A new model for jet energy loss in heavy-ion collisions

Iurii KARPENKO[1]

with Joerg Aichelin[2], Alexander Lind[2], Pol Gossiaux[2], Martin Rohrmoser[3]

[1] FNSPE CTU in Prague
[2] CNRS/SUBATECH Nantes
[3] Jan Kochanowski University

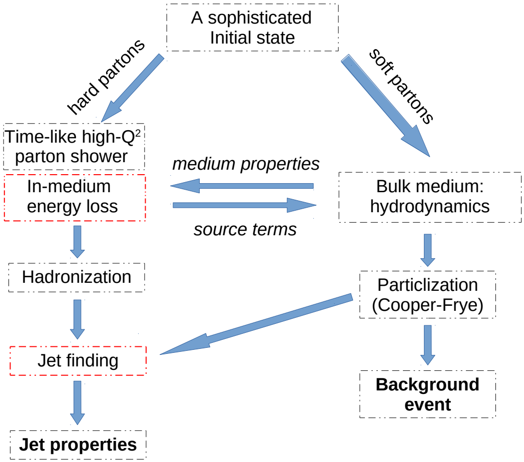
We acknowledge support by the Region Pays de la Loire (France) under contract no. 2015-08473.

The work was supported from European Regional Development Fund-Project "Center of Advanced Applied Science" No. CZ.02.1.01/0.0/0.0/16-019/0000778.

EUROPEAN UNION
European Structural and Investment Funds
Operational Programme Research, Development and Education

Our project

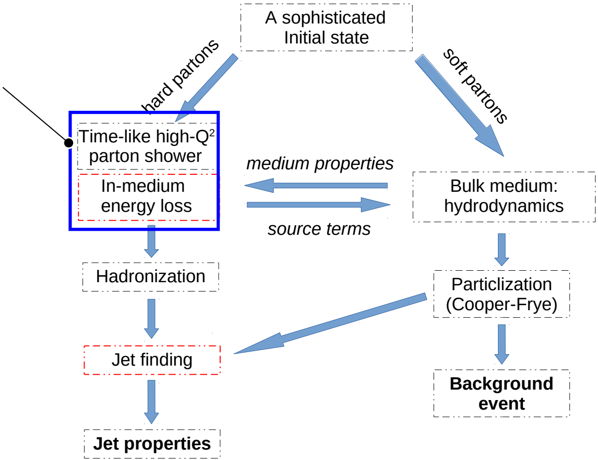
To get both hydrodynamic IS and initial hard partons from preferrably the same initial state, make hydrodynamic and jet parts talk to each other, add hadronization scheme and jet finding.



Our project

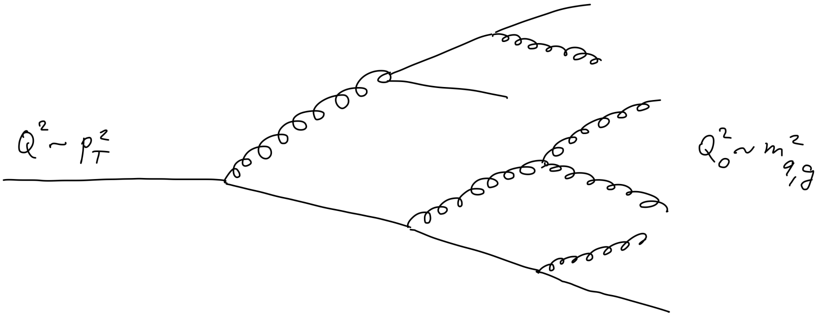
To get both hydrodynamic IS and initial hard partons from preferrably the same initial state, make hydrodynamic and jet parts talk to each other, add hadronization scheme and jet finding.

what will be discussed



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.

