Heavy Flavor Energy Loss with JETSCAPE

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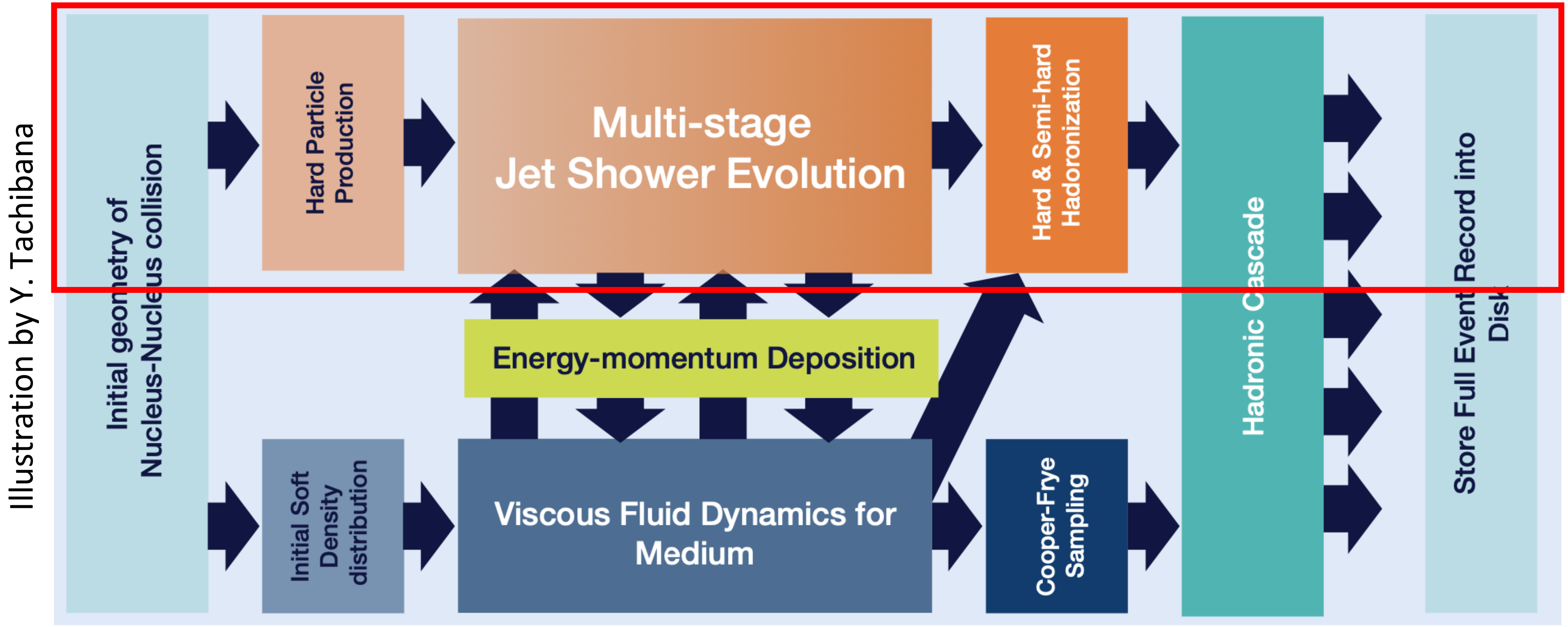
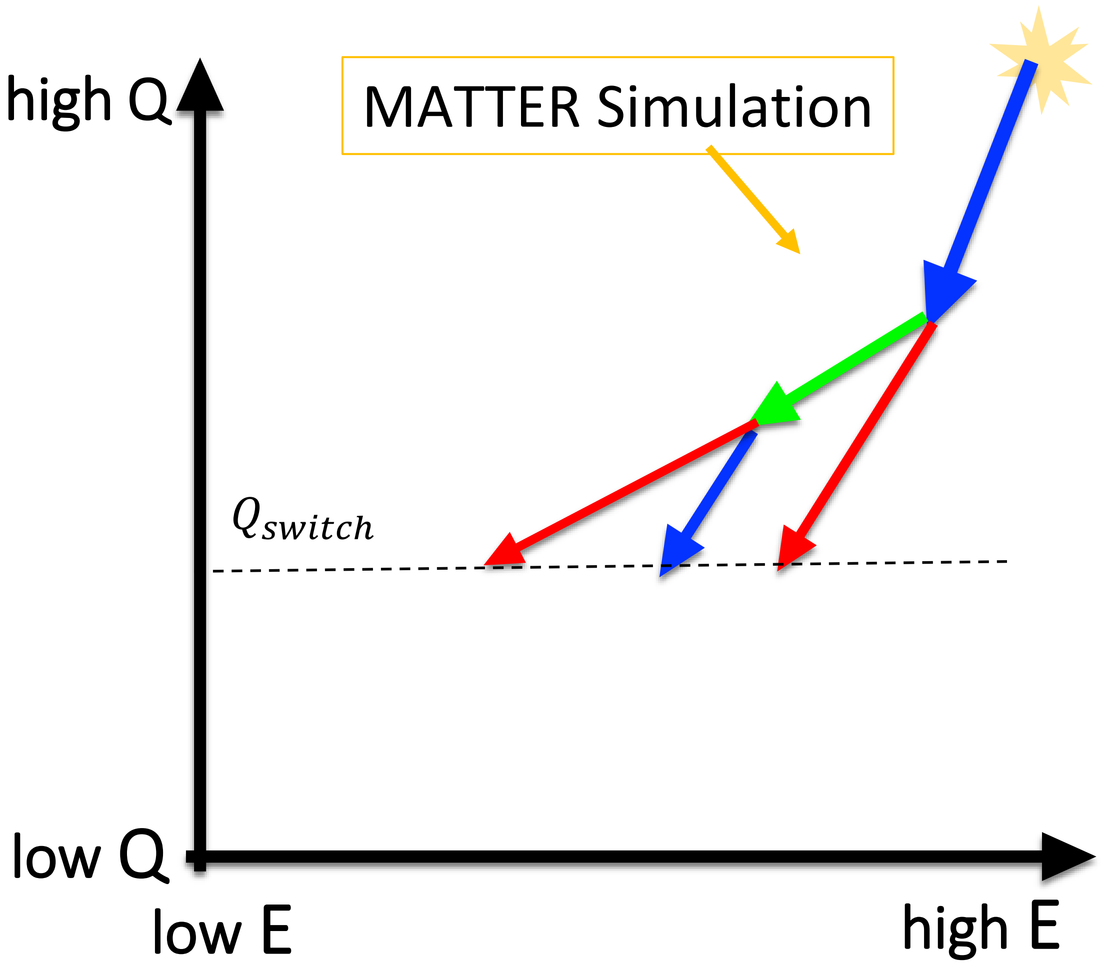
The JETSCAPE Framework



- JETSCAPE framework allows :
  - Multiple energy loss formalisms to be present simultaneously, each applied in its region of validity.
  - Provides a set of Bayesian tools to characterize the interaction of hard probes with the QGP.

Multistage parton evolution in JETSCAPE



- High→Lower Q, High E: Rapid virtuality loss through radiation. MATTER (via Higher Twist) generates scattering-modified radiation.

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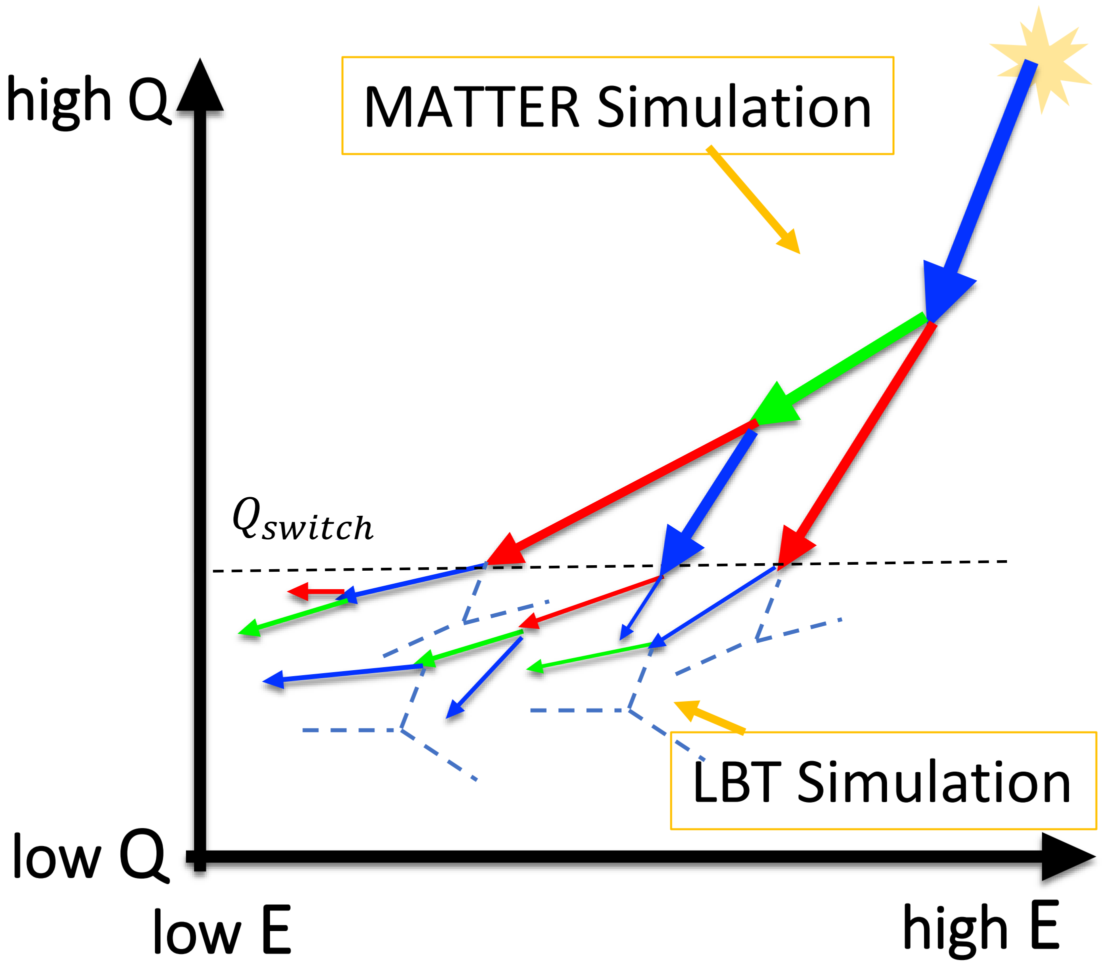

