Jets and medium evolution in Pb-Pb collisions at the LHC energies from the EPOS initial state

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Outline

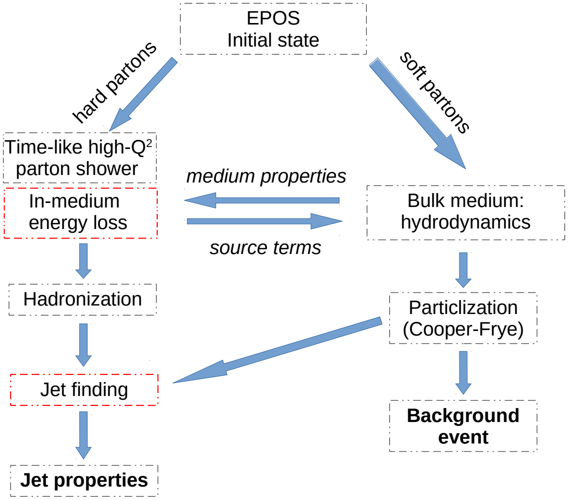
The talk consists of two separate parts:

- our developments of jet energy loss in medium
  (a new development)

- jet reconstruction and jet overlap effects
  (IK, Aichelin, Gossiaux, Rohrmoser, Werner, Phys. Rev. C 101, 014905 (2020))

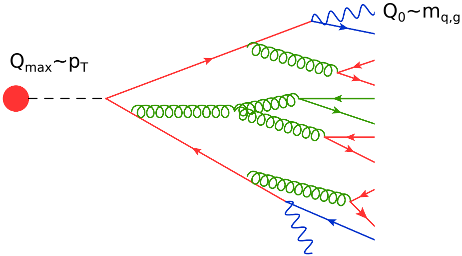
Our project

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

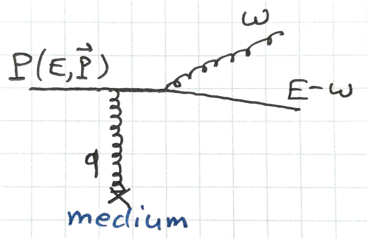
On top of that:

- 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

Part I: Jet energy loss

The goal here is to implement a microscopic treatment for the medium-induced gluon radiation of quarks/gluons at low virtuality Q^2.

Medium-induced radiation: single 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* QCD[1], which at high energy leads to a factorized formula for the total cross section of the radiation process:

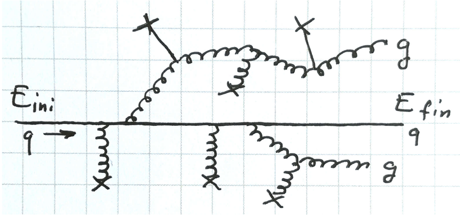
$$\frac{d\sigma^{Qq\to Qqg}}{dxd^2k_Td^2l_T} = \frac{d\sigma_{\text{el}}}{d^2l_T}P_g(x,k_T,l_T)\theta(\Delta), \qquad \text{where}$$

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

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

[1]Scalar QCD is a case of spin-0 quarks interacting with non-Abelian gauge field (gluons).

Multiple radiations and coherence effects

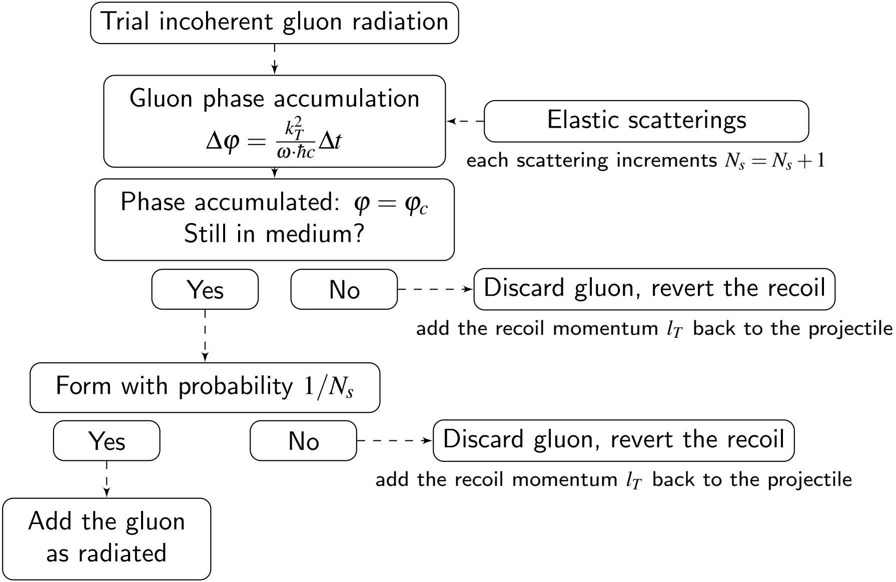


For the multiple scatterings in medium, one has to take into account coherence effects: Landau-Pomeranchuk-Migdal (LPM) effect in QED, or BDMPS-Z in QCD.

