Jet modifications in QGP

The 16th Workshop on QCD Phase Transition & Relativistic Heavy-Ion Physics, October 24-28, 2025, Guilin

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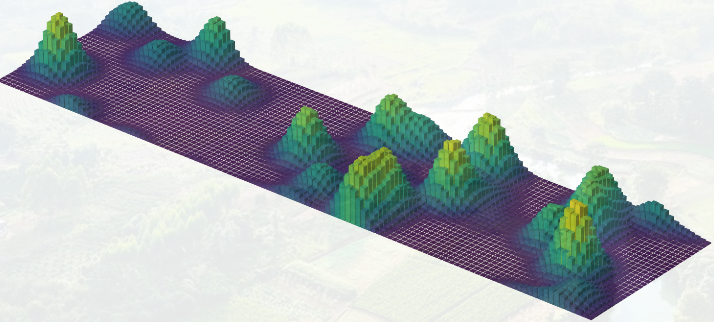
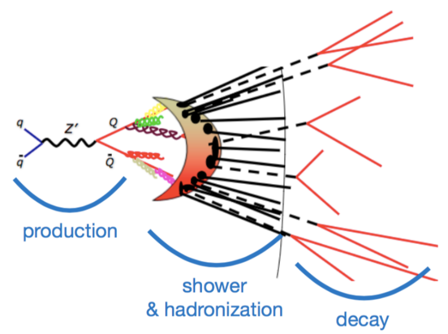


Jet physics and QCD



[Illustration of jet formation, taken from JPG47(2020)090501]

$\mathcal{L}_{\mathrm{QCD}}$ is written in terms of quark & gluon fields

$$\mathcal{L} = \sum_q \bar{q}\left[i\gamma^\mu(\partial_\mu + ig_s A^a_\mu)t^a - m_q\right]\bar{q} - \frac{1}{4}F^{\mu\nu,a}F^a_{\mu\nu}$$

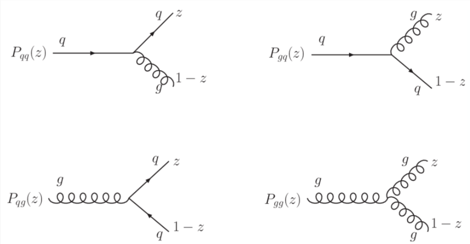
- QCD dynamics spans both perturbative and non-perturbative regimes.
- Jet produced at high-energy scales allows one to test QCD at $\alpha_s(\mu) \ll 1$, quark and gluon as quasi-particles (partons).
- Provide the hard probes of QGP in AA.

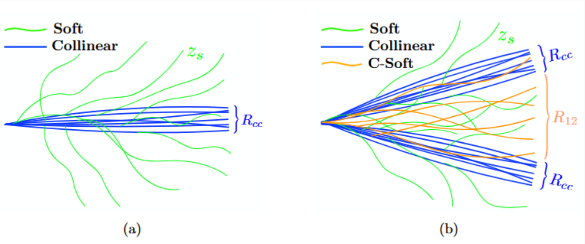
Collinear and soft fluctuations

- The perturbative regime of QCD contains almost massless quarks (u, d, s) & gluons:

$$dP_{g\to gg} \sim \frac{\alpha_s C_A}{2\pi} \frac{dz}{z(1-z)} \frac{d\mathbf{k}^2}{\mathbf{k}^2}$$ enhanced **soft** and **collinear** radiations

- Which quantum fluctuations are relevant is specific to observables





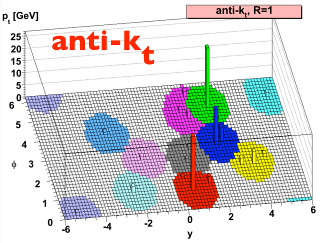
[LO QCD splitting functions]

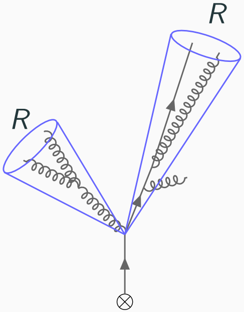
[Illustration from Larkoski, Moult, Neill, JHEP12(2014)009]

Inclusive jets in the vacuum

Jet cross-section perturbatively calculable using the factorization formula

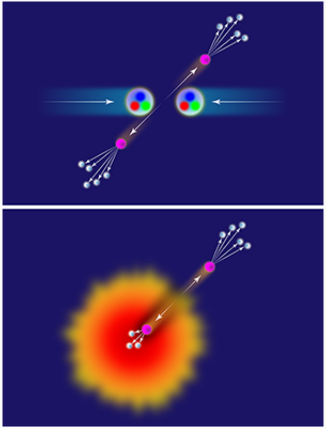
$$\frac{d\sigma_{pp\to\text{jet}}}{dy dp_T} = \sum_{ijkX} \int dx_1 dx_2 f_{i/p}(x_1,\mu') f_{j/p}(x_2,\mu') \left.\frac{d\sigma_{ij\to kX}}{dy dp'_T}\right|_{p'_T=\frac{p_T}{z}} \mathcal{J}_{k\to\text{jets}}(z,R,\mu)\frac{dz}{z}$$





- A jet is characterized by a jet cone of radius parameter R.
- Out-of-cone radiations take away energy, or form new jets.
- Radiations in the cone do not change $\mathcal{J}$ at the same order, but changes substructure.