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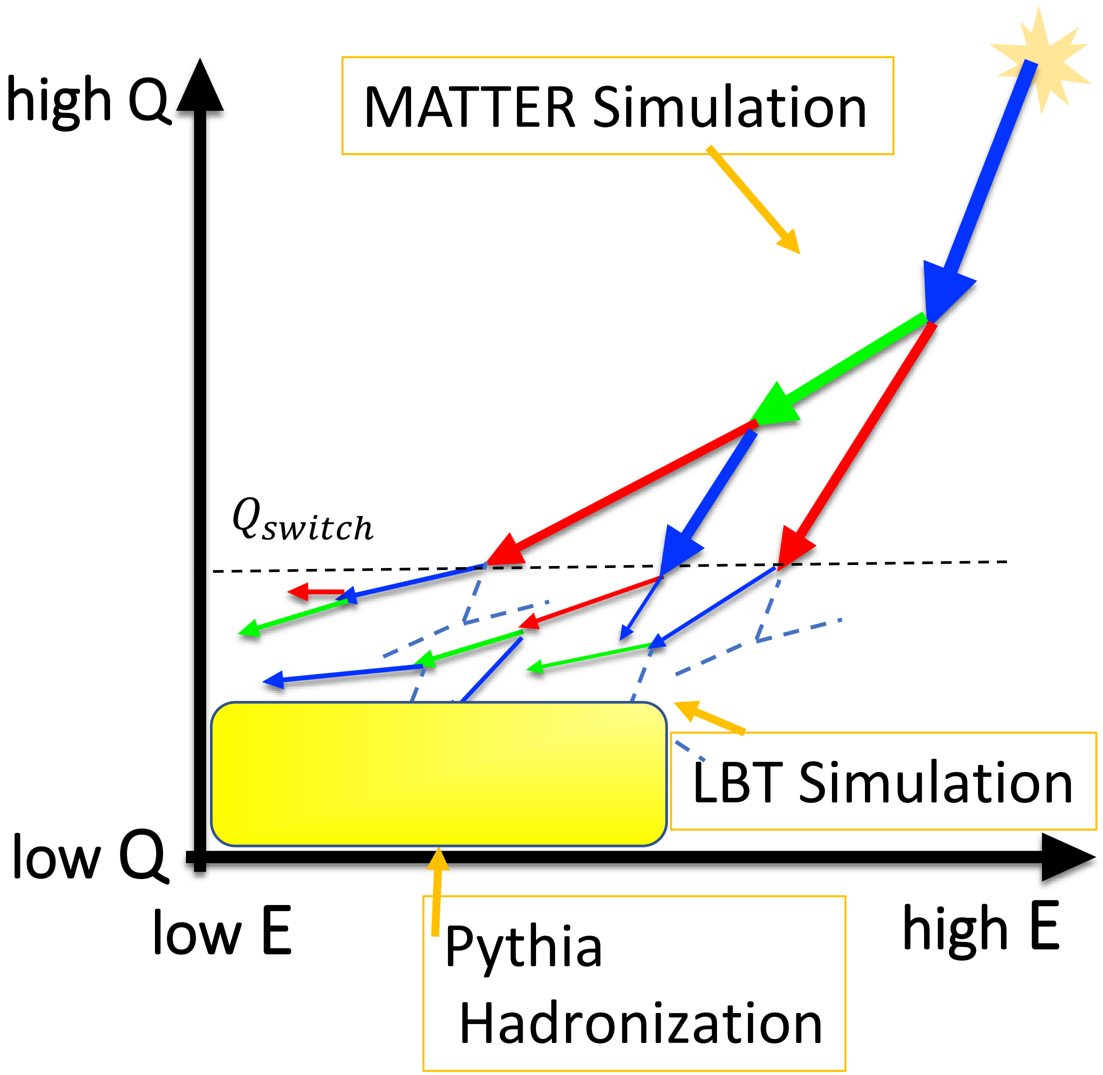

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- Low Q, Low E: Hadronization physics important (partons→Pythia for hadronization)

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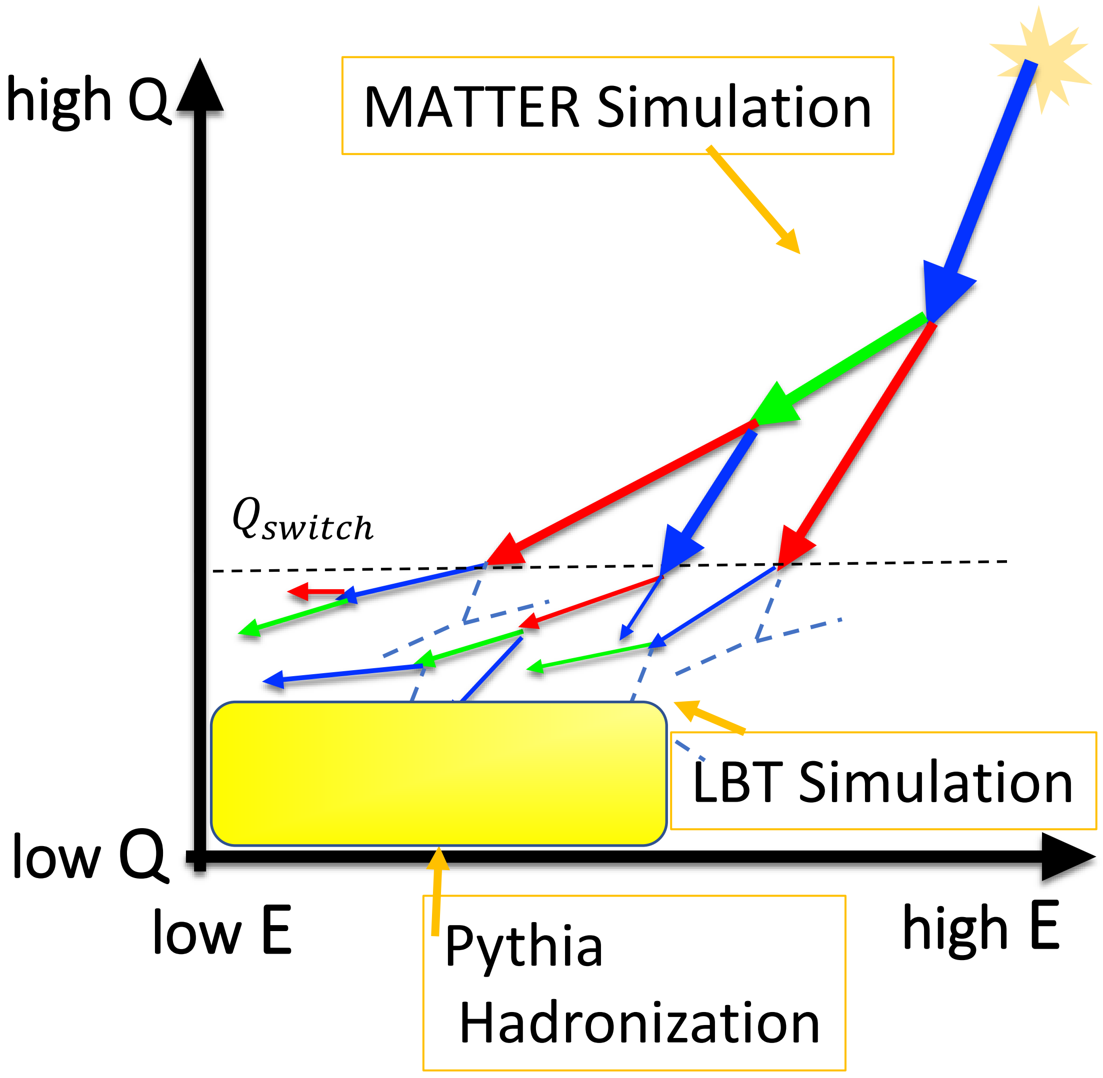

