The Quark-Gluon Plasma through Energy Correlators

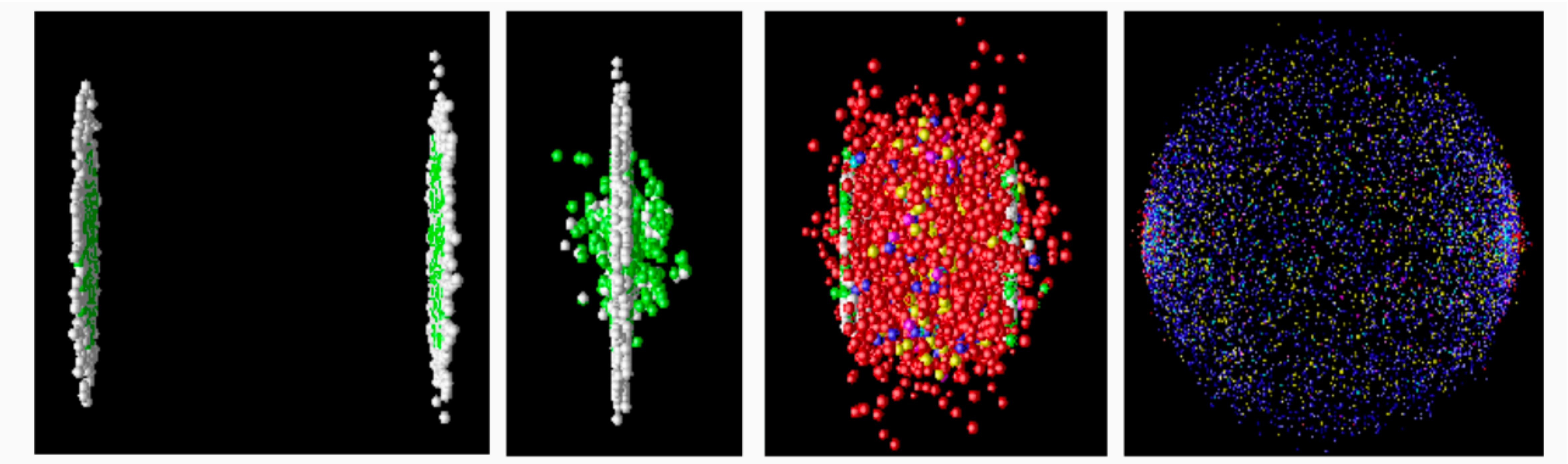
Carlota Andres (she/her)

LIP, Lisbon

LIP, Lisbon, February 28, 2024

Heavy-ion collisions

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



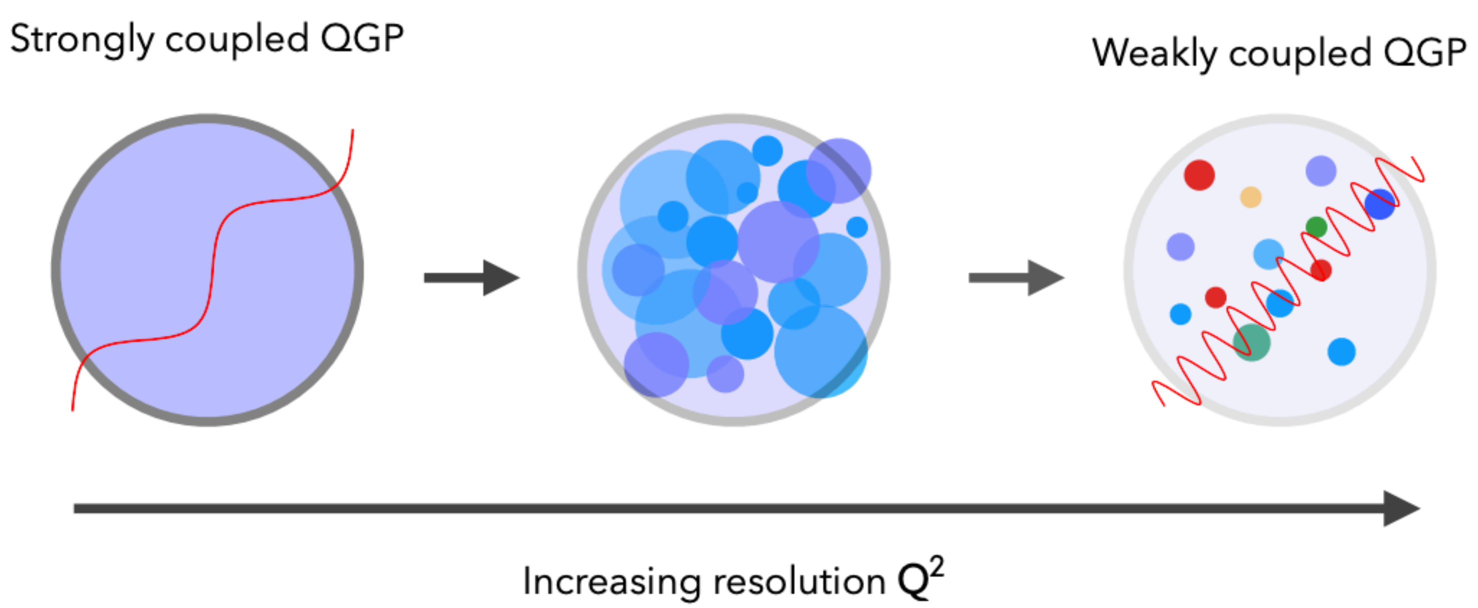
- Extremely high temperatures are achieved (300-500 MeV/trillions of ºC):
    - quarks and gluons are **deconfined**
    - new state of matter: **quark-gluon plasma (QGP)!**
- Behaves as a liquid: very well described by relativistic hydrodynamics

Very small η/s: **most strongly-coupled** fluid in Nature

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

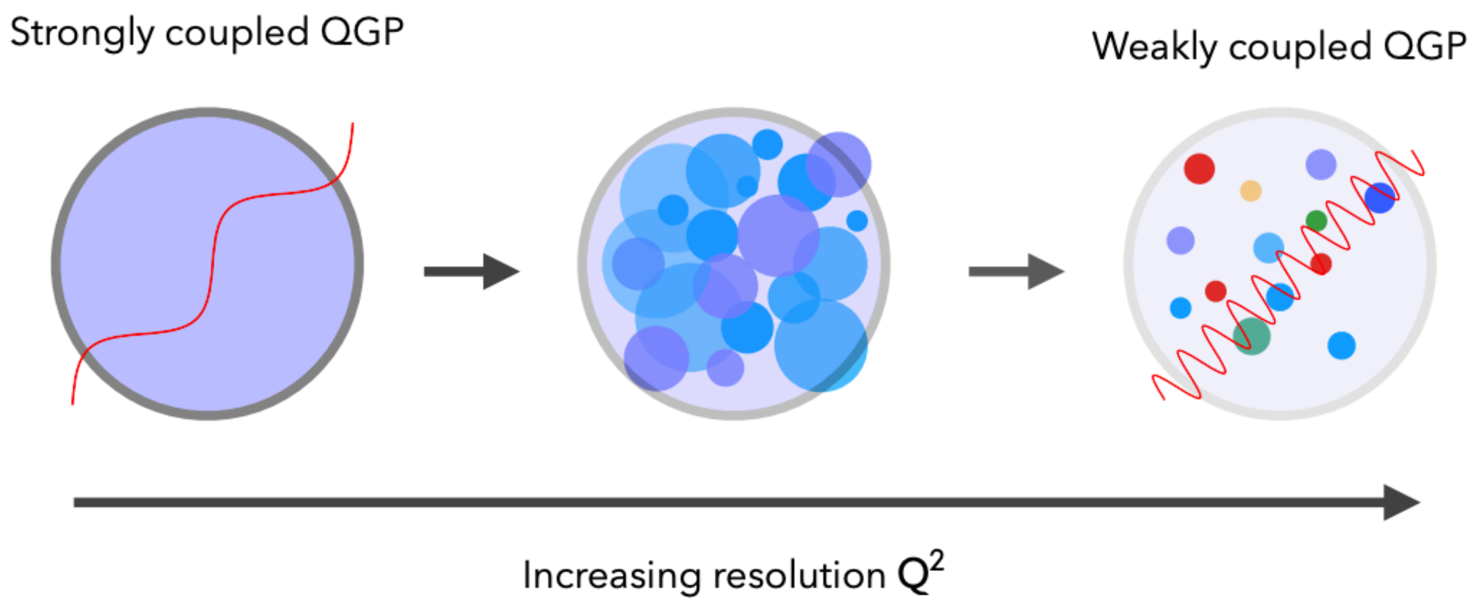
How does a **strongly-coupled fluid** emerge from the **weakly-coupled quarks and gluons**?

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



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

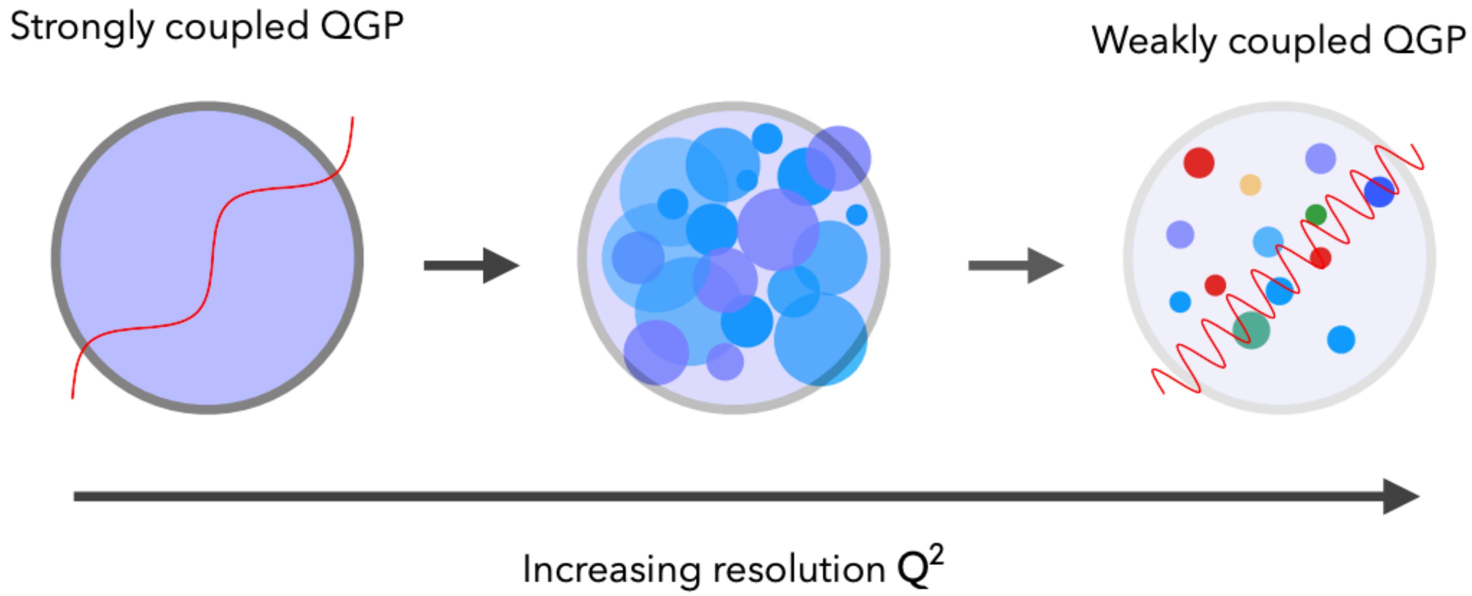
We must probe the QGP at **various resolution scales**



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**



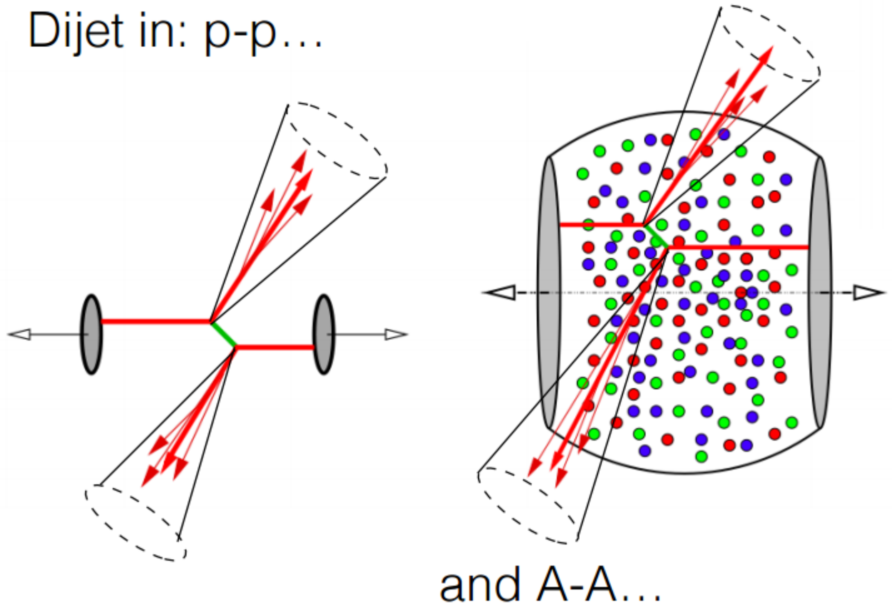
QGP **too short-lived** for external probes: need of **multi-scale probes produced in the same collision as the QGP**:

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

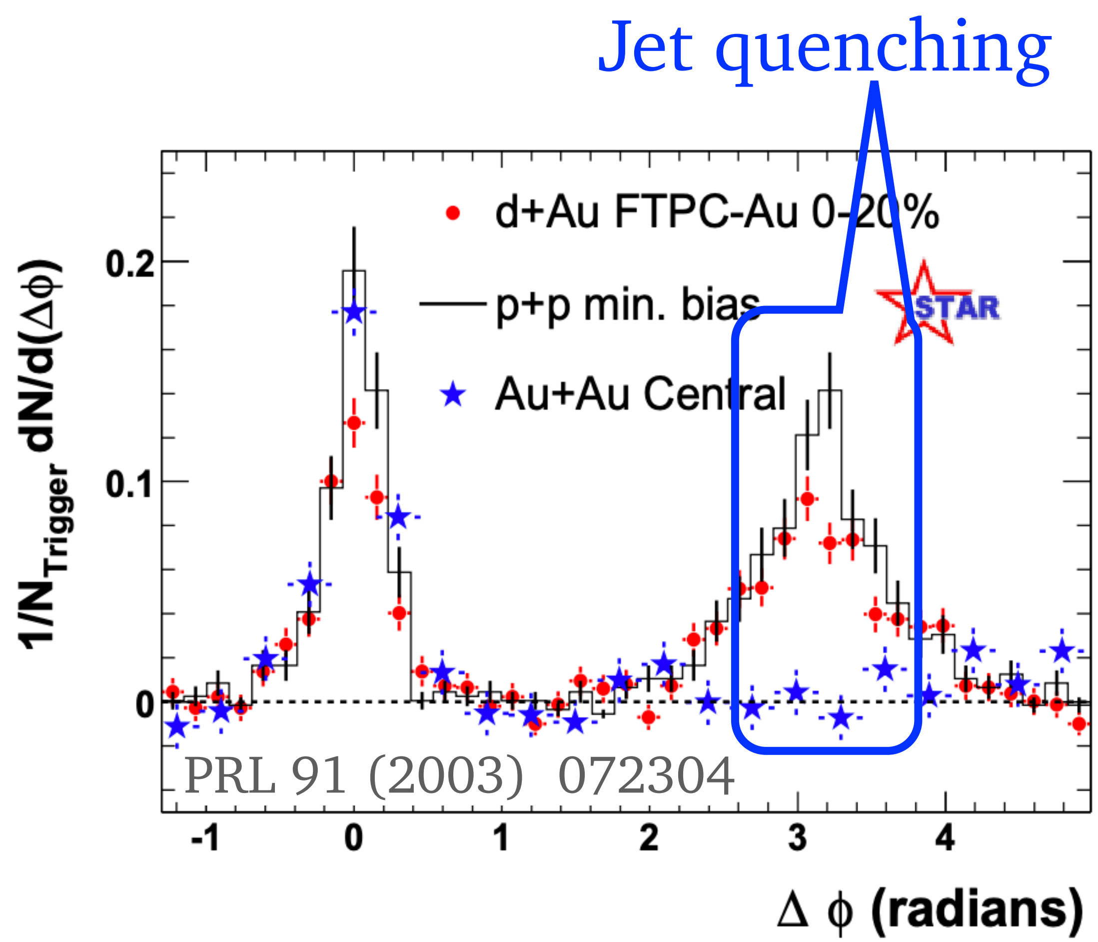
- **Multi-scale** objects: broad range of momentum and spatial scales involved in the jet evolution

- **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**

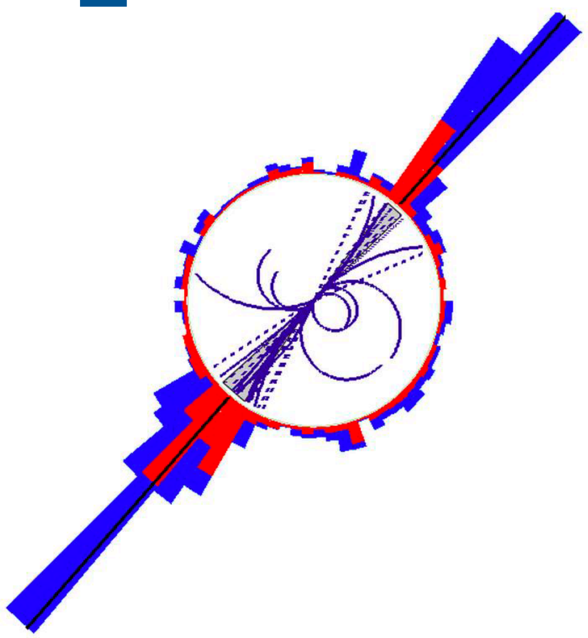


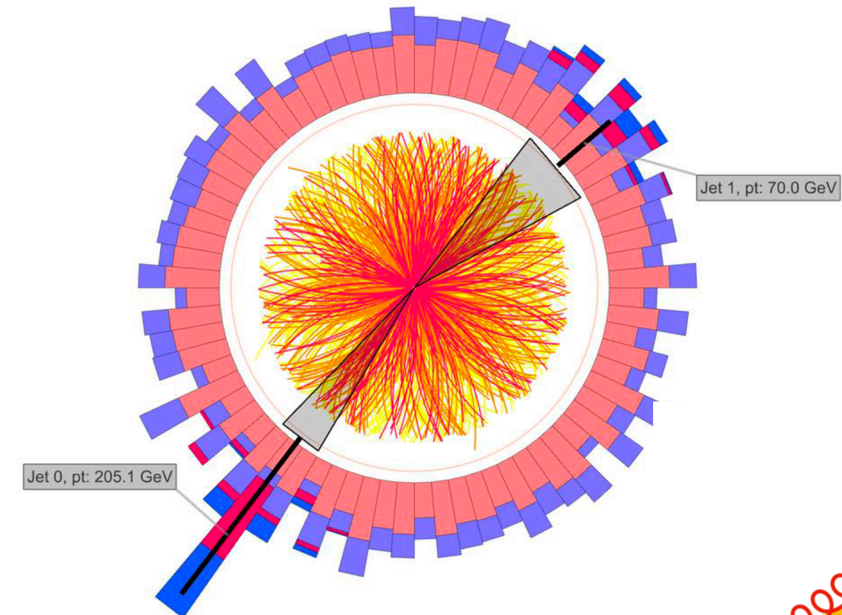
- In principle: under control in p-p collisions

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

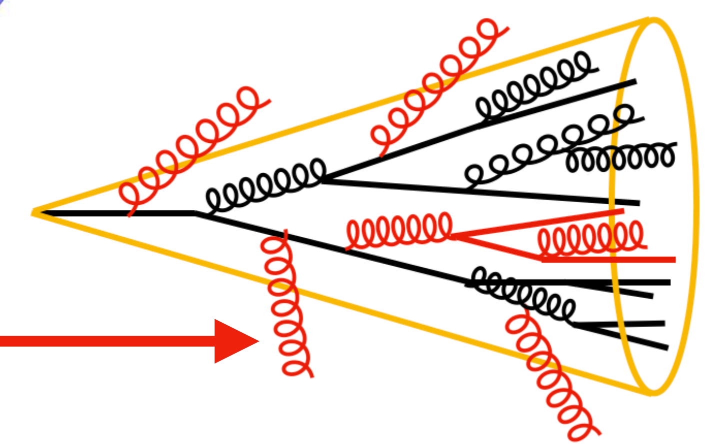
- **Multi-observable**: different observable jet properties sensitive to different QGP scales and properties?

