Data driven jet tomography

What does the QGP resolve inside a jet?

Yacine Mehtar-Tani (BNL)

Collaboration with: Hannah Bossi (MIT) and Maxence Larose (SBU)

2609.05609 [hep-ph]

Assemblée Générale 2026 du GDR QCD

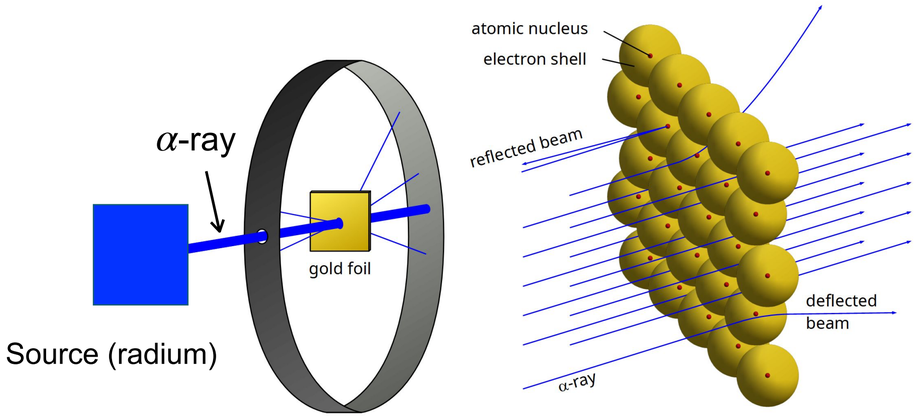
October 7-9, 2026 @ IMT Atlantique Nantes



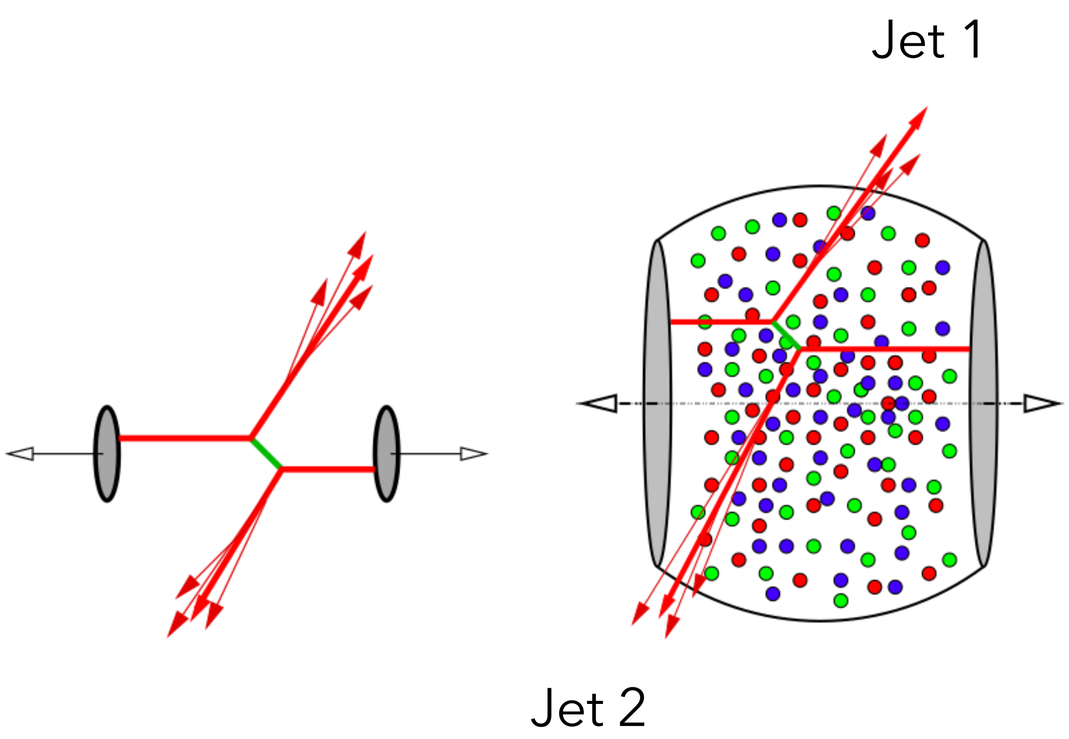
Brookhaven National Laboratory

Jet quenching: a Rutherford experiment for the QGP

- Jet modification provides a unique window into the fundamental QCD dynamics of the QGP.



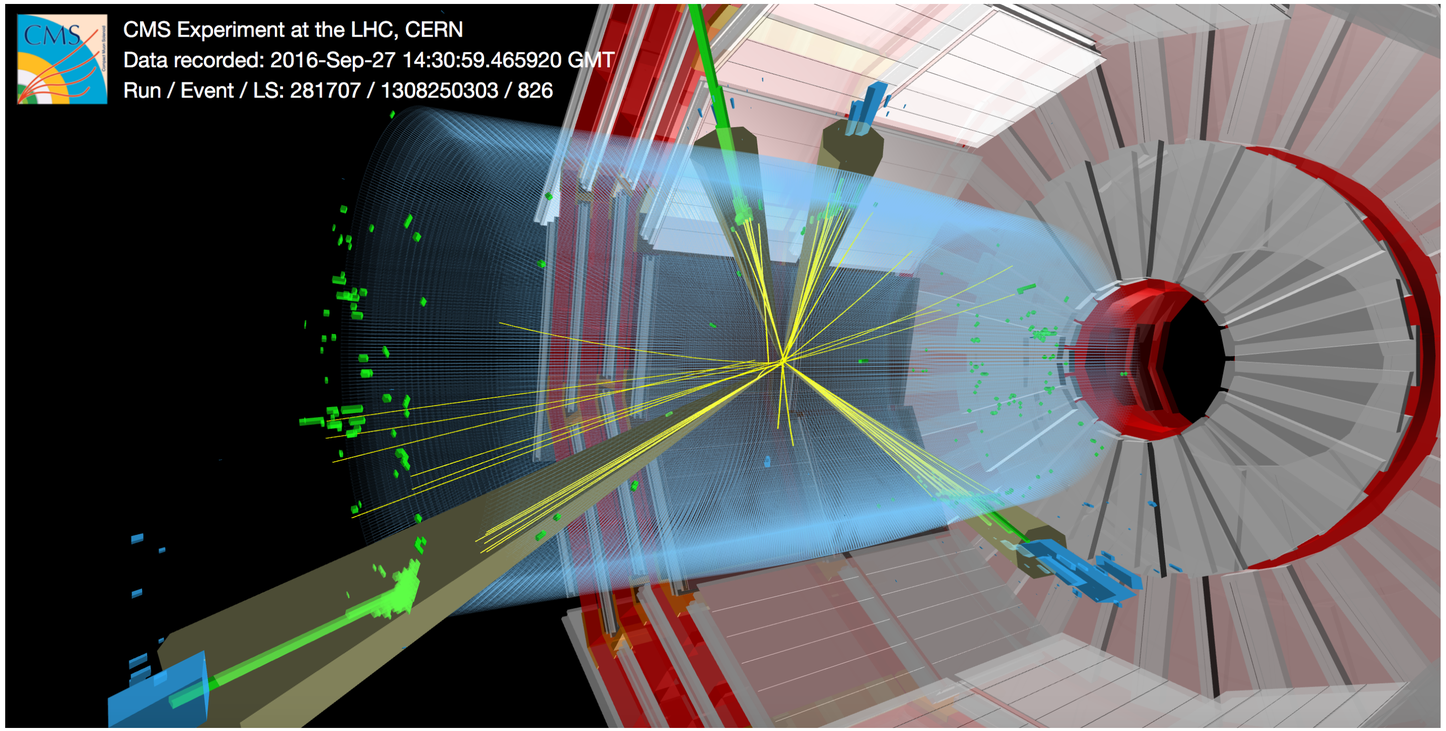
Discovery of the atomic nucleus



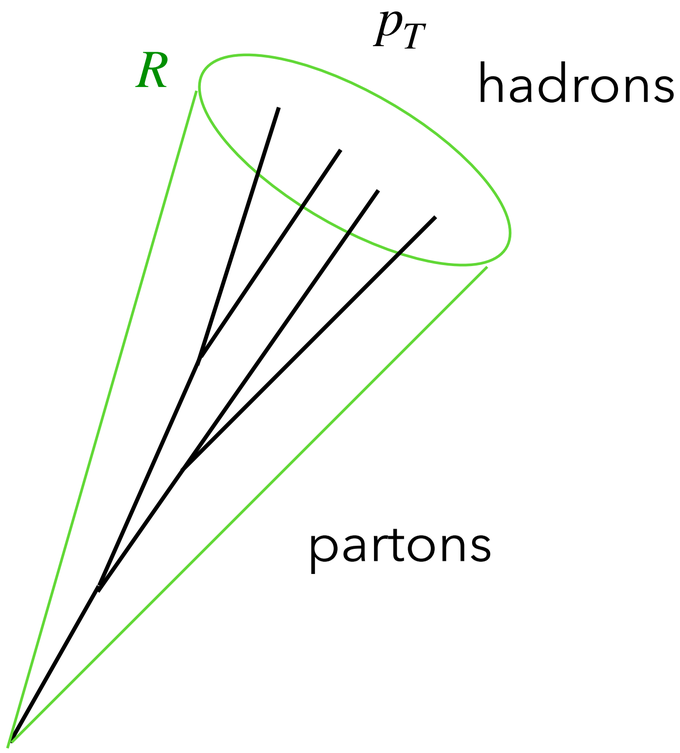
Probing the microscopic properties of the QGP with jets

QCD jets from early days to the Higgs discovery

- QCD Jets are the experimental manifestation of energetic quarks and gluons and constitute one of the most quantitative probes of QCD



