Multistage Jet Evolution in Heavy-Ion Collisions

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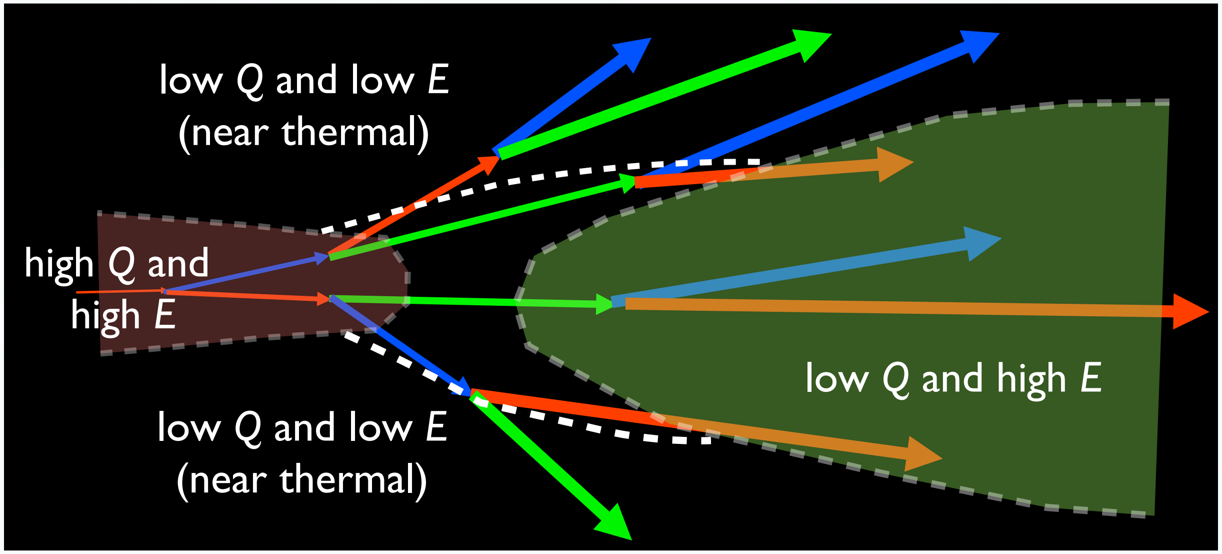
(On behalf of the **JETSCAPE** Collaboration work **arxiv:1705.00050**)

Outline

- Introduction
- Combining theories at different stages of jet evolution: high and low virtuality
- Numerical results on medium modification of jet fragmentation function and jet shape
- Summary and outlook

Full evolution of jets in heavy-ion collisions



low *Q* and low *E*
(near thermal)

high *Q* and
high *E*

low *Q* and high *E*

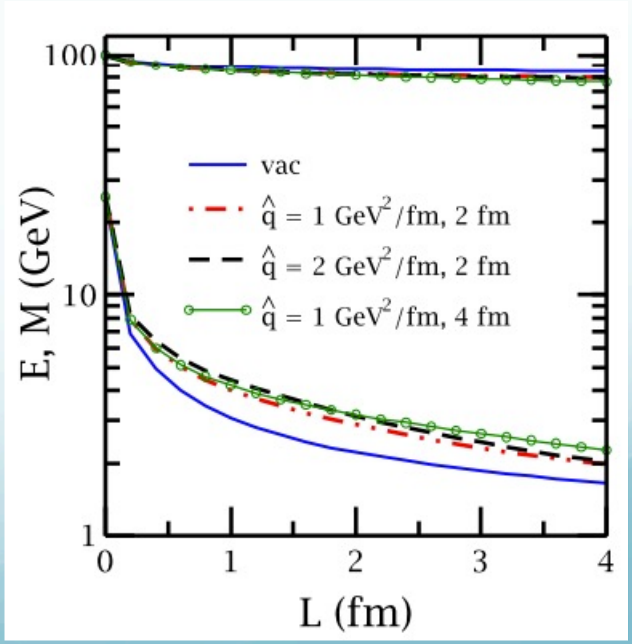
low *Q* and low *E*
(near thermal)

Jet partons are produced with high *Q* and high *E* (**DGLAP, higher-twist**)

-> lose *Q* faster than *E* [Majumder and Putschke, PRC 93 (2016) 054909]

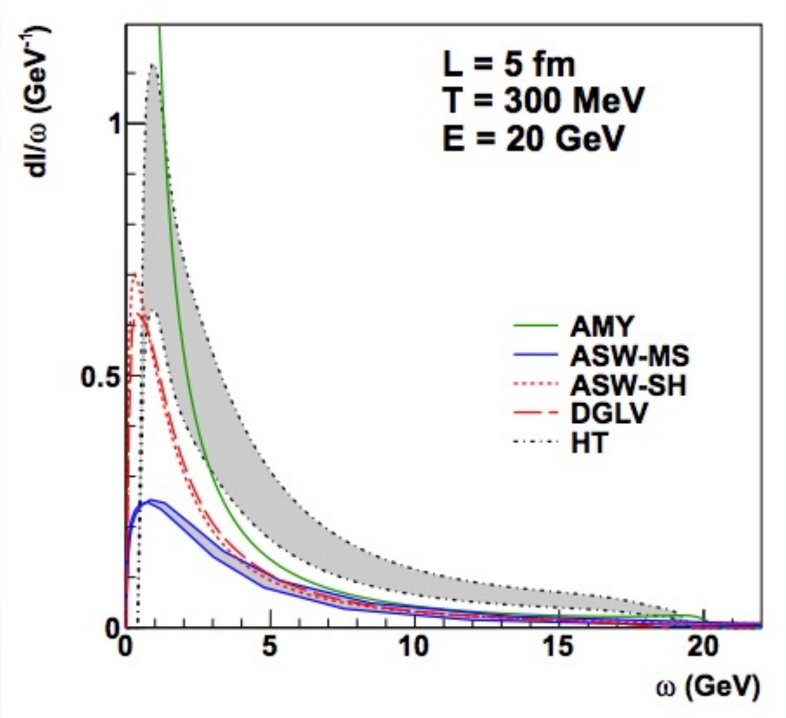
-> low *Q* and high *E* -> low *Q* and low *E* (**Transport, higher-twist, AMY**)

