

# Jets-medium coupled evolution in AA collisions: the parton shower

Pol B. Gossiaux<sup>2</sup>

with **Iurii KARPENKO**<sup>1</sup>, Joerg Aichelin<sup>2</sup>, Martin Rohrmoser<sup>3</sup>, Klaus Werner<sup>2</sup>

<sup>1</sup> FNSPE CTU in Prague

<sup>2</sup> CNRS/SUBATECH Nantes

<sup>3</sup> Jan Kochanowski University



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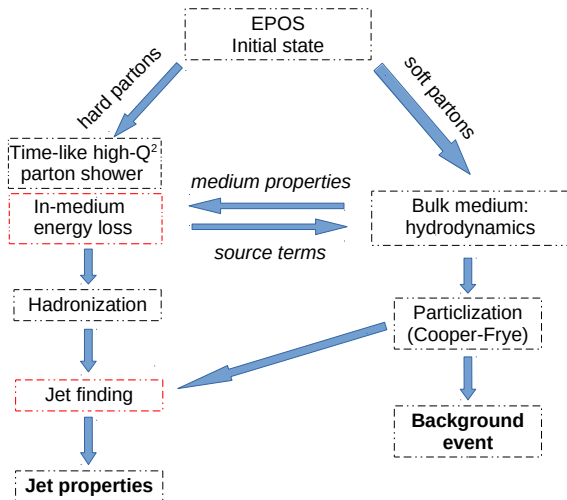
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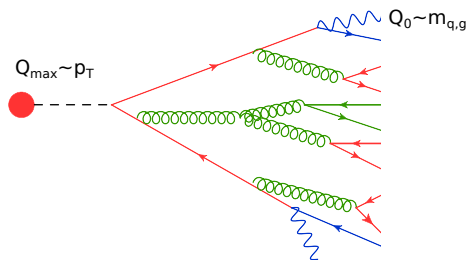
## Our project

To get both hydrodynamic IS and initial hard partons from EPOS3 (currently), make hydrodynamic and jet parts talk to each other, add hadronization scheme and jet finding.



## Time-like parton shower

- Monte Carlo simulation of DGLAP equations for a parton shower between virtuality scales  $Q_{\uparrow}$  (from Born process in EPOS) and  $Q_{\downarrow} = 0.6$  GeV. Vacuum shower developed by **Martin Rohrmoser**

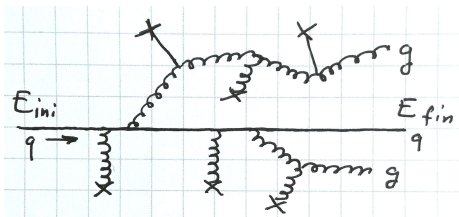


sketch taken from Liliana Apolinário's talk

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  $\Delta t = E/Q^2$ .
- Elastic scatterings off medium partons
- Medium-induced radiation for low- $Q^2$  (below  $Q_{\downarrow}$ ): see next slides

## Multiple radiations and coherence effects



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.

We adopted a faithful implementation of the BDMPS-Z by Zapp, Stachel, Wiedemann, JHEP **07** (2011), 118

- For low- $Q^2$  partons: at each timestep, an elastic scattering and/or a radiation of pre-formed gluon happens with a probability  $R_{el}\Delta t$ ,  $R_{inel}\Delta t$  respectively.
- Each formed parton can generate arbitrary number of pre-formed gluons ( $\propto$  blob).
- Implementation of BDMPS-Z: see the next slide.

## The Monte Carlo algorithm for coherent radiation

Trial **incoherent** gluon radiation

Gluon phase accumulation

$$\Delta\varphi = \frac{k_T^2(t) + m_g^2}{\omega} \times \frac{\Delta t}{\hbar c}$$

Elastic scatterings

each scattering increments  $N_s = N_s + 1$

Phase accumulated:  $\varphi = \Phi_{\text{form}}$   
and still in medium?