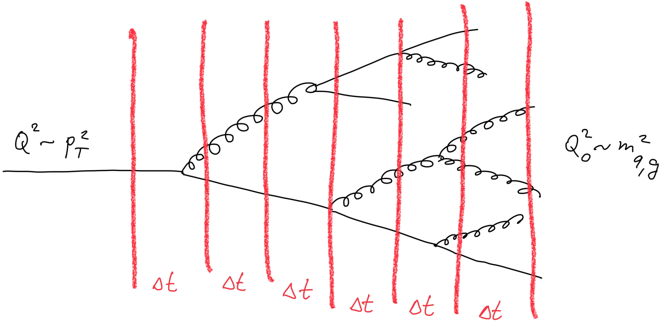


$$S_a(Q_{a\uparrow}, Q_a)\left(\frac{\alpha_s(F(\chi, Q^2))}{2\pi} P_{a\to b,c}(\chi)\right) = p(Q_a, \chi)\,.$$

Vacuum shower developed by **Martin Rohrmoser**

Time-like parton shower + spacetime picture

- 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.

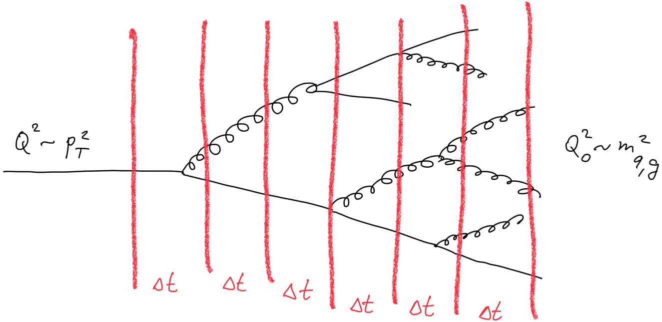


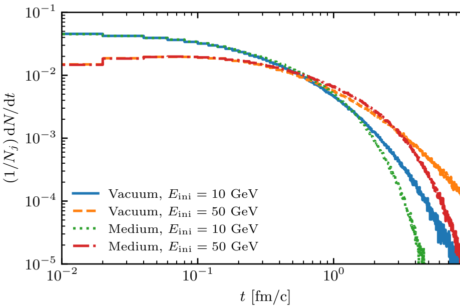
On top of that:

- 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 $\Delta t = E/Q^2$.

Time-like parton shower + spacetime picture

- 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.



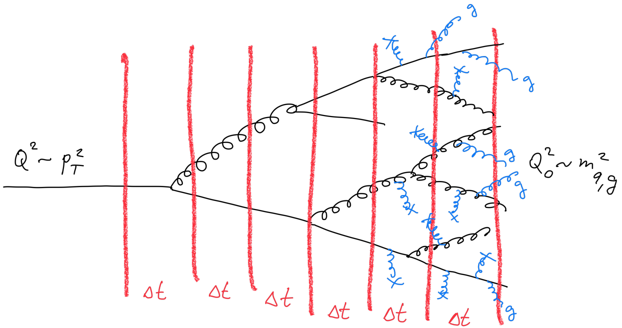


On top of that:

- 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 $\Delta t = E/Q^2$.

Time-like parton shower + spacetime picture

- 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.

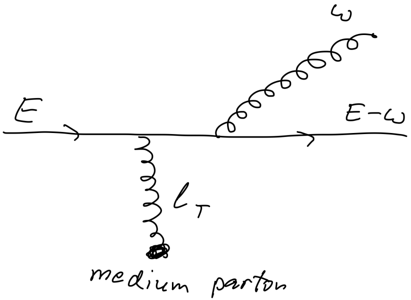


+medium-induced radiation

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-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):

