SUBA-jet, a new model for jet energy loss in heavy-ion collisions

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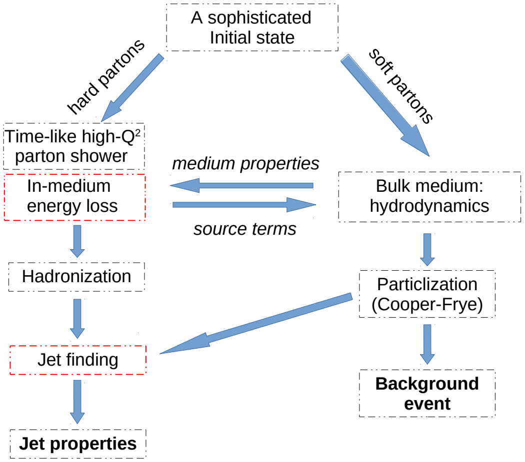
Our project

To get both hydrodynamic IS and initial hard partons from preferrably the same initial state, make hydrodynamic and jet parts talk to each other, add hadronization scheme and jet finding.



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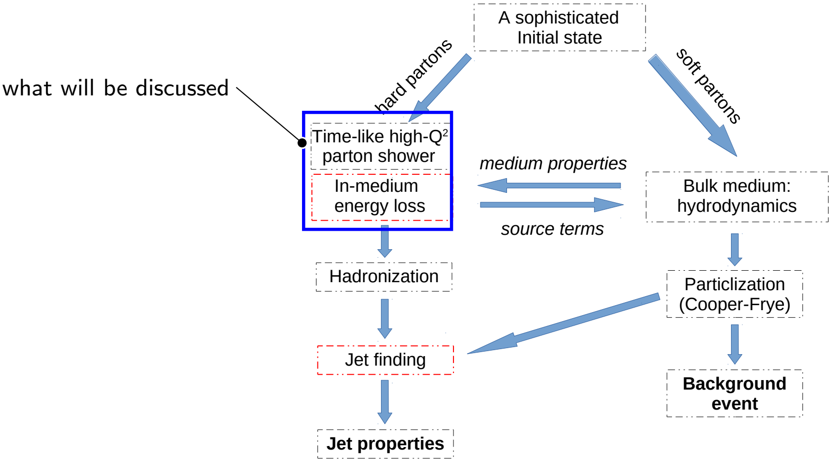
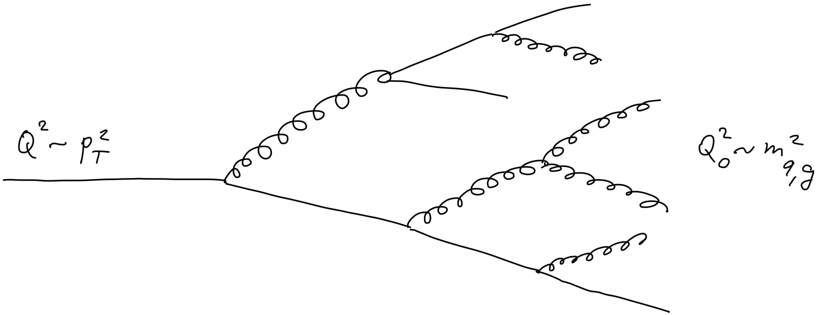


Time-like parton shower

- Monte Carlo simulation of DGLAP equations for a parton shower between virtuality scales $Q_{\uparrow}$ (from Born process in hard scattering) and $Q_{\downarrow} = 0.6$ GeV.



$$S_a(Q_{a\uparrow}, Q_a)\left(\frac{\alpha_s(F(\chi, Q^2))}{2\pi} P_{a\to b,c}(\chi)\right) = p\,(Q_a, \chi)\,.$$

