# Flavor dependence of jet quenching in heavy-ion collisions from a Bayesian analysis

Shan-Liang Zhang

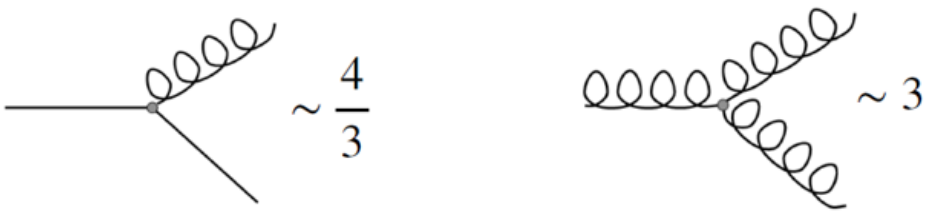
Department of Physics, Hubei University, Wuhan
In collaboration with Enke Wang, Hongxi Xing and Ben-Wei Zhang

Jet Modification and Hard-Soft Correlations
Sep. 29, 2024, University of Tokyo


# Outline

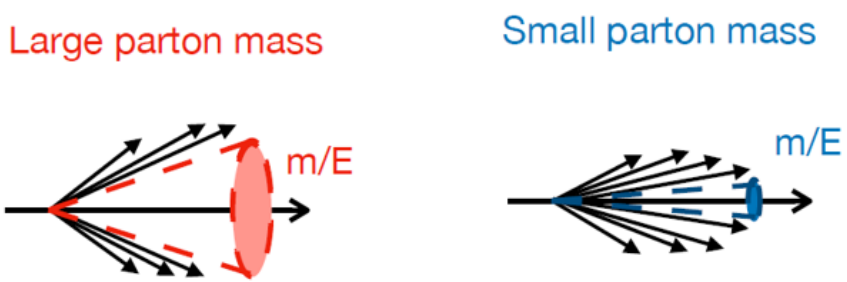
# Energy loss dependence on parton flavor/mass

- The interactions between high-energy partons and the QGP depend on the parton's QCD colour charge and mass.
- Color-charge dependence




QCD suggest, gluons are more likely to radiate than quark

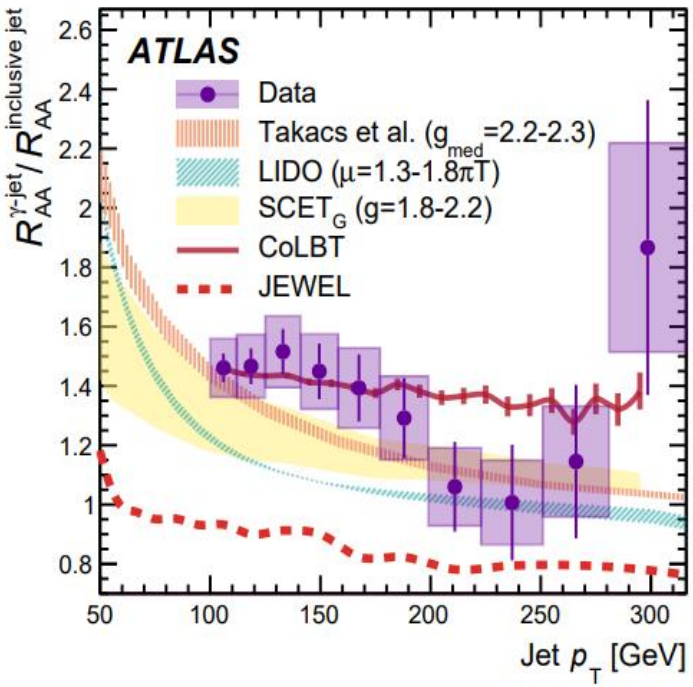
- Mass dependence expected due to "dead-cone effect"