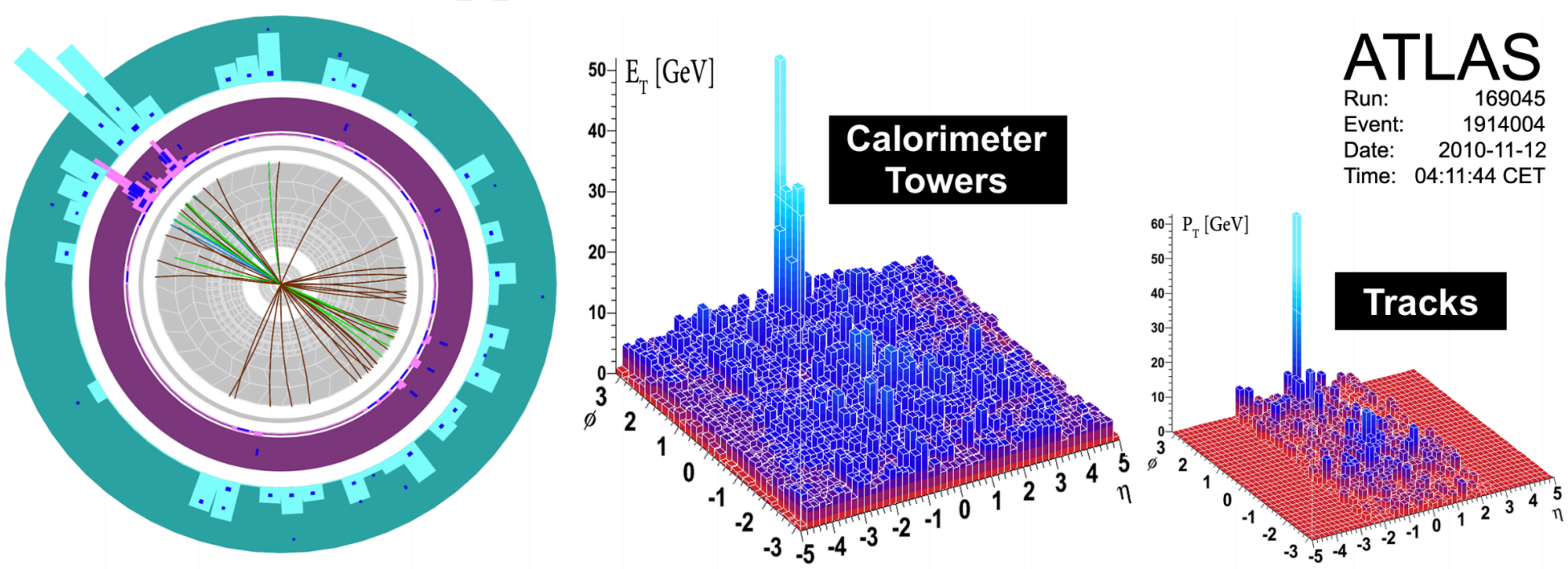
Jet quenching





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





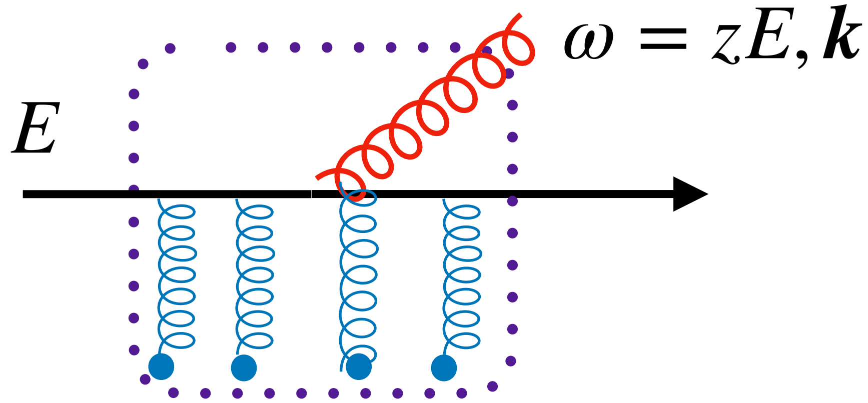
Medium-induced radiation

- The main contribution to energy loss in the QGP is radiative energy loss
  Dominant for light quarks and gluons

High-energy partons experience **multiple scatterings with the medium** which induce **extra gluon radiation** (w.r.t. p-p)

- During the formation time of the gluon **multiple scatterings** act **coherently**

LPM effect $t_f \sim \frac{\omega}{\boldsymbol{k}^2}$



Suppression of the spectrum for **large formation times**

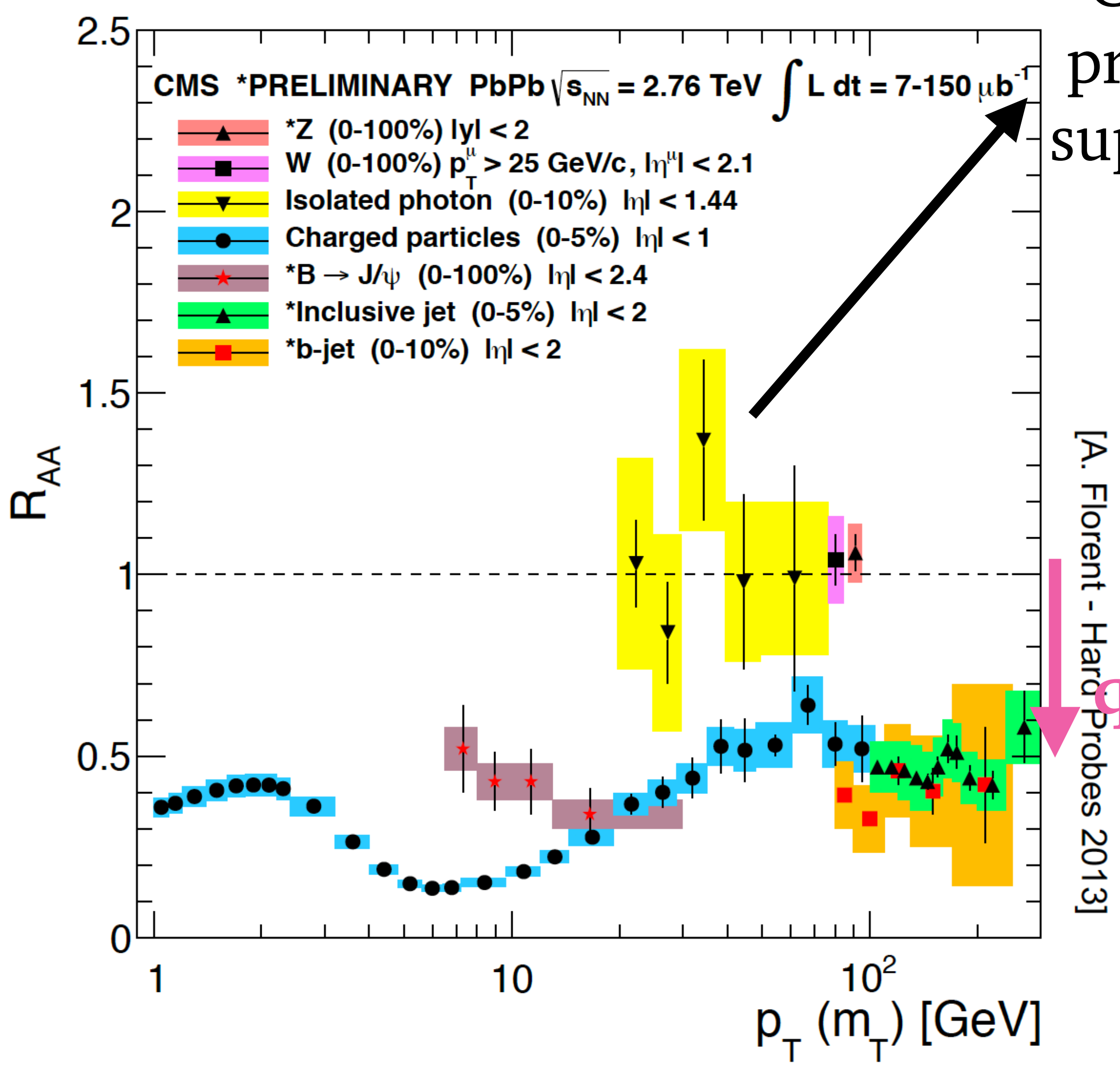
- Resummation of multiple scatterings: **BDMPS-Z formalism (1990's)**

CA, **Apolinário (LIP)**, Martinez, Dominguez,
2002.01517, 2011.06522, 2307.06226

Hadron suppression

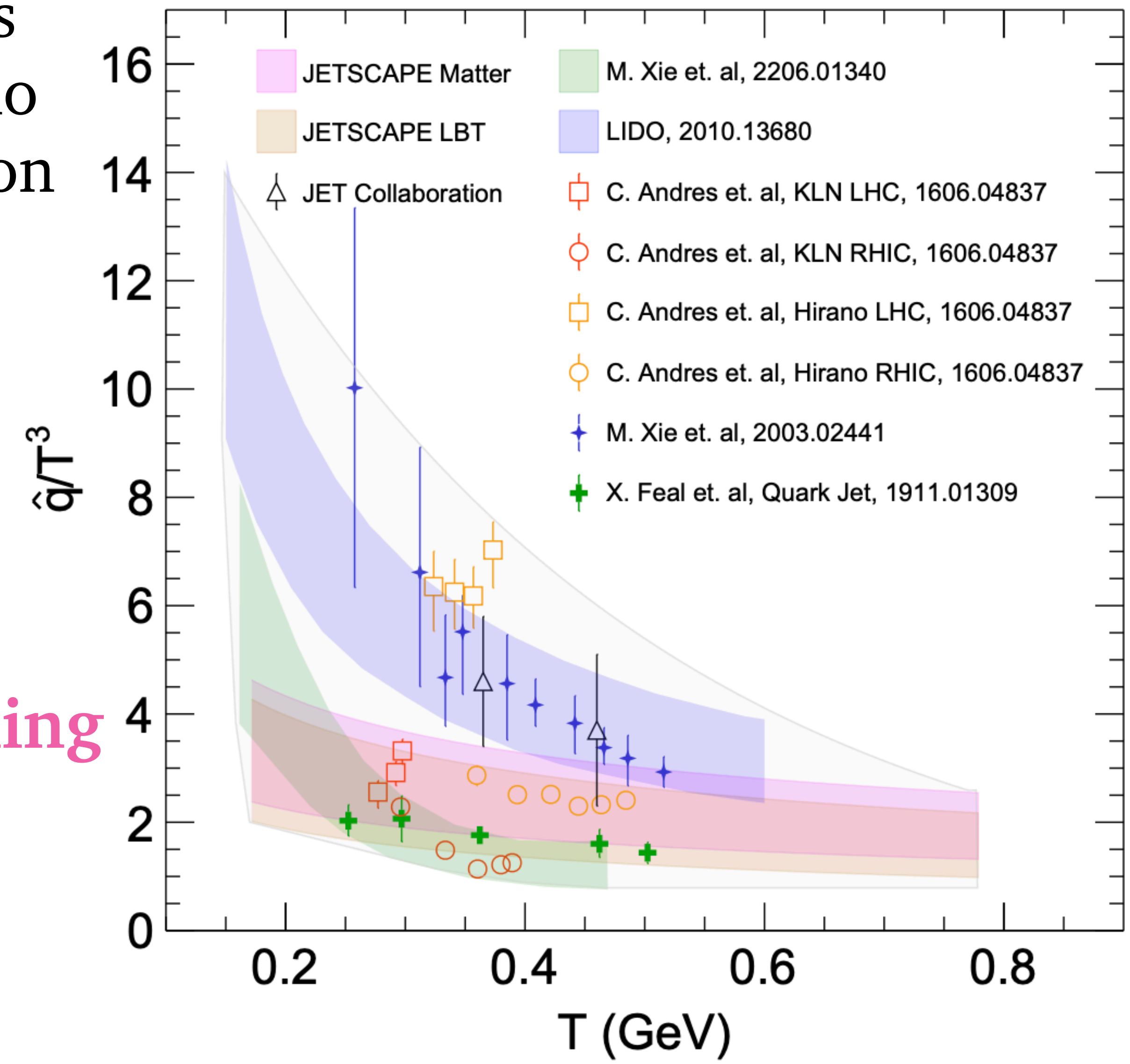
- Traditionally, jet quenching aimed at extracting **properties of the QGP**
- $\hat{q}$: average transverse momentum transfer per unit length

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



Colorless probes: no suppression

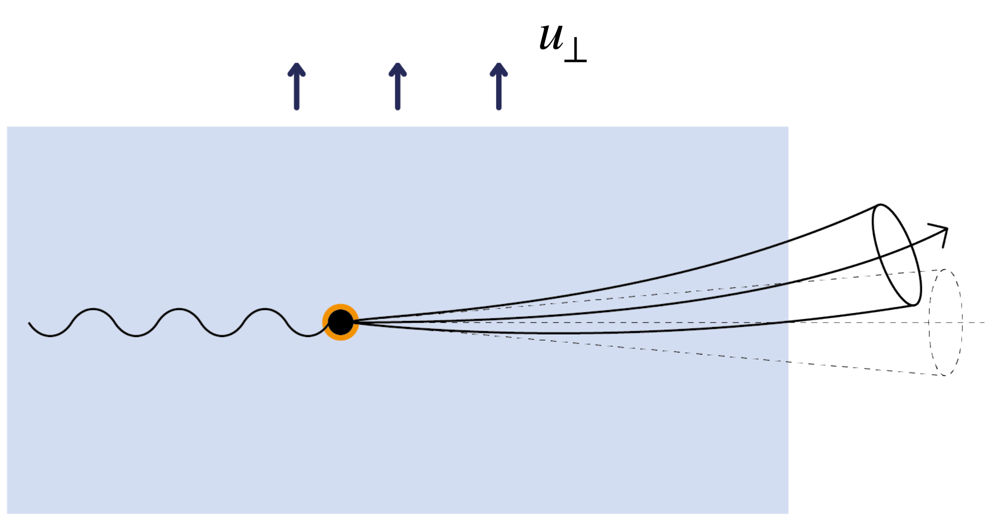
Jet quenching



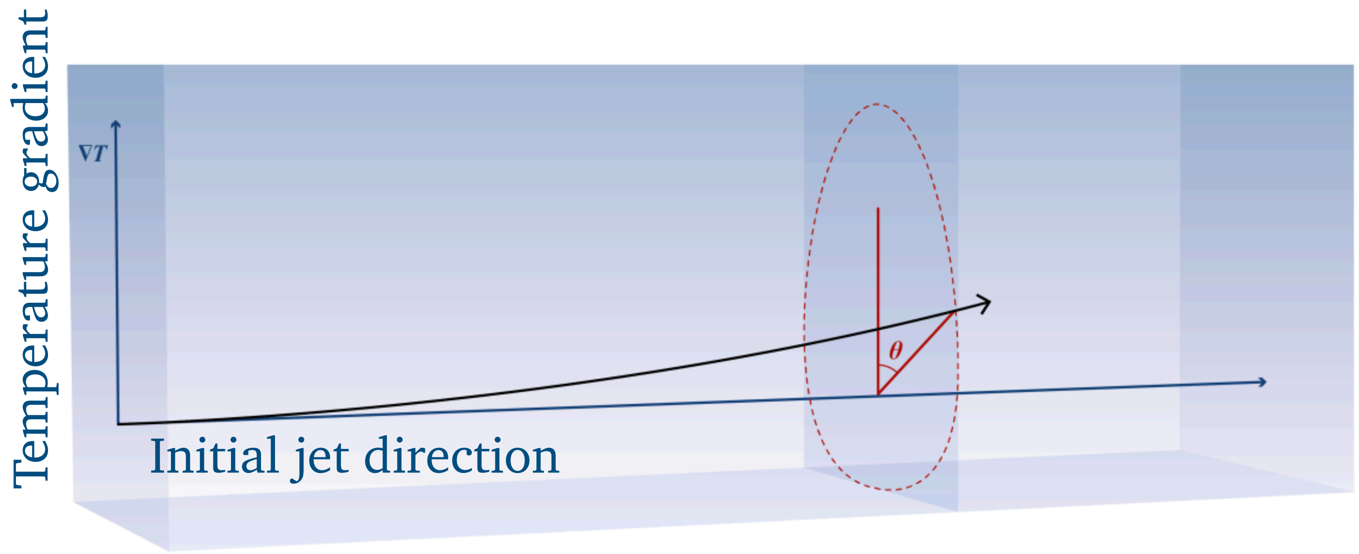
Apolinário (LIP), Lee, Winn, 2203.16352

Medium-induced radiation and transverse dynamics

- **Jets decouple** from the medium **transverse** dynamics in the **usual** (*eikonal*) **medium-induced approaches**



Uniform transverse flow



Transverse temperature gradients

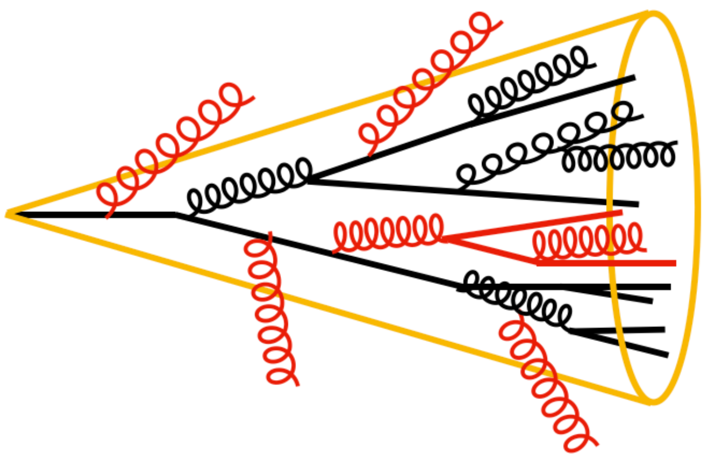
- Need of **generalizing** the medium-induced formalisms to account for $\mathcal{O}(1/\omega)$ *(subeikonal)* terms   **Sadofyev (LIP)**, Sievert, Vitev, 2104.09513

Barata, **Sadofyev (LIP)**, Wang 2210.06519

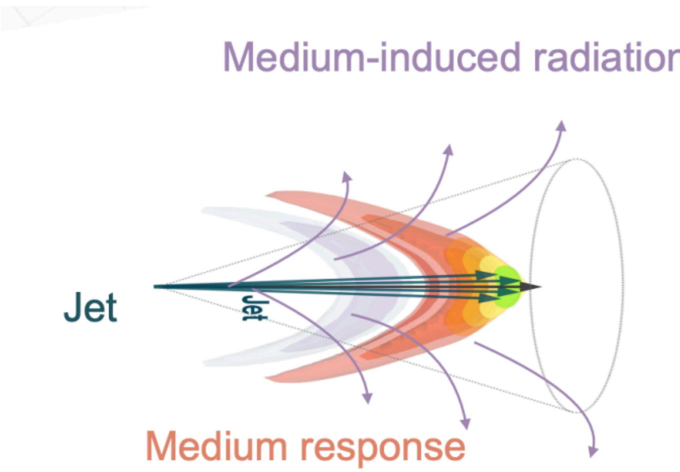
CA, Dominguez, **Sadofyev (LIP)**, Salgado, 2207.07141   Barata, Mayo López, **Sadofyev (LIP)**, Salgado, 2304.03712

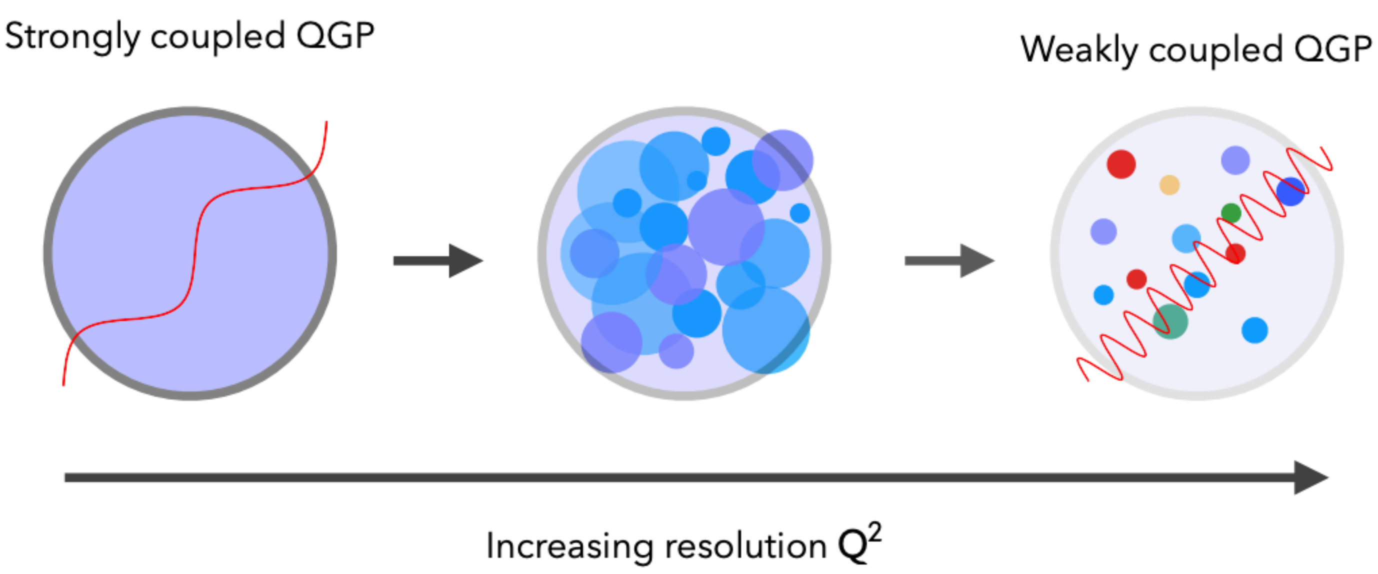
Kuzmin, Mayo López, and Reiten, and **Sadofyev (LIP)**, 2309.00683