Vacuum shower developed by **Martin Rohrmoser**

Time-like parton shower + spacetime picture

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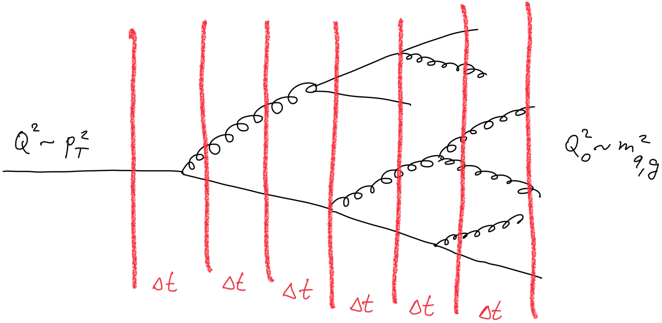
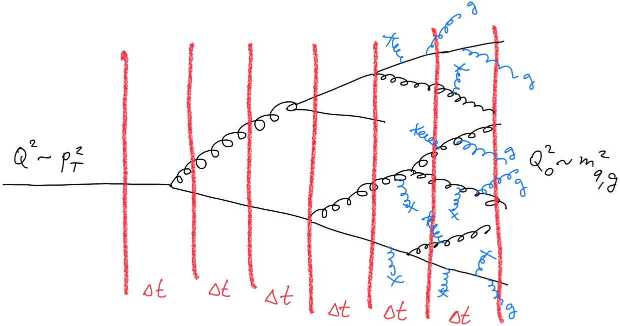


On top of that:

- The *time* evolution is split into timesteps (ideal for merging with hydrodynamic medium evolution)
- Parton splitting (for high-Q^2 partons) happens with a probability according to mean life times between the splittings $\Delta t = E/Q^2$.

Medium modifications

In Nature: continuous change with Q^2, in our model: separation into two regimes.



High-Q^2 regime:

$$\frac{dQ^2}{dt} = \hat{q}(T,p)$$

Low-Q^2 regime:

- elastic scatterings off medium partons
- medium-induced radiation

Medium modifications: high-Q^2 sector

We adopt effective treatment from T. Renk, Phys. Rev. C78 (2008) 034908: $\frac{dQ^2}{dt} = \hat{q}(T,p)$

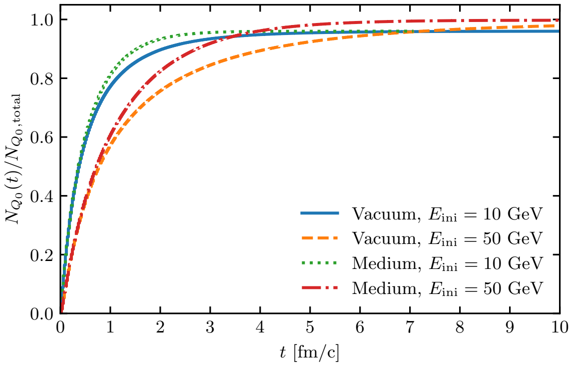
$$\hat{q}(T,p) = \hat{q}_{\mathrm{JET}}(T) \times q_{\mathrm{cof}}(p)$$

$\hat{q}_{\mathrm{JET}}(T) = 5.5 \cdot T^3 \frac{2}{1+T/T_c}$ from K. M. Burke et al. Phys. Rev. C 90 no. 1, (2014) 014909,
$q_{\mathrm{cof}}(p) = \frac{1.69+1.25\cdot p}{4.07+p+0.85\ln(p+1)}$ [p in GeV] from Gossiaux, Aichelin, Phys. Rev. C 78 (2008) 014904,
such that $q_{\mathrm{cof}}(20\mathrm{GeV}) = 1$.

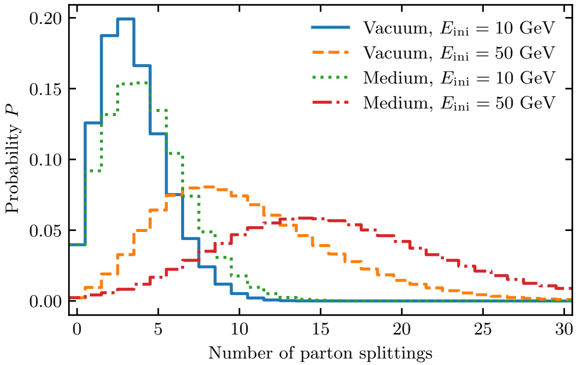
There is a small continuous virtuality increase, which causes more splittings, leads to a wider jet with some *apparent* energy loss.