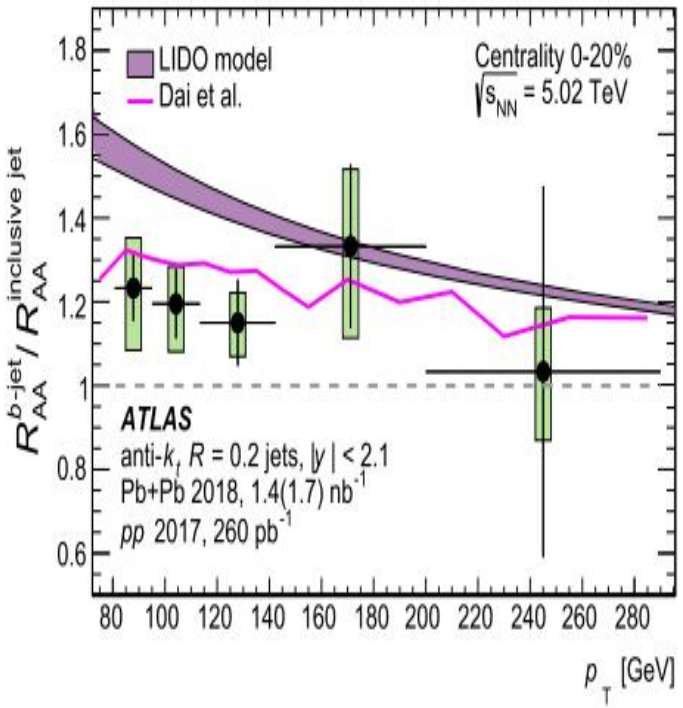

Radiation is suppressed in $\theta < m/E$

# ATLAS measurements of $\gamma$/b-jet $R_{AA}$

PLB 846(2023)138154




EPJC 83(2023)5,438




- $R_{AA}^{\gamma\text{-jet}} > R_{AA}^{\text{jet}}$, color factor dependence of parton-QGP interaction.
- $R_{AA}^{b\text{-jet}} > R_{AA}^{\text{jet}}$, suggest a role for mass and colour-charge effects in partonic energy loss.

# Flavor decomposition of jet $R_{AA}$

Nuclear modification factor $R_{AA}$

$$R^{C}_{\rm AA} = \frac{\sum_i R^{i,C}_{\rm AA} d\sigma^{i}_{\rm pp}}{\sum_i d\sigma^{i}_{\rm pp}} = R^{g,C}_{\rm AA} + \sum_{i\neq g}(R^{i,C}_{\rm AA} - R^{g,C}_{\rm AA}) f_i \tag{1}$$

where $f_i = d\sigma^{i}_{pp}/\sum_i d\sigma^{i}_{pp}$ is the fraction of parton $i$ initiated jet.
The flavor dependent $R^{i,C}_{AA}$

$$R^{i,C}_{\rm AA}(p_{\rm T}) = \frac{\int d\Delta p_{\rm T}\, d\sigma^{i}_{\rm pp}(p_{\rm T}+\Delta p_{\rm T}) \otimes W^{i,C}_{\rm AA}(x)}{d\sigma^{i}_{\rm pp}(p_{\rm T})}, \tag{2}$$

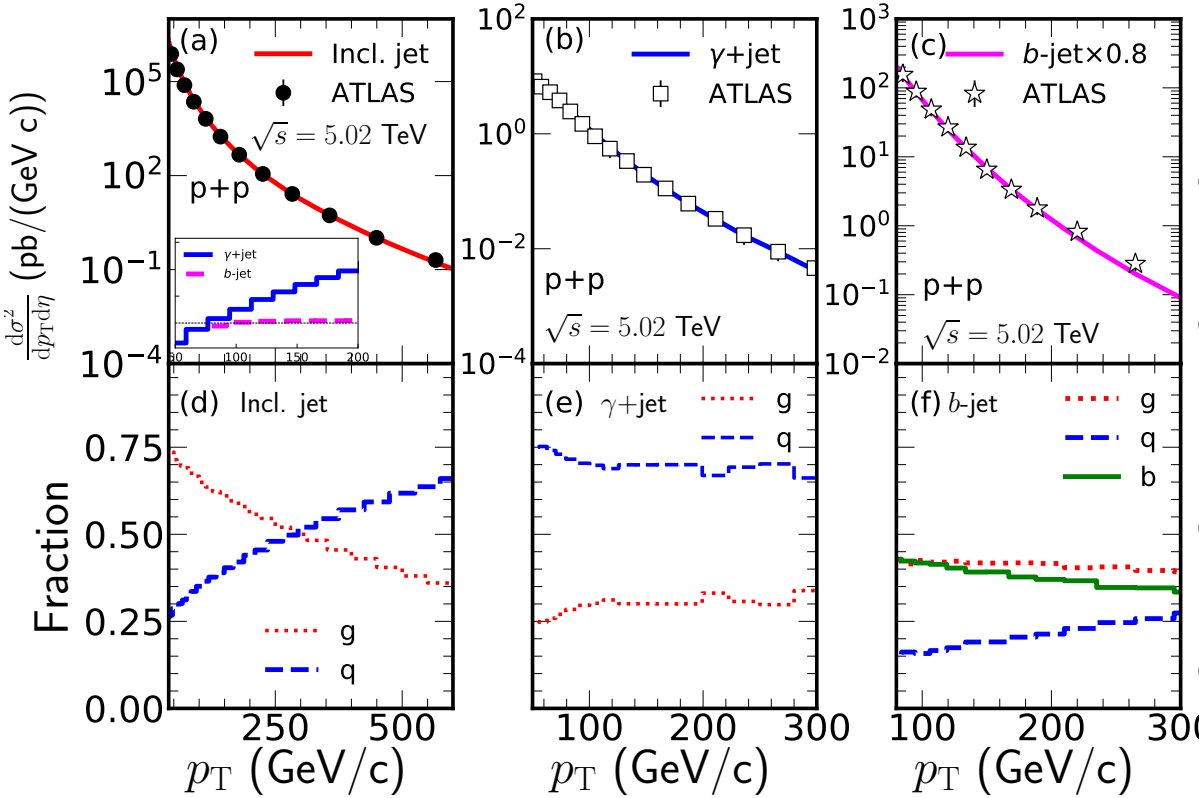
Energy loss distributions Y.He, L.G.Pang and X.N.Wang, PhysRevLett.122.252302

