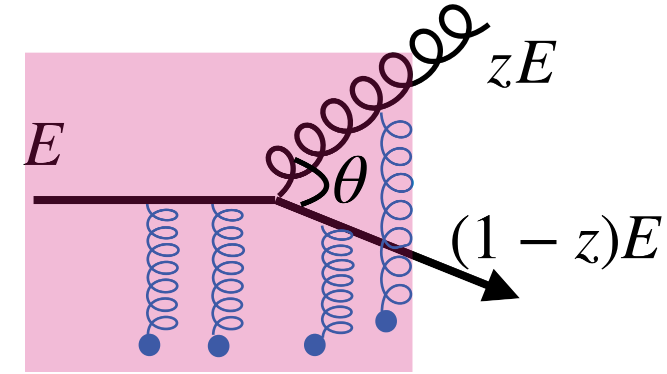

**Energy Correlators at the Collider Frontier**, Mainz Institute for Theoretical Physics

CA (LIP, Lisbon), Jack Holguin (Manchester U.), Aditya Pathak (DESY), and Massimiliano Procura (U. of Vienna)

indico link

# Merci!

# EEC in HICs




- EEC for a **heavy-ion** jet initiated by a **massless quark:**

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

- We can always define $F_{\text{med}}$ such as

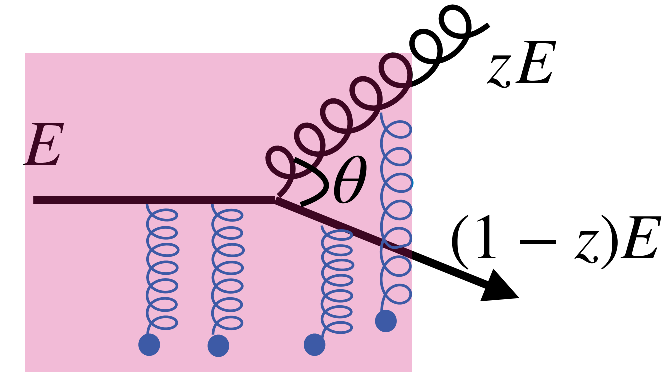
$$\frac{d\sigma_{qg}}{d\theta dz} = \left(1 + F_{\text{med}}(z,\theta)\right) \frac{d\sigma_{qg}^{\text{vac}}}{d\theta dz} \qquad F_{\text{med}}(z,\theta) \xrightarrow{\theta<\theta_L} 0$$

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

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

$$g^{(1)}(\theta,\alpha) = \theta^{\gamma(3)} + \mathcal{O}(\theta) \quad \Longrightarrow \quad \frac{d\Sigma^{(1)}}{d\theta} \sim \frac{1}{\theta^{1-\gamma(3)}}^{\text{vac}}$$

# EEC in HICs




- EEC for a **heavy-ion** jet initiated by a **massless quark:**

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

- We can always define $F_{\text{med}}$ such as

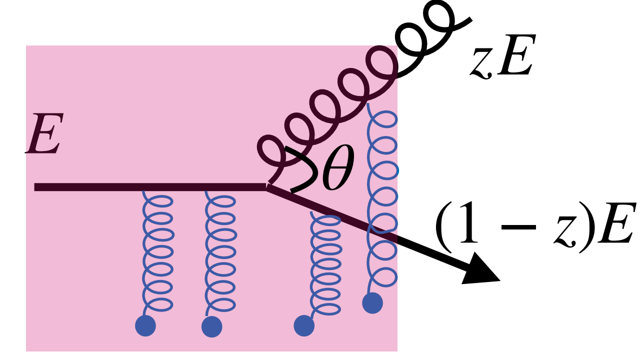
$$\frac{\mathrm{d}\sigma_{qg}}{\mathrm{d}\theta dz} = \left(1 + F_{\text{med}}(z,\theta)\right) \frac{\mathrm{d}\sigma^{\text{vac}}_{qg}}{\mathrm{d}\theta dz} \qquad\qquad F_{\text{med}}(z,\theta) \xrightarrow{\theta<\theta_L} 0$$

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

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

$$g^{(1)}(\theta, \alpha) = \theta^{\gamma(3)} + \mathcal{O}(\theta) \quad \Rightarrow \quad \frac{d\Sigma^{(1)}}{d\theta} \sim \frac{1}{\theta^{1-\gamma(3)}}^{\text{vac}}$$

# Our idealized model




- Multiple medium scatterings destroy the color coherence between the daughter partons
- Complete (multiple scatterings) medium-induced emission spectrum keeping $z$ and $\theta$ not yet available

  Recent results for the $\gamma \to q\bar{q}$ case (computationally costly) Isaksen, Tywoniuk, 2303.12119

  - We **use** a ***semi-hard*** splittings ($z$ not too small) Dominguez, Milhano, Salgado, Tywoniuk, Vila, 1907.03653
  - All partons propagate along straight line trajectories Isaksen, Tywoniuk 2107.02542
- **Static brick** with length $L$
- **Harmonic oscillator** (HO) approximation employed $n\sigma(r) \approx \hat{q}r^2/2$
- The strength of the interactions is encoded in the **jet quenching parameter** $\hat{q}$, which measures the average transverse momentum transferred per unit length

# Time and angular scales (HO)

- For a static medium of length $L$ within the HO one can read off the relevant scales directly from the formulas:
- 2 competing angular scales: $\theta_L$ and $\theta_c$
  - (Vacuum) formation time:

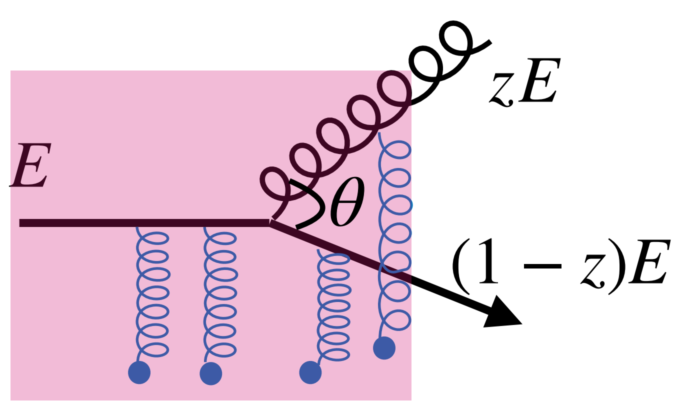
$$t_f = \frac{2}{z(1-z)E\theta^2} \xrightarrow{t_f \leq L} \theta_L \sim (EL)^{-1/2}$$

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

  - Decoherence time:

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

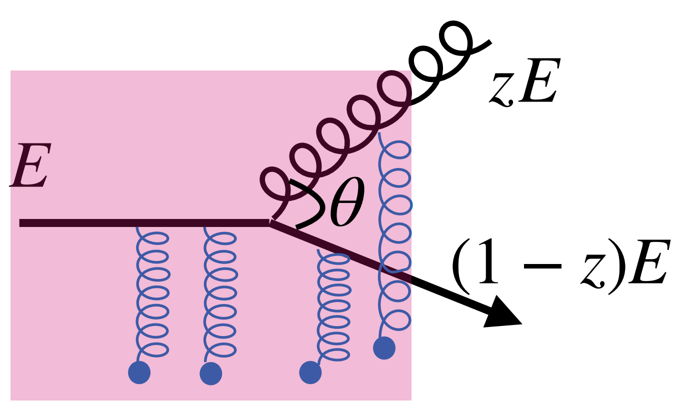
Below $\theta_c$ splittings do not color decohere and the medium does not resolve them




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

# Time and angular scales (HO)

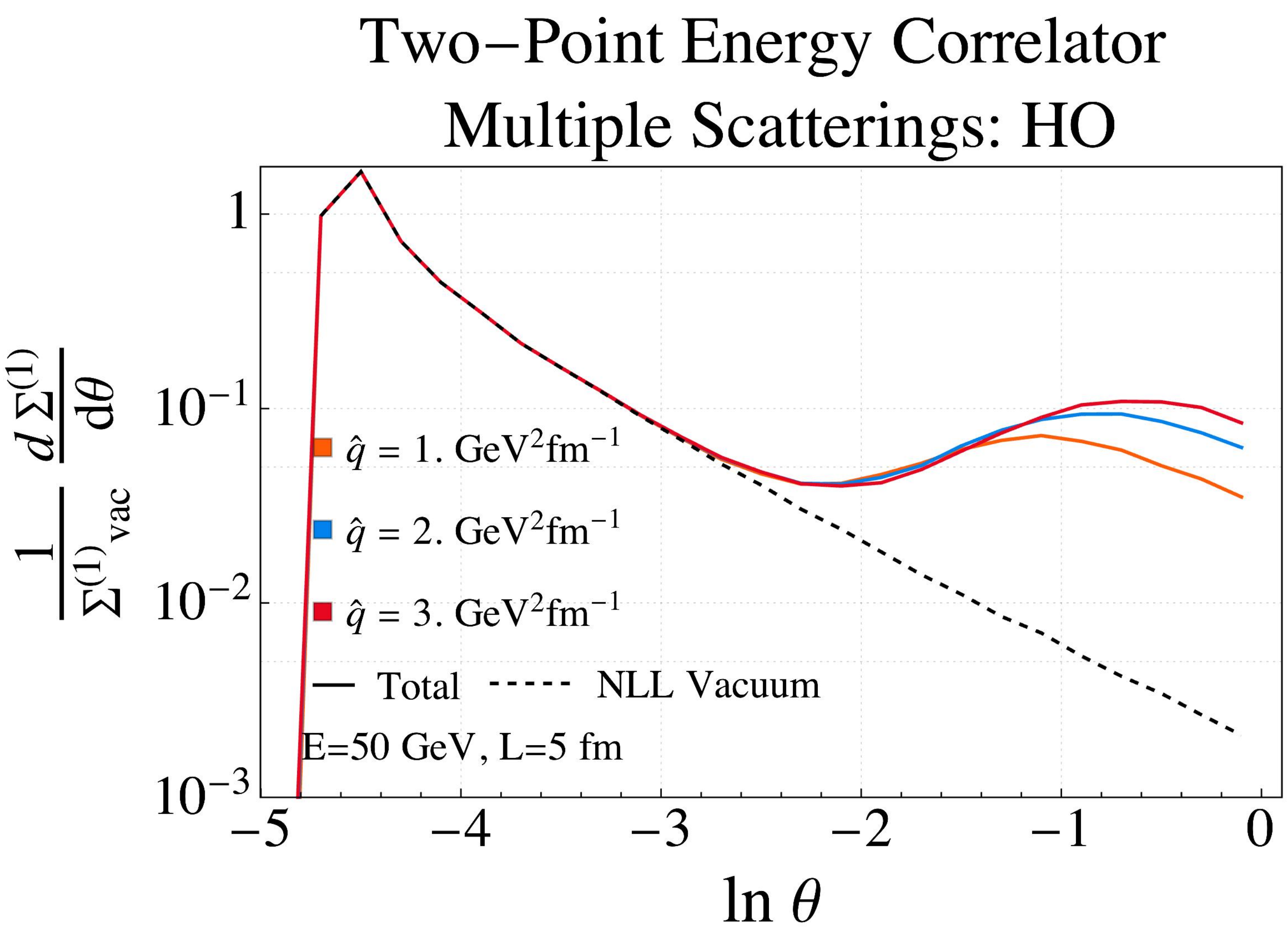
**Can be extended** to include a more **realistic interactions or expanding media**, but then we would not know the scales directly from the equations



