In-medium Evolution of Energy-Energy Correlators

QCD Evolution 2026
Madrid, Spain

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Based on *JHEP* 04 (2026) 155 with Ivan Vitev and Weiyao Ke

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Outline

Energy Correlators for Jet Substructure

- Small-angle limit and OPE

In-Medium Factorization for Energy Correlators

- SCET with Glauber gluons

Medium-Modified Renormalization Group Evolution

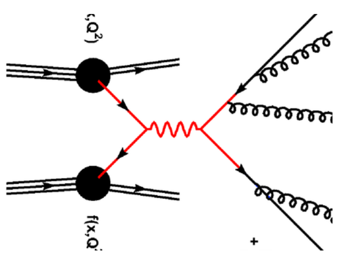
- Modified anomalous dimensions

Phenomenology

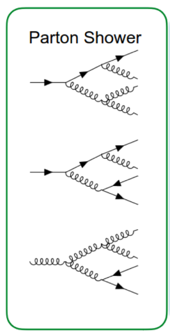
- Nuclear modification factor in p–Pb
- Comparison with ALICE
- Projections for O–O collisions

Jets in QCD

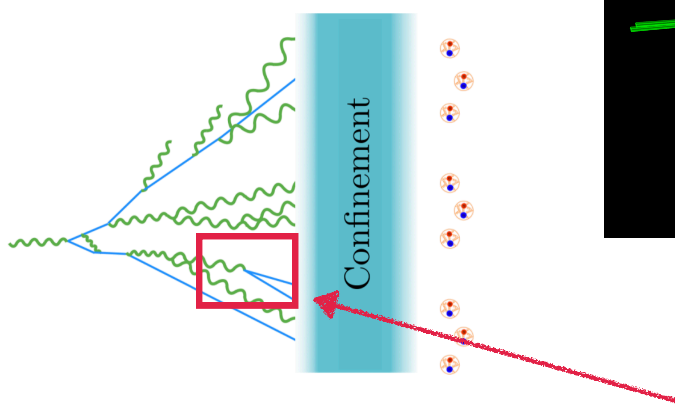
Jets are the effective degrees of freedom at particle colliders. They are the long-distance manifestation of quarks and gluons at high energies.



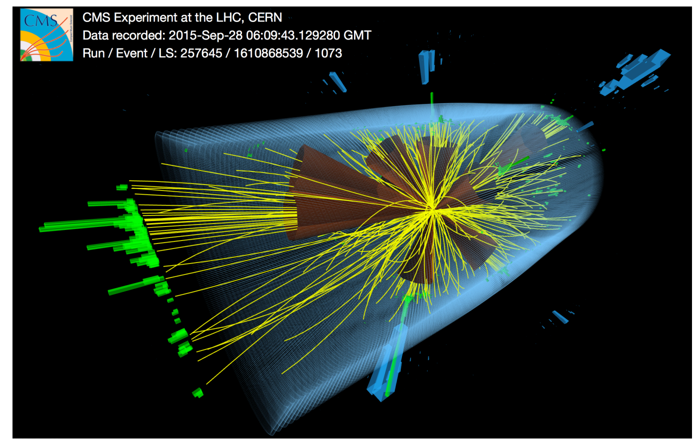
The hard process: Quarks and Gluons



Energy loss through a cascade of radiation



Collimated final state hadrons



Studies of the substructure of jets reveals fundamental properties of the underlying quark and gluon interactions.

Distribution of Energy Inside a Jet

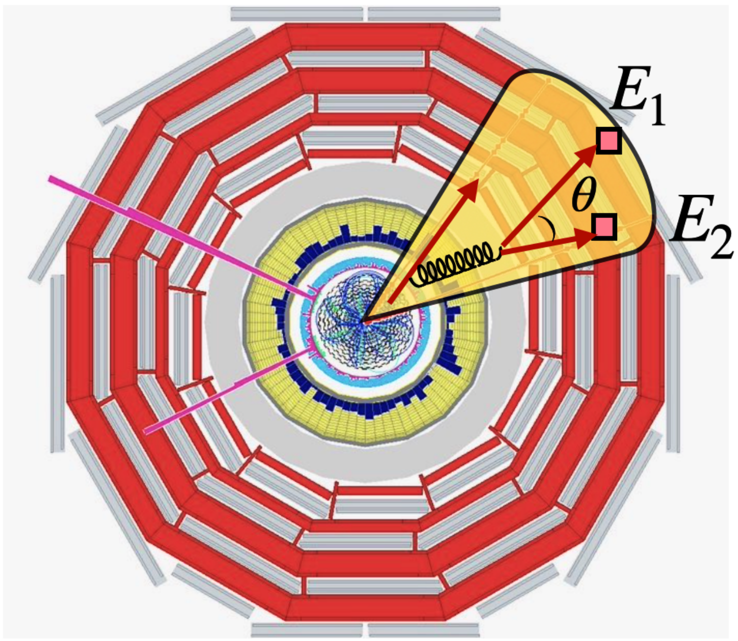
- Weighted cross section by the energy of particles inside the jet

Energy weight

$$\frac{d\sigma_{EEC}}{d\theta} = \sum_{i,j} d\sigma \frac{2E_iE_j}{Q^2\sigma_{\text{tot}}} \delta(\cos\theta - \cos\theta_{ij})$$

Angular distance between particles i and j inside the jet

- Generally can study EEC for any angular distance θ_{ij}
- For jet substructure take the limit $\theta_{ij} \to 0$

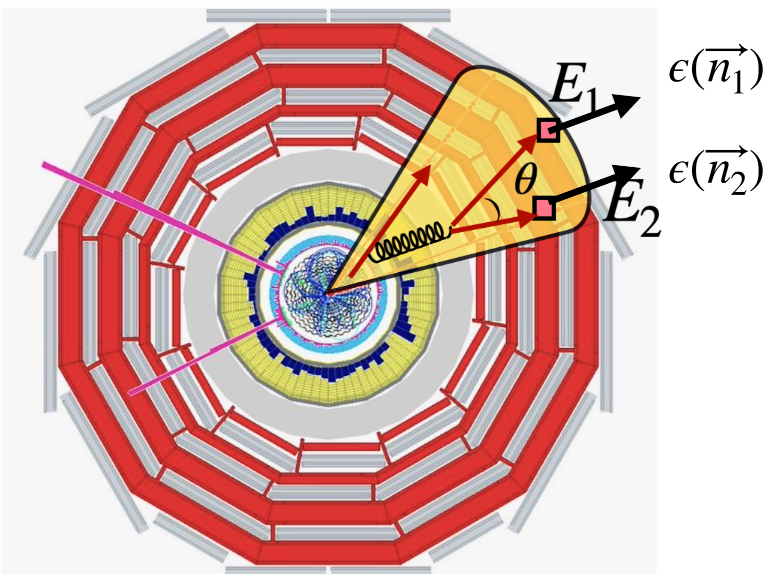


New Observable: Energy-Energy Correlator (EEC)

- **The EEC can be written in terms of QFT operators as the expectation value of the correlation functions of the energy flux operator $\epsilon(\vec{n})$ inside the jet.**
- **Energy weighted $\Rightarrow$ IR safe**
- **Most importantly: calculable in pQCD even for small angle θ (as long as $p_t\theta$ is still a perturbative scale)**

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

Energy momentum tensor



Weighted cross section

$$\text{EEC} = \sum_{i,j} d\sigma \frac{2E_iE_j}{Q^2\sigma_{\text{tot}}} \delta(\cos\theta_{ij} - \cos\theta)$$

