SUBA-Jet

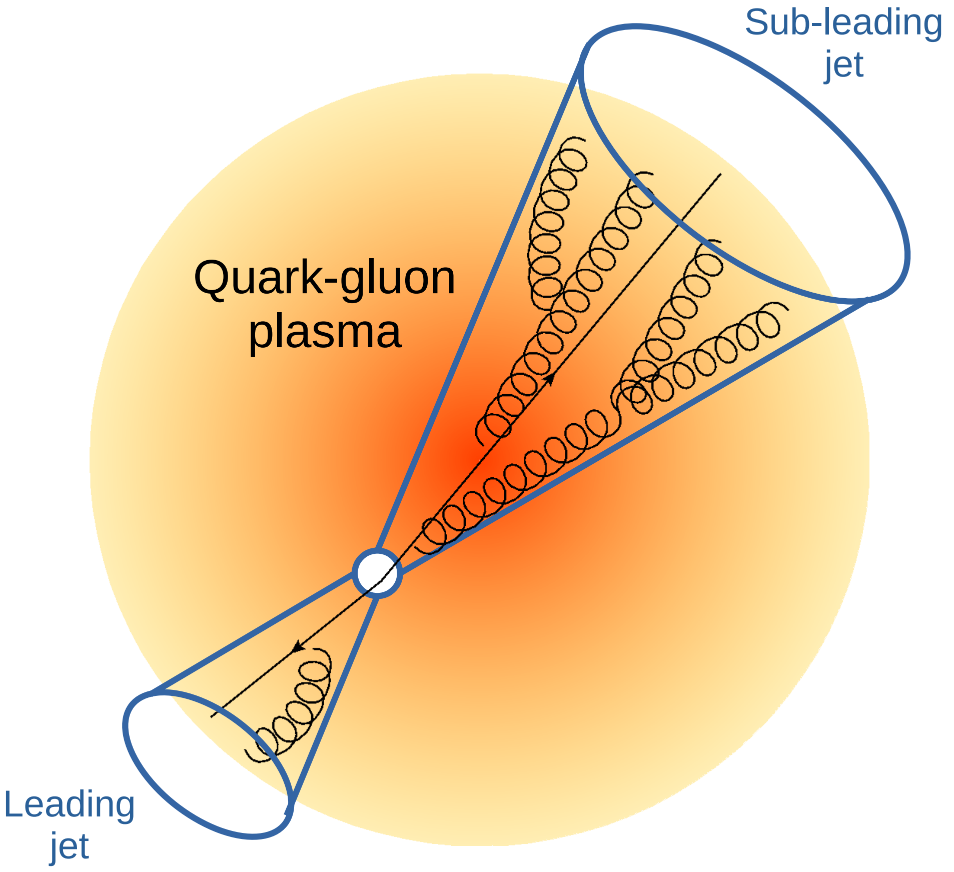
A New Coherent Jet Energy Loss Model For Heavy Ion Collisions

Alexander Lind

with Iurii Karpenko, Joerg Aichelin, Pol-Bernard Gossiaux, Martin Rohrmoser, and Klaus Werner

INT Workshop 21r-2b
Probing QCD at High Energy and Density with Jets
Institute for Nuclear Theory, University of Washington
Seattle, Washington, USA
20 October 2023

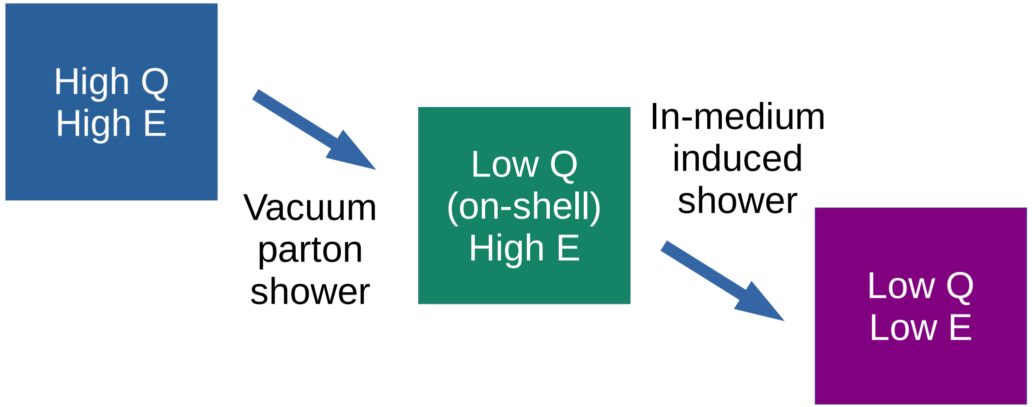
Jets in Heavy Ion Collisions



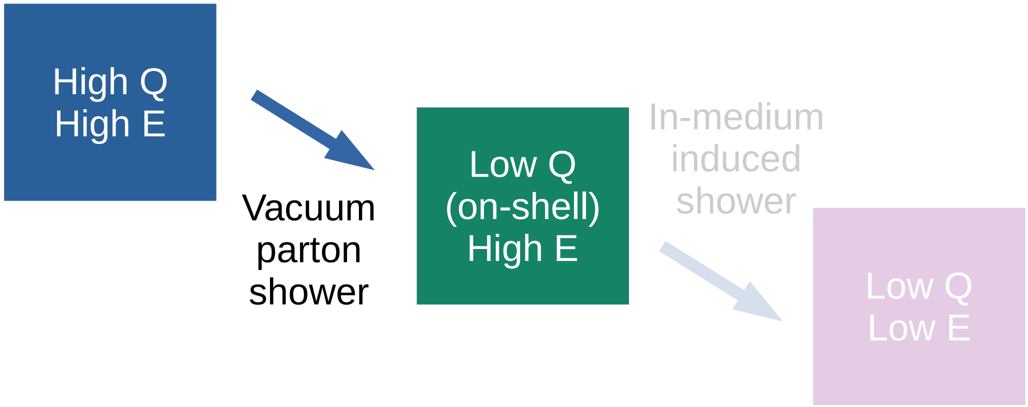
- Interactions between jet partons and the QGP medium leads to modifications of jet properties

→ **Jet Energy Loss / Quenching**

- **SUBA-Jet:**
  Monte Carlo for jet energy loss in heavy ion collisions



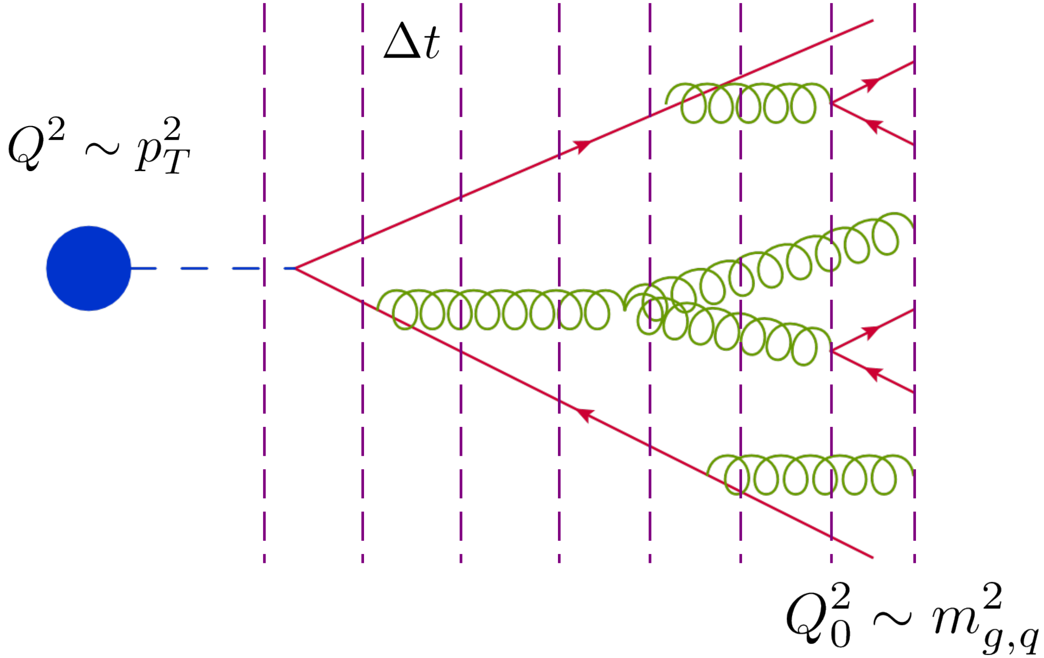
High Virtuality Regime

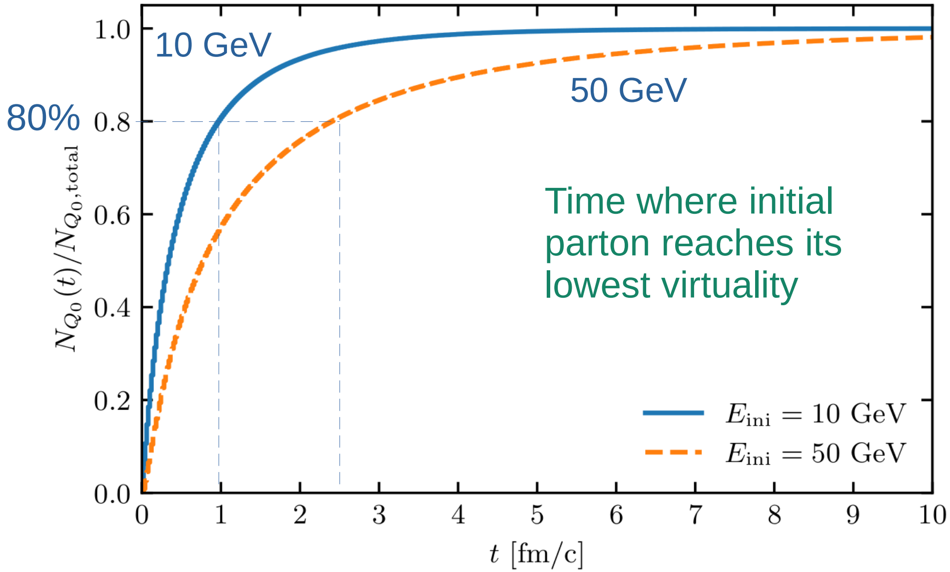


Vacuum Parton Shower

- Monte Carlo of a vacuum parton shower originally developed by Martin Rohrmoser
- Evolution according to the DGLAP equations from high virtuality $Q_{max} \sim p_T$ to low virtuality Q_0
- Time evolution split into time steps, mean life time

$$\Delta t = \tau = \frac{E}{Q^2}$$

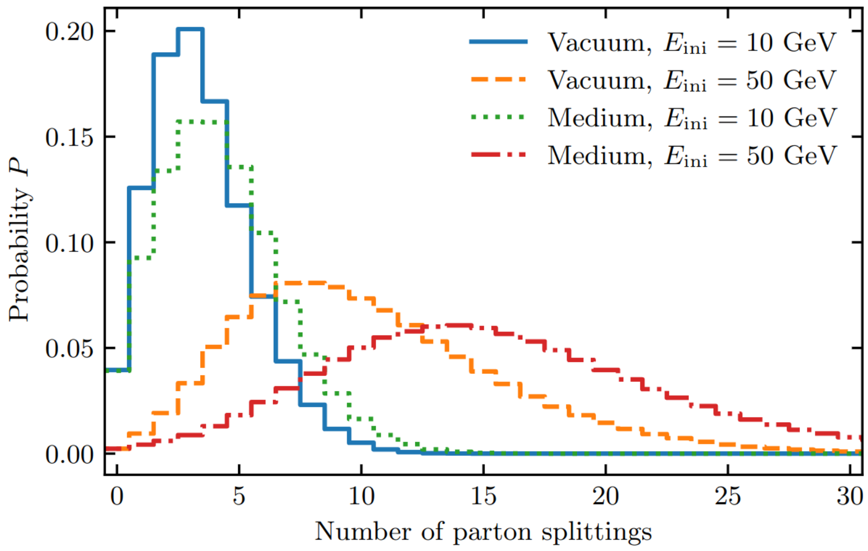


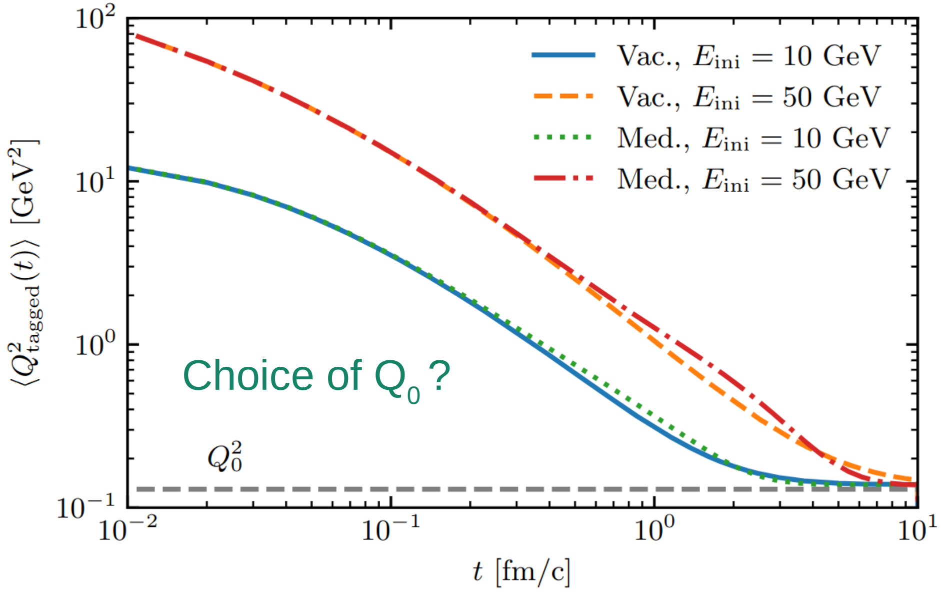


“Vacuum” Parton Shower in Medium

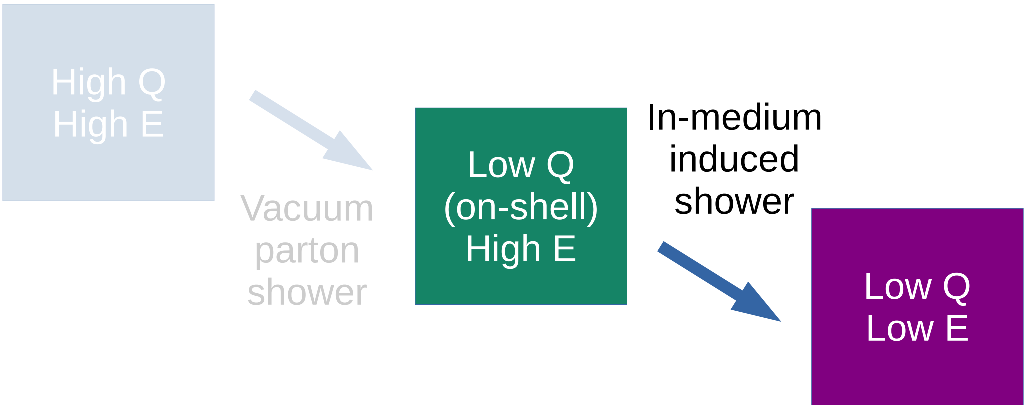
- Medium interactions for high Q regime resulting in virtuality increase, similar to YaJEM (T. Renk, 2008)

$$\frac{\mathrm{d}Q^2}{\mathrm{d}t} = \hat{q}(T)$$



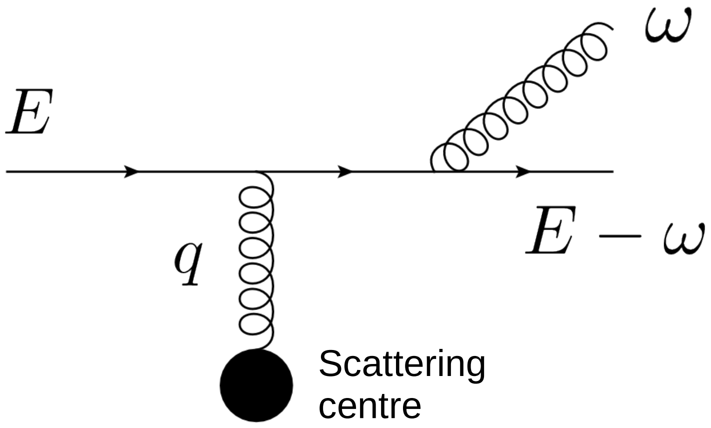


Low Virtuality Regime



Medium-Induced Single Radiation

- **Inelastic collision:**
  Single gluon emission from single medium scattering



- Original result from Gunion-Bertsch (1982)
  Generalised to massive case by Aichelin, Gossiaux, Gousset (2014)

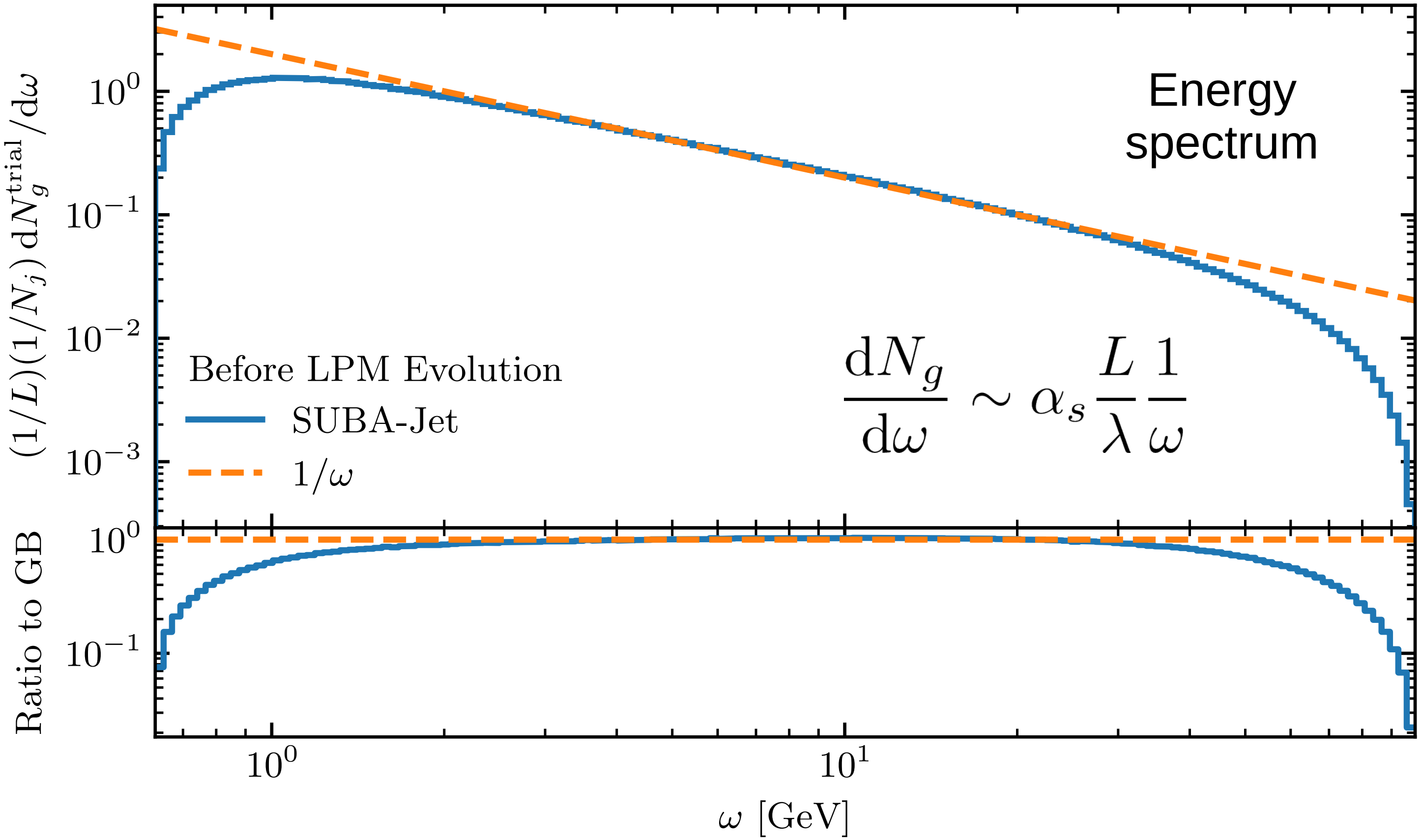
- Initial Gunion-Bertsch seed: i.e. radiation of a **preformed gluon** from a single scattering (Each parton can generate a number of preformed gluons)

