Flavor dependence of jet quenching in heavy-ion collisions

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Motivation

- Quark-gluon plasma (QGP) is expected in heavy-ion collisions (HICs) experiments.
- Jet quenching has long been identified as a very powerful tool to investigate the properties of QGP.
- The interaction between an energetic parton and the QGP is sensitive to the colour charge and the mass of the parton.
- A separate determination of quark and gluon jet energy loss could play a significant role in revealing the fundamental color structures of the QGP and testing the color representation dependence of the jet-medium interaction. This however proves difficult, as the final state hadronic observables are a mixture of quark and gluon contributions..

We investigate the flavor dependence of jet quenching, by performing a systematic analysis of medium modifications on the inclusive jet, γ+jet, and b-jet in Pb+Pb collisions at the LHC.

Framework

The final observable of the nuclear modification factor R_{AA} in a given centrality in terms of the flavor dependent $R_{AA}^{i,C}$ can be expressed as,

$$R_{AA}^{C} = \frac{\sum_i R_{AA}^{i,C} d\sigma_{pp}^{i}}{\sum_i d\sigma_{pp}^{i}} = R_{AA}^{g,C} + \sum_{i\neq g}(R_{AA}^{i,C} - R_{AA}^{g,C}) f_i, \quad (1)$$

where $f_i = d\sigma_{pp}^{i}/\sum_i d\sigma_{pp}^{i}$ is the fraction of the total jet cross section from the parton i initiated one, $R_{AA}^{i,C}$ is the flavor and centrality dependent nuclear modification factor of parton i and assumed to be factorized as [1, 2]:

$$R_{AA}^{i,C}(p_T) = \frac{\int d\Delta p_T d\sigma_{pp}^{i}(p_T+\Delta p_T)\otimes W_{AA}^{i,C}(x)}{d\sigma_{pp}^{i}(p_T)}, \quad (2)$$

where $x = \Delta p_T/\langle \Delta p_T\rangle$ is the scaled variable with Δp_T the amount of energy loss and $\langle \Delta p_T\rangle$ the averaged jet energy loss, which can be parametrized as $\langle \Delta p_T\rangle = \beta_i(p_T)^{\gamma_i}\log(p_T)$ following Refs. [2]. $W_{AA}^{i,C}$ is the scaled energy loss distribution of parton i in a given centrality class C of A+A collisions and can be assumed as:

$$W_{AA}^{i}(x) = \frac{\alpha_i^{\alpha_i} x^{\alpha_i-1} e^{-\alpha_i x}}{\Gamma(\alpha_i)} \quad (3)$$

where Γ is the standard Gamma-function.
According to this flavor decomposition, one can extract $\alpha_i, \beta_i, \gamma_i$, for each parton flavor i to determine the flavor and centrality dependent jet energy loss distributions $W_{AA}^{i}(x)$ through a Bayesian analysis, which can be summarized as

$$P(\theta|data) = \frac{P(\theta)P(data|\theta)}{P(data)}, \quad (4)$$

where $P(\theta|data)$ is the posterior distribution of parameters θ given the experimental data, $P(\theta)$ is the prior distribution of θ, $P(data|\theta)$ is the Gaussian likelihood between experimental data and the output for any given set of parameters and $P(data)$ is the evidence. A uniform prior distribution $P(\theta)$ in the region $[\alpha_i, \beta_i, \gamma_i] \in [(0,10),(0,8),(0,0.8)]$ is used for the Bayesian analysis. We first run 1×10^6 burn-in MCMC steps to allow the chain to reach equilibrium, and then generate 1×10^6 MCMC steps in parameter space.