Multi-jet event at the LHC



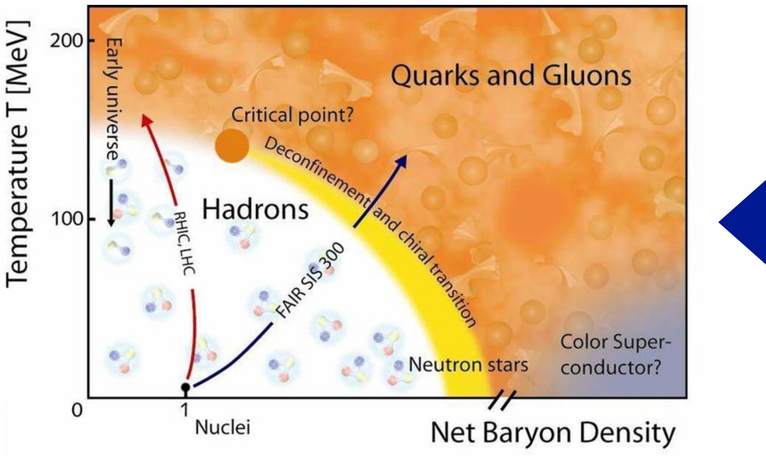
- Jets provide calibrated probes whose properties are accurately predicted in vacuum

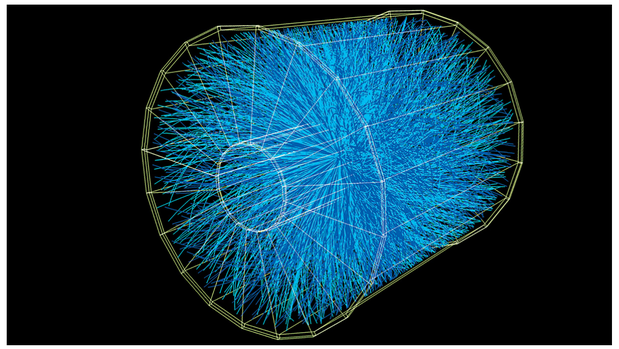
Jets in heavy ion collisions: multi-scale dynamics

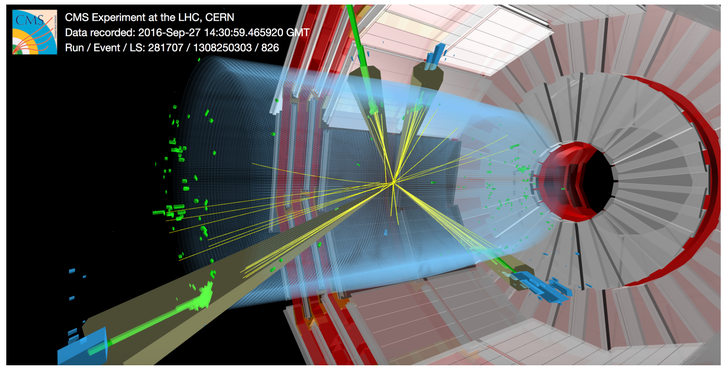
Thermal equilibrium ($T \neq 0$)

Non-equilibrium

$T=0$



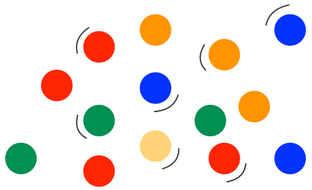




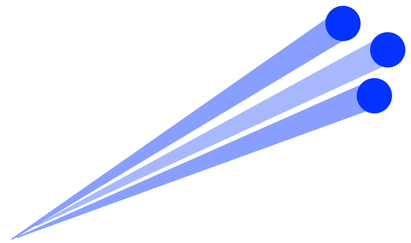
Heavy ion event

~ 1000's particles

Jets in pp







How is energy transported and dissipated?

Energy

$T \sim 1$ GeV

$p_T \sim 1$ TeV

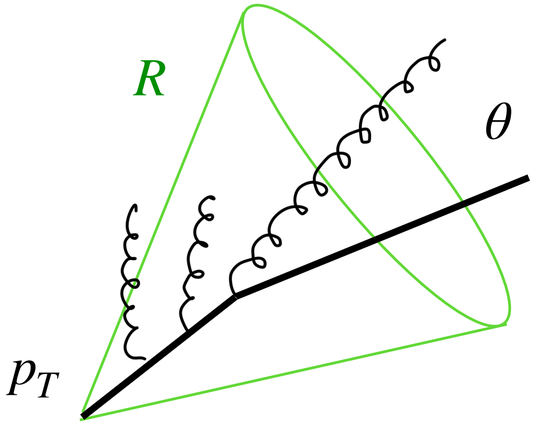
25 years of jet tomography: a plethora of measurements

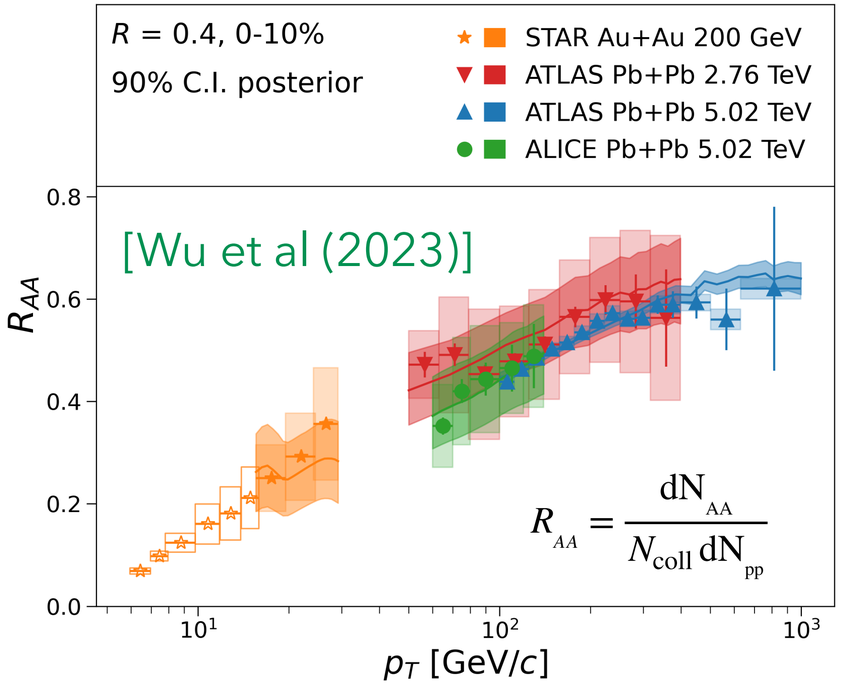
Inclusive observables (p_T)

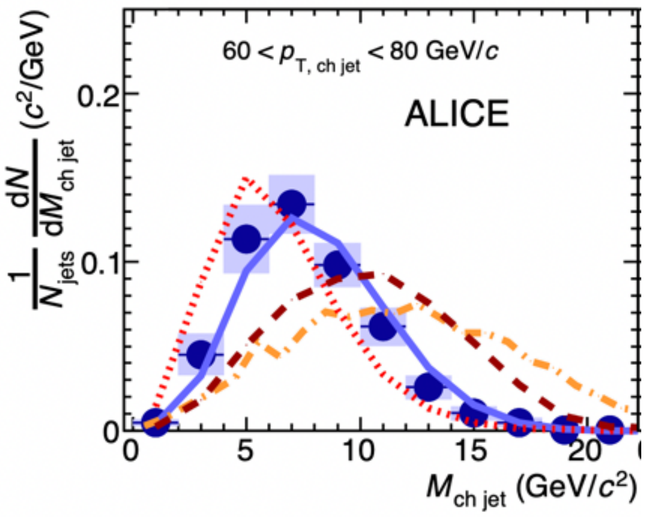
- Inclusive jet production
- Gamma-jet
- Dijets

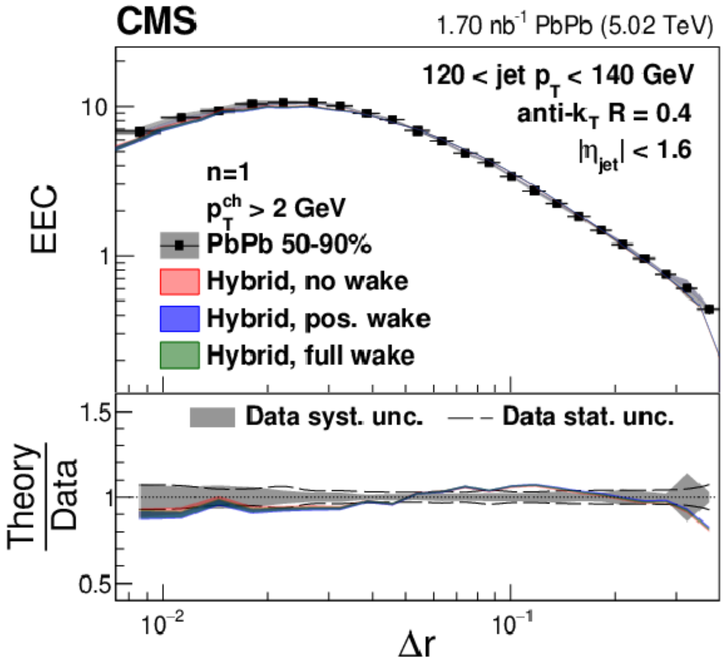
Jet substructure ($\theta, k_\perp, M$)

- Jet mass, thrust, angularities
- Fragmentation functions, jet shapes
- Gloomed jets observables
- Energy correlators