-> low *Q* and low *E* (near thermal) (**strongly coupled approach**)

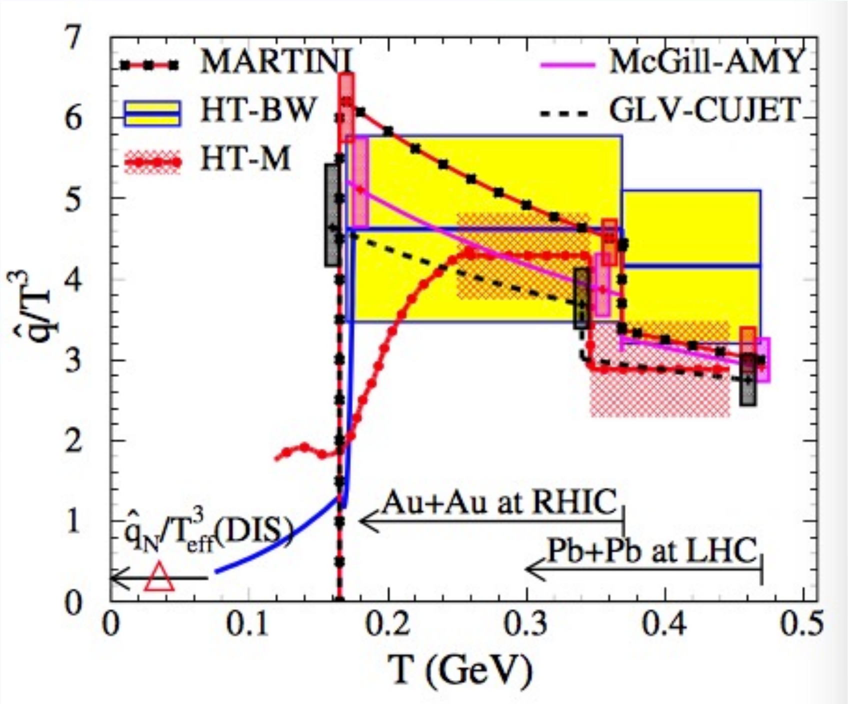


Milestones of collaboration work

[**TECHQM**: PRC 86 (2012) 064904]



[**JET**: PRC 90 (2014) 014909]



TECHQM: comparison of medium-induced gluon spectra in a brick

JET: constraint of $\hat{q}$ in realistic hydro medium using different theories

JETSCAPE: to ***combine*** different theories into a unified approach and provide a ***Monte-Carlo generator***: DGLAP (high *Q*) + transport (low *Q*) + strongly coupled (thermal)

JETSCAPE

Stage 1: high *Q* and high *E*

DGLAP evolution for parton fragmentation function at high *Q*:

$$\frac{\partial}{\partial Q^2} D(z, Q^2) = \frac{\alpha_s}{2\pi} \frac{1}{Q^2} \int_z^1 \frac{dy}{y} P(y) D\left(\frac{z}{y}, Q^2\right)$$

Sudakov form factor (probability of NO detectable splitting between *Q* and $Q_{\rm max}$):

$$\Delta(Q_{\rm max}, Q) = \exp\left[-\frac{\alpha_s}{2\pi} \int_{Q^2}^{Q^2_{\rm max}} \frac{dQ^2}{Q^2} \int_{z_c}^{1-z_c} \frac{dy}{y} P(y)\right]$$

Splitting function:

$$P_i(y) = P_i^{\rm vac}(y) + P_i^{\rm med}(y)$$

$$P_i^{\rm med}(y, k_\perp^2) = \frac{2C_A\alpha_s}{\pi k_\perp^4} P_i^{\rm vac}(y) \int_{t_i}^{t_{\rm max}} dt \hat{q}_i(t) \sin^2\left(\frac{t - t_i}{2\tau_f}\right)$$

[*higher-twist* energy loss formalism: Guo and Wang (2000), Majumder (2012)]

i: *q->qg, g->gg, or g->q$\bar{q}$*

$\hat{q}$: $dp_\perp^2/dt$ of quark/gluon due to 2->2 scatterings

Stage 1: high *Q* and high *E*

MATTER (The **M**odular **A**ll **T**wist **T**ransverse-scattering **E**lastic-drag and **R**adiation) [Wayne: PRC 88, 014909, arXiv:1702.05862)]

Monte-Carlo Implementation: $0 < r < 1$

$r \geq \Delta(Q_{\max}, Q_0)$ splitting happens above Q_0 (min. allowed virtuality)

$r \leq \Delta(Q_{\max}, Q) = \dfrac{\Delta(Q_{\max}, Q_0)}{\Delta(Q, Q_0)}$ no splitting above *Q*

→ splitting happens at (or below) scale *Q*

For a given splitting, the p^+ fraction of the two daughter partons are determined by *P*(*z*), and p_T w.r.t. the parent parton is determined by the difference in invariant mass between the parent and daughters.

This *Q* also becomes the new $Q_{\max}$ for the next splitting (iteration)

→ a vituality-ordered parton showers from initial $Q_{\max}$ to Q_0

Stage 2: low *Q* and high *E*

LBT or **MARTINI** (time-ordered transport model) simulates parton showers at (or below) Q_0 (with on-shell approximation)

LBT (**L**inear **B**oltzmann **T**ransport) [talk by T. Luo and W. Chen on Wed.]

