Heavy Ion Theory
(addressed in the above facilities)

Néstor Armesto
Departamento de Física de Partículas and IGFAE
Universidade de Santiago de Compostela
nestor.armesto@usc.es
Status of Heavy Ions:

- **HI programme**: QCD at extreme conditions of $T$ & $\rho$.
- **Current status**: matter created at RHIC and the LHC, with energy densities $> \text{those expected in lattice QCD for deconfinement}/\chi\text{SBR}$,

1) Shows collective features in the soft sector that are well described by relativistic hydrodynamics if applied very early ($\lesssim 1$ fm/c) after the collision, suggesting $\approx$ equilibration.

2) Is very opaque to energetic partons/particles traversing it: strong modification of the yield of hard probes like high-$p_T$ particles, jets, quarkonia.

Open questions:

Why is the medium describable by hydrodynamics (so early) even in small systems (that show QGP-like features)?

[emergence]
Open questions:

1701.07145, proton as 3 hot spots

FIG. 2. Elliptic ($v_2$), triangular ($v_3$) and quadrupolar ($v_4$) flow coefficients from superSONIC simulations (bands) compared to experimental data from ATLAS, CMS and ALICE (symbols) for p+p (left panel), p+Pb (center panel) and Pb+Pb (right panel) collisions at $\sqrt{s} = 5.02$ TeV [58–62]. Simulation parameters used were $\Delta = 0.08$ and $\delta = 0.01$ for all systems. Note that ATLAS results for $v_2, v_4$ are only available for $\sqrt{s} = 13$ TeV, while all simulation results are for $\sqrt{s} = 5.02$ TeV.
Open questions:

- How does it get \(\approx\) isotropised? Weak or strong coupling dynamics?
- How to reduce the uncertainty in the extraction of QCD medium parameters?
  - Initial conditions for collective behaviour (nuclear wave function, transverse hadron structure, factorisation - if any - to compute initial parton production,…).
  - Modification of perturbative processes in a medium versus medium response for hard probes.

1701.07145, proton as 3 hot spots

FIG. 2. Elliptic \(v_2\), triangular \(v_3\) and quadrupolar \(v_4\) flow coefficients from superSONIC simulations (bands) compared to experimental data from ATLAS, CMS and ALICE (symbols) for p+p (left panel), p+Pb (center panel) and Pb+Pb (right panel) collisions at \(\sqrt{s} = 5.02\) TeV [58–62]. Simulation parameters used were \(\Delta = 0.08\) and \(\beta = 0.01\) for all systems. Note that ATLAS results for \(v_3, v_4\) are only available for \(\sqrt{s} = 13\) TeV, while all simulation results are for \(\sqrt{s} = 5.02\) TeV.
Future apart from eA:

- **RHIC:** RHIC-II, Beam Energy Scan: 10 times statistics, improved vertex and calorimetry, sPHENIX.
Future apart from eA:

- **RHIC**: RHIC-II, Beam Energy Scan: 10 times statistics, improved vertex and calorimetry, sPHENIX.

  J. Jowett in Chamonix 2017

- **LHC 2018 and Run 3 and 4 (HL-LHC for ions)**, 10 nb$^{-1}$ integrated luminosity in PbPb per experiment (ALICE, ATLAS, CMS), discussions about how many pp and pPb runs, smaller ions, fixed target program (LHCb, ALICE, AFTER).

Future apart from eA:

- **RHIC**: RHIC-II, Beam Energy Scan: 10 times statistics, improved vertex and calorimetry, sPHENIX.

- **LHC 2018 and Run 3 and 4 (HL-LHC for ions)**, 10 nb\(^{-1}\) integrated luminosity in PbPb per experiment (ALICE, ATLAS, CMS), discussions about how many pp and pPb runs, smaller ions, fixed target program (LHCb, ALICE, AFTER).

- **Studies of AA @ HE-LHC & FCC** (1605.01389).

---

**LHC heavy-ion runs, past & approved future**

LHC will have done 12 ~ one month heavy ion runs between 2010 and 2030 (LS4). 5/12 done already.