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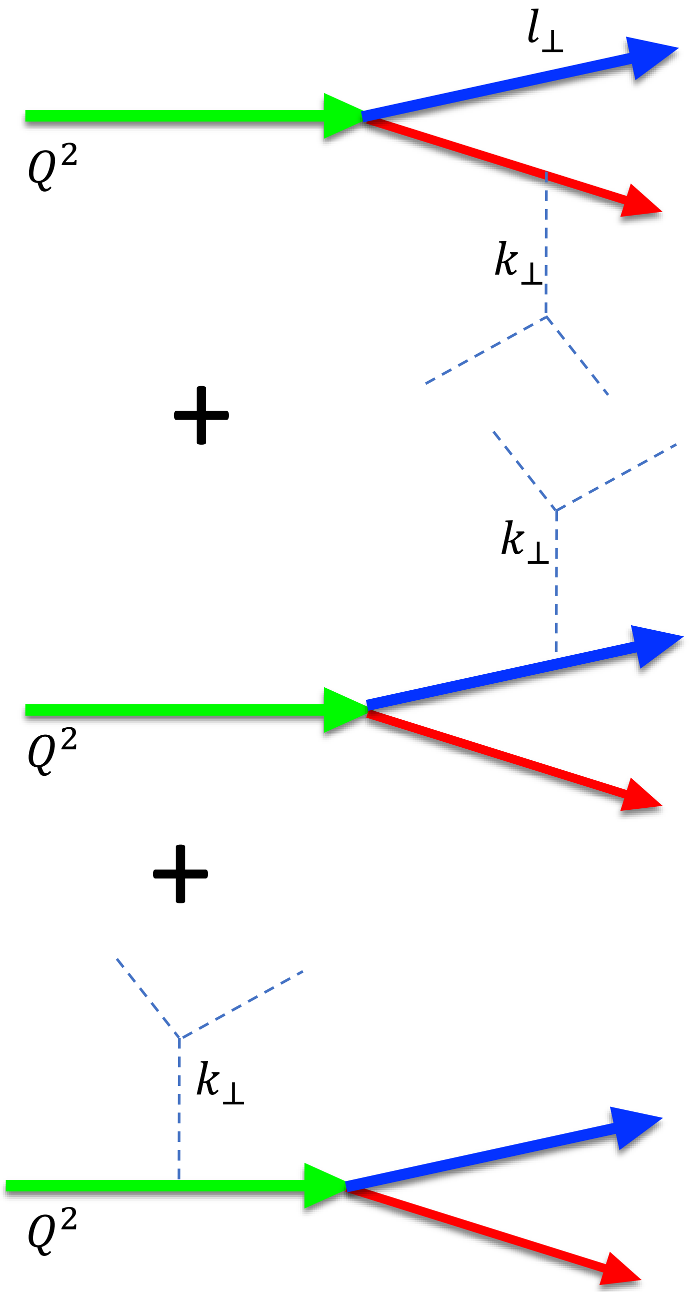
The JETSCAPE framework combines these multiple stages for an improved description of parton energy loss.

Virtuality-dependent $\hat{q}$

- If $l_\perp^2 \sim k_\perp^2 \Rightarrow$ medium can resolve the two daughter partons [**PRC 101, 034908 (2020)**].



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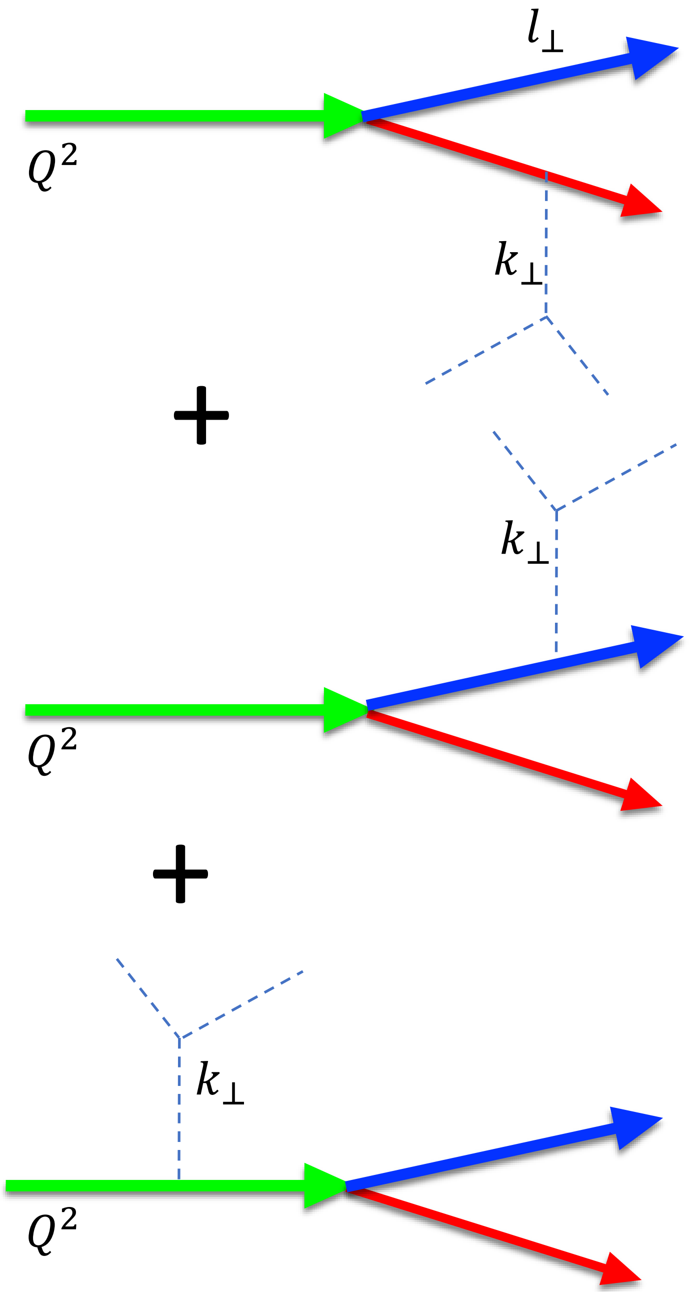

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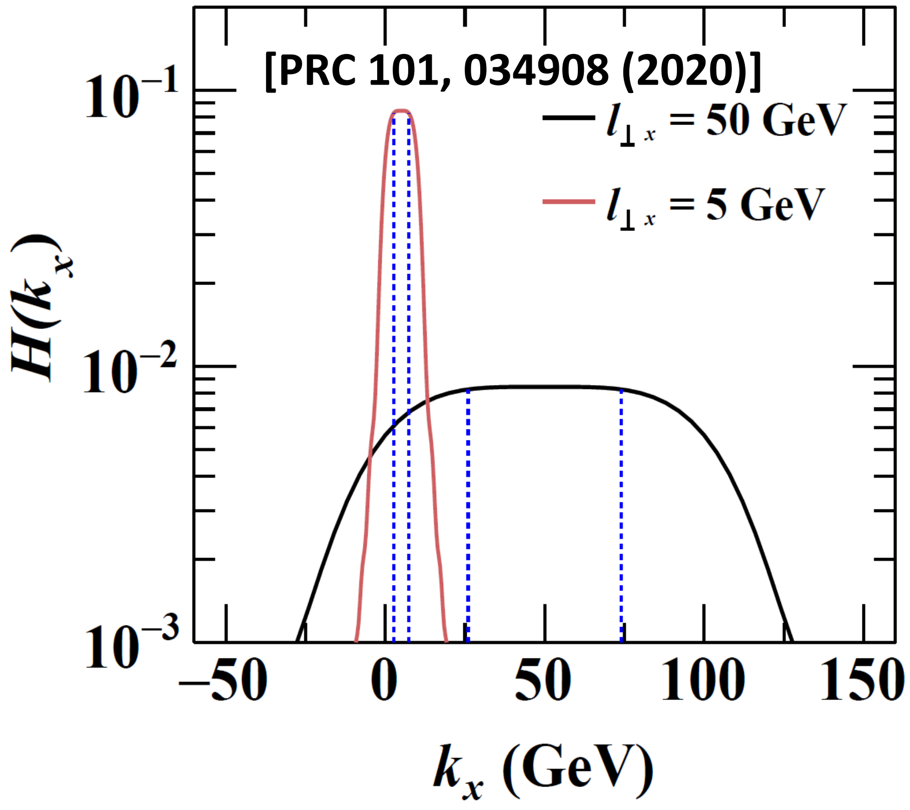

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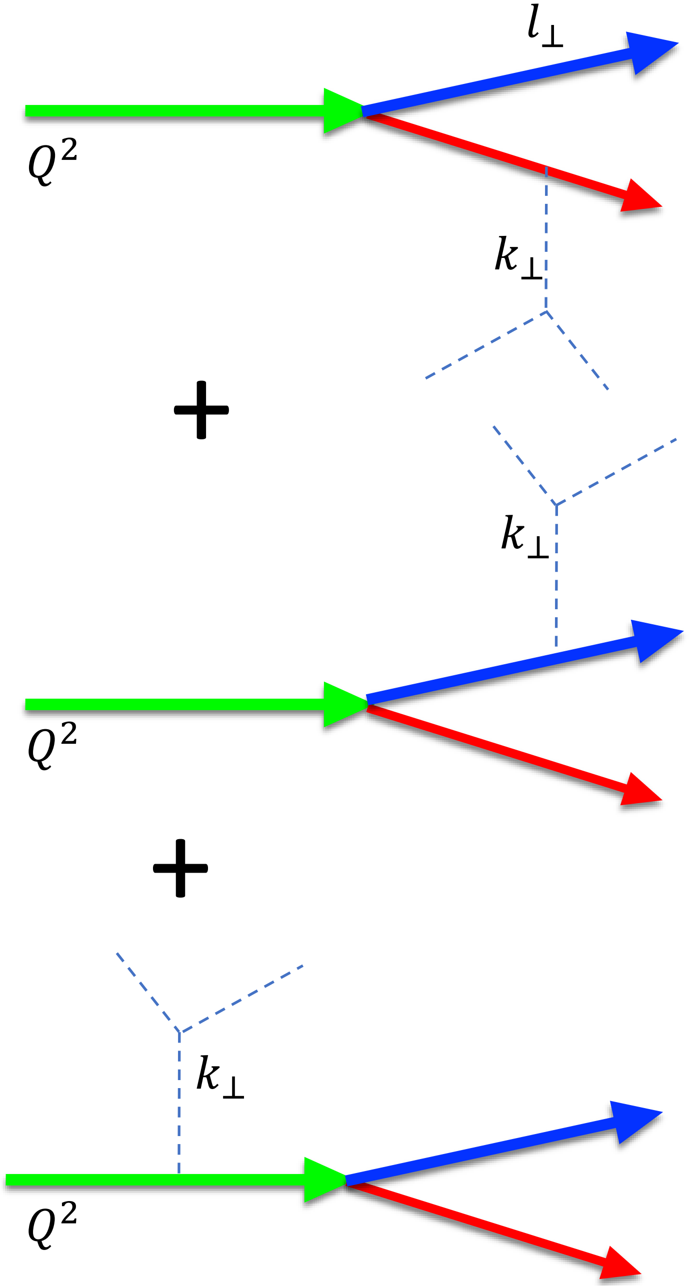