Jet substructure



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

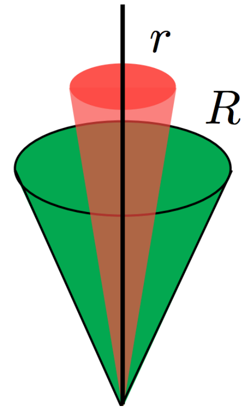




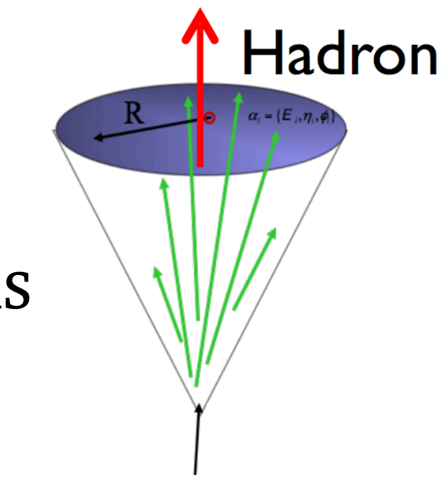
Use **jets' inner structure** to probe the QGP at **various length scales**

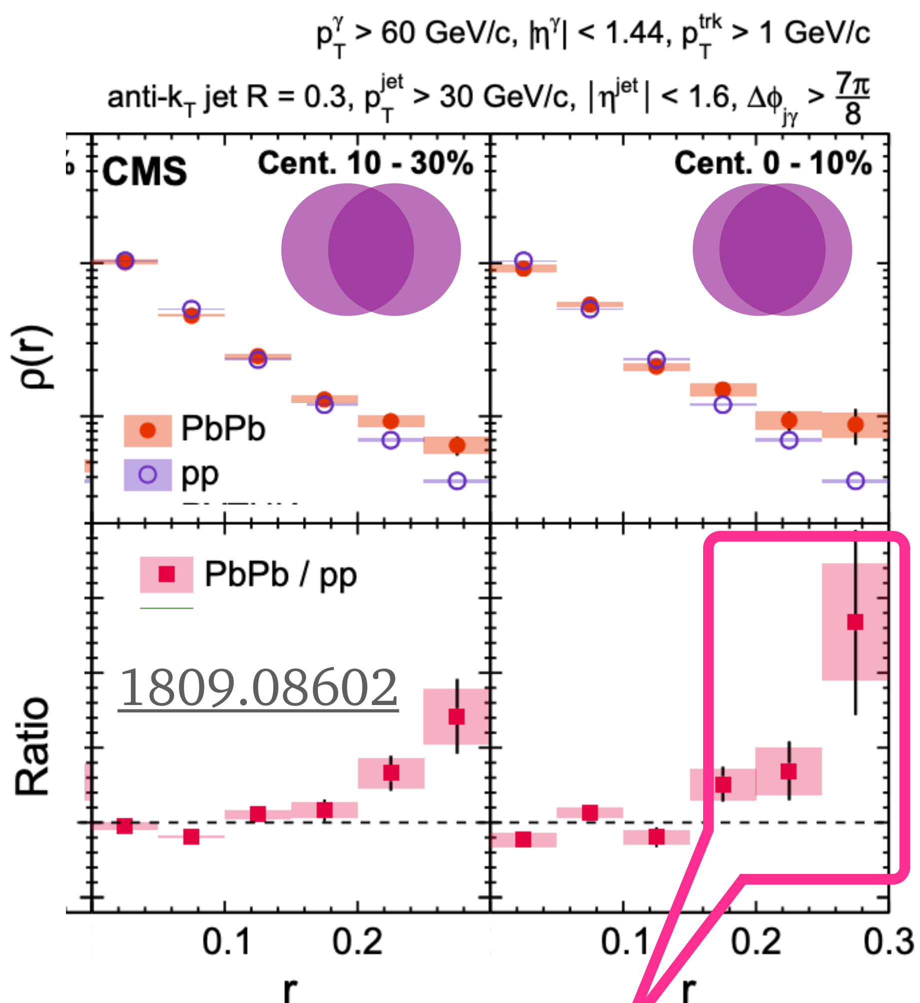
Jet substructure

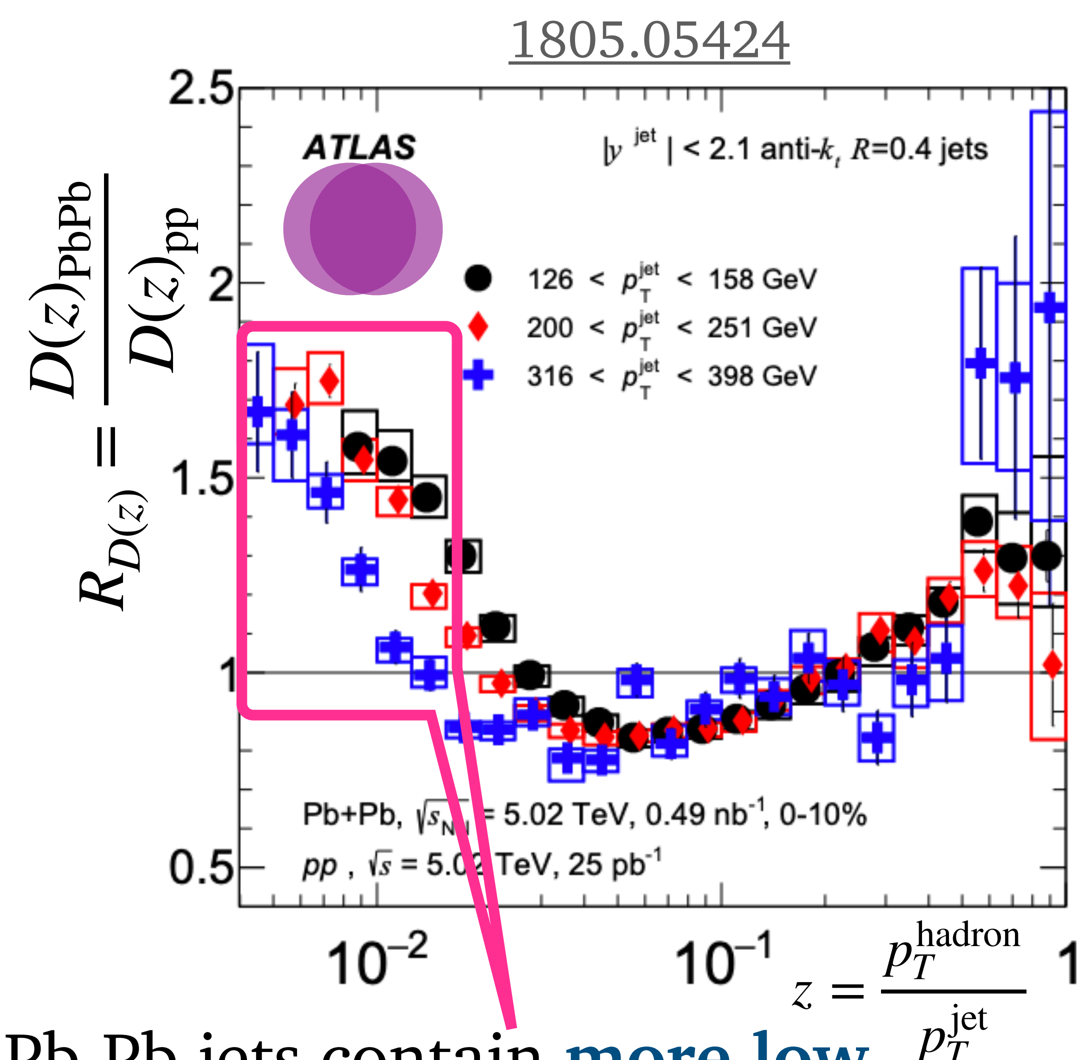
Jet shapes



Jet fragmentations





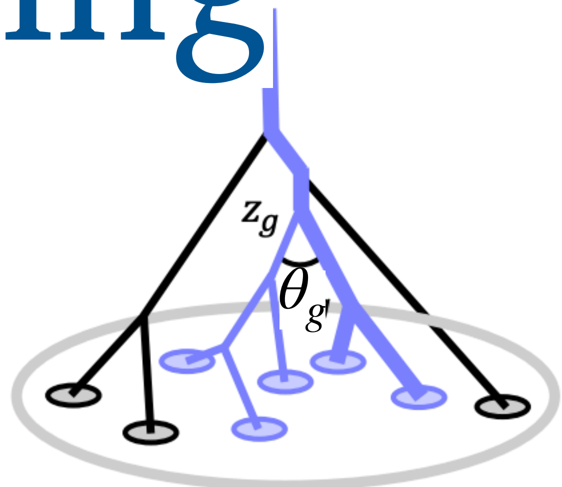


Pb-Pb jets **more energy toward the edge of the cone** than p-p jets

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

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

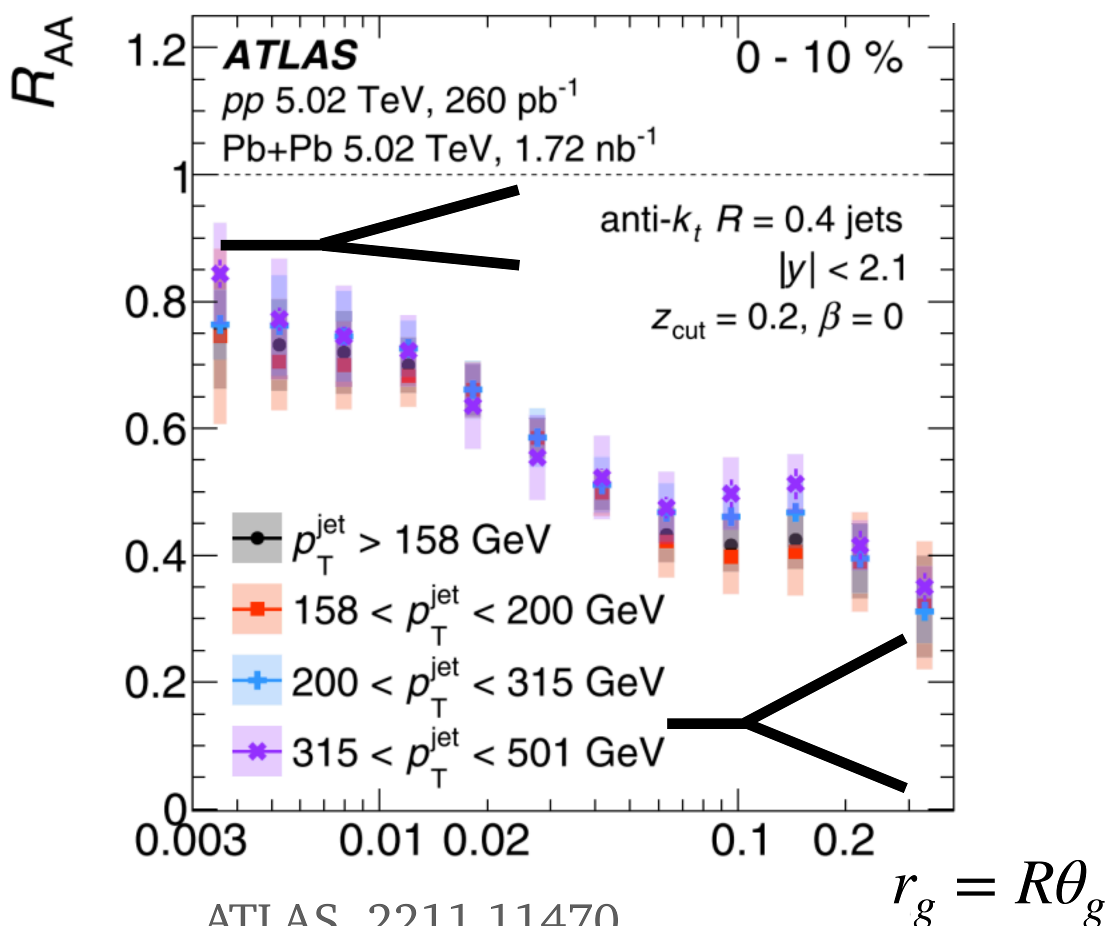
Jet substructure: grooming



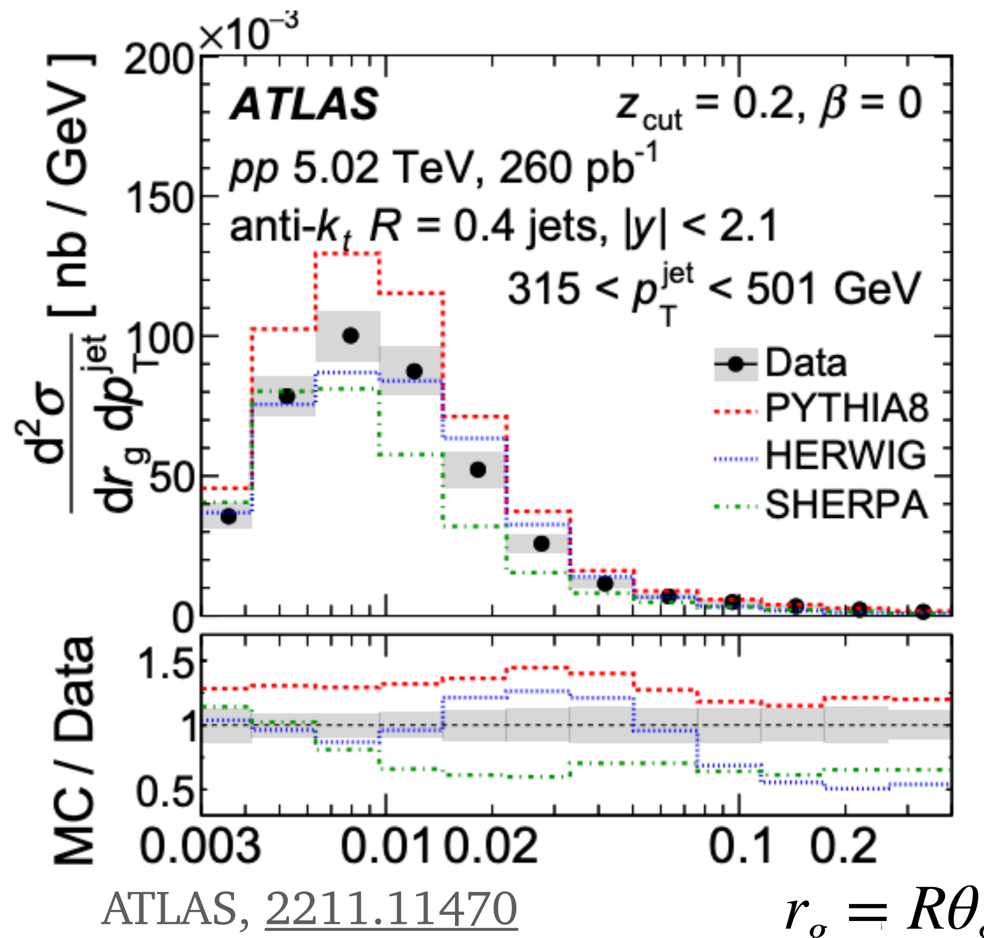
- What about grooming away soft physics?

  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, 2211.11470



ATLAS, 2211.11470

Broad angular structures are more suppressed in PbPb collisions

Large discrepancies between MC and data in p-p collisions

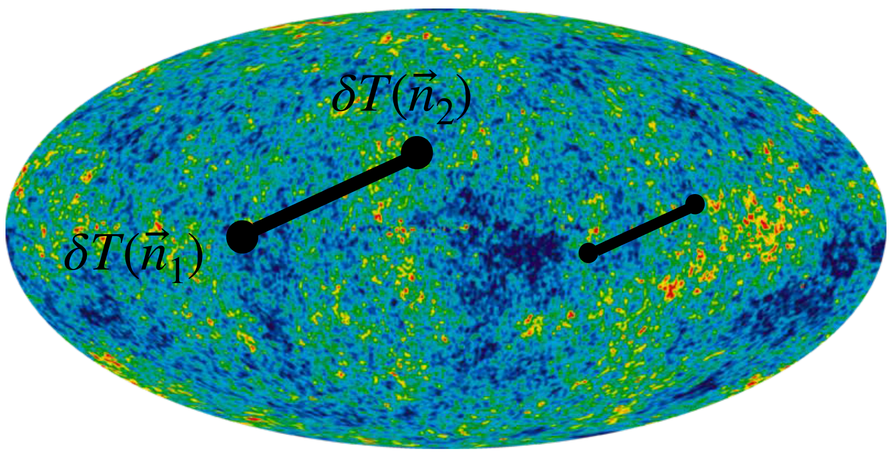
A new (old) idea?

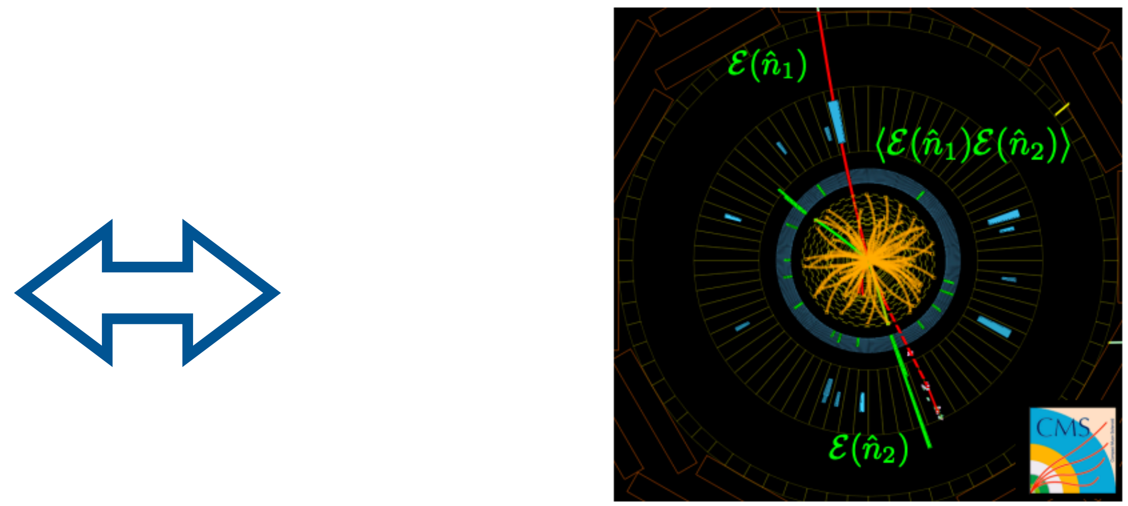
Energy-Energy correlators!

