A color-tracking transport model for hadron and jet suppression in high-energy nuclear collisions

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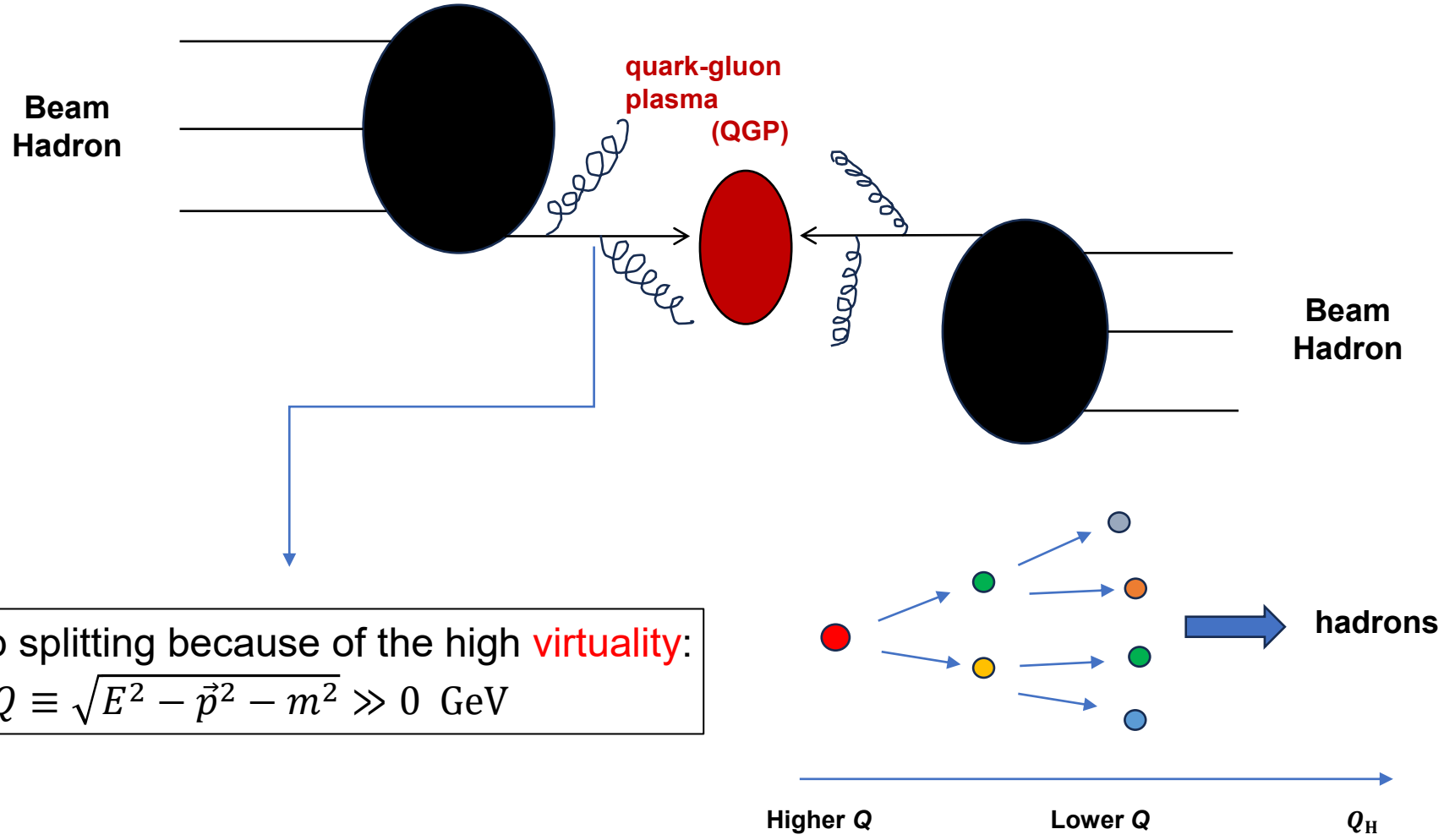
Outline

1. Introduction
2. A color-tracking transport model based on LBT
3. A unified description of nuclear modification of jets and hadrons
4. Summary