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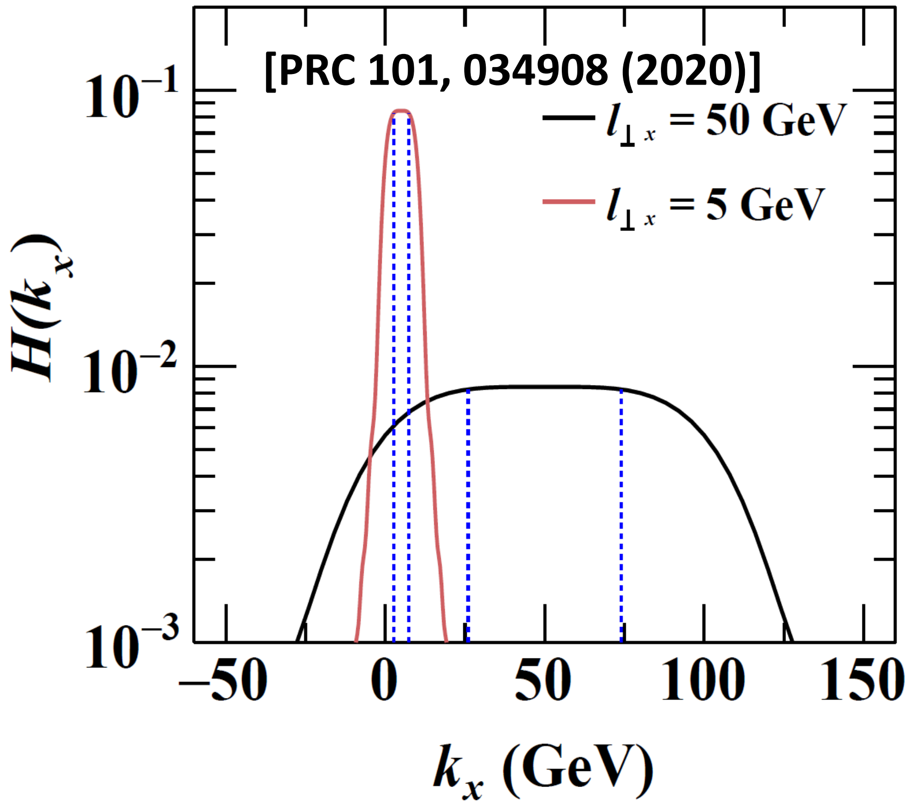
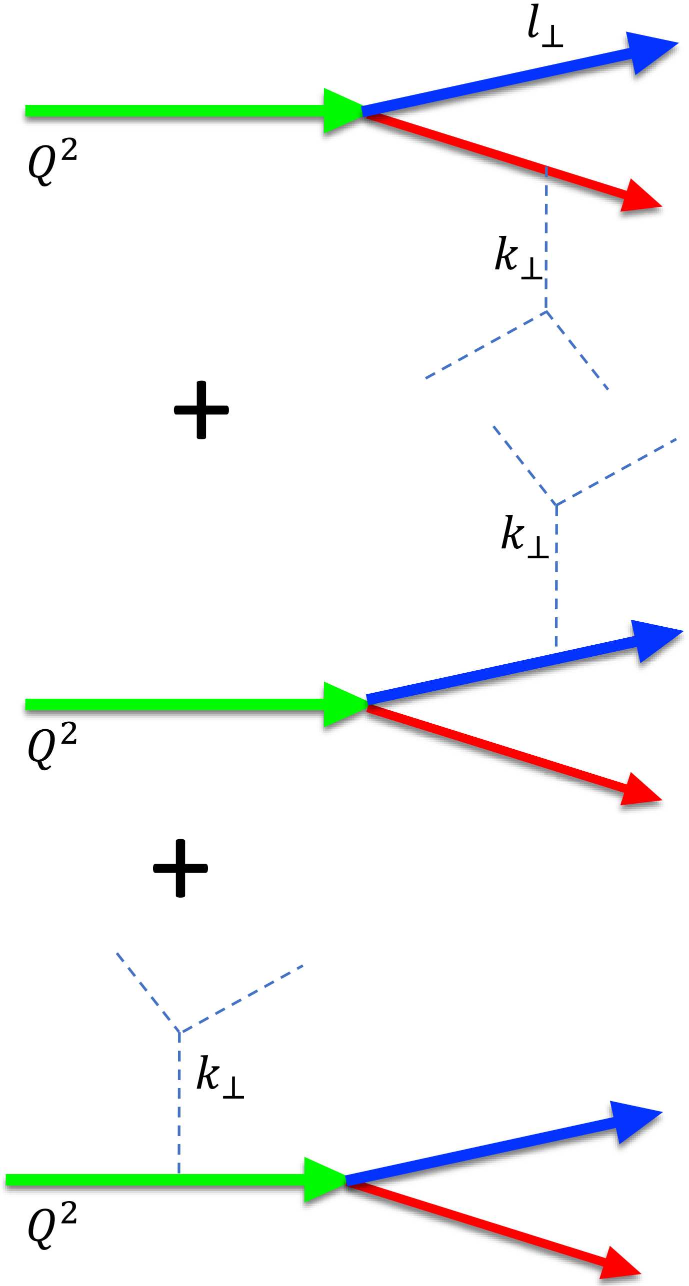


- The scattering is coherent over a range in $k_\perp$(dotted blue lines), which after converting $\mathrm{k}_\perp^2 \to Q^2$, gives

Virtuality-dependent $\hat{q}$



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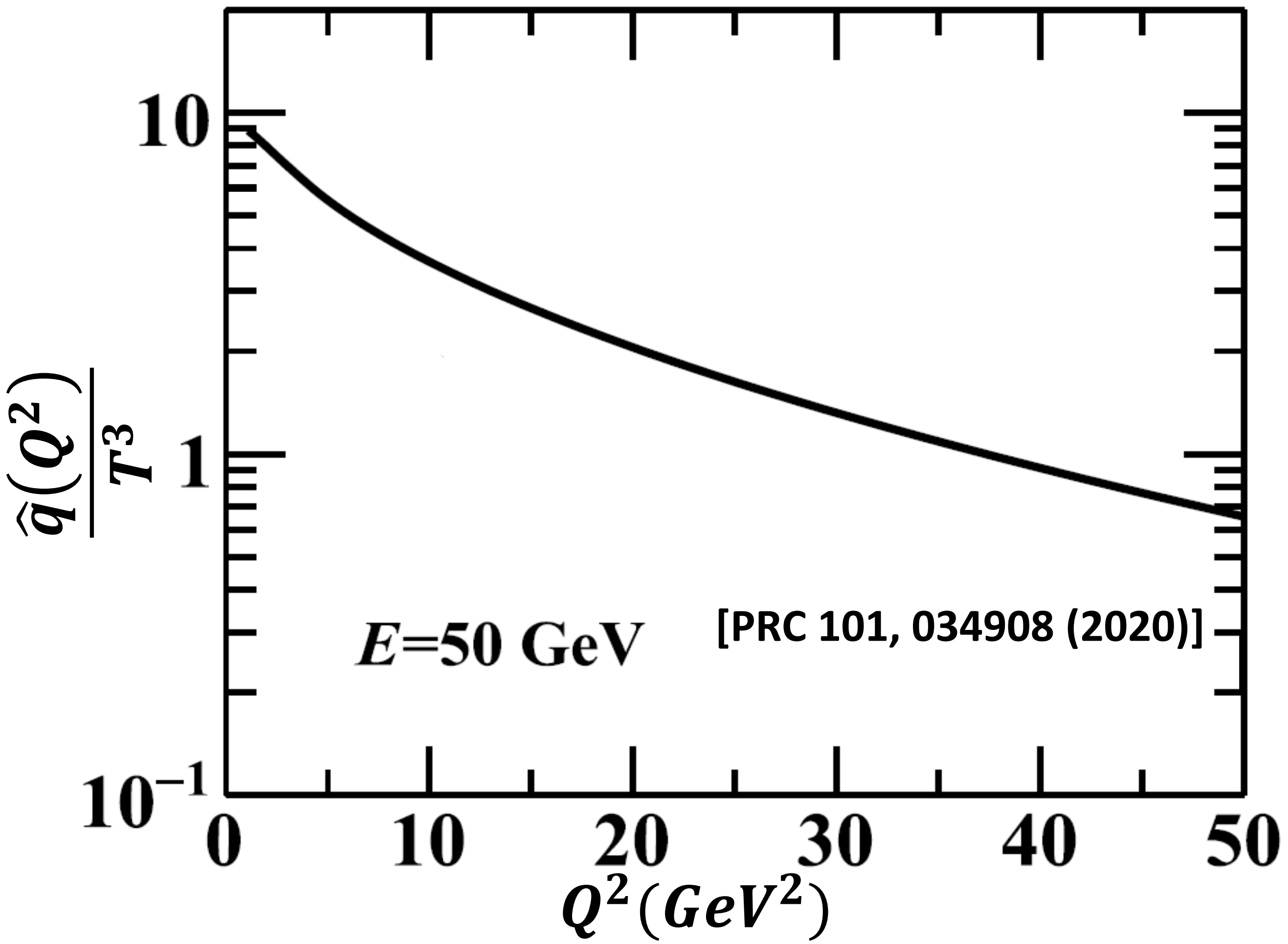
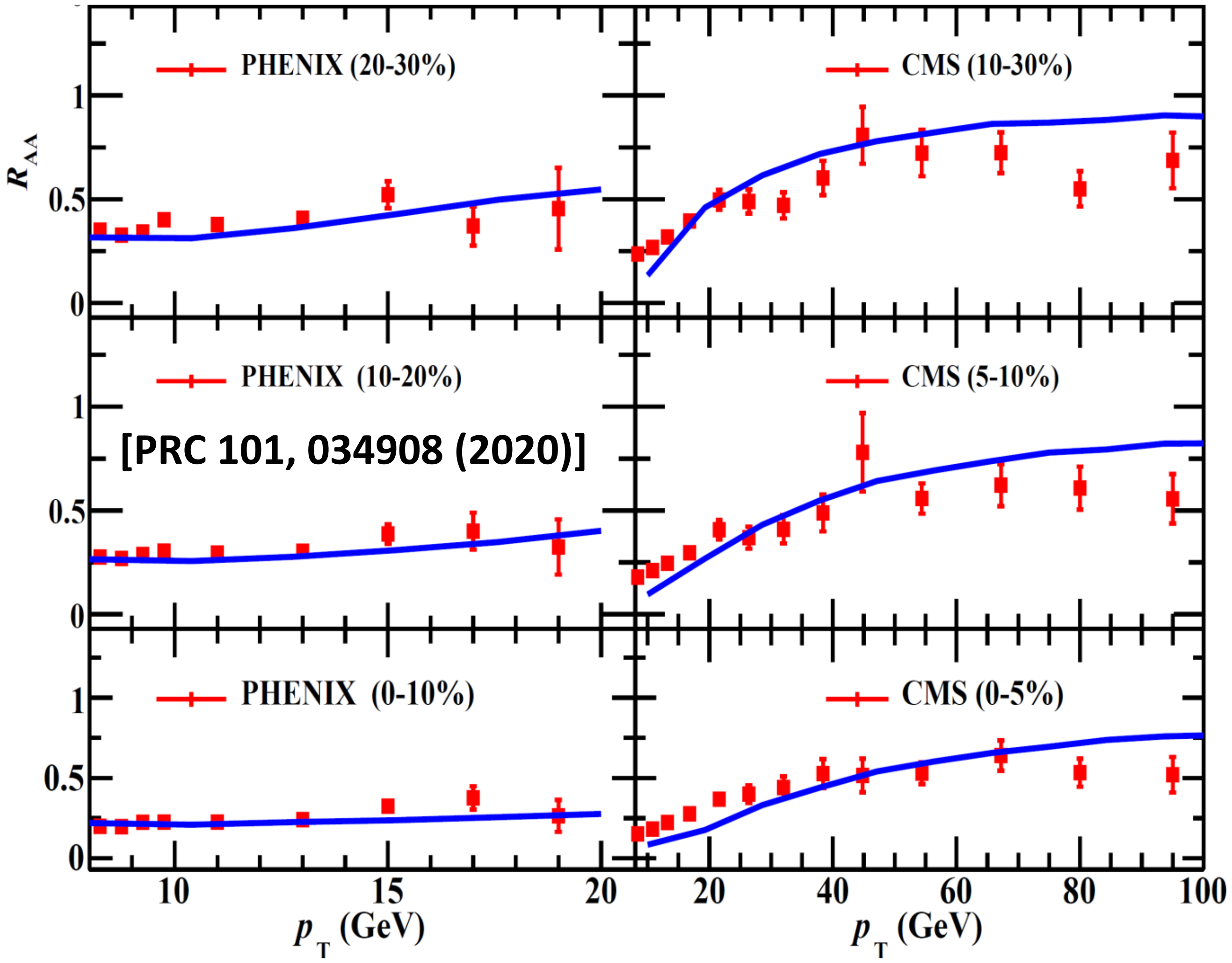


