Measuring parton energy loss at the LHC

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Jets as probes of the medium

1. The QGP is a background hydrodynamic medium in which the energetic jets propagate
2. Since the early days of RHIC, jets in heavy ion collisions have been seen as useful probes of the medium. If we can pin down the theory of jet propagation, they can be used as tomographic tools to characterize the medium *[Xin-Nian. Wang, (2004)]*

Jet era

1. We are in the era of high statistics analysis of fully reconstructed jets in heavy ion collisions at the LHC
2. Modification of jet spectra and properties studied at ATLAS, CMS and ALICE
3. The ultimate goal is obtaining quantitative information about medium properties from the data

Energy loss versus R_{AA}

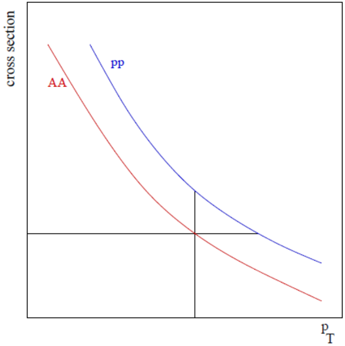
1. The most basic measurement is the measurement the yields of jets in heavy ion (AA) collisions and pp collisions
2. Rich data set since measurements depend on p_T, jet cone radius R, and centrality and we can explore these dependencies
3. Very familiar with the modification factor between pp and AA R_{AA}

$$R_{AA} = \frac{d\sigma_{AA}}{dp_T dy} \bigg/ \frac{d\sigma_{pp}}{dp_T dy}, \text{ where } \frac{d\sigma_{AA}}{dp_T dy} = \frac{1}{N_{\rm evt}\, T_{AA}} \frac{dN_{\rm jet}}{dp_T dy}.$$

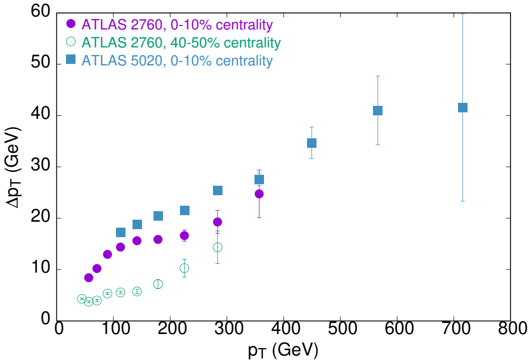
Energy loss versus R_{AA}

- The same information is encoded differently in the Energy loss or equivalently transverse momentum loss. We will focus on central rapidity
- Can be immediately connected with the microscopic details
- Δp_T is given by the condition

$$\left.\frac{d\sigma_{AA}}{dp_T dy}\right|_{p_T} = \left.\frac{d\sigma_{pp}}{dp_T dy}\right|_{p_T+\Delta p_T}$$

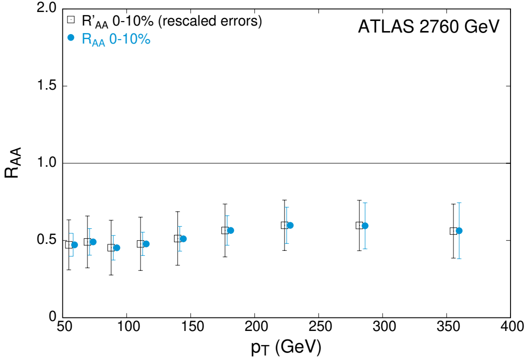


Δp_T



- Using data from *[ATLAS (2014, 2018)]* we can extract Δp_T. Only statistical errors are shown
- Systematic errors for *AA* cross-sections are $\sim 15 - 20\%$

R_{AA}



- *[ATLAS (2014)]* (Cyan points)
- Black points *[Gupta, Sharma (2022)]*

$$R'_{AA}(p_T) = \left.\frac{d\sigma_{pp}}{dp_T dy}\right|_{p_T+\Delta p_T} \Bigg/ \left.\frac{d\sigma_{pp}}{dp_T dy}\right|_{p_T}$$

  Provide a consistency check. Errors added in quadrature and the net error divided by 5 for comparison
- Note experimental errors are much smaller than a naïve estimate

Δp_T versus L

- Δp_T has a direct connection with the path length L from microscopic dynamics
- L is related with centrality (for simplicity using the Glauber model)