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

Energy Correlators

- Fundamental objects that encode the dynamics of the underlying theory



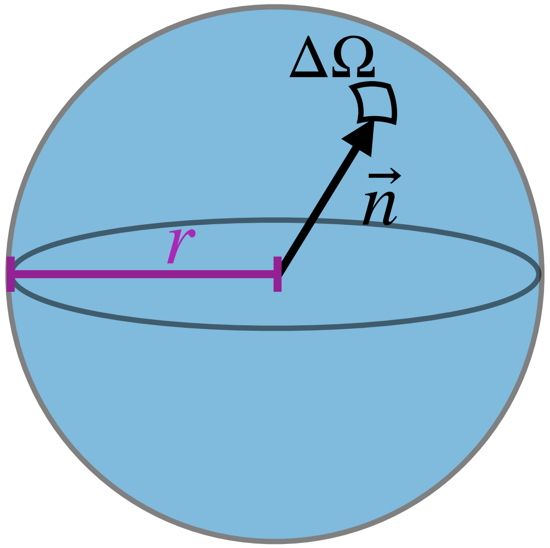


- Correlators $\langle \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\cdots\mathcal{E}(\vec{n}_k)\rangle$ of the **energy flux**:

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

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

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



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

Total energy flux through an area element

Two-point correlator

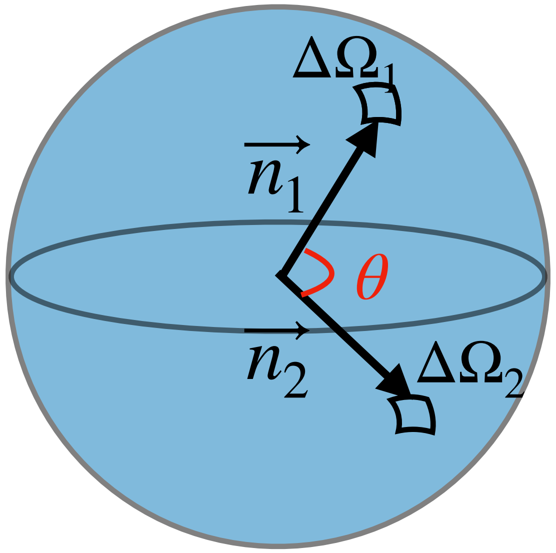
- 2-point correlator **(EEC):**

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

Energy weights

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

Hard scale of the process

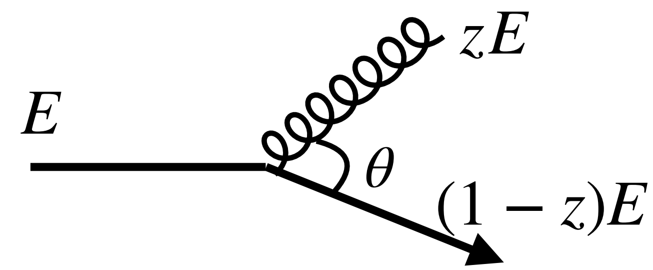


- As function of the **relative angle** only:

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

EEC within p-p jets

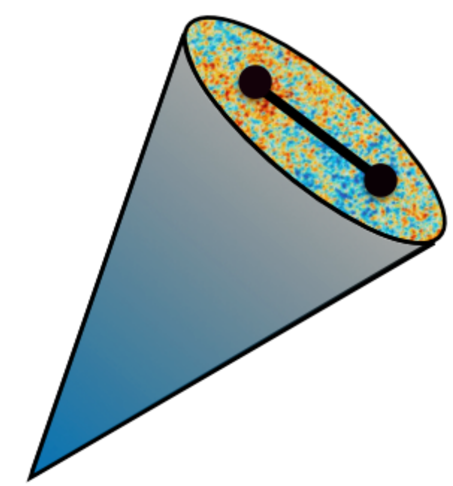
$$\frac{d\Sigma^{(n)}}{d\theta} = \frac{1}{\sigma}\sum_{i,j}\int dE_{i,j}\,\frac{d\sigma}{d\theta dE_i dE_j}\,\frac{E_i^n E_j^n}{Q^{2n}}$$



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

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

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



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

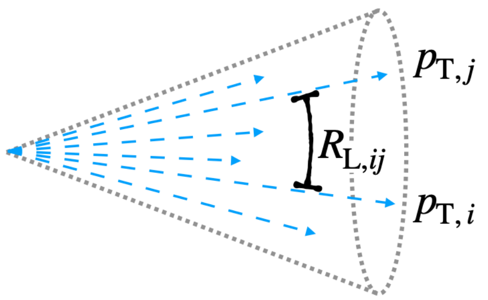
Power-law scaling according to CFT!

Hoffman, Maldacena, 0803.1467

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

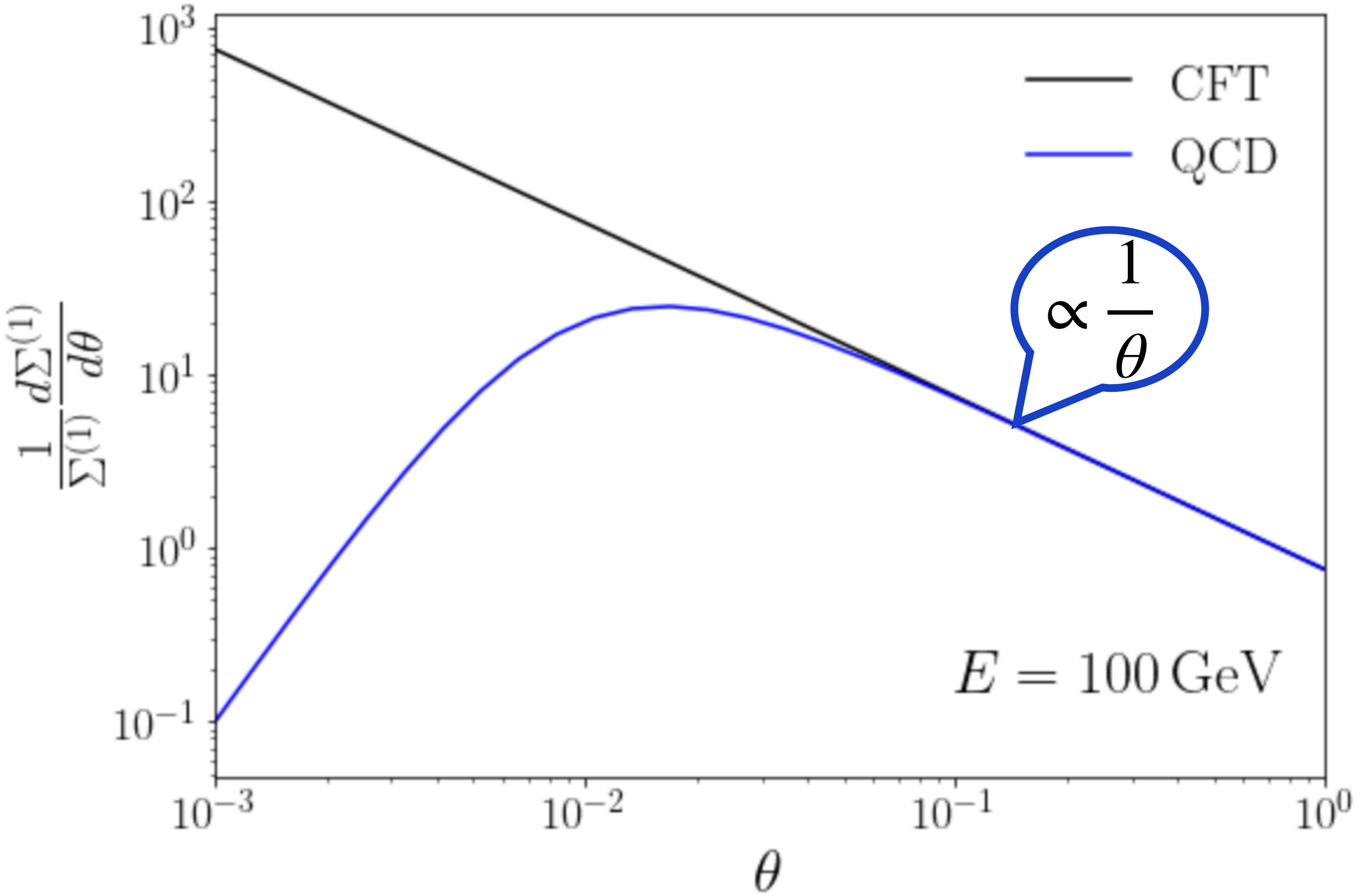
$\gamma(3)$: twist-2 spin-3 QCD anomalous dimension

EEC in p-p jets

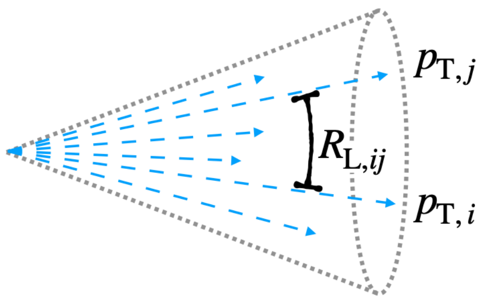


$R_L = \sqrt{\Delta\phi^2 + \Delta\eta^2}$

- 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

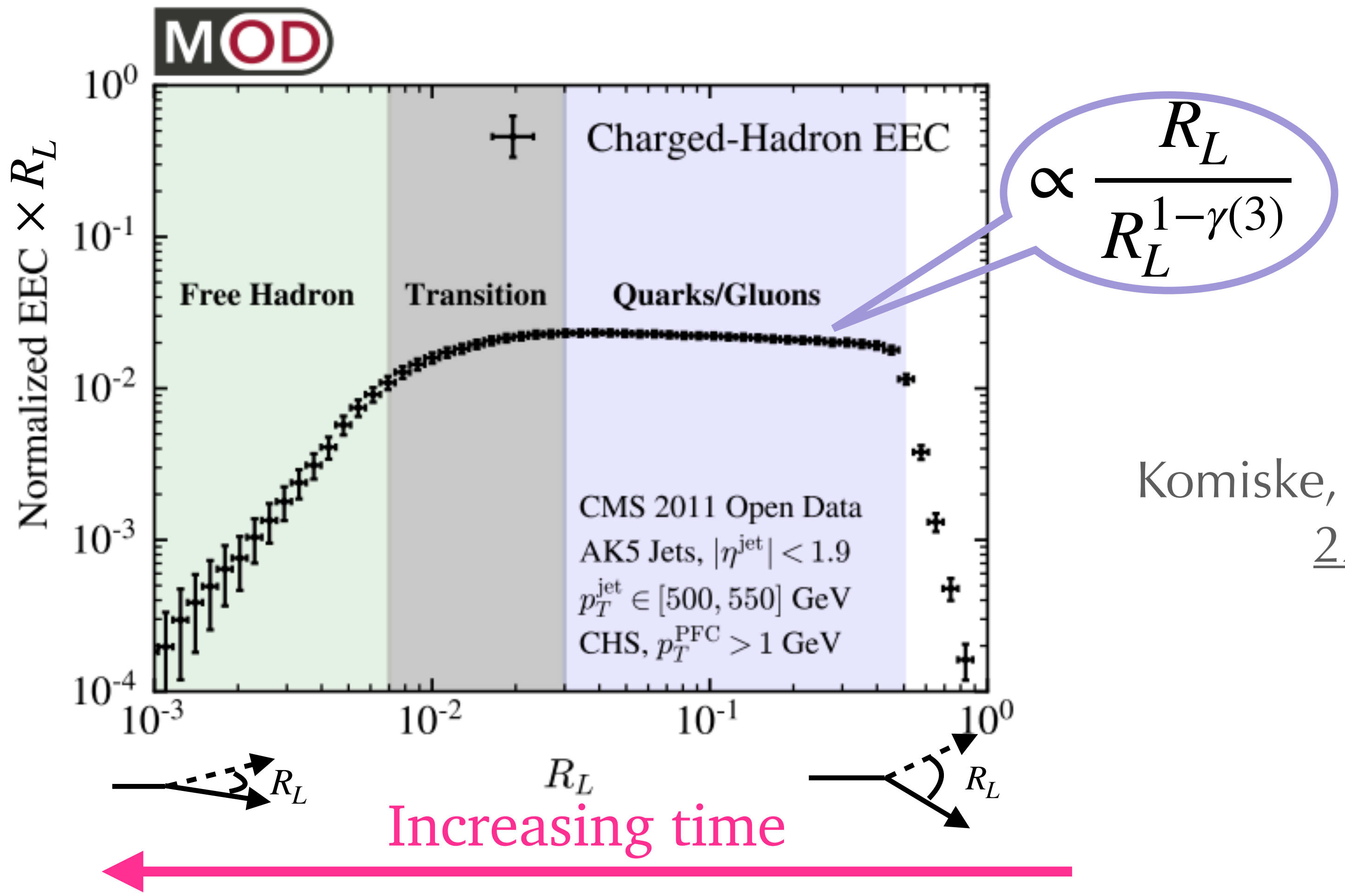


EEC in p-p jets



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

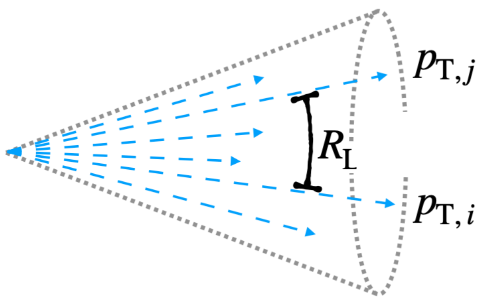
- QCD is **NOT** conformal
- Confinement must break the power-law behavior below: $\sim \Lambda_{QCD}/E$
    - Small angles (late times): hadronization is dominant
    - Large angles (initial times): power-law pQCD behavior



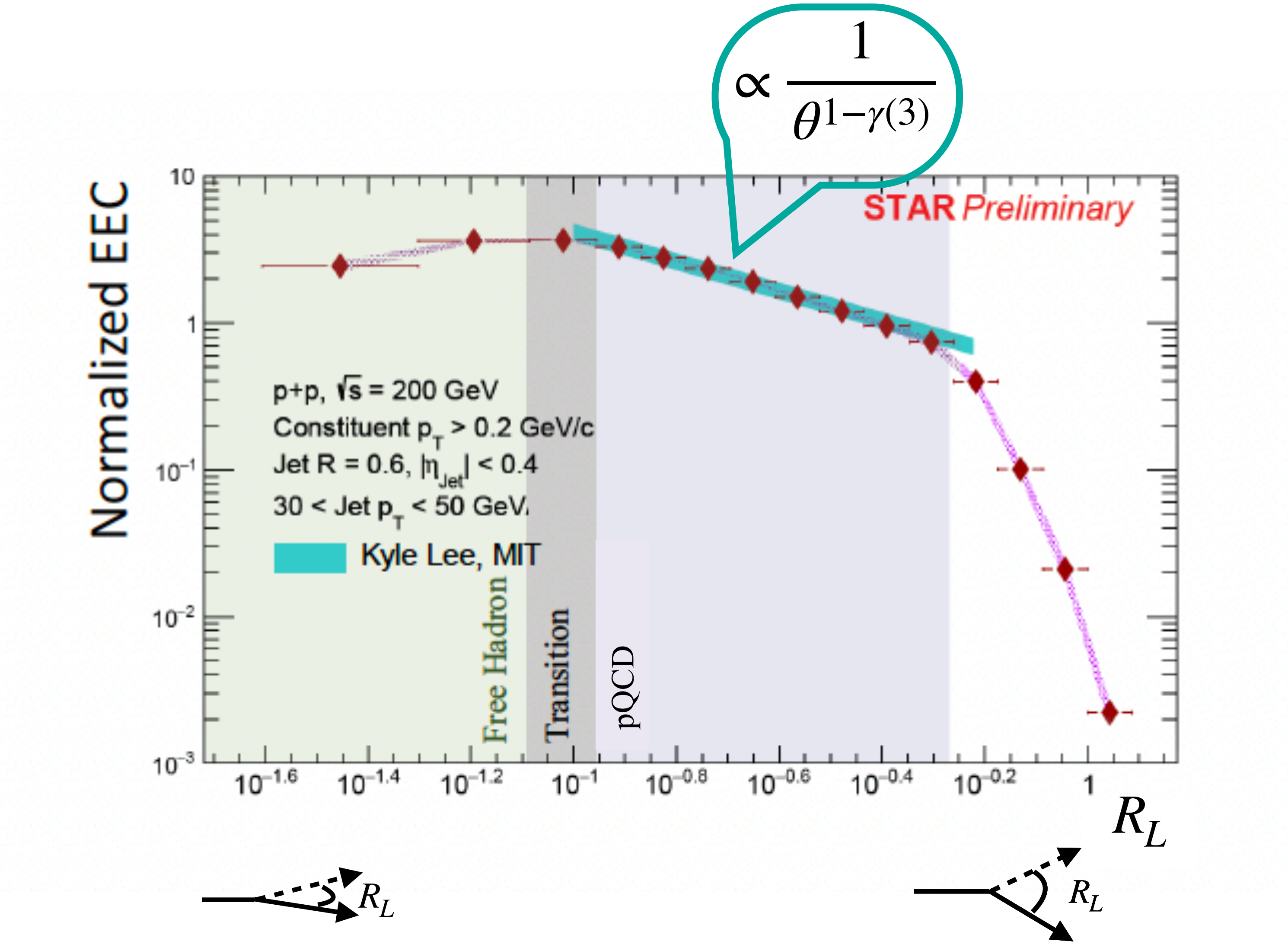
Komiske, Moult, Thaler, Zhu
2201.07800

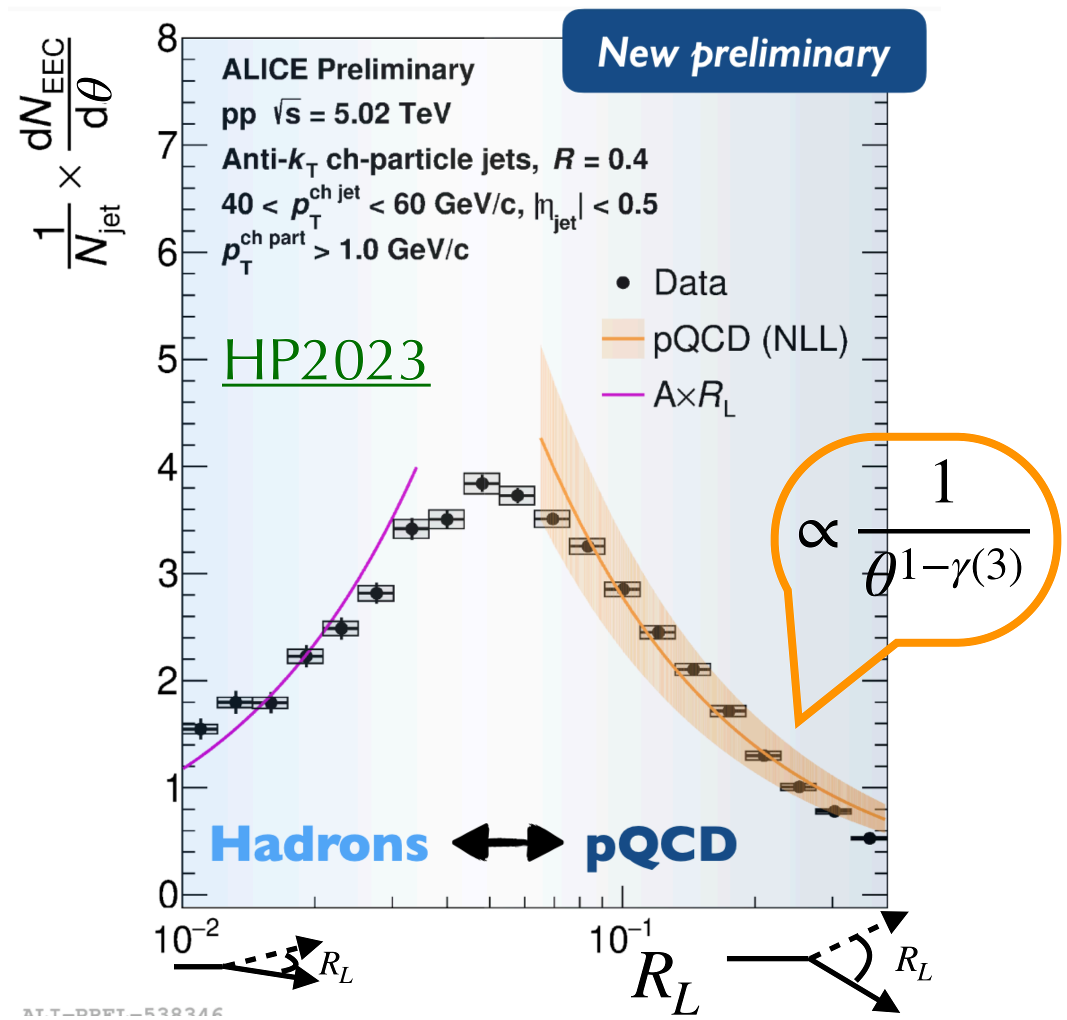
EEC in p-p jets

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



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



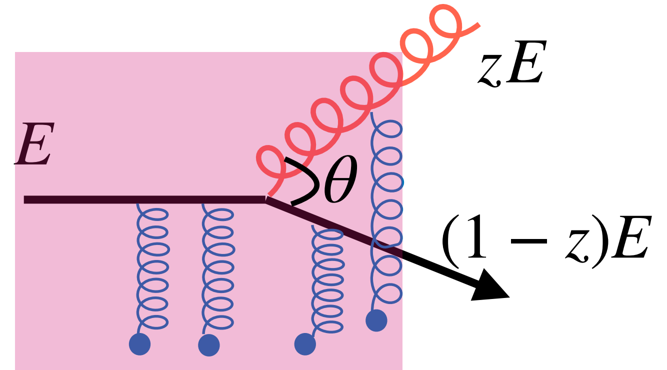


Energy correlators in HICs

- 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 (γ/Z-jet)

$$\frac{d\Sigma^{(n)}}{d\theta} = \frac{1}{\sigma_{qg}}\int dz \, \frac{d\sigma_{qg}}{dz d\theta} \frac{(zE)^n \left((1-z)E\right)^n}{E^{2n}} + \mathcal{O}\left(\frac{\mu_s}{E}\right)$$