Cross sections in p+p and in Pb+Pb

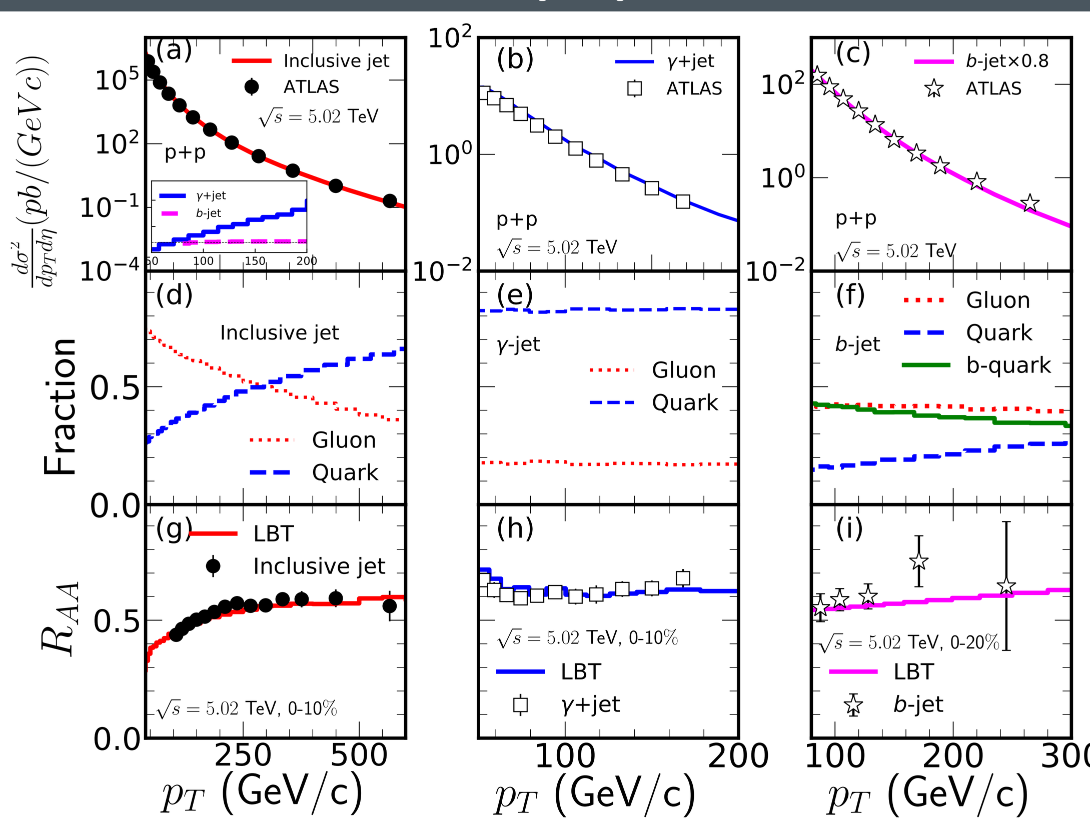

Figure 1: Up: Transverse momentum distributions of: (a) inclusive jet, (b) γ-tagged jet, and (c) b-jet simulated by MadGraph+Pythia8 (lines) and the comparison with experimental data (samples) [3, 4, 5] in p+p collisions. The inset in (a) is the ratio of γ-tagged jet (blue solid) and b-jet (red dashed) to inclusive jet cross section. Middle: fraction of quark (Dashed blue line) and gluon (Solid red line) initiated jet of : (d) inclusive jet, (e) γ-tagged jet, and (f) b-jet in p+p collisions. Bottom: nuclear modification factor of: (g) inclusive jet, (h) γ-tagged jet, and (i) b-jet calculated by LBT (lines) and the comparison with experimental data [3, 4, 5] in Pb+Pb collisions.