Yes

No

Discard gluon, revert the recoil

add the recoil momentum  $l_T$  back to the projectile

Form with probability  $1/N_s$

Yes

No

Discard gluon, revert the recoil

add the recoil momentum  $l_T$  back to the projectile

Add the gluon  
as formed/radiated

A test: reproducing the  $\omega \cdot dN/d\omega \propto 1/\sqrt{\omega}, 1/\omega$

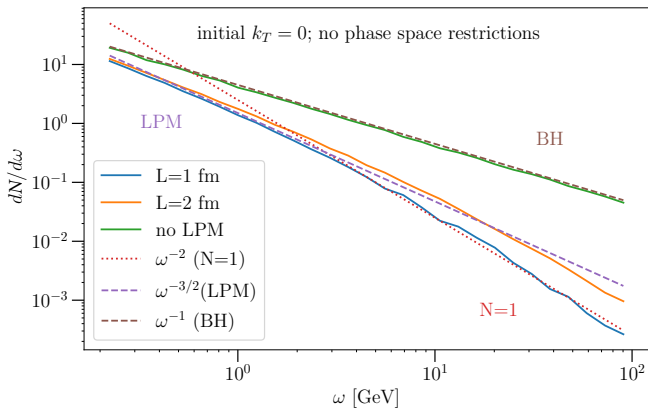
A simplified setup a-là Zapp, Stachel, Wiedemann, JHEP **07** (2011), 118

Restrictions:

- mono-energetic quark gun, quarks on the mass-shell
- incoherent gluon radiation  
 $dN^{\text{incoh}}/d\omega = 1/\omega$  with cut-offs  $[\omega_{\text{min}}, \omega_{\text{max}}]$ .
- initial  $k_T = 0$  for the trial radiated gluons
- eikonal limit: projectile is not affected by scatterings,  $k_T \ll \omega$ , no phase space treatment

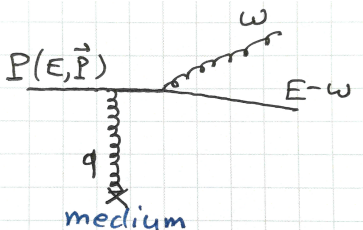
## A test: reproducing the $\omega \cdot dN/d\omega \propto 1/\sqrt{\omega}, 1/\omega$

- projectile:  $E = 100$  GeV quark, medium: box  $L = 1$  fm and  $R_{\text{el}} = R_{\text{inel}} = 0.1$  fm.
- change in regime for  $\omega \cdot dN/d\omega$  from  $1/\sqrt{\omega}$  to  $1/\omega$  happens at  $\omega = \omega_c$ , where  $\omega_c \approx \frac{\hat{q}L^2}{2\Phi_{\text{form}}\hbar}$ . With the present settings,  $\omega_c \approx 3.4$  GeV for  $L = 1$  fm.



- Also, by setting  $\Phi_{\text{form}} = 0$  we reproduce the incoherent limit  $1/\omega$ .

## From $1/\omega$ to full Gunion-Bertsch radiation seed



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* QCD<sup>1</sup>, which at high energy leads to a factorized formula for the total cross section of the radiation process:

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

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

and  $\frac{d\sigma_{\text{el}}}{d^2l_T} \rightarrow \frac{8\alpha_s^2}{9(\vec{l}_T^2 + \mu^2)^2}$ . **Allows for finite quark/gluon masses  $\rightarrow$  heavy quark jets**

<sup>1</sup>Scalar QCD is a case of spin-0 quarks interacting with non-Abelian gauge field (gluons).

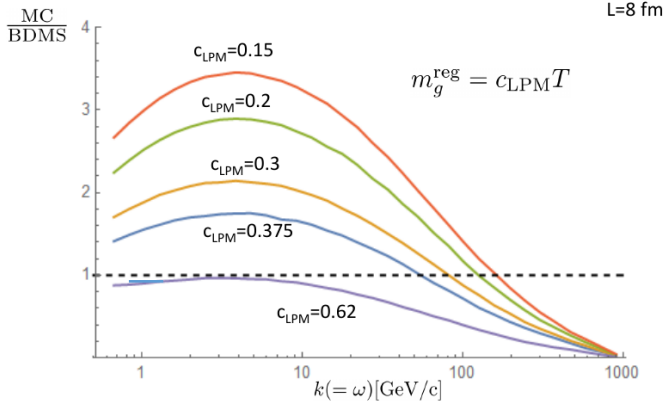


## Benchmark on BDMS for intermediate gluon $\omega$ (extended medium)

BDMS (NPB 531 (1998) 403) :  $\omega \frac{d^2 N_g}{d\omega dL} \approx \frac{\sqrt{2\alpha_s C_F}}{\pi \tilde{\lambda}} \sqrt{\tilde{\kappa} \ln \frac{1}{\tilde{\kappa}}}$  with  $\tilde{\kappa} = \frac{\tilde{\lambda} \mu^2}{2\omega(1-x)}$ .