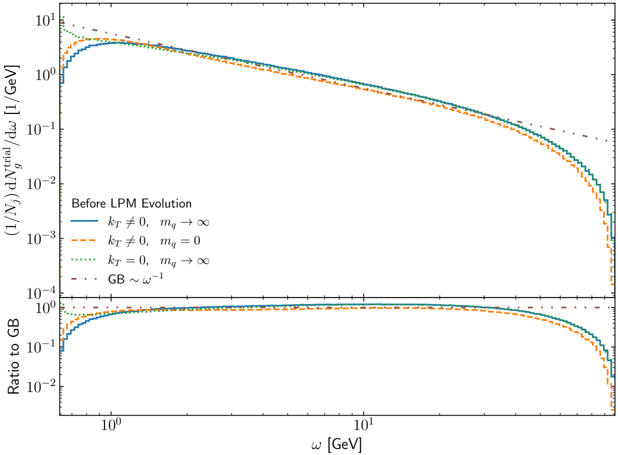
In the region of small x, the matrix elements from QCD can be approximated by so-called *scalar* QCDwhich at high energy leads to a factorized formula for the total cross section of the radiation process:

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

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

Allows for finite quark/gluon masses
→ heavy quark jets

Medium-induced radiation: single (incoherent) radiation process

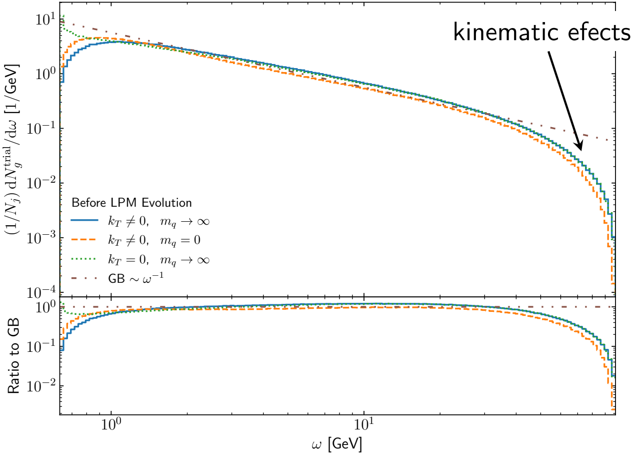


Setup:

- Medium: $T = 400$ MeV
  length $L = 4$ fm
  $\alpha_s = 0.3$
- projectile:
  $E = 100$ GeV
  low virtuality

- At most energies, the radiation spectrum behaves as ω^{-1}.

Medium-induced radiation: single (incoherent) radiation process

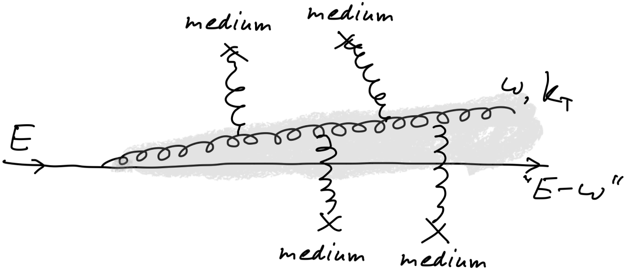


Setup:

- Medium: $T = 400$ MeV
  length $L = 4$ fm
  $\alpha_s = 0.3$
- projectile:
  $E = 100$ GeV
  low virtuality

- At most energies, the radiation spectrum behaves as ω^{-1}.