- **Inclusive jet spectrum is steeper than γ+jet, while b-jet have similar slope as the inclusive jet.**
- **For inclusive jet, gluon (quark) initiated jet dominates in low (large) p_T region. While, quark initiated jet dominates ($\sim 80\%$) γ+jet production. Gluon initiated jet contributes about 40% to b-jet.**
- **γ+jet and b-jet are less suppressed than inclusive jet due to the different q/g origins and the reference spectra in p+p collisions.**

Colour-charge dependence of R_{AA}

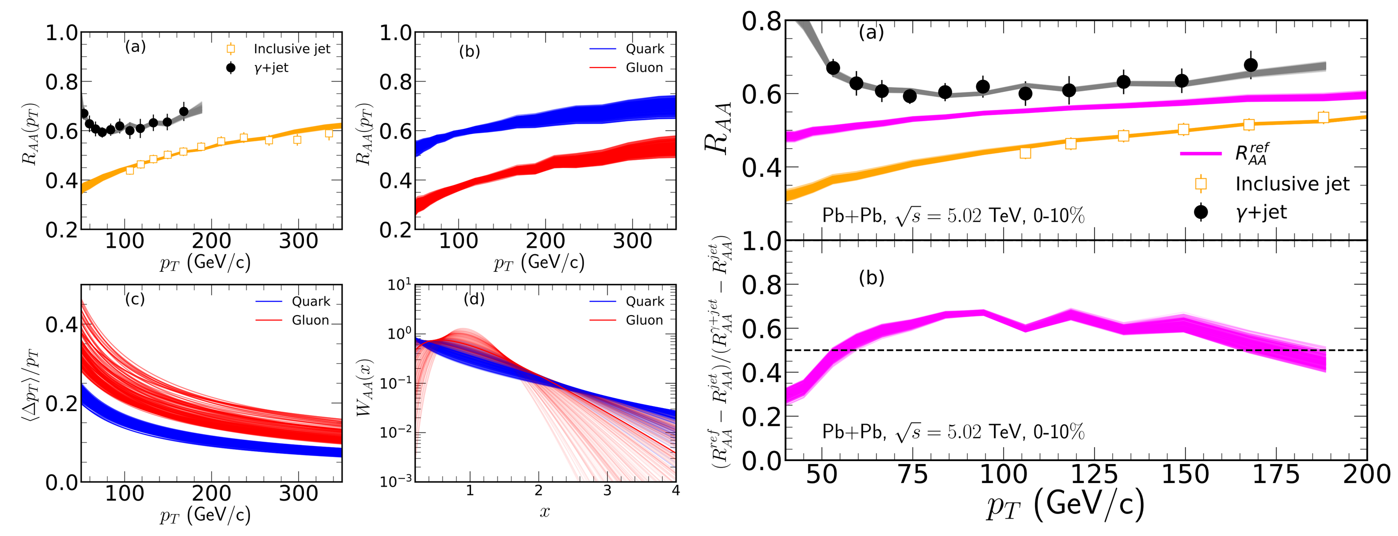

Figure 2: (left) Final fitted R_{AA} of inclusive jet (orange) and γ+jet (gray) in 0-10% and final extracted energy lose distributions of quark and gluon initiated jet . (right)The relative contribution fraction from large quark fraction to the difference between γ+jet R_{AA} and inclusive jet R_{AA}.

- **γ-tagged jet R_{AA} is less suppressed compared to that for inclusive jet, which is a mix effect of the slope of initial spectra and parton color-charge in p+p collisions.**
- **The quark-initiated jets lose less fraction of its energy and shows a weaker dependence on the jet p_T compared to gluon-initiated jets due to its color factor.**
- **R_{AA}^{ref} is shown by assuming that inclusive jet has the same quark fraction as γ+jet.**
- **Large quark-initiated jet fraction underlies γ+jet suppression at large p_T, while the flat spectra give the dominate contribution to γ+jet suppression at low p_T.**