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 $R_{\text{el}}\Delta t$, $R_{\text{inel}}\Delta t$ respectively.
- Each parton can generate arbitrary number of pre-formed gluons ($\propto$blob).
- Implementation ob BDMPS-Z: see the next slide.

The Monte Carlo algorithm for coherent radiation block



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

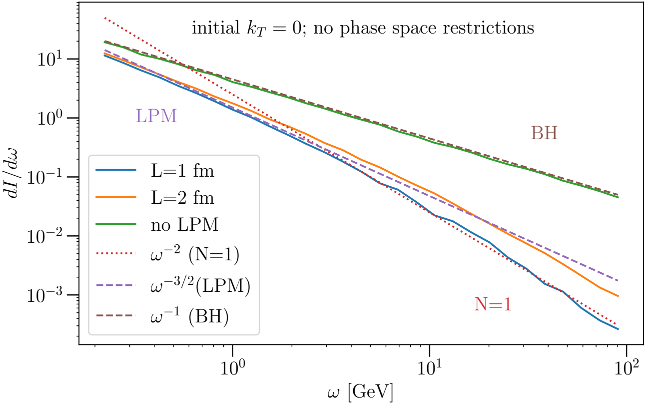
A simplified setup a-là Zapp, Stachel, Wiedemann, JHEP **07** (2011), 118

- mono-energetic quark gun, quarks at the mass-shell
- incoherent gluon radiation
  $dI^{\text{incoh}}/d\omega = 1/\omega$ 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 $\omega \cdot dI/d\omega \propto 1/\sqrt{\omega}, 1/\omega$

- projectile: $E = 100$ GeV quark, medium: box $L = 1$ fm and $R_{\mathrm{el}} = R_{\mathrm{inel}} = 0.1$ 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.

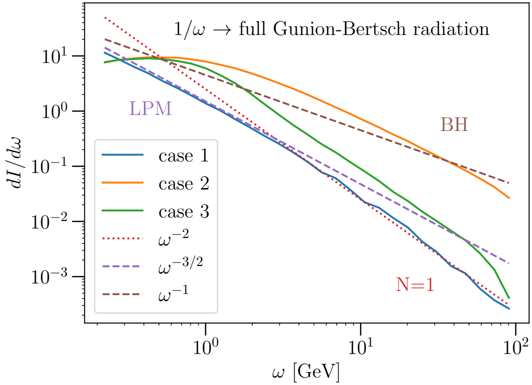


- Also, by setting $\varphi_c = 0$ we reproduce the incoherent limit $1/\omega$.

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

Projectile: $E = 100$ GeV quark,   medium: box $L = 1$ fm and $R_{\text{el}} = R_{\text{inel}} = 0.1$ fm.

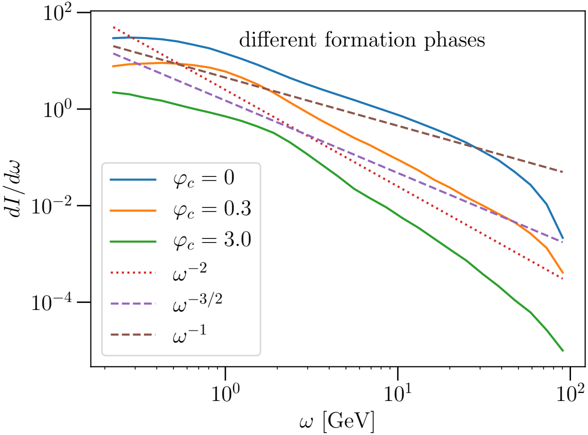
- **case 1**: $\frac{dI^{\text{incoh}}}{d\omega} = \frac{1}{\omega}$
- **case 2**: Gunion-Bertsch radiation seed without phase space restrictions
- **case 3**: +phase space restriction $\theta(\Delta)$



With the full Gunion-Bertsch (GB) radiation seed (**case 3**), one can hardly identify any region where $dI/d\omega \propto \omega^{-3/2}$, because the underlying incoherent radiation is far from ω^{-1}, $k_T \ll \omega$ behaviour.

