SUBA-Jet

A New Model for Jet Energy Loss in Heavy Ion Collisions

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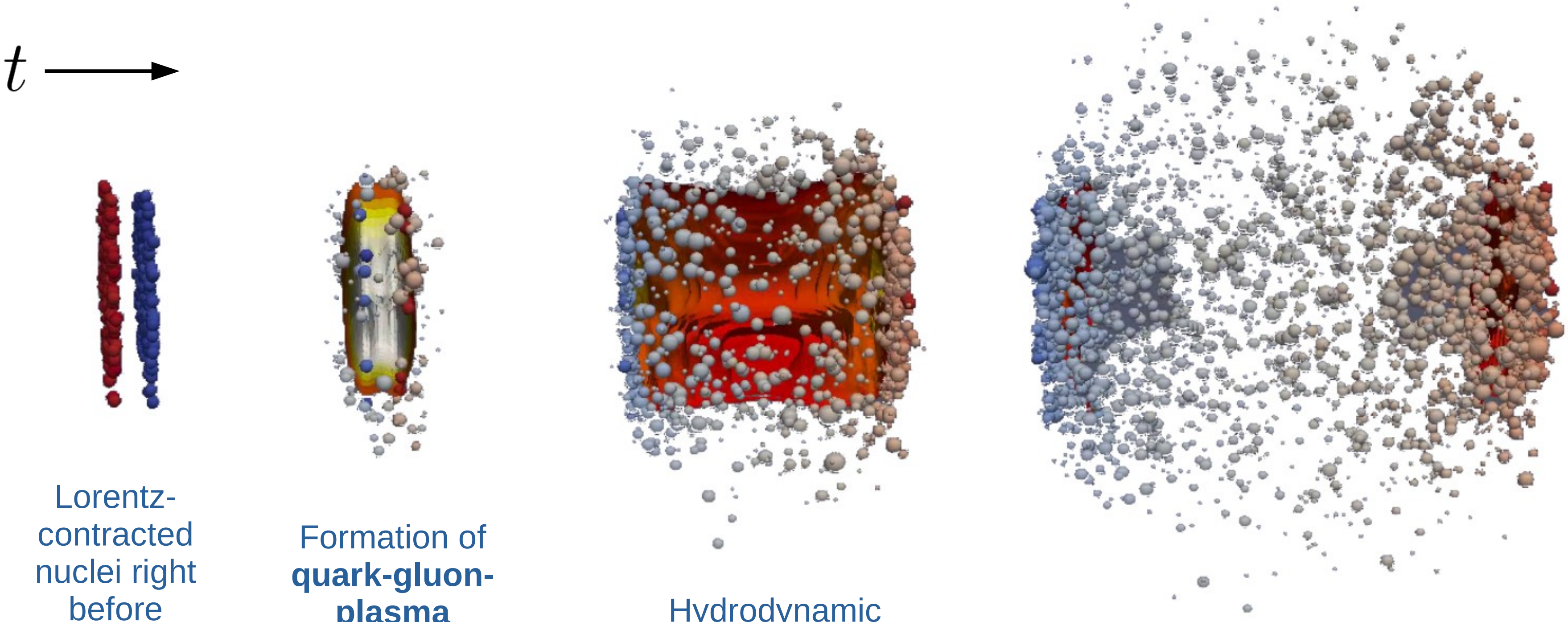
Outline

- Introduction
  - Heavy Ion Collisions
  - Jet Energy Loss
- Description of algorithm
- Simulated results
- Outlook to future studies

