Heavy-ions theory

Carlos A. Salgado
Universidade de Santiago de Compostela and CERN

ICHEP 2012 - Melbourne - July 2012

carlos.salgado@usc.es  http://cern.ch/csalgado
QCD: An apparently simple lagrangian hides a wealth of **emerging phenomena**

Asymptotic freedom; confinement; chiral symmetry breaking; mass generation; new phases of matter; a rich hadronic spectrum; etc

High-energy nuclear collisions are the experimental tools to access (some of) these collective properties - high density states of matter

\[ T_c = 154 \pm 9 \text{MeV} \]

HotQCD Coll. 2012, in agreement with previous results from Wuppertal-Budapest
Kinematical reach in nuclear collisions

![Graph showing kinematical reach in nuclear collisions](image)

- Present nuclear DIS and Drell-Yan in p+A
- $Q^2$ $(GeV^2)$
- $Q^2_{sat,Pb}(x)$
- $x_A$

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Kinematical reach in nuclear collisions

- Present nuclear DIS and Drell-Yan in p+A
- d+Au @ RHIC
- 0 < y < 3.2

\[ Q^2_{\text{sat,Pb}}(x) \]

\[ Q^2 \text{ (GeV}^2) \]

\[ x_A \]

\[ 10^{-7}, 10^{-6}, 10^{-5}, 10^{-4}, 10^{-3}, 10^{-2}, 10^{-1}, 1 \]
Kinematical reach in nuclear collisions

\[ Q^2 (\text{GeV}^2) \]

- \( p+Pb @ LHC \) (7 TeV+2.75 TeV)
- Present nuclear DIS and Drell-Yan in p+A
- \( d+Au @ RHIC \)
- \( 0 < y < 3.2 \)

\[ Q_{\text{sat},Pb}^2(x) \]

\[ y_{\text{lab}} = 6.6 \]
\[ y_{\text{lab}} = 6 \]
\[ y_{\text{lab}} = 4 \]
\[ y_{\text{lab}} = 2 \]
\[ y_{\text{lab}} = 0 \]
Kinematical reach in nuclear collisions

New regions never explored in nuclear collisions: small-x and large-Q

Present DIS+DY

\(Q^2_{\text{sat,Pb}}(x)\)

\(y_{\text{lab}} = 6.6\)

\(y_{\text{lab}} = 6\)

\(y_{\text{lab}} = 4\)

\(y_{\text{lab}} = 2\)

\(y_{\text{lab}} = 1\)

\(0 < y < 3.2\)

\(x_A\)
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?
Present knowledge

— Screening in the partonic wave functions $\rightarrow$ color coherence effects
— Very low viscosities in hydrodynamics $\rightarrow$ ideal fluid behavior
— Strong suppression of high-$p_T$ jet quenching $\rightarrow$ dense deconfined matter
Present knowledge

- Screening in the partonic wave functions → color coherence effects
- Very low viscosities in hydrodynamics → ideal fluid behavior
- Strong suppression of high-$p_T$ jet quenching → dense deconfined matter

LHC first run: 2010
**Initial state: Saturation of partonic densities**

**Color coherence in the initial wave function**

- A new scale expected to determine partonic properties at high energies
- Strong fields and large occupation numbers.
- Semiclassical approach: Color Glass Condensate

\[ Q_{\text{sat}}^2 \sim \frac{A^{1/3}}{x^\lambda} \]

[Also, talk by L. Lonnblad]
Initial state: Saturation of partonic densities

Color coherence in the initial wave function

Notice that the underlying event is what we want to study...

