Heavy Ion Physics
Hot and dense QCD after the first LHC running period

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Garderen - the Netherlands - June 2014

@CASSalgado    @HotLHC
Some of the questions accessible with heavy-ion collisions

What is the structure of hadrons/nuclei at high energy?
   — color coherence effects in the small-x partonic wave function
   — fix the initial conditions in well-controlled theoretical framework

Is the created medium thermalized? How?
   — presence of a hydrodynamical behavior
   — what is the mechanism of thermalization in a non-abelian gauge theory?

What are the properties of the produced medium?
   — identify signals to characterize the medium with well-controlled observables
   — what are the building blocks and how they organize?
   — is it strongly-coupled? quasiparticle description? phases?
Menu

- Initial State Partonic densities & Multiparticle Production
- Hydrodynamics & Harmonics
- Jets in medium Jet quenching
INITIAL STAGES

- Structure of the collision objects
- Built of collective behavior
QCD is a Quantum Field Theory

\[ \Rightarrow \text{Quantum fluctuations } \leftrightarrow \text{virtual particles} \]

Structure of the colliding objects

\begin{itemize}
  \item quark up
  \item forza forte (gluons)
  \item quark down
\end{itemize}

proton
Splitting probability: the building block

The splitting probability of an off-shell parton computed in pQCD

\[ dP(z, \theta) \sim \alpha_s \frac{dz}{z} \frac{d\theta}{\theta} \]

Soft and collinear divergent

- Large probability to emit soft and collinear gluons
- Divergencies need to be resumed (renormalization techniques)

The picture is a shower of partons produced by subsequent splittings
Heuristic: Collision “counts” partons

(Incoherent) cross section proportional to the number of partons in hadron
  ▶ Quantum fluctuations put on-shell by the probe

Lifetime of the fluctuation of the order of the size of the probe
  ▶ The probe cannot resolve smaller fluctuations (stay virtual)
  ▶ Harder probes resolve smaller components (basic idea of pQCD factorization)
Heuristic: Collision “counts” partons II

Coherent cross section: the probe can interact with more than one parton

- TAMES the cross section

Saturation of partonic densities (gluon fusion) - aka Color Glass Condensate

- Color correlations among different partons in the proton/nucleus

A proton at high-energy

Saturation
Quantum fluctuations: Linear/non-linear dynamics

Different kinematical regions: dominated by different dynamics
- Large-$Q$: Linear
- Small-$x$: Non-linear (eventually)

Where is the boundary? (Information from experiment needed)
Collinear factorization

\[ \sigma_{AB \to h} = \int f_i^A(x_1, Q^2) \otimes f_j^B(x_2, Q^2) \otimes \tilde{\sigma}_{ij \to h} \]

- A hard cross section is the convolution of universal PDFs and partonic cross sections

**Factorization of long-distance and short distance terms in the cross section**

- Short-distance (perturbative) in the partonic cross section
- Long-distance (non-perturbative) in the PDFs and Fragmentation Functions (FF)
Global fits for nucleus

Comparison: Valence quarks

Some differences between EPS09, HKN07 & DSSZ... (data constraints for x=0.1...1)

but the preliminary nCTEQ curves show a really drastic difference

Clear disagreement at large x. An isospin effect?

(RuV & RdV almost the same for EPS09, DSSZ, HKN07)

Comparison: Sea Quarks

No qualitative disagreements in the data constrained region (x=0.01...0.1)

No qualitative disagreements to preliminary nCTEQ results either

The large-x behaviour reflects the gluons (above the parametrization scale)

Comparison: Gluons

Difference between EPS09 & DSSZ:
The antishadowing and EMC effect in EPS09 comes from the RHIC pion data

DSSZ advocated nuclear modifications in the fragmentation functions. No antishadowing nor EMC effect.

Both can fit the pion data, but the origin of the effect is different physics.

