# SUBA-Jet

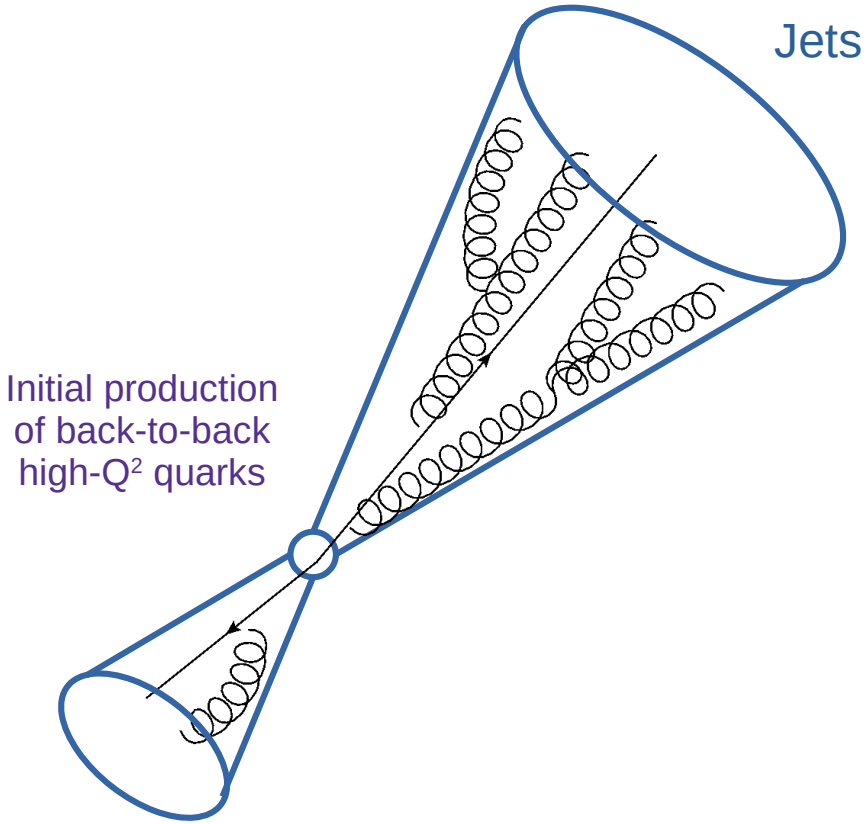
## A New Model for Jet Energy Loss in Heavy Ion Collisions

Alexander Lind

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

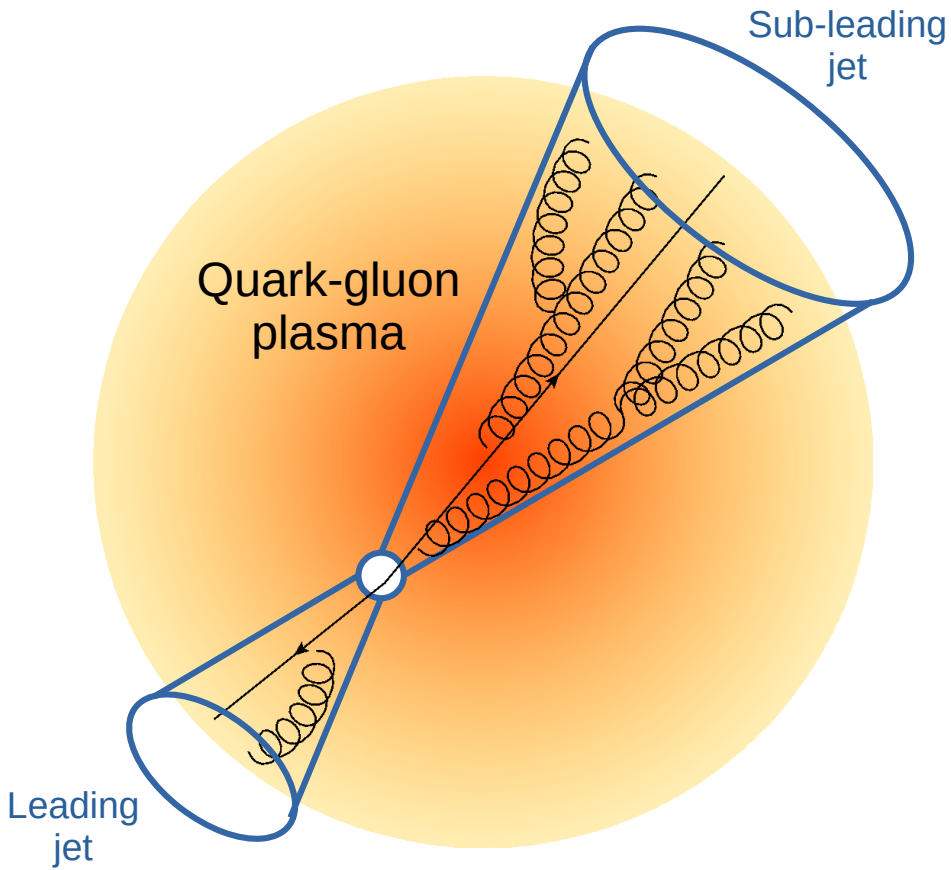

Rencontres QGP France 2023
Hôtel du Béryl, Bagnoles de l'Orne
27 June 2023

# Jets in Proton-Proton Collisions




- **Jets**:
  Collimated sprays of high $p_T$ partons/hadrons
- **Vacuum cascade** of quarks and gluons, going from high to low virtuality
- Simulated in event generators by **parton shower algorithms**

# Jets in Heavy Ion Collisions



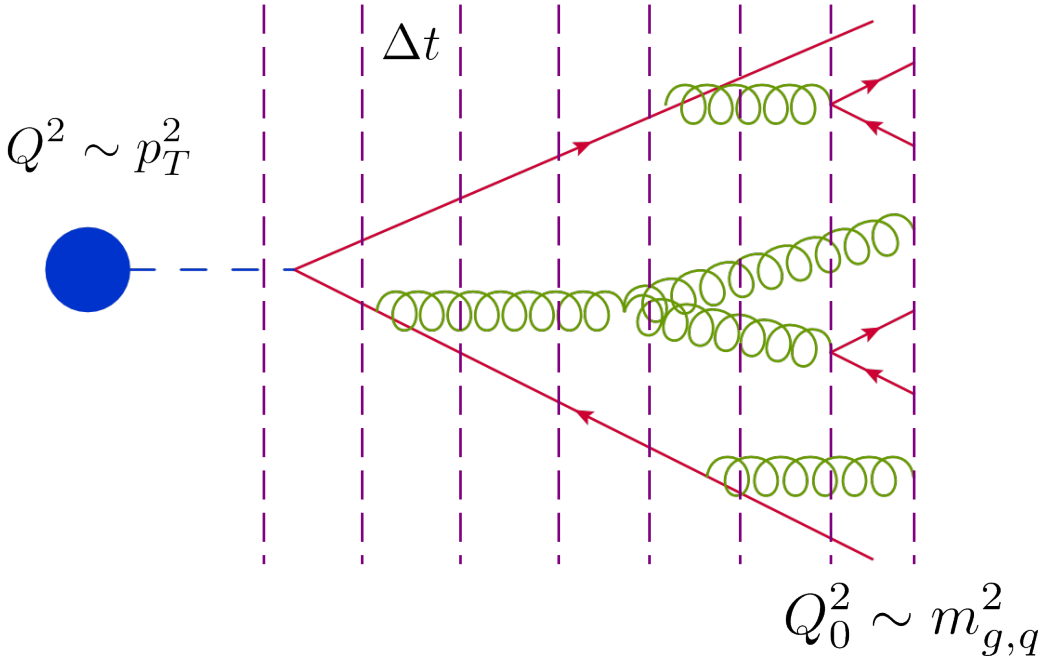

- Jets can be produced alongside the QGP in heavy ion collisions
- Interactions between jet partons and the QGP medium leads to modifications of jet properties