QCD MASTER CLASS

SAINT-JACUT-DE-LA-MER, FRANCE

Heavy Ion Collisions



Lorentz-contracted nuclei right before collision

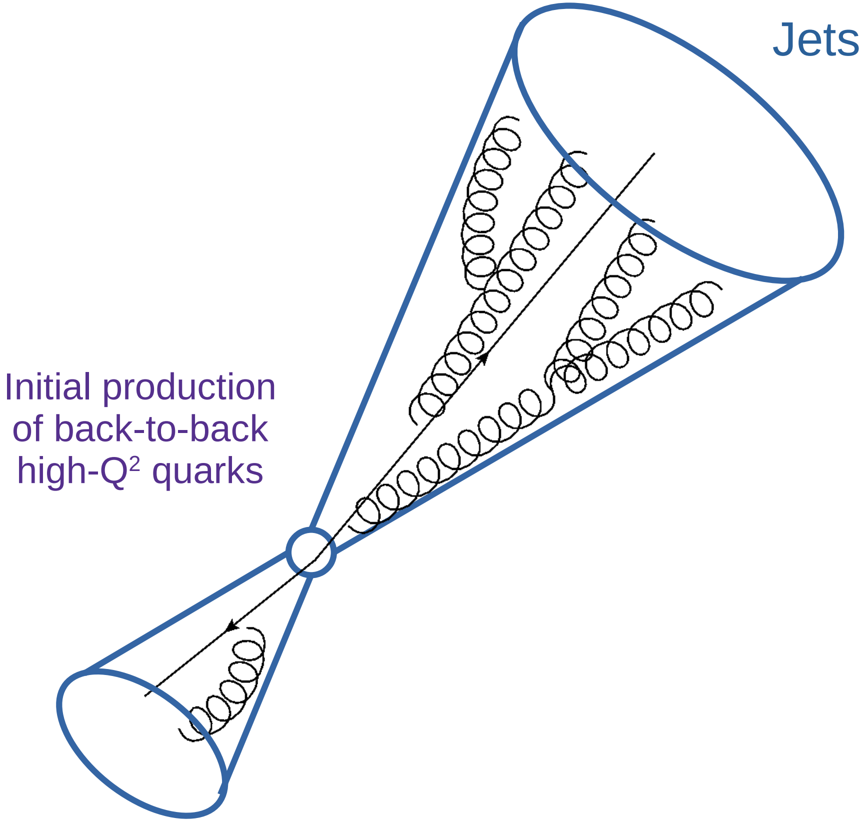
Formation of **quark-gluon-plasma**

Hydrodynamic expansion of plasma

Final-state hadronisation

Images from an animation by MADAI

Jets in Proton-Proton Collisions

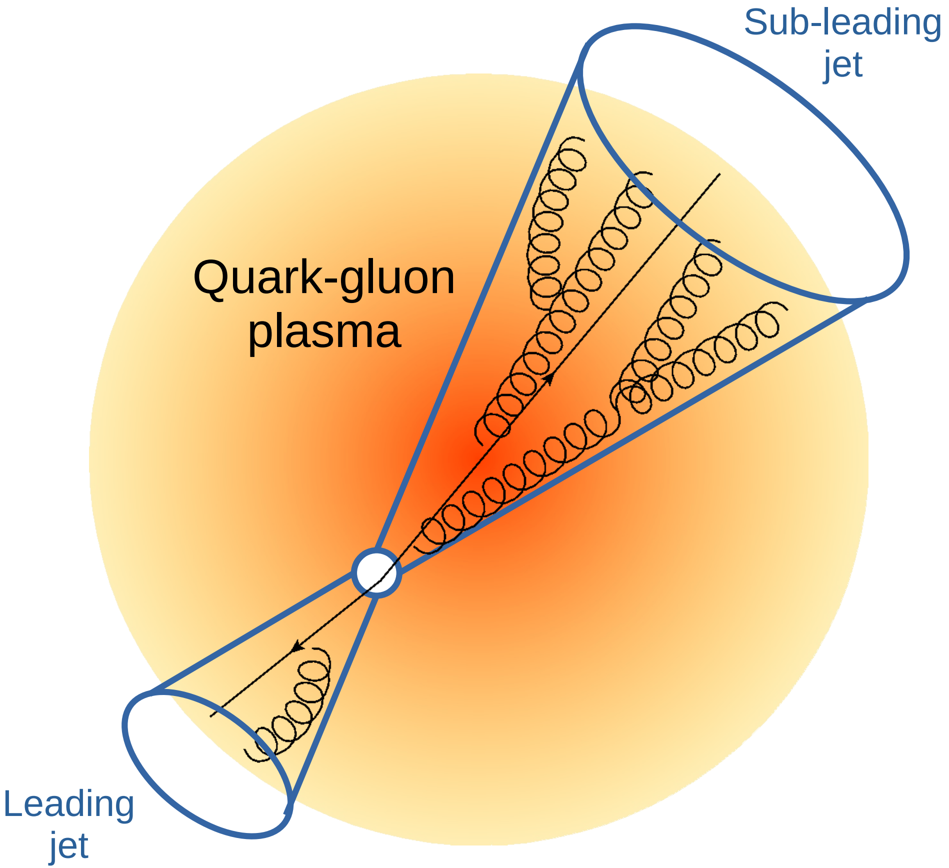


- **Jets**:
  Collimated sprays of high p_T partons/hadrons

- **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



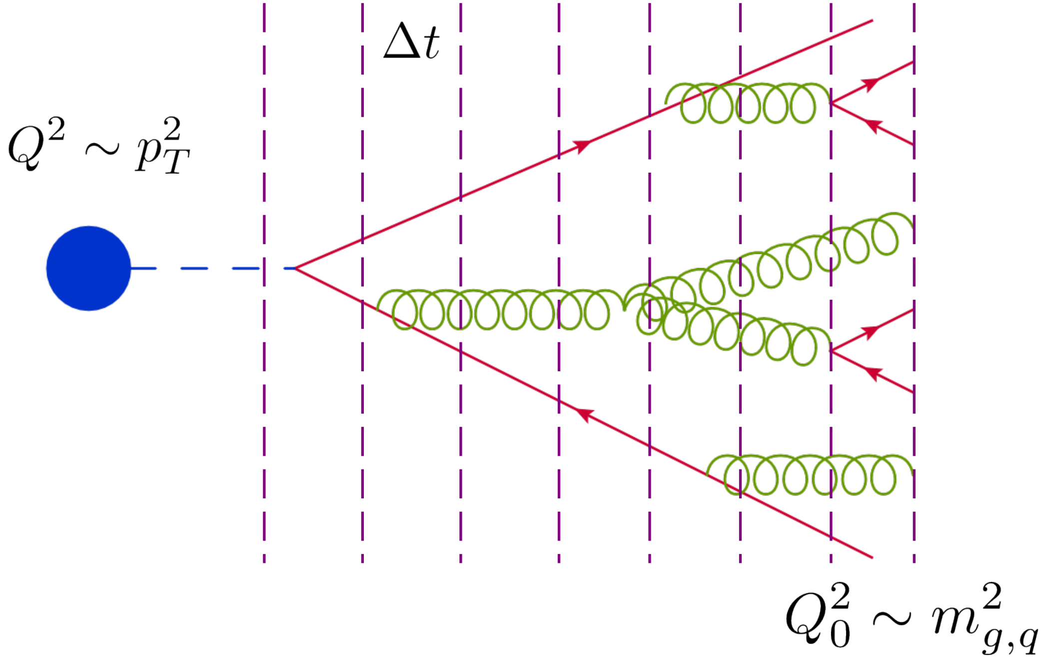
- Jets can be produced alongside the QGP in heavy ion collisions
- Interactions between jet partons and the QGP medium leads to modifications of jet properties

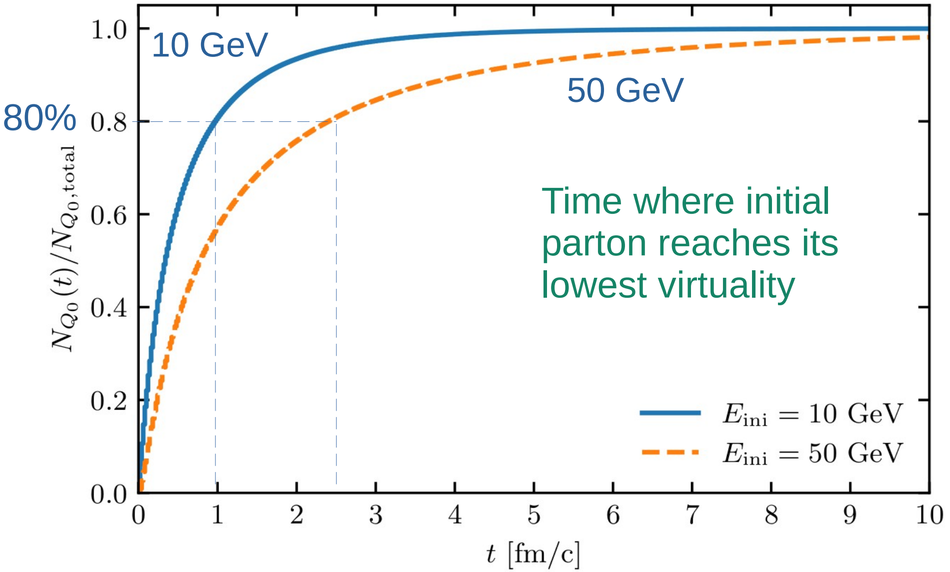
→ **Jet Energy Loss / Quenching**

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



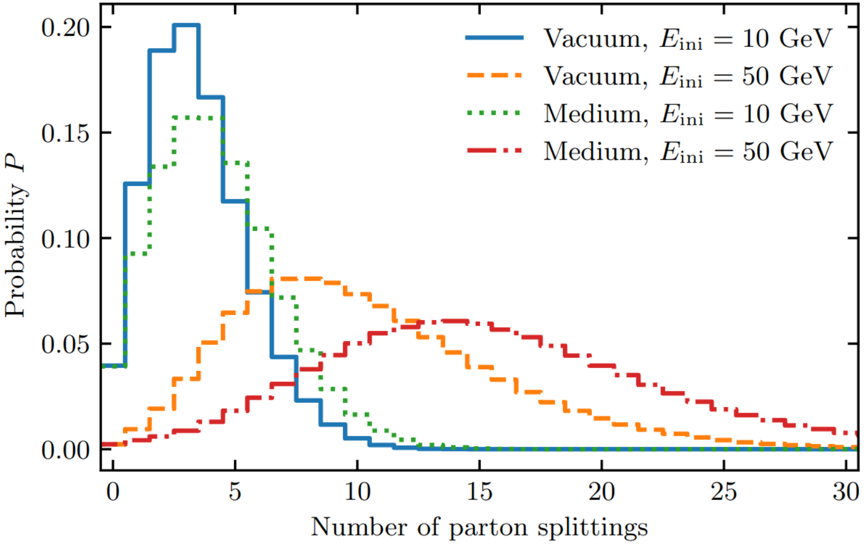


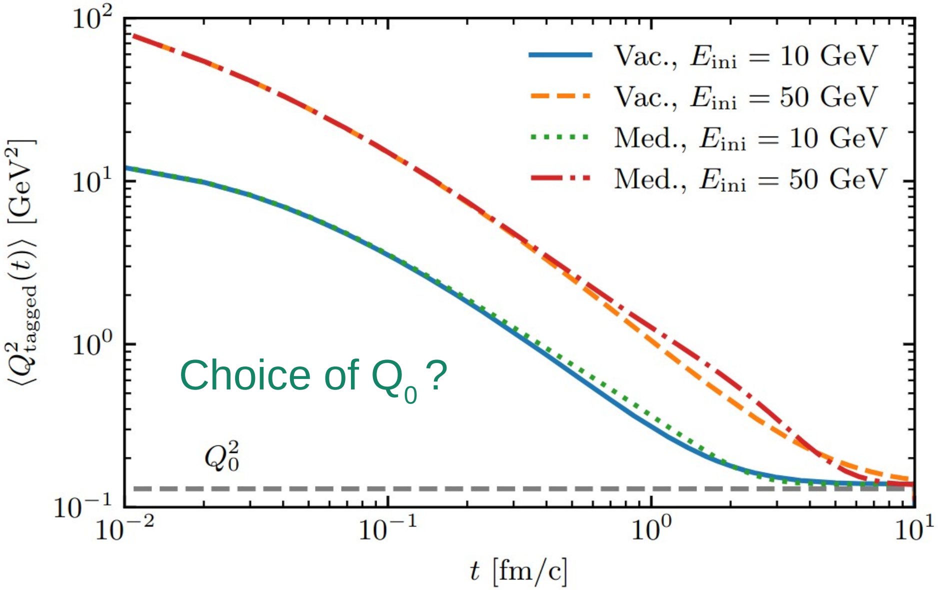
Time where initial parton reaches its lowest virtuality