Heavy-ion collision

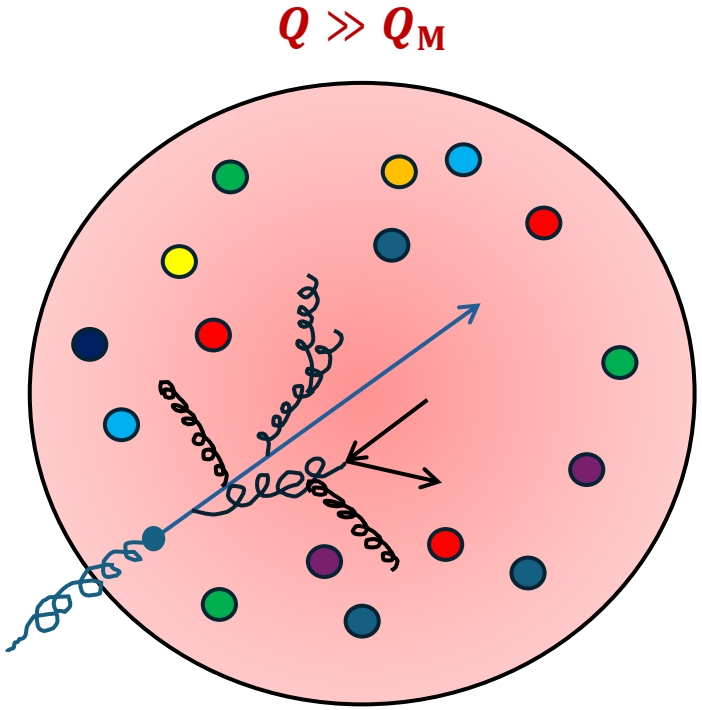


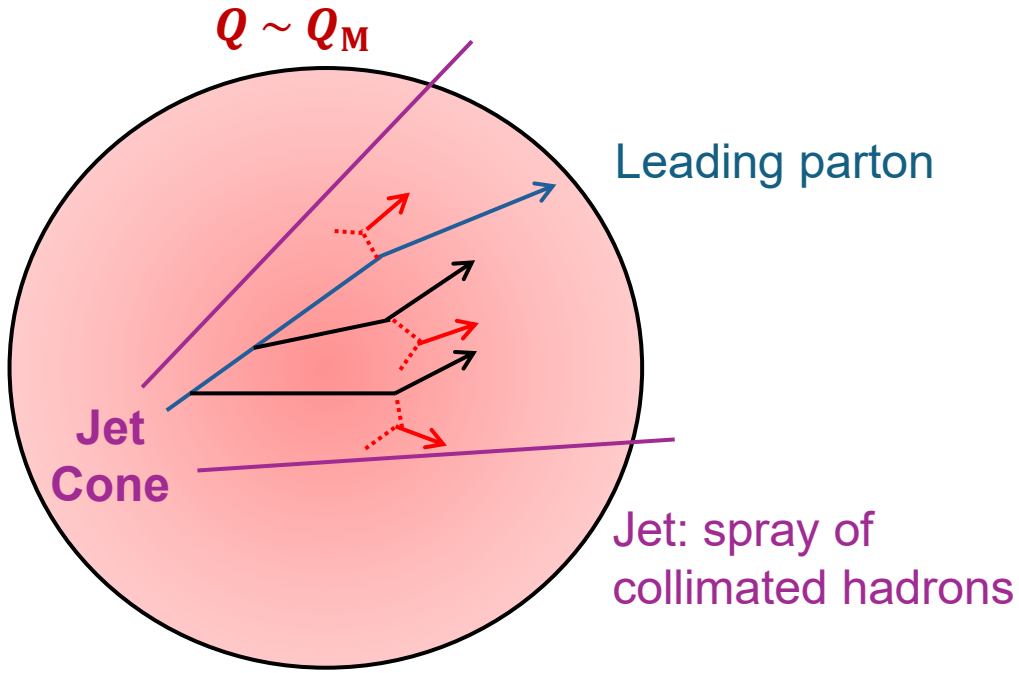
- Parton keep splitting because of the high virtuality:

$$Q \equiv \sqrt{E^2 - \vec{p}^2 - m^2} \gg 0 \ \text{GeV}$$

- The **quark-gluon plasma (QGP)** is our primary research focus.

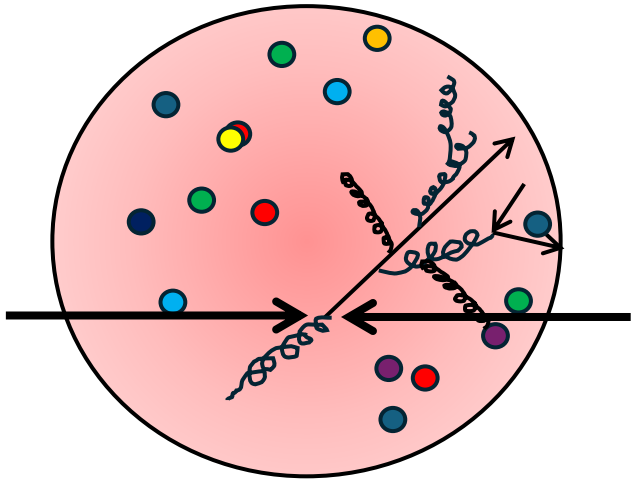
Jet partons evolve in QGP



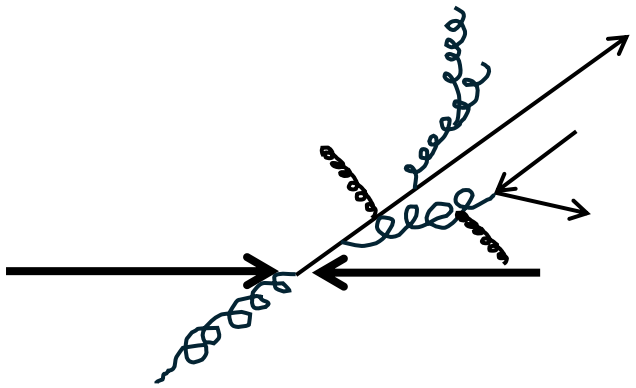


- Highly virtual partons radiate like in vacuum until their virtuality scale is down to the energy scale of QGP, Q_M.
- The jet partons maintain a certain virtuality scale Q_M through the medium.
- The jets and high energy hadrons are good probes for studying QGP.

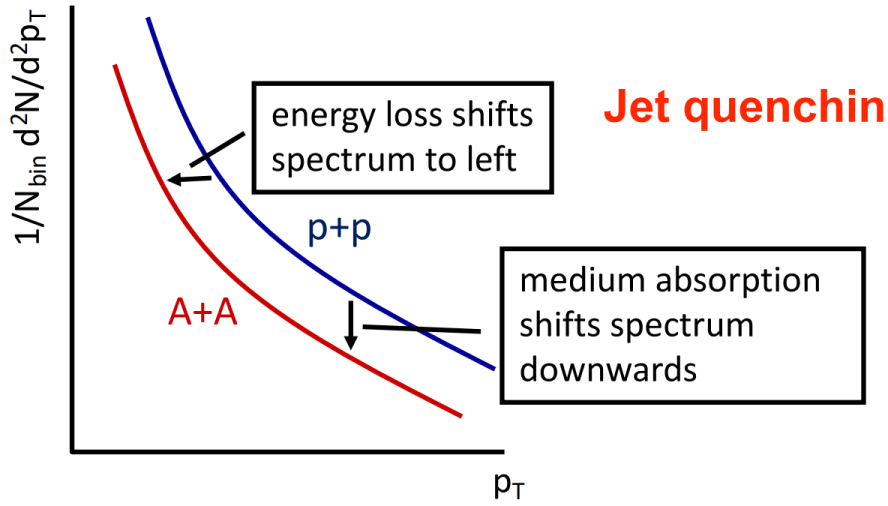
Nuclear modification factor R_{AA}



Heavy-ion collision (**AA**)