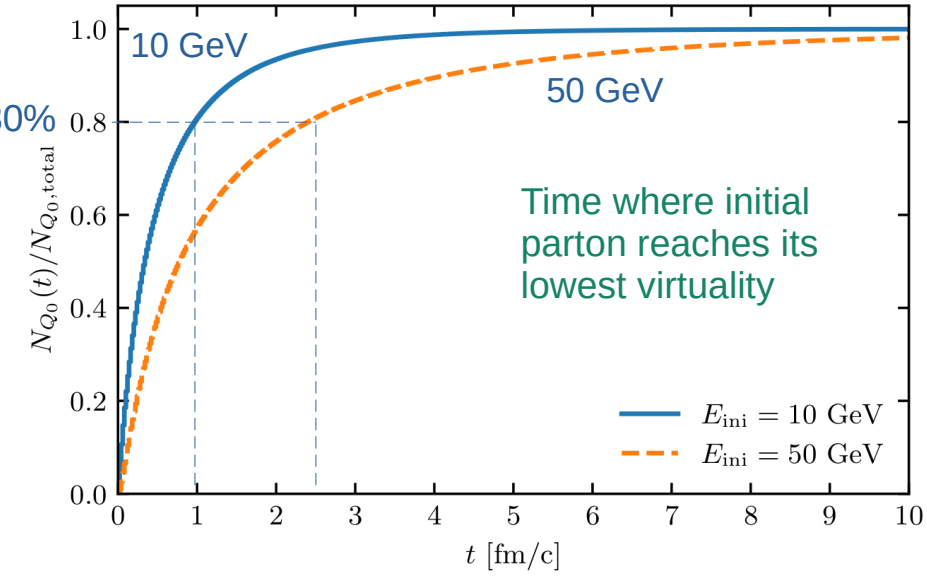
  → **Jet Energy Loss / Quenching**
- **SUBA-Jet:**
  Monte Carlo for jet energy loss in heavy ion collisions

# 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

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

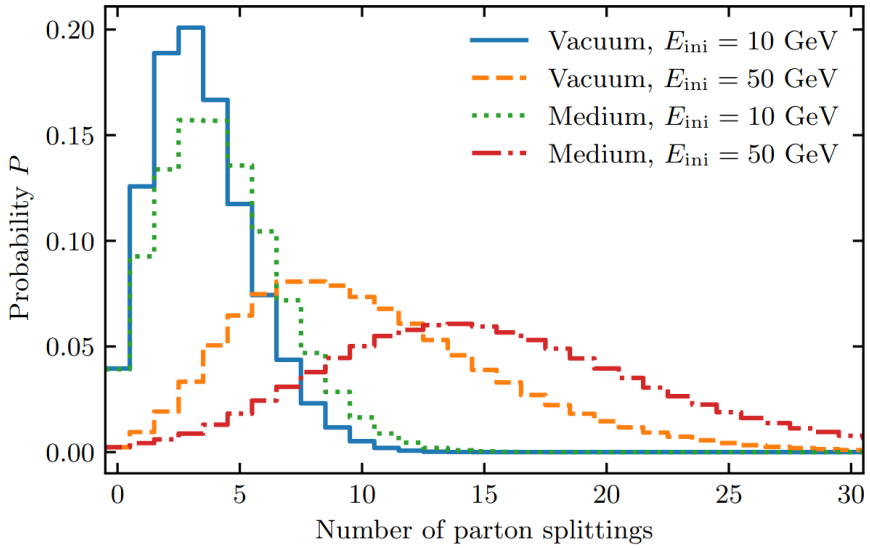


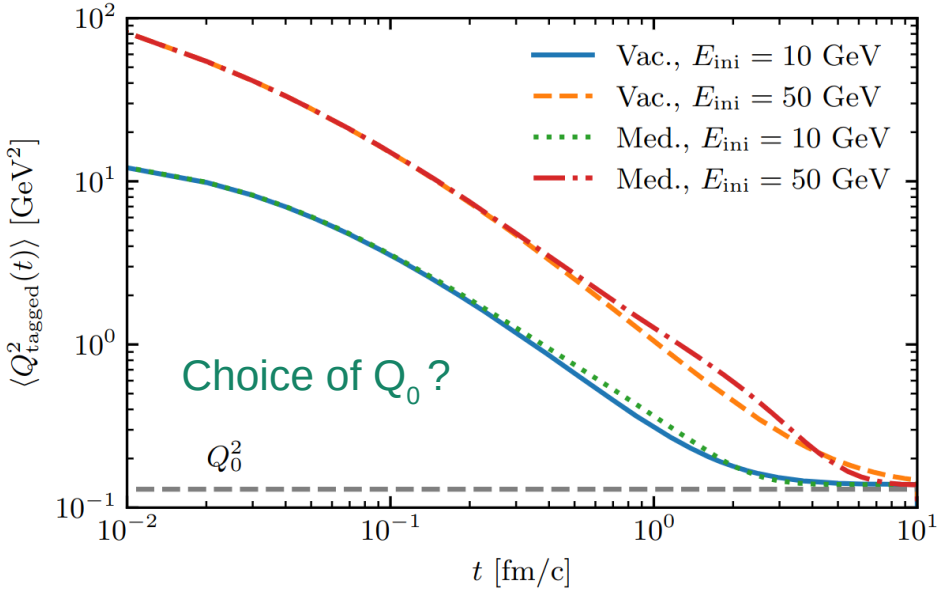



# “Vacuum” Parton Shower in Medium

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

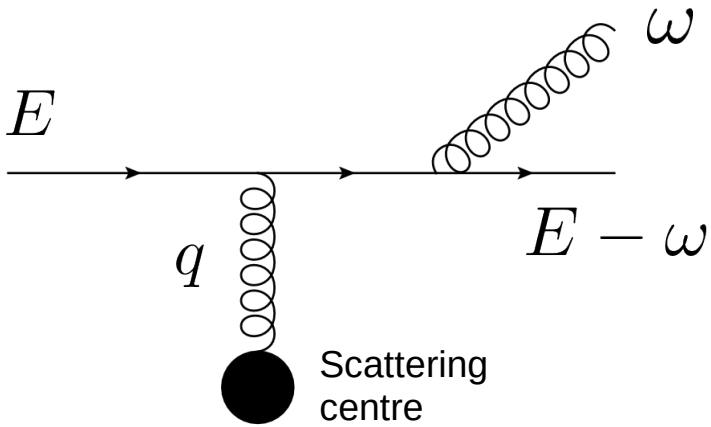
$$\frac{\mathrm{d}Q^2}{\mathrm{d}t} = \hat{q}(T)$$