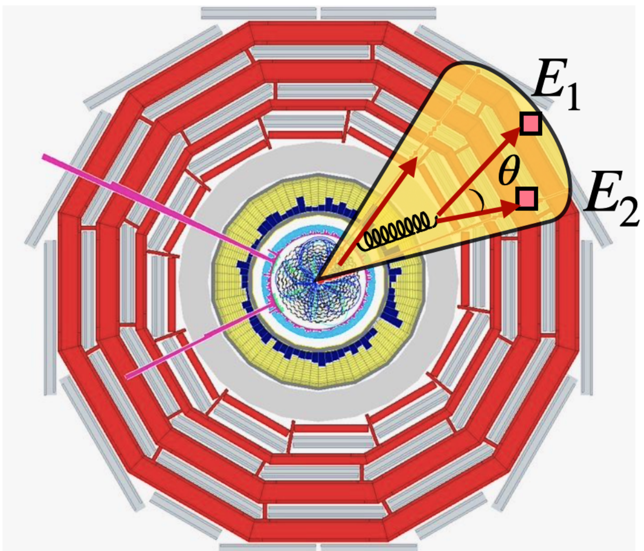
Correlation functions

$$\text{EEC} = \langle \Psi \mid \varepsilon(\vec{n}_1)\varepsilon(\vec{n}_2) \mid \Psi \rangle$$

Hofman and Maldacena (2008)

The Small Angle Limit

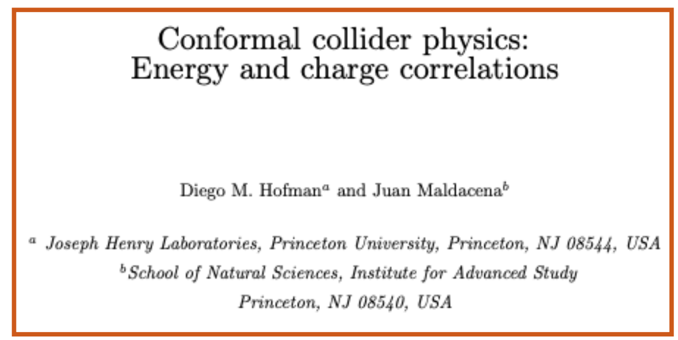
- **Energy correlators inside high energy jets at the LHC $\Rightarrow$small angle limit**



$$\langle \Psi \mid \varepsilon(\vec{n}_1)\varepsilon(\vec{n}_2) \mid \Psi \rangle$$

$$\overset{\theta \ll}{\sim} \sum \theta^{\gamma_i} \mathcal{O}_i$$

Hofman and Maldacena (2008)



Conformal collider physics:
Energy and charge correlations

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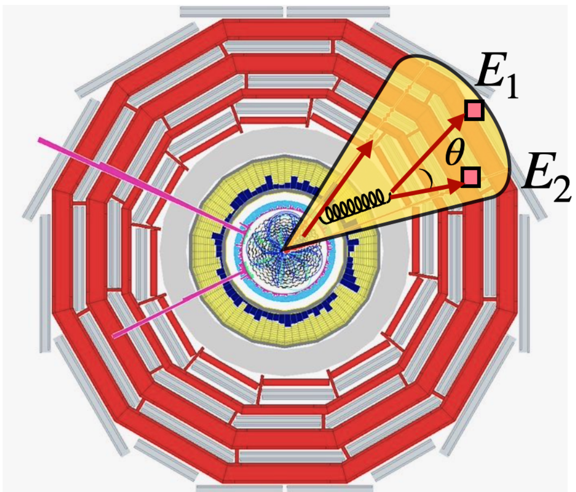
- **Energy correlators admit a simplified Operator Product Expansion (OPE)**

The Small Angle Limit

- **Energy correlators inside high energy jets at the LHC $\Rightarrow$small angle limit**



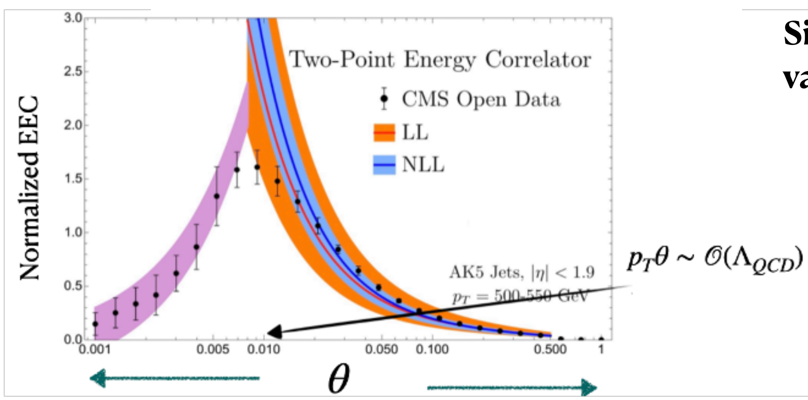
$$\langle \Psi \mid \varepsilon(\vec{n}_1)\varepsilon(\vec{n}_2) \mid \Psi \rangle$$

$$\overset{\theta \ll}{\sim} \sum \theta^{\gamma_i} \mathcal{O}_i$$

Scaling parameter

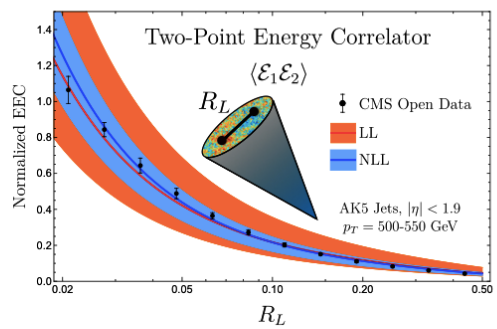
QCD operators

$\Rightarrow$ Use jets to test the leading QCD operators in this expansion



Significant progress has been made to compute the EECs perturbatively in the vacuum for collider processes.

Chen et al (2019); Dixon et al (2019); Lee et al (2022); Komiske et al (2022); Craft et al (2023); Jaarsma et al (2023)....

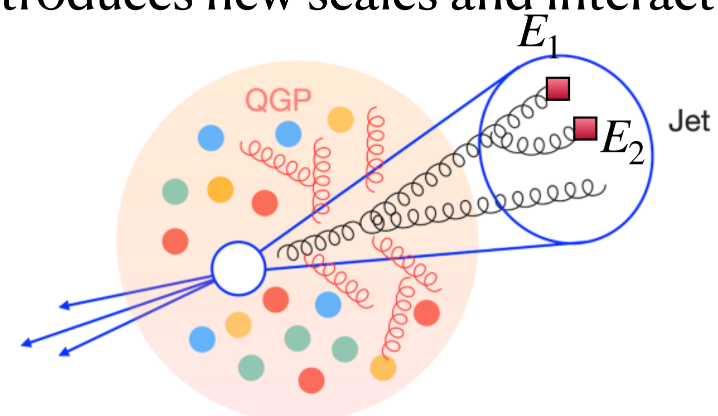


Lee, Mecaj, Moult (2022)

Does the Medium Modify the Scaling Structure?

- In the presence of a medium: jets undergo multiple scattering + induced radiation

introduces new scales and interactions



$$\theta \ll \quad \sim \sum \theta^{\gamma_i} \mathcal{O}_i$$

Scaling parameter ?

QCD operators?

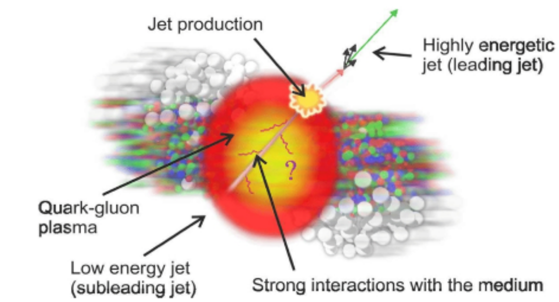
⇒Capture how the scaling behavior is modified by interactions of the jet with QCD medium!!