- A new scale expected to determine partonic properties at high energies
  - Strong fields and large occupation numbers.
  - Semiclassical approach: Color Glass Condensate

\[ Q_{\text{sat}}^2 \sim \frac{A^{1/3}}{x^\lambda} \]

[Also, talk by L. Lonnblad]
Non-linear evolution equations

Screening leads to non-linear terms. E.g. Balitsky-Kovchegov eqs.

\[ \frac{\partial \phi(x, k_t)}{\partial \log(x/x_0)} \approx \mathcal{K} \otimes \phi(x, k_t) - \phi(x, k_t)^2 \]

Splitting [BFKL]  Merging [restores unitarity]

(unintegrated) gluon distributions fitted to HERA data reproduce pp

[Albacete, Dumitru 2011]
Extrapolation to nuclei

Small sensitivity to hard part of the gluon distributions in multiplicities

... which is larger in quantities affected by final state effects (hydro)

Proton-nucleus collisions to reduce these uncertainties and further constrain parton distributions
Extrapolation to nuclei

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pPb collisions at the end of the present running period - December 2012
Extrapolation to nuclei

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Proton-nucleus collisions to reduce these uncertainties and further constrain parton distributions

pPb collisions at the end of the present running period - December 2012

February 2013
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

Lowest viscosity known

“perfect liquid”: sQGP

AdS/CFT bound

\[ \frac{\eta}{s} \geq \frac{1}{4\pi} \]

Charm also flows

LHC similar to RHIC

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Heavy Ions theory

[Schenke, Jeon, Gale 2010]

[ALICE: talk C. Perez Lara]
Higher harmonics $v_n$ [talks M. Nyatha (ALICE), E. Duchovni (ATLAS) and S. Padula (CMS)]

Fluctuations in initial conditions show-up in higher harmonics

Precise tests of hydro: constraints to viscosity
Higher harmonics $v_n$

Fluctuations in initial conditions show-up in higher harmonics

Fluctuations in initial conditions show-up in higher harmonics

$\tau = 0.4 \text{ fm/c}$

$\tau = 6.0 \text{ fm/c, ideal}$

$\tau = 6.0 \text{ fm/c, } \eta/s = 0.16$

Precise tests of hydro: constraints to viscosity

Consistency checks with 2-particle correlations

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Higher harmonics $v_n$ (RHIC)

**Fig. 1.** (Color online) Results for $v_n$ for $n = 2 – 5$, compared to published data from the PHENIX collaboration [9].

Closed and open symbols correspond to two different ways of averaging over events (mean and rms value, respectively). Error bars represent statistical uncertainty from the finite number of events. The left column (0–10%) represents the 10% most central collisions, which each column to the right increasingly peripheral.

...the brackets indicate an average over events.

The value of $\alpha$ depends on the event plane resolution $\text{Res}_{\{\Psi_n\}} \sim \sqrt{N}$ [26]: If the resolution is poor, $\alpha \approx 2$, and the measured $v_n$ is a rms value, while if the resolution is large, $\alpha \approx 1$, and the result gets closer to the mean value.

The most recent data from PHENIX has a maximum event plane resolution of 0.74 (for $v_2$ around 30% centrality [14]) and much smaller for $v_3$ and $v_4$ [9], which implies $\alpha > 1$. So in general the results are very close to a rms value of $v_n$. Nevertheless, in the following we compute both limiting cases $\alpha = 2$ and $\alpha = 1$ in order to show the size of the effect of fluctuations on event-plane analyses.

Similarly, the measured value $v_4\{\Psi_2\}$ depends on the resolution [27], and is usually close to $\langle v_4/v_2^2 \rangle = \langle v_4 \cos(4\Psi_4 - 4\Psi_2) \rangle / \langle v_2^2 \rangle$, but with increasing resolution approaches $\langle v_4 \cos(4\Psi_4 - 4\Psi_2) \rangle$.

**III. RESULTS**

Using the hydrodynamic code NeXSPheRIO [28], we simulate top-energy Au-Au collisions at RHIC. This code solves the equations of ideal relativistic hydrodynamics using fluctuating initial conditions from the event generator NeXus [29]. At the end of the hydrodynamic evolution, discrete particles are emitted using a Monte-Carlo generator. NeXSPheRIO provides a good description of rapidity and transverse momentum spectra [30], elliptic flow $v_2$ [31], and the rapidity-even $v_1$ observable, directed flow at midrapidity [32]. In addition, it is known to reproduce the long-range structures observed in two-particle correlations [33]. All parameters were fixed from these earlier investigations, before any of the new observables ($v_3, v_4$) were measured — nothing has been tuned here.

