

Heavy Flavor Jet Quenching in Pb–Pb Collisions Using JETSCAPE Framework

HOT QCD MATTER - 2025

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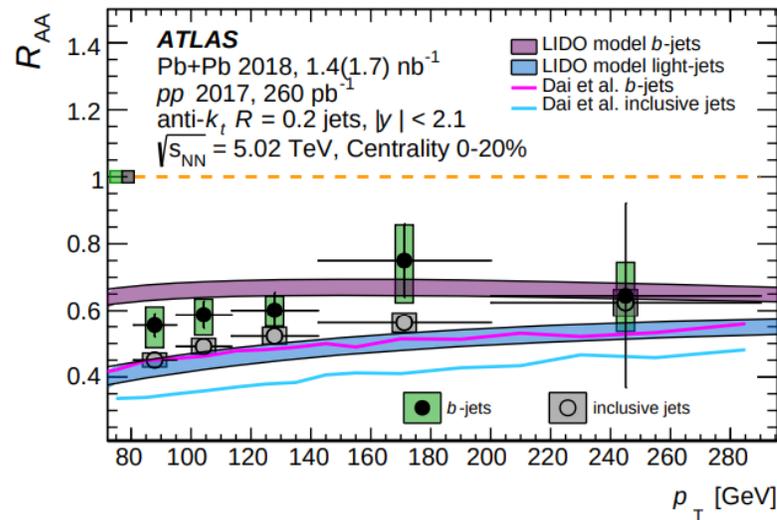


Outline

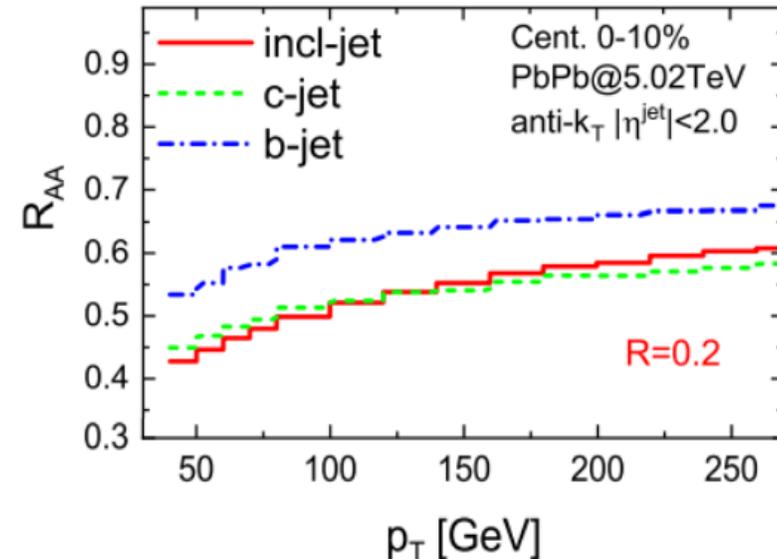
- Motivation of the study
- Nuclear modification Factor
- Mass Hierarchy of Jet Quenching
- JETSCAPE Framework
 - i. MATTER
 - ii. LBT and AdS/CFT
- Results and discussions
- Conclusions

Motivation of The Study

- **Heavy-flavor jets (b, c)** serve as precision probes of the QGP because their large quark masses significantly modify their interactions with the medium, which helps in disentangling the role of quark mass in parton energy loss.
- We investigate the mass hierarchy of jet quenching by comparing b- and c-jets to inclusive jets to probe the QCD-predicted energy-loss ordering $\Delta E_b < \Delta E_c < \Delta E_{light}$.



[Eur. Phys. J. C (2023) 83, 438]

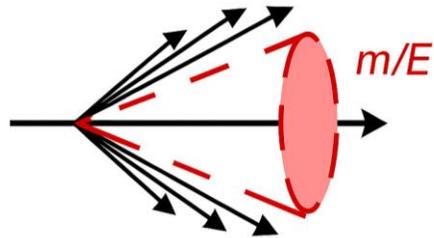


[Chinese Physics C Vol. 49, No. 6 (2025) 064101]

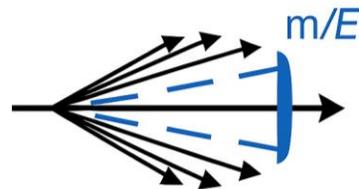
Motivation of The Study

- **Dead-cone effect** as a key signature: Heavy quarks (b, c) radiate less at small angles due to their finite mass, leading to suppressed gluon emission. This modifies internal jet substructure and produces distinct quenching patterns compared to light jets.

Large parton mass



Small parton mass



$$\theta_q \sim \frac{m_q}{E_q}$$

- Larger mass (m_q) \rightarrow larger dead cone angle
- Higher energy ($E_q \gg m_q$) \rightarrow smaller dead cone angle

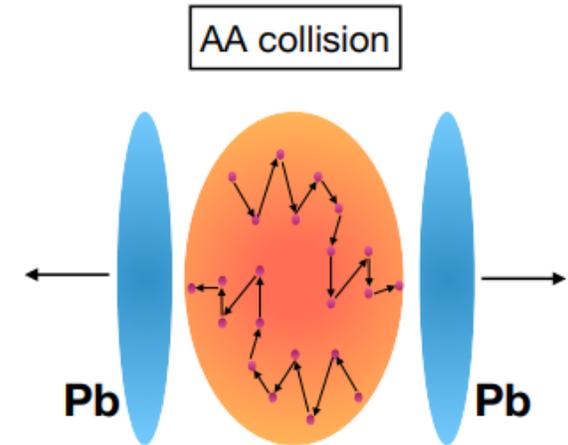
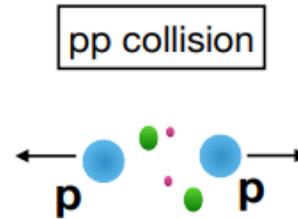
Motivation of The Study

- We also study double ratios $R_{AA}^{b-jet} / R_{AA}^{inclusive\ jet}$ and $R_{AA}^{c-jet} / R_{AA}^{inclusive\ jet}$ to cancel common systematics, which provides a cleaner measurement of quark-mass–dependent energy loss in the QGP.
- In this study, we use **JETSCAPE**, which is a unified multi-model framework (**MATTER, LBT, AdS/CFT**) that seamlessly connects perturbative showering, parton transport, and strong-coupling dynamics, providing the most comprehensive and unbiased description of heavy-flavor jet quenching in the QGP.

Nuclear Modification Factor

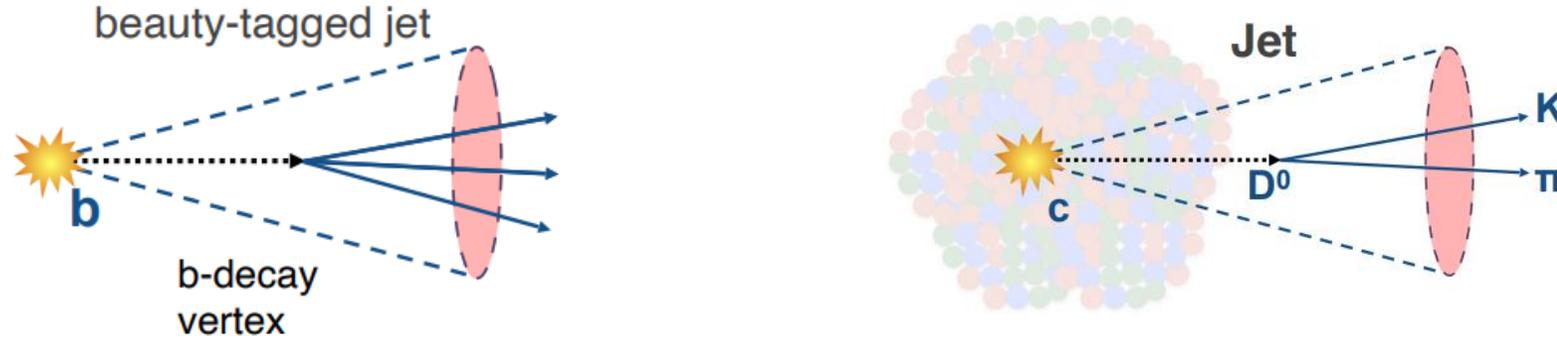
- Measures jet suppression in heavy-ion collisions (A+A) compared to proton-proton collisions.

$$R_{AA} = \frac{\frac{1}{N_{evt}} \frac{d^2 N_{jet}}{dy_{jet} dp_T^{jet}} |_{AA}}{\langle T_{AA} \rangle \frac{d^2 \sigma_{jet}}{dy_{jet} dp_T^{jet}} |_{pp}}$$



- We study –
 - b-, c- and inclusive jets in p-p and Pb-Pb collisions.
 - $\sqrt{s} = 5.02$ TeV and Centrality (0-20%).
 - $|y| < 2.1$ for jet-R = 0.2 and 0.4.

Mass Hierarchy of Jet Quenching



[JETSCAPE online summer school 2023]

- Energy loss in the medium depends on parton type: (i) **color charge** and (ii) **mass**.
 - Gluons & light quarks (u, d, s): Strongest energy loss due to large color charge and no mass suppression.
 - Charm quarks (c): Moderate energy loss due to reduced dead cone effect.
 - Bottom quarks (b): Least energy loss due to large dead cone effect.

$$\Delta E(g) > \Delta E(u, d, s) > \Delta E(c) > \Delta E(b) \quad \longrightarrow \quad R_{AA} (\textit{inclusive jets}) < R_{AA} (\textit{c-jets}) < R_{AA} (\textit{b-jets})$$

JETSCAPE Framework

- **JETSCAPE** – a modular, task-based framework for simulating all aspects of heavy-ion collisions.
- **PYTHIA 8** – a program for the generation of high-energy physics events.
- **TRENTo** – a module that sets up the initial conditions.
- **MUSIC** – a model, that generates a hydrodynamical medium conditions.
- **Jet energy loss** induced by scattering is calculated in a succession of two stages :
 - High Virtuality Phase: Described by modules like MATTER. ($Q^2 > Q_{SW}^2$)
 - Low Virtuality Phase: Simulated by modules like LBT, MARTINI and AdS/CFT. ($Q^2 < Q_{SW}^2$)
- **Features of energy loss modules:**
 - LBT models both collisional energy loss (via elastic scatterings with medium constituents) and medium-induced radiation.
 - AdS/CFT model offers insights into strongly coupled plasma behavior.

Inclusive Jets in p-p

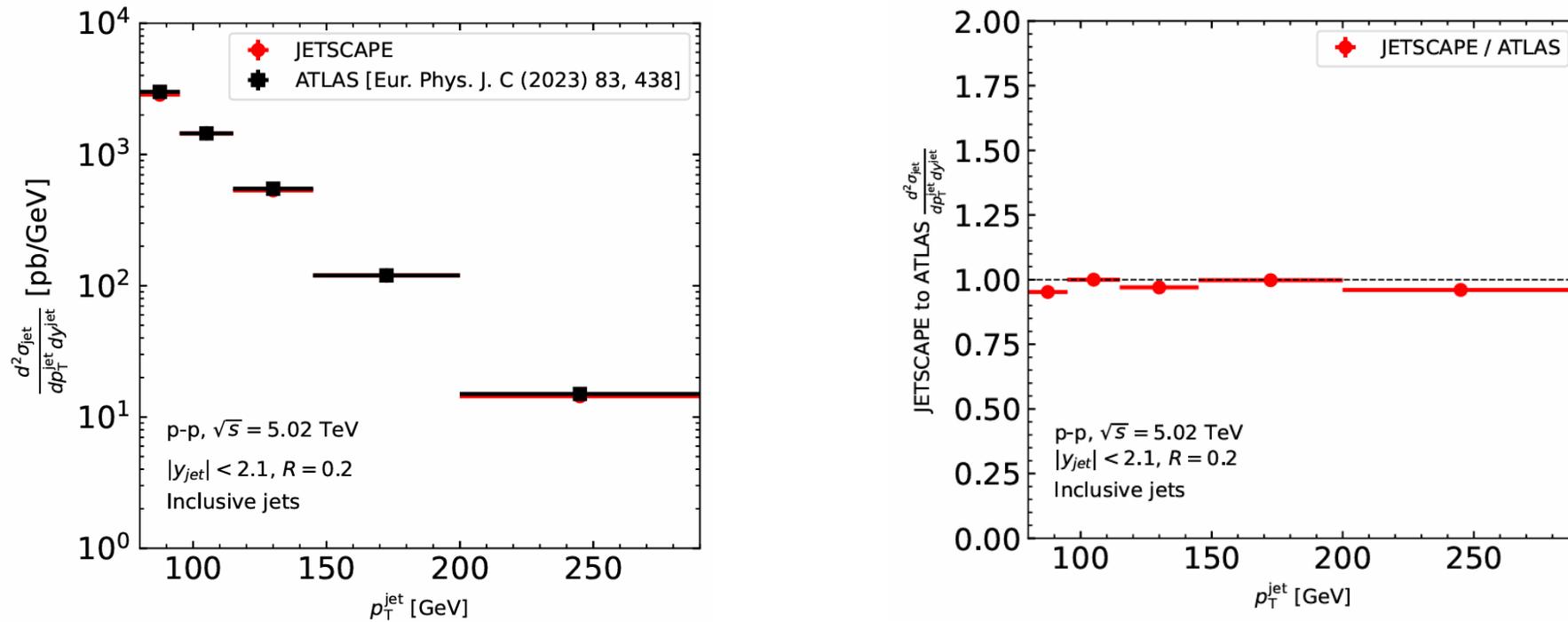


Fig: Differential cross section of inclusive jets in pp collisions for jet radius $R = 0.2$, obtained from JETSCAPE and compared with ATLAS measurements.

- The **JETSCAPE** simulation shows excellent agreement with **ATLAS** data for inclusive jet cross sections in p-p, validating the framework for jet production modelling.

b-jets in p-p

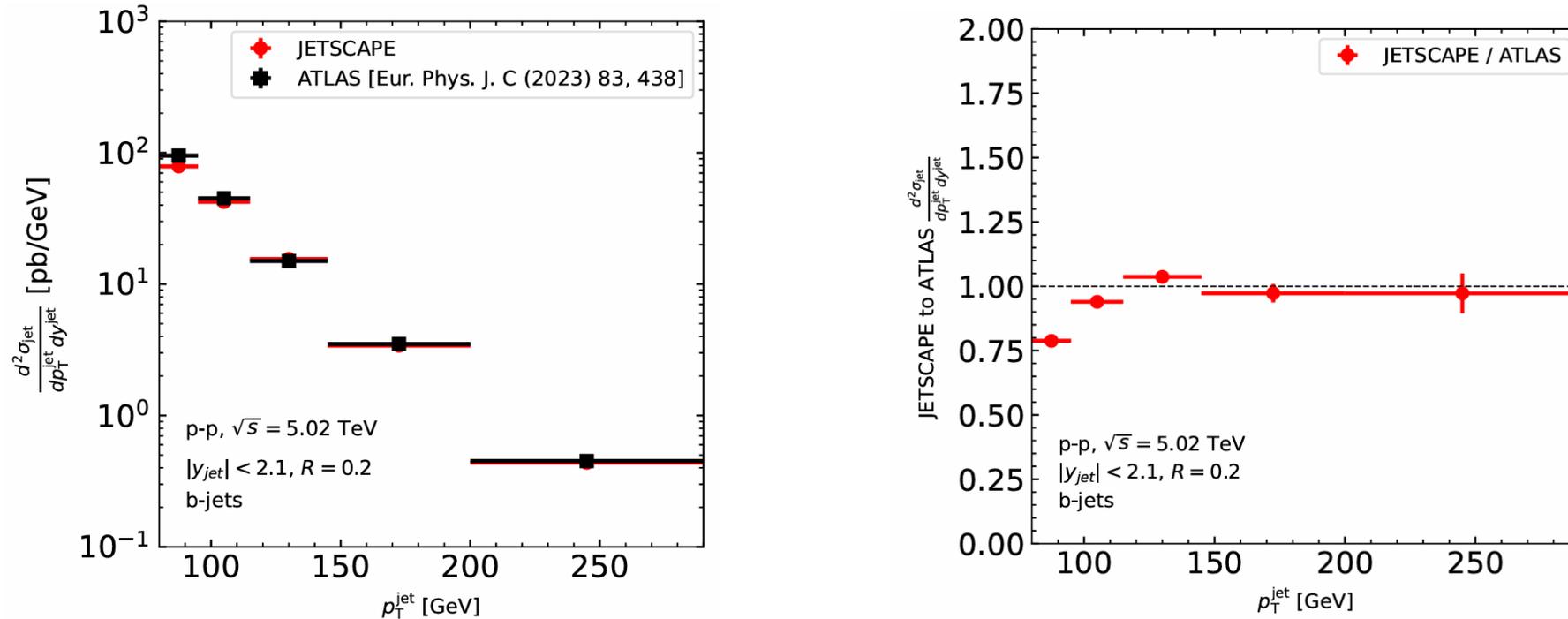


Fig: Differential cross section of b-jets in pp collisions for jet radius $R = 0.2$, obtained from JETSCAPE and compared with ATLAS measurements.

- The **JETSCAPE** framework accurately reproduces the differential cross section of b-jets in p-p collisions, showing good agreement with **ATLAS** measurements across a wide p_T range.

Inclusive, b- and c- jets in p-p

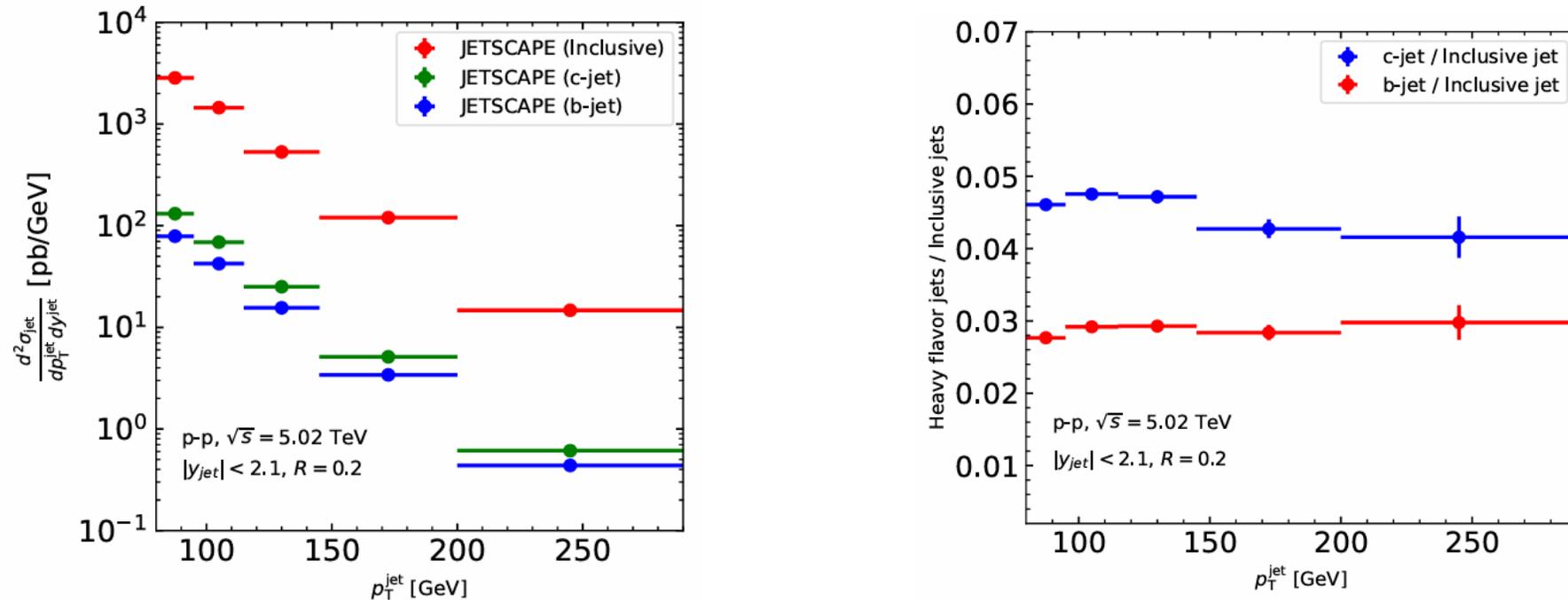


Fig: Differential cross section of heavy flavor (b and c) jets and inclusive jets in pp collision for $R = 0.2$

- The differential cross sections show that inclusive jet production dominates over heavy-flavor jets, with c-jets contributing more than b-jets, as seen from their respective ratios to inclusive jets across the p_T range.

b-jets for Different Jet- R in p-p and Pb-Pb

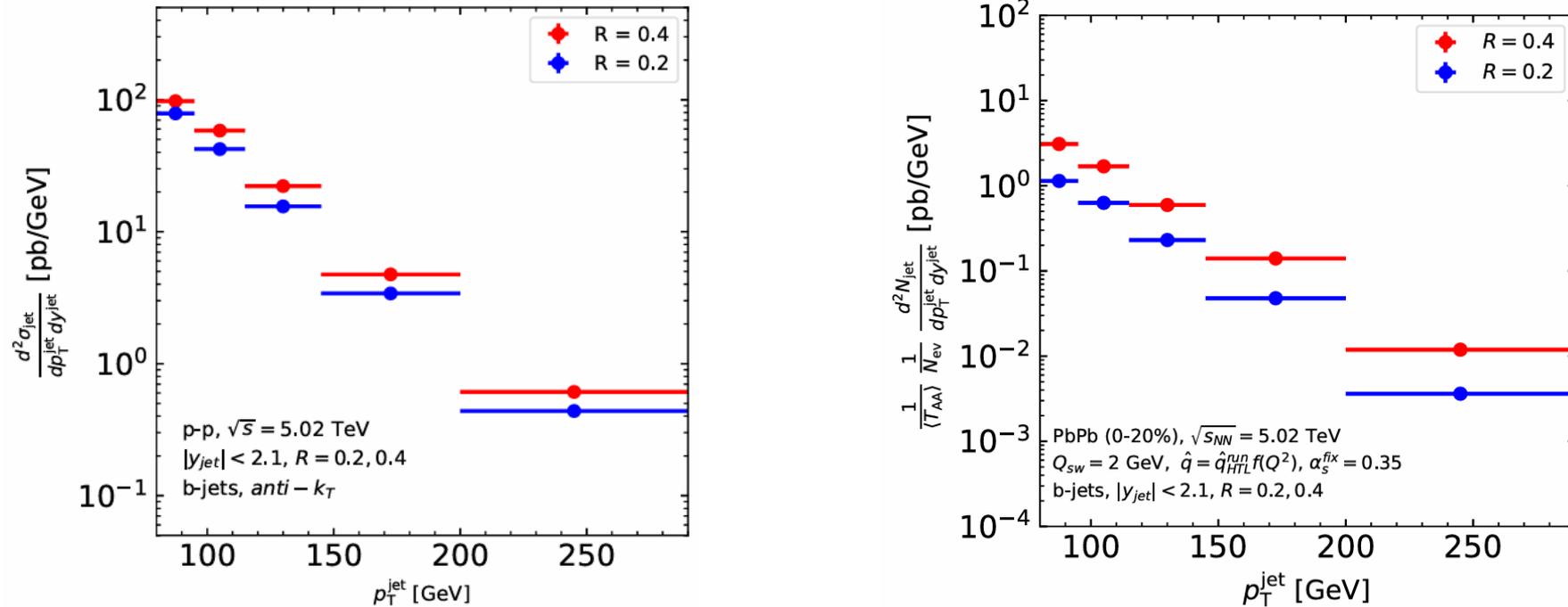


Fig: b-jet spectra in both p-p and Pb-Pb collisions at $\sqrt{s} = 5.02 \text{ TeV}$ for jet radii $R = 0.2$ and 0.4

- The b-jet spectra show higher yields for larger jet radii ($R = 0.4$) compared to smaller radii ($R = 0.2$) in both p-p and Pb-Pb collisions, with a more pronounced suppression in Pb-Pb due to strong jet quenching effects in the QGP medium.

Inclusive Jets in Pb-Pb

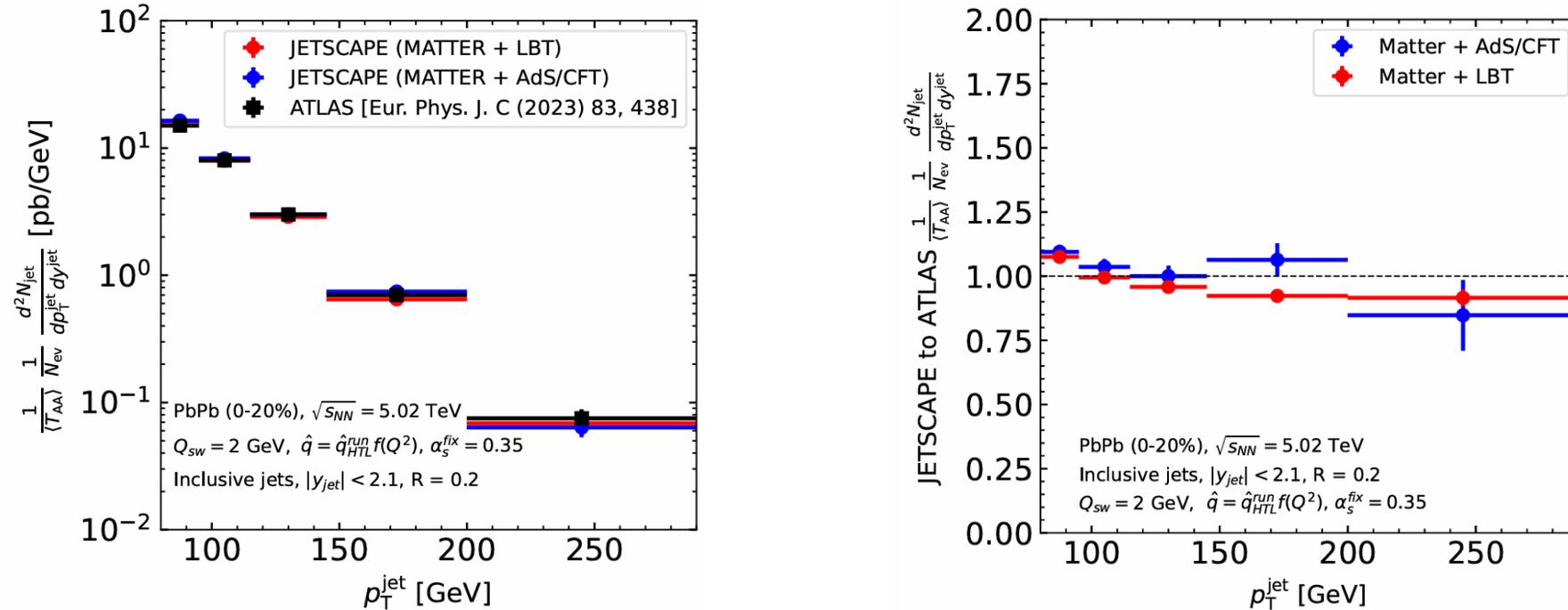


Fig: Differential cross section of inclusive jets in Pb-Pb collisions for jet radius $R = 0.2$, obtained from JETSCAPE and compared with ATLAS measurements.

- In central Pb–Pb collisions, both **MATTER + LBT** and **MATTER + AdS/CFT** models within **JETSCAPE** successfully reproduce the measured inclusive jet spectra, providing well agreement with **ATLAS** measurements.

b-jets in Pb-Pb

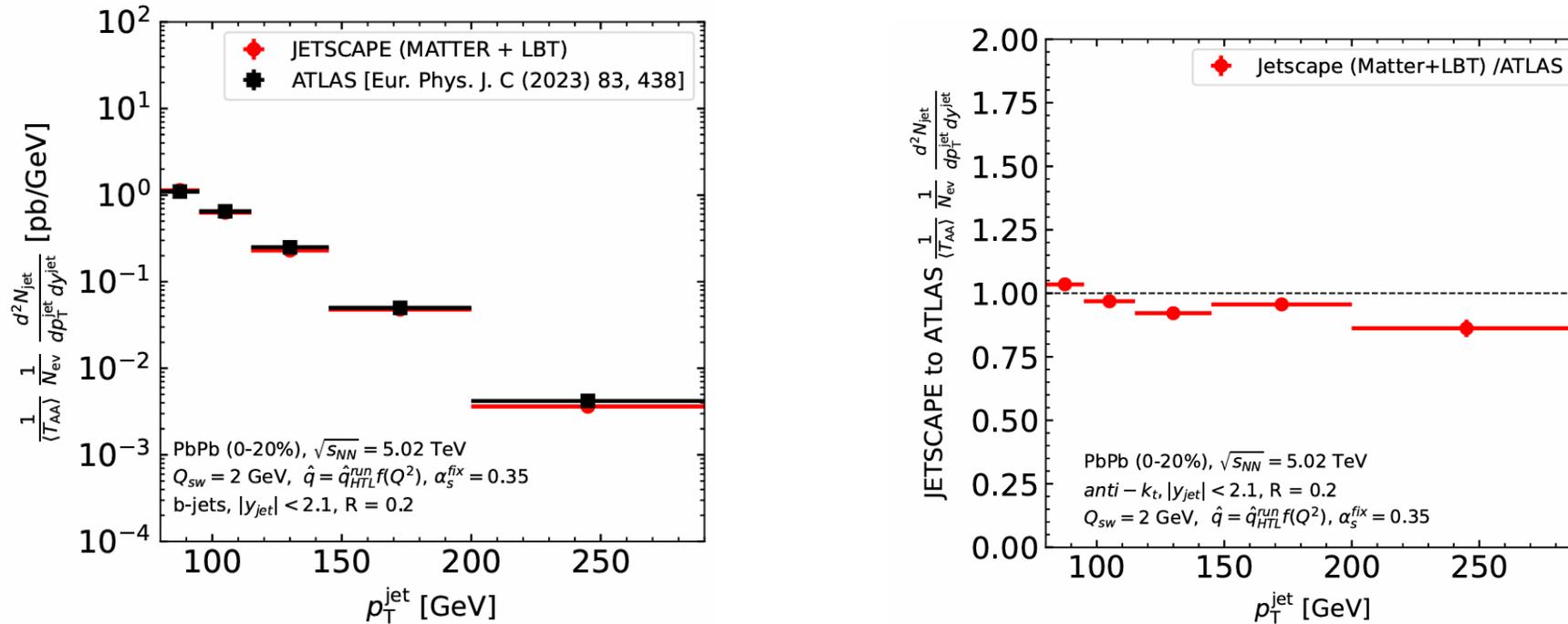


Fig: Differential cross section of b-jets in Pb-Pb collisions for jet radius $R = 0.2$, obtained from JETSCAPE and compared with ATLAS measurements.

- **JETSCAPE (MATTER+LBT)** successfully captures b-jet spectra in central Pb–Pb collisions, showing excellent agreement with **ATLAS** data.

R_{AA} in Pb-Pb Collision (0-20%)

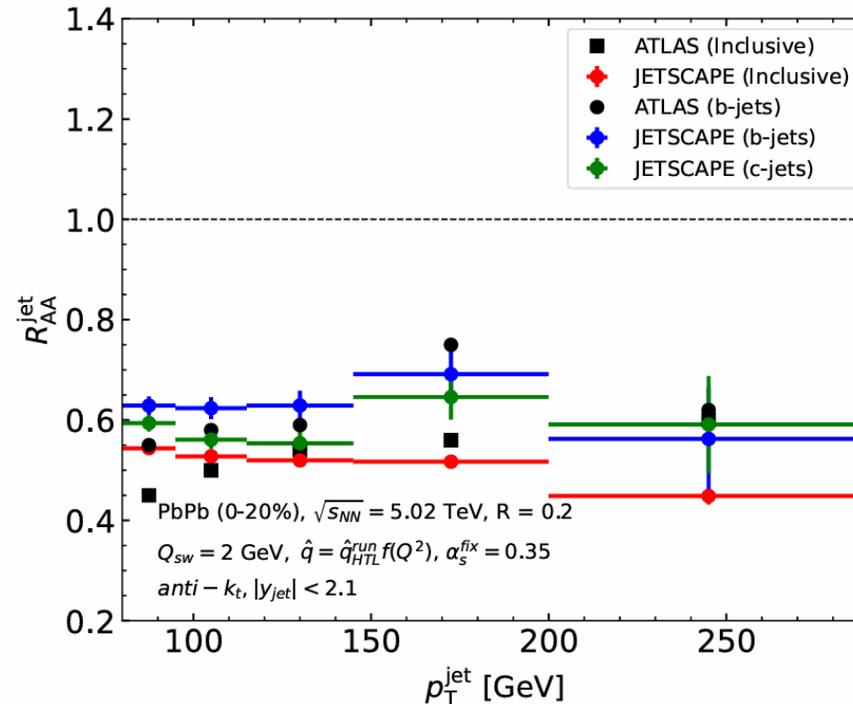


fig: Jet- R_{AA} as a function of jet- p_T for the central (0-20%) Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for the b-, c- and inclusive jets.

- The R_{AA} follows the expected energy loss hierarchy: R_{AA} (*inclusive jets*) $<$ R_{AA} (*c-jets*) $<$ R_{AA} (*b-jets*), reflecting the mass-dependent suppression where heavier quarks lose less energy in the QGP.

Comparison of R_{AA} of Heavy Jets with Inclusive Jets

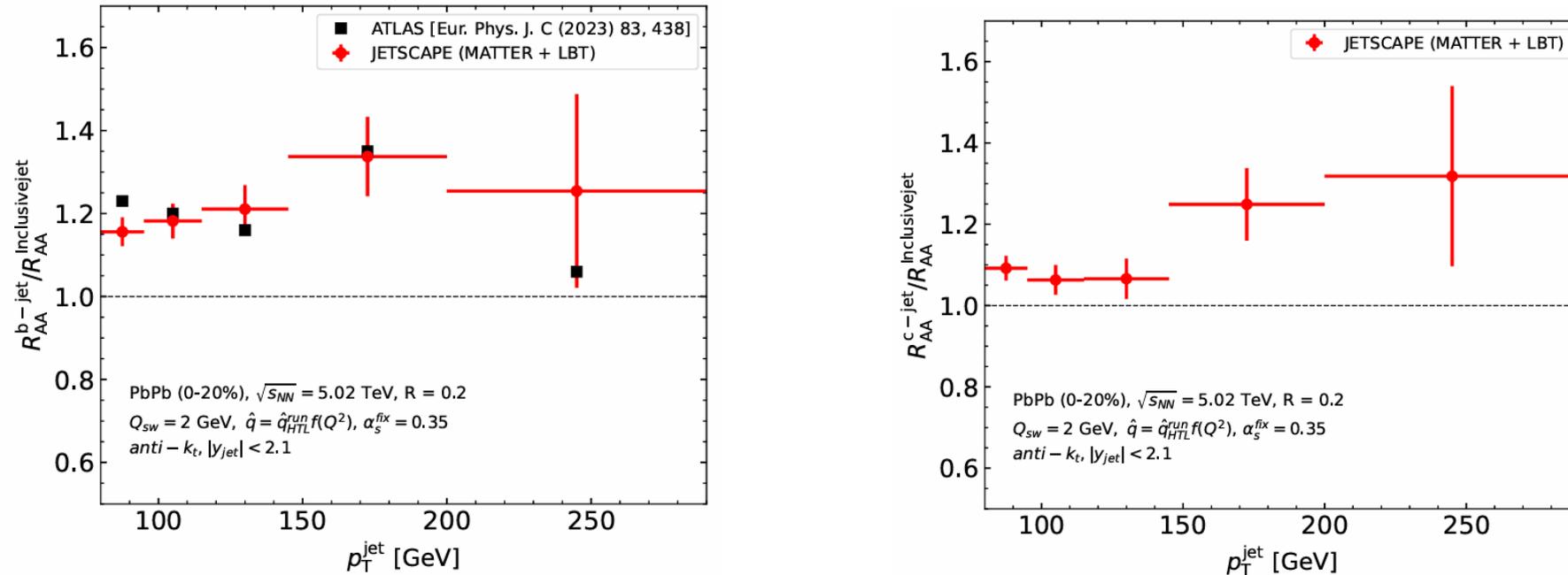


fig: Jet- R_{AA} double ratio of b- and c- jets with respect to inclusive jets.

- The double ratios obtained using **MATTER + LBT** within JETSCAPE are consistently above unity, showing that heavy-flavor jets (b and c) are less suppressed than inclusive jets, in agreement with the expected mass hierarchy of parton energy loss.

Comparison of R_{AA} of Heavy Jets with Inclusive Jets

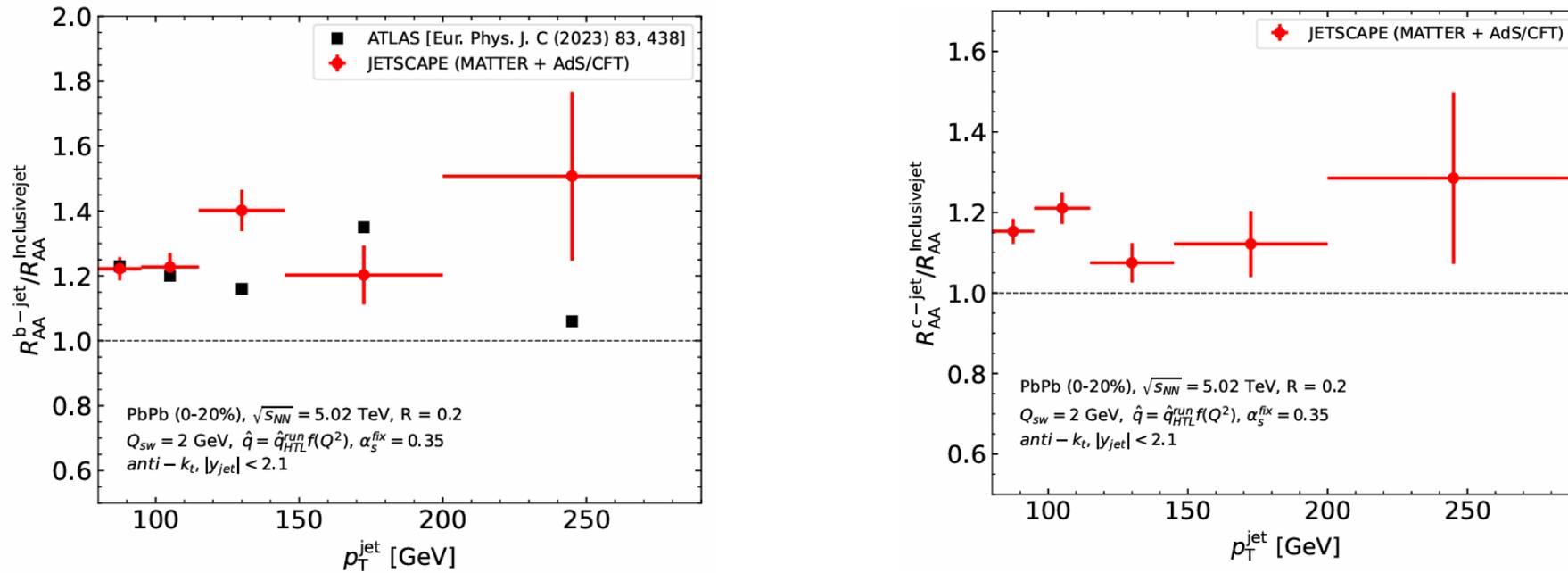


fig: Jet- R_{AA} double ratio of b- and c- jets with respect to inclusive jets.

- With **MATTER + AdS/CFT**, the double ratios show a larger enhancement than **MATTER+LBT**, reflecting the stronger coupling and drag-dominated energy loss in **AdS/CFT**.

Conclusion

- JETSCAPE predictions are well consistent with the ATLAS data for both b- and inclusive jets, validating the framework in describing heavy flavor jet suppression patterns.
- The prediction from AdS/CFT gives a stronger mass hierarchy in jet quenching than LBT, highlighting the sensitivity of heavy-flavor suppression patterns to the underlying energy-loss mechanism and providing a way to discriminate between weakly- and strongly-coupled QGP descriptions.
- Radius-dependent b-jet spectra studies reveal that smaller- R jets experience stronger suppression due to enhanced out-of-cone energy loss, offering key insights into medium-induced jet broadening and QGP transport properties.
- R_{AA} for bottom and charm jets being higher than those for inclusive jets suggest that heavy-flavor jets experience less suppression in the medium, indicating that they are less quenched compared to inclusive jets.
- We also studied the double ratios $R_{AA}^{b-jet} / R_{AA}^{inclusive jet}$ and $R_{AA}^{c-jet} / R_{AA}^{inclusive jet}$ that significantly reduce systematics, allowing cleaner extraction of quark-mass effects.

Thank You For Your Attention !!!



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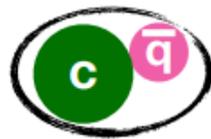
Measurement of Heavy Flavor:

Heavy Flavour:

- Heavy quarks (**c**, **b**) hadronize with light quarks (**q**)
- Form mesons:
 - **D mesons** (D^0 , D^+ , D_s , D^{*+})
 - **B mesons** (B^0 , B^+ , ...)
- Probe **in-medium interactions**
 - Depend on **quark mass and color charge**
- Study **fragmentation & hadronization** in presence of medium

$$\Delta E(g) > \Delta E(u, d, s) > \Delta E(c) > \Delta E(b)$$

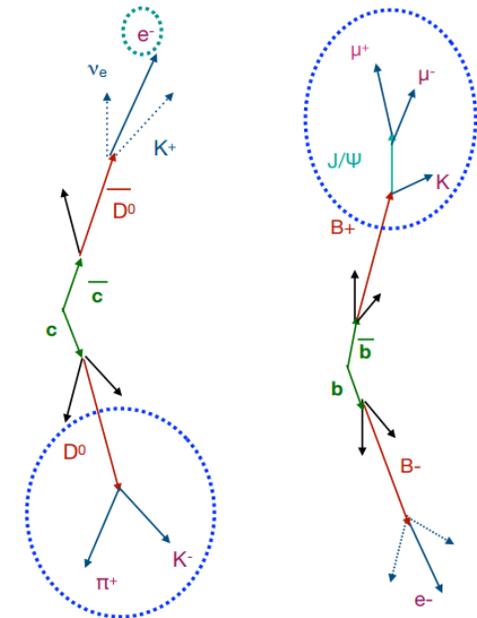
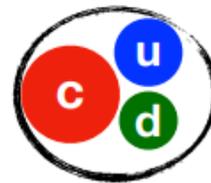
D meson



B meson



Λ_c baryon



c-jets in p-p:

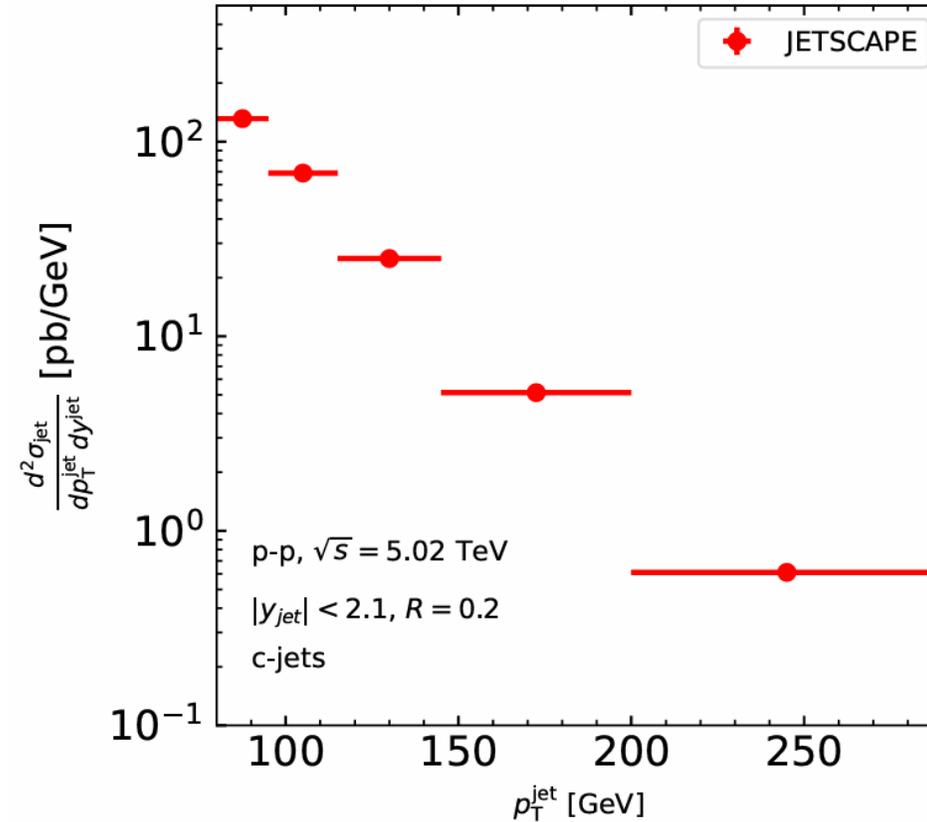
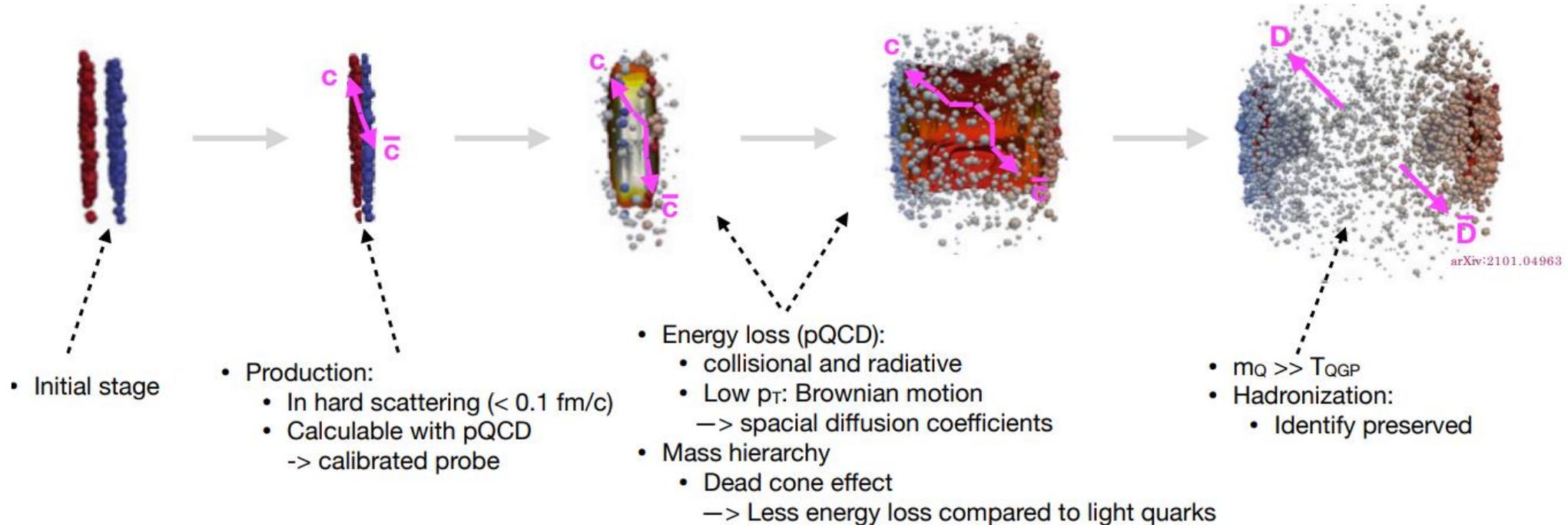


Fig: Differential cross section of c-jets in pp collisions for jet radius $R = 0.2$, obtained using JETSCAPE framework.

Heavy quarks in HOT QCD medium:

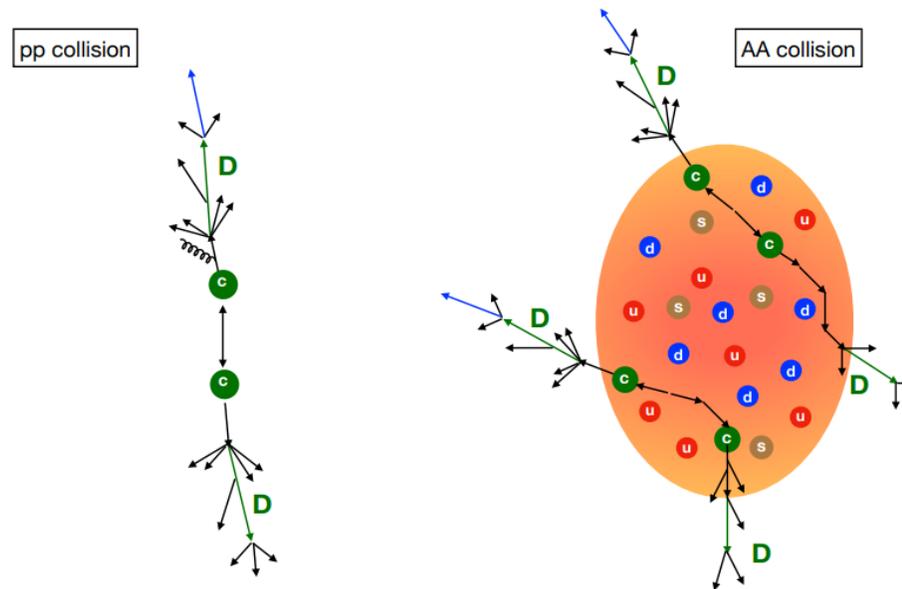
- Heavy quarks (c, b) are produced early in hard scatterings, calculable using pQCD, and serve as calibrated probes to study the QGP.



[JETSCAPE online summer school 2023]

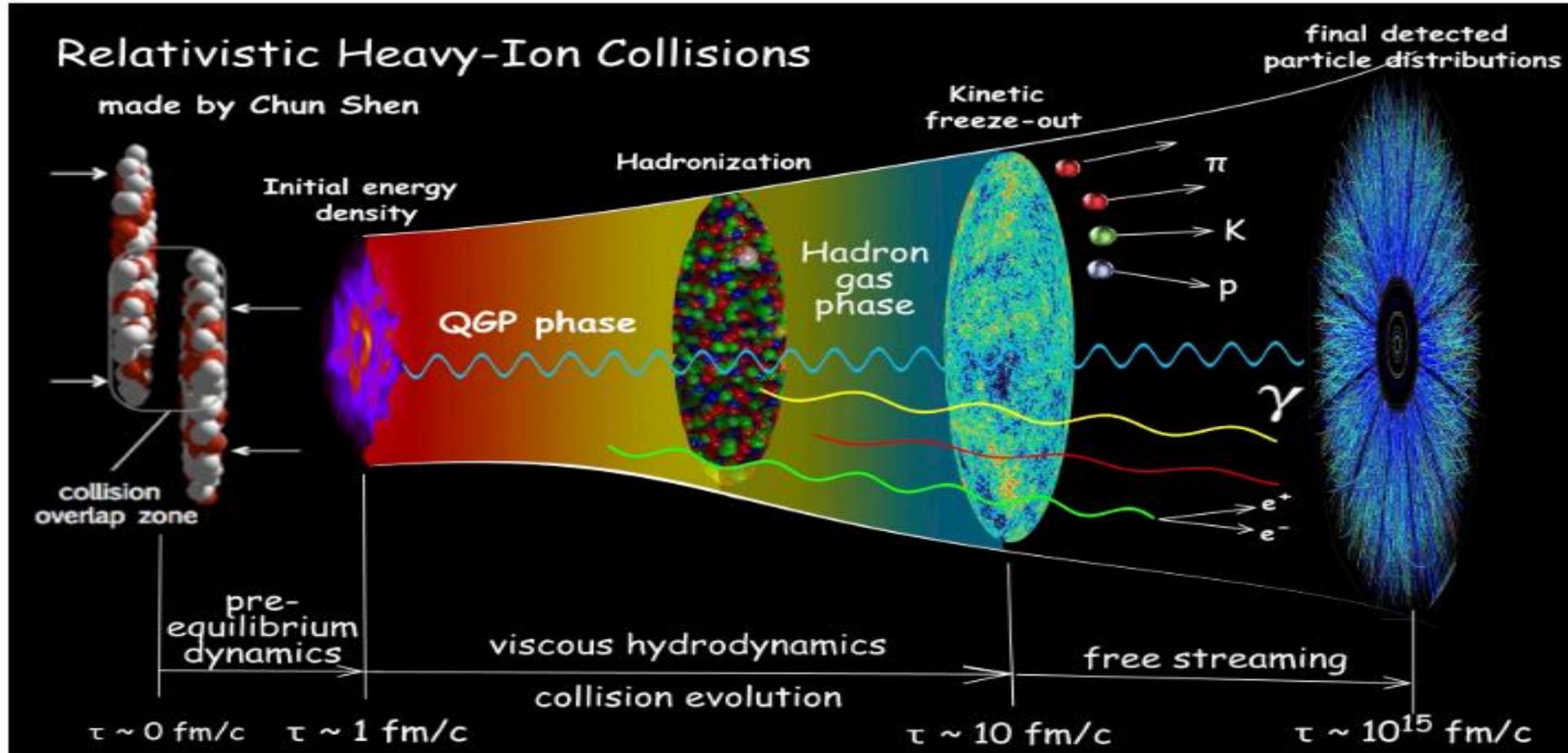
Jet Structure and fragmentation:

- In heavy-ion (AA) collisions, the jet shower interacts with the hot QGP medium, leading to modifications in jet structure and fragmentation compared to proton-proton (pp) collisions.
- The medium-induced interactions in AA collisions cause additional energy loss and broadening of the jet, altering the distribution of final-state hadrons like D mesons.

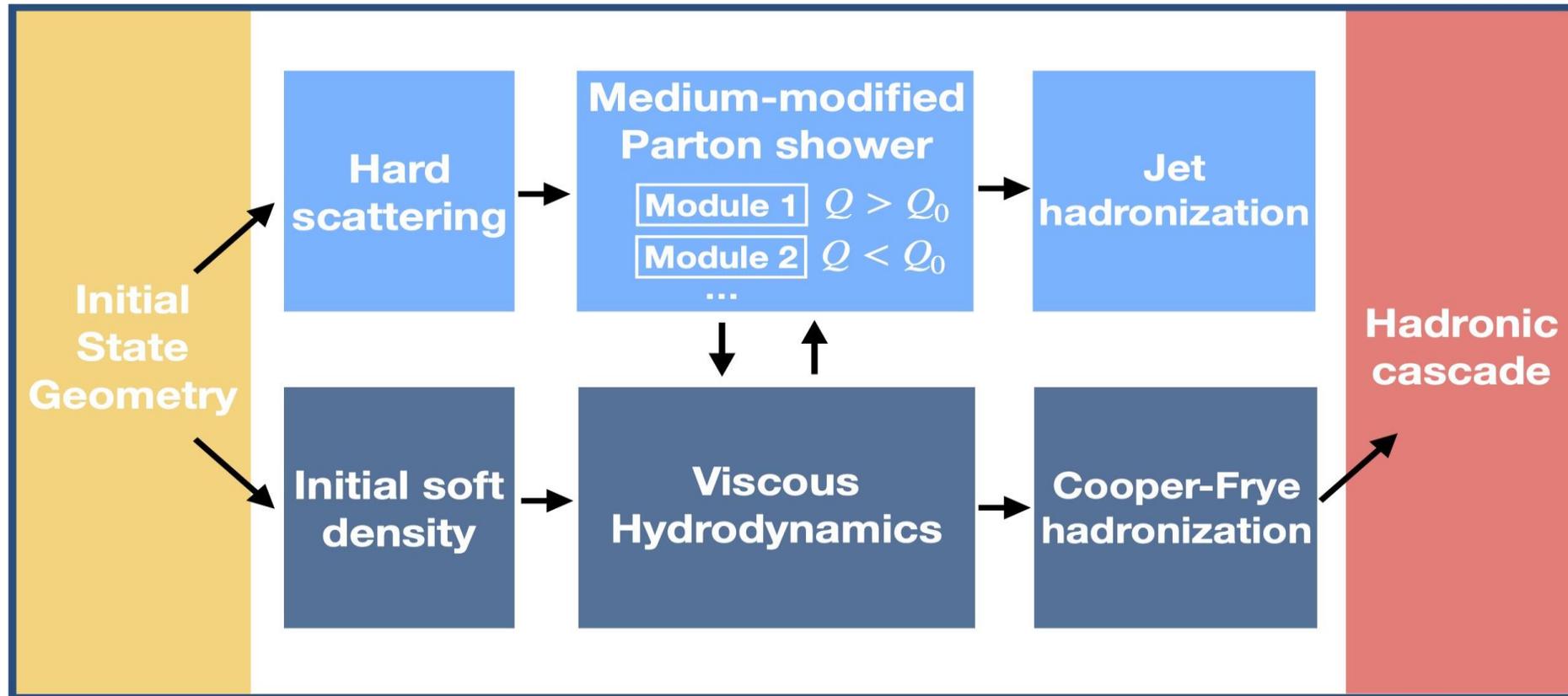


[JETSCAPE online summer school 2023]

Relativistic Heavy-ion Collision:



JETSCAPE Framework



[<https://github.com/JETSCAPE/JETSCAPE> JETSCAPE Manual: arXiv:1903.07706]

Coherence Effect

The coherence effects are represented by the effective jet quenching strength \hat{q} which is defined as:

$$\hat{q} = \hat{q}_{HTL} f(Q^2)$$

where $f(Q^2)$ is virtuality dependent modulation factor and is given by:

$$f(Q^2) = \begin{cases} \frac{1+10(\ln(Q_{SW}^2))^2+100(\ln(Q_{SW}^2))^4}{1+10(\ln(Q^2))^2+100((\ln(Q^2))^4)} & \text{if } Q > Q_{SW} \\ 1 & \text{if } Q < Q_{SW} \end{cases}$$

and \hat{q}_{HTL} is the jet quenching parameter for on-shell partons calculated by Hard Thermal Loop (HTL) effective theory.