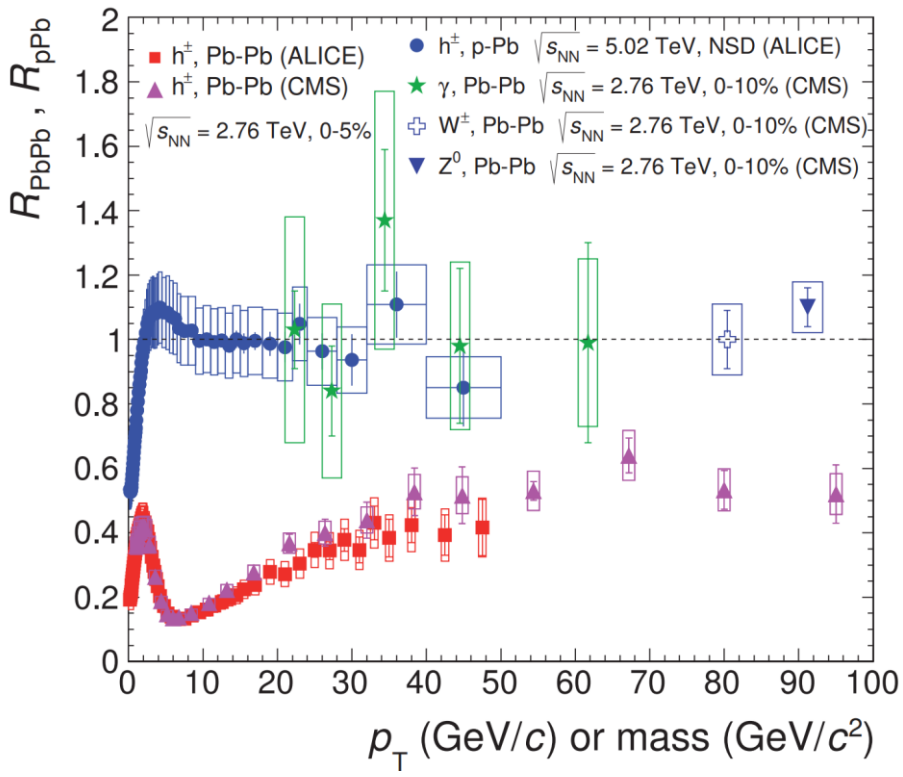


Nucleon-nucleon collision (**pp**)



Jet quenching

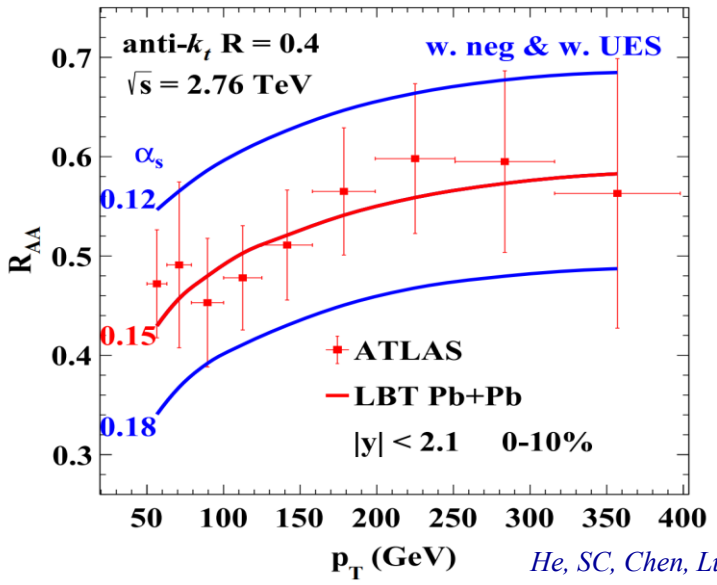
ALICE, Eur. Phys. J. C 74 (2014) 3054



$$R_{AA} \equiv \frac{d^2 N^{AA}/d\,y dp_\perp}{d^2 N^{pp}/d\,y dp_\perp \times \langle N_{coll}^{AA} \rangle}$$

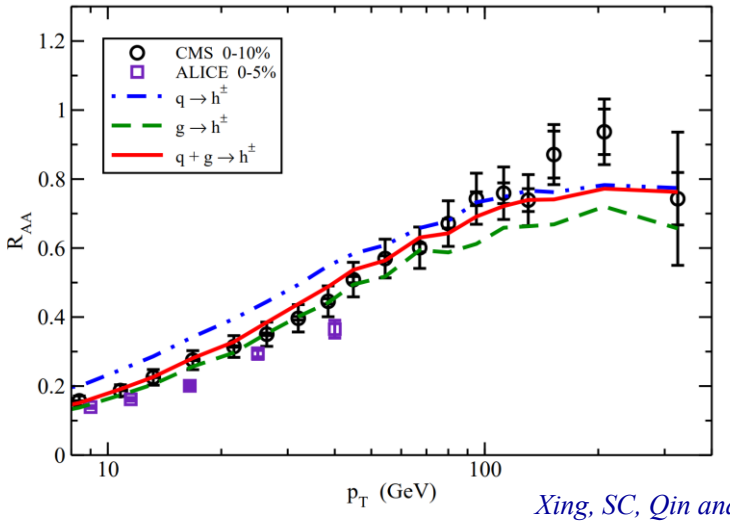
A challenge in simultaneously describing hadrons and jets

Jet R_{AA}



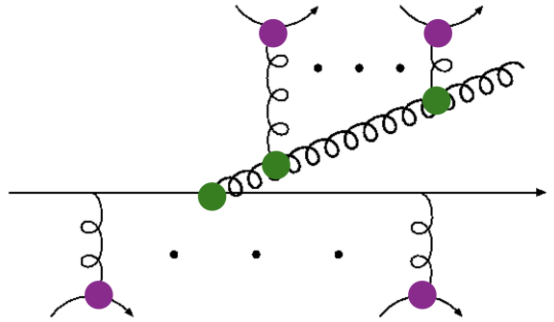
He, SC, Chen, Luo, Pang, Wang
Phys. Rev.C 99 (2019) 054911