μ_s a softer scale over which the cross section is inclusive

- We define

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

$$F_{med}(z,\theta) \xrightarrow{\theta<\theta_L} 0$$

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

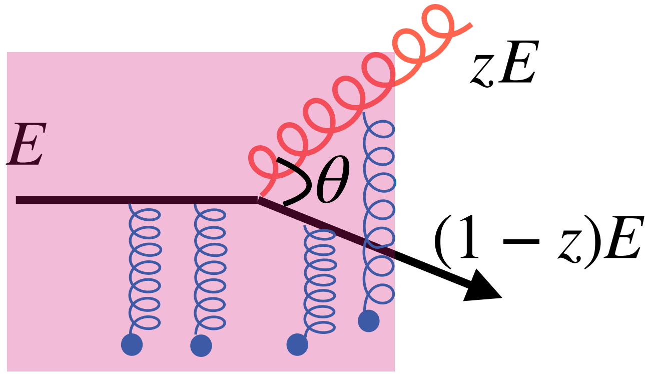
$$\frac{d\Sigma^{(n)}}{d\theta} = \left(\frac{1}{\sigma_{qg}}\int dz \, \left(g^{(n)}(\theta,\alpha_s) + F_{med}(z,\theta)\right) \frac{d\sigma^{vac}}{d\theta dz} z^n(1-z)^n\right)\left(1 + \mathcal{O}\left(\frac{\bar{\mu}_s}{Q}\right)\right) + \mathcal{O}\left(\frac{\Lambda_{QCD}}{\theta Q}\right)$$

Complete calculation not available. We use approximations

CA, Dominguez, Elayavalli, Holguin, Marquet, Moult, Phys. Rev. Lett. 130 (2023) 262301, JHEP 09 (2023) 088

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 (γ/Z-jet)

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

μ_s a softer scale over which the cross section is inclusive

- We define

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

$$F_{\text{med}}(z, \theta) \xrightarrow{\theta<\theta_L} 0$$

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

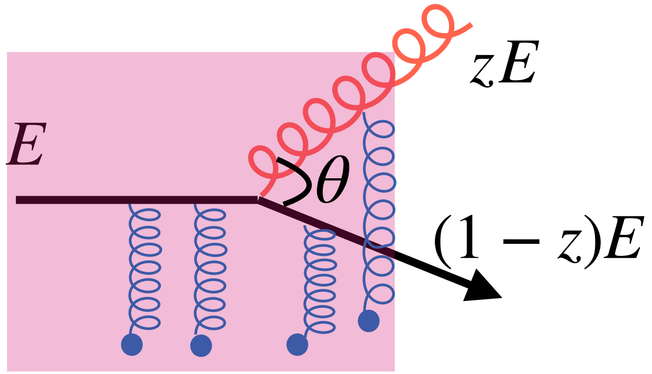
$$\frac{d\Sigma^{(n)}}{d\theta} = \left(\frac{1}{\sigma_{qg}} \int dz \, \left(g^{(n)}(\theta, \alpha_s) + F_{\text{med}}(z, \theta)\right) \frac{d\sigma^{\text{vac}}}{d\theta dz} z^n (1-z)^n \right) \left(1 + \mathcal{O}\left(\frac{\bar{\mu}_s}{Q}\right)\right) + \mathcal{O}\left(\frac{\Lambda_{\text{QCD}}}{\theta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

CA, Dominguez, Elayavalli, Holguin, Marquet, Moult, Phys. Rev. Lett. 130 (2023) 262301, JHEP 09 (2023) 088

Complete calculation not available. We use approximations

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 (γ/Z-jet)

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

μ_s a softer scale over which the cross section is inclusive

- We define

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

$$F_{\text{med}}(z, \theta) \xrightarrow{\theta < \theta_L} 0$$

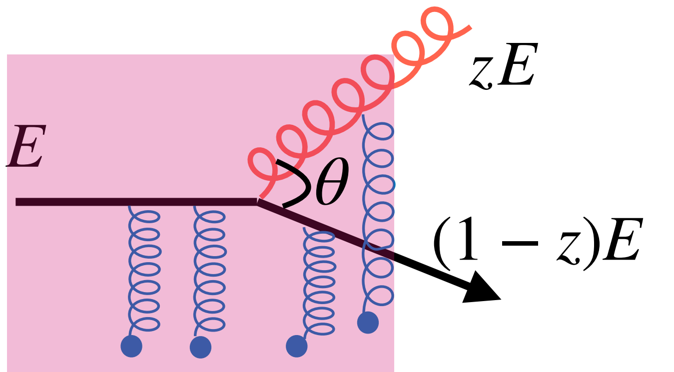
- We do not expect medium modification at small angles, thus **p-p collinear resummation** should still be **valid**

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

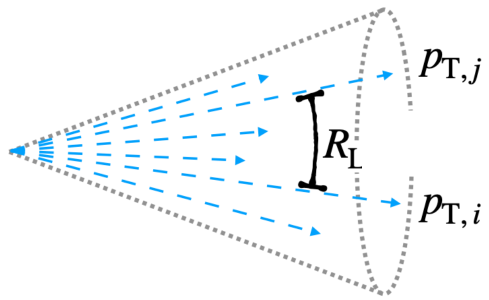
Complete calculation not available. We use approximations

CA, Dominguez, Elayavalli, Holguin, Marquet, Moult, Phys. Rev. Lett. 130 (2023) 262301, JHEP 09 (2023) 088

EEC in A-A: results

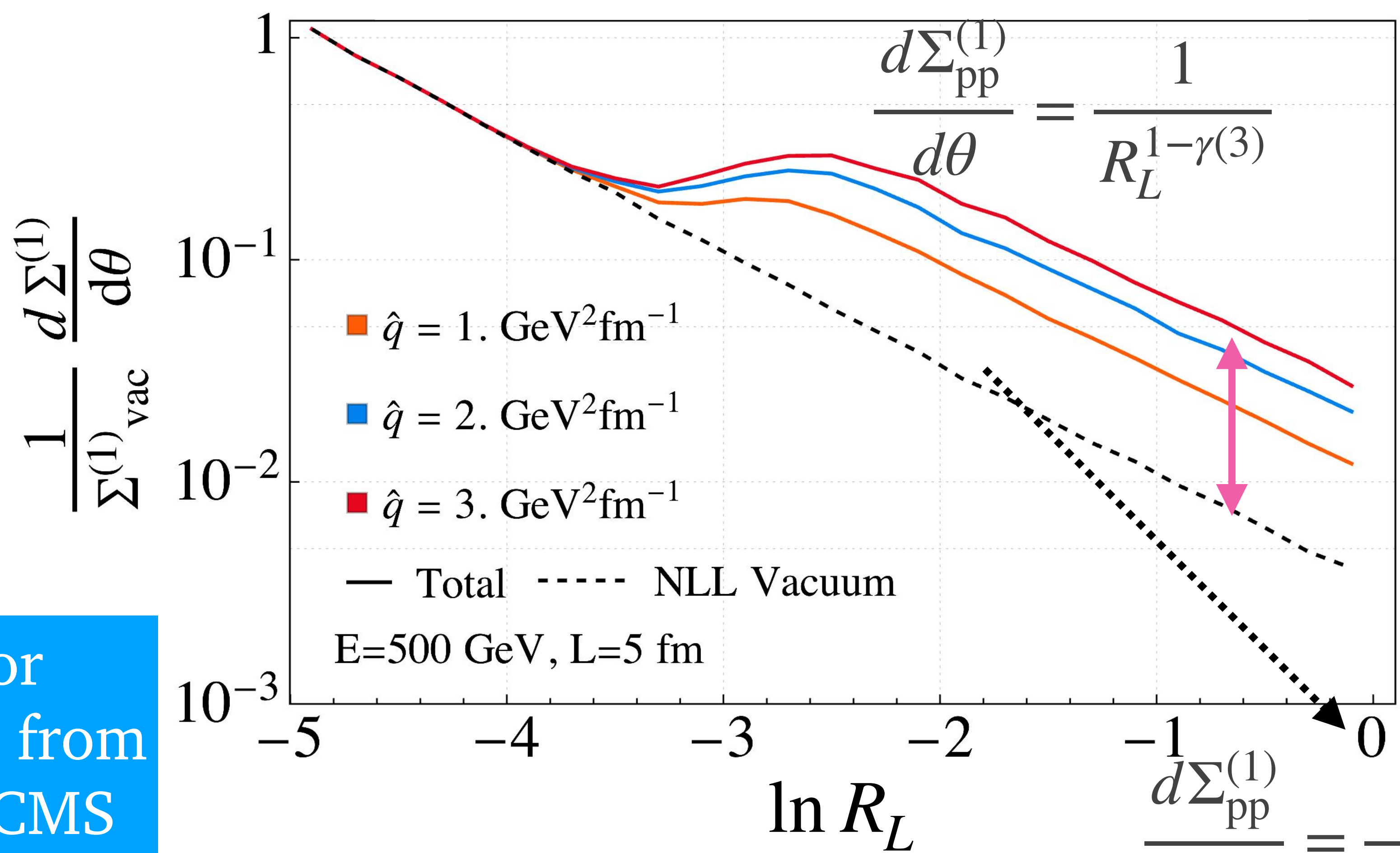


- EEC for a **massless quark jet**: $Q = E$



Medium-induced radiation

2-point EEC in A-A



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

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

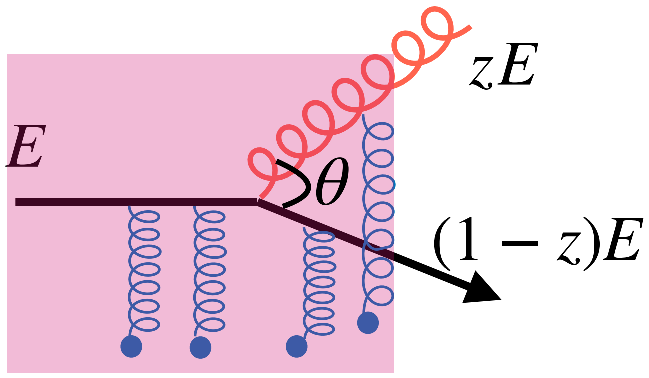
JHEP 09 (2023) 088

Medium-induced radiation

$$\frac{d\Sigma^{(1)}_{\mathrm{pp}}}{d\theta} = \frac{1}{R_L^{1-\gamma(3)}}$$

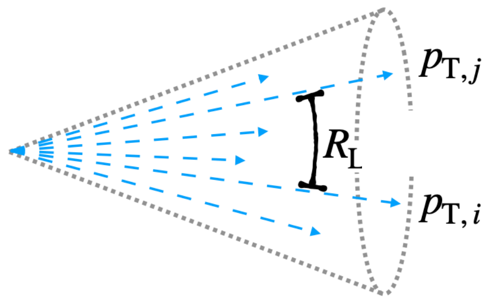
Results for inclusive jets from ALICE and CMS underway!

EEC in A-A: results



Medium-induced radiation

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

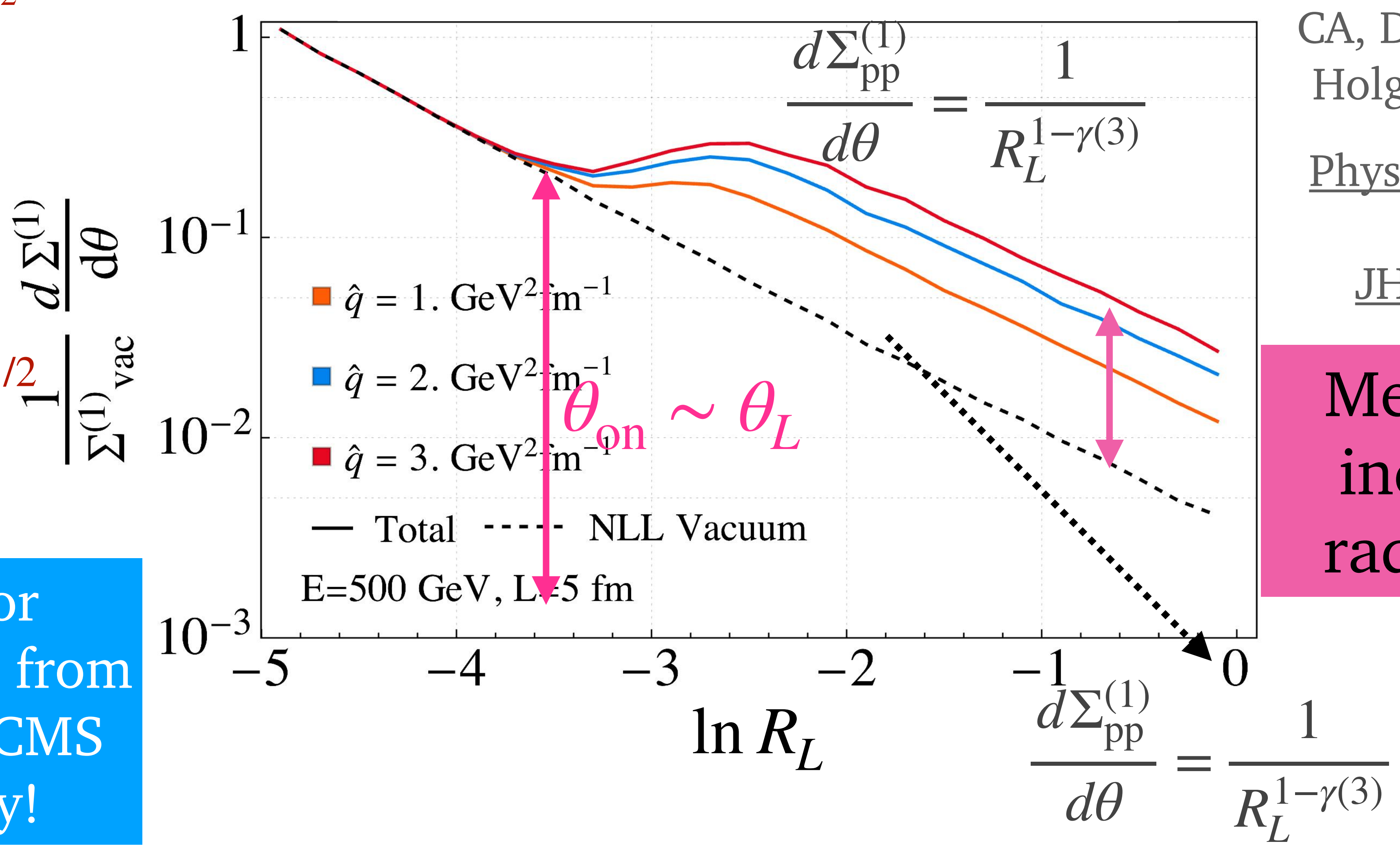


$$t_f = \frac{2}{z(1-z)E\theta^2}$$

$t_f \leq L$

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

2-point EEC in A-A



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

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

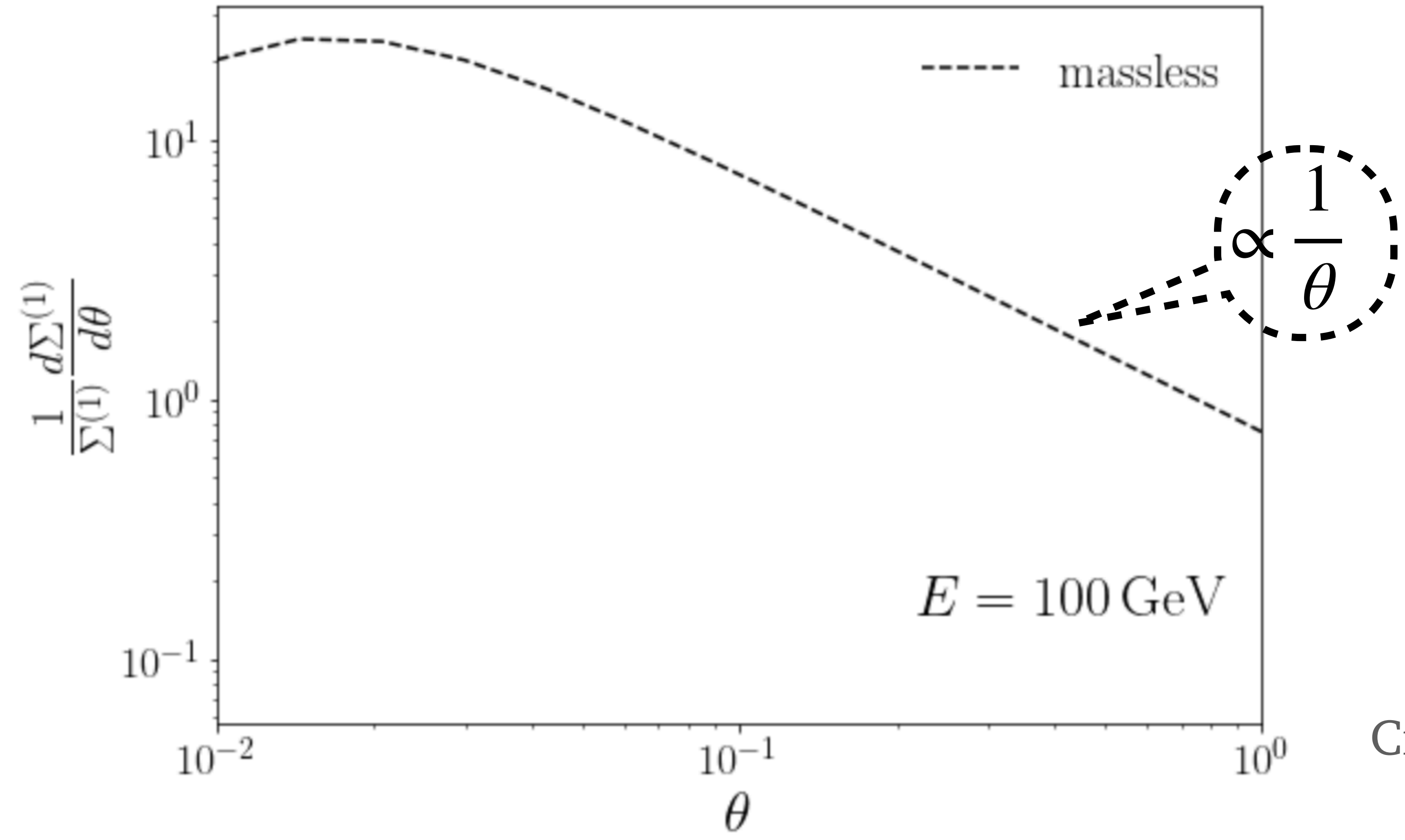
JHEP 09 (2023) 088

Medium-induced radiation

Results for inclusive jets from ALICE and CMS underway!