<table>
<thead>
<tr>
<th>Year</th>
<th>Species</th>
<th>Goals</th>
</tr>
</thead>
<tbody>
<tr>
<td>2019</td>
<td>Au+Au</td>
<td>High-statistics Beam Energy Scan; Search for QCD Critical Point</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Collider mode: (a_s = 11.5, 14.5, 19.6) GeV</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fixed target: 3.0, 3.5, 3.9, 4.5, 5.2, 6.2, 7.7 GeV</td>
</tr>
<tr>
<td>2020</td>
<td>Au+Au</td>
<td>High-statistics Beam Energy Scan; Search for QCD Critical Point</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Collider mode: (a_s = 7.7, 9.1) GeV</td>
</tr>
<tr>
<td>2021</td>
<td>Au+Au</td>
<td>Completion of high-statistics beam energy scan?</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Forward measurements in p+p and p+Au?</td>
</tr>
<tr>
<td>2022</td>
<td></td>
<td>No run sPHENIX installation</td>
</tr>
<tr>
<td>2023</td>
<td>Au+Au</td>
<td>sPHENIX Commissioning</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Single jet, di-jet, photon-tagged jet, b-tagged jet spectra</td>
</tr>
<tr>
<td></td>
<td>p+p</td>
<td>Di-jet asymmetry, Upolation spectra</td>
</tr>
<tr>
<td></td>
<td>p+Au</td>
<td>Reference data for modification of jets, di-jets, b-tagged jets</td>
</tr>
<tr>
<td></td>
<td>p+p</td>
<td>Reference data for cold nuclear matter effects</td>
</tr>
<tr>
<td>2024</td>
<td>p+p</td>
<td>Direct photon measurement</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Study of flavor dependence of jet observables</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Modification of jet fragmentation functions, jet splitting functions, other complex jet observables</td>
</tr>
</tbody>
</table>

---

**J. Jowett in Chamonix 2017**

**Studies of AA @ HE-LHC & FCC (1605.01389).**
Future apart from eA:

- RHIC: RHIC-II, Beam Energy Scan: 10 times statistics, improved vertex and calorimetry, sPHENIX.

- LHC 2018 and Run 3 and 4 (HL-LHC for ions), 10 nb⁻¹ integrated luminosity in PbPb per experiment (ALICE, ATLAS, CMS), discussions about how many pp and pPb runs, smaller ions, fixed target program (LHCb, ALICE, AFTER).

- Studies of AA @ HE-LHC & FCC (1605.01389).

- Present pPb / UPC data do not have a large impact (e.g. on nPDFs in EPPS16; uncertainties?), discussions undergoing (LHCb, ALICE FoCal): forward γ, jets and correlations / jets and exclusive VMs.
What eA can contribute:

Gluons from saturated nuclei $\rightarrow$ Glasma? $\rightarrow$ QGP $\rightarrow$ Reconfinement
What eA can contribute:

- Nucleus ≠ Zp+(A-Z)n.
- Particle production at large scales similar to pp (dilute regime).

Gluons from saturated nuclei → Glasma? → QGP → Reconfinement
What eA can contribute:

- Nucleus \( \neq \mathbb{Z}_p^+(A-Z)n \).
- Particle production at large scales similar to pp (dilute regime).
- Lack of information about small-\( x \) partons, correlations and transverse structure.
- We do not understand the dense regime.
What eA can contribute:

- Nucleus ≠ Zp+(A-Z)n.
- Particle production at large scales similar to pp (dilute regime).
- Lack of information about small-x partons, correlations and transverse structure.
- We do not understand the dense regime.

Gluons from saturated nuclei → Glasma? → QGP → Reconfinement

→ ep and eA: nuclear WF and mechanism of particle production.

What eA can contribute:

- Nucleus $\neq \text{Zp}+(A-Z)n.$
- Particle production at large scales similar to pp (dilute regime).

- Medium behaves very early like a low viscosity liquid: macroscopic description.

- Lack of information about small-x partons, correlations and transverse structure.
- We do not understand the dense regime.

- How isotropised the system becomes?
- Why is hydro effective so fast, which dynamics?

- ep and eA: initial conditions; how small can a system become and still show ‘collectivity’?

What eA can contribute:

- Nucleus ≠ Zp+(A-Z)n.
- Particle production at large scales similar to pp (dilute regime).

- Medium behaves very early like a low viscosity liquid: macroscopic description.
- Medium is very opaque to colour.

- Lack of information about small-x partons, correlations and transverse structure.
- We do not understand the dense regime.

- How isotropised the system becomes?
- Why is hydro effective so fast, which dynamics?

- What are the dynamical mechanisms for such opacity? Weak or strong coupling?
- How to extract accurately medium parameters?

- ep and eA: in-medium QCD radiation, cold nuclear effects on hard probes.