“Vacuum” Parton Shower in Medium

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

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

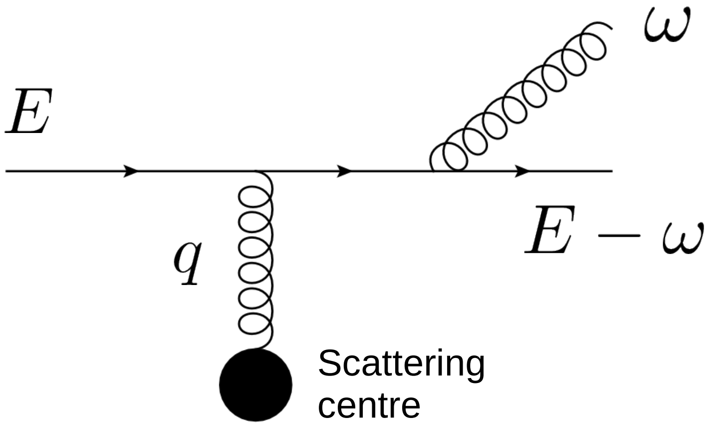




Choice of Q_0 ?

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)

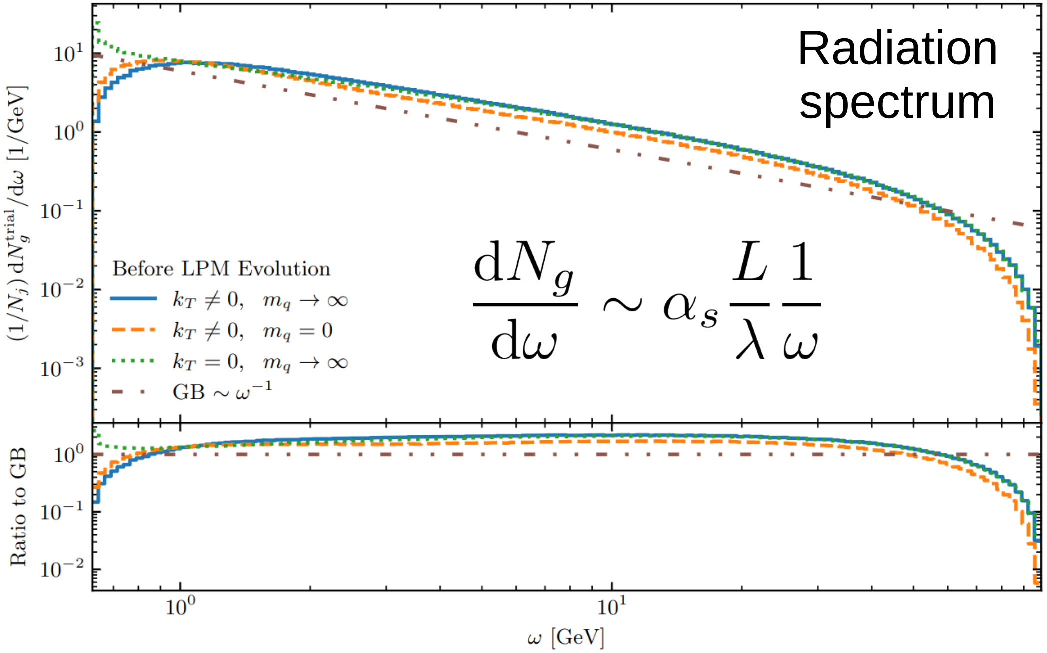


- Initial Gunion-Bertsch seed: i.e. radiation of a **preformed gluon** from a single scattering
  (Each parton can generate a number of preformed gluons)
- Gunion-Bertsch cross-section from scalar QCD

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

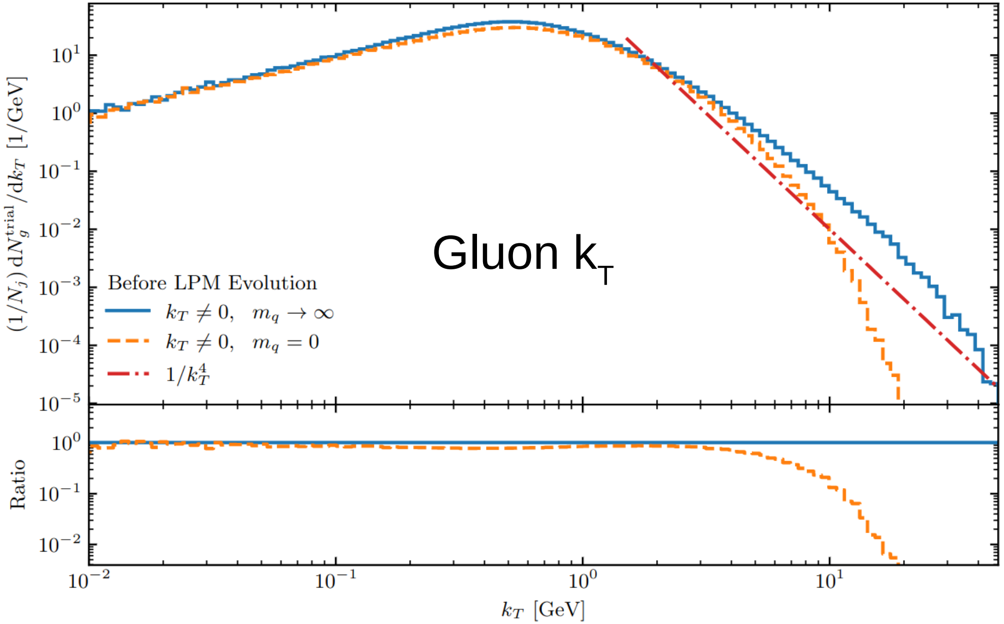
$$\frac{\mathrm{d}\sigma_{\mathrm{el}}}{\mathrm{d}^2l_t} \sim \frac{8\alpha_s^2}{9(l_T^2+\mu^2)^2}$$

Medium-Induced Single Radiation



Radiation spectrum

$$\frac{\mathrm{d}N_g}{\mathrm{d}\omega} \sim \alpha_s \frac{L}{\lambda}\frac{1}{\omega}$$



Gluon k_T

Coherency and the LPM Effect

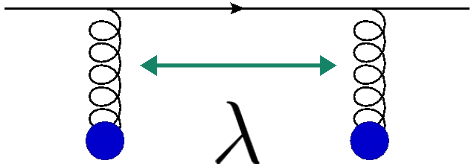
- The formation of the radiated gluon is a quantum mechanical process