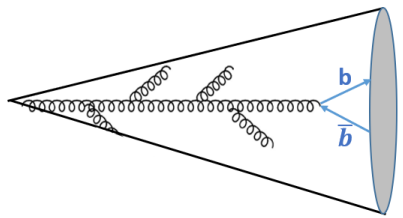
$$W^{i}(x) = \frac{\alpha_i^{\alpha_i} x^{\alpha_i - 1} e^{-\alpha_i x}}{\Gamma(\alpha_i)}, \begin{cases} x = \Delta p^{i}_{\rm T}/\langle \Delta p^{i}_{\rm T}\rangle \\ \langle \Delta p^{i}_{\rm T}\rangle = \beta_i (p_{\rm T}/p^{0}_{\rm T})^{\gamma_i} \log(p_{\rm T}/p^{0}_{\rm T}) \end{cases} \tag{3}$$

Three parameters in the above for each parton type: $[\alpha_i, \beta_i, \gamma_i]$
Bayesian analysis:

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

# Cross sections in p+p

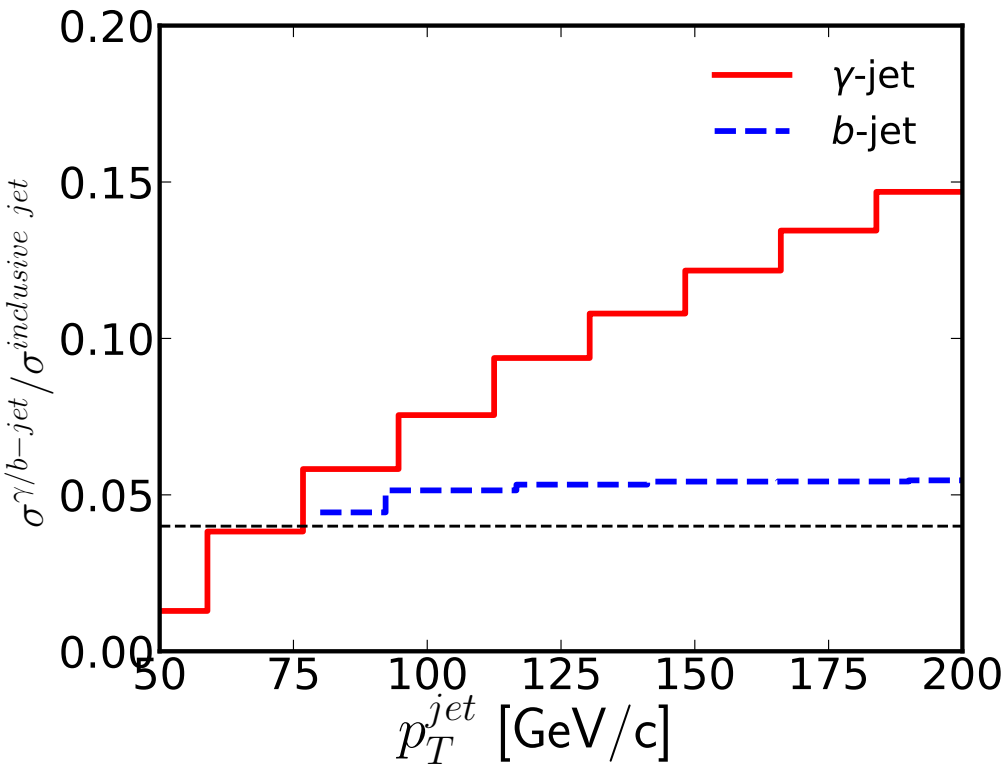



- Give well descriptions of all experimental data.
- Incl. jet: gluon(quark) jet dominates in low (large) $p_T$.
- $\gamma$+jet: quark initiated jet dominates ($\sim 80\%$).
- $b$-jet: gluon initiated jet contributes about $40\%$.

- $R_{AA}^{\gamma+\text{jet}} / R_{AA}^{\text{jet}} > 1$, color-charge effect.
- $R_{AA}^{b\text{-jet}} / R_{AA}^{\text{jet}} > 1$, the mixture of mass effect and color effect.