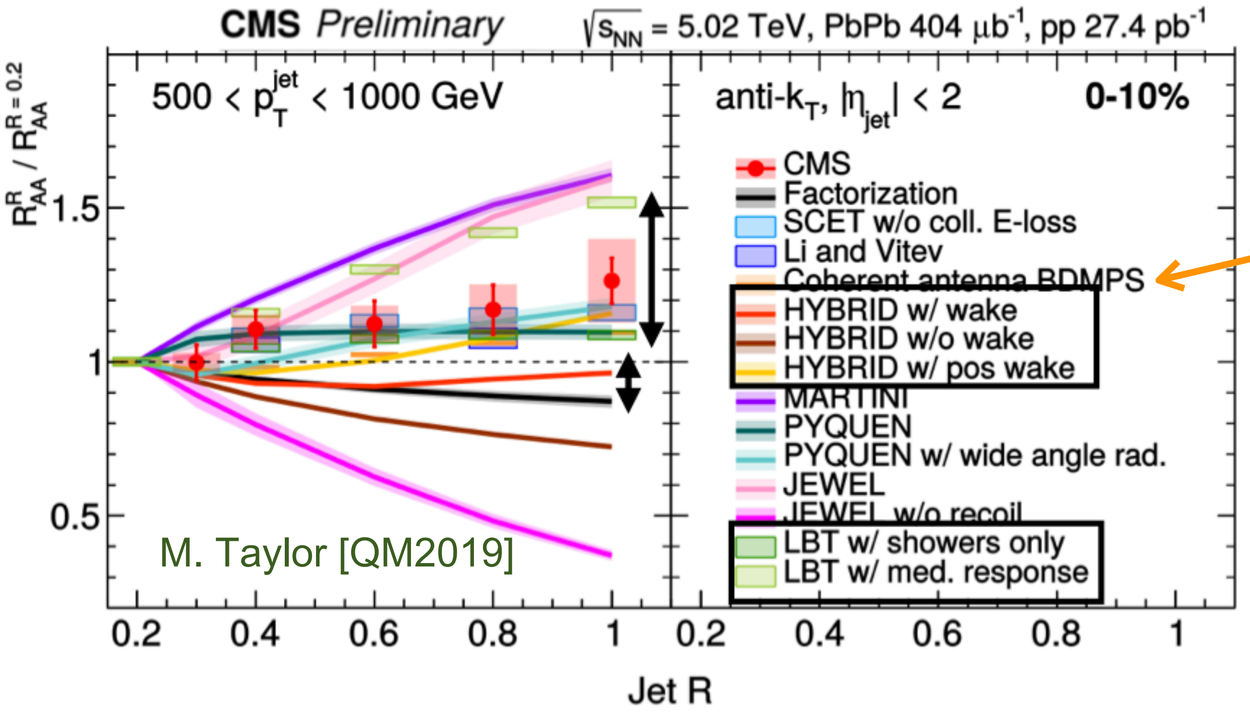






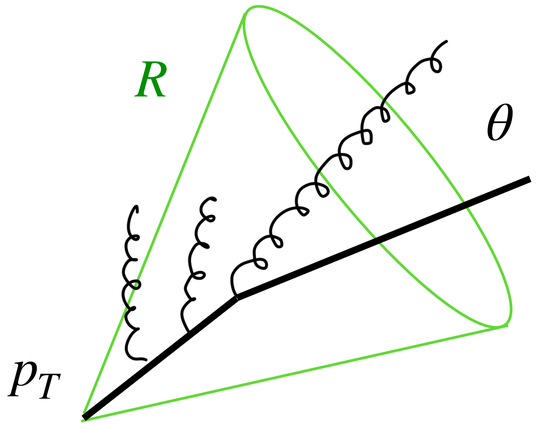


How can we harness the wealth of RHIC and LHC data to uncover new QCD physics?



Non-linear DGLAP

MT, Pablos, Tywoniuk (2019)



Complex system dynamics, many competing models

– how much predictive power do we really have?

- **Theory control:** Quantify and systematically reduce theoretical and modeling uncertainties
- **Methodology:** Combine complementary observables in theoretically controlled regimes to break model degeneracies

Quenching factors connect data to soft physics



Quenching factors connect data to soft physics

Full modeling

$\boxed{\text{Data}}$ $\longleftrightarrow$ $\boxed{\hat{q}, \hat{e}, T, g}$

factorization

$\boxed{\text{Data}}$ $\longleftrightarrow$ $\boxed{S_q, S_g, S_{\text{dip}}}$ $\longleftrightarrow$ $\boxed{\hat{q}, \hat{e}, T, g}$

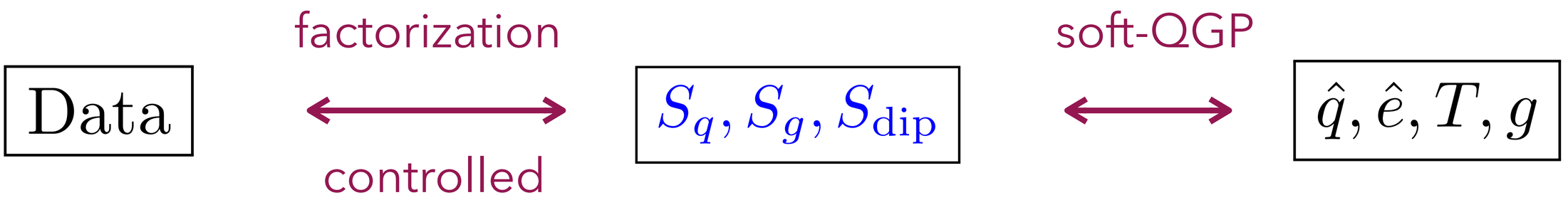
controlled

soft-QGP

Quenching factors connect data to soft physics

Full modeling

$\boxed{\text{Data}} \longleftrightarrow \boxed{\hat{q}, \hat{e}, T, g}$

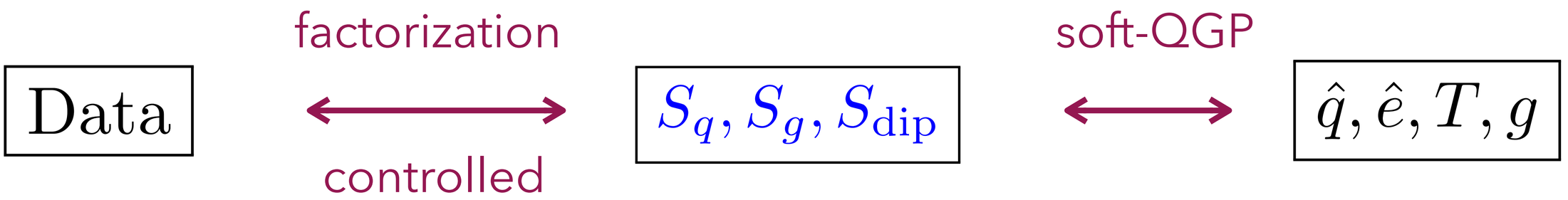


Extract (quasi)universal quantities encoding soft QGP physics:
quark, gluon, and dipole energy-loss distributions

Quenching factors connect data to soft physics

Full modeling

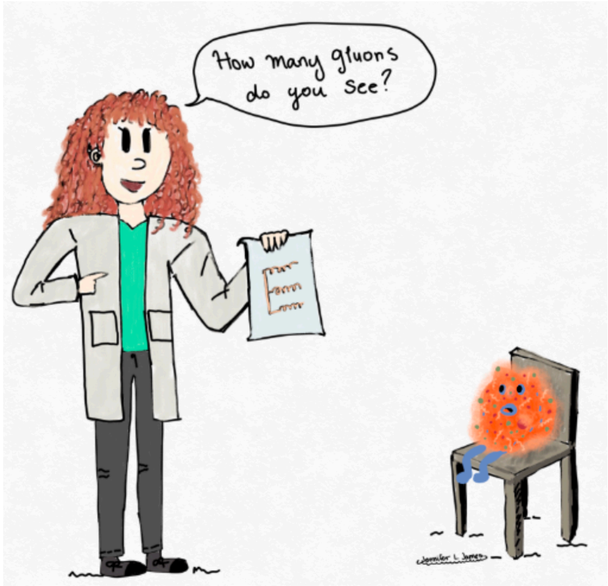
$\boxed{\text{Data}} \longleftrightarrow \boxed{\hat{q}, \hat{e}, T, g}$



Similar to PDF extraction from fits to structure functions

What do we want to learn?

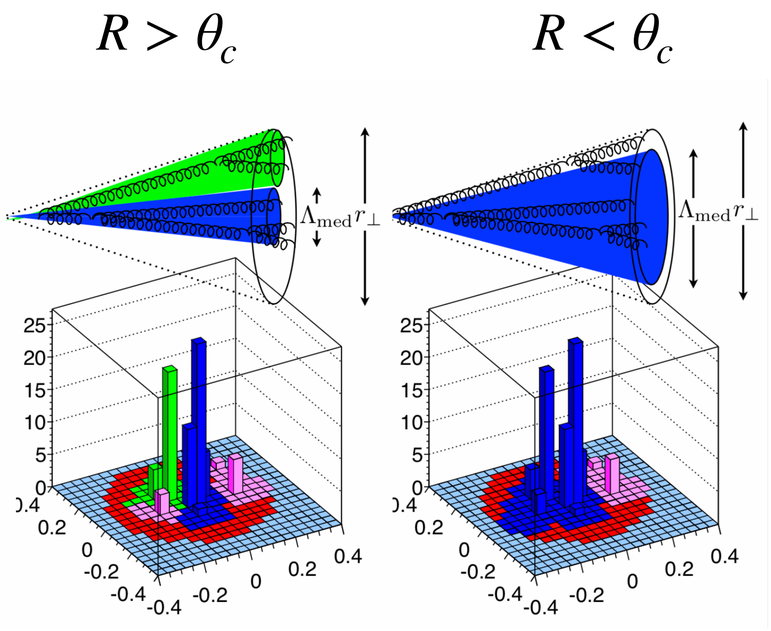
- The QGP resolution power: Beyond energy loss, how many effective color charges does the medium resolve inside the jet?



Credit: Jeniffer James (Vanderbilt)

What do we want to extract?

- The QGP resolution power: Beyond energy loss, how many effective color charges does the medium resolve inside the jet?