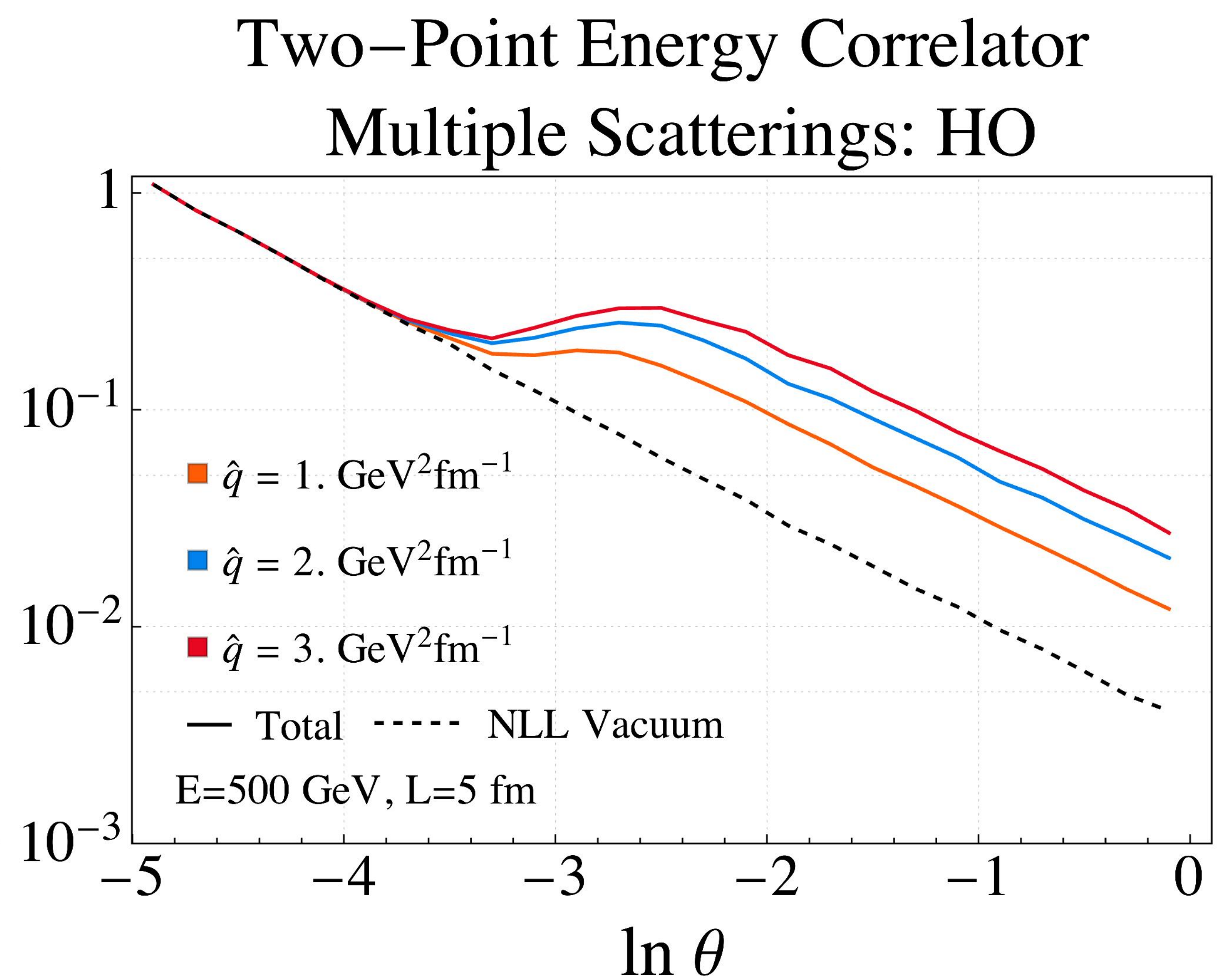

If $\theta_L > \theta_c$: $\theta_c$ becomes irrelevant

# Results HO

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