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

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

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

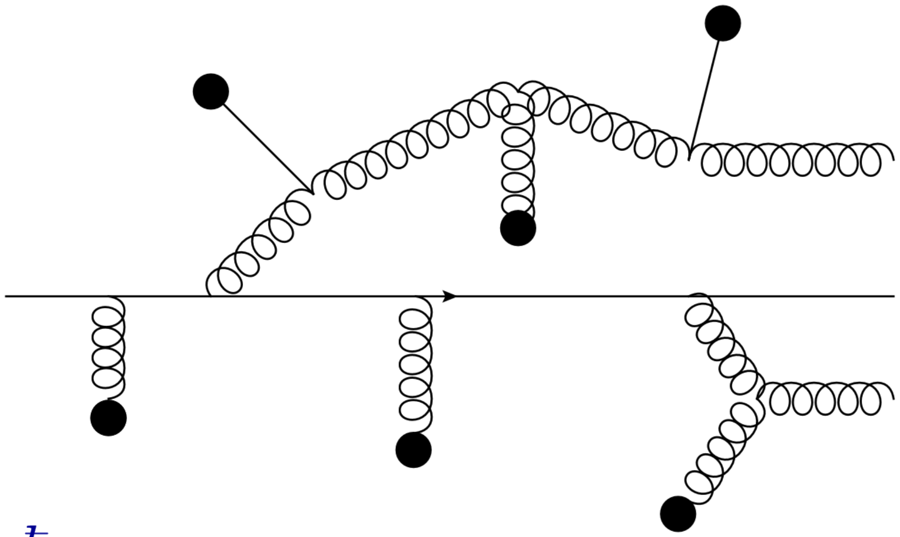
$$N_s = \frac{t_f}{\lambda}$$



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

$\omega =$ gluon energy

$\hat{q} =$ medium modifications



$L =$ path length of medium

Implementation of LPM Effect

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

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

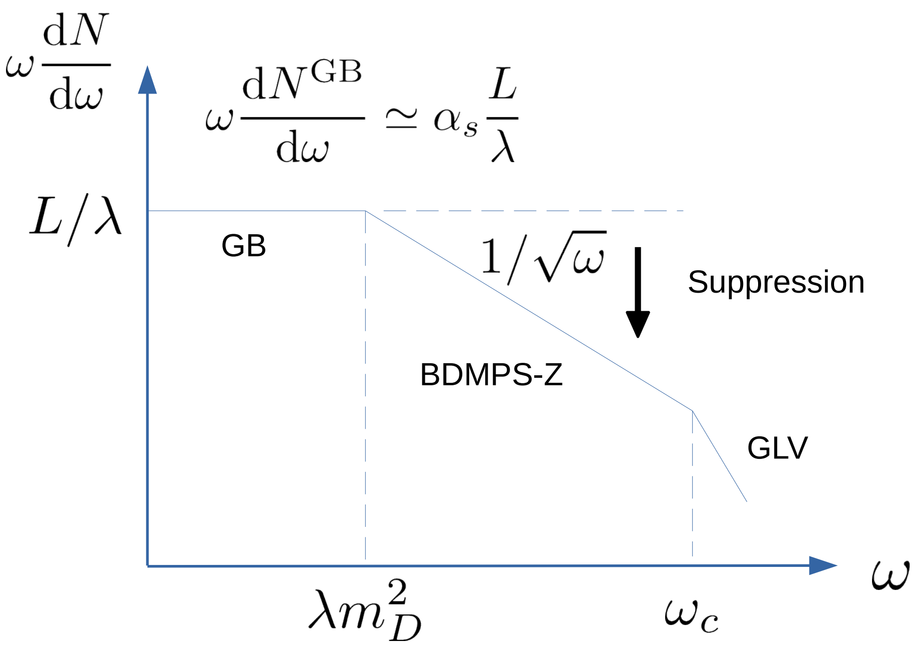
  - Radiation of preformed gluon with prob. $\Gamma_{\mathrm{inel}}\Delta t$

- 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:



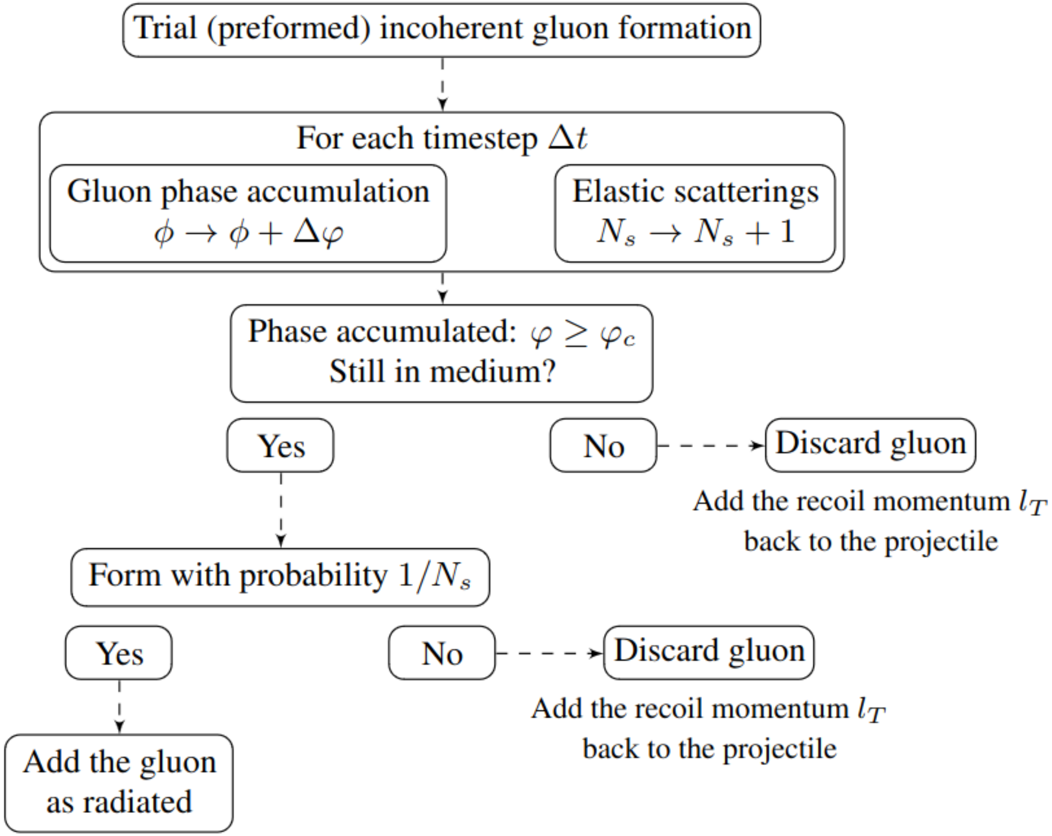
$$\omega\frac{\mathrm{d}N^{\mathrm{BDMPS\text{-}Z}}}{\mathrm{d}\omega} \simeq \alpha_s\sqrt{\frac{\hat{q}L^2}{\omega}}$$

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



Trial (preformed) incoherent gluon formation

For each timestep Δt

Gluon phase accumulation $\phi \to \phi + \Delta\varphi$

Elastic scatterings $N_s \to N_s + 1$

Phase accumulated: $\varphi \geq \varphi_c$
Still in medium?

