High Energy Probes of nuclear media:

Selected topics from quark gluon plasma studies

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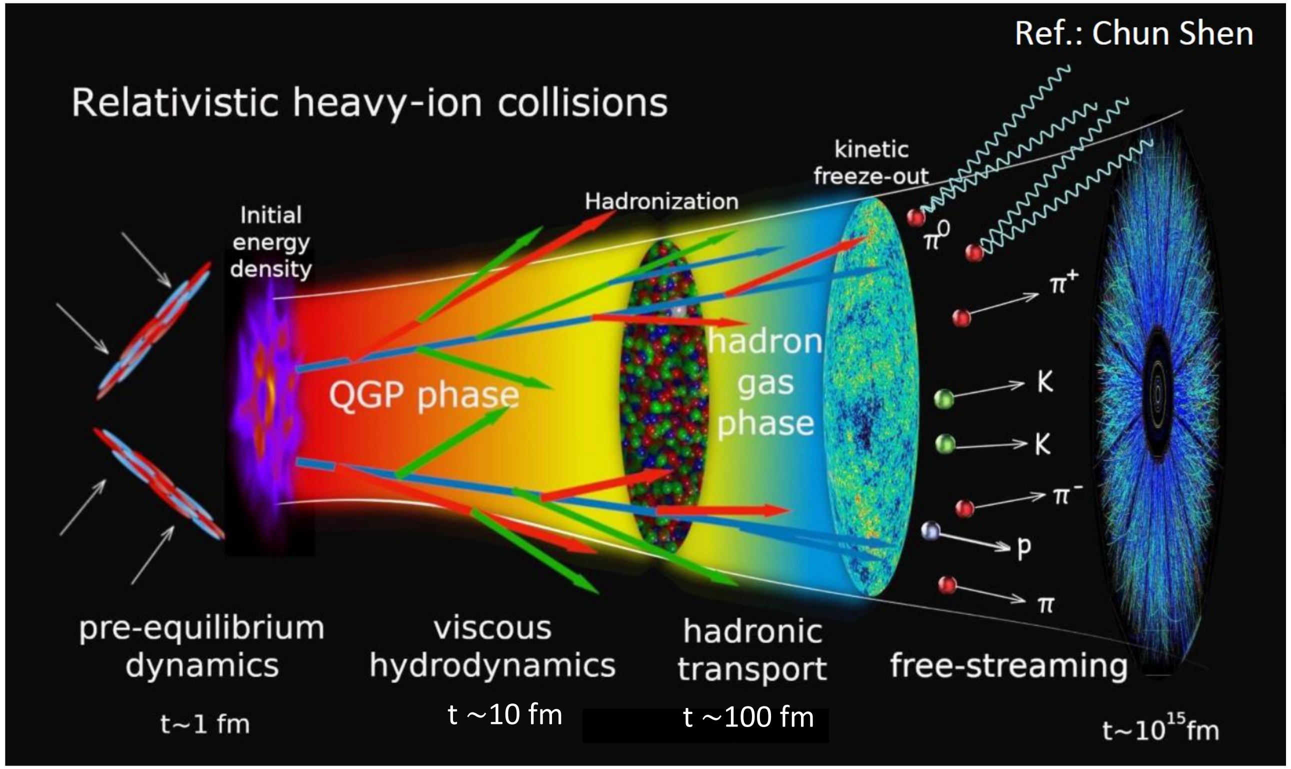
Conseil de recherches en sciences naturelles et en génie du Canada

Canada

Evolution of the nuclear medium as seen through jets



- Distribution of energy in heavy-ion collisions:
  - 3 stages of heavy-ion collisions:
    - Pre-equilibrium stage: production of hard jets
    - Evolution of the nuclear fluid: viscous hydro
    - Last stage: Boltzmann transport/free-streaming
  - Most of $T^{\mu\nu}$ is described by hydrodynamics Boltzmann hadronic transport.

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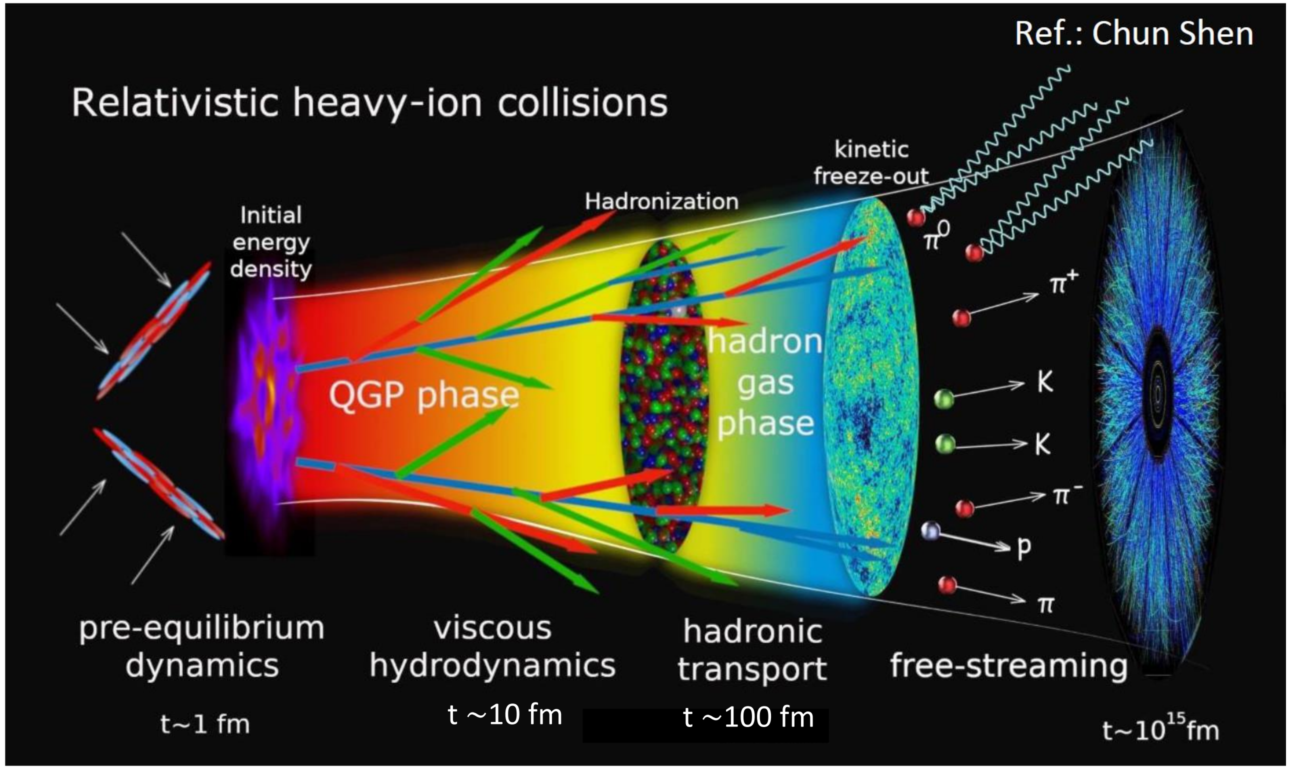

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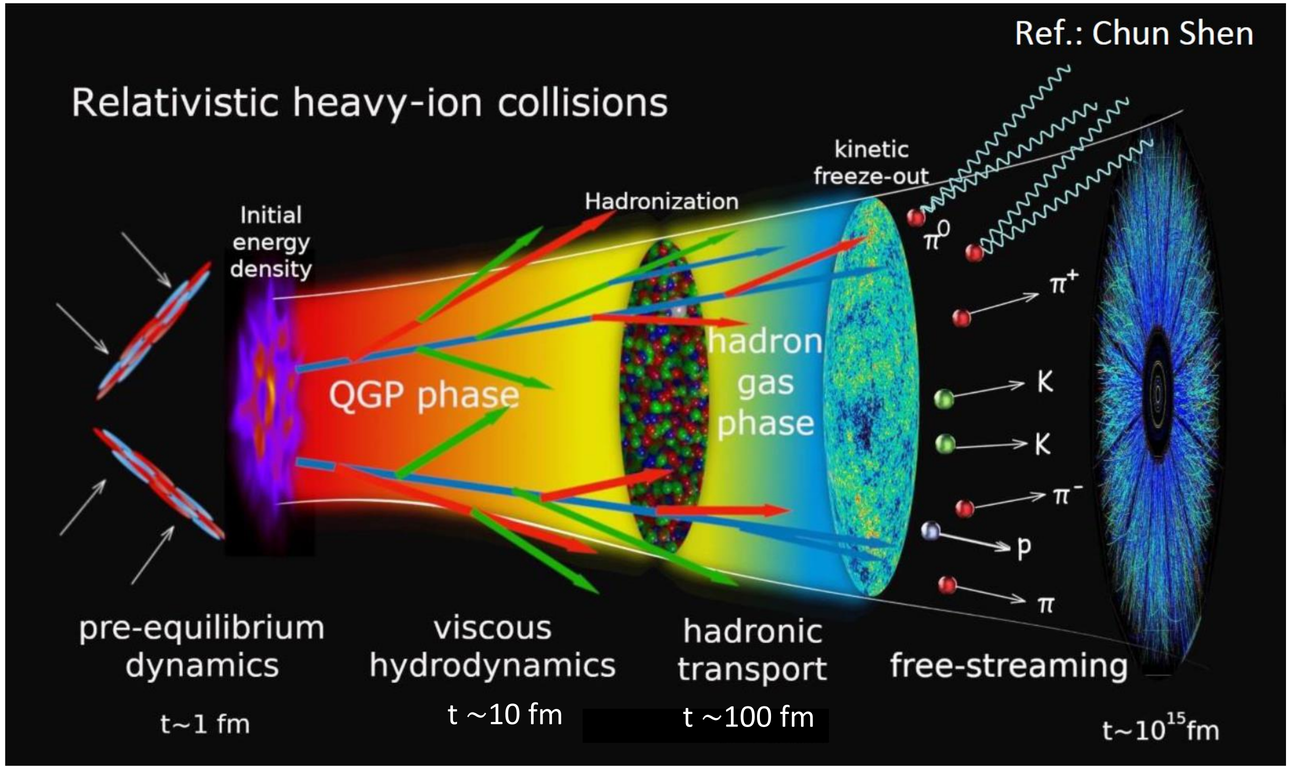

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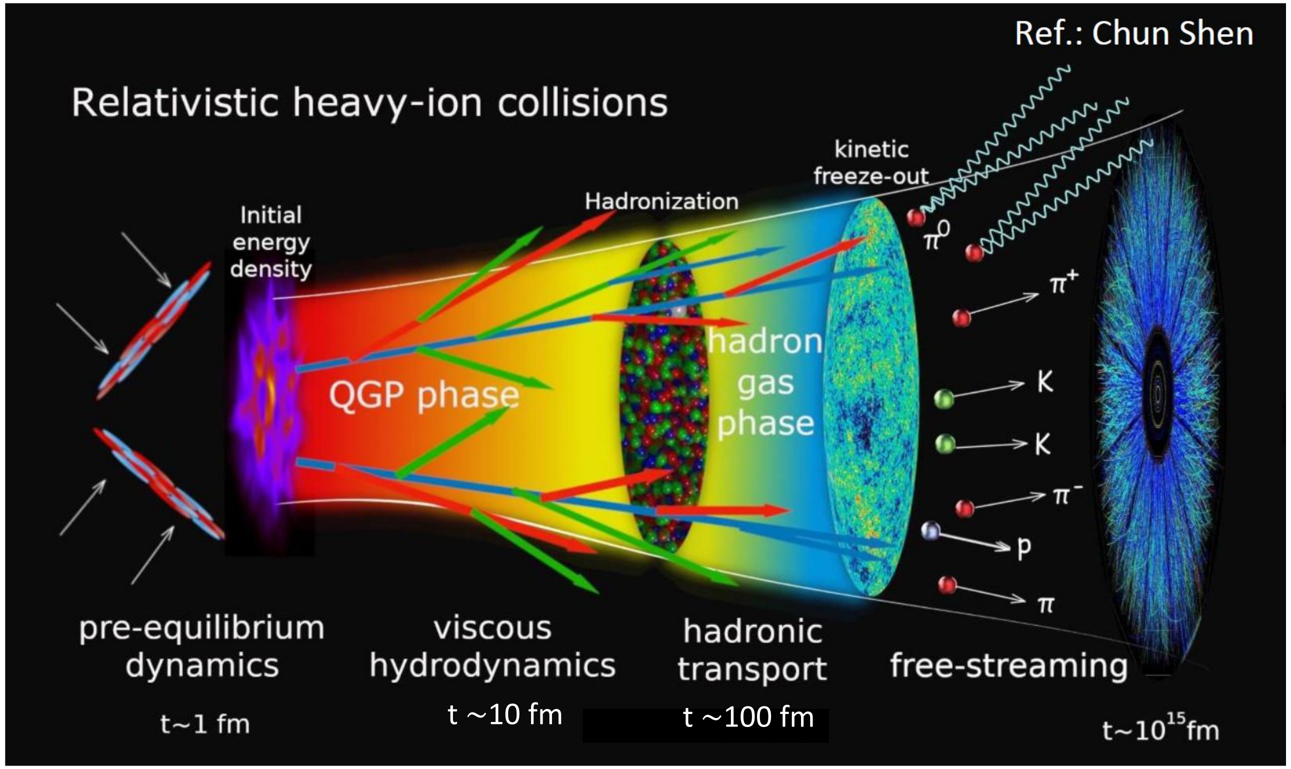