[LBL-CCNU: PRL 111 (2013) 062301, PRC 94 (2016) 014909, arXiv:1704.03648]

Evolution of jet parton "1": $p_1 \cdot \partial f_1(x_1, p_1) = E_1(\mathcal{C}_{\mathrm{el}} + \mathcal{C}_{\mathrm{inel}})$

Elastic Scattering rate:

$$\Gamma^{\mathrm{el}}_{12\to 34}(\vec{p}_1) = \frac{\gamma_2}{2E_1}\int \frac{d^3p_2}{(2\pi)^3 2E_2}\int \frac{d^3p_3}{(2\pi)^3 2E_3}\int \frac{d^3p_4}{(2\pi)^3 2E_4}$$
$$\times f_2(\vec{p}_2) S_2(s,t,u)(2\pi)^4 \delta^{(4)}(p_1+p_2-p_3-p_4)|\mathcal{M}_{12\to 34}|^2$$

Inelastic scattering rate (average gluon number per *Δt*):

$$\Gamma^{\mathrm{inel}} = \langle N_g\rangle(E,T,t,\Delta t)/\Delta t = \int dx dk_\perp^2 \frac{dN_g}{dx dk_\perp^2 dt}$$

- Medium-induced gluon spectrum is taken from HT (same as MATTER)
- Multiple gluon emission in *Δ*t is allowed – assuming Possion distribution

Stage 2: low *Q* and high *E*

MARTINI (**M**odular **A**lgorithm for **R**elativistic **T**reatment of heavy **IoN** **I**nteractions) [McGill: PRC 80 (2009) 054913, arXiv:0909.2037]

Energy loss mechanism in MARTINI is based on the AMY radiative formalism coupled with collisional energy loss

AMY formalism for 1-2 splittings where LPM effect is included:

$$\frac{d\Gamma(p,k)}{dk} = \frac{C_s g_s^2}{16\pi p^7}\frac{1}{1\pm e^{-k/T}}\frac{1}{1\pm e^{-(p-k)/T}} \times \begin{Bmatrix} \frac{1+(1-x)^2}{x^3(1-x)^2} & q\to qg \\ N_f\frac{x^2+(1-x)^2}{x^2(1-x)^2} & g\to qq \\ \frac{1+x^4+(1-x)^4}{x^3(1-x)^3} & g\to gg \end{Bmatrix} \times \int \frac{d^2\mathbf{h}}{(2\pi)^2} 2\mathbf{h}\cdot \mathrm{Re}\,\mathbf{F}(\mathbf{h},p,k)$$

[S. Jeon and G. Moore PRC 71 (2005) 034901, S. Jeon NPA 830 (2009) 107]

F(*h*, *p*, *k*) [*p* – jet parton, *k* – emitted gluon, **h** = **p** × **k**] is the solution of an integral (Schwinger-Dyson) equation describing how $|p - k; k\rangle\langle p|$ evolves with *t* due to collisions and the energy difference between the two states.

Elastic scattering rate for 2->2 scattering process is included:

$$\frac{d\Gamma_{\rm el}}{d\omega}(E,\omega,T) = d_k\int_{kk'}\frac{2\pi}{4pp'}\delta(p-p'-\omega)\delta(k'-k-\omega)\,|\mathcal{M}|^2 f(k,T)(1\pm f(k',T))$$

Stage 2: low *Q* and high *E*

Monte-Carlo implementation of MARTINI

The evolution of jet momentum in MARTINI is governed by a set of coupled Fokker-Planck type rate equations:

$$\frac{dP(p)}{dt} = \int_{\infty}^{\infty} dk \left(P(p+k)\frac{d\Gamma(p+k,k)}{dk} - P(p)\frac{d\Gamma(p,k)}{dk} \right)$$

The integral for k < 0 represents energy gain for the parton

For Monte-Carlo implementation

- Every parton is treated individually
- At each time step, transition rates are determined according to the local temperature of background and energy of partons
- When scattering happens, new momentum (momentum transfer) *k* is sampled using the differential transition rate
- Evolution continues if momentum of the parton is above certain threshold (~2 GeV)

Separation scale between MATTER and LBT/MARTINI

MATTER (*virtuality-ordered*) evolves partons down to Q_0 and LBT/MARTINI (*time-ordered*) continues parton evolution at (or below) Q_0

- **Fixed Q_0** (both in vacuum and medium): 1, 2 or 3 GeV will be used and compared.
- **Dynamical Q_0** (virtuality gain from scattering with the medium):