Medium resolution angle θ_c

(emergent scale)

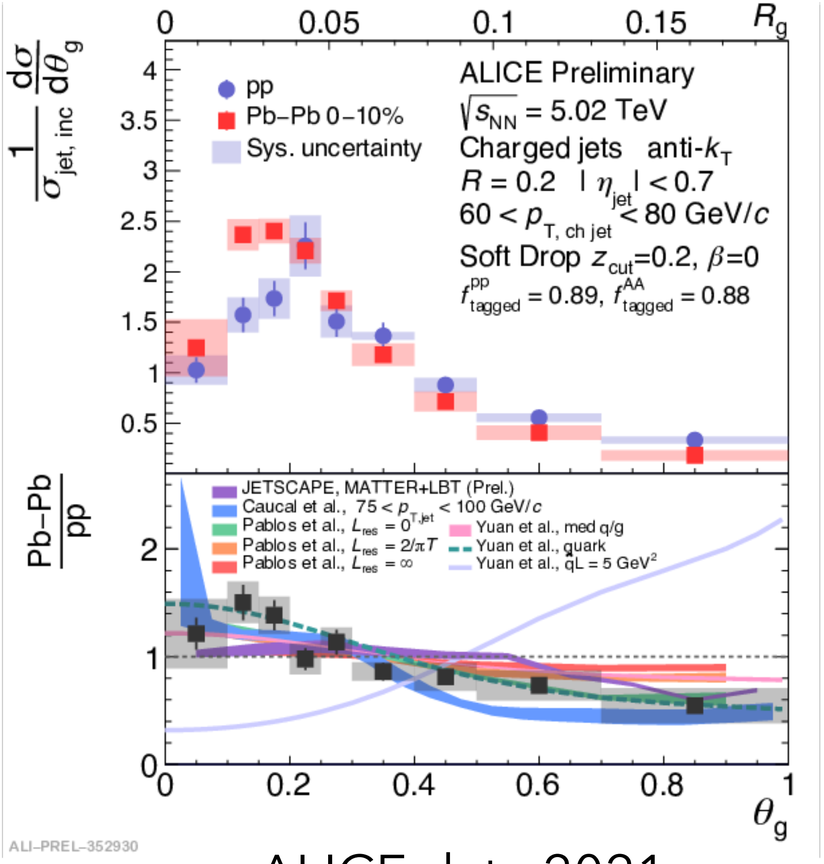
$$\theta_c \simeq \frac{1}{\sqrt{\hat{q} L^3}}$$

[MT, Tywoniuk, Salgado, Casalderrey-Solana, Iancu (2011-2013)]

Can one extract the medium resolution scale from data?

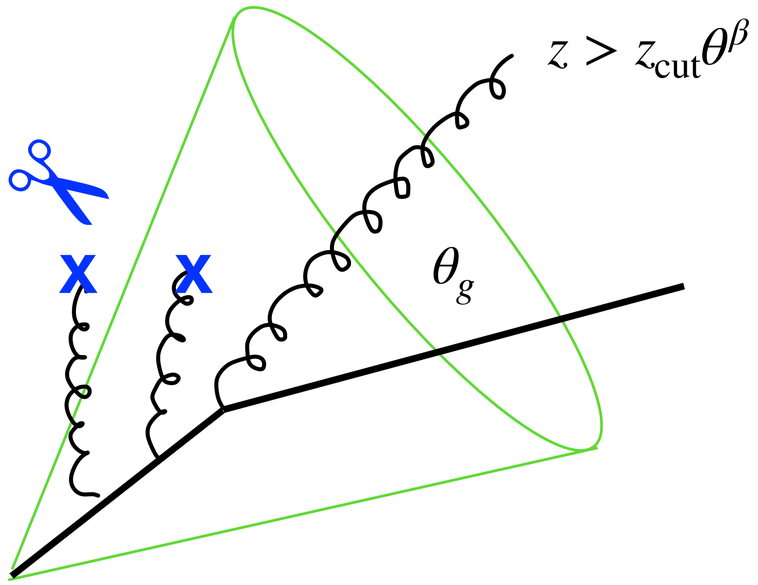
Color decoherence from the data

- Groomed-angle data can also be described with coherent energy loss due to selection bias: gluons lose more energy than quarks, leading to a narrower distribution.



ALICE data 2021

Groomed jet angle

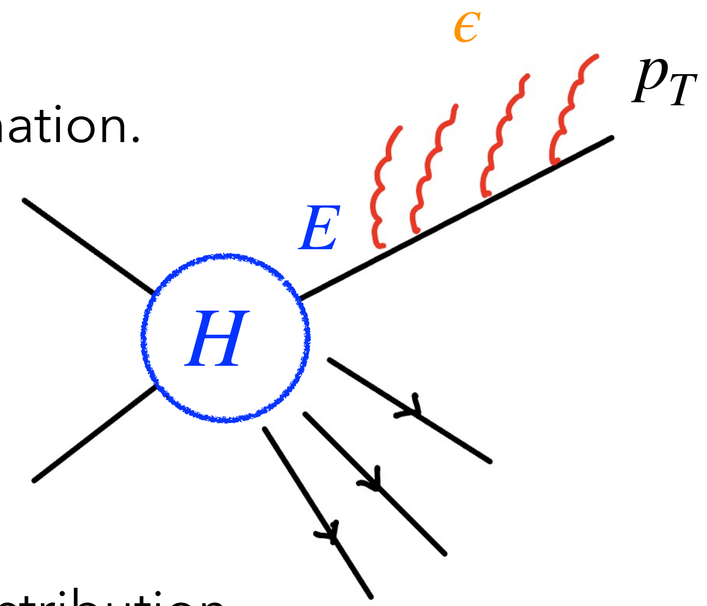


[Larkoski et al (2014)]

- A resolution test needs complementary observables and uncertainty control.

Inclusive suppression + energy correlators

- Inclusive suppression alone constrains one flavor-weighted combination.



$$R_{AA} = f_q\, S_q(p_T) + f_g\, S_g(p_T)$$

- The quenching factor is the Laplace transform of the energy loss distribution

$$S_q(p_T) = \int_0^\infty P_q(\epsilon) \frac{\mathrm{d}\sigma_q(p_T+\epsilon)}{\mathrm{d}p_T} \Big/ \frac{\mathrm{d}\sigma_q(p_T)}{\mathrm{d}p_T} \simeq \int_0^\infty \mathrm{d}\epsilon\, P_q(\epsilon)\, \mathrm{e}^{-\epsilon N_q/p_T}$$

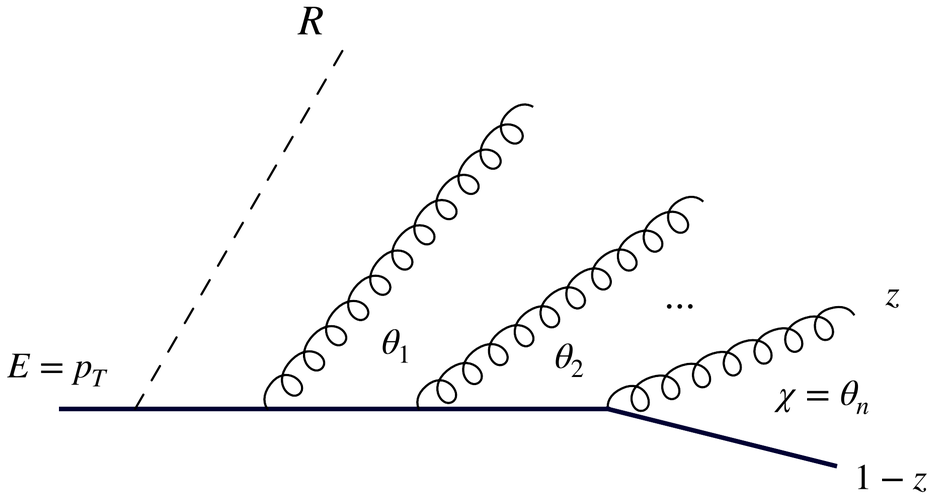
- One equation of two unknowns: S_q and S_g

Different quark and gluon EEC shapes provide the second constraint (quasi-universality)

Energy-energy correlators (EEC)

$$\frac{\mathrm{d}\Sigma}{\mathrm{d}\chi} = \sum_{i\neq j} \int \mathrm{d}\sigma \, \frac{p_{Ti} p_{Tj}}{p_T^2} \delta(\chi - \theta_{ij})$$

[Basham et al (1978) Dixon et al (2019)]



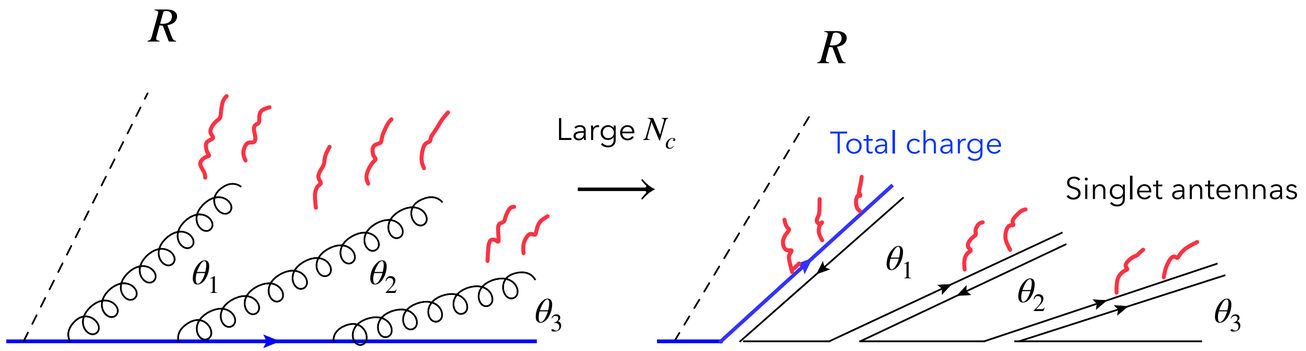
- At leading log accuracy EEC measures the smallest angle in an angular ordered parton cascade ($\Sigma \equiv (\Sigma_q, \Sigma_g)$)

$$\Sigma(\chi) \simeq \exp\left[-\alpha_s \gamma(3) \ln(R/\chi)\right]$$

- $\gamma(j) = -\int_0^1 \mathrm{d}z \, z^{j-1} P(z)$ is DGLAP anomalous dimension matrix

[Heavy ion application: Andres et al (2021-2026)]

EEC's in the medium in EFT framework



- Factorization of hard-collinear modes and soft-collinear modes encoded in Wilson line correlators