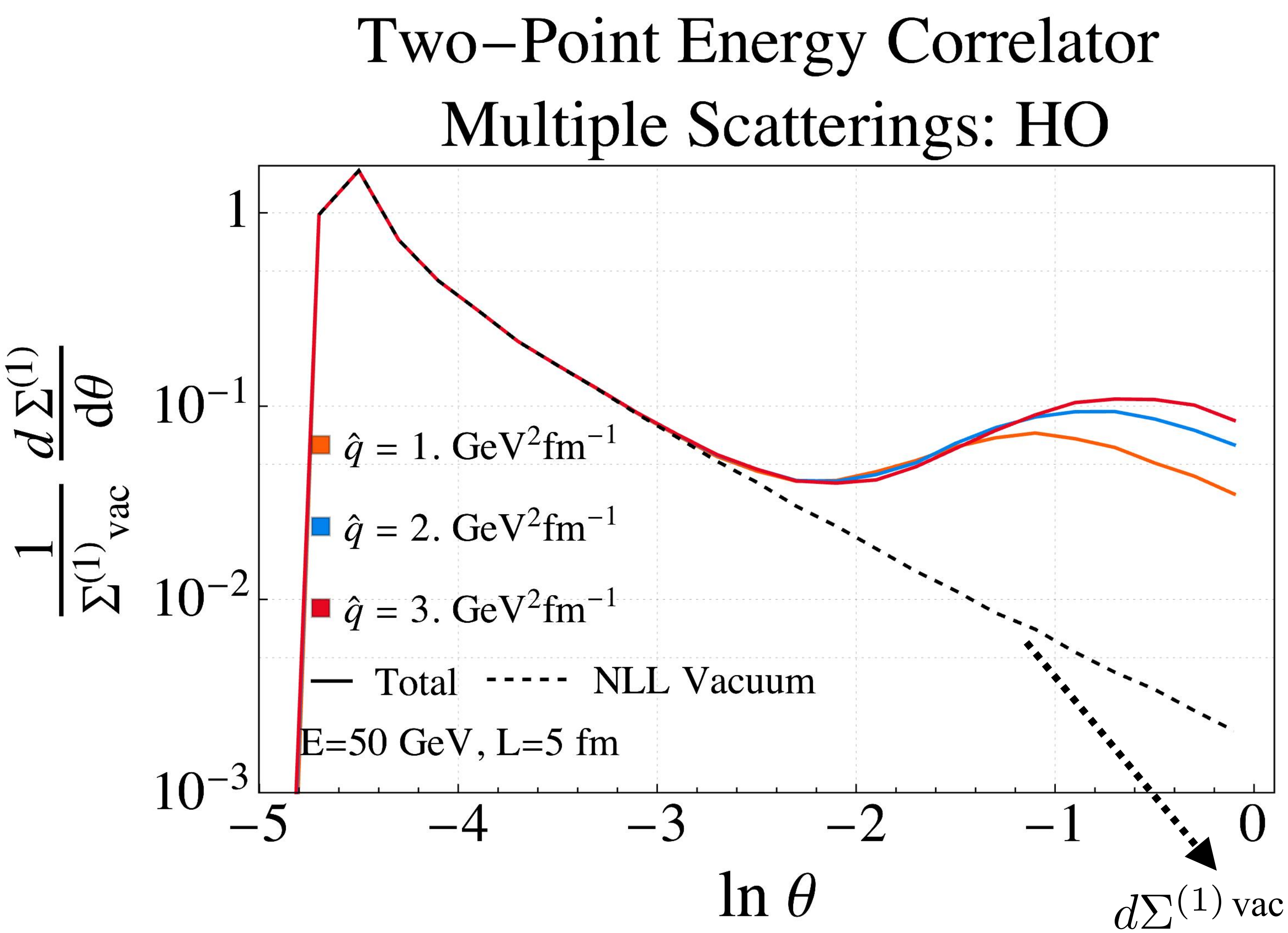



$\theta_L \ll \theta_c \ (E \gg \hat{q}L^2)$



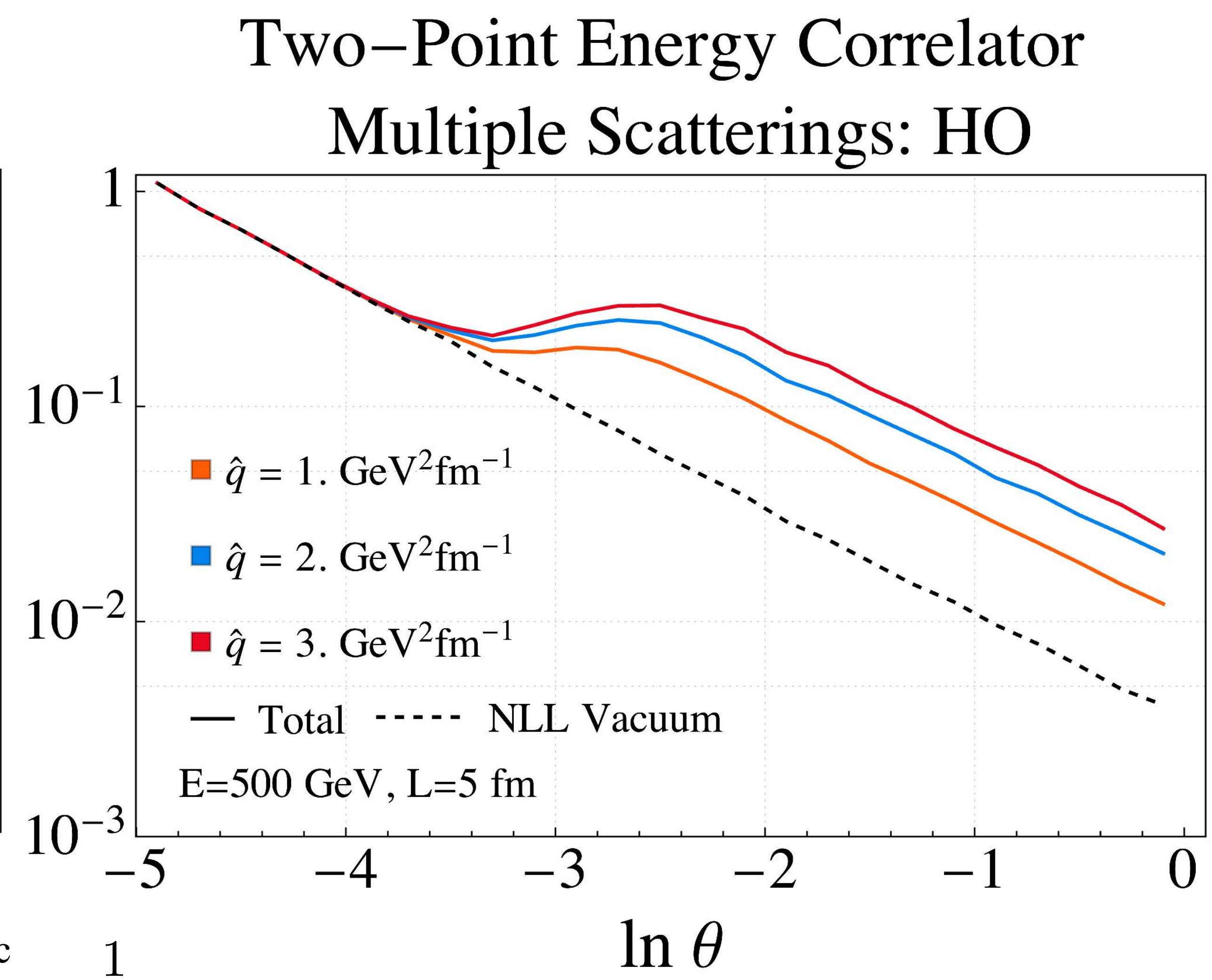
# Results HO

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