Phenomenology of virtuality-dependent $\hat{q}$



- $\hat{q}(Q^2)$ is a key ingredient to simultaneously describe leading hadron R_{AA} at different $\sqrt{s_{NN}}$ [**PRC 101, 034908 (2020)**].

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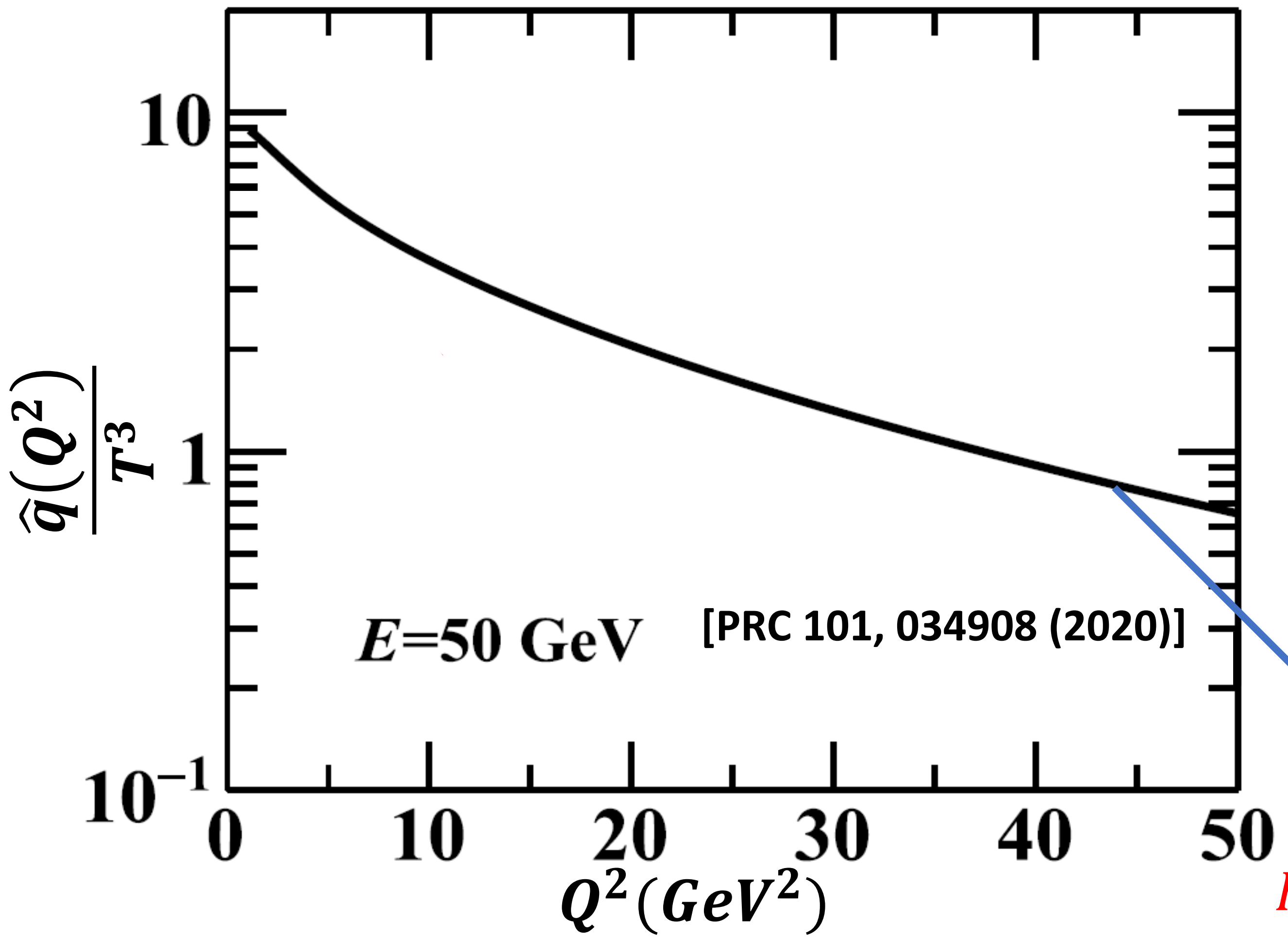

- $\hat{q}(Q^2)$ is a key ingredient to simultaneously describe leading hadron R_{AA} at different $\sqrt{s_{NN}}$ [**PRC 101, 034908 (2020)**].

- Explore how this $\hat{q}(Q^2)$ affects heavy quarks in a multi-scale MATTER+LBT simulation using a parametrization:

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

$$\hat{q}_{HTL} \propto \alpha_s^2 T^3 \ln\left[\frac{cE}{\alpha_s T}\right]$$

$$H(Q^2) = \begin{cases} 1 & Q^2 < Q_s^2 \\ \dfrac{1 + c_1 \ln^2(Q_s^2) + c_2 \ln^4(Q_s^2)}{1 + c_1 \ln^2(Q^2) + c_2 \ln^4(Q^2)} & Q^2 \geq Q_s^2 \end{cases}$$

Higher Twist Energy Loss for Heavy Quarks

- **MATTER** (The **M**odular **A**ll **T**wist **T**ransverse-scattering **E**lastic-drag and **R**adiation) valid for High E, High Q
  - Virtuality-ordered shower with splittings above $Q \gg Q_{\mathrm{min}}$
  - The Sudakov form factor assigns virtuality to each parton [**Adv.Ser.Direct.HEP, 573 (1989); NPA 696, 788 (2001)**] and includes in-medium corrections

$$\Delta(Q_{\mathrm{max}}, Q \geq Q_{\mathrm{min}}) = \exp\left[-\int_{Q^2}^{Q^2_{\mathrm{max}}} \frac{d\left(Q^2\right)}{Q^2} \frac{\alpha_s(Q^2)}{2\pi} \int_{y_{\mathrm{min}}}^{y_{\mathrm{max}}} dy\, \mathcal{P}(y, Q^2)\right]$$

  - The splitting function $\mathcal{P}$ depends on the incoming and outgoing species.