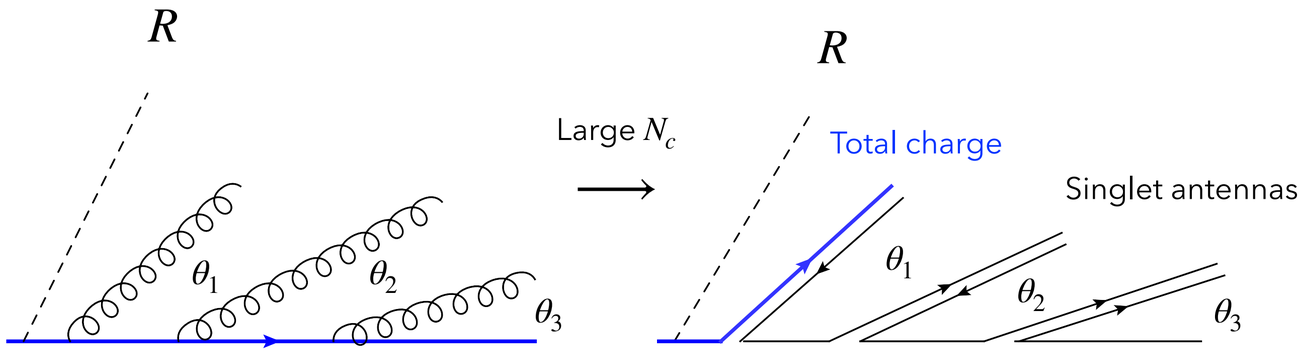
$$S_q \sim \sum_X \delta(\epsilon - n\cdot k_{\rm out})\langle {\rm med}|U^\dagger|X\rangle\langle X|U|{\rm med}\rangle$$

$$S_{\rm dip} \sim \sum_X \delta(\epsilon - n\cdot k_{\rm out})\langle {\rm med}|U_2^\dagger U_1^\dagger|X\rangle\langle X|U_1U_2|{\rm med}\rangle$$

MT, Caucal, 2608.25984 [hep-ph]

MT, Ringer, Singh, Vaidya, 2409.05957, 2504.00101 [hep-ph]

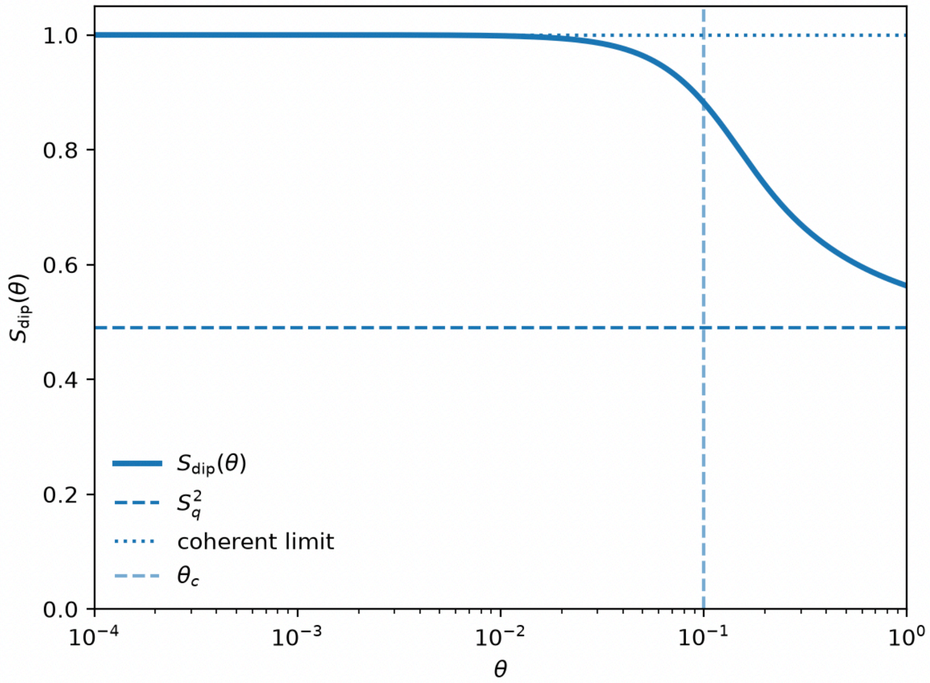
Dipole quenching encodes color decoherence



MT, Tywoniuk (2017)

- In addition to the quark and gluon (total color charge) quenching factor we need the singlet dipole $S_{\rm dip}(\theta)$ factor that encodes physics of interferences characterized by θ_c

$$\gamma_{\rm med}(3) \equiv \begin{pmatrix} \frac{25}{6} C_F\, S_{\rm dip}(\theta) & -\frac{7}{15} n_f \\ -\frac{7}{6} C_F\, S_{\rm dip}(\theta) & \frac{14}{5} C_A S_{\rm dip}(\theta) + \frac{2}{3} n_f \end{pmatrix}$$



Generating functional: MT 2609.05614 [hep-ph]

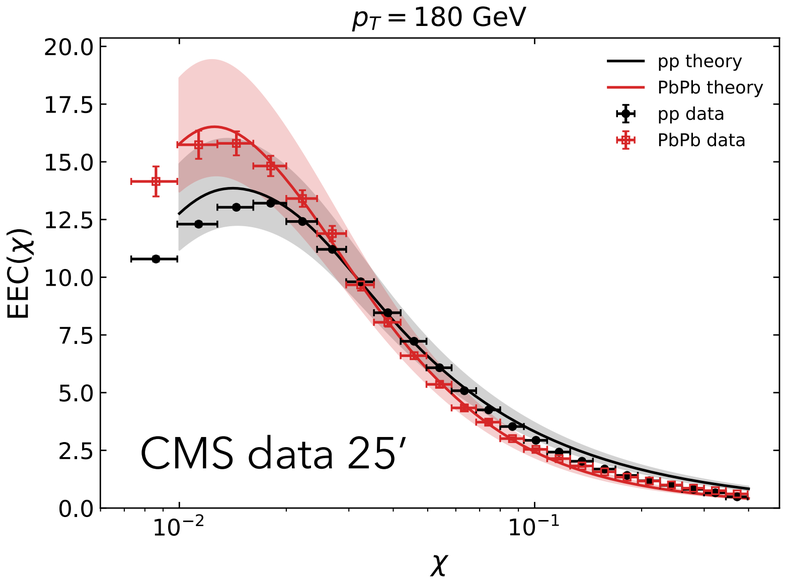
Phenomenology: bridging theory and experiment

Coherent energy loss strains Casimir scaling

- **Null hypothesis:** The simplest model is the coherent energy loss approximation
- Fit the pp baseline then fit extract S_q and S_g from PbPb

$$R_{AA} = f_q\, S_q + f_g\, S_g$$

$$\Sigma_{AA}(\chi) = \left[\, S_q\, f_q \Sigma_q^{\rm vac}(\chi) + \, S_g\, f_g \Sigma_g^{\rm vac}(\chi)\right] / R_{AA}$$



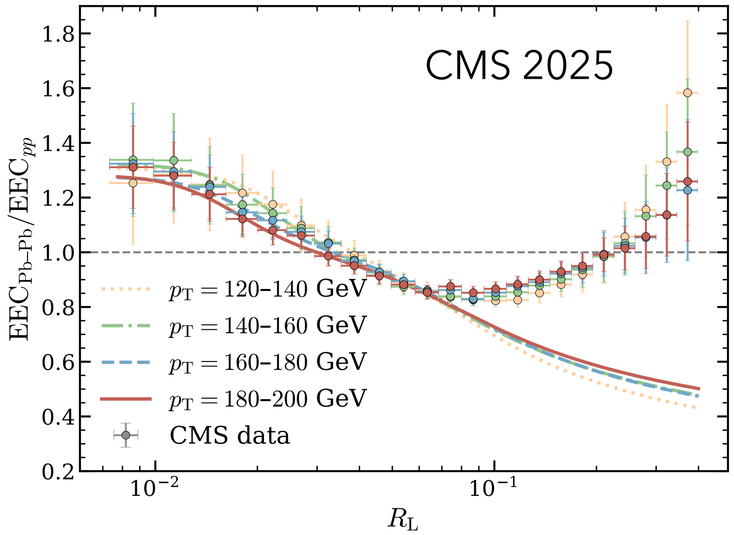
- The extracted quenching factors are incompatible with expected Casimir scaling ($S_g \sim S_q^{C_A/C_F}$)

$$S_q \simeq 0.8 \qquad\qquad S_g \simeq 0.3$$

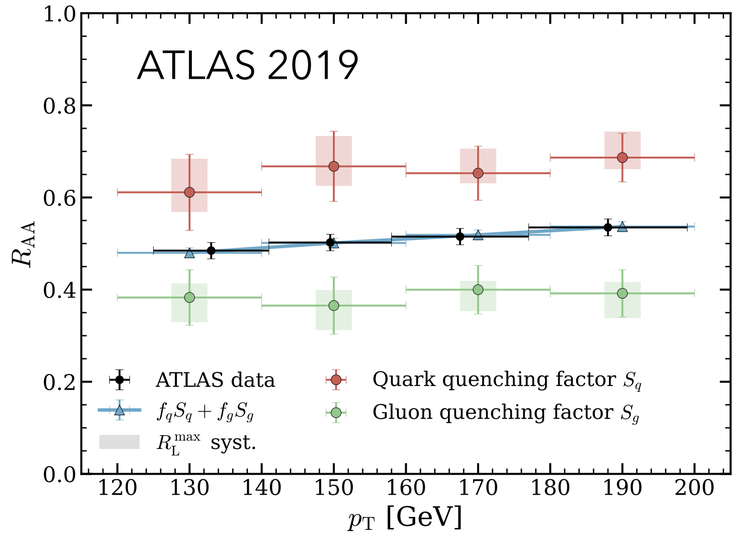
Flavor dependence of jet quenching

Bossi, Larose, MT, 2609.05609 [hep-ph]