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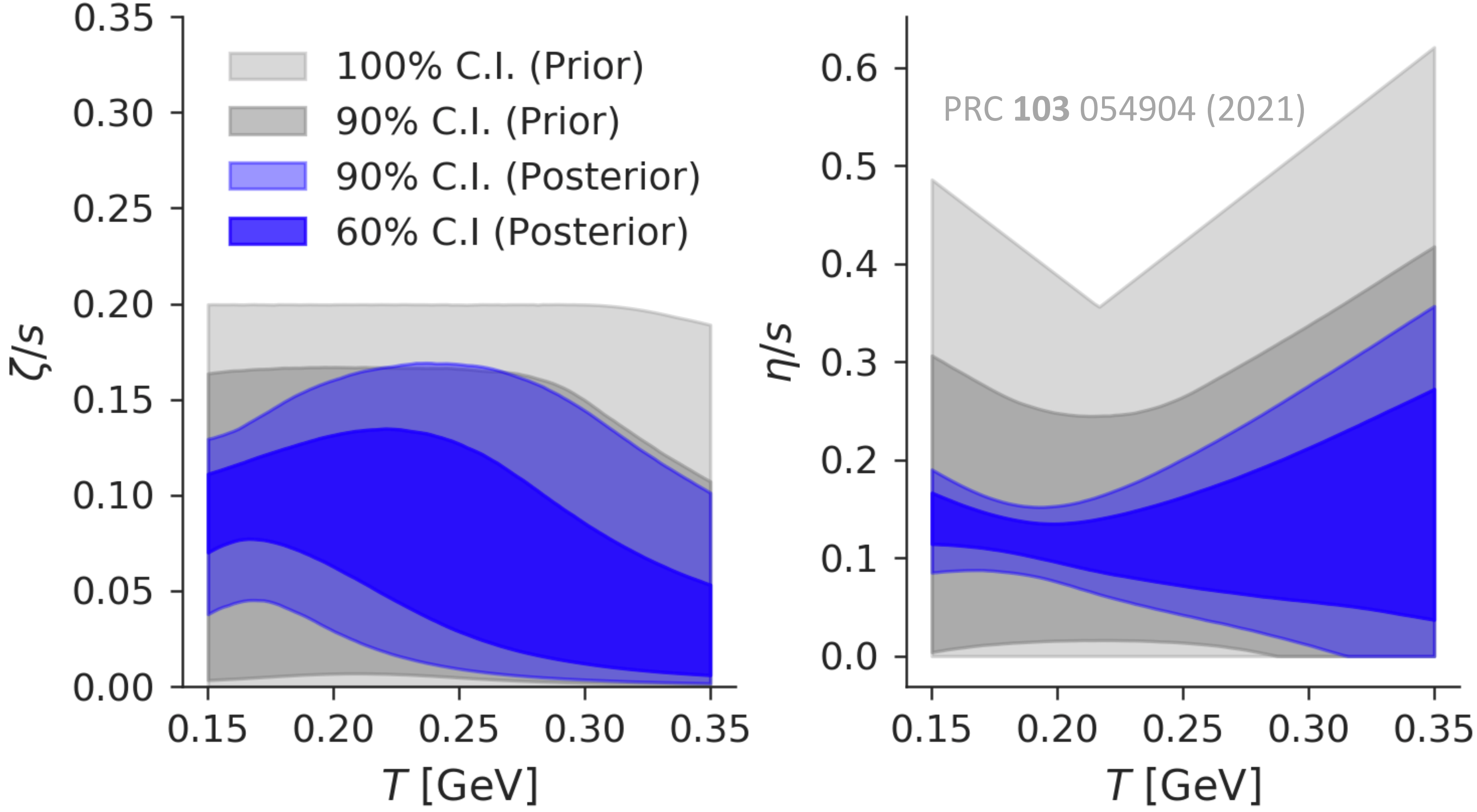
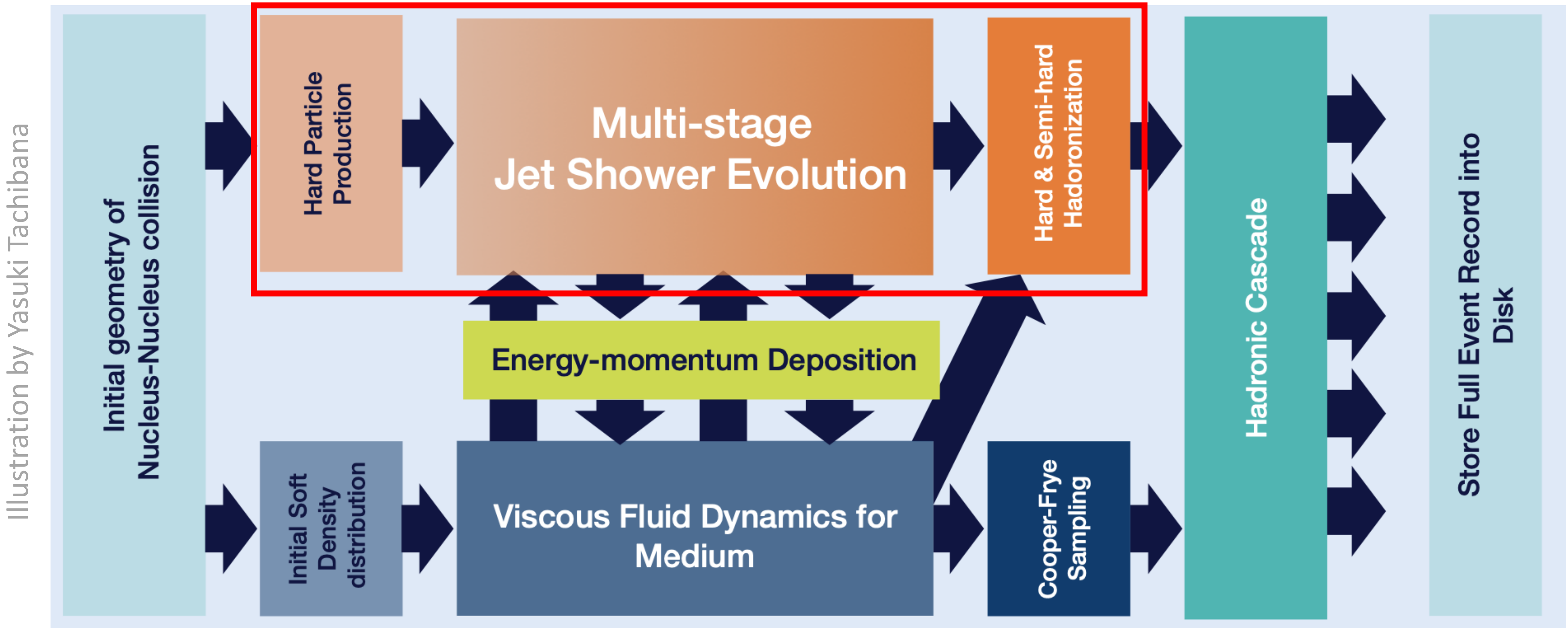
- To help simulate these different aspects of heavy-ion collisions, the JETSCAPE (Jet Energy-loss Tomography with a Statistically and Computationally Advanced Program Envelope) framework was established.

Nuclear medium viscosities



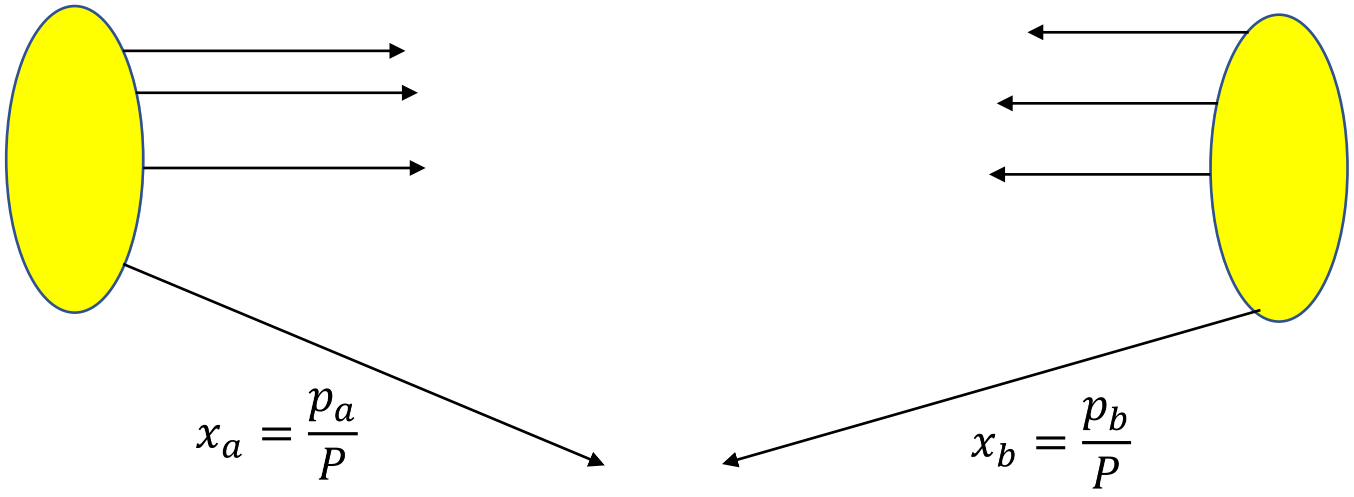
- The latest Bayesian constraints in the viscosities of the nuclear medium $T^{\mu\nu}$ done by JETSCAPE (see talk on Wed, 1:45pm)

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

Factorization at work: Leading order diagram



- Parton Distribution Function (PDF) G: Prob. of finding a parton from the hardon
  - a non-perturbative process, most easily measured in $e + p$ experiment (e.g. HERA)

$$\frac{d\sigma_1^h}{dy dp_{T_1}} \sim \int dx_a dx_b G(x_a) G(x_b) \left[\frac{d\hat{\sigma}}{d\hat{t}}\right] D(z_1)$$

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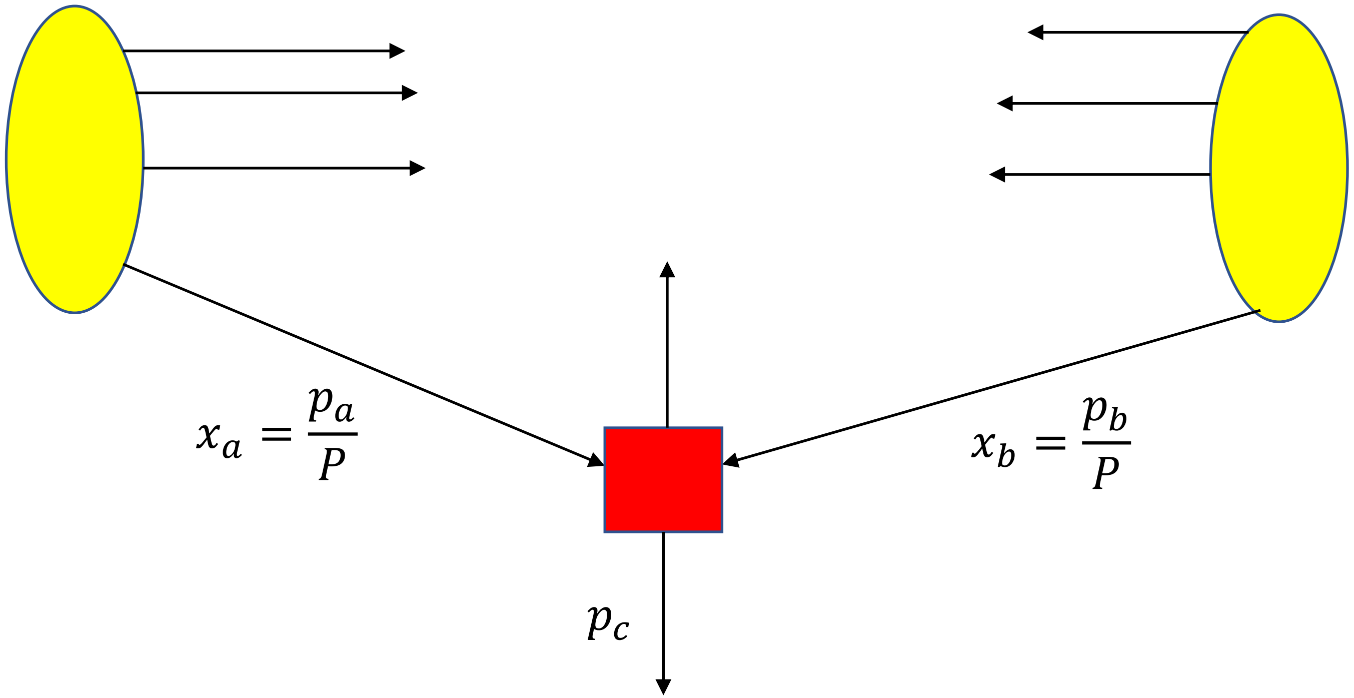

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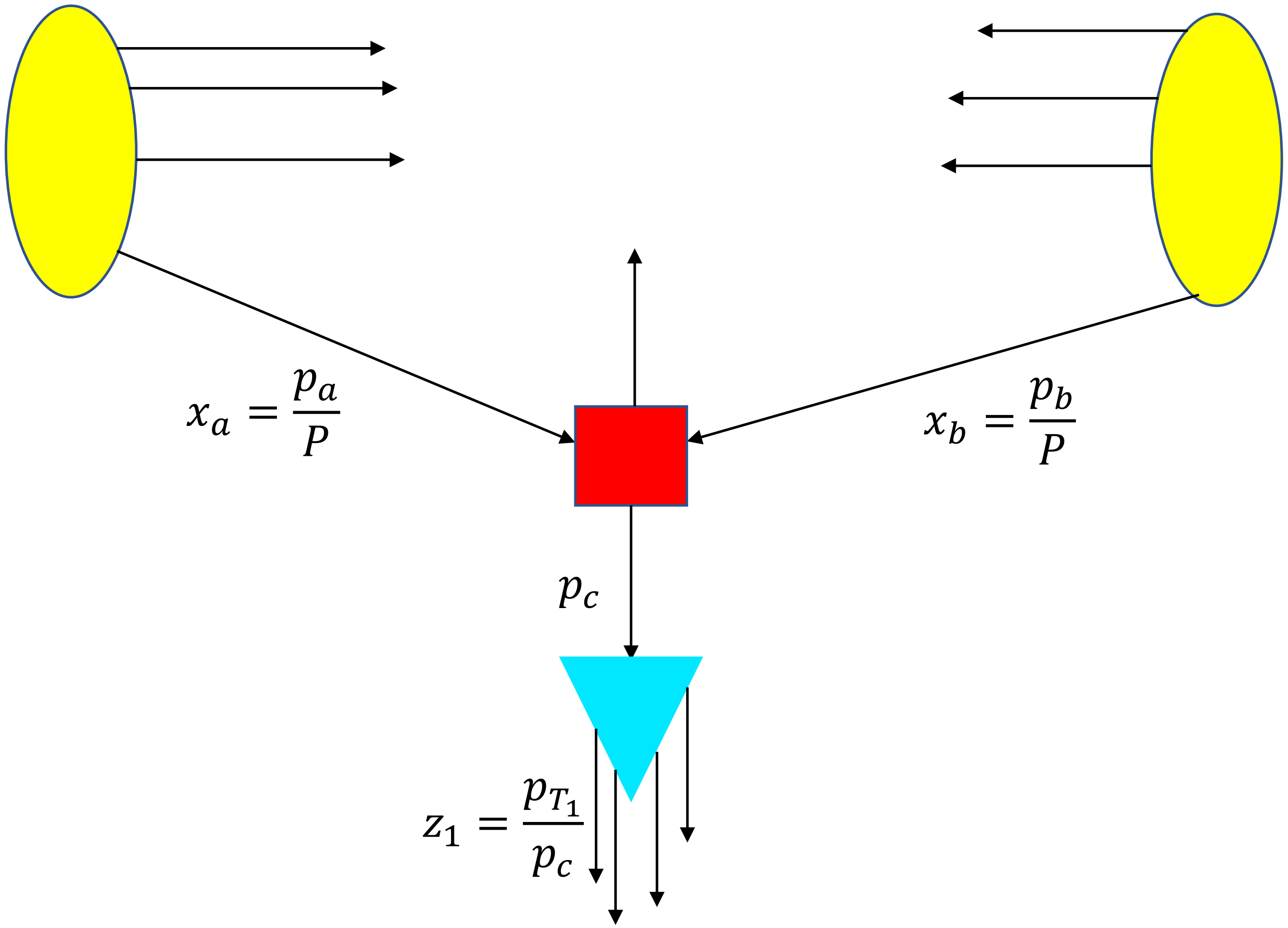