Scaling parameter: Related to anomalous dimensions of the QCD operators.

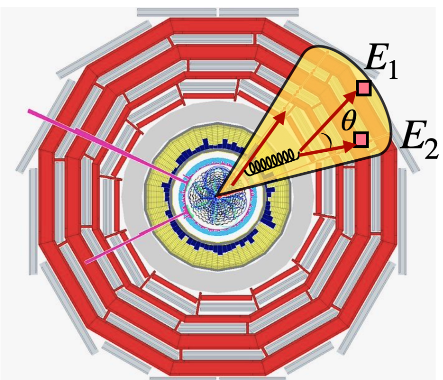
⇒ modifications due to medium effects will propagate through <u>changes in the RGE</u>

Distribution of Energy Inside Jets Moving Through the QGP

- Weighted cross-section for a jet propagating the QGP



$$\frac{1}{\sigma_{\rm jet}}\frac{d\Sigma}{d\theta\, dp_T\, dy}(p_T, y; R) = \frac{1}{\sigma_{\rm jet}}\sum_{i,j\in {\rm jet}}\int d\sigma_{\rm jet}(p_T, y; R; \{p_k\})\,\frac{p_{T,i}p_{T,j}}{p_{T,{\rm jet}}^2}\,\delta(\cos\vec{\theta} - \cos\vec{\theta}_{ij})$$



- This is a multi-scale problem:

$Q \sim p_T$	hard production scale,
$\mu_R \sim p_T R$	hard-collinear scale, jet cone,
$\mu_\theta \sim \theta p_T$	collinear virtuality of EEC .

$M_{\rm LPM} \sim \sqrt{2p_T/L}$	LPM scale,
$\sqrt{\langle \delta k_T^2\rangle} \sim \sqrt{g_s^4 T^3 L}$	medium k_T broadening scale,
$m_{\rm eff} \sim g_s T, \quad \Lambda_{\rm QCD}$	medium screening scale,

Scenario I: $\Lambda_{\rm QCD} \lesssim m_{\rm eff} \lesssim \sqrt{\langle \delta k_T^2\rangle} \ll \mu_\theta \ll M_{\rm LPM} \ll \mu_R \lesssim Q$

Scenario II: $\Lambda_{\rm QCD} \lesssim m_{\rm eff} \lesssim \sqrt{\langle \delta k_T^2\rangle} \ll M_{\rm LPM} \ll \mu_\theta \ll \mu_R \lesssim Q$

multiple scattering effect

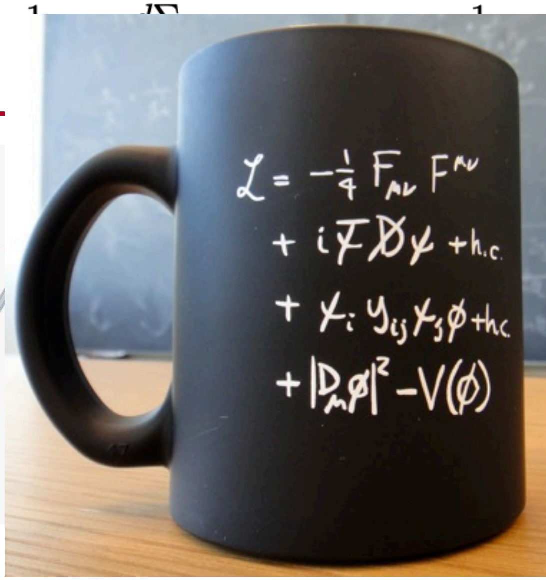
semi-hard scale

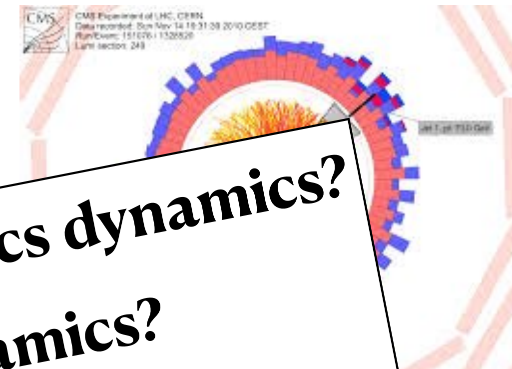
Different angular regions probe different physical regimes.

Distribution of Energy Inside Jets Moving Through the QGP

- Weighted cross-section for a jet propagating the QGP

$$\sum_{i\in \text{jet}} \int d\sigma_{\text{jet}}(p_T, y; R; \{p_k\})\, \frac{p_{T,i}\,p_{T,j}}{p_T^2}\, \delta(\cos ...$$





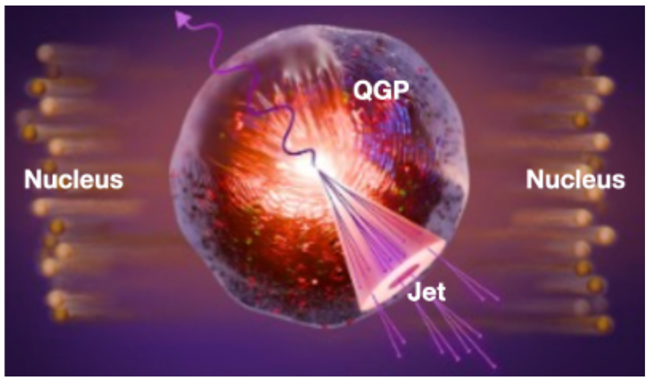
- **What is the underlying physics dynamics?**
- **What is the scale of the dynamics?**

$\sim p_T$	
$\sim p_T R$	hard-collinear scale, jet cone,
$\sim \theta p_T$	collinear virtuality of EEC .

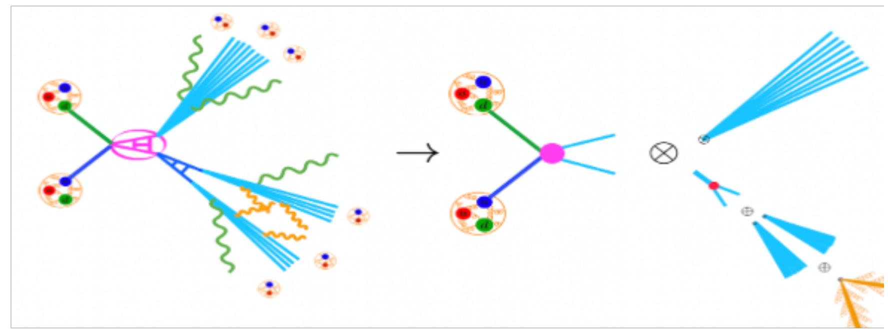
$M_{\text{LPM}} \sim \sqrt{2p_T/L}$	LPM scale,
$\sqrt{\langle \delta k_T^2 \rangle} \sim \sqrt{g_s^4 T^3 L}$	medium k_T broadening scale,
$m_{\text{eff}} \sim g_s T, \quad \Lambda_{\text{QCD}}$	medium screening scale,

EEC Factorization Formula for In-medium Jets

Multiple scales that can be resolved through an in-medium factorization theorem.



EEC + Soft Collinear Effective Theory (SCET)



Production of a high energy particles that initiate the jet.