Accumulating phase algorithm provides a good trend for  $\frac{dN}{d\omega}$ , but recovering the absolute spectrum requires some tuning.

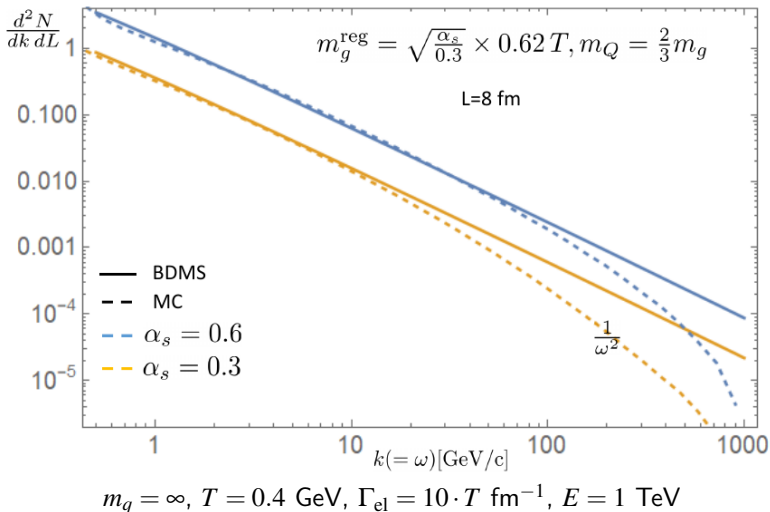
We consider effective  $m_g^{\text{reg}}$  for  $k \gg T$  :



$$m_q = \infty, \alpha_s = 0.3, T = 0.4 \text{ GeV}, \Gamma_{\text{el}} = 10 \cdot T \text{ fm}^{-1}, E = 1 \text{ TeV}$$

## Benchmark on BDMS for intermediate gluon $\omega$ (extended medium)

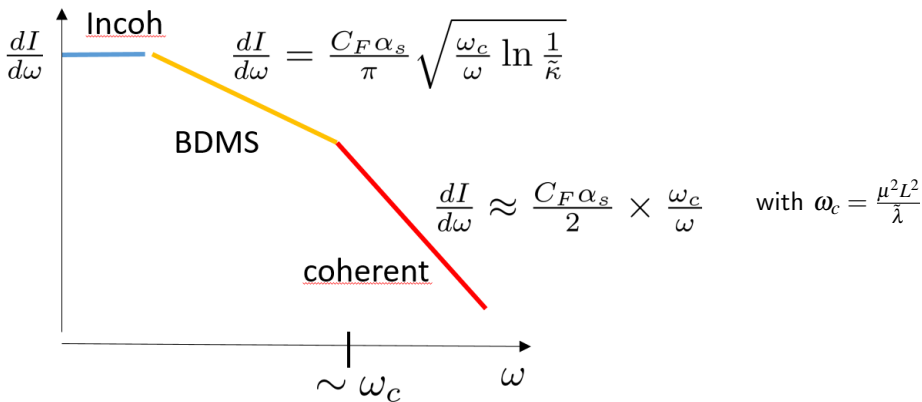
Good agreement between the MC and BDMS :



## From BDMS to coherent regime for gluon emission

Intermediate gluon energy : BDMS NPB 531 (1998) 403

Coherent regime : Zakharov FZJ-IKP(Th)-2000-31 (hep-ph/0012360v1)



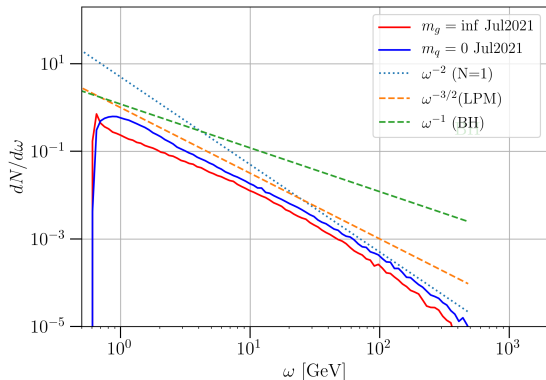
MC also has this  $1/\omega$  tail (cond. prob  $\sim \frac{\omega_c}{\omega \Phi_{\text{form}}}$  for Coulomb-like scattering).  
 Allows to fix  $\Phi_{\text{form}}$ .