As a result:

jets form a little faster:

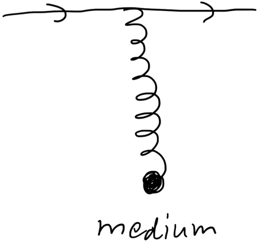


jets split more:

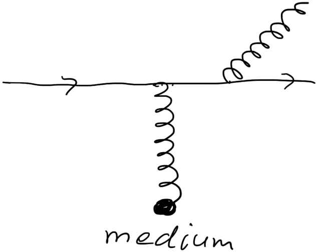


Medium modifications: low Q^2 sector

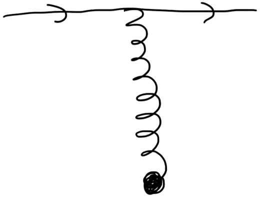
elastic scatterings



Medium-induced gluon radiation



Elastic scatterings



$t-$channel, IR-regulated (next slide)

$$\frac{d^2\sigma_{el}^{qq(\bar{q})}}{d^2q_T} = \frac{2C_F}{N_c}\frac{\alpha_s^2}{(q_T^2+\mu^2)^2} \quad \text{and} \quad \frac{d^2\sigma_{el}^{qg}}{d^2q_T} = \frac{C_A}{C_F}\frac{d^2\sigma_{el}^{qq}}{d^2q_T},$$

$\mu^2 = \kappa m_D^2$ [Gossiaux, Aichelin, Phys. Rev. C 78 (2008) 014904], $\kappa = 0.16$.

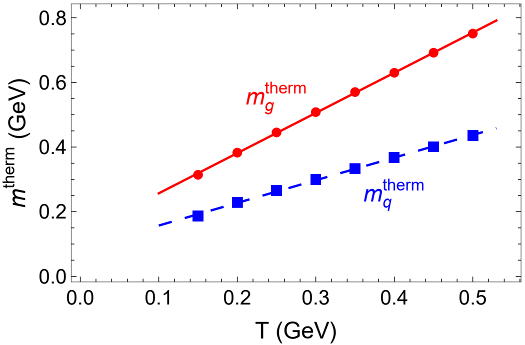
$$\alpha_{s,\text{eff}}(T) \approx \frac{0.42}{\ln\left(1.15 + 0.64\frac{T}{T_c}\right)}, \quad \text{with } T_c = 0.15 \text{ GeV}.$$

Medium model

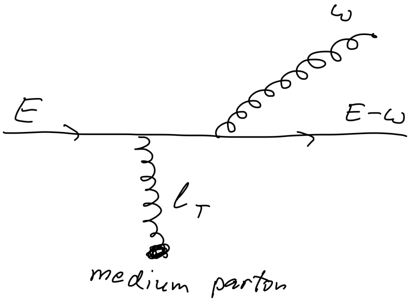
Coming from a well-established heavy-quark production model.

- Debye mass $m_D^2 = \left(1 + \frac{N_f}{2N_c}\right) 4\pi\alpha_{s,\mathrm{eff}} T^2$
- quark/gluon masses $m_g^{\mathrm{therm}} = m_D/\sqrt{3}$,
  $m_q^{\mathrm{therm}} = \sqrt{\frac{\pi C_F \alpha_{s,\mathrm{eff}}}{2}}\, T$
  J.-P. Blaizot and E. Iancu Phys. Rept. 359 (2002) 355–528
- Effective coupling
  Gossiaux, Aichelin, Phys. Rev. C 78 (2008) 014904

$$\alpha_{s,\mathrm{eff}}(T) \approx \frac{0.42}{\ln\left(1.15 + 0.64\frac{T}{T_c}\right)}, \quad \text{with } T_c = 0.15 \text{ GeV}.$$