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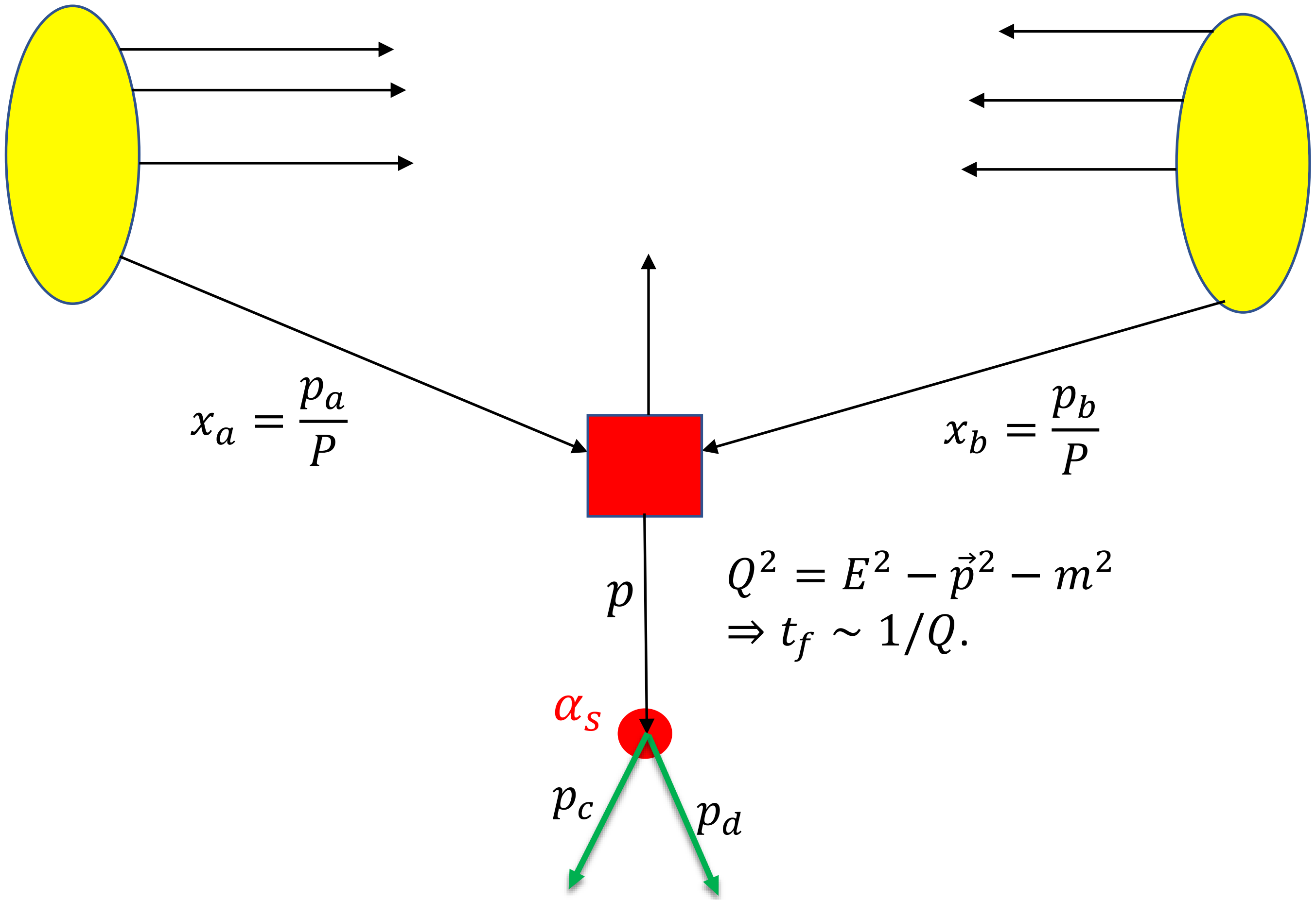
- The showering and hadronization of quarks and gluons is encapsulated in the Fragmentation Function (FF) D: converts partons into hadrons
  - non-perturbative process measured in $e^+ + e^-$ (e.g. LEP)

Sketch of possible corrections



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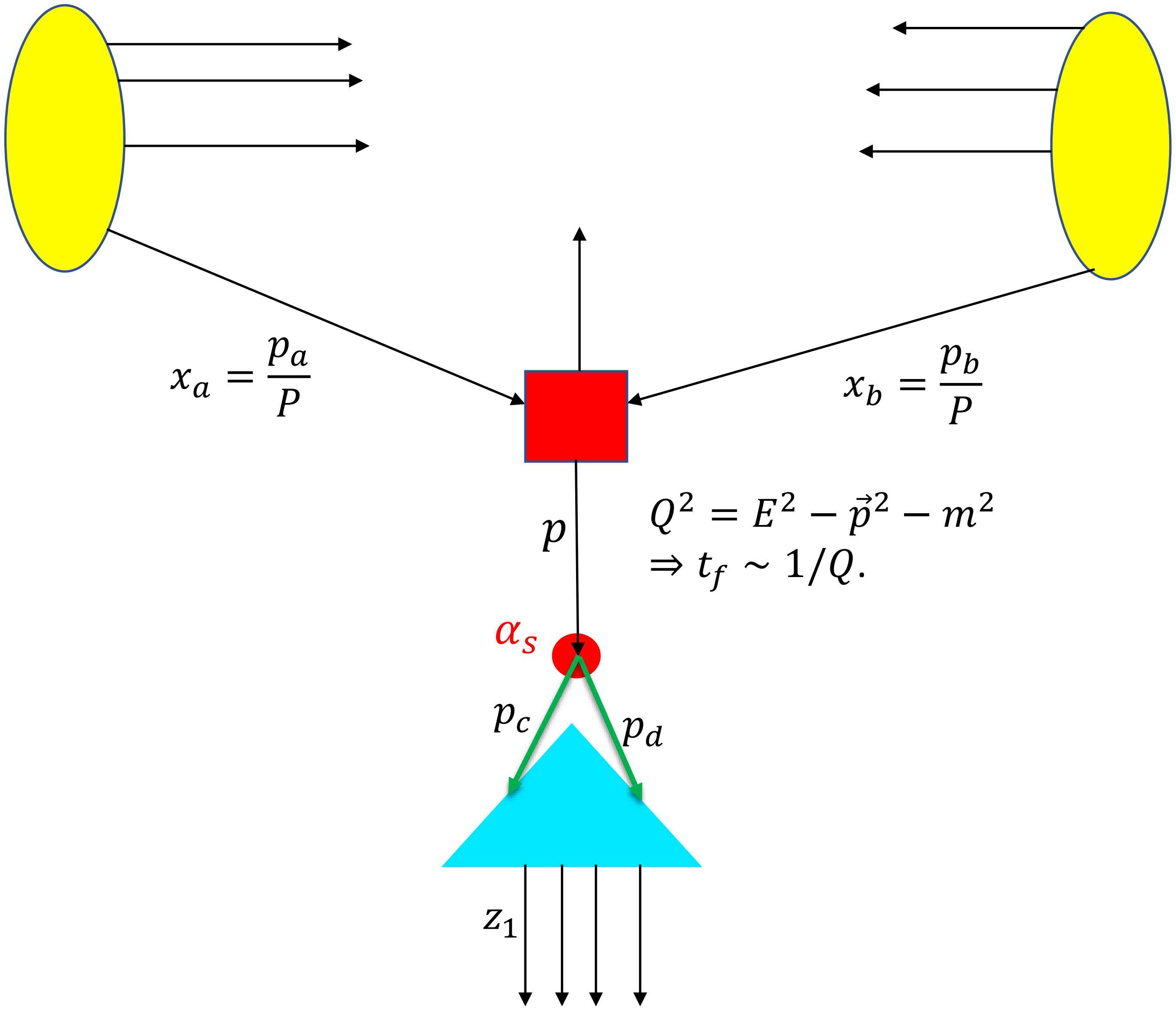

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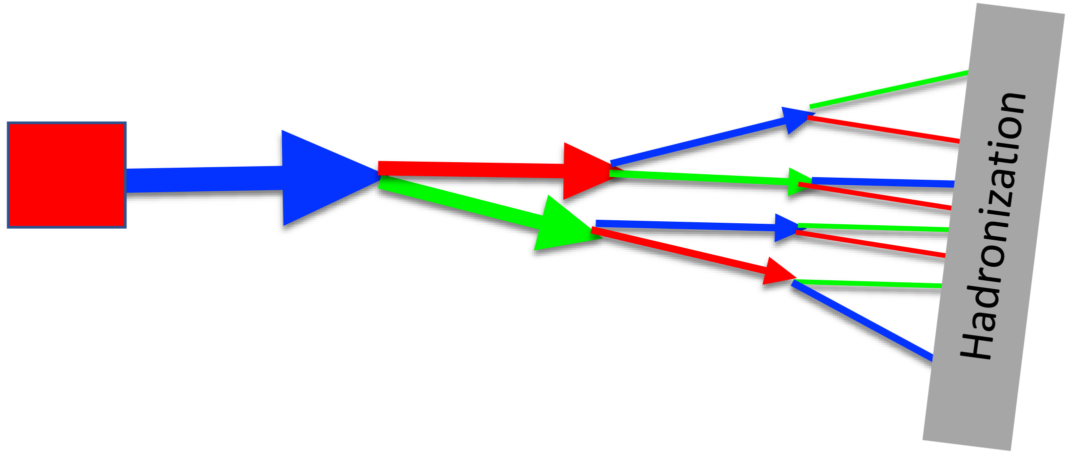
- Need to use scale (Q) dependent PDFs and FFs

$$G(x_a) \to G(Q, x_a); \quad D(z_1) \to D(Q, z_1)$$

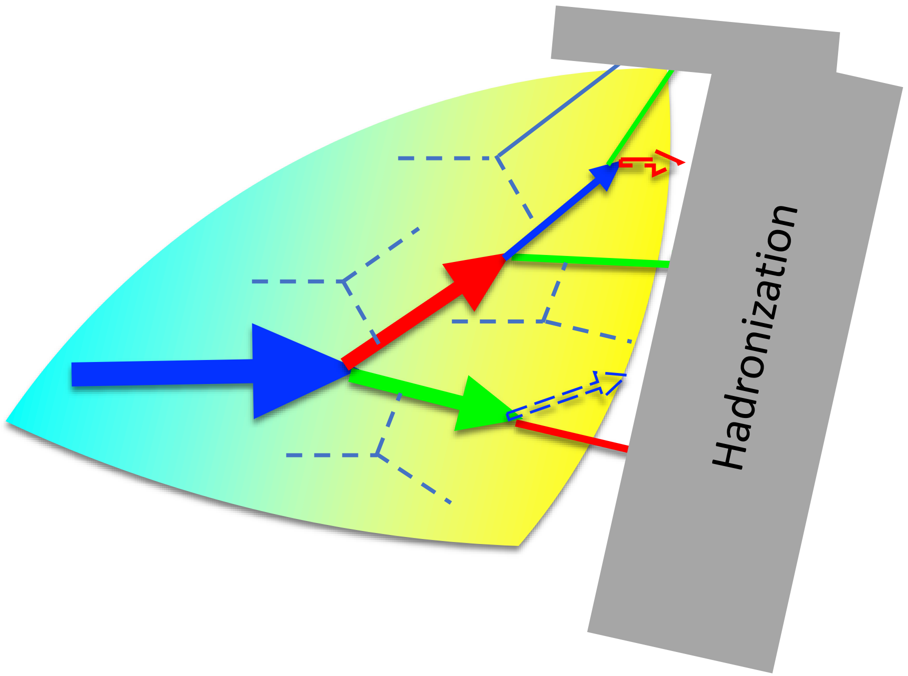
- Repeat the split recursively to get a shower

Monte Carlo jet shower simulation in vacuum



- Monte Carlo simulations (e.g., Pythia) develop a shower at the quark/gluon level in vacuum by adding multiple splits.
- In vacuum, the particles in a jet after hadronization occupy a narrow cone.

Modified splitting inside the QGP



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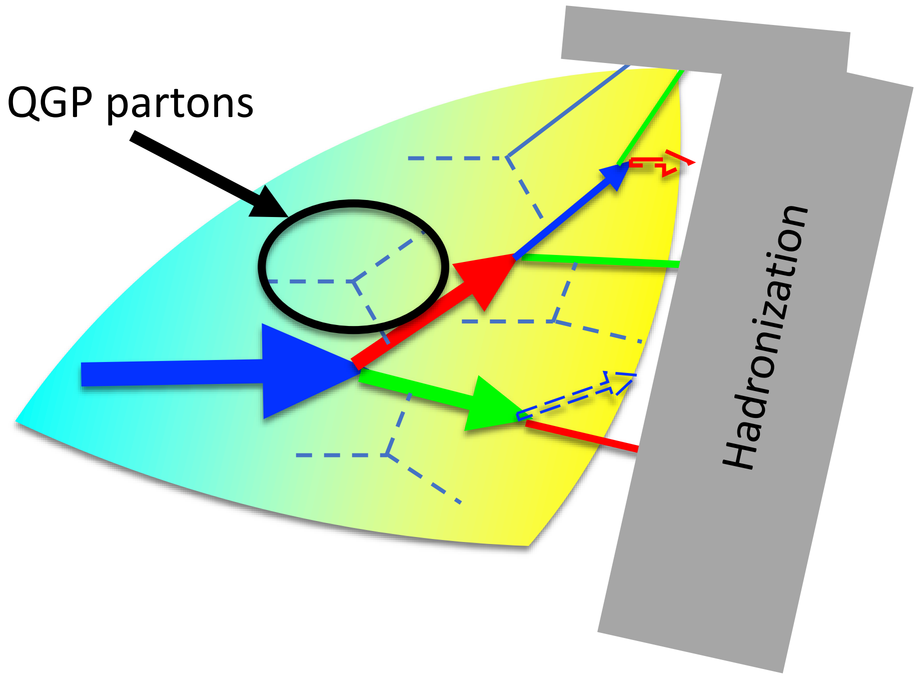

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  - multiple scatterings in the QGP induce
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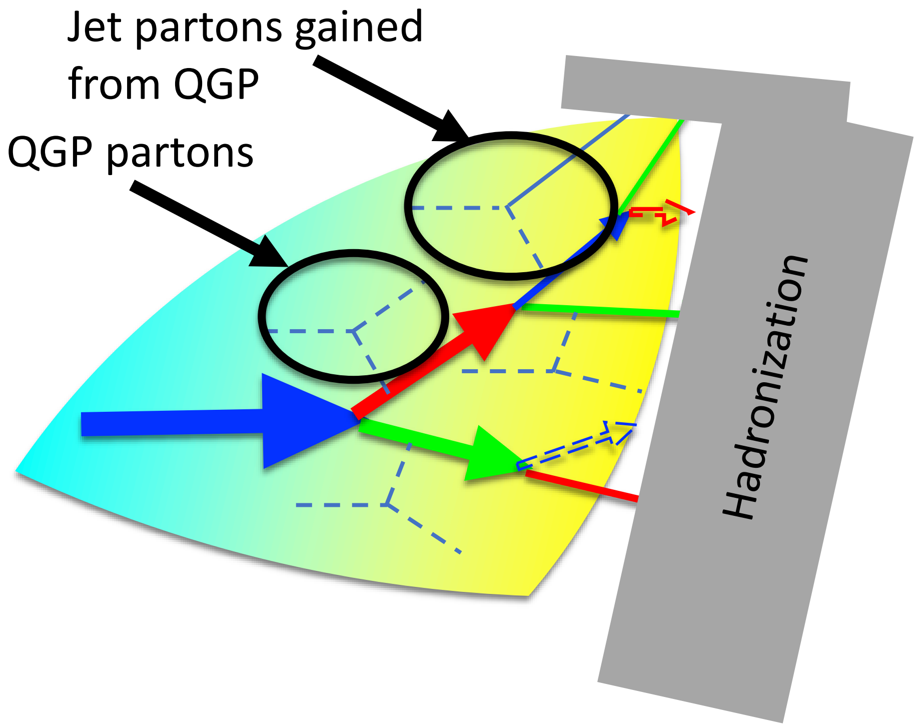