# 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)

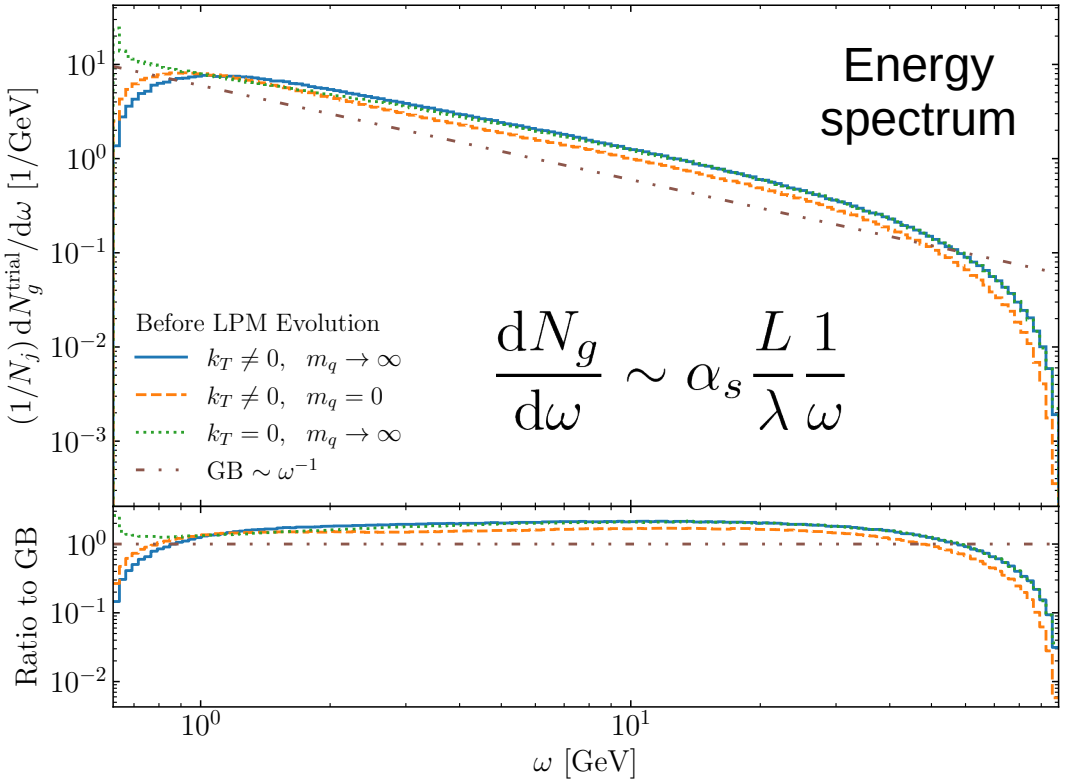


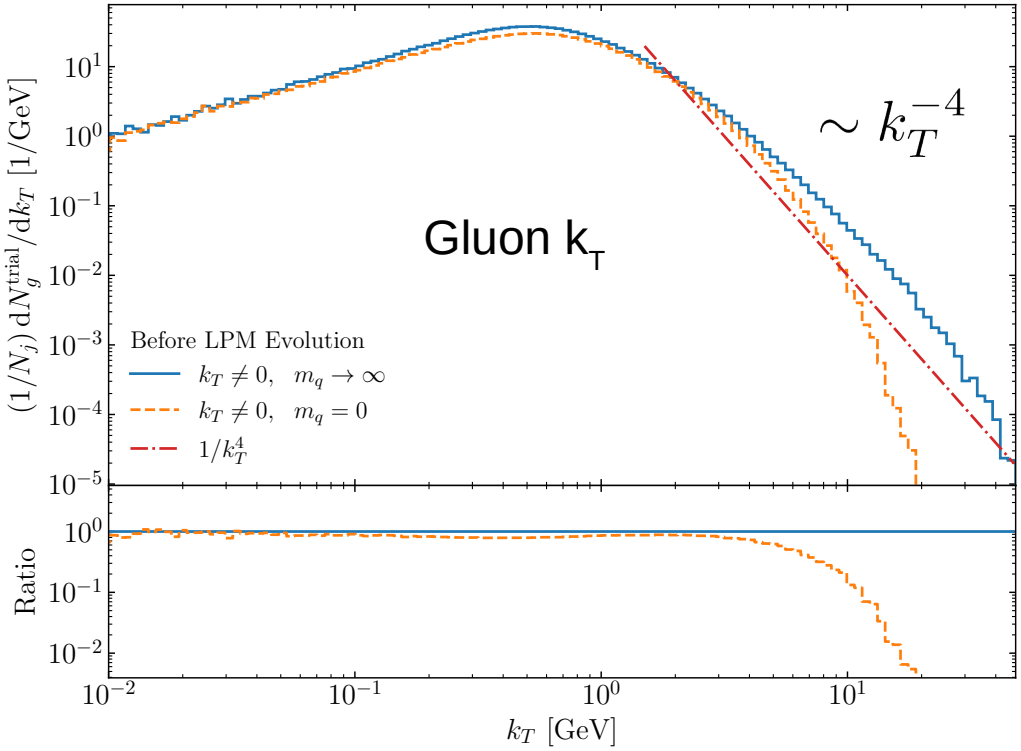

- Initial Gunion-Bertsch seed: i.e. radiation of a **preformed gluon** from a single scattering
  (Each parton can generate a number of preformed gluons)
- Gunion-Bertsch cross-section from scalar QCD

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

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

# Medium-Induced Single Radiation



# Coherency and the LPM Effect

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

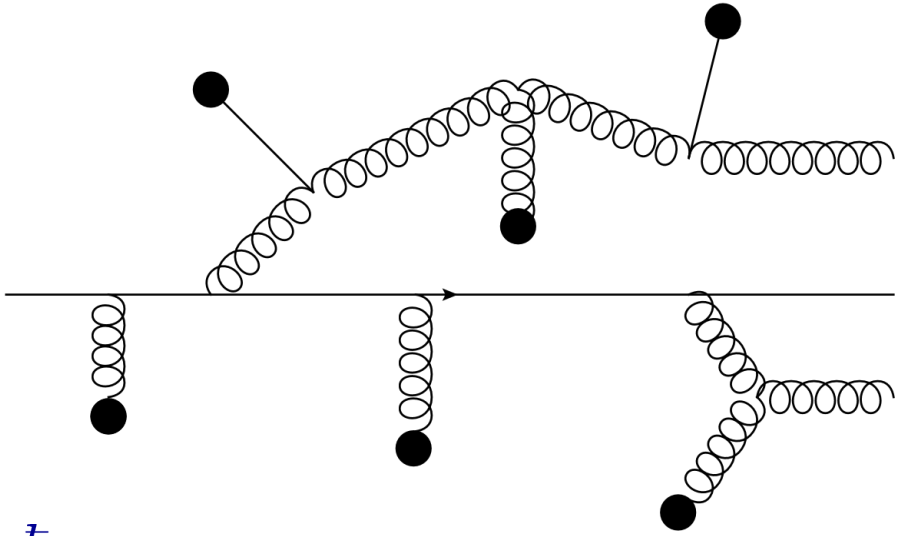
  **Formation time:** $t_f \sim \sqrt{\frac{\omega}{\hat{q}}}$

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

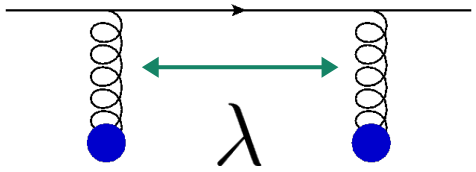
- Have to take into account multiple scatterings with the medium during the formation time

$\omega =$ gluon energy

$\hat{q} =$ medium modifications



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




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

$L =$ path length of medium

# Implementation of the LPM Effect

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

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

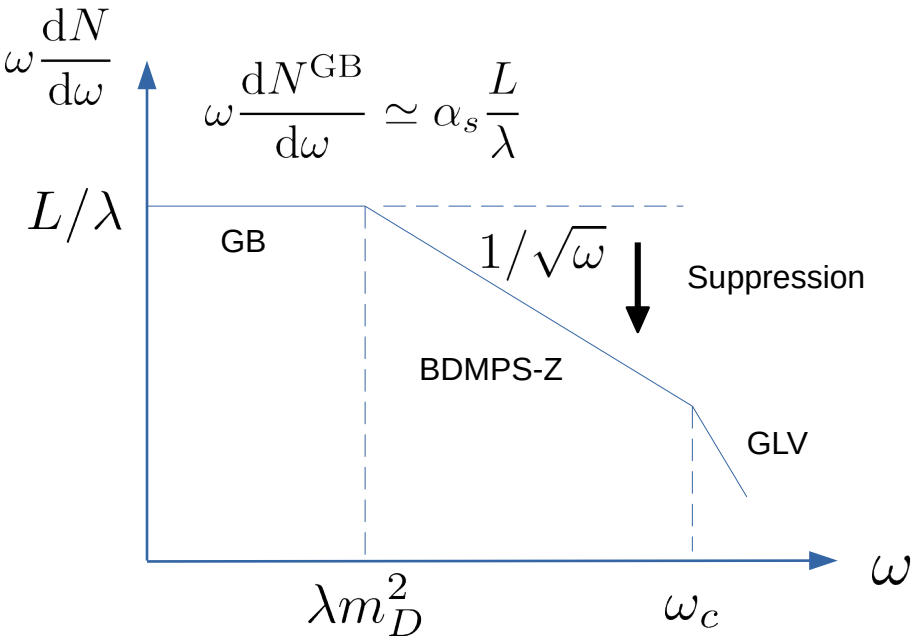
  - Radiation of preformed gluon with prob. $\Gamma_{\mathrm{inel}}\Delta t$

- BDMPS 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:



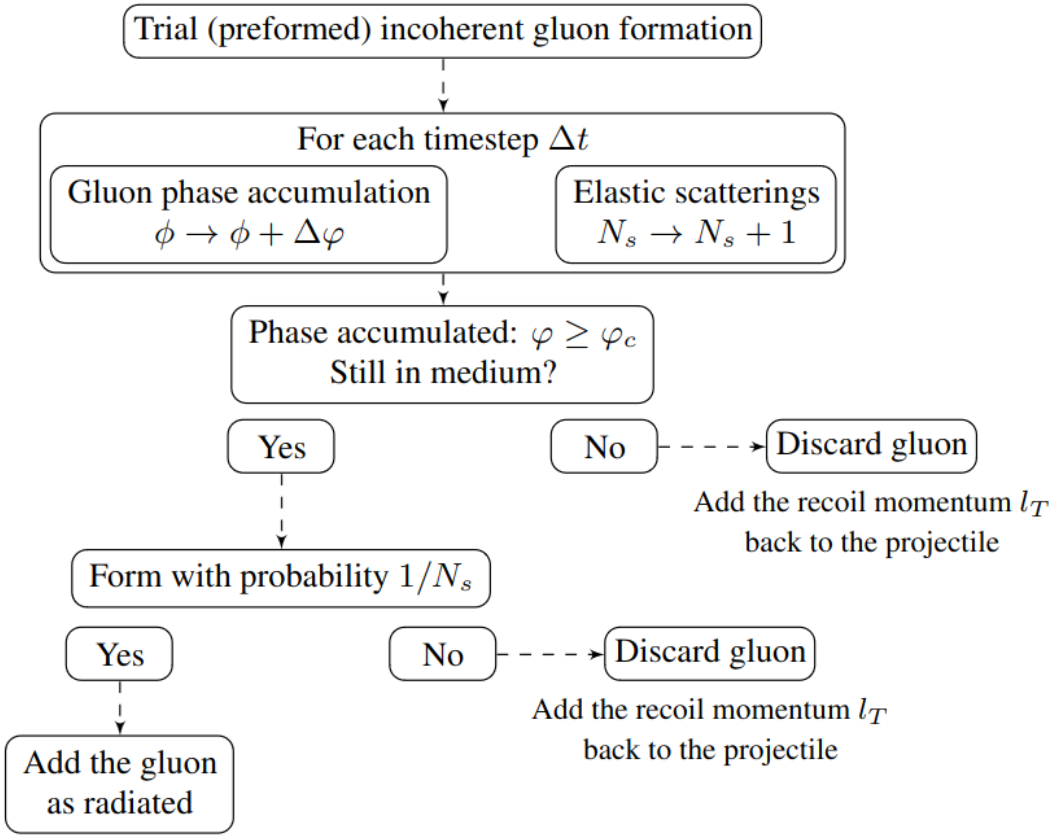

$$\omega \frac{\mathrm{d}N^{\mathrm{BDMPS\text{-}Z}}}{\mathrm{d}\omega} \simeq \alpha_s \sqrt{\frac{\hat{q}L^2}{\omega}}$$

# The Algorithm

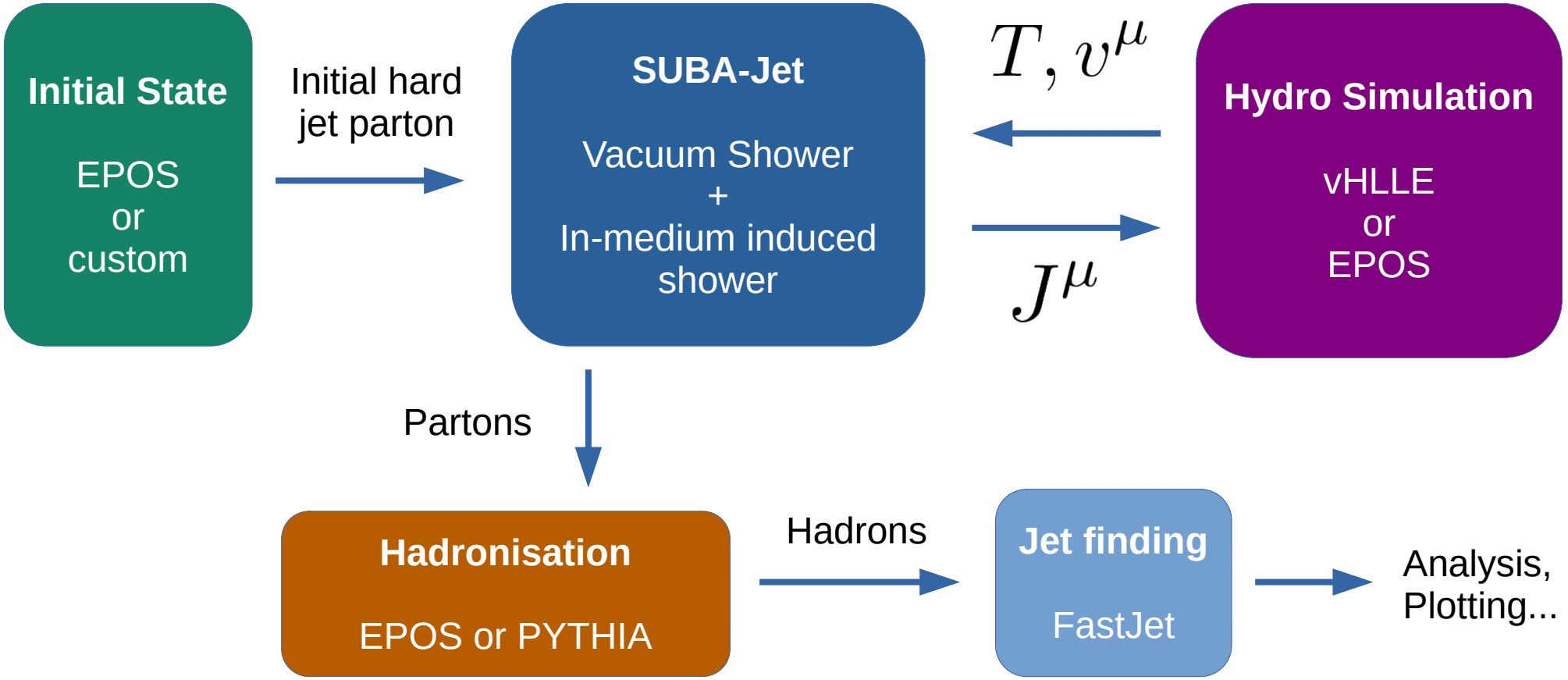
Flow diagram:

Monte Carlo algorithm for the coherent medium-induced gluon radiation in our model

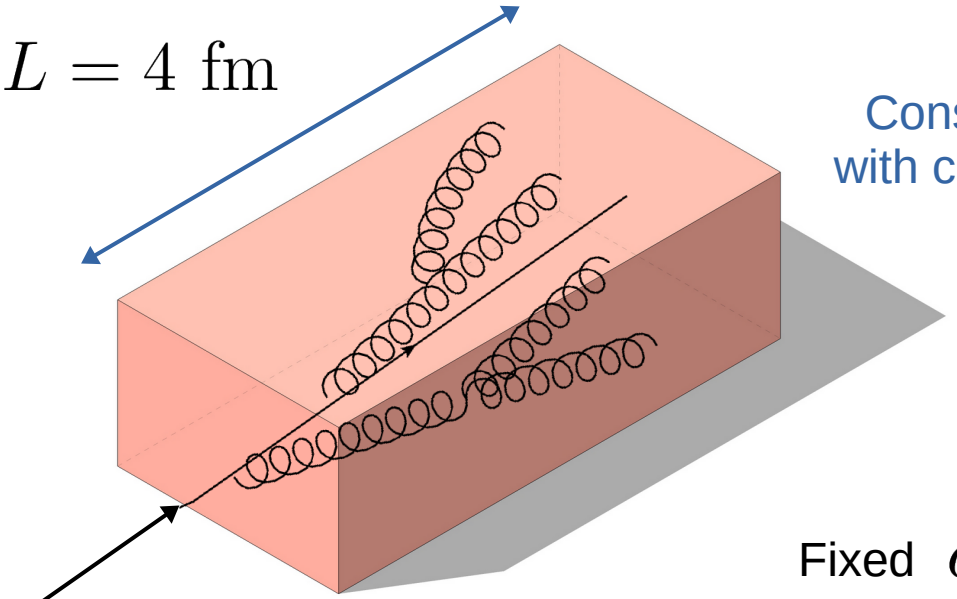
Various parameters and settings can be changed and tuned to compare distributions