Medium-induced radiation: single (incoherent) radiation process



Basic idea: Gunion, Bertsch '82

Extension for heavy quark projectile and dynamical light quarks:
Aichelin, Gossiaux, Gousset, Phys. Rev. D**89**, 074018 (2014):

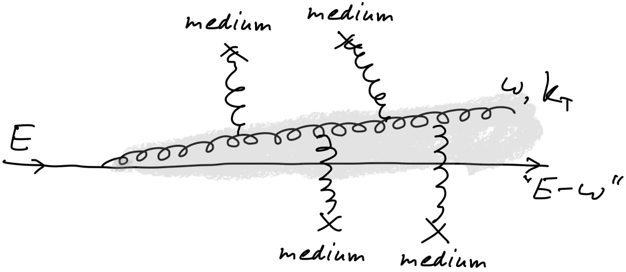
In the region of small x, the matrix elements from QCD can be approximated by so-called *scalar* QCDwhich at high energy leads to a factorized formula for the total cross section of the radiation process:

$$\frac{d\sigma^{Qq\to Qqg}}{dx d^2k_T d^2l_T} = \frac{d\sigma_{\text{el}}}{d^2l_T} P_g(x, k_T, l_T)\theta(\Delta), \qquad \text{where}$$

$$P_g(x, \vec{k_T}, \vec{l_T}; M) = \frac{C_A\alpha_s}{\pi^2}\frac{1-x}{x}\left(\frac{\vec{k_T}}{\vec{k_T}^{\,2} + x^2M^2} - \frac{\vec{k_T} - \vec{l_T}}{(\vec{k_T} - \vec{l_T})^2 + x^2M^2}\right)^2,$$

Allows for finite quark/gluon masses
→ heavy quark jets

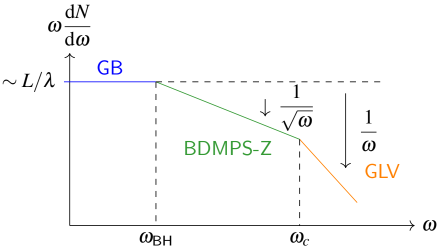
Towards coherent radiation



For the multiple scatterings in medium, one has to take into account coherence effects:

- QED: Landau-Pomeranchuk-Migdal (LPM) effect,

- QCD: Baier-Dokshitzer-Mueller-Peigne-Schiff-Zakharov (BDMPS-Z)

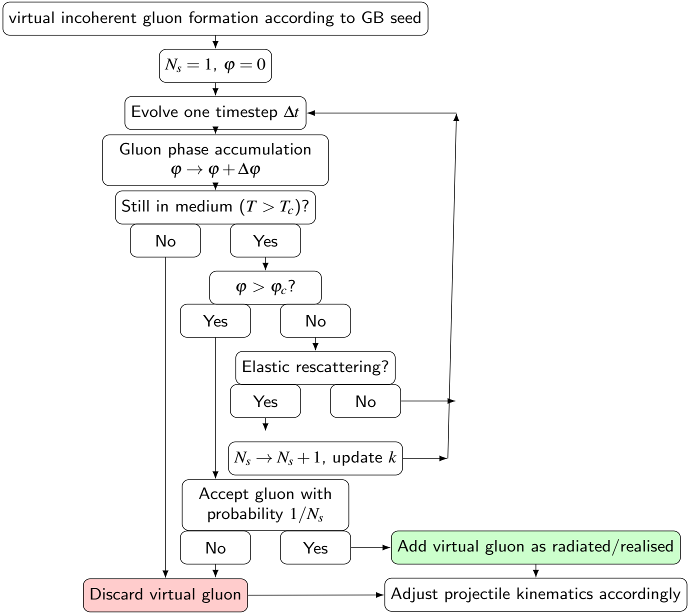


One expects to have three regimes:

- GB: Gunion-Bertsch regime, incoherent radiation
- BDMPS-Z: radiation from multiple coherent scatterings
- GLV: radiation with a single hard scattering