$$Q_0^2 = \hat{q}\tau_f \qquad \tau_f = 2E/Q_0^2$$

$$\Longrightarrow \qquad Q_0^2 = \sqrt{2E\hat{q}}$$

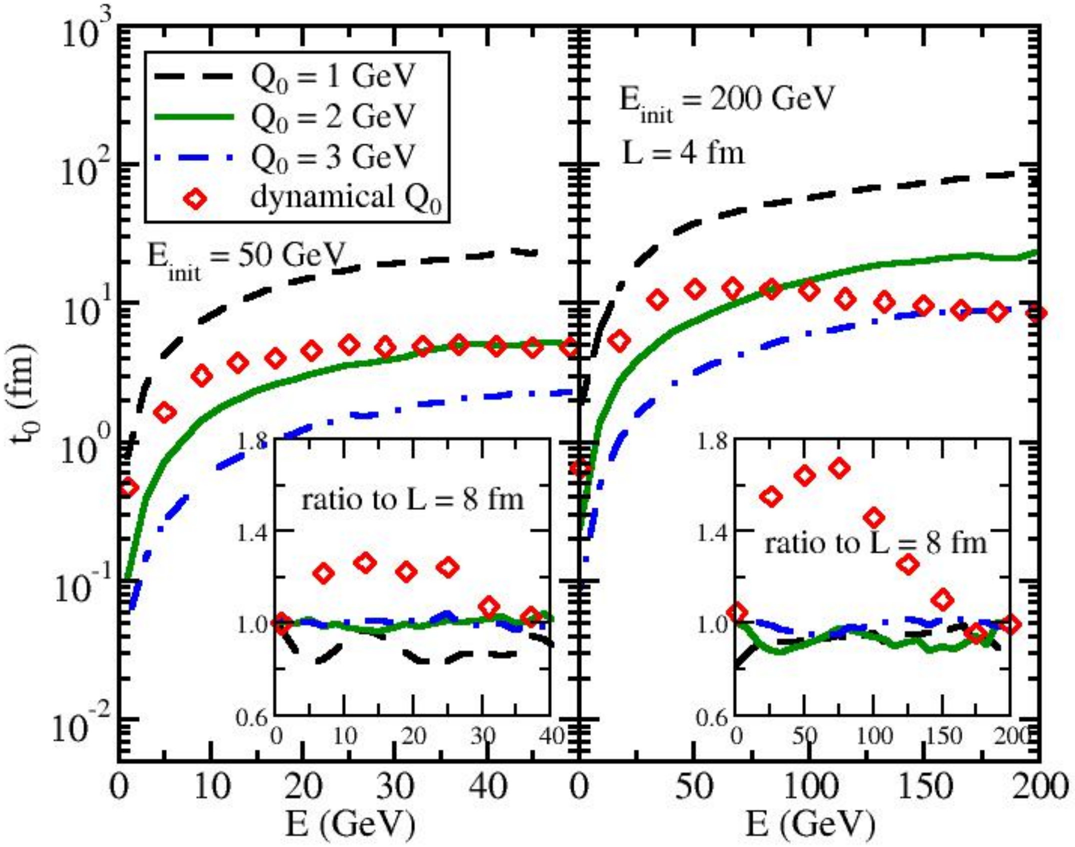
$$\hat{q} = C_R \alpha_s \mu_D^2 T \log\left(\frac{6ET}{\mu_D^2}\right) \qquad \mu_D^2 = 6\pi\alpha_s T^2$$

* Dynamical Q_0 is only meaningful in a thermal medium, in vacuum, Q_0 = 1 GeV vacuum

In this work, static medium with T = 250 MeV is used. Effects of medium length L and initial parton (quark) energy E will be investigated.

Switching t_0 between MATTER and LBT/MARTINI

$t_0 = \sum_i 2E_i/Q_i^2$ when a given parton hit Q_0 after multiple splittings



The time MATTER takes to evolve jet parton down to Q_0 is NOT small (vs. τ_0).

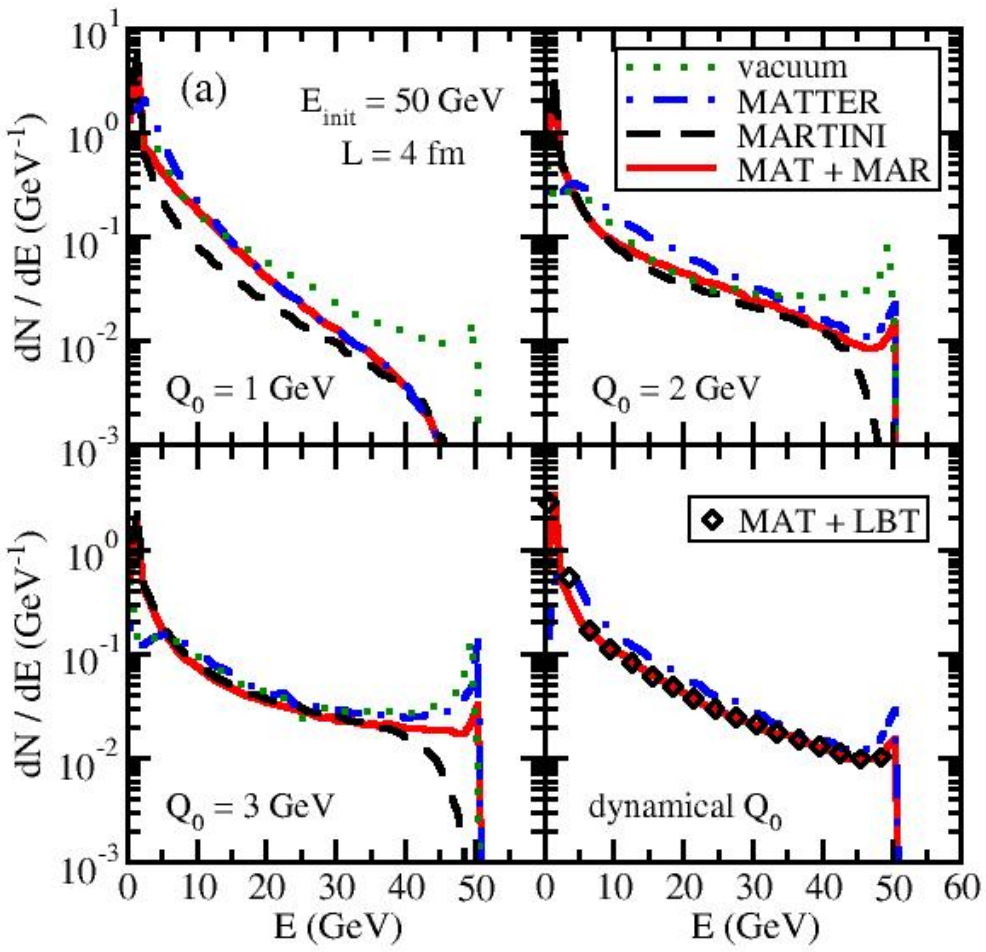
Separation time (t_0) increases if Q_0 decreases or E_{init} increases.

For E_{init} = 50 GeV, L = 4 fm, dynamical Q_0 is consistent with 2 GeV at the high E end, but approaches 1 GeV at low energy. For E_{init} = 200 GeV, dynamical Q_0 starts at 3 GeV at the high E end.