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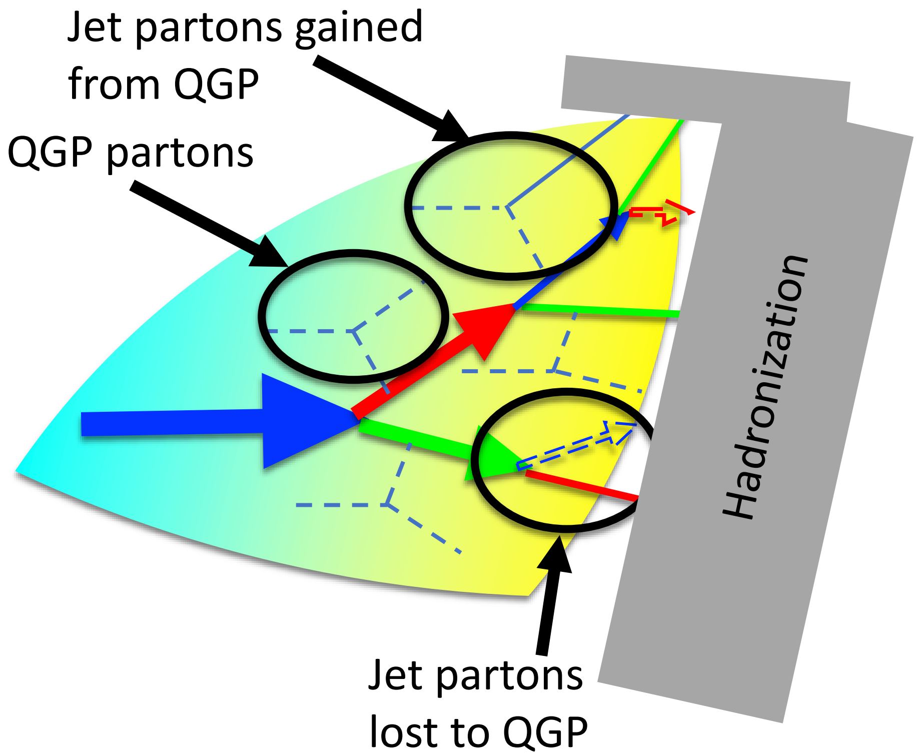

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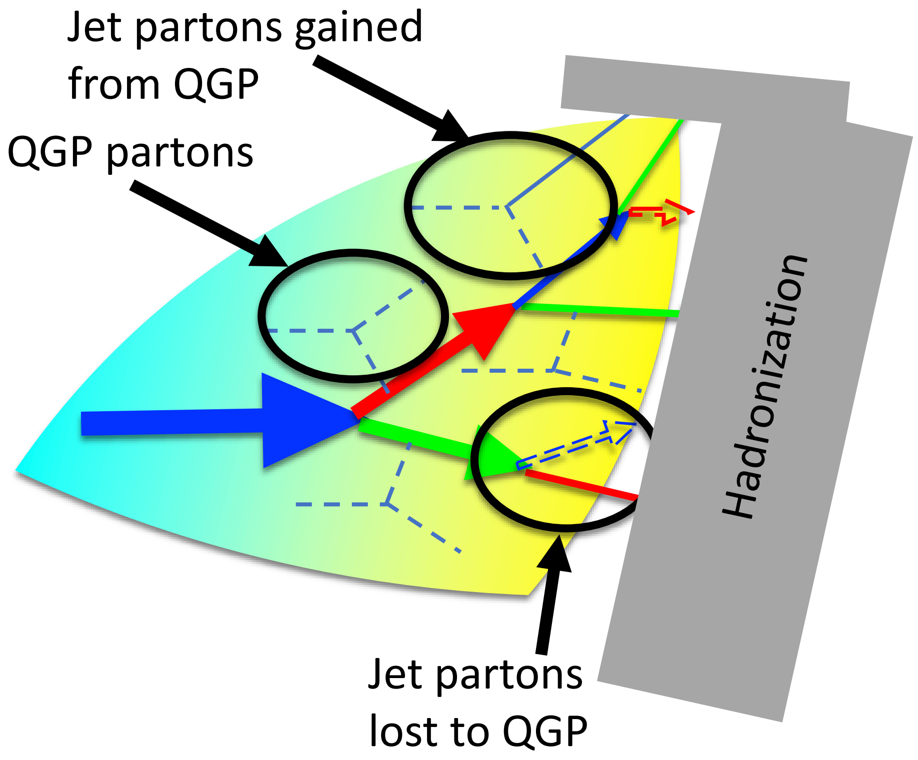

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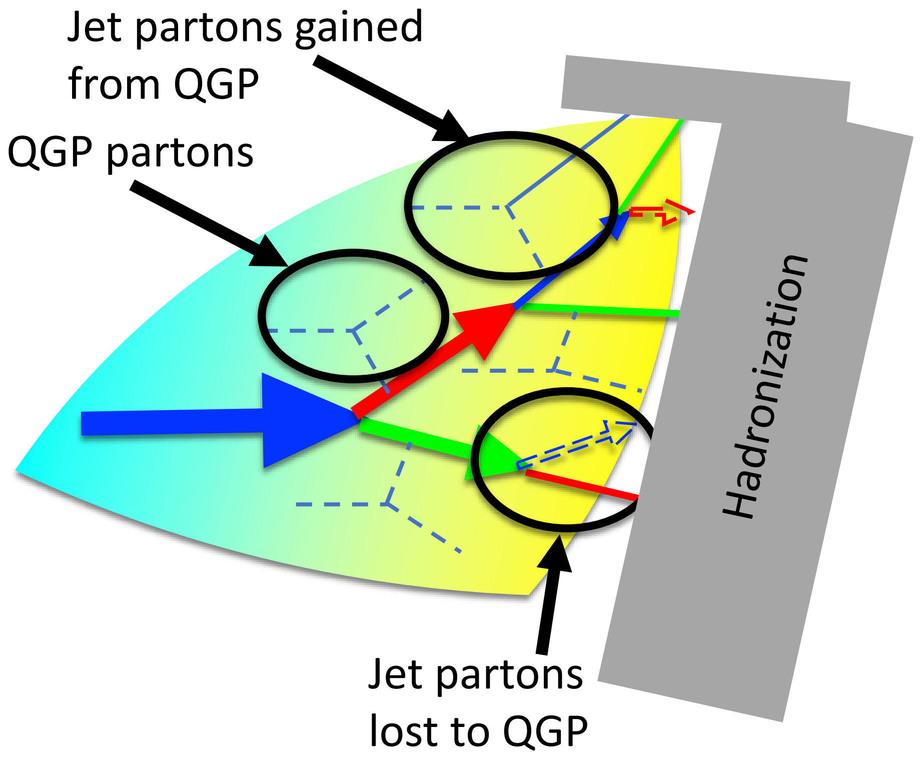

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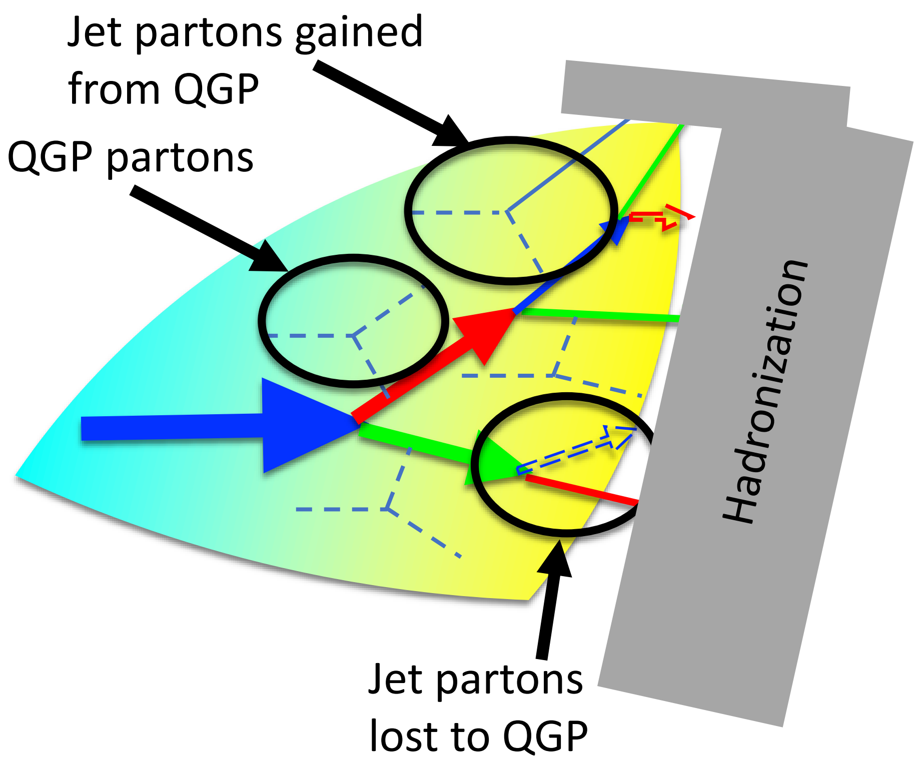

The JETSCAPE framework combines high/low virtuality stages for an improved description of parton energy loss.

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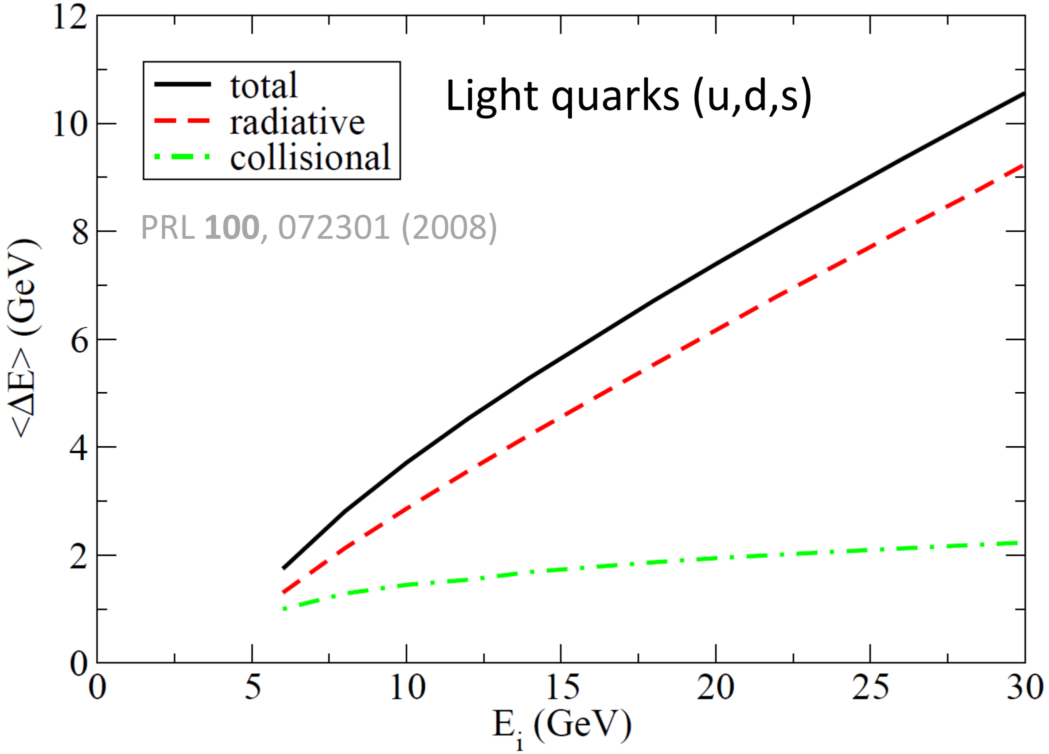
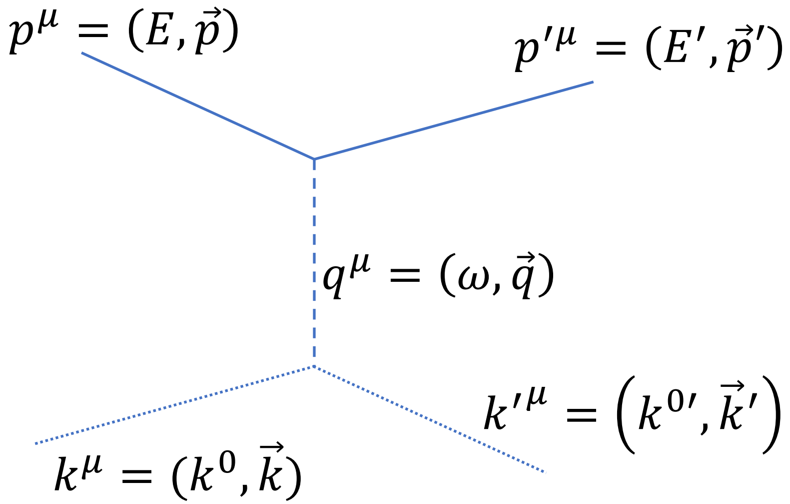
Scatterings inside the nuclear medium at low virtuality





- Collisional energy-loss (from 2 → 2 scattering):

$$\langle \Delta E \rangle = E - \int dx \, \frac{dE}{dx}$$

$$-\frac{dE}{dx} = \sum_{a=q,g} \int d^2q \int \underbrace{d^3k \, J \, \rho_a(k)}_{\text{Flux of incoming particles}} \underbrace{(\omega = E - E')}_{\text{Exchanged energy}} \underbrace{\frac{d\sigma^{Qa \to Qa}}{dq^2}}_{\text{differential cross-section}}$$