- Gunion-Bertsch cross-section from scalar QCD

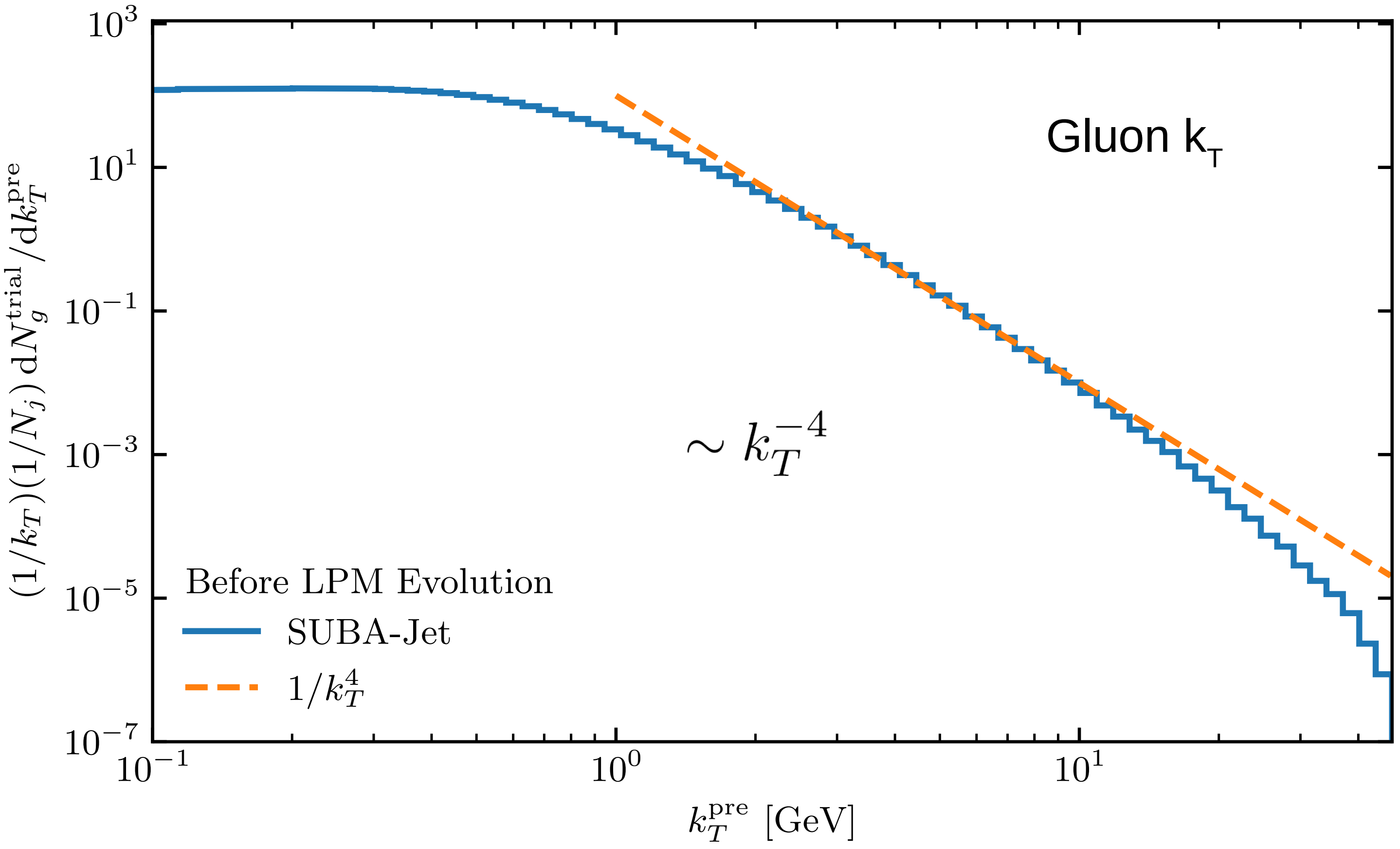
$$\frac{\mathrm{d}\sigma^{Qq\to Qqg}}{\mathrm{d}x\,\mathrm{d}^2k_T\,\mathrm{d}^2l_t} = \frac{\mathrm{d}\sigma_{\mathrm{el}}}{\mathrm{d}^2l_t} P_g(x, k_T, l_T)\theta(\Delta)$$

$$\frac{\mathrm{d}\sigma_{\mathrm{el}}}{\mathrm{d}^2l_t} \sim \frac{8\alpha_s^2}{9(l_T^2+\mu^2)^2}$$

Medium-Induced Single Radiation



Medium-Induced Single Radiation



Coherency and the LPM Effect

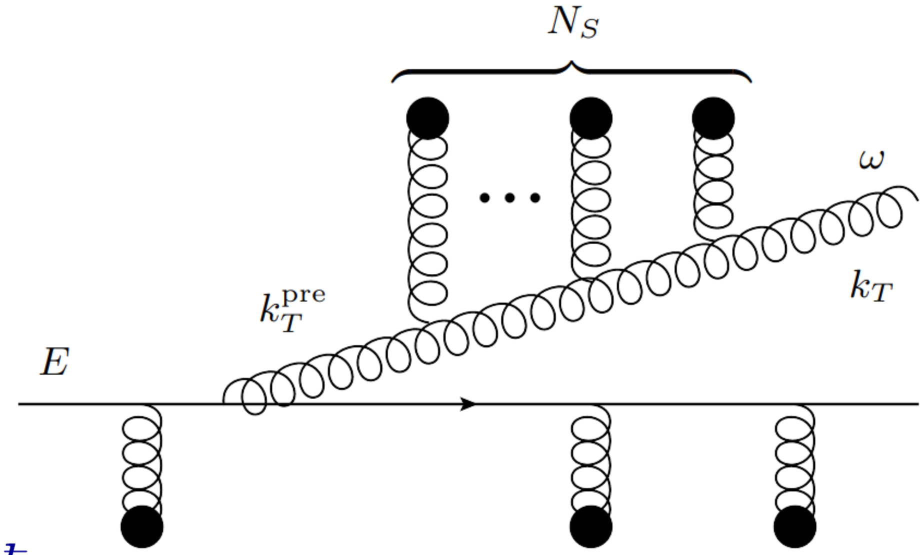
$\omega =$ gluon energy

$\hat{q} =$ medium modifications

- The formation of the radiated gluon is a quantum mechanical process

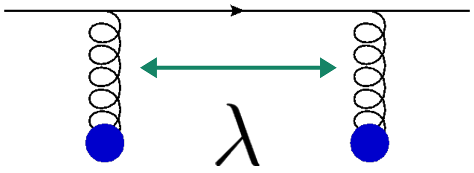
Formation time: $t_f \sim \sqrt{\frac{\omega}{\hat{q}}}$

- Coherence effects:
  Landau-Pomeranchuk-Migdal (LPM) effect



- Have to take into account multiple scatterings with the medium during the formation time

$$N_s = \frac{t_f}{\lambda}$$



$$\lambda \simeq \frac{\hbar c}{\alpha_s T}$$

$L =$ path length of medium

Implementation of the LPM Effect

- At each timestep:
  - Elastic scattering with prob. $\Gamma_{\mathrm{el}}\Delta t$

$$\Gamma^q_{\mathrm{el}} = \left(1 + \frac{N_f}{N}\right)\frac{(N^2-1)T^3}{\pi\hbar c}\frac{4\alpha_s^2}{\mu^2}$$

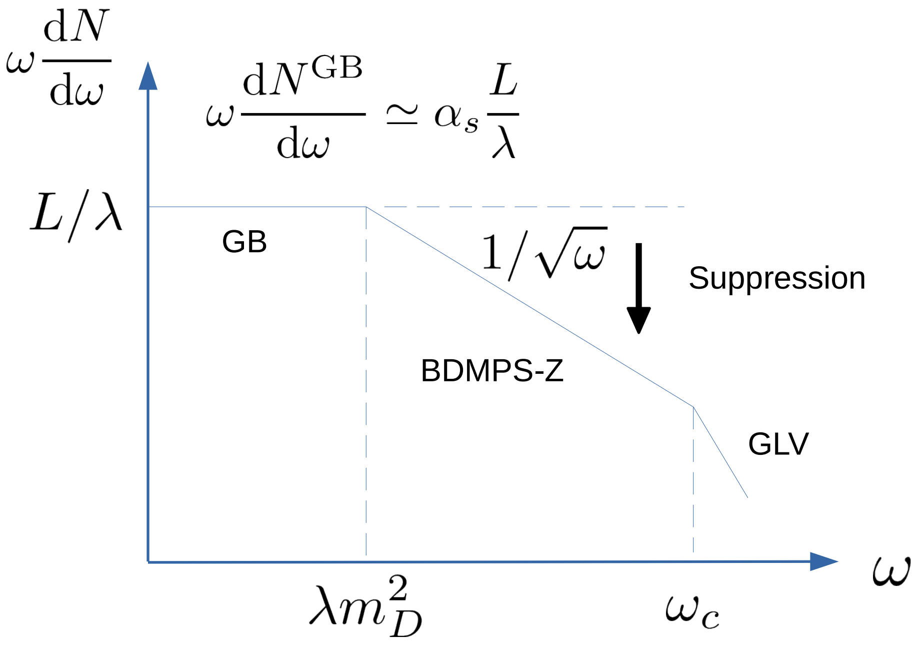
  - Radiation of preformed gluon with prob. $\Gamma_{\mathrm{inel}}\Delta t$

- BDMPS-Z spectrum at intermediate energies achieved by suppressing GB seed by

$$1/N_s$$

Like in Zapp, Stachel, Wiedemann, JHEP 07 (2011), 118

Radiation energy spectrum:



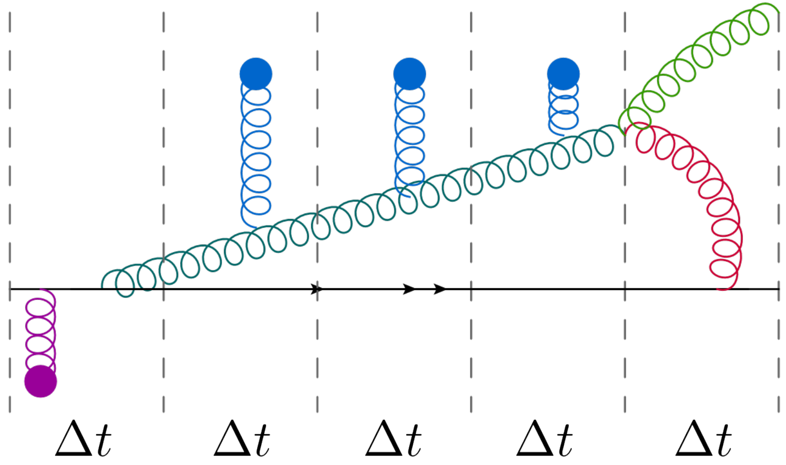
$$\omega\frac{\mathrm{d}N^{\mathrm{BDMPS\text{-}Z}}}{\mathrm{d}\omega} \simeq \alpha_s\sqrt{\frac{\hat{q}L^2}{\omega}}$$

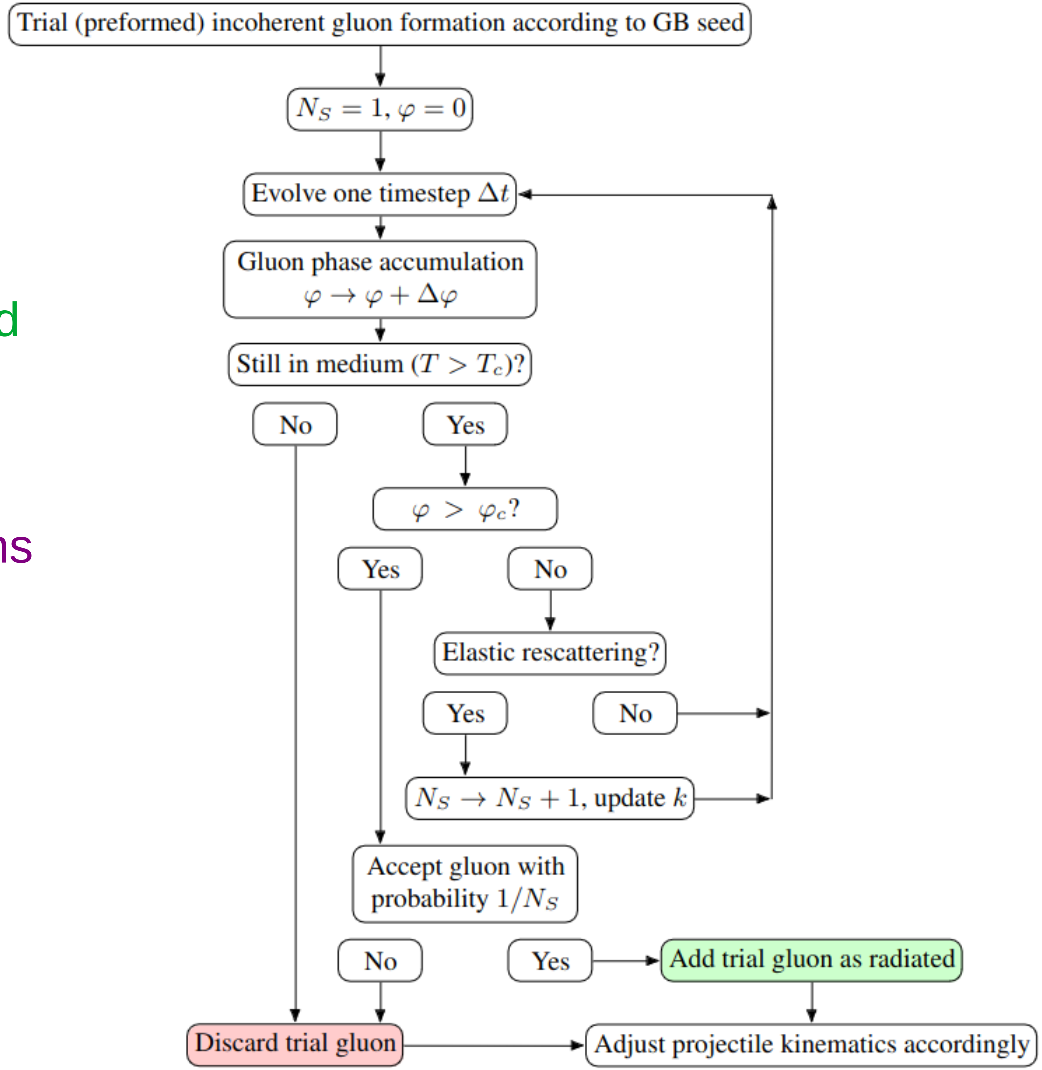
The Algorithm

Flow diagram:

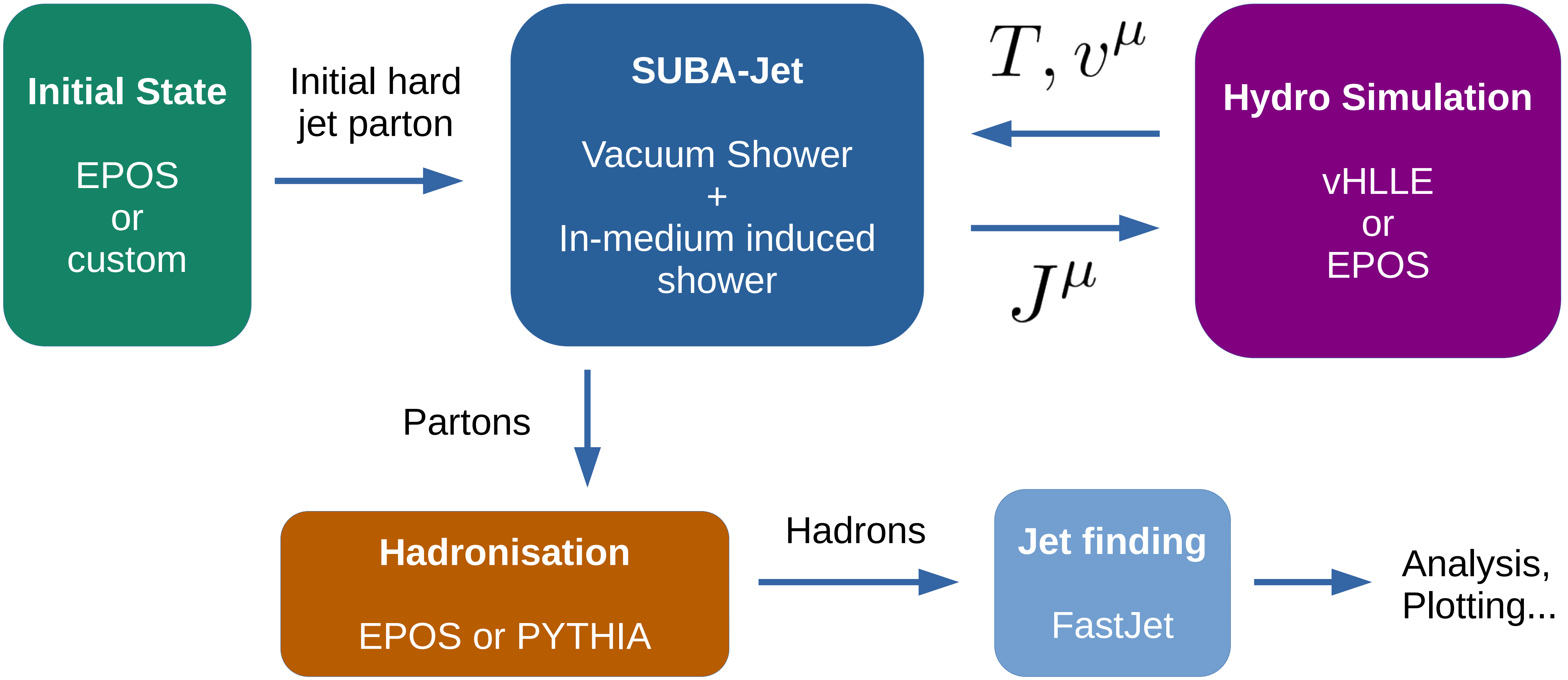
Algorithm for the coherent medium-induced gluon radiation in our model