For fixed Q_0, changing from L = 4 to 8 fm increases scattering process (virtuality gain) and thus may delay t_0; for dynamical Q_0, extending L increases the range where larger Q_0 is applied and shortens t_0.

dN/*dE* for E_i = 50 GeV and *L* = 4 fm

Energy distribution of final shower partons from a single quark at *E* = 50 GeV through a brick with *T* = 250 MeV and *L* = 4 fm



Vacuum: Sudakov type of shower with vacuum splitting function

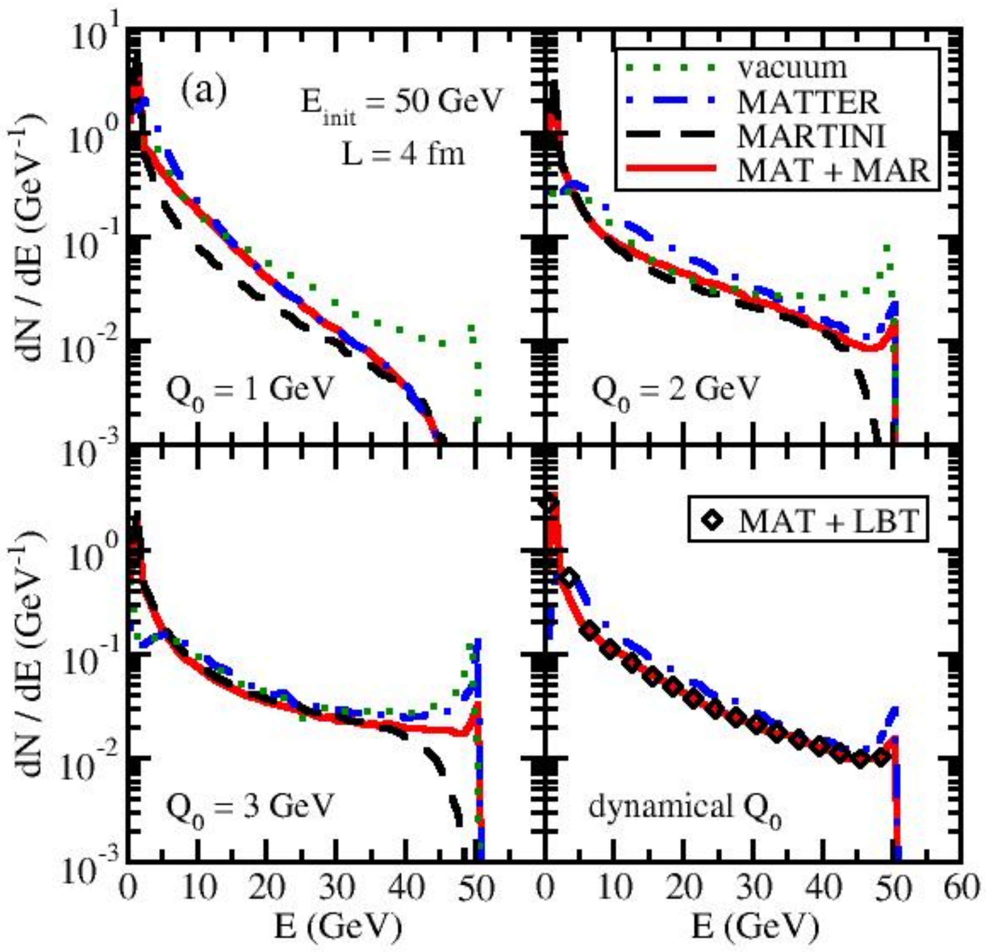
MATTER: Sudakov type of shower with vacuum + medium modified splitting function

LBT/MARTINI: Partons from vacuum shower evolve the entire 4 fm in LBT/MARTINI

MATTER+LBT/MARTINI: Combined scheme – partons evolve in MATTER up to t_0 and then in LBT/MARTINI up to 4 fm

dN/*dE* for E_i = 50 GeV and *L* = 4 fm

Energy distribution of final shower partons from a single quark at *E* = 50 GeV through a brick with *T* = 250 MeV and *L* = 4 fm



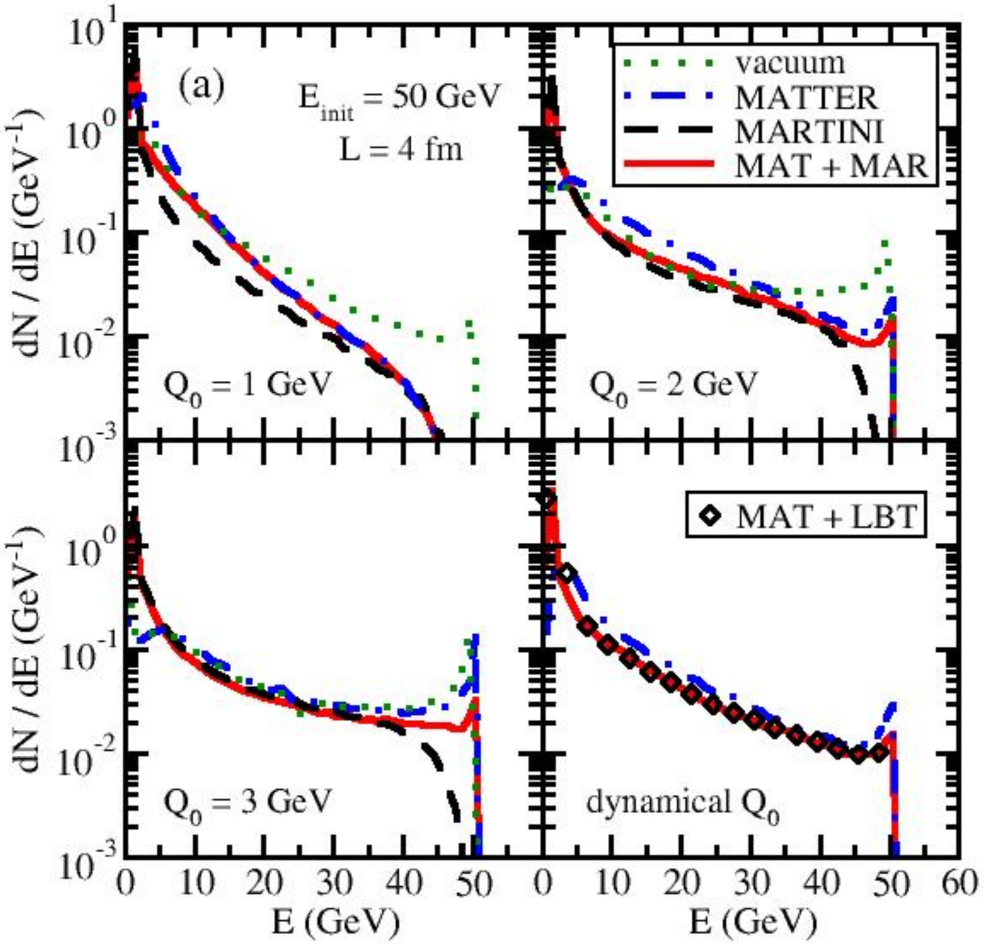
MARTINI and LBT provide consistent results despite different single gluon spectrum from AMY vs. HT – washed out by multiple emission implementation.