LPM suppression in the full GB case

Projectile: $E = 100$ GeV quark,   medium: box $L = 1$ fm and $R_{\text{el}} = R_{\text{inel}} = 0.1$ fm.

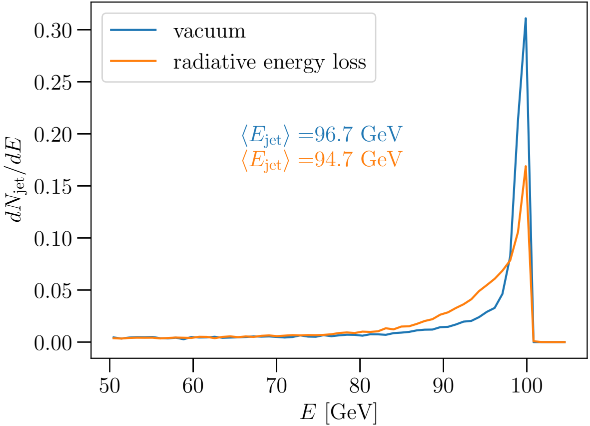


LPM (BDMPS-Z) effect has a strong influence on the radiation rate.

A more realistic calculation

- Medium: box $L = 4$ fm of QGP with $T = 350$ MeV
  massive medium constituents: $m_q = 330$ MeV, $m_q = 564$ MeV
- mono-energetic "quark gun" with $E_{\text{ini}} = Q_{\uparrow} = 100$ GeV.
- DGLAP shower down to $Q_{\downarrow} = 0.6$ 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, $R = 0.5$ with FASTJET 3.3

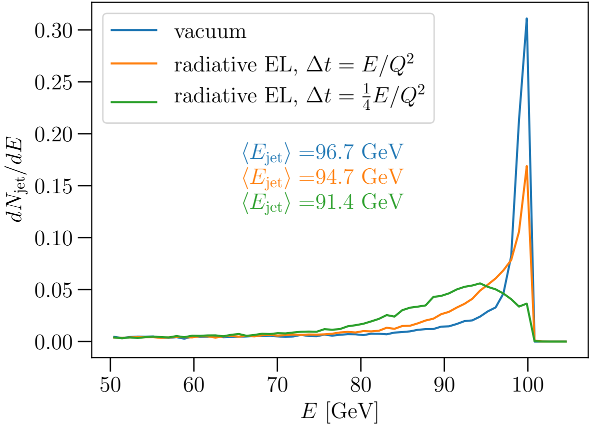
Projectile: $E = Q_{\uparrow} = 100$ GeV quark, medium: $L = 4$ fm $T = 350$ MeV QGP box.



With the current setup, we observe around 2 GeV in-medium energy loss for the initial 100 GeV hard parton.

Projectile: $E = Q_\uparrow = 100$ GeV quark, medium: $L = 4$ fm $T = 350$ MeV QGP box.

- Two different settings for the parton lifetimes between the splittings: $\Delta t = E/Q^2$ (used above) and $\Delta t = \frac{1}{4}E/Q^2$:



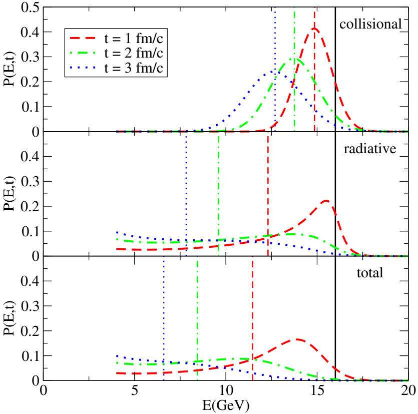
$\rightarrow$ The energy loss strongly depends on the formation time setting for the high-Q^2 DGLAP! Jet formation (DGLAP) and BDMPS happen consecutively in the same box, so the faster the jet is formed, the more time/space is there for the BDMPS radiative EL.