How **multiple scattering and induced gluon emission** modify the jet substructure.

$$\frac{1}{\sigma_{\rm jet}}\frac{d\Sigma}{d\theta\, dp_T\, dy}(p_T,y;R) = \frac{1}{\sigma_{\rm jet}}\sum_{i,j\in{\rm jet}}\int d\sigma_{\rm jet}(p_T,y;R;\{p_k\})\,\frac{p_{T,i}\,p_{T,j}}{p_{T,{\rm jet}}^2}\,\delta(\cos\vec{\theta}-\cos\vec{\theta}_{ij})$$

In-medium Factorization Theorem

$$\frac{d\Sigma}{d\theta\, dp_T\, dy} = \sum_{a,b,c}\int dx_a\, dx_b\, dz_J\, f_{a/A}(x_a,\mu)\, f_{b/B}(x_b,\mu)\, \mathcal{H}_{ab\to c}\left(\frac{p_T}{z_J},\, y,\mu\right) \times \left[\mathcal{J}^{\rm vac}_{\rm EEC,c}(\theta;\, z_J,\, p_T, R,\mu) + \mathcal{J}^{\rm med}_{\rm EEC,c}(\theta;\, z_J,\, p_T, R,\mu;\, L, m_{\rm eff})\right]$$

EEC jet function captures the redistribution of energy inside the jet caused by multiple scatterings in the medium.

W.Ke, B. Mecaj, I. Vitev (2025)

Medium effects enter through the jet function, not through the hard operator structure.

Soft Collinear Effective Theory with Glauber Gluons

- Soft-Collinear Effective Theory (SCET) describes the **soft** and **collinear** mode interactions in QCD.
- **Medium interactions** are described by **Glauber gluon** exchanges: transverse momentum transfer between the QGP and the energetic patrons (jet)

Bauer et al (2002)

Ovanesyan and Vitev (2011); Ringer et al (2017)

Glauber gluons: $q_+ \sim q_- \ll q_\perp$

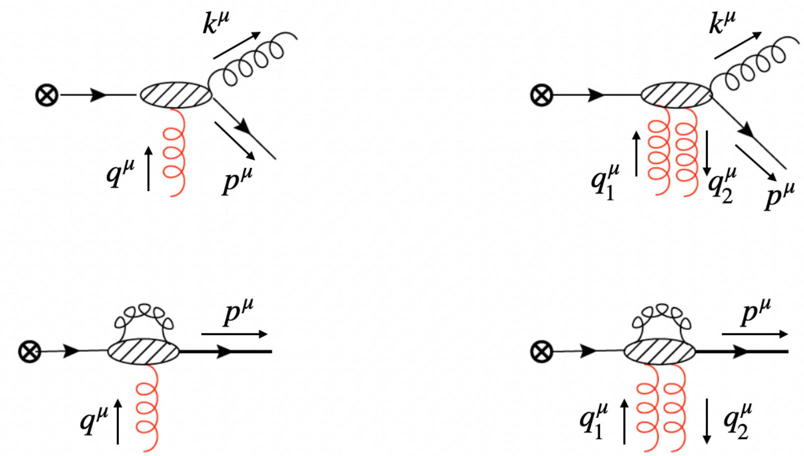
$q^\mu \sim (0,0,\vec{q}_\perp)$

- **Medium interactions are quantified via medium-induced splitting functions corresponding to these Feynman diagrams.**

Example: Energetic quark interacting with the QGP

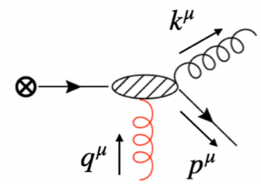
$$P_{i\to jk}(z) = P^{\rm vac}_{i\to jk}(z) + P^{\rm med}_{i\to jk}(z, q_\perp)$$

$$P^{\rm med}_{q\to qg}(x, p_\perp) = \mathcal{R}_{\rm RR} + \mathcal{R}_{\rm RV} + \mathcal{R}_{\rm VR} + \mathcal{R}_{\rm VV}$$

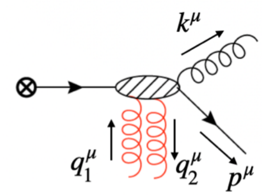


TMD Splitting Functions at First Order in Opacity

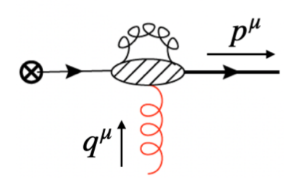
$$\frac{dN_{qq}^{RR}}{dx\, d^{2-2\epsilon}\mathbf{p}} = \frac{g^2 C_F}{(2\pi)^3} P_{qq,\epsilon}(x) \int_0^\infty dz^+ \rho_T^-(z^+) \int \frac{d^{2-2\epsilon}\mathbf{q}}{(2\pi)^{2-2\epsilon}} \frac{1}{C_F} \frac{d\sigma_{FT}}{d^{2-2\epsilon}\mathbf{q}} \quad \times \int \frac{d^{2-2\epsilon}\mathbf{k}}{(2\pi)^{2-2\epsilon}} N_q(\mathbf{p}+\mathbf{k}-\mathbf{q}) \left\{ C_F \frac{1}{\mathbf{Q}_2^2} + (2C_F - C_A)\left(\frac{1}{\mathbf{Q}_1^2} - \frac{\mathbf{Q}_1}{\mathbf{Q}_1^2} \cdot \frac{\mathbf{Q}_2}{\mathbf{Q}_2^2} \right) \phi_1 + \cdots \right\}$$



$$\frac{dN_{qq}^{RV}}{dx\, d^{2-2\epsilon}\mathbf{p}} = \frac{g^2 C_F}{(2\pi)^3} P_{qq,\epsilon}(x) \int_0^\infty dz^+ \rho_T^-(z^+) \int \frac{d^{2-2\epsilon}\mathbf{q}}{(2\pi)^{2-2\epsilon}} \frac{1}{C_F} \frac{d\sigma_{FT}}{d^{2-2\epsilon}\mathbf{q}} \quad \times \int \frac{d^{2-2\epsilon}\mathbf{k}}{(2\pi)^{2-2\epsilon}} N_q(\mathbf{p}+\mathbf{k}) \left\{ -C_F \frac{1}{\mathbf{Q}_2^2} - C_A \frac{\mathbf{Q}_2}{\mathbf{Q}_2^2} \cdot \frac{\mathbf{Q}_4}{\mathbf{Q}_4^2} \phi_{2,4} - C_A \left(\frac{1}{\mathbf{Q}_2^2} - \frac{\mathbf{Q}_2}{\mathbf{Q}_2^2} \cdot \frac{\mathbf{Q}_4}{\mathbf{Q}_4^2} \right) \phi_2 \right\}$$



$$\frac{dN_{qq}^{VR}}{dx\, d^{2-2\epsilon}\mathbf{p}} = \delta(1-x) \int_0^\infty dz^+ \rho_T^-(z^+) \int \frac{d^{2-2\epsilon}\mathbf{q}}{(2\pi)^{2-2\epsilon}} \frac{1}{C_F} \frac{d\sigma_{FT}}{d^{2-2\epsilon}\mathbf{q}} N_q(\mathbf{p}-\mathbf{q}) \quad \times \int_0^1 dx' \frac{g^2 C_F}{(2\pi)^3} P_{qq,\epsilon}(x') \int \frac{d^{2-2\epsilon}\mathbf{k}}{(2\pi)^{2-2\epsilon}} \left\{ -2C_F \frac{1}{\mathbf{Q}_5'^2} \phi_5' - C_F \frac{1}{\mathbf{k}^2} + (2C_F - C_A) \frac{\mathbf{Q}_5'}{\mathbf{Q}_5'^2} \cdot \frac{\mathbf{Q}_6'}{\mathbf{Q}_6'^2} \phi_5' + C_A \frac{\mathbf{Q}_6'}{\mathbf{Q}_6'^2} \cdot \frac{\mathbf{Q}_7'}{\mathbf{Q}_7'^2} \phi_7' \right\}$$