Yes

No

Discard gluon

Add the recoil momentum l_T back to the projectile

Form with probability $1/N_s$

Yes

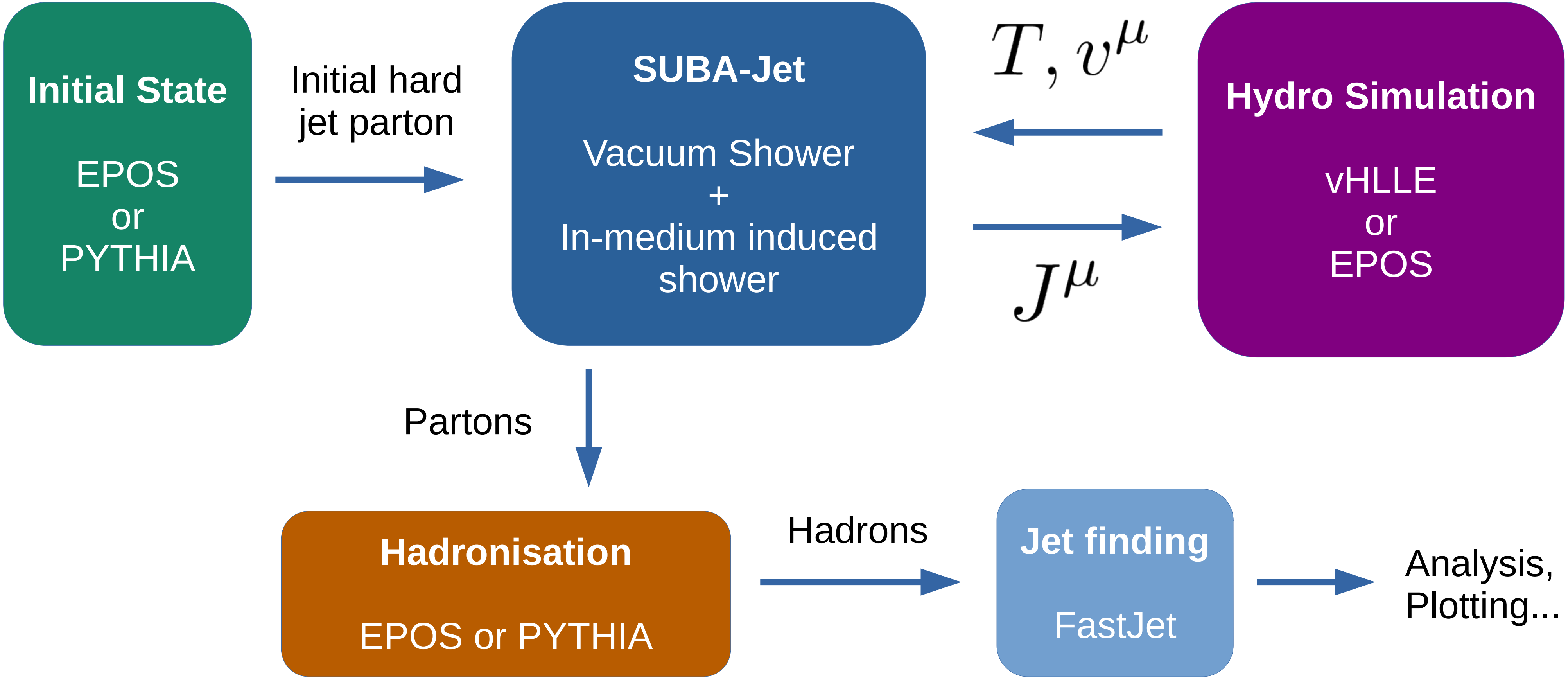
No

Discard gluon

Add the recoil momentum l_T back to the projectile

Add the gluon as radiated

The Monte Carlo



Initial State

EPOS
or
PYTHIA

Initial hard
jet parton

SUBA-Jet

Vacuum Shower
+
In-medium induced
shower

T, v^μ

J^μ

Hydro Simulation

vHLLE
or
EPOS

Partons

Hadronisation

EPOS or PYTHIA

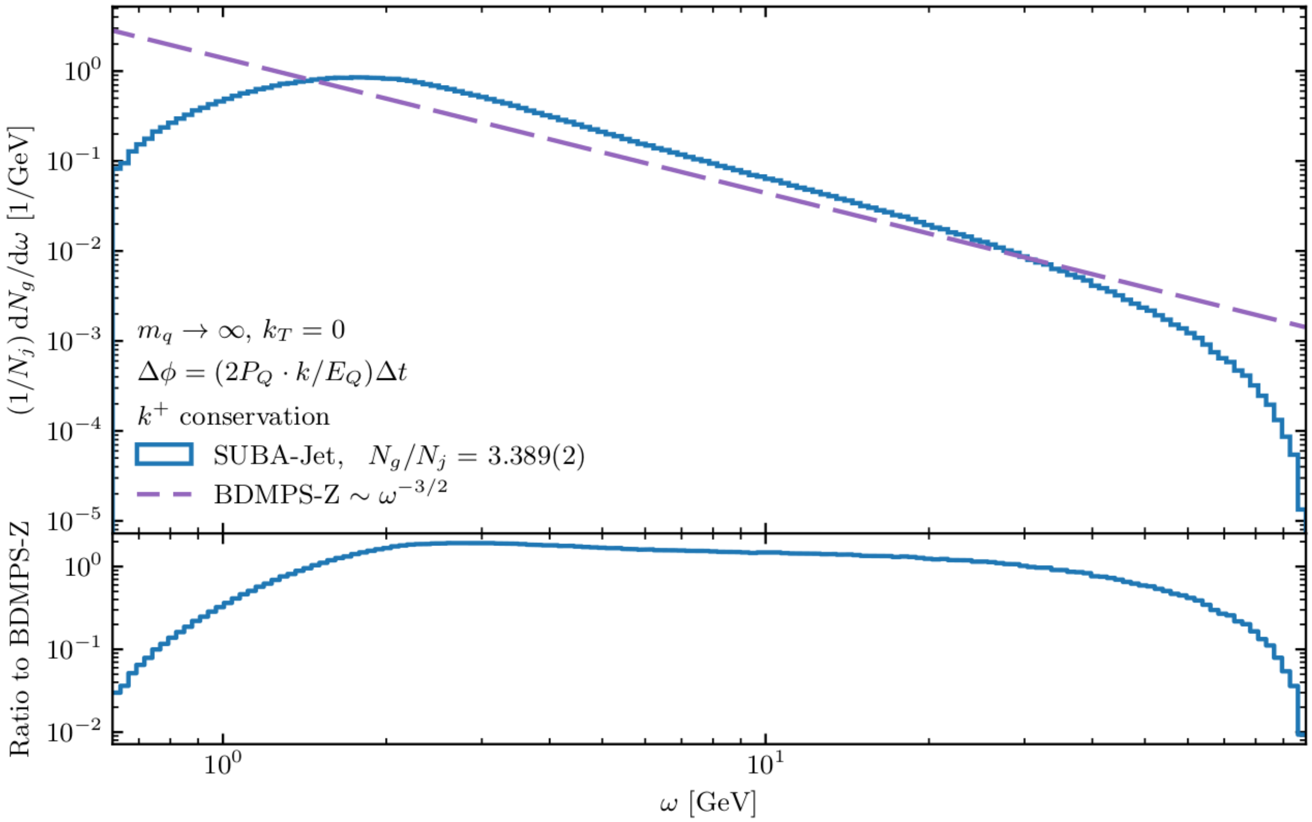
Hadrons

Jet finding

FastJet

Analysis,
Plotting...

Reproduction of BDMPS-Z Limit



Energy spectrum

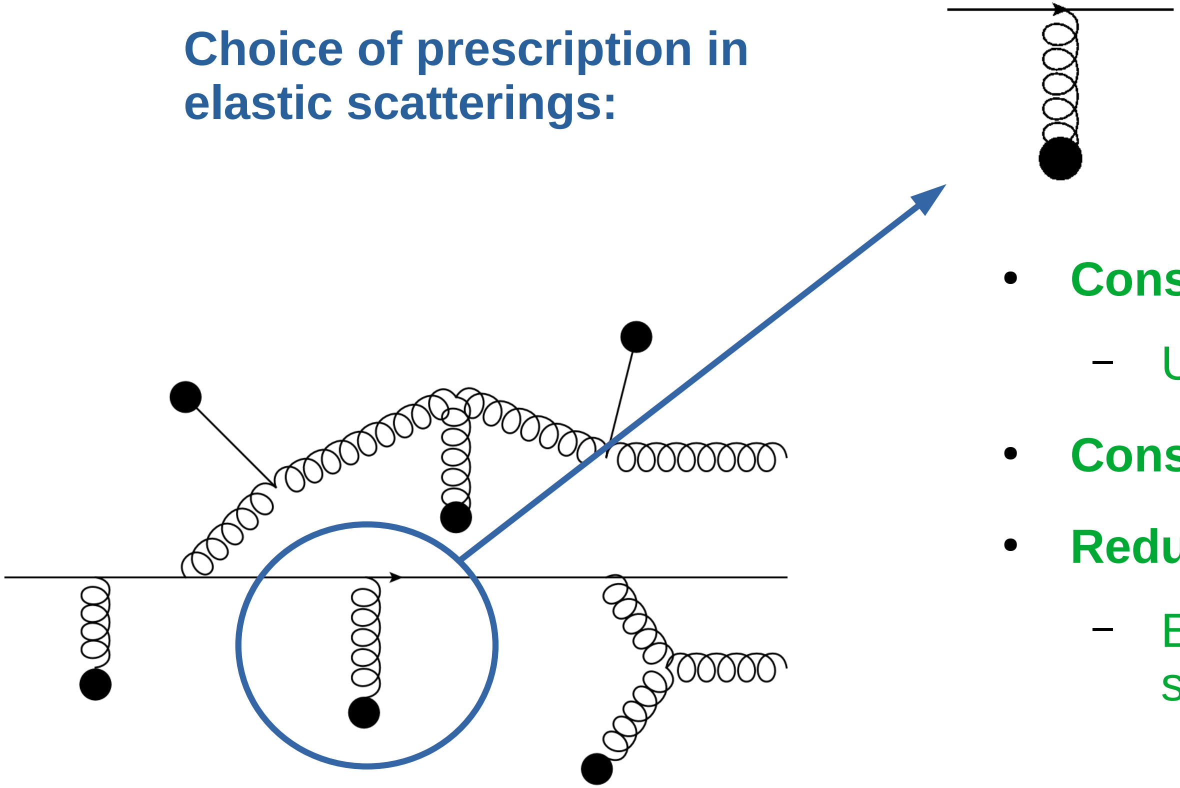
$$\frac{\mathrm{d}N}{\mathrm{d}\omega} \quad \text{vs} \quad \omega$$