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  - For $Q \rightarrow Qg$ at LO in $\left(\alpha_s, \frac{\mathrm{M}^2}{\mathrm{Q}^2}\right)$ [**PRC 94, 054902 (2016)**]

$$\mathcal{P}\left(y, Q^2\right) = P(y) + \frac{P(y)\left[\left\{\left(1-\frac{y}{2}\right) - \chi + \left(1-\frac{y}{2}\right)\chi^2\right\}\left\{\int_0^{\tau_f^+} d\tau^+\, \hat{q}\left(Q^2\right)\left[2 - 2\cos\left[\frac{\tau^+}{\tau_f^+}\right]\right]\right\}\right]}{y(1-y)Q^2(1+\chi)^2}$$

$$\chi = \frac{y^2 M^2}{l_\perp^2} = \frac{y^2 M^2}{y(1-y)Q^2 - y^2 M^2} \qquad \tau_f^+ = \frac{2q^+ y(1-y)}{l_\perp^2\,(1+\chi)}$$

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$$y_{\text{max}} = 1 - \frac{Q_0^2}{2Q^2}$$

$$y_{\text{min}} = \frac{Q_0^2}{2Q^2} + \frac{M^2}{M^2 + Q^2}$$

$$Q^2_{\text{min}} = \frac{Q_0^2}{2}\left[1 + \sqrt{1 + \frac{4M^2}{Q_0^2}}\right]$$

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  - For $g \to Q + \bar{Q}$, the splitting function is phenomenologically estimated using light flavor $g \to q + \bar{q}$, with appropriate kinematic cuts to account for heavy flavor mass.

$$\mathcal{P}(y, Q^2) = P(y) + \frac{P(y) \int_0^{\tau_f^+} d\tau^+ \hat{q}(Q^2) \left[2 - 2\cos\left[\frac{\tau^+}{\tau_f^+}\right]\right]}{y(1-y)Q^2}$$

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$$Q^2_{\min} = Q_0^2 + 2M^2$$

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Linear Boltzmann Transport for Heavy Quarks

- Valid for high E, assuming particles are on-shell
- Solves the time-ordered evolution for the phase space distribution function

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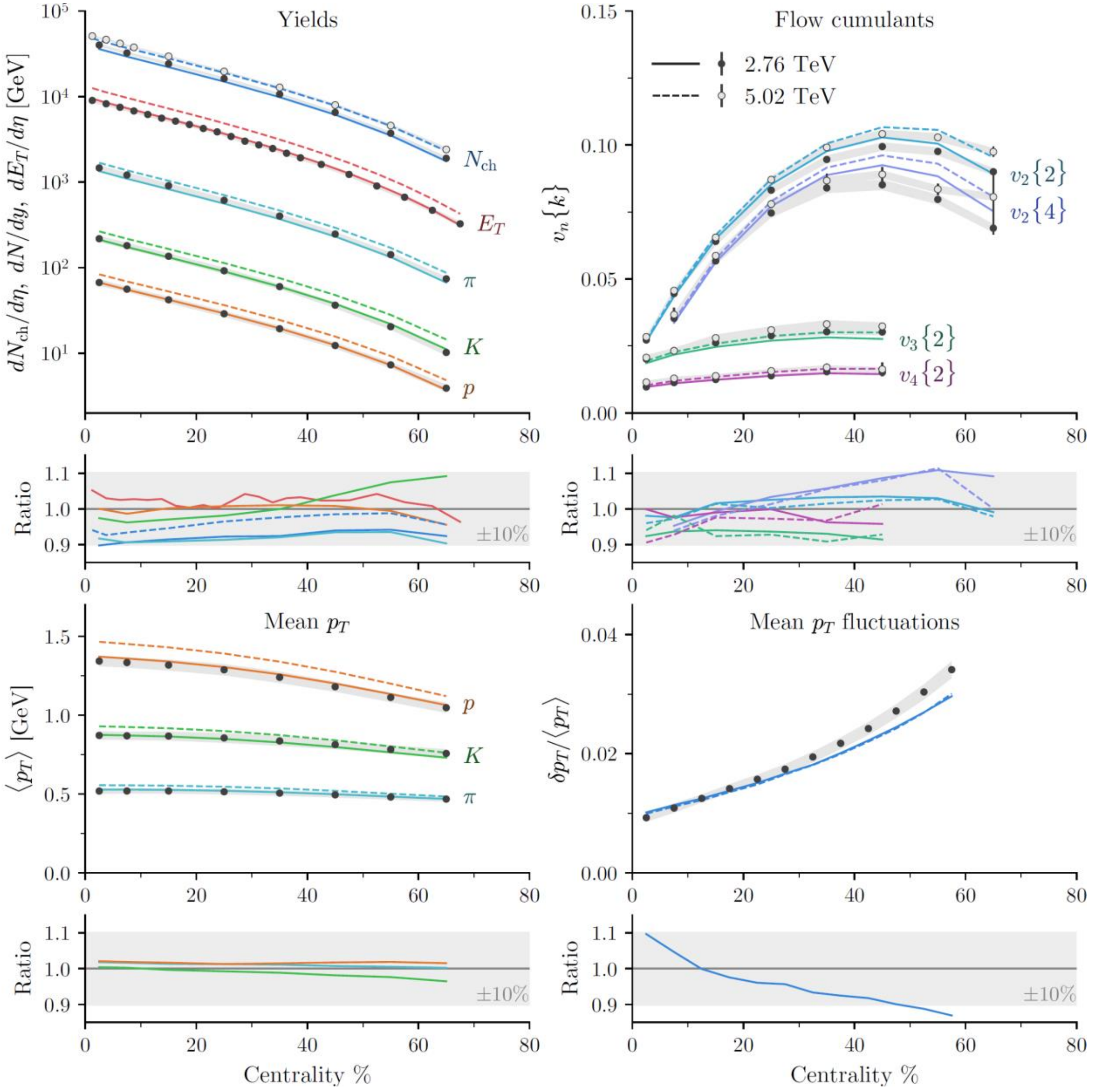
- The $\mathcal{G}_{inel}$ calculates medium-induced stimulated $1 \rightarrow 2$ emission at LO in $\left(\alpha_s, \frac{\mathrm{M}^2}{\mathrm{Q}^2}\right)$ [see **PRC 94, 054902 (2016)**]

$$\mathcal{G}_{inel} = \int \frac{d(Q^2)}{Q^2} \frac{\alpha_s(Q^2)}{2\pi} \int dy\, \hat{\mathcal{P}}(y)$$

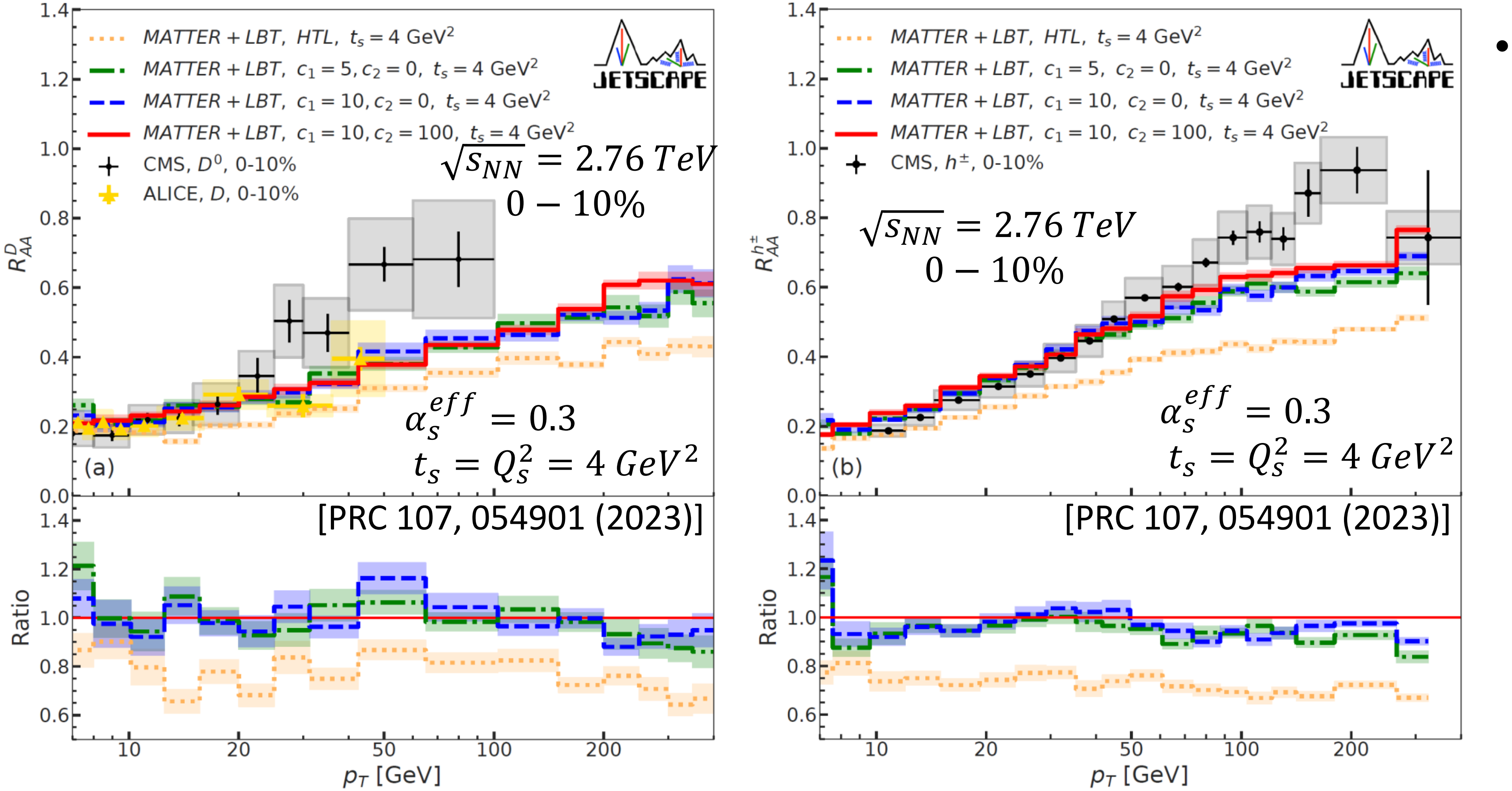
$$\hat{\mathcal{P}}(y) = \frac{P(y)\left[\left\{\left(1-\frac{y}{2}\right) - \chi + \left(1-\frac{y}{2}\right)\chi^2\right\}\left\{\int_0^{\tau_f^+} d\tau^+\, \hat{q}_{HTL}\left[2 - 2\cos\left[\frac{\tau^+}{\tau_f^+}\right]\right]\right\}\right]}{y(1-y)Q^2(1+\chi)^2}$$