Various parameters and settings can be changed and tuned to compare distributions



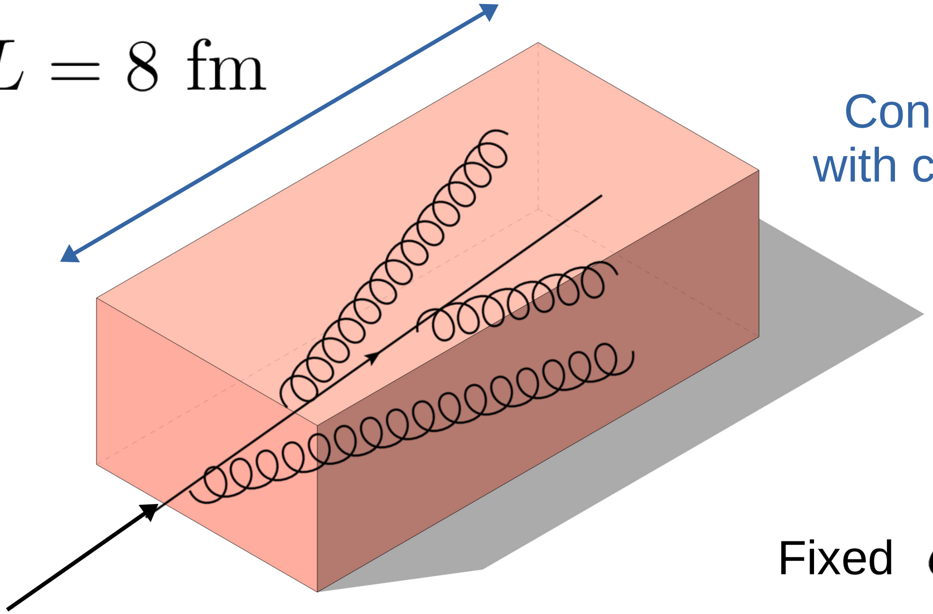


The Monte Carlo



First Results

$L = 8 \text{ fm}$



Consider brick medium with constant temperature

$T = 400 \text{ MeV}$

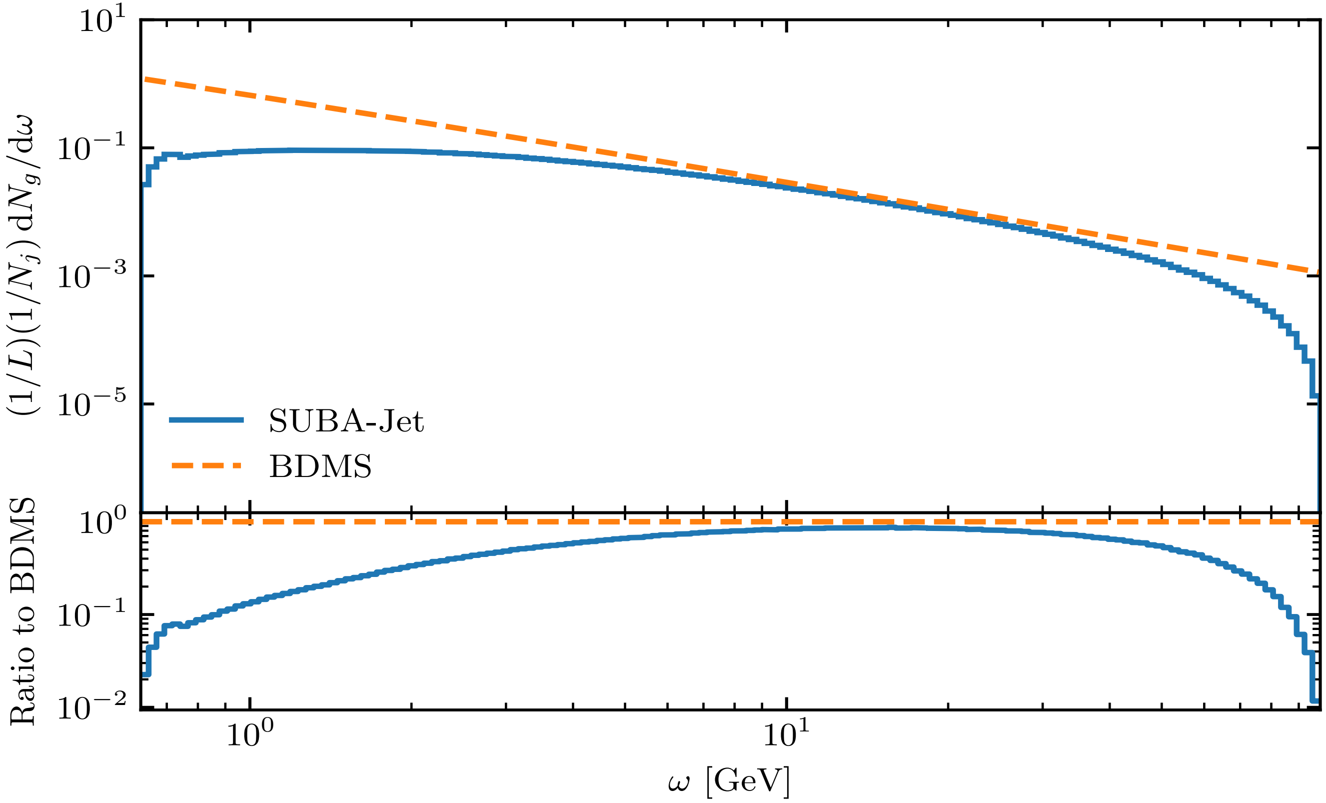
Mono-energy (low virtuality) quark gun

$E = 100 \text{ GeV}$

Fixed $\alpha_s = 0.4$

We want to reproduce theoretical expectation and check effect of model parameters

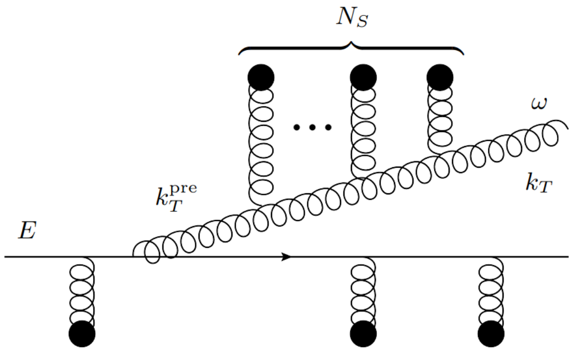
Reproduction of the BDMPS-Z Limit



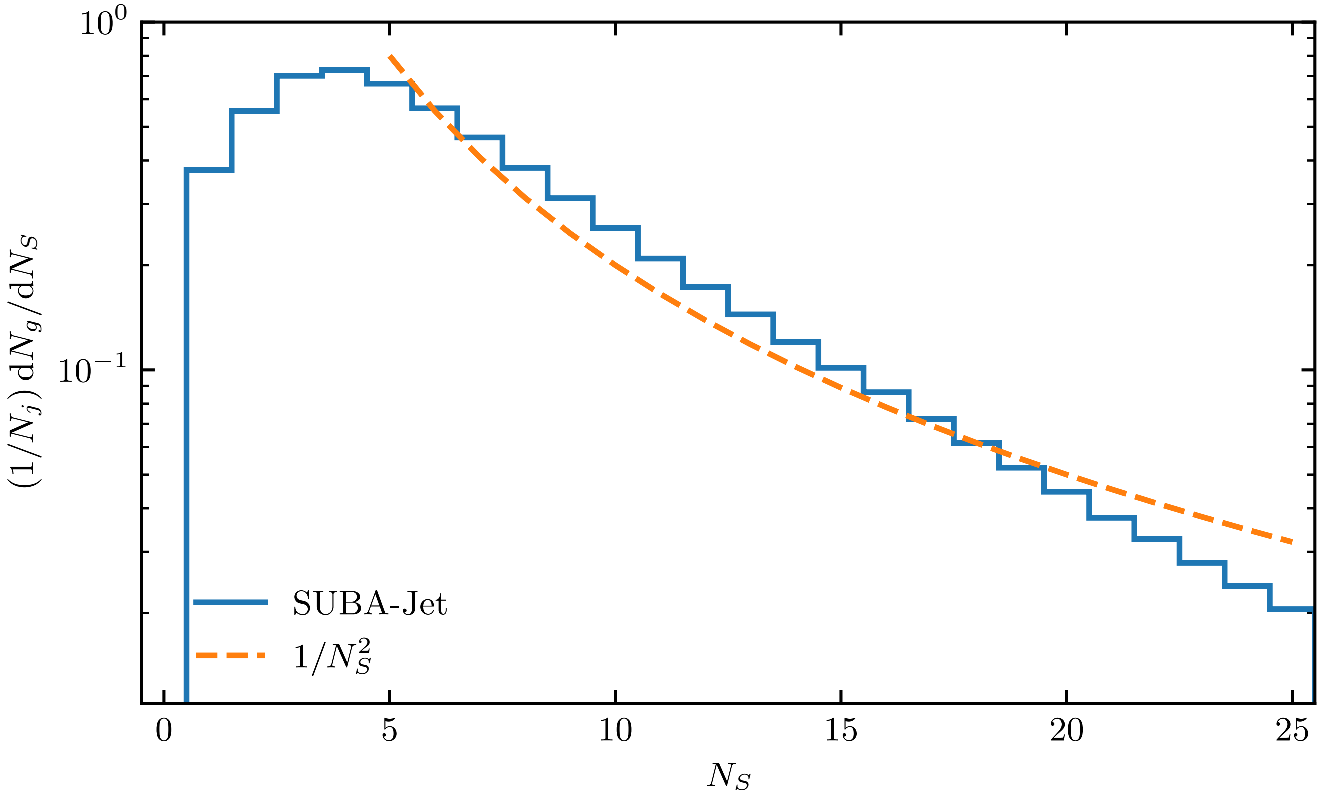
Gluon energy ω spectrum

Reproduces BDMPS-Z for intermediate energies

$$\frac{\mathrm{d}N}{\mathrm{d}\omega} \sim \frac{1}{\omega^{3/2}}$$



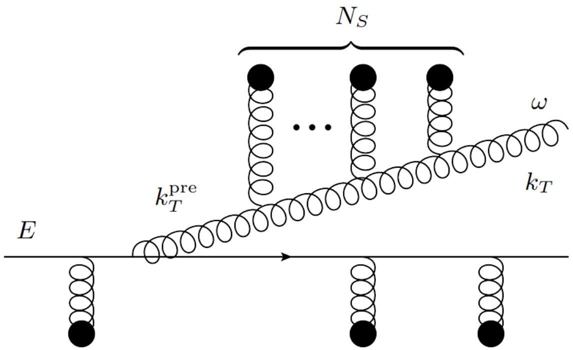
Reproduction of the BDMPS-Z Limit



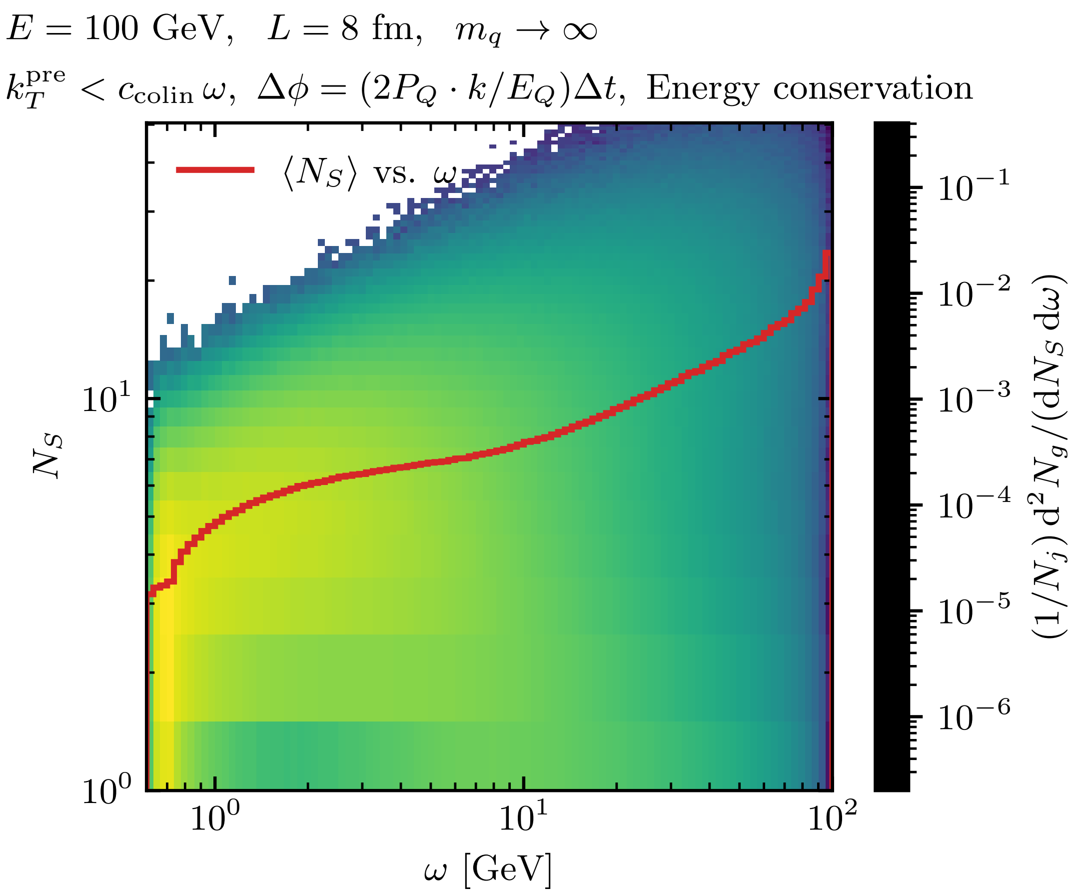
Number of elastic scatterings N_S

Reproduces BDMPS-Z expectation

$$\frac{\mathrm{d}N}{\mathrm{d}N_S} \sim \frac{1}{N_S^2}$$



Reproduction of the 3 Regimes



Double differential plot in N_s and ω

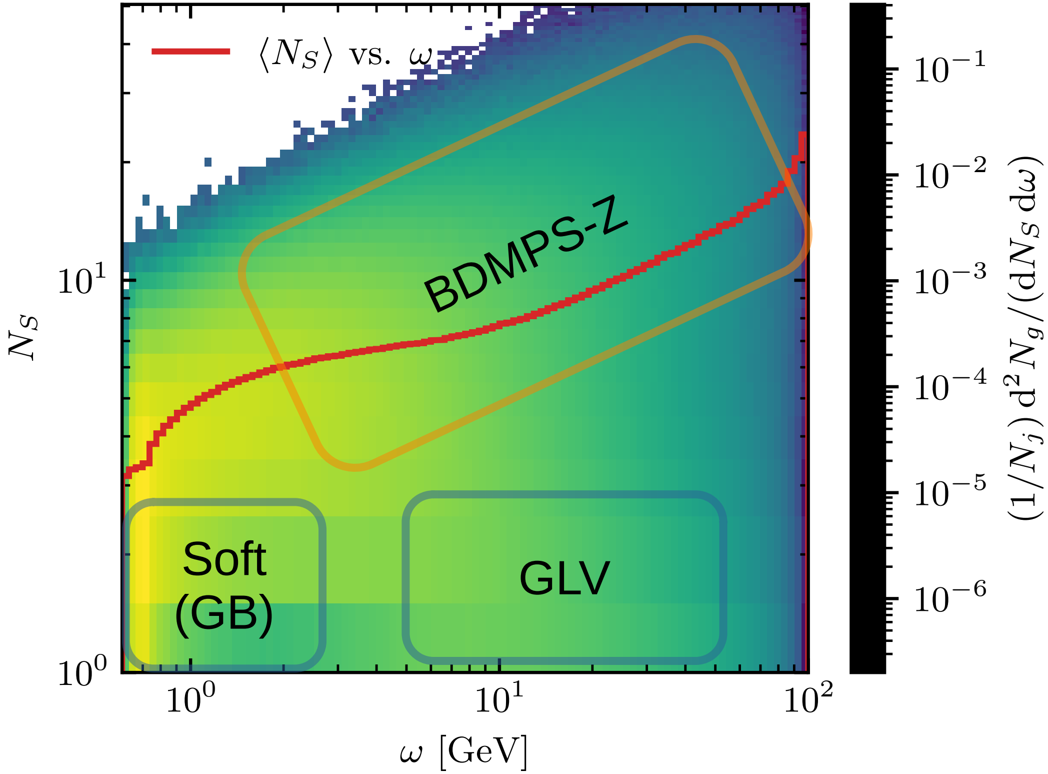
Red line: ‹N_s› vs. ω

$$N_S \sim t_f \sim \sqrt{\omega}$$

Reproduction of the 3 Regimes

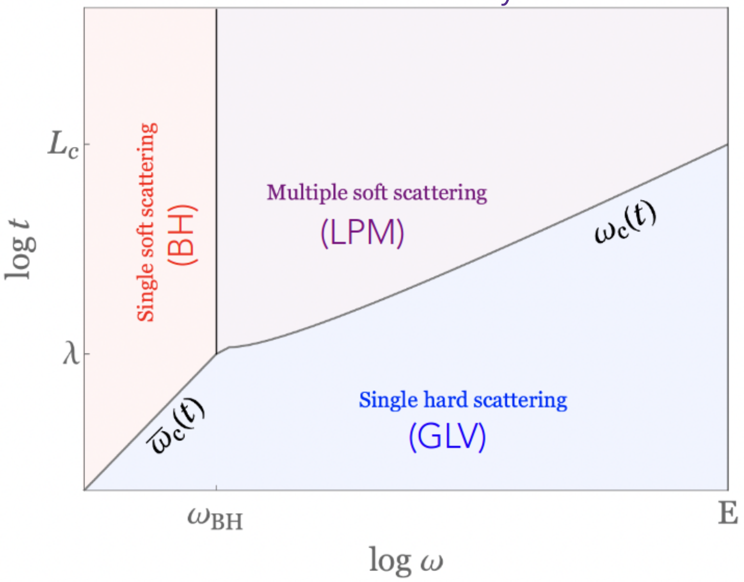
$E = 100$ GeV, $L = 8$ fm, $m_q \to \infty$

