Physics with heavy ion collisions at LHC beyond Run-2

Andrea Dainese
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Outline

- Timeline of future HI running
- HI physics programme beyond Run-2
- Experiment upgrades and strategies
- Selected performance studies
- Besides Pb-Pb: pA, pp reference, light ions
- Summary
Timeline of HI running at the LHC

- **Run 2:**
  - Pb-Pb: few/nb (0.7/nb in 2015, ~1/nb in 2018), at $\sqrt{s_{NN}} = 5$ TeV
  - p-Pb at 5 and 8 TeV (in 2016)
  - pp reference at Pb-Pb energy (5 TeV, Nov 2017)

- **LS2:**
  - LHC injector upgrades; bunch spacing reduced to 50 ns (possibly 25); Pb-Pb interaction rate up to 50 kHz (now <10 kHz)
  - Experiments upgrades (LS2 and LS3)

- **Runs 3+4:**
  - Experiments request for **Pb-Pb: >10/nb** (ALICE: 10/nb at 0.5T + 3/nb at 0.2T)
  - In line with projections by machine group (Chamonix 2017): 3.1/nb/month
**Jets**: characterization of energy loss mechanism both as a testing ground for the multi-particle aspects of QCD and as a probe of medium density &dofs

- Differential studies of jets, b-jets, di-jets, γ/Z-jet at very high $p_T$
- (Flavour-dependent) in-medium fragmentation functions and jet structure observables
HL-LHC Programme (AA)\(^{(\text{not exhaustively})}\)

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Quarkonium: precision study of quarkonium dissociation pattern and regeneration, as probes of deconfinement and of the medium temperature
  - Low-$p_T$ charmonia ($J/\psi$ and $\psi(2S)$) and their elliptic flow
  - Multi-differential studies of $\Upsilon$ states
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- Yield and flow harmonics of (anti-)nuclei and hypernuclei
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Detector upgrades most relevant to HI

- **ALICE (LS2)**
  - New inner tracker: precision and efficiency at low $p_T$
  - New pixel forward muon tracker: precise tracking and vertexing for $\mu$
  - New TPC readout chambers, upgraded readout for other detectors and new integrated Online-Offline: x50 faster readout (up to 50 kHz for Pb-Pb)

- **ATLAS (LS2/LS3)**
  - Completely new tracker (LS3): tracking and b-tag
  - Fast tracking trigger (LS2): high-multiplicity tracking
  - Calorimeter and muon upgrades (LS2): electron, $\gamma$, muon triggers

- **CMS (mainly LS3)**
  - Completely new tracker (LS3): tracking and b-tag up to $\eta=4$
  - Extension of forward muon system (LS2): muon acceptance
  - Upgrade forward calorimeter (LS3): forward jets in HI

- **LHCb (LS2)**
  - New vertexing and tracking detectors: full-rate readout in Pb-Pb; track reconstruction being verified
  - Fixed-target programme with SMOG + possible extensions
ALICE (and LHCb) trigger/readout

- Main focus on “untriggerable” signals (extremely low S/B)
- Trigger approach: write all events at 50 kHz in Pb-Pb
  - e.g. ALICE: ~1.1 TB/s \( \text{O}^2 \text{ facility} \) ~90 GB/s (50 kHz)
  - increase of minimum-bias sample \( x_{50-100} \) wrt Run-2

ATLAS and CMS trigger/readout

- Main focus on muon, jet, displaced track triggers
- Trigger approach: strong event number reduction
  - e.g. CMS: 50 kHz L1 ~ few kHz HLT ~ 100 Hz
  - increase of (rare-trigger) sample \( x_{10} \) wrt Run-2
Timeline of future HI running

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- Low-\( p_T \) charmonia (\( J/\psi \) and \( \psi(2S) \)) and their elliptic flow
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**Low-mass di-leptons:** thermal radiation to map time-dep. of temperature; modification of \( \rho \) spectral function and chiral symmetry restoration at \( \mu_B = 0 \)