For E_{init} = 50 GeV, MATTER evolution (w.r.t vacuum shower) is weak if Q_0 > 2 GeV (scale of the medium $\hat{q}\tau_f$).

Pure MARTINI evolution is stronger than pure MATTER since there is no constraint from scale dependence in time-ordered transport model.

dN/*dE* for E_i = 50 GeV and *L* = 4 fm

Energy distribution of final shower partons from a single quark at *E* = 50 GeV through a brick with *T* = 250 MeV and *L* = 4 fm

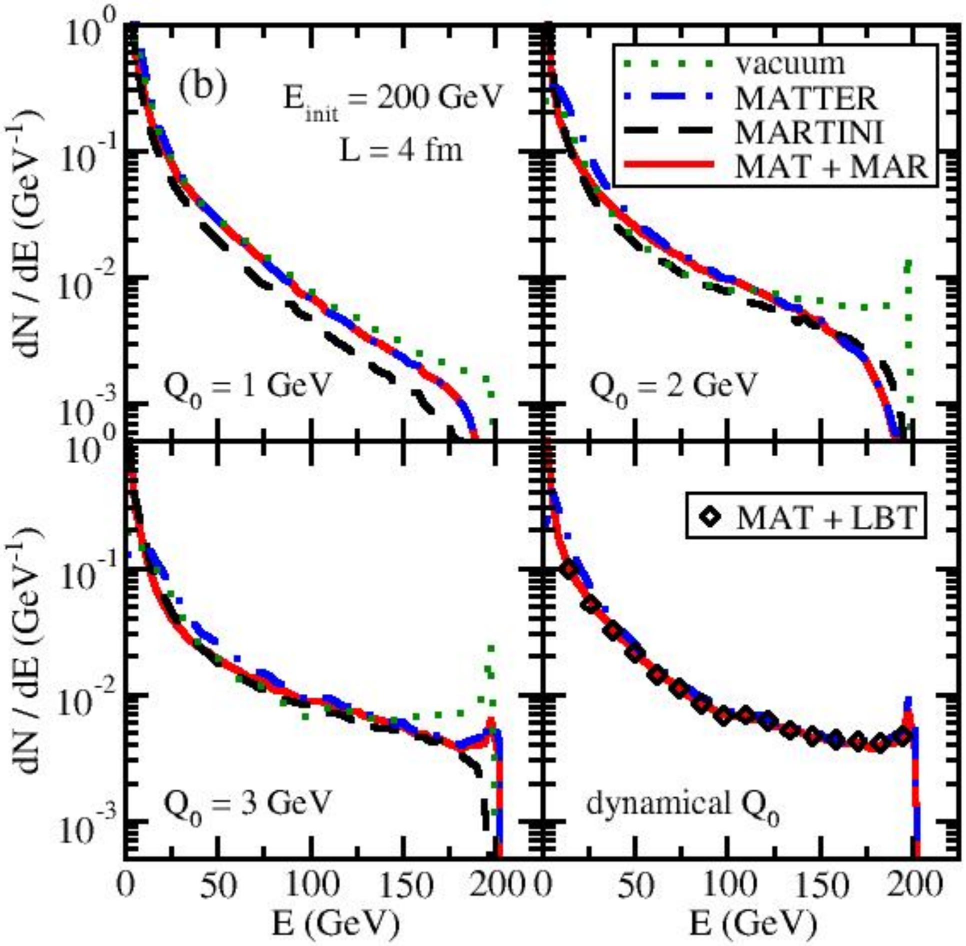


Effect of MARTINI in MATTER + MARTINI is strong for low energy partons, but is weaker for high energy ones since it took longer time for them to hit Q_0 in MATTER and leaves no time for MARTINI evolution. This is more obvious when Q_0 is smaller.

Dynamical Q_0 is close to the fixed Q_0 = 2 GeV case when E_{init} = 50 GeV.

dN/*dE* for E_i = 200 GeV and *L* = 4 fm

Energy distribution of final shower partons from a single quark at *E* = 200 GeV through a brick with *T* = 250 MeV and *L* = 4 fm