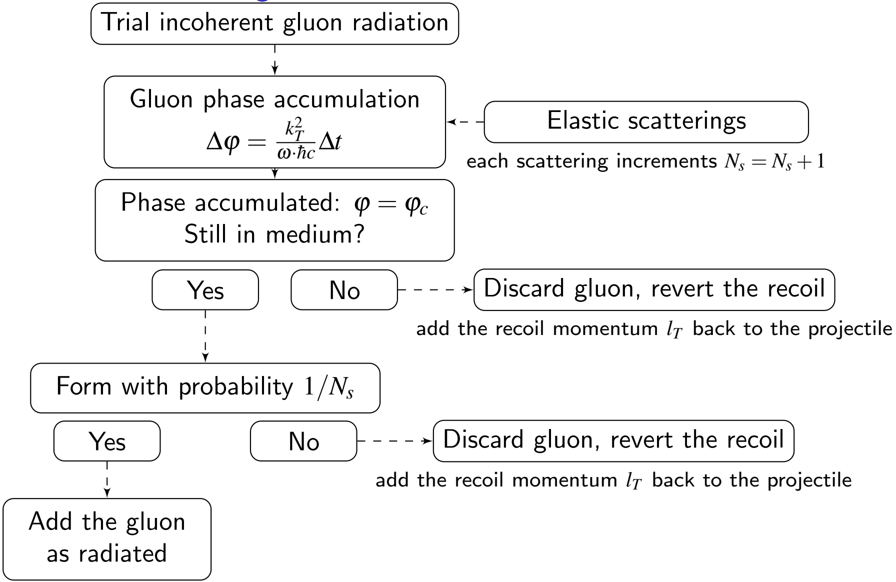
Coherent radiation



For the multiple scatterings in medium, one has to take into account coherence effects: Landau-Pomeranchuk-Migdal (LPM) effect in QED, or BDMPS-Z in QCD.

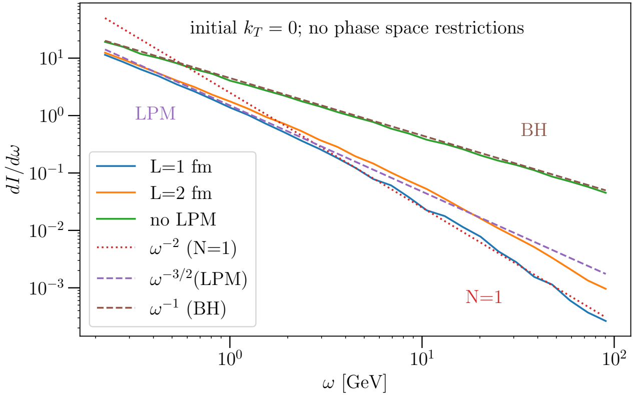
- For low-Q^2 partons: at each timestep, an elastic scattering and/or a radiation of pre-formed gluon happens with a probability $R_{\mathrm{el}}\Delta t$, $R_{\mathrm{inel}}\Delta t$ respectively.
- Each parton can generate arbitrary number of pre-formed gluons ($\propto$blob).
- We adopted a faithful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

The Monte Carlo algorithm for coherent radiation block



Reproducing BDMS limit

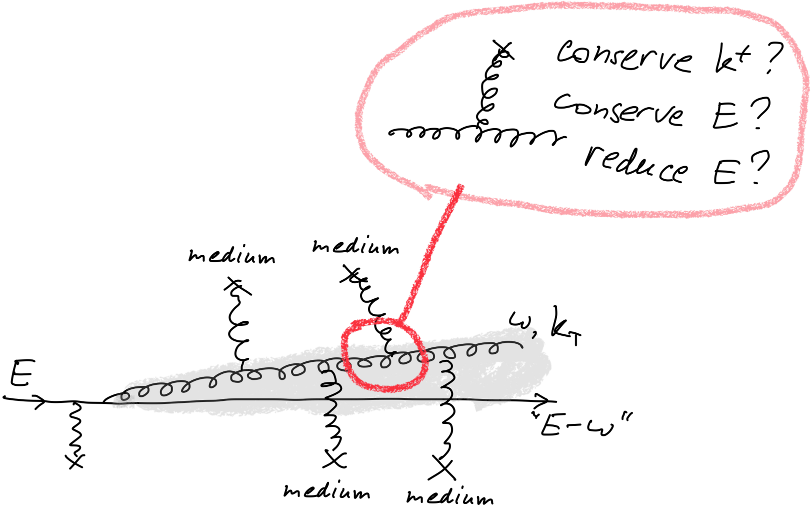
A simplified setup a-là Zapp, Stachel, Wiedemann, JHEP **07** (2011), 118



- A simplified radiaiton seed, essentially $1/\omega$
- projectile: $E = 100$ GeV quark, medium: box $L = 1$ fm and $R_{\text{el}} = R_{\text{inel}} = 0.1$ fm.
- change in regime for $\omega \cdot dI/d\omega$ from $1/\sqrt{\omega}$ to $1/\omega$ happens at $\omega = \omega_c$, where $\omega_c \approx \frac{\hat{q}L^2}{2\varphi_c\hbar}$. With the present settings, $\omega_c \approx 3.4$ GeV for $L = 1$ fm.
- Also, by setting $\varphi_c = 0$ we reproduce the incoherent limit $1/\omega$.