Centrality dependence of R_{AA}

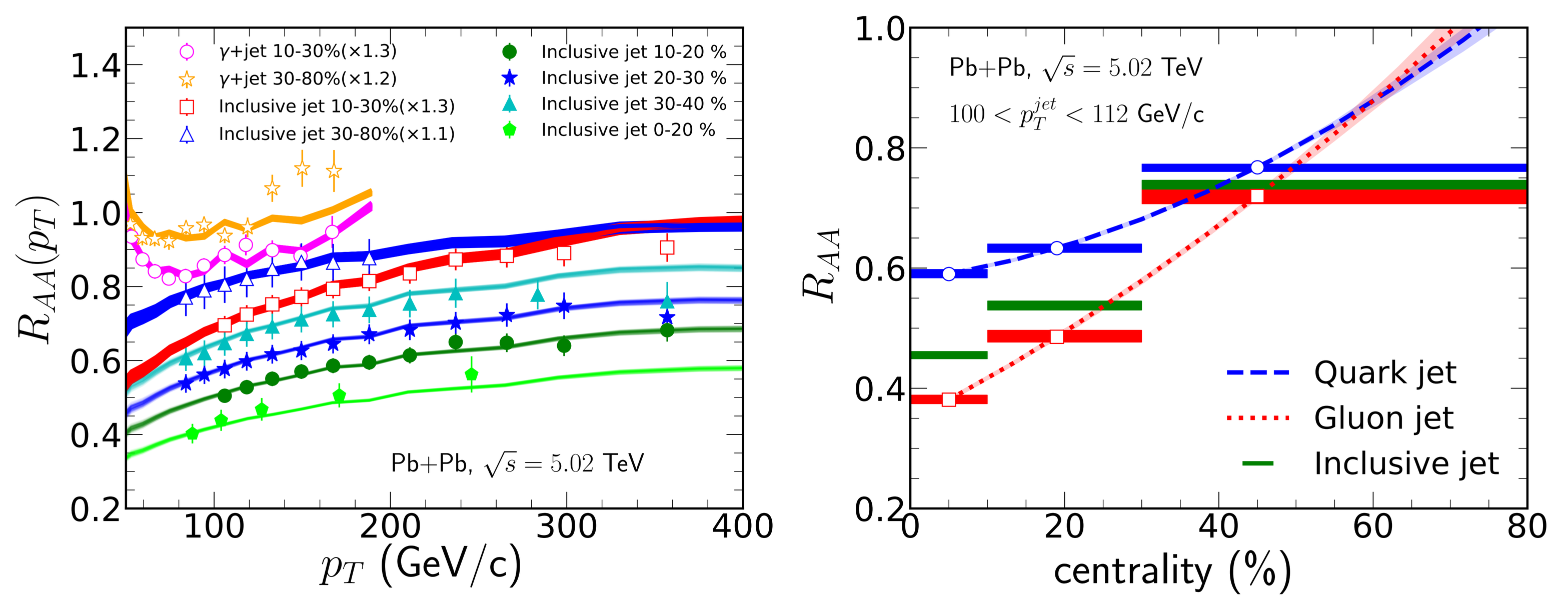

Figure 3: (left) Data-driven fitted R_{AA} of the inclusive jet [5] and γ+jet [3] in 10-30%, 30-80% centrality bins and predictions of inclusive jet R_{AA} in 10-20%, 20-30%, 30-40% and 0-20% centrality bins as well as the comparison with experimental data [5]. (right) The centrality dependence of final fitted gluon jet (red), quark jet (blue) and inclusive jet (green) R_{AA} in Pb+Pb collisions at 5.02 TeV.

- **All final fitted R_{AA} are in nice agreement with the experimental data.**
- **Gluon and quark initiated jet energy loss distributions are well constrained in 0-10%, 10-30%, and 30-80% centrality.**
- **The quark-initiated jet has weaker dependence on the centrality than that for gluon-initiated jet.**

		α_i	β_i	γ_i
0-10%	gluon	5.44±2.15	1.46±0.22	0.25±0.03
	quark	0.47±0.06	1.09±0.21	0.24±0.04
10-30%	gluon	1.48±0.45	1.65±0.32	0.21±0.03
	quark	3.96±1.05	1.47±0.13	0.11±0.02
30-80%	gluon	4.84±2.72	0.89±0.14	0.14±0.03
	quark	2.28±0.88	1.07±0.07	0.07±0.01

Table 1: Parameters $[\alpha_i, \gamma_i, \beta_i]$ of quark and gluon jet energy loss distribution from Bayesian fits to experimental data [3, 5] on inclusive jet and γ+jet suppressions at 5.02 TeV.