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**“Light” nuclear states:** production mechanisms of multi-baryon bound states (recombination? coalescence?); search for exotic states with hyperons

- Yield and flow harmonics of (anti-)nuclei and hypernuclei
Jet quenching: (some) future directions

- Increased luminosity and detector upgrades enable:
  - Increased precision
  - More exclusive and theoretically well-defined final states
- High precision $\gamma$-jet, Z-jet, di-jet correlations, also with b-jets (quark tag)

E.g.: b-tagged di-jets $\rightarrow$ select quark-quark state and compare with g-g
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E.g.: $Z$-jet $\rightarrow$ “select” initial jet energy

Run-2 2015 (0.4/nb)

- $p_T^Z > 100$, $p_T^{\text{jet}} > 25$ GeV, $\Delta\varphi > 7\pi/8$
  - 3/nb
  - 1.5/nb
  - 150/µb

CMS, arXiv:1702.01060

E.g.: CMS

CMS Projection

ATLAS MC

HL-LHC (10/nb)

CMS, PAS-FTR-13-025
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$\mathbf{3/nb}$

$\mathbf{1.5/nb}$

$\mathbf{150/\mu b}$

ATLAS MC

Q: can this become one of the main ways to search for jet quenching in high-mult $pp$ or $p-Pb$? how much $L_{int}$?
Jet quenching: (some) future directions

- Increased luminosity and detector upgrades enable:
  - Increased precision
  - More exclusive and theoretically well-defined final states
- Fragmentation functions (FF) and substructure measurements for jets with leading (identified) light and heavy flavour hadrons

E.g.: D-in-jet FF → select quark jet and study flavour-dependence of FF modification
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Heavy flavour $R_{AA}$ after LS2

Present data (example)

$\Rightarrow$ Large uncertainties for D $p_T \to 0$ and no measurement for B $p_T \to 0$

Upgrade: Charm and beauty $R_{AA}$ down to $p_T \sim 0$ using $D^0$ and B-decay $J/\psi$

ALICE, CERN-LHCC-2013-024
Heavy flavour $R_{AA}$ after LS2

Present data (example)

Upgrade: Charm and beauty $R_{AA}$ down to $p_T \sim 0$ using $D^0$ and $B$-decay $J/\psi$

Q: how can we disentangle different E-loss dependencies and different radial flow effects for $\pi$, $D$ and $B$?
Heavy flavour $v_2$ after LS2

Present data (example)

Upgrade: Charm and beauty $v_2$ down to $p_T \sim 0$ using prompt and B-decay $D^0$

→ Need it also for beauty, which can be calculated more accurately in lattice QCD

ALICE, CERN-LHCC-2013-024

+ $v_3$, ESE ($\rightarrow v_2^D$ vs $v_2^\pi$), new studies being done
**In-medium heavy-flavour hadronization?**

- From RHIC and LHC data, some hints that charm *could* recombine in the medium (J/ψ regeneration, D meson flow, $D_s$, $R_{AA}$ in ALICE, $Λ_c/D$ in STAR)
- Precise measurements of HF mesons (non-strange and strange) and baryons

**Example: charm recombination**

- enhancement of $Λ_c/D$ (also $D_s/D^{0,+}$ and $Λ_b/B$)

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Plumari et al. SQM2017
HF “hadrochemistry” after LS2

◆ ALICE inner tracker upgrade and x100 min.bias Pb-Pb sample
  - $\Lambda_c$ and $D_s$ ($c\tau=60$ and $150\,\mu$m) will be measured with good precision for $p_T>2\,\text{GeV/c}$
  - $\Lambda_b$ ($c\tau=450\,\mu$m) accessible for $p_T>7\,\text{GeV/c}$

D$^0$ and D$^0$ $R_{AA}$

$\Lambda_c/D$ “enhancement”

$\Lambda_b$ significance

ALICE, CERN-LHCC-2013-024
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- **Q:** if recombination is at play, which observables are more informative on its dynamics?
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**J/ψ v₂: Run-2 vs. Upgrade**