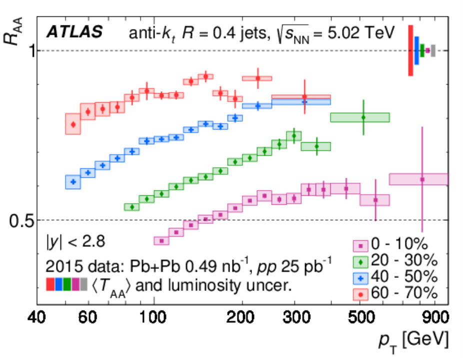
Jets in heavy ion collisions



[Figure from Cristina Manuel physics.aps.org/articles/v7/97]

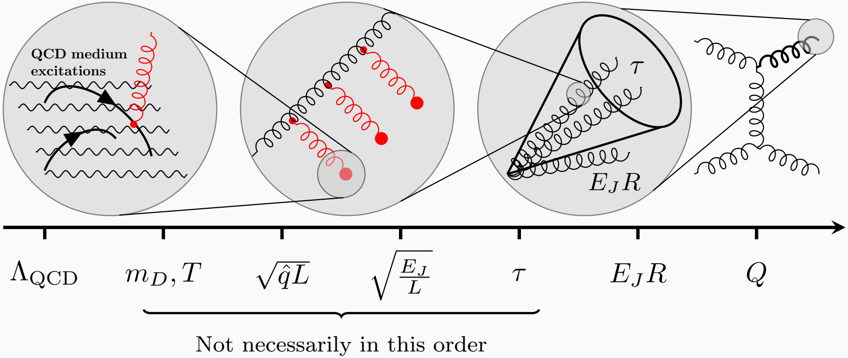
Jet quenching: suppression of jet cross section in *AA* relative to *pp*.

“Simple” cause: interactions between energetic parton and the hot medium.



The full picture is complicated

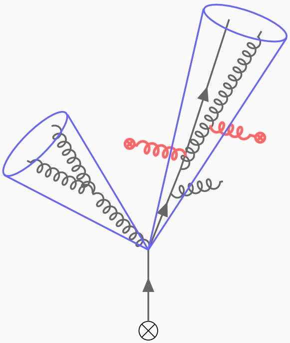
A simple cause leads to a surprisingly complicated multi-scale problem.



Medium emergent scales *versus* Controllable jet scales Q, $E_J R$, τ.

Theory descriptions of jets in QGP

I. Collision rates of jet parton in medium



- Large angle + small-angle deflection with plasma screening

$$\frac{d\Gamma_R}{d\mathbf{q}^2} \xrightarrow{|q| \gtrsim T} \text{density} \times \text{cross-section in vacuum}$$

$$\frac{d\Gamma_R}{d\mathbf{q}^2} \xrightarrow{|q| < T} \alpha_s C_R T \int \frac{d\omega}{2\pi} \frac{\rho_L(\omega, \mathbf{q}, q_z)}{\omega} = \frac{\alpha_s C_R T m_D^2}{\mathbf{q}^2(\mathbf{q}^2 + m_D^2)}$$

[Aurenche, Gelis, Zaraket, JHEP0205(2002)043]

- A more useful characterization is jet transport parameter:

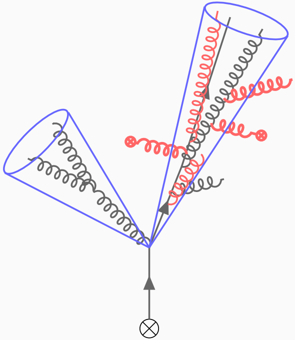
$$\hat{q}_R = \int d\mathbf{q}^2 \mathbf{q}^2 \frac{d\Gamma_R}{d\mathbf{q}^2}$$

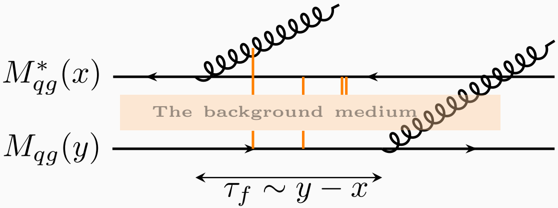
- Cause energy loss and transverse momentum broadening of each parton.

$$\mathcal{J}_{k\to\text{jet}}(E, E_0, R) \to \mathcal{J}_{k\to\text{jet}}(E + \Delta E, E_0, R)$$

More partons in jet $\to$ larger ΔE. $\sigma_{AA\to\text{jet}}$ depends on emissions in the cone!