Hadron R_{AA}



Xing, SC, Qin and Xing
Phys. Lett. B805 (2020) 135424

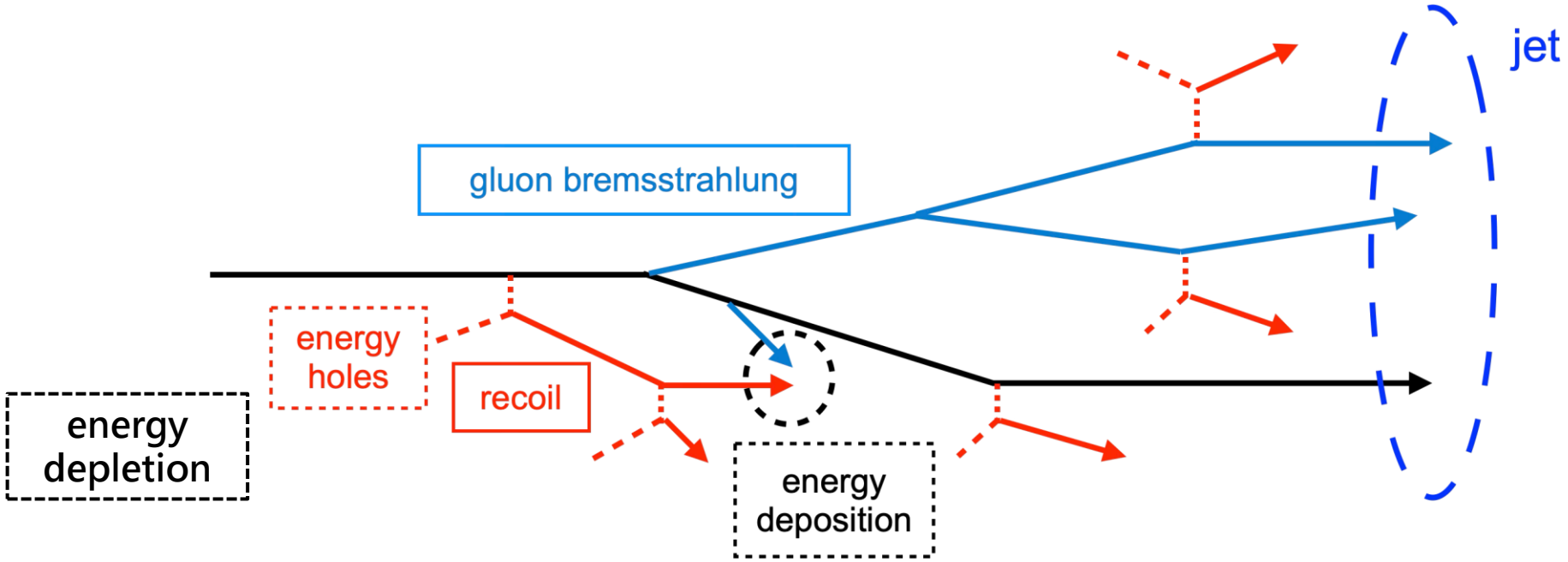
- **A fixed $\alpha_s = 0.15$ is sufficient for jets**
- **Running coupling is required for hadrons**



- $\alpha_s^{\mathrm{run}} = \frac{4\pi}{\left[9 \ln\left(\frac{2ET}{\Lambda^2}\right)\right]}$
- $\alpha_s^{\mathrm{fixed}} = 0.2$

- Different energy scale of jet partons.
- Hadron spectrum is mostly related to the high energy partons in the jet.
- Partons of both high energy and low energy contribute to jet spectrum.

Linear Boltzmann transport model



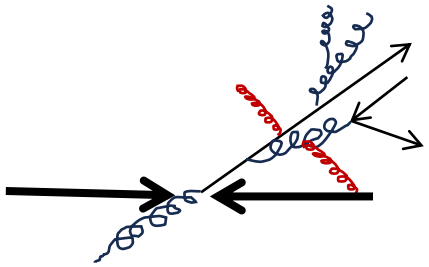
- Jet partons and medium background cannot be cleanly separated in reality.
- Medium response is considered as energy deposition and depletion.
- Jet-medium interactions: medium modification of jets + medium response.

Flow chart

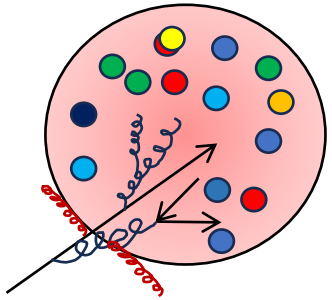
Q_{H} : hadronization scale Q_{M} : medium scale

Old framework

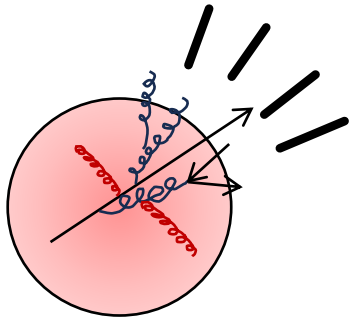
$Q > Q_{\mathrm{H}}$
Pythia shower



$Q \sim Q_{\mathrm{H}}$
LBT

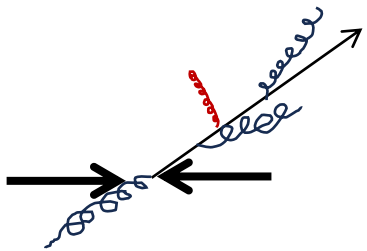


$Q \sim Q_{\mathrm{H}}$
Pythia string frag.

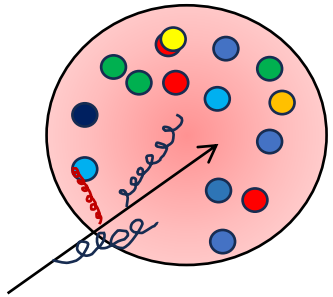


New framework

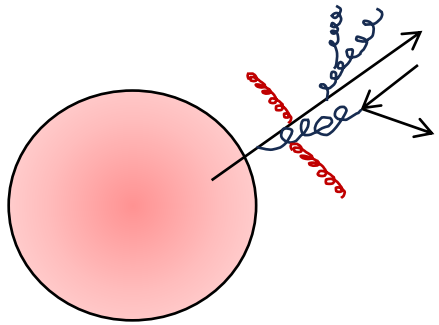
$Q > Q_{\mathrm{M}}$
Pythia shower



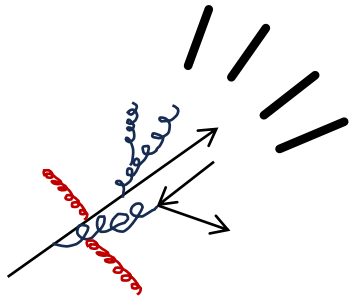
$Q \sim Q_{\mathrm{M}}$
LBT



$Q_{\mathrm{M}} > Q > Q_{\mathrm{H}}$
Pythia shower



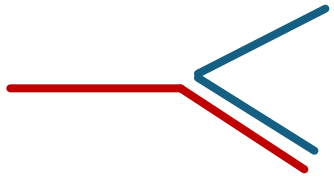
$Q \sim Q_{\mathrm{H}}$
Pythia string frag.