EEC in HF p-p jets

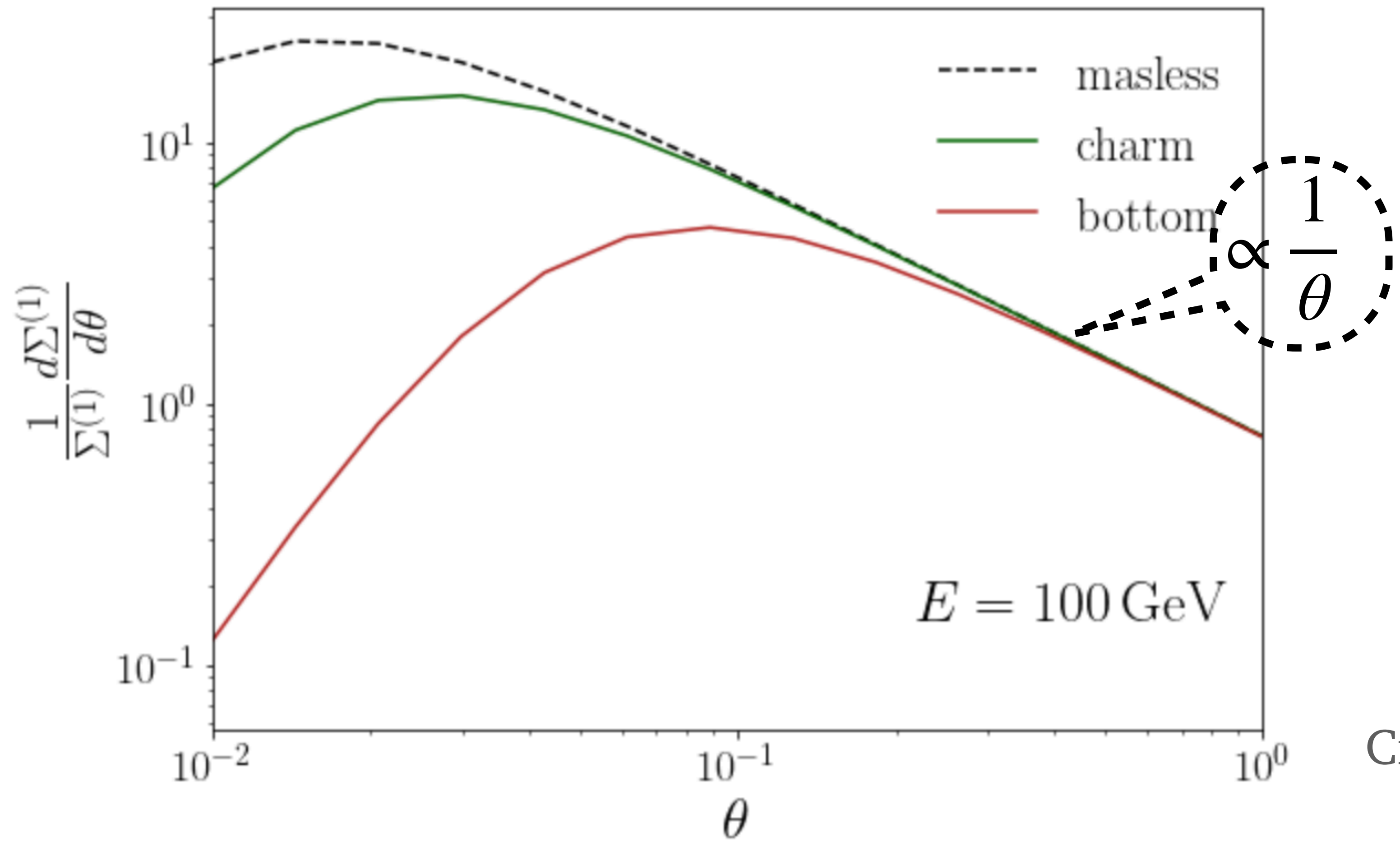
- **Dead-cone effect**: collider radiation off heavy quarks is suppressed at small angles
- Dead-cone angle: $\Theta_0 \propto \frac{m_Q}{E_Q}$
- $m_Q > \Lambda_{QCD}$: **deviation from power-law behavior in the pQCD regime**



Craft, Lee, Meçaj, Moult, arXiv:2210.09311

EEC in HF p-p jets

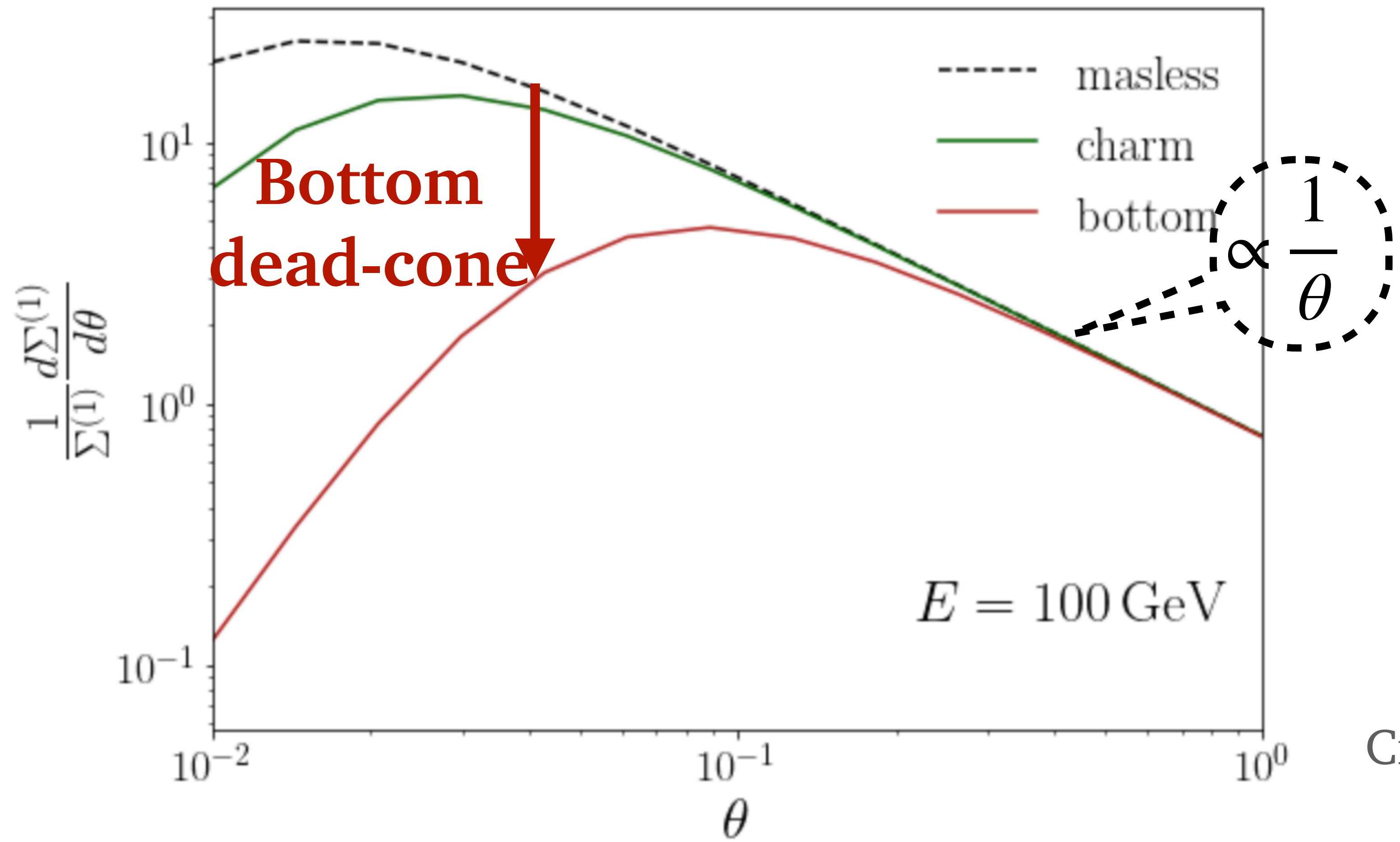
- **Dead-cone effect**: collider radiation off heavy quarks is suppressed at small angles
- Dead-cone angle: $\Theta_0 \propto \dfrac{m_Q}{E_Q}$
- $m_Q > \Lambda_{\mathrm{QCD}}$: **deviation from power-law behavior in the pQCD regime**



Craft, Lee, Meçaj, Moult, arXiv:2210.09311

EEC in HF p-p jets

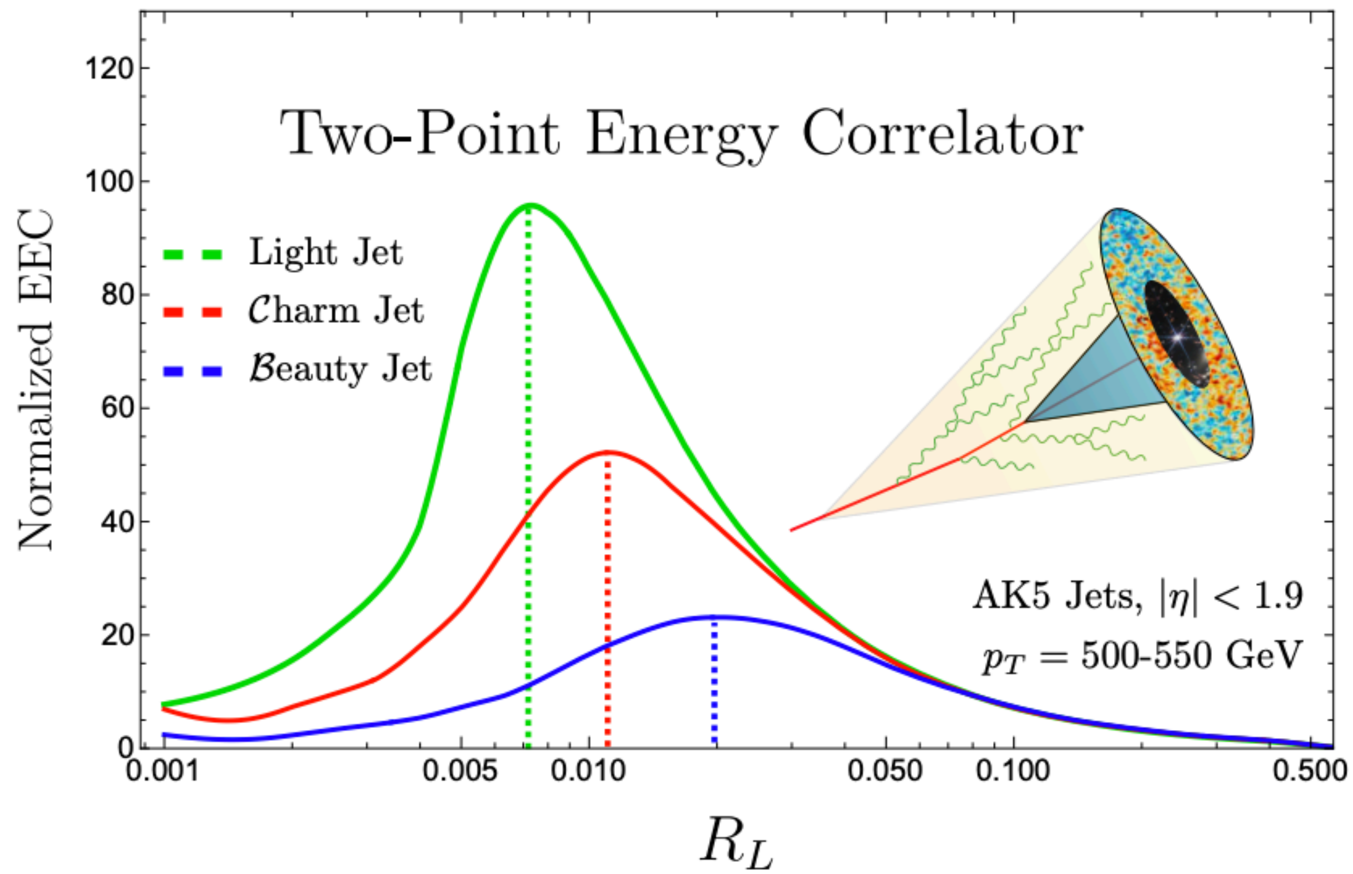
- **Dead-cone effect**: collider radiation off heavy quarks is suppressed at small angles
- Dead-cone angle: $\Theta_0 \propto \frac{m_Q}{E_Q}$
- $m_Q > \Lambda_{QCD}$: **deviation from power-law behavior in the pQCD regime**



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

EEC in HF jets in A-A

- Same formalism:

$\mathcal{O}(\alpha_s)$ $Q \to Qg$ collinear splitting function

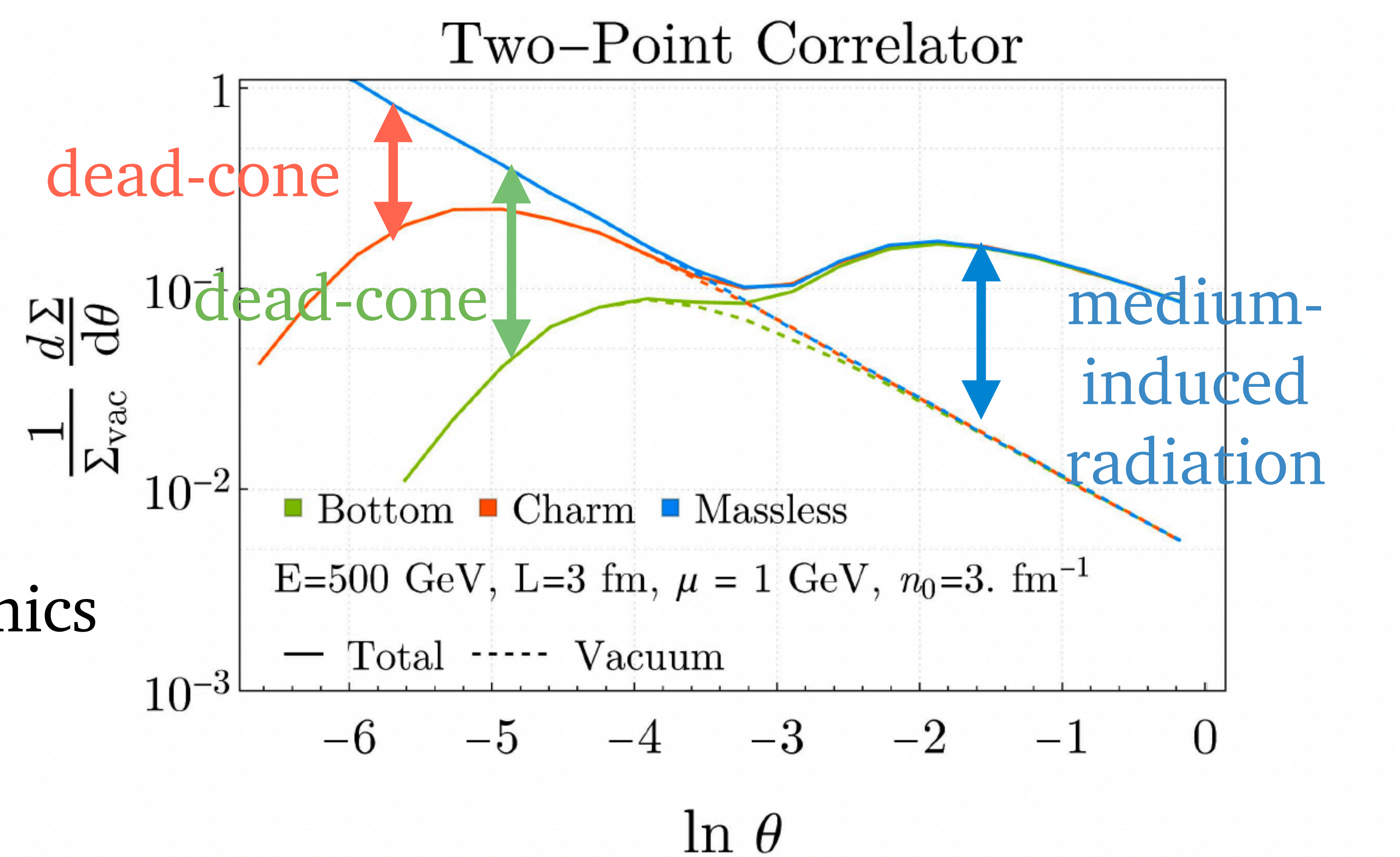
$$\frac{d\Sigma^{(n)}}{d\theta} = \left(\frac{1}{\sigma_{qg}} \int dz \, \left(g^{(n)}(\theta, \alpha_s) + F_{\text{med}}(z, \theta) \right) \frac{d\sigma^{\text{vac}}}{d\theta dz} z^n (1-z)^n \right) \left(1 + \mathcal{O}\left(\frac{\bar{\mu}_s}{Q} \right) \right) + \mathcal{O}\left(\frac{\Lambda_{\text{QCD}}}{\theta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

$$t_f = \frac{2}{z(1-z)E\theta^2} \Rightarrow t_f = \frac{2}{z(1-z)E\left(\theta + \frac{\Theta_0}{1-z}\right)^2}$$

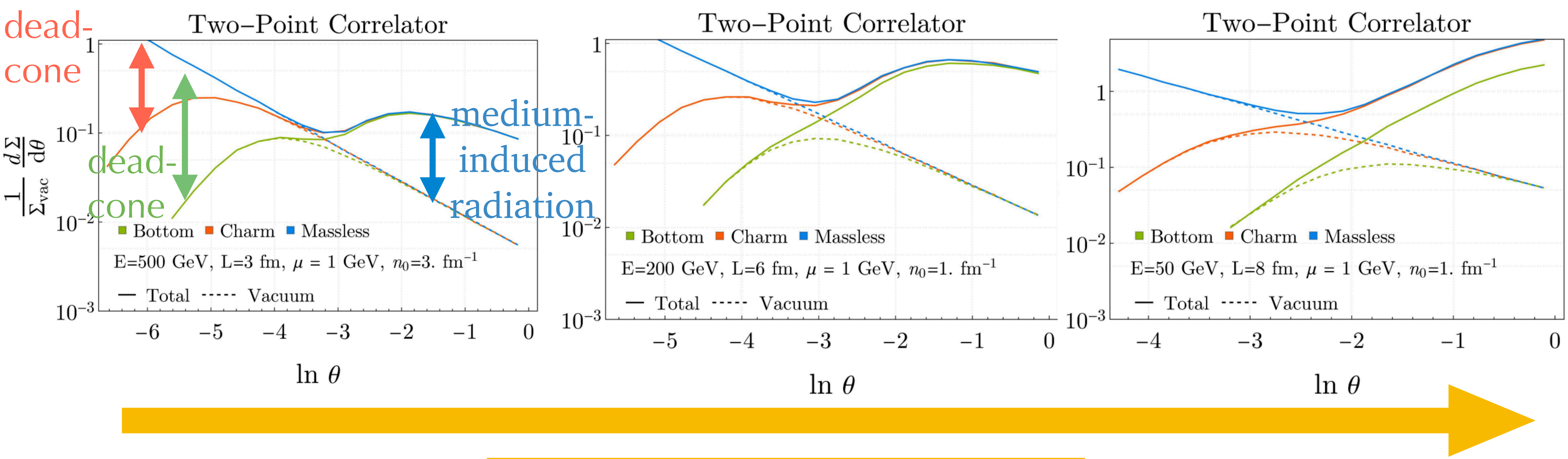
- Two competing scales:

$$\Theta_0 \propto \frac{m_Q}{E} \qquad \theta_L \propto \frac{1}{\sqrt{EL}}$$

If $\theta_L \gg \Theta_0$: two separate dynamics



HF jets: filling the dead-cone



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

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

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

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

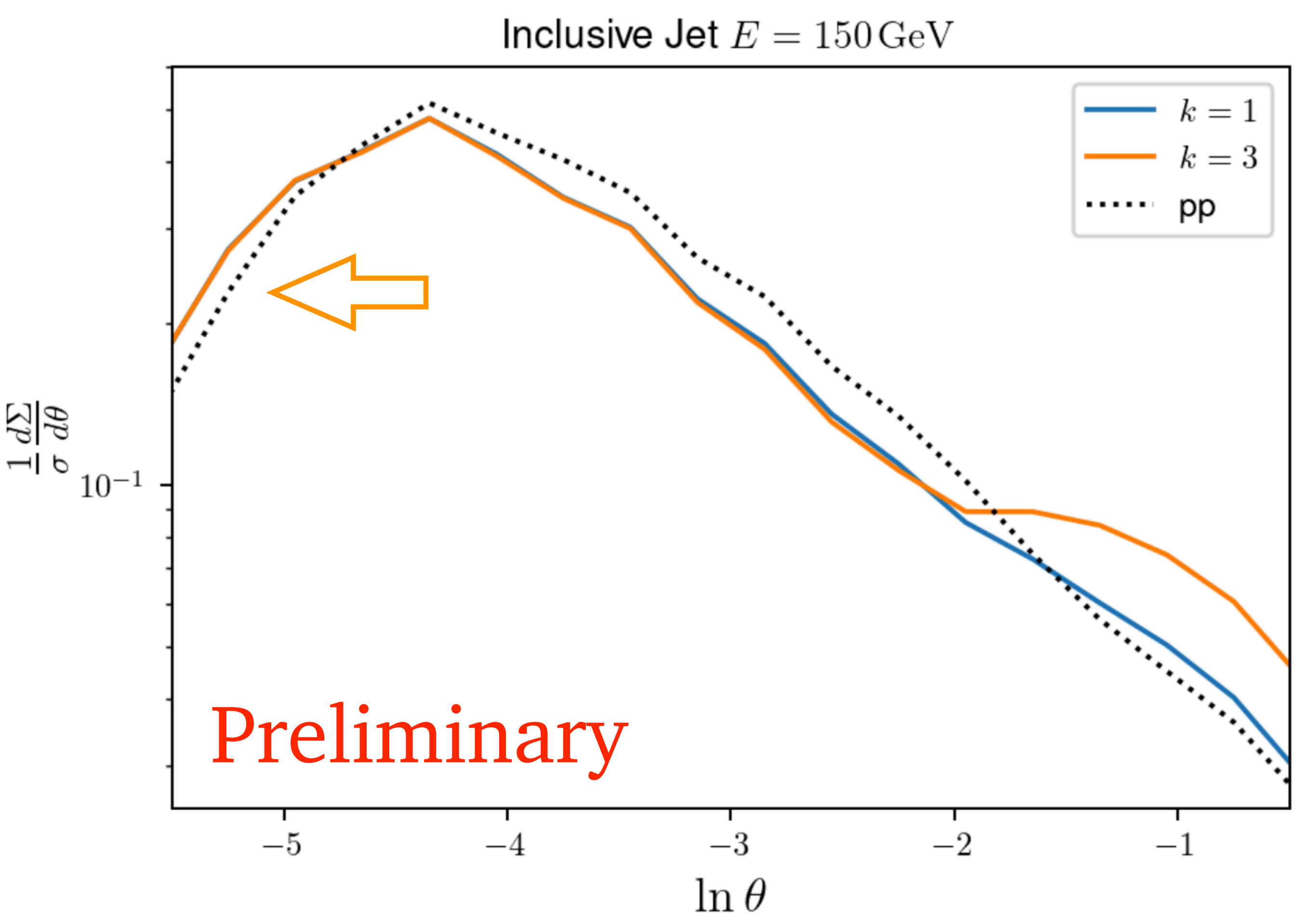
ALICE and CMS are measuring the two-point EEC in LHC Run 2 PbPb data