Parton-mass dependence of R_{AA}

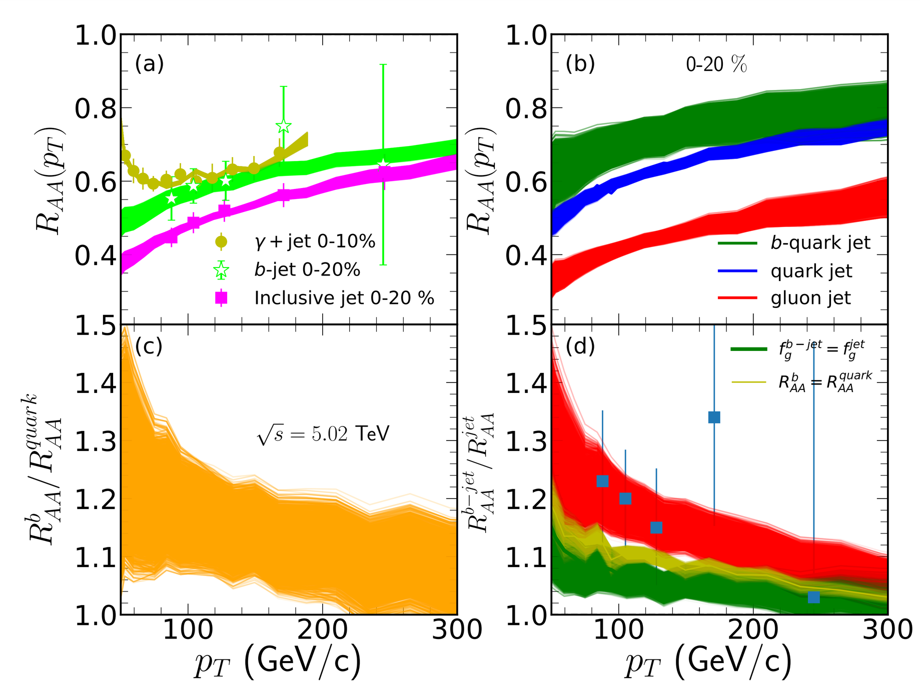

Figure 4: (Color online) (a): final fitted R_{AA} of b-jets (lime green lines), inclusive jet (magenta lines) and γ-tagged jet (yellow lines) and the comparison with experimental data [3, 4, 5]. The data-driven extracted: (b) R_{AA} of gluon (red), light quark (blue), and b-quark (green) initiated jets, (c) The ratio of $R_{AA}^{b}/R_{AA}^{quark}$, (d) the ratio of $R_{AA}^{b\text{-jet}}/R_{AA}^{jet}$. The quark mass effect (green) and less gluon fraction effect (yellow) to the ratio of R_{AA} are also presented.

- **b-jets is less suppressed compared to inclusive jet due to the mixture of mass effect and color effect.**
- **The quark mass effect and color charge effect have comparable impacts to the ratio $R_{AA}^{b\text{-jet}}/R_{AA}^{jet}$, though their influence may decrease significantly at $p_T \sim 300$ GeV/c.**

References

[1] Y. He, L. G. Pang and X. N. Wang, Phys. Rev. Lett. **122**, no.25, 252302 (2019)
[2] Y. He, S. Cao, W. Chen, T. Luo, L. G. Pang and X. N. Wang, Phys. Rev. C **99**, no.5, 054911 (2019)
[3] [ATLAS], [arXiv:2303.10090 [nucl-ex]].
[4] [ATLAS], [arXiv:2204.13530 [nucl-ex]].
[5] M. Aaboud *et al.* [ATLAS], Phys. Lett. B **790**, 108-128 (2019)

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