# The Monte Carlo

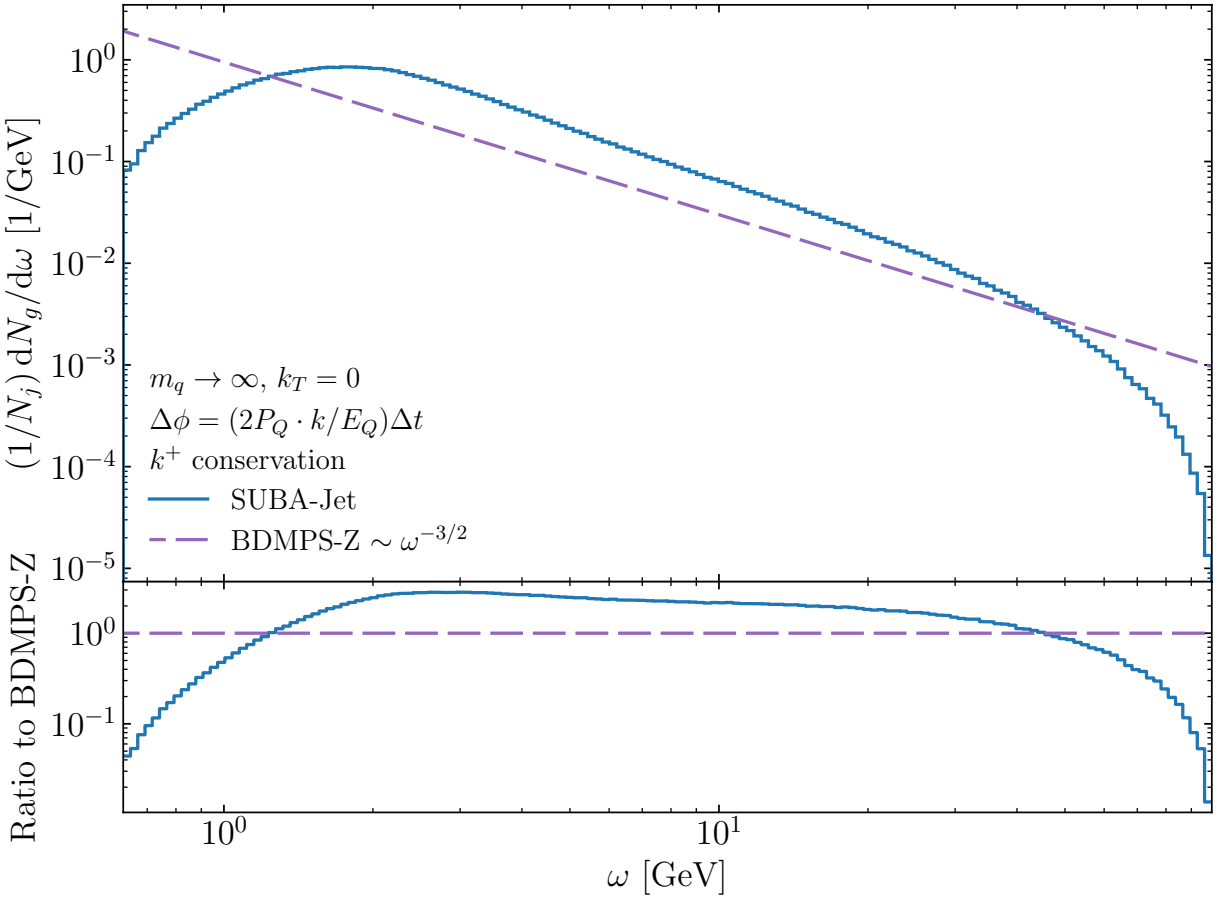


# First Results




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

# Reproduction of the BDMPS-Z Limit




Energy spectrum

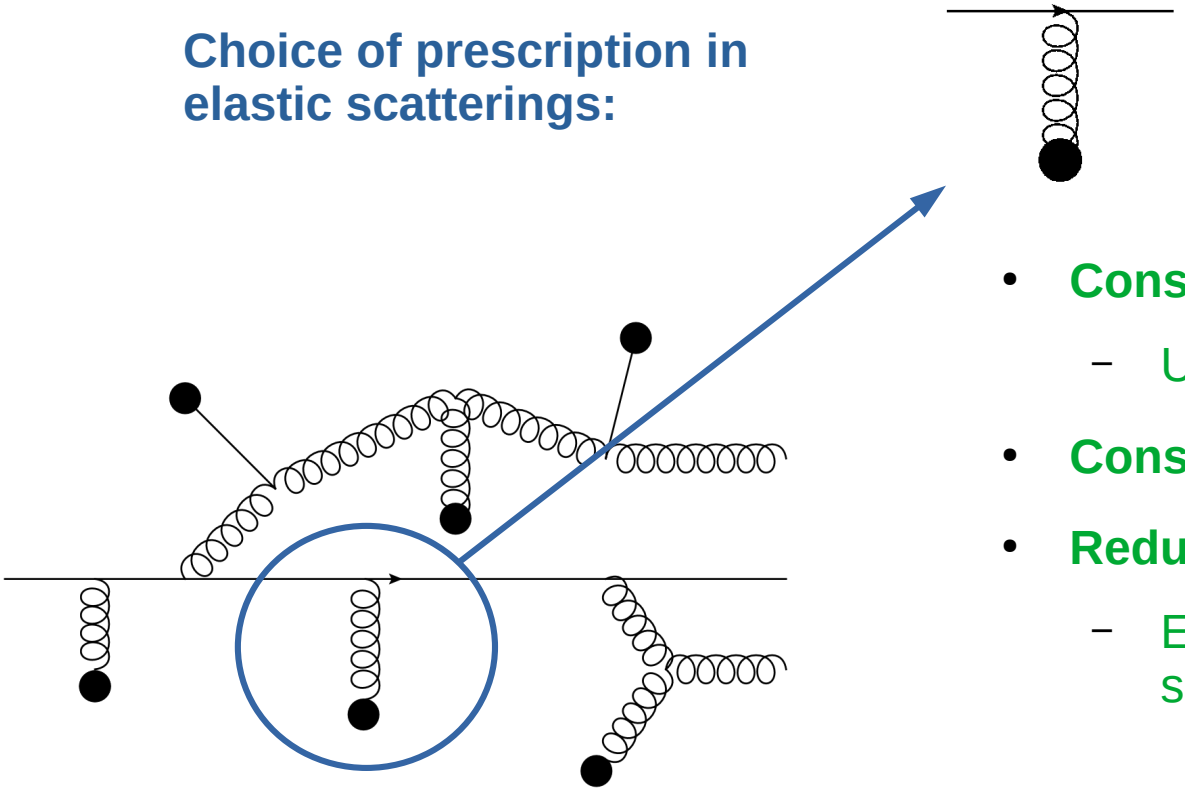
$$\frac{\mathrm{d}N}{\mathrm{d}\omega} \quad \text{vs} \quad \omega$$

Reproduces BDMPS-Z for intermediate energies

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

# Reproduction of the BDMPS-Z Limit

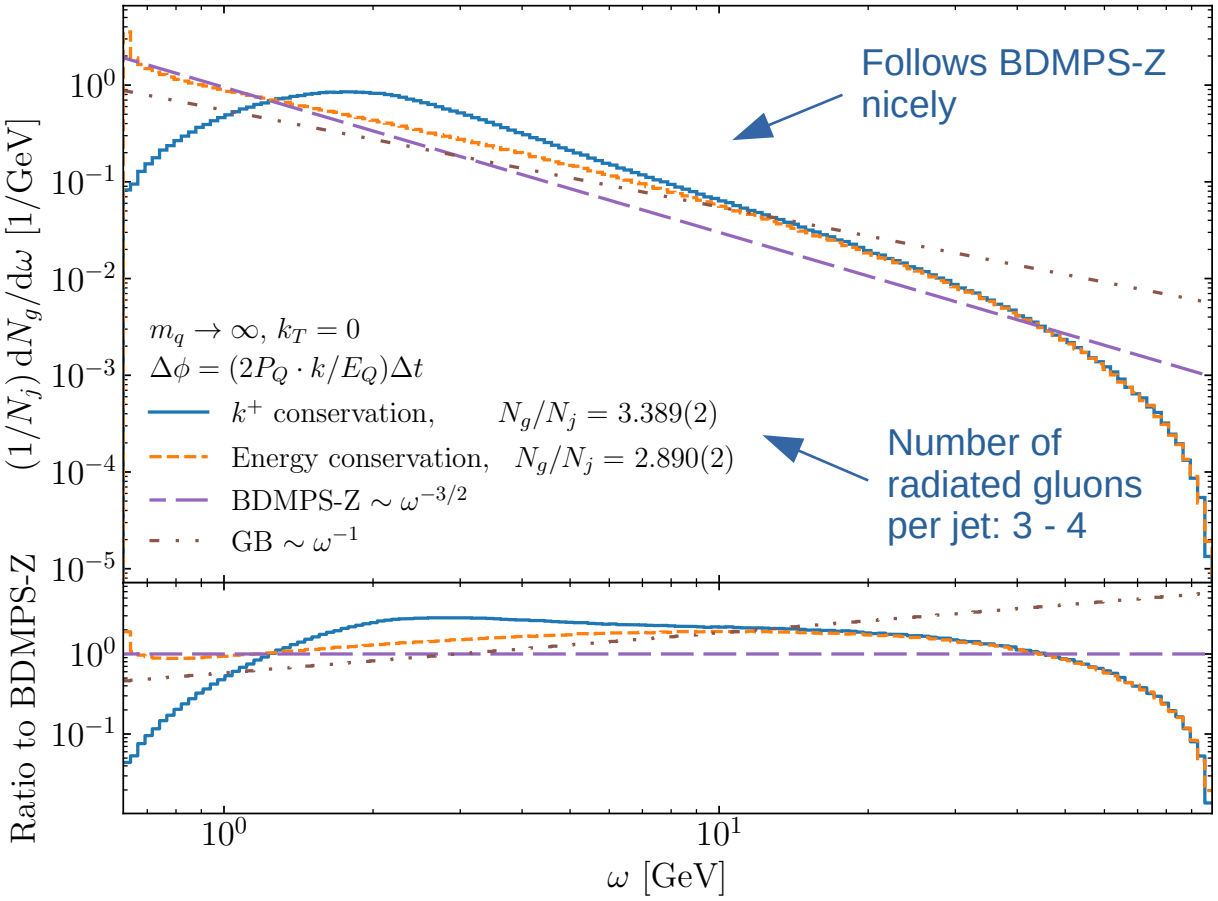
**Choice of prescription in elastic scatterings:**