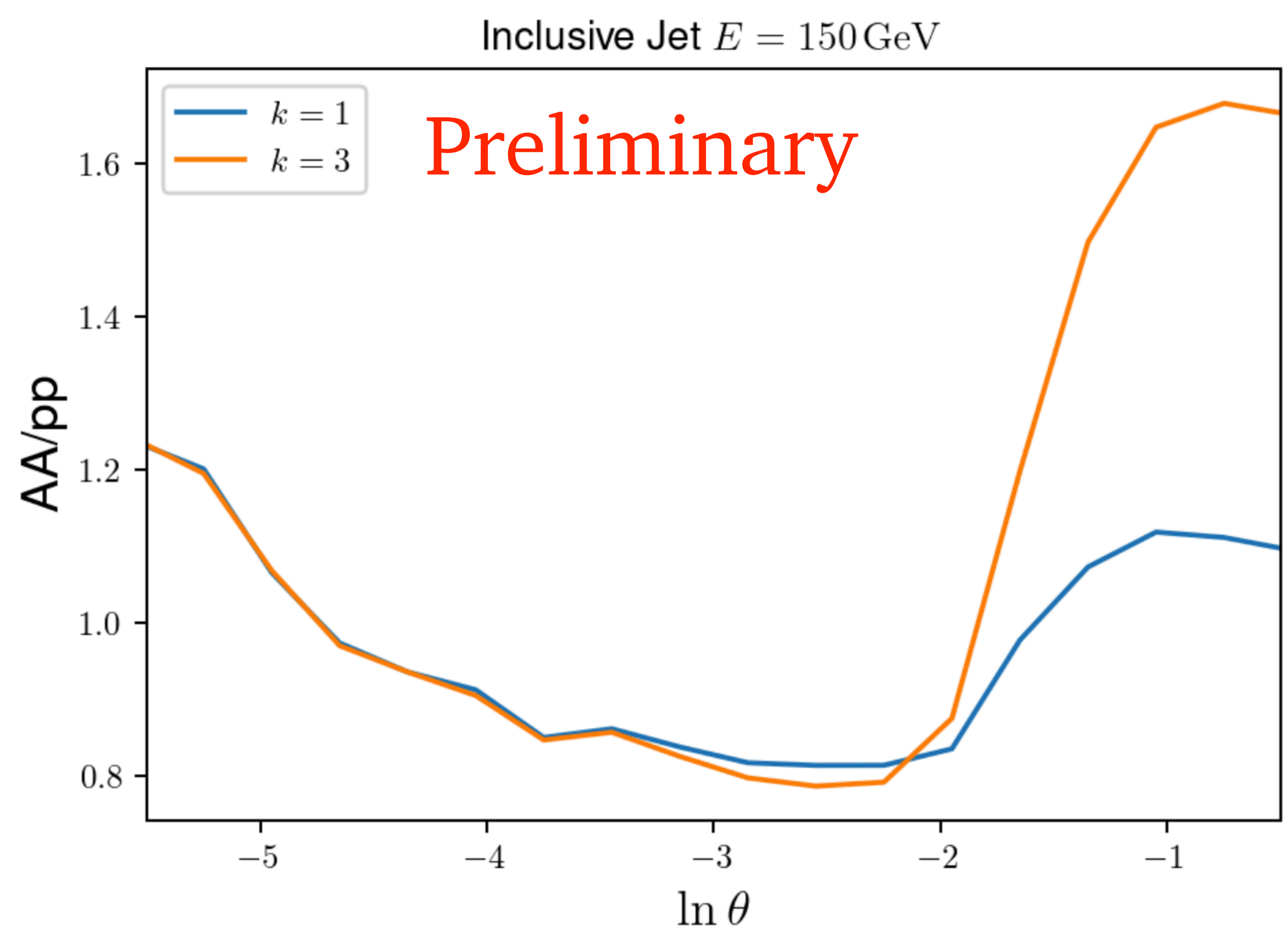
But… they are looking at **inclusive jet** samples

What should we expect?

EEC on inclusive jets in A-A

- We don't know the initial hard parton energy
- HI-jets have a higher initial energy than p-p jets, then their **transition to non-perturbative regime happens at smaller angles**





K is just a free-parameter in our medium-induced calculation

Conclusions

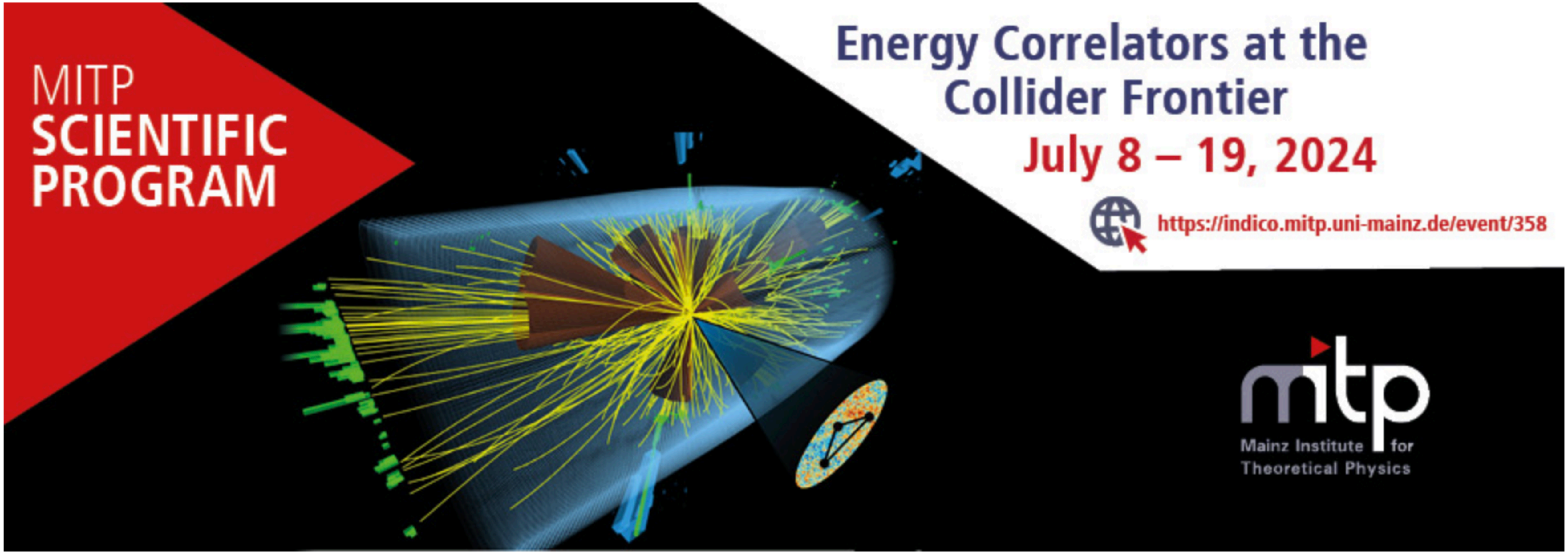
- **QCD collectivity at experimental reach** at RHIC and the LHC
  - Continuous progress on the characterization of the QGP
  - Many interesting questions to be answered in the next 15 years of HICs

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!



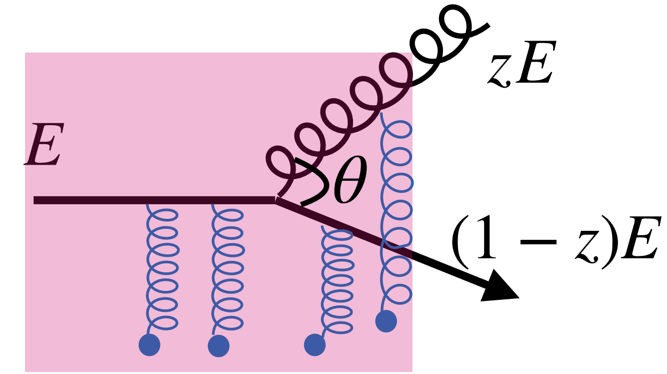
Energy Correlators at the Collider Frontier, Mainz Institute for Theoretical Physics

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

indico link

Obrigada!

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_{med} such as

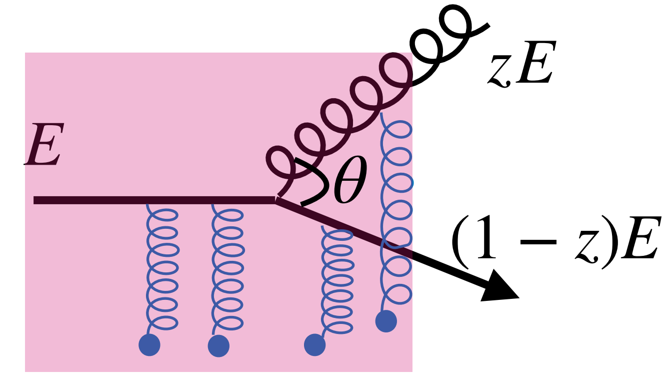
$$\frac{\mathrm{d}\sigma_{qg}}{\mathrm{d}\theta dz} = \left(1 + F_{\text{med}}(z,\theta)\right) \frac{\mathrm{d}\sigma_{qg}^{\text{vac}}}{\mathrm{d}\theta dz} \qquad F_{\text{med}}(z,\theta) \xrightarrow{\theta<\theta_L} 0$$

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

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

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

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_{med} such as

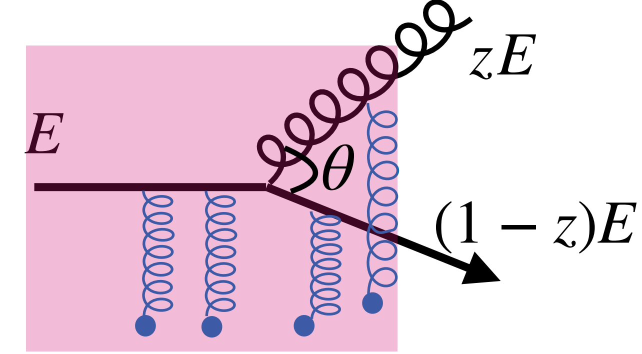
$$\frac{d\sigma_{qg}}{d\theta dz} = \left(1 + F_{\mathrm{med}}(z,\theta)\right) \frac{d\sigma_{qg}^{\mathrm{vac}}}{d\theta dz} \qquad F_{\mathrm{med}}(z,\theta) \xrightarrow{\theta<\theta_L} 0$$

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

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

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

Our idealized model



- Multiple medium scatterings destroy the color coherence between the daughter partons
- Complete (multiple scatterings) medium-induced emission spectrum keeping z and θ 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: θ_L and θ_c
  - (Vacuum) formation time:

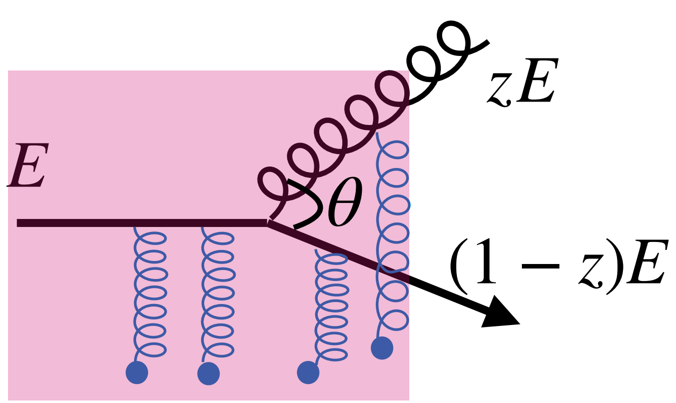
$$t_f = \frac{2}{z(1-z)E\theta^2} \xrightarrow{t_f \leq L} \theta_L \sim (EL)^{-1/2}$$

Below θ_L all emissions have a formation time larger than L

  - Decoherence time:

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

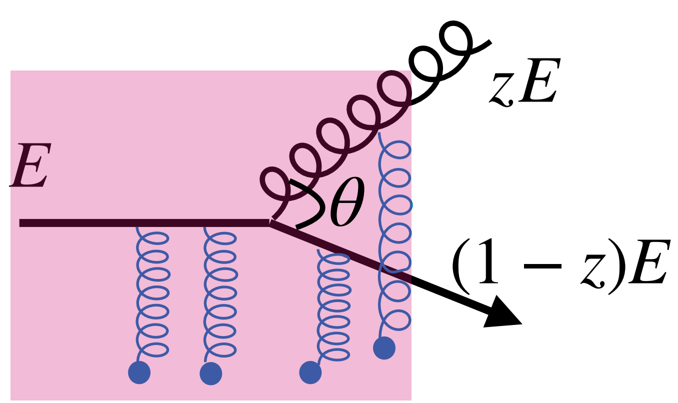
Below θ_c splittings do not color decohere and the medium does not resolve them



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

Time and angular scales (HO)

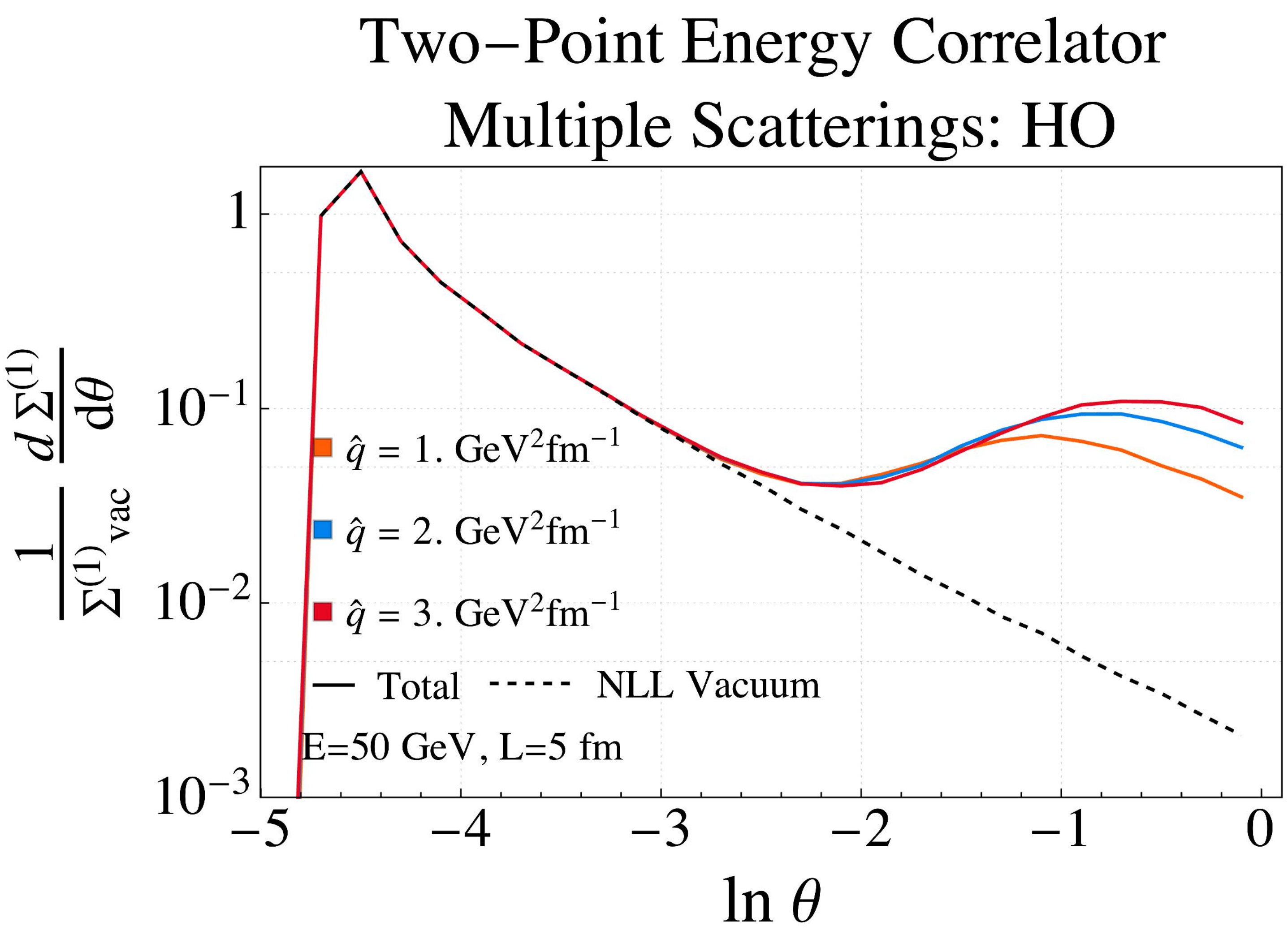
Can be extended to include a more **realistic interactions or expanding media**, but then we would not know the scales directly from the equations



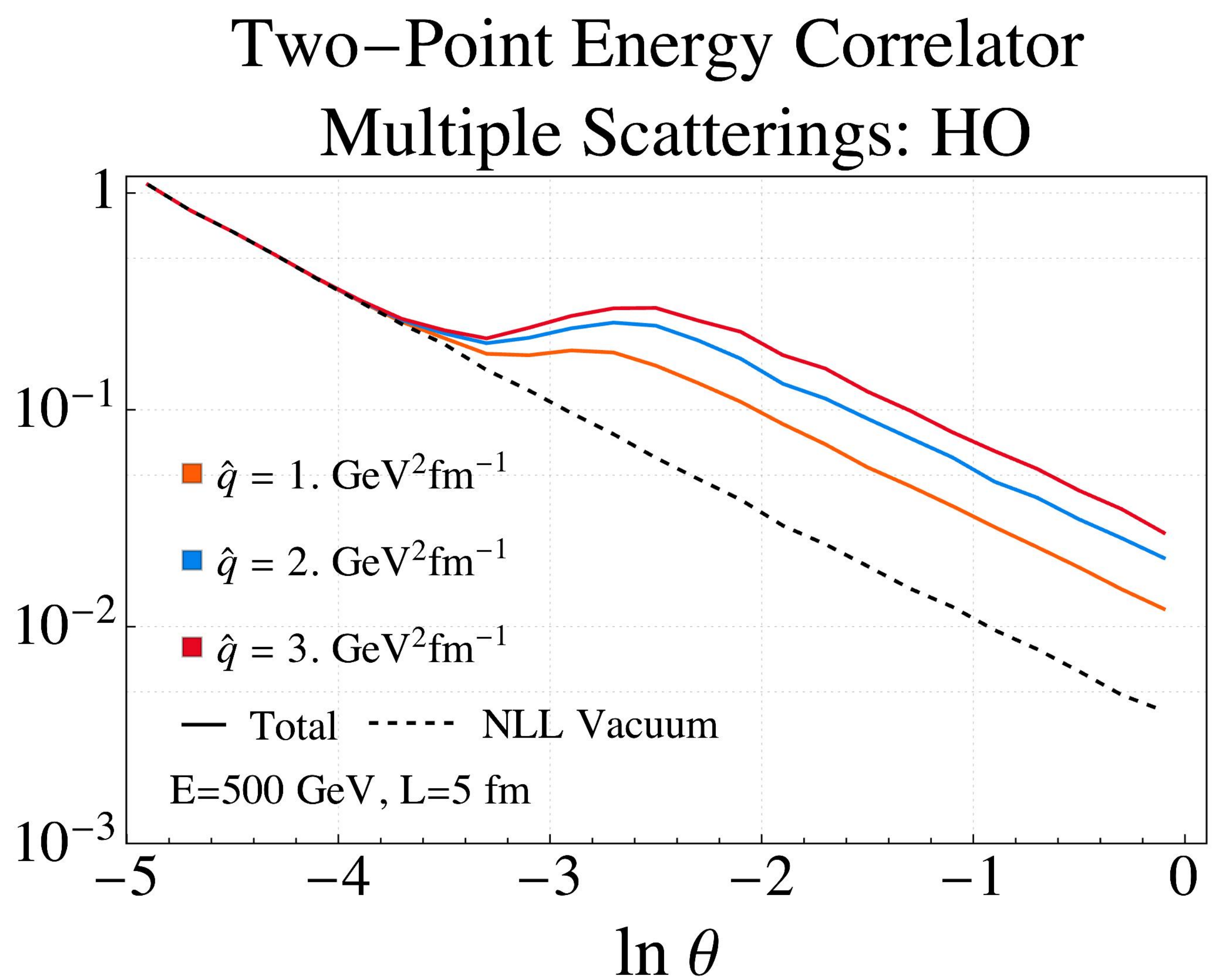
If $\theta_L > \theta_c$: θ_c becomes irrelevant