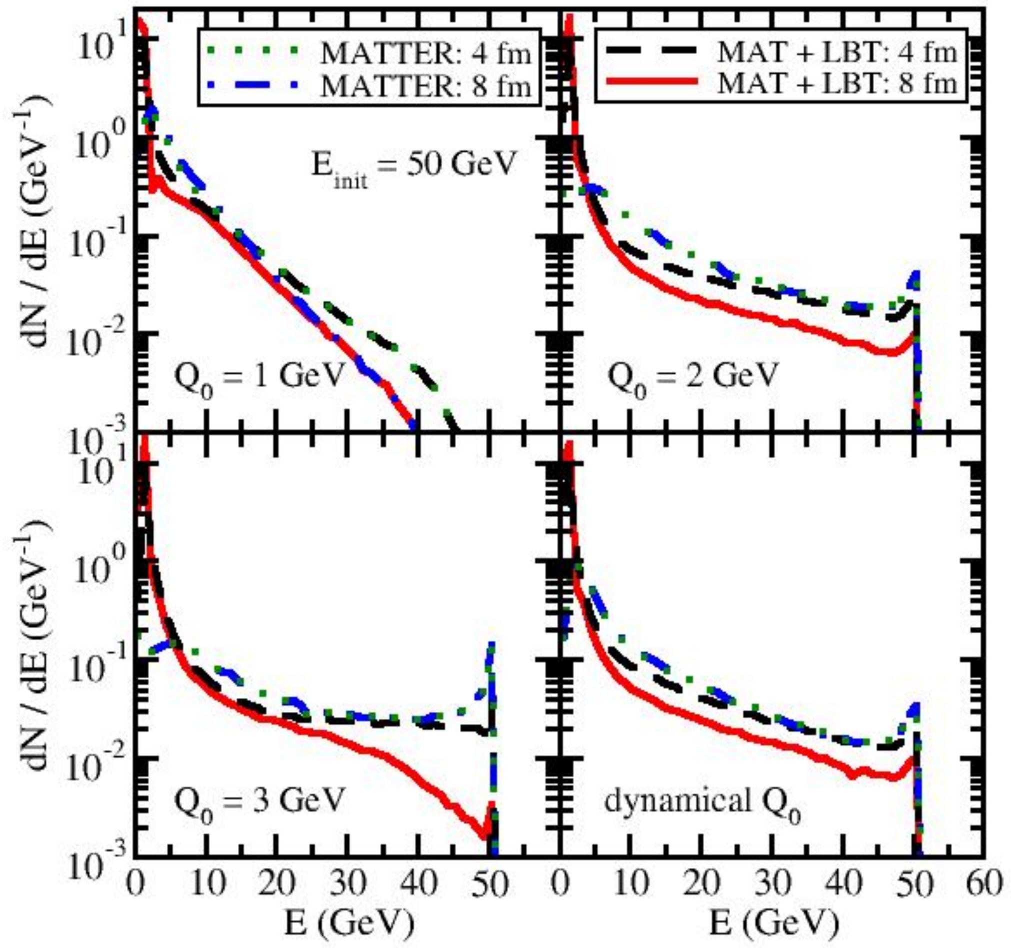


Compared to E_init = 50 GeV, effect of MATTER (vs. vac) is extended to higher Q_0 cut (scale of medium $\hat{q}\tau_f$ increases with jet energy).

Effect of MARTINI in MATTER + MARTINI is weaker now compared to the previous E_init = 50 GeV scenario since the switching t_0 is larger.

For E_init = 200 GeV, dynamical Q_0 is closer to the fixed Q_0 = 3 GeV case.

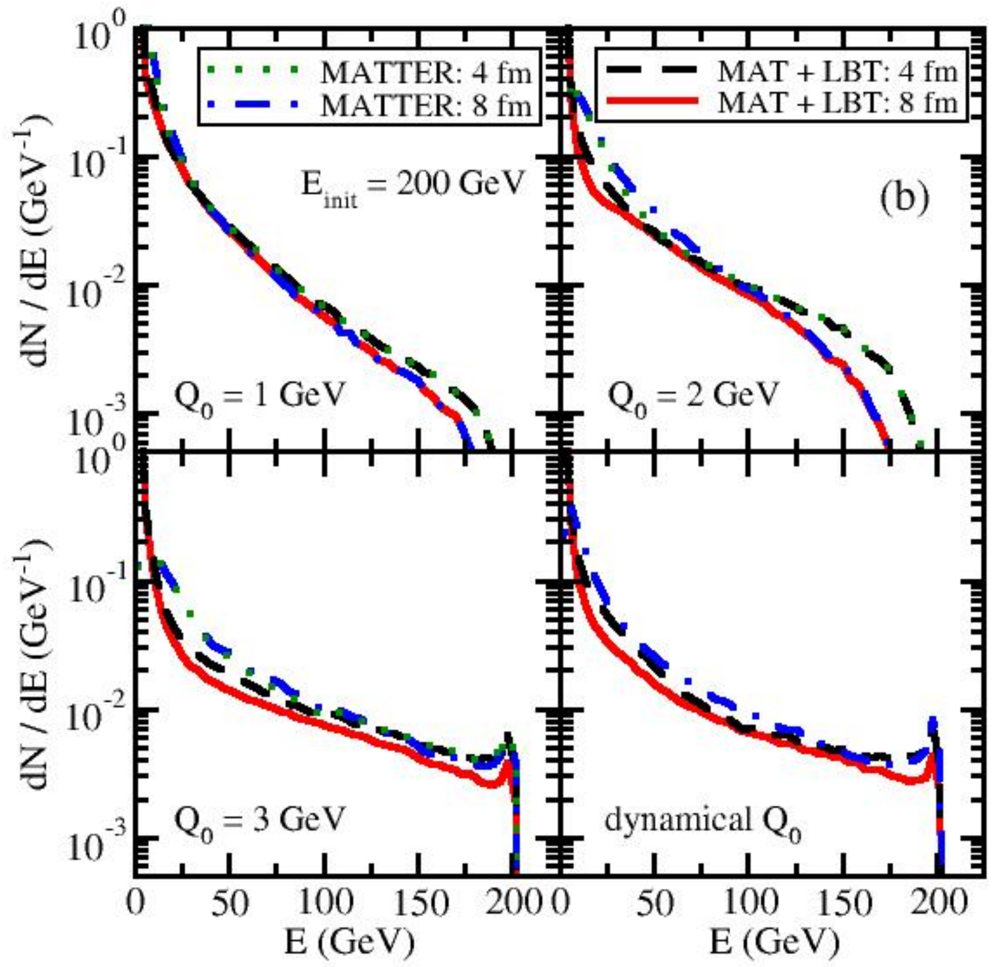
L Dependence *of dN/dE* for E_i = 50 GeV



For pure MATTER, when Q_0 = 1 GeV, stronger energy loss of hard paton is observed when *L* is extended from 4 to 8 fm. However, for $Q_0 \geq 2$ GeV, no obvious difference can be observed since most partons hit Q_0 before *L* = 4 fm (no more effect between 4 and 8 fm).