Plots from Hannu Paukkunen

Ratios of the PDF of a proton inside a nucleus over that in a free proton

Isospin effects may be important (e.g. W production in pPb@LHC)

$$R_i^A(x, Q^2) = \frac{f_i^p/A(x, Q^2)}{f_i^p(x, Q^2)}$$
Agreement of EPS09 with neutrino DIS data

Collinear factorization works - universal set of nPDFs

Neutrino data important for proton global fits
Dijet data in proton-nucleus collisions at LHC - CMS

Preliminary CMS data “by eye"

\[ \sqrt{s} = 5.02 \text{TeV} \]

CT10
CT10×EPS09
CT10×DSSZ
CT10×HKN07

\[ \mu = \text{p}_T, \text{average}/2 \]

NLO/CT10

Relative uncertainty

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Provide new constraints to gluon distributions

[Eska, Paukkunen, Salgado, 2013]

[Plots from Paukkunen - LHeC workshop - Jan 2014]
DGLAP approach - Some recent results II

- **Dijet data in proton-nucleus collisions at LHC - CMS**

  Preliminary CMS data “by eye”

  $\sqrt{s} = 5.02\text{TeV}$

  \[ \mu = p_{T,\text{average}}/2 \]

  \[ \eta_{\text{dijet}} = (\eta_1 + \eta_2)/2 \]

  \[ \text{Relative uncertainty} \]

  [Eskola, Paukkunen, Salgado, 2013]
  [Plots from Paukkunen - LHeC workshop - Jan 2014]

  \[ \text{Data NLO} \]

  [Eskola, Paukkunen, Salgado, 2013]

  Provide new constraints to gluon distributions

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Heavy Ion Collisions
From Dilute to Dense

Parton Saturation

Color Correlation in the transverse plane

Color Glass Condensate $\rightarrow$ General framework
From Dilute to Dense

Parton Saturation

Color Correlation in the transverse plane $\rightarrow \frac{1}{Q_{sat}}$

Color Glass Condensate $\rightarrow$ General framework

$Q_{sat}^2 \sim \frac{x g(x, Q_{sat}^2)}{\pi R^2} \sim \frac{A^{\frac{5}{3}}}{x^4}$
Saturation in the dipole picture

A convenient way of discussing the problem is the dipole picture:

- A dipole measures the **color correlations** in transverse plane.

**Propagator of the quark - Wilson line**

\[ W(x) = \mathcal{P} \exp \left[ i \int dx^- A^+(x_\perp, x^-) \right] \]

So that the **S-matrix is**

\[ |\alpha'; \beta'\rangle \equiv S_{\alpha'\beta'\alpha\beta}|\alpha; \beta\rangle = W_{\alpha'\alpha}(x_\perp) W_{\beta'\beta}^\dagger(\bar{x}_\perp)|\alpha; \beta\rangle \]

and the total interaction probability (cross section w/ needed factors)

\[ P_{t o t}^{qq} = \left\langle 2 - \frac{2}{N_C} \text{Tr} \left[ W(x_\perp) W^\dagger(\bar{x}_\perp) \right] \rightangle \]
Medium averages

All the medium properties are encoded in the averages of Wilson lines

Several prescriptions used. Here, just focus on a simple one

\[
\frac{1}{N} \text{Tr} \langle W(x_\perp) W^\dagger(\bar{x}_\perp) \rangle \approx \exp \left\{ -\frac{1}{8} Q_{\text{sat}}^2 (x_\perp - \bar{x}_\perp)^2 \right\}
\]

The dipole “counts” the number of gluons, the unintegrated gluon distribution

\[ N(r) = 1 - \exp \left[ -\frac{1}{8} Q_{\text{sat}}^2 r^2 \right] \quad \implies \quad \phi(k) = \int \frac{d^2 r}{2\pi r^2} e^{i\mathbf{r} \cdot \mathbf{k}} N(r) \]

[up to logs: McLerran, Venugopalan 1994]

Two important consequences

- Q_{\text{sat}} cuts-off the low momentum
- Geometric scaling

\[ \phi = \phi \left( \frac{k^2}{Q_{\text{sat}}^2} \right) \]
A way of including QCD evolution in the dipole picture (in $x$)

- Boost the dipole: the splitting probability can be computed
- Use the large-$N_c$ limit

\[ \frac{\partial N(r,y)}{\partial y} = \int dr' K(r,r') \left[ N(r') + N(r-r') - N(r) - N(r') N(r-r') \right] \]

[Balitsky-Kovchegov eqs]
Fits using non-linear evolution eqs.