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

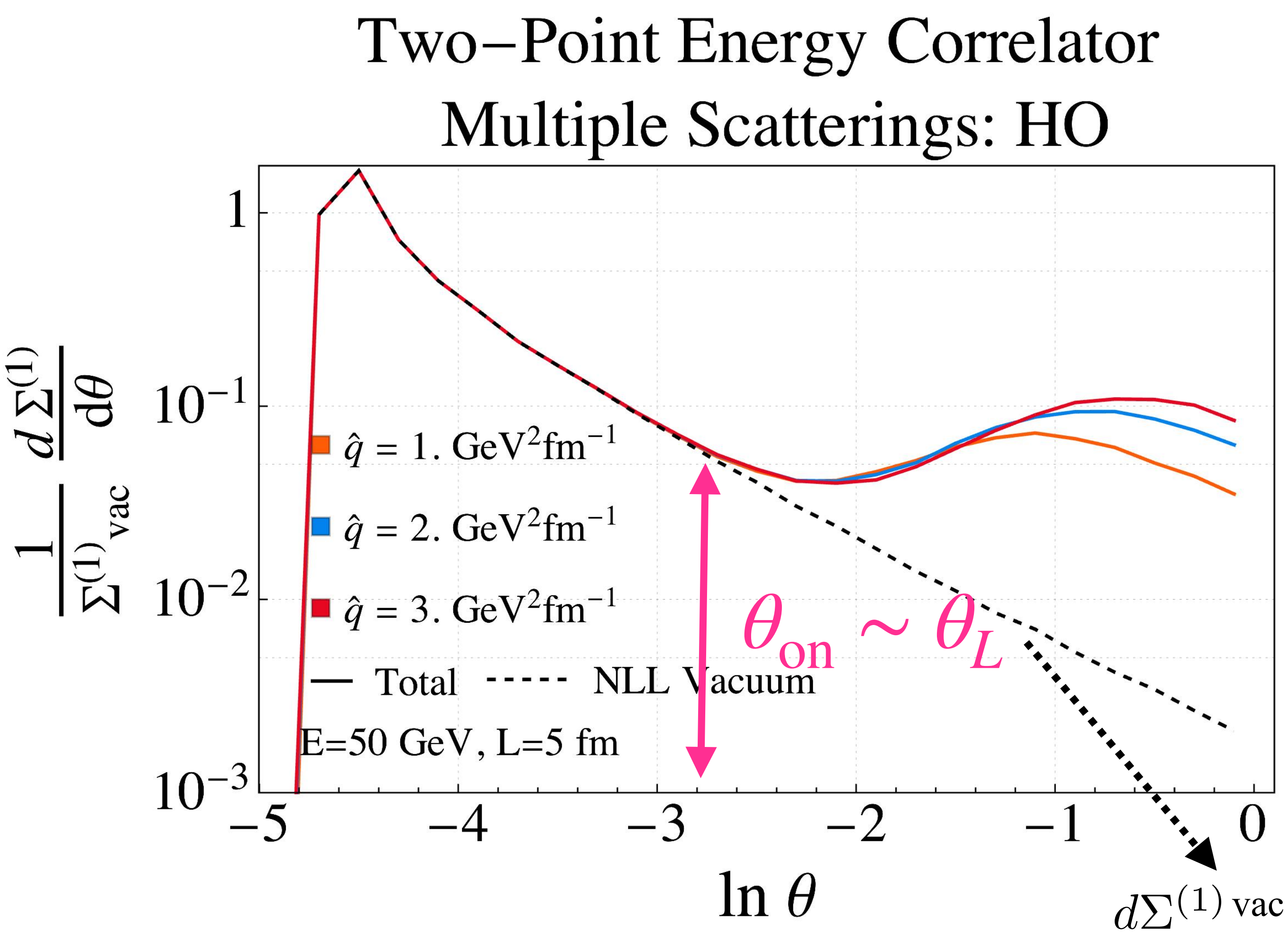
$\theta_L \ll \theta_c \left(E \gg \hat{q}L^2\right)$