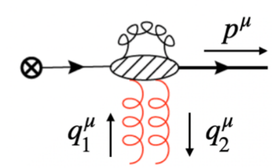
$$\frac{dN_{qq}^{VV}}{dx\, d^{2-2\epsilon}\mathbf{p}} = \delta(1-x) N_q(\mathbf{p}) \int_0^\infty dz^+ \rho_T^-(z^+) \int \frac{d^{2-2\epsilon}\mathbf{q}}{(2\pi)^{2-2\epsilon}} \frac{1}{C_F} \frac{d\sigma_{FT}}{d^{2-2\epsilon}\mathbf{q}} \times \int_0^1 dx' \frac{g^2 C_F}{(2\pi)^3} P_{qq}(x') \int \frac{d^{2-2\epsilon}\mathbf{k}}{(2\pi)^{2-2\epsilon}} \left\{ C_A \frac{\mathbf{Q}_6'}{\mathbf{Q}_6'^2} \cdot \frac{\mathbf{Q}_8'}{\mathbf{Q}_8'^2} \phi_8' - C_A \frac{1}{\mathbf{Q}_6'^2} \phi_6' + C_F \frac{1}{\mathbf{k}^2} \right\}$$

Ke et al (2025)

- **Splitting probability becomes transverse-momentum dependent (TMD)**

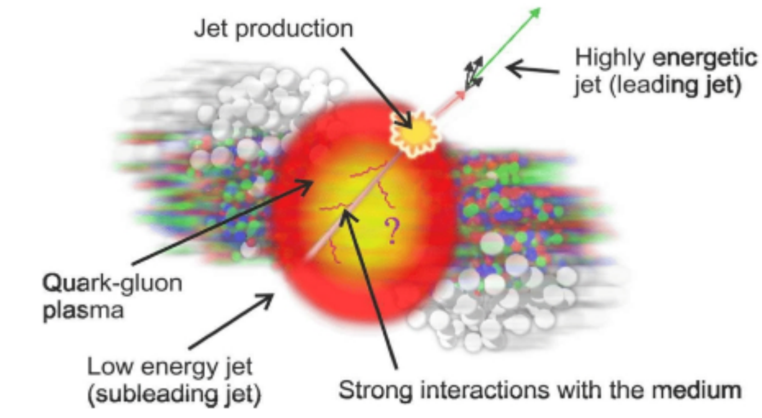
$\mathbf{Q}_1 = x\mathbf{k} - (1-x)(\mathbf{p}-\mathbf{q})\,, \quad \mathbf{Q}_2 = x\mathbf{k} - (1-x)\mathbf{p}\,,$
$\mathbf{Q}_3 = x(\mathbf{k}-\mathbf{q}) - (1-x)\mathbf{p}\,, \quad \mathbf{Q}_4 = x(\mathbf{k}-\mathbf{q}) - (1-x)(\mathbf{q}+\mathbf{q})\,,$
$\mathbf{Q}_5 = x\mathbf{k} - (1-x)(\mathbf{p}-\mathbf{q}-\mathbf{k})\,, \quad \mathbf{Q}_6 = x\mathbf{k} - (1-x)(\mathbf{p}-\mathbf{k})\,,$
$\mathbf{Q}_7 = x(\mathbf{k}-\mathbf{q}) - (1-x)(\mathbf{p}-\mathbf{k})\,, \quad \mathbf{Q}_8 = x(\mathbf{k}+\mathbf{q}) - (1-x)(\mathbf{p}-\mathbf{k}-\mathbf{q})$

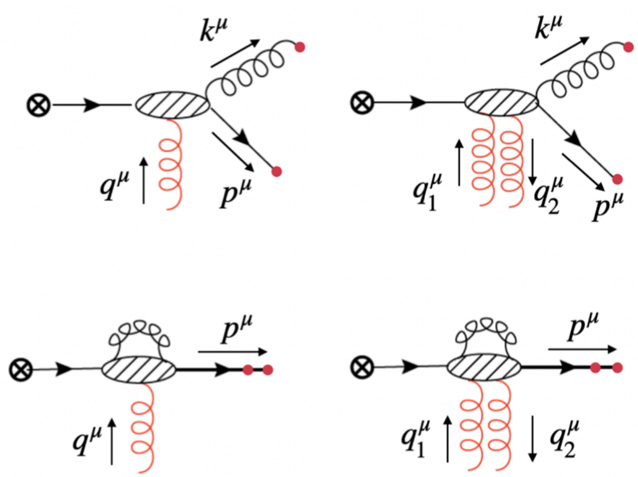
$$\Phi_n = \Phi\left(\frac{\mathbf{Q}_n^2 z^+}{2x(1-x)P^+} \right) \qquad \Phi(u) = 1 - \cos(u)$$



Energy Correlators for Medium-Modified Jets

- EEC captures the **redistribution of energy** inside the jet caused by multiple scatterings in the medium.
- Medium interactions are described via **medium induced splitting function** at any order in opacity ⇨ SCET with **Glauber gluons**
- The EEC in the medium becomes a weighted cross section using the **TMD splitting functions in SCET-G**



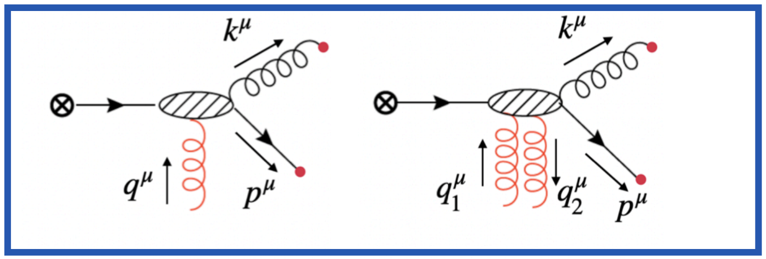


$$\frac{d\Sigma^{RR}}{d^{2-2\epsilon}\vec{\theta}} = \frac{g^2 C_F}{(2\pi)^3}\int dx P_{qq,\epsilon}(x\, x(1-x) \int \frac{d^{2-2\epsilon}\mathbf{k}}{(2\pi)^{-2\epsilon}} \sum_T \int_0^\infty dz^+ \rho_T^-(z^+) \int \frac{d^{2-2\epsilon}\mathbf{q}}{(2\pi)^{2-2\epsilon}} \frac{g^2 C_T/d_A}{(\mathbf{q}^2+m^2)^2}$$
$$\delta^{(2-2\epsilon)}\left(\vec{\theta} - \frac{\mathbf{k}-(1-x)\mathbf{q}}{x(1-x)P^+/2}\right) g^2 \left\{ \frac{C_F}{[\mathbf{k}-(1-x)\mathbf{q}]^2} + (2C_F - C_A)\left[\frac{1}{\mathbf{k}^2} - \frac{\mathbf{k}\cdot(\mathbf{k}-(1-x)\mathbf{q})}{\mathbf{k}^2(\mathbf{k}-(1-x)\mathbf{q})^2}\right]\phi\left(\frac{\mathbf{k}^2 z^+}{2x(1-x)P^+}\right)\right.$$
$$+ C_A\left[\frac{1}{(\mathbf{k}-\mathbf{q})^2} - \frac{(\mathbf{k}-\mathbf{q})\cdot(\mathbf{k}-(1-x)\mathbf{q})}{(\mathbf{k}-\mathbf{q})^2(\mathbf{k}-(1-x)\mathbf{q})^2}\right]\phi\left(\frac{(\mathbf{k}-\mathbf{q})^2 z^+}{2x(1-x)P^+}\right) + C_A\left[\frac{1}{(\mathbf{k}-\mathbf{q})^2} - \frac{\mathbf{k}\cdot(\mathbf{k}-\mathbf{q})}{\mathbf{k}^2(\mathbf{k}-\mathbf{q})^2}\right]\phi\left(\frac{(\mathbf{k}-\mathbf{q})^2 z^+}{2x(1-x)P^+}\right)$$
$$\left. + C_A\left[\frac{1}{\mathbf{k}^2} - \frac{(\mathbf{k}-\mathbf{q})\cdot\mathbf{k}}{(\mathbf{k}-\mathbf{q})^2\mathbf{k}^2}\right]\phi\left(\frac{\mathbf{k}^2 z^+}{2x(1-x)P^+}\right) + C_A\frac{\mathbf{k}\cdot(\mathbf{k}-\mathbf{q})}{\mathbf{k}^2(\mathbf{k}-\mathbf{q})^2}\phi\left(\frac{[\mathbf{k}^2-(\mathbf{k}-\mathbf{q})^2]z^+}{2x(1-x)P^+}\right)\right\}$$

