Aspects of the phenomenology of nucleus–nucleus collisions

Nicolas BORGHINI

CERN

Phenomenology of nucleus-nucleus collisions

- Heavy-ion collisions: general issues
- A global observable: anisotropic collective flow
 - underlying physics: thermalization of the medium?
 - a not-so-trivial problem: measuring anisotropic flow
- A hard probe: jets propagating through the medium
 - modification of the jet shape

Why heavy ion collisions?

Prediction of (lattice) QCD/ effective models:

Temperature



Experimental efforts



Heavy-ion collisions

In order to characterize the medium created in heavy-ion collisions, plenty of observables have been proposed.

Global" observables quantify bulk features in the collisions

Particle multiplicity, abundance ratios, momentum distributions, flow phenomena...

Is naturally call for *macroscopic* concepts: statistical physics, hydrodynamics, ...

"Hard" probes address the medium-induced modification of processes known in elementary-particle collisions

 J/ψ suppression, jets...

IF rely on more *microscopic* approaches

Heavy-ion collisions: bulk vs. hard probes



Particles with high momenta are rare, but their production mechanism is *a priori* better understood (perturbative QCD): can probe the bulk

Heavy ion collision: hydrodynamic description

0. Creation of a dense "gas" of particles

(1) At some time τ_0 , the mean free path λ is much smaller than *all* dimensions in the system

 \Rightarrow thermalization (T_0), ideal fluid dynamics applies

2) The fluid expands: density decreases, λ increases (system size also)

(3) At some time, the mean free path is of the same order as the system size: ideal fluid dynamics is no longer valid

"(kinetic) freeze-out"

Freeze-out usually parameterized in terms of a temperature $T_{\rm f.o.}$

If the mean free path varies smoothly with temperature, consistency requires $T_{\rm f.o.} \ll T_0$

Heavy ion collision: hydrodynamic description

At freeze-out, particles are emitted according to thermal distributions (Bose–Einstein, Fermi–Dirac) boosted with the <u>fluid velocity</u>:

$$E\frac{\mathrm{d}N}{\mathrm{d}^{3}\mathbf{p}} = C\int_{\Sigma} \exp\left(-\frac{p^{\mu}u_{\mu}(x)}{T_{\mathrm{f.o.}}}\right) p^{\mu} \mathrm{d}\sigma_{\mu}$$
particle momentum freeze-out hypersurface
Consistent ideal fluid dynamics picture requires $T_{\mathrm{f.o.}} \ll T_{0}$

 \Leftrightarrow **Ideal-fluid** limit = small- $T_{f.o.}$ limit

in a model-independent way using saddle-point approximations (or the steepest-descent method)

N.B. & J.-Y. Ollitrault, nucl-th/0506045

Similarly, one can obtain analytical results for anisotropic flow...

Heavy-ion observable: Anisotropic flow



Anisotropic flow: predictions of hydro

- Characteristic build-up time of v_2 is \overline{R}/c_s typical system size speed of sound
- v_2/ϵ constant across different centralities system eccentricity
- v₂ roughly independent of the system size (Au–Au vs. Cu–Cu)
- v_2 increases with increasing speed of sound c_s
- Mass-ordering of the v₂(p_T) of different particles
 (the heavier the particle, the smaller its v₂ at a given momentum)
- Relationship between different harmonics: $\frac{v_4}{(v_2)^2} = \frac{1}{2}$

... can be tested experimentally!

Anisotropic flow: out-of-equilibrium scenario

The flow grows with the number of collisions per particle $\frac{1}{Kn} = \frac{R}{\lambda}$: fully thermalized (hydro) incomplete thermalization Kn^{-1} \mathbf{D} varies with the number of collisions undergone by particles If v_2 depends on the system size R: breakdown of the scale-invariance of hydrodynamics • $\frac{v_4}{(v_2)^2} > \frac{1}{2}$

R.S. Bhalerao, J.-P. Blaizot, N.B., J.-Y. Ollitrault, PLB 627 (2005) 49

Incomplete equilibration & RHIC data

Experimental results seem to favor the out-of-equilibrium scenario:



NA49 Collaboration, Phys. Rev. C 68 (2003) 034903

Scaling law seems to work for RHIC data (+ matching with SPS) $v_2(Kn^{-1})$ increases steadily (no hint at hydro saturation in the data)

Measuring collective flow

Complicated issue $v_n = \langle \cos n(\phi - \Phi_R) \rangle$...but the impact parameter (and its direction Φ_R) is not measured

- We showed that "standard" methods used to determine flow are unreliable
- We developed new methods, which allow the measurement of unambiguous v_n values

Original application of several tools of statistical physics: generating functions, cumulants, Lee–Yang zeroes

These new methods have been adopted by experimentalists! STAR, PHENIX, PHOBOS, NA49, NA45, WA98, E895, FOPI...