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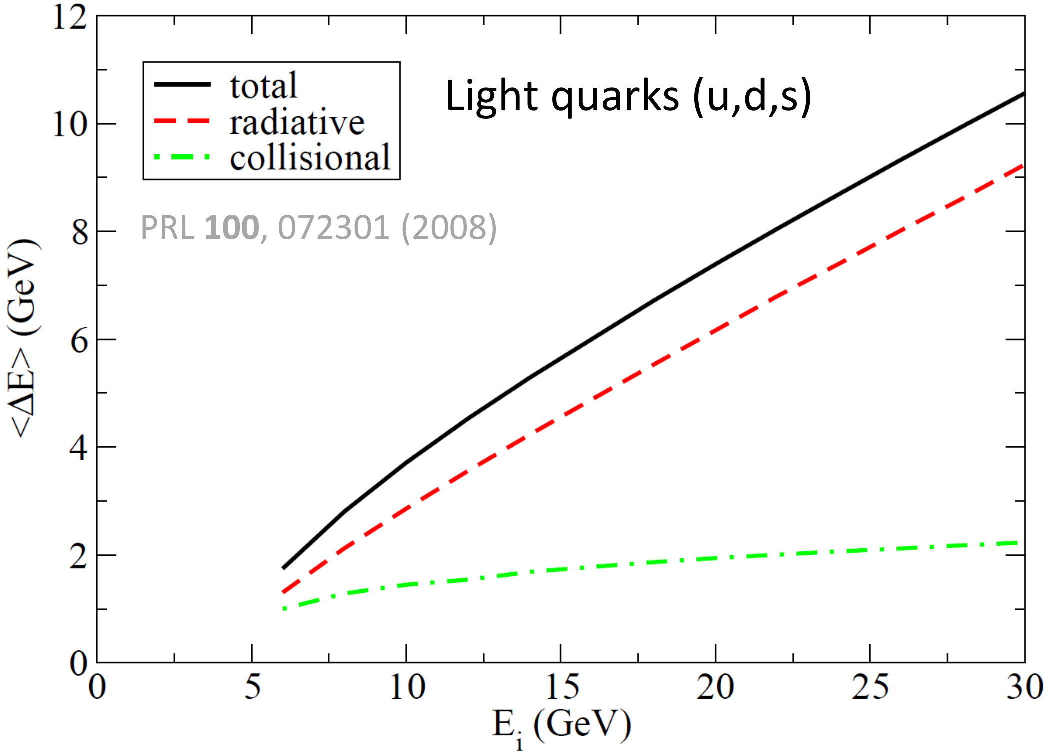
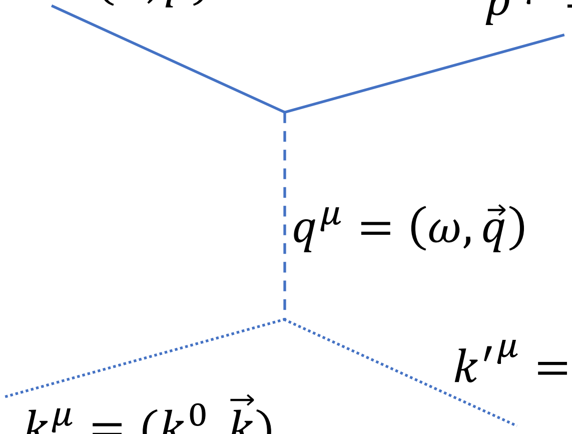


$p^\mu = (E, \vec{p})$ $\quad p'^\mu = (E', \vec{p}')$



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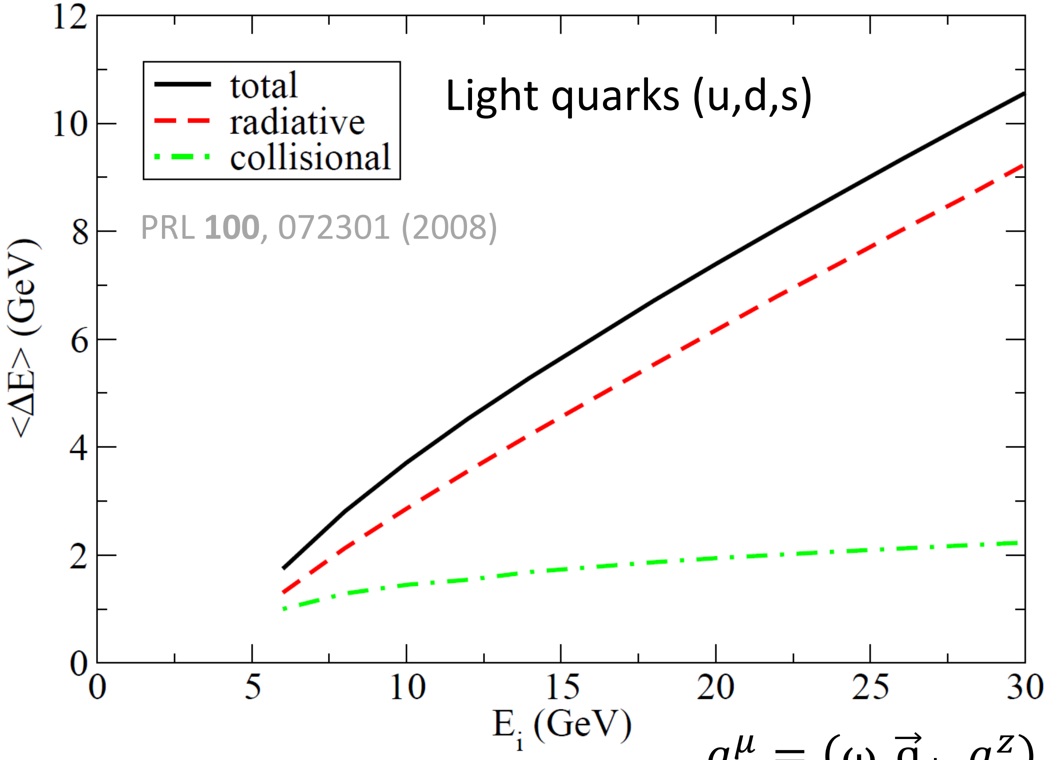
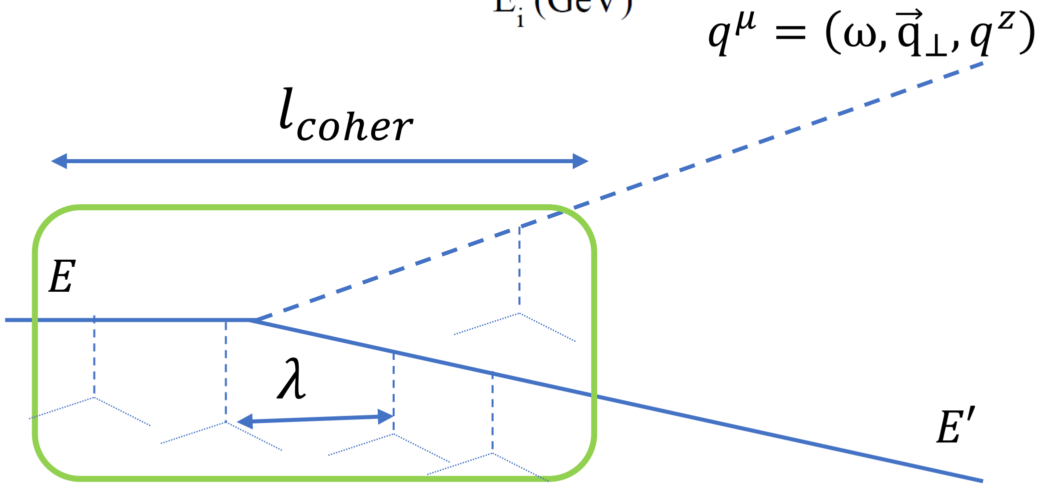
$$-\frac{dE}{dx} \approx \sum_{a=q,g} \int d^3k \, \frac{1}{\exp\frac{k^0}{T} \pm 1} \int dq^2 \, \frac{q^2}{2k} C_a \frac{2\pi\alpha_s^2}{(q^2)^2}$$

$$-\frac{dE}{dx} \sim \alpha_s T^2 \ln \frac{E}{T}$$

Radiation inside the nuclear medium at low virtuality





- Radiative energy-loss of long-lived partons via stimulated emission (induced by multiple coherent scatterings):

$$-\frac{dE}{dx} = \int_0^E d\omega\ \omega\ \frac{d^2N}{d\omega dx} \approx \int_0^E d\omega\ \underbrace{\frac{1}{l_{coher}}}_{\text{Length dependence}}\ \underbrace{\omega\ \frac{dN}{d\omega}}_{\text{Energy dependence}}$$

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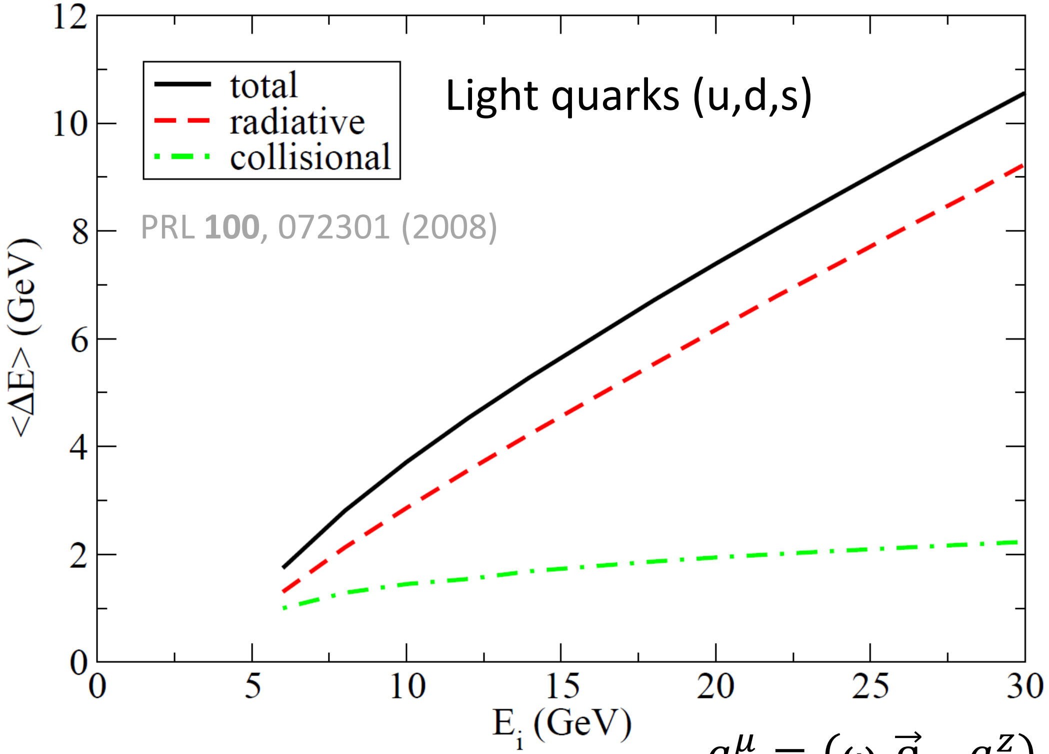

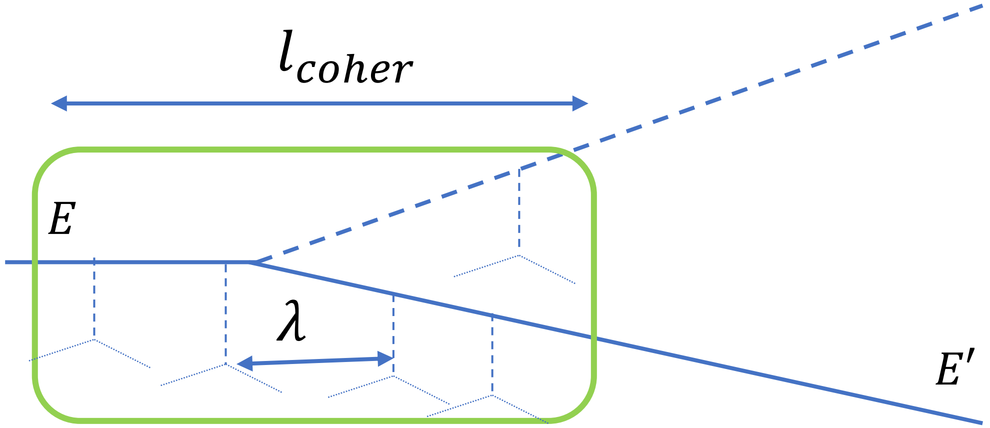

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Brownian-like motion ansatz

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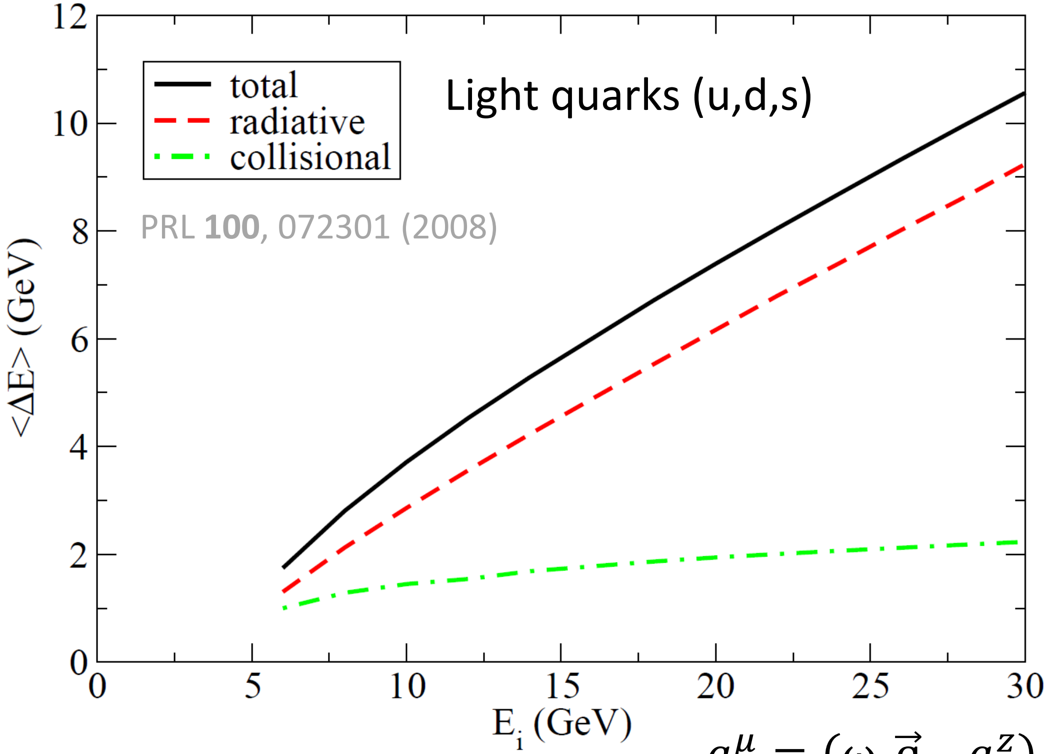