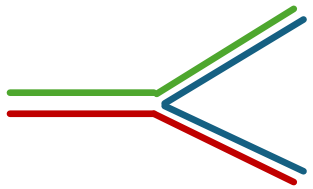
Color schemes in elastic and inelastic scatterings

Parton splittings

$q \to q\,g$

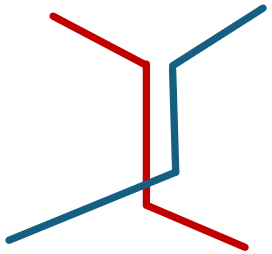


$g \to g\,g$



Jet-medium scatterings

$q\,q \to q\,q$



$q\,g \to q\,g$

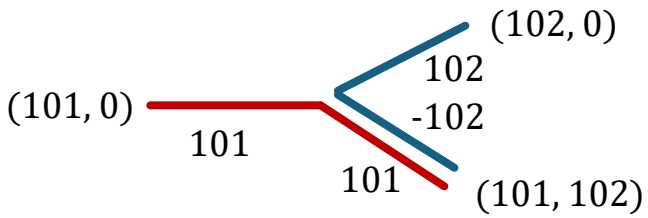
$g\,g \to g\,g$

- Large N_c color scheme in Pythia, (color, anticolor), e.g., q (101, 0), $\bar{q}$(0, 102), g(103, 104).
- Same color scheme for parton splitting processes.
- Introduce color information for jet-medium scatterings.

Color schemes in elastic and inelastic scatterings

Parton splittings

$q \to q\,g$



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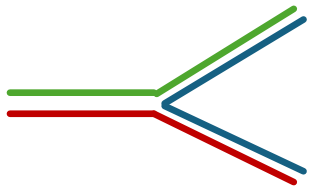

Jet-medium scatterings

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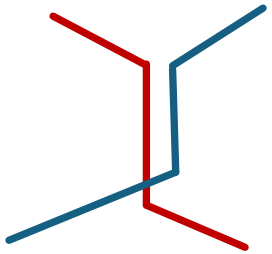

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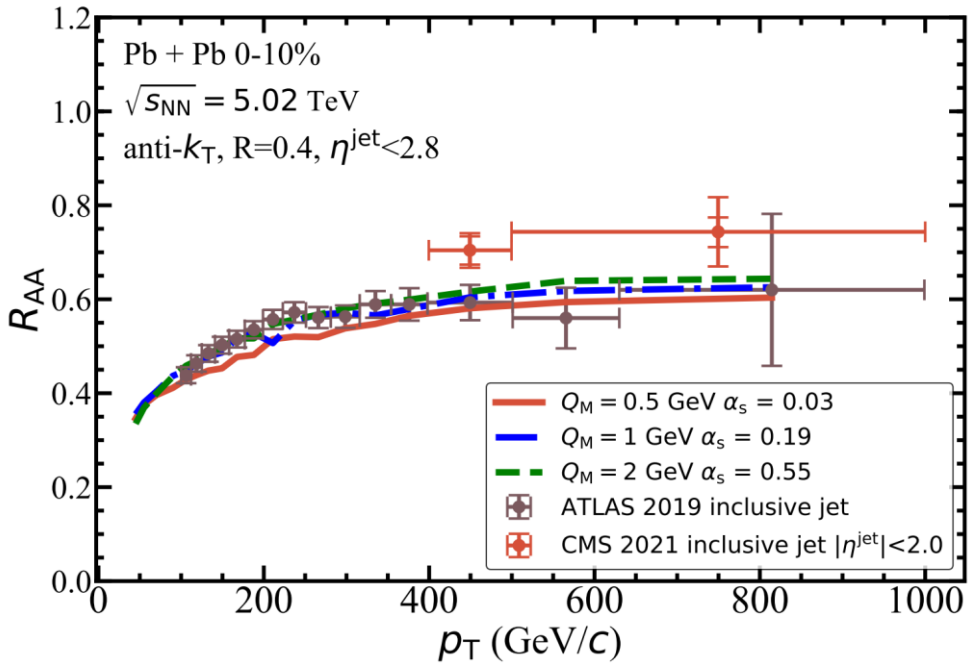
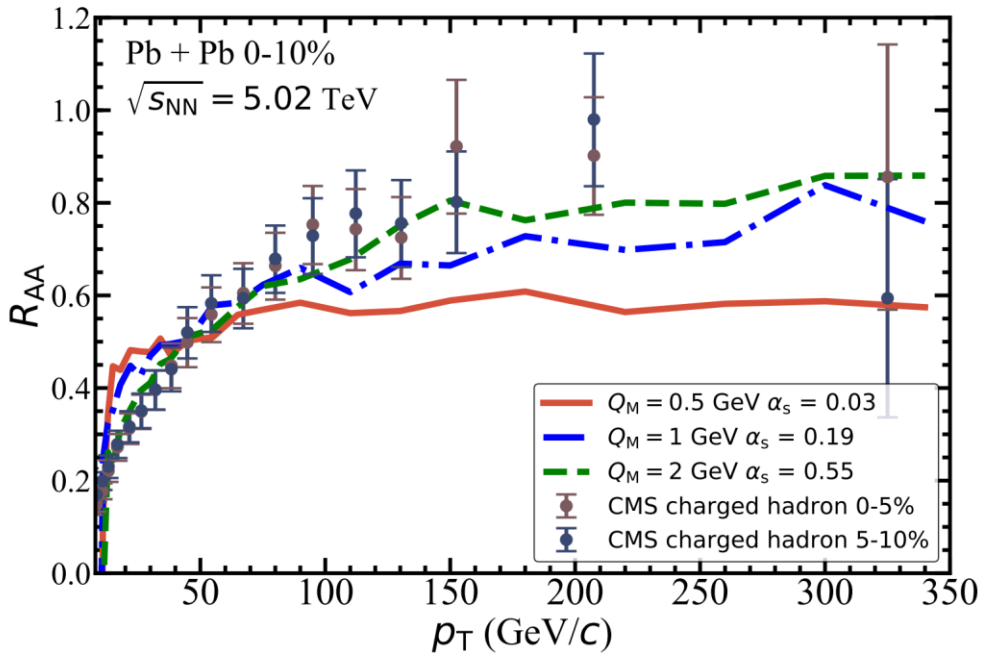
- Introduce color information for jet-medium scatterings.