- Is J/ψ v₂ consistent with that of D mesons in a regeneration scenario?
- J/ψ v₂ with expected precision better than 0.005 (x3 better than in Run-2), also for *prompt* J/ψ (more direct comparison with models)

**Q: puzzle at high p_T? which other measurements could shed light?**
Low-$p_T$ charmonium: Run 1 vs. Upgrade

- Low-$p_T$ $\psi'/\psi$ could allow to discriminate between models of recombination (transport vs. statistical)

$$R_{AA}(\psi')/R_{AA}(\psi)$$

Run 2: limited precision for $R_{AA}(\psi')$

Upgrade: precision <10%

Q: is $\psi'$ too fragile to be informative about in-medium effects? (see $p$-$Pb$ high-mult)
Quarkonium suppression

- First hint of sequential pattern

- Sensitivity to $\eta/s$?

High statistics → precise multi-differential measurements. E.g. (CMS, 10/nb):

<table>
<thead>
<tr>
<th>$Y(1s)$</th>
<th>$Y(2s)$</th>
<th>$Y(3s)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>270k</td>
<td>40k</td>
<td>7k</td>
</tr>
</tbody>
</table>

+ ALICE&LHCb at forward rapidity

Q: is it still conceivable to extract “a” temperature from quarkonium data? Is it still the goal?
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Light multi-baryon bound states

- Abundant (hyper)nuclei and (strange) exotica
  - Dynamical coalescence vs. statistical thermal production (dynamics?)
  - Sensitivity to freeze-out temperature

- Discovery potential
  - (anti-)(hyper-)nuclei with $A = 4$ ($A = 5$?)
  - Discovery/exclusion for $\Lambda\Lambda$ and $\Lambda n$ dibaryon beyond currently set limit [PLB 752 (2016) 267]
  - Search for strange dibaryon $\Xi\Xi$, $\Omega\Omega$

- Precision
  - (improved) precision measurement of the $^3\Lambda H$ lifetime and spectrum
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Small systems: pp, p-Pb

- pp reference at 5.5 TeV required by all experiments
- p-Pb at high luminosity: explore partonic structure of high-energy nuclei → also to disentangle cold nuclear matter effects for the QGP studies
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Constrain high-$Q^2$ and high-$x$ nPDFs with W,Z, top production in p-Pb
Small systems: pp, p-Pb

- pp reference at 5.5 TeV required by all experiments
- p-Pb at high luminosity: explore partonic structure of high-energy nuclei → also to disentangle cold nuclear matter effects for the QGP studies

Constrain low-$Q^2$ and low-$x$ nPDFs and search for onset of saturation with charm, quarkonia, photons, di-hadrons at low $p_T$ and forward rapidity in p-Pb (+UPC)

**Forward direct $\gamma$ → ALICE FoCal?**

Forward D meson in LHCb

arXiv:1707.02750
Small systems – high multiplicity

- pp 14 TeV (and p-Pb 8 TeV)
  - Higher statistics for already covered multiplicity region → charm?
  - Extension to higher multiplicities
    - 5-6 x \( <N_{ch,pp} > \) with Run-2
    - 10 x \( <N_{ch,pp} > \) with Run-3 (~10 /pb)
    - 15 x \( <N_{ch,pp} > \) needs > 1/fb; out of reach?

Figure by J.F. Grosse-Oetringhaus

Small systems: looking for small signals

- Very large statistics at few $x < N_{ch}$ in pp and p-Pb, together with the upgraded detectors:
  - Precise measurements of “flow-like” effects for open HF and quarkonia

HF (decay lepton) $v_2$

J/ψ $v_2$

ALICE and ATLAS, Initial Stages 2017

ALICE, arXiv:1709.06807
Small systems: looking for small signals

- Very large statistics at few $x < N_{ch}$ in pp and p-Pb, together with the upgraded detectors:
  - Searches for two of the classical hot-medium signals in small systems, namely parton energy loss ($\gamma$-jet?) and thermal radiation.

