Heavy-Ion Physics at the LHC

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Why relativistic heavy-ion collisions?

- QCD studies at low $Q$, finite temperature $T$ and baryon chemical potential $\mu_B$
- Deconfinement (+ chiral symmetry restoration): hadron gas $\rightarrow$ Quark-Gluon Plasma
  - Smooth cross-over at small $\mu_B$
  - Critical temperature from Lattice QCD: $T_c \sim 156$ MeV
Why relativistic heavy-ion collisions?

- Critical point and first order phase transition at large $\mu_B$: main physics target for several collaborations (STAR-BES, NA61, CBM, MPD)
- Color superconducting phases (low $T$, very high $\mu_B$): neutron stars
Astrophysics and heavy-ion collisions


- Neutron stars mass controlled by the equation of state (EoS) of nuclear matter
  - “Canonical” mass: $1.4 \, M_{\text{sun}}$
  - How can the outliers exist?
    - Stiffer EoS at larger nuclear densities (hyperon matter? QGP cores?)
- Neutron star mergers
  - EoS an important parameter
Cosmology and relativistic heavy-ion collisions

ALICE Collaboration, PLB754 (2016) 235

Direct photon production

Cosmic microwave background seen by Planck

$T_{\text{CMB}} = 2.7 \text{ K} \ (\sim 2 \times 10^{-4} \text{ eV})$

$T_{\text{QGP}} = 3500000000000 \text{ K} \ (3 \times 10^8 \text{ eV})$

- Access early Universe conditions ($10^{-5} \text{ s}$):
  - QGP temperature in Pb-Pb collisions from direct photon measurements:
    $T \sim 300 \text{ MeV}$
"Standard Model" of high-energy nuclear collisions

We measure only at the latest stages but we want to understand the hard partonic and the QGP stages... extremely challenging!

- Initial state
- Hard partonic collisions
- QGP
- Chemical freeze-out
- Kinetic freeze-out

<table>
<thead>
<tr>
<th>Stage</th>
<th>Time (fm/c)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial state</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.01-1</td>
<td>10^{-26}-10^{-24}</td>
<td>0.01-1 and Modified gluon PDF (saturation, shadowing), Fermi motion, ...</td>
</tr>
<tr>
<td>Hard partonic collisions</td>
<td>1-10</td>
<td>10^{-24}-10^{-23} Gluon and quark-pair creation</td>
</tr>
<tr>
<td>QGP</td>
<td>~10^{-23}</td>
<td>1-10 Deconfined nuclear matter expanding hydrodynamically</td>
</tr>
<tr>
<td>Chemical freeze-out</td>
<td>~10</td>
<td>~10 Inelastic collisions cease; hadronization</td>
</tr>
<tr>
<td>Kinetic freeze-out</td>
<td>10^{-22}-10^{-23}</td>
<td>10-100 Elastic collisions cease; free streaming particles</td>
</tr>
</tbody>
</table>

I. Arsene, ICPPA 2018, Moscow
LHC experiments

I. Arsene, ICPPA 2018, Moscow
Bulk (soft) observables
Charged particle production

- Power law increase of produced multiplicity per participant pair with collision energy
- Stronger increase in AA than in pp collisions!

- Charged multiplicity per participant pair grows from peripheral towards central collisions
- Larger number of binary collisions $\rightarrow$ more entropy production

I. Arsene, ICPPA 2018, Moscow
Identified particle production

- Screenshot of the fireball at the chemical freeze-out
- Particle yields described by thermodynamics over 7 orders of magnitude with just 3 parameters: volume, temperature and $\mu_B$
- Chemical freeze-out temperature: $\sim 153 +/- 2$ MeV (similar to Lattice QCD calculations)
Strangeness production

- Characteristic of QGP formation
  - Rafelski and Mueller 1982

- Universal dependence of strangeness production as a function of event multiplicity independent on collision system (pp, p-Pb and Pb-Pb collisions)

- Strangeness enhancement saturation in central Pb-Pb collisions (grand-canonical regime)
Anisotropic flow