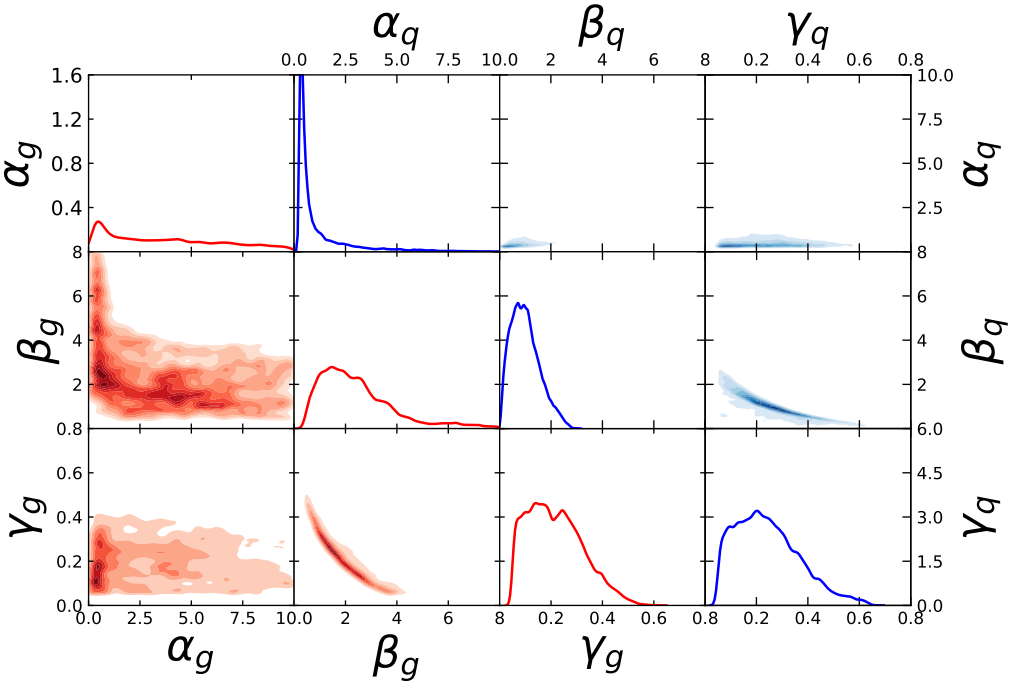
# Cross sections in p+p




- Incl. jet: gluon(quark) jet dominates in low (large) $p_{\mathrm{T}}$.
- $\gamma$+jet: quark initiated jet dominates ($\sim 80\%$).
- *b*-jet: gluon initiated jet contributes about $40\%$.
- Inclusive jet spectrum is steeper than $\gamma$+jet.
- *b*-jet spectrum has similar slope as Incl. jet.

- $R_{\mathrm{AA}}^{\gamma+\mathrm{jet}}/R_{\mathrm{AA}}^{\mathrm{jet}} > 1$, a mix effect of the initial spectra and color-charge.
- $R_{\mathrm{AA}}^{b\text{-jet}}/R_{\mathrm{AA}}^{\mathrm{jet}} > 1$, the mixture of mass effect and color effect.

# Gluon and quark jet energy loss in Pb+Pb

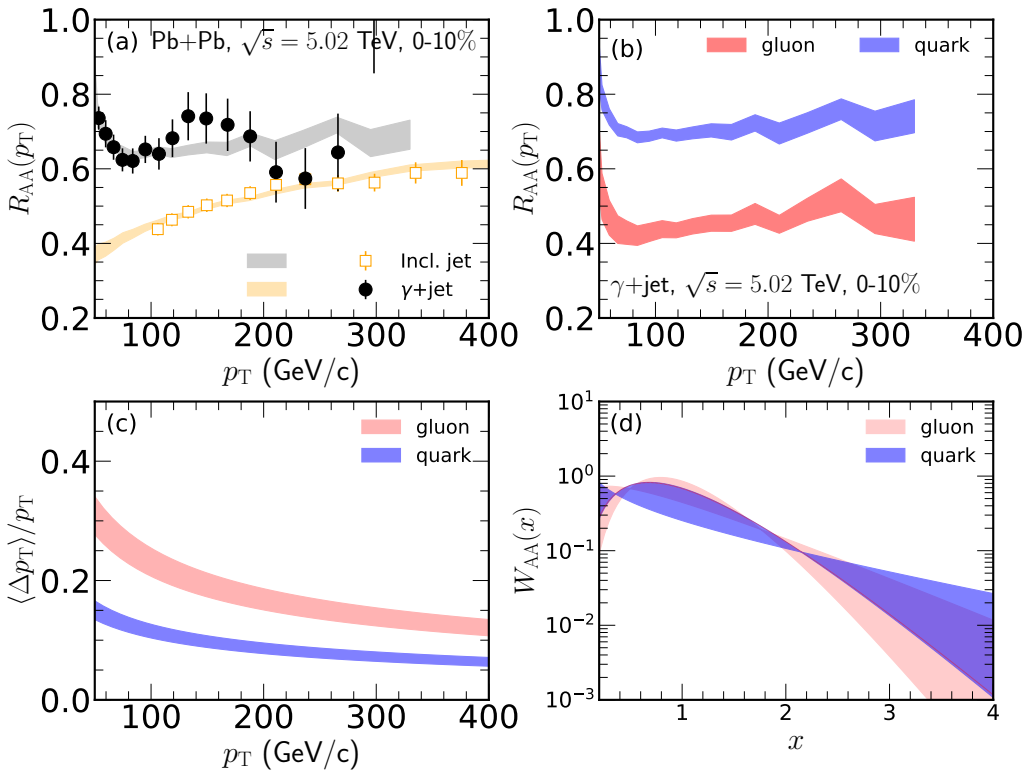



- Uniform prior distribution for $[\alpha_i, \beta_i, \gamma_i] \in [(0, 10), (0, 8), (0, 0.8)]$
- 2M MCMC steps for training, then 2M steps for scanning the parameter space
- All parameters are well constrained.