![Graphs showing $R_{AA}^{\text{jet}}$ and $dN_{\text{ee}}/dM$ for p-Pb and Pb-Pb collisions.](Tywoniuk, NPA926(2014)85)

![Graphs showing CMS PbPb data (preliminary) and ALICE Preliminary results for p-Pb(5.02 TeV).](Tywoniuk, NPA926(2014)85)
Running with lighter ions at LHC?

- Lighter ions would allow to reach higher inst. luminosity than Pb-Pb
  - BFPP cross section drops with $Z^7$, EMD cross section with $Z^4$
  - Increase in lumi is larger than decrease in $N_{\text{coll}}$ (x0.5 from Pb-Pb to Xe-Xe) → higher yields for hard processes
  - No detailed machine studies yet, first estimates in this thesis
  - Nucleon-nucleon lumi ($L_{NN}=A^2 \times L_{AA}$) – hard yields scale with $L_{NN}$ –
    - $L_{NN}^{\text{XeXe (cons)}} \sim 1.5 \ L_{NN}^{\text{PbPb}}$; $L_{NN}^{\text{ArAr (cons)}} \sim 4.5 \ L_{NN}^{\text{PbPb}}$
- Physics?
  - Xe-Xe: similar QGP as Pb-Pb, but no large gain in yields?
  - Ar-Ar: lower size/density QGP
    - → smaller jet quenching signals
    - → interesting overlap in $N_{\text{ch}}$ with pp, p-Pb, Pb-Pb, but needed?
    - → additional constraints for quarkonium suppression vs. regeneration?
  - Pilot Xe-Xe run in two days will help to clarify the LHC performance and (partly) the physics motivation
Summary

- Beyond LS2: fully exploit the potential of the machine as a high-luminosity HI collider

- Rich **baseline** programme prepared by the experiments
  - Upgraded detectors, very large samples, diverse trigger approaches

- LHC findings in small systems / high-mult have opened many new questions that need luminosity and precision
  - Now it is the time to optimize the future programme to address these

HL-LHC Physics WS (Oct 30-Nov 1)

https://indico.cern.ch/event/647676/
EXTRA SLIDES
Available Documents

- ALICE Upgrade LOI: CERN-LHCC-2012-012
  - Addendum (Muon Forward Tracker): CERN-LHCC-2013-014
- ALICE inner tracker upgrade TDR: CERN-LHCC-2013-024
- ALICE muon tracker upgrade TDR: CERN-LHCC-2015-001
- Presentations at the Heavy Ion Town Meeting (June 2012):
  - http://indico.cern.ch/event/HItownmeeting
- Inputs by ALICE, ATLAS, CMS to the ESPG meeting Cracow (Sep 2012)
  - http://indico.cern.ch/confdId=182232
  - HI community presentation (H. Appelshaueueser): http://indico.cern.ch/getFile.py/access?contribId=16&sessionId=2&resId=0&materialId=slides&confdId=182232
Jet quenching: where are we?

- Some lessons from LHC data on jets:
  - Hadron and jet $R_{AA}$ (AA/pp) “suppressed” out to $p_T \sim 1$ TeV/c
  - First direct observation of energy loss via di-jet momentum balance
  - “Lost energy” goes to low $p_T$ particles at large angles (“out of cone”)
  - Moderate modification of fragm. functions and little/no mod. of jet shapes
  - Can tag parton energy and flavour: $\gamma/Z$-jet balance, $b$-jet tagging

- Lively theoretical development, first studies to extract QGP properties

**Di-jet imbalance**

**Transport coeff.** $\hat{q} \sim \sigma \cdot \rho$
Heavy flavour: where are we?

- Suppression of D mesons measured up to 100 GeV/c, similar to charged hadrons (pions) above 5 GeV/c
- First indication of mass dependence of energy loss: $R_{AA}^{J/\psi}$ from B > $R_{AA}^D$

→ Large uncertainties for D $p_T \rightarrow 0$ and no measurement for B $p_T \rightarrow 0$

Heavy flavour: where are we?