- Initial geometry of the collision is non-uniform (almond shaped)
- Large initial energy density gradients
- Multiple rescatterings in the system

- Sensitive to initial state and key QGP properties like the equation of state, viscosity, transport coefficients

Fourier decomposition:
\[
\frac{dN}{d\phi} \approx 1 + 2 \sum_n v_n \cos[n(\phi - \Psi_n)]
\]
Elliptic (v2) and triangular (v3) flow

- **2\(^{nd}\) harmonic**: dominant; exhibits a maximum at mid-central collisions
- **3\(^{rd}\) harmonic**: less sensitive on centrality → mainly related to initial state energy density fluctuations

**ALICE, arxiv:1805.01832**
Elliptic flow ($v_2$) measurements available for all colliding systems

Challenge to understand results in small systems $\rightarrow$ collective effects in small systems?
Identified particles $v_2$

- **Low-$p_T$**: mass ordering $v_2(\pi) > v_2(K) > v_2(p, \varphi, \Lambda)$ → strong collective radial flow
- **High-$p_T$**: splitting in meson and baryon branches → hadronization via quark coalescence
Hard and electro-magnetic probes
High-$p_T$ hadron suppression

- High-$p_T$ hadrons are suppressed even at 100 GeV/c
- Strong energy loss in the QGP medium
- Important measurement for the extraction of transport properties: $\hat{q}$
Jet suppression in nuclear collisions

ATLAS, arXiv:1805.05635

- Strong centrality dependence → quenching grows with the energy density of the medium
- Jets still suppressed even at ~1 TeV
Photon tagged jets

- Photon-tagging: well calibrated initial energy
- Direct measure of energy loss $\Delta E$ of the recoil jet
- Energy imbalance grows towards central collisions
Flavour dependence of energy loss

- Low $p_T$: mass hierarchy
  \[ R_{AA}(b) < R_{AA}(c) < R_{AA}(u,d,s) \]
- High $p_T$: flavor independence of energy loss
Heavy strange mesons

- First $\Lambda_c$ measurement in Pb-Pb!
- Charmed baryons less suppressed than mesons

- First $B_s^0$ measurement in Pb-Pb!
- Hint of enhancement of $B_s^0$ wrt $B^+$
Elliptic flow of D mesons

CMS, PRL 120(2018)202301

ALICE PRL 120 (2018) 102301

• Significant elliptic flow $v_2$ of charm at the LHC
• Stronger in semi-central collisions
• Does charm take part in the collective motion?
Event shape engineering and D-meson elliptic flow

- Event shape engineering technique
- D-meson elliptic flow correlated with the overall hydrodynamic flow of the bulk charged particles
**J/ψ suppression**

- Striking observation in central collisions: J/ψ less suppressed at LHC wrt RHIC

![Graph showing the suppression of J/ψ in central collisions]
- Striking observation in central collisions: J/ψ less suppressed at LHC wrt RHIC
- Low-$p_T$: less suppression at LHC wrt RHIC
  - New mechanism of charmonium production $\rightarrow$ in-medium $c\bar{c}$ recombination

**J/ψ suppression**

ALICE, PLB 734 (2014) 314  
ALICE, PLB 766 (2017) 212  
PHENIX, PRC 84 (2011) 054912
**J/ψ suppression**

**Striking observation in central collisions:** $J/ψ$ less suppressed at LHC wrt RHIC

**Low-$p_T$:** less suppression at LHC wrt RHIC

- New mechanism of charmonium production → in-medium $c\bar{c}$ recombination

**High-$p_T$:** strong centrality dependent $J/ψ$ suppression
Bottomonia and high-\(p_T\) charmonia

Increasing suppression towards more central collisions

Sequential suppression:

\[ R_{AA} \{ \Upsilon(1S) \} > R_{AA} \{ \Upsilon(2S) \} > R_{AA} \{ \Upsilon(3S) \} \]

\[ R_{AA} \{ \mathrm{J}/\psi \} > R_{AA} \{ \psi(2S) \} \] (NB: Only at high \(p_T\))