Extending *L* from 4 to 8 fm leaves longer time for LBT evolution. (LBT evolution is more important if the path length is longer.) It's obvious for $Q_0 \geq 2$ GeV. For Q_0 = 1 GeV, the separation point between MATTER and MATTER+LBT curves is also shifted to the right (10 -> 20 GeV) when *L* is extended from 4 to 8 fm.

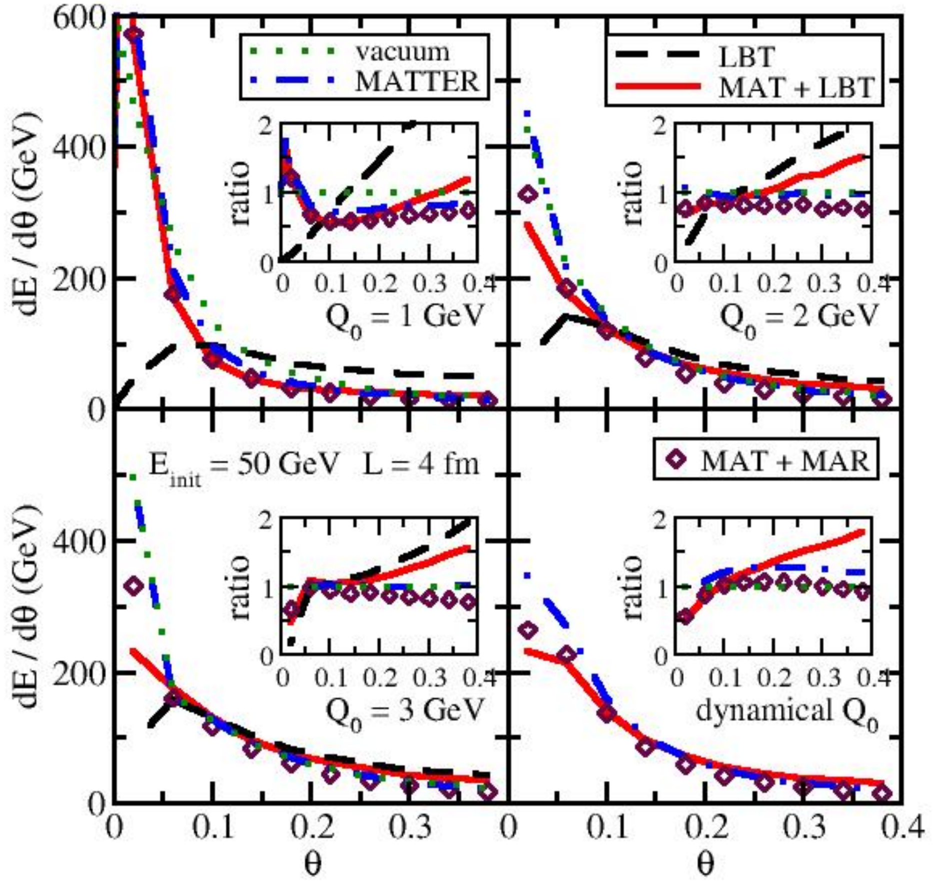
L Dependence *of dN/dE* for E_i = 200 GeV



For pure MATTER, difference between *L* = 4 and 8 fm is not only obvious for Q_0 = 1 GeV, but also for Q_0 = 2 GeV now. Since with E_{init} = 200 GeV, it takes longer than 4 fm for MATTER to bring partons down to 2 GeV and thus evolution between 4 and 8 fm becomes important.

Since with larger E_{init}, it takes longer time for MATTER to evolve partons down to a given Q_0, the difference introduced by the LBT evolution between *L* = 4 and 8 fm is smaller compared to the previous E_{init} = 50 GeV case.

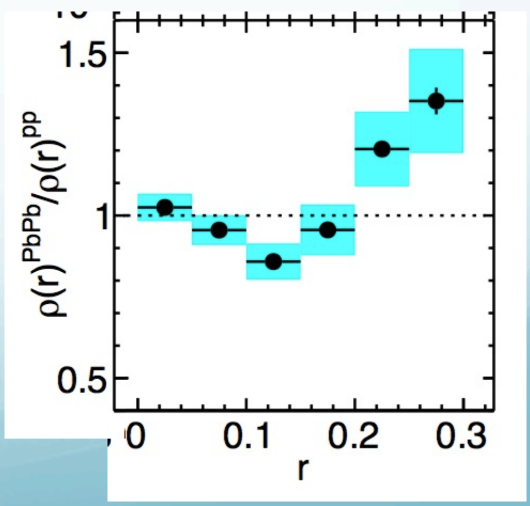
$dE/d\vartheta$ for E_i = 50 GeV and L = 4 fm



In medium evolution changes the jet shape – depletes energy in small cone and enhance energy in large cone.

LBT is more effective than MATTER in shifting energy distribution into larger angle since elastic scattering is included in LBT.

Interesting non-monotonic behavior at Q_0 = 1 GeV -- enhanced Sudakov type splitting at very small r and LBT scattering at large r. (Never seen when single energy loss formalism is applied)



Summary

- Combined theories at high and low virtuality into a unified approach for the first time
- Investigated contribution from MATTER vs. LBT/MARTINI to parton shower spectrum and jet shape and its dependence on jet energy E, system size L and separation scale Q_0
- Noticed possible non-monotonic behavior in the medium modification of jet shape when MATTER+LBT is applied

Outlook

- Will implement the combined energy loss approach in realistic hydrodynamic medium, and study observables at hadron level with fragmentation + coalescence model
- Will include more approaches into the same framework, such as the strongly coupled approach for the near thermal partons

Thank you!

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