Reproduces BDMPS-Z for intermediate energies

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

Reproduction of BDMPS-Z Limit

Choice of prescription in elastic scatterings:



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

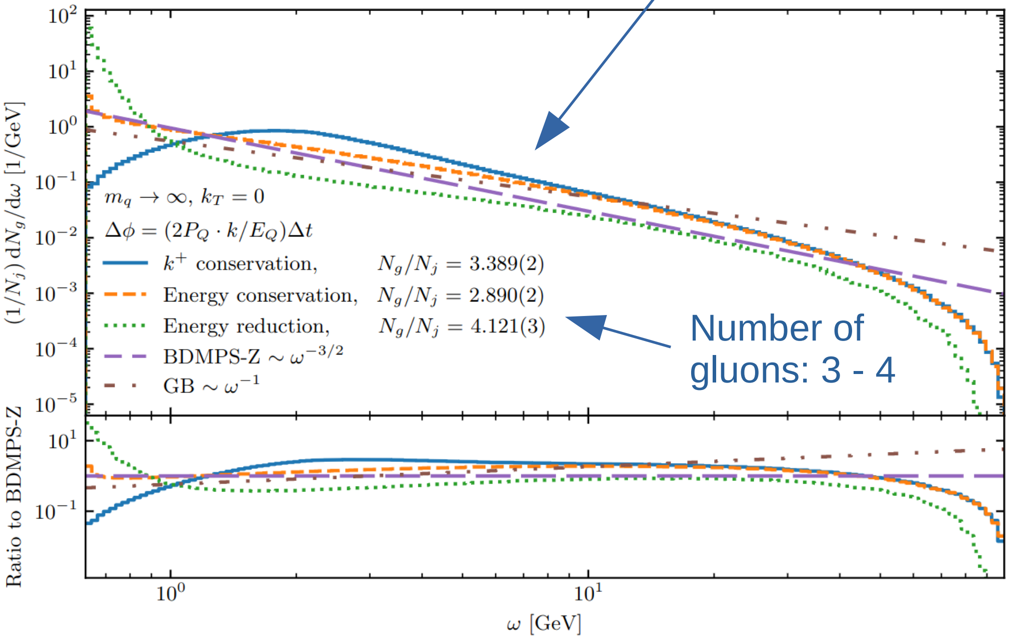
Reproduction of BDMPS-Z Limit

- Initial state: Low Q
  Mono-energetic quark gun of 100 GeV
- Medium:
  Brick of constants temperature 400 MeV
  Path length: L = 4 fm $\alpha_s = 0.3$
- Scattering centres with infinite mass
- Initial $k_T = 0$
- Phase accumulation:

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

- BDMS normalisation:

$$\frac{\mathrm{d}N_g}{\mathrm{d}\omega} \sim \alpha_s \sqrt{\frac{Lm_D^2}{\hbar c}} \frac{1}{\omega^{3/2}}$$