EEC PbPb to pp ratio



Nuclear modification factor



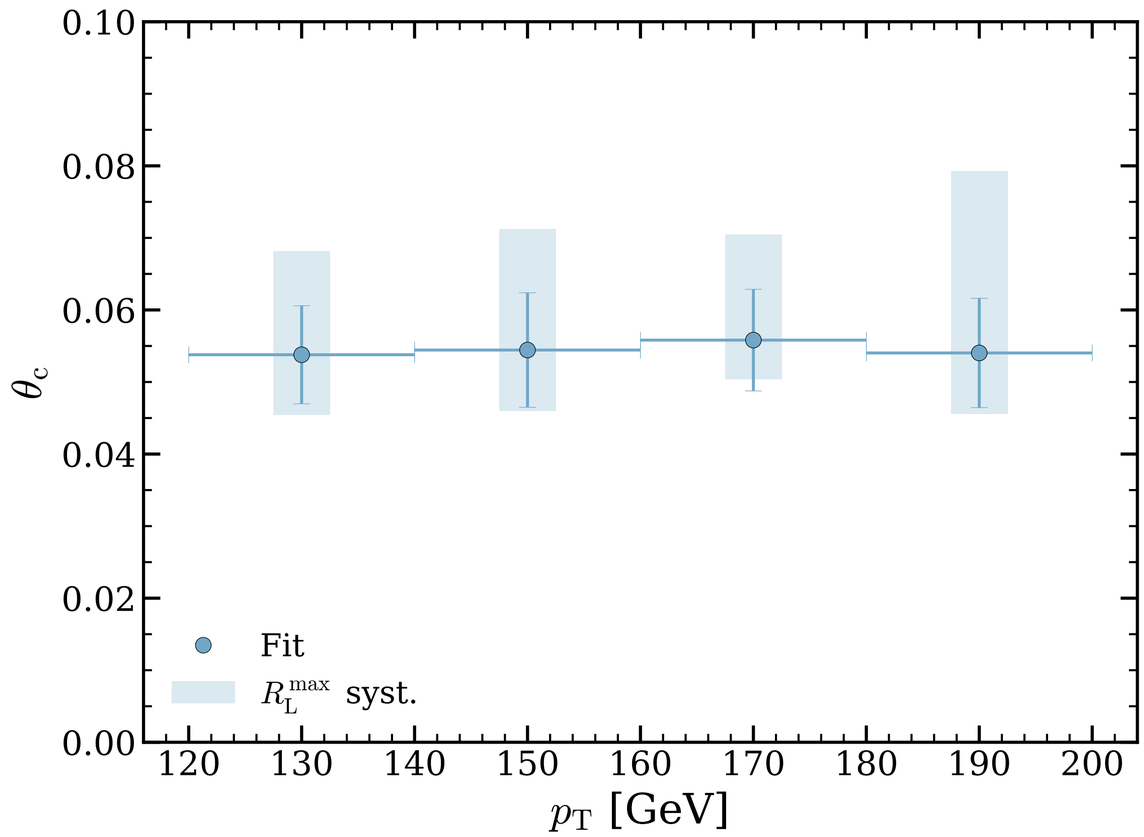
quarks

inclusive

Gluons

- NB: Fits restricted to the collinear hard region $\chi \equiv R_L \lesssim 0.1$ – large angles involve soft processes
- Including color decoherence in $S_{\mathrm{dip}}(\theta)$ restores compatibility with Casimir scaling and improves fits and

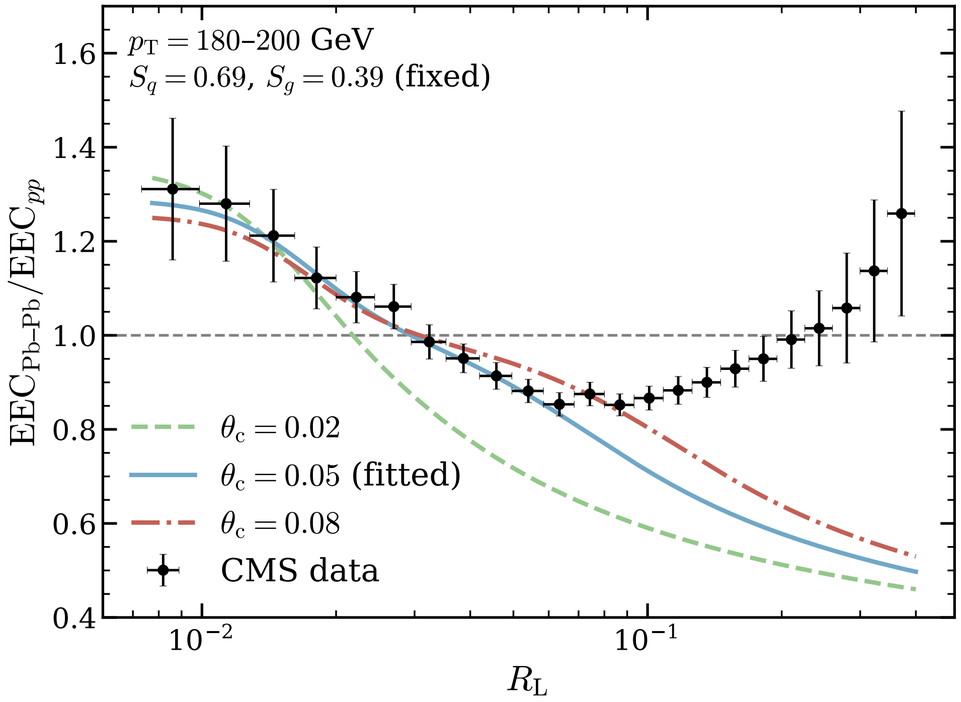
Evidence for medium resolution scale



$$\theta_c \simeq 0.05 - 0.06$$

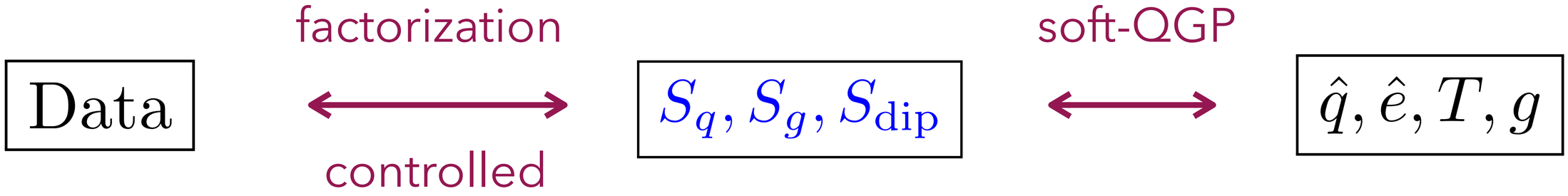
- Theory-informed fits of inclusive and substructure observables point to a p_T-independent emergent scale – analogous to the saturation scale in high-energy hadron structure.

Evidence for medium resolution scale



- Theory-informed fits of inclusive and substructure observables point to a p_T-independent emergent scale – analogous to the saturation scale in high-energy hadron structure.

Towards global fits of QGP distributions



Extract (quasi)universal quantities encoding soft QGP physics:

quark, gluon, and dipole energy-loss distributions

Summary and outlook

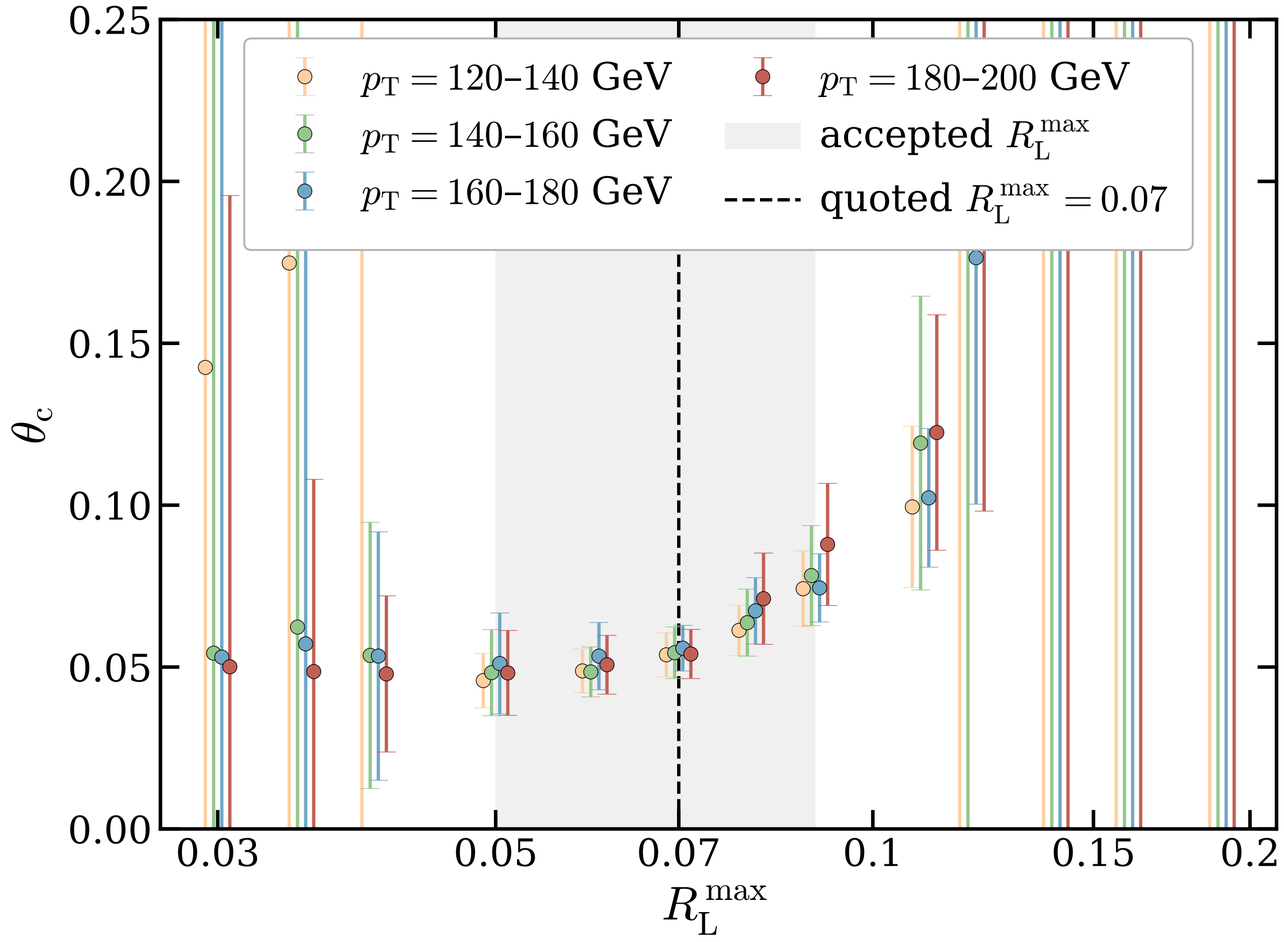
- Inclusive suppression + EECs jointly constrain quark and gluon quenching and the medium resolution scale
- Color decoherence significantly improves the description and restores compatibility with Casimir scaling $S_q \simeq 0.65 \quad S_g \simeq 0.35$
- The fit favors a finite resolution angle $\theta_c \simeq 0.06$: evidence for an emergent QGP resolution scale?