Extracted parameters for parton energy loss distributions

| $(0-10\%)$5.02 TeV | | | |
|---|---|---|---|
| | $\alpha$ | $\beta$ | $\gamma$ |
| gluon | 4.36±2.07 | 1.78±0.38 | 0.25±0.03 |
| quark | 0.5±0.07 | 0.39±0.17 | 0.32±0.13 |

# Gluon and quark jet energy loss in Pb+Pb



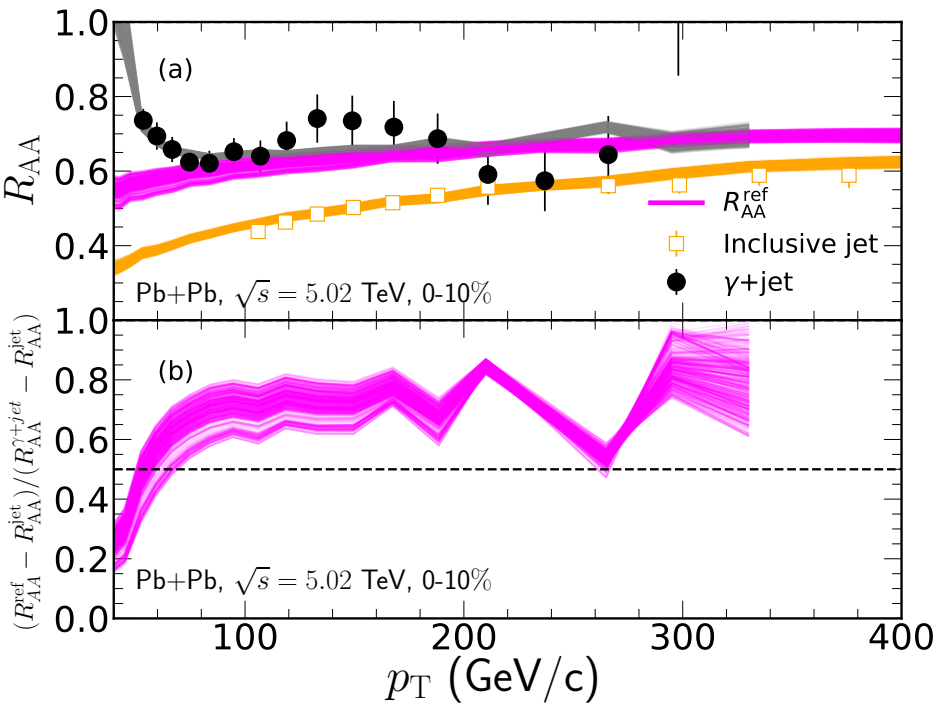

[PLB 850(2024)138549]

The optimized results agree perfectly with data.

In turn, gluon and quark jet $R_{AA}$ and energy loss distributions are extracted.

- Clear flavor hierarchy of jet energy loss, $\Delta E_g > \Delta E_q$.
- Quark jet energy loss shows a weaker $p_T$ dependence.

# Colour-charge dependence of $R_{AA}$

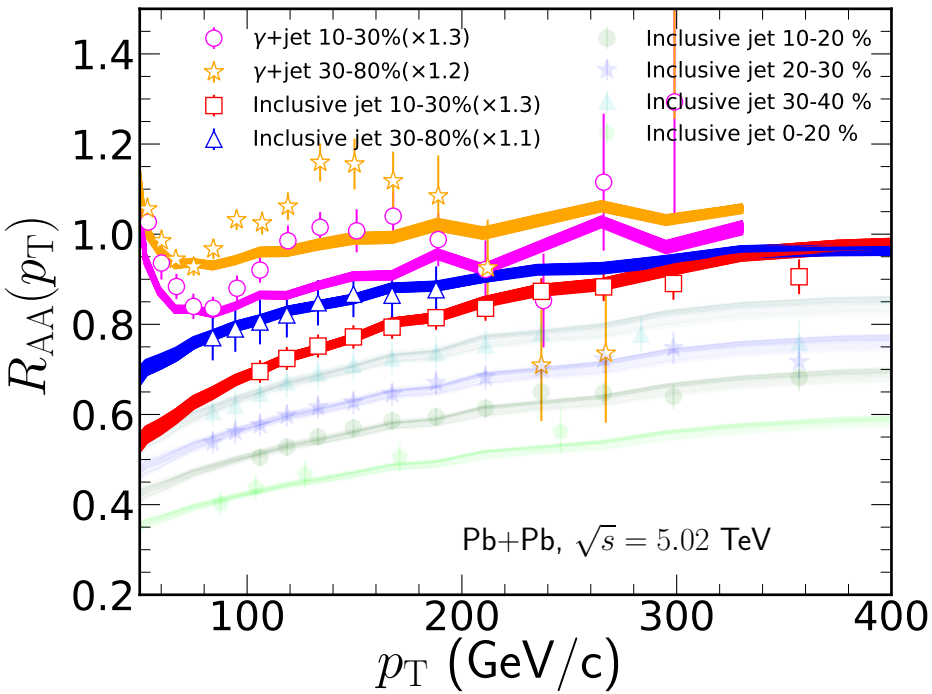



[PLB 850(2024)138549]