- **Conserve $k^+$?**
  - Used in BDMPS-Z
- **Conserve E?**
- **Reduce E?**
  - Energy gain by the medium parton is subtracted from the projectile parton

# Reproduction of the BDMPS-Z Limit

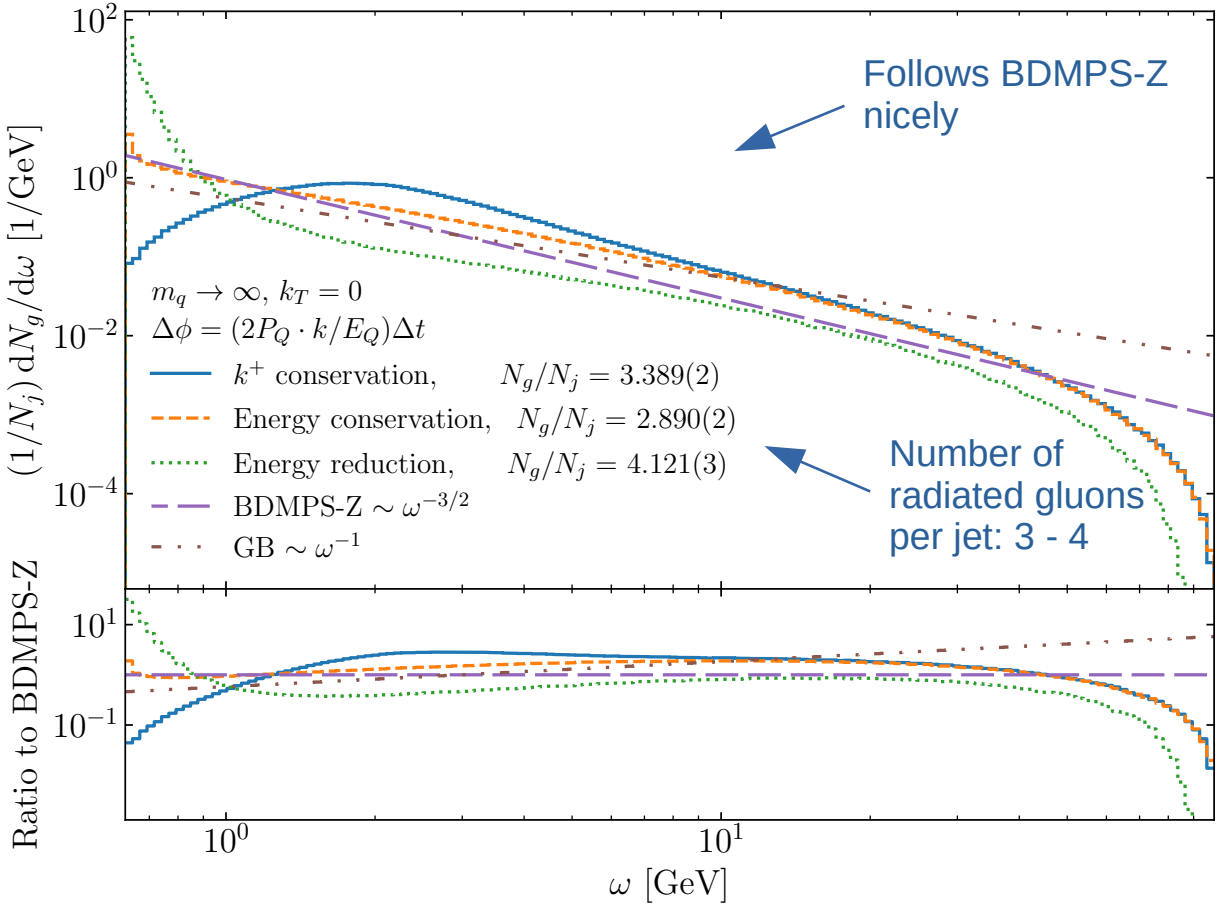



- Scattering centres with infinite mass
- Initial $k_T = 0$
- Phase accumulation according to:

$$\Delta\phi = (2P_Q \cdot k/E_Q)\Delta t/(\hbar c)$$

Add curve for energy conservation

# Reproduction of the BDMPS-Z Limit



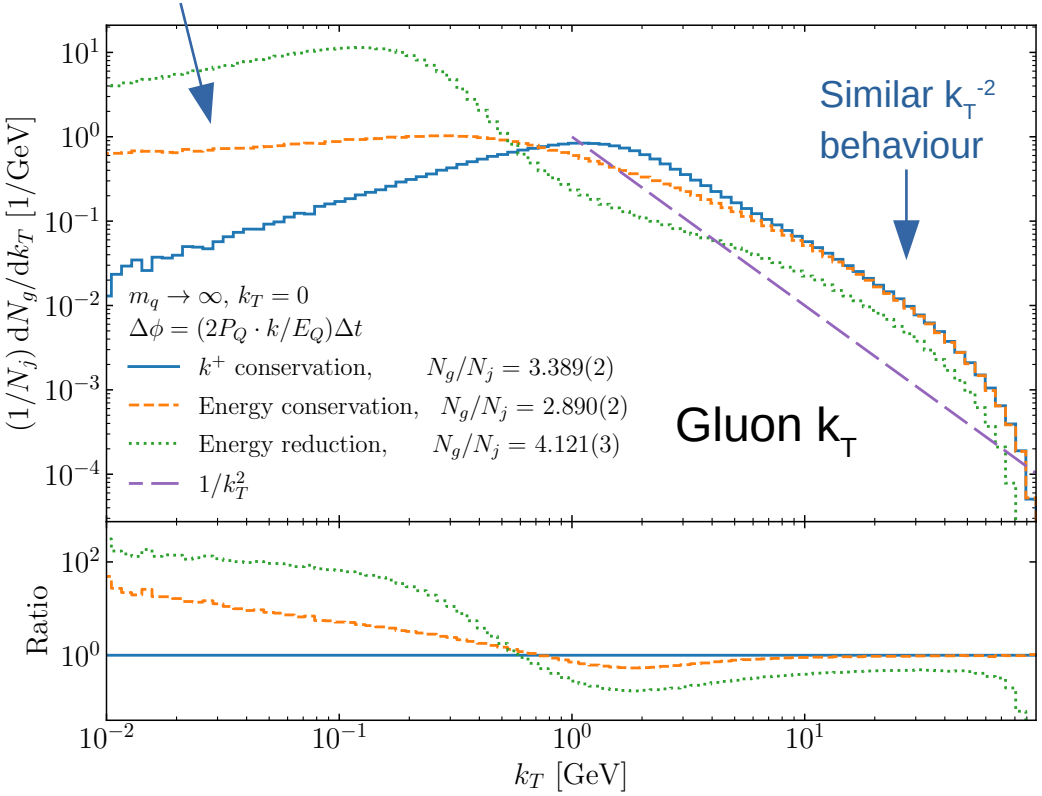

- Scattering centres with infinite mass
- Initial $k_T = 0$
- Phase accumulation according to:

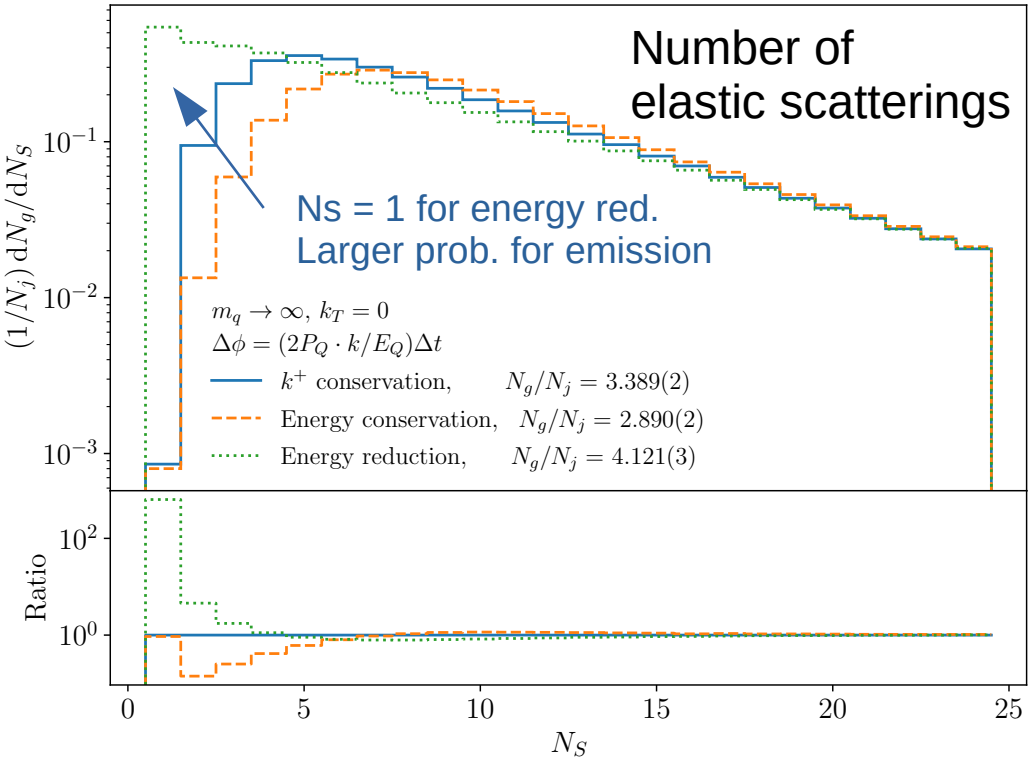
$$\Delta\phi = (2P_Q \cdot k/E_Q)\Delta t/(\hbar c)$$

Add curve for energy reduction

# Reproduction of the BDMPS-Z Limit

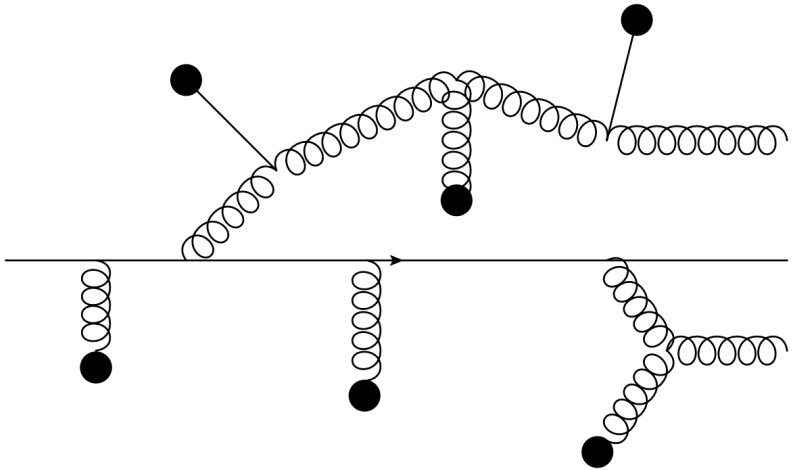
Large difference



# The Effect of the Phase Accumulation

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



- **What is used in JEWEL:**

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

- **Including thermal gluon mass:**

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

- **More general formula:**

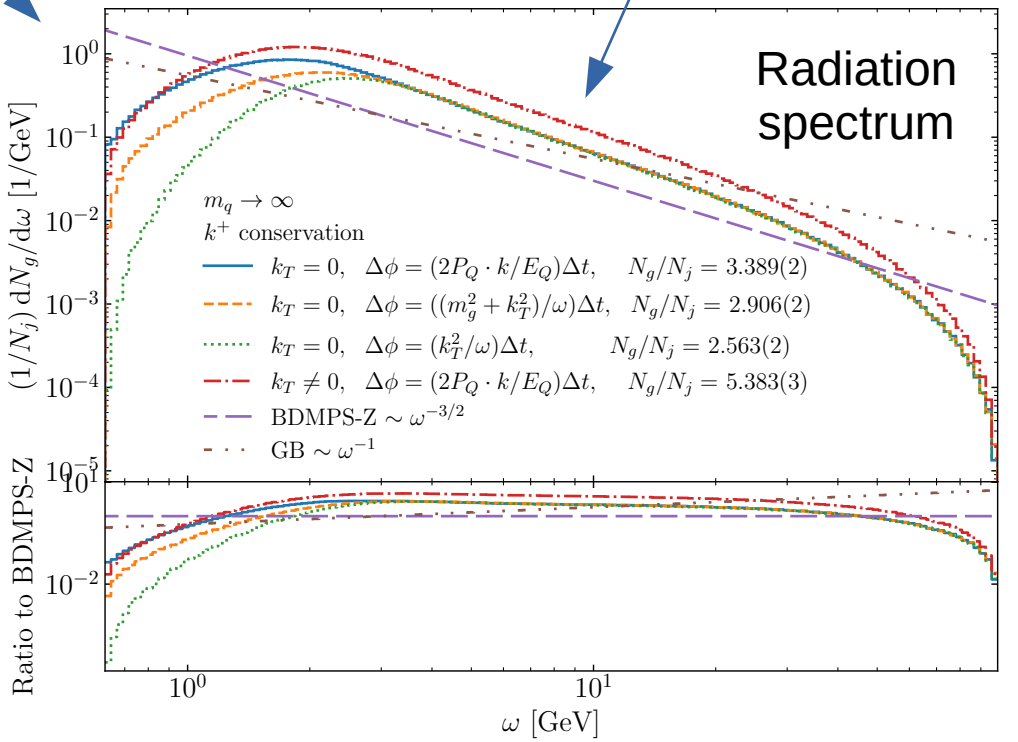
$$\Delta\varphi = \frac{2P_Q \cdot k}{E_Q}\Delta t$$

# The Effect of the Phase Accumulation

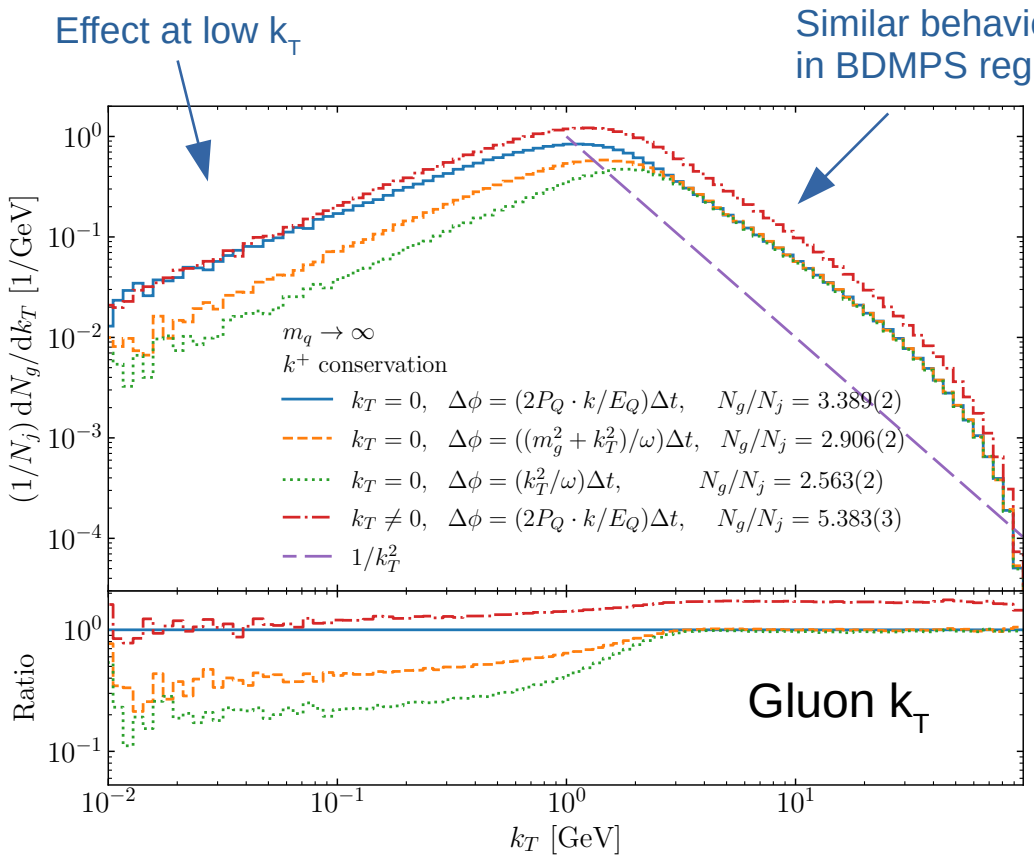
- Same details as before, but …
  - Keep $k^+$ conservation in the elastic scatterings
  - Vary the form of the phase accumulation
  - Also see effect of $k_T$