About the QGP medium simulations



- MAP from Bernhard et al. **NPA 967 67 (2017); 1804.06469** used for QGP evolution profiles
- Event-by-event simulations consist of
  - TRENTO initial conditions
  - 2+1D Pre-equilibrium dynamics (free-streaming)
  - 2+1D 2nd order dissipative hydrodynamics of QGP
  - UrQMD

R_{AA} sensitivity to the presence of $\hat{q}(Q^2)$



- In all cases, parameters were tuned using light flavor jets and charged hadron R_{AA} [**see PRC 107, 034911 (2023)**]

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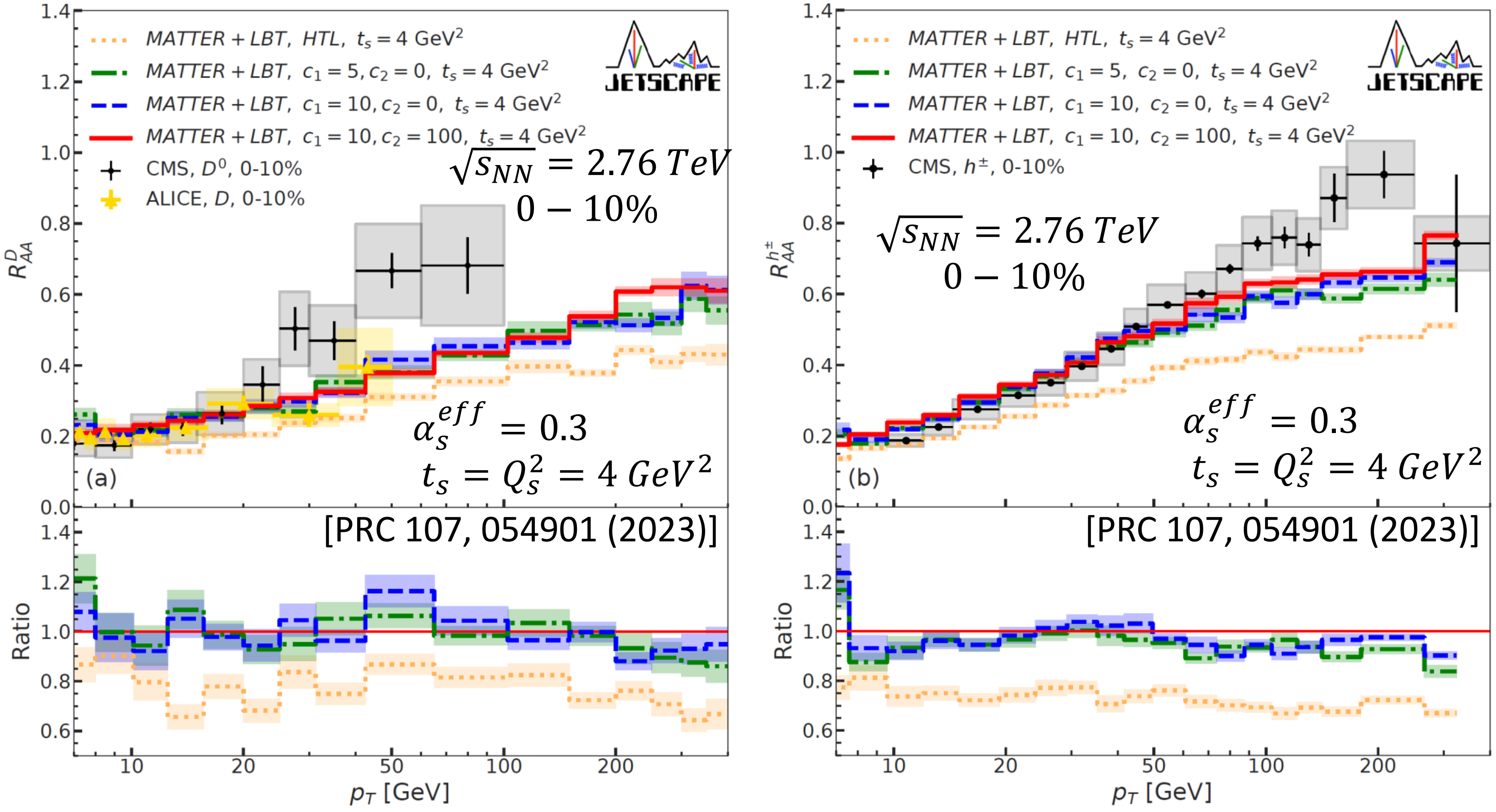
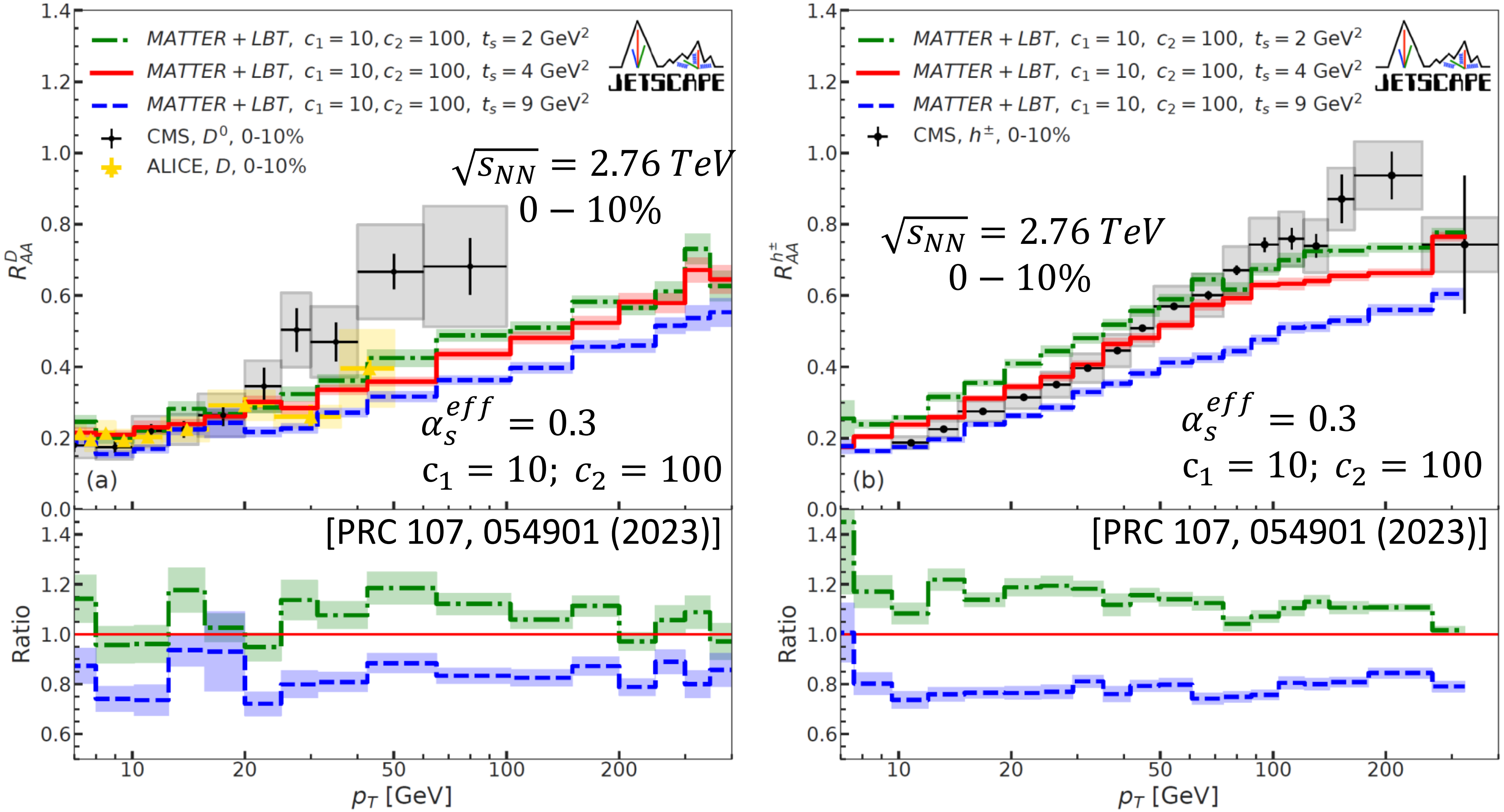


$$\hat{q}(Q^2) = \hat{q}_{HTL} \frac{c_0}{1 + c_1 \ln^2(Q^2) + c_2 \ln^4(Q^2)}$$

- The orange curve is for $\hat{q}_{HTL}$ only.
- Red, green, and blue curves use different values of c_1 & c_2 in $\hat{q}(Q^2)$. Same $\hat{q}$ for light and heavy quarks
- Beyond a threshold, ($c_1 = 5$ and $c_2 = 0$) a low sensitivity to c_1 & c_2 is seen.