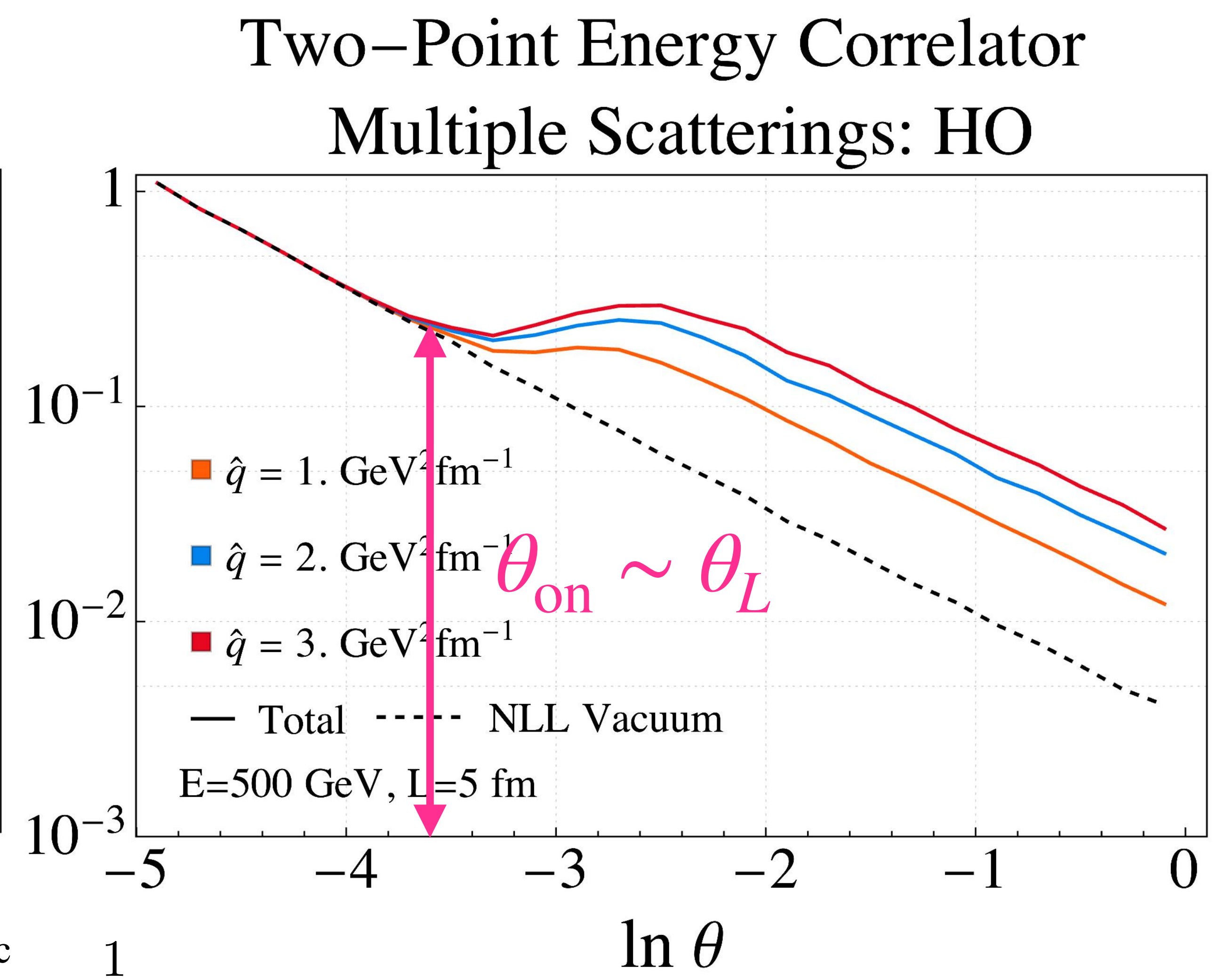

- **No** medium-induced enhancement at **small angles**

# Results HO

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




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

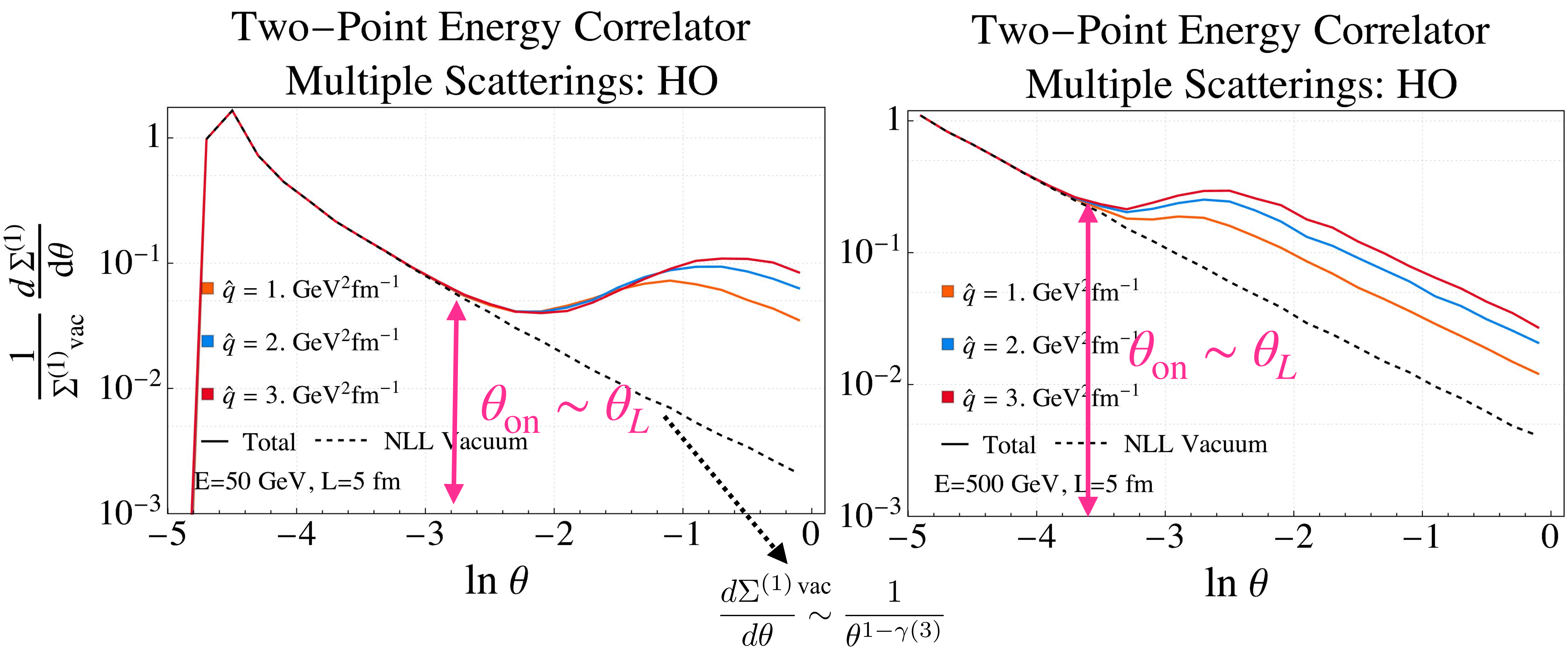



$$\frac{d\Sigma^{(1)\,\mathrm{vac}}}{d\theta} \sim \frac{1}{\theta^{1-\gamma(3)}}$$

- **No** medium-induced enhancement at **small angles**