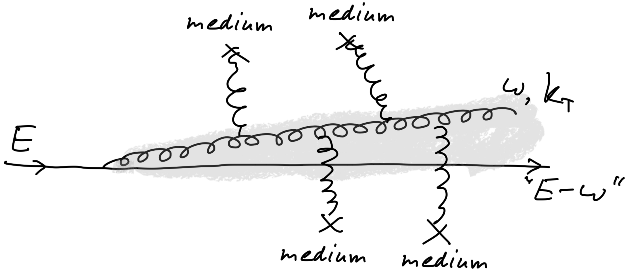
The implementation

- For low-Q^2 partons: at each timestep, an elastic scattering and/or a radiation of pre-formed gluon happens with a probability $R_{\text{el}}\Delta t$, $R_{\text{inel}}\Delta t$ respectively.
- Each parton can generate arbitrary number of pre-formed gluons ($\propto$blob).
- We adopted a variant of the faithful implementation of the BDMPS-Z by Zapp, Stachel, Wiedemann, JHEP **07** (2011), 118 $\Longrightarrow$



Coherent radiation benchmark in SUBA-Jet

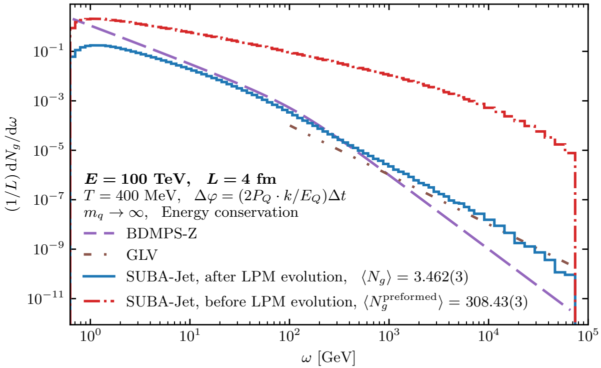
In order to reproduce BDMPS-Z behaviour, one has to assume that:



- jet = energetic low-Q quark
- quark only radiates gluons
- radiated gluons only scatter elastically
- QGP scattering centers have infinite mass
- ω is conserved in elastic scatterings
- besides, $k_\perp \ll \omega \ll E$

Coherent radiation benchmark (2)

1) 100 **TeV** jet, a proxy for $E \to \infty$ limit.



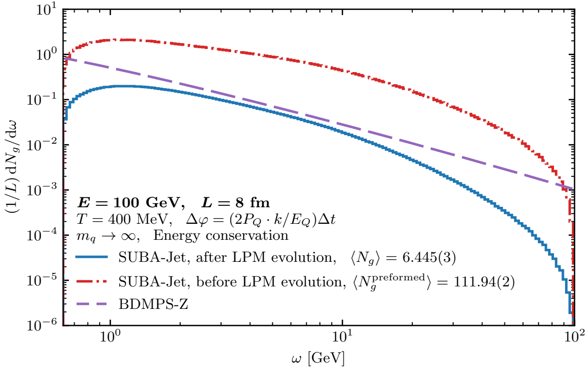
Setup:
$T = 400$ MeV, $\alpha_s = 0.4$
$\mu \approx 0.44$ GeV, $m_g^{\rm therm} = 0.626$ GeV,
$m_q^{\rm therm} = 0.367$ GeV, $\lambda_{\rm el}^q = 0.18$ fm, and
$\lambda_{\rm el}^g = 0.08$ fm.

- LPM modifies radiation spectrum at all scales (BH behaviour not present at small ω - too dense medium)
- At large ω, GLV limit is reproduced.
- A very strong LPM suppression:
  out of 300 virtual gluons only 1% become real radiated gluons.

$$\omega \frac{dN^{\text{BDMPS-Z}}}{d\omega} \simeq \frac{2\alpha_s C_R}{\pi} \ln|\cos(\Omega L)|$$