For this work, we generated 110 NeXus events each in 5% centrality classes up to 60% centrality, solving the hydrodynamic equations independently for each event. As in Ref. [34], at the end of each hydro event, we run the Monte-Carlo generator many times, so that we can do the flow analysis using approximately $6 \times 10^5$ particles per event. This significantly reduces statistical noise and...
Hard Probes

Long distance terms modified by the presence of medium

- Nuclear PDFs and new (non-linear) evolution equations
- Modification of hadronization probes the medium properties
- EW processes (no hadronization) used as benchmark

\[
\sigma_{AB \rightarrow h} = f_A^i(x_1, Q^2) \otimes f_B^j(x_2, Q^2) \otimes \sigma(ij \rightarrow k) \otimes D_{k \rightarrow h}(z, Q^2)
\]

Nuclear PDFs

Hadronization

\(J/\Psi\) paradigmatic example
Hard Probes

Long distance terms modified by the presence of medium

- Nuclear PDFs and new (non-linear) evolution equations
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\[ \sigma^{AB \rightarrow h} = \left(f^i_A(x_1, Q^2) \otimes f^j_B(x_2, Q^2)\right) \otimes \sigma(ij \rightarrow k) \otimes D_{k \rightarrow h}(z, Q^2) \]

Nuclear PDFs

Hadronization

\( J/\Psi \) paradigmatic example

Background subtraction of “cold” nuclear matter effects

- proto-nucleus needed: nuclear PDFs badly constrained at small-\( x \)
**Simple intuitive picture** [Matsui & Satz 1986]

- Potential screened at high-$T$
- Bound states not possible
- Suppression of J/Psi in nuclear collisions
- Sequential suppression of excited states

**Interpretation of the data traditionally difficult**

![Graph showing the evolution of potential with temperature](image)

Lattice results for spectral functions
Larger suppression of excited states

\[
\frac{Y(2S)/Y(1S)}{Y(2S)/Y(1S)}_{\text{PbPb}} = 0.21 \pm 0.07 \pm 0.02
\]

\[
\frac{Y(3S)/Y(1S)}{Y(3S)/Y(1S)}_{\text{PbPb}} < 0.17 \quad (95\% \text{ C.L.})
\]

Sequential suppression (lattice)?
Quarkonia at the LHC

**Larger suppression of excited states**

\[
\frac{Y(2S)/Y(1S)_{PbPb}}{Y(2S)/Y(1S)_{pp}} = 0.21 \pm 0.07 \pm 0.02
\]

\[
\frac{Y(3S)/Y(1S)_{PbPb}}{Y(3S)/Y(1S)_{pp}} < 0.17 \ (95\% \ C.L.)
\]

Sequential suppression (lattice)?

**Sequential suppression (lattice)?**

**J/Psi less suppressed at the LHC than at RHIC?**

Recombination?

**A clearer picture is emerging, pPb data essential**

[talk J-P Lansberg]
Jet quenching

What are the effects of a medium in the jet evolution?
Jet quenching with inclusive particles: LHC

- Suppression at the LHC is slightly stronger than at RHIC

Formalisms tested at RHIC provides reasonable description of the dense partonic system.

Inclusive particle suppression is sensitive to energy loss.

EW probes are not suppressed

Hadrons are suppressed

Summary of CMS results:

- Charged hadrons
- EW probes
- b-quarks

Krisztián Krajczár (MIT) - Hard Probes 2012, 27 May – 1 June, Cagliari, Sardinia

Centrality 0-20%

$D^0$, $D^+$, $D^*$

[ALICE] [Talk A. Dainese]
Jet quenching with inclusive particles: LHC

- Suppression at the LHC is slightly stronger than at RHIC

- Formalisms tested at RHIC provides reasonable description

- dense partonic system

Inclusive particle suppression sensitive to energy loss

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Di-jet asymmetry at the LHC

- Energy imbalance indicates **strong energy loss**
  \[ A_\text{jet} = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}} \]

- Reconstructed jet measurements **sensitive to broadening**

- Jets are suppressed: Studied sample is a subset of the total

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Energy taken by soft particles at large angles

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

(My) summary of the experimental situation (ALICE+ATLAS+CMS)