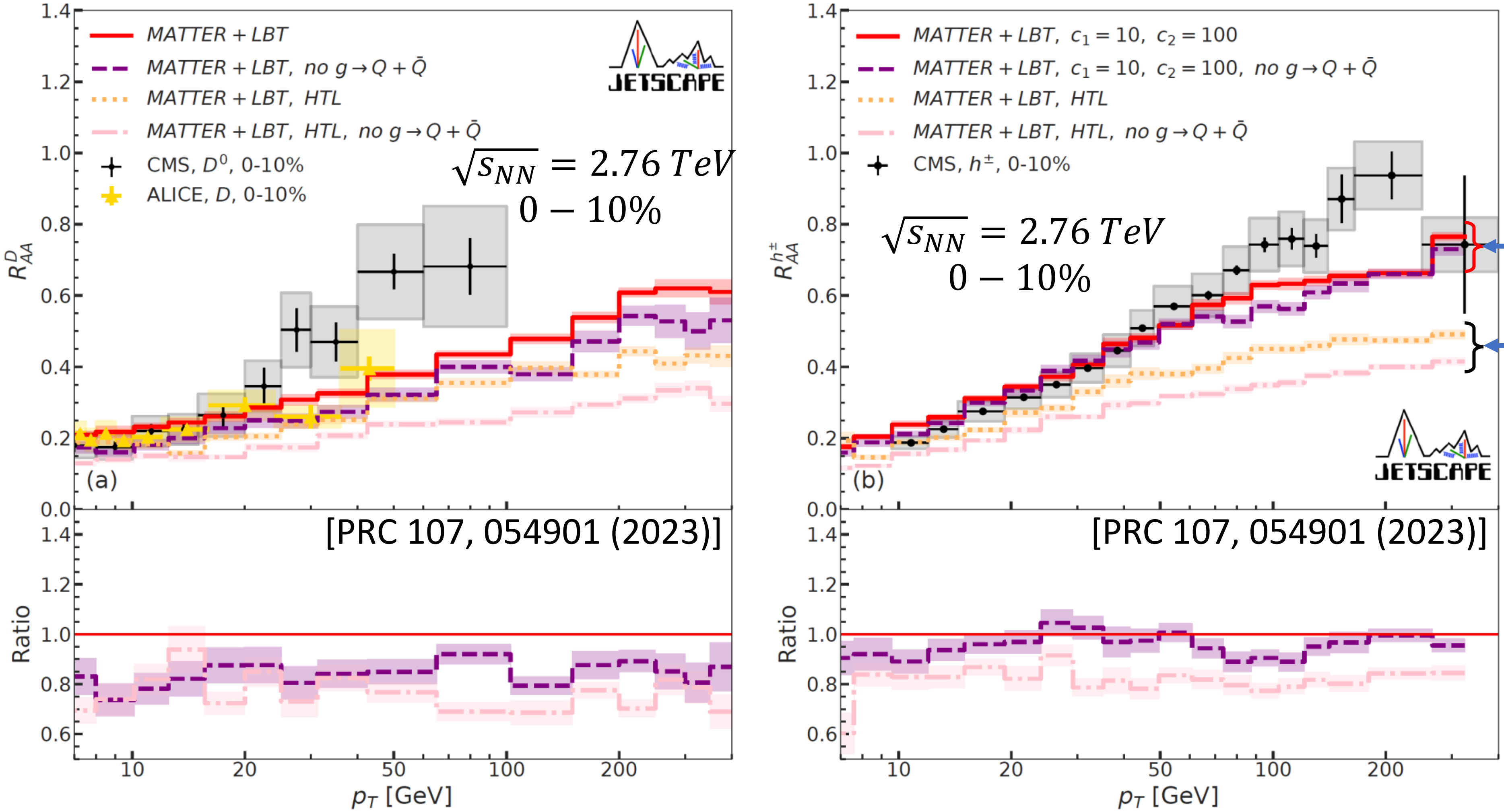
R_{AA} sensitivity to the switching virtuality Q_s^2 between MATTER & LBT



- Green curve: $Q_s^2 = 2\ \mathrm{GeV}^2$
- Red curve: $Q_s^2 = 4\ \mathrm{GeV}^2$
- Blue curve: $Q_s^2 = 9\ \mathrm{GeV}^2$

- The same $\hat{q}(Q^2)$ used for light and heavy flavor ⇒ similar sensitivity to the switching virtuality $t_s = Q_s^2$.
- Will explore how the HF mass <u>*scale*</u> M and virtuality scale Q^2 affects $\hat{q}$ together, i.e. $\hat{q}(Q^2, M)$.

Sensitinity of R_{AA} to $g \to Q + \bar{Q}$



$\hat{q}(Q^2)$: $R_{AA}^{h^\pm}$ is modestly sensitive to $g \to Q + \bar{Q}$

$\hat{q}_{\mathrm{HTL}}$: $R_{AA}^{h^\pm}$ is sensitive to $g \to Q + \bar{Q}$

Ratio: relative importance of $g \to Q + \bar{Q}$ for $\hat{q}(Q^2)$ and $\hat{q}_{HTL}$.

- D-meson R_{AA} is sensitive to $g \to Q + \bar{Q}$ at the ~20% level for both parametrizations of $\hat{q}$ (i.e., $\hat{q}(Q^2)$ and $\hat{q}_{HTL}$)

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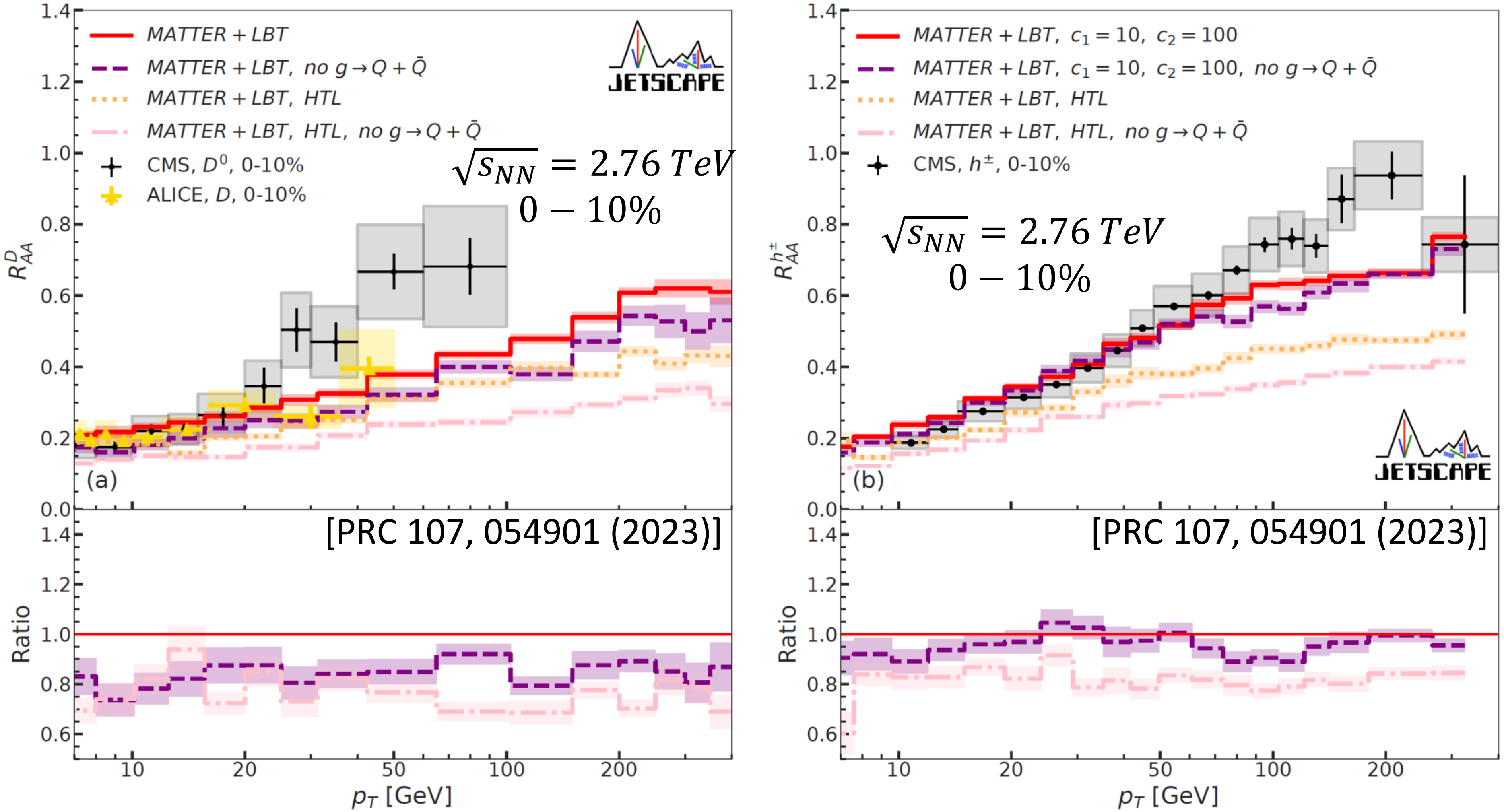

- To explore further: (i) $\hat{q}(Q^2, M)$ and, also,
  (ii) $\mathcal{P}_{g\to Q+\bar{Q}}\left(y, Q^2, M\right)$ beyond the phenomenological approach used here.
- Key message: future simulations of charm energy loss must include $g \to Q + \bar{Q}$!

Conclusion and outlook

- A multi-scale formalism, such as that present inside the JETSCAPE framework, allows for a simultaneous description of light flavor and heavy flavor energy loss inside QGP.
- Realistic simulations of charm energy loss must include dynamical generation of heavy quarks via $g \to Q + \bar{Q}$.
- Future physics improvement for heavy flavors energy loss to include:
  - A multiscale-dependent $\hat{q}\left(Q^2, M\right)$
  - A more realistic splitting function for $g \to Q + \bar{Q}$
  - Including additional energy loss physics, such as long. energy loss $(\hat{e})$, and long. drag $(\hat{e}_2)$
  - Explore bottom quark energy loss
- A Bayesian analysis including heavy flavors is ongoing…

Thank you