- The algorithm behaves as we expect it to.

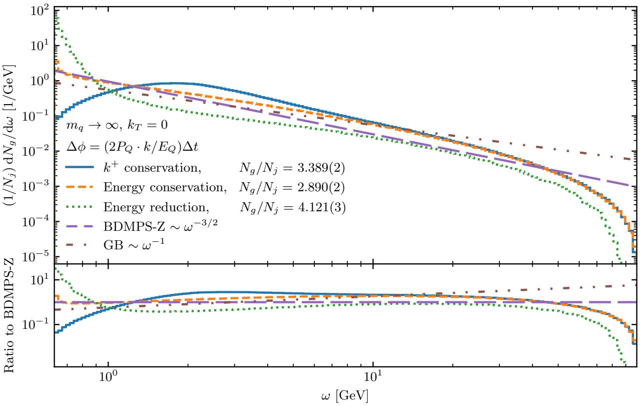
Reproducing BDMS limit *with full GB seed*



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

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

Reproducing BDMS limit *with full GB seed*

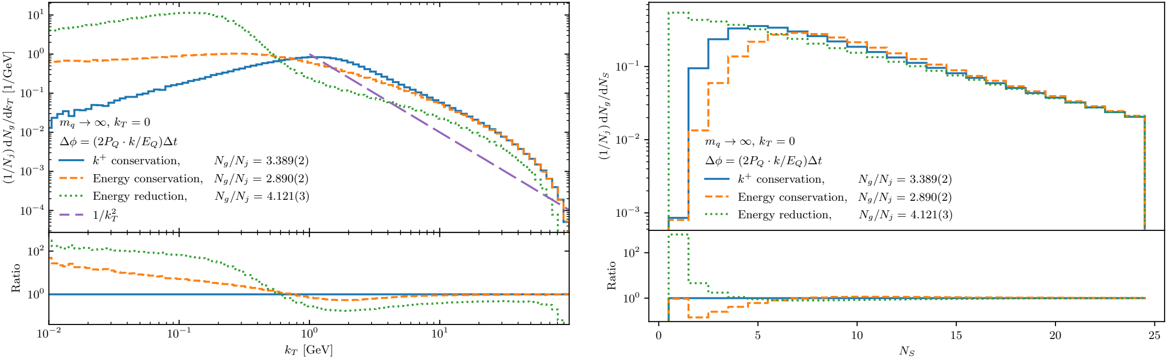


Setup:

- Medium: $T = 400$ MeV
  length $L = 4$ fm
  $\alpha_s = 0.3$
- projectile:
  $E = 100$ GeV
  low virtuality
- scattering centers with infinite mass,
  initial $k_T = 0$,
  eikonal limit: P_Q does not change
- phase accumulation:
  $\Delta\phi = (2P_Q \cdot k/E_Q)\Delta t/\hbar c$
- BDMS curve:
  $dN_g/d\omega \propto \alpha_s \sqrt{\frac{Lm_D^2}{\hbar c}} \frac{1}{\omega^{3/2}}$

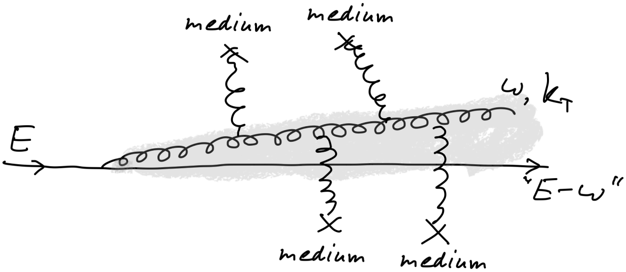
- A good reproduction of $\omega^{-3/2}$ behaviour in the middle of ω range.