II. Medium-induced radiations





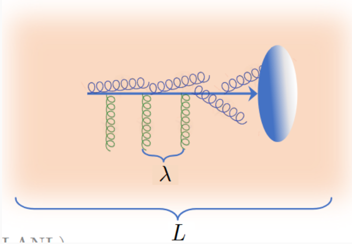
Various approximations, numerical solution available. Generally:

- Induced radiations are softer with a typical range of k_T.
- Multiple interactions contribute coherently: the LPM effect.
- Introduces additional scales $\sqrt{\int \hat{q} d\tau}$, $\int \hat{q}\tau d\tau$, $\sqrt{E/\tau}$, etc.

For observables:

- Induced radiations out of cone cause radiative jet energy loss.
- Induced radiations inside cone alters jet substructures.

Summing multiple emissions



- At early times $\Delta t \sim \hbar/\Delta E \ll L$. Integrated out time, perform scale evolution using a modified DGLAP eq. [e.g., Deng, Wang PRC81(2010)024902]

$$\frac{\partial}{\partial \ln \mu^2} f_{\rm i}(\mu, zE) = \left[\frac{\alpha_s}{2\pi} P_{ij}^{\rm vac}(z) + \frac{dN_{ij}^{\rm med}}{dz}\right] \otimes f_{\rm j}(\mu, zE)$$

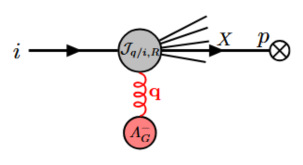
Resum $(\alpha_s \frac{\hat{q}_0 L}{E/L} \ln \frac{E/\tau}{m_D^2} \partial_z)^n f(zE)$ [Ke, Vitev, PLB854(2024)138751]

- At late times $\Delta E \sim \hbar/\Delta t \ll Q$. Integrate out energy uncertainty, perform time evolution with kinetic equations [LBT, MARTINI, LIDO, JetMed, etc]. Resum terms $\propto t$.

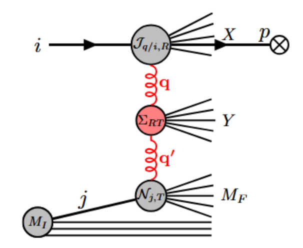
$$\text{Linearized Boltzmann equation:} \quad p^\mu \partial_\mu f_{\rm hard}(t, x, p) = \mathcal{C}_{2\to 2}[f_{\rm hard}] + \mathcal{C}_{1\to 2}[f_{\rm hard}]$$

How to perform both & interfacing? Require a more serious theory investigation.

What types of quantum fluctuations are important? Specific to observables



v.s.



◁ Medium probed by energy-loss sensitive observables:

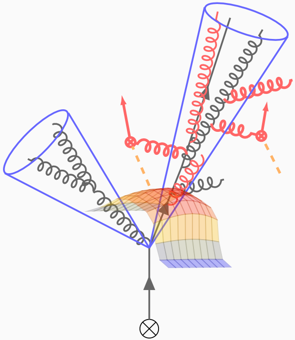
- Medium quantum fluctuations are less important.
- $\Delta E_{\rm rad} \propto \alpha_s \int \hat{q}_0 \tau d\tau$

◁ Medium probed by p_T-broadening sensitive observables:

- Fluctuations in exchanged gluon & medium are important.
- Collision kernel further improved by BFKL equation, or via $\hat{q}$ renormalization $\hat{q} \sim \hat{q}_0 (L/L_0)^\gamma$ [Blaizot, Mehtar-Tani, Wu (2013-2015), V Vaidya, B. Singh, (2021-2024), Ke, Terry, Vitev (2025)]

⋆ In addition to MC studies, it is necessary to use effective field theory to decide what types of fluctuations are important.

III. Jets induced medium response



- Jet recoils medium parton to semi-hard partons, which continue to propagate and diffuses in the medium:

$$\frac{df_{\rm semi\ hard}}{dt} = \int W(p,p';T)[f(p',x) - f(p,x)]dp'$$

A **quasi-particle type** of response.

- Collective response to jet energy-momentum deposition:

$$\partial_\mu(T^{\mu\nu} + \delta T^{\mu\nu}) = \delta J^\nu, \text{[Chen, Cao, Luo, Pang, Wang, CoLBT]}$$

Contains both **sound and diffusive modes** .

For observables: correlated soft particle production from the bulk, $\propto R^2$.