$R_{AA}^{ref}$ is shown by assuming that inclusive jet has the same quark fraction as $\gamma$+jet.

- Large quark-initiated jet fraction underlies $R_{AA}^{\gamma+jet}/R_{AA}^{jet}$ at large $p_T$
- The flat spectra give the dominate contribution to $R_{AA}^{\gamma+jet}/R_{AA}^{jet}$ at low $p_T$.

# Extract quark/gluon jet $R_{AA}$ in different Centrality

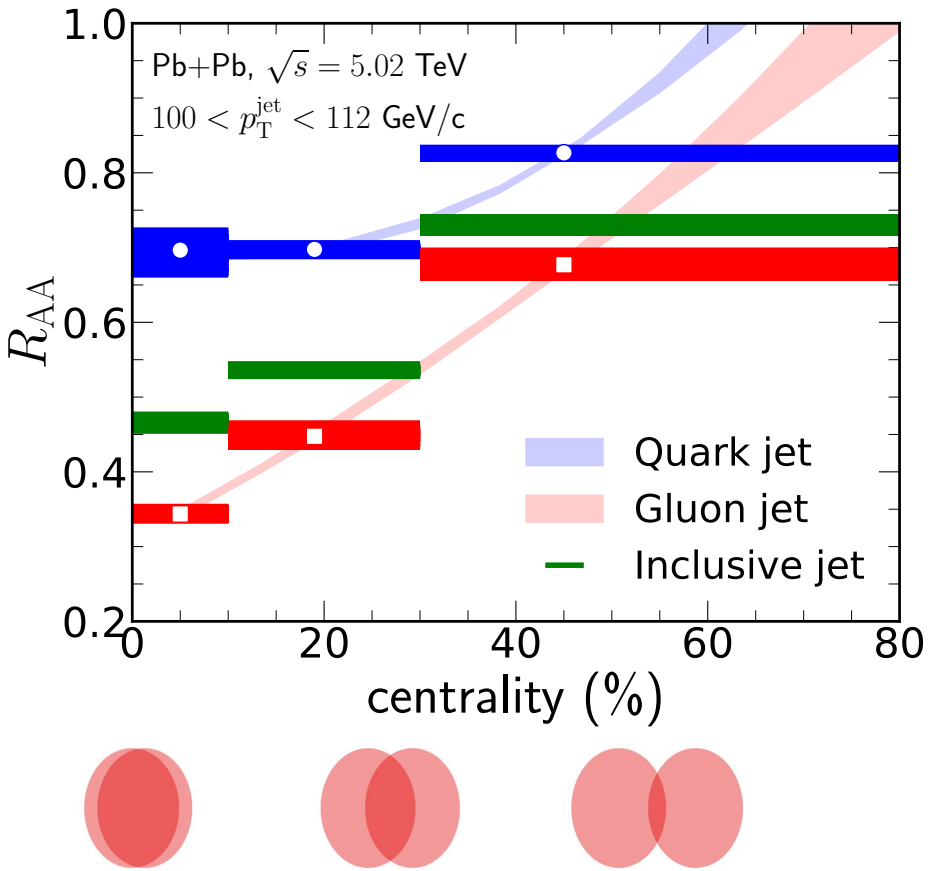



- Uniform prior distribution for $[\alpha_i, \beta_i, \gamma_i] \in [(0, 10), (0, 8), (0, 0.8)]$
- Fitting to inclusive jet $R_{AA}$ and $\gamma$+jet $R_{AA}$ in 10-30% and 30-80% centrality separately.
- The optimized results agree perfectly with data.
- $R_{AA}$ for quark/gluon-initiated jets in 10-30%, 30-80% centrality are extracted.