Transport model calculations in agreement with data
**J/ψ photo-production in Pb-Pb collisions with b<2R**

- J/ψ excess observed at very low-\(p_T\) in peripheral Pb-Pb collisions
  - Likely origin: coherent photo-production

- Challenge for theoretical models
  - Sensitivity to nuclear gluon PDFs
  - Probe of QGP?
Direct photons sensitive to the entire history of the collision
Strong measured elliptic not described by models: puzzle!
Top-quark production in p-Pb collisions

First observation of the top quark in nuclear collisions
Light-by-light scattering

ATLAS, Nature Physics 13 (2017) 9, 852-858

- Forbidden by classical electro-dynamics
- Natural consequence of QED
- First direct observation of this process
- $>4 \sigma$ significance
- Cross-section consistent with Standard Model
Photo-produced di-muons in Pb-Pb collisions

- \( \mu^+\mu^- \) pairs balanced in energy and small acoplanarity
- Origin from photo-nuclear interactions
- Acoplanarity broadens towards central collisions
- Muons scatter off electric charges in the plasma

\[
\alpha = 1 - \left| \varphi^+ - \varphi^- \right| \div \pi
\]
Summary

- A wealth of results from heavy-ion physics at the LHC
- Many first time observations of various processes in heavy-ion collisions
- LHC prepares for a new Pb-Pb run (November 2018) bringing a boost in statistics

- LHC talks in the parallel sessions:
  - **Jakub Kremer**, Quarkonia and open heavy flavour with ATLAS *(Thursday 16:30)*
  - **Piotr Janus**, Electroweak bosons with ATLAS *(Thursday 16:50)*
  - **Arkadiy Taranenko**, Anisotropic flow from LHC to SIS *(Thursday 17:10)*
  - **Victor Riabov**, Light flavors with ALICE *(Friday 10:00)*
  - **Roman Lavicka**, J/ψ photo-production in UPC with ALICE *(Friday 10:20)*
  - **Dimitri Peresounko**, Direct photons with ALICE *(Friday 10:35)*
Relativistic heavy-ion collisions

- QCD studies (low-\(Q\), finite \(T\) and \(\mu\))
  - Phase diagram of nuclear matter:
    - deconfinement phase transition
    - Lattice QCD calculations conclude transition is cross-over type
  - “Critical” temperature: \(T_c \approx 155-160\) MeV

Collision centrality

- Centrality determination in ALICE, using the charged particle measurement at forward rapidity (VZERO)
- Multiplicity distribution fitted well by an optical Glauber model which allows the determination of $<N_{\text{part}}>$ and $<N_{\text{coll}}>$ for each centrality interval

ALICE Collaboration, PRC88 (2013) 4, 044909
The nuclear modification factor

\[ R_{AA} = \frac{1}{N_{\text{coll}}} \times \frac{Y_{AA}}{Y_{pp}} \]

- \( N_{\text{coll}} \): the number of binary nucleon-nucleon collisions
- \( Y_{AA} \): yield in AA collisions
- \( Y_{pp} \): yield in pp collisions

- Superposition of NN collisions → \( R_{AA} = 1 \)
- Suppression → \( R_{AA} < 1 \)
- Enhancement → \( R_{AA} > 1 \)
- Weakly interacting particles are not affected by the QGP
  - Photons, \( W^{\pm} \) and \( Z^{0} \) bosons \( R_{AA} \) are compatible with 1

\( N_{\text{ch}} \) p-Pb: ALICE PRL110(2013)082302
\( N_{\text{ch}} \) Pb-Pb: ALICE, Phys.Lett.B720 (2013)52
\( N_{\text{ch}} \) Pb-Pb: CMS, EPJC (2012) 72
\( \gamma \): CMS, PLB 710 (2012) 256
\( W^{\pm} \), CMS, PLB715 (2012) 66
\( Z^{0} \), CMS, PRL106 (2011) 212301