Effect of medium scale on jet vs. hadron R_{AA}

Inclusive jet

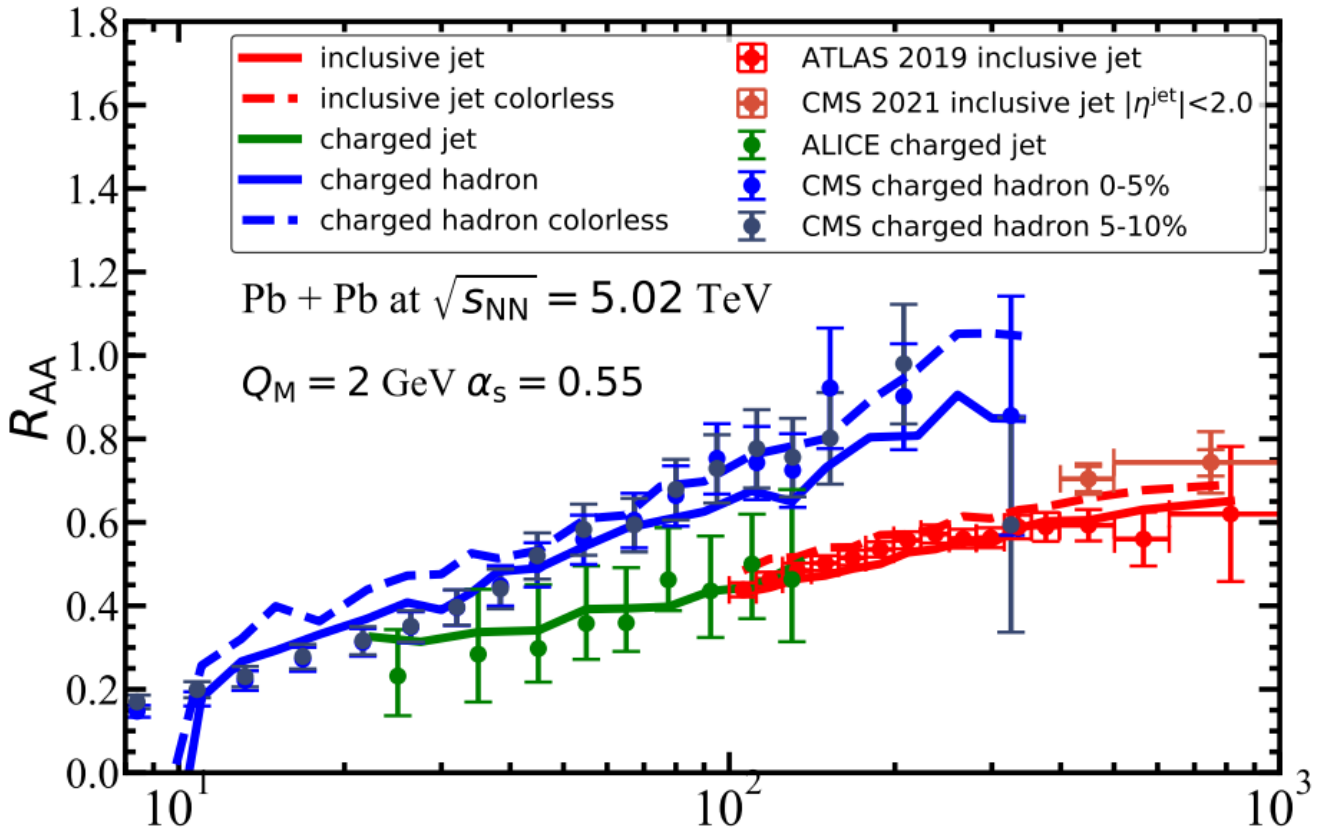


Charged hadron



- Adjust α_s for the jet R_{AA} and examine the hadron R_{AA}.
- Setting Q_M = 2 GeV provides a simultaneous description of jet and hadron R_{AA}.
- Start the parton–medium interaction at a higher virtuality scale → low-energy partons in jets lose more energy → leading hadrons in jets lose relatively less energy → increased hadron R_{AA}.