Extracted parameters for parton energy loss distributions

| | | $\alpha_i$ | $\beta_i$ | $\gamma_i$ |
|---|---|---|---|---|
| 10-30% | gluon | 2.17±0.94 | 1.47±0.44 | 0.25±0.04 |
| | quark | 5.81±1.8 | 1.27±0.12 | 0.09±0.02 |
| 30-80% | gluon | 4.78±1.87 | 1.16±0.17 | 0.11±0.03 |
| | quark | 6.4±2.63 | 0.7±0.05 | 0.09±0.01 |

# Centrality dependent of quark/gluon jet $R_{AA}$




[PLB 850(2024)138549]

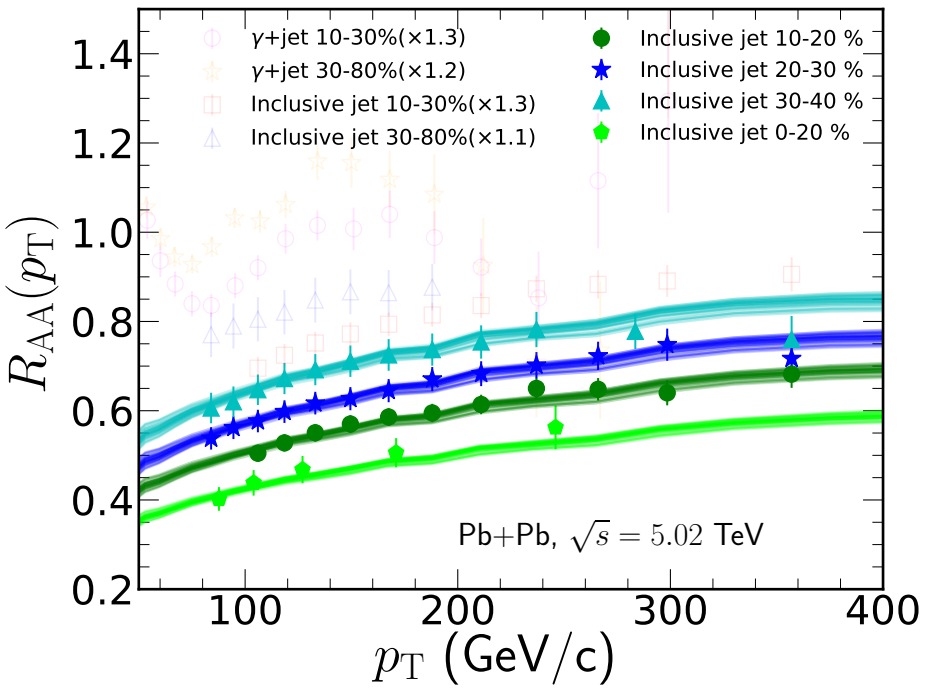
Fitting the centrality dependent $R_{AA}$ of quark- and gluon- initiated jet via a simple parametrization:

$$h^i(C) = a_i C^2 + b_i C + c_i$$

| | gluon | quark |
|---|---|---|
| $a_i$ $(\times 10^{-5})$ | 12.39±2.83 | 3.36±2.45 |
| $b_i$ $(\times 10^{-3})$ | -2.95±1.74 | 6.65±1.20 |
| $c_i$ | 0.7±0.021 | 0.309±0.009 |

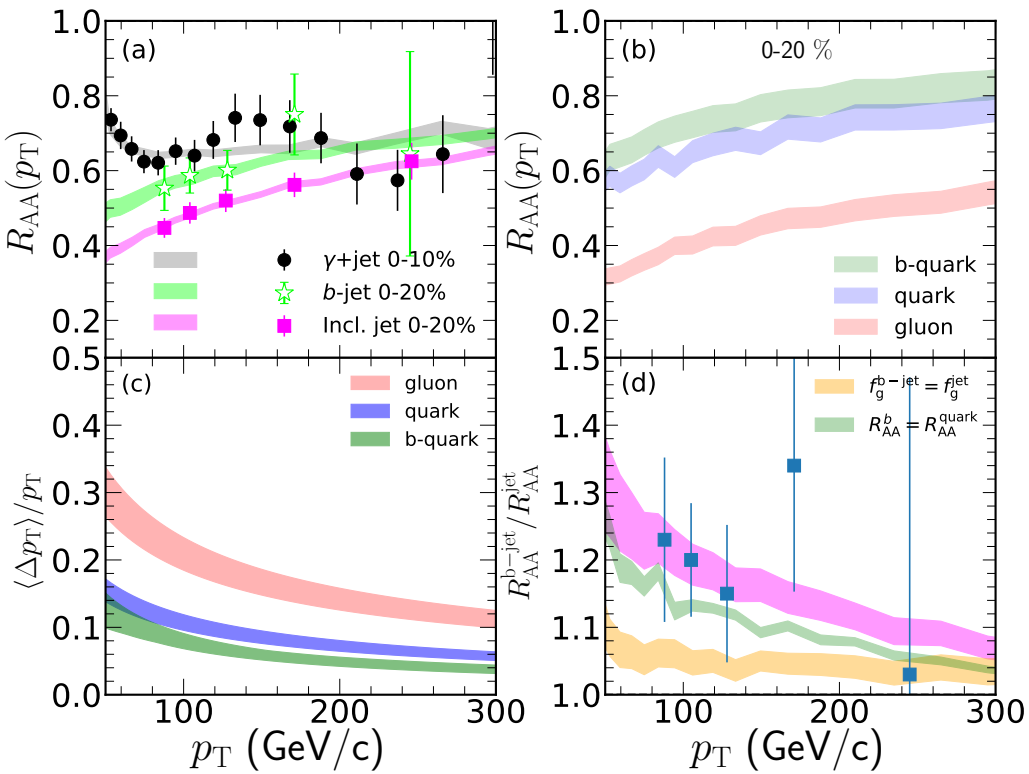
- Quark-initiated jet has weaker dependence on the centrality.
- Need more data to identify the jet $R_{AA}$ in peripheral collisions ($> 60\%$).