$k_T^{\mathrm{pre}} < c_{\mathrm{colin}}\,\omega$, $\Delta\phi = (2P_Q \cdot k/E_Q)\Delta t$, Energy conservation

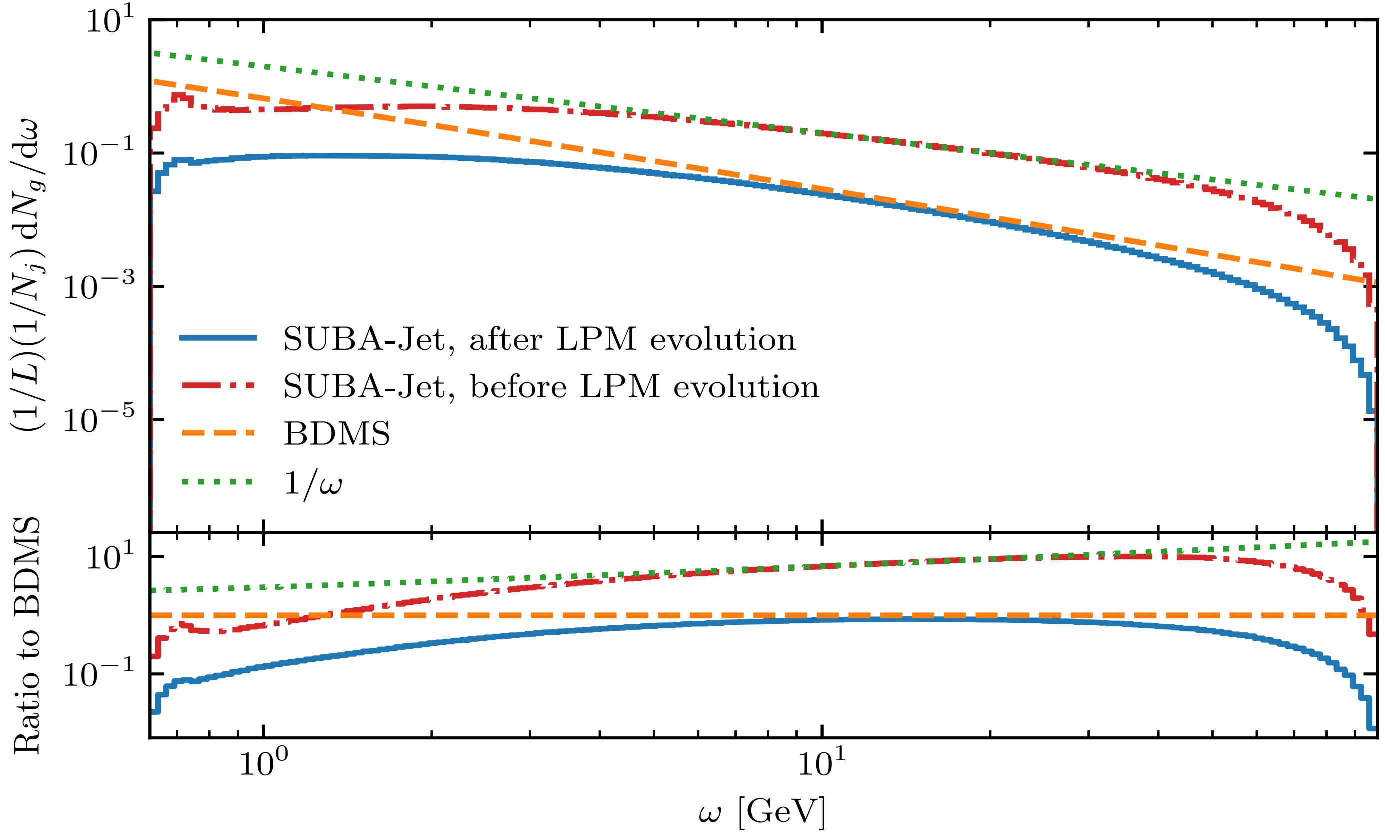


Convolution of different distributions

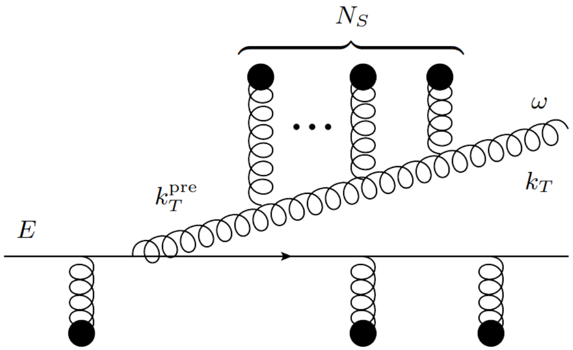
From K. Tywoniuk lectures



The Role of the Phase Accumulation

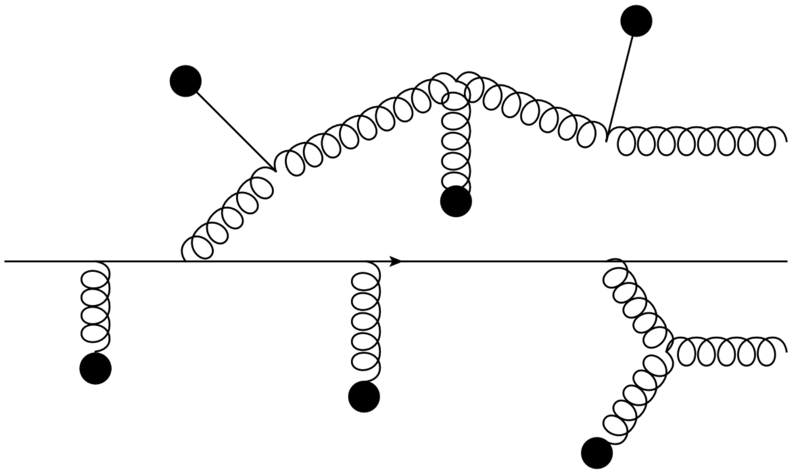


Effect of the phase accumulation on the energy spectrum



The Role of the Phase Accumulation

Choice of phase accumulation of the preformed (trial) gluons:



- **More general formula:**

$$\Delta\varphi = \frac{2P_Q \cdot k}{E_Q}\Delta t$$

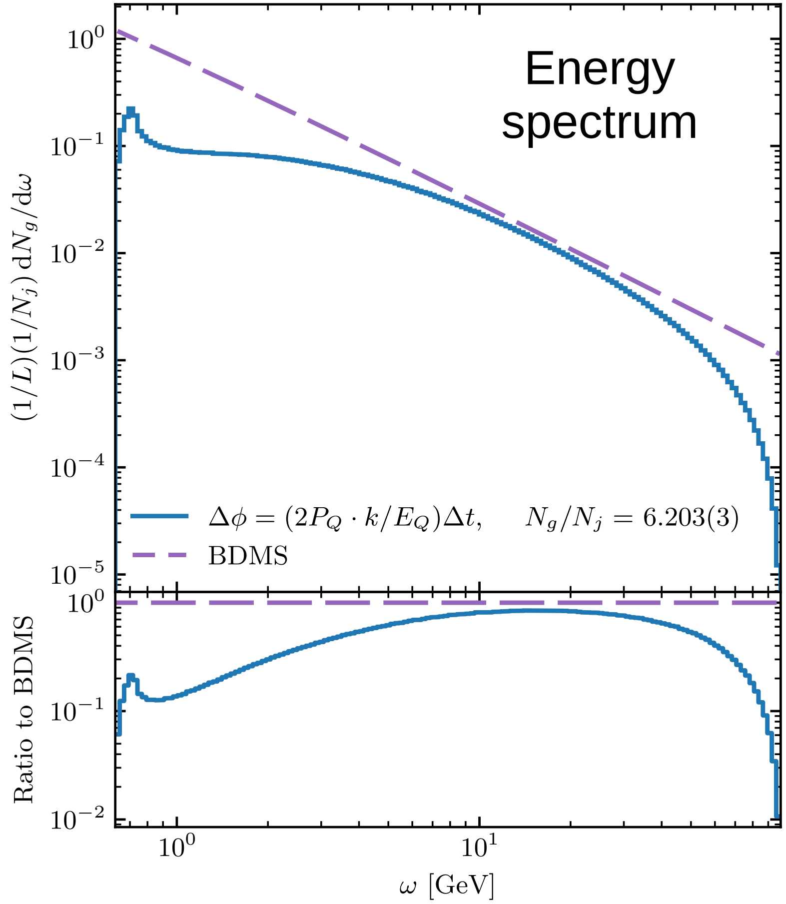
- **What is used in JEWEL:**

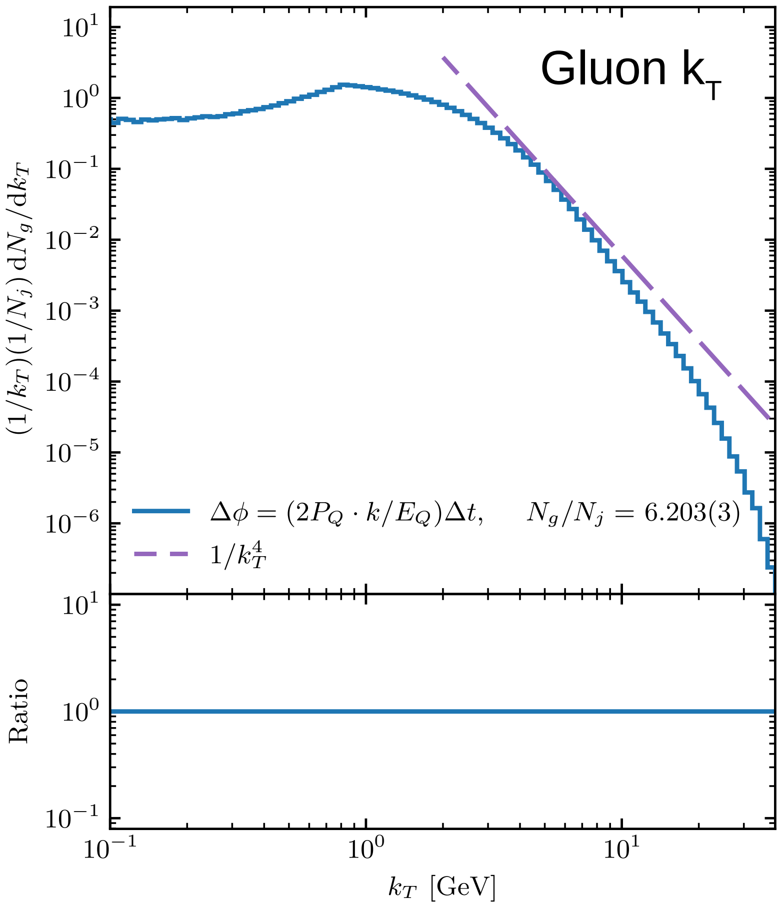
$$\Delta\varphi = \frac{k_T^2}{\omega}\Delta t$$