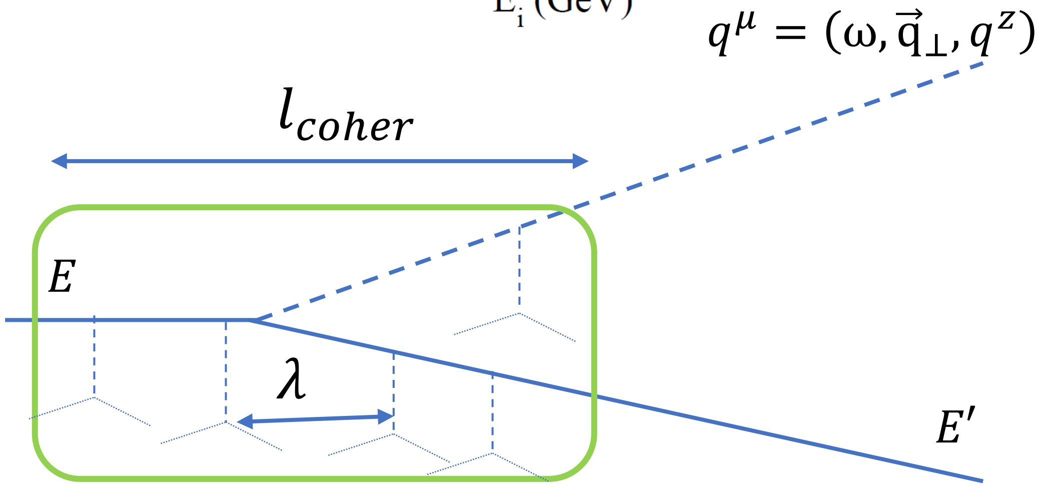

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$$\langle q_\perp^2 \rangle_{coher} \approx \frac{l_{coher}}{\lambda}\mu^2 \Rightarrow l_{coher} \approx \sqrt{\frac{\omega\lambda}{\mu^2}}$$

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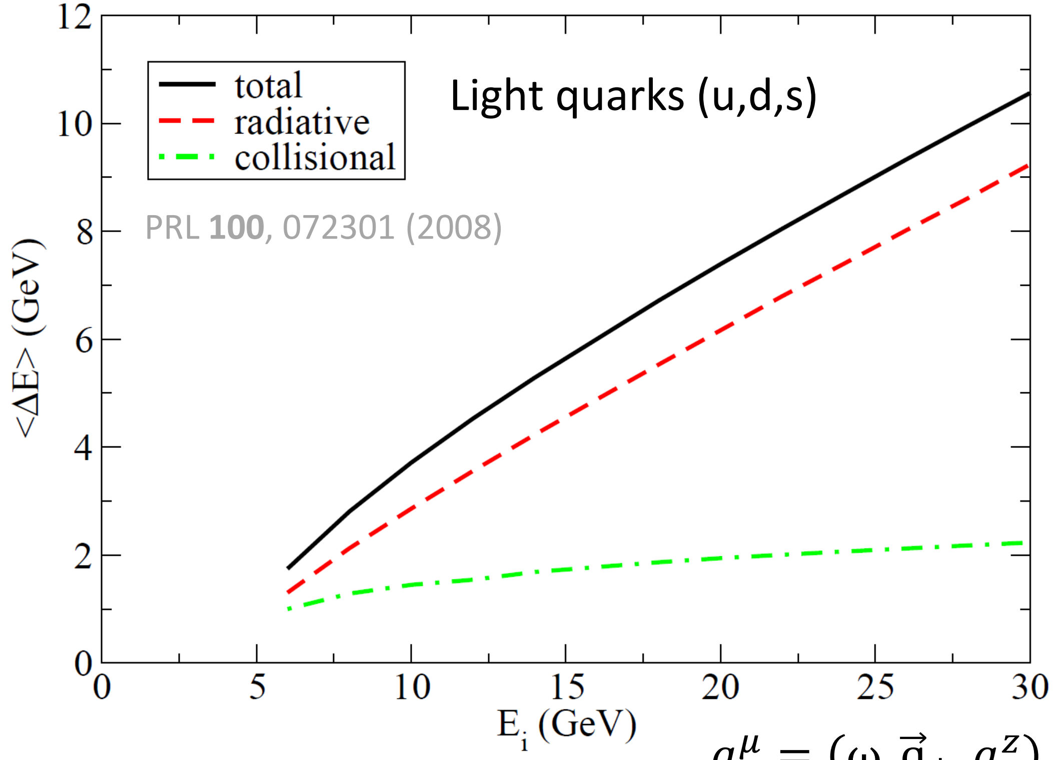
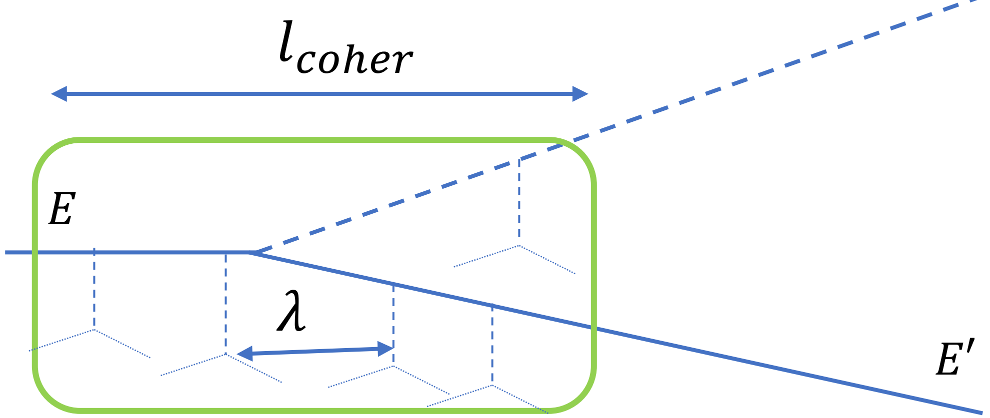


$q^{\mu} = (\omega, \vec{q}_{\perp}, q^z)$



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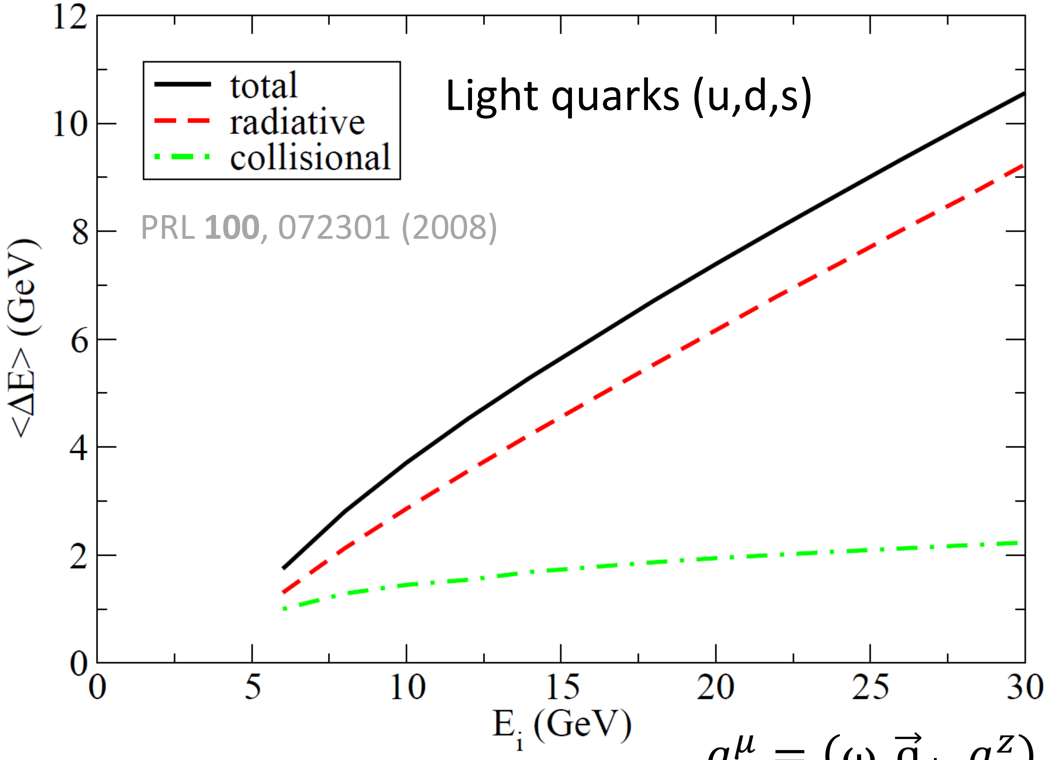
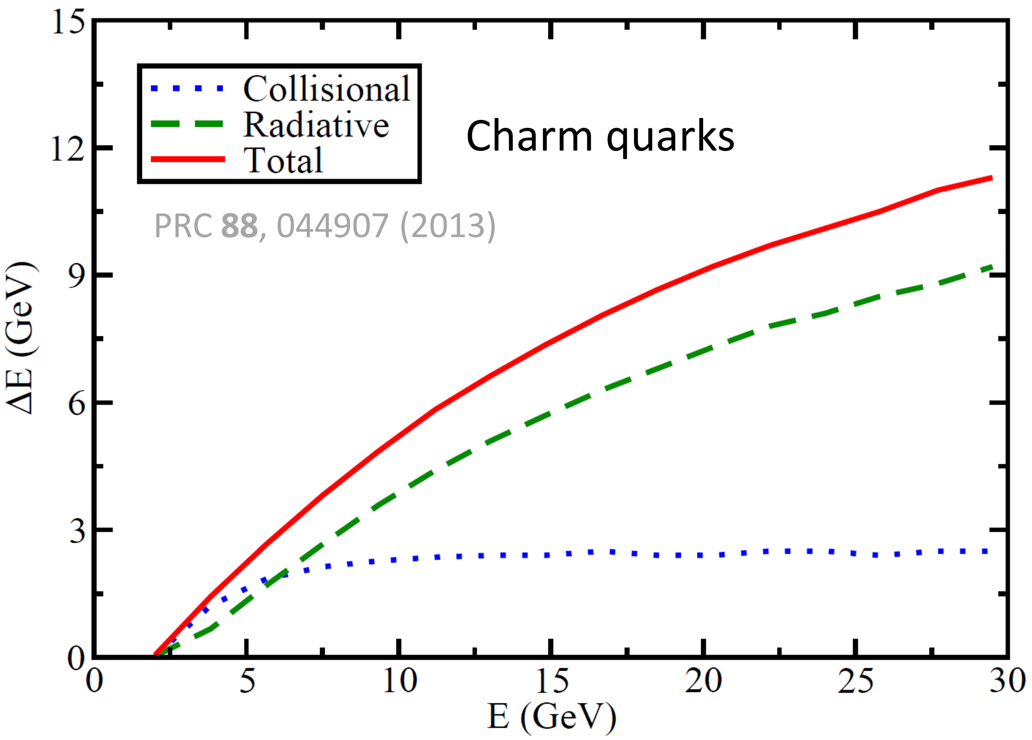
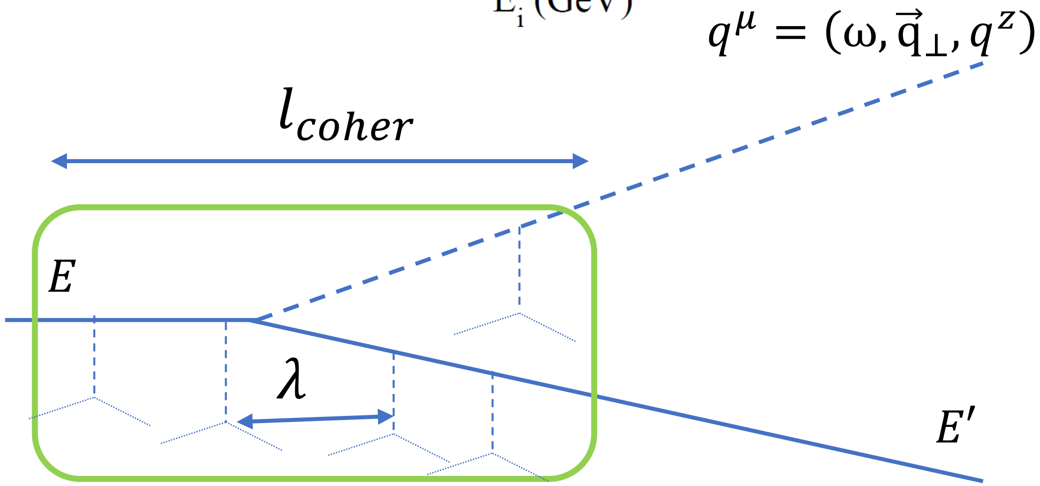
$$\omega \frac{dN}{d\omega} \to \frac{\alpha_s}{\pi} N_c \text{ (for } \omega \to 0\text{)}$$ Bethe-Heitler radiation spectrum

$$-\frac{dE}{dx} \approx \int_0^E d\omega \sqrt{\frac{\mu^2}{\lambda}} \frac{1}{\sqrt{\omega}} \frac{\alpha_s}{\pi} N_c \sim \sqrt{\frac{\mu^2}{\lambda}}\sqrt{E}$$

Radiation inside the nuclear medium at low virtuality





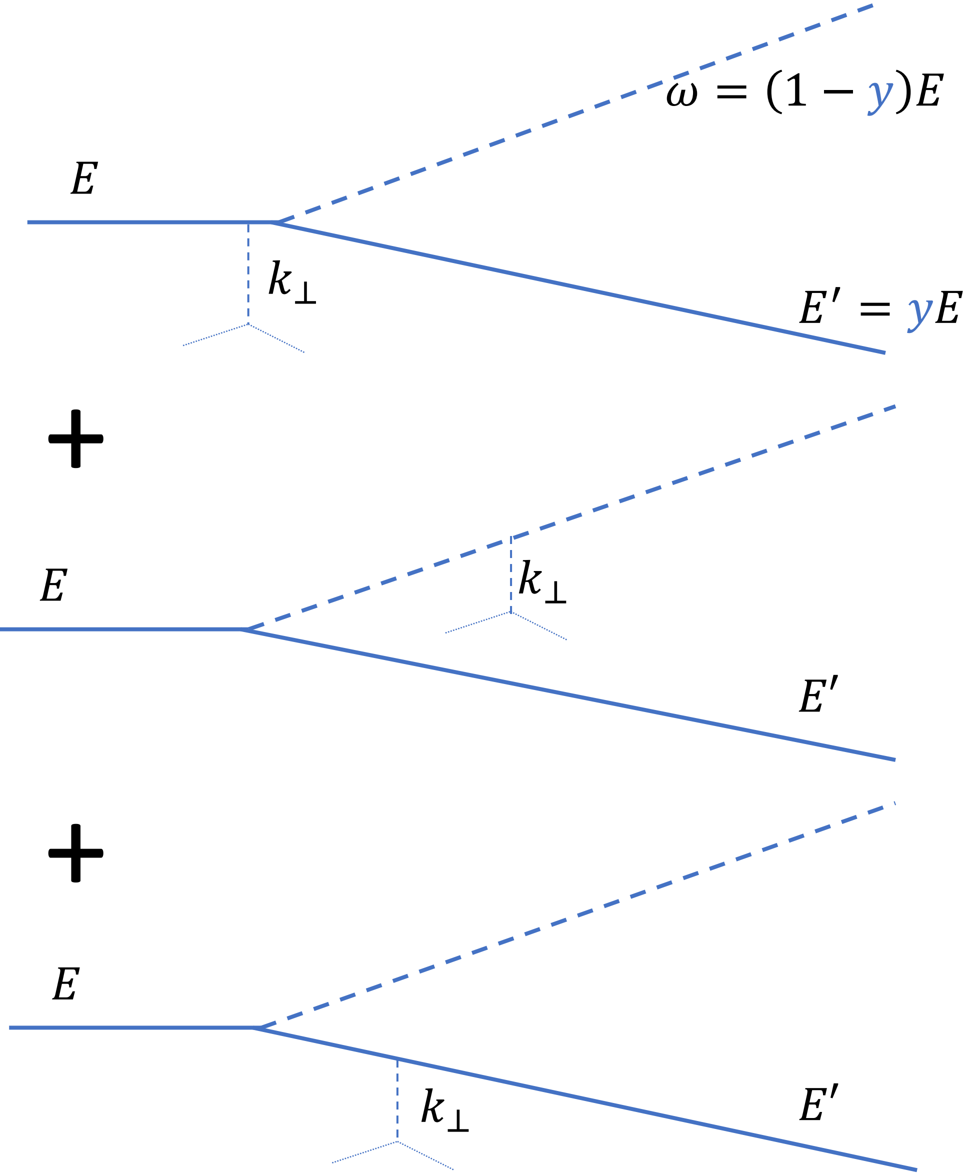


- Charm quarks behave similarly to light flavors, modulo finite mass effects on kinematics
- Together, scattering & radiation are used to solve the Boltzmann Transport (BT) equation:

$$p \cdot \partial f(x,p) = \mathcal{C}_{scatt} + \mathcal{G}_{rad}$$

- Linear BT (LBT) solves the Boltzmann eq. inside JETSCAPE

Radiation inside the nuclear medium at high virtuality

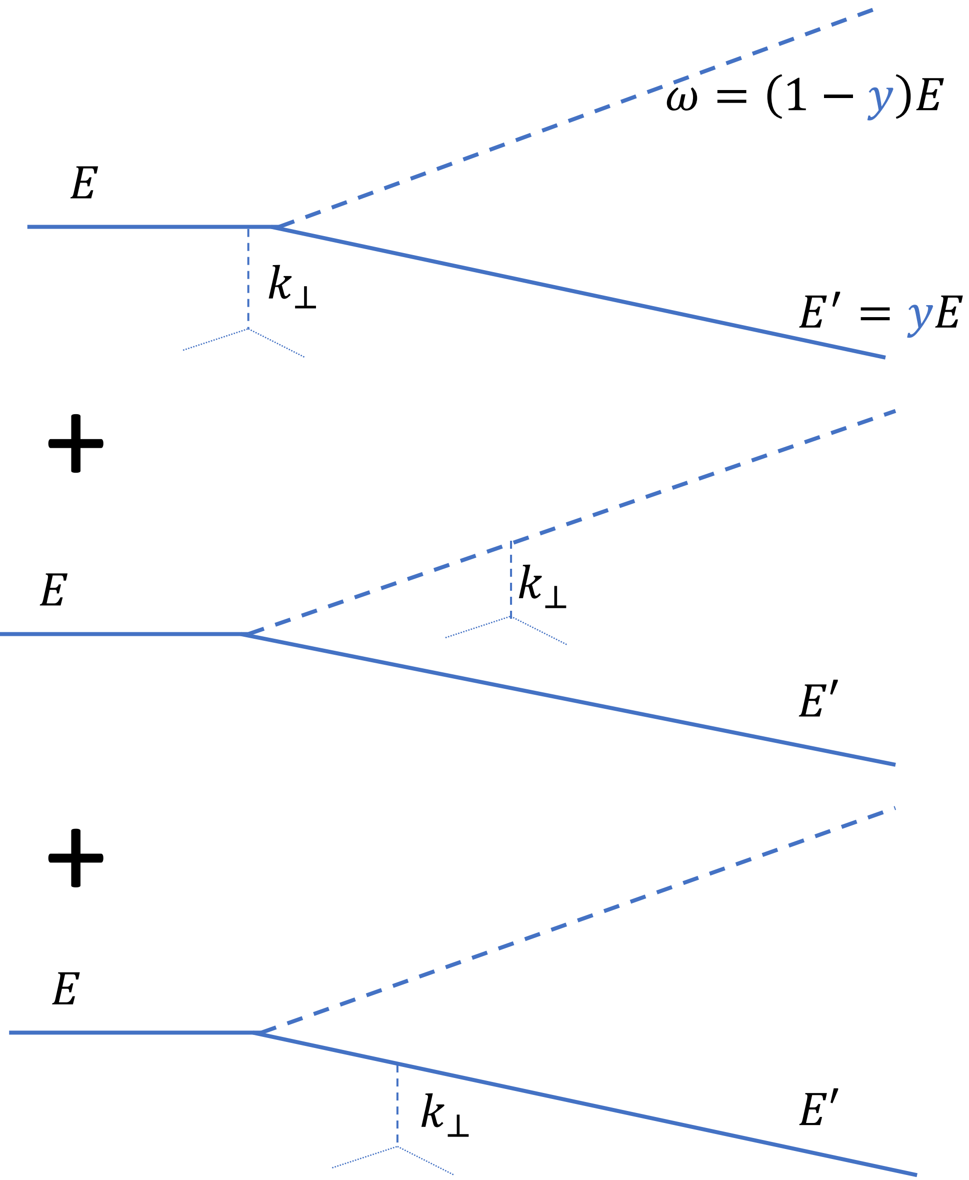


- Radiative energy-loss of short-lived partons (modified by single-scattering):

$$\frac{dN}{dy\,dQ^2} = \frac{\alpha_s}{2\pi Q^2}\mathcal{P}\left(y, Q^2\right) = \frac{\alpha_s}{2\pi\left(E^2 - \vec{p}^{\,2}\right)}\mathcal{P}\left(y, Q^2\right)$$

How much the splitting function $\mathcal{P}$ is modified in the medium depends on the lifetime/formation time $t_f(Q^2)$ of the split?

Radiation inside the nuclear medium at high virtuality



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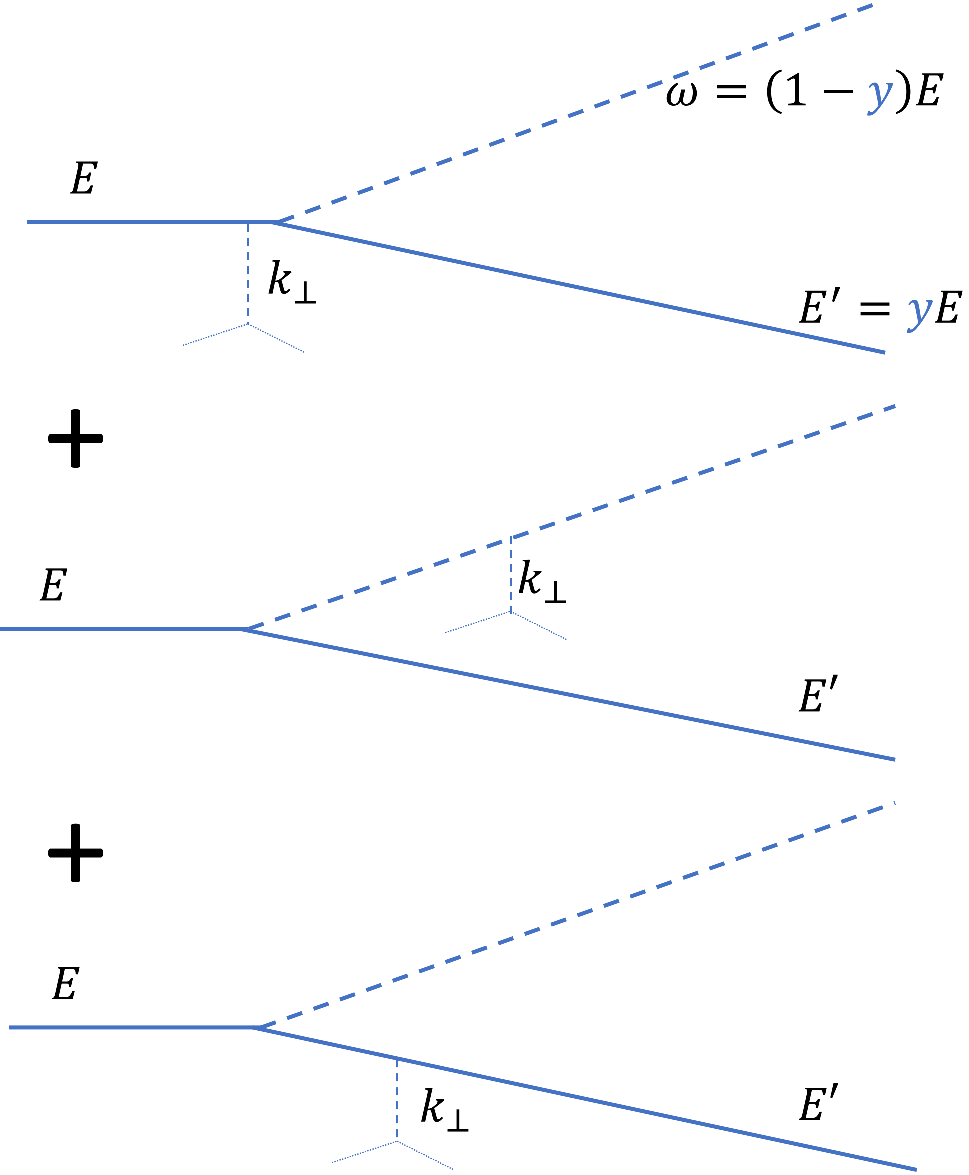
$$t_f(Q^2) = \frac{\omega}{y(1-y)Q^2} = \frac{\omega}{q_\perp^2} \approx \frac{\omega}{\langle q_\perp^2\rangle} \qquad \hat{q} = \frac{\langle q_\perp^2\rangle}{\lambda}$$

We parametrize $\hat{q}$ and fit it to data!

Radiation inside the nuclear medium at high virtuality



- Radiative energy-loss of short-lived partons (modified by single-scattering):

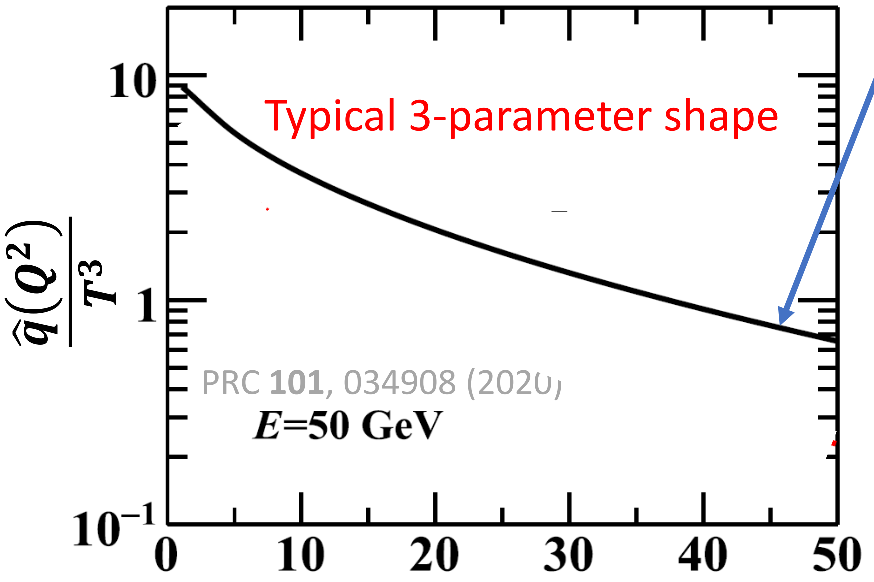
$$\frac{dN}{dy\,dQ^2} = \frac{\alpha_s}{2\pi Q^2}\mathcal{P}(y,Q^2) = \frac{\alpha_s}{2\pi(E^2-\vec{p}^2)}\mathcal{P}(y,Q^2)$$

$$t_f(Q^2) = \frac{\omega}{y(1-y)Q^2} = \frac{\omega}{q_\perp^2} \approx \frac{\omega}{\langle q_\perp^2\rangle} \qquad \hat{q} = \frac{\langle q_\perp^2\rangle}{\lambda}$$

We parametrize $\hat{q}$ and fit it to data!

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

$$P_{g\leftarrow q}(y) = \frac{1+y^2}{1-y}$$



An experimental observable

- To study the nuclear medium's effects on parton shower, one computes nuclear modification factor

$$R_{AA}^X = \frac{\frac{d\sigma_{AA}^X}{dp_T}}{N_{bin}\frac{d\sigma_{pp}^X}{dp_T}}$$

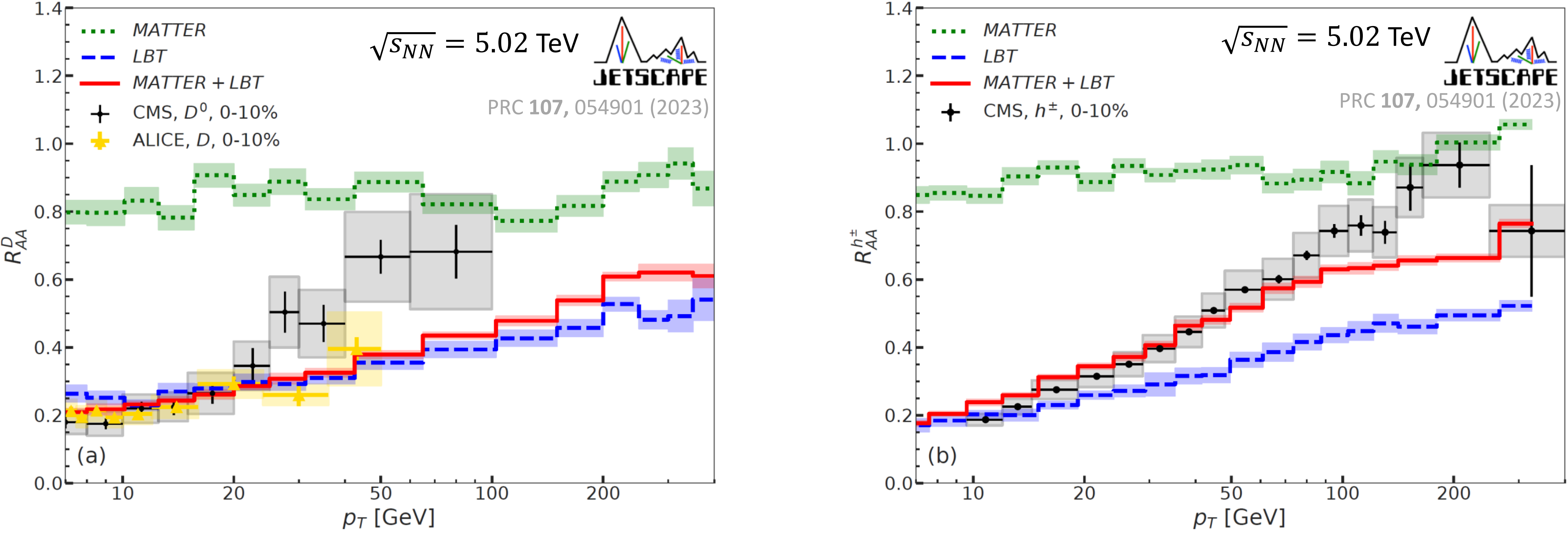
X is the leading (highest energy) hadron in a jet (which can be of an identified species or not)

- If an A-A collisions was the same as p-p collisions, then we can rescale the p-p collision by the N_{bin} binary collisions $\Rightarrow R_{AA}^X \rightarrow 1$.