Energy Correlators for Medium-Modified Jets

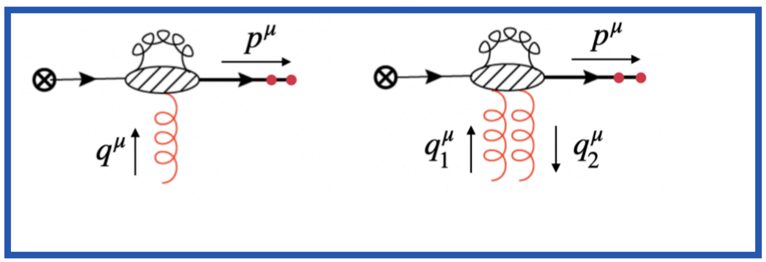
Non-Contact terms (non-trivial angular separation)

$$\theta_{jk}^{RR} = \left|\vec{\theta}_j - \vec{\theta}_k\right| = \frac{|\mathbf{k} - (1-x)\mathbf{q}|}{x_j x_k E_i} \qquad \theta_{jk}^{RV} = \left|\vec{\theta}_j - \vec{\theta}_k\right| = \frac{|\mathbf{k}|}{x_j x_k E_i}$$



$$\frac{d\Sigma^i_{\text{non-contact}}}{d\theta^2} = \sum_{(jk)} \int_0^\infty dz^+ \int_0^1 dx \int d^2\mathbf{k} \int d^2\mathbf{q}$$
$$\times\, x_j x_k \left[\delta\left(\vec{\theta}^2 - \left(\theta_{jk}^{RR}\right)^2\right) \frac{dN^{RR}_{i\to jk}}{dz^+ dx d^2\mathbf{k} d^2\mathbf{q}} + \delta\left(\vec{\theta}^2 - \left(\theta_{jk}^{RV}\right)^2\right) \delta^{(2)}(\mathbf{q}) \frac{dN^{RV}_{i\to jk}}{dz^+ dx d^2\mathbf{k}}\right]$$

Depend only on two TMD splitting functions

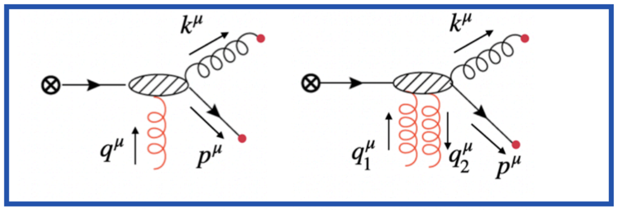


Contact terms (trivial angular delta functions)

$$\frac{d\Sigma^i_{\text{contact}}}{d\theta^2}(\theta, E)$$
$$= \sum_{(jk)} \int_0^\infty dz^+ \int_0^1 dx \int d^2\mathbf{k} \int d^2\mathbf{q}$$
$$\times \left\{\left(\frac{d\Sigma^j}{d\theta^2}(\theta, x_j E) + \frac{d\Sigma^k}{d\theta^2}(\theta, x_k E)\right)\left[\frac{dN^{RR}_{i\to jk}}{dz^+ dx d^2\mathbf{k} d^2\mathbf{q}} + \delta^{(2)}(\mathbf{q}) \frac{dN^{RV}_{i\to jk}}{dz^+ dx d^2\mathbf{k}}\right]\right.$$
$$\left. + \frac{d\Sigma^i}{d\theta^2}(\theta, E)\delta(1-x)\left[\delta^{(2)}(\mathbf{k}-\mathbf{q}) \frac{dN^{VR}_{i\to i}}{dz^+ d^2\mathbf{q}} + \delta^{(2)}(\mathbf{q})\delta^{(2)}(\mathbf{k}) \frac{dN^{VV}_{i\to i}}{dz^+}\right]\right\}.$$

Contributions from all four splitting functions

Non-contact Energy-Energy Corrector



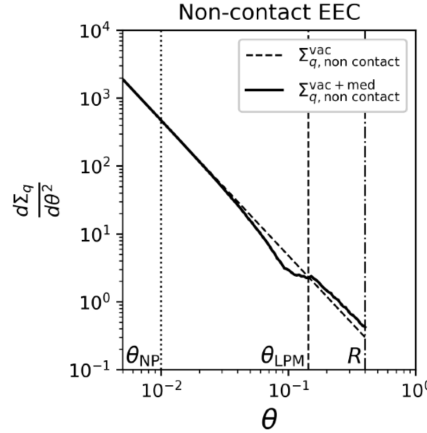
$$\frac{d\Sigma^i_{\rm non-contact}}{d\theta^2} = \sum_{(jk)}\int_0^\infty dz^+ \int_0^1 dx \int d^2\mathbf{k}\int d^2\mathbf{q}$$
$$\times\, x_j x_k \left[\delta\left(\vec{\theta}^2 - \left(\theta^{RR}_{jk}\right)^2\right)\frac{dN^{RR}_{i\to jk}}{dz^+dxd^2\mathbf{k}d^2\mathbf{q}} + \delta\left(\vec{\theta}^2 - \left(\theta^{RV}_{jk}\right)^2\right)\delta^{(2)}(\mathbf{q})\frac{dN^{RV}_{i\to jk}}{dz^+dxd^2\mathbf{k}}\right]$$

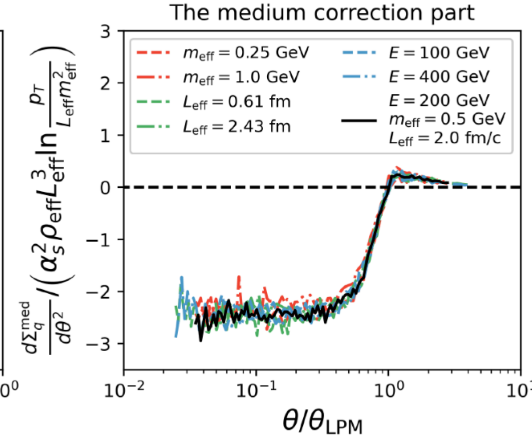
$$\theta_{\rm LPM} = \sqrt{\frac{8\pi}{P^+L^+}}$$

- **These terms give rise to a Coulomb logarithm due to the transverse momentum exchange with the medium:**

$$\int \frac{d^2q_\perp}{q_\perp^2 + m_D^2}$$

- **The logarithmic enhancement is regulated in the IR by the plasma screening mass.**