... and corresponding dN/dk_T (transverse momentum) and dN/dN_s (number of coherent elastic interactions) distributions



- Right panel: in k^+ conservation an denergy conservation scenarios, most of the gluons accumulate several coherent elastic kicks in order to become formed. Not the case for the energy reduction scenario: only few kicks are needed.

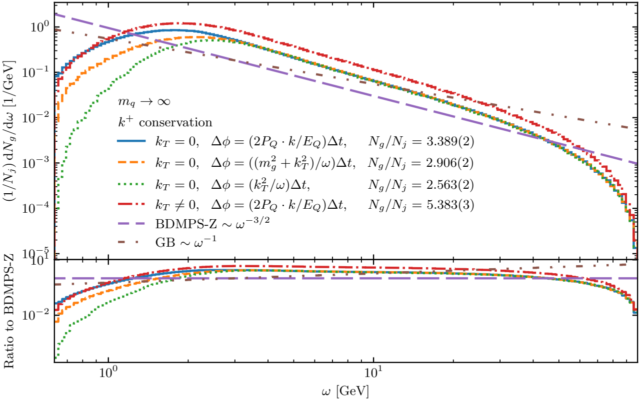
Howto accumulate the formation phase?



It looks like different choices exist in the literature:

- $\Delta\phi = \frac{k_T^2}{\omega}\Delta t$
  (used in JEWEL)
- $\Delta\phi = \frac{m_g^2+k_T^2}{\omega}\Delta t$
  (to smhw include the gluon mass)
- $\Delta\phi = \frac{2P\cdot k}{E}\Delta t$
  (a more generic formula)

Effects of phase accumulation

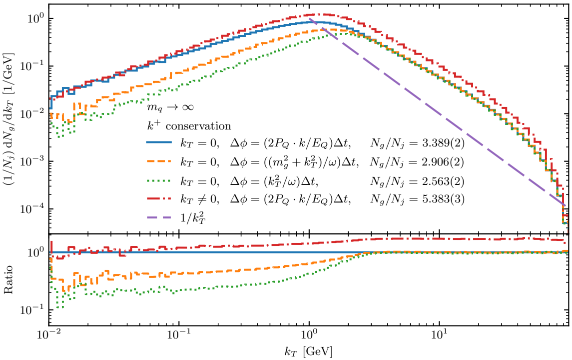


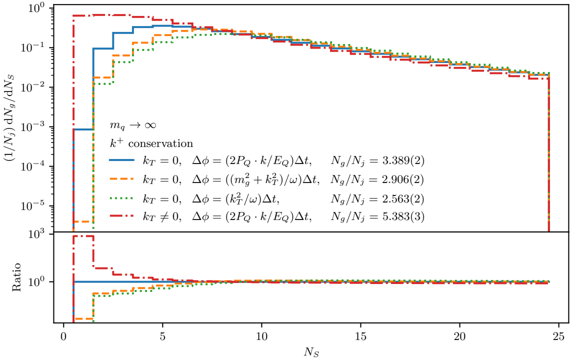
Setup:

- Medium: $T = 400$ MeV
  length $L = 4$ fm
  $\alpha_s = 0.3$
- projectile:
  $E = 100$ GeV
  low virtuality
- scattering centers with infinite mass,
  eikonal limit: P_Q does not change
- phase accumulation:
  $\Delta\phi = (2P_Q \cdot k/E_Q)\Delta t/\hbar c$
- BDMS curve:
  $dN_g/d\omega \propto \alpha_s \sqrt{\frac{Lm_D^2}{\hbar c}}\frac{1}{\omega^{3/2}}$

- Relaxing the zero-k_T limit enhances the radiation: gluons are formed faster.