Jet phenomenology in HIC

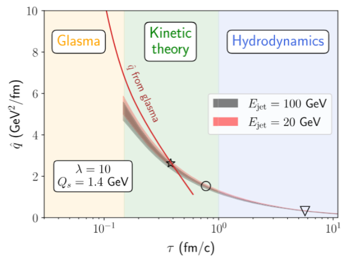
I. Jet transport parameter & nature of the medium

From coherent fields to highly-occupied gluon system

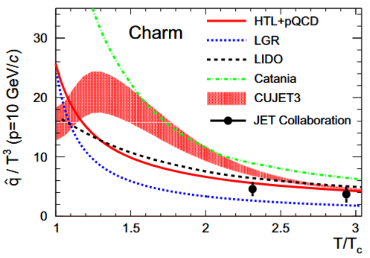
Near local thermal distributions of quarks & gluons

Finite-T hadron system, from dense to dilute

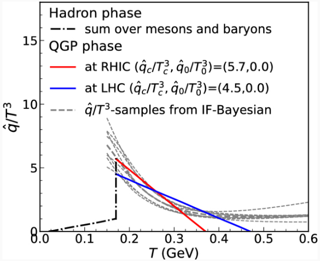
τ



[K. Boguslavski et al., PLB850(2024)138525]

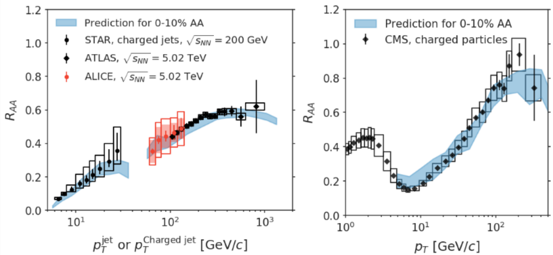


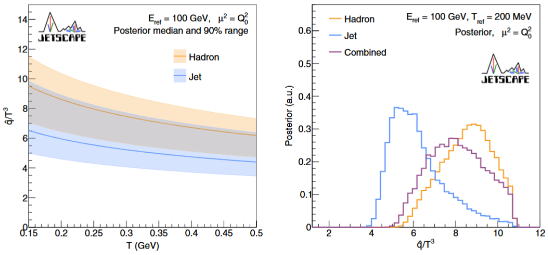
[(charm $\hat{q}$) S. Li et al. EPJC81(2021)536]



[M. Xie et al. arXiv:2409.18773]

I. Jet transport parameter & nature of the medium



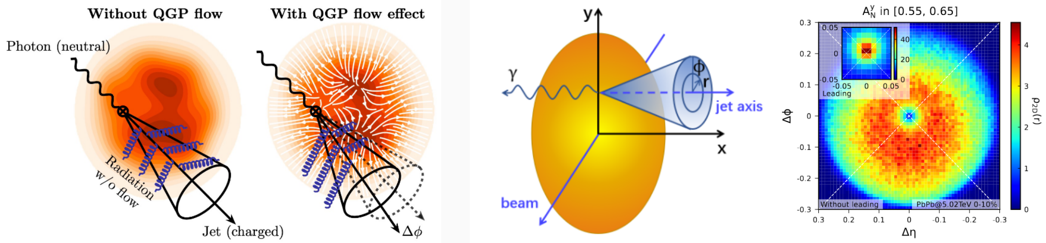


[Ke, Wang JHEP05(2021)041]

[JETSCAPE PRC111(2025)054913]

- Jets and hadron suppression prefers slightly different $\hat{q}$. Also found in other transport models.
- May suggest other effects to be included in the shower simulation, e.g., color (de)coherence [Mehtar-Tani, Pablos, Tywoniuk PRL127(2021)252301].

II. Anisotropic jet substructures



Anisotropic jet shape due to flow and density gradient from transport mdoel

[Y.-X. Xiao, Y. He, L.-G. Pang, X.-N. Wang, Phys.Rev.C 109 (2024) 5, 054906]

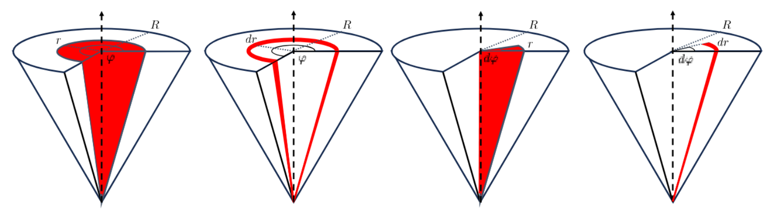
First-principle jet coupled to gradient/flow: [Sadofyev, Sievert, Vitev PRD104(2021)094044].