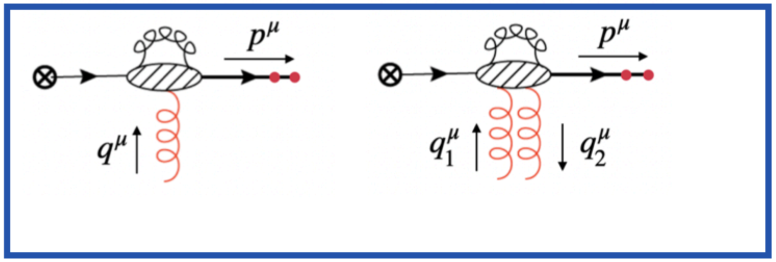


- **Explicit example for an exponentially decaying medium:**

$$\int_0^\infty \rho^-(z^+)\Phi\left(\frac{\mathbf{Q}_n^2 z^+}{2x(1-x)P^+}\right)dz^+ = \int_0^\infty \rho_0^- e^{-z^+/L^+}\left[1-\cos\left(\frac{\mathbf{Q}_n^2 z^+}{2x(1-x)P^+}\right)\right]dz^+$$
$$= \rho_0^- L^+ \frac{(\mathbf{Q}_n^2)^2}{(\mathbf{Q}_n^2 + iQ^2_{\rm LPM})(\mathbf{Q}_n^2 - iQ^2_{\rm LPM})}\,,$$

$$\frac{d\Sigma^{RR+RV}_{\rm non\ contact}}{d\theta^2}\ (\theta \ll \theta_{\rm LPM};\ \text{in an exponential medium})$$
$$= \frac{\left[\alpha_s(\mu^2)\right]^2 C_F \rho_0 L^3}{32\pi}\left\{\frac{3C_F + 16C_A}{15}\ln\frac{p_T/L}{m^2_{\rm eff}} + \text{non-log enhanced terms}\right\}$$

Contact Energy-Energy Correlator



$$
\begin{aligned}
\frac{dN^{N=1}_{q\to q+g}}{dx} =& \frac{g^2 C_F}{(2\pi)^3} P_{qq,\epsilon}(x) \sum_T \int_0^\infty dz^+ \rho_T^-(z^+) g^2 C_T/d_A \int \frac{d^{2-2\epsilon}\mathbf{k}}{(2\pi)^{-2\epsilon}} \frac{1}{\mathbf{k}^2}\Phi\left(\frac{\mathbf{k}^2 z^+}{2x(1-x)P^+}\right) \\
&\times \int \frac{d^{2-2\epsilon}\mathbf{q}}{(2\pi)^{2-2\epsilon}} \frac{g^2 C_F}{(\mathbf{q}^2)^2} \Bigg\{ (2C_F - C_A)\left[\frac{-(1-x)\mathbf{q}\cdot(\mathbf{k}-(1-x)\mathbf{q})}{(\mathbf{k}-(1-x)\mathbf{q})^2}\right] \\
&+ C_A\left[\frac{x\mathbf{q}\cdot(\mathbf{k}+x\mathbf{q})}{(\mathbf{k}+x\mathbf{q})^2}\right] + C_A\left[\frac{\mathbf{q}\cdot(\mathbf{k}+\mathbf{q})}{(\mathbf{k}+\mathbf{q})^2}\right]\Bigg\} \\
=& F_\epsilon^{q\to qg}(x) \times \kappa_\epsilon^{\text{med}} \times T_\epsilon\left(\frac{\mu^2}{2P^+/L^+_{\text{eff}}}\right) . \qquad (4.18)
\end{aligned}
$$

The contact contribution does not generate a Coulomb logarithm; its transverse momentum integral is regulated and does not produce logarithmic enhancement.

Integration is performed in a very similar form for different kinematic terms assuming: $P^+/L^+ \gg m^2_{\text{eff}}$

$$F_\epsilon^{q\to qg}(x) \times \kappa_\epsilon^{\text{med}} \times T_\epsilon\left(\frac{\mu^2}{2P^+/L^+_{\text{eff}}}\right)$$

Weighting effects: EEC kinematics

$$F_\epsilon^{q\to qg}(x) = C_F P_{qq,\epsilon}(x) \frac{1}{[x(1-x)]^{1+2\epsilon}} \left[(1-x)^{2+2\epsilon}(2C_F - C_A) + x^{2+2\epsilon} C_A + C_A\right]$$

Medium properties

$$\kappa^{\text{med}} = \frac{\rho^-_{\text{eff}} L^+_{\text{eff}}}{2P^+/L^+_{\text{eff}}}$$

Medium properties + EEC kinematics

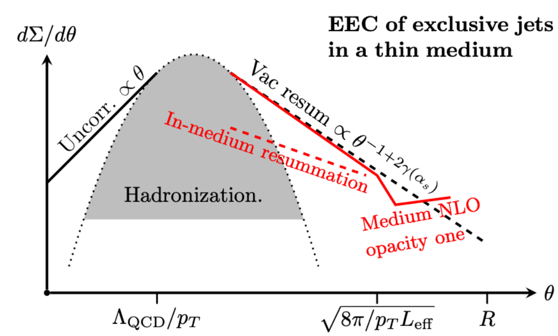
$$T_\epsilon\left(\frac{\mu^2}{2P^+/L^+_{\text{eff}}}\right) = \alpha_s^2(\mu^2)\frac{1}{2}\left[\frac{\mu^2 e^{\gamma_E - 1}}{2P^+/L^+_{\text{eff}}}\right]^{2\epsilon}\left(1 + \mathcal{O}(\epsilon^2)\right)$$

Renormalization Group Evolution

- The factorization theorem enables a clean separation of scales as well as separation of medium and vacuum effects: **track down evolution effects due to medium and scales in the medium**.

$$\frac{d\Sigma}{d\theta^2} = \frac{d\Sigma^{vac}}{d\theta^2} + \boxed{\frac{d\Sigma^{med}}{d\theta^2}}$$

Modifications to the anomalous dimensions due to medium effects.

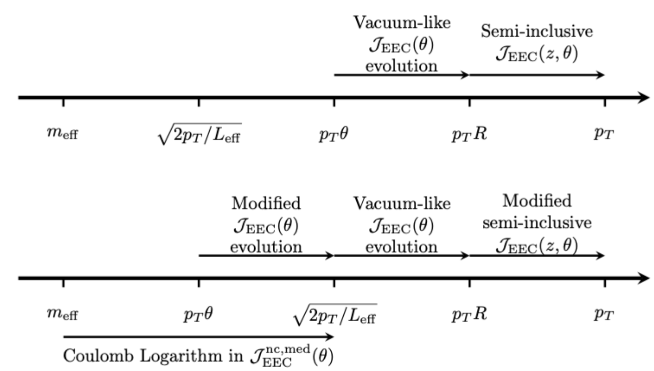


- RGE describes how collinear radiation evolves as it traverses the QCD medium.