- **Including thermal gluon mass:**

$$\Delta\varphi = \frac{m_g^2 + k_T^2}{\omega}\Delta t$$

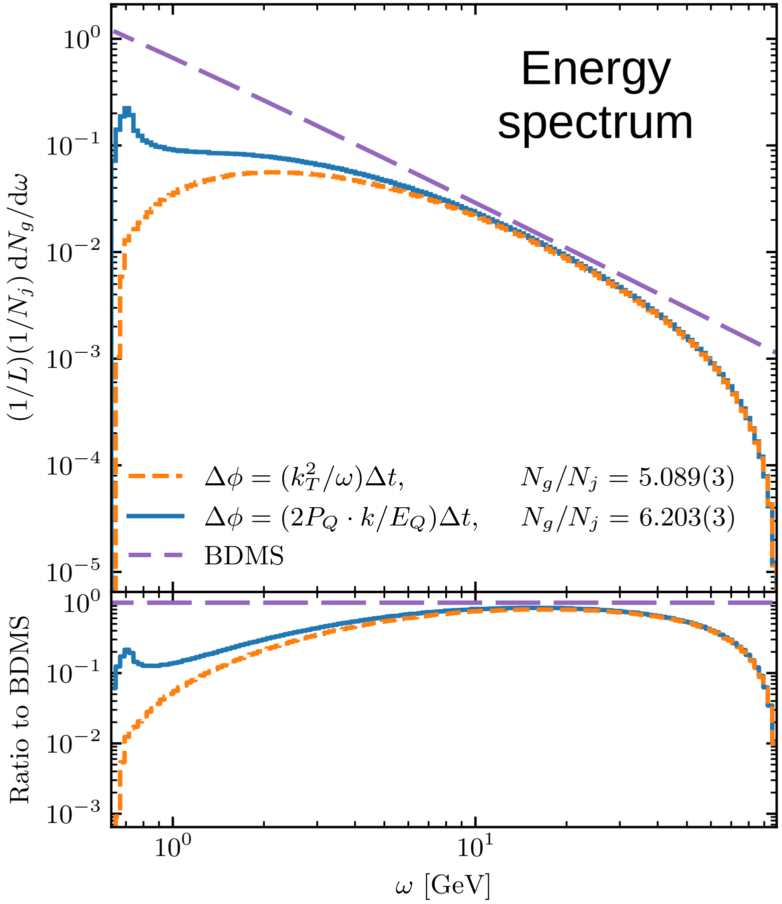
The Role of the Phase Accumulation

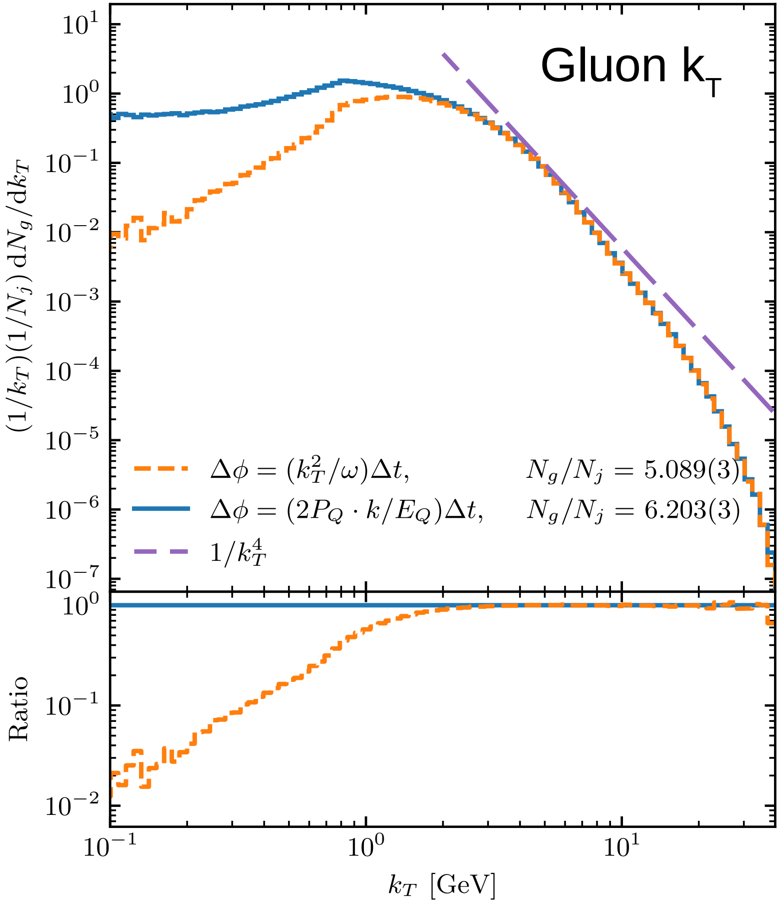




The Role of the Phase Accumulation

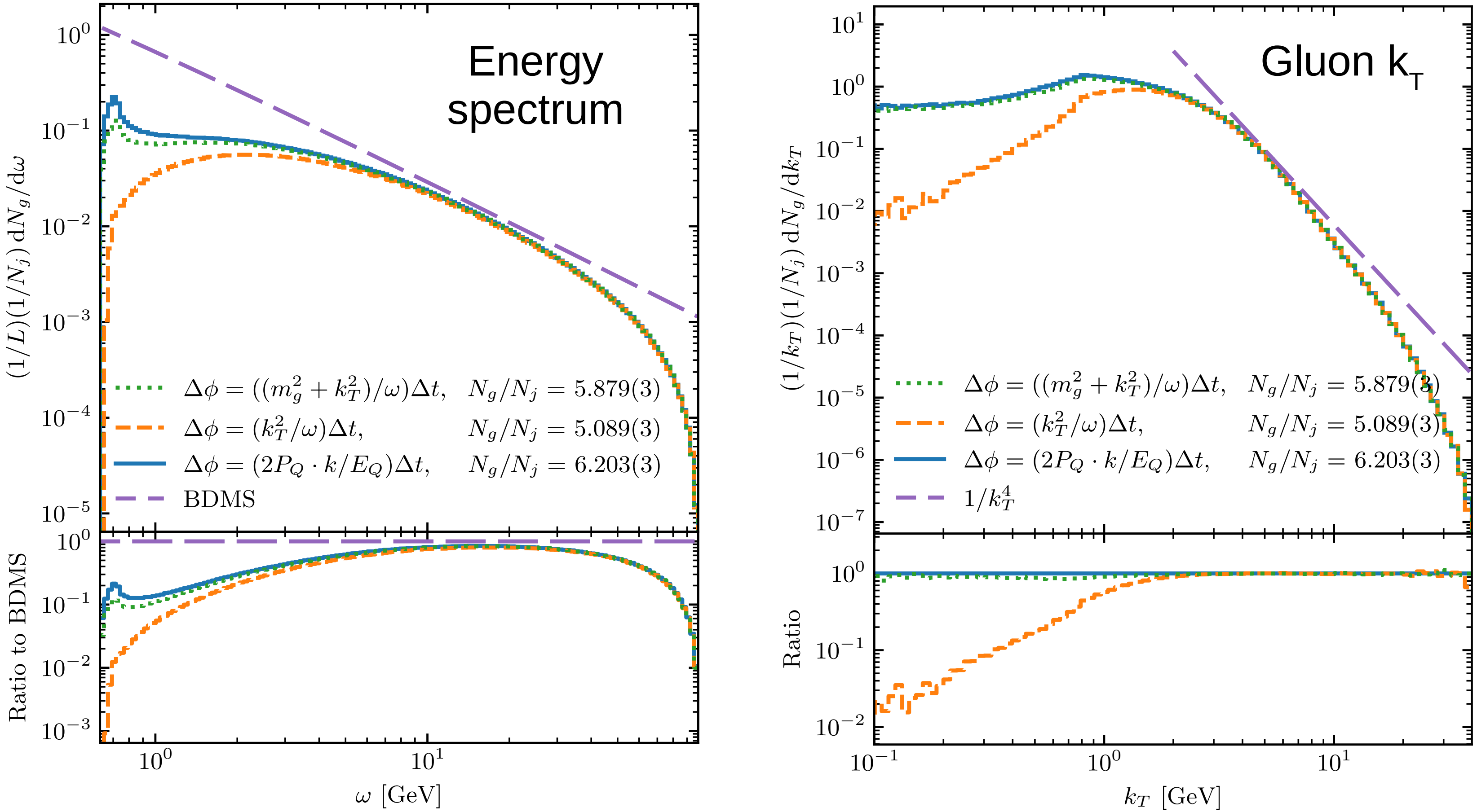
Effects at low energy & low k_T





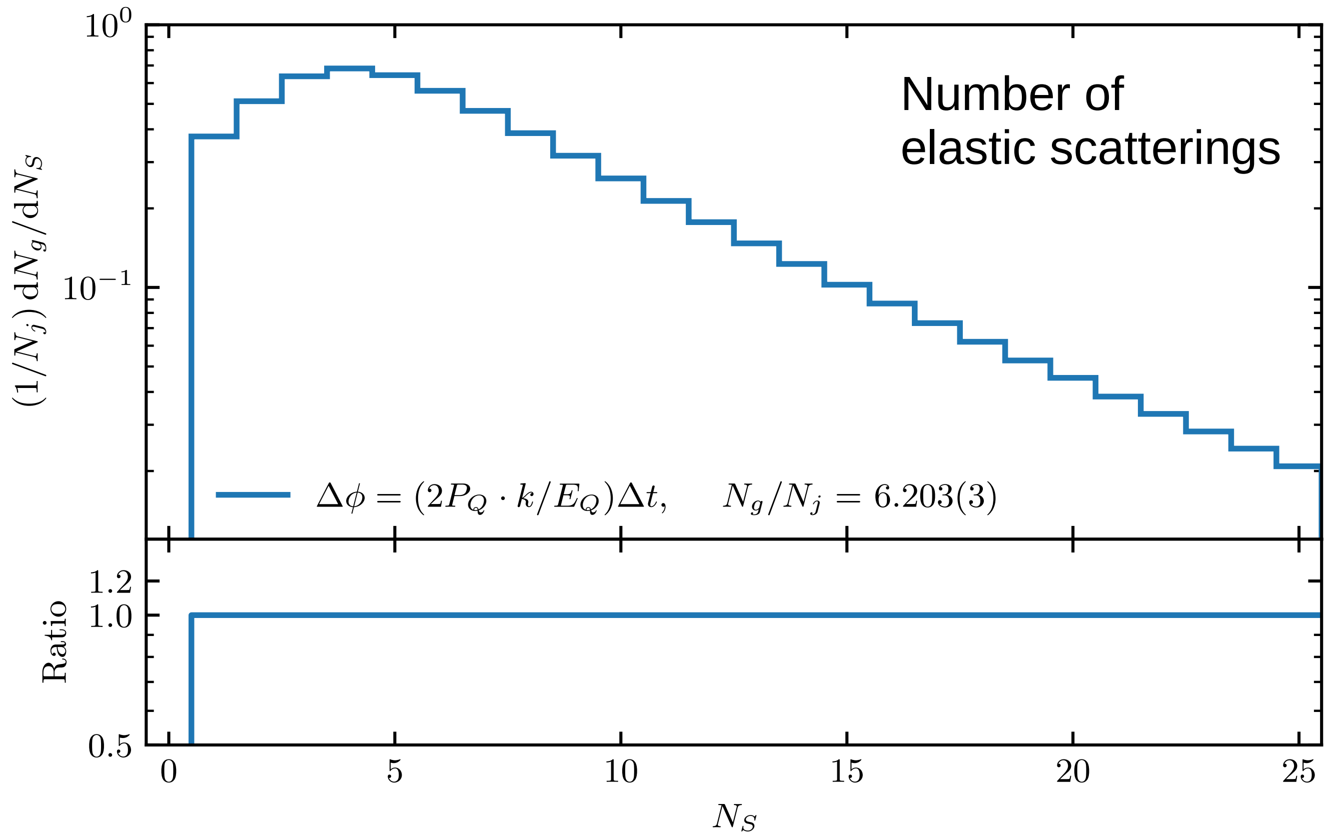
The Role of the Phase Accumulation

Effects at low energy & low k_T

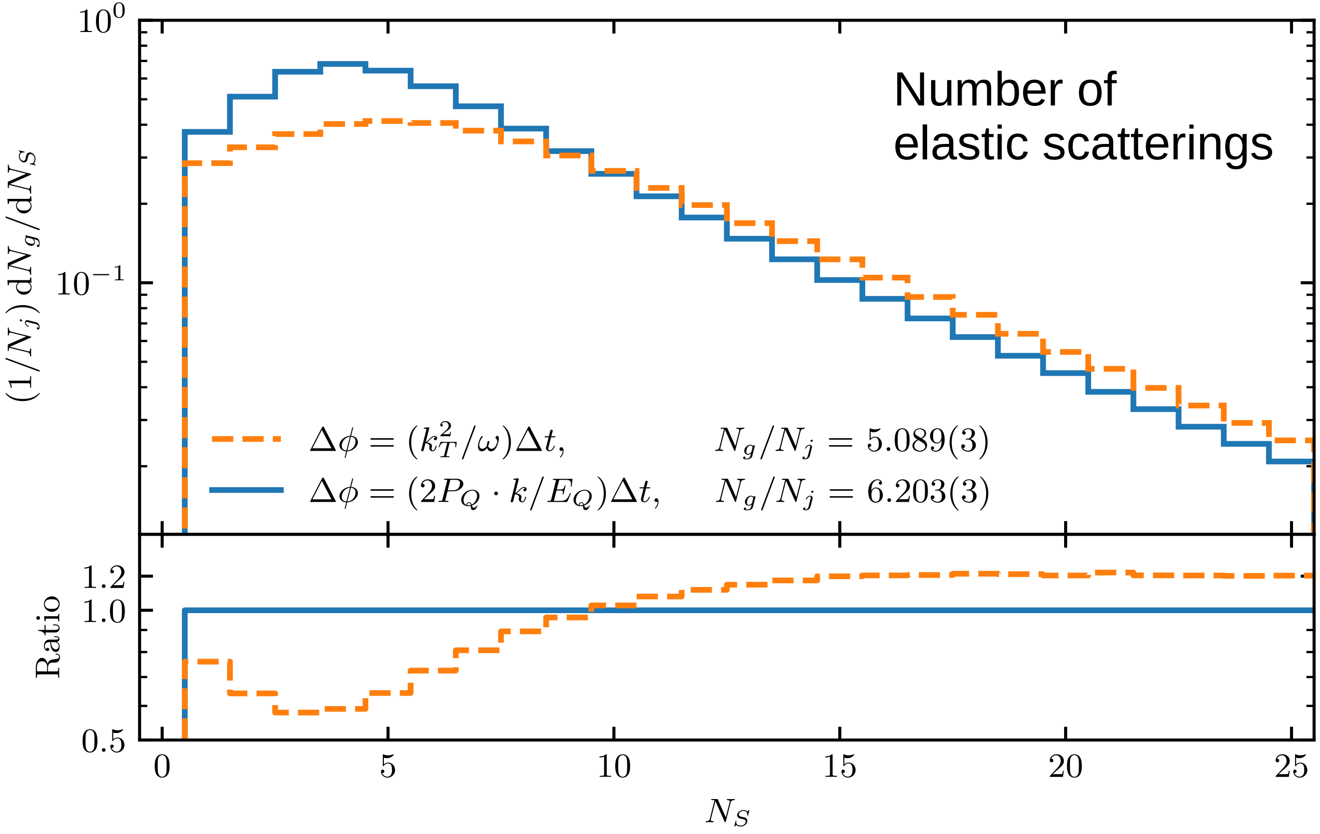


Number of radiated gluons per jet ~ 5 -- 6

The Role of the Phase Accumulation



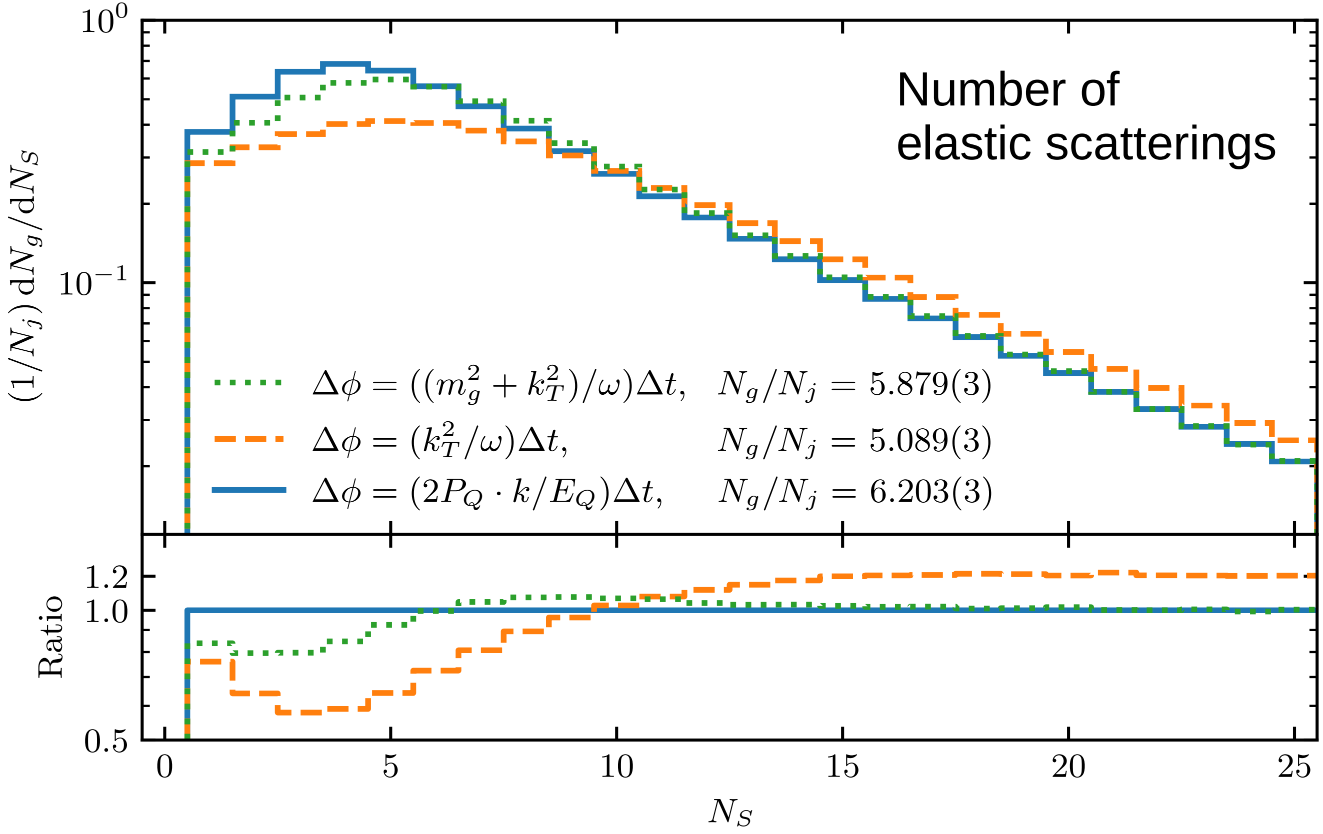
The Role of the Phase Accumulation



When neglecting the gluon mass in the phase accumulation, a larger path length is required to have a comparable overall number off radiations

The Role of the Phase Accumulation

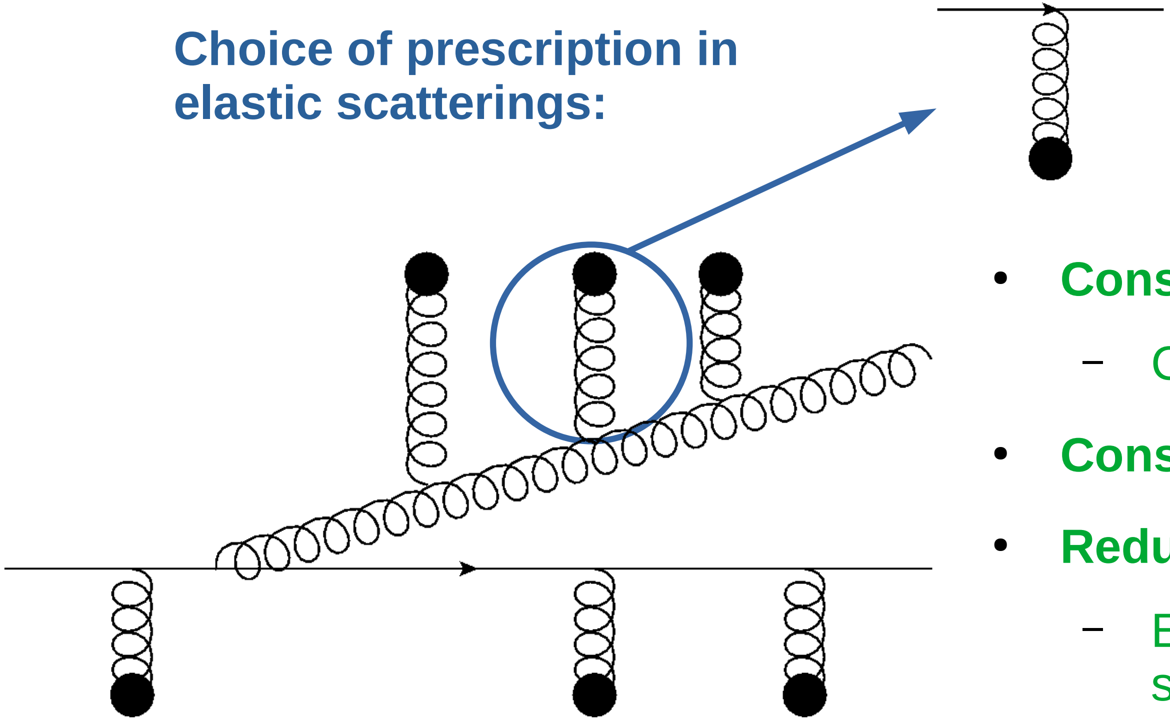
Effects at low N_S



When neglecting the gluon mass in the phase accumulation, a larger path length is required to have a comparable overall number off radiations

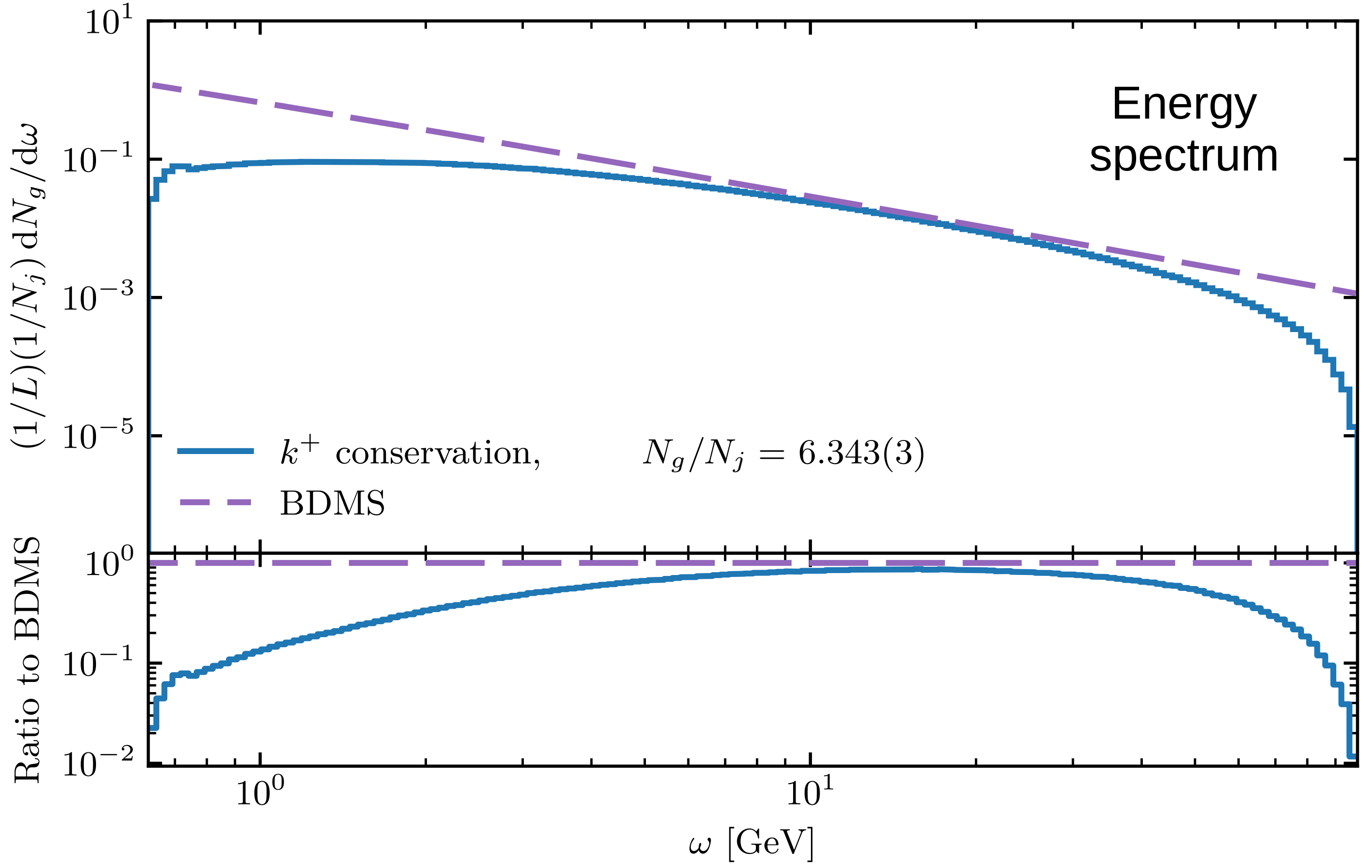
The Role of the Elastic Scatterings

Choice of prescription in elastic scatterings:



- **Conserve k^+?**
  - Considered by BDMPS-Z
- **Conserve energy?**
- **Reduce energy?**
  - Energy gain by the medium parton is subtracted from the projectile parton