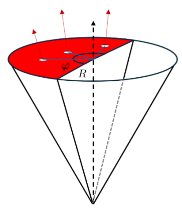
Attract great attention in the past years [Fu, Casalderrey-Solana, Wang PRD107(2023)054038, Barata, Sadofyev, Wang PRD107(2023)L051503, Barata,Mayo López, Sadofyev,Salgado,PRD108(2023)034018.]

Tan Luo's Talk on *Three-dimensional Coupling between Jet and Flow in HIC*.

II. Anisotropic jet substructures

Progress in the factorization calculation of anisotropic jet shape and jet angularity in vacuum using SCET [Ke, *Terry*, Vitev, JHEP07 (2025)097]. Should be generalized to AA.



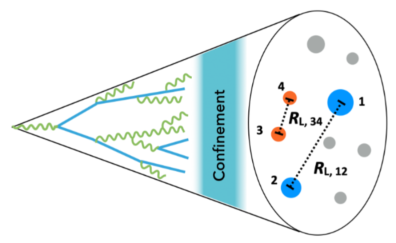


It is also found that Winner-Take-All jet axis greatly simplify such anisotropic calculation.

Anisotropic jet angularity

$$\tau_\phi^a = \frac{1}{p_{T,\mathrm{jet}}} \sum_{i \in J_\phi} p_T^i |\Delta r_{iJ}|^{2-a}$$

III. Energy correlators



[An illustration by W. Fan.]

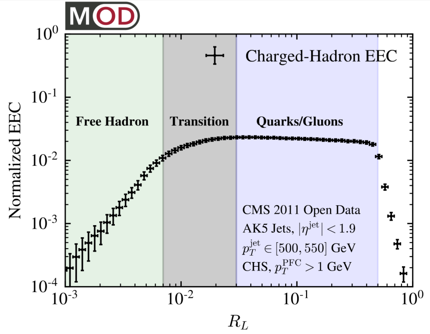
An energy weighted, multi-angular distances differential cross section

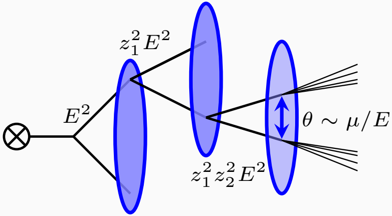
For two-point correlator: $$\frac{d\Sigma_2}{d\theta^2} = \frac{1}{N_{\text{jet}}} \sum_{\text{jet}} \sum_{ij \in \text{jet}} \delta(\theta^2 - \theta_{ij}^2) \frac{E_i^n}{E_{\text{jet}}^n} \frac{E_j^n}{E_{\text{jet}}^n}$$

and in theory $\Sigma_N = \langle \hat{\mathcal{E}}_1^n \hat{\mathcal{E}}_2^n \cdots \hat{\mathcal{E}}_N^n \rangle$ [Hofman, Maldacena, JHEP05(2008)012]

$$\hat{\mathcal{E}}_n = \lim_{r\to\infty} \int_0^\infty dt\, r^2 n^i\, \hat{T}_{0i}(t, r\vec{n})\,.$$

E2C in pp

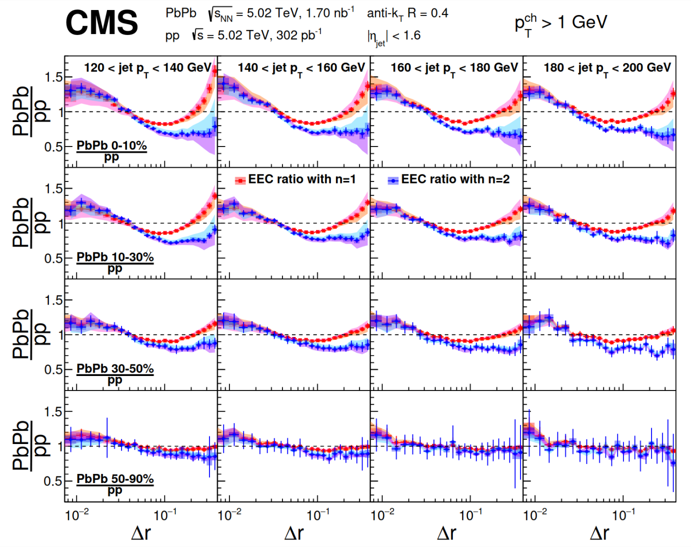




For asymptotics high-E jets in vacuum, EEC separates perturbative, hadronic, and uncorrelated regimes. The perturbative regime probes moments of QCD splitting

$$\theta^2 \frac{d\Sigma_2}{d\theta^2} \sim \frac{\alpha_s^{\text{fix}}}{2\pi} \frac{1}{\theta^{2\gamma(3)}}, \quad \gamma_{ji}(N) = -\frac{\alpha_s}{2\pi} \int_0^1 dx x^{N-1} [P_{ji}(x)]_+$$

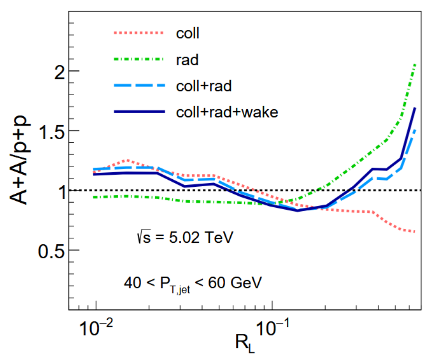
In the medium, things get complicated again



[CMS PLB866(2025)139556]

Combination of many medium modification mechanisms...