## Releasing the restrictions

" $m_q = \infty$ "  $\rightarrow$  Full " $m_q = 0$ " :

- fixed scat. centers  $\rightarrow$  recoil allowed and initial thermal motion
- $k_T = 0$  at pre-gluon emission  $\rightarrow$  arbitrary  $k_T$  after GB pre-gluon emission
- no secondary emission  $\rightarrow$  secondary emissions allowed

Induced gluon spectrum:



$p_Q = 1 \text{ TeV}$ ,  $T = 0.4 \text{ GeV}$ ,  
 $L = 8 \text{ fm}$ ,  $\alpha_s = 0.3$ , elastic  
rate  $\Gamma = 4 \text{ fm}^{-1}$

Increase of gluon radiation, especially at low energy (subsequent emissions)

## More realistic calculations

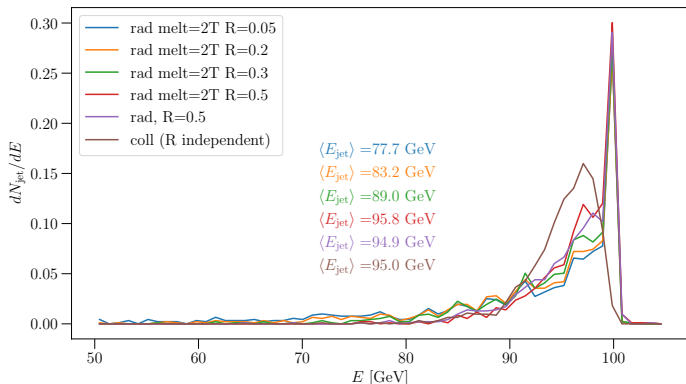
- Medium: box  $L = 4$  fm of QGP with  $T = 350$  MeV
- massive medium constituents:  $m_q = 330$  MeV,  $m_g = 564$  MeV
- mono-energetic "quark gun" with  $E_{\text{ini}} = 100$  GeV
- energy loss via the medium-induced coherent radiation from above; fixed  $\alpha_s = 0.4$ , infrared regularisation  $\mu = 623$  MeV (derived from Debye mass)
- hadronisation via Pythia8
- jet reconstruction: anti- $k_T$  with FASTJET 3.3

## On-shell initial parton

In this case, the composition of the energy losses of the  $E = 100$  GeV parton-projectile is: radiative energy loss  $\approx 11.2$  GeV, collisional one  $\approx 5.2$  GeV.

**Radiative Energy Loss dominates as expected.**

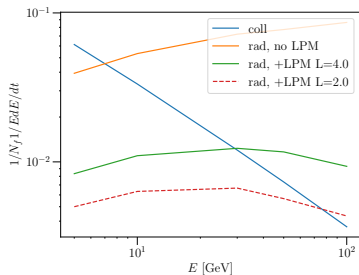
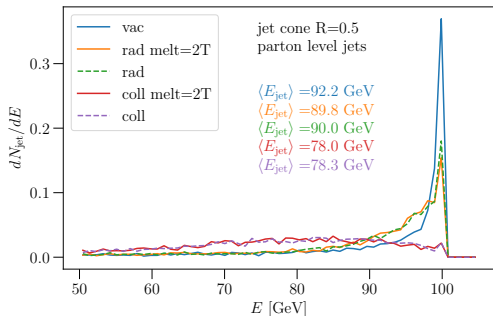
What happens after the jet reconstruction with FASTJET is the following:



Half of the energy of radiated gluons is recovered with the jet cone  $R = 0.5$ . Thermalization ("melting") of jet partons with  $E < 2T \rightarrow$  medium has a negligible influence.

## Off-shell initial parton

Same, but  $Q_{\uparrow} = E_{\text{ini}} = 100 \text{ GeV} \Rightarrow$  DGLAP shower down to  $Q_{\downarrow} = 0.6 \text{ GeV}$



Left panel: Collisional energy loss dominates ! The difference between the red/purple and blue is much bigger than between the orange/green and blue. This collisional energy loss dominantly affects the secondary gluons (see right panel)

No single number/parameter can reproduce the full jet evolution !

## Summary

- We've constructed a Monte Carlo implementation of the incoherent + coherent radiative energy loss in BDMPS-Z formalism, based on an extension of the Gunion-Bertsch model to massive quarks/gluons.
- The code has been calibrated against established results in the literature in the main regimes (incoherent, coherent, finite path length)
- First AA studies with full-coupling to the hydro will come soon.