Checks of validity of the formalism with proton-nucleus data
Multiparticle production and the CGC

Gluon distributions obtained in the fits with BK reproduce multiplicities

Multiplicities are reproduced in a QCD-based approach

- QCD evolution equations with initial conditions from DIS experiments
- Uncertainties in geometry, kinematics, etc
- First results at NLO available [Chirilli, Xiao, Yuan 2012; Stasto, Xiao, Zaslavsky 2013]
Mutatis mutandis...
Mutatis mutandis...
Checks of hydrodynamics

[degree of thermalization of the medium]

\[ \partial_\mu T^{\mu\nu} = 0 \]

\[ T^{\mu\nu} = (\varepsilon + p)u^\mu u^\nu - pg^{\mu\nu} + \text{viscosity corrections} \]

+ Equation of state

Does not address the question on **how thermal equilibrium is reached**

— Far from equilibrium initial state needs to equilibrate fast (less than 1 fm)

**Most of the theoretical progress in the last years:**

— Viscosity corrections

— Fluctuations in initial conditions
The essential measurement for hydro

Recall the Euler equation

\[
\frac{d\beta}{dt} = - \frac{c^2}{\epsilon + P} \nabla P
\]
The essential measurement for hydro

Recall the Euler equation

\[ \frac{d\beta}{dt} = -\frac{c^2}{\epsilon + P} \nabla P \]

\[ \epsilon = 3P \implies \nabla_x P < \nabla_y P \]

Elliptic flow normally measured by the second term in the Fourier expansion

\[ \frac{dN}{d\phi} \propto 1 + 2v_2 \cos(2\phi) \]

Initial anisotropies in spacial distributions translate into final (measurable) anisotropies in momentum
Fluid behavior from hydro: viscosity of the QGP

[Schenke, Jeon, Gale 2010]

- Lowest viscosity known
- "perfect liquid": sQGP
- AdS/CFT bound

$$\frac{\eta}{s} \geq \frac{1}{4\pi}$$

[PHENIX]

[ALICE 2010]

⇒ LHC similar to RHIC

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Hydro: description of the data

FIG. 3. (Color online) Centrality dependence of the charged hadron multiplicity at the LHC (a) and RHIC (b). Transverse momentum spectra of charged hadrons at the LHC (c) and RHIC (d), in the same centrality classes as the ALICE data in panel (a), and scaled down by increasing powers of 10. Elliptic flow coefficients $v_2(p_T)$ at the LHC (e) and RHIC (f), compared with the measured 4-particle cumulant $v_2^4(p_T)$. Labeling of the theory curves in each panel is identical, and the parameter sets $\{K_{\text{sat}}, \beta, \frac{BJ}{FS}, \frac{\eta}{s}(T)\}$ are indicated. The labels H and L refer to Fig. 2.

[Paatelainen, Eskola, Niemi, Tuominen 2013]
Event-by-event fluctuations

The event-by-event fluctuations and transverse momentum dependences of both the anisotropic flow coefficients indicate the average of the result over many Little Bangs of the selected class. One sees that the subset of particles in the event with a given magnitude of the transverse momentum cannot be measured experimentally. The viscous hydrodynamic evolution relates the probability distribution for the initial complex eccentricity coefficient to the integrated flow ratio of which is the power spectrum shown in Fig. 3. For different transverse energy density profiles, one particular asymmetry in the initial state of this particular event (visible as a left-right asymmetry of the density profile in the left panel) is seen to generate a dipole (“directed flow”) component in the hydrodynamic flow pattern that depends on the viscosity of the Little Bang.

Due to limited statistics arising from the finite number of particles emitted by each Little Bang, the experimental reconstruction of the final multi-dimensional distributions characterizing each class of collisions depends on the viscosity of the Little Bang. One goal of the relativistic heavy-ion program is to both constrain the QGP viscosity and identify the correct theory for the initial-state quantum fluctuations by performing a complete fluid dynamics, assuming pressure components are set to zero at the matching time) and henceforth evolved with viscous Israel-Stewart tensor from the IP-Glasma evolution is Landau-matched to ideal fluid form (for technical reasons the viscous term is suppressed the dependence of both types of flow coefficients deterministically to probability...
CGC as initial conditions for hydro

- Initial conditions from MV model (IPsat)
- Hydro evolution with viscosity
- (made event-by-event)

[Figure showing the degree of correlation and fluctuations in the gluon fields]

\[ \langle v_n^2 \rangle^{1/2} \] vs centrality percentile

\[ \langle v_n^2 \rangle \] vs \( p_T [\text{GeV}] \)

Data: ALICE \( v_n(2), p_T > 0.2 \text{ GeV} \)

\( \eta/s = 0.2 \)

ATLAS 20-30\%, EP

\( \eta/s = 0.2 \)

[Gale, Jeon, Schenke, Tribedy, Venugopalan 2013]
Towards isotropization...