- Characterized jets are sub-samples of the total (jets are suppressed: inclusive jet RAA)
- Energy loss of the jets taken by soft particles at large angles (dijet analyses)
- No modification of dijet azimuthal correlations or fragmentation function (dijet analyses)
- Photon-jet qualitatively agree with this picture

[ATLAS, talk Etzion]
The standard mechanism:
Medium-induced gluon radiation

A highly energetic quark or gluon traversing a medium can:

A. Rotate color
B. Change direction (kicks in transverse plane)
C. Lose energy by collisions

Asymptotically A >> B >> C

- Radiation dominates energy loss
- Jet parton shower modified: broadening
Medium-induced radiation: role of color coherence

**Medium-induced radiation off a single quark/gluon (dense medium)**

\[
R_q \approx 4\omega \int_0^L dt \int \frac{d^2 k'}{(2\pi)^2} \sin \left( \frac{k'^2}{2\sqrt{q}\omega} \right) \exp \left( -\frac{k'^2}{2\sqrt{q}\omega} \right) P(k-k', L-t)
\]

[Mehtar-Tani, Salgado, Tywoniuk 2012]

**Quantum emission during decoherence time**

\[
\tau_f = \sqrt{\frac{\omega}{q}}
\]

**Medium length vs formation time**

- Radiation suppressed for \( t_{\text{form}} > L \) (LPM suppression)
- Spectrum IR and collinear finite
- Complete parton shower still unknown

[Baier-Dokshitzer-Mueller Peigne-Schiff, Zakharov and many others...]

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Medium-induced radiation: role of color coherence

Subsequent emissions: the antenna as a laboratory

Color coherence of qqbar pair survival probability (no color rotation)

\[ \Delta_{\text{med}} = 1 - \exp \left\{ -\frac{1}{12} \hat{q} \theta_{q\bar{q}}^2 t^3 \right\} \]

Defines time above which emitters are color decorrelated \( \tau_d \sim \left( \frac{1}{\hat{q} \theta_{q\bar{q}}^2} \right)^{1/3} \)

**Total decoherence when** \( L > \tau_d \)

- Enhances phase space for radiation (antiangular ordering)
- Total decoherence: two independent emitters

Angular ordering in vacuum

Anti-angular ordering in the medium
More theoretical developments, mostly work in progress

**Color rotation with the medium changes jet color flow**

[Beraudo, Milhano, Wiedemann 2012]

Role of finite kinematics studied in MCs

- Jewell, Q-Pythia, Martini, YAJEM, Pyquen, etc... Big effort in developing a MC for jet quenching

First (very preliminary!) comp. of qhat in lattice [Majumder]

Strongly-coupled vs. quasiparticle [D’Eramo, Lekaveckas, Liu, Rajagopal]

\[ \mathcal{P}(k_\perp) \sim \exp \left( -\# \frac{k_\perp^2}{T^3 L} \right) \rightarrow \mathcal{P}(k_\perp) \sim \frac{1}{k_\perp^2} \]
Proton-nucleus at the LHC

LHC two-in-one magnet

- Equal rigidity :: $p_{\text{Pb}} = Z p_{\text{proton}}$

Estimated parameters for the 2012/2013 pPb run

- Center of mass energy 5 TeV/A
- Integrated luminosity $\sim 25$ nb$^{-1}$
- Luminosity still very uncertain

Physics goals

- Benchmarking: hard probes, Initial conditions, nuclear PDFs
- Study small-x region of the phase space (best experimental option before an eventual electron-ion collider) [talk P. Newman]
Summary

With LHC new era also for nuclear collisions: TeV’s

- Access to the small-x and large virtualities jets, EW bosons, HQ ...
- New theoretical tools (evolution equations, in-medium jet evolution)
- New RHIC data important for the complete picture

Created medium (RHIC+LHC) very dense ideal fluid

- Very small viscosity - difficult to reconcile with weak-coupling
- Very large energy loss
- Jet measurements to characterize the medium parameters
- Knowledge on initial conditions essential: next pPb run

Is it a liquid? Strongly coupled? Are quasiparticles the relevant d.o.f.? Mechanism of thermalization?