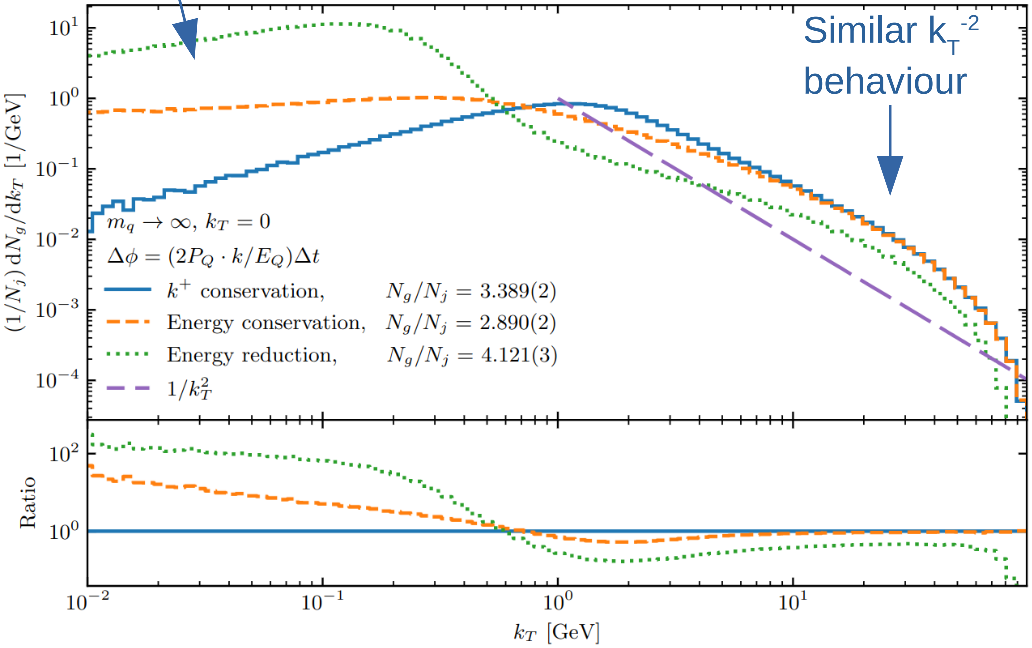
Follows BDMPS-Z nicely

Number of gluons: 3 - 4

Radiation spectrum

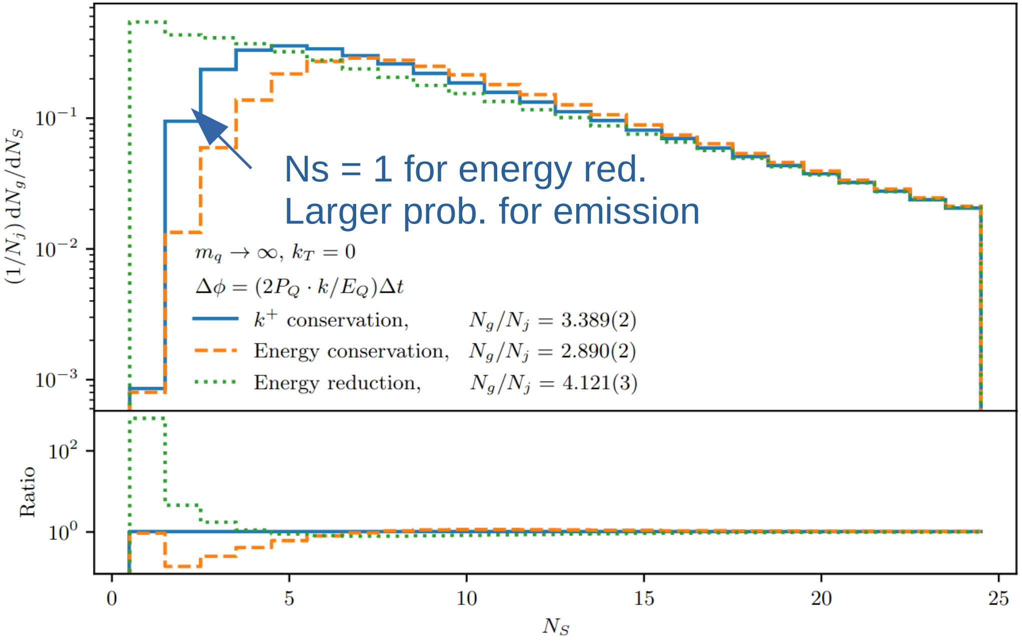
Reproduction of BDMPS-Z Limit

Large difference



Similar k_T^{-2} behaviour

Gluon k_T

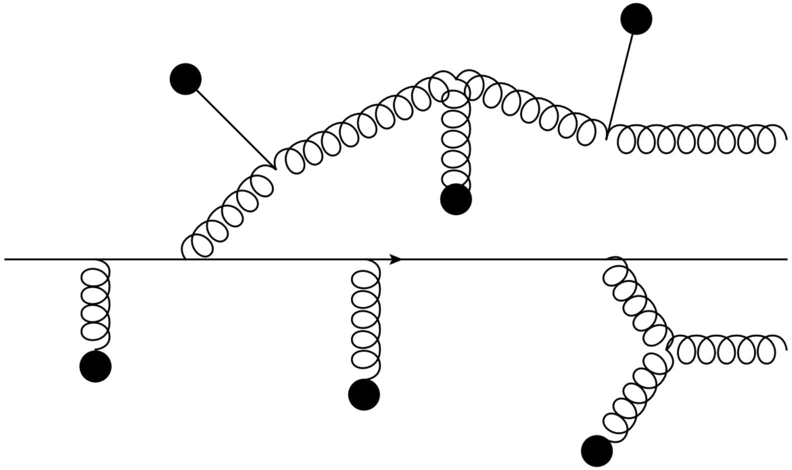


Ns = 1 for energy red.
Larger prob. for emission

Number of
elastic scatterings

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:**

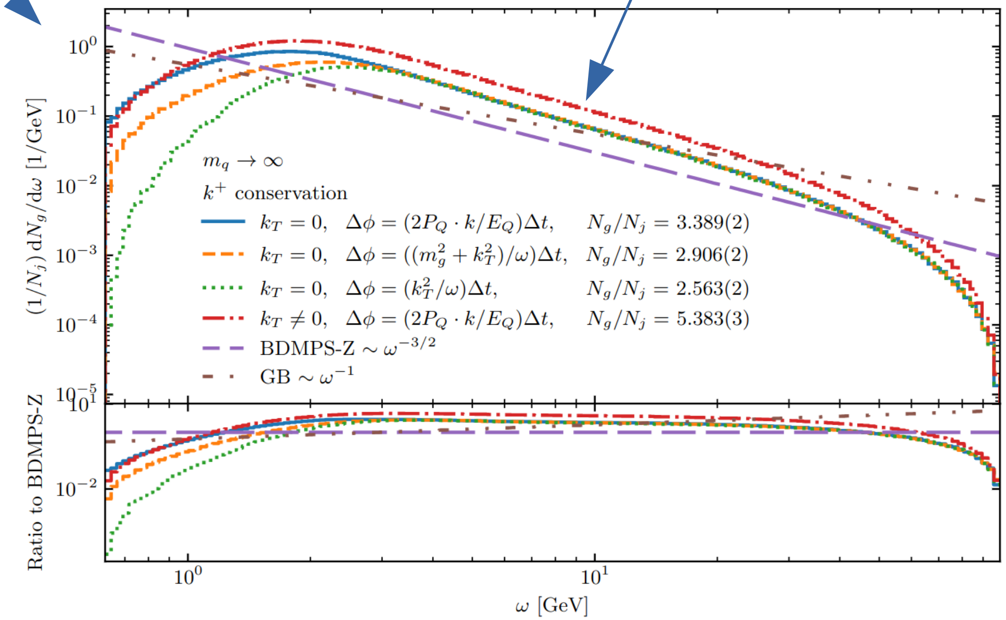
$$\Delta\varphi = \frac{2P_Q \cdot k}{E_Q}\Delta t$$