Results HO

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

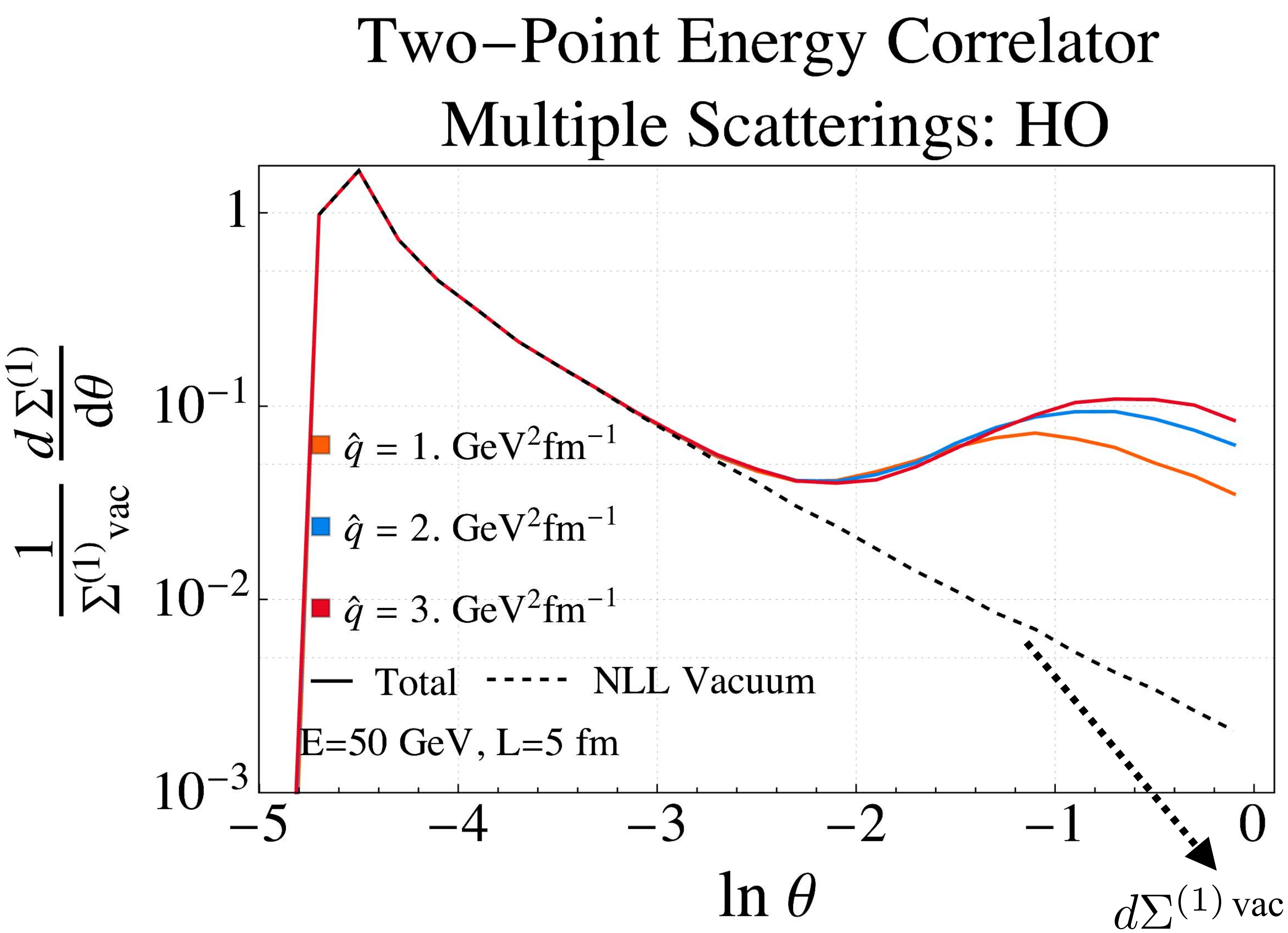


$\theta_L \ll \theta_c (E \gg \hat{q}L^2)$



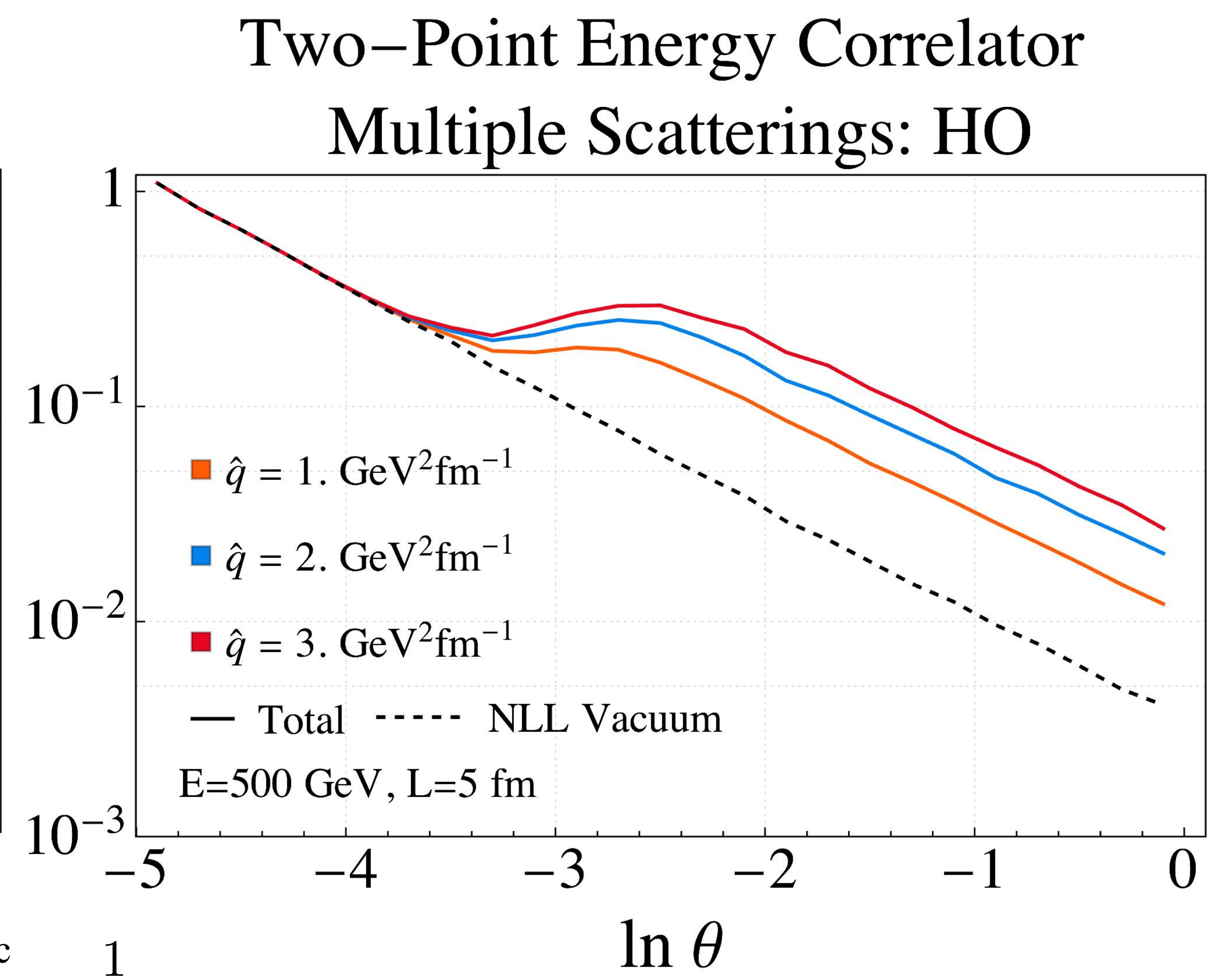
Results HO

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



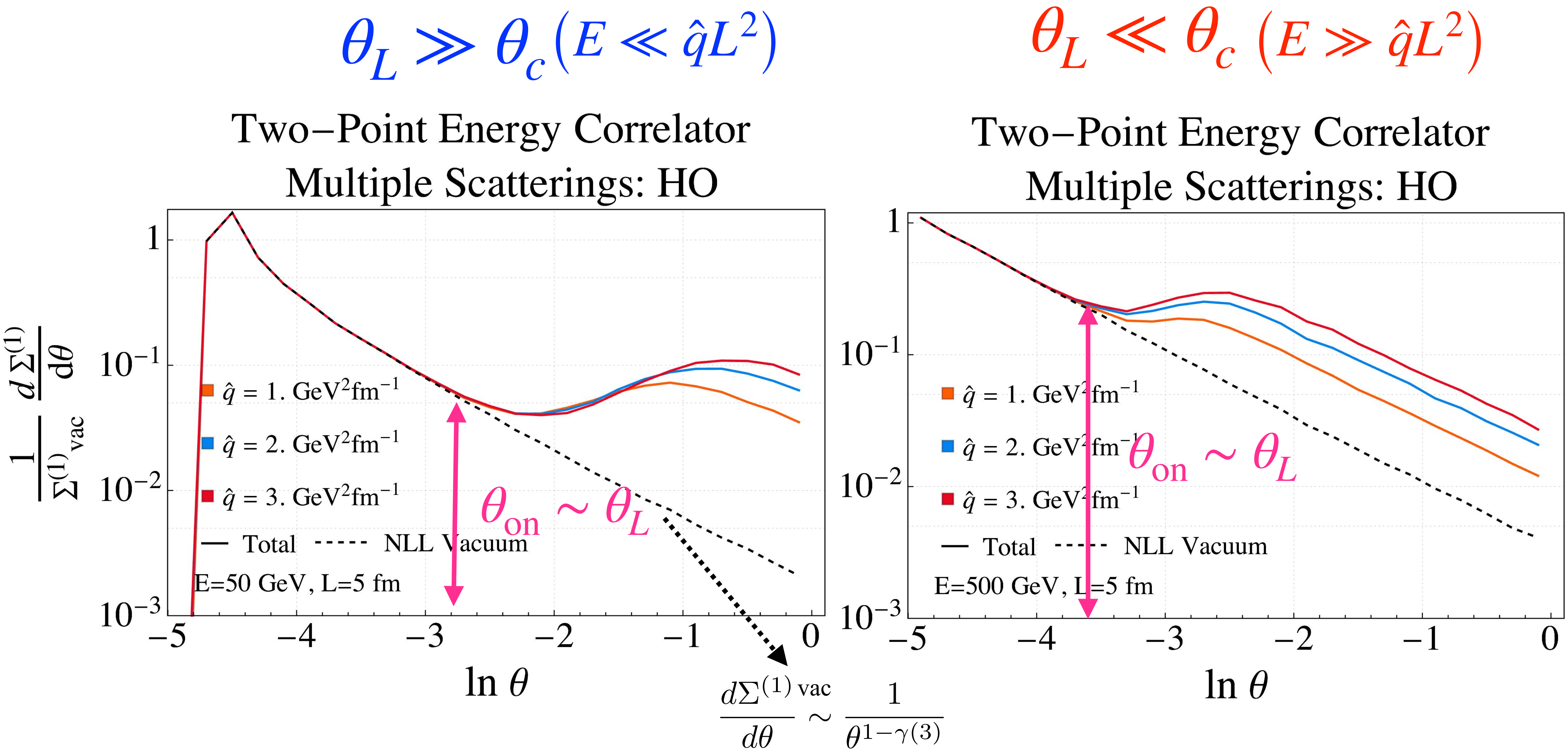
$\frac{d\Sigma^{(1)\,vac}}{d\theta} \sim \frac{1}{\theta^{1-\gamma(3)}}$

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



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

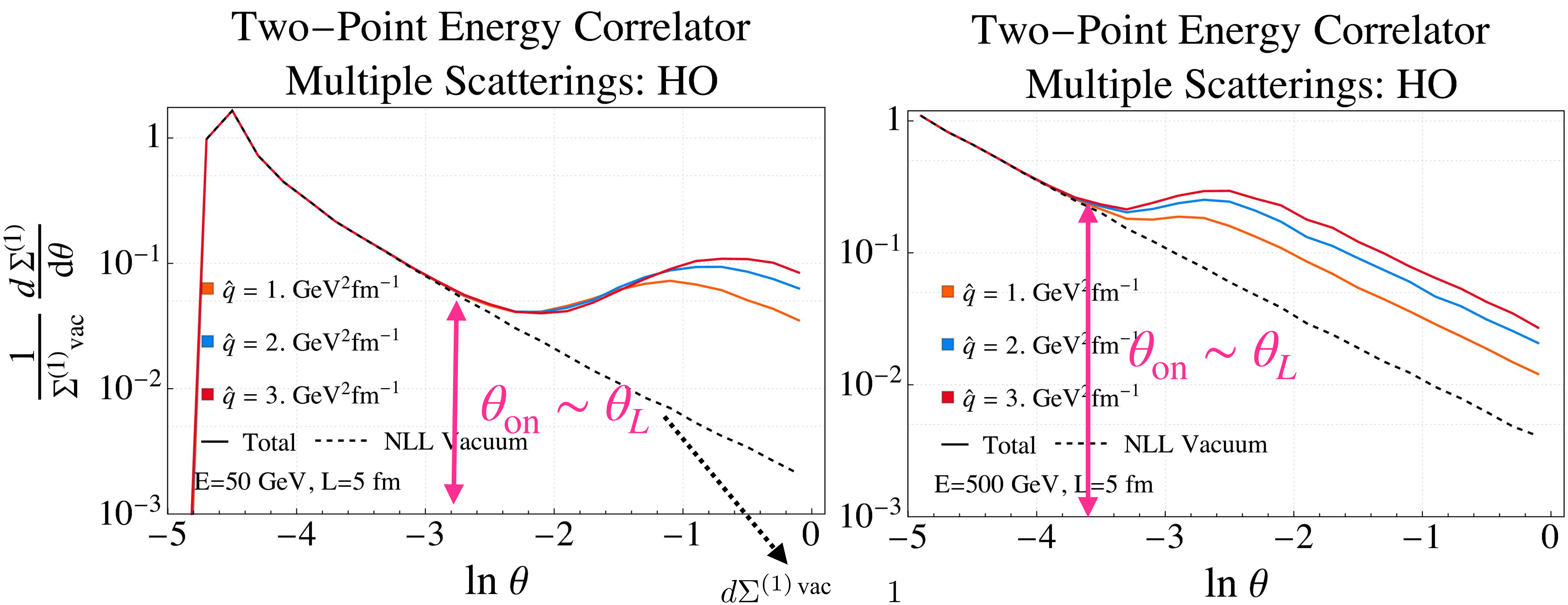
Results HO



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

Results HO

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

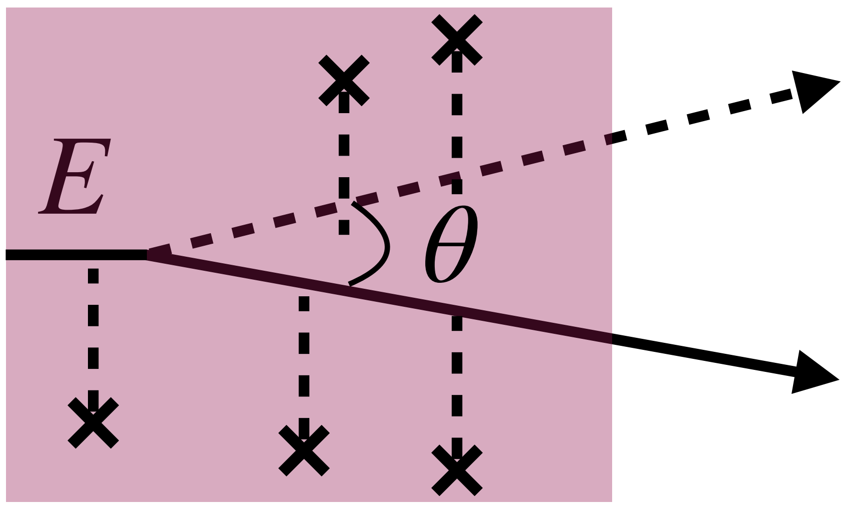


$$\frac{d\Sigma^{(1)\,\text{vac}}}{d\theta} \sim \frac{1}{\theta^{1-\gamma(3)}}$$

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

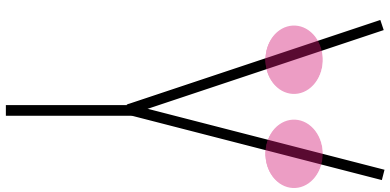
Interpretation

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

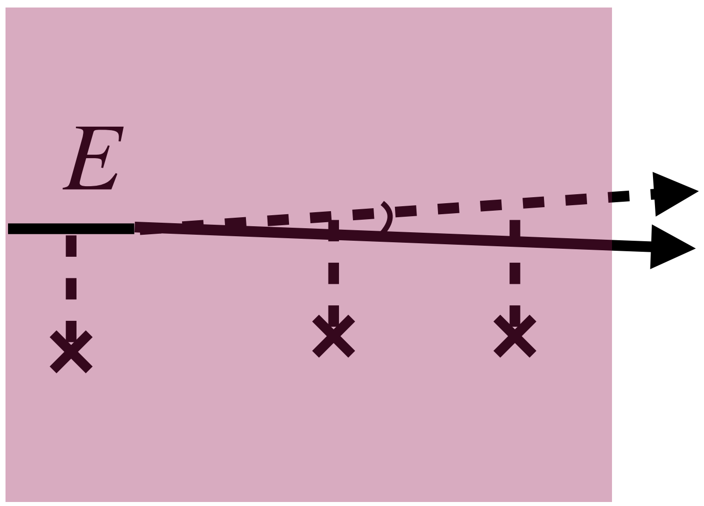


For $\theta \gg \theta_L \Rightarrow \theta \gg \theta_c$

The medium resolves the emission

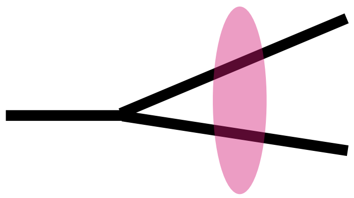


$\theta_L \ll \theta_c \quad (E \gg \hat{q}L^2)$

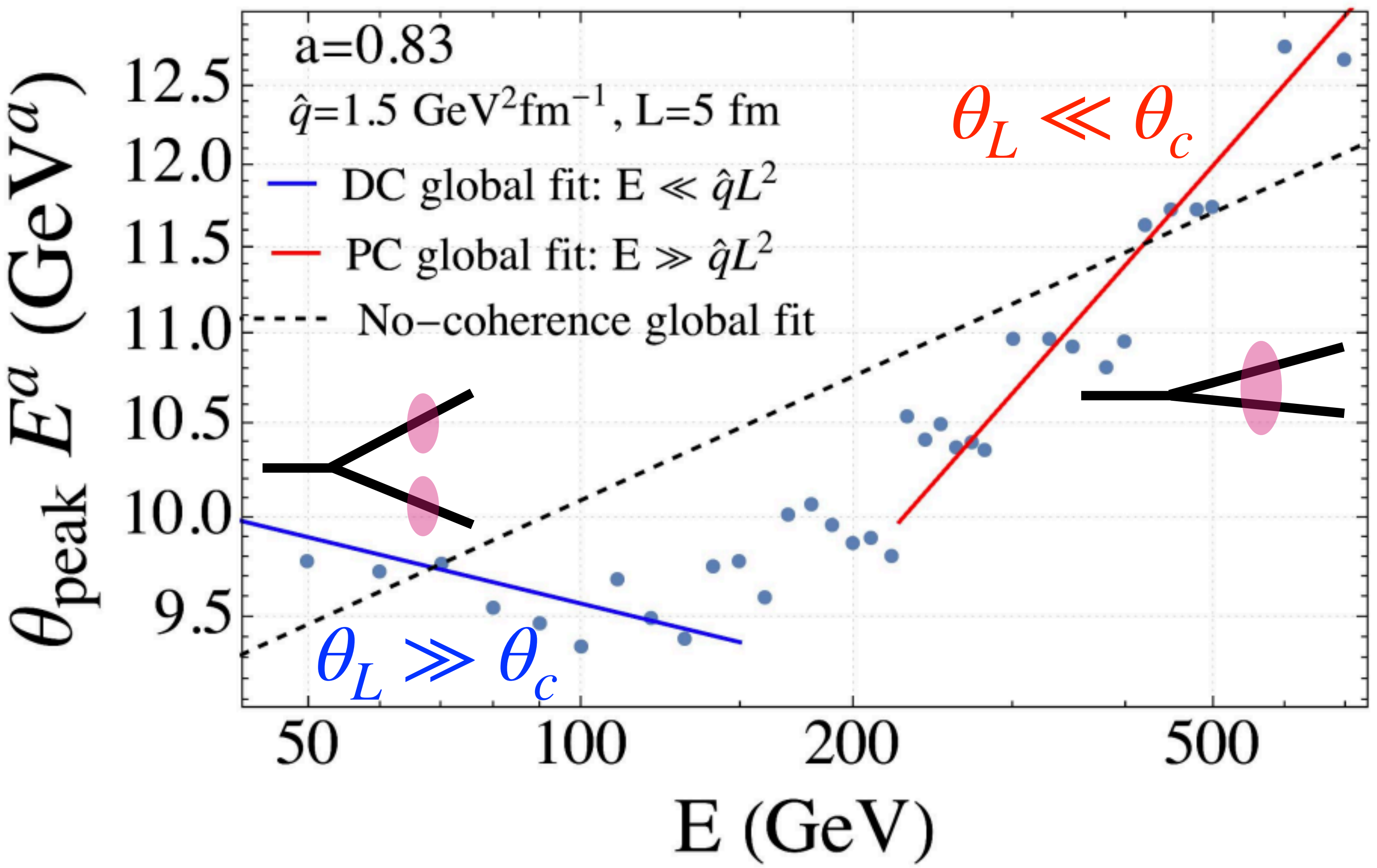


For $\theta_c \gg \theta \gg \theta_L$:

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

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