Holmganga - Some nonequilibrium transport ideas

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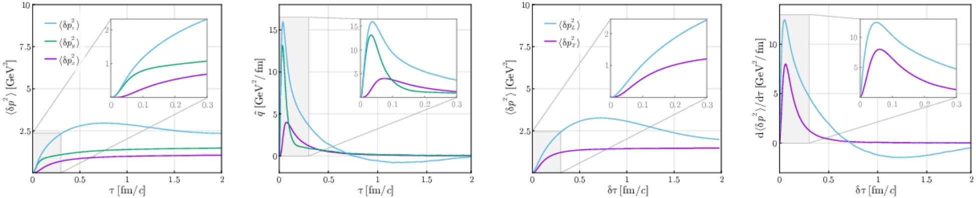
Introduction

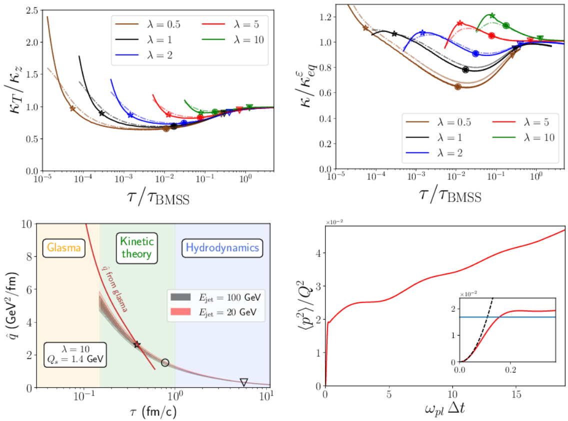
- Main point of the introduction: illustrate what has been done in the weak coupling community in terms of transport coefficients.
- Personal opinion: strong connection to phenomenology missing from weak coupling community. Everyone would be very interested in having one (interest is potentially wider than establishing a comparison with Pythia).

For discussion (more detailed in the end):

- Q: Can something be done/studied based on existing results?
- Q: Is there a new observable Pythia community is interested in that weak coupling community can provide?

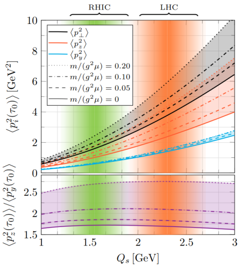


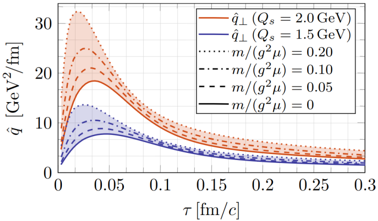
- Heavy quarks/jets on top of glasma. Wong equations: charged particle in a colored plasma.
- δp change of momentum squared since $\tau = \tau_{\mathrm{form}}$
- Left & far left: jet momentum broadening and $\hat{q}$. $m = 1\mathrm{Gev}\ p^x = 10\mathrm{GeV}$.
- Right: Beauty quark momentum broadening, $\tau_{\mathrm{form}} = 0.02\mathrm{fm}$. Far right: Momentum diffusion coefficient $\kappa = \frac{\mathrm{d}\langle \delta p^2 \rangle}{\mathrm{d}\tau}$.



- Top: Heavy quark momentum diffusion coefficient during the kinetic evolution compared to equilibrium, and ratio between transverse and longitudinal diffusion coefficients. (2303.12520 [hep-ph])
- Bottom left: $\hat{q}$ schematic evolution between the glasma and hydro stage (2303.12595 [hep-ph])
- Bottom right: Momentum of broadening of a infinitely heavy quark in the glasma (nonexpanding)

Müller and Ipp (2009.14206 [hep-ph], 2001.10001 [hep-ph])





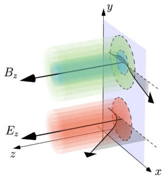


Figure 3: Physical origin of the momentum broadening in the Glasma. A high-energy quark is differently accelerated in a color-electric Glasma flux tube (red) and a color-magnetic Glasma flux tube (blue and green). Although electric and magnetic flux tubes are of similar size and field strength, electric flux tubes consist of uniformly oriented fields, while magnetic flux tubes exhibit a ring of anti-correlated fields with opposite sign (green ring around blue center). This leads to a suppression of momentum broadening along the y-axis (azimuthal direction) compared to the z-axis (rapidity direction).