- Scales of induced radiations imprints in EEC [Andres, Dominguez, Kunnawalkam Elayavalli, Holguin, Marquet, Moult PRL130(2023)262301].
- Energy loss differences among quarks & gluon jets. [Barata et al JHEP11(2024)060, Chen et al. 2409.13996].
- Medium responses affects N-point correlator via enhanced low-momentum particle production. [Bossi, Kudinoor, Moult, Pablos, Rai, Rajagopal JHEP12(2024)073].
- Sensitivity to medium screening mass, radiation, medium response [Yang, He, Moult, Wang, PRL132(1024)011901]



A decomposition of different medium effects. [Chen, Xu, Shen, Dai, Zhang, Wang 2409.13996]

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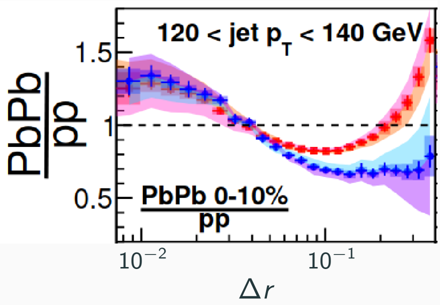
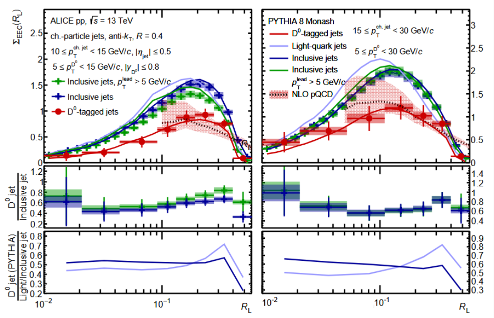


$\langle \hat{\mathcal{E}}_1^n \hat{\mathcal{E}}_2^n \cdots \hat{\mathcal{E}}_N^n \rangle$. Tuning weighting power $\mathcal{E}^n$, angular distances, order of correlation, may disentangle them.

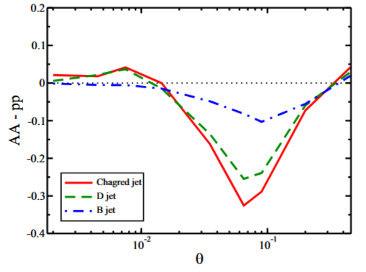
EEC of Heavy flavor jets: investigate “dead cone” in the *pp* and *AA*

$$P_{qq}(z)\frac{\mathbf{k}}{\mathbf{k}^2}\cdot\frac{\mathbf{k}}{\mathbf{k}^2}\rightarrow P_{qq}(z)\frac{\mathbf{k}}{\mathbf{k}^2+z^2M^2}\cdot\frac{\mathbf{k}}{\mathbf{k}^2+z^2M^2}+z^3\frac{M}{\mathbf{k}^2+z^2M^2}\cdot\frac{M}{\mathbf{k}^2+z^2M^2}$$

$$P_{qq}(z)\mathcal{C}\left[\frac{\mathbf{k}}{\mathbf{k}^2+z^2M^2}\right]\cdot\frac{\mathbf{k}}{\mathbf{k}^2+z^2M^2}+z^3\mathcal{C}\left[\frac{M}{\mathbf{k}^2+z^2M^2}\right]\cdot\frac{M}{\mathbf{k}^2+z^2M^2}$$



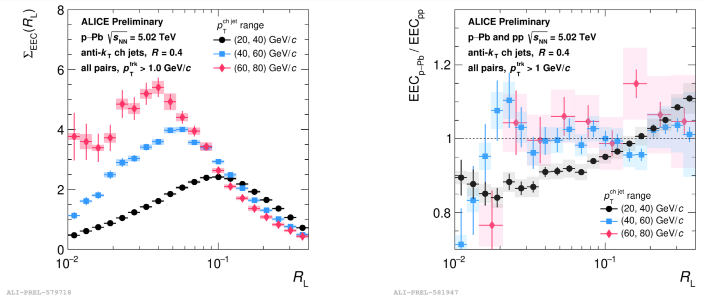
D^0 jets E2C in *pp* [ALICE CERN-EP-2025-082]



Predicted heavy jet E2C in *AA*. Higher-twist formula +LBT[Xing, Cao, Qin, Wang, PRL134(2025)052301]

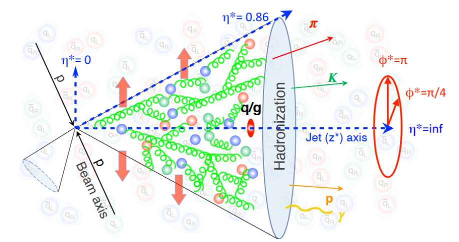
May be used to differentiate theories.