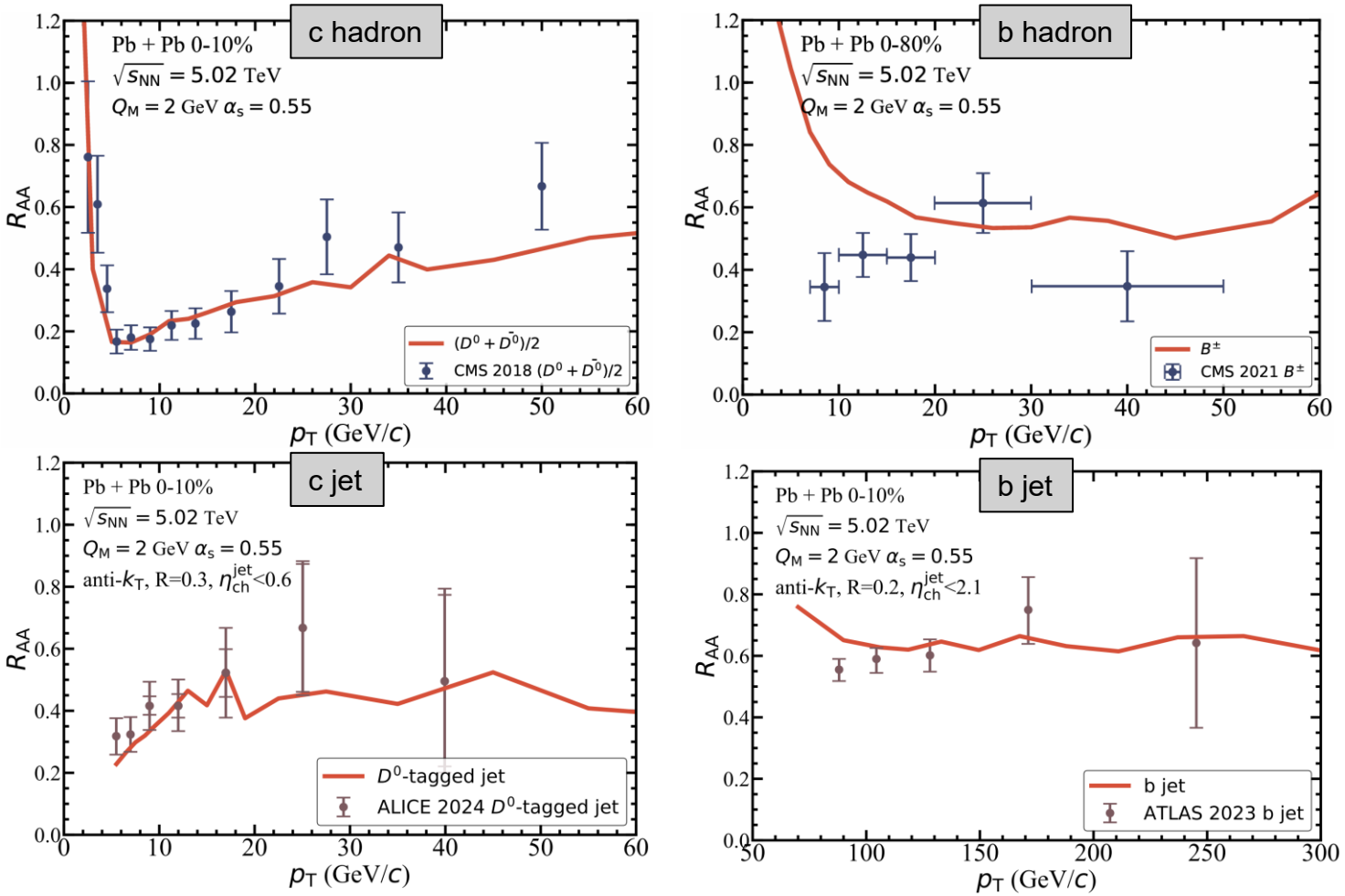
Light flavor observation

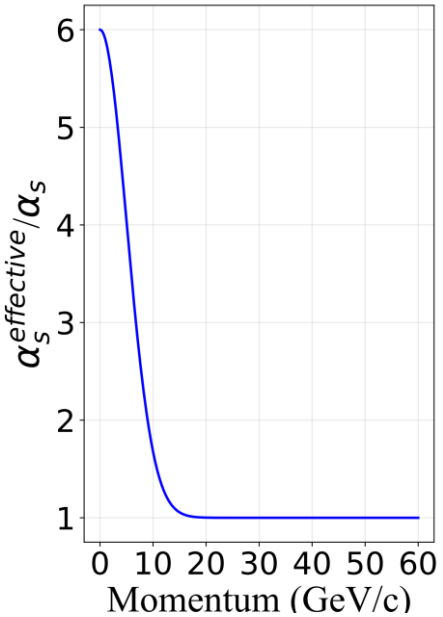


- We successfully describe the R_{AA} of inclusive jet (red line), charged jet (green line), charged hadron (blue line).
- We use another hadronization approach (dash line) as an estimate of systematic errors.
- Colorless hadronization: Strings are formed by connecting the particles that are closest in phase space, rather than by their color connections.

Zhao, Ko, Liu, Qin, Song, Phys. Rev. Lett.125, (2020) no.7, 072301.

Heavy flavor observation





α_s for heavy quarks is scaled by a gaussian distribution factor to consider NP effect.

A stricter treatment can be found in Xing, Qin, Cao, *Phys.Lett.B* 838 (2023) 137733

Non-perturbative effect should be considered:

- Heavy flavor quarks have larger mass.
- The heavy flavor observation can be measured down to very low p_T.

Summary and outlook

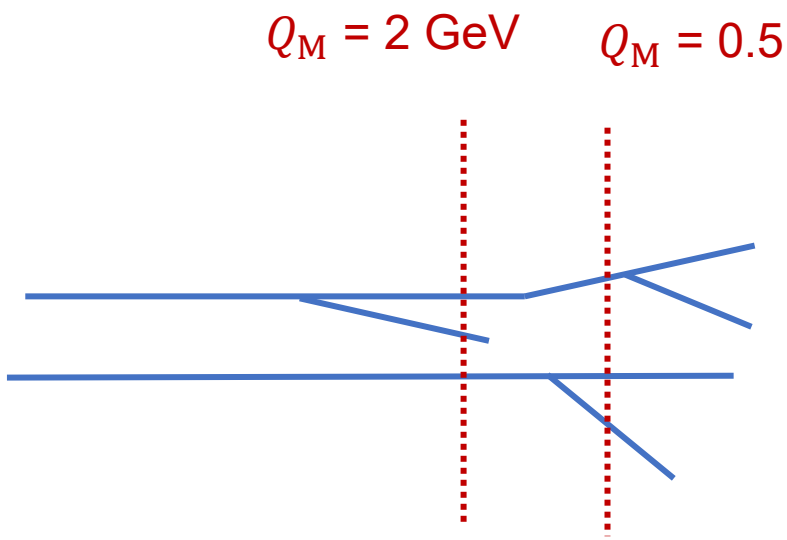
Summary

- We refined the model framework by incorporating a Q_{M} cutoff, aligning the model more closely with the physics mechanisms.
- We incorporated color-tracking in LBT parton evolution for the first time, and enabled a multiscale evolution of jet partons.
- We achieved a simultaneous description of R_{AA} of hadrons and jets for different flavors.

Outlook

- In future studies, we will utilize this model framework to systematically characterize jet substructure with higher precision.
- The code for this framework will be open access on github.

Thank You!