Quantitative flow physics is now within reach

N.B., P.M. Dinh, J.-Y. Ollitrault, R.S. Bhalerao, 2000–2004

Measuring collective flow



 \leftarrow with a new method

 v_2 differs by about 20% according to the method...

the new values are now compatible with well-established physical constraints (symmetry)

+ 1st measurement of v_1 at RHIC

+ 1st determination of the sign of v_2 (positive) at RHIC

Jet physics in elementary collisions

In proton–(anti)proton or e^+e^- interactions, one observes jets of collimated particles.

These jets are perfectly described by QCD:

A jet = the shower resulting from the successive emission of partons (mainly gluons) by a fast parton (quark or gluon) as it propagates in the vacuum.

MLLA: main ingredients

- Modified Leading Logarithmic Approximation
- Resummation of double- and single-logarithms in $\ln \frac{1}{x}$ and $\ln \frac{E_{jet}}{\Lambda_{off}}$
- Intra-jet colour coherence:
 - independent successive branchings $g \rightarrow gg, g \rightarrow q\bar{q}, q \rightarrow qg$
 - with angular ordering of the sequential parton decays:
 at each step in the evolution, the angle between father and offspring partons decreases

• Includes in a systematic way <u>next-to-leading-order corrections</u> $\mathcal{O}(\sqrt{\alpha_s(\tau)})$!

Hadronization through "Local Parton-Hadron Duality" (LPHD)

MLLA: generating functional

Central object : generating functional $Z_i[Q, \Theta; u(k)]$

If generates the various cross sections ($\rightarrow ggg, \rightarrow ggq\bar{q}...$) for a jet coming from a parton $i (= q, q, \bar{q})$ with energy Q in a cone of angle Θ

$$Z_{i}[Q,\Theta;u(k)] = e^{-w_{i}(Q,\Theta)} u(Q) + \sum_{j} \int_{-\infty}^{\Theta} \frac{\mathrm{d}\Theta'}{\Theta'} \int_{0}^{1} \mathrm{d}z \ e^{w_{i}(Q,\Theta') - w_{i}(Q,\Theta)} \frac{\alpha_{s}(k_{\perp})}{2\pi} \times P_{ii}(z) \ Z_{i}[zQ,\Theta':u] \ Z_{k}[(1-z)Q,\Theta':u]$$

 $\wedge I j_{l}(2) \Delta j[2Q, O, u] \Delta k[(I - 2)Q, O, u]$



MLLA: generating functional

Central object : generating functional $Z_i[Q, \Theta; u(k)]$

for a parton i (= g, q, \bar{q}) with energy Q in a cone of angle Θ



MLLA: limiting spectrum

The parton distribution in a jet with "energy" $\tau \equiv \ln \frac{Q}{\Lambda_{\text{eff}}}$ is given by $\bar{D}_i(x,\tau) \equiv Q \frac{\delta}{\delta u(xQ)} Z_i[\tau;u(k)] \Big|_{u \equiv 1}$ infrared cutoff "Limiting spectrum": $\bar{D}^{\lim}(x,\tau,\Lambda_{\text{eff}}) = \frac{4N_c\tau}{bB(B+1)} \int_{\epsilon-i\infty}^{\epsilon+i\infty} \frac{\mathrm{d}\nu}{2\pi \mathrm{i}} \, x^{-\nu} \Phi(-A+B+1,B+2;-\nu\tau)$ with

$$A \equiv \frac{4N_c}{b\nu}, \qquad B \equiv \frac{a}{b}, \qquad a \equiv \frac{11}{3}N_c + \frac{2N_f}{3N_c^2}, \qquad b \equiv \frac{11}{3}N_c - \frac{2}{3}N_f$$

Jets in elementary collisions: MLLA vs. data



Jets in elementary collisions: MLLA vs. data



Influence of the medium: the emerging view



Influence of the medium: a possibility

- The hump of the limiting spectrum is mostly due to the singular parts of the splitting functions
- In medium, the emission of soft gluons by a fast parton increases

If One can model medium-induced effects by modifying the parton splitting functions $P_{ji}(z)$...