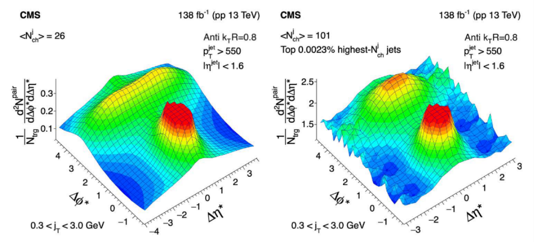
The puzzling small systems: E2C modifications in p-Pb



- Medium effects can also modify the non-perturbative regime (a medium TMD function) [Barata, Kang, Mayo López, Penttala, PRL134(2025)251903].
- Cold nuclear matter higher twist effects [Fu, Müller, Sirimanna, PRL135(2025)112302].
- Still difficult to explain the observed jet p_T dependence.
- Predict E2C in OO: Li Lin's poster *Energy correlators from large to small systems*.

New thoughts: study jet substructures versus its internal multiplicities

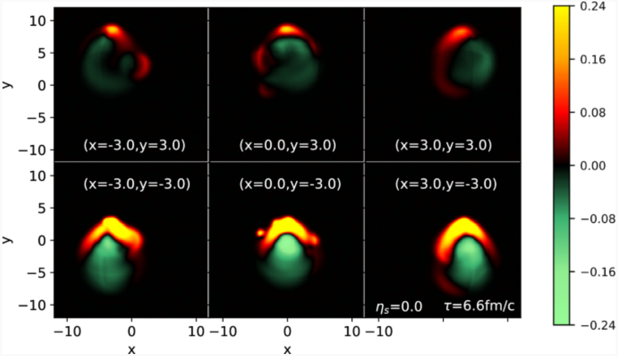




[CMS Phys.Rev.Lett. 133 (2024) 14, 142301]

- Study jet substructure as a function of its internal multiplicity in *pp* and *AA*.
- Does it suggest final-state interaction or collectivity? [Zhao, Lin, Wang, 2401.13137].
- Talk by Xiang-Pan Duan: *Multiplicity distributions in QCD jets and Jet Topics*.
- Talk by Pi Duan: *Differentiating EEC with Charged Particle Multiplicity in a jet*.

IV. Medium response: Mach cone versus diffusion wake



[Fig. from Yang et al. EPJC83(2023)652]

Medium response to jet perturbations $e^{-i(\omega t - kx)}$

- Sound channel: $\omega = \pm c_s k - i\Gamma_L k^2$
- Diffusion channel: $\omega = -i\Gamma_T k^2$

CMS find evidence of the negative diffusion wake. Both hydro model or particle recoil model predicts the depletion.

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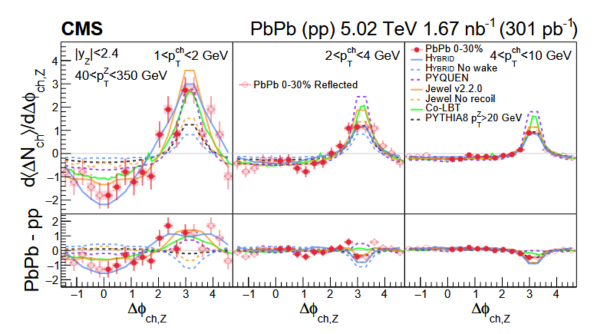

[CMS 2507.09307, Z-boson+jet events]