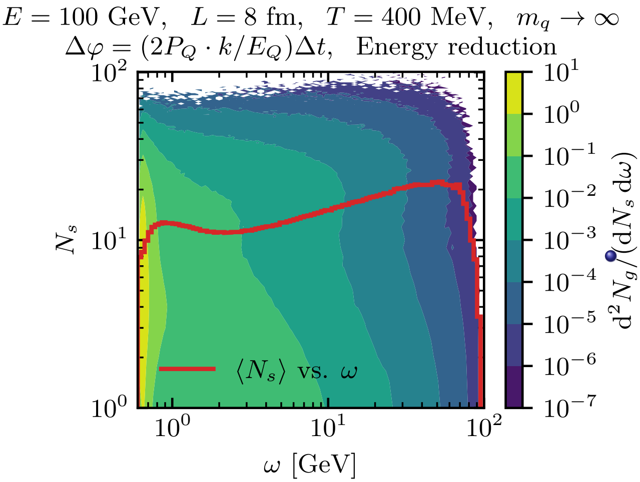
(Caron-Huot, Gale, 2010; Mehtar-Tani, 2019)

2) A more realistic 100 **GeV** jet.

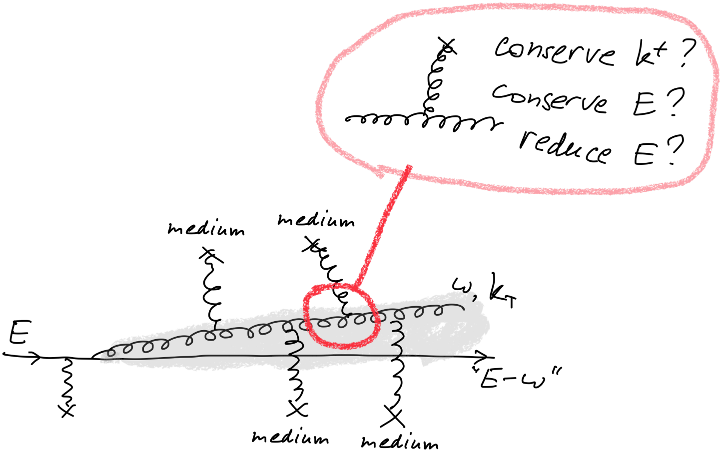


- At large ω, the spectrum resembles GLV,
- but in fact the fall-off is due to energy conservation.
- Also a very strong LPM suppression here: only 6% of virtual gluons become real ones.

Indeed, on average multiple scatterings are needed to radiate a single gluon.
However the spread in N_s is large.



Relaxing BDMS-Z assumptions

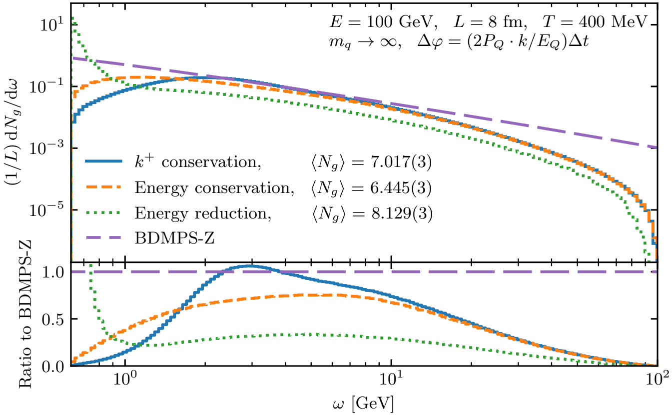


$$\frac{d\sigma_{\rm el}}{d^2 l_T} \to \frac{8\alpha_s^2}{9(\vec{l_T}^2 + \mu^2)^2}$$

- w conservation is used in BDMS calculation,
- we explore two other choices:
- k^+ conservation
- energy reduction (energy gain by the medium parton is subtracted from the projectile gluon)

Relaxing BDMPS-Z assumptions (2)

Realistically, energy of the trial radiated gluons is not conserved but reduced in subsequent scatterings.