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



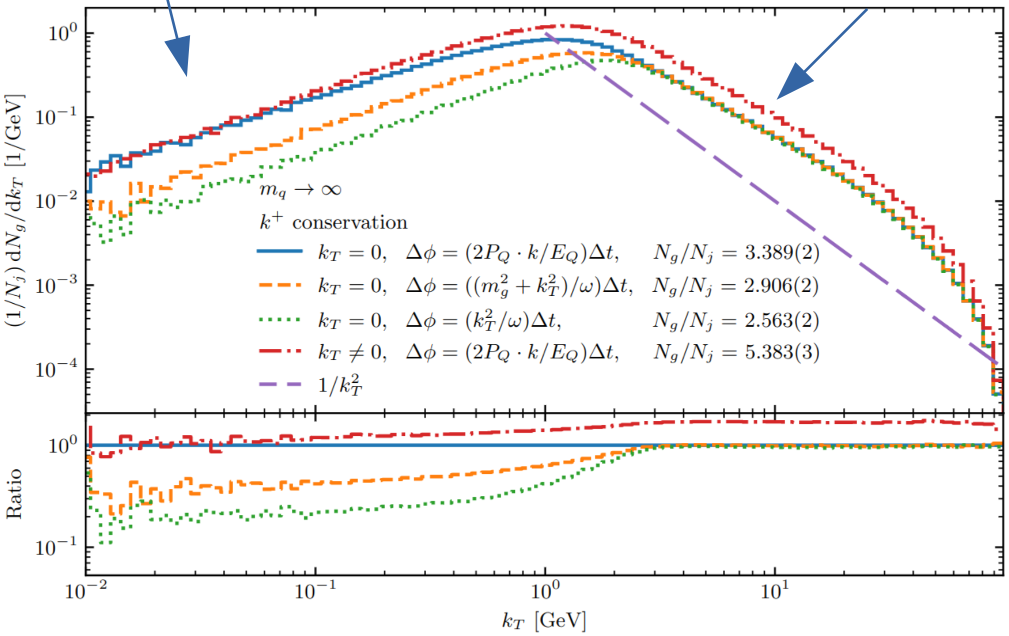
Radiation spectrum

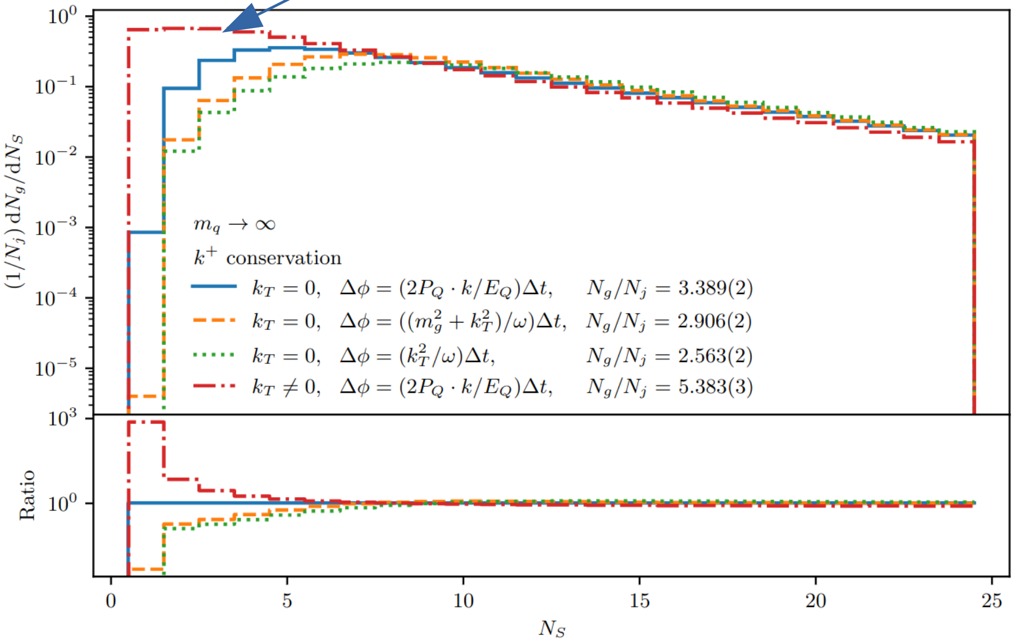
The Effect of the Phase Accumulation

Effect at low k_T

Similar behaviour in BDMPS region

Non-zero kT means earlier formation





Gluon k_T

Number of elastic scatterings

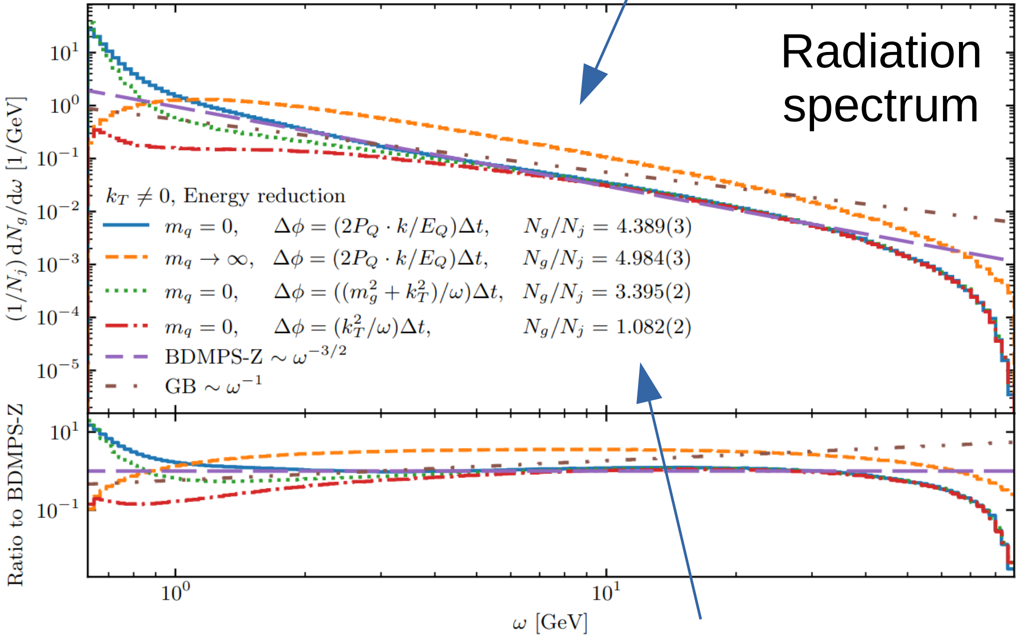
More Realistic Case

- 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

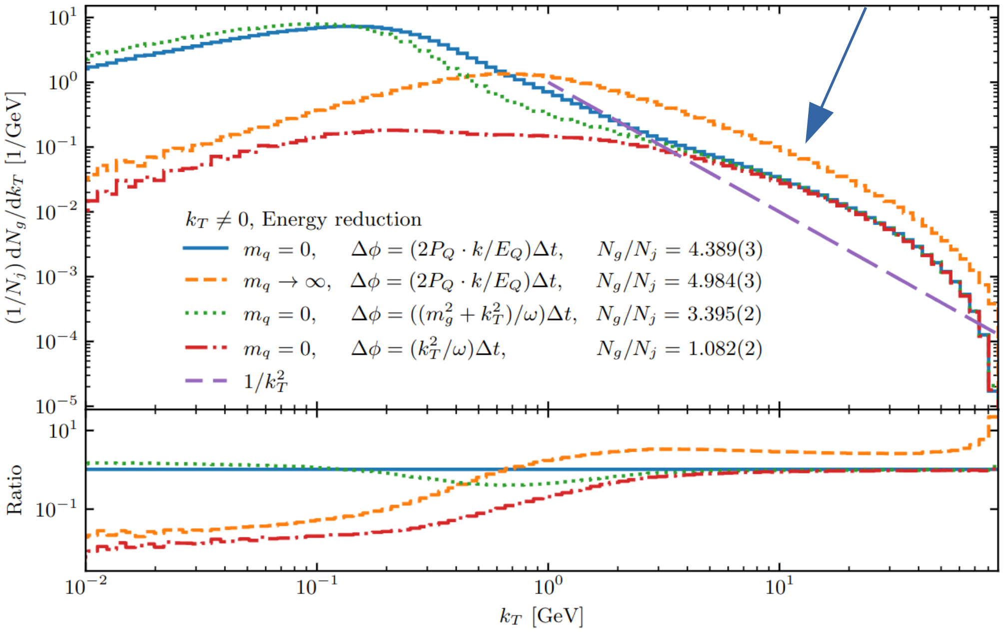
Similar shapes but larger yield



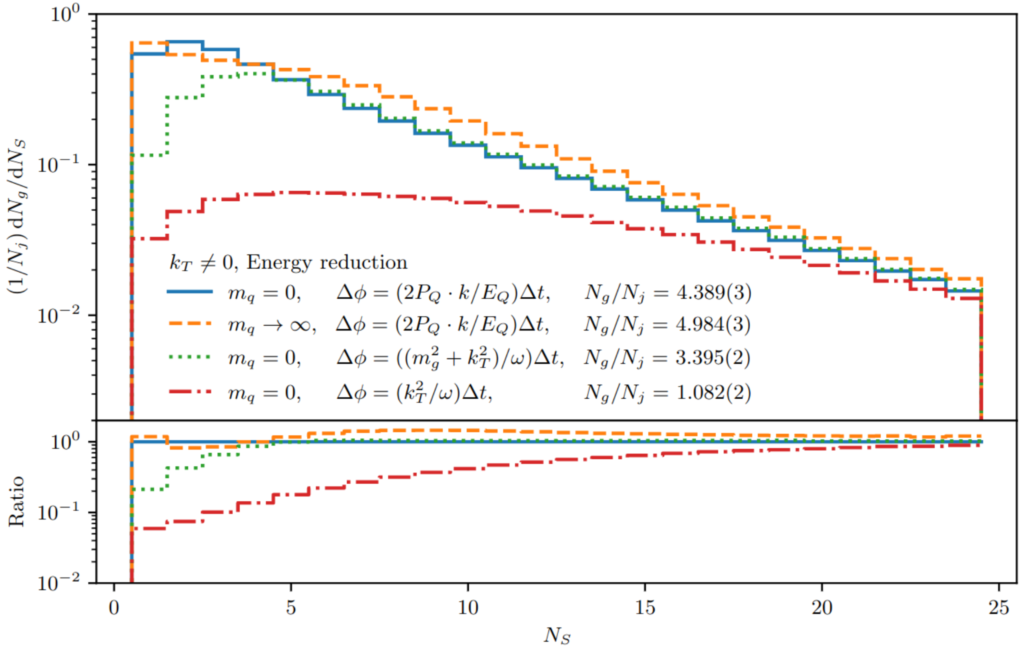
But no overall effect due to compensation at low energies

More Realistic Case

Similar shapes
but larger yield



Gluon k_T



Number of
elastic scatterings

Looking Forward: Towards More Realism

Next step:

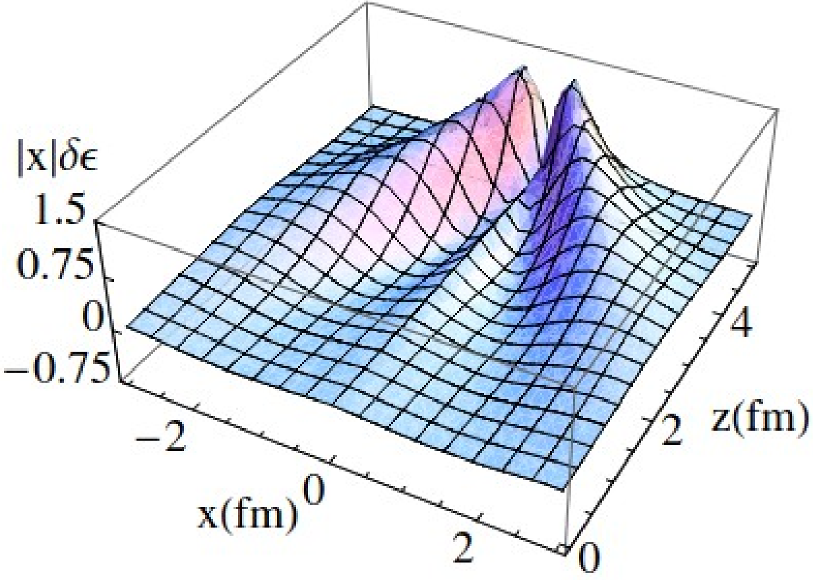
- Interface with vHLLE to get hydro evolution of the medium
- Running strong coupling in elastic scatterings
- Start with high Q, high E partons
- Sampling of initial parton p_T

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

- 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

- Reproduction of the BDMPS radiation energy spectrum
- Shown effects of different model assumptions

- **Next step:** First results with hydro evolution interface to vHLLE
- **Later goal:** Implementation within the new EPOS4
    - Initial state, hydro, and hadronisation from EPOS