The CGC picture provides a framework to study the evolution to equilibrium

- State just after the collision has a very strong anisotropy (MV model)
- Solving Color Yan Mills equations to larger times with NLO corrections
- Anisotropy greatly reduced with still tiny coupling constants

\[
\alpha_s = 0.0008
\]

\[
\alpha_s = 0.02
\]

A lot of activity not quoted here - both weak and strong (AdS/CFT) coupling

[Epelbaum, Gelis 2013]
Structure needs to be formed very early by causality requirements
Observed in pp, pA (LHC) and AA (RHIC+LHC)
The Ridge & the CGC

Uncorrelated

Correlated (short range)

Correlated (long range)

\textbf{COLOR} correlations in transverse plane \( \sim Q_s^{-1} \)
The Ridge & the CGC

Uncorrelated

Correlated (short range)

Correlated (long range)

Color correlations in transverse plane $\sim Q_s^{-1}$

Is the Ridge Initial State / Final State / Both?
Summary

- Linear evolution
  - DGLAP → STANDARD
    - Make fits & check universality
    - New pPb results

- Non-linear evolution → CGC
  - General framework to include collectivity
  - Gluon saturation → color coherence → QCD
  - Towards equilibrium
  - CGC → hydro?

Some of the most fundamental questions in QCD
Jets in medium
Jet quenching

Hard scattering

Parton shower + color structure

Identify leading behavior

Non-perturbative hadronization

HADRONS
Jets in medium
Jet quenching

All the action here (for this talk)

Hard scattering

Parton shower + color structure
Identify leading behavior

Non-perturbative hadronization

HADRONS
Jets in medium
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Hard scattering

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Put now a medium here

Hard scattering

Parton shower + Color structure
Identify leading behavior

Non-perturbative hadronization

HADRONS
Jet quenching

What are the effects of a medium in the jet evolution?
Suppression in one plot

\[ R_{AA} = \frac{dN^{AA}/d\rho}{\langle N_{coll} \rangle dN^{pp}/d\rho} \]

CMS *PRELIMINARY* PbPb \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \int L \, dt = 7-150 \mu b^{-1} \)

- *Z* (0-100%) |y| < 2
- *W* (0-100%) |p_{T}| > 25 GeV/c, |η| < 2.1
- Isolated photon (0-10%) |η| < 1.44
- Charged particles (0-5%) |η| < 1
- *B → J/ψ* (0-100%) |η| < 2.4
- *Inclusive jet* (0-5%) |η| < 2
- *b-jet* (0-10%) |η| < 2

\[ f_i(x_i) \]

\[ f_j(x_j) \]

\[ D_{k-g_0}(z) \]

\[ W^+ \eta^0 \]

\[ \sigma \]

\[ \langle N_{coll} \rangle \]

\[ \int \]

\[ \mu \]

\[ b \]

\[ \text{CMS} \]

\[ \text{ESHEP - Garderen - June 2014} \]

Heavy Ion Collisions
Di-jet asymmetry at the LHC

- Energy imbalance indicates strong energy loss
  \[ A_j = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}} \]

- Reconstructed jet measurements sensitive to broadening
- Jets are suppressed: Studied sample is a subset of the total

**PLB 712 (2012) 176**

**Krofcheck**

**ICHEP, Melbourne**

**Dijet Imbalance in 2.76 TeV PbPb Collisions**

**Talk Krofcheck**
Reconstructed jets at the LHC - jet shapes

What is the distribution in energy for different jet angles?

- Not strong changes with respect to pp
- Small broadening seen
- Jets with larger-R are less suppressed
Fragmentation functions

Distribution of particles inside a jet: fragmentation functions

\[ z = \frac{p_T^{\text{hadron}}}{p_T^{\text{jet}}} \]

- Fragmentation functions carry “longitudinal” information
- **Modifications:** enhancement in soft (expected) no suppression at hard (unexpected)
- **Strong constraints to underlying dynamics**

\[ \text{ATLAS, Quark Matter 2012} \]
\[ \text{CMS - similar results} \]
Di-jet asymmetry at the LHC

Azimuthal distribution of two most energetic jets

[CMS 2011; ATLAS similar results]

No strong change with respect to the vacuum jets
Di-jet asymmetry at the LHC

> Where does the energy go?