# Prediction of jet $R_{AA}$ in PbPb




- Our extracted centrality dependence of quark and gluon jet energy loss distributions can describe the experimental data $R_{AA}$ very well.

# Extract flavor dependent jet energy loss in Pb+Pb




[PLB 850(2024)138549]

$f^{b\text{-jet}} = f^{jet}$: assuming $b$-jet has the same fraction of gluon initiated jet as inclusive jet.

$R_{AA}^{b} = R_{AA}^{quark}$: $b$-quark jet lose the same fraction of energy as light-quark initiated jet.

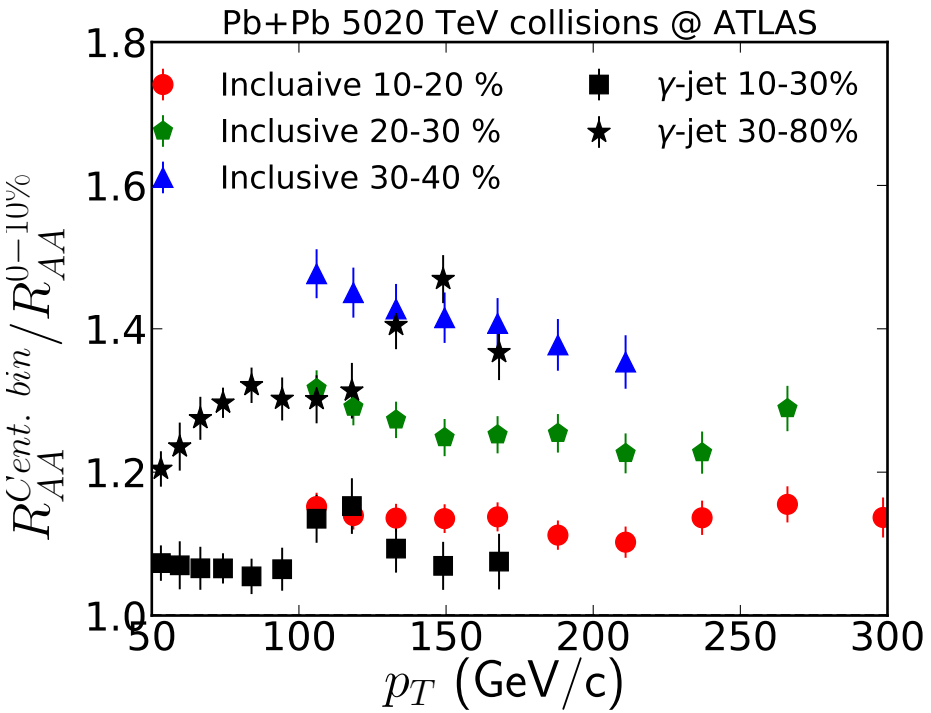
- Clear flavor hierarchy of jet energy loss, $\Delta E_g > \Delta E_q > \Delta E_b$.
- The color charge effect have greater impacts on the ratio $R_{AA}^{b\text{-jet}}/R_{AA}^{jet}$ than parton mass effect, which decrease moderately at $p_T \sim 300$ GeV/$c$.

# Summary

- The flavor-dependent jet energy loss distributions are extracted via a Bayesian data-driven method from experimental data.
- Clear flavor hierarchy of jet energy loss, $\Delta E_g > \Delta E_q > \Delta E_b$.
- The energy loss of quark-initiated jets shows weaker $p_{\mathrm{T}}$ and weaker centrality dependence.
- Large quark jet fraction underlies $R_{\mathrm{AA}}^{\gamma+\mathrm{jet}}/R_{\mathrm{AA}}^{\mathrm{jet}}$ at large $p_{\mathrm{T}}$, while the flat spectra give the dominate contribution to $R_{\mathrm{AA}}^{\gamma+\mathrm{jet}}/R_{\mathrm{AA}}^{\mathrm{jet}}$ at low $p_{\mathrm{T}}$.
- The color charge effect have greater impacts on the ratio $R_{\mathrm{AA}}^{b\text{-jet}}/R_{\mathrm{AA}}^{\mathrm{jet}}$ than parton mass effect, which decrease moderately at $p_{\mathrm{T}} \sim 300$ GeV/$c$.

*Thanks!*

# Centrality dependent jet $R_{AA}$




- Inclusive jet $R_{AA}$ show stronger dependence on centrality than $\gamma$+jet $R_{AA}$.
- different quark/gluon fraction or quark-initiated jet has weaker dependence on the centrality?