- ep and eA: initial conditions; how small can a system become and still show ‘collectivity’?

Gluons from saturated nuclei → Glasma? → QGP → Reconfinement

→ ep and eA: nuclear WF and mechanism of particle production.
What we need:

- We need ep and eA:
  - To unravel linear/non-linear dynamics at small x (ep).
  - To establish genuine nuclear effects, p as reference.
  - To disentangle density (saturation?) from energy (linear resummation?) effects.
What we need:

● We need ep and eA:
  ➔ To unravel linear/non-linear dynamics at small x (ep).
  ➔ To establish genuine nuclear effects, p as reference.
  ➔ To disentangle density (saturation?) from energy (linear resummation?) effects.

● We need energy:
  ➔ To determine the partonic structure (nPDFs, transverse profiles) and the validity of factorisation for hh/AA.
  ➔ To completely unfold nuclear structure as in the proton (Pb/Au PDFs, not ratios): NC+CC, heavy flavours,…
  ➔ To have lever arm in $Q^2$ at low x.
  ➔ To explore rarer hard probes (jets, W/ Z, tops @ HL/HE-LHC, H @ FCC).
What we need:

- **We need ep and eA:**
  - To unravel linear/non-linear dynamics at small $x$ (ep).
  - To establish genuine nuclear effects, $p$ as reference.
  - To disentangle density (saturation?) from energy (linear resummation?) effects.

- **We need energy:**
  - To determine the partonic structure (nPDFs, transverse profiles) and the validity of factorisation for $hh/AA$.
  - To completely unfold nuclear structure as in the proton (Pb/Au PDFs, not ratios): NC+CC, heavy flavours,…
  - To have lever arm in $Q^2$ at low $x$.
  - To explore rarer hard probes (jets, $W/Z$, tops @ HL/HE-LHC, $H$ @ FCC).
What we need:

- **We need ep and eA:**
  - To unravel linear/non-linear dynamics at small x (ep).
  - To establish genuine nuclear effects, p as reference.
  - To disentangle density (saturation?) from energy (linear resummation?) effects.

- **We need energy:**
  - To determine the partonic structure (nPDFs, transverse profiles) and the validity of factorisation for hh/AA.
  - To completely unfold nuclear structure as in the proton (Pb/Au PDFs, not ratios): NC+CC, heavy flavours,…
  - To have lever arm in $Q^2$ at low x.
  - To explore rarer hard probes (jets, W/Z, tops @ HL/HE-LHC, H @ FCC).
What we need:

- **We need ep and eA:**
  - To unravel linear/non-linear dynamics at small x (ep).
  - To establish genuine nuclear effects, p as reference.
  - To disentangle density (saturation?) from energy (linear resummation?) effects.

- **We need energy:**
  - To determine the partonic structure (nPDFs, transverse profiles) and the validity of factorisation for hh/AA.
  - To completely unfold nuclear structure as in the proton (Pb/Au PDFs, not ratios): NC+CC, heavy flavours,…
  - To have lever arm in $Q^2$ at low x.
  - To explore rarer hard probes (jets, W/Z, tops @ HL/HE-LHC, H @ FCC).
Summary:

- Some open problems in high-energy heavy ion physics: transition from microscopic dynamics to macroscopic behaviour, collectivity in small systems, determination of medium parameters,…
Summary:

- Some open problems in high-energy heavy ion physics: transition from microscopic dynamics to macroscopic behaviour, collectivity in small systems, determination of medium parameters,…

- ep/eA will provide key information:
  - Initial conditions for collective behaviour.
  - The small systems puzzle.
  - nPDFs and other cold nuclear matter effects for hard probes.
  - …
Summary:

- Some open problems in high-energy heavy ion physics: transition from microscopic dynamics to macroscopic behaviour, collectivity in small systems, determination of medium parameters,…

- ep/eA will provide key information:
  - Initial conditions for collective behaviour.
  - The small systems puzzle.
  - nPDFs and other cold nuclear matter effects for hard probes.
  - …

- We need:
  - ep and eA.
  - The largest possible lever arm in energy for present and future hh/AA colliders, and for exploring new regimes of QCD.
  - An EIC (several A’s, overlap with FT, precision, versatility) and the LHeC/FCC-eh (large $\sqrt{s_{NN}}$, access to small $x$ and large $Q^2$).
  - They are complementary, also to pA/UPC at hadron colliders.