NB: the energy loss profile cannot be captured by a single number ΔE_{jet}:

The plot on the last slide is in the same spirit and qualitatively similar to:

Qin, Ruppert, Gale, Jeon, Moore, and Mustafa, Phys. Rev. Lett. 100, 072301 (2008)

$E_{\text{ini}} = 16$ GeV, $T = 400$ GeV plasma



- collisonal energy loss profile: a Gaussian centered around E_{jet}
- radiative energy loss: a wide distribution extending down to small E_{jet} (large energy loss ΔE_{rad})

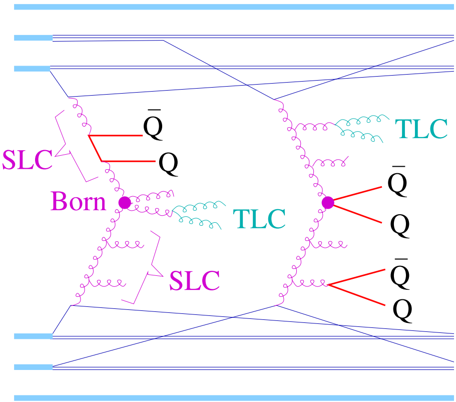
To go from this plot to R_{AA}, one has to convolute the $\Delta E(p_T)$ with the initial spectrum of hard partons $d\sigma/dp_T \Rightarrow$ the magnitude of the p_T shift of final jet spectrum from pp to AA might not be equal to ΔE.

Part II: Jet reconstruction and jet overlap

In the rest of the talk:

- medium effects are switched off
- there are no medium partons/hadrons

EPOS initial state



Parton-Based Gribov-Regge Theory

H. J. Drescher, M. Hladik, S. Ostapchenko, T. Pierog, K. Werner, Phys. Rept. 350, 93, 2001

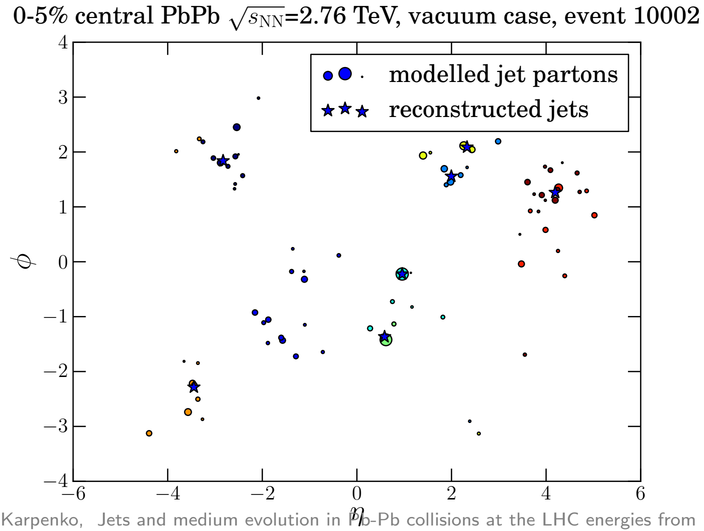
Pomeron = parton ladder, treated as a kinky string.

Spacelike cascades including Born process in the EPOS IS provide partons with all p_T which are further separated into core and corona.

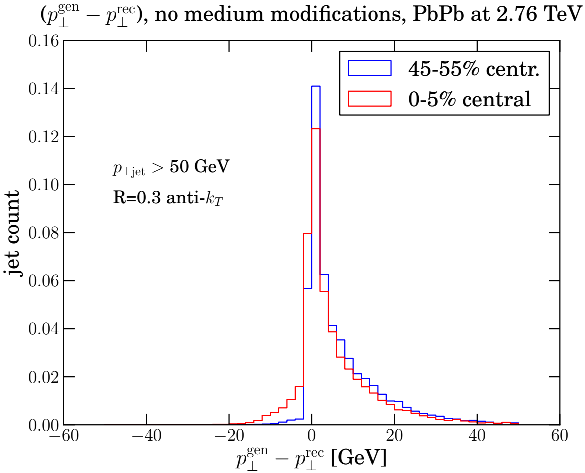
The IS produces multiple hard partons in each (central) Pb-Pb collision!

Jet reconstruction

A current shortcut:
Final state of a jet (partons) → **no** hadronization → jet finding.
Jet finding: vanilla FASTJET 3.3, anti-k_T algorithm