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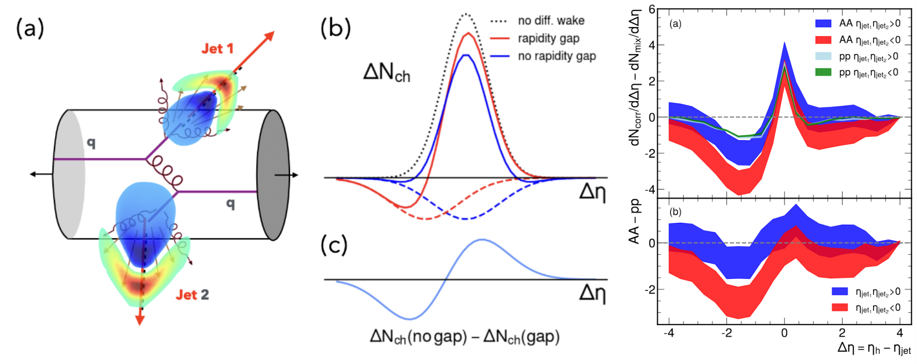
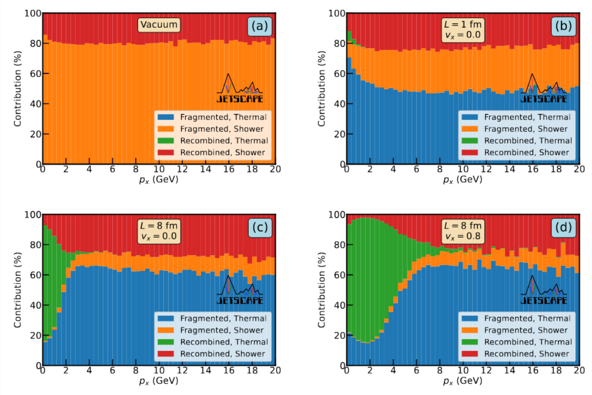
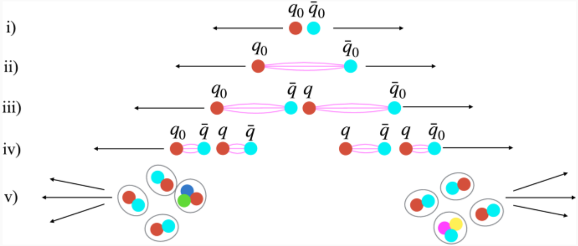
New ideas to search jet-induced medium response in di-jet events



Use jets with η gap to avoid interferences of medium response among the two jets [Z. Yang, and X.-N. Wang, Phys.Rev.Lett. 135 (2025) 7, 072302]

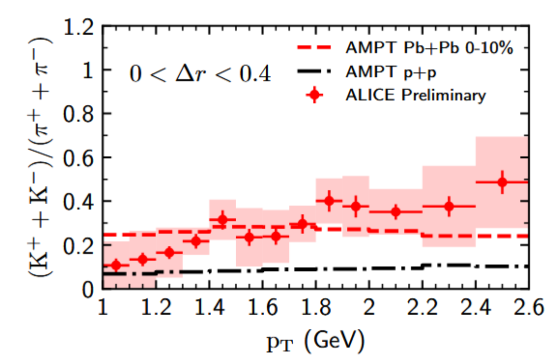
V. Understanding hadronization mechanisms in medium





- **Vacuum**: mostly fragmentation.
- **In hot medium**: fragmentation & recombination among jet and medium partons [JETSCAPE 2501.16482].

Hadron chemistry of jets in medium



[Luo, Cao, Qin, PLB866(2025)139520]

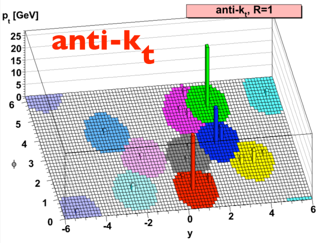
- Recombination between jet and medium partons changes the hadron chemistry in the jet cone.
- Predicted strangeness enhancement is consistent with ALICE prelim data.
- Serve as another probe of medium response.

Summary

- Jet modifications in QGP are caused by jet-medium multiple interactions.
- However, it turns out to be a surprisingly complicated multiple problem.
- We have seen a boom in new tools and observables
  - The energy correlators, anisotropic observables, and many more.
  - Developments in MC models with more detailed physics, in-medium EFT framework.
- Use versatile jet observables and controllable scales to understand:
  - The emergent scales in medium-modified parton shower.
  - The jet-medium interaction strength and its scale dependence.
  - Identify the medium response and confirm its collective nature.
  - Understand hadronization from pp to AA.

Questions?

Jet in practice



[Cacciari, Salam, Soyez, EPJC72(2012)1896]

Cluster "close" pairs of final-state particles into a jet of angular radius R:

Algorithms	Metric d_{ij}	$d_{i-\text{beam}}$	Key Feature
k_T	$\min(p_{Ti}^2, p_{Tj}^2)\frac{\Delta R_{ij}^2}{R^2}$	p_{Ti}^2	Clusters soft first
anti-k_T	$\min(p_{Ti}^{-2}, p_{Tj}^{-2})\frac{\Delta R_{ij}^2}{R^2}$	p_{Ti}^{-2}	Cone-like jets
CA	$\frac{\Delta R_{ij}^2}{R^2}$	1	Geometry only

Angular distance is $\Delta R_{ij} = \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2}$

For the talk: a jet is bunch of particles in a cone R.

R makes a distinction for radiations inside/outside the cone.