- Onset angle seems to be independent of $\hat{q}$

# Results HO

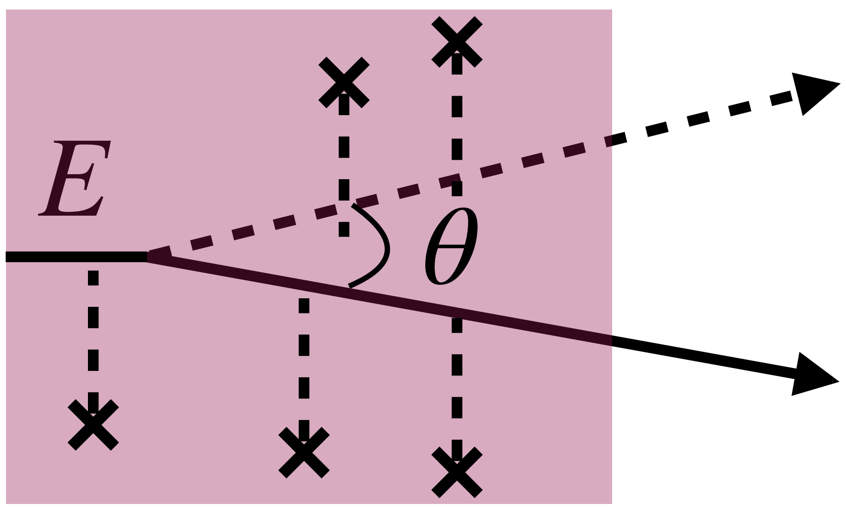
$\theta_L \gg \theta_c \left(E \ll \hat{q}L^2\right)$ $\theta_L \ll \theta_c \; \left(E \gg \hat{q}L^2\right)$




- **No** medium-induced enhancement at **small angles**
- Onset angle seems to be independent of $\hat{q}$
- Varying $\hat{q}$ has different effects in the two regimes