[CMS 2011]

\[
\hat{p}_T^\parallel = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos (\phi_{\text{Track}} - \phi_{\text{Leading Jet}})
\]

> Energy taken by soft particles at large angles
Summary of experimental data

Reconstructed jets

- Suppression similar to inclusive hadrons for similar $p_T$
- Fragmentation functions are mildly modified - more in soft
- Jet shapes have mild modifications
- Azimuthal decorrelation of di-jets as in proton-proton
- Energy taken by soft particles at large angles

Small modifications of the jet structure but energy loss
Medium-induced gluon radiation

\[ \omega \frac{dI}{d\omega dk} \sim \alpha_s C_R \int dy \int dy' \int d\mathbf{u} e^{i\mathbf{k} \cdot \mathbf{u}} \partial_u \cdot \partial_y \mathcal{K}(y', \mathbf{u}; y, y) \bigg|_{y=0} \tilde{\mathcal{P}}(L, y'; \mathbf{u}) \]

kharov, Baier, Dokshitzer, Mueller, Peigne, Schiff, Wiedemann, Gyulassy, Levai, Vitev, and many others...
Medium-induced gluon radiation

\[ \frac{dI}{d\omega dk} \sim \alpha_s C_R \int dy \int dy' \int du e^{i k \cdot u} \left( \partial_u \cdot \partial_y \mathcal{K}(y', u; y, y) \right) \bigg|_{y=0} \tilde{\mathcal{P}}(L, y'; u) \]

\[ \mathcal{K}(y', u; y, y) = \int_{y(y')}^{u(y')} Dr \ exp \left\{ i \frac{\omega}{2} \int d\xi \left( \frac{d\mathbf{r}(\xi)}{d\xi} \right)^2 \right\} \tilde{\mathcal{P}}(y', y, r) \]

Kharlov, Baier, Dokshitzer, Mueller, Peigne, Schiff, Wiedemann, Gyulassy, Levai, Vitev, and many others...

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Medium-induced gluon radiation

\[
\omega \frac{dI}{d\omega dk} \sim \alpha_s C_R \int dy \int dy' \int du e^{ik \cdot u} \partial_u \cdot \partial_y K(y', u; y, y) \bigg|_{y=0} \tilde{P}(L, y'; u)
\]

\[
\mathcal{K}(y', u; y, y) = \int_{y(y')}^u du' \mathcal{D}r \exp \left\{ \frac{i}{2} \int d\xi \left( \frac{dr(\xi)}{d\xi} \right)^2 \right\} \tilde{P}(y', y, r)
\]

kharov, Baier, Dokshitzer, Mueller, Peigne, Schiff, Wiedemann, Gyulassy, Levai, Vitev, and many others...
In the extreme case of only one subjet

- **The whole jet radiates (medium-induced) as a single object**
- The inner structure of the jet is (almost) unmodified
A new picture of jet quenching

The parton shower is composed of **un-modified subjets** (vacuum-like)

- **With a typical radius given by the medium scale**
- For medium-induced radiation **each subject is one single emitter**

[Casalderrey-Solana, Mehtar-Tani, Salgado, Tywoniuk 2013]
Observable consequences

A simple model implementation

- Assume complete coherence
- Include both BDMPS and anti-angular ordering (modifying MLLA)

i) intra-jet shape modified
ii) branching+broadening depletes energy inside
iii) AAO enhances soft gluons inside!

\[ dN/dl \]

\[ \omega_{BH} = 0.5 \text{ GeV} \]
\[ \omega_c = 70 \text{ GeV} \]
\[ Q_s = 2 \text{ GeV} \]

\[ Q_0 = 0.270 \text{ GeV} \]
\[ Q = 30.00 \text{ GeV} \]
Summary

Remarkable progress in the last years

- Saturation at NLO and fixing IC event-by-event for hydro
- Hydrodynamic models reaching precision
- Jet quenching calculations

Finite energy corrections; resummation; next orders in alphaS
Computations of qhat in lattice, renormalization...

A complete picture of LHC data still work in progress

- Proton-nucleus collisions showing unexpected behavior

Is a QCD medium created in proton-nucleus as well?