- $R_{AA} < 1$ stems from two different sources:
  - Initial state effects: nuclear modifications to the parton distribution function.
  - Final state effects: creation of the QGP through which partons loose energy and the jet is quenched.

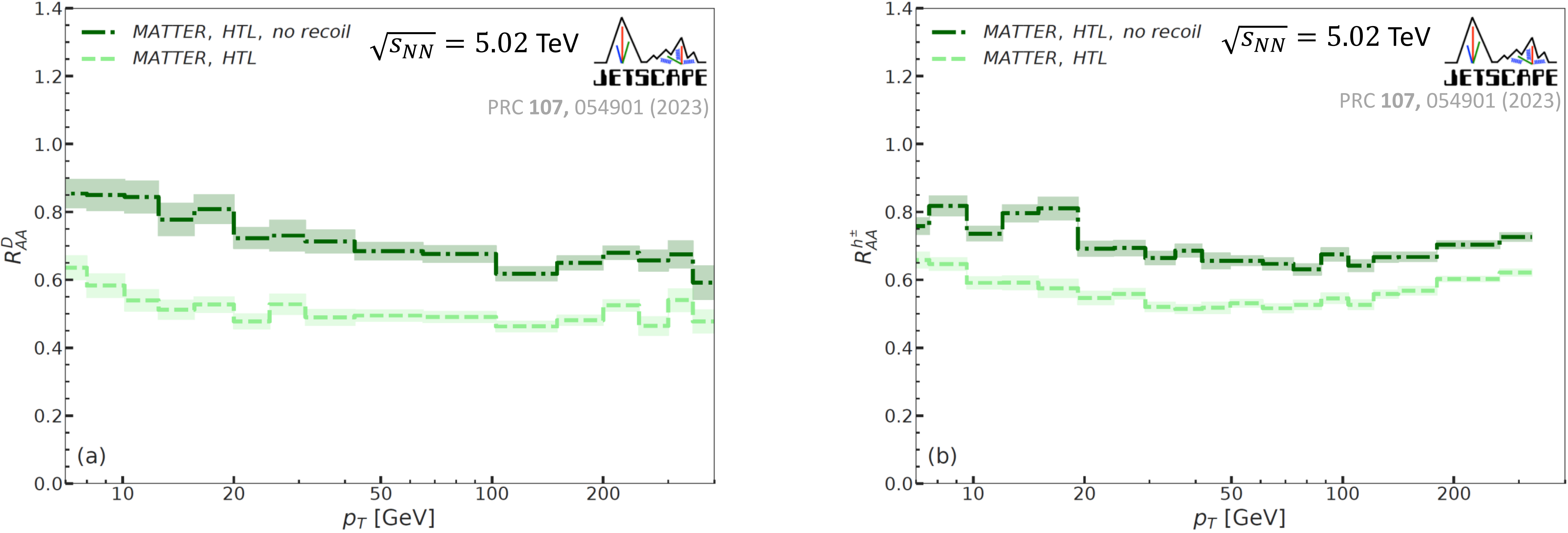
- The other extreme $R_{AA}^X \rightarrow 0$, means that all jets in A-A collisions get absorbed by the nuclear medium, i.e. there is no leading hadron.

Comparison with experiment



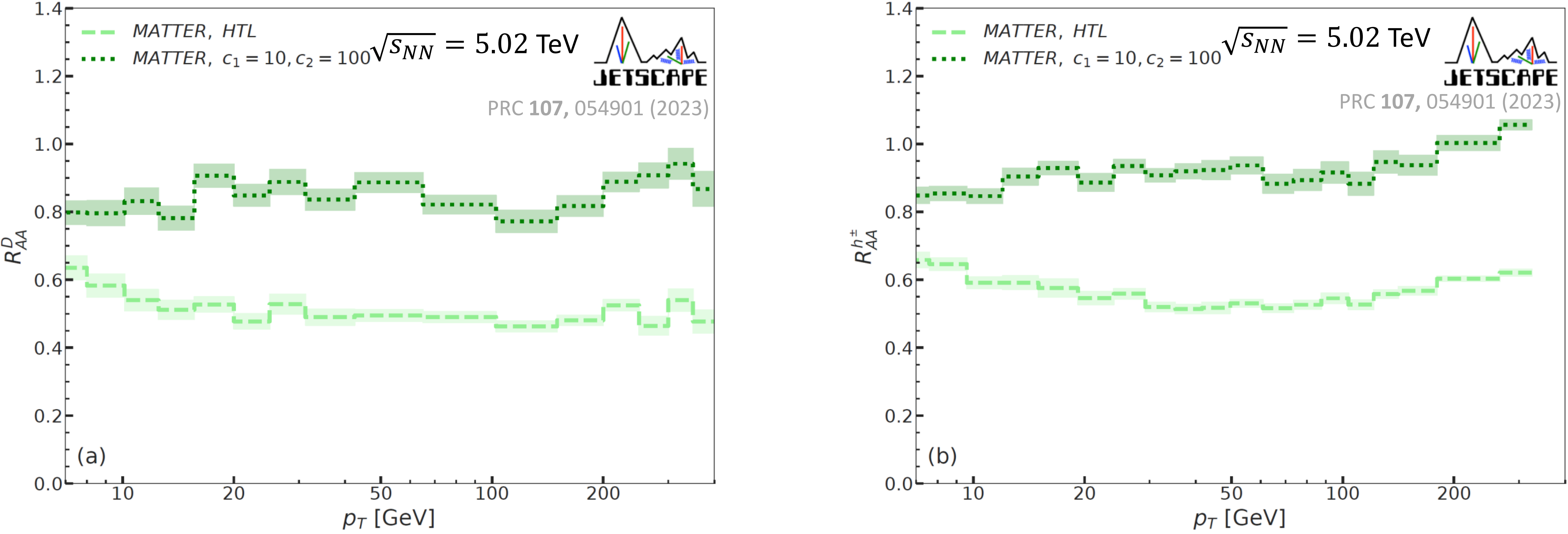
- To explain the experimental data (charged hadrons/D-mesons), a combination of high- and low-virtuality energy-loss models is needed.

Effects of scattering at high virtuality



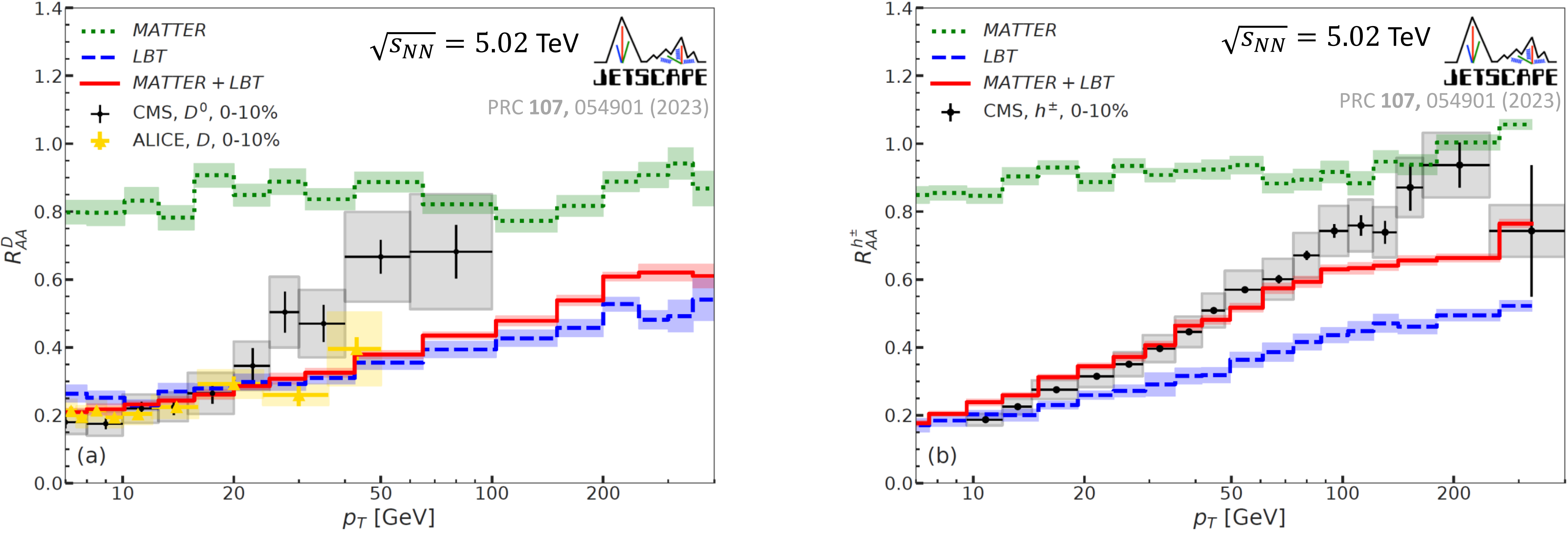
- For short-lived partons, it is unclear how important scattering really is.
- Using Q^2-independent, i.e. formation-time independent $\hat{q}_{HTL}$, and turning on/off the scattering, we see that the latter has a dramatic effect on the nuclear modification factor R_{AA}.

Effects of scattering at high virtuality



- Keeping scattering on and including $\hat{q}(Q^2)$ removes the high amount of quenching seen at high p_T.

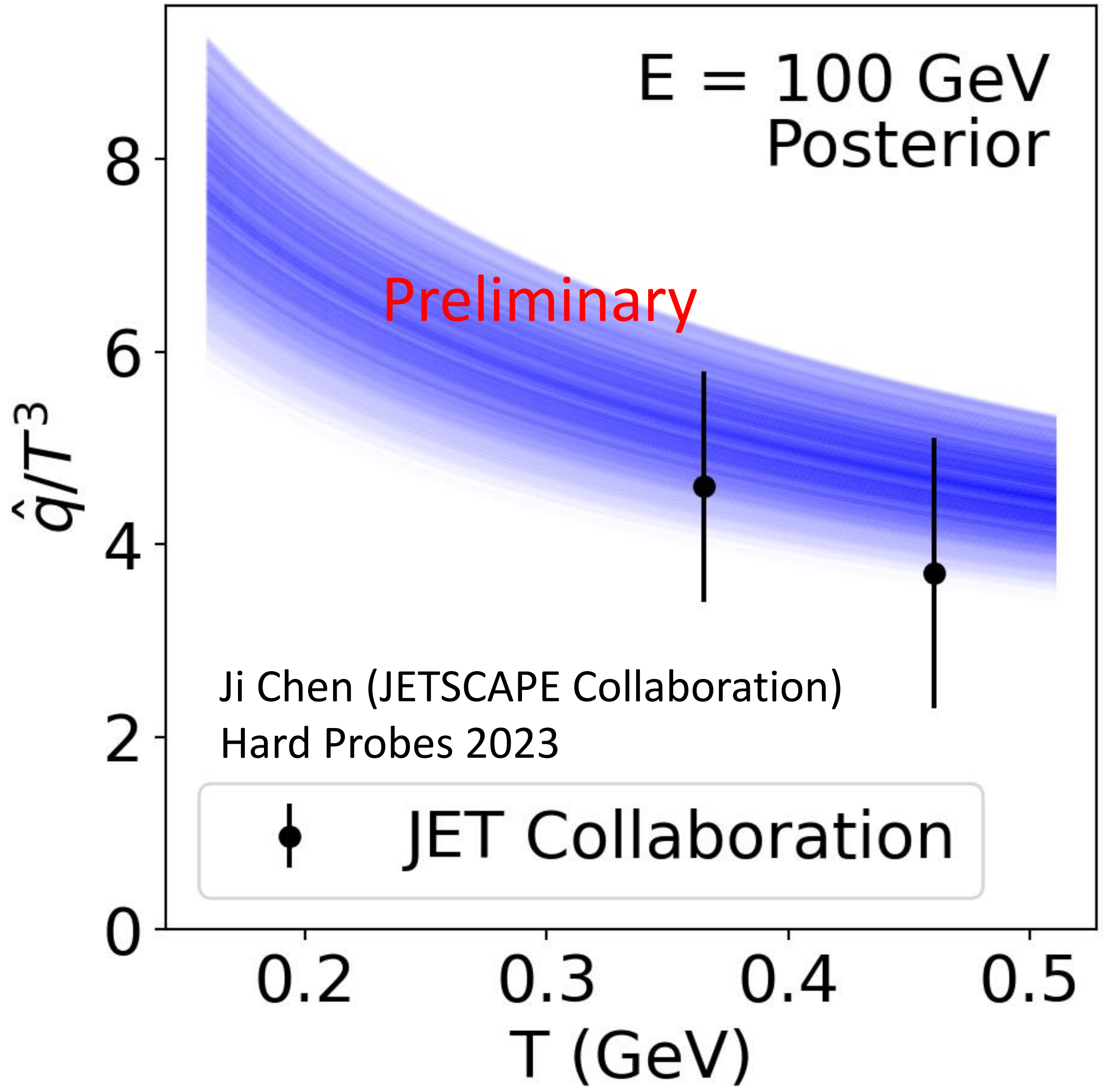
Effects of scattering at high virtuality



- Keeping scattering on and including $\hat{q}(Q^2)$ removes the high amount of quenching seen at high p_T.

$\Rightarrow$ Scattering and coherence effects are needed to explain the data.

First results and outlook



- A holistic Bayesian analysis is ongoing to determine $\hat{q}$ phenomenologically:
  - More collision energies and nuclear species:
    $\sqrt{s_{NN}} = 0.2$ TeV Au-Au
    $\sqrt{s_{NN}} = 2.76, 5.02$ TeV Pb-Pb
  - More centralities:

    From central (0-5%) to
    semi-peripheral (40-50%) collisions.
  - Different observables:
    $R_{AA}^{\pi}, \mathrm{R}^{\mathrm{h}^{\pm}}, \mathrm{R}_{\mathrm{AA}}^{\mathrm{jet}}(R = 0.2,0.3,0.4,0.8,1.0)$, …
- $\hat{q}(Q, T)$ is upcoming. Stay tuned…

Conclusions and Outlook

- There are two complementary ongoing efforts studying nuclear matter at high-energies:
  - Explore the nuclear viscous transport coefficients ($\zeta(T), \eta(T)$, …)
  - Explore how calibrated observables are modified owing to in-medium interactions (e.g., $\hat{q}$)

- Bayesian analysis are starting to become commonly used to constrain the above-mentioned properties of nuclear medium.
- As Bayesian analysis become more holistic (i.e., simultaneous extraction of viscous and jet-related transport coefficients) and computationally expensive $\Rightarrow$ more robust extraction (hot) nuclear medium properties is foreseen.
- However, rigorously accounting for both theoretical systematic uncertainties (e.g. higher order corrections need to be calculated) and experimental systematic uncertainties (experiments need to publish the full covariance matrix of measurements) is a must.
- An era of concentrated and great collaborative work is foreseen!