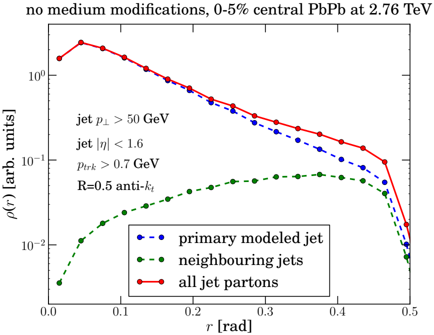


The artefacts

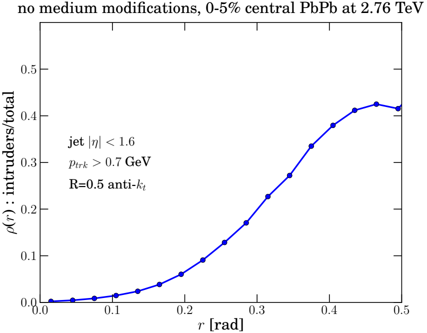


- 'runaway' jet partons are not clustered with the rest (loss, $\Delta p_\perp < 0$)
- partons from neighbouring jets are clustered together (gain, $\Delta p_\perp > 0$)

Jet shape for $R = 0.5$ cone size



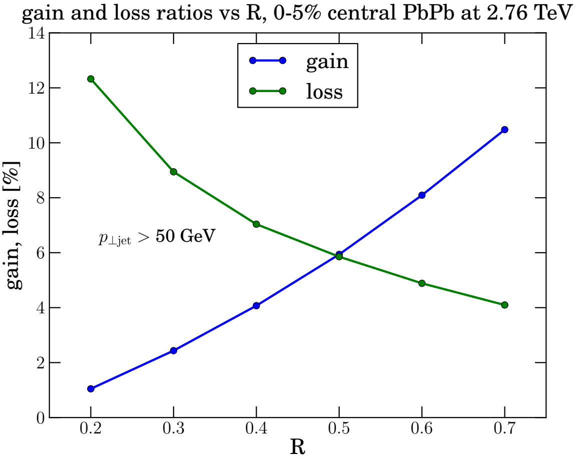
Right: ratio of neighbours/principal



- The core of the jet ($r < 0.2$) has negligible contribution from the jet overlap.
- For the periphery of the jet the jet overlap starts to be important.
- The ratio of intruders/total weakly depends on the $p_\perp$ of the jet
  The effect persists up to $p_\perp = 80$ GeV and presumably above.

More details: see my JETSCAPE2020 contribution here.

Gain and loss to the reconstructed jet $p_\perp$



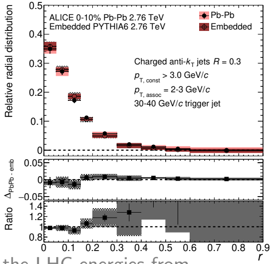
- For smaller R, more jet momentum is lost (outside of the cone).
- The larger R, more jet momentum is gained (from the neighbouring jets).

How do the experiments deal with it

- CMS performs a background subtraction in a statistical way based on PYTHIA+HYDJET simulations - which also removes the jet overlap effects.
  $\Rightarrow$ It should remove the overlap effect as the background jets are not correlated with the jet of interest.
  CMS Collaboration, JHEP 1805 (2018) 006

- ALICE reports the ratio of actual jet shape in PbPb events relative to the shape of (vacuum) PYTHIA jets embedded into actual PbPb events, as a proxy for the PbPb/pp ratio.
  $\Rightarrow$ It should remove the overlap effect as well, provided that PYHIA gives correct shape of vacuum jets.
  ALICE Collaboration, Phys.Lett. B796 (2019) 204-219

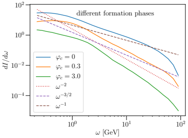
  - In order to have apple-to-apple comparison with the experiment, we should:
    - Either degrade the model so that we have solitary jets
    - Or keep all jets together but add all the machinery (medium hadrons, background subtraction)



Summary

Part I:

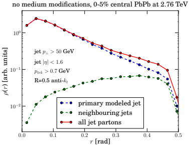
- We've constructed a Monte Carlo implementation of the coherent radiative enegry loss in BDMPS-Z formalism, based on an extension of the Gunion-Bertsch model to massive quarks/gluons.



- We find that with such Gunion-Bertsch-like radiation seed, the energy spectrum of radiated gluons does not manifest the $\omega^{-3/2}$ behaviour.
- The energy loss profile is wide and it cannot be characterized by a single quantity ΔE_{rad}.

Part II:

- EPOS3 initial state produces multiple hard partons = jet seeds in each **central** Pb-Pb event at the LHC energies.
- This leads to the effect of jet overlap in momentum space, once we reconstruct all the jets together in a HI event with FASTJET.



- The effect influences the jet shape.
- As experiments correct for that, the most practical solution is to treat the modelled jets separately.

(IK, Aichelin, Gossiaux, Rohrmoser, Werner, Phys. Rev. C 101, 014905 (2020))