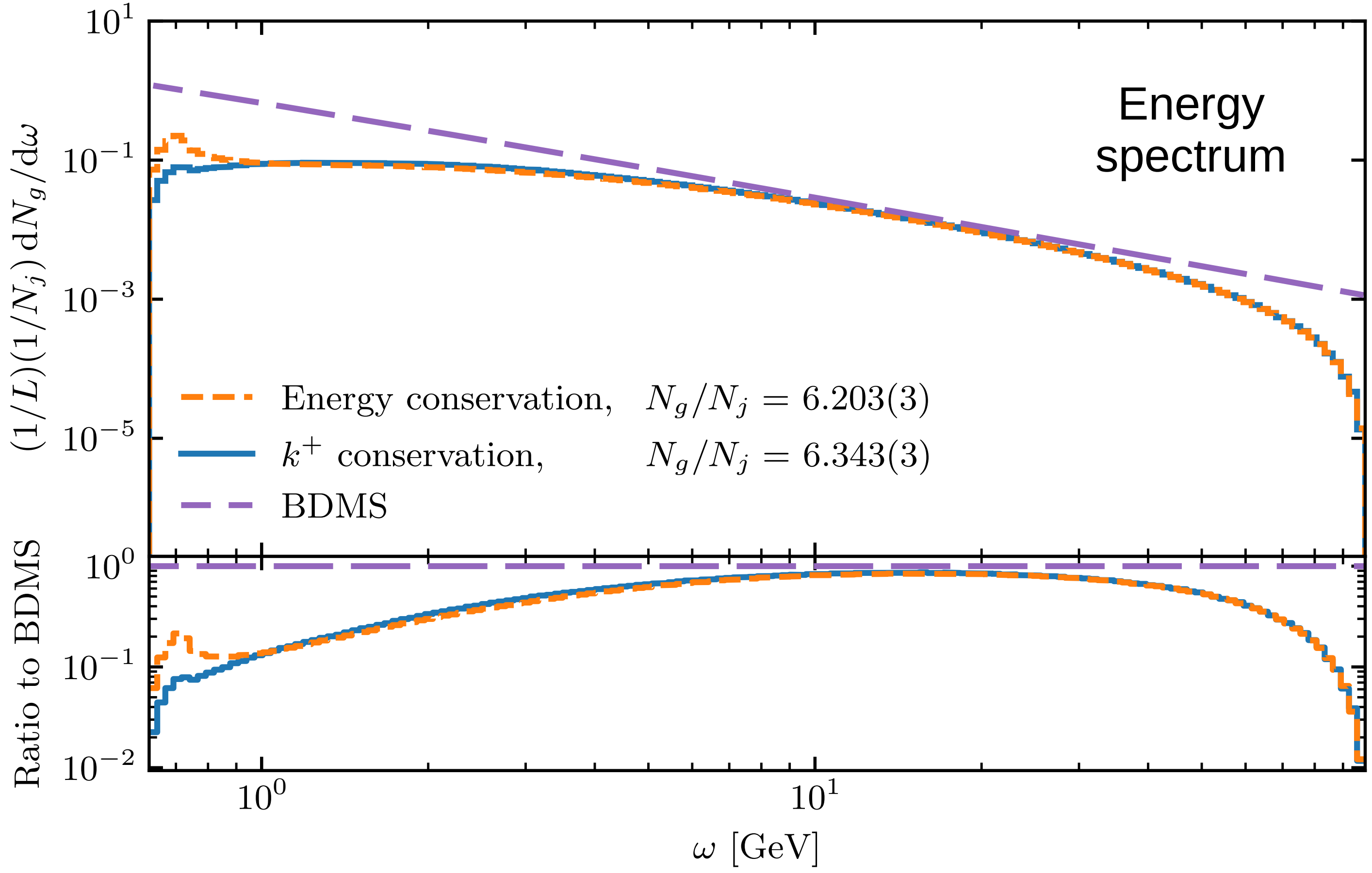
The Role of the Elastic Scatterings



Same BDMS behaviour at intermediate energies

Difference at small energies

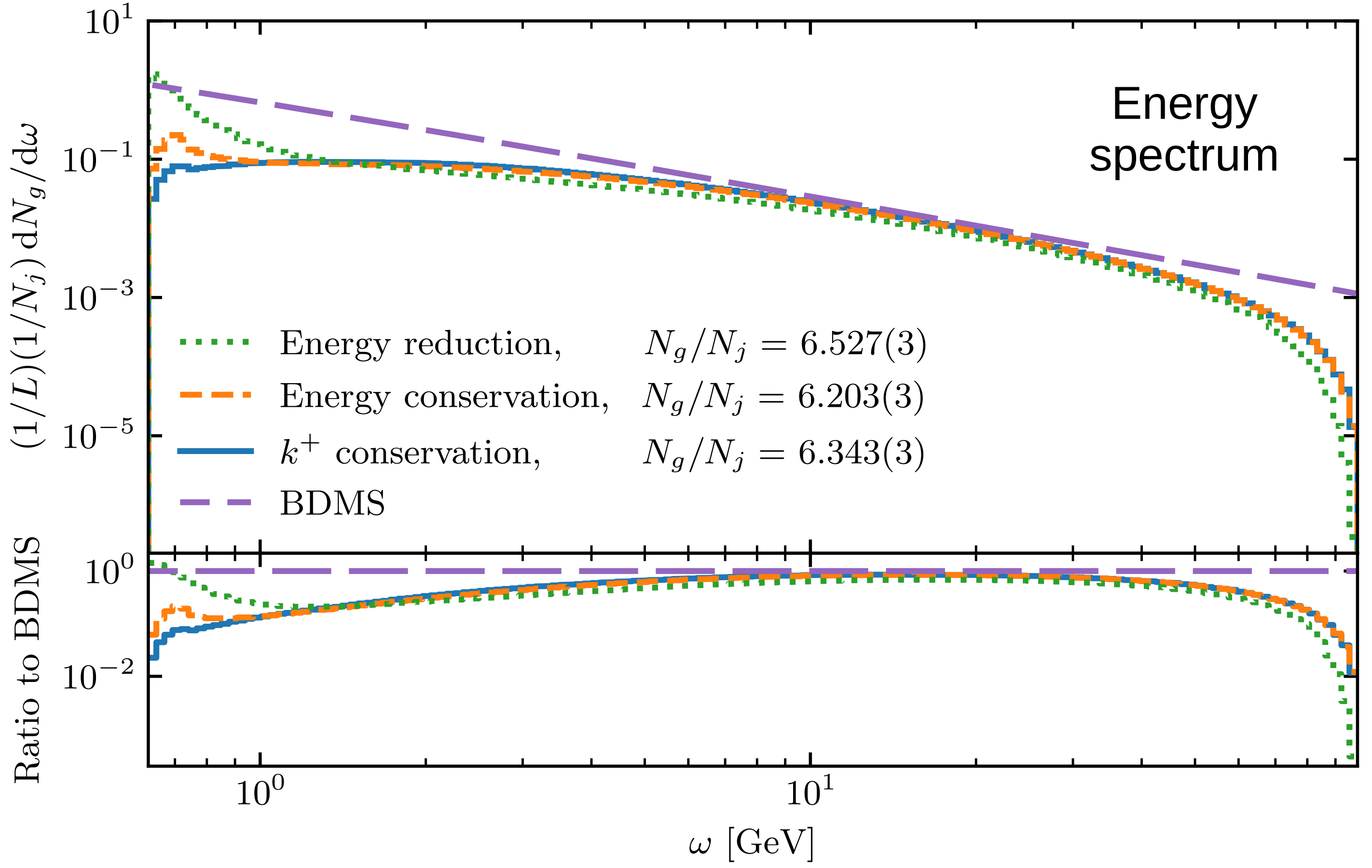
The Role of the Elastic Scatterings



Same BDMS behaviour at intermediate energies

Difference at small energies

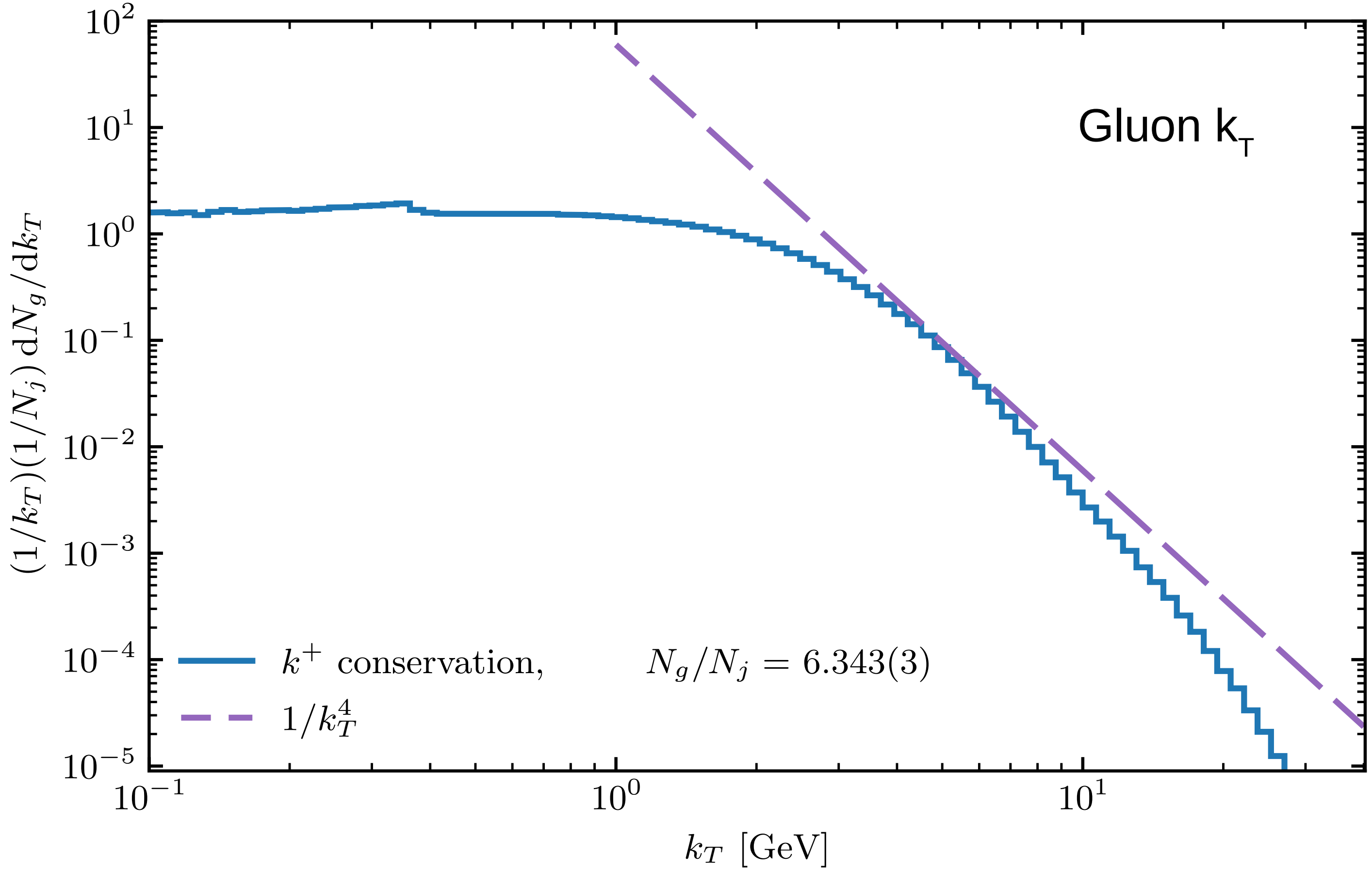
The Role of the Elastic Scatterings



Same BDMS behaviour at intermediate energies

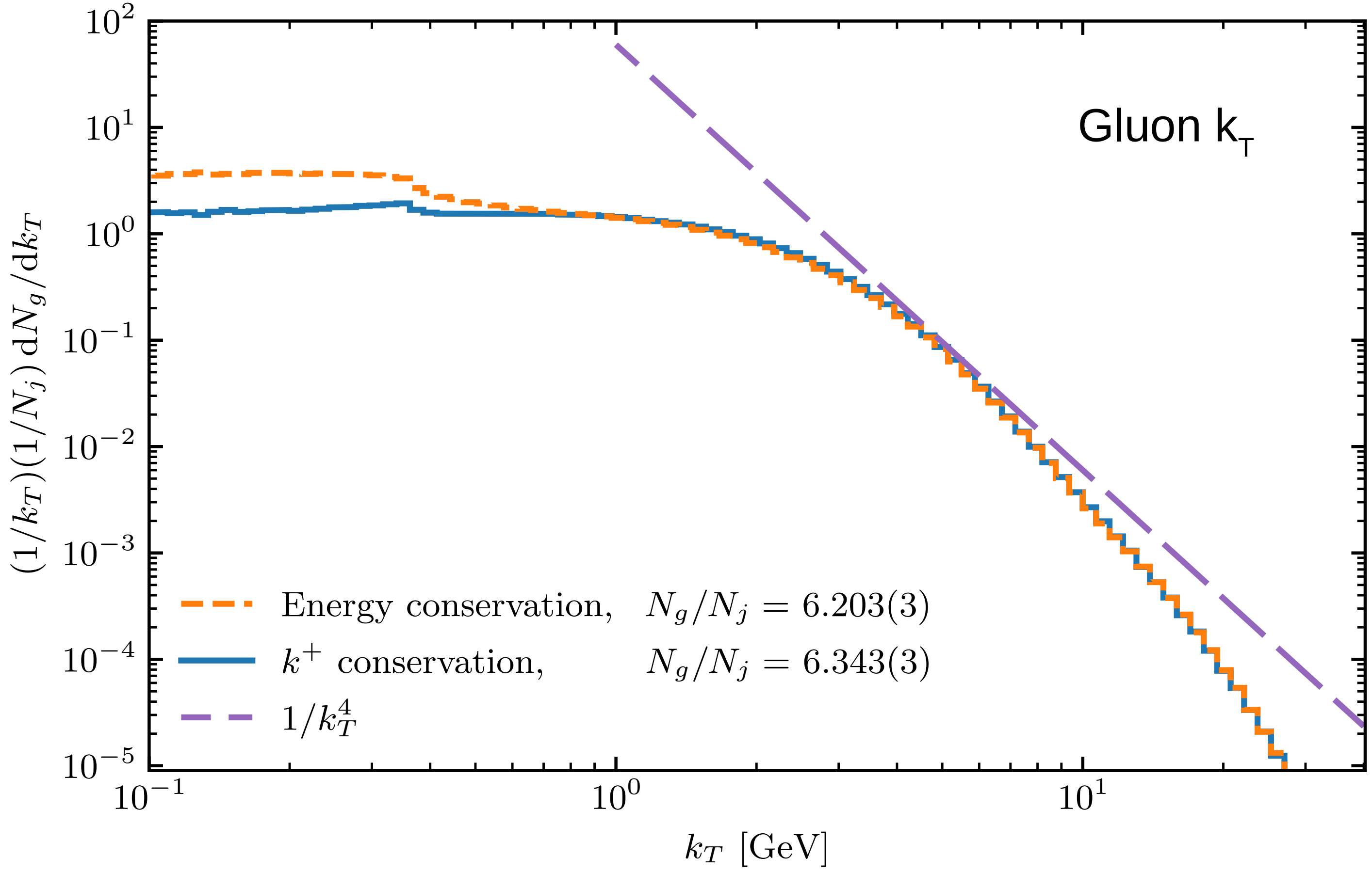
Difference at small energies

The Role of the Elastic Scatterings



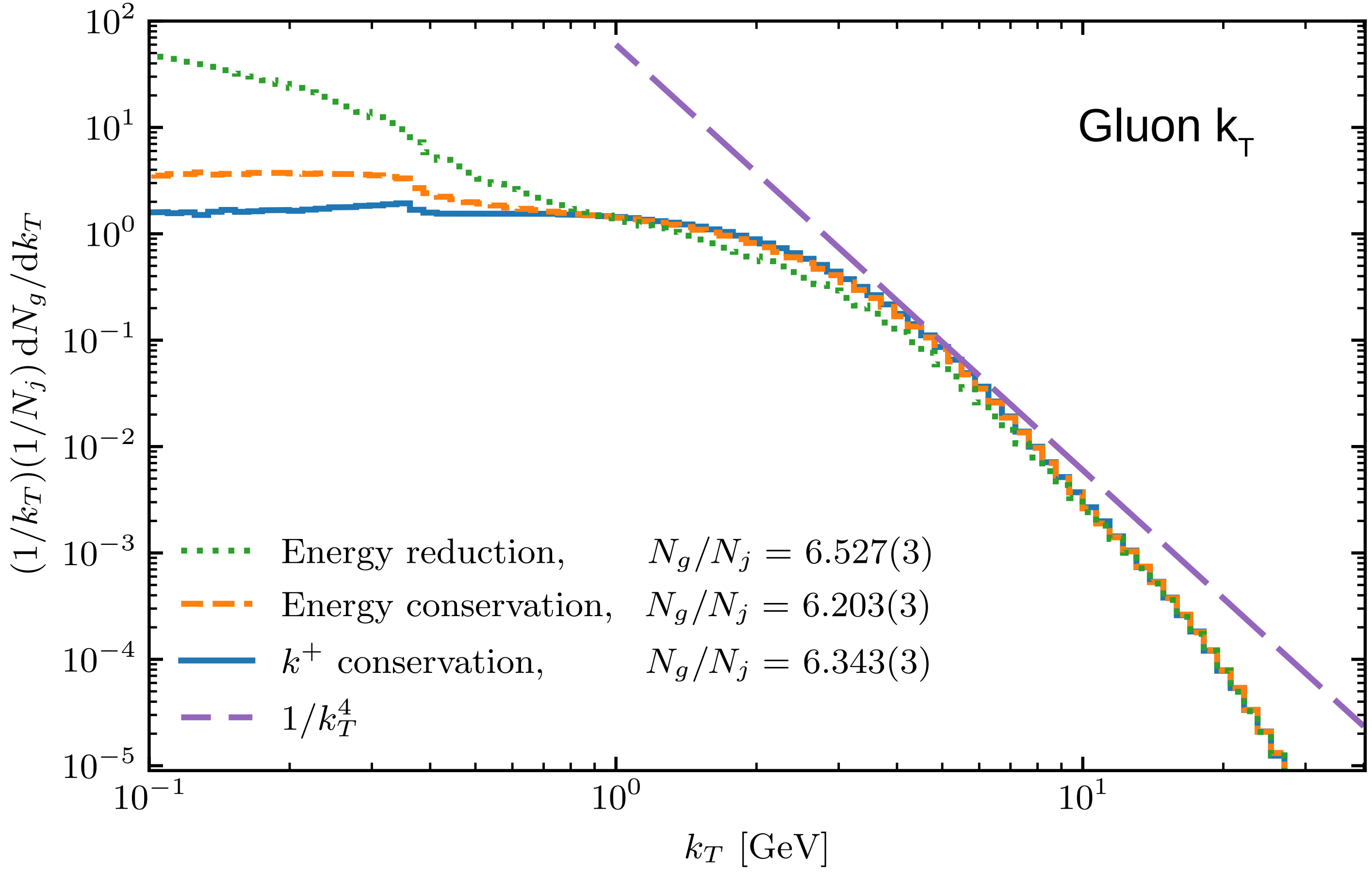
Large difference at small k_T

The Role of the Elastic Scatterings



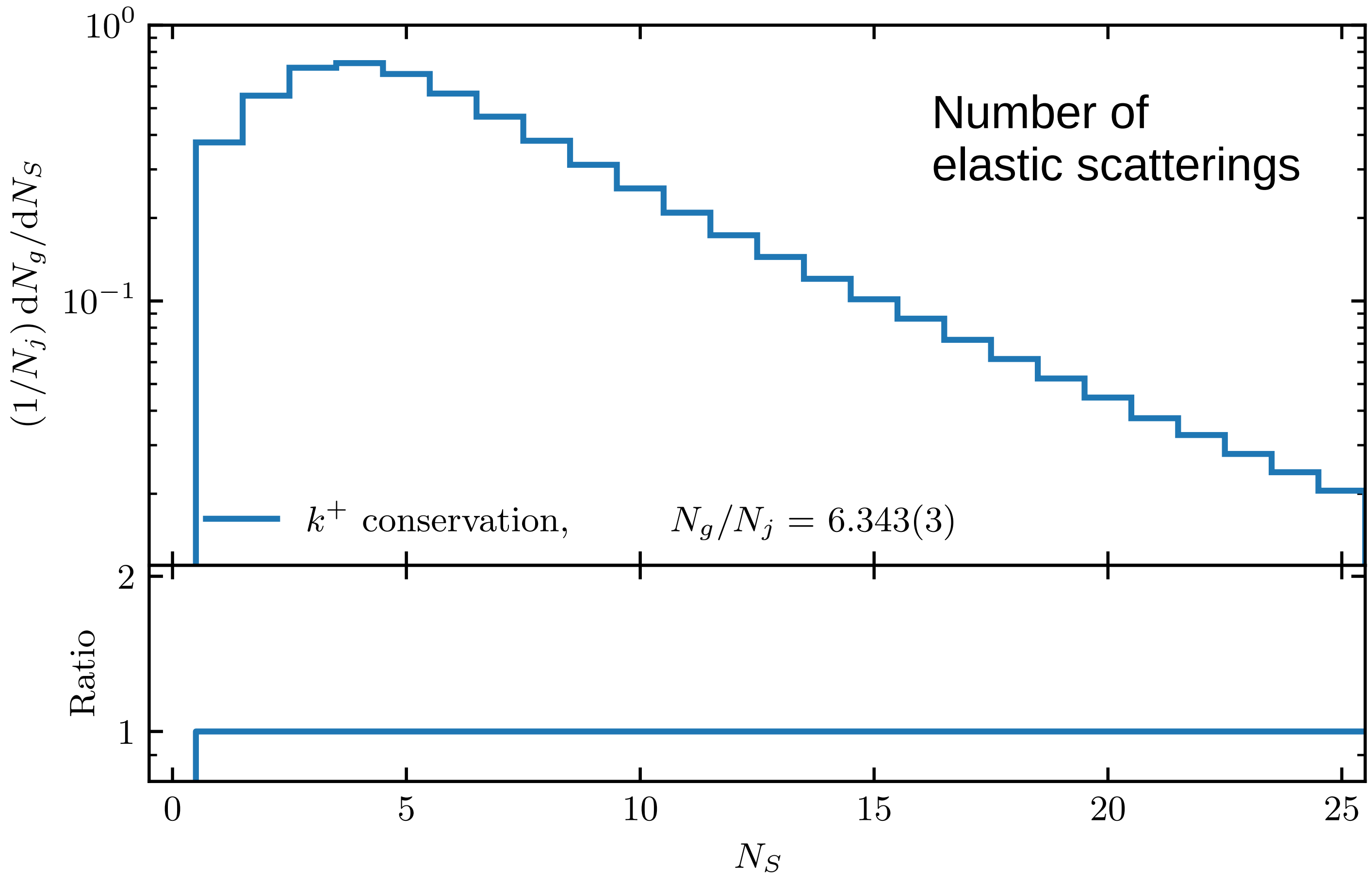