... and especially their singular parts:

$$P_{qq}(z) = \frac{4}{3} \left[\frac{2(1+f_{\text{med}})}{1-z} - (1+z) \right]$$

 $f_{\rm med} > 0 \Rightarrow$ Bremsstrahlung increases

N.B. & U.A. Wiedemann, hep-ph/0506218

Influence of the medium on the parton spectrum



Medium-induced modification of the associated multiplicity

Ideal case: photon + jet

IF photon gives jet energy E_T

• Count how many jet particles have a momentum larger than some given cut P_T^{cut} after propagating through the medium:

 $\mathcal{N}(P_T \ge P_T^{\mathrm{cut}})_{\mathrm{medium}}$

Solution For a jet *in vacuum* with energy E_T , the spectrum is known ⇒ one knows (measurement / *in vacuum* MLLA)

 $\mathcal{N}(P_T \ge P_T^{\mathrm{cut}})_{\mathrm{vacuum}}$

• Compare $\mathcal{N}(P_T \ge P_T^{\text{cut}})_{\text{medium}}$ with $\mathcal{N}(P_T \ge P_T^{\text{cut}})_{\text{vacuum}}$

Medium-induced modification of the associated multiplicity



In the presence of a medium, less particles for $P_T \gtrsim 1.5 \text{ GeV}$ (particle excess for $P_T \lesssim 1.5 \text{ GeV}$!)

Medium-induced modification of the associated multiplicity



In the presence of a medium, less particles for $P_T \gtrsim 1.5 \text{ GeV}$ (particle excess for $P_T \lesssim 1.5 \text{ GeV}$!)

Hadron spectra

What if the jet energy is unknown...

The measured hadron spectrum is the convolution of

- a parton spectrum $\propto 1/(p_T)^n$
- the "fragmentation function" $\overline{D}^h(x,\tau)$

$$\frac{\mathrm{d}N}{\mathrm{d}P_T} \propto \int \frac{\mathrm{d}x}{x^2} \frac{1}{p_T^n} \bar{D}^h(x, p_T) = \int \frac{\mathrm{d}x}{x^2} \frac{x^n}{P_T^n} \bar{D}^h\left(x, \frac{P_T}{x}\right)$$

which can be computed within MLLA for both a jet in vacuum and a jet propagating through a medium

 \Rightarrow gives the nuclear modification factor R_{AA}

Nuclear modification factor



Phenomenology of nucleus–nucleus collisions

Complementary observables yield alternative views of the physics involved in heavy ion collisions at ultrarelativistic energies

Collective flow: a mature observable, which provides information on the bulk: equilibration (kinetic and/or chemical)?

If macroscopic approaches (fluid dynamics, statistical physics) ...but not only: flow of rare or of high- p_T particles

jets: rare phenomena, but which involve processes that can be computed from first principles: reliable reference!

Numerous jets at LHC, over a wide kinematic range

Monte-Carlo implementation(s) of the new formalism

Phenomenology of nucleus–nucleus collisions



(to-do list?)

Jet physics in the medium

A bridge between micro- and macroscopic description: dissipative phenomena

Microscopic energy redistribution, using a realistic Monte-Carlo code of medium-induced effects, vs. viscous fluid dynamics (gluon Bremsstrahlung vs. Mach cone)

Interplay between the Yang–Mills fields invoked in mechanisms of fast-thermalization and prompt partons?

Phenomenology of nucleus-nucleus collisions

Extra slides

Methods of flow analysis

Anisotropic flow is usually measured using two-particle correlations:

 $\langle \cos 2(\phi_1 - \phi_2) \rangle \approx \langle \cos 2(\phi_1 - \Phi_R) \rangle \langle \cos 2(\Phi_R - \phi_2) \rangle = (v_2)^2$

Assumption: all two-particle correlations are due to flow...

... which is obviously wrong!

"Non-flow" sources of correlations: jets, decays of short-lived particles, global momentum conservation, quantum effects between identical particles, etc. can bias the "standard" flow analysis The bias is comparatively larger for smaller systems

New methods for measuring flow have been developed cumulants of multiparticle correlations, Lee–Yang zeroes

(N.B., P.M. Dinh, J.-Y. Ollitrault, R.S. Bhalerao, 2000–2004)

Measuring collective flow

Generating function
$$G_n(z) \equiv \left\langle \prod_{j=1}^M (1 + z \cos n\phi_j) \right\rangle$$

• If no flow: system made of independent sub-systems $G_n(z) = \prod_{\text{subsyst.}} G_{\text{sub.}}(z)$

 \Rightarrow the zeroes of G_n are unchanged when M increases

In the presence of collective flow: the position of the zeroes is $\propto 1/M$

 \Rightarrow The first ("Lee–Yang") zero of $G_n(z)$ gives v_n

Jets in Au–Au collisions at RHIC

Study of the azimuthal correlations between

(1) a "leading particle", momentum $P_{T \max}$, origin of azimuths, and (2) "associated particles: momentum $P_{T \operatorname{cut}} < P_T < P_{T \max}$, azimuth ϕ



IF No recoil jet ($\phi \sim 180^{\circ}$) in central Au–Au events