The initial state, its non-equilibrium evolution and Hard Probes

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HEAVY ION EVENT, ATLAS DETECTOR
**Ab initio** approaches to early time dynamics

Two ``clean'' theoretical limits:

- Holographic thermalization (based on duality of strongly coupled
  \[(g^2 N_c \rightarrow \infty; N_c \rightarrow \infty)\] N=4 SUSY YM to classical gravity in \(\text{AdS}_5 \times S_5\)

- Highly occupied QCD at weak coupling
  \[(g^2 \rightarrow 0; g^2 f \sim 1)\]

Our focus: strongly correlated gluodynamics of the
Initial state and early time dynamics in weak coupling
The initial state: a strongly correlated lumpy, gluon shock wave at high energies

Color charge fluctuations on a screening length scale $1/Q_S$ - smaller than proton size

Dumitru, Jalilian-Marian, Lappi, Schenke, Venugopalan
PLB706 (2011) 219
Quantum evolution of CGC wavefunction

Fast hadron

Dipole

\[ \frac{\partial}{\partial Y} < O[\alpha] >_Y = \frac{1}{2} \int_{x,y} \frac{\delta}{\delta \alpha^a_Y(x)} \chi_{x,y}^{ab} \frac{\delta}{\delta \alpha^b_Y(y)} O[\alpha] >_Y \]

“time”

“diffusion coefficient”

Balitsky-JIMWLK “Fokker-Planck” hierarchy describes QCD evolution of n-point parton correlation functions

Balitsky (1996)
Quantum evolution of CGC: state of the art

- State of the theory art: resummations of gluon ladders to next-to-leading logarithmic accuracy: “NLO JIMWLK”
  
  Balitsky, Chirilli, arXiv:1309.7644
  Kovner, Lublinsky, Mulian, 1310.0378

  See plenary talk by Guillaume Beuf for detailed discussion of theory status

- Practical applications in DIS and hadron-hadron collisions use
  
  i) The running coupling Balitsky-Kovchegov (BK) eqn.
  -- describes 2-point correlators in the JIMWLK hierarchy
  
  ii) The IP-Sat dipole model – evolution of $Q_S$ from fits to HERA data

  See parallel session talk by Tuomas Lappi on numerical solutions of the NLO BK equation
Quantum evolution of CGC: state of the art

A recent development:
color fluctuations of proton shape /Q_s in IP-Glasma model/JIMWLK

Explains DIS HERA data on incoherent diffractive J/ψ production

IP-Glasma: IP-sat color dist.+YM fields

Schenke,Tribedy,RV, arXiv:1202.6646
Colliding gluon shock waves

CGC power counting:

Dilute-Dilute: \( \frac{Q_{S,A}^2}{k_{T,A}^2} \ll 1 \) and \( \frac{Q_{S,B}^2}{k_{T,B}^2} \ll 1 \)
--match to pQCD computation of hard processes at small x

Dilute-Dense: \( \frac{Q_{S,A}^2}{k_{T,A}^2} \ll 1 \) and \( \frac{Q_{S,B}^2}{k_{T,B}^2} \sim 1 \)
-- “hybrid” pQCD/CGC description

Dense-Dense: \( \frac{Q_{S,A}^2}{k_{T,A}^2} \sim 1 \) and \( \frac{Q_{S,B}^2}{k_{T,B}^2} \sim 1 \)
-- solve classical Yang-Mills eqns. (CYM) in 2+1-D/3+1-D

CGC paradigm: all these regimes are found in p+p/p+A/A+A depending on √s, centrality, rapidity, k_T

Review: Gelis,Lappi,RV arXiv:0708.0047
Single inclusive hadron production

Single inclusive hadron computations in the “hybrid” dilute-dense framework are now available to NLO accuracy

Kinematical constraints become increasingly important when matching to the high $p_T$ collinear regime -- differing factorization schemes in rapidity

Chirilli, Xiao, Yuan, arXiv:1112.1061
Altinoluk, Armesto, Beuf, Kovner, Lublinsky, arXiv:1411.2869
Iancu, Mueller, Triantafyllopoulos, arXiv:1608.05293

Watanabe, Xiao, Yuan, Zaslavsky, arXiv:1505.05183
Review: Stasto, Zaslavsky, 1608.02285

Parallel talk by Yan Zhu
Onia in p+p and p+A collisions

CGC/pQCD +NRQCD formalism

Ma, RV, PRL113 (2014) 192301

Similar framework for direct photon production in p+A – less sensitive to hadronization

Benic,Fukushima,Garcia-Montero,RV, in preparation

See parallel talk by Benic
Onia in p+p and p+A collisions

CGC/pQCD +NRQCD formalism

Ma, RV, PRL113 (2014) 192301

Ma, RV, Zhang, 1503.07772

\[ \frac{d\sigma_H}{d^2P_{\perp}dy} = F_H \int \left( \frac{2m_D - \Lambda}{2m_c} \right)^2 \frac{d\sigma_{cc}}{d^2M^2 d^2P_{\perp}dY} \]

\( \Lambda \sim 30 \text{ MeV} \)

Parallel talk: Ducloue on CGC+CEM model
Glasma: the non-equilibrium QGP

How does one explain the “unreasonable effectiveness” of hydrodynamics in describing the dynamics of such small systems?

What are the smallest systems to which hydrodynamics is applicable?