Different types of logarithms: Coulomb + medium modified EEC kinematics

$$\ln\frac{E/L}{m_D^2} \quad \ln\frac{Q^2}{(Q\theta)^2} \quad \ln\frac{(Q\theta)^2}{M_{\rm LPM}^2}$$

$$\frac{\partial}{\partial \ln\mu^2}\begin{bmatrix}\Sigma_q \\ \Sigma_g\end{bmatrix} = \frac{\alpha_s(\mu^2)}{2\pi}\begin{bmatrix}\gamma_{qq}^{\rm vac} + \Delta\gamma_{qq}^{\rm N=1} & \gamma_{gq}^{\rm vac} + \Delta\gamma_{gq}^{\rm N=1} \\ \gamma_{qg}^{\rm vac} + \Delta\gamma_{qg}^{\rm N=1} & \gamma_{gg}^{\rm vac} + \Delta\gamma_{gg}^{\rm N=1}\end{bmatrix}$$



Medium Modified RGE

Modified anomalous dimensions

$$\gamma_{ji}(N) = \begin{cases} \gamma_{ji}^{\rm vac}(N) + \Delta\gamma_{ji}^{\rm med}(N), & \Lambda_{\rm QCD}/p_T \ll \theta \ll \theta_{\rm LPM} \\ \gamma_{ji}^{\rm vac}(N), & \theta_{\rm LPM} \ll \theta \ll R\,. \end{cases}$$

$$\Delta\gamma_{qq}^{\rm med}(N) = w_{\rm med} \times \left(2(N-1)C_F C_A + C_F^2\right)\,,$$
$$\Delta\gamma_{gq}^{\rm med}(N) = w_{\rm med} \times \left(-C_F^2\right)\,,$$
$$\Delta\gamma_{gg}^{\rm med}(N) = w_{\rm med} \times \left(2(N-1)C_A^2 + 2N_f T_F C_F\right)$$
$$\Delta\gamma_{qg}^{\rm N=1}(N) = w_{\rm med} \times \left(-2N_f T_F C_F\right)\,,$$

$$w_{\rm med} \equiv 4\pi\alpha_s(\mu^2)\kappa^{\rm med} = \frac{4\pi\alpha_s(\mu^2)\rho_{\rm eff}L_{\rm eff}}{2p_T/L_{\rm eff}} \ll 1$$

ω_{med} is an indicator of whether we can consider the medium effect as perturbative compared to the vacuum evolution.

This is realistic for p-Pp and other small systems.

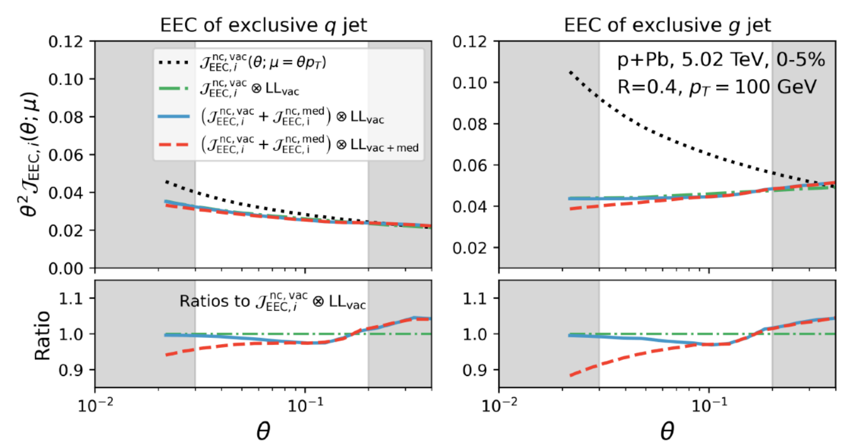
- For in-medium evolution there are two regions:

$M_{\rm LPM} \ll p_T\theta \ll p_T R < p_T$.

No log enhancement ⇒perform vacuum resumption from $p_T\theta$ to pT

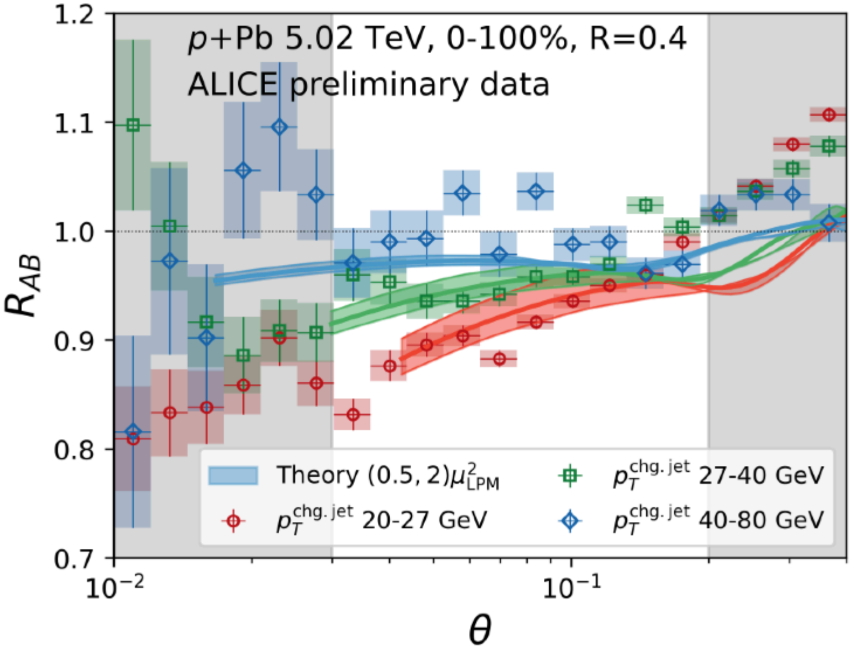
$p_T\theta \ll M_{\rm LPM} \ll p_T R < p_T$

Evolution is two-stages: vacuum+medium modified LL evolution from $p_T\theta$ to M_{LPM}, then at the scale M_{LPM} include medium fixed-order correction from contact and non-contact term. Then, perform vacuum evolution from M_{LPM} to $p_T R$

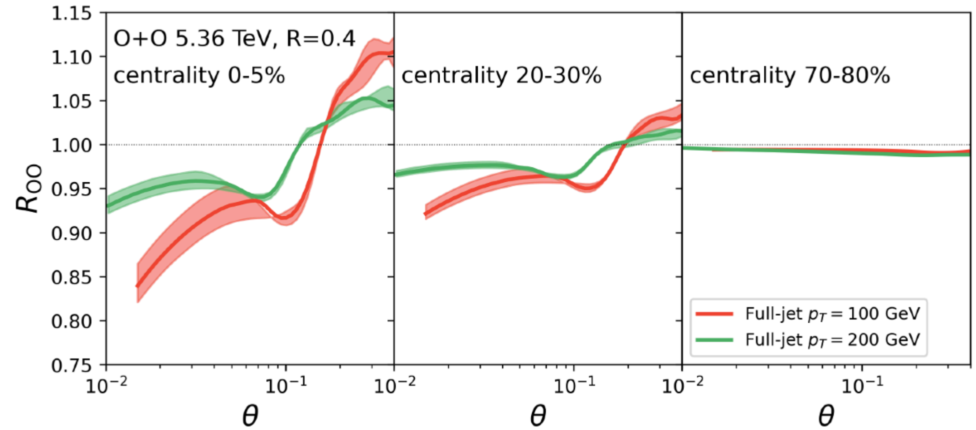


Phenomenology

Comparison with ALICE preliminary



Full-jet EEC projections in O–O collisions



- R_{pA} **shows suppression at small angles and recovers at large angles: medium-induced broadening and energy redistribution.**
- **Small-angle suppression comes from medium-modified anomalous dimension from multiple soft scatterings: stronger effect at lower-** pT.

- **Future O–O measurements can test medium-induced resummation in the asymptotic region and constrain medium corrections to the anomalous dimension (effective opacity).**

•Even in small systems, the medium effect induces a few-percent angular redistribution of jet energy: **probe of its microscopic and collective dynamics**.

Conclusions

- **Energy–energy correlators provide a clean, IR-safe probe of jet substructure and anomalous dimensions in QCD.**
- **In a QCD medium, the small-angle expansion is modified through medium-induced corrections to the anomalous dimensions.**
- **Glauber exchange generates a Coulomb logarithm and introduces the LPM scale, reshaping the RG evolution of the EEC.**
- **Full LL resummation shows that medium effects persist after evolution and produce characteristic angular distortions.**
- **The small-angle asymptotic region offers a robust, RG-controlled way to extract medium properties from data.**

Thank you!