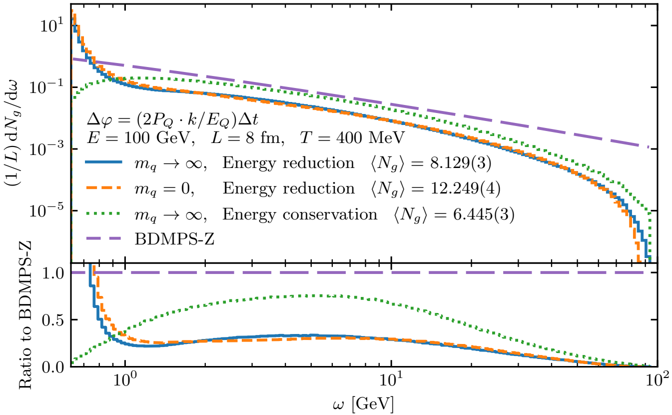


Different assumptions for elastic scatterings:

- (dashed) energy conservation *original BDMPS*
- (solid) $k^+ = E + p_z$ conservation
- (dotted) energy reduction the most realistic

$\Rightarrow$ at low ω the treatment of elastic scatterings becomes quite important

Relaxing BDMPS-Z assumptions (3)



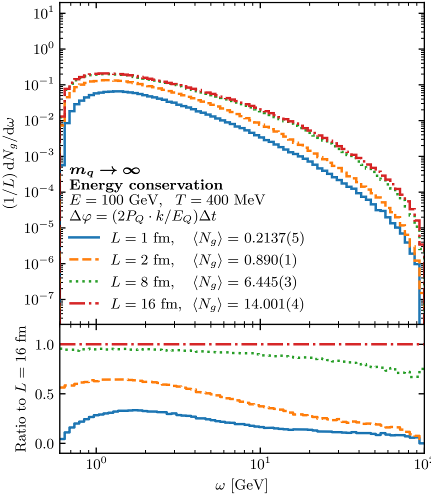
Curves in reverse order:

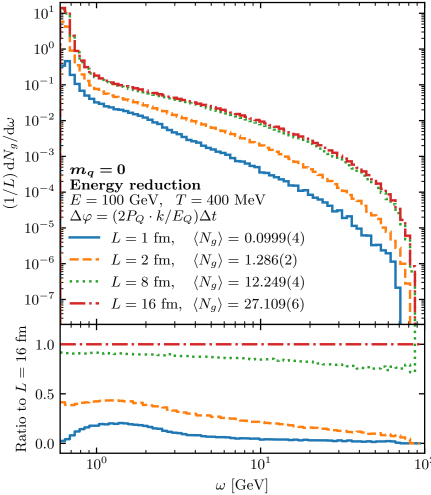
- $m_q \to \infty$ + energy conservation: (dotted) original BDMPS-Z
- $m_q \to \infty$ + energy reduction: (solid) account for energy reduction in scatterings
- $m_q = 0$ + energy reduction: (dashed) the most realistic case

$\Rightarrow$ both improvements change the low-ω spectrum significantly w/r/t/ BDMPS-Z.

Path length dependence of radiative energy loss

In both BDMPS-Z mimicking (left) and realistic (right) cases, the pathlength dependence is:





- for large L approx. $\propto L$
- for smaller L: $\propto L^{\alpha}$, $\alpha > 1$

Summary

A building block of the state-of-the-art jet+medium framework `SUBA-Jet`:

- We've constructed a Monte Carlo implementation of coherent radiative enegry loss.
- Radiation seed is based on Gunion-Bertsch $\Rightarrow$ massive quarks/gluons.
- In a benchmark setup, BDMPS-Z spectrum of radiated gluons is reproduced
- At very large ω, GLV limit is reproduced as well.
- In a more realistic setup, gluon radiation spectrum changes considerably with respect to BDMPS-Z form *even in static medium*.
- One way to state the reason is that there is no clear separation of scales: $E \gg \omega \gg k_T$ in theory, but in practice they may and do overlap.

Outlook $\rightarrow$ **Josef's talk**:
Run the jet energy loss model over a realistic medium background (vHLLE, already in progress), employ hollistic initial state, compute basic observables, look at the effects of medium response.