- Momentum broadening and $\hat{q}$ computed from a glasma simulation.
- Idea from 2009.14206: Initial fluxtubes and momentum broadening. Momentum broadening from glasma fluxtubes should be different from Angantyr? In Pythia only electric "flux tubes"?

Carrington,Czajka,Mrówczyński (2202.00357 [nucl-th], 2112.06812 [hep-ph],2105.05327 [hep-ph])

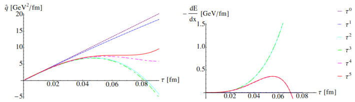


FIG. 2. Transport coefficients of a ultra-relativistic quark, with $v = v_\perp = 1$. Left panel: time evolution of the momentum broadening coefficient. Right panel: time evolution of the collisional energy loss. The results are shown at cumulative orders of τ, see text for discussion.

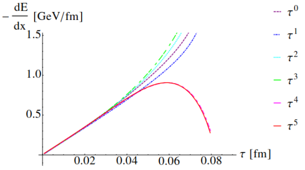


FIG. 3. Time evolution of dE/dx for $v = 1$ and $v_{\|} = v_\perp = 1/\sqrt{2}$.

- 2202.00357 [nucl-th]: Instead of glasma simulation, this is semi-analytical calculation using Focker-Planck equation, expansion in proper time.
- 2105.05327 [hep-ph]: Can also compute $T^{\mu\nu}$ in this approach, and quantities derived from there (pressure anisotropies etc.)

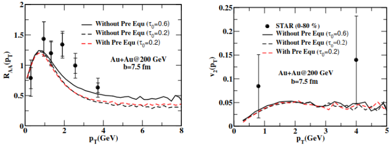


Figure 1. R_{AA} (left panel) and v_2 (right panel) as a function p_T with and without the pre-equilibration phase at RHIC energy in minimum bias.

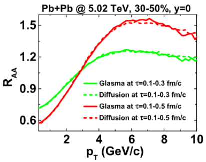


FIG. 1: (Color online) R_{AA} of charm quarks affected by the glasma or diffusion dynamics for different evolving times for Pb+Pb 30%-50% centrality collisions at 5.02 TeV.

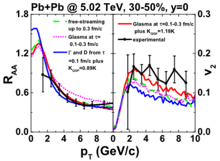


FIG. 3: (Color online) R_{AA} (left) and v_2 (right) of D mesons for the cases: (a) free streaming up to 0.3 fm/c followed by drag and diffusion in a hydro bulk (green dashed line); (b) glasma dynamics up to 0.3 fm/c and then evolution as in (a) shown by magenta dotted line; (c) drag and diffusion dynamics starting at $\tau_0 = 0.1$ fm/c shown by blue solid line with K factor decreasing by 11% relative to (a); (d) glasma dynamics up to 0.3 fm/c and then evolution with K factor increasing by 18% relative to (a) shown by red solid line. Experimental data are taken from Refs. [55, 56].

- Left: (1701.05123) R_{AA} and v_2 for heavy quarks. Here pre-equilibrium is simulated using Boltzmann equation.
- Middle: (1902.06254) charm quark R_{AA}, glasma simulation.
- Center: (1902.06254) v_2 and R_{AA} of D-mesons.

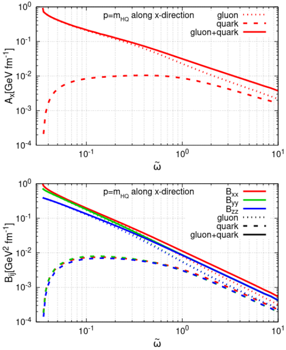


FIG. 2: Drag and diffusion coefficients $A_x(\tilde{\omega})$, $B_{xx}(\tilde{\omega})$ (red), $B_{yy}(\tilde{\omega})$ (green), $B_{zz}(\tilde{\omega})$ (blue) for gluon and quark (with factor $2N_f$), as a function of universal time $\tilde{\omega}$, with heavy quark momentum p=1.5 GeV and mass $m_{\mathrm{HQ}} = 1.5$ GeV. Gluon and quarks are plotted as dotted and dashed curves respectively.