Can explore systematically in the CGC “dense-dense” framework
Advances in Nonequilibrium Statistical Mechanics: large deviations and long-range correlations, extreme value statistics, anomalous transport and long-range interactions

May 5, 2014 - July 4, 2014

The main topics of the workshop include:

- Large deviations
- Fluctuation and work relations
- Statistics of extreme events
- Anomalous transport
- Long-range correlations and interactions

The aim of the workshop is to bring together leading researchers, young scientists and PhD students working in different areas of nonequilibrium statistical mechanics. This workshop aims at strengthening the interaction among different communities in this field and at exploring open problems and new directions of research. Let us mention: the characterization of many-body probability distributions relying on what has been done for simple exclusion or zero range processes; the study of long-range correlations that determine a variety of collective phenomena; the derivation of universal current distributions in driven diffusive systems and novel universal distributions for extreme values of correlated random variables; the relevance of ensemble inequivalence observed in systems with long-range interactions for driven nonequilibrium systems; the study of anomalous transport processes in kinetic and dynamical models in one and two spatial dimensions.
Long range rapidity correlations

LR correlations sensitive to early time dynamics

Dumitru, Gelis, McLerran, RV, arXiv:0804.3858
Dusling, Gelis, Lappi, RV, arXiv:0911.2720

JIMWLK + 2+1-D Classical Yang-Mills evolution

Schenke, Schlichting, arXiv:1605.07158

Decorrelation of initial spatial eccentricities in relative rapidity
Quantum fluctuations + 3+1-D Yang-Mills

Classical-statistical framework: 3+1-D CYM evolution of stochastic (quantum) initial conditions

Real time numerical lattice simulations of an expanding gauge theory generate overpopulated gluons in a very short time after collision
Simulations identify kinetic approach

\[ f(p_z, p_T, \tau) = (Q_S \tau)^\alpha f_S((Q_S \tau)^\beta p_T, (Q_S \tau)^\gamma p_z) \]

The kinetic theory that interpolates between the classical overoccupied regime and hydrodynamics is the "bottom up" thermalization scenario of Baier et al (BMSS)

- Increasing anisotropy
- Decreasing occupancy with expansion


Baier, Mueller, Schiff, Son, hep-ph/0009237
From nuts to soup: thermalization *ab initio*

Bottom-up thermalization

1 < $Q_S \tau < \ln(1/\alpha_S)$: Early time instabilities decohere classical YM fields

1 << $Q_S \tau < \alpha_S^{-3/2}$: Hard gluons scatter elastically and inelastically

$\alpha_S^{-3/2} < Q_S \tau < \alpha_S^{-5/2}$: Gluon radiation significant – “soft” sector thermalizes

$\alpha_S^{-5/2} < Q_S \tau < \alpha_S^{-13/5}$: Hard gluons at scale $Q_S$ are *quenched* – lose energy to bath

For further discussions of stage 1 in CYM, see talks by Fries and McDonald
From nuts to soup: thermalization \textit{ab initio}

colliding nuclei

Q_s \tau \sim 1

\sim 0.1 \text{ fm/c}

Q_s \tau_{\text{Inst}} \sim \log^2(\alpha_s^{-1})

\sim 0.4 \text{ fm/c}

Q_s \tau_{\text{Eq}} \sim \alpha_s^{-13/5}

\sim 1 \text{ fm/c}

\text{classical-statistical lattice gauge theory}

\text{eff. kinetic theory}

\text{hydro}
Consequences for photon production?

In hydro, can push thermal radiation to early times - delicate balance of yield and $v_2$

Paquet et al, arXiv:1509.06738

In bottom-up, thermalization occurs > 1 fm:

i) photons produced in quenching of “hard” quarks to heat bath more sensitive to $v_2$

ii) pre-equilibrium photons generate more yield but less $v_2$

Berges, Reygers, Tanji, RV, in preparation

Parallel talk by Marco Ruggeri

For smaller systems, in bottom up scenario, pre-equilibrium photons may be more significant

Parallel talk by Chun Shen
Collectivity in small systems: the role of mini-jets?

In initial state frameworks, copious production of mini-jets -- their theoretical treatment and “subtraction” is not fully understood.
Collectivity in small systems: the role of mini-jets?

Coherent 2+1-D Classical YM gives trend in $v_2, v_3$ -- but source of collectivity depends on size and distribution of color domains

Schenke, Schlichting, RV, 1502.01331

Kovner, Lublinsky, arXiv:1109.0347,
Dumitru, McLerran, Skokov, arXiv: 1410.4844
Lappi, Schenke, Schlichting, RV, arXiv:1509.03499
Collectivity in small systems: CGC+PYTHIA

CGC+PYTHIA connects strings to gluons produced from CYM evolution
-- reproduces systematics of multiplicity dist., \langle p_T \rangle \text{ and } v_2 \text{ mass ordering}
-- useful tool in determining if collectivity is Glasma or hydro with increasing $N_{ch}$

Schenke, Schlichting, Tribedy, RV, arXiv:1607.02496
Summary

Lots of progress in initial state and pre-equilibrium dynamics since McGill – emerging consensus in weak coupling approaches

The consequences of detailed thermalization scenarios for hard probes need to be fleshed out more

Hard & EM probes in small systems are particularly sensitive to the interplay of initial/final state dynamics

Several interesting talks on related topics I was unable to cover and hope to attend...look forward to the rest of the conference!
Back up