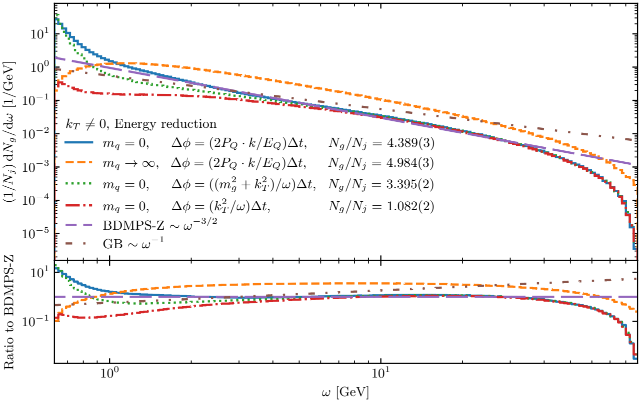
... and corresponding dN/dk_T and dN/dN_s distributions





- non-zero initial k_T makes it easier for the pre-formed gluons to accumulate their formation phase $\to$ fewer coherent elastic kicks are needed.

A more realistic case: scattering off maseless medium partons

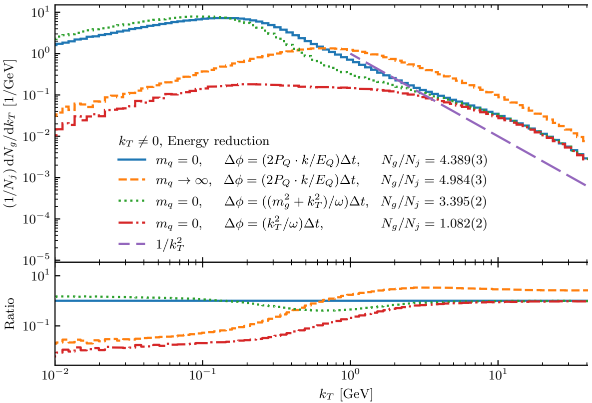


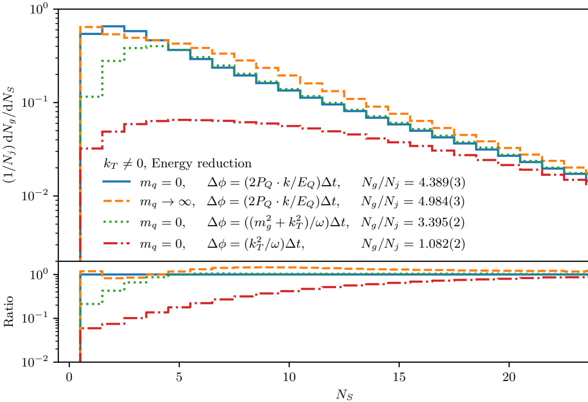
Setup:

- Medium: $T = 400$ MeV
  length $L = 4$ fm
  $\alpha_s = 0.3$
- projectile:
  $E = 100$ GeV
  low virtuality
- eikonal limit: P_Q does not change
- phase accumulation:
  $\Delta\phi = (2P_Q \cdot k/E_Q)\Delta t/\hbar c$
- BDMS curve:
  $dN_g/d\omega \propto \alpha_s \sqrt{\frac{Lm_D^2}{\hbar c}} \frac{1}{\omega^{3/2}}$

- The blue curve corresponds to the most realistic scenario (or at least we think so), and it exhibits a nice $\omega^{-3/2}$ behaviour but it is a non-trivial interplay of different features plugged in!

... and corresponding dN/dk_T and dN/dN_s distributions





Summary

- We've constructed a Monte Carlo implementation of the coherent radiative enegry loss in BDMPS-Z formalism, based on an extension of the Gunion-Bertsch model to massive quarks/gluons.

- In a BDMS-mimicking setup, we reproduce the $\omega^{-3/2}$ behaviour.
- In the transition towards more realistic setup, details and choices made in the algorithm seem to be important
- *I guess* 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:
Run the jet energy loss model over a realistic medium background (vHLLE, already in progress), compute basic observables, look at the effects of medium response.