- D mesons have elliptic flow $\nu_2 > 0$
- QGP expansion transmitted to charm quarks via multiple scatterings (diffusion mechanism)

$u$ $D$ mesons have elliptic flow $\nu_2 > 0$
$QGP$ expansion transmitted to charm quarks via multiple scatterings (diffusion mechanism)

- Model calculations extract c-quark diffusion coefficient in the QGP: can be compared with first-principle QCD calculations on the lattice

$\rightarrow$ Need it also for beauty, which can be calculated more accurately in lattice QCD


Catania group, arXiv:1707.05452
Azimuthal anisotropy: collective flow

- System geometry asymmetric in non-central collisions
- Expansion under azimuth-dep. pressure gradient results in azimuth-dep. momentum distributions
- Measured by the elliptic flow parameter $v_2(p_T)$

\[
\frac{dN}{Nd\phi} \sim 1 + 2v_2 \cos \left(2(\phi - \Psi_{RP})\right) + \text{higher harmonics } (v_3, v_4, \ldots)
\]

- $v_2$ at low $p_T$ provides a measure of the strength of collectivity (mean free path of outgoing partons)
In-medium heavy-flavour hadronization?

- From LHC Run 1 data, some hints that charm could recombine in the medium
- Precise measurements of HF mesons (non-strange and strange) and baryons
- Precise measurements of their $\nu_2$ (+ that of $J/\psi$, discussed later)

$\Lambda_c/D$

- Rapp et al., based on PRL110 (2013)

$\Lambda_c/D$

- Greco et al. PRD90 (2014)

$\Lambda_c/D$ and $\Lambda_b/B$

- Ko et al. PRC79 (2008)
QGP temperature: where are we?

- Temperature from QGP radiation
  - Additional handle on temperature from quarkonium melting (not discussed today)

- First measurement at LHC from soft exponential component of photon $p_T$ spectrum: $T \approx 300$ MeV

An effective temperature, averaged over system evolution (and cooling)
Temperature evolution: low-mass di-leptons

- Measurement of low-mass di-leptons allows mapping the temperature during the system evolution.

Di-leptons from real and virtual photons $\gamma \rightarrow e^+e^-$

Complex measurement: need to disentangle all di-lepton sources.

0-10%

$dN_{ch}/d\eta = 1750$

$N_{coll} = 1625$
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Di-leptons from real and virtual photons $\gamma \rightarrow e^+e^-$

High masses $\rightarrow$ high $T$, early stage
Intermediate masses
Low masses $\rightarrow$ low $T$, late stage
Low-mass di-leptons after LS2

- **ALICE:** lighter tracker + **dedicated run at low B (0.2 T)**
  - electron acceptance down to $p_T = 50$ MeV/c
  - Needs minimum-bias trigger (low S/B)
  - **HL-LHC = 100x Run2 stat.**

Di-electron mass spectrum after bkg subtraction:

Run 1

Run 2 (MC)

Precision of ~10% on the inverse slope $\Rightarrow T$

ALICE, CERN-LHCC-2013-024
Study for a forward calorimeter in ALICE

- FoCal: R&D for a high-granularity calorimeter at $\eta \sim 3-5$ with focus on saturation physics studies
  - Possible installation during LS3
- Benchmark measurement: direct photons $\eta \sim 4-5$ in p-Pb ($x \sim 10^{-5}$)
  - Sensitive to Shadowing vs. Saturation

![Theoretical predictions chart](chart1.png)

**Projected performance**

- Direct Photons $\gamma = 4$
  - p+Pb $\sqrt{s} = 8.8$ TeV
- JETPHOX with EPS09 at NLO, $R_{\text{iso}} = 0.4$
- CGC (A. Rezaeian)
- Theoretical predictions

- ALICE simulation
  - $4.0 < \eta < 5.0$
- FoCal upgrade
- Statistical
- Systematic (PYTHIA)
- Systematic (JETPHOX)

- p-Pb, $L_{\text{int}} = 50$/nb