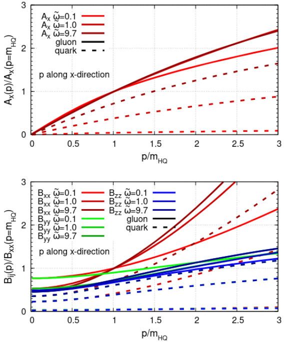


FIG. 3: Drag and diffusion coefficients $A_x(\vec{p})$, $B_{xx}(\vec{p})$ (red), $B_{yy}(\vec{p})$ (green), $B_{zz}(\vec{p})$ (blue) for gluon and quark (with factor $2N_f$), as a function of rescaled momentum p/m_{HQ}. Coefficients are normalized by either $A_x(p = m_{\mathrm{HQ}})$ or $B_{xx}(p = m_{\mathrm{HQ}})$. The early time coefficients are in lighter colors and the late time coefficients are in darker colors.

- Draq and diffusion coefficients for heavy quarks during the equilibration using EKT.
- The paper also has an approximate formula for energy loss.

Ideas for discussion

- Is there an observable in the existing literature that Pythia people are interested in or could compare with? What has been done with various levels of cheating: $\hat{q}, \kappa, \frac{\mathrm{d}E}{\mathrm{d}x}, \langle p^2 \rangle$
- Is there an observable that Pythia people would like to have, but has not been predicted? On the weak coupling side, is such an observable calculable?
- Is there an observable that can be easily studied with Pythia, and be compared to weak coupling calculations?
- Also: converting results for transport coefficients at the initial stages into actual physics predictions? How should the weak coupling community try to bridge the gap?
- The most studied observables from the weak coupling side seem to be heavy quark observables. Is there something related that can be done in Pythia?

Questions from discussions with Christian

- Joint CGC + Pythia description: hard particles should act as color sources for the classical fields? Yes?
- Choice of the unphysical cutoff scale between Pythia and classical fields? How large would the effect be?
- There's a partial overlap with Weizs acker-Williams fields and ISR/FSR/MPI. Is there a way to eliminate double counting?
- Classical fields have gauge degree of freedom. There is no unambiguous definition for particle spectrum in classical fields. How to treat this properly (this problem concerns many other applications too).
- How to combine the notion of time in classical fields into the Pythia simulation? Pythia generates events starting from $\tau = 0$.
- At the end of classical evolution one would pass classical fields to Pythia. How should we introduce color connections? Minimize free energy?

Papers

Müller, Avramescu, Ruggieri et. al:

- Simulating jets and heavy quarks in the Glasma using the colored particle-in-cell method, 2303.05599 [hep-ph]

D. Müller & A. Ipp:

- Jet momentum broadening in the pre-equilibrium Glasma, 2009.14206 [hep-ph]
- Anisotropic momentum broadening in the 2+1D Glasma: analytic weak field approximation and lattice simulations, 2001.10001 [hep-ph]

Boguslavski, Kurkela, Lappi, Lindenbauer, Peuron:

- Heavy quark diffusion in an overoccupied gluon plasma, 2005.02418 [hep-ph]
- Jet momentum broadening during initial stages in heavy-ion collisions, 2303.12595 [hep-ph]
- Heavy quark diffusion coefficient in heavy-ion collisions via kinetic theory, 2303.12520 [hep-ph]

Papers cont.

Carrington,Czajka,Mrówczyński

- Transport of hard probes through glasma, arXiv:2202.00357 [nucl-th]
- Jet quenching in glasma, 2112.06812 [hep-ph]
- Physical characteristics of glasma from the earliest stage of relativistic heavy ion collisions, 2105.05327 [hep-ph]

Xiaojian Du.

- Heavy quark drag and diffusion coefficients in the pre-hydrodynamic QCD plasma, 2306.02530 [hep-ph]

Papers cont.

Ruggieri & Das et. al

- Impact of Glasma on heavy quark observables in nucleus-nucleus collisions at LHC, arXiv:1902.06254 [nucl-th]
- Ballistic diffusion of heavy quarks in the early stage of relativistic heavy ion collisions at RHIC and LHC, arXiv:2011.05818v2 [hep-ph]
- Heavy quarks in the early stage of high energy nuclear collisions at RHIC and LHC: Brownian motion versus diffusion in the evolving Glasma, arXiv:2110.14610 [hep-ph]
- Memory effects on energy loss and diffusion of heavy quarks in the quark-gluon plasma, arXiv:2203.06712 [hep-ph]
- Effect of pre-equilibrium phase on RAA and v2 of heavy quarks in heavy ion collisions, arXiv:1701.05123 [nucl-th]