Next steps

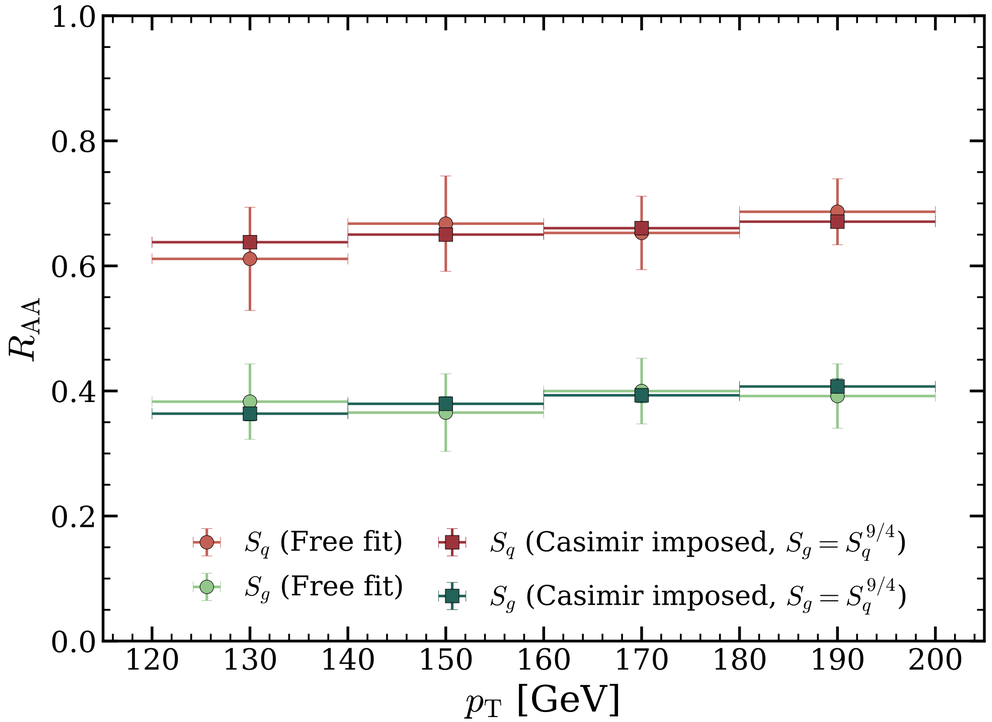
- **Reduce systematics:** refine the (pp) baseline and include additional observables, centralities, system sizes
- **Probe medium-induced radiation:** exploit the large-angle region
- **Improve theoretical precision:** incorporate higher-order corrections and build MC event generator