Large difference at small k_T

The Role of the Elastic Scatterings

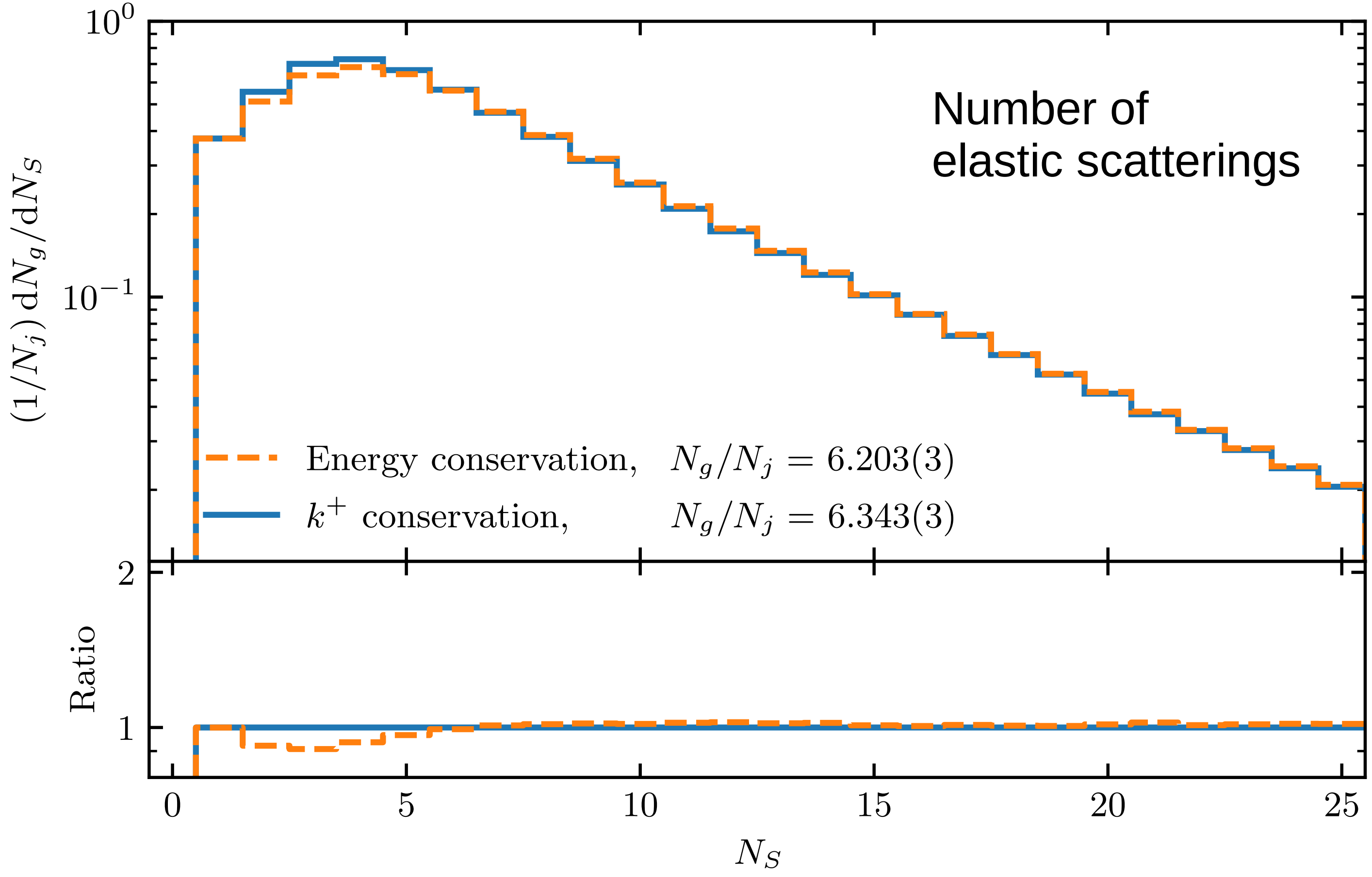


Large difference at small k_T

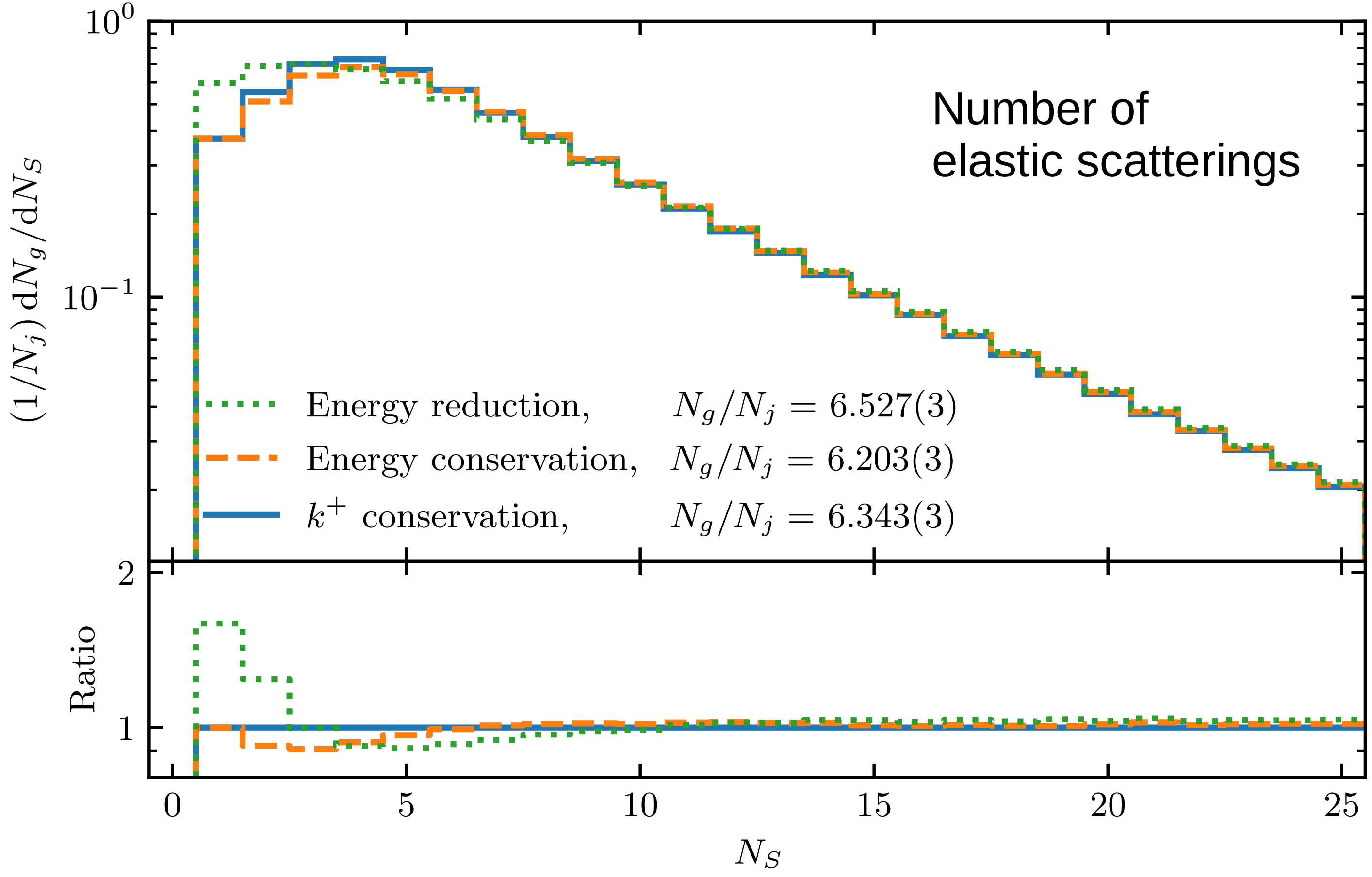
The Role of the Elastic Scatterings



The Role of the Elastic Scatterings



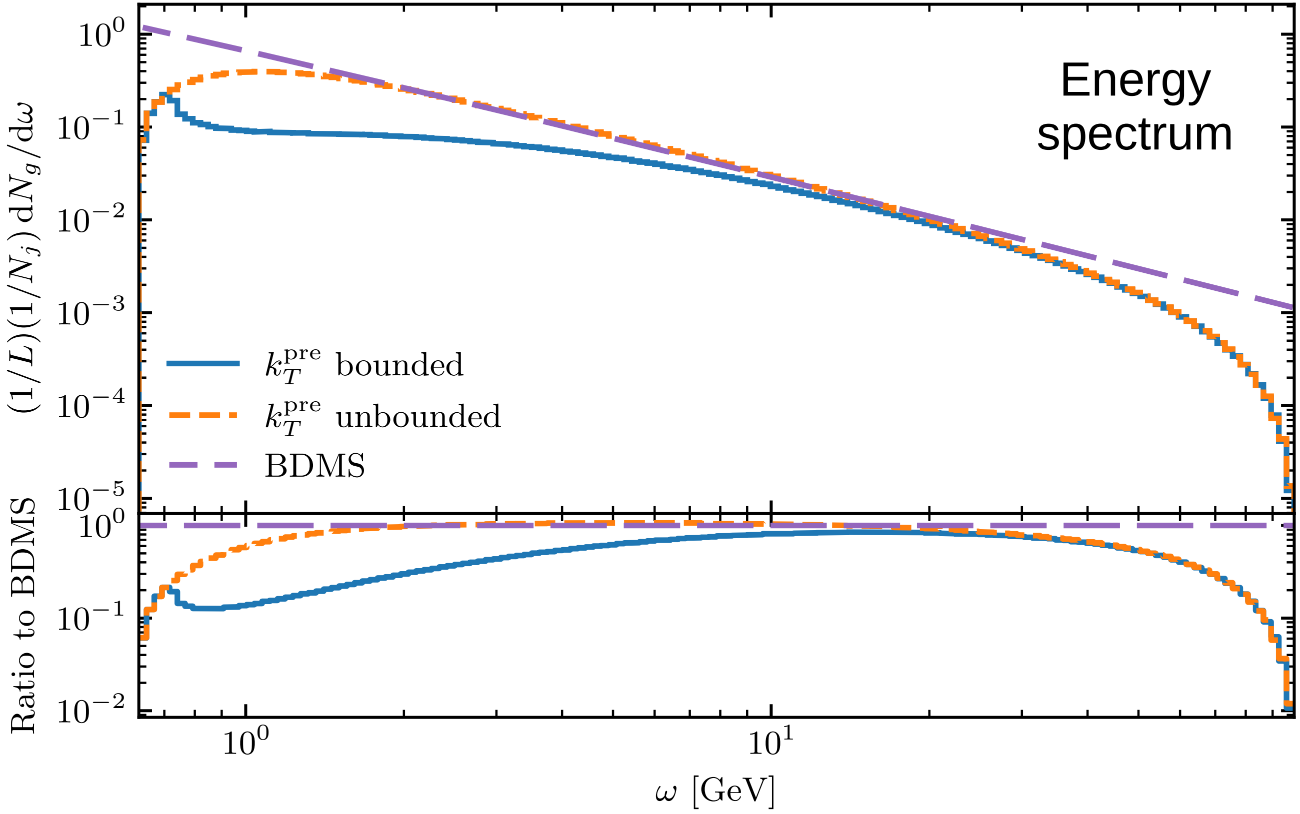
The Role of the Elastic Scatterings



The energy reduction case is larger at $N_s = 1$

→ Larger probability of emission

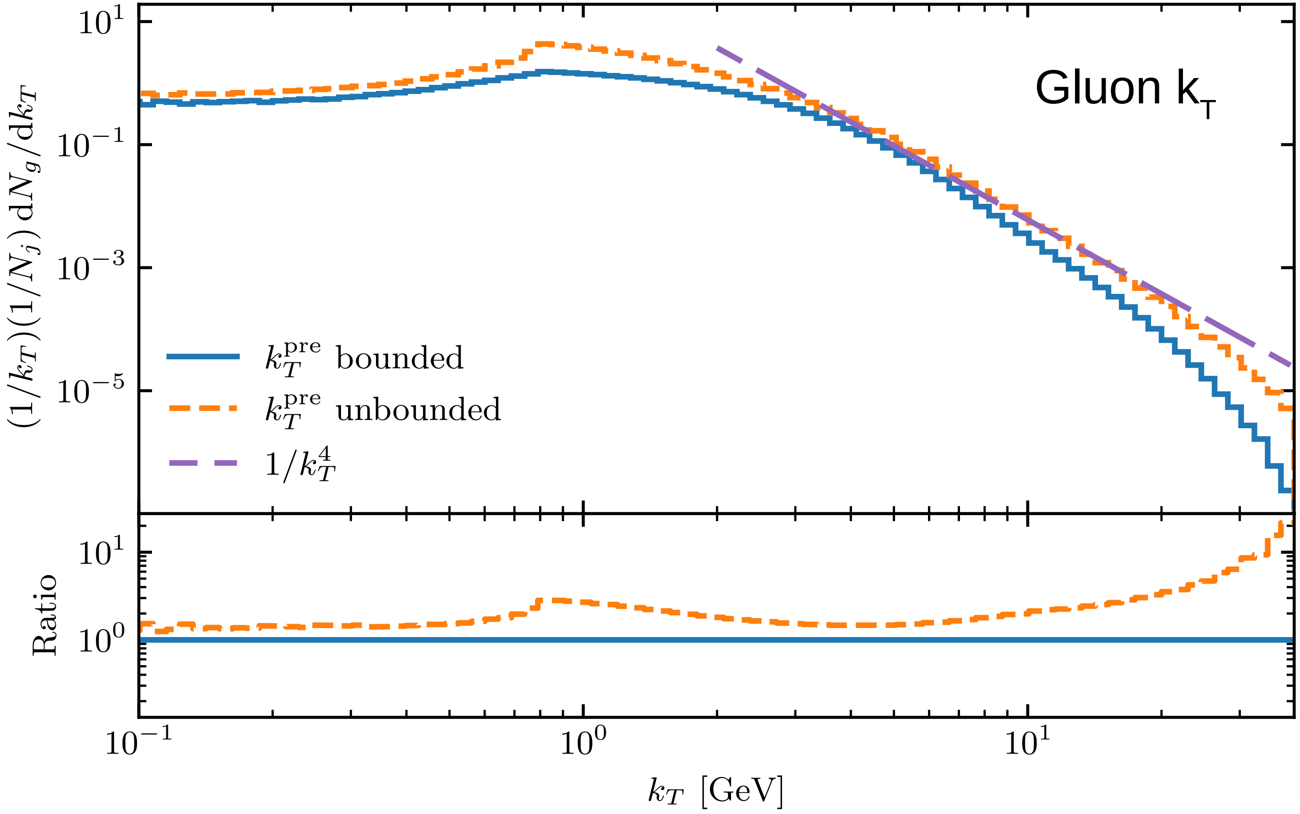
The Role of the Colinearity Hypothesis



Colinearity hypothesis

$$k_T \ll \omega$$

The Role of the Colinearity Hypothesis



Colinearity hypothesis

$$k_T \ll \omega$$

Looking Forward: Towards More Realism

Next step:

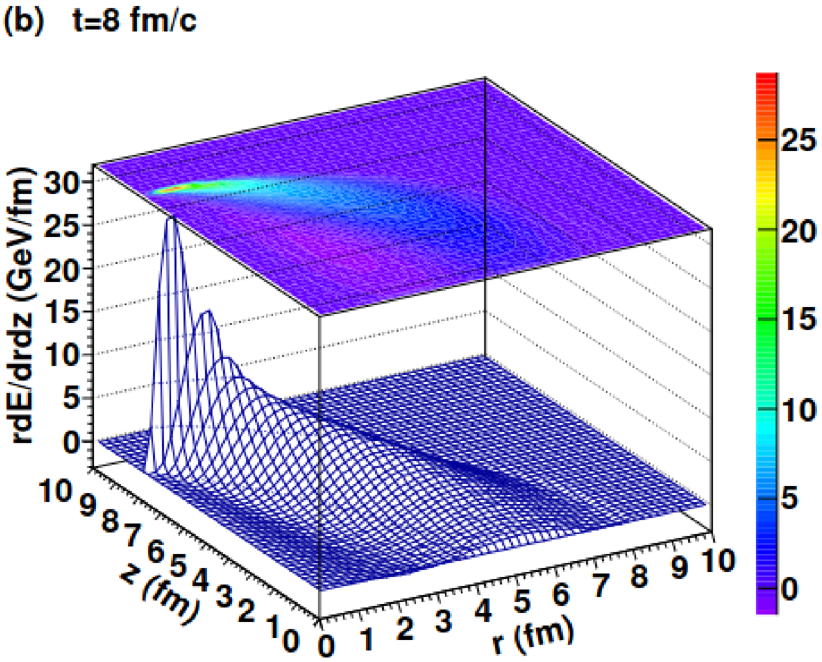
- Interface with vHLLE to get hydro evolution of the medium
- Running strong coupling in elastic scatterings
- Start with high virtuality partons
- Sampling of initial parton p_T

$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_T} \sim p_T^{-6.5}$$

- Run with hadronisation and jet finding

Looking Forward: Effect on the Medium

The jet also affects the medium



‘Wake wave’
in the medium
due to the jet

Xin-Nian Wang’s talk from Monday

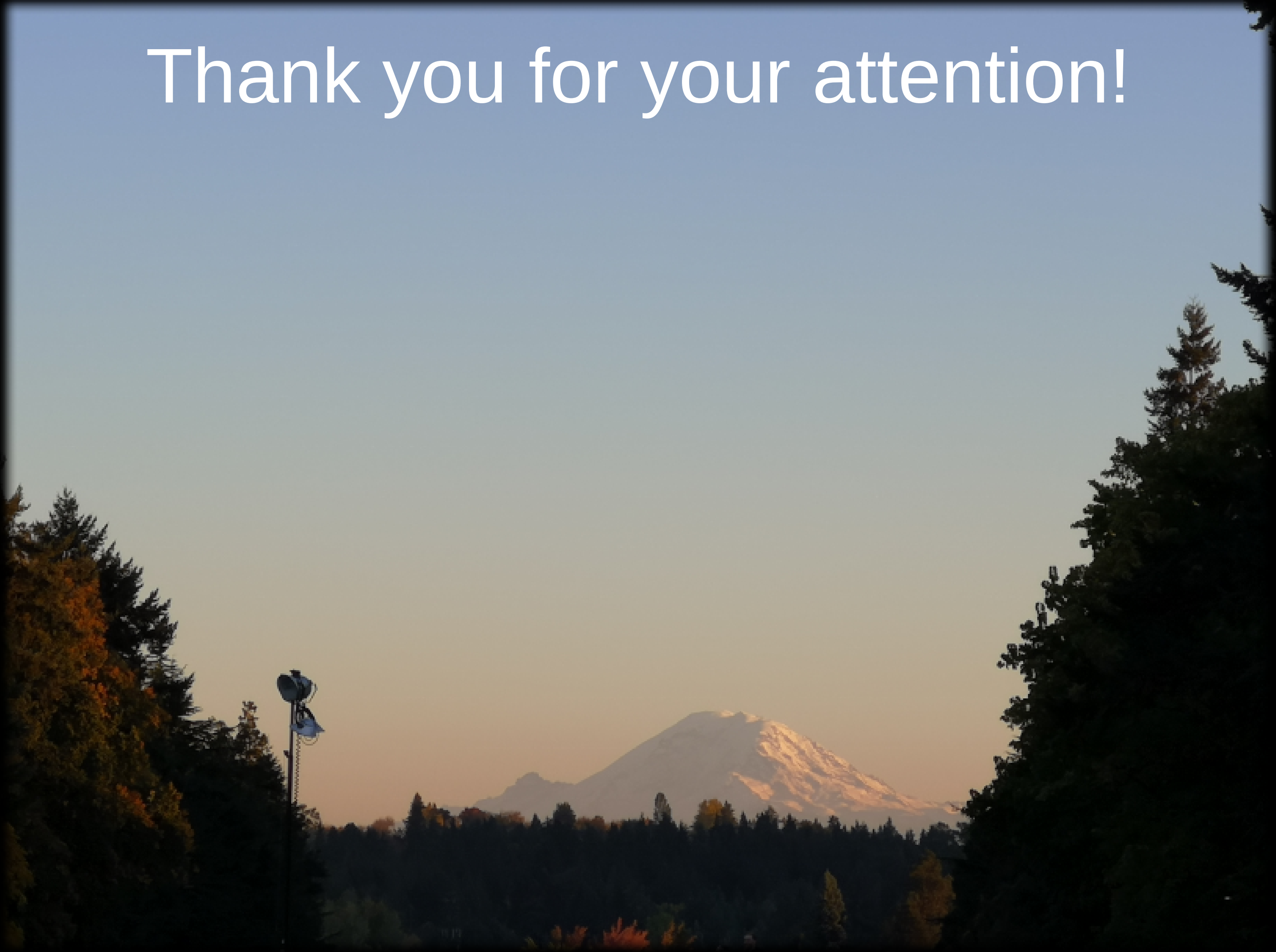
Summary

- We have presented a new model for jet energy loss in heavy ion collisions
- Implementation in a Monte Carlo framework

- **1st step done**:
  - Reproduction of the BDMS radiation energy spectrum
  - Shown effects of different model assumptions

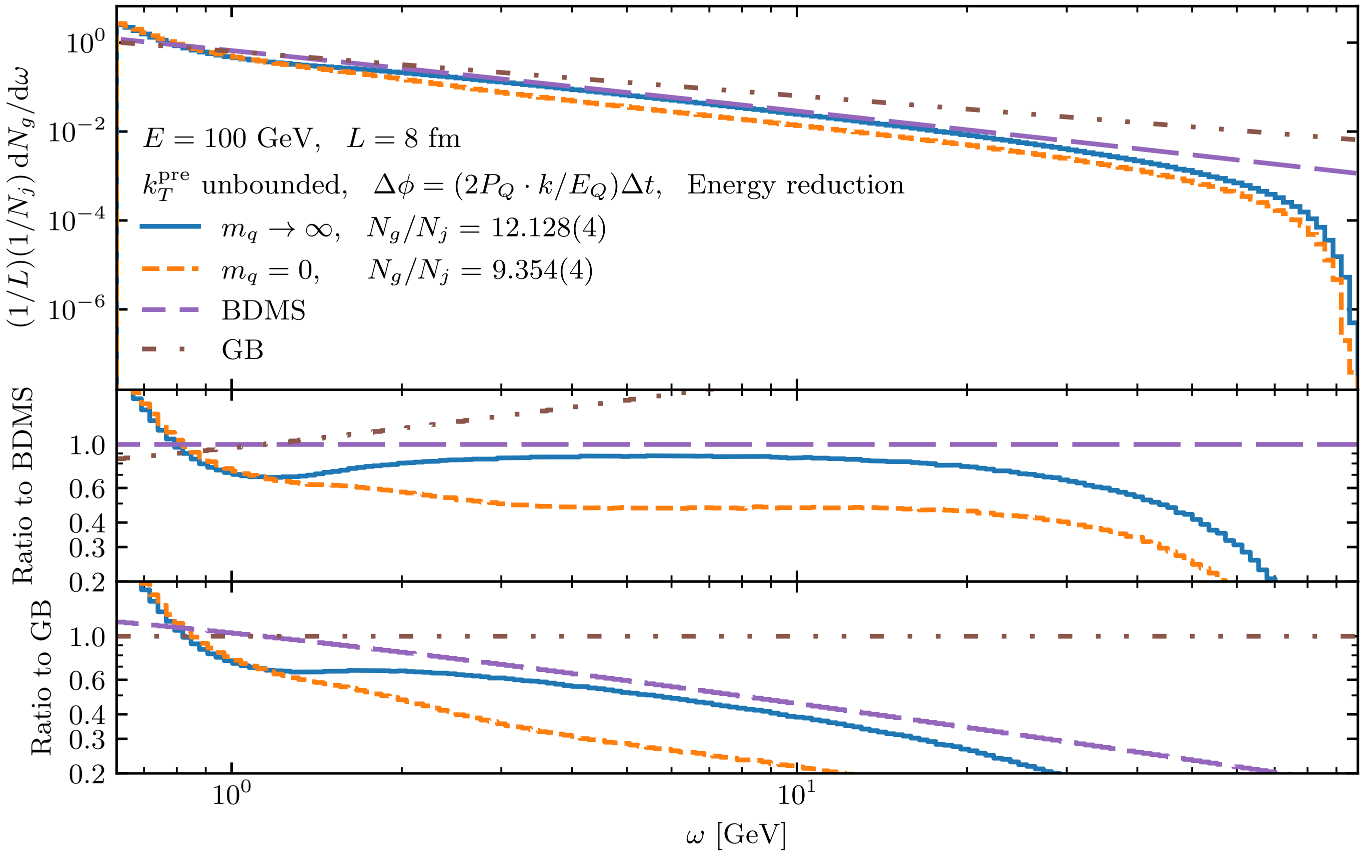
- **2nd step:** First results with hydro evolution interface to vHLLE
- **3rd step:** Implementation within the new EPOS4
  - **EPOS4+JETS –** Initial state, hydro, and hadronisation from EPOS4

Thank you for your attention!



Backup Slides

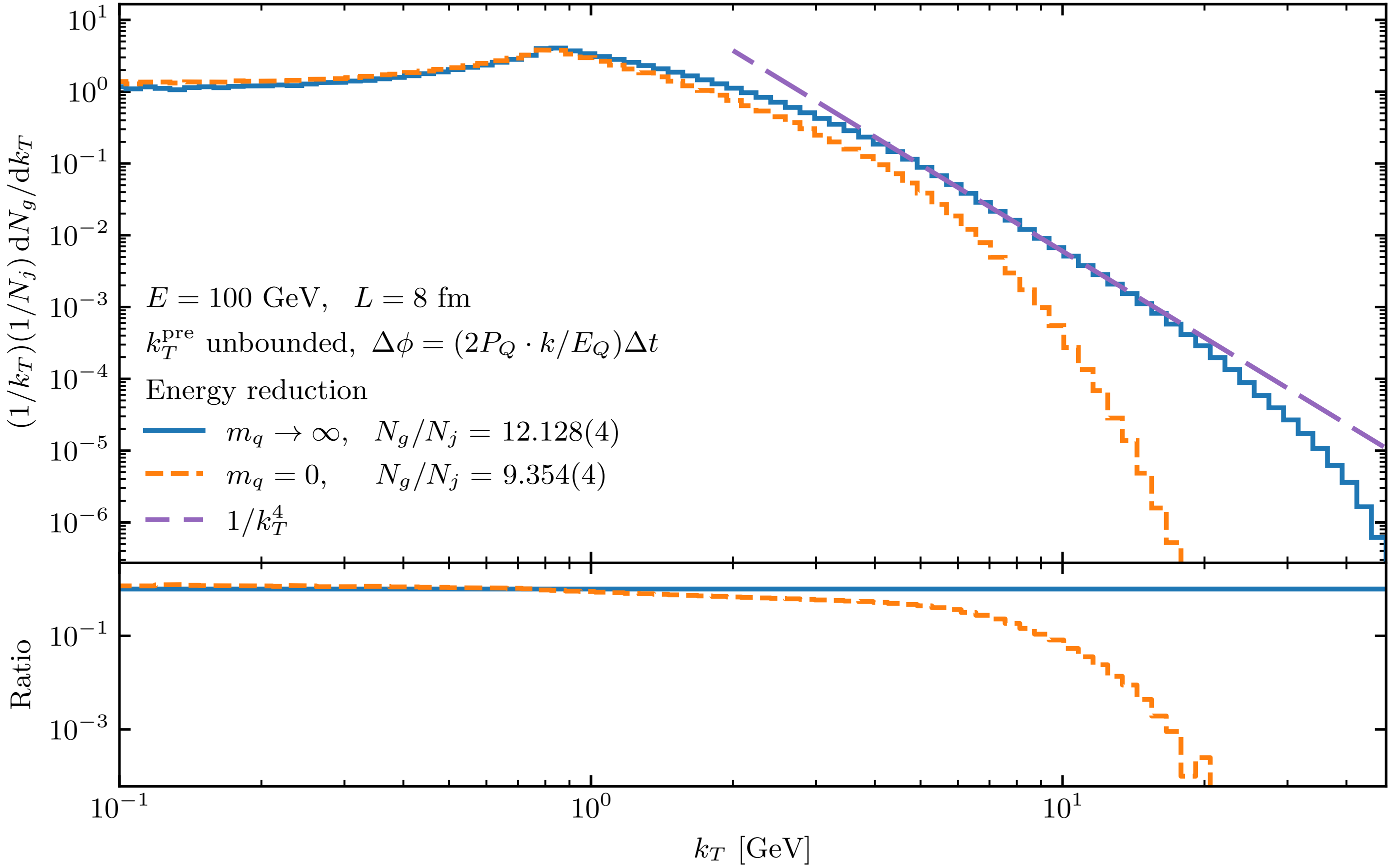
The Role of Scattering Centre mass m_q



Energy spectrum

Effect of mass of scattering centre in the initial GB seed

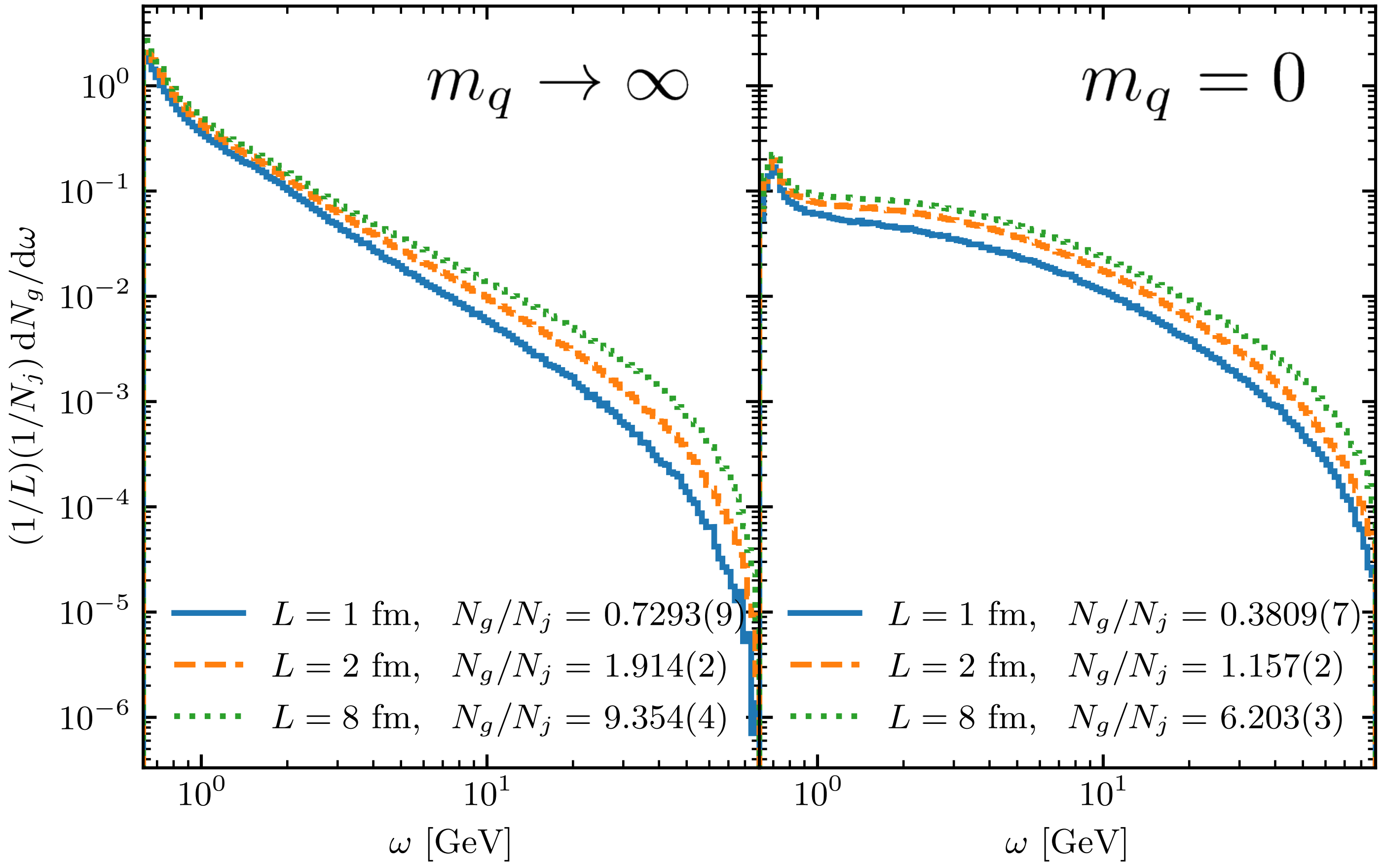
The Role of Scattering Centre mass m_q



Gluon k_T

Effect of mass of scattering centre in the initial GB seed

Effect of Path Length



Energy spectrum
for different path lengths
(medium sizes)