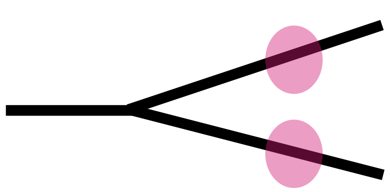
# Interpretation

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

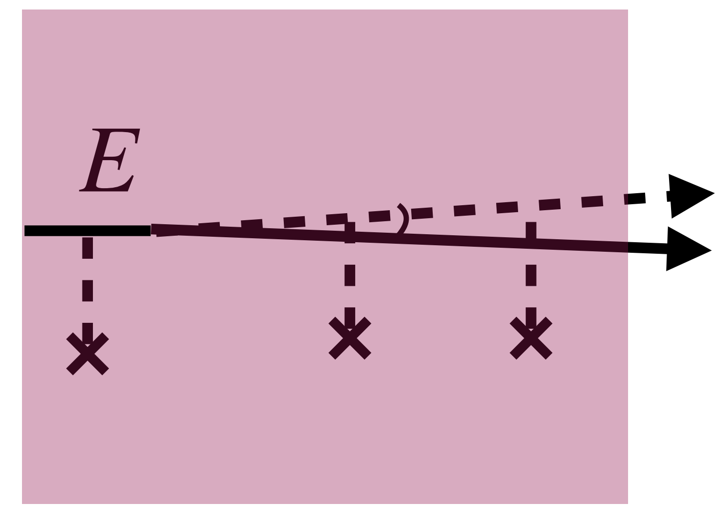



For $\theta \gg \theta_L \Rightarrow \theta \gg \theta_c$

The medium resolves the emission

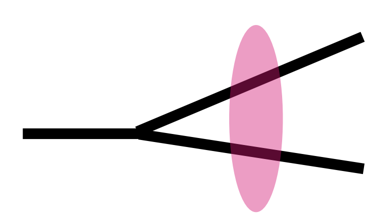


$\theta_L \ll \theta_c \quad (E \gg \hat{q}L^2)$

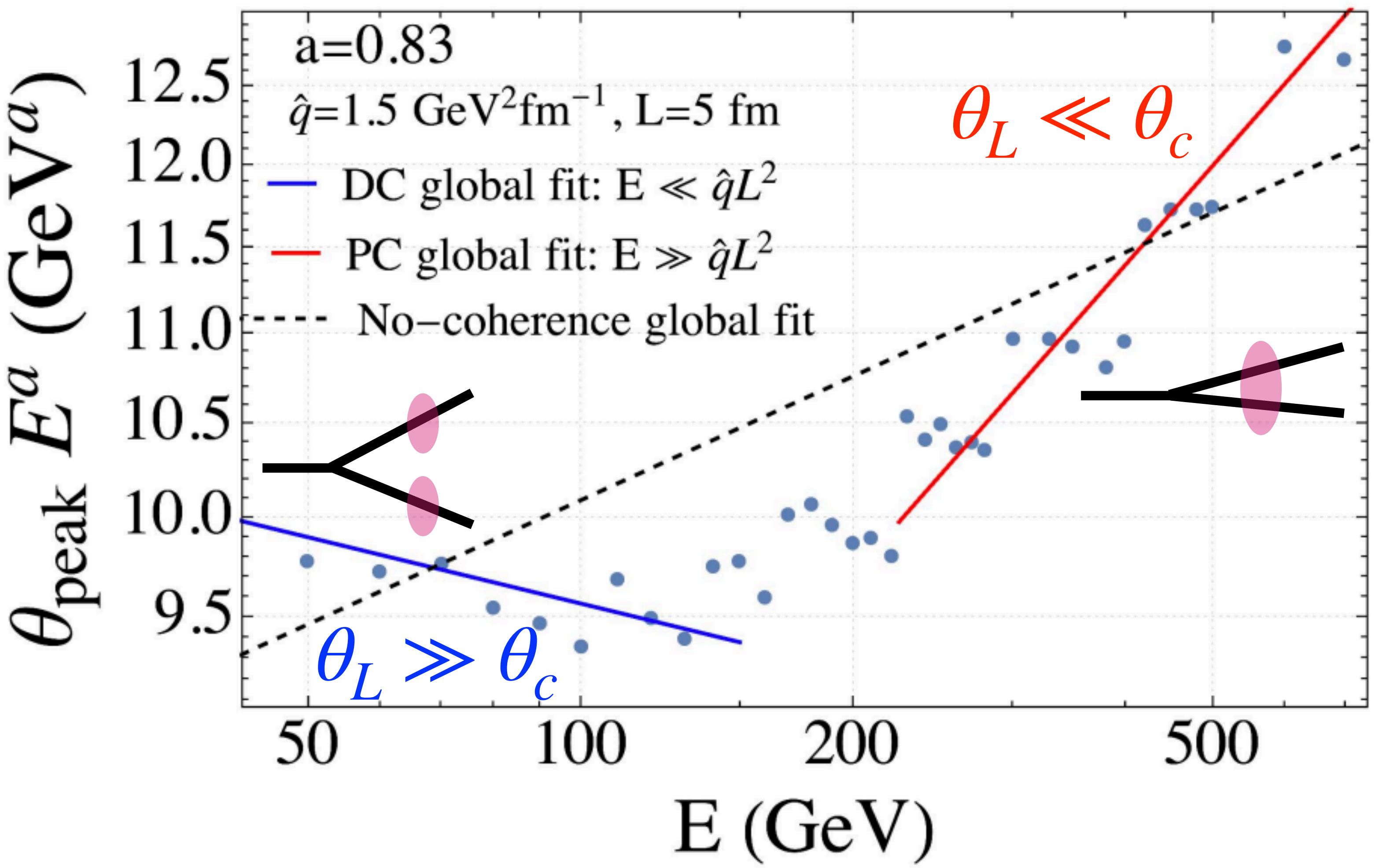



For $\theta_c \gg \theta \gg \theta_L$:

The medium does NOT resolve the emission



# Coherence transition




- Extracted the peak angle $\theta_{\rm peak}$ 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

# 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

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