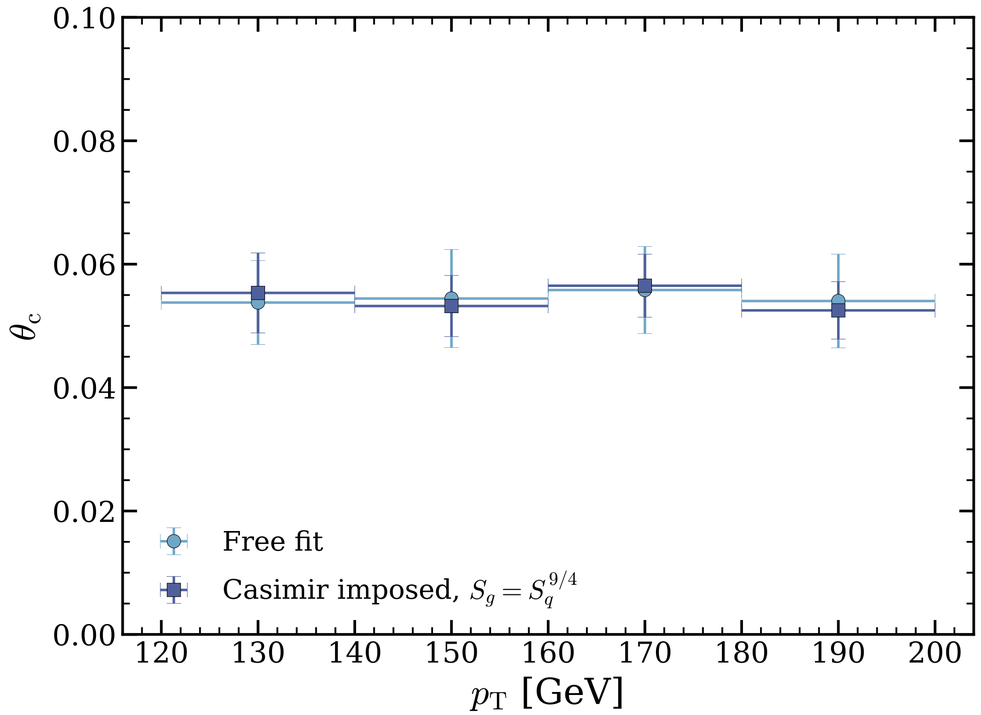
Backup

Complementary systematic tests

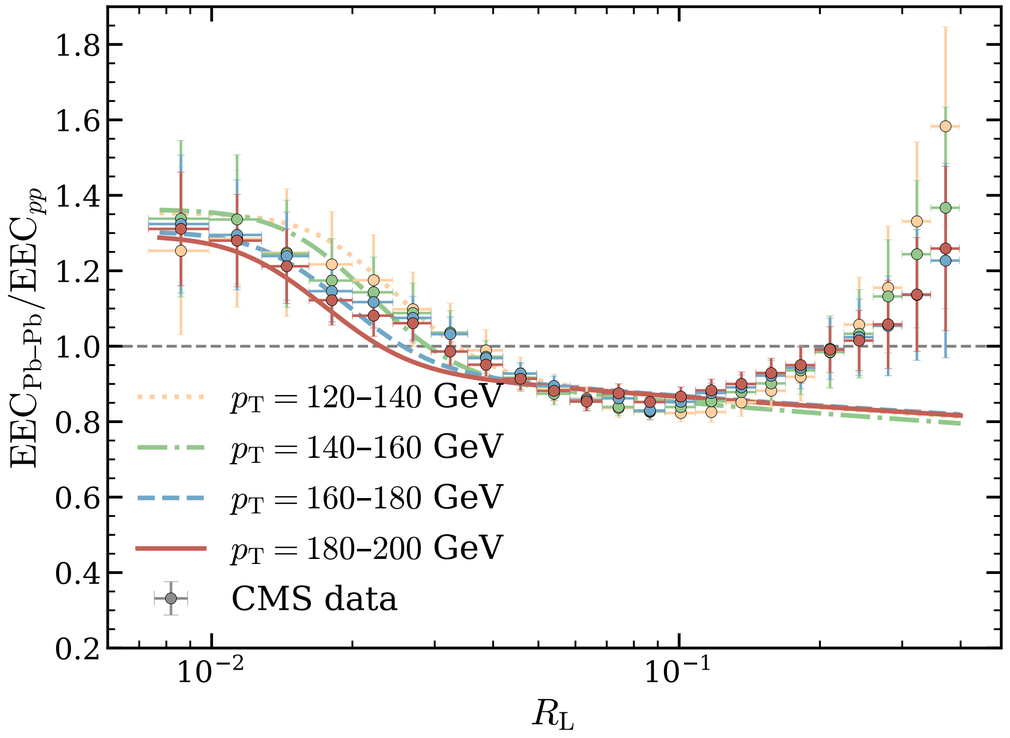


Imposing Casimir



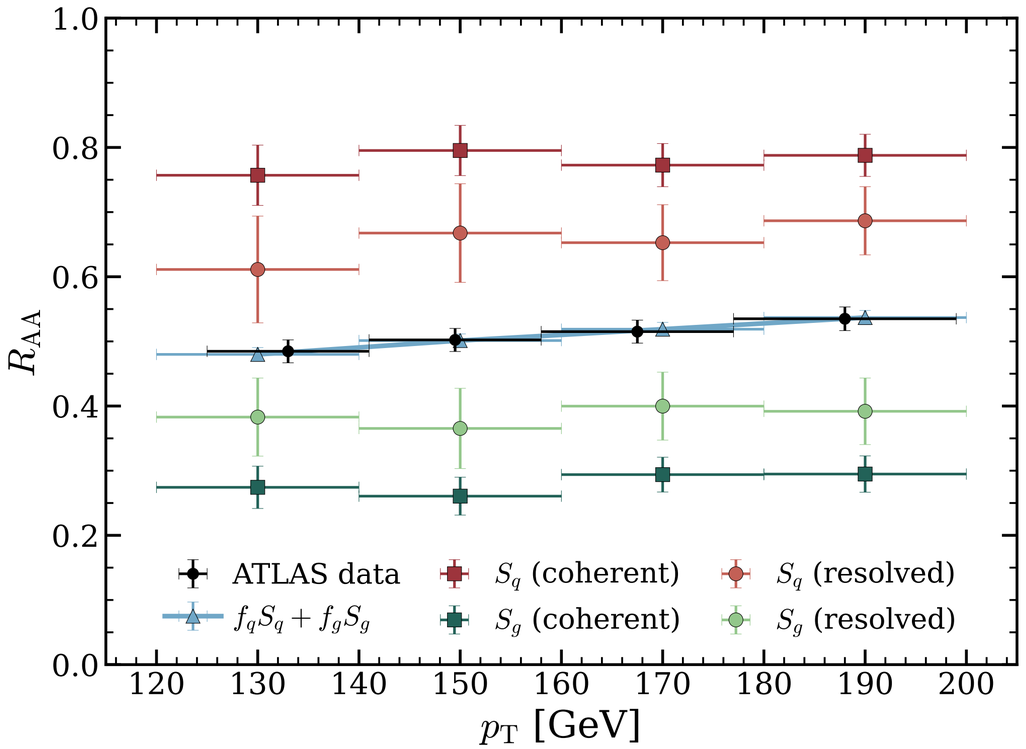


EEC in the coherent case

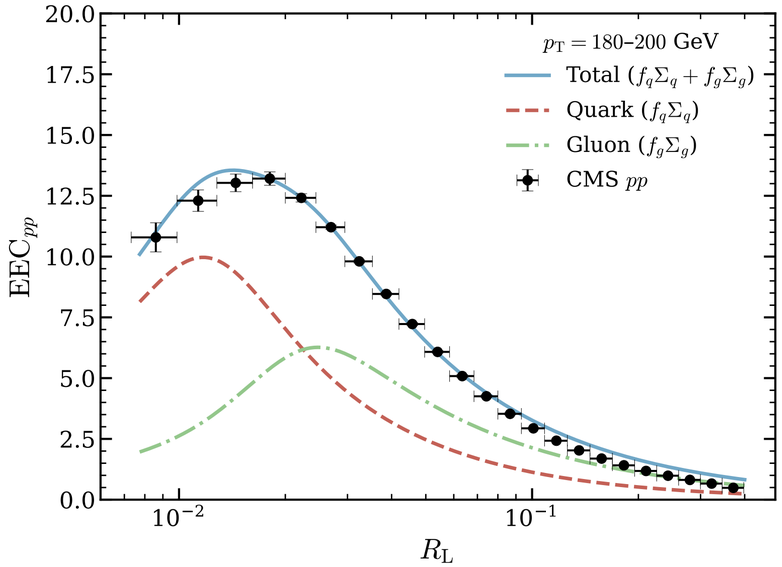


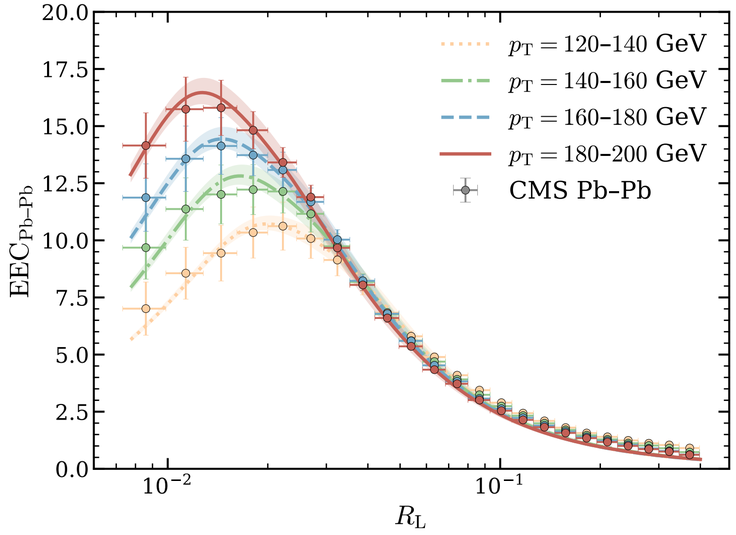
$$\chi^2/\mathrm{d.o.f.} = 0.10 \rightarrow 0.79$$

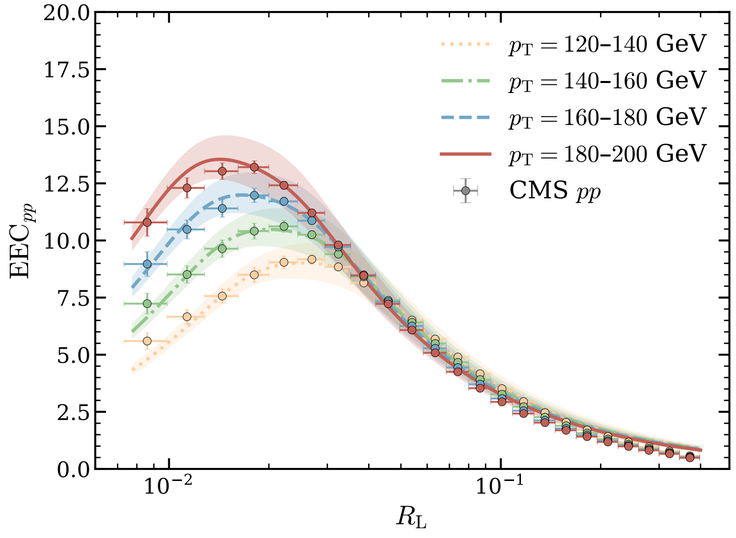
Coherent vs resolved jet



EEC pp and PbPb fits







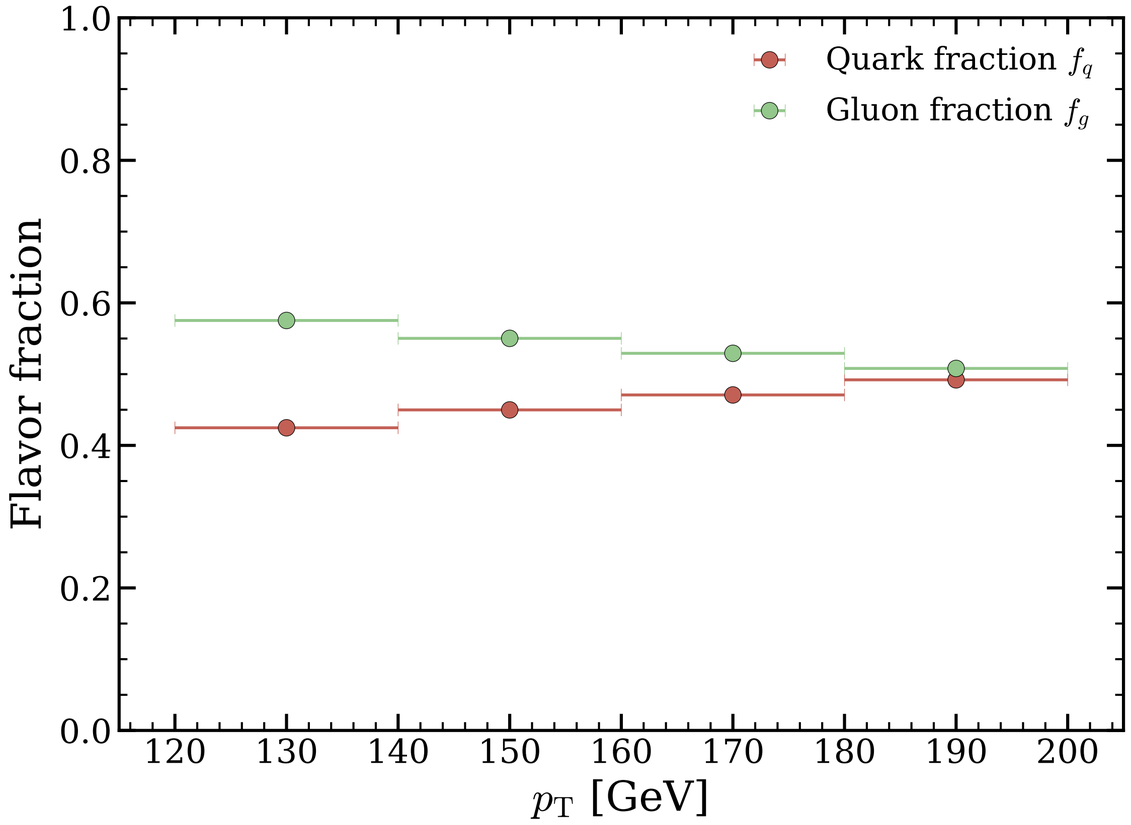
IR regulator

$$\mu^2 = (p_T R)^2 \rightarrow \left[(p_T R)^\beta + m_{q,g}^\beta\right]^{2/\beta}$$

Baseline parameters

$$K = 2.51, \quad \beta = 5.52, \quad m_q = 2.16, \quad m_g = 4.21$$

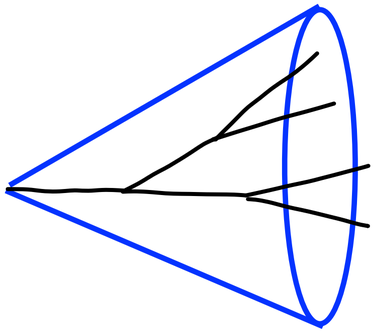
Flavor fractions



Two classes of observables

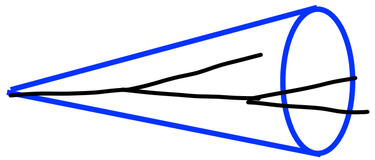
- R dependence of nuclear modification factor

$$R_{\mathrm{AA}} = \frac{\mathrm{Yield}_{\mathrm{AA}}}{N_{\mathrm{coll}}\ \mathrm{Yield}_{\mathrm{pp}}}$$

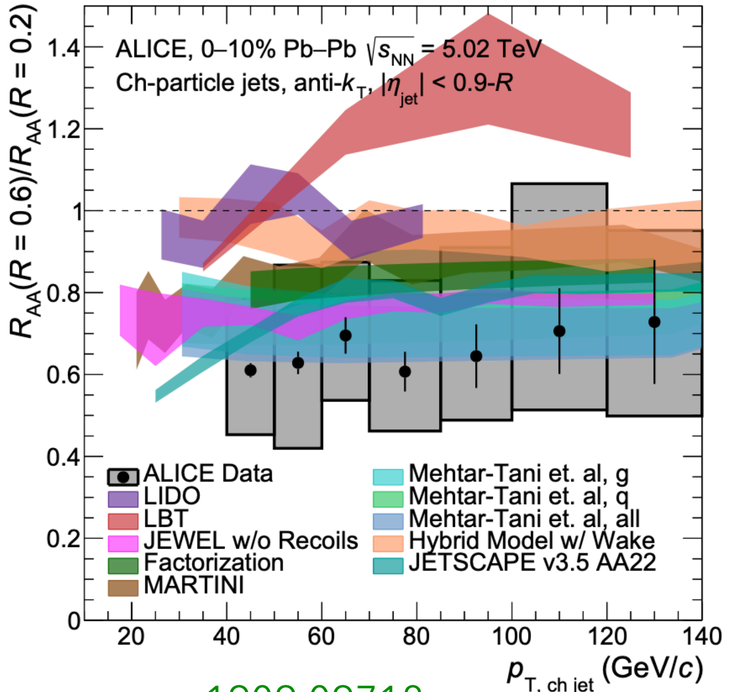


$R = 0.6$

Vs.



$R = 0.2$



1909.09718

- Remarkably weak R dependence

- Sensitivity to color coherence, not well encoded in some models