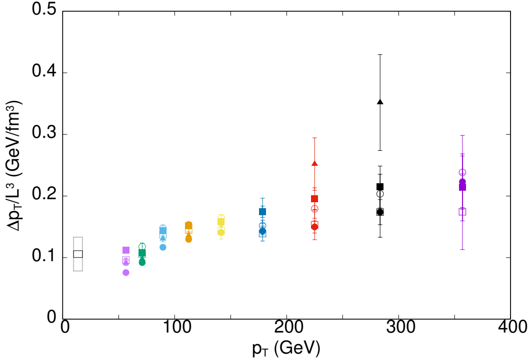
Centrality	0–10%	10–20%	20–30%	30–40%	40–50%
L/R	0.50	0.47	0.44	0.41	0.38

- The relationship between L and Δp_T depends on the medium properties

Strongly coupled medium

- $\Delta p_T \propto L^3$ *[Marquet, Renk (2009); Chesler, Rajagopal (2014, 2015)]*
- Independence of $\Delta p_T/L^3$ on p_T and centrality would suggest strongly coupled dynamics
- Data is consistent with this interpretation

Strongly coupled medium

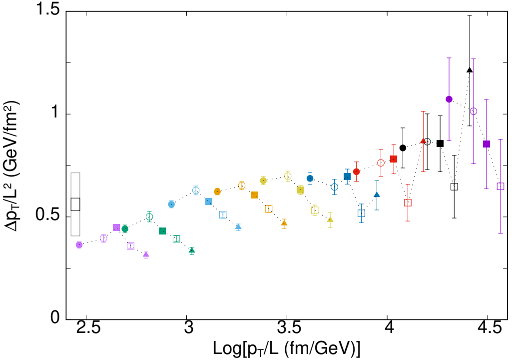


- Most central 0-10% of events — filled circles, 10-20% — unfilled circles, 20–30% — filled boxes, 30–40% — unfilled boxes, 40-50% — filled triangles.
- For fixed p_T, dependence on centrality is weak
- The gray box at the left is the typical systematic uncertainty

Weakly coupled medium

- In a weakly coupled quark gluon plasma, famously up to log terms, $\Delta p_T \sim L^2$ (*BDMPS (1993, 1994)*)
- Consequence of coherent addition of amplitudes over the formation time of the emitted gluon in the LPM regime
- $\Delta p_T = \kappa L^2 \log(\frac{p_T}{\omega^2 L})$ (*Zakharov (2000)*)
- ω is related to medium scales

Weakly coupled medium

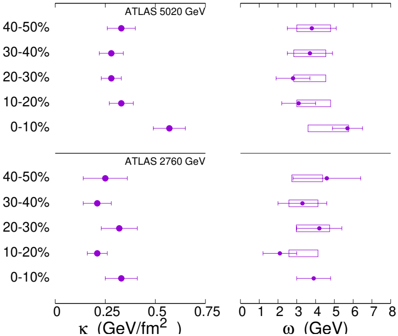


- Points at the same p_T connected with dotted lines (one color)
- Interesting systematic dependence on centrality [from $\log(p_T/L)$] for a fixed p_T. See an increase and then a decrease in $\Delta p_T/L^2$ as we go to more central
- Systematic errors (gray box) substantial. Hence data also consistent with a BDMPS-Z picture

Parameters of a weakly coupled medium

- $\Delta p_T = \kappa L^2 \log(\frac{p_T}{\omega^2 L})$
- $\kappa = C\alpha_s \frac{\hat{q}}{4}$
- $C = C_F$ for quark jets and $C = C_A$ for gluon jets
- Using the fraction of gluon and quark initiated jets from perturbative QCD estimates, we get a weighted κ
- We can extract κ and ω, and then $\hat{q}$ from the data

Medium parameters



- Error bars include systematic and statistical uncertainties

Medium parameters

- Using $\kappa = C\alpha_s \frac{\hat{q}}{4}$, $C \simeq 2.3 - 2.4$, $\alpha_s \simeq 0.15 - 0.25$
- Obtain $\hat{q} = 1.2 - 5.4\text{GeV}/\text{fm}^2$ which is consistent with other results from the literature *JET Collaboration (2013); Yacine Mehtar-Tani et. al. (2021); JETSCAPE Collaboration (2021).*

Summary

- R_{AA} and Δp_T two different ways of looking at the AA jet spectrum and comparing it to the spectrum in pp
- Δp_T directly connects to the microscopic details of the energy loss
- Taking systematic errors into account in the simplest manner (quadrature) we find that both weak coupling and strong coupling dynamics of jets is consistent with the present data, with a minor preference for strong coupling
- Taking into account correlations in the errors might help in making a more discriminatory deduction