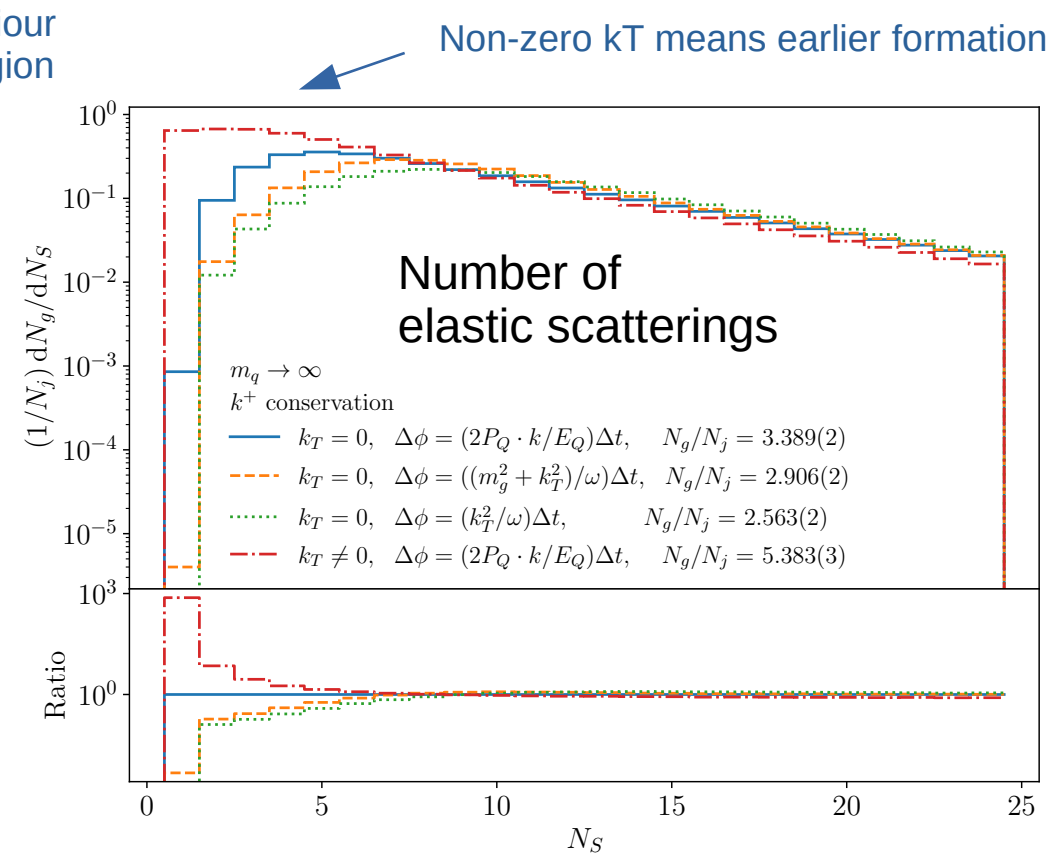
Effects at low energy

Non-zero kT means earlier formation



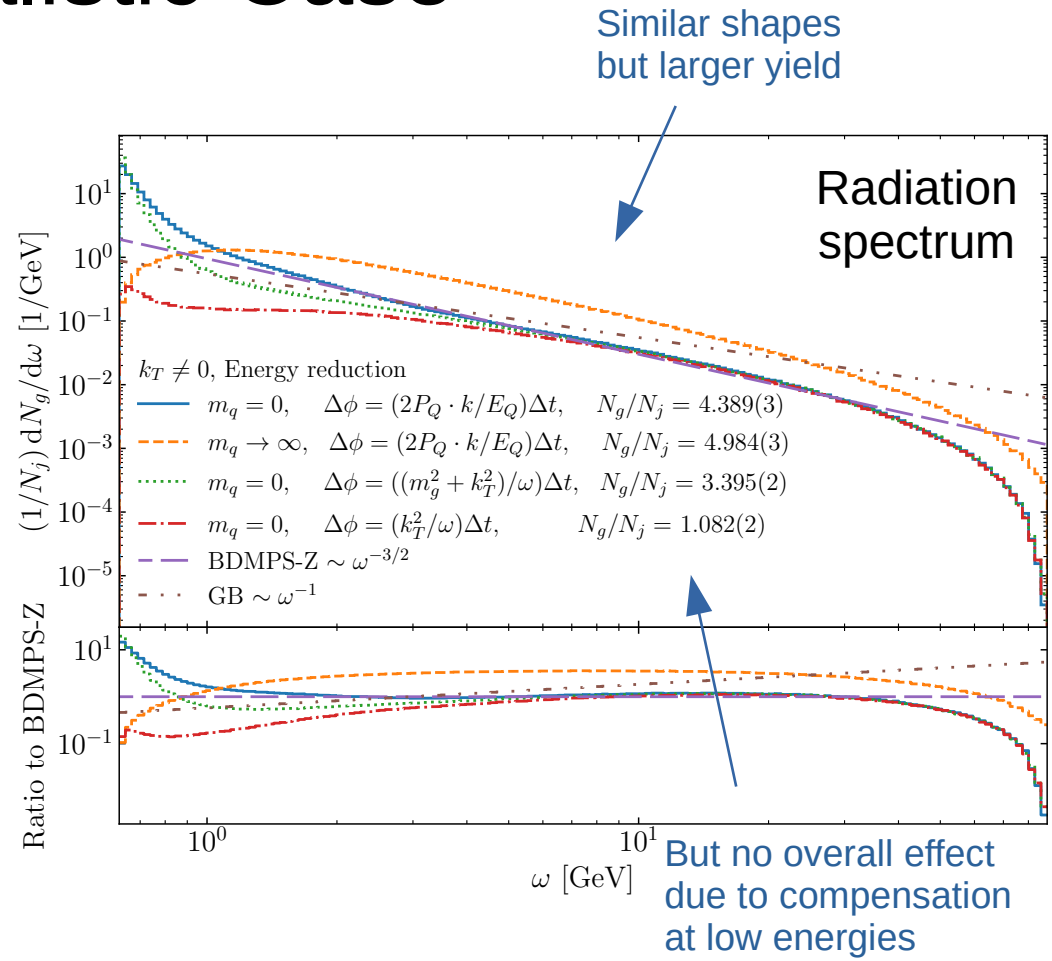
# The Effect of the Phase Accumulation



# More Realistic Case

- Relax assumptions and consider a more realistic scenario:
  - Scattering centres of zero mass
    $$m_q = 0$$
  - Energy reduction
  - Non-zero $k_T$
- And vary the phase space accumulation



# Looking Forward: Towards More Realism

**Next step:**

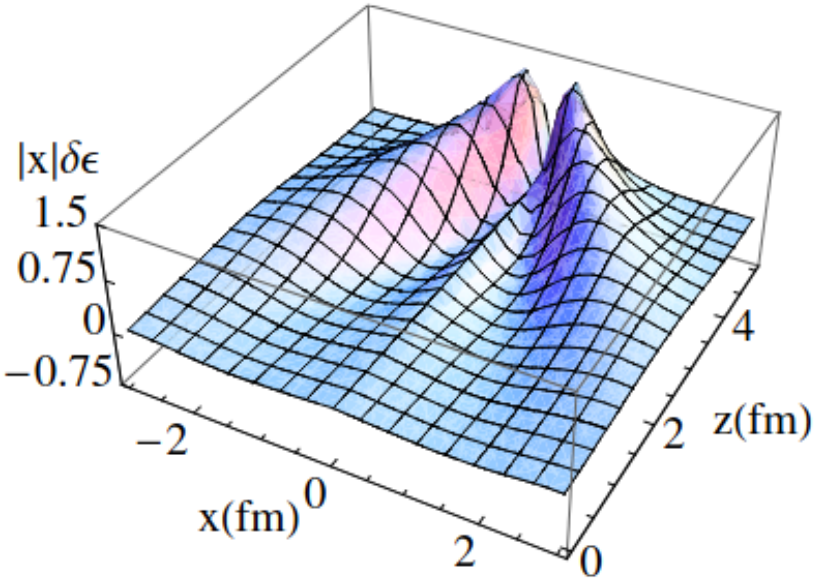
- Interface with vHLLE to get hydro evolution of the medium
- Running strong coupling in elastic scatterings
- Start with high virtuality partons
- Sampling of initial parton $p_T$

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

- Run with hadronisation and jet finding

# Looking Forward: Effect on the Medium

The jet also affects the medium




G.-Y. Qin, A. Majumder, H. Song, U. Heinz
0903.2255 [nucl-th]

‘Wake wave’
in the medium
due to the jet

# 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 BDMPS-Z 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
  - Klaus Werner's EPOS4 Overview (Monday) – **EPOS4+JETS**
  - Initial state, hydro, and hadronisation from EPOS4

Merci de votre attention !