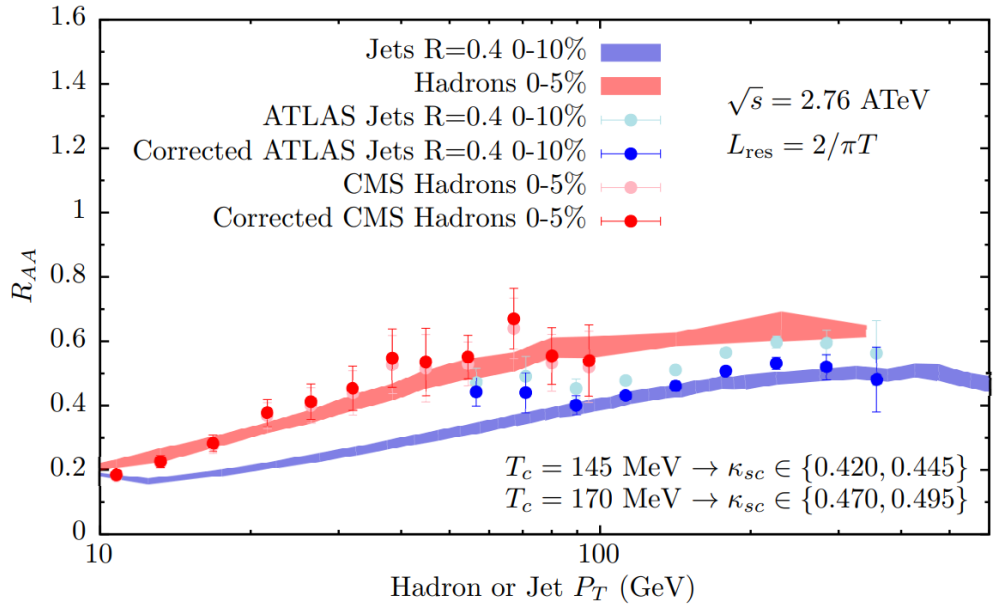


Formation time ~ 1/*Q*

- Virtuality ~ energy，and Formation time ~ 1/*Q*.
- Splitting will lower the virtuality.
- Formation time decreases with the increasing virtrality.
- The short the formation time is the stronger the modification factor is.

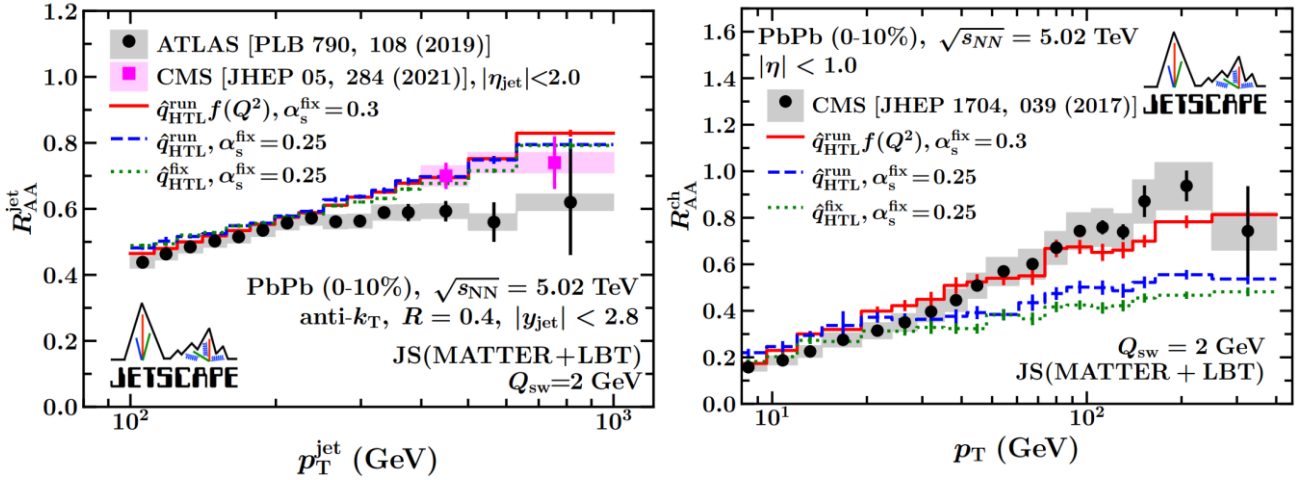
Prior efforts

Casalderrey-Solana,Hulcher, Milhano, Pablos, Rajagopal, Phys. Rev. C 99, 051901(R) (2019)



- Selection bias: more energetic partons ↔ narrower jet.
- Medium can't resolve two hard partons extremely close, the resolution length is $L_{\rm res}$.
- Correct the original data by considering the correlated error from other data in the total data set.

JETSCAPE, Phys. Rev. C 107, no.3, 034911 (2023)



- Multistage evolution of partons.
- The interaction strength ($\hat{q}$) decreases with increasing virtuality, leading to less energy loss of high energy partons in jet.

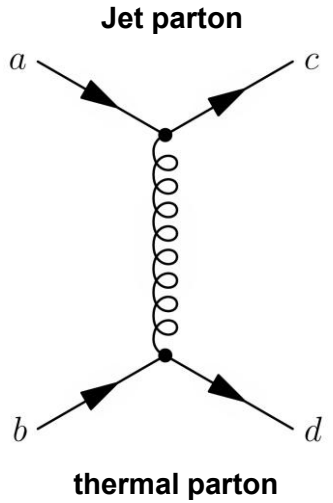
Linear Boltzmann transport model

- The Boltzmann Transport equation:

$$\frac{\mathrm{d}}{\mathrm{d}t} f(\vec{x}, \vec{p}, t) = \mathrm{C}[f] = C^{\mathrm{el}} + C^{\mathrm{inel}}$$

For scattering channel $a + b \to c + d$, the collision term is:

$$C^{\mathrm{el}} = \int \mathrm{d}^3 p_b \, \mathrm{d}^3 p_c \mathrm{d}^3 p_d \, [f_c f_d \omega(p_a p_b | p_c p_d) - f_a f_b \omega(p_c p_d | p_a p_b)]$$



- Considering one single particle to traverse QGP, the integral of $f_b * \omega$ can be regarded as elastic scattering rate Γ^{el}, which is related to the matrix element M:

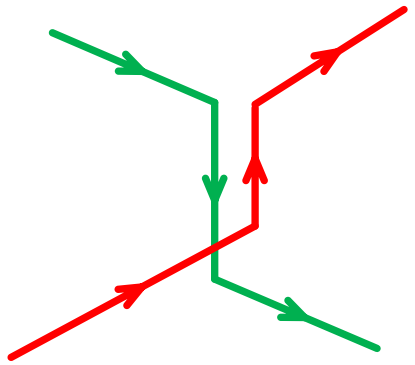
$$\Gamma^{\mathrm{el}} = -\int \mathrm{d}^3 k \, \omega(\vec{p}, \vec{k}) f_b \sim |M_{a+b\to c+d}|^2$$ (for Monte-Carlo simulation)

- **Inelastic scattering:**

$$\frac{\mathrm{d}\Gamma^{\mathrm{inel}}}{\mathrm{d}z dp_\perp^2} = \frac{\mathrm{d}N_g(\hat{q})}{\mathrm{d}z dp_\perp^2 dt}$$

  - the Medium information absorbed in $\hat{q}$.

qq->qq